QST-P-8

International Workshop on Advanced Neutron Sources and its Applications (IWANS-1) Nov. 4 & 5

National Institutes for Quantum and Radiological Science and Technology

http://www.qst.go.jp

QST-P-8

Presentations at the International Workshop on Advanced Neutron Sources and its Applications (IWANS)

先進中性子源とその応用についての国際ワークショップ発表資料集

Nov. 4 & 5, 2017 (Received - January, 2019)

Rokkasho Fusion Institute
六ヶ所核融合研究所

国立研究開発法人 量子科学技術研究開発機構

National Institutes for
Quantum and Radiological Science and Technology

Presentations at the International Workshop on Advanced Neutron Sources and its Applications (IWANS)

National Institutes for Quantum and
Radiological Science and Technology (QST)

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Presentations at the International Workshop on Advanced Neutron Sources and its Applications (IWANS)

(Eds.) Shigeru O'HIRA, Kentaro OCHIAI

Rokkasho Fusion Institute, Fusion Energy Research and Development Directorate,

Rokkasho, Aomori

An International Workshop on Advanced Neutron Sources and its Applications (IWANS) was held on 4&5 November 2017 in Aomori city hosted by Rokkasho Fusion Institute of the National Institutes for Quantum and Radiological Science and Technology (QST). Advanced neutron sources are now being planned concurrently with fusion neutron irradiation on fusion reactor materials, like application for industrial and medical purposes, such as production of radio-isotope medicine, Boron Neutron Capture Treatment (BNCT) facilities, etc. This 1st worldwide workshop on the topic aimed to discuss about the required development and potential application of available advanced neutron sources concepts, to build up a global international forum for discussions on the common technological challenges among neutron sources. The present report has been complied the presentation files in this workshop.

Keywords: Fusion reactor materials, Advanced neutron source, BNCT, Radio-isotope production, Industrial application

QST-P-8

先進中性子源とその応用に関する国際ワークショップ発表資料集

量子科学技術研究開発機構 核融合エネルギー研究開発部門 六ヶ所核融合研究所

（編） 大平　茂、落合謙太郎

先端中性子源とその応用に関する国際ワークショップ（IWANS）は、2017 年 11 月 4 日と 5 日に六ヶ所核融合科学技術研究所（QST）の主催により青森市で開催された。先進中性子源は、核融合炉材料の核融合中性子照射と並行して放射性同位体医薬品の製造、BNCT（中性子補足セラピー）施設など、産業および医療目的の用途に計画されている。この最初の国際ワークショップでは、利用可能な最新の中性子源概念の必要な開発と潜在的な応用について議論し、中性子源開発における共通の技術課題に関する議論のための国際フォーラムを構築することを目的とした。本報告書は、このワークショップにおける発表資料を編集したものである。

六ヶ所核融合研究所 〒039-3212　青森県上北郡六ヶ所村大字尾駮字表舘２番地１６６

Contents

1. Introduction 1
2. Agenda 3
3. Presentations
3.1 Technical Session 1: Overview of neutron sources development
Users' perspective on neutron sources for materials development: T. Muroga (NIFS) 5
3.2 Technical Session 2-1: Presentations about the neutron sources developed or being developed
3.2.1 DONES: A. Ibarra (CIEMAT) 22
3.2.2 A-FNS: K. Ochiai (QST) 37
3.2.3 BISOL: Y. Wang (Peking Univ.) 45
3.2.4 Neutron sources for transmutation of long-lived fission products: H. Okuno (RIKEN) 74
3.3 Technical Session 2-2: Presentations about the neutron sources developed or being developed (cont.)
3.3.1 Neutron sources for transmutation applications (incl. MYRRHA): D. Terentiev, (SCK-CEN) 95
3.3.2 D-T neutron sources (including HINEG, SORGENTINA, etc): Y. Wu (FDS)............................119
3.3.3 Present status of neutron sources development: Y. Kiyanagi (Nagoya Univ.)............................ 136
3.4 Technical Session 3: Panel Discussion on development of High/Low power neutron sources
3.4.1Accelerator related issues
3.4.1-i) Comparison of a few schemes of RFQ-based compact neutron sources:
S. Kurokawa (KEK).. 156
3.4.1-ii) High power linacs: J. Knaster (IFMIF/EVEDA)... 169
3.4.2 Target-related issues
3.4.2-i) Design and technical challenges of Li target for IFMIF-based neutron sources:
D. Bernardi (ENEA) 181
3.4.2-ii) Target challenge for High power compact accelerator based neutron source;
as status of the iBNCT: T. Kurihara (iBNCT)... 191
3.4.2-iii) Present status of neutron target on J-Parc Presentaer: T. Naoe (JAEA/J-Parc)............. 214
3.4.3 Irradiation area- related issues
3.4.3-i) Irradiation area- related issues: F. Arbeiter (KIT) 231
3.4.3-ii) Complementary Experiments at DONES: Wojciech Królas (CIEMAT)........................ 236
3.4.3-iii) Comment on the middle flux module: Takeo Nishitani (NIFS) 241
3.4.3-iv) Tools and procedures for radiation damage modelling and intercomparison of experiments:
Fernando Mota (CIEMAT) 244
3.5 Technical Session 4: Summary session
Summary: J. Knaster (F4E)... 248
4. Appendix 253

目　次

1.はじめに……………………………………………………………………………………………………1

2.アジェンダ…………………………………………………………………………………………………3

3.発表資料

3.1 テクニカルセッション 1：中性子源開発の概要

材料開発のための中性子源に関するユーザの視点：室賀（NIFS）..……………………………………5

3.2 テクニカルセッション 2-1：開発中または開発中の中性子源に関する発表

3.2.1 DONES：A.イバラ（CIEMAT）………………………………………………….……………..22

3.2.2 A-FNS：落合（QST）…………………………………………………....……...…………37

3.2.3 BISOL：Y. Wang（北京大）……………………………………………………..………………45

3.2.4 長寿命核分裂生成物の核変換のための中性子源：奥野（理研）…………………...……………74

3.3 テクニカルセッション 2-2：開発中または開発中の中性子源に関する発表（続き）

3.3.1 核変換用途のための中性子源（MYRRHA を含む）: D.Terentiev、（SCK-CEN）…………………95

3.3.2 D-T 中性子源（HINEG、SORGENTINA などを含む）: Y. Wu（FDS）……………...……………119

3.3.3 中性子源開発の現状：鬼柳（名古屋大）…………………………………………………..…………136

3.4 テクニカルセッション 3：高／低出力中性子源の開発に関するパネルディスカッション

3.4.1 加速器関連の課題

3.4.1-i）RFQ に基づく小型中性子源のいくつかの方式の比較：黒川（KEK）…….…………………156

3.4.1-ii）ハイパワーライナック：J. Knaster（IFMIF/EVEDA）…………………………………………169

3.4.2 ターゲット関連の問題

3.4.2-i）IFMIF ベースの中性子源の Li ターゲットの設計と技術課題：D. Bernardi（ENEA）……..181

3.4.2-ii）高出力小型加速器ベースの中性子源ターゲットの挑戦：iBNCT の状況：栗原（iBNCT）191

3.4.2-iii）J-PARC 発表者の中性子ターゲットの現状：直江（JAEA/J-PARC）…………….....………214

3.4.3 照射施設関連の課題

3.4.3-i）照射エリア関連の問題：F. Arbeiter（KIT）………….…………………….…………………231

3.4.3-ii）DONES の相補的実験：W. Królas（CIEMAT）……………………………………….………236

3.4.3-iii）中間フラックスモジュールに関するコメント：西谷（NIFS）……….……………………241

3.4.3-iv）放射線損傷のモデル化と実験の相互比較のためのツールと手順：F. Mota（CIEMAT）.....244

3.5 テクニカルセッション 4：サマリーセッション

サマリー：J. Knaster（F4E）…………….……………………….………………………………….…...…248

4.付録……………………………….…………………………………………………………………...……..253

1. Introduction

An International Workshop on Advanced Neutron Sources and its Applications (IWANS) was held on 4&5 November 2017 in Aomori city hosted by Rokkasho Fusion Institute of the Japanese's National Institutes for Quantum and Radiological Science and Technology (QST), promoting the Broader Approach Activities at the International Fusion Energy Research Centre (IFERC) site. The event took place in conjunction with the 18th International Conference of Fusion Reactor Materials (ICFRM-18), which developed the ensuing week in the same location. Advanced neutron sources are now being planned concurrently with fusion neutron irradiation on fusion reactor materials, like application for industrial and medical purposes, such as production of radio-isotope medicine, Boron Neutron Capture Treatment (BNCT) facilities, etc. This 1st worldwide workshop on the topic aimed to discuss about the required development and potential application of available advanced neutron sources concepts, to build up a global international forum for discussions on the common technological challenges among neutron sources. The program of the workshop consisted of technical sessions as follows;

Review of status of accelerator driven neutron sources applications

Overview of status of developing accelerator driven neutron sources applications worldwide

Current status of development of accelerator driven neutron sources in different parties

Presentations about the neutron sources developed or being developed

Panel discussion on development of neutron sources issues

This panel discussion consists of two parts, high power neutron sources and low power neutron sources. Accelerator-related issues, target-related issues and irradiation area- related issues were tried to identify and discussed.

Summary session

Conclusions and discussion on how an efficient collaboration can be implemented

In this workshop, there were 18 presentations with 48 attendees of 25 persons form Japan, 2 persons from Korea, 5 persons from China and 16 persons from EU including three IFMIF Project Team members. Before starting the workshop, a technical tour to LIPAc (Linear IFMIF Prototype Accelerator) located in the IFERC site of QST at Rokkasho was held.

1.はじめに

2017 年 11 月 4、5 日に、国際融合エネルギー研究センター（IFERC）のサイトにある日本原子力研究開発機構六ヶ所核融合研究所の主催により、青森市で中性子源とその応用に関する国際ワークショップ（IWANS）が開催された。このワークショップは、第 18 回核融合炉国際会議（ICFRM-18）のサテライト会合として開催され、ICFRM-18 は同じ青森で次の週に開かれました。先進中性子源は、核融合炉材料の核融合中性子照射と並行して放射性同位体医薬品の製造、BNCT（中性子補足セラピー）施設など、産業および医療目的の用途に計画されている。この最初の国際ワークショップでは、利用可能な最新の中性子源概念の必要な開発と潜在的な応用について議論し、中性子源開発における共通の技術課題に関する議論のための国際フォーラムを構築することを目的とした。ワークショップのプログラムは以下のようなテクニカルセッションで構成されていました。

加速器駆動中性子源の応用状況のレビュー
世界中で加速器駆動中性子源の開発状況の概要

世界の研究所等における加速器駆動中性子源の開発の現状
開発中または開発中の中性子源に関するプレゼンテーション

中性子源問題の開発に関するパネルディスカッション
このパネルディスカッションは、高出力中性子源と低出力中性子源の 2 つの部分で構成されています。加速器関連の問題、ターゲット関連の問題、照射施設関連の問題に絞っての議論

サマリーセッション
効率的な協力実現方法に関する議論

今回のワークショップでは、25 名の出席者 48 名、韓国出身者 2 名、中国出身者 5 名、IFMIF プロジェクトチームメンバー3 名を含む EU 出身者 16 名が参加した。 ワークショップを開始する前に、六ヶ所の QST の IFERC サイトにある IFMIF 原型加速器へのツアーが行われた。

2. Agenda

Workshop on Advanced Neutron Source and its Application

4-5 November, 2017

Aomori-city, Japan

Saturday, 4 November 2017 (@IFERC site and Festival city Auga)

(Technical tour to LIPAc)

8:30 Departing from Nebuta museum "WA RASSE" nearby Hotel Route Inn Aomori Station

(See the detailed information)

10:00 Arriving the IFERC Site and tour to LIPAc

12:00 Departing the IFERC Site (Light meal will be provided at the site for lunch)

13:30 Arriving at Auga

(Main Meeting)

14:00 Opening (A. Ibarra, S. O`hira)

14:15 Technical Session 1: Users' perspective on neutron sources for materials development: T. Muroga (NIFS)

15:00 Technical Session 2-1: Presentations about the neutron sources developed or being developed (30 +10 min x 4 presentations) Chair: Shigeru O'hira (QST)

- DONES: A. Ibarra (CIEMAT)
- A-FNS: K. Ochiai (QST)
  (+ coffee break 15 min.)
- BISOL: Y. Wang (Peking Univ.)
- Neutron sources for transmutation of long-lived fission products: H. Okuno (Riken,)

18:00 Adjourn

19:00 Workshop dinner

Sunday, 5 November 2017 (@Link-Station Aomori)

9:30Technical Session 2-2: Presentations about the neutron sources developed or being developed (30 min x 3 presentations + discussion) Chair: Juan Knaster (F4E)

- Neutron sources for transmutation applications (including MYRRHA): D. Terentiev, (SCK-CEN)

- D-T neutron sources (including HINEG, SORGENTINA, etc): Y. Wu (FDS)
- Present status of neutron sources development: Y. Kiyanagi (Nagoya Univ.)

11:30 Lunch

12:45 Technical Session 3: Panel Discussion on development of neutron sources

Chair: Angel Ibarra (CIRMAT)

High/Low power neutron sources (4-5 items, 10-15 min. each + discussion)

- Accelerator-related issues. *Promoter: F4E J. Knaster (F4E)*
  - Comparison of a few schemes of RFQ-based compact neutron sources: S. Kurokawa
  - High power linacs: J. Knaster (IFMIF/EVEDA)
- Target-related issues. *Promoter: K. Ochiai (QST)*
  - Design and technical challenges of Li target for IFMIF-based neutron sources by D. Bernardi (ENEA)
  - Target challenge for High power compact accelerator based neutron source; as status of the iBNCT: the heat issue and blistering T. Kurihara (iBNCT)
  - Present status of neutron target on J-Parc Presentaer: T. Naoe (JAEA/J-Parc)
- Irradiation area- related issues. *Promoter: F. Arbeiter (KIT)*

(4-5 items, 10-15 min. each + discussion)

(+ coffee break 15 min.)

16:30 Technical Session 4: Summary session Chair: Kentaro Ochiai (QST)

- From IFMIF users committee: IEA/W-GIFT history and proposal (15 min.)

  : E. Diegele (EUROfusione)

- Summary: *J. Knaster (F4E)*

17:30 Adjourn

3. Presentations

3.1 Technical Session 1: Overview of neutron sources development

Users' perspective on neutron sources for materials development: T. Muroga (NIFS)

Workshop on Advanced Neutron Source and its Application

November 4-5, Aomori, Japan

Users' perspective on neutron sources for materials development

Takeo Muroga

National Institute for Fusion Science, Toki, Gifu, Japan

Outline of Presentation

1. Japanese fusion materials development program and neutron sources

2. The need for fundamental research

Japanese fusion materials development program and neutron sources

Outline of Japanese Fusion Structural Materials Development Program

1. Categorizes the candidate materials into Primary Option (RAFM) and Advanced Option (V-alloy, SiC/SiC, ODS-S)
2. Adopts staged developments corresponding to Decision Points DP1, DP2 and DP3.
3. Position D-Li neutron sources (near-term : A-FNS and long term : IFMIF) as key facilities for the development.
4. Emphasize the necessity of "standardization" of materials specifications and test technology as a crucial step toward DEMO design qualification.
5. Emphasize the necessity of establishing structural design criteria for the materials property requirements and standard specification of the structural materials.

Recent Reports from Japanese Fusion Community

The following documents were recently issued by Governmental Committees. Japanese DEMO development strategy is under reconstruction based on these documents.

1. Report by the Joint-Core Team for Establishment of Technology Bases Required for the Development of a Fusion DEMO Reactor

    1-1. Basic concept of DEMO and Structure of Technological Issues (19, January 2015)

    1-2. Chart of Establishment of Technology Base for DEMO (1, March 2015)

2. Action Plan toward DEMO Development (18, March 2016) – in Japanese

Joint-Core Team Report

In these reports "Material Development and Establishment of Codes and Standards" is one of the eleven technological issues.

DEMO Reference Concept and Important Decision Points (Joint-Core Team Report)

DEMO Reference Concept

Medium size steady state Tokamak, with availability reachable for commercialization and having T breeding to fulfil self-sufficiency.
(This does not preclude potential selection of non-Tokamak concepts for DEMO)

Three Important Decision Points (DPs)

Rescheduling is being made in 2017 according to the delay of ITER schedule, but is not yet official

(1) Intermediate Check and Review (DP1)

~2020 → ~2020 (DP1-1) and 2025~ (DP1-2)

(2) Decision of transition to DEMO (DP2)

~2027 → in 2030s

(3) Decision of DEMO construction (DP3)

in 2030s → in 2030~2040s

Primary and Advanced Materials Options

RAFM steel is widely accepted as primary materials option

Parallel efforts for developing advanced materials are being made

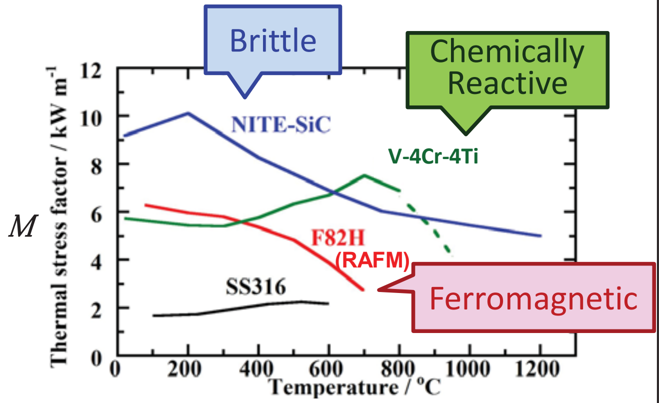
(1) Limited operation window of RAFM
Need advanced materials for advanced DEMO and fusion reactor options with high competitiveness relative to other energy options

(2) Ferromagnetism issue of RAFM
Backup options of non-magnetic materials are necessary for risk mitigation

This talk focuses on RAFM development.

$$M = \frac{\lambda \sigma_{UTS}(1-\nu)}{\alpha E}$$

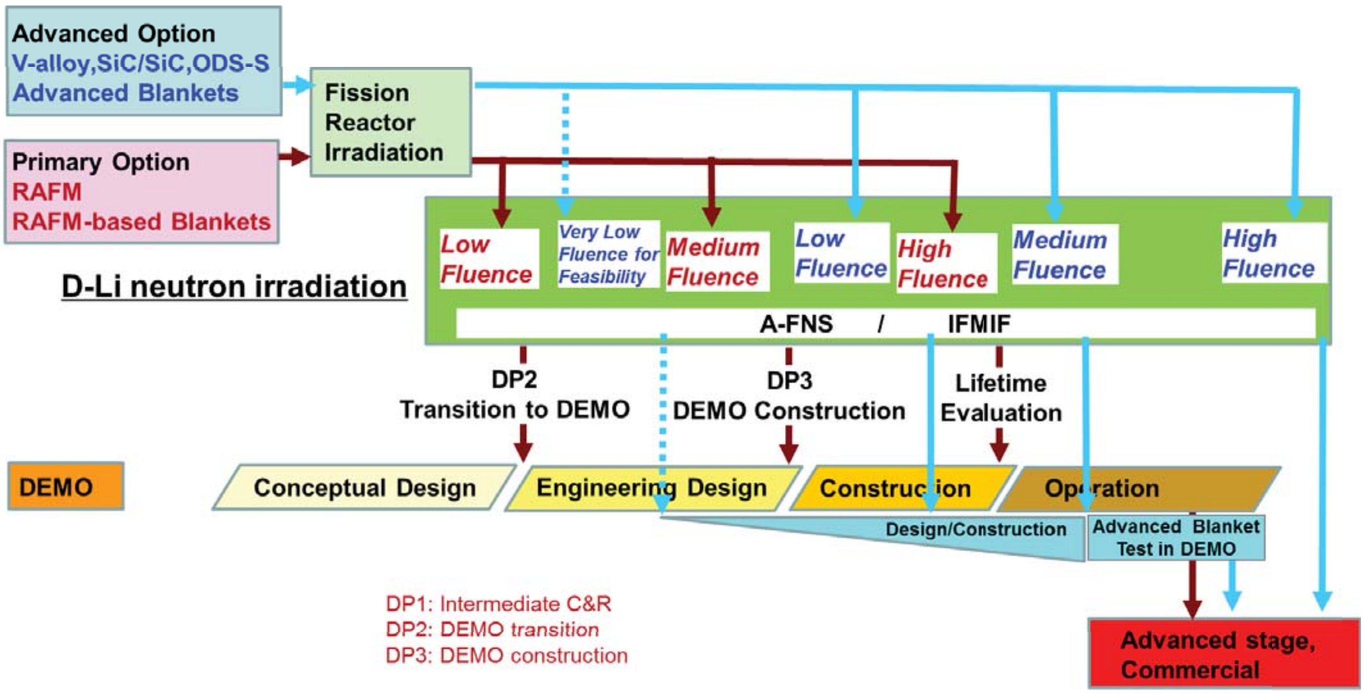
M : Thermal Stress factor
λ : thermal conductivity
σ : tensile strength
ν : Poisson ratio
α : thermal expansion coeff.
E : Young's modulus



Heat flux tolerance of candidate materials
(thermal creep not considered)
Nagasaka 2012

Each candidate has its own inherent key feasibility issue

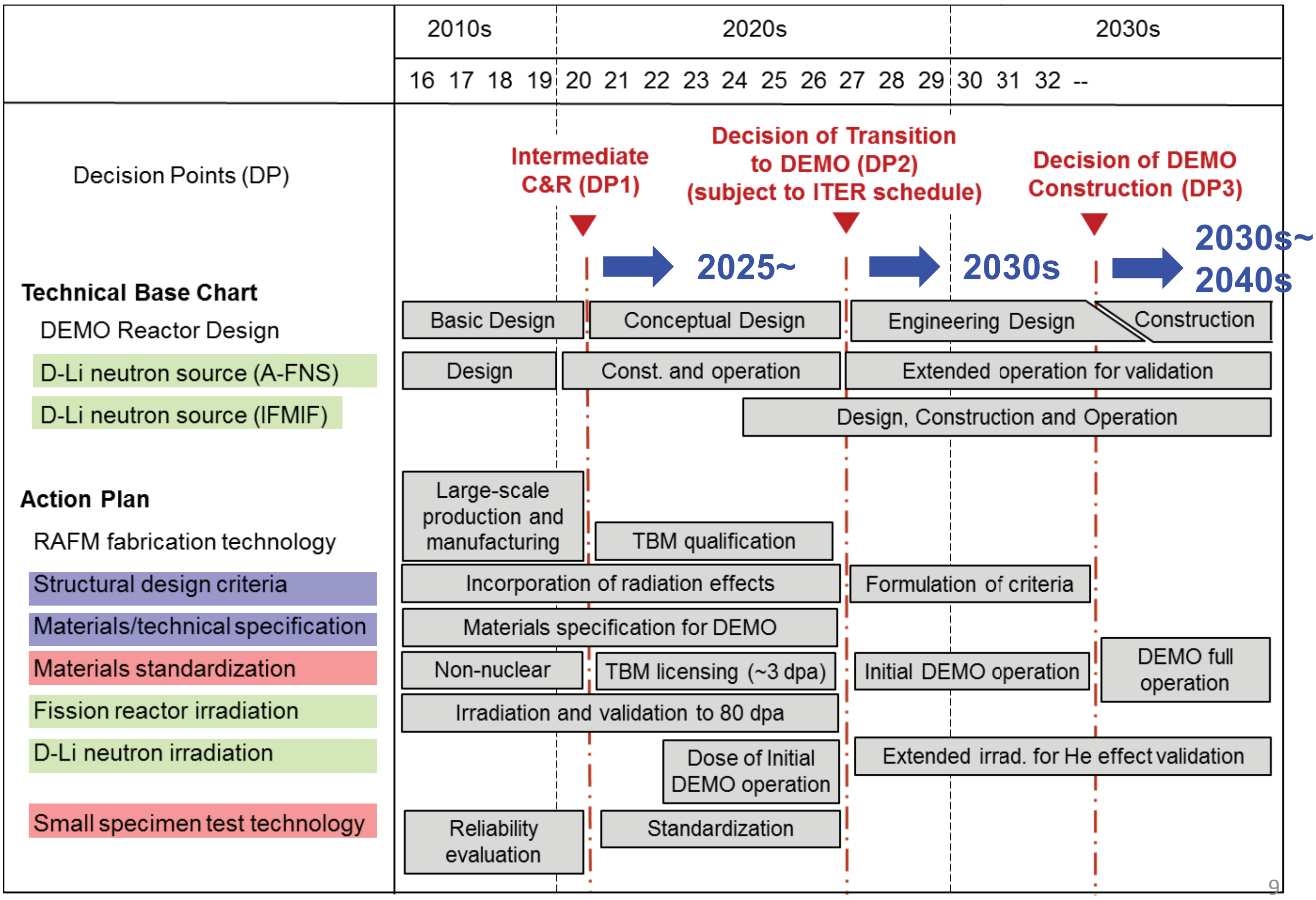
Primary and Advanced Materials Irradiation Tests and Development



Initial effort will be focused on RAFM and RAFM-based blanket systems for early realization of DEMO

Later efforts will shift to advanced materials and advanced high temperature blanket systems, toward development of advanced fusion systems

Basic Chart and Action Plan for RAFM Development



Irradiation Facility Options

Charged Particles

For fundamental studies and model prediction

Fission Reactors

Primary screening of candidates

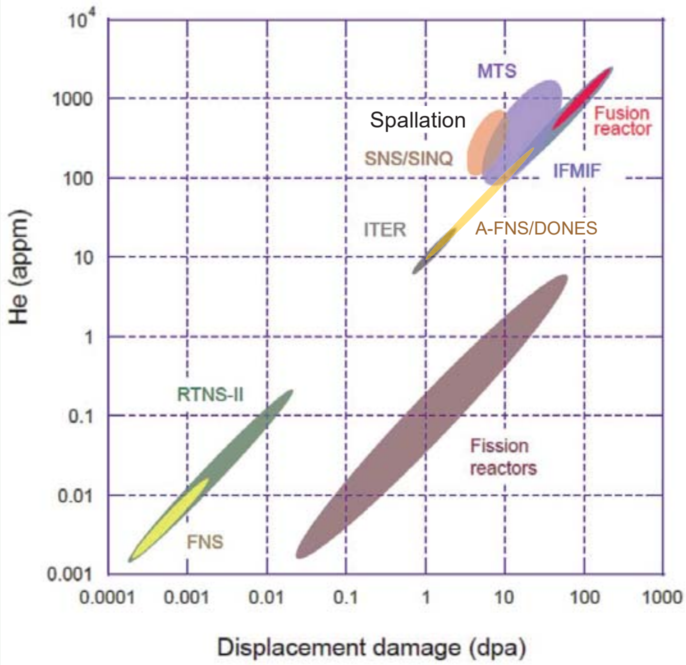
Difficult to simulation He effect

Near term D-Li neutron source (A-FNS)

Database for decision of transition to DEMO

IFMIF or equivalents

Database for decision of DEMO construction and operation period



Damage and helium production of surrogate neutron irradiation facilities

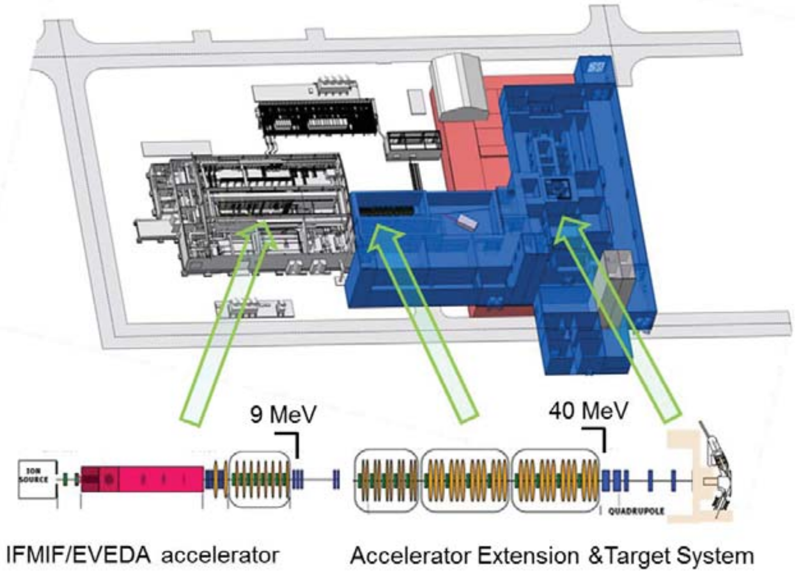
Knaster, Moeslang, Muroga (2015)
Modified from S.J. Zinkle and L.L. Snead (2014)

IFMIF/EVEDA and A-FNS

IFMIF/EVEDA accelerator tests (~9 MeV d⁺) will be completed in 2019. → 2020~2025

A-FNS (~ 40 MeV d⁺) is being planned as post-EVEDA project. → 2025~

A-FNS is expected to contribute to DP2 and DP3.



Layout of A-FNS

D-Li Neutron Source Development

Name	Accelerating Voltage	d⁺ beam current	Objective
IFMIF/ EVEDA (LIPAC)	9 MeV	125 mA	Engineering validation (no neutron)
A-FNS	40 MeV	125 mA	Medium Fluence 14 MeV neutron Irradiation
IFMIF	40 Mev	250 mA	High Fluence 14 MeV neutron Irradiation

DP1: Intermediate C&R
DP2: Transition to DEMO
DP3: DEMO construction

Courtesy of K. Ochiai (QST)

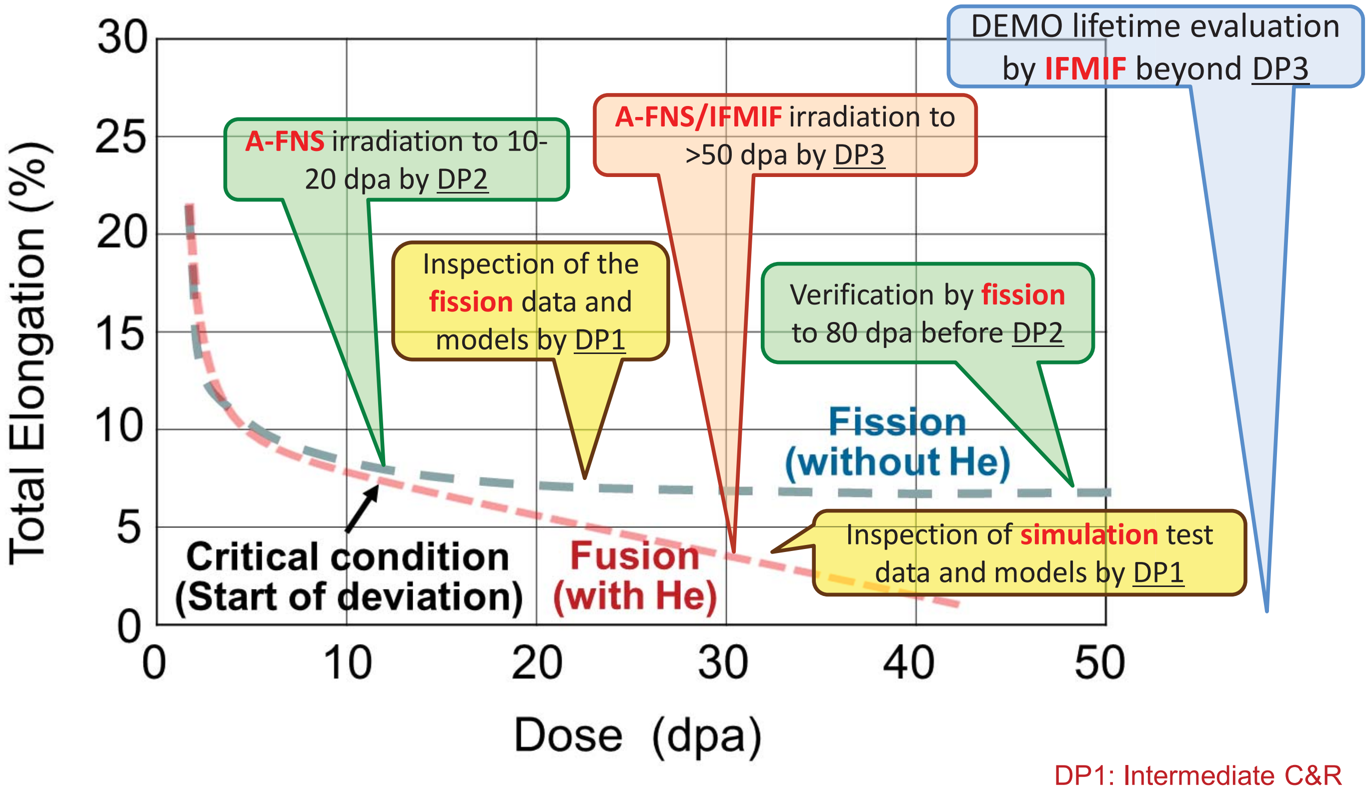
Characterization of Neutron Irradiation Facility

Purposes	Candidate Selection	Model Validation	Lifetime Evaluation
Required Characteristics	Timely availability	Precise Control	High Fluence
Fission Reactors	Timely use possible Difficult to simulate He effect	Difficult to simulate He effect	Difficult to simulate He effect
A-FNS	Limited timely use	Low fluence validation	Medium fluence evaluation
IFMIF	Not timely	Medium fluence validation	High fluence evaluation

DP1-DP2 emphasis (green) | DP2-DP3 emphasis (yellow) | Beyond DP3 (pink)

DP1: Intermediate C&R
DP2: Transition to DEMO
DP3: DEMO construction

Irradiation Test Strategy to Quantify Loss of Ductility of RAFM

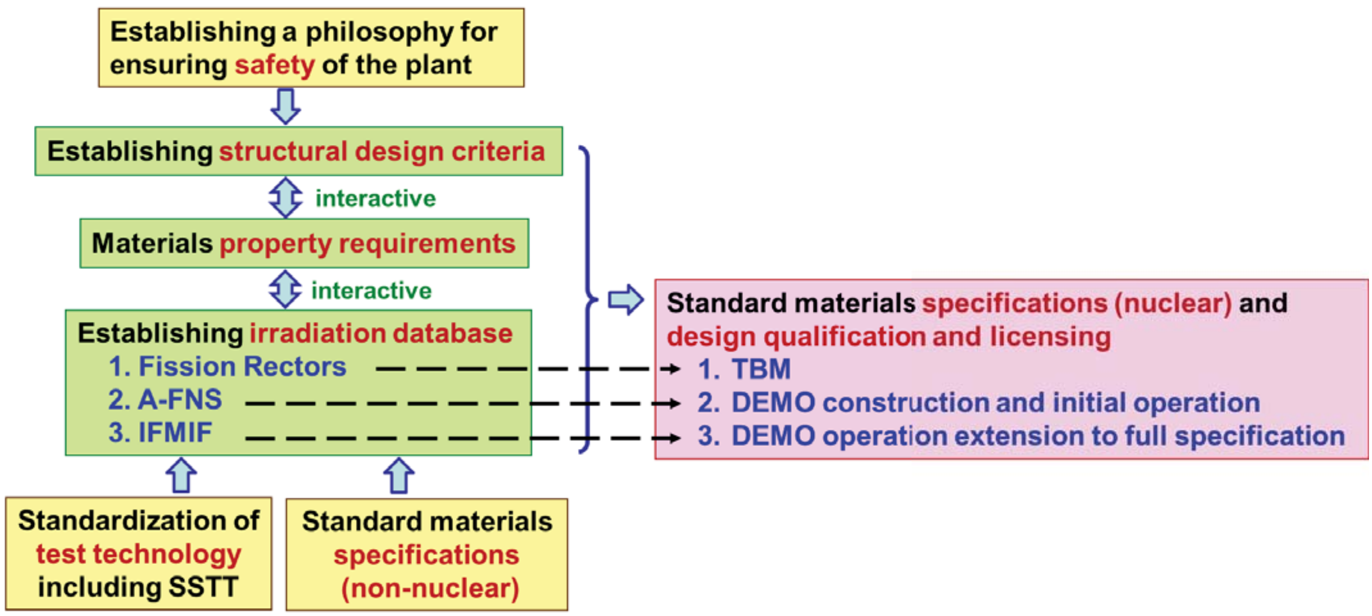


Prediction of loss of elongation of RAFM by irradiation and strategy of testing

DP1: Intermediate C&R
DP2: Transition to DEMO
DP3: DEMO construction

Modified from H. Tanigawa et al., Nucl. Fusion 2017

Materials Development for DEMO Licensing



SSTT : Small Specimen Test Technology

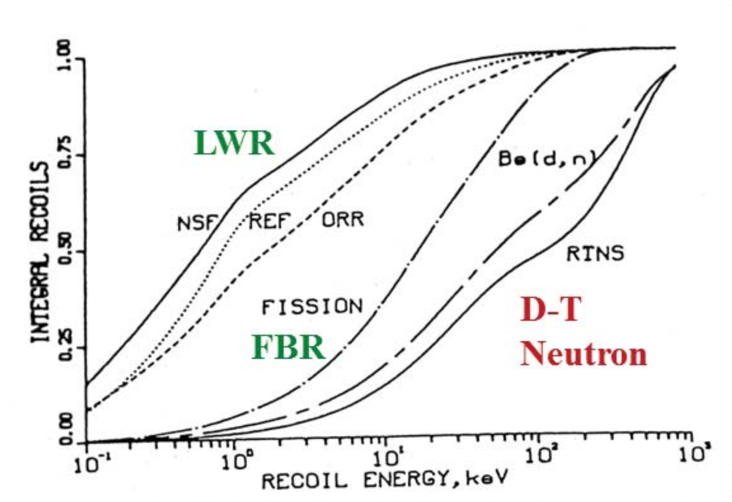
In reality, the standardization and reactor design must be carried out without sufficient materials irradiation data.

Careful manipulation of the schedule in the development of irradiation facilities, acquisition of irradiation data, and auxiliary fundamental/modeling efforts are essential.

T. Muroga and H. Tanigawa, Fusion Tech. 2017

Need for Fundamental Research

PKA Energy Spectra



Weighted Integral PKA Energy Spectra

Greenwood (1983)

PKA energy spectra was considered for correlating different kind of irradiations

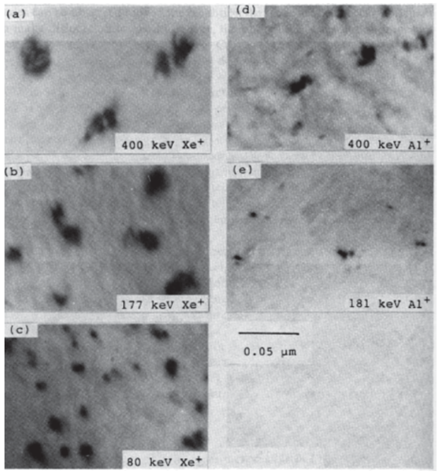
PKA spectra weighted with displacements can be the effective correlation measure

Average or weighted average PKA spectra was used as correlation parameters

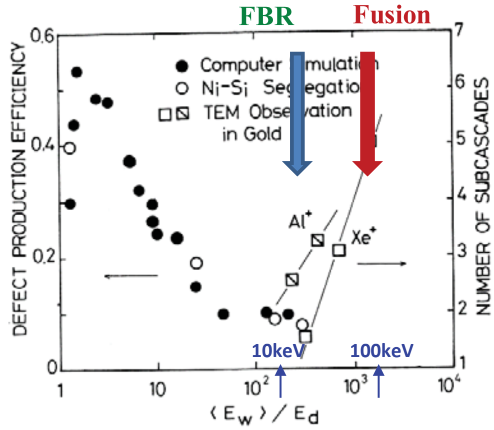
Effects of PKA Energy Spectra

Effects of PKA energy spectra have been investigated

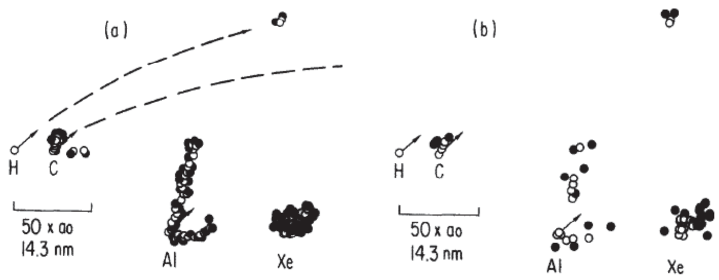
Collision cascades were separated into sub-cascades above ~10keV, whose performance does not change



Cascade splitting into subcascades in gold by Xe and Al ions



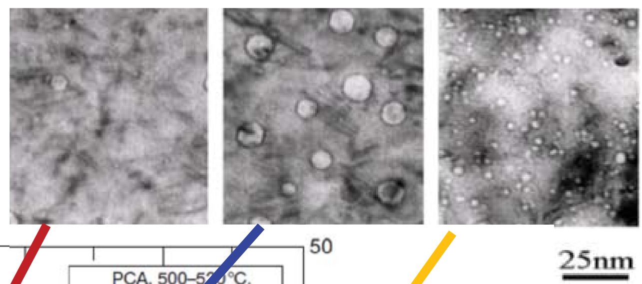
Correlation by Weighted Average PKA Spectra

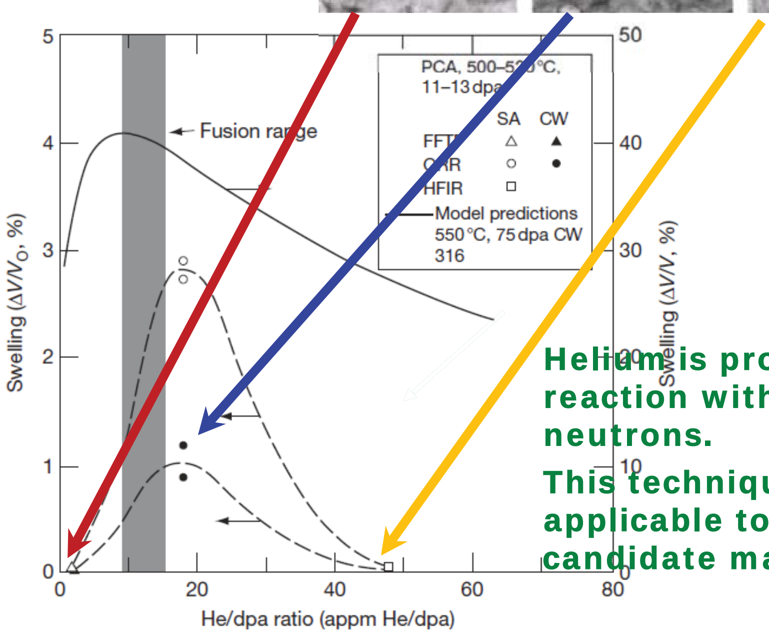


After cascade After thermal annealing

Muroga (1985)

He/dpa Dependence





Helium is produced by Ni's reaction with thermal neutrons.

This technique is not applicable to low activation candidate materials

He effect in an austenitic steel

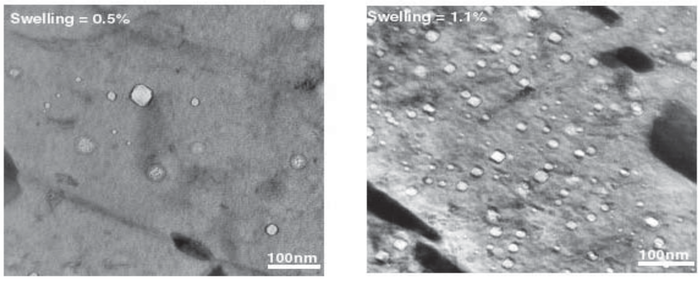
Efforts to Evaluate He Effects

Boron addition

$^{10}B + n$ (thermal) $\rightarrow$ $^{4}He + ^{7}Li$

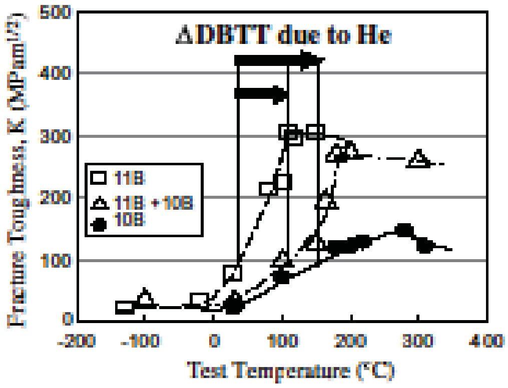
^{10}B addition enhanced swelling and embrittlement
Boron addition can change the steel properties (chemical effects)

^{10}B / ^{11}B ratio control tests showed ^{10}B can enhance DBTT shift
However, it was also shown that Li can enhance cavity formation and enhance DBTT shift.
It is quite difficult to evaluate He effects explicitly



F82H (36 appmHe) ^{10}B-doped F82H (330 appmHe)

^{10}B addition enhanced cavities(HFIR 673K, 51dpa)

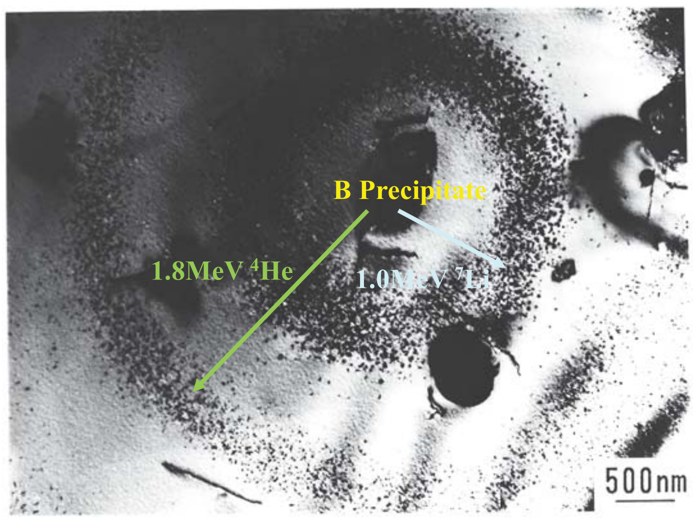


DBTT shift by isotope-controlled boron addition (JMTR 473K) (Wakai)

^{4}He, ^{7}Li ejection from ^{10}B

B doped austenitic steel has B rich precipitates, whoing double ring damage structure

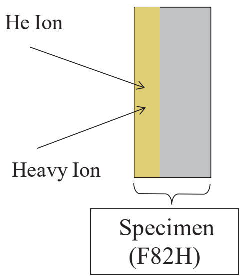
Both ^{7}Li and ^{4}He depositing enhance loop and canity formation



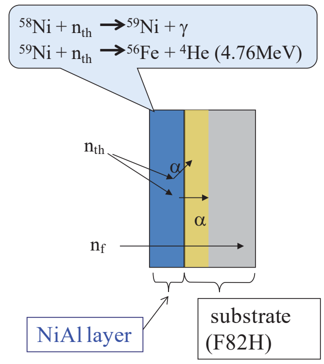
JMTR 400°C, 5.5x10^{23}n/m^{2} (E>1MeV), JPCA

Helium Injection in HFIR

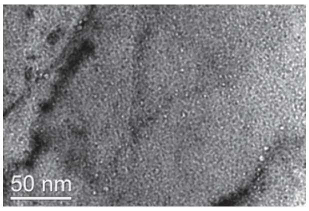
Helium injection to F82H during irradiation

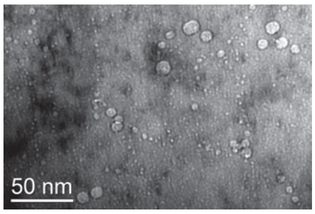


Dual beam irradiation (Kyoto U.)



He injection during neutron irradiation in HFIR using Ni reaction with thermal neutrons





10 dpa, 380 appm He **（Yamamoto）**
Different microstructure with the same dpa and He level

Both ion irradiation and helium injection can produce fusion relevant He/dpa only near-surface area

The difference in microstructure may be attributed to the extreme difference in damage rate (10 dpa by some hours and some months)

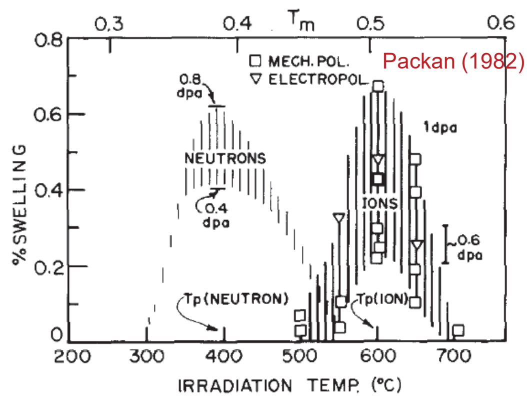
Effects of Accelerated Irradiation

Most irradiation tests are "accelerated" tests

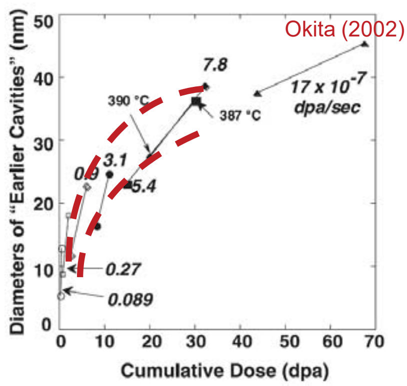
Acceleration can induce very different materials performance, especially when multiple mechanisms with different activation energies operates.

Sometimes misleading

Modeling is critically important

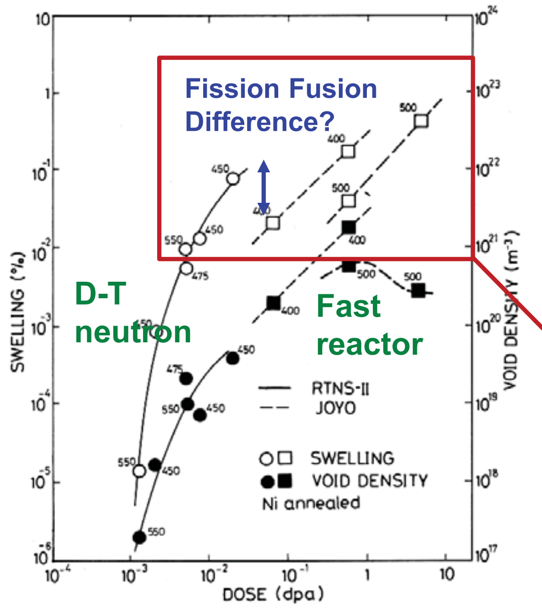


Temperature shift of swelling in Ni

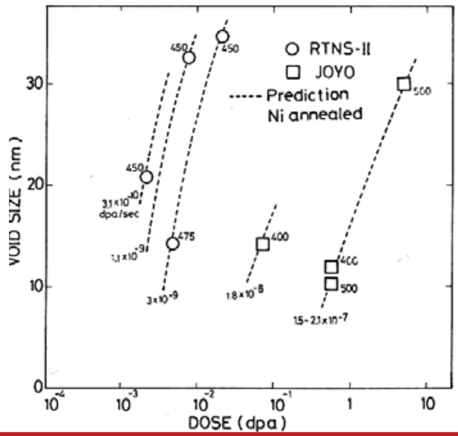


Void size evolution in austenitic steels

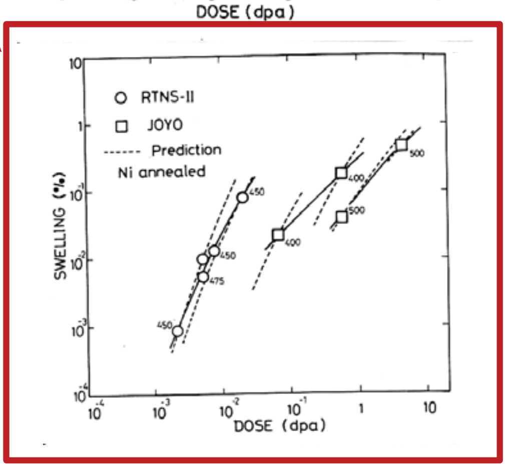
An Example is Misleading Fission-Fusion Correlation



Void swelling and density in Ni



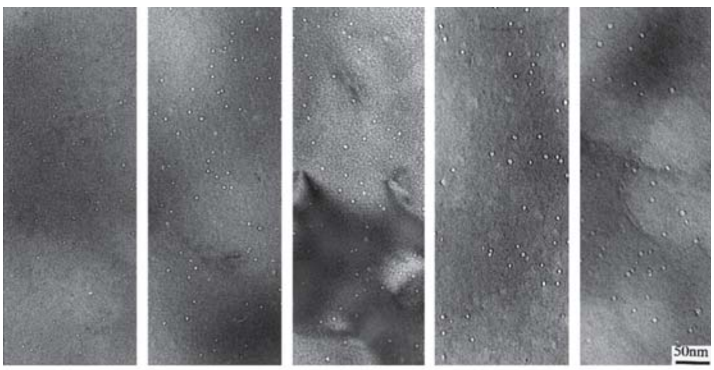
Muroga (1988)



Damage rate effects dominate over fission-fusion difference

Irradiation Rig Development for JMTR

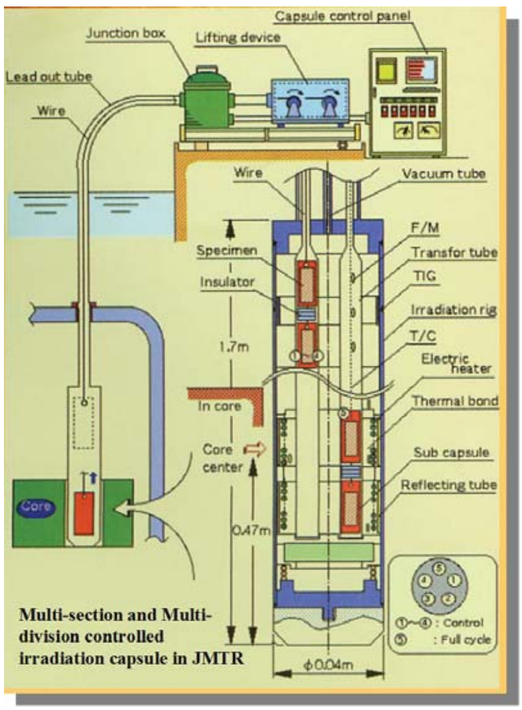
- In-situ resistivity
- Intentional temperature variation during irradiation
- Specimen pulling out during irradiation.



0.026 0.062 0.13 0.24 0.40 dpa

Microstructural evolution of Ni at low dose with a constant dose rate

Yoshiie 2000



Specimen pulling-out during irradiation using sectioned capsules

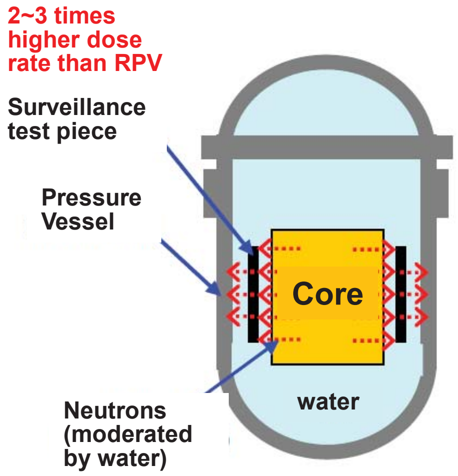
Issues for fundamental understaning

1. He effects in fusion conditions still need validation
   - Fundamental studies
   - Modeling prediction
   - Validation by A-FNS/IFMIF

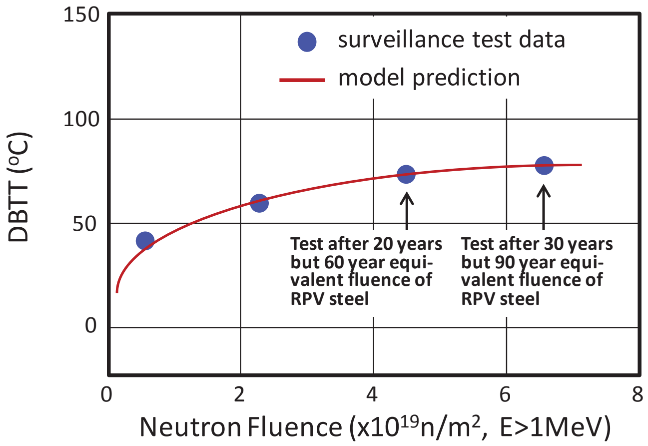
2. Dose and dose rate effects are mixed in most cases
   - Compilation of single-variable experiments is essential
     - Property change vs dose with constant dose rate
     - Property change vs dose rate with constant dose
   - Fission reactors have limitation in performing controlled experiments because of limited accessibility

Current issue – fission power reactor and materials

Surveillance test in LWR



Surveillance test in LWR



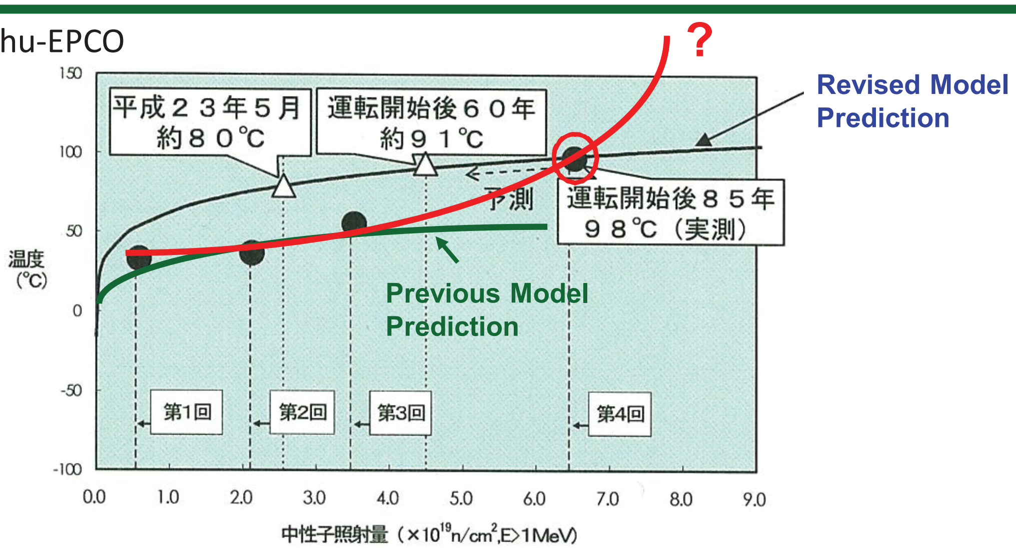
Concept of Surveillance test

Surveillance test data can predict future performance of PV

Prediction is based on an embrittlement model

Anomalous DBTT Shift in Surveillance of Genkai-1 Power Plant

After HP of Kyushu-EPCO



Criticism emerged toward the model revision.

1. Model is wrong (should have a different fluence dependence).
2. Surveillance (accelerated simulation) is misleading. (impact of flux effects)

Had seriously negative effects on the discussion of extended operation of the present power plants

This is clearly showing a lesson we should learn.

Fundamental understanding on materials performance in fusion condition is crucial even in the stage of commercial operation

Future neutron sources must contribute to enhancing fundamental understanding of radiation effects as well as constructing database

High controllability

Single variable experiment capability

Summary (1)

Recently, Japanese fusion community issued some reports on the strategy for technological developing toward DEMO. Japanese DEMO development strategy is under reconstruction based on these documents.

Three decision points (DPs) were scheduled allowing a staged development toward DEMO.

DP1 : Intermediate C&R ~2020, ~2025

DP2 : Transition to DEMO phase in 2030s

DP3 : DEMO construction ~2040s

The standard materials specifications are recognized as a crucial step toward DEMO design qualification and licensing. For this purpose, the materials property requirements to be derived by establishing the structural design criteria is necessary as well as establishing irradiation database.

Summary (2)

The challenges in this process includes that the reactor design must be carried out without sufficient materials irradiation data.

Thus, careful manipulation of the schedule in the development of irradiation facilities, acquisition of irradiation data and auxiliary basic and modeling research efforts are essential for materials development toward DEMO.

Recent controversy in Reactor Press Vessel performance clearly shows necessity for fundamental understanding of materials performance under irradiation in every stage of reactor development, including licensing phase and commercial operation phase. The materials irradiation facilities need to have capability to carry out fundamental researches such as single-variable experiments.

3.2 Technical Session 2-1: Presentations about the neutron sources developed or being developed

3.2.1 DONES: A. Ibarra (CIEMAT)

EUROfusion

IFMIF DONES

DONES: DEMO-Oriented Neutron Source

Workshop on Advanced Neutron Sources and its Applications. Aomori (Japan) November 4-5, 2017

A. Ibarra (CIEMAT) representing the complete WPENS team

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Outline

- DONES objective and overall approach
- Accelerator Systems summary
- Test Systems summary
- Li systems summary
- Remote Handling & Building systems
- Summary

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Neutron source requirements

Along the time, it has been widely recognized that a fusion-like neutron source is needed for fusion materials qualification both for DEMO and the power plant development

Requirements based on EU DEMO needs

The requirements are to produce **fusion-like neutrons**

- Intensity large enough to allow accelerated (as compared to DEMO) testing, — **> 10 dpa(Fe)/fpy**
- Damage level above the expected operational lifetime, — **20 dpa(Fe) in 1.5 y; 50 dpa(Fe) in 3.5 y**
- Irradiation volume large enough to allow the characterization of the macroscopic properties of the materials of interest required for the engineering design of DEMO (and the Power Plant) — **300 cm3**

The most feasible approach based on **Li(d,xn) sources**

The IFMIF project since 90´s

The IFMIF-DONES project!!!

What is IFMIF-DONES?

It is the minimum neutron source required to fulfill the materials fusion-like irradiations needs of DEMO

IFMIF-DONES (Demo-Oriented Neutron Source)

Main technical characteristics

Based on **IFMIF** Preliminary Engineering Design simplified as much as possible:

- One full energy (40 MeV) accelerator with angular incidence
- Full size IFMIF Test Cell: only half cooling needed
- Full size IFMIF Li loop: only half cooling, half purification system needed
- Reduced number of irradiation modules to be used: no need of Tritium online measurements and strong simplification of Pipes & Cables Plugs
- Minimum irradiated materials (modules, target,…) manipulation in the plant: irradiated materials transferred to external facilities, if possible
- Waste management reduced to the minimum

- **Upgrade to full IFMIF could be feasible**

Design process of IFMIF-DONES Plant

IFMIF-EVEDA validation activities: Orai loop, Heloka, Lifus6, LIPAc

IFMIF-DONES validation activities

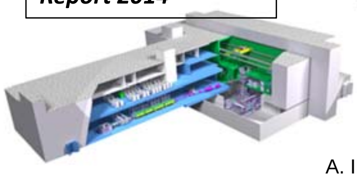
Critical technical issues analysis (quench tank location, TA approach, AC configuration,…

IFMIF EDR 2013

WPENS Project timeline

Plant and systems requirements definition
Design guidelines
Boundaries and interfaces identification
Implementation of design choices
Systems design
Integrated analysis

IFMIF-DONES Conceptual Design Report 2014

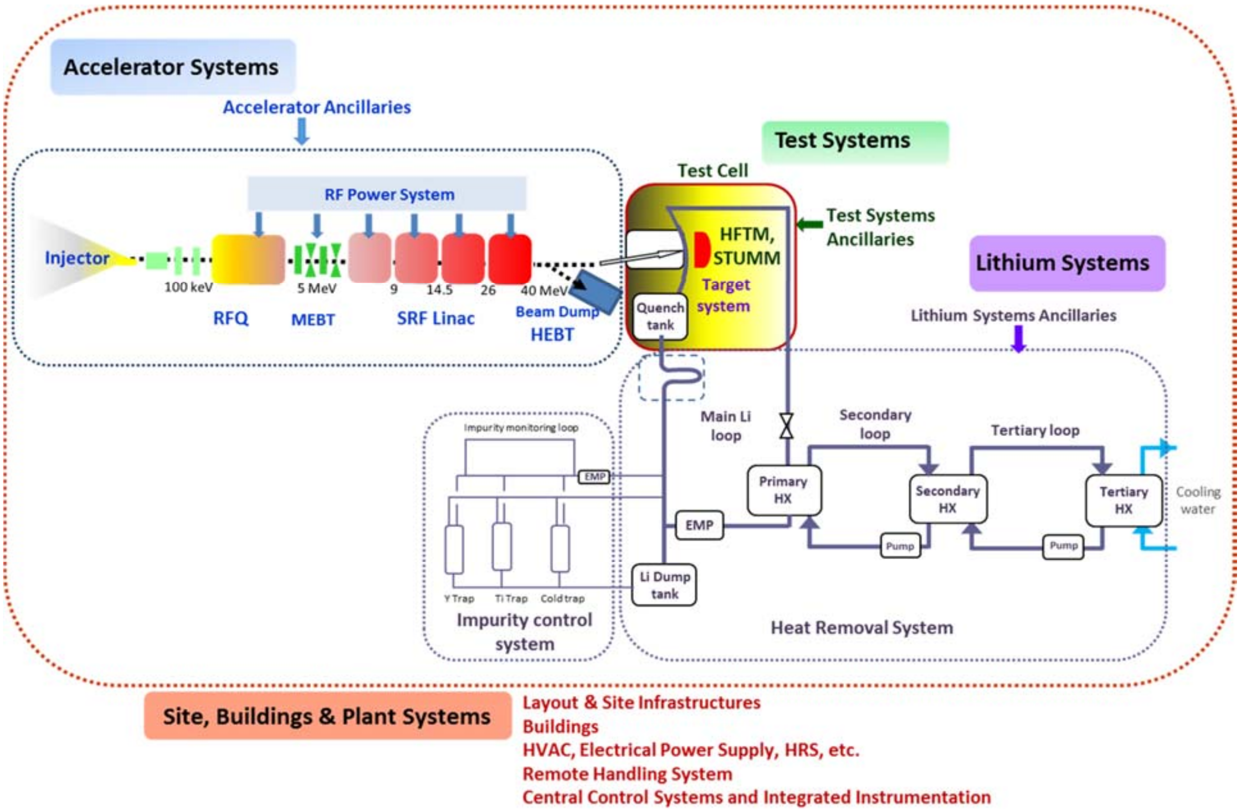


Reference Design
Second half 2016

Preliminary Engineering Design report
2017

Preliminary Safety Analysis Report

IFMIF-DONES Plant Configuration



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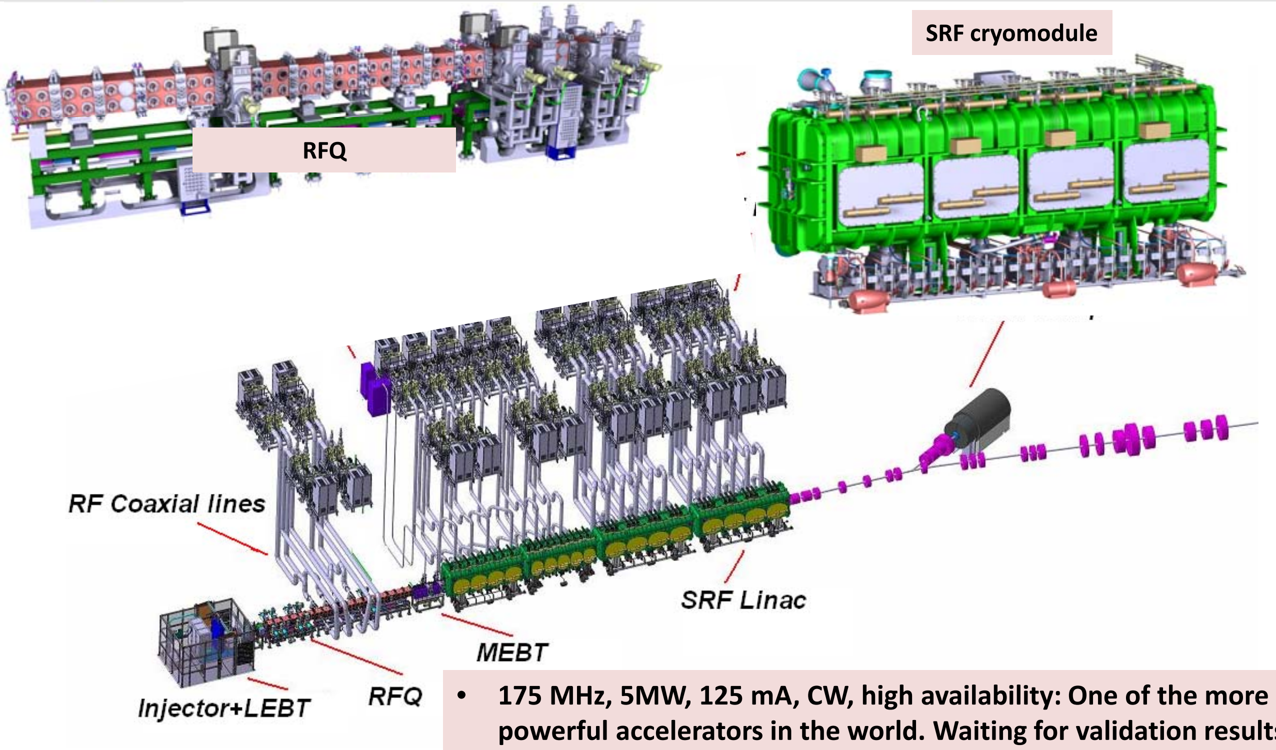
Accelerator systems summary

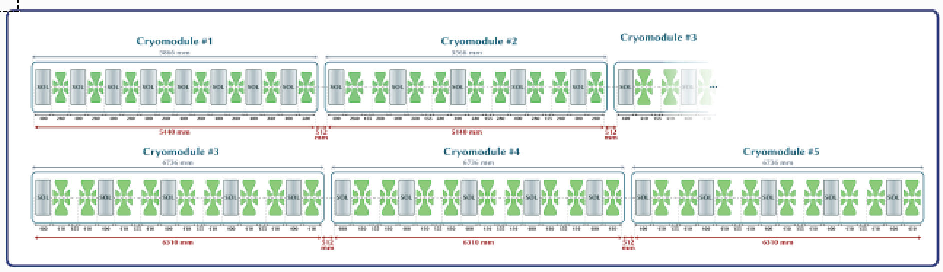


- **175 MHz, 5MW, 125 mA, CW, high availability: One of the more powerful accelerators in the world. Waiting for validation results from LIPAc (Rokkasho)**
- **Very similar to the IFMIF one but some changes implemented….**

AS main changes: SRF configuration

Reference design for SRF linac system: 5 Cryomodules!

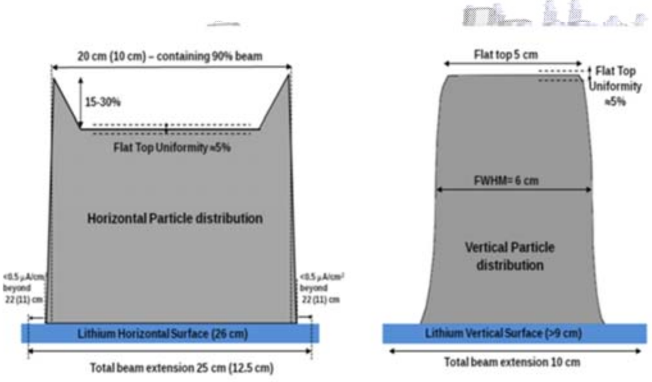
Implemented to assure the D final energy and reduced beam losses



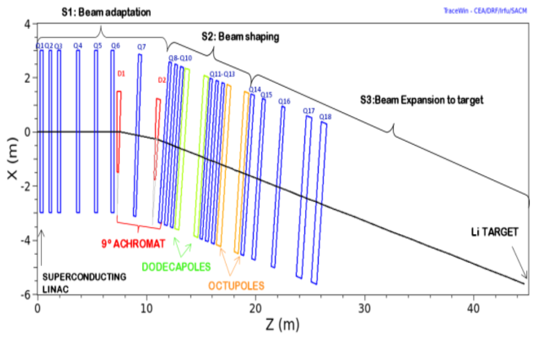
DONES SRF Linac Main Parameters – 5 cryomodules

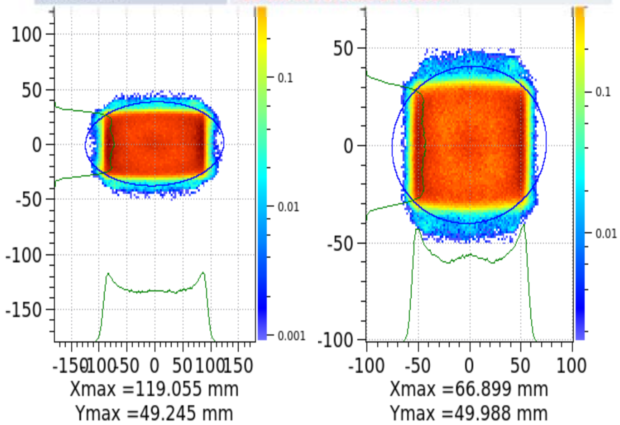
- 5 cryomodules
- 2 families of HWR (17 + 27)
- Transverse focusing by solenoids (28)
- BPM and steerers for orbit correction
- Simulations with cavity field maps (1D)
- 3 identical high-β cryomodules
- Shorter high-β lattices
- Shorter final lattices for cryomodules 2,3,4 & 5
- Total Length: 31.6 m

AS main changes: Beam specifications on target

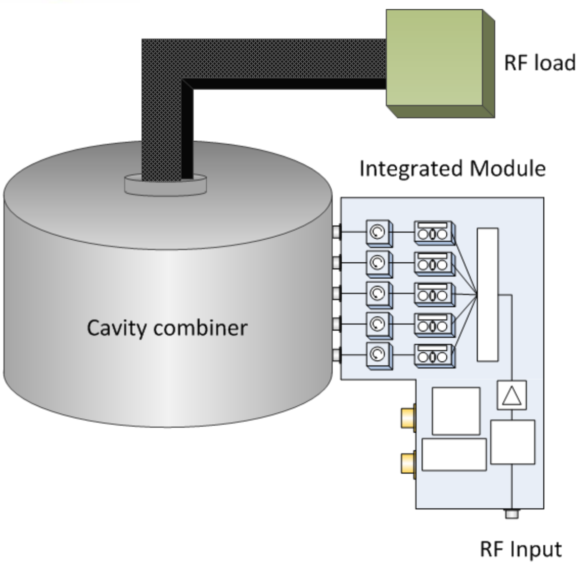


Beam Energy	40 MeV
Beam current	125 mA
Beam energy spread	±0.5 MeV FWHM
Beam profile	20 x 5 cm²
	10 x 5 cm² (optional)
Angle incidence	9°
Beam position	**± 5 mm**
Beam uniformity	± 5% (across the flat top)
Beam tails	< 0.5 μA/cm² beyond ± 11 cm in horizontal
Edge peak	edge peak current density in x profile between **15% and 30%** of average density
Maximum beam extension	25 cm in horizontal direction 10 cm in vertical direction

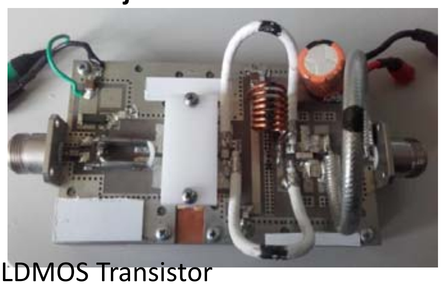




AS main changes: Solid state RF

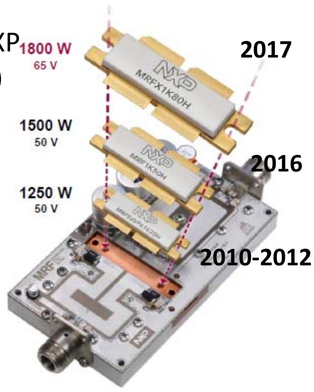


LIPAc Project: 2x20kW SS RF chains



50V 1200W LDMOS Transistor
Freescale MRFE6VP61K25H

New 65V 1800W LDMOS NXP
MRFX1K80 (pin-compatible)



- **RF source can be tuned for each cavity**
- **On-operation maintenance is feasible**
- **Higher availability**

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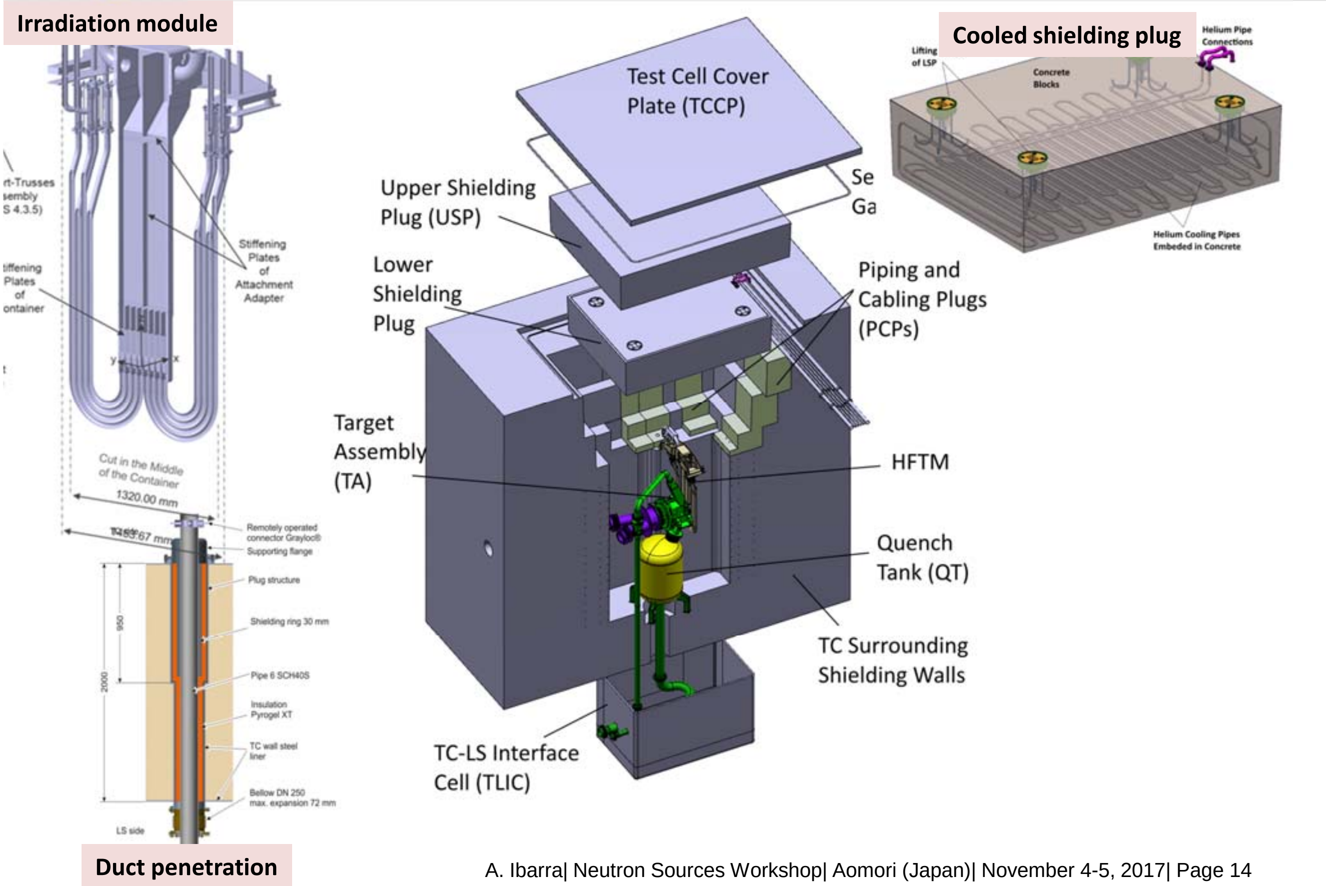
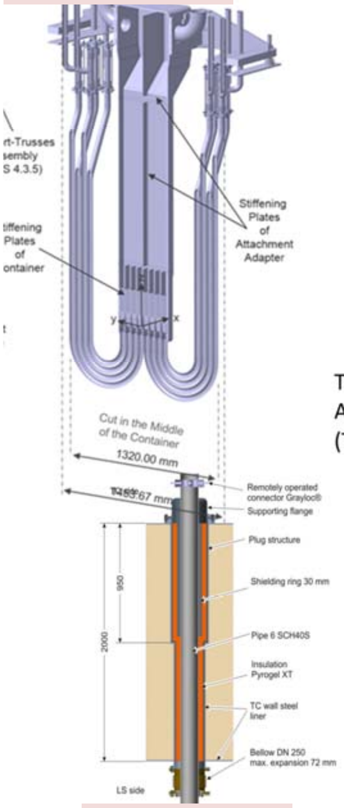
Test Systems summary

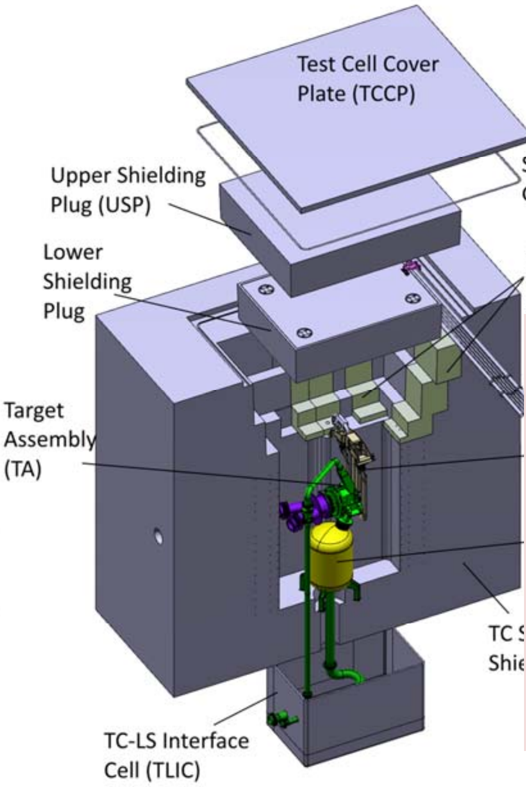


Test Systems summary

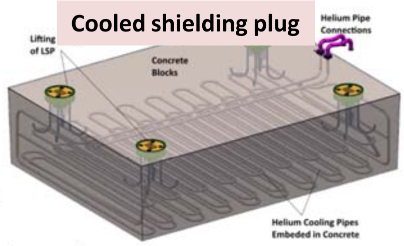
Irradiation module



Duct penetration



Cooled shielding plug



Main characteristics driven by the presence of neutrons and Li

- **Internal components cooling by He**
- **Remote Maintenance required**

Similar to the IFMIF one but some changes implemented (or to be implemented)…

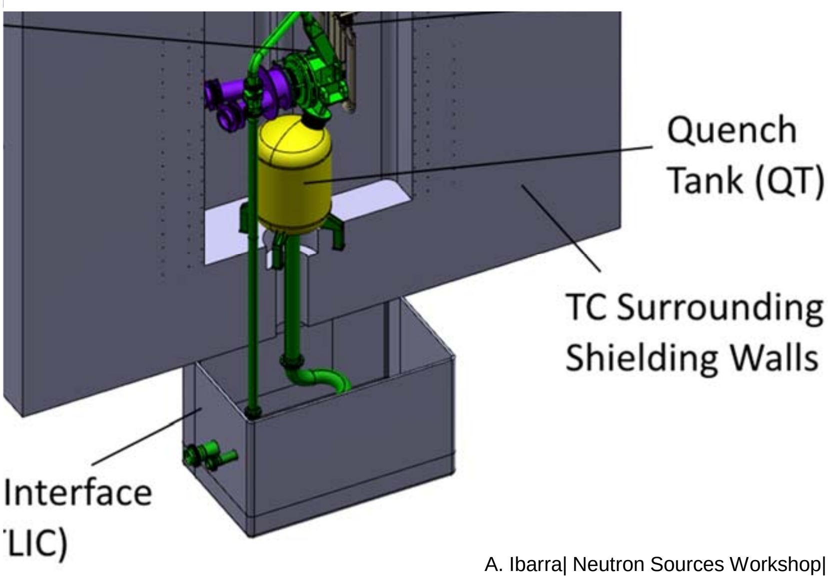
Test Systems Changes: Test Cell configuration & others

Test Cell configuration:

- **Enlarged to host the Quench Tank**
- **New volume added to define Li loop fixed points:TC-LS Interface Cell (extended liner)**

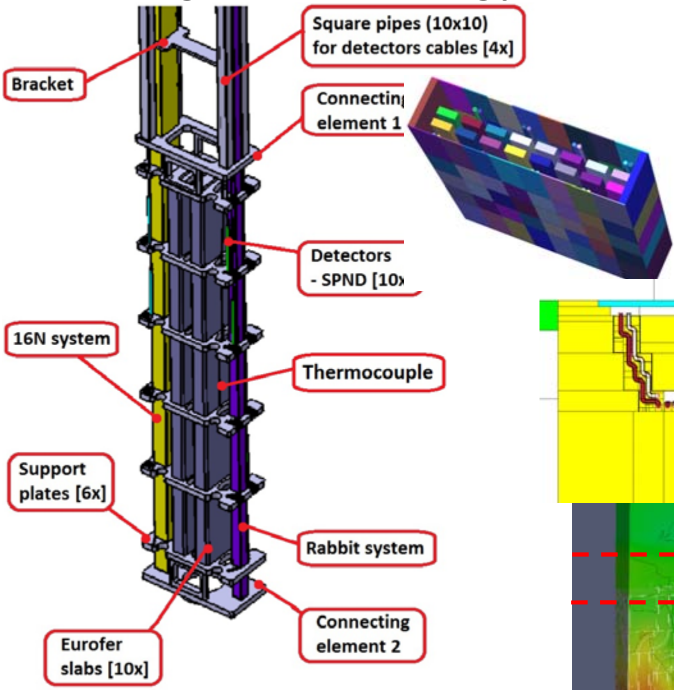
HFTM design:

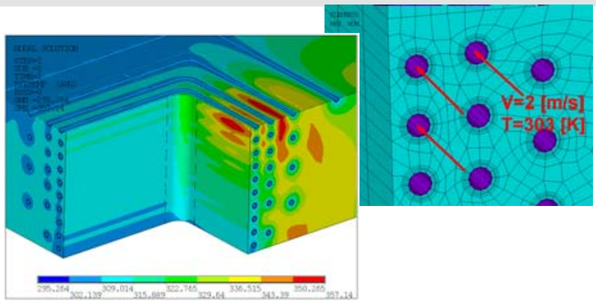
- **NaK must be avoided (Na filled proposed)**
- **Improved fabrication methods**



Test Systems: Progress of engineering design

STUMM module to characterize the facility during the commissioning phase

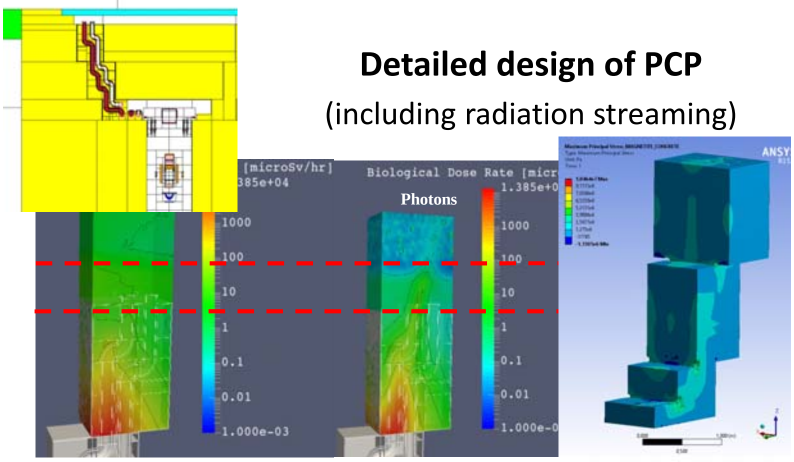




Water cooling of concrete walls

Detailed design of PCP

(including radiation streaming)



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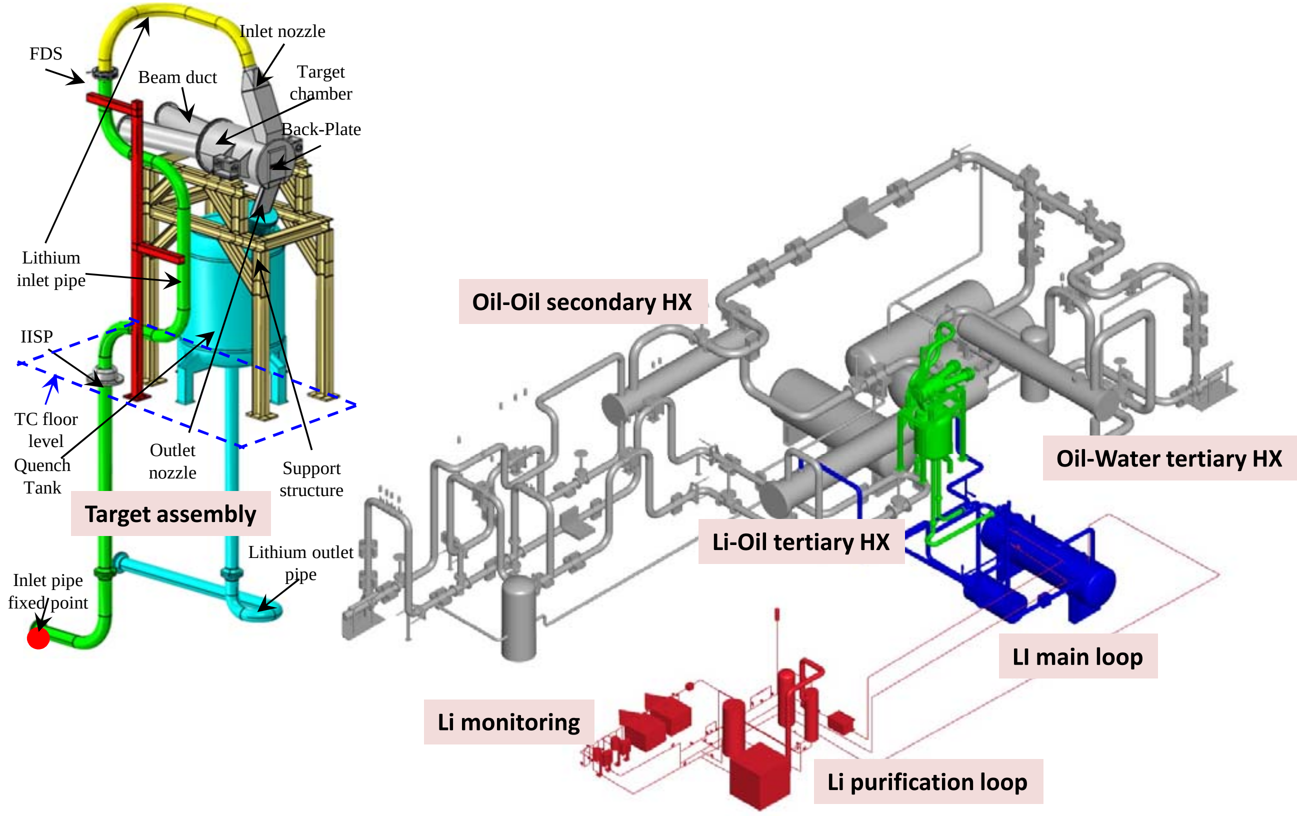
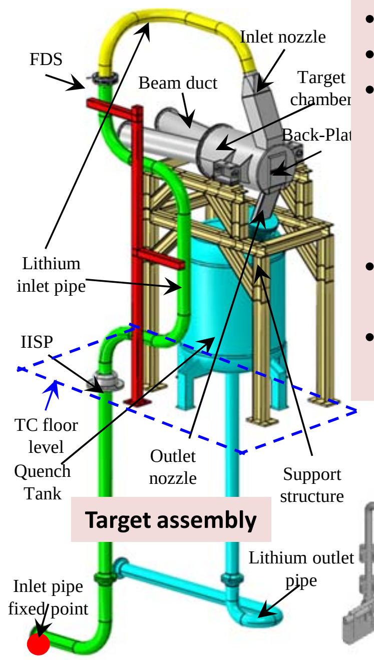
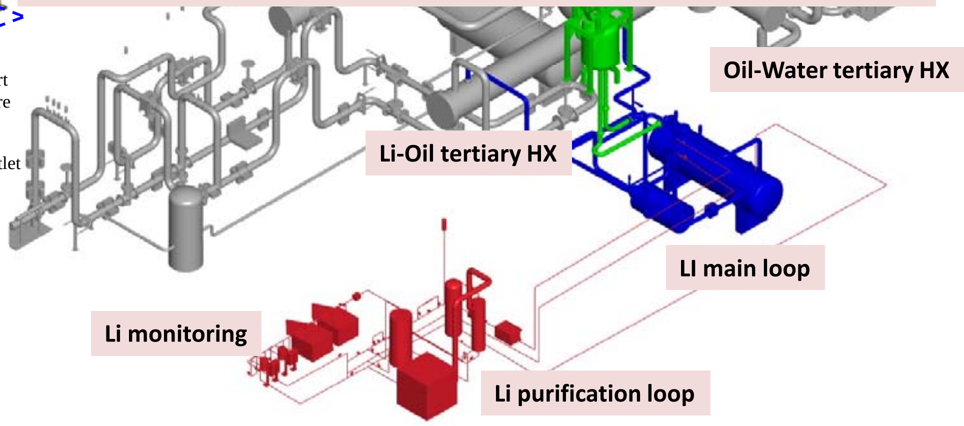


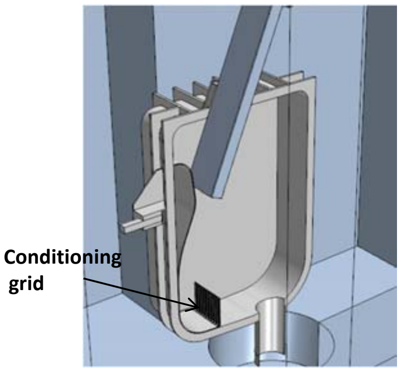
Li systems summary

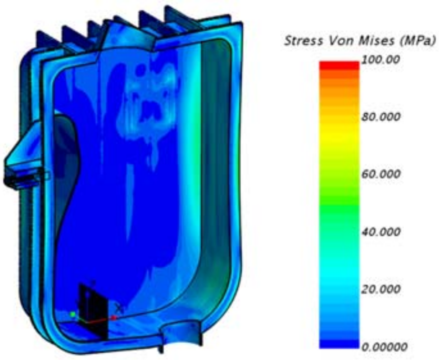


- **5 MW power handling, 15 m/s Li velocity, remote handling**
- **Main requirements: Li flow stability and Li impurities control**
- **Main challenges to be considered:**
    - **Target Assembly lifetime**
    - **Risk of cavitation, Li evaporation**
    - **T (and other radioactive ions) inventory**
- **Very relevant results from IFMIF/EVEDA validation activities**
- **Very similar to the IFMIF one but some changes implemented…**

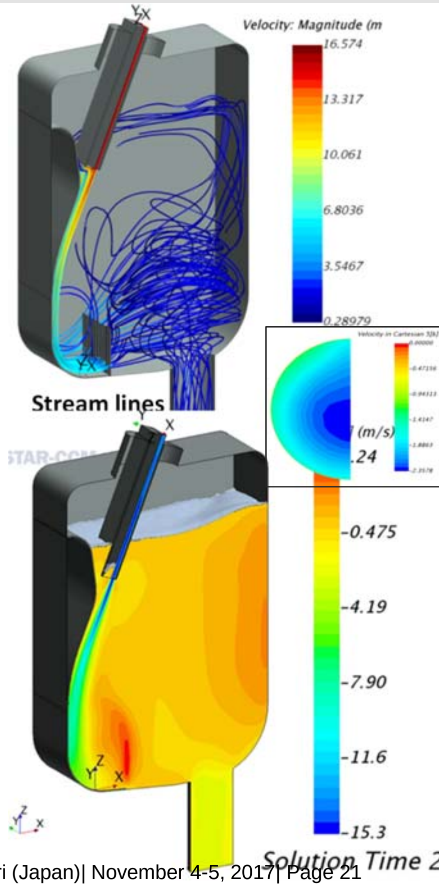


LS main changes: quench tank design





Stress distribution



Stream lines

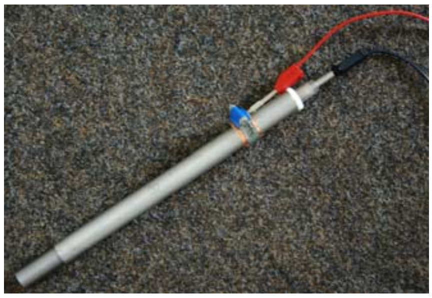
- Quench tank must be located as close as possible to the target assembly outlet to reduce the risk of cavitation
- Quench tank must have some internal structure to assure uniform outlet flow with a reduced volume (and stable surface)
- Remote maintenance must be feasible

LS main changes: Impurities control

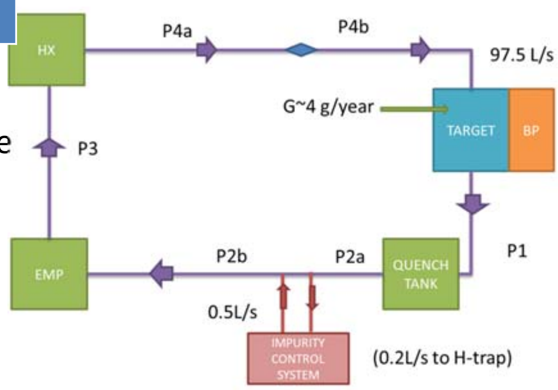
Purification requirements

Item	Value	Remarks
H content in Li	(≤10 wppm)	target values, *Under review*
T content in Li	(≤1 wppm)	
N content in Li	**(≤30 wppm)**	
O content in Li	(≤10 wppm)	
Be-7 content in Li	(-)	*Under review*
Corrosion product content in Li	(-)	*Under review*
Erosion/corrosion rate	(≤1 m m/year)	for nozzle and BP. *Under review*
	(≤ 50 m m/30 years)	for the other. *Under review*

Hydrogen electrochemical sensor



Tritium modelling by Ecosimpro

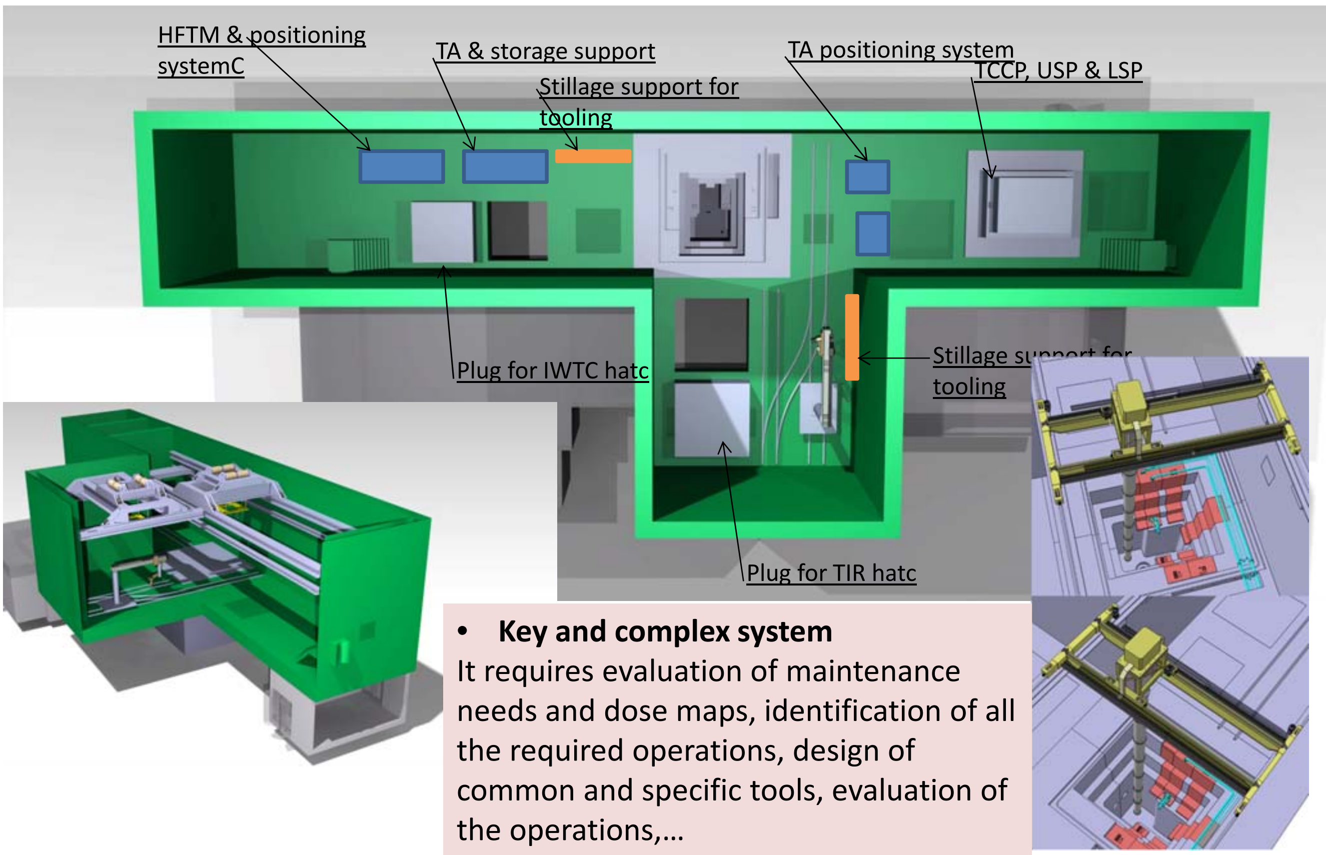


- Review of impurity contents requirements
- Purification strategy improved: N trap off-line integrated in the dump tank
- Mass transfer modelling
- Hydrogen isotopes modelling
- Target and Li monitoring diagnostics

Outline

- DONES objective and overall approach
- Accelerator Systems summary
- Test Systems summary
- Li systems summary
- Remote Handling and Building systems
- Summary

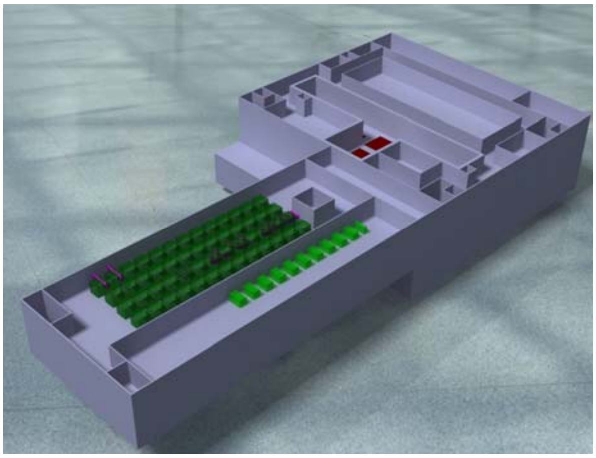
Remote Handling System



- **Key and complex system**

It requires evaluation of maintenance needs and dose maps, identification of all the required operations, design of common and specific tools, evaluation of the operations,…

Building and Plant Systems



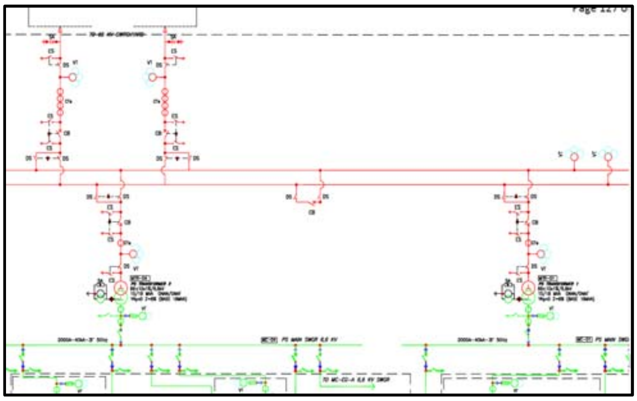
Main Building (generic site)

Dimensions ~ 160 x 75 ; Three – story

Basement/foundation slab, three suspended floors at different elevations, and one additional roof slab

Main structural system is formed by a combination of bearing walls, columns, suspended slabs and beams, all of them in-situ cast with concrete.

Included and area for Other Complementary experiments



Plant Systems

HVAC; Electrical Power System (~45 MVA); Heat Rejection System (~18 MW); Service Water System (Potable/Industrial/Demi); Service Gas Systems (Argon, Helium, Nitrogen, CA)

Radioactive Waste Treatment System (Solid, Liquid and Gas/Detritiation)

Fire Protection System (Det./ Ext.)

Outline

- DONES objective and overall approach
- Accelerator Systems summary
- Test Systems summary
- Li systems summary
- Remote Handling and Building systems
- Summary

Summary

- A fusion-like neutron source is needed as soon as possible for DEMO design and IFMIF-DONES is the proposed European alternative to be implemented in the near future
- IFMIF-DONES design is based on IFMIF design evolved to take into account a reduced scope and results obtained during the prototyping phase
- If everything moves on properly, construction can start in 2020
- Engineering design for the different systems is progressing steadily. Key results must be obtained from LIPAc in Rokkasho

End

3.2.2 A-FNS: K. Ochiai (QST)

Workshop on Advanced Neutron Source and its Application
4-5 November, 2017
Aomori-city, Japan

Advanced-Fusion Neutron Source

Kentaro OCHIAI
National Institutes for Quantum and Radiological Science and Technology (QST)
Fusion Energy Research and Development Directorate Department of Fusion Reactor Materials Research Advanced Fusion Neutron Source Design Group

CONTENTS

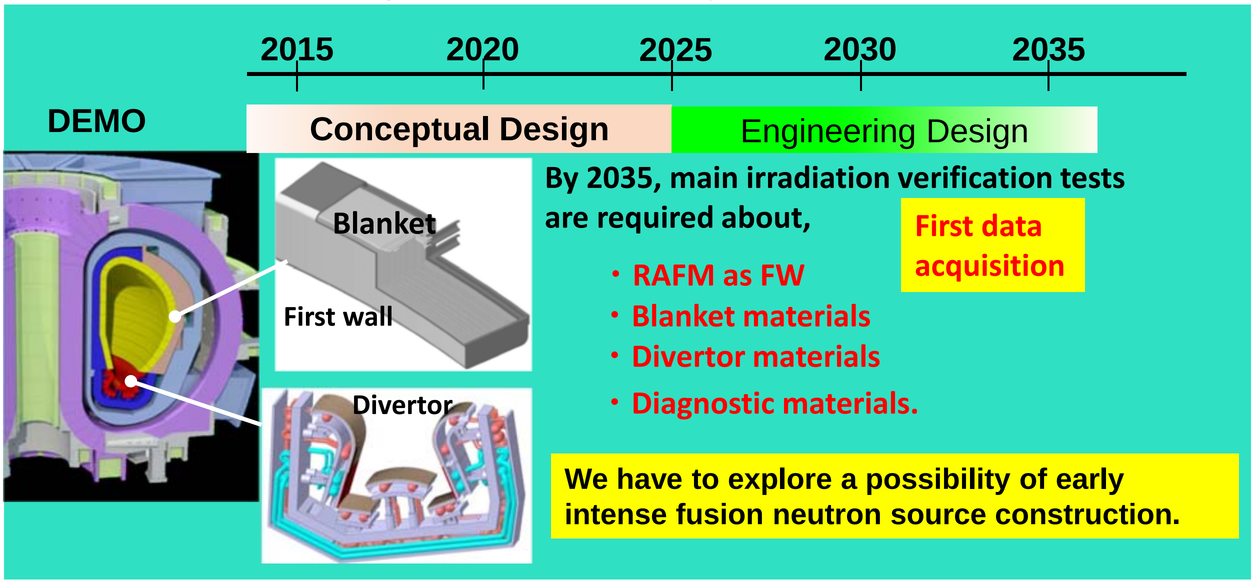
- **Background and objectives**
  - Requirement from DEMO fusion reactor design
  - Necessity of early neutron source
  - Present status of IFMIF/EVEDA
- **Advanced Fusion Neutron Source**
  - A-FNS project based on IFMIF/EVEDA
  - Site
  - Basic parameters of A-FNS
  - Schedule for A-FNS construction
  - Issues for construction and operation
- **Summary**

Background and objectives

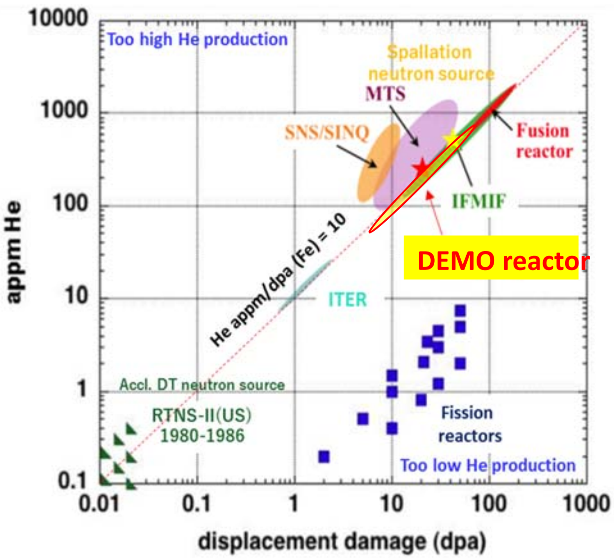
Requirement from DEMO fusion reactor design

Candidate material validation test by fusion neutron source irradiation is an essential issue for DEMO design and it should be done by the end of engineering design phase.

Relation of DEMO design (JA) schedule and required irradiation data for materials



Necessity of early neutron source



Contour map of helium production rate and displacement per atom (dpa) for fusion reactor and neutron source.

The DEMO reactor will finally exposed the structure materials up to around 80 dpa.

As an initial data for the DEMO design, we think to need the irradiation up to 10 dpa/year at least.

DT neutron source including ITER is quite not sufficient from the objectives.

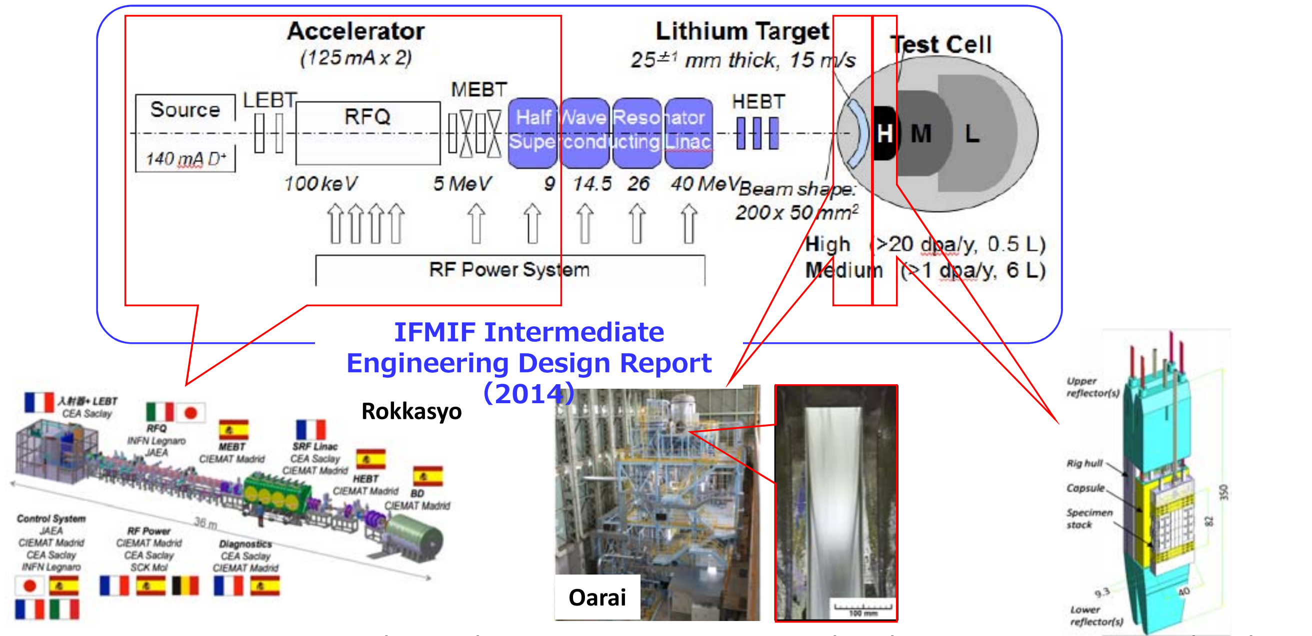
Fission reactor and spallation neutron sources will not be appropriate for the verification in the viewpoint of the ratio of He and dpa.

Therefore, **an fusion neutron source like a IFMIF should be operated around 2030 for the material irradiation.**

We propose the complete achievement of irradiation examination with an advanced fusion neutron source facility ,A-FNS which is like a half intensity of IFMIF by 2035.

Present status of IFMIF/EVEDA

From 2007, IFMIF/EVEDA has started to validate the construction of IFMIF on BA phase.



Linear IFMIF Prototype Accelerator (ongoing)

To achieve 9 MeV(CW) operation

EVEDA Lithium Test Loop (2014)

Long-term stability of high speed liquid flow validated!

High Flux Test Module (2015)

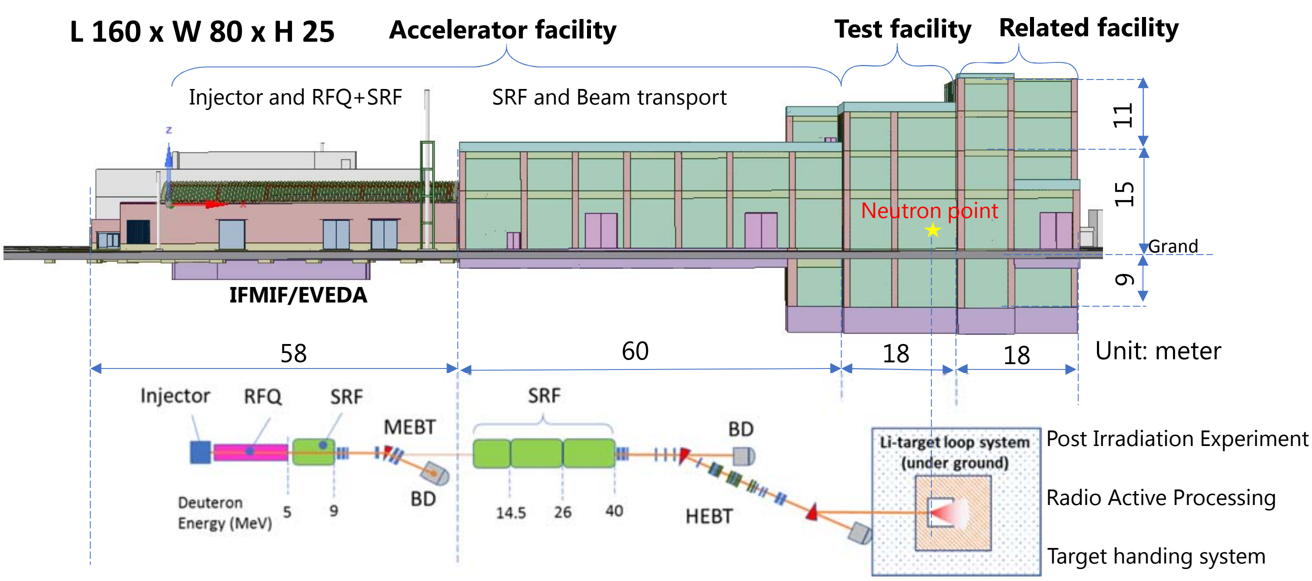
Prototype manufactured, remote handling tested!

We propose an A-FNS construction using by the IFMIF/EVEDA intellectual properties.

Advanced Fusion Neutron Source

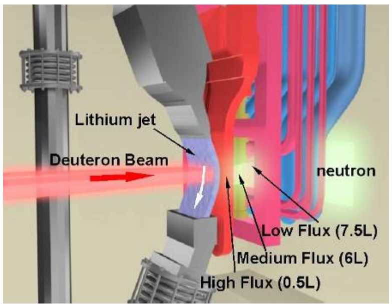
Advanced Fusion Neutron Source based on IFMIF/EVEDA

From the viewpoint of the effective use, we will start to an conceptual design activity of an using by the IFMIF/EVEDA.

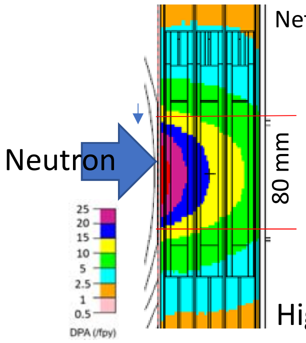


Cross sectional views of an A-FNS construction

Basic parameters of A-FNS



Schematic view of test cell (Ref. IFMIF design)



Net volume for Irradiation

3cc at 25dpa/fpy
15cc at 20 dpa/fpy
30cc at 15 dpa/fpy
60cc at 10 dpa/fpy

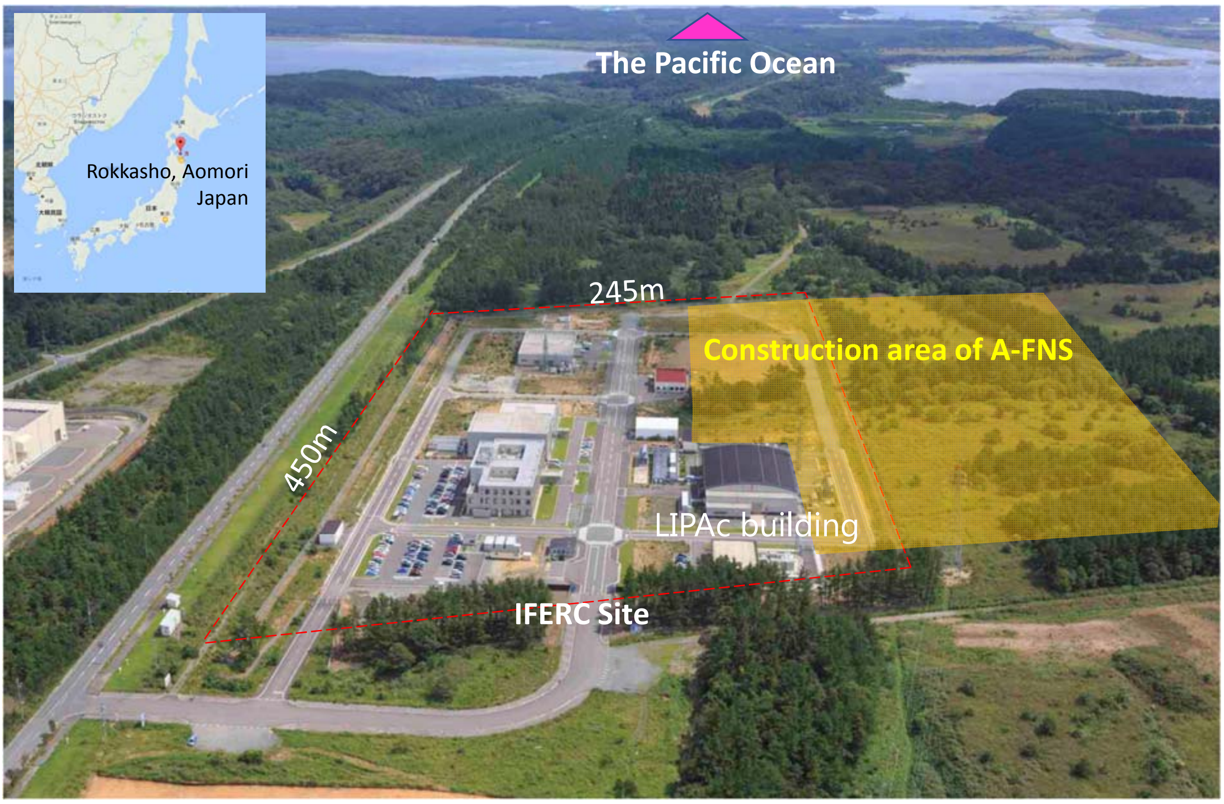
High Flux Test Module

Relation of irradiation volume and dpa/fpy (A-FNS)

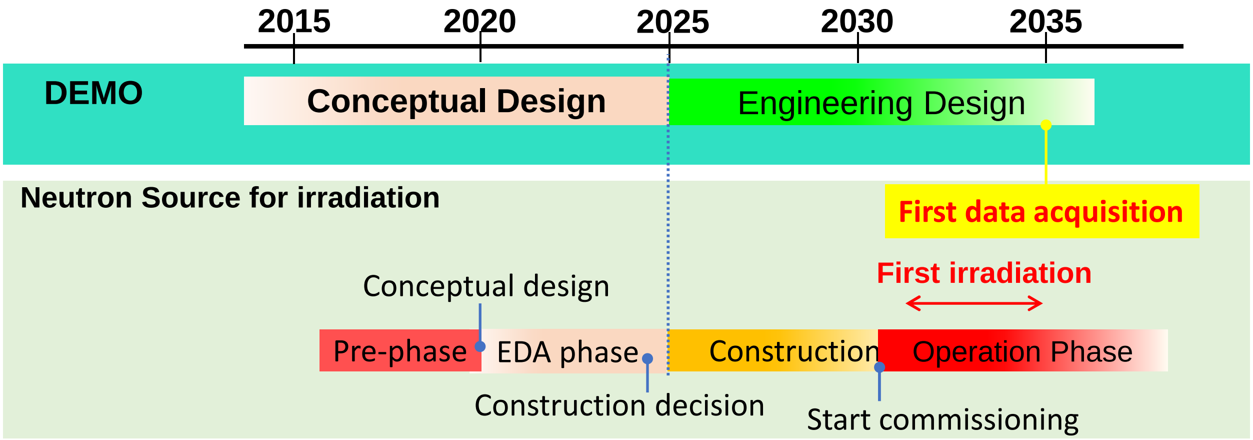
Beam	Particle Energy Current Foot print Incident angle Availability	Deuteron 40 MeV 125 mA (CW) 200 x 50 mm^2 Normal 33% at least
Target	Material Temp. Velocity Thickness Window	lithium Liquid target (jet) 200 - 270 ℃ 10-15 m/s at target 25 mm Free surface (no window)
Neutron	Intensity (at back plate) Average flux Helium P. R Displacement HePR/dpa	6.8 x 10^{16} neutron/s 6.0x 10^{14} n/cm^2/s 3.12×10^2 appm/fpy 24.7 dpa/fpy 12.6

fpy: full power year

Site of A-FNS



Schedule for A-FNS construction



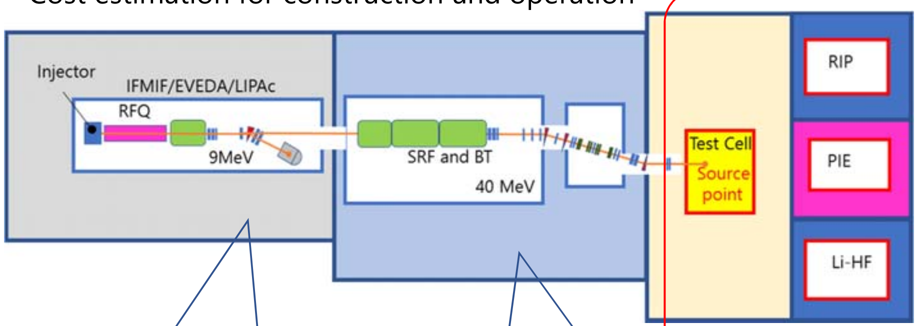
Issues for construction and operation

Technical issues must be solved by 2025 based on the following items.

Precise irradiation plans and their schedules

Technical issues for plant safety and regulation

Cost estimation for construction and operation



As others

Storage building

Console area or building

- Achievement of LIPAc
- Technical feedback from the LIPAc long operation
- Safety

- Extension of building
- Extension of SRF and beam line
- Safety

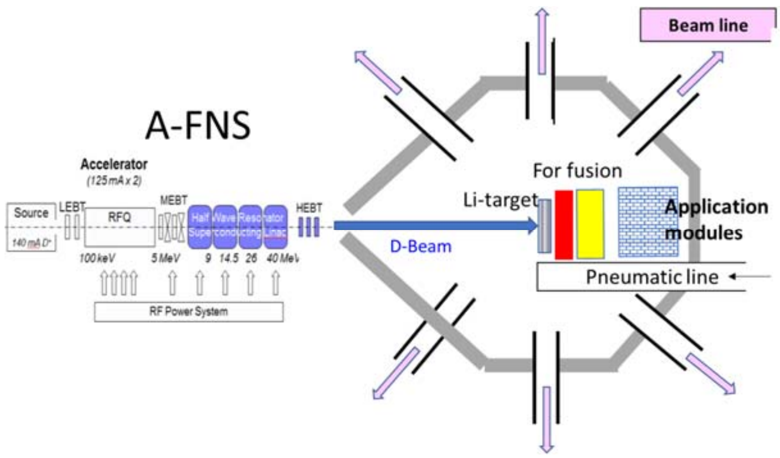
- Purification system of Li target
- Optimization of lithium target system
- Optimization of HFTM
- Remote handing for TA and TM
- Remote handing from TC to PIE
- Designs of PIE, RIP and Li-HF

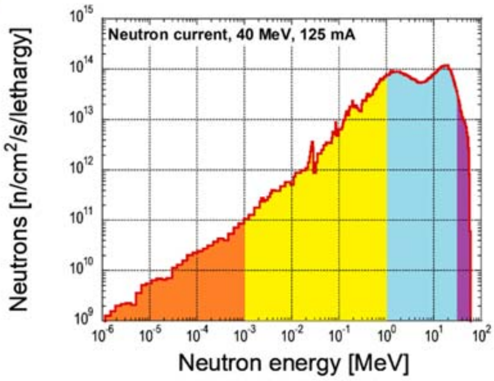
We just start to verify the design and their development.

Another application proposal of A-FNS

A-FNS should be also utilized like multi-purposes neutron source.

Neutron beam station of A-FNS for material analysis
(it will be available to not only for general material analysises also fusion material micro-analysis)
RI production module installation (ex. Mo-99)
Pneumatic line to use the intense neutron field





We just start to the investigations for the muti-purpose on A-FNS

Summary

- For fusion DEMO reactor design, we have started the design activity of an advanced fusion neutron source (A-FNS) facility.
- From the viewpoint of the effective use of IFMIF/EVEDA intellectual properties, as a candidate, first of all, we propose the extension type .
- A-FNS will be like a half size of IFMIF. The volume of irradiation will be narrow than half of IFMIF case.
- A-FNS should be operated around 2030 for the data acquisition and the availability have to be 33% at least.
- In case of the test facility, the hot area of remote handing will be most important issue. Especially, the exchange of Li-target assembly will be most serious action.
- For the construction of A-FNS, we will need to organize a consortium, not only QST, also institutes, universities and corporations.

Related presentations in ICFRM-18

- 11.6 17:00-19:00 6PT56 S.Kwon (QST, Japan) Investigation on A-FNS Neutron Spectrum Monitor System

- 11.7 16:40-18:40 7PT55 M. Nakamura (QST, Japan) Impact of the Beam Injection Momentum on the Free Surface of the Liquid Lithium Target of Advanced Fusion Neutron Source

- 11.8 16:40 - 18:40 8PT56 Investigation of Mo-99 Radioisotope Production by d-Li Neutron Source M. Ohta

- 11.9 16:00-18:00 9PT55 H. Kondo (QST, Japan) Experimental Study on Application of Large-Scale Cold Trap and Impurity Monitoring to Liquid Lithium for Intense Fusion Neutron Source

3.2.3 BISOL: Y. Wang (Peking Univ.)

北京大學 PEKING UNIVERSITY

BisoL 中国原子能科学研究院 CHINA INSTITUTE OF ATOMIC ENERGY 北京大學 PEKING UNIVERSITY

Multi-Aimed Intense Neutron Source (MAINS) based on BISOL

Yan Sha (on behalf of BISOL-MAINS team)
State Key Laboratory of Nuclear Physics and Technology
Peking University

Workshop on Advanced Neutron Source and its Application
Nov. 04-05, 2017 Aomori, Japan

北京大學 PEKING UNIVERSITY

OUTLINE

- Background
- Brief history of BISOL
- Concept of MAINS
  - D^+ Accelerator
  - Liquid Lithium Target and Irradiation Unit
  - Liquid Li Loop
  - Neutron field properties
- Outlook

OUTLINE

- Background
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  - LLi Loop
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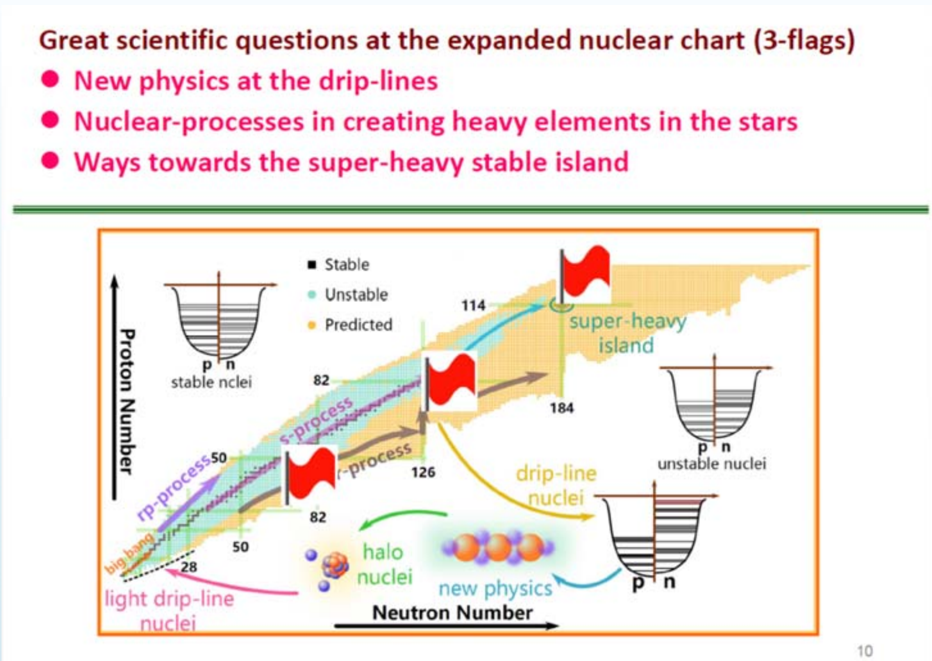
- Outlook

BISOL

Beijing Isotope-Separation-On-Line Neutron-Rich Beam Facility

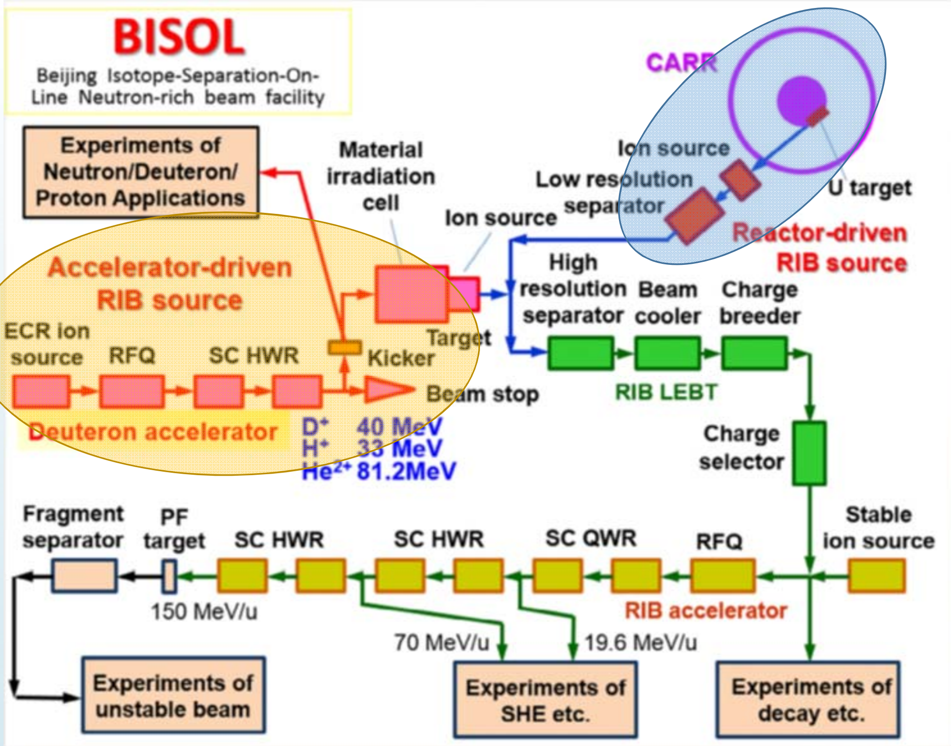
— A facility to producing neutron rich rare isotope ions by means of ISOL+PF



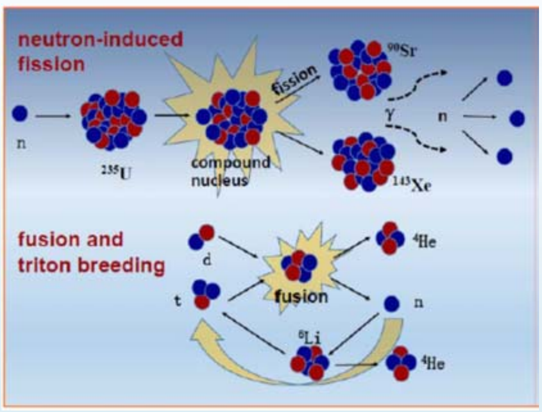
Double sources

I. CARR (China advanced research reactor)

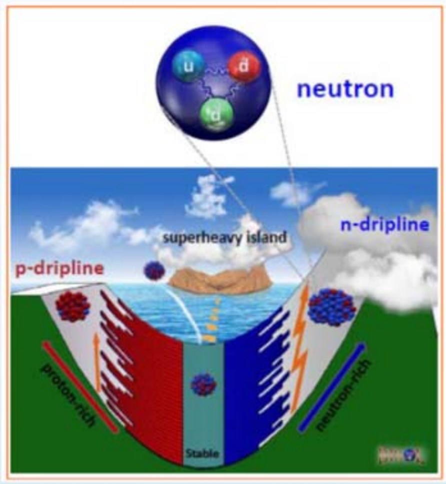
II. Intense D^+ Accelerator



Requirements of Intense Fast Neutron Source



Material research for fusion and fission energy, neutronics, imaging, material analysis,single particle effects……



Basic nuclear scientific research

China fusion energy roadmap

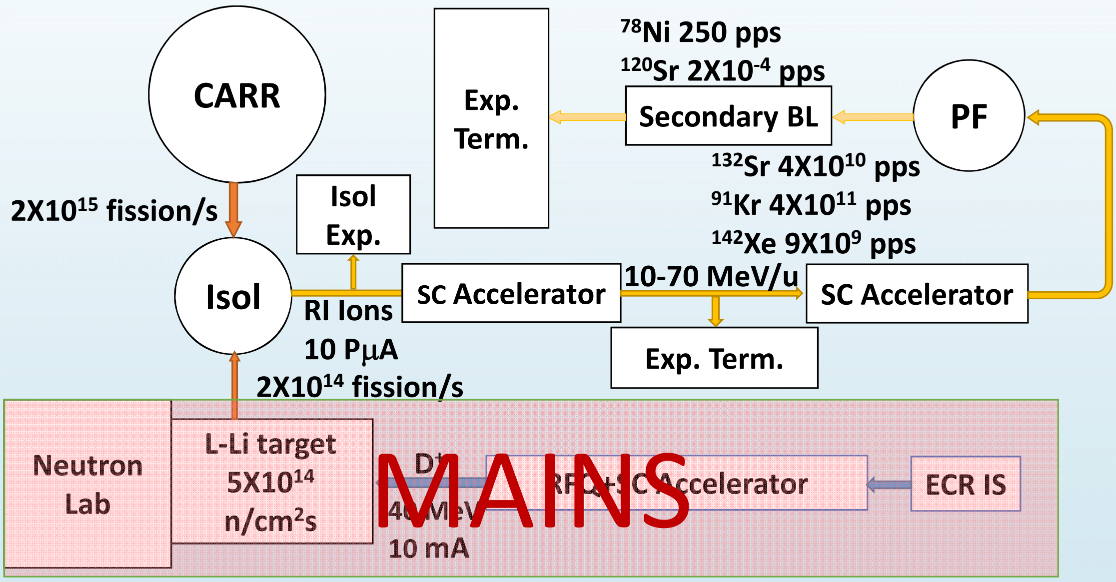
CFETR:

5-10 dpa in Phase I
50-100 dpa in Phase II

Wan, et. al., Nucl. Fusion, 57, 102009, 2017

BISOL-MAINS

Multi-Aimed Intense Neutron Source driven by D^+ accelerator



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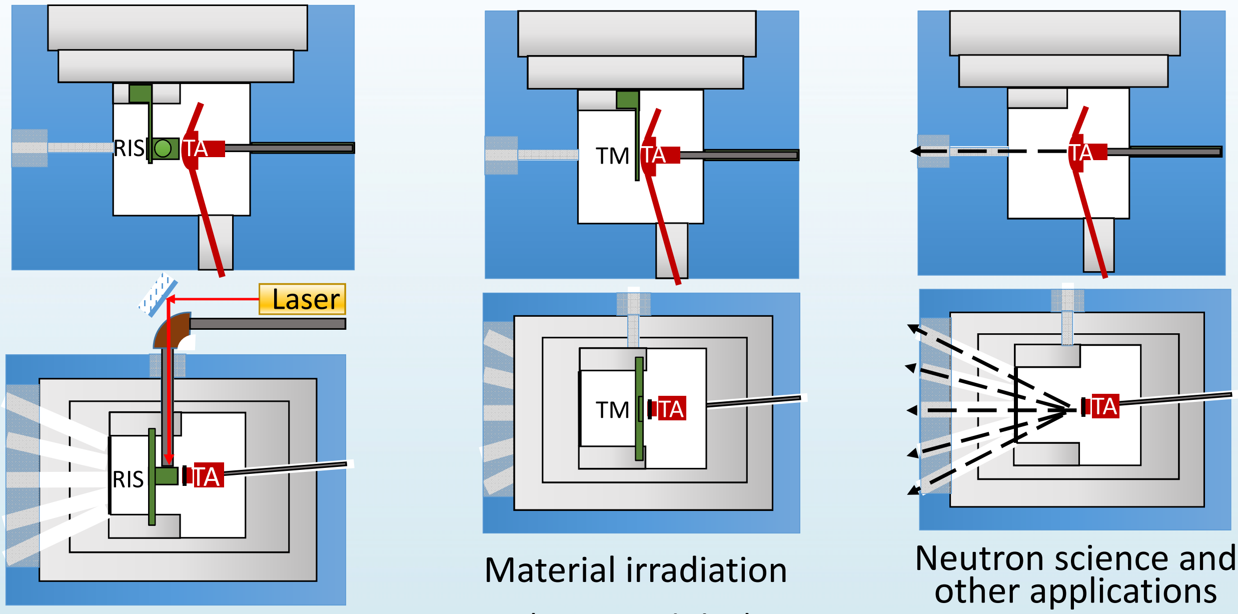
MAINS

Multi-Aimed Intense Neutron Source driven by D+ accelerator

Irradiation Unit

Side view

Top view



ISOL (Fission ion source)

Material irradiation

(Test modules)

Neutron science and other applications

(neutron beams)

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OUTLINE

- Background
- Brief history of BISOL
- Concept of MAINS
  - D^+ Accelerator
  - Liquid Lithium Target and Irradiation Unit
  - LLi Loop
  - Neutron field properties
- Outlook

Major Milestones

2011: **CIAE and PKU signed agreement to jointly promoting an ISOL-type RIB facility in Beijing area. As a result the previously proposed CARIF and ImPUF were merged into Beijing-ISOL**

北京大学与中国原子能科学研究院
共同推动建设 ISOL 型大科学装置的协议

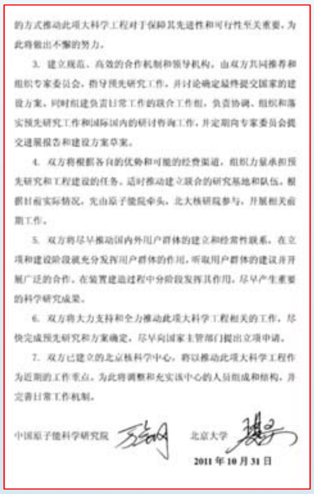
中国原子能科学研究院创建于 1950 年，是我国第一个核科学技术研究机构，是我国重要的核科学技术先导性、基础性、前瞻性的综合研究基地，拥有中国先进研究堆、中国实验快堆、北京串列加速器升级工程和核燃料后处理放化实验设施等众多科技创新平台。

北京大学创办于 1898 年，是我国第一所国立综合性大学，是国家"985 工程"重点建设的大学之一。1955 年，北京大学建立了我国高校中第一个核科技专业，几十年来为国家的核事业培养了大批骨干人才。近年来，在我国核科技行业率先建立了国家重点实验室和核物理人才培养基地。

根据国际核科学技术发展的态势，以双方各自提出的 CARIF 和 ImPUF 计划为基础，共同提出在北京地区建设国际先进水平的 ISOL 型大科学装置，以此为基础建立国际一流的基础和应用研究基地。

1. 双方共同商定的目标是：在北京周边适当地区建设一个国际先进水平的 ISOL 型大科学装置，该装置瞄准核科学的重大前沿问题及核能和多学科应用中的某些关键问题，同时带动相关高新技术的发展和突破，并在合作建设运行大科学装置的过程中，形成大学和科研院所联合研究和人才培养的创新模式。

2. 为实现上述目标，双方将联合规划并提出申请，并结合各自的优势，分工开展必要的预先研究工作，包括不同方案的研究和比较；同时协同在国内国际开展广泛的研讨和咨询，以期未来提出的正式方案得到科技界的广泛认同和支持。双方均认为，始终以开放和国际化



的方式推动此项大科学工程对于保障其先进性和可行性至关重要，为此将做出不懈的努力。

3. 建立规范、高效的合作机制和领导机构。由双方共同推荐和组织专家委员会，指导预先研究工作，并讨论确定最终提交国家的建设方案。同时组建负责日常工作的联合工作组，负责协调、组织和落实预先研究工作和国际国内的研讨咨询工作，并定期向专家委员会提交进展报告和建设方案草案。

4. 双方将根据各自的优势和可能的经费渠道，组织力量承担预先研究和工程建设的任务，适时推动建立联合的研究基地和队伍。根据目前实际情况，先由原子能院牵头，北大核研院参与，开展相关前期工作。

5. 双方将尽早推动国内外用户群体的建立和经常性联系，在立项和建设阶段就充分发挥用户群体的作用，听取用户群体的建议并开展广泛的合作，在装置建造过程中分阶段发挥其作用，尽早产生重要的科学研究成果。

6. 双方将大力支持和全力推动此项大科学工程相关的工作，尽快完成预先研究和方案确定，尽早向国家主管部门提出立项申请。

7. 双方已建立的北京核科学中心，将以推动此项大科学工程作为近期的工作重点，为此将调整和充实该中心的人员组成和结构，并完善日常工作机制。

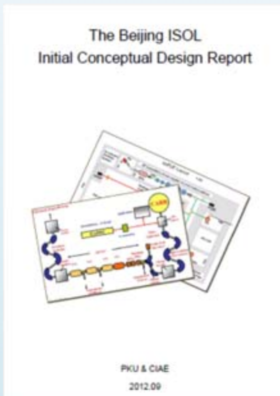
中国原子能科学研究院 北京大学

2011 年 10 月 31 日

Major Milestones

Oct. 2012: **An IAC was formed and a review meeting was held at PKU to evaluate *the "Initial Conceptual Design of the BISOL".***

"The Committee considers the research potential of the proposed facility in both, basic as well as applied and interdisciplinary research, as excellent and highly competitive on the world level. It promises a unique science reach in several respects, in particular with regard to the most neutron rich exotic nuclei and the study of the astrophysical r-process."



北京大学 PEKING UNIVERSITY

Major Milestones

2013: the advanced ISOL-type facility was adopted in "the national mid- and long-range plan (till 2030) of the major facilities for science and technology development".

Aug. 2014: a Xiang Shan Forum (503th meeting in the series) was successfully organized and a road map for major nuclear physics research facilities was established, including the BISOL as the next major facility.

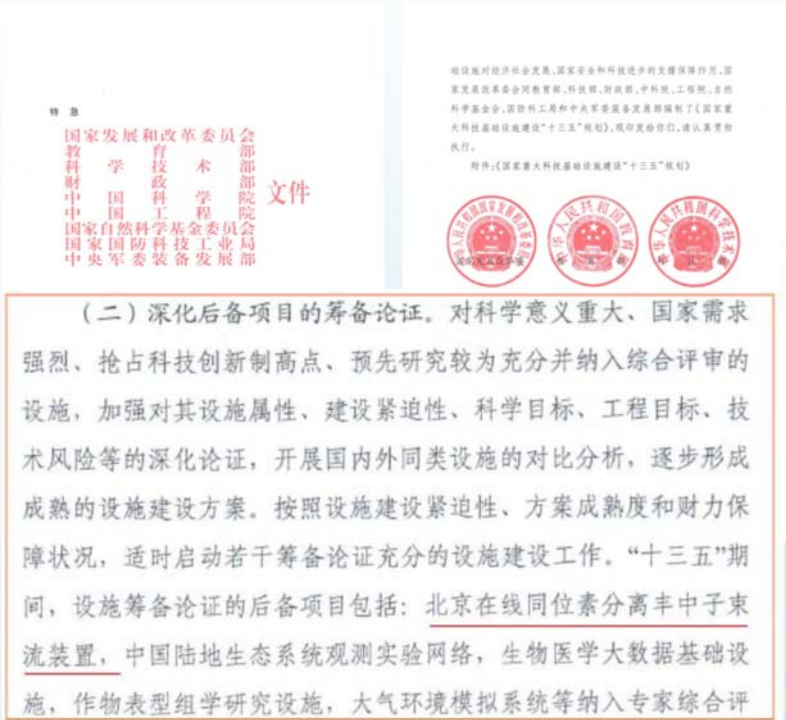
May 2016: a domestic expert meeting was held at CIAE to evaluate the preparation works of the BISOL, aiming at a proposal to the 13th 5-year plan of the central government of China.

北京大学 PEKING UNIVERSITY

Major Milestones

May-June 2016: proposed large-scale science facilities (more than 50 proposals in all) were reviewed by the National Development and Reform Council. BISOL was successfully classed into the list of the preparation facilities (10+5 facilities in total).

Dec. 2016: the government has officially announced the results for the 13th 5-year plan.



特急

国家发展和改革委员会
教育部
科学技术部
财政部
中国科学院
中国工程院
国家自然科学基金委员会
国家国防科技工业局
中央军委装备发展部
文件

础设施对经济社会发展、国家安全和科技进步的支撑保障作用，国家发展改革委会同教育部、科技部、财政部、中科院、工程院、自然科学基金会、国防科工局和中央军委装备发展部编制了《国家重大科技基础设施建设"十三五"规划》，现印发给你们，请认真贯彻执行。

附件：《国家重大科技基础设施建设"十三五"规划》

（二）深化后备项目的筹备论证。对科学意义重大、国家需求强烈、抢占科技创新制高点、预先研究较为充分并纳入综合评审的设施，加强对其设施属性、建设紧迫性、科学目标、工程目标、技术风险等的深化论证，开展国内外同类设施的对比分析，逐步形成成熟的设施建设方案。按照设施建设紧迫性、方案成熟度和财力保障状况，适时启动若干筹备论证充分的设施建设工作。"十三五"期间，设施筹备论证的后备项目包括：北京在线同位素分离丰中子束流装置，中国陆地生态系统观测实验网络，生物医学大数据基础设施，作物表型组学研究设施，大气环境模拟系统等纳入专家综合评

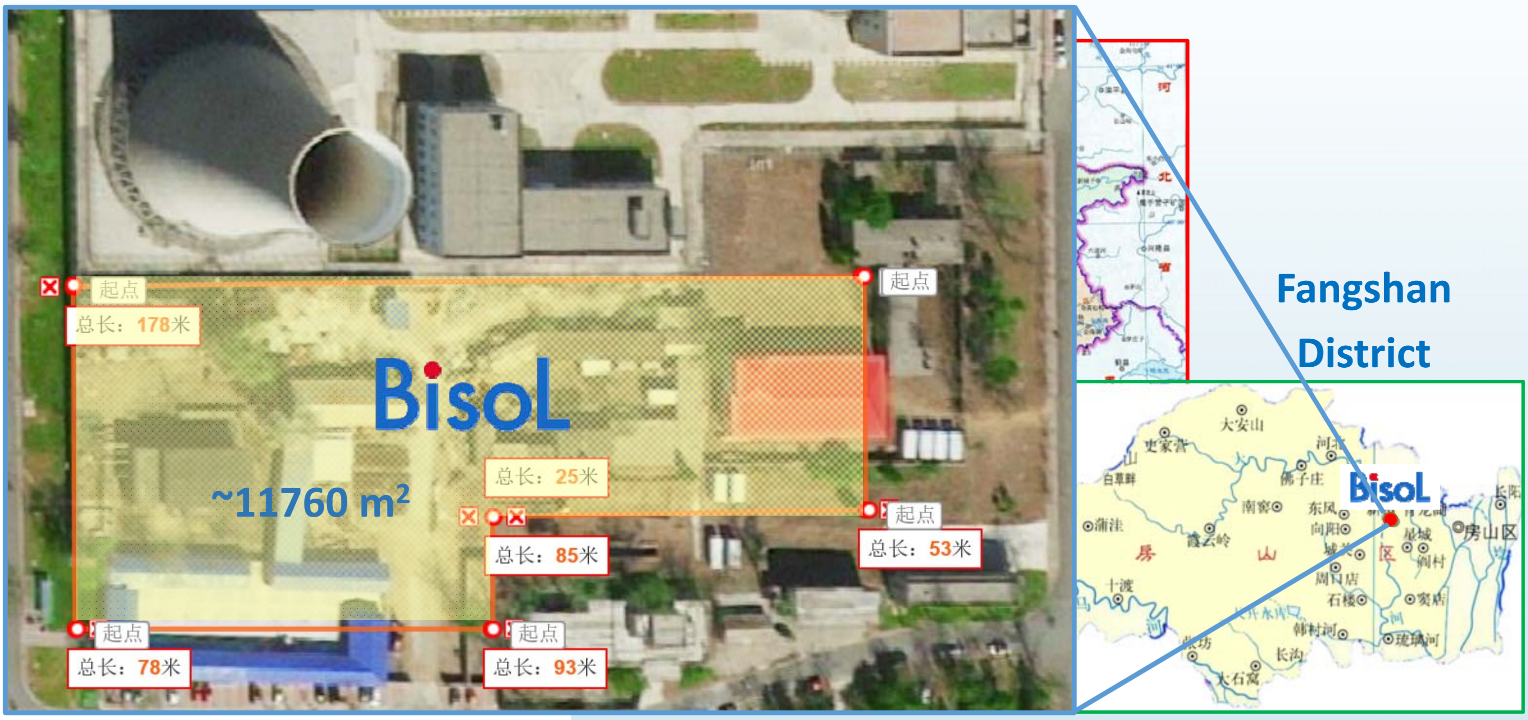
Major Milestones

Jan. 2017: a specialized IAC meeting was held at PKU-CIAE, **dedicated to the accelerator based intense neutron source, in particular the high-power target systems**.

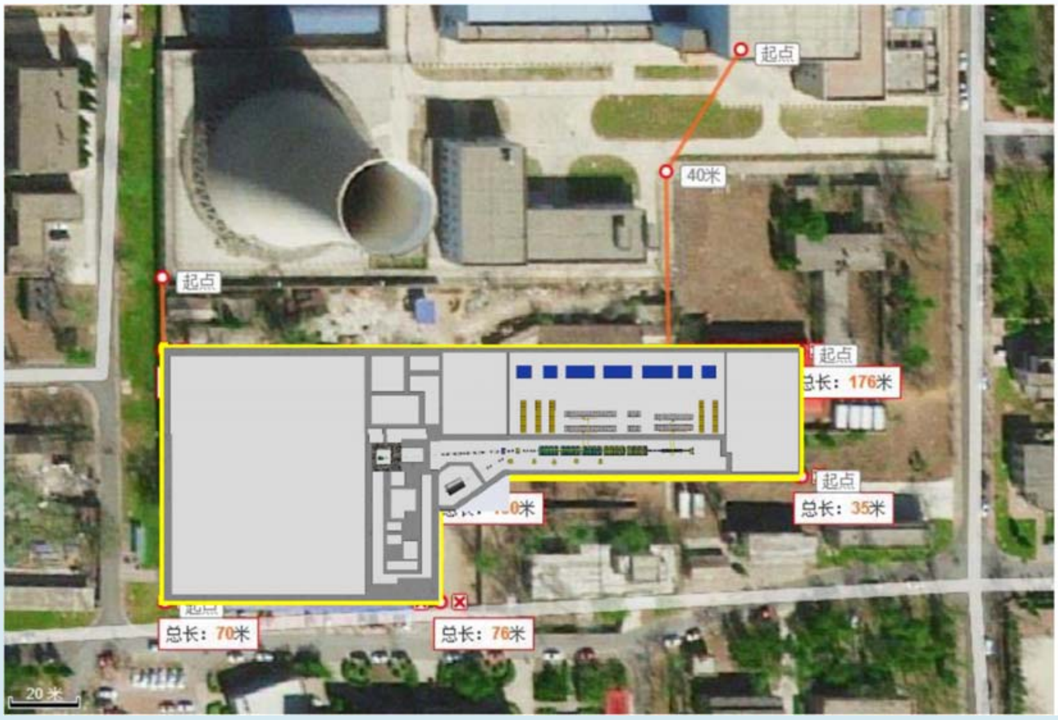
Mar. 2017: the 1st BISOL user meeting was held at PKU, with ～ 150 participants and very active discussions.

Jun. 2017: BISOL proposal was finalized and evaluated by an internal committee, being ready for the next national review and the next IAC review.

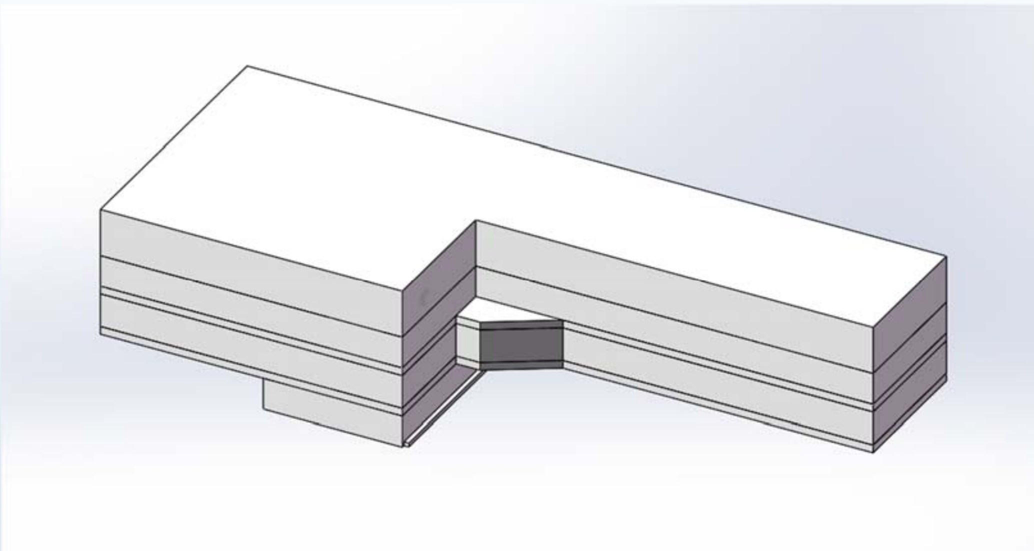
SITE of BISOL - CIAE



SITE of BISOL - MAINS



Infrastructure



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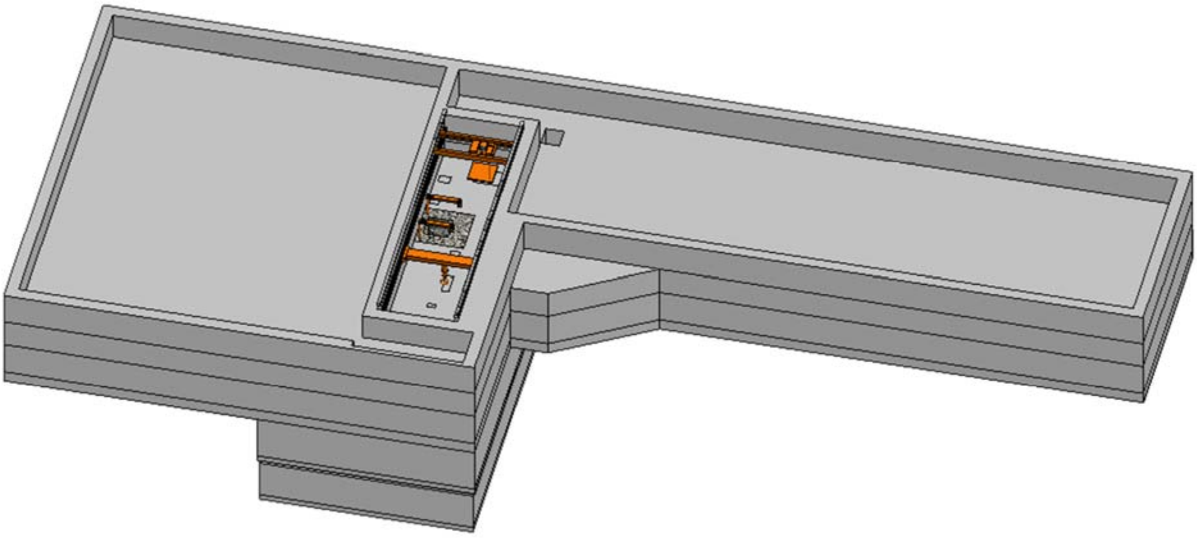
Infrastructure



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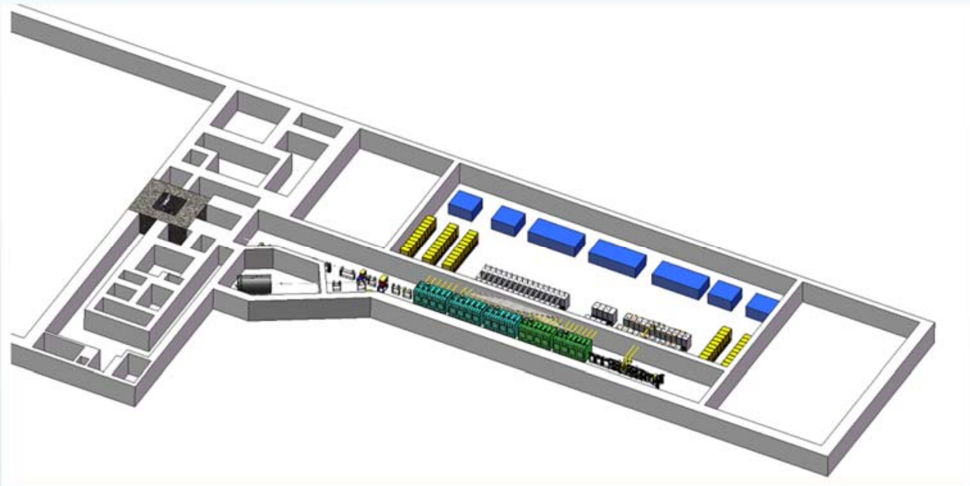
OUTLINE

- Background
- Brief history of BISOL
- Concept of MAINS
  - D^+ Accelerator preliminary design
  - Liquid Lithium Target and Irradiation Unit
  - LLi Loop
  - Neutron field properties
- Outlook

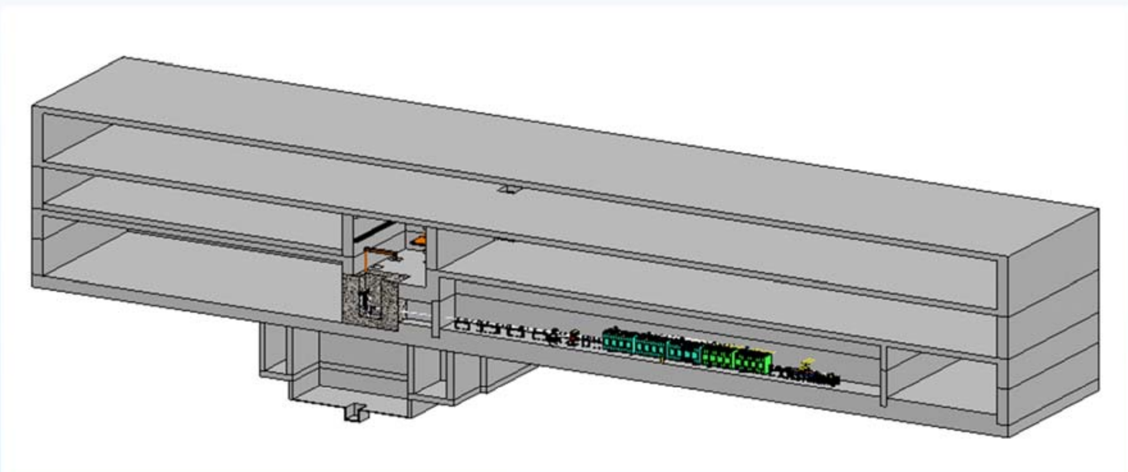
MAINS

CW D^+ beam: 40 MeV, 10mA (Phase I); L-Li target: 100(W)×25(T), 20 m/s



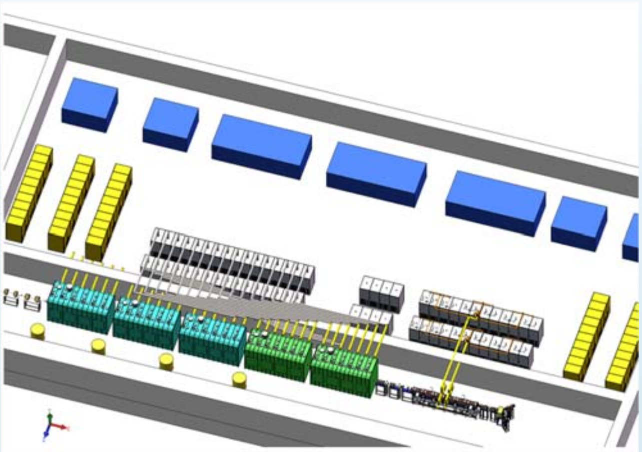
main part in -1 ~-3 layer of the BISOL building

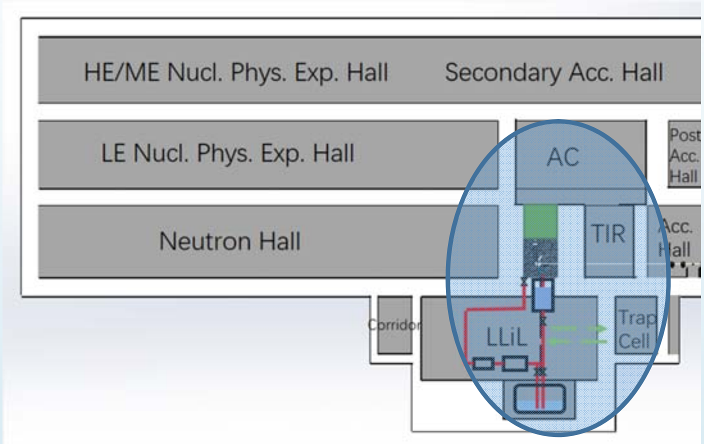
MAINS



MAINS

Accelerator





Irradiation facility, Li target and Li Loop

BISOL-MAINS

BISOL-MAINS parameters compared to IFMIF

	Energy (MeV)	Ion	Current (mA)	Target	Irradiation Volume (cm^3)				
					$>10^{15}$ $n/cm^2 \cdot s$	$>5 \cdot 10^{14}$ $n/cm^2 \cdot s$	$>10^{14}$ $n/cm^2 \cdot s$	$>5 \cdot 10^{13}$ $n/cm^2 \cdot s$	$>10^{13}$ $n/cm^2 \cdot s$
BISOL-MAINS I	**40**	**D^+**	**10**	**Liquid Li**	**0**	**0**	**~12**	**~60**	**~700**
BISOL-MAINS II	40	D^+	20	Liquid Li	0	0	~60	~170	~2000
BISOL-MAINS III	40	D^+	50	Liquid Li	0	~12	~240	~700	~7900
IFMIF	40	D^+	2×125	Liquid Li	BP	~500 (HF)	~6000 (MF)		LF

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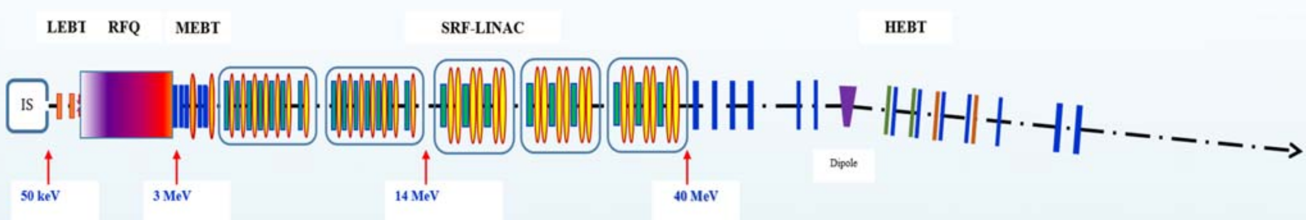
D^+ accelerator



- LEBT, RFQ, MEBT, SRF, HEBT
- SRF Linac: 5 cryomodules, HWR
- Total length: 75 m
- Code: ParmteqM, Toutatis, TraceWin

Particles	Deuteron	
Energy	40	MeV
Current	10	mA
Beam power	400	kW
rf frequency	162.5	MHz
Duty factor	100	%
Beam loss (E>3 MeV)	<1	W/m

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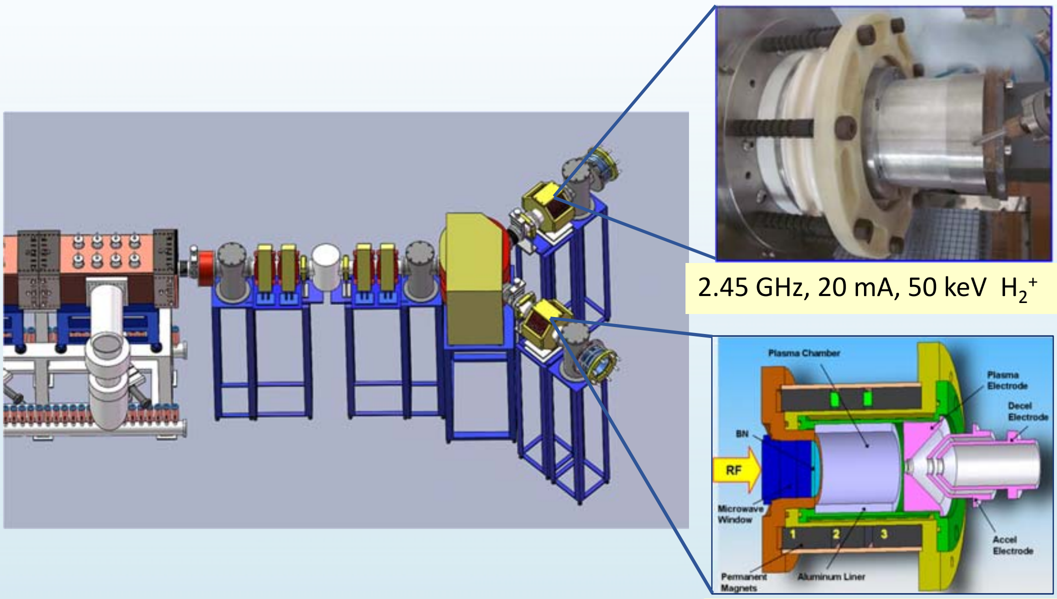
Ion Sources



2.45 GHz, 20 mA, 50 keV H_2^+

2.45 GHz, 20 mA, 50 keV D^+

- For commissioning of accelerator instead of D^+
- Providing H_2^+ beam for experiment terminal;
- As a redundancy of D^+ source

PKU PMECRIS

120 mA H^+
83 mA D^+

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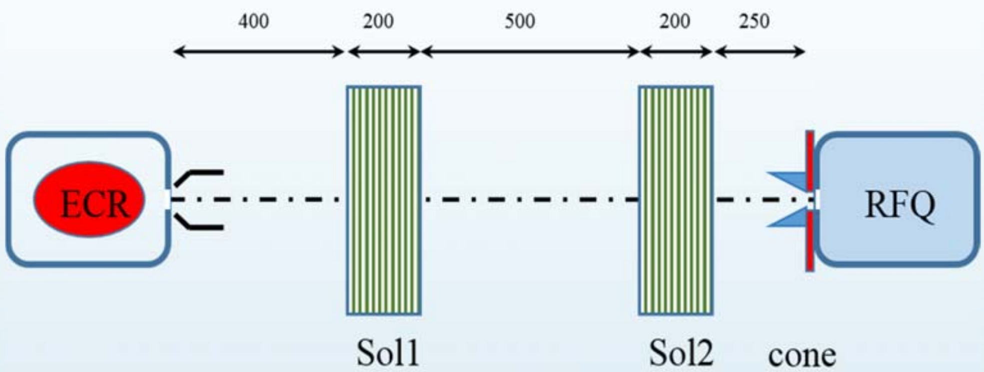
LEBT



- 2 identical solenoids whose effective pole length is 200 mm.
- 2 steerers (BPMs) in solenoids.
- Solenoids magnetic field: 0.35T & 0.41 T, aperture 120 mm.
- The total length of beam line: 1.55 m
- diagnose instruments: ACCT, FC, emittance meter

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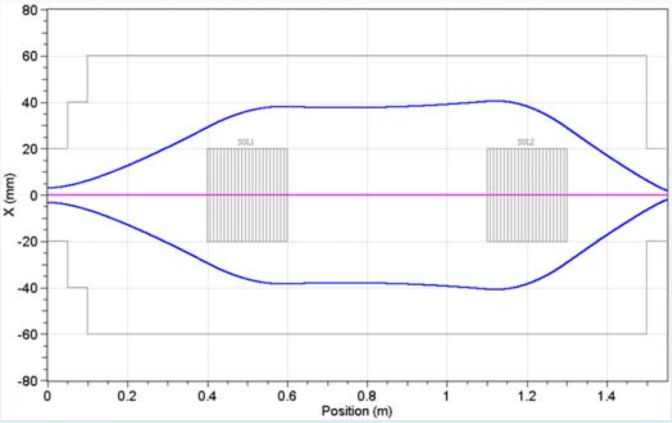
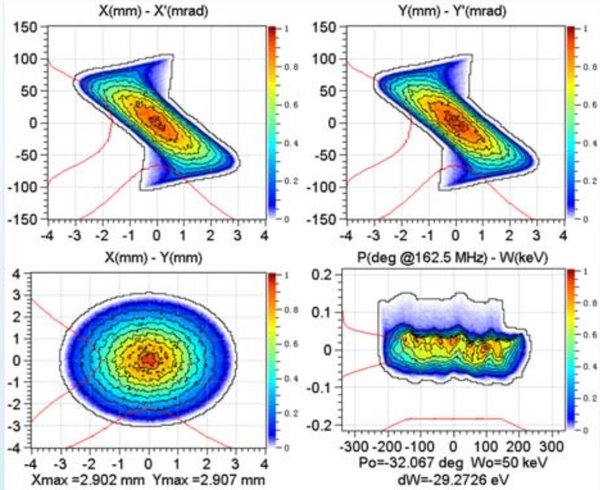
LEBT





- ECR-IS extraction beam parameters: $\varepsilon_n = 0.17$ mm · mrad
- RFQ entrance beam parameters:
  $\varepsilon_n = 0.195$ mm · mrad, $\alpha = 1.33$ and $\beta = 0.042$ mm/mrad
- Match to RFQ

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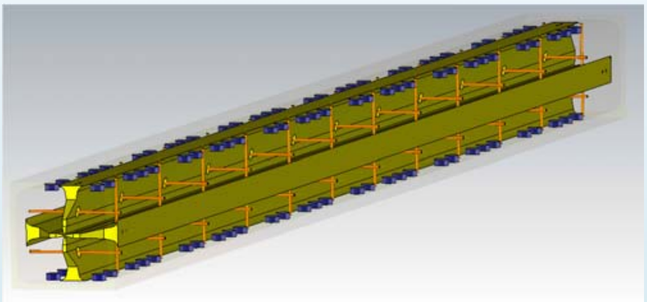
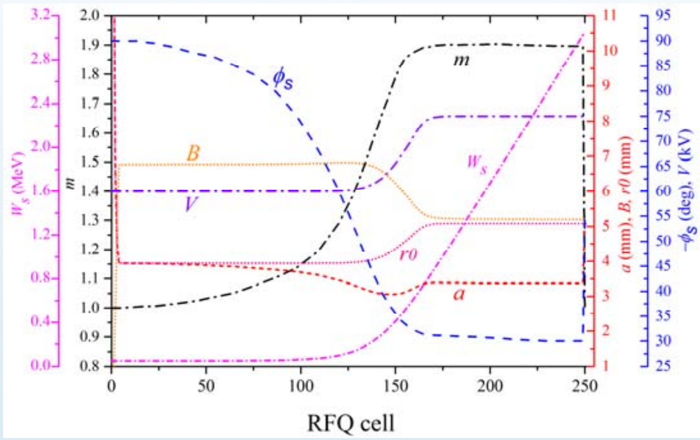
RFQ accelerator

4 vane RFQ, quadrilateral cavity
with π mode stabilizing rods
Deposited power 96 W



RFQ CST model



RFQ kinetic parameter curves

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RFQ

Design strategy:

- *High beam transmission*
- *Low rf power dissipation*
- *Low surface peak field*
- *High beam quality at the RFQ exit*
- *Short RFQ length*

Parameter	Value	Unit
Particle	D^+	
Frequency	162.5	MHz
Input energy	50	keV
Output energy	3.0	MeV
Beam Current	20	mA
Inter-vane voltage min/max	60/75	kV
Vane length	5.03	m
Maximum peak surface electric field	19.87	MV/m
Kilpatrick coefficient	1.46	
Minimum aperture radius	3.05	mm
Average aperture min/max	3.94/5.09	mm
Synchronous phase	-90 ~ -30	deg
Max. modulation factor	1.90	
Trans. input normalized rms emit.	0.20	mm·mrad
Trans. output normalized rms emit.	0.21	mm·mrad
Long. output rms emittance	0.09	MeV· deg
Transmission ratio (PARMTEQM) (W_{limit} = 0.08 MeV)	99.41	%
Transmission ratio (Toutatis)	99.68	%
Accelerator ratio (Toutatis)	99.44	%

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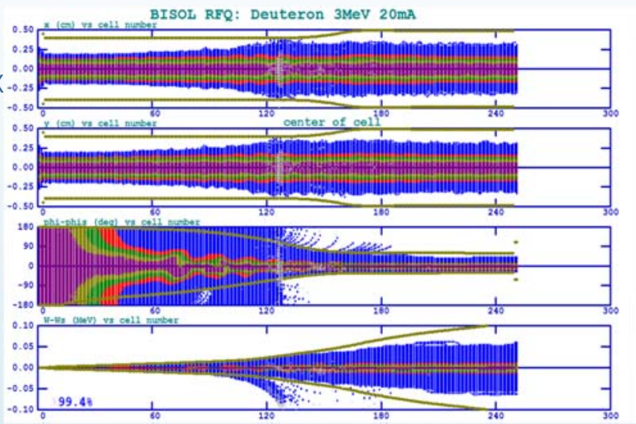
RFQ

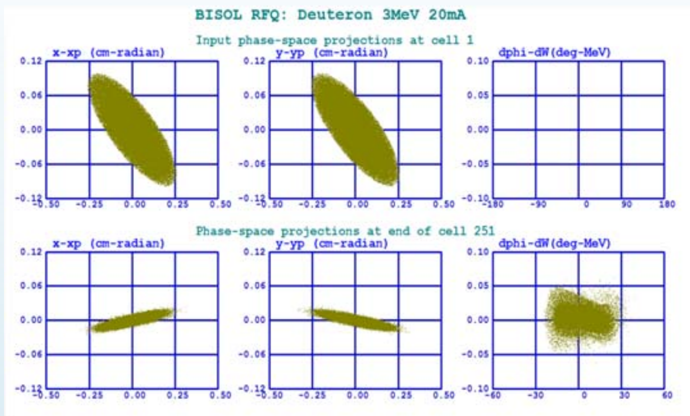
Envelope-X

Envelope-Y

Phase disperse

Energy disperse





- ParmteqM multi-particle tracking with 10^5 macro-particles

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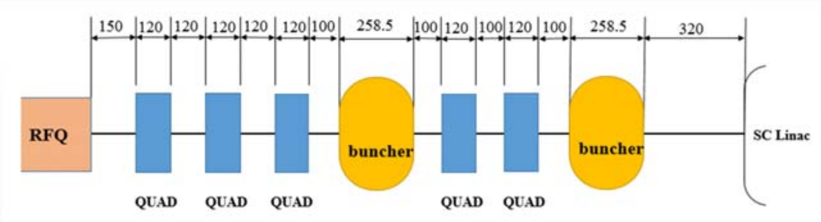
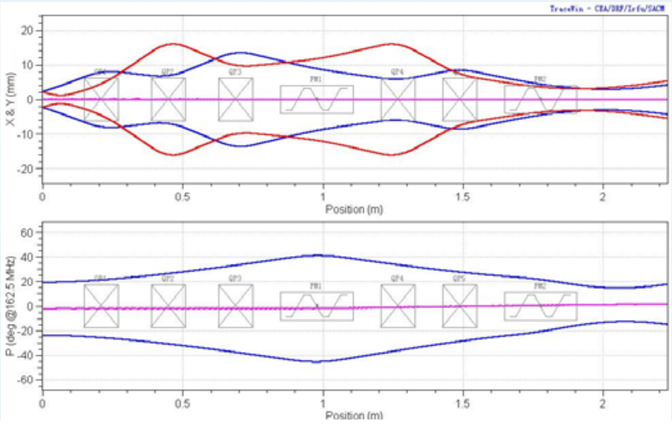
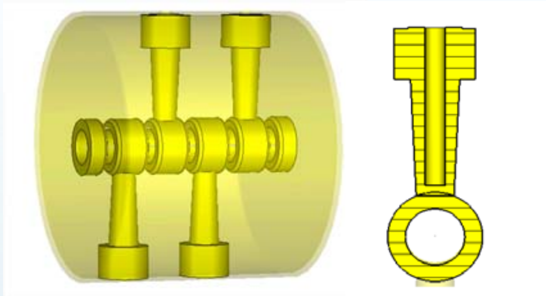
MEBT



3σ envelope





five gaps IH buncher

Element	Value
Cavity diameter (mm)	370
Aperture diameter (mm)	44
Cavity length (mm)	320
Q value	12000
Power (kW)	1.9
Mode separation (MHz)	162.3

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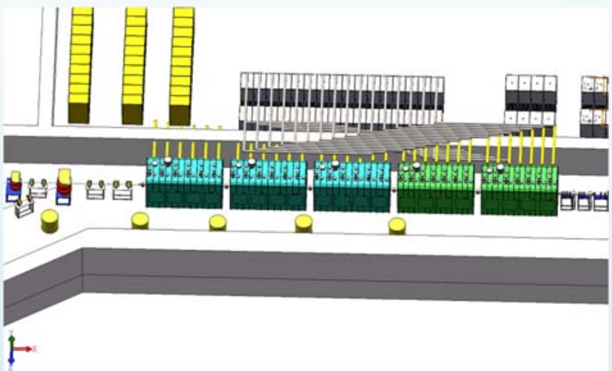
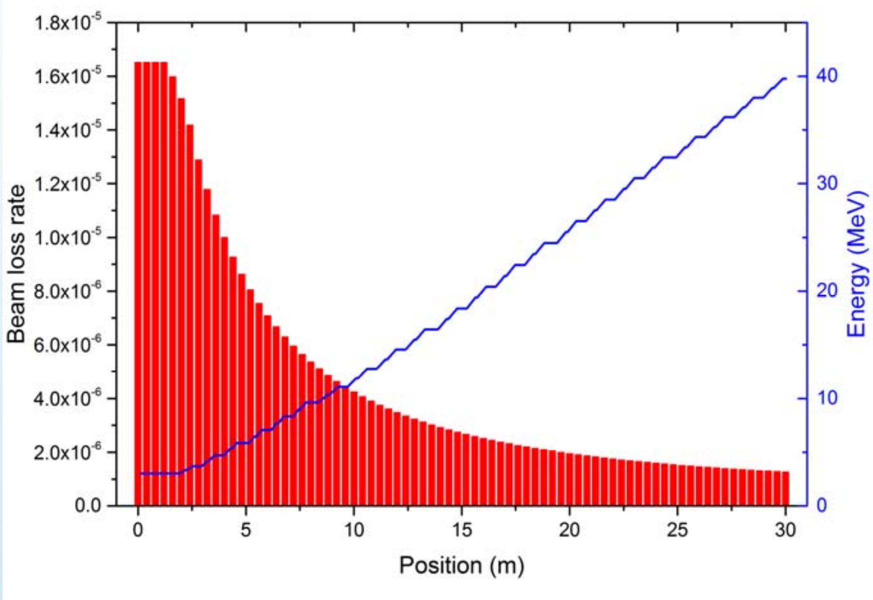
SRF linac



5 cryomodules, 23 SC solenoid, 32 HWR SC cavities, main coupler, and so on.

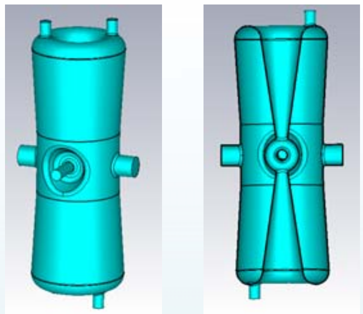
Beam loss control



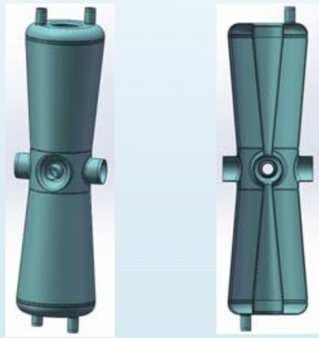
SRF linac

Parameters of HWR cavities

Property	Low-beta	High-beta
β_{opt}	0.09	0.15
Bore diameter [mm]	40	40
E_p/E_{acc}	5.3	4.7
B_p/E_{acc} [mG/(MV/m)]	6.4	6.8
r/Q [Ω]	255	300
Operating E_{acc} [MV/m]	6	6
Cavity length [mm]	271	350
Thickness [mm]	3.0	3.0



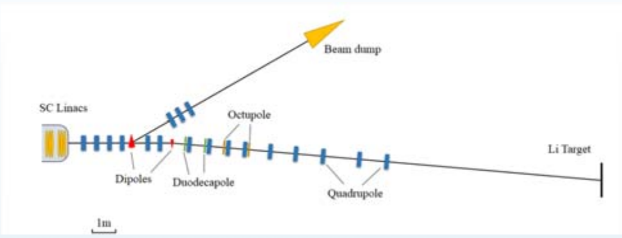
β=0.09

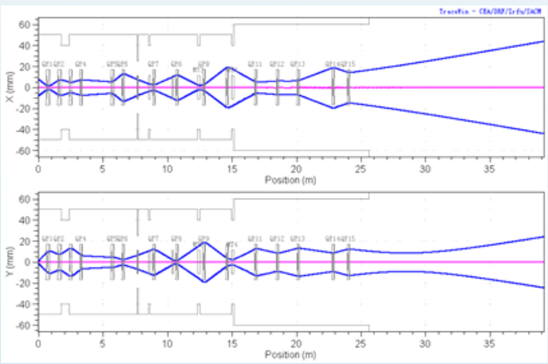


β=0.15

HEBT

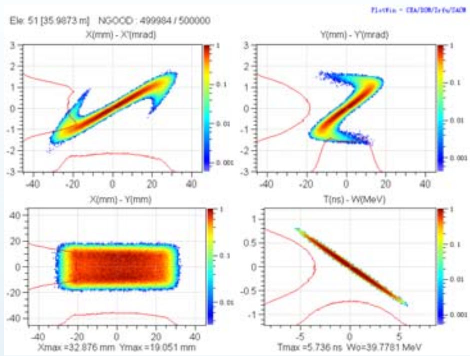
Layout of HEBT

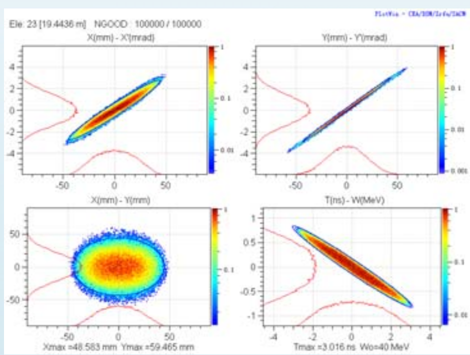




Beam 3σ envelope

Beam on Li target





Beam dump

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OUTLINE

- Background
- Brief history of BISOL
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  - Lithium target and Irradiation Unit
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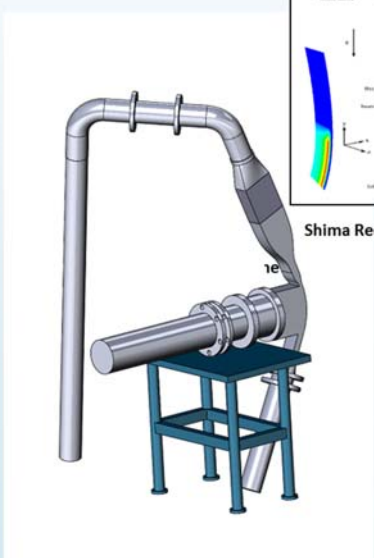
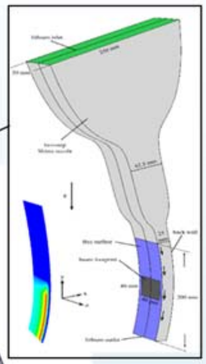
Liquid Lithium Target

Energy and current	40 MeV, 10 mA
Beam Power	400 kW
Footprint	2x(2~4) cm^2
Li jet width	10 cm
Power Density	100 kW/cm^2
Li jet thickness	25 mm
Inlet/outlet temperature	250/300 ^oC
Target Flow velocity/rate	20 m/s, 50 L/s
Incidence angle	5 ^{o}
Pressure in beam ducts	10^{-4} Pa
Pressure in target chamber	10^{-3}-10^{-2} Pa





Shima Reduced Nozzle

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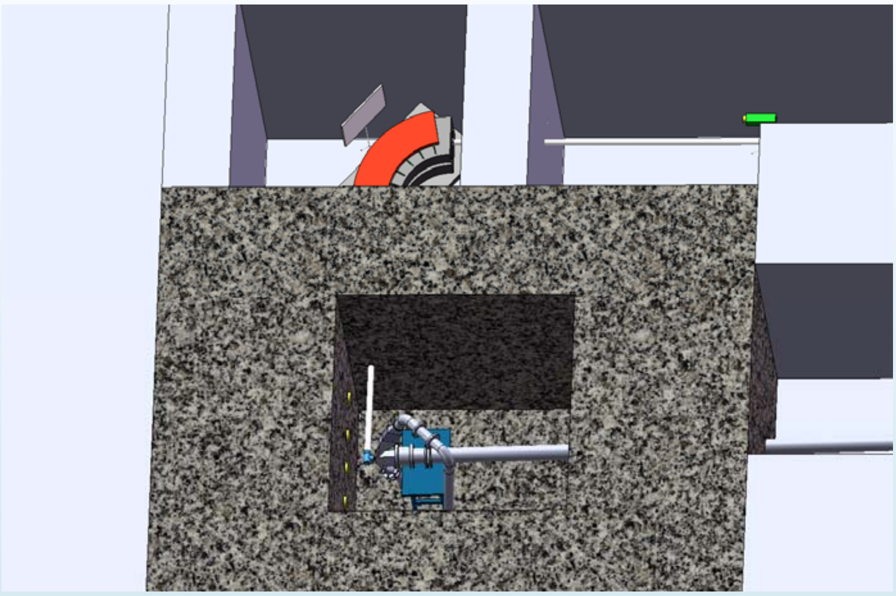
Operation Mode I: RIS



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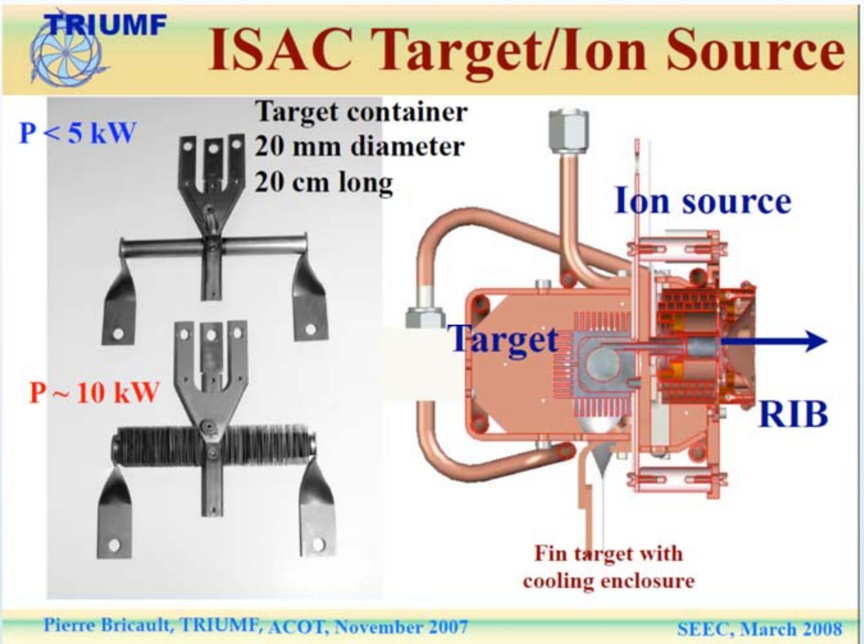
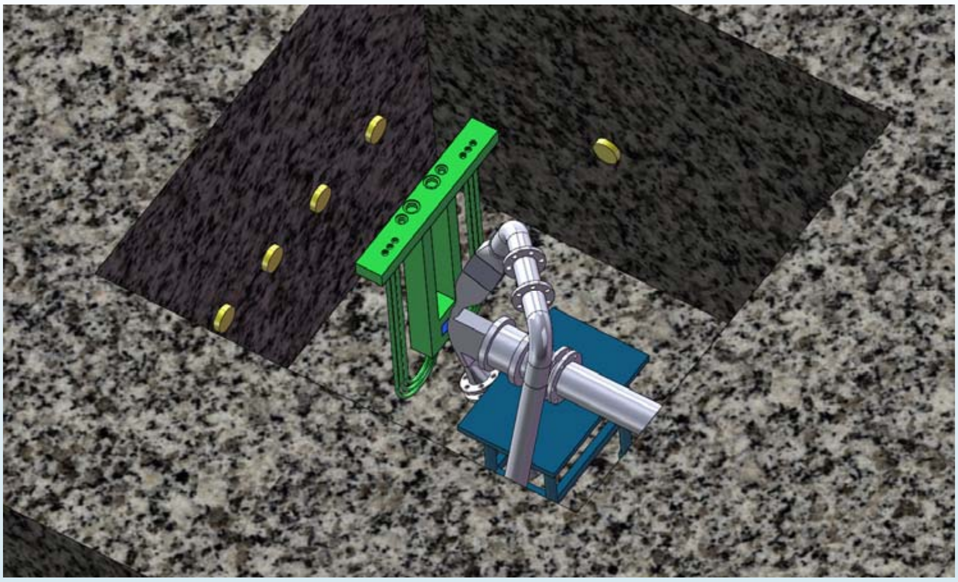
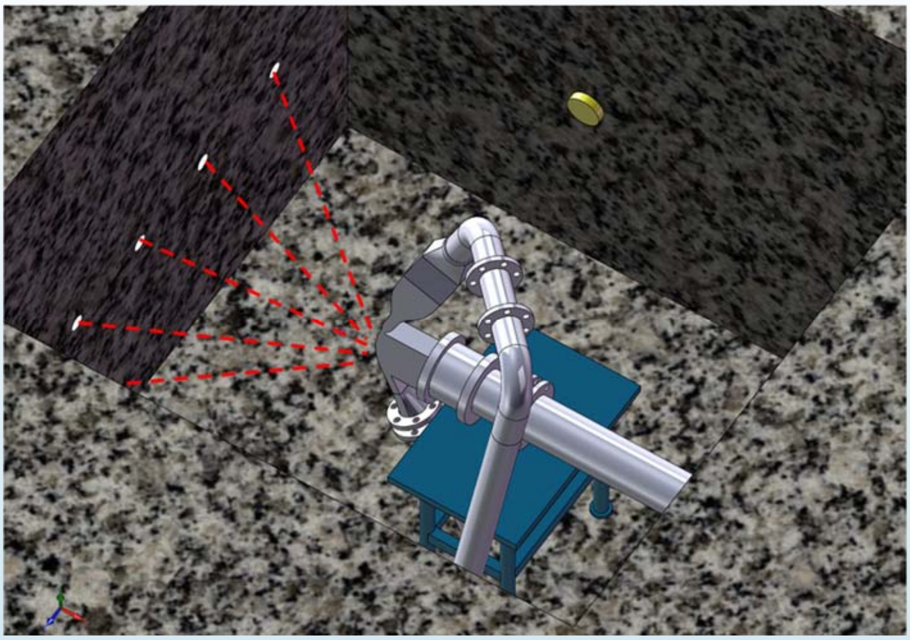
Rare Isotope Ion Source



Operation Mode II: TMs



Operation Mode III: Neutron Science



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OUTLINE

- Background
- Brief history of BISOL
- Concept design of MAINS
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  - Lithium Target and Irradiation Unit
  - L-Li Loop
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- Outlook

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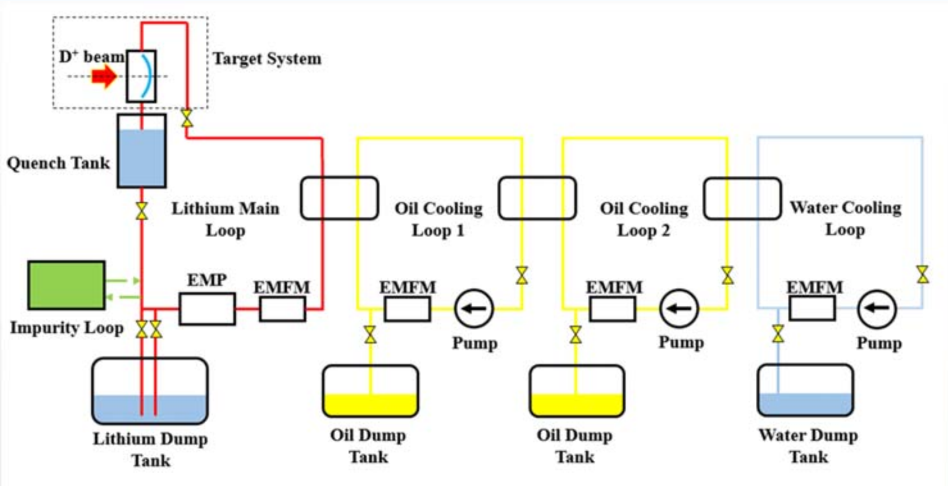
Li Loop



	Main loop	Secondary loop	Third loop	Impurity loop		
				Cold trap	Heat trap 1	Heat trap 2
Working Substance	L-Li	oil	oil	Ar	Ti	Y
Temperature(℃)	250	185-220	50-75	200	600	280-300
Pressure (bar)	4	5	5			
Max Flux (l/s)	65	85	130			

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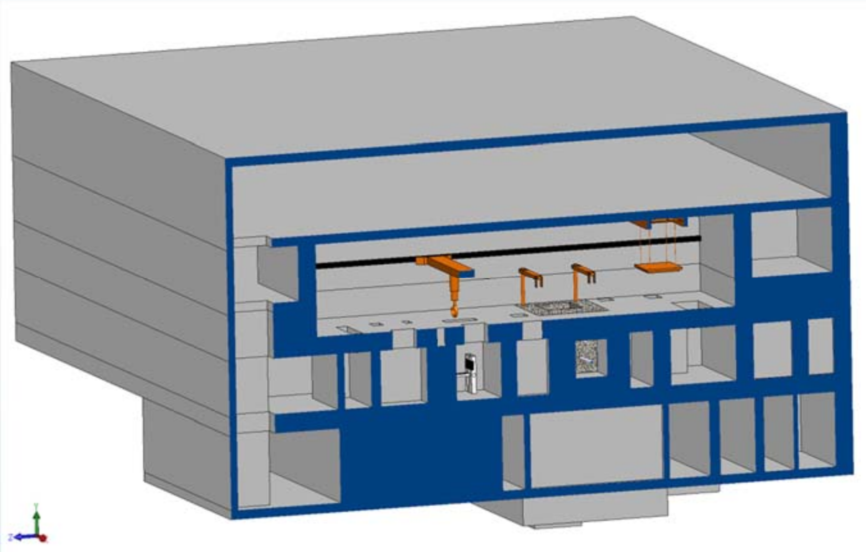
Access Cell



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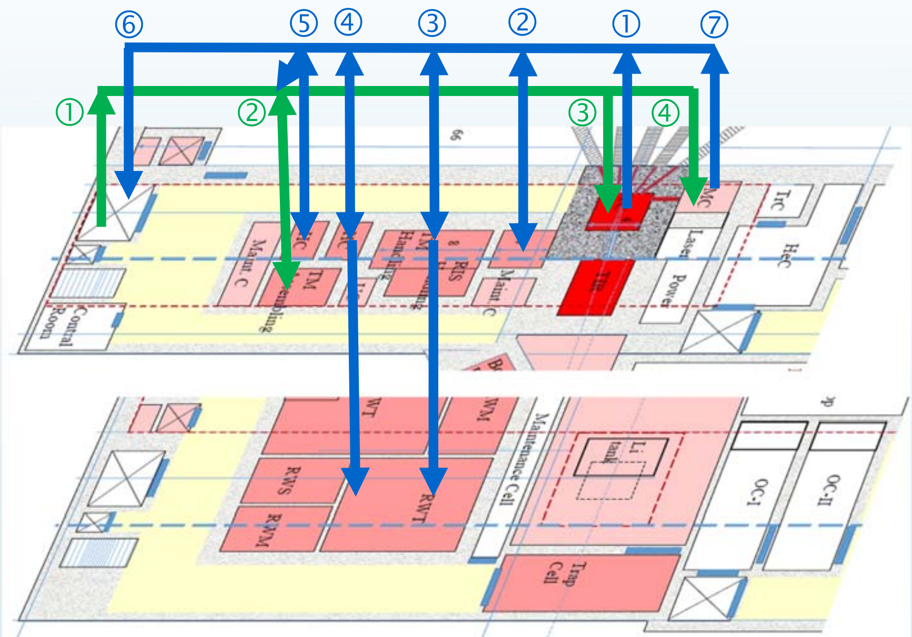
Access route

① Taking out TA/TMs/RIS from TC
② Waiting for cooling (short life Isotopes)
③ Disassembling TA/TMs/RIS (radioactive waste directly down)
④ Component handling
⑤ Rig handling
⑥ To PIE
⑦ Magnet maintenance
① New components
② Finished new TA/TMs/RIS
③ Replacing TA/TMs/RIS into TC
④ Magnet maintenance



OUTLINE

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  - Li target and Irradiation Unit
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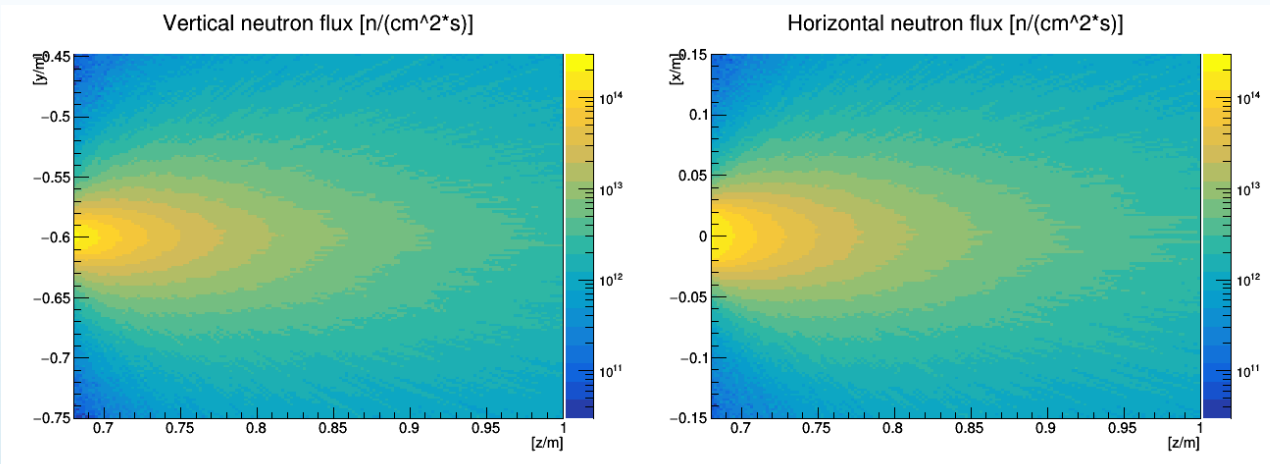
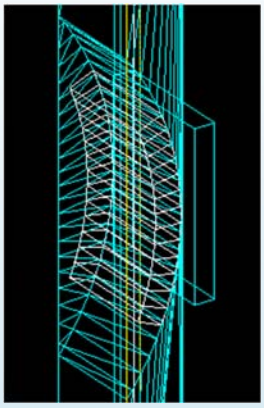
Neutron flux density distribution



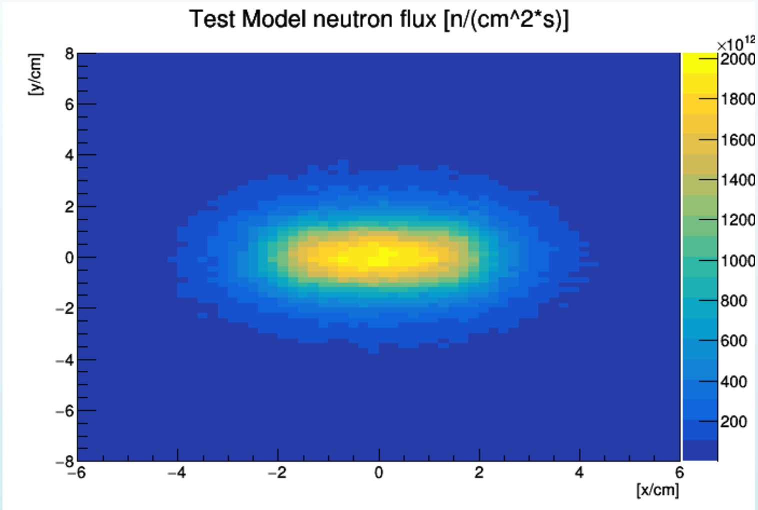
Phase I	n flux:	> 10^{14} n/cm^{2}s	> 5X10^{13} n/cm^{2}s	> 10^{13} n/cm^{2}s
40 MeV 10 mA	dpa in steel	> 8 dpa/fpy	> 4.4 dpa/fpy	> 1.3 dpa/fpy
D+→Li	Volume:	~ 12 cm^3	~ 60 cm^3	~ 700 cm^3

BISOL-MAINS

The neutron flux density distribution at the Test Module position (2 mm beyond BP)



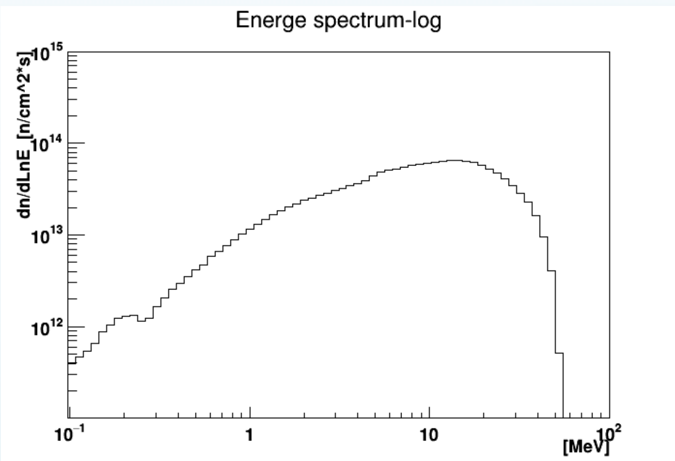
Li target and the test module



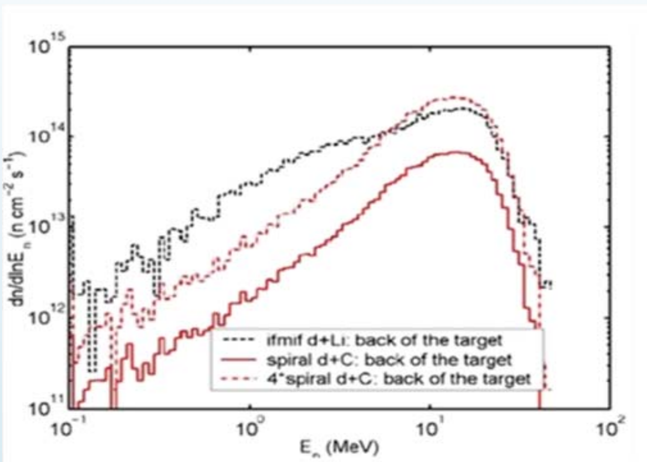
The maximum neutron flux density reaches 2X10^{14} cm^{-2}s^{-1} on test module

Neutron Energy

0° Neutron energy spectrum



BISOL-MAINS @10 mA D$^+$



IFMIF and SPIRA II

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OUTLINE

- Background
- Brief history of BISOL
- MAINS concept D^+ Accelerator
  - Lithium Target and Irradiation Unit
  - L-Li Loop
  - Transportation and Waste Treatment
- **Outlook**

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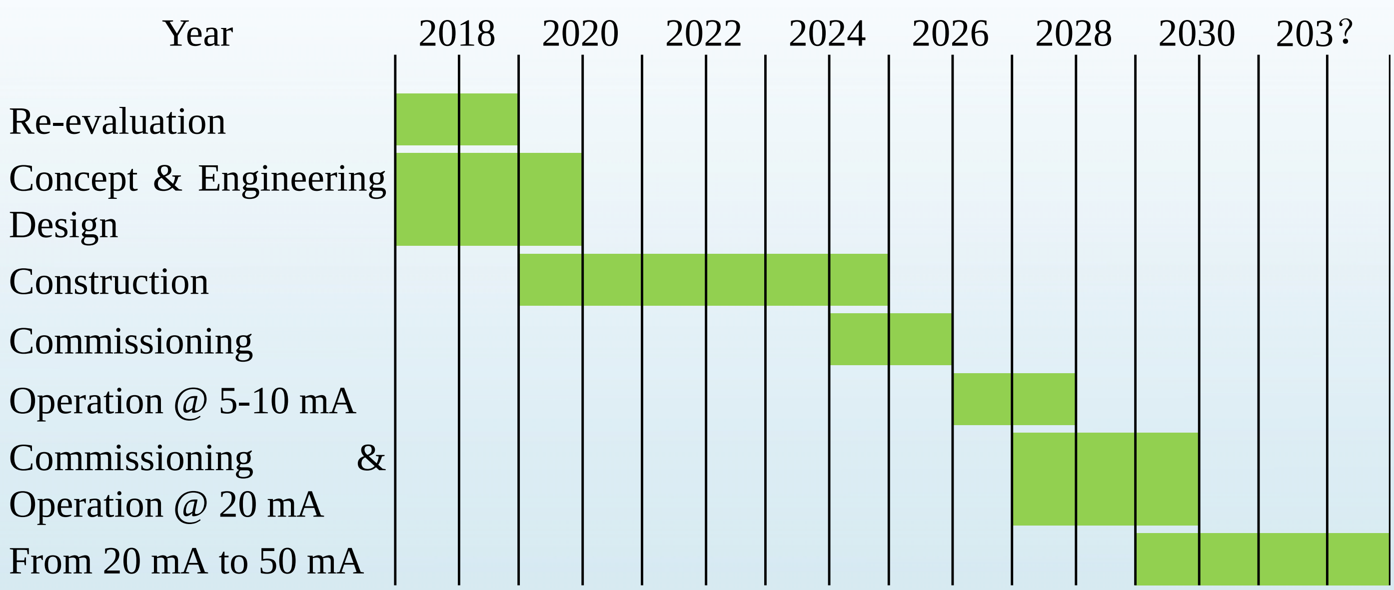
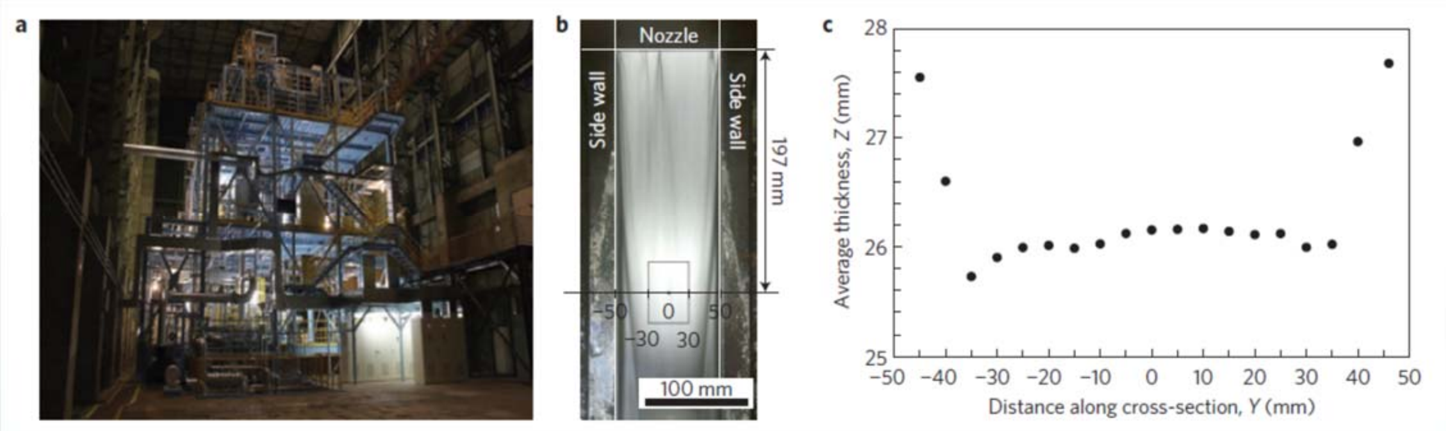
Time Schedule for BISOL-MAINS



Oct. 2015
ELTL running 1560 h



Accumulated operation time of EVEDA Lithium Test Loop (ELTL) of the lithium target reached 1,560 h.

June 5, 2017
25MeV 150-200 μA CW P Beam!

CiADS 25 MeV proton linac past CW proton beam with 150-200 μA CW current and >10 mA peak current (IMP and IHEP)

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Appreciation

- We appreciate all helps and support from domestic and international experts and colleagues.
- We need more communication, and cooperation with IFMIF-like neutron source partners.

3.2.4 Neutron sources for transmutation of long-lived fission products: H. Okuno (Riken,)

Neutron sources for transmutation of long-lived fission products in the ImPACT* Program

Nov. 4, 2017
Hiroki OKUNO
RIKEN Nishina Center for Accelerator-based Science

This work was funded by ImPACT Program of Council for Science, Technology and Innovation (Cabinet Office, Government of Japan).

www8.cao.go.jp/cstp/sentan/about-kakushin.html

Contents

- Introduction to ImPACT program (PJ 1,2,3,4,5)
- Project 1-3,5 Outline and current progresses
  - PJ1: (Separation and Recovery technique namely Partitioning)
  - PJ2: (Nuclear data measurement for transmutation and new control system of Nuclear reactions)
  - PJ3: (development of nuclear reaction model and improvement of PHITS reaction model)
  - PJ5: (scenario of resource recycling and reduction of HLW, conceptual design of Partitioning and Transmutation (P&T) system)
- Project 4: Transmutation system and elemental technologies development (Accelerators and targets for high power beams)

ImPACT (Impulsing PAradigm Change through disruptive Technology)

革新的研究開発推進プログラム(ImPACT)
Impulsing PAradigm Change through disruptive Technologies Program

The Japanese Government declared the new R&D Program named "ImPACT" has started 2014 till 2019 after the "First" Program.

Characteristics

- ハイリスク研究による非連続イノベーションの創出において成功を収めた米国DARPA（国防高等研究計画局）の仕組みを参考
- 研究者に対してではなく、プロデューサーとして研究開発の企画・遂行・管理等の役割を担うプログラム・マネージャー(PM)に予算と権限を与える、我が国ではかつてない方式を導入
- PMが目利き力を発揮し、トップレベルの研究開発力を結集して革新的な研究開発を強力に推進

Structure

- ➢ Objectives of the ImPACT Program

Promotion of high-risk and high-impact R&D for societies or industries with not-continuous innovations.

- ➢ Features of the ImPACT Program

The DARPA in the US is the model of ImPACT Program.
The Program Manager is not a researcher but completely managing the whole program with the budget and the authority.

- 平成25年度補正予算に550億円を計上し、「独立行政法人科学技術振興機構法」の一部を改正して5年間の基金を設置
- CSTIがPMを公募し、平成26年6月に12名、平成27年9月に4名を選定し、平成30年度末まで研究開発プログラムを実施

ImPACT (Impulsing PAradigm Change through disruptive Technology)

Theme 1. Release from constraints on resources and innovation in manufacturing capabilities
"Japan-Style Value Creation for the New Century"

Theme 2. Realization of an ecologically sound society and innovative energy conservation that changes lifestyles
"Living in Harmony with the World"

Awareness of Issues

- There are no effective methods of achieving large-scale energy conservation while also improving the quality of life (mobile infrastructure, lighting, heating and cooling, information appliances, etc.).
- There are no methods for drastically reducing the volume of waste, which is trending always upward. And other such issues.

Theme 3. Realization of a society of highly advanced functionality that surpasses the information networked society
"Smart Community that Links People with Society"

Awareness of Issues

Issues involved in making the transition to an information-based society and an increasingly sophisticated information society:
- The vast amounts of information available near-at-hand are not yet effectively utilized in the lives of the people or in the activities of the economy.
- The present telecommunications and information networking environment is subject to security vulnerabilities and is exposed to many risks.
- IT infrastructure in its present state will not be able to keep up with the explosive increases in information volume that are expected to occur in the times ahead. And other such issues.

Theme 4. Provide the world's most comfortable living environment in a society with a declining birthrate and aging population
"Realize Healthy and Comfortable Lives for Everybody"

Awareness of Issues

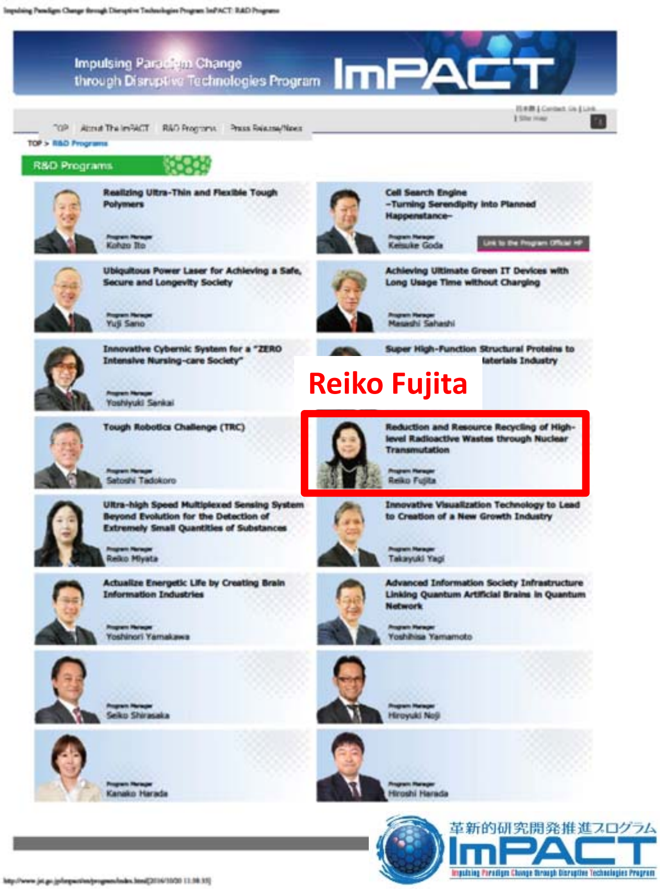
- Health problems of elderly people, inconveniences of everyday life, and concerns about the healthy growth of children have not been resolved.
- There are no effective ways for people to be freed from the din of motor vehicles, railways, and so on, and to lead lives that bring them healing relief.
- There are no simple, convenient, effective ways for people to protect themselves from the toxins and hazardous substances (viruses, bacteria, explosives, substances impacting food safety, etc.) they find close at hand in their lives. And other such issues.

Theme 5. Control the impact and minimize the damage from hazards and natural disasters that are beyond human knowing
"Realize a Resilience that is Keenly Felt by Every Individual Japanese"

Awareness of Issues

- There is insufficient capability for prediction of natural phenomena, control of their effects, rapid search, rescue, and transportation when disasters occur, restoration of bridges, roads, and other such infrastructure, and assuring access in times of emergency, dealing with toxic substances, hazardous substances, and other such substances generated by disasters, accidents, or other such events by decontamination or preventing their spread, and other such readiness for dealing with natural disasters.
- There are impediments to advanced mobility in rainstorms, windstorms, nighttime, and other extreme environments, and to increasing the safety and speed of remote demolition of structures and other such heavy work. And other such issues.

Title: Reduction and resource recycling of High-level radioactive wastes through nuclear transmutation



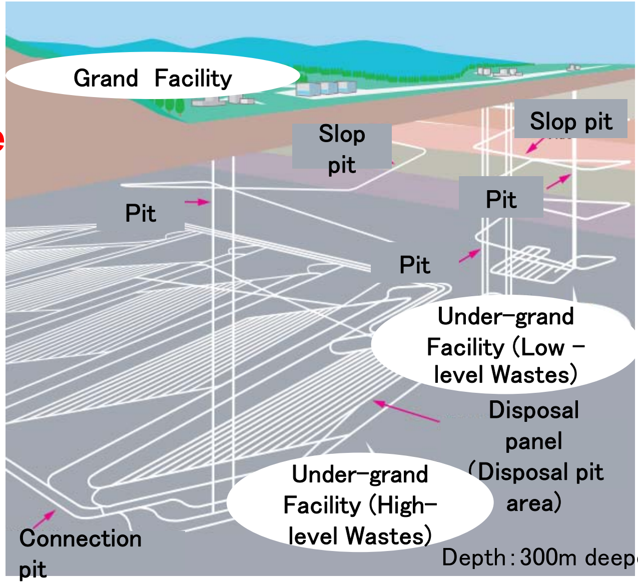
Issues of HLW (High-Level radioactive Wastes) disposal

- ➢ High level radioactive wastes (HLW) are vitrified in glass* and disposed in geological repository.

- ➢ **However, Japanese public are worried about HLW disposal scenario for long-term storage.**

We would like to propose some of solution candidates for HLW disposal in geological repository.

● Example of disposal in geological repository



https://www.numo.or.jp/q_and_a/01/

*Already production about 24,800

Long Lived Fission Products of Spent Nuclear Fuel

Ac / TRU

Nuclides	Half life (Billion year)	Radiation conversion coefficient (μ Sv/ kBq)	Content (Spent fuel /ton)
U-235	0.7	47	10 kg
U-238	4.5	45	930 kg

Nuclides	Half life (year)	Radiation conversion coefficient (μ Sv/ kBq)	Content (Spent fuel/ ton)
Pu-238	87.7	230	0.3 kg
Pu-239	24000	250	6 kg
Pu-240	6564	250	3 kg
Pu-241	14.3	4.8	1 kg

MA

Nuclides	Half life (year)	Radiation conversion coefficient (μ Sv/ kBq)	Content (Spent fuel/ ton)
Np-237	2.14Million	110	0.6 kg
Am-241	432	200	0.4 kg
Am-243	7370	200	0.2 kg
Cm-244	18.1	120	60 g

FP

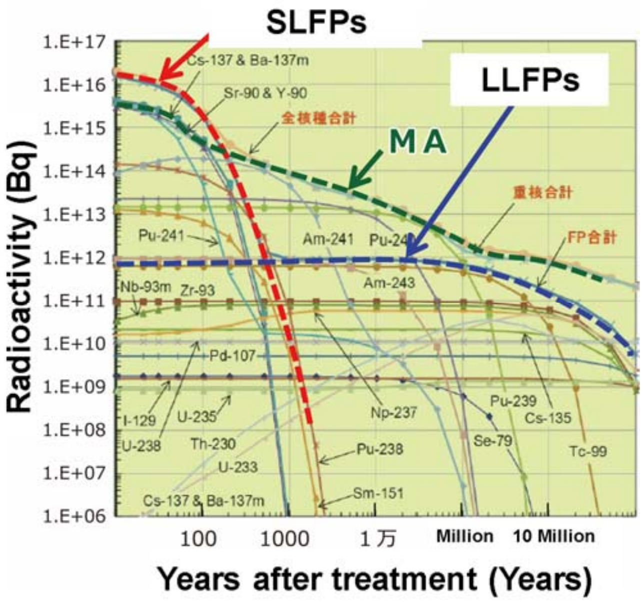
Nuclides	Half life (Million year)	Radiation conversion coefficient (μ Sv/ kBq)	Content (kg/ Spent fuel ton)
Se-79	2.95	2.9	6g
Sr-90	28.8 year	28	0.6
Zr-93	15.3	1.1	1
Tc-99	2.11	0.64	1
Pd-107	65	0.037	0.3
Sn-126	1	4.7	30g
I-129	157	110	0.2
Cs-135	23	2.0	0.5
Cs-137	30.1year	13	1.5

Radiation Conversion Coefficient:
The effect coefficient of nuclides on Human

Citation: Hiroyuki Oigawa, "Tokai Forum lecture 9" (2014)

High Level Wastes (HLW) converted to ILW or LLW

- Both Minor Actinides（MAs）and Long Lived Fission Products (LLFPs*）should be reduced.
- MAs Transmutation research has already started in the Nuclear Fuel Cycle by JAEA's ADS-PJ.
- **LLFPs transmutation research has no started yet.**
- LLFPs in radioactive wastes are contained in vitrification as HLW for deep disposal which has still issue of no candidate of disposal site in Japan.



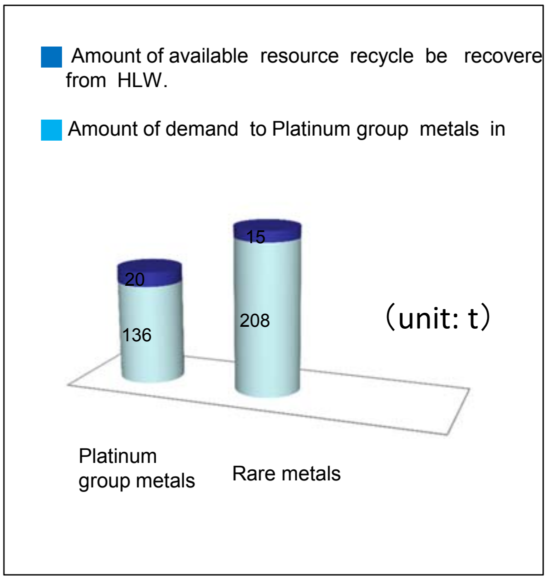
*LLFPs：Long Lived Fission Products, Cesium（Cs）-135, Palladium (Pd)-107 etc.

LLFPs transmutation research should be done to show alterative options to deep disposal for Japanese public.

革新的研究開発推進プログラム ImPACT

High Level wastes (HLW) for Resource Recycling

- LLFPs in HLW contain some of rare metals for usable elements.
- Rare metals can be easily recovered from HLW, but it is impossible to recycle for re-use because the rare metals contain radioactive nuclides.
- Transmutation research in the reactors, OMEGA Project has been started since 1980's in Japan but new data for various nuclear reactions couldn't be obtained because there was no facility which make such measurements possible.



革新的研究開発推進プログラム ImPACT

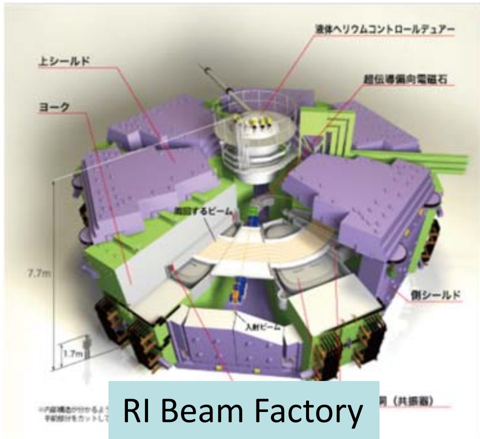
Scientific Progress and Present Situation

21st Century

- Recently, the most powerful accelerator, RI beams factory such as 100 times stronger of heavy ion beam strength in any other facilities at present has been completed, and any kind of nuclear reaction data is possible to be measured by the innovative technique.

- The excellent simulation software "PHTIS" and evaluated nuclear database "JENDL" have already been developed in Japan.

Such scientific progresses make the advanced transmutation system possible to be developed by combination with partitioning technique.



PHTIS

Previous Studies on Transmutation of MAs and LLFPs in HLW

	Actinides			Fission Products (FP)		Reactor	ADS	Others	Issues
	U	Pu	MA	Long lived FP					
			Np, Am, Cm	129I、99Tc	79Se、93Zr、107Pd、135Cs、(126Sn)				
EU			○	○		○	○		Risks of disposal of HLW and LLFPs
US		○	○			○	○		Ibid.
OMEGA (Japan)			○	○		○	○		Risks of LLFPs
SCNES* (Japan)			○	○	○	○			Need of Isotope separation
ADS-MA (JAEA)			○				○		Risks of LLFPs
ImPACT (Japan)			Use of results of ADS-MA	Use of results of OMEGA and SCNES	●			○	Need of Accelarator technology toward zero of HLW without Isotope separation with OMEGA, SCNES and ADS of MA TM

*SCNES: Self-Consistent Nuclear Energy System

Changing the definition of LLFPs on industries and societies

Nuclides	Half-life	Disposal	Resource recycling
Cs(Cesium)-135	2.3million year	Disposal of Ba (Barium) transmuted from Cs-135	
Cs(Cesium)-137	30.1year		
Sr(Strontium)-90	28.5 year	Disposal of Rb (Rubidium) -85,87 and Sr-86,88 transmuted from Sr-90	
Pd(Palladium)-107	6.5million year		Reuse of stable Pd transmuted from Pd -107 for catalysts for vehicles
Sn(Tin)-126	0.23million year	Transmutation for stable nuclides of Sn(Tin) or Sb(Antimony)	
Zr(Zirconium)-93	1.53 million year		Reuse of stable Zr transmuted from Zr-93 for Zircalloy cladding and Channel boxes
Se(Selenium)-79	0.30million yesr	Stable Se transmuted from Se-79	
Tc(Technetium)-99	0.21million year	Ru(Ruthenium)-110 transmuted from Tc-99	
I(Iodine)-129	15.70 million year	Xe(Xenon)-130 transmuted from I-129	

・Contribution to safety and security of disposal with converting from High level radioactive wastes to Transuranium (TRU) wastes (ILW) or low level radioactive wastes.
・Most-advanced and only one technology will be established and activate our country's economy.

Effect on Partitioning &Transmutation

➢ Long term risk reduction

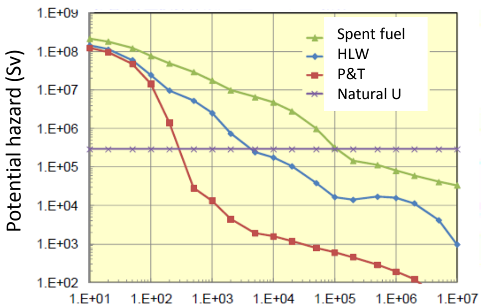
Reduction of potential risk on HLW

➢ Decrease of volume of HLW in disposal

Possible Integrated disposal by MAs transmutation and long storage for Cs & Sr as heat nuclides in the future : the present glass solid system and present technology in the spent fuel reprocessing plant should not be changed

Reduction of burden in HLW disposal

Potential Hazard: Influence of radiation dose of parameter in human



Years after treatment (Years)
43 GW/dt of burn up, 5 years cooling time, 99.5% removal of U & Pu and MA

Sr and Cs storage for about 100 years

Decrease of disposal area by 1/100
Because of converting HLW to TRU waste, namely ILW

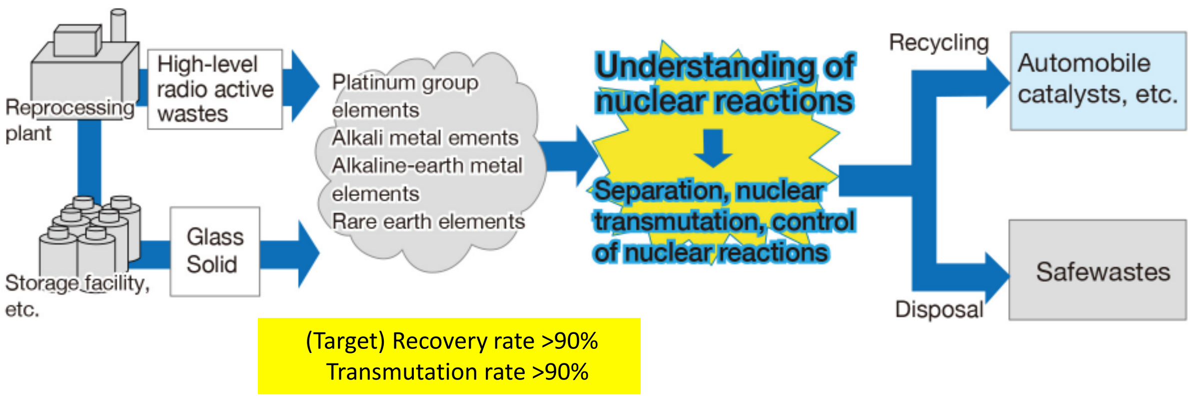
Citation: JAEA presentation in P&T committee of MEXT, Sep.9 2013

ImPACT* Program

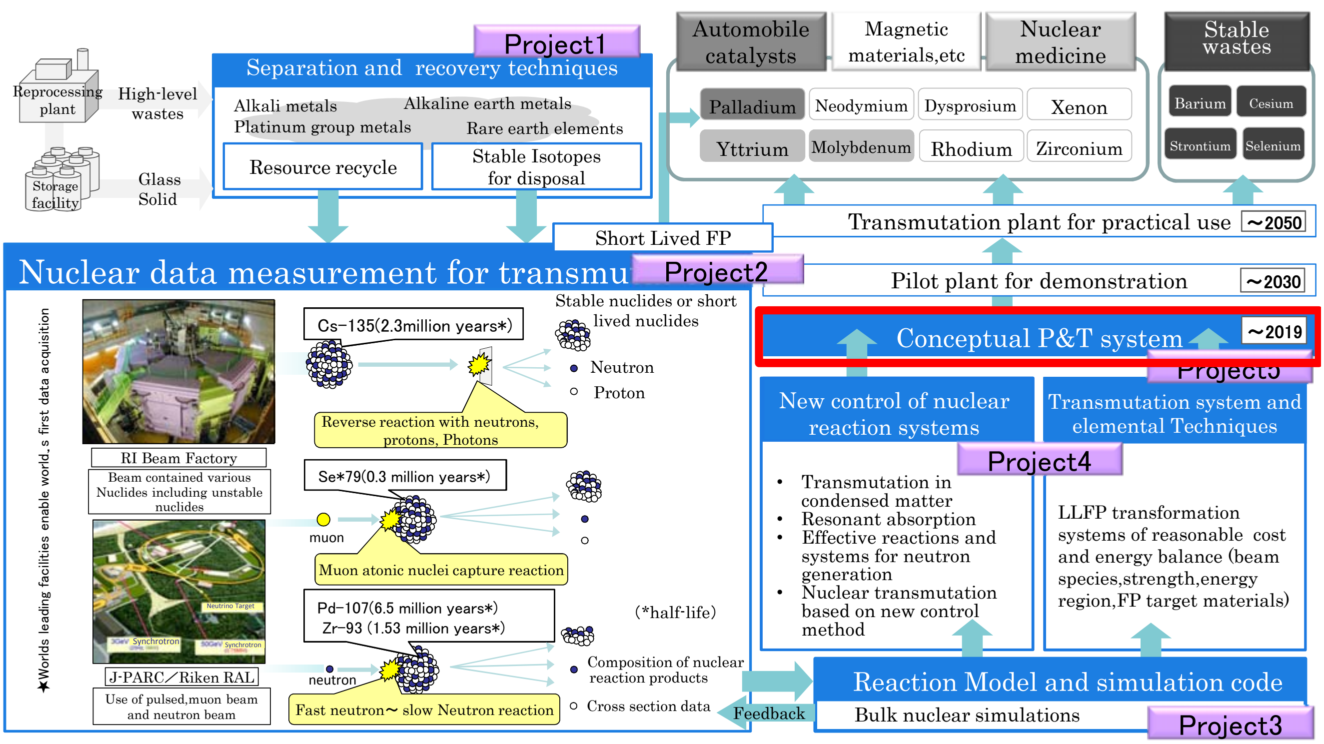
Reduction and Resource Recycling of HLW through Nuclear Transmutation

Goal: To be the first in the world to obtain nuclear reaction data for LLFPs, and to confirm the world's first nuclear reaction path for conversion to short lived nuclides or stable nuclides without isotope separation

*One of the ImPACT (Impulsing PAradigm Change through disruptive Technology) publicly offered research program by Japanese Cabinet (JFY2014-JFY2018)



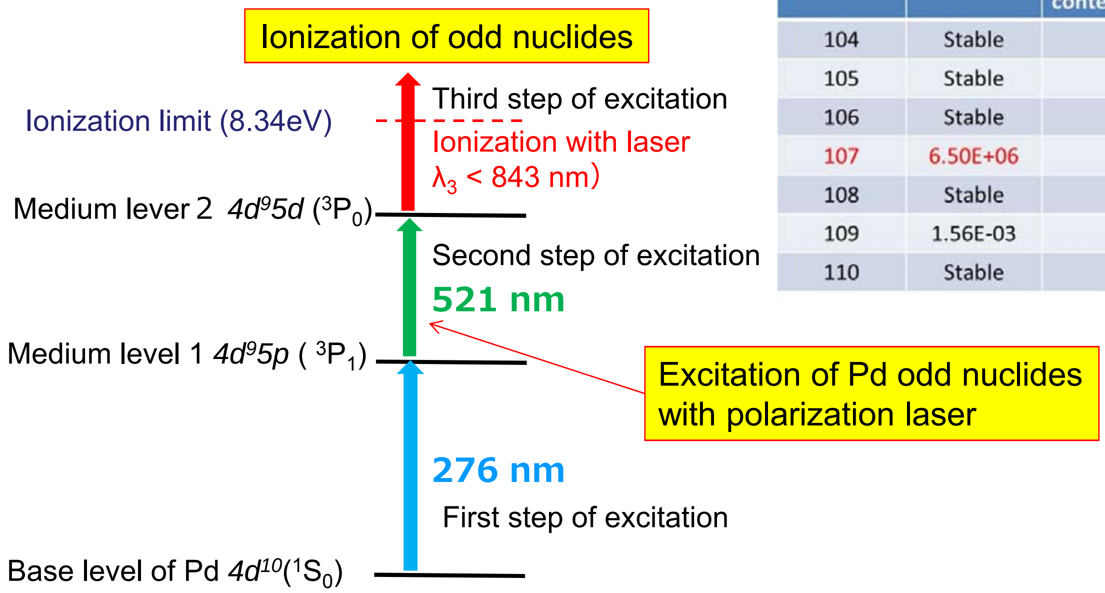
Outline of Our program



Project 1 Current Progress (I)

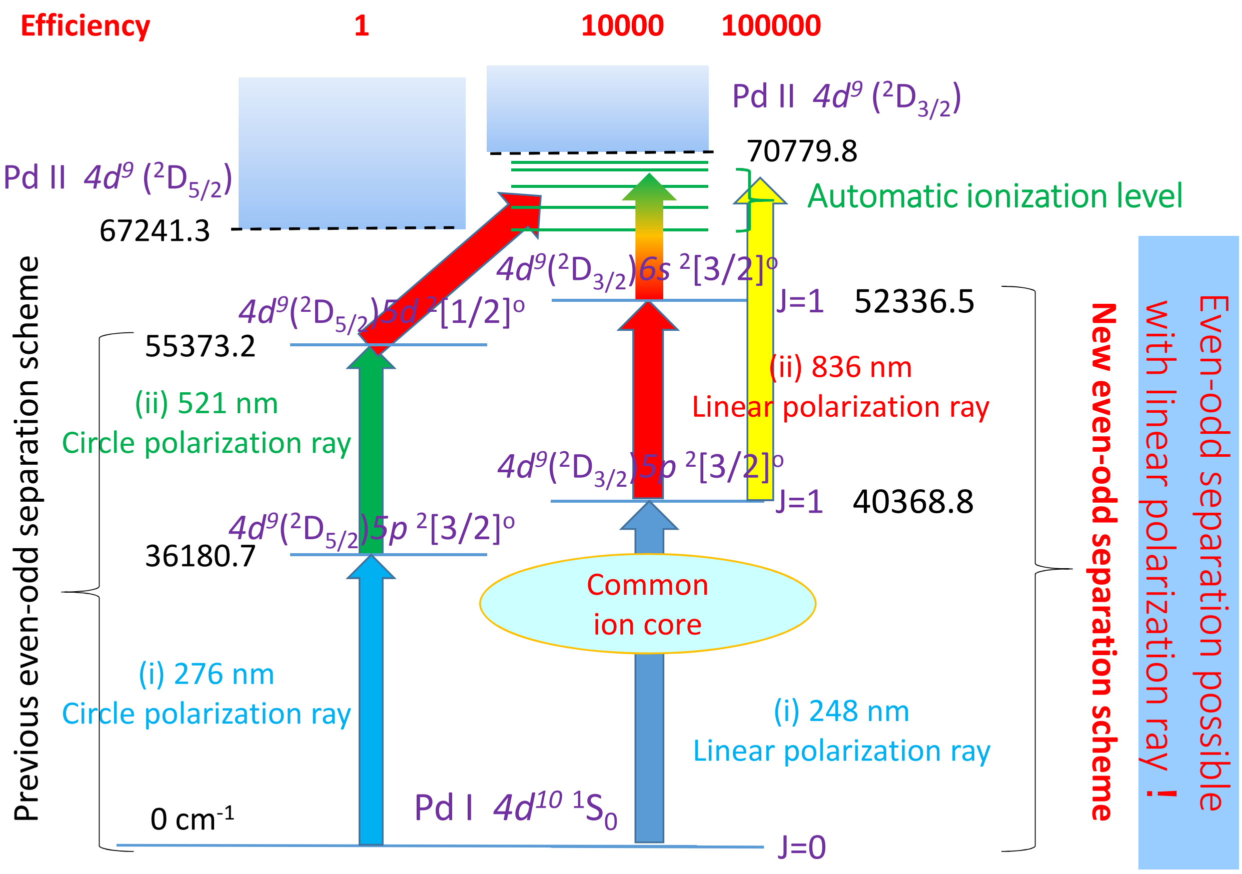
Purpose : Separation of odd nuclides from even ones by ionization of odd ones for easy transmutations

Principle of even-odd separations with polarizing laser



Pd isotope	Half life (y)	Ratio of contents (%)	After
104	Stable	17.7	
105	Stable	26.6	62.7
106	Stable	26.2	
107	6.50E+06	15.8	37.3
108	Stable	10.6	
109	1.56E-03	0.0	
110	Stable	3.2	

Project 1 Current progress (II)



Project 2　Contents

Purpose：Measurement of nuclear reaction data to find the best path

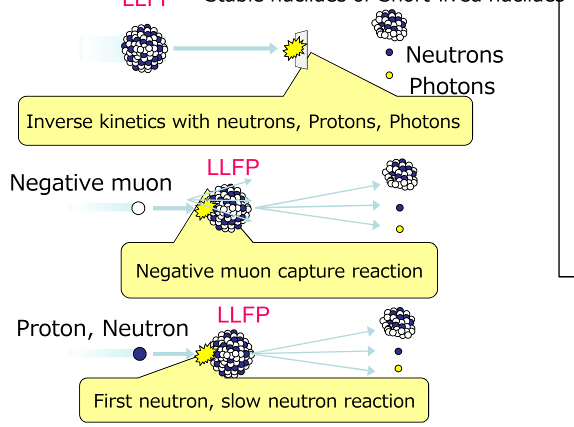
Target LLFP	Half life
Palladium 107	6.50 M.Y
Zirconium 93	1.53 M.Y
Selenium 79	0.30 M.Y
Cesium 135	2.30 M.Y

Project 2
(Obtained nuclear reaction data)
・Neutron Knockout（RIKEN）
・First neutron nuclear spallation（Kyushu University）
・Coulomb breakup（TIT）
・Negative muon capture reaction（RIKEN）
・Neutron capture（JAEA）
・Low-speed RI beam（The university of Tokyo, RIKEN）

(New nuclear reaction control method)

・Nuclear fusion（NIFS/Chubu Univ.）
・Compact cyclotron（Osaka Univ.）
・Muon（Kyoto Univ./JAEA）

➢ Adaption and overhaul of measure apparatus



➢ Others, new neutron reaction control methods

RIKEN RI Beam Factory

Measurement of reaction cross section with inverse kinematics

J-PARC RIKEN RAL

Measurement of neutron and muon capture cross section

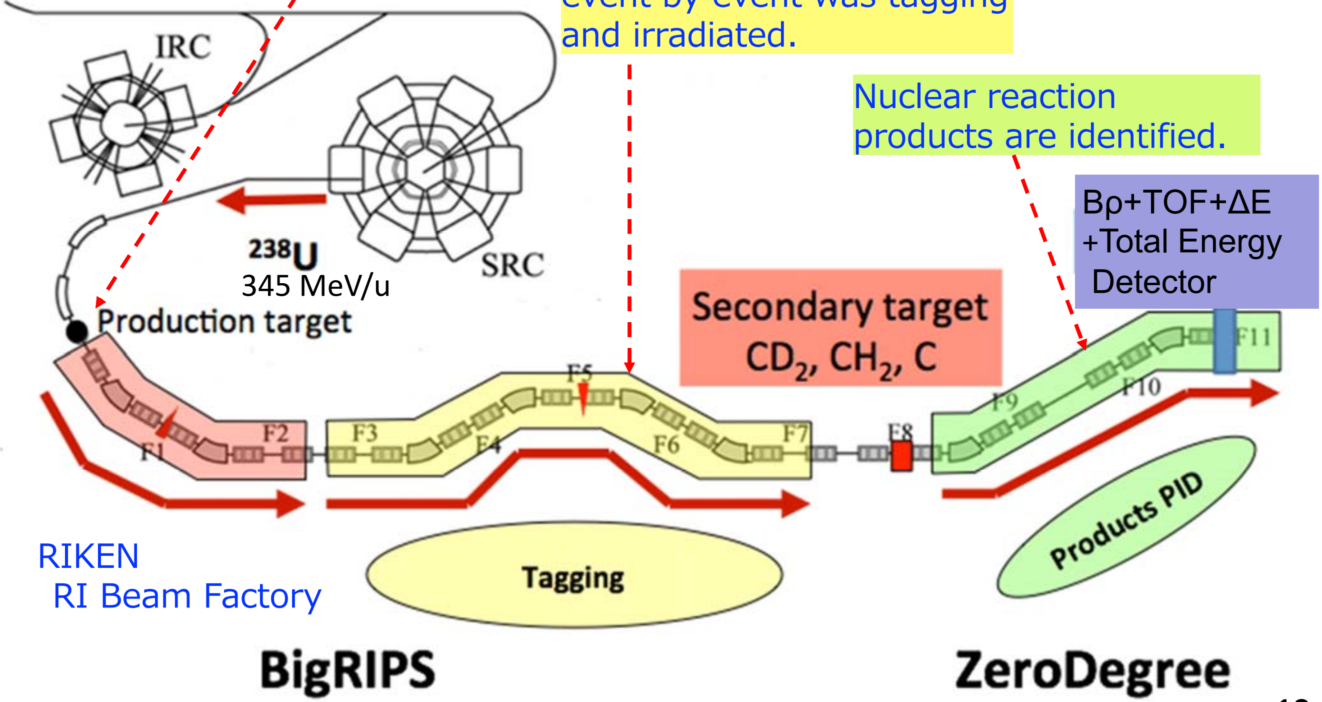
Project 2 Current Progress

Four experiments have been carried out to obtain new nuclear reaction data at RIKEN RIBF.

LLFP : Pd-107, Zr-93(+Sr-90), Cs-135(+137), (Se-79) production

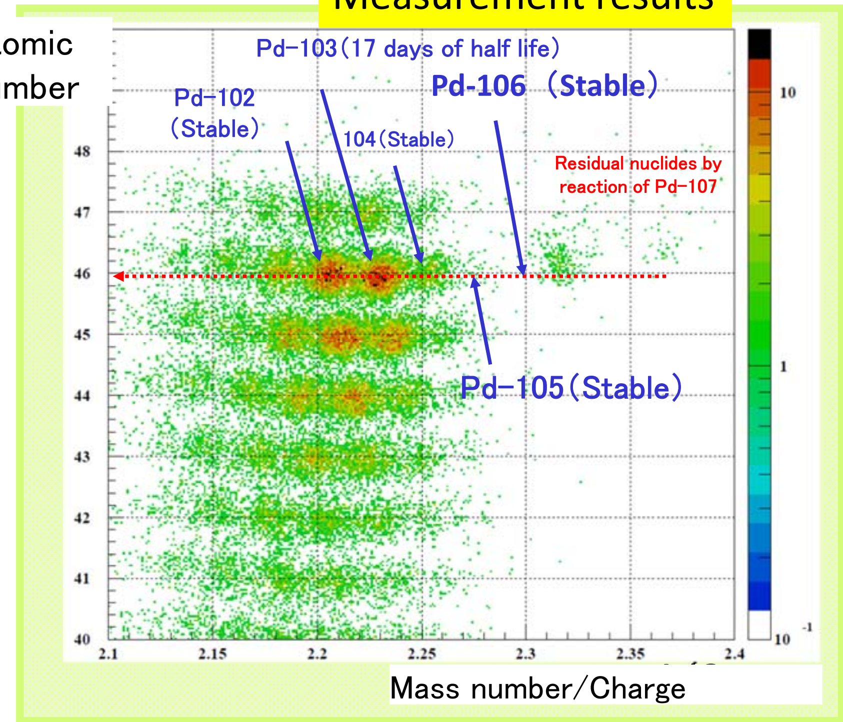
event by event was tagging and irradiated.

Nuclear reaction products are identified.



Project 2　Current Progress

Measurement results



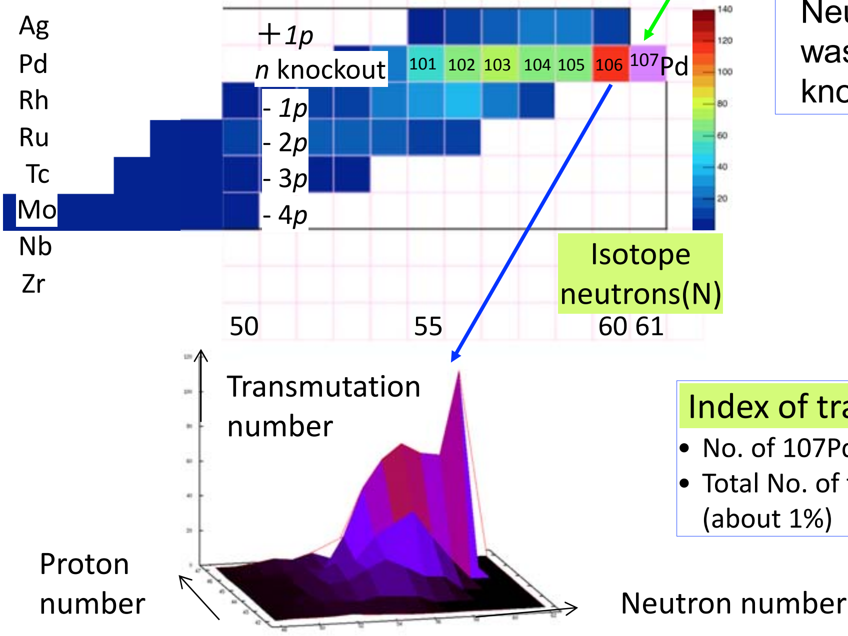
Nuclides	Pd-101	Pd-102	Pd-103	Pd-104	Pd-105	Pd-106	Pd-107
Half life	8.47h	Stable	16.991d	Stable	Stable	Stable	$6.5x10^6y$

Project 2 Current Progress

Pd-107 is transmuted by nuclear reaction with H^+ .

The estimation for ^{107}Pd 100 MeV/u

Distribution after nuclear reaction ; H^+ target



- Main channel for transmutation: Neutron knockout from ^{107}Pd was transmuted by Neutron knockout reaction

Index of transmutation volume

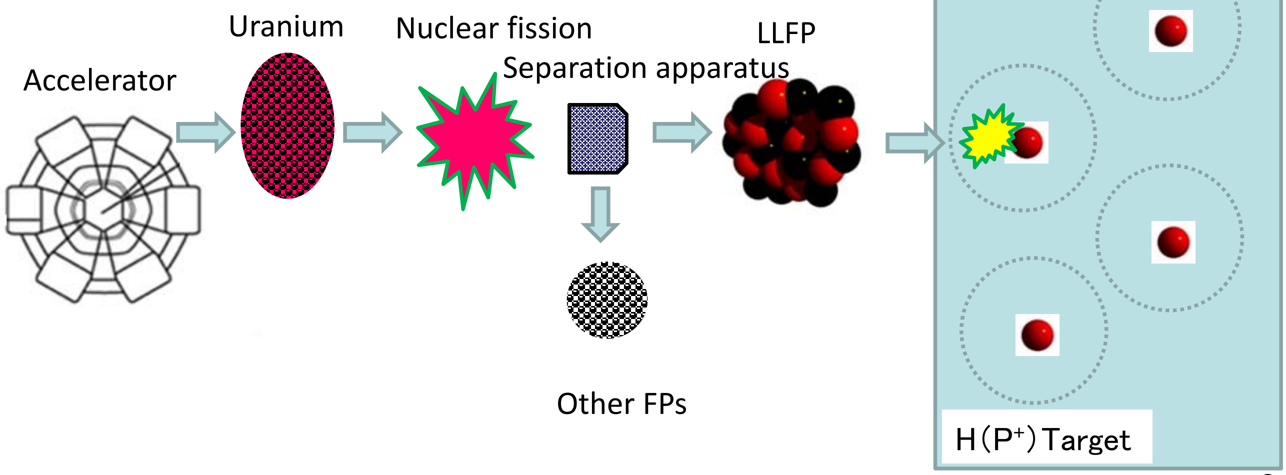
- No. of 107Pd = 1 million/hour
- Total No. of transmutation =10 k/hour (about 1%)

Nuclides	Pd-101	Pd-102	Pd-103	Pd-104	Pd-105	Pd-106	Pd-107
Half life	8.47h	Stable	16.991d	Stable	Stable	Stable	$6.5x10^6y$

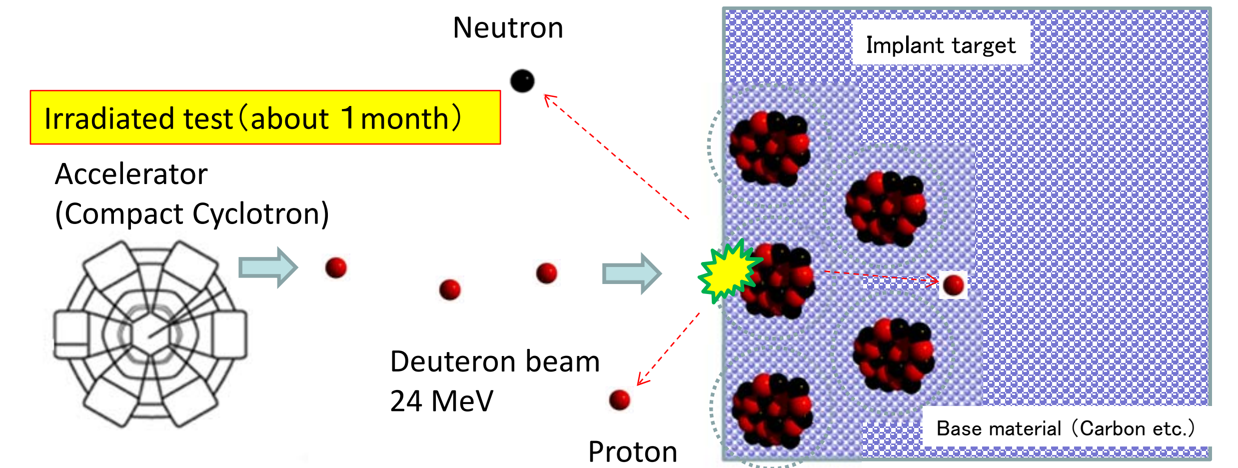
Current estimation of transmutation rate

Inverse kinematics ＋ Simulation code

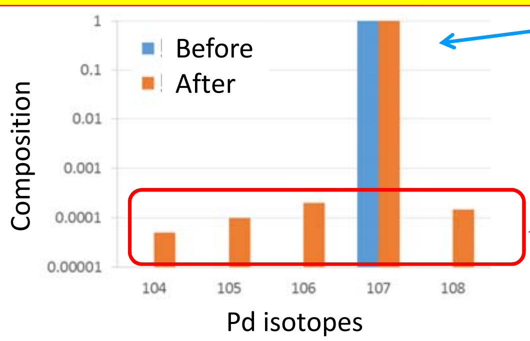
- Uranium (U) beam is made nuclear fission by accelerator to produce fission product beams, which are separated to long-lived fission product one.
- Separated LLFPs collide hydrogen (P+) target in Figure.
- Many kind of nuclides produced from collision are tagged and measured to estimate cross section of ones.
- The nuclear reaction rate is estimated by **cross section data** and by **simulation code such as PHITS code** and developed to design of actual apparatus.



How to do nuclear reaction experiments



Produced nuclides by nuclear reactions detected



It is necessary to be irradiated for long time in order to detect amount of nuclear reaction.

If Amount of increase of $^{104-108}$Pd are detected and measured, it is possible to confirm ^{107}Pd knockout reaction with ratio of isotopes by TIMS (Thermal Ion Mass Spectro.).

Project 3　Contents

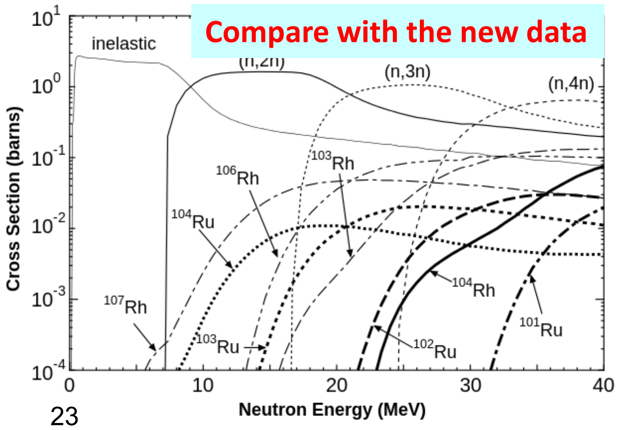
Purpose：Improvement of simulating precision for LLFP nuclear reactions

Project 3 (Reaction model and simulation)
・Standard model based on theory (Osaka University)
・Achievement of high precision through structural calculation (University of Tsukuba)
・Database for nuclear spallation (JAEA)
・Nuclear reaction simulation (RIST)
・Nuclear reaction data compiling (Hokkaido University)

◆ Improvement of nuclear data base
◆ Pre-estimation of nuclear reactions

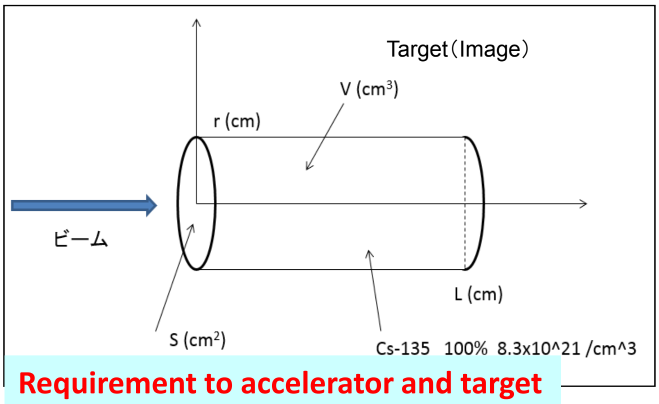
◆ Improvements of PHITS code for nuclear reactions

An example of calculations for cross sections of Pd-107 nuclear reactions by fast neutrons



23

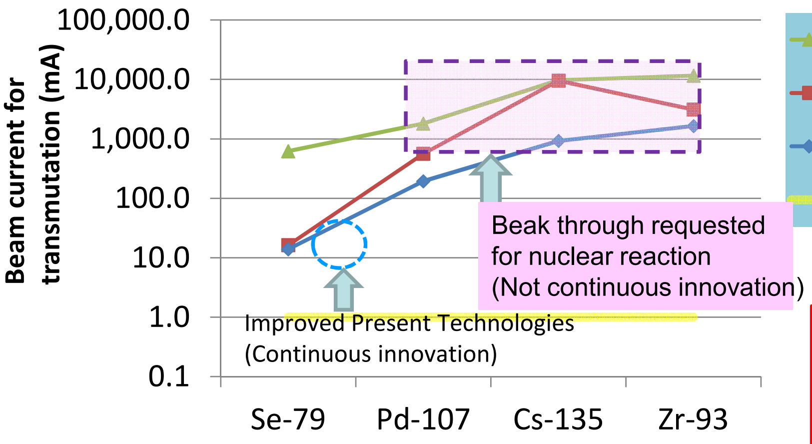
Ratios of nuclear reactions estimated in target of practical apparatus with a cascade reaction calculated by single nuclear reactions



Requirement to accelerator and target (Energy, intensity, heat deposit)

Project 3　Current Progress

➢ Beam current requested for LLFP transmutation in actual nuclear reaction time* is much higher than present one such as 1mA in every case of isotope separation, even-odd separation and spent fuel without isotope separation.



Not-Continuous innovation to have breakthrough in the technology of accelerator and target.

Yield of year (kg/y)	5	250	417	767

＊: one year yield of LLFP transmuted by proton beam with 1000 MeV for 3 years of effectual half years

Project 4 Contents

Purpose : Development of elemental technologies for transmutation.

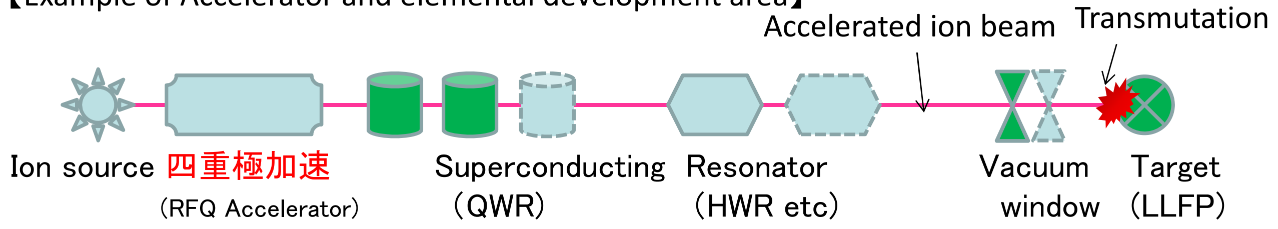
◆ **Accelerator and Target development of elemental technologies**

・ **Superconducting Quarter-Wave Resonators (Key in the low energy)**

・ **Vacuum window between accelerator area (High vacuum)and target area (Atmosphere)**

・**Target development using liquid metal（Heat removal at Transmutation）**

【Example of Accelerator and elemental development area】

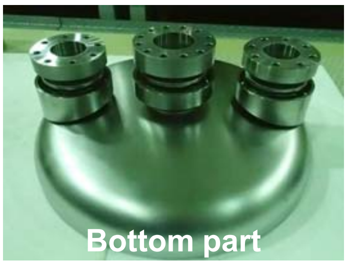


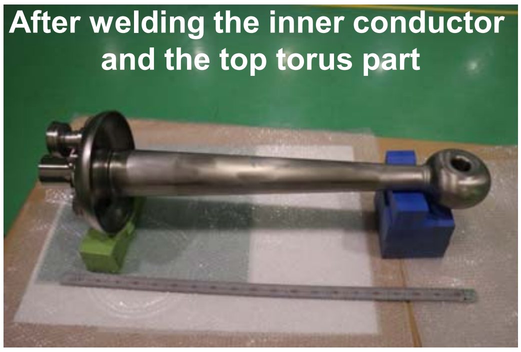
◆ **Evaluation of nuclear transmutation system**

・**Competitive evaluation in nuclear transmutation techniques**

・**Chosen nuclear transmutation system**

Development of SC-QWR





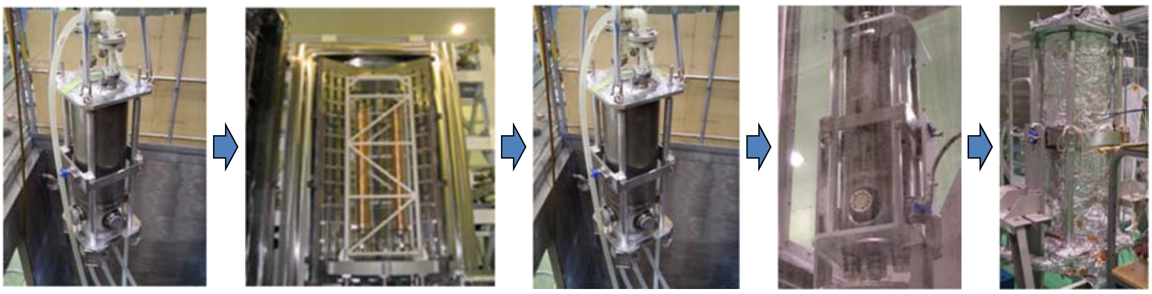
Courtesy of N. Sakamoto

Development of SC-QWR

Cleaning procedure of the inner surface of the resonator is one of the most important issues in the fabrication of bulk Nb resonator.

- Fairly standard processing.
- Processing should be made under clean circumstances.

BCP(100 μm) → **Annealing** → **BCP(20 μm)** → **HPR** → **Baking**

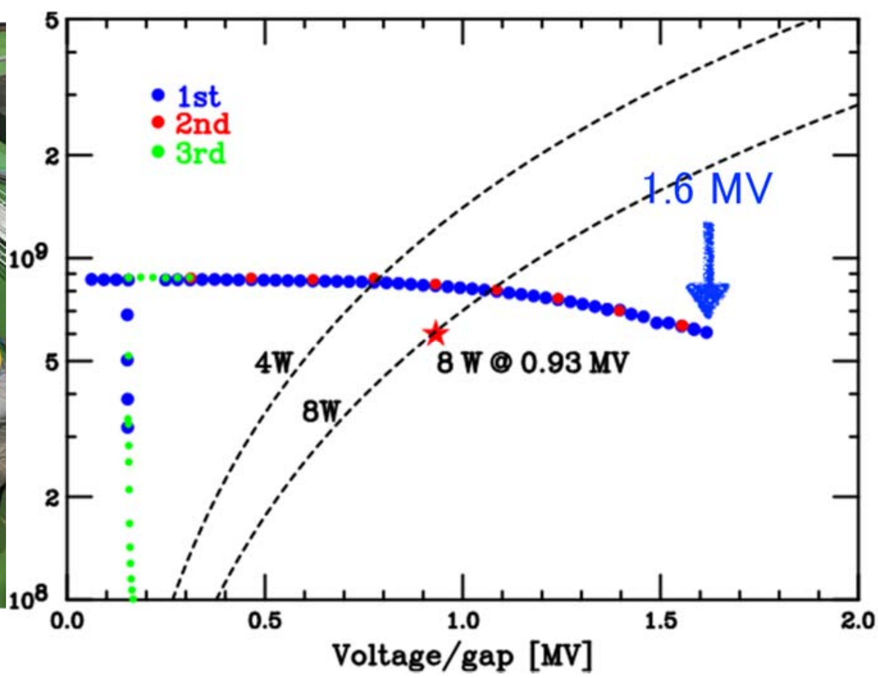


<u>Manufacturing and surface preparation</u> was made by Mitsubhisi Heavy Industries Co., Ltd
<u>Observation of the inner surface</u> was performed carefully.
<u>Low Power RF test</u> has been performed at AR-Higashi (KEK) since July 2016

Courtesy of N. Sakamoto

Development of SC-QWR

・ Performance test was carried out at KEK on September 7th, 2016.
・ The bulk Nb resonator was cooled down to 4 K by liquid He.



High acceleration voltage of 1.6 MV was successfully obtained.

Courtesy of N. Sakamoto

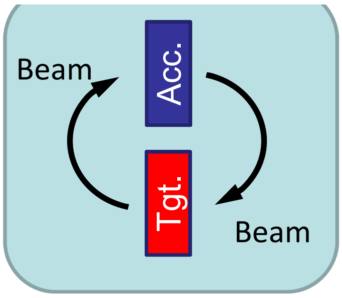
Introduction to R&D on Targets in PJ4

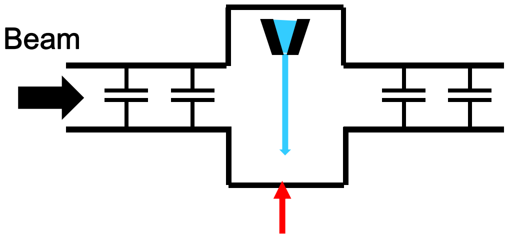
The technical challenge

1：High capability of heat removal, uniformity in thickness

2：Beam window for high power beam

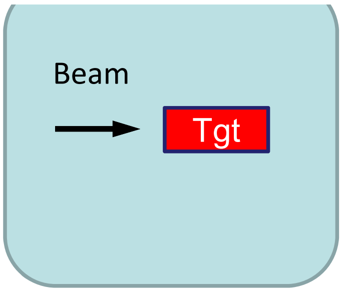
Beam transmits the target

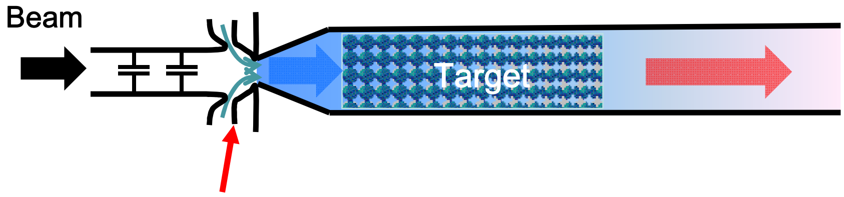




Thin liquid lithium target, Granular target

Beam stops in the target

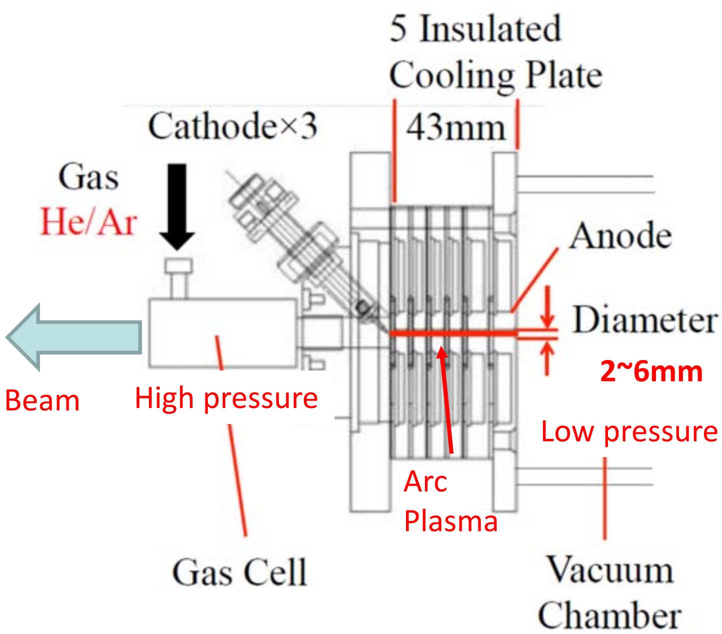




“Windowless” vacuum interface （Plasma window）

Toward Large aperture plasma window

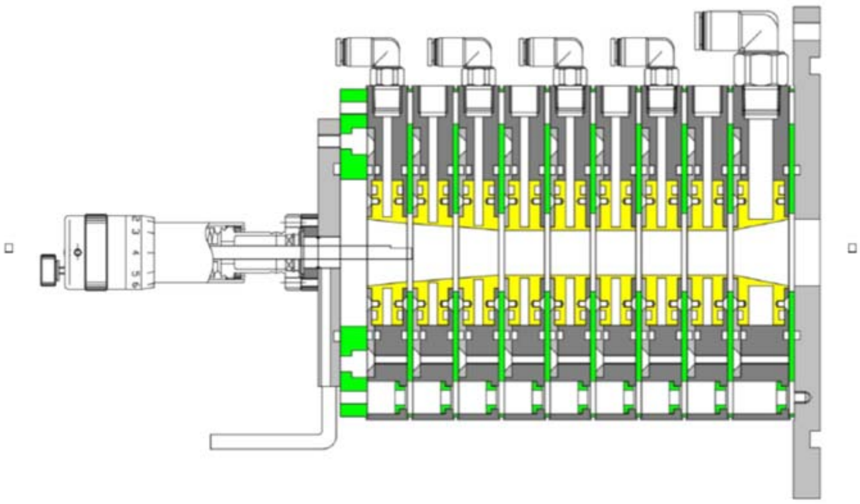
Plasma Window: vacuum interface using arc plasma



Plasma Window (1995~)
Inventor：
Ady Hershcovitch (BNL)

Motivation: Large aperture for high power beam

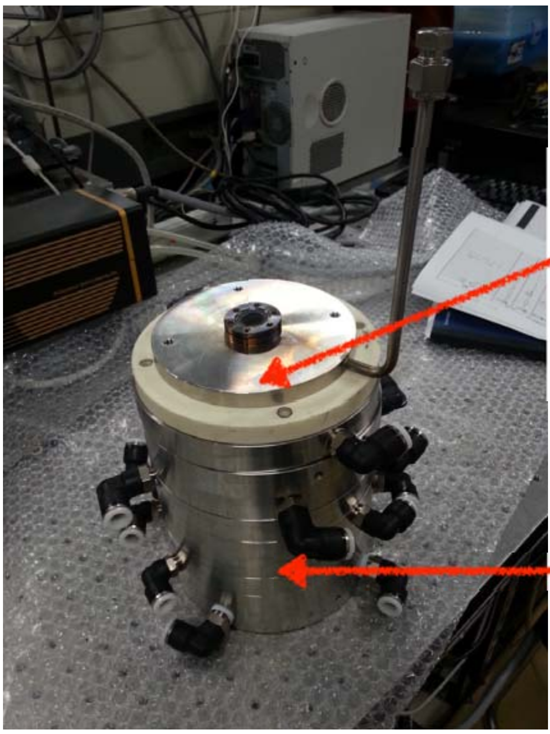
Large aperture plasma window (<20 mm))



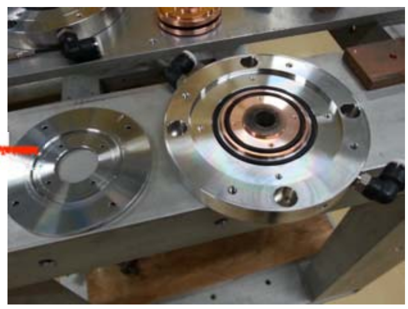
・Design is based on the PW developed at Namba Laboratory[1], Hiroshima University.
・Cathode : CeW
・Insulator : Alumina
・Inside and outside of electrode are made CuW and SUS respectively.
 (CuW high melting point and high thermal conductivity)
・Diameter is variable.

[1] S. Namba et. al., Rev. Sci. Inst., 87, 083503 (2016).

Large aperture plasma window



CeW cathode



Cooling plate (SUS & CuW)

Performance test is underway.

R&D on high power target

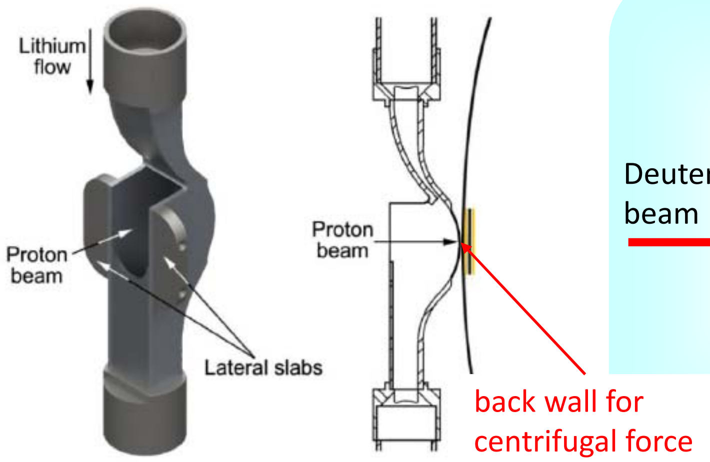
- Technical issues
  - High capability of heat removal
  - Target made of LLFP (Pd or Zr)
  - Uniformity in thickness (internal target)

- **Candidates**
  - **Liquid Metal (Liquid Lithium)**
  - **Granular target**

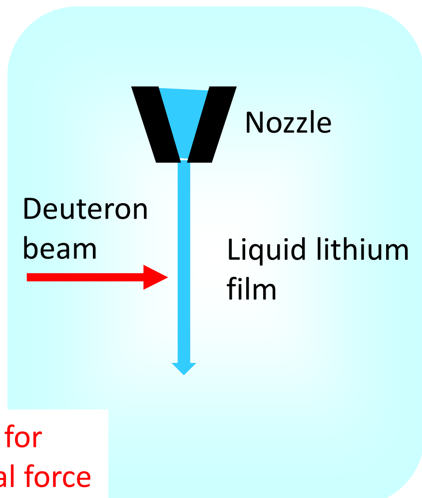
- Previous Studies
  - Liquid lithium: IFMIF/EVEDA, BNCT
  - Granular target: Chinese-ADS

Liquid Lithium target

- Direct ejection to produce free surface flow with out back wall (internal target、frequent change of back wall, etc))

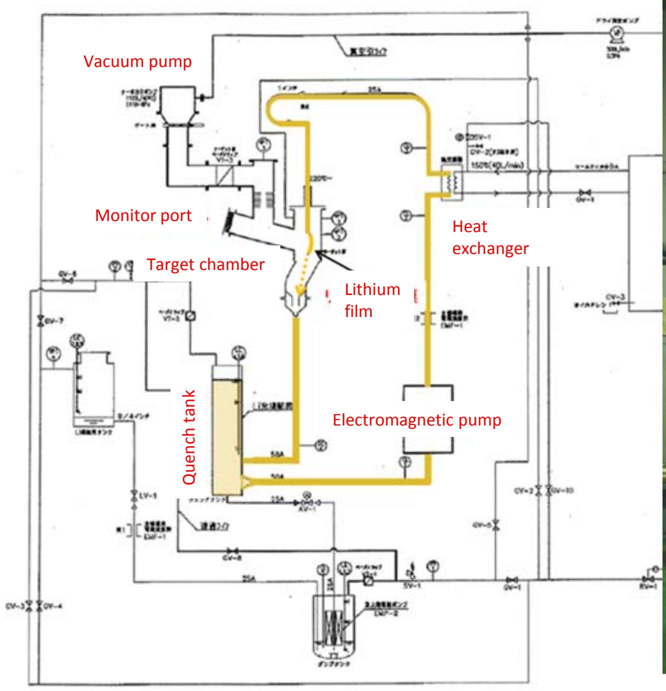


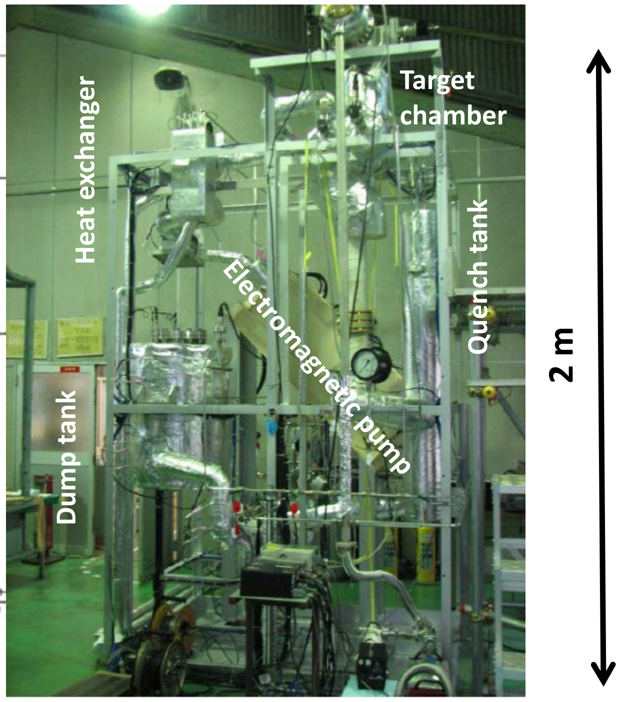
Nozzle with a back wall for BNCT



Nozzle for ImPACT

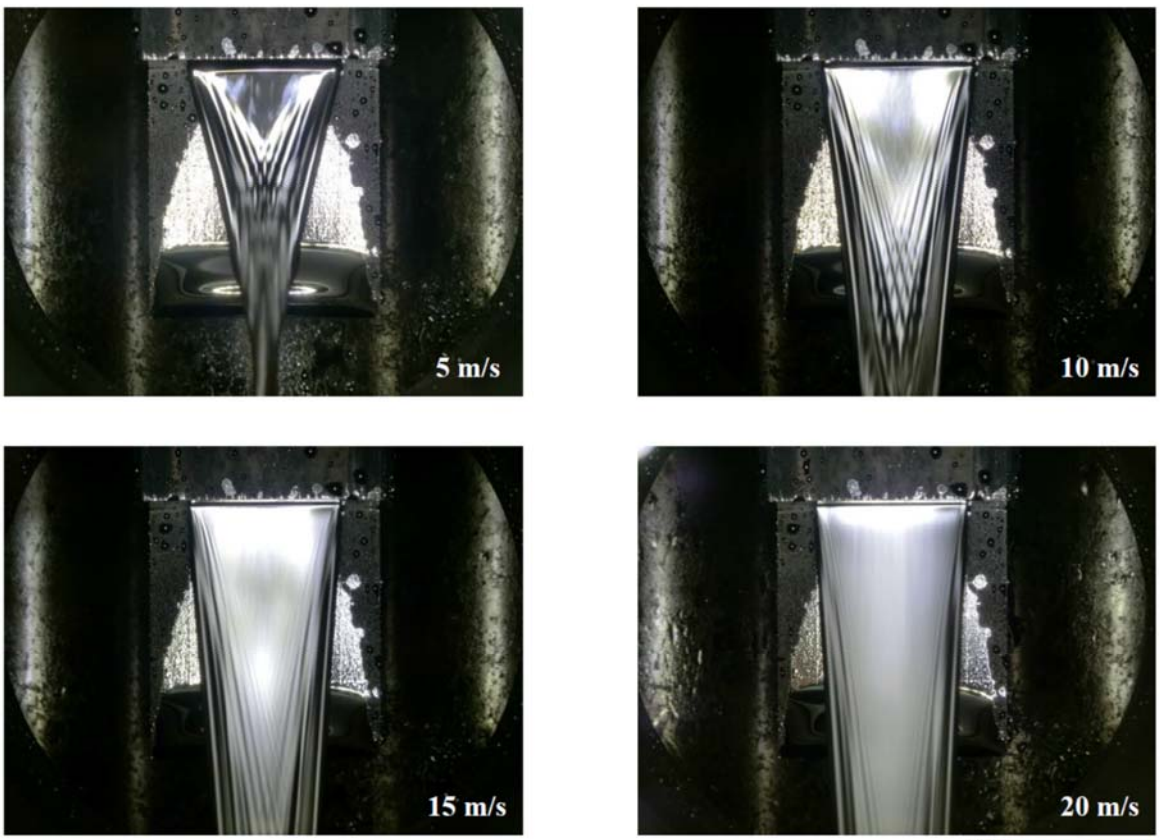
Test loop for liquid lithium target



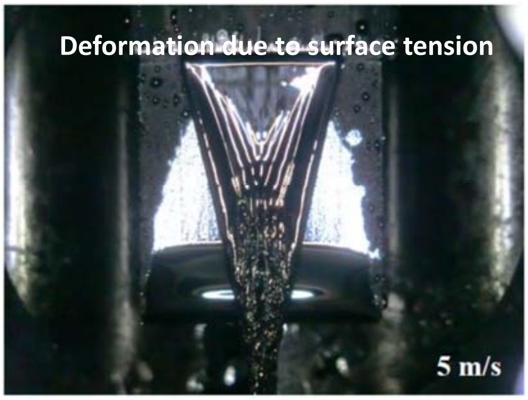


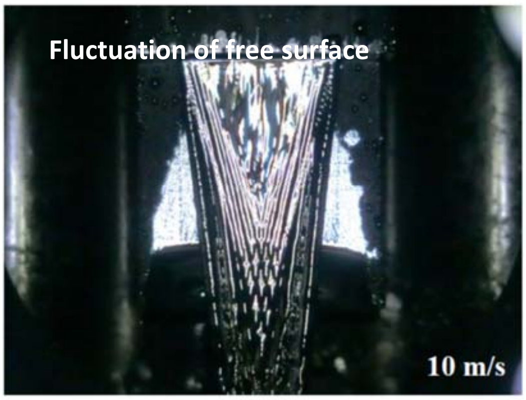
This loop was developed for BNCT by Prof. Hayashizaki (TIT) .
The back wall was removed for this study.

Photos of liquid lithium film with long exposure

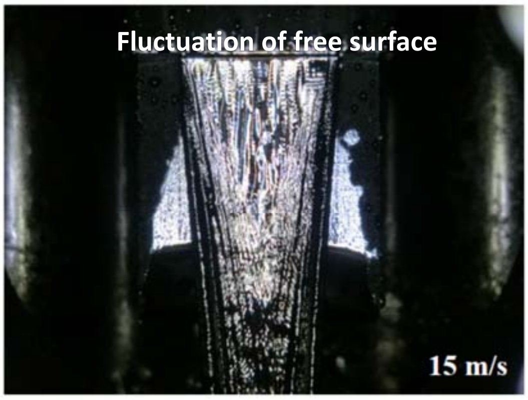


Photos of liquid lithium film with 10μs exposure





How to suppress the deformation and fluctuation → Magnetic field



Project 4 Contents (Nuclear Reaction Experiments)

◆ **Advanced control technique of nuclear reaction（Selected candidates in PJ2）**

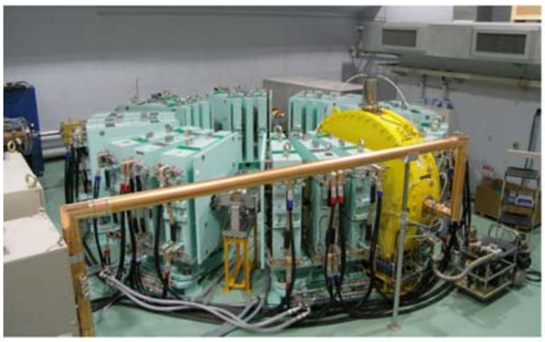
・Energy recovering Internal target（ERIT) with acceleration（Accelerating efficiency improvement ＋Higher current＋Neutron utilization）

・Efficiency improvement of Small cyclotron（r.t. superconducting or mermanent magnet + multi layer cyclotron）

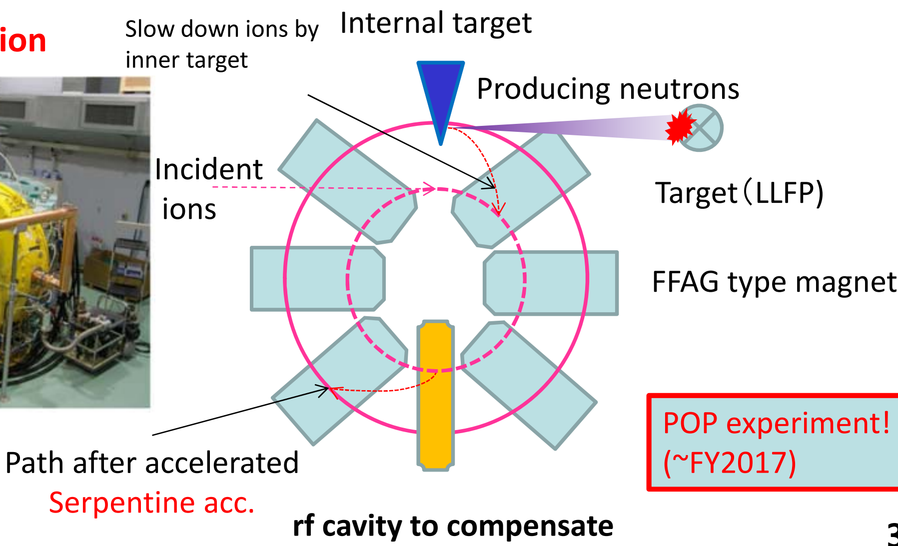
・Transmutation facility using fusion neutrons（Millar type fusion＋Muon catalized fusion）

【Principle of ERIT accelerator & Transmutation by neutrons 】

Acceleration+Accumulation



ERIT at KURRI (2005~)



POP experiment! (~FY2017)

Summary

- **"Reduction and Resource Recycling of HLW through Nuclear Transmutation"**
- PJ1: Separation and Recovery technique namely Partitioning
  - **The new scheme of Odd-even separation (gain efficiency by 100000)**
- PJ2: Nuclear data measurement for transmutation
  - **We successfully obtained various reaction data for LLFPs using RIBF and J-PARC**
- PJ3: development of nuclear reaction model and improvement of PHITS reaction model
  - **Requirement to Accelerator**
- PJ4: Transmutation system and elemental technologies development (Accelerators and targets)
  - **Superconducting Cavity of QWR (Quarter Wave Resonator) was successfully test.**
  - **Large aperture plasma window**
  - **Liquid Lithium target and granular target**
  - **New types of ERIT which allows acceleration and accumulation**
  - **Design of 1A linac is underway.**

Project 5 Contents

Purpose：to evaluate of practicability with specific scenario of LLFP P&T system and proposed conceptual design of new transmutation system by using results of PJ1 to PJ4.

◆ **Scenario study of LLFP P&T**

・Disposal improvement by P&T
（Volume reduction of high-level radioactive waste both LLFP and MA Transmutation）

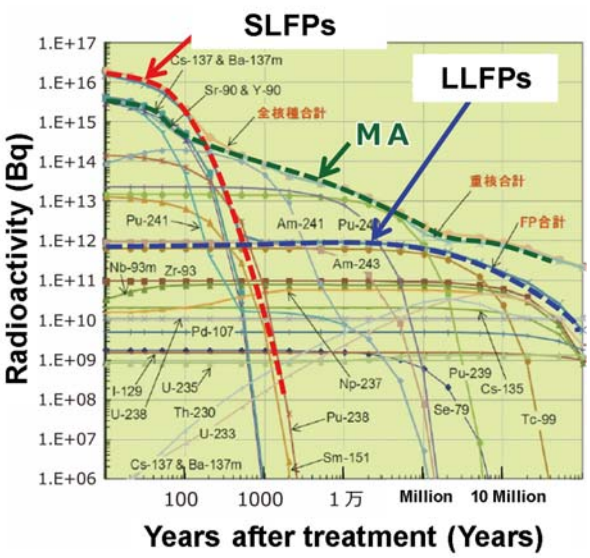
・Rare metal materials for resource recycling by P&T
（LLFP's Pd and Zr for resource recycling）

◆ **Conceptual design of process**

・Study on separation and recovery system

・Study on transmutation system

・Specific design of P&T system and economic feasibility assessment



3.3 Technical Session 2-2: Presentations about the neutron sources developed or being developed (cont.)

3.3.1 Neutron sources for transmutation applications (incl. MYRRHA): D. Terentiev, (SCK-CEN)

The MYRRHA project

2017

Outline

What is Project MYRRHA?

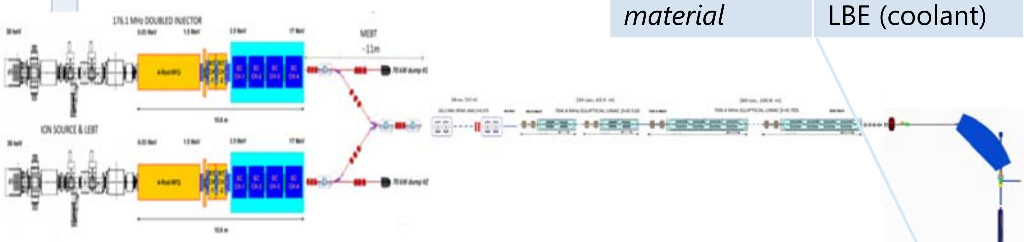
- MYRRHA technical description
- MYRRHA Research & Development effort
- MYRRHA planning

Key technical objective of the MYRRHA-project: an Accelerator Driven System

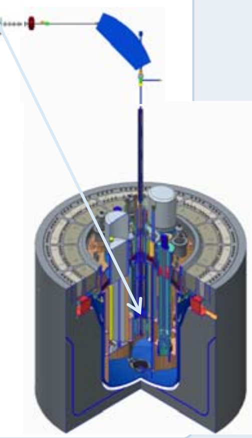
Construction of an Accelerator-Driven System (ADS) consisting of

- A 600 MeV – 2,5 mA to 4,0 mA proton linear accelerator
- A spallation target/source
- A lead-Bismuth Eutectic (LBE) cooled reactor able to operate in subcritical & critical mode

Accelerator	
particles	protons
beam energy	600 MeV
beam current	2.4 to 4 mA



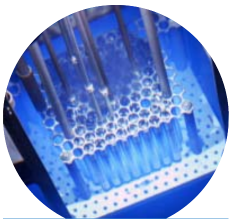
Target	
main reaction	spallation
output	$2{\cdot}10^{17}$ n/s
material	LBE (coolant)



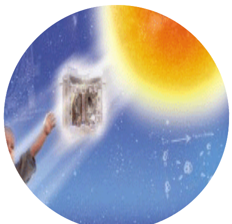
Reactor	
power	65 to 100 MW_{th}
k_{eff}	0,95
spectrum	fast
coolant	LBE

Source: SCK•CEN MYRRHA Project Team

MYRRHA application portfolio



Fission GEN IV



Fusion

Multipurpose
h**Y**brid
Research
Reactor for
High-tech
Applications

SNF*/ Waste

Fundamental research

Radio-isotopes

SMR LFR

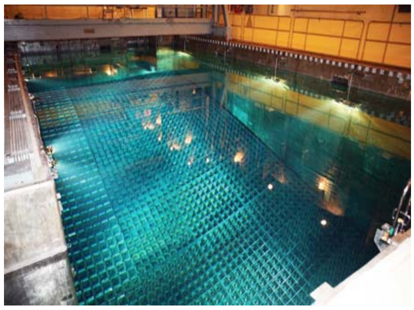
*SNF = Spent Nuclear Fuel

Source: SCK•CEN MYRRHA Project Team, MYRRHA Business Plan

Global challenges for nuclear energy today: Closing the fuel cycle is priority number one

Common needs

- Burning legacy of the past
- Reducing cost of ultimate waste
- Better use of resources
- Enhance Safety



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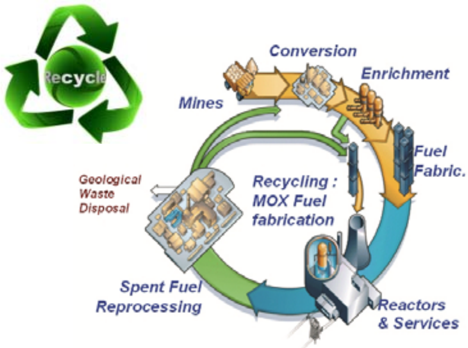
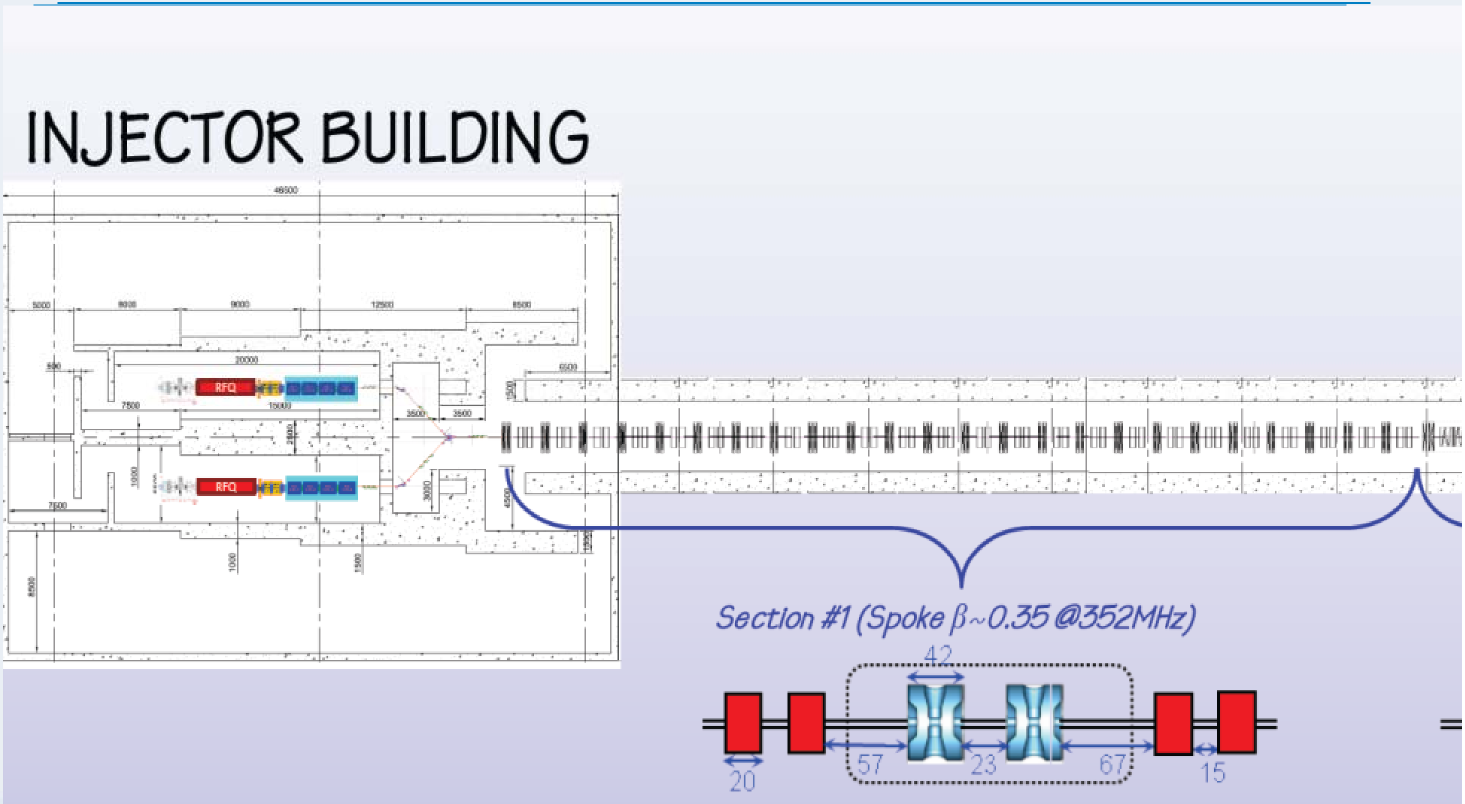


Source: SCK•CEN MYRRHA Project Team

Outline

- What is Project MYRRHA?
- **MYRRHA technical description**
- MYRRHA Research & Development effort
- MYRRHA planning

MYRRHA linac



Specific requirements of MYRRHA Accelerator

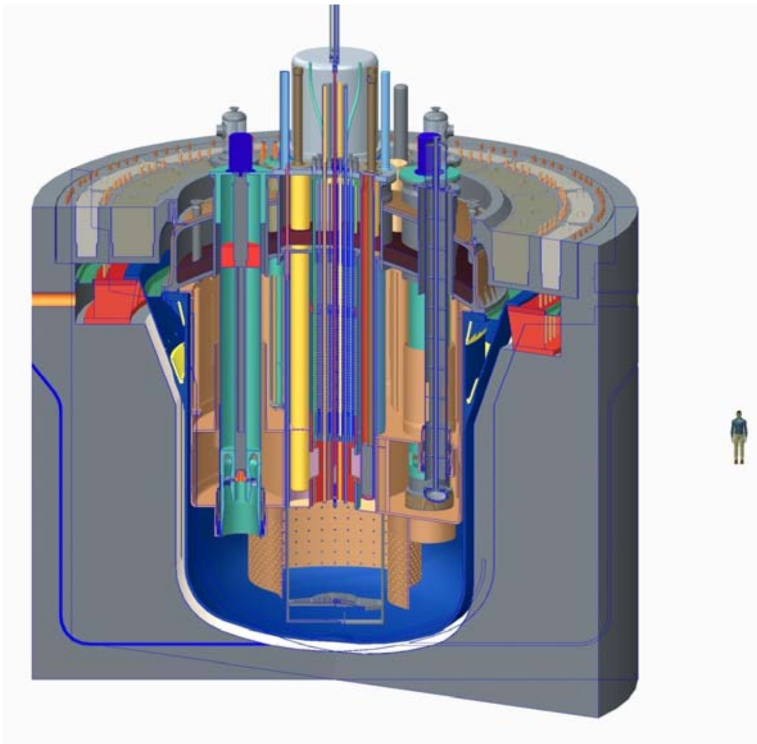
→ High power proton beam (up to 2.4 MW)

Proton energy	600 MeV
Beam current	0.1 to 4.0 mA
Repetition rate	Continuous Wave, 250 Hz
Beam duty cycle	10^{-4} to 1
Beam power stability	< ± 2% on a time scale of 100ms
Beam footprint on reactor window	Circular ∅85mm
Beam footprint stability	< ± 10% on a time scale of 1s
# of allowed beam trips on reactor longer than 3 sec	10 maximum per 3-month operation period
# of allowed beam trips on reactor longer than 0.1 sec	100 maximum per day
# of allowed beam trips on reactor shorter than 0.1 sec	unlimited

→ Extreme reliability level: MTBF > 250 hrs

Reactor – Current Primary System design (v1.6)

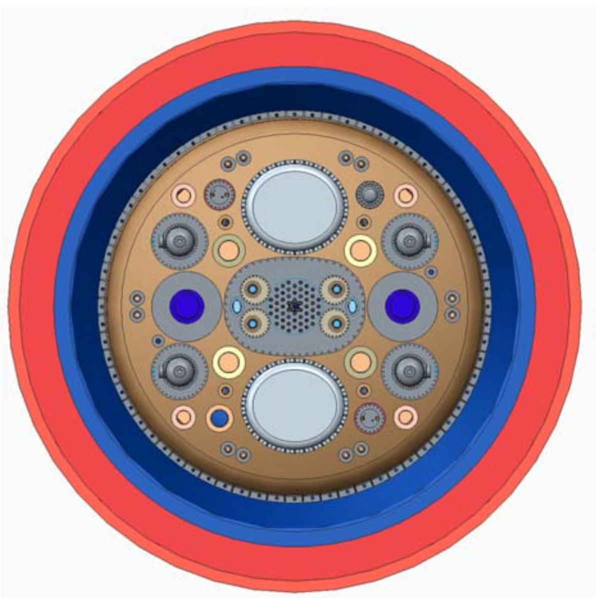
- Reactor layout
  - Vessel
  - Cover
  - Core barrel and Multi-functional plugs
  - Above Core Structure
  - Cradle, Core Restraint System, beam line and window target
  - Si-doping units, Mo-irradiation units, control rods and safety rods
  - Primary Heat Exchangers
  - Primary Pumps
  - In-Vessel Fuel Handling Machines, Fuel Transfer Devices, Failed Fuel Detection Devices, Extraction Pumps
  - Diaphragm and support structure
  - Reactor pit, Reactor Vessel Auxiliary Cooling System

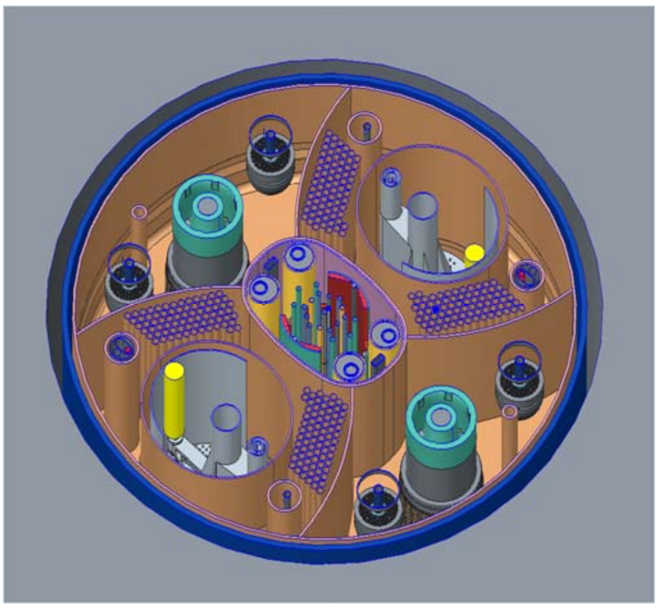


Source:SCK•CEN MYRRHA Project Team

Current Primary System design

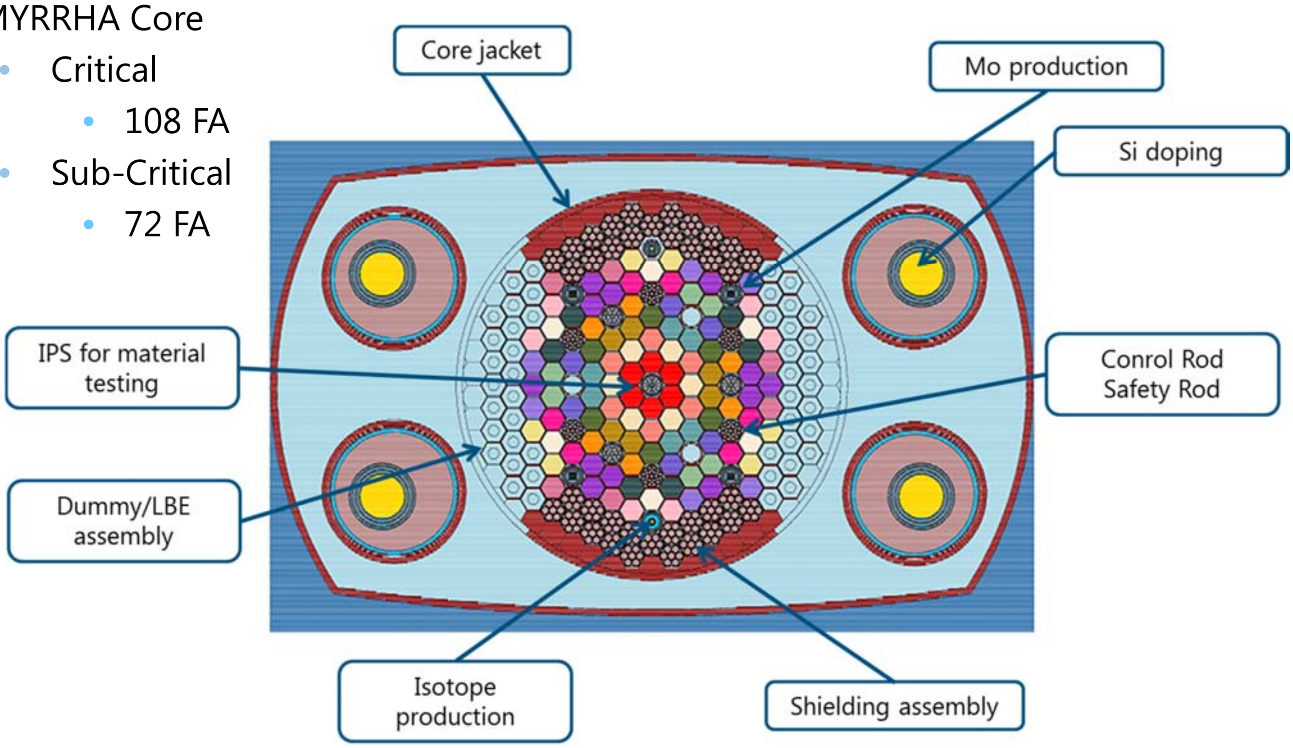
- Reactor layout
  - Top and core mid-plane





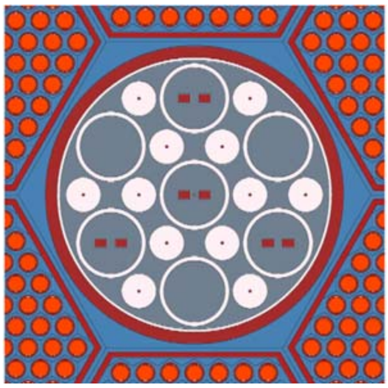
Current Primary System design

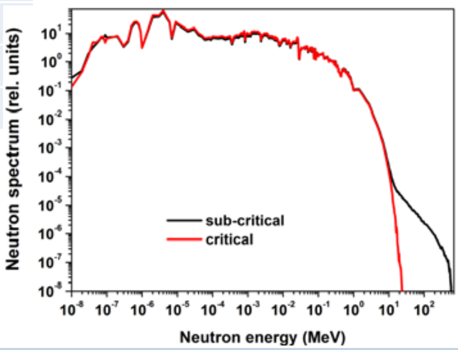
- MYRRHA Core
  - Critical
    - 108 FA
  - Sub-Critical
    - 72 FA



Irradiation performances

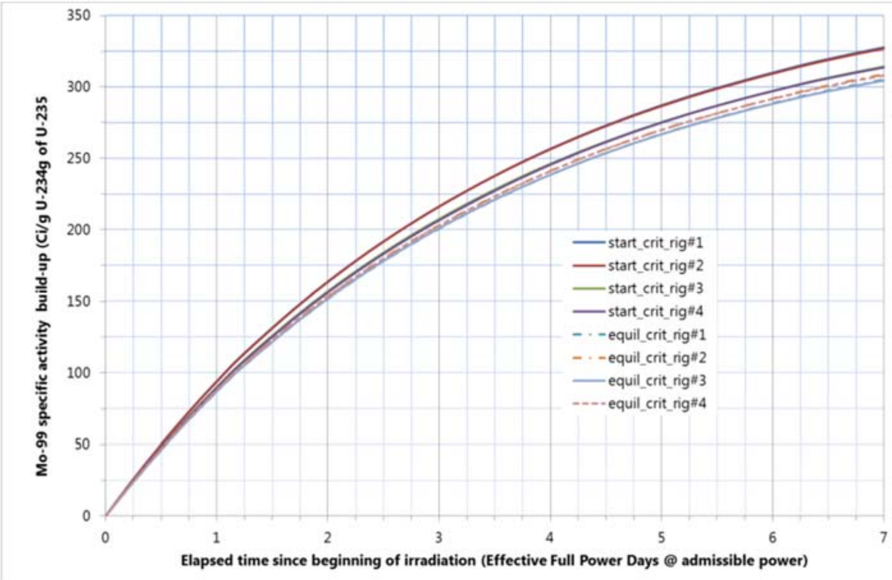
		Critical	Sub-critical
Flux and DPA values normalised to	MWth	96	72
Beam current	mA	-	1.74 – 2.52
DPA damage in IPS			
IPS in central channel	DPA/FPY	21.7	-
IPSs in off-central channel	DPA/FPY	13.9	31
Neutron Flux in IPS			
IPS in central channel / target			
Φ≥ 0.75 MeV	n/cm² s	4.05E+14	1.01E+15
Φtot	n/cm² s	2.61E+15	3.75E+15
IPSs in off-central channel			
Φ≥ 0.75 MeV	n/cm² s	2.56E+14	4.2E+14
Φtot	n/cm² s	1.75E+15	2.6E+15





Radioisotope production

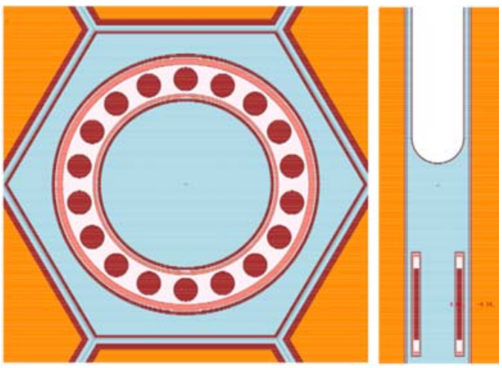
- Mo99 production
  - Fission of U targets
  - Moderation needed!
  - H_2O device

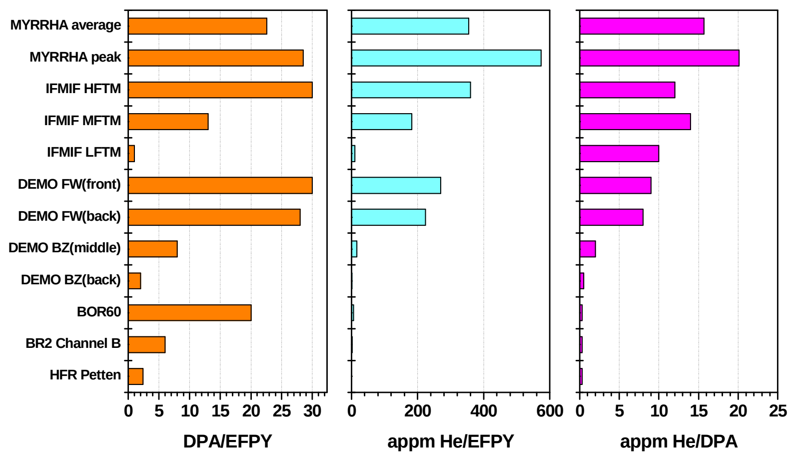


Irradiation for fusion-like conditions

- Below spallation target
  - Very high + hard neutron flux
  - Proton flux

- Irradiation of samples
  - High dpa's & dpa rates
  - High appmHe/dpa rates





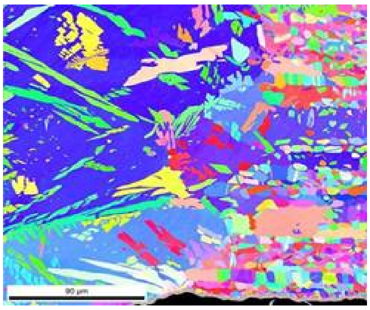
Damage of W samples

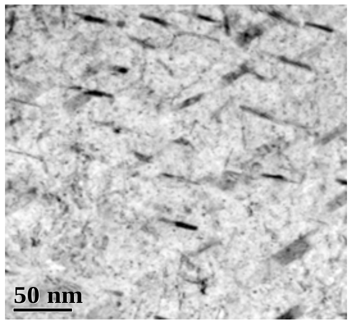
- Candidate material for DEMO divertor
- Transmutation of W into Re and Os affects more the mechanical properties than He production because:
    - He production cross section is much less than for Fe
    - Re and Os segregate and precipitate on radiation defects
- Re and Os are produced by neutron capture and (n,2n) reactions:

$$^{186}W(n,\gamma)^{187}W \rightarrow (\beta^-)^{187}Re \begin{cases} (n,\gamma)^{188m}Re \rightarrow (\gamma)^{188}Re \rightarrow (\beta)^{188}Os \\ (n,2n)^{186}Re \rightarrow (\beta^-)^{186}Os \end{cases}$$

$$^{184}W(n,\gamma)^{185}W \rightarrow (\beta^-)^{185}Re(n,\gamma)^{186}Re \rightarrow (\beta^-)^{186}Os$$

Need for dedicated neutron irradiation source
- High neutron flux
- Specific/adjustable transmutation rates

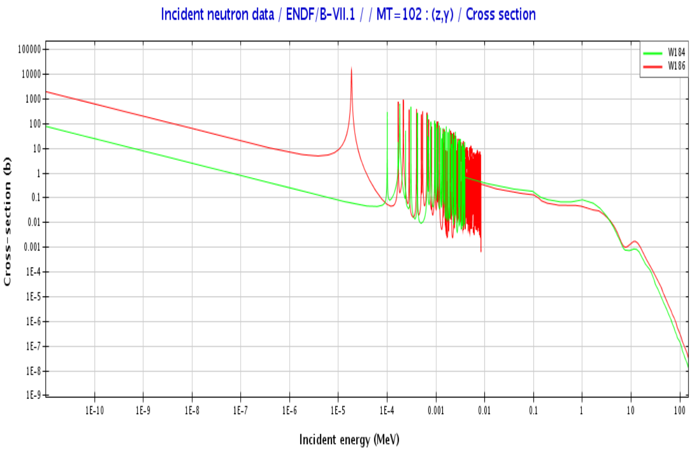


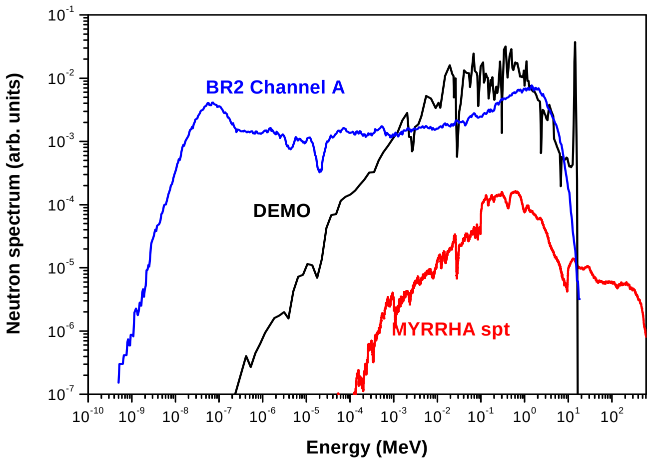


Transmutation of W

- MYRRHA conditions require adjustment:

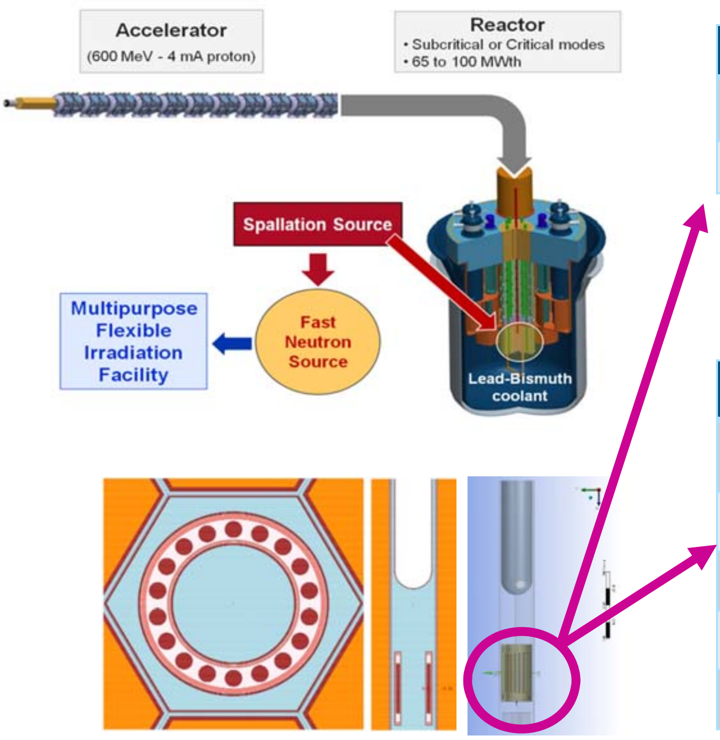
spectrum is harder than in DEMO divertor → lower production rates by (n,γ)





- But dpa damage is accumulated much faster → the ratio of W transmutation/dpa could be close to DEMO values !

MYRRHA-IMIFF (600 MeV@ 2.5 mA)
Innovative Material Irradiation Facility for Fusion



Damage of steels:
Dpa faster, more He

	DEMO	MYRRHA
Time to 1 dpa, days	39.9	11.4
appmHe/dpa	10.4	7 to 18

Damage of tungsten:
Transmutation into Re and Os is important

	DEMO	MYRRHA
Time to 1 dpa, days	123.5	67.7
Elemental fractions at 1 dpa		
74-W, %	99.86	99.84
75-Re, %	0.12	0.153
76-Os, %	0.02	0.005

Comparable transmutation rates !

Outline

- What is Project MYRRHA?
- MYRRHA technical description
- **MYRRHA Research & Development effort**
- MYRRHA planning

R&D Topics

- Materials
- Fuel
- LBE Technology
  - Components & Experiments
  - Chemical Conditioning Programme
- Instrumentation & Control
- Computer codes
- Accelerator
- ISOL@MYRRHA

LBE Facilities @ SCK•CEN

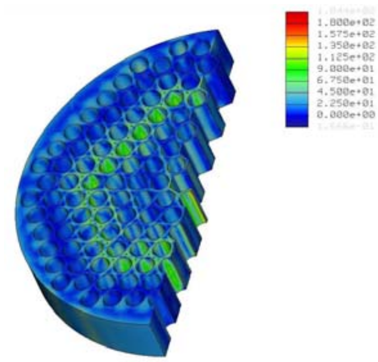
Facilities	Topic
CRAFT LIMETS 1,2,3,4	Materials
HELIOS 3 Heavy Liquid Metal Lab MEXICO LiLiPuTTeR-II	LBE conditionning
RHAPTER COMPLOT ESCAPE	Component testing & TH
US lab	Instrumentation

Role of materials research for development of MYRRHA

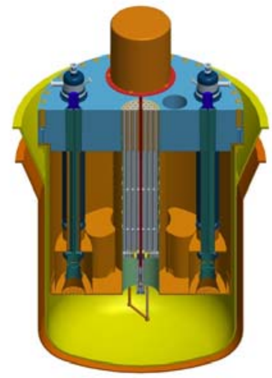
Design tools:

- Nuclear manufacturing codes: RCC-MRx, …
- Fuel codes
- FE calculations

Design

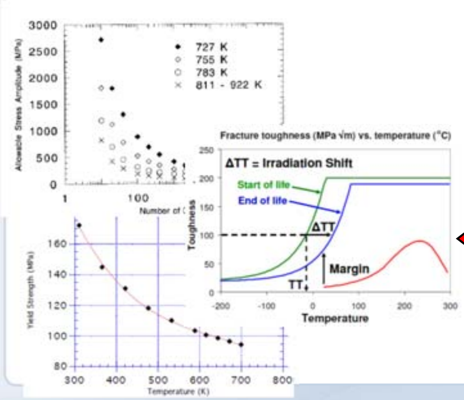


Construction



Approaches

Materials properties



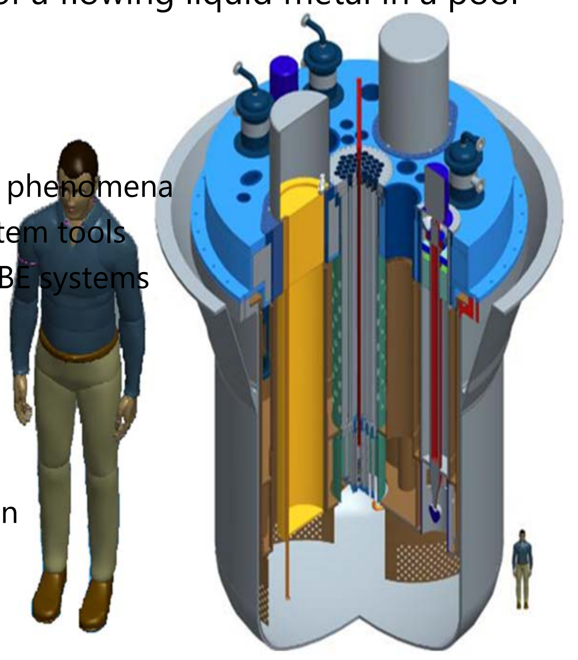
Data

Missing data for MYRRHA:

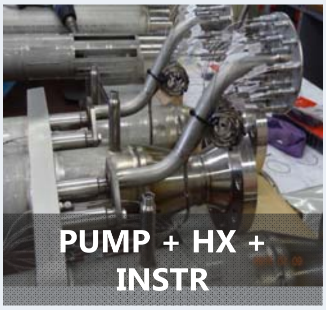
- Basic characteristics of candidate materials
- Effects of LBE & irradiation on material properties
- Physical effects

E-SCAPE

- E-SCAPE = **E**uropean **SCA**led **P**ool **E**xperiment
- Thermal-hydraulic behaviour of a flowing liquid metal in a pool geometry
- Purpose
  - Characterisation of pool T/H phenomena
  - Qualification of CFD and system tools
  - Operational experience on LBE systems
- Characteristics
  - 1/6 geometrical scale factor
  - LBE as working fluid
  - Forced and natural circulation
- Partially funded by FP7 THINS

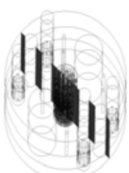


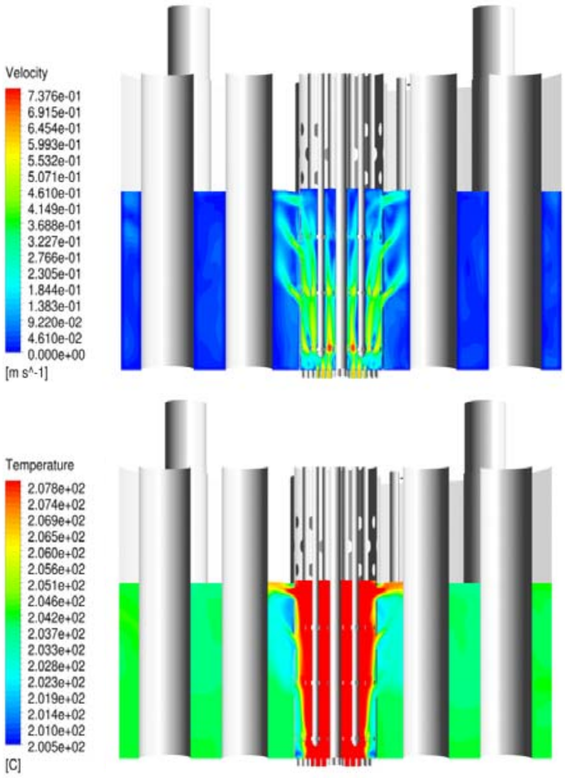
E-SCAPE facility



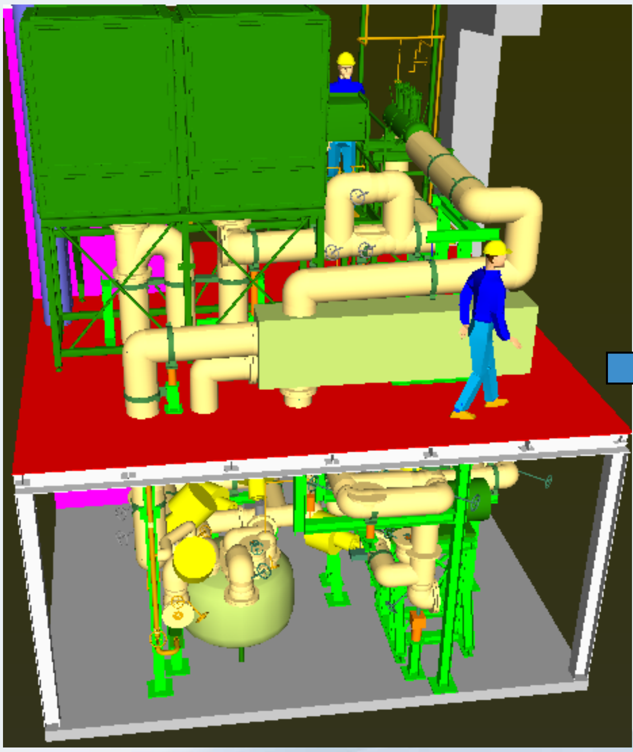
Forced circulation simulation

Forced Circulation	
Core power (kW)	82.9
Bypass power (kW)	8.29
Core mass flow rate (kg/s)	62.5
Bypass mass flow rate (kg/s)	57.5
Average HX mass flow rate (kg/s)	~30
Core outlet temperature (˚C)	208
Core inlet temperature (˚C)	200
Average HX inlet temperature (˚C)	204





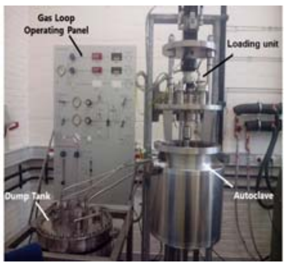
CRAFT corrosion/erosion loop

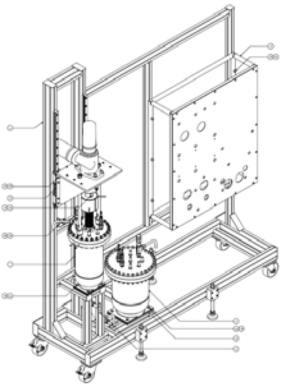


Set-ups for mechanical tests in LBE

LIMETS 1
Tensile & Fracture toughness tests in LBE

LIMETS 3
Fatigue tests in LBE

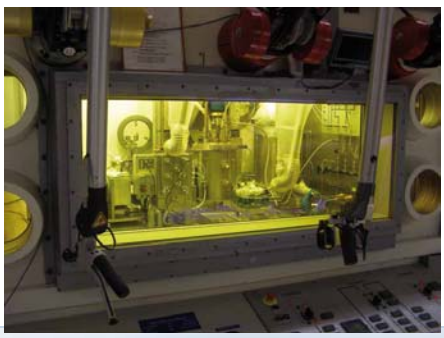




LIMETS 4
Tensile & Fracture toughness tests in LBE

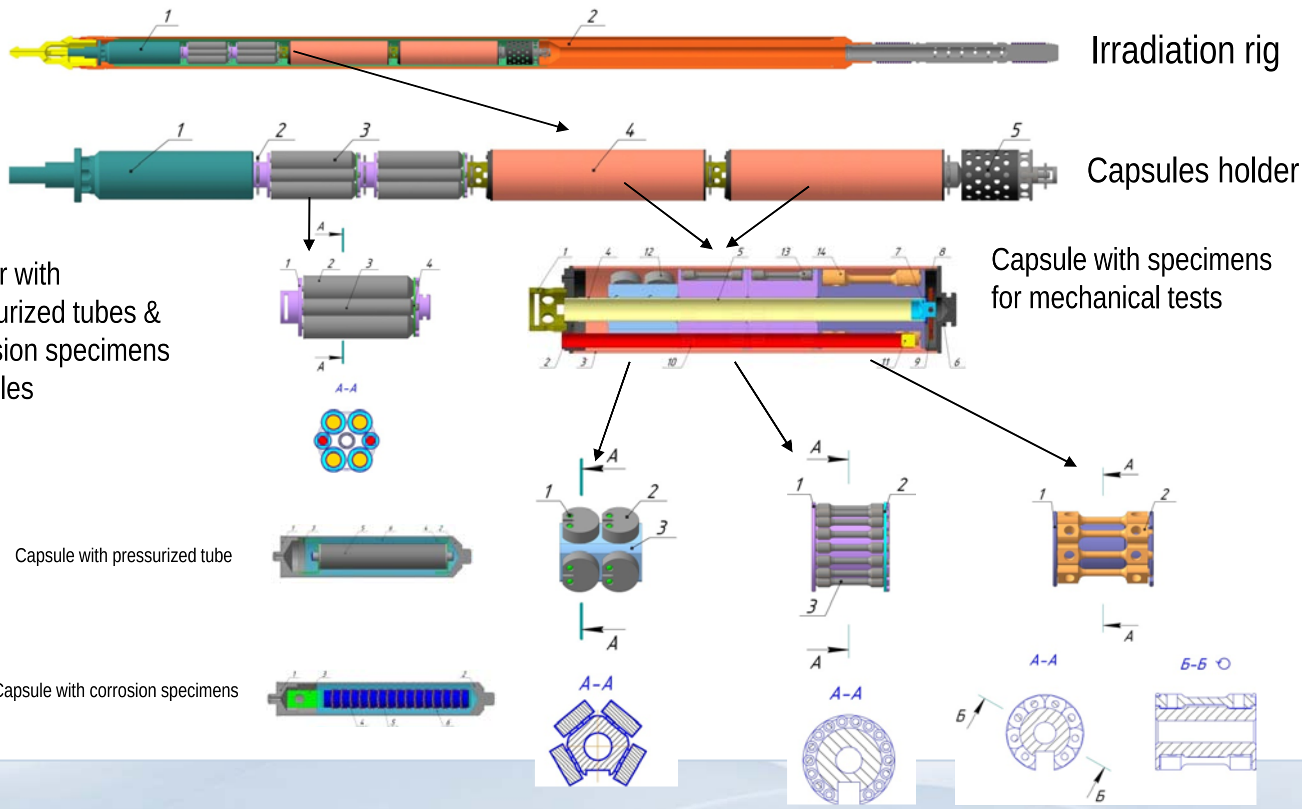
Hot cell 12 & LIMETS 2

Tensile and FT tests of irradiated* steels in liquid metal
*Licensed for α (Po) contaminated specimens



Irradiation of materials

Irradiation of MYRRHA candidate materials in LBE environment

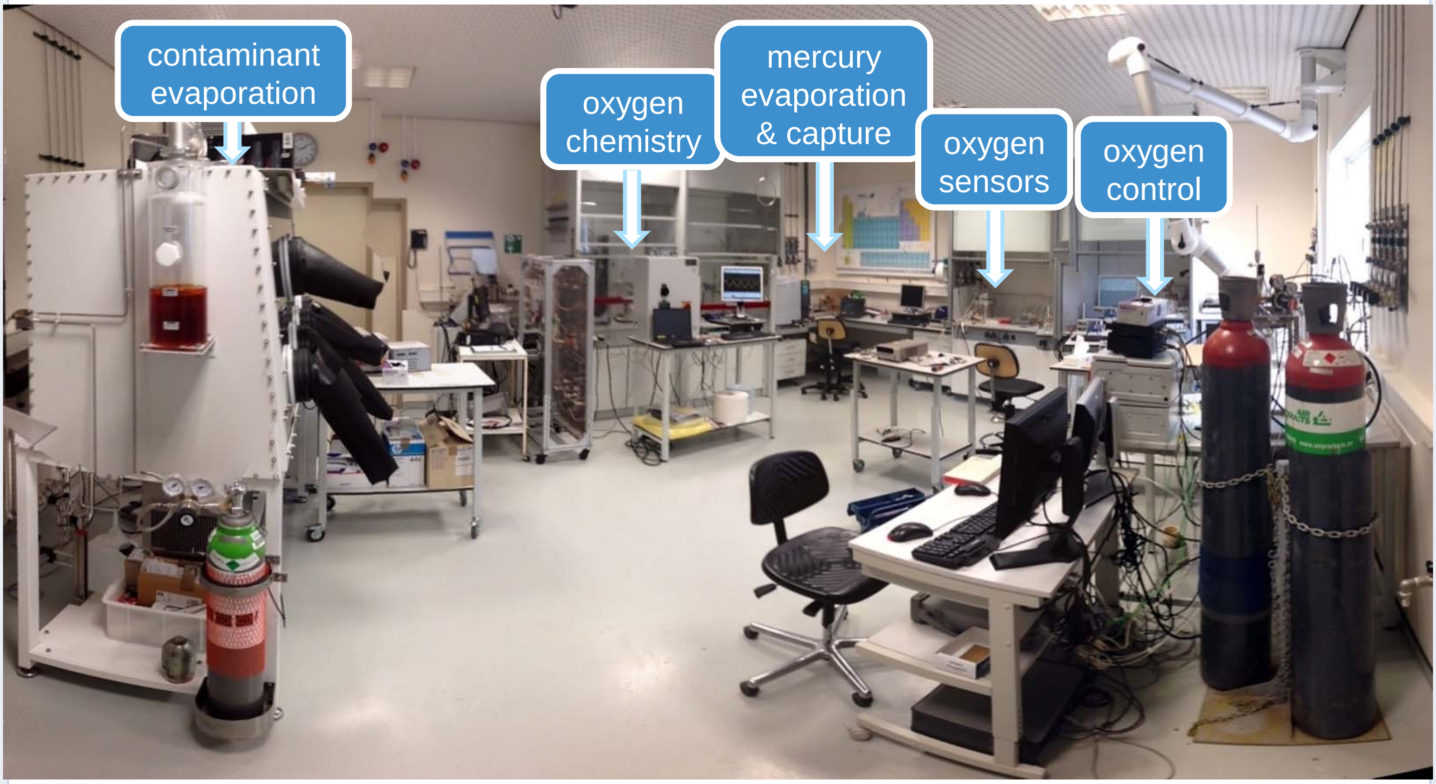


Heavy Metal lab

Heavy Metal lab

- R&D activities on chemistry in LBE
  - chemistry and control of dissolved oxygen in LBE
  - oxygen sensor development
  - evaporation spallation and fission products from LBE
  - Capture of spallation and fission products

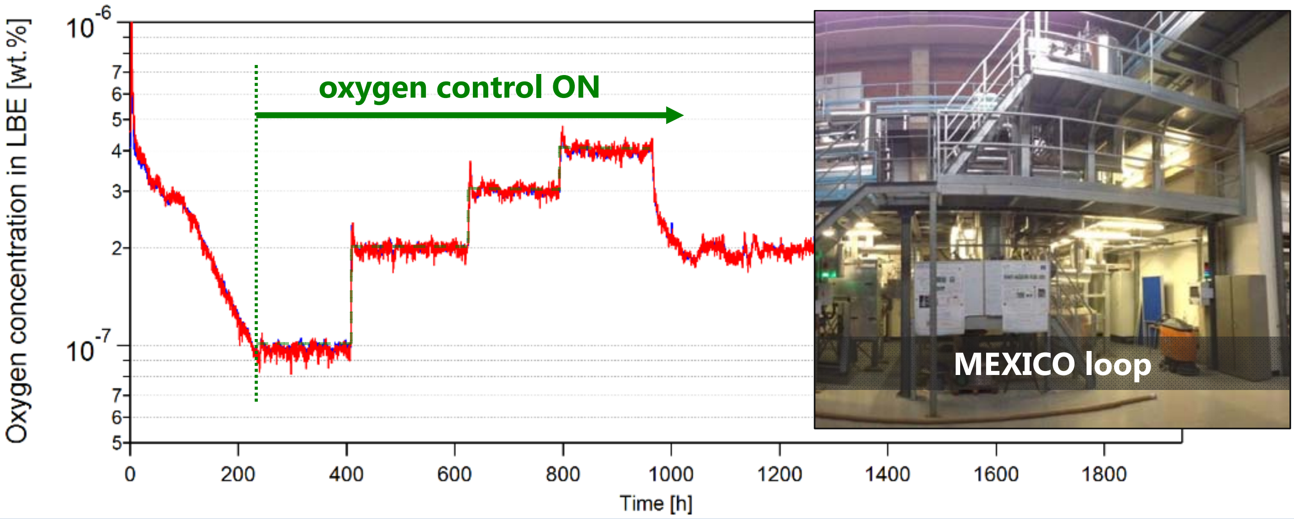
Heavy metal lab - R&D



MEXICO LBE loop

- over 10000 h of experiment time, $100 \cdot 10^6$ kg LBE circulated
  pilot-scale demonstration of oxygen control technologies:

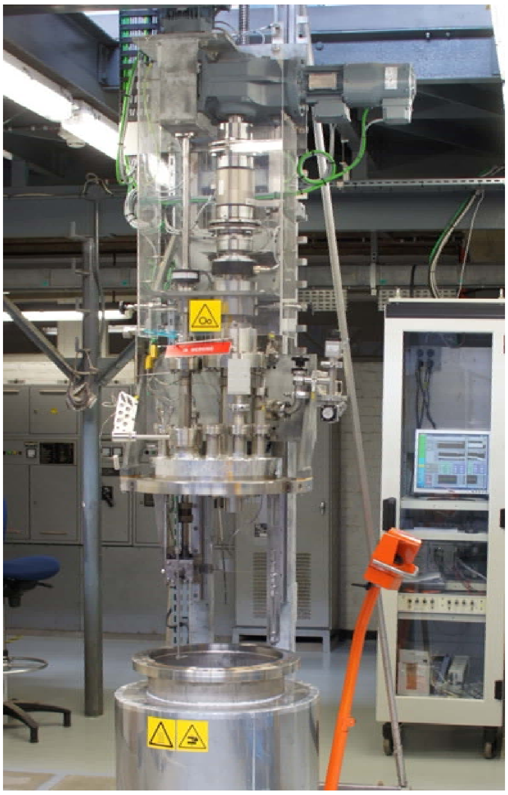
- accurate & stable oxygen control of 7000 kg of LBE



RHAPTER
Mechanical component tests for in-LBE robotics

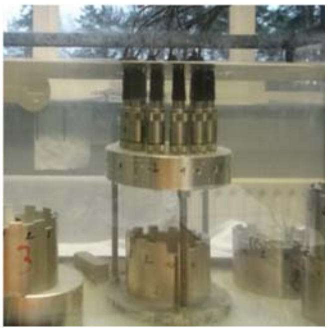
- Isothermal pool facility
- Interchangeable test modules
- Specifications
  - 150 - 450°C
  - 50 l LBE
  - Vacuum or gas cover
- Drive axle and load axle
  - Variable torque and rotation speed
- Instrumentation
  - Torque sensor
  - Position encoder
  - Accelerometer
  - Thermocouples
  - Pressure gauge

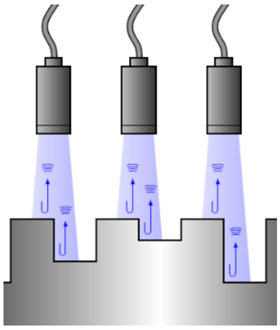
- Status: in operation since September 2011

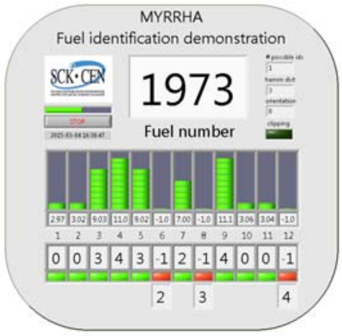


Fuel identification system

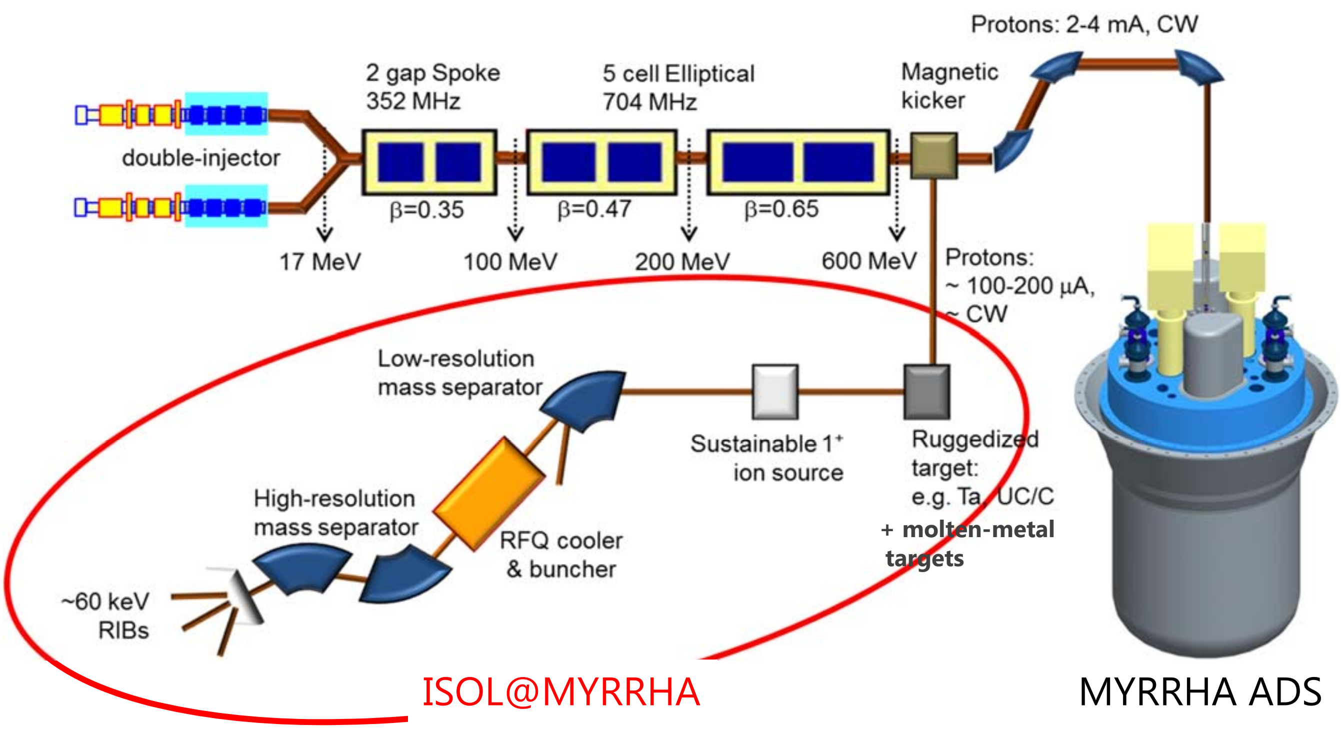
- Physical code on fuel assemblies
  - 12 notches at the entrance nozzle of a MYRRHA fuel assembly
  - Each notch can have five different depths
- Ultrasonic code reader
  - 12 ultrasonic transducers at the gripper of the fuel manipulators
  - Differential depth measurement allows for reliable notch depth measurement
  - Error detection and error correction algorithms make the system robust against failing transducers or other misreadings





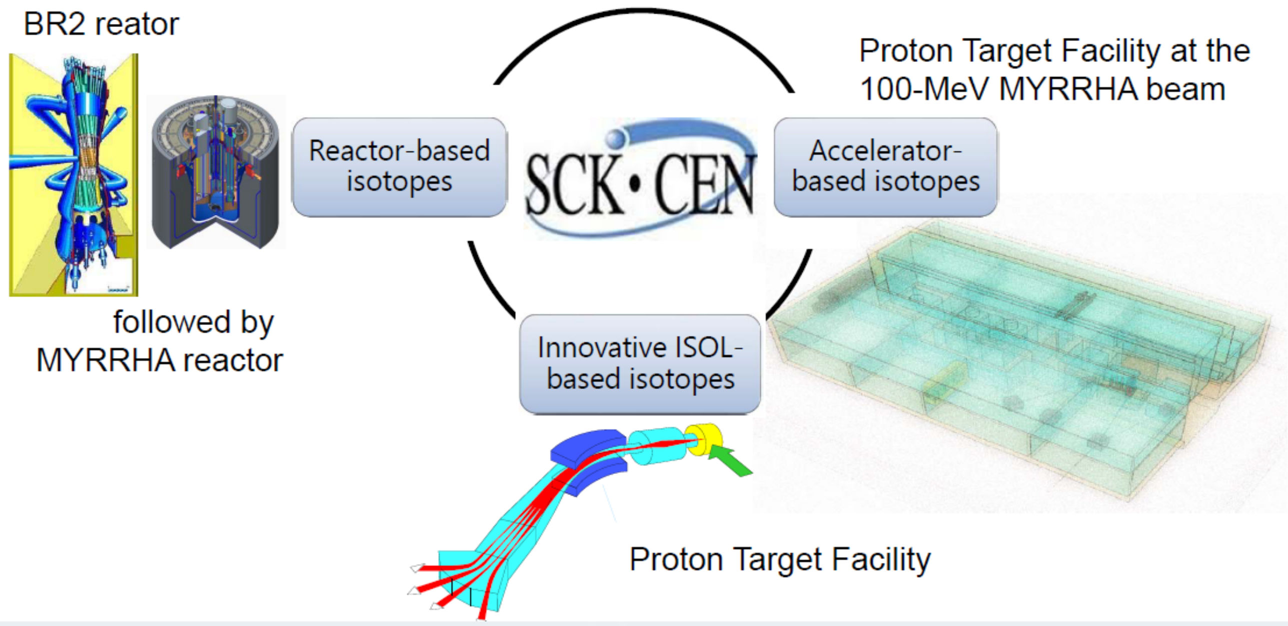


ISOL@MYRRHA Concept



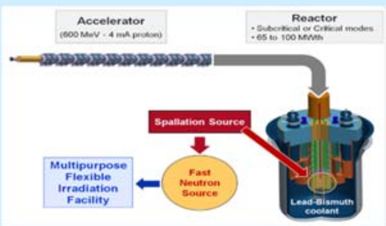
Focus on long-term operation without interruption

- MYRRHA places SCK•CEN on unique position in the world of medical isotopes production & research



Challenges of 100 MeV proton accelerator regarding fusion material testing

MYRRHA-IMIFF: proton beam 600 MeV,@ 2.5 mA

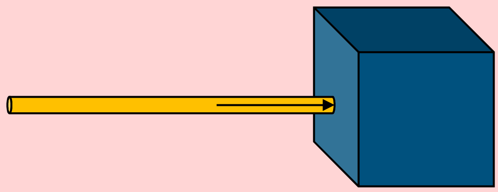


15 neutrons per proton

Neutron flux **> 2×10^{15}** n/(cm^{2}s)

Neutron spectrum:
mostly fission neutrons easy to thermalize
(for tungsten transmutation)

Proton beam 100 MeV @ 4 mA protons + target



0.3 neutrons per proton

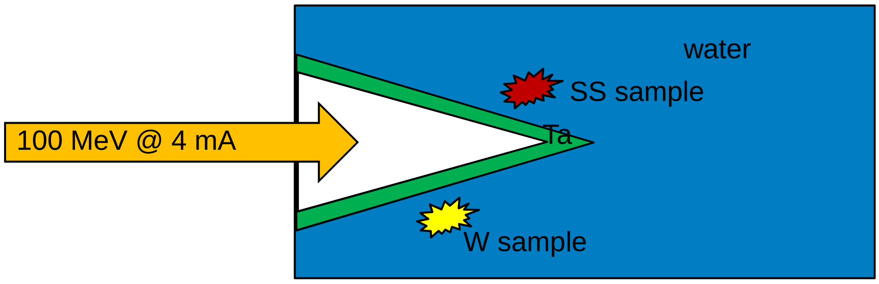
Neutron flux **< 1×10^{14}** n/(cm^{2}s)

Neutron spectrum:
Spallation neutrons difficult to thermalize

To achieve similar damage rates:

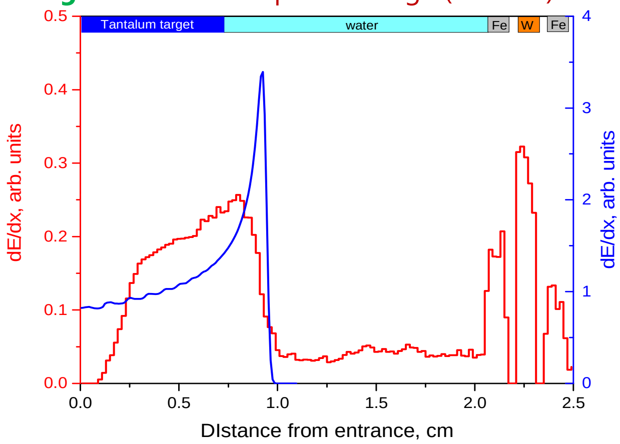
- the displacement damage (dpa) must contain the proton component
- use moderated neutrons to transmute tungsten

Irradiation by 100 MeV protons: feasibility



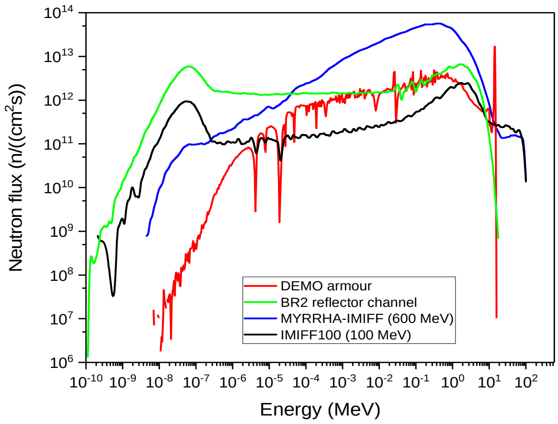
Target material: Tantalum

Target thickness: < proton range (~ 1 cm)



Optimal thickness: ~7.5 mm

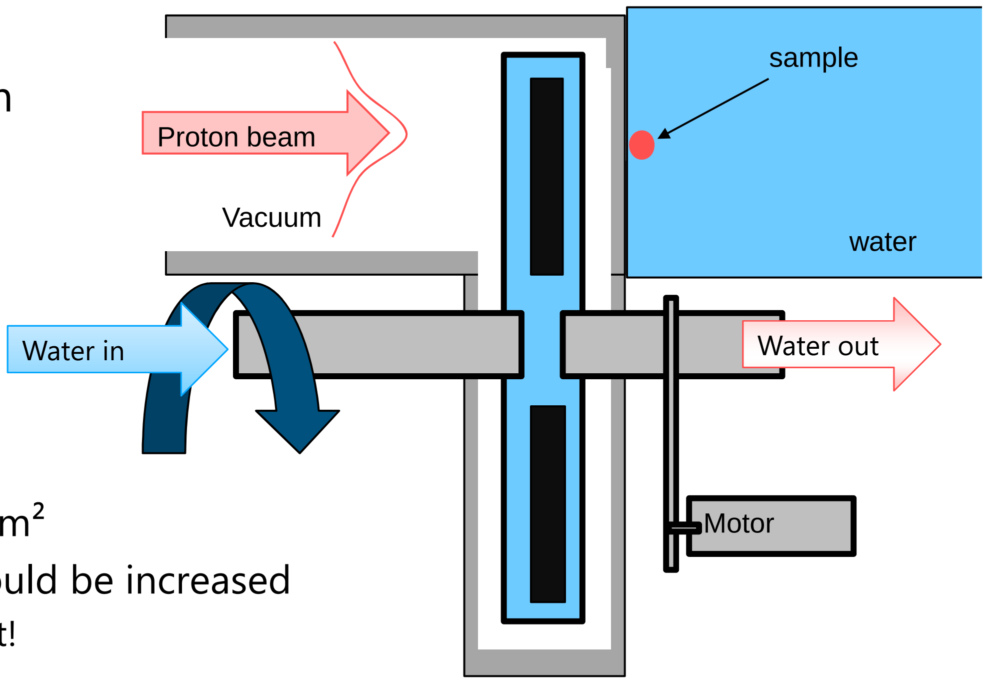
Moderator: water



Neutron spectrum is softer than in DEMO: to compensate reduction of neutron flux

Rotation window and converter DISK

- Rotative disc with Ta converter
- Heat flux 2x2 3 mm Al
  - → 60 MW/m^2
- Rotative 1 m disk 3,14 m
- 3,14/0,02=157
  - 0,4 Mw/m^2



- Ta converter +- 350 kw
- Area = 0,02*3m x2
  - Heat flux about 3 MW/m^2
  - is possible and area could be increased
    - Not structural element!

Preliminary results

Irradiation of tungsten samples

	IMIFF100	MYRRHA-IMIFF	DEMO
Time to reach 1 dpa, days	123.27	67.47	123.45
Appm He/dpa	1.26	1.76	0.58
Neutron flux, n/(cm^{2}s)	8.21×10^{13}	2.40×10^{15}	5.27×10^{14}
$^{184}W(n,\gamma)^{185}W$ cross section, b	0.36	0.21	0.33
$^{186}W(n,\gamma)^{187}W$ cross section, b	0.64	0.30	0.52
Elemental concentrations at 1 dpa			
72-Hf, %	1.5×10^{-4}	1.04×10^{-3}	8×10^{-5}
73-Ta, %	6.2×10^{-4}	1.31×10^{-3}	0.012
74-W, %	99.85	99.84	99.86
75-Re, %	0.149	0.153	0.12
76-Os, %	8.2×10^{-4}	4.86×10^{-3}	2.3×10^{-3}

dpa @ transmutation rates comparable to DEMO

Irradiation of steel samples

	IMIFF100	MYRRHA-IMIFF (max/min) [2]	DEMO [2],[7]
Radiation damage rate, dpa/s	3.29×10^{-7}	1.65×10^{-6} / 1.01×10^{-6}	2.90×10^{-7}
Time to reach 1 dpa, days	35.20	11.41 / 7.02	39.90
appm He/dpa	14.27	18.04 / 7.12	10.42

dpa rates comparable to DEMO
He production rates 40% higher

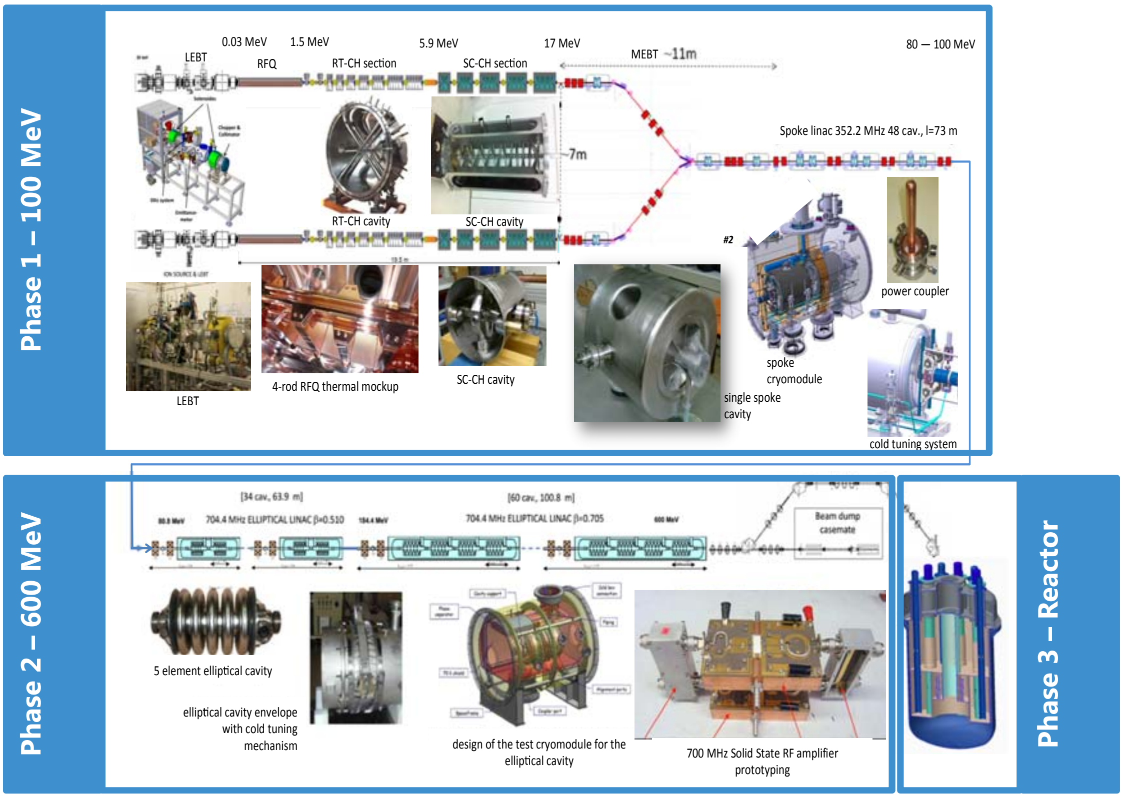
Outline

- What is Project MYRRHA?
- MYRRHA technical description
- MYRRHA Research & Development effort
- **MYRRHA planning**

MYRRHA's phased implementation strategy

Benefits of phased approach:

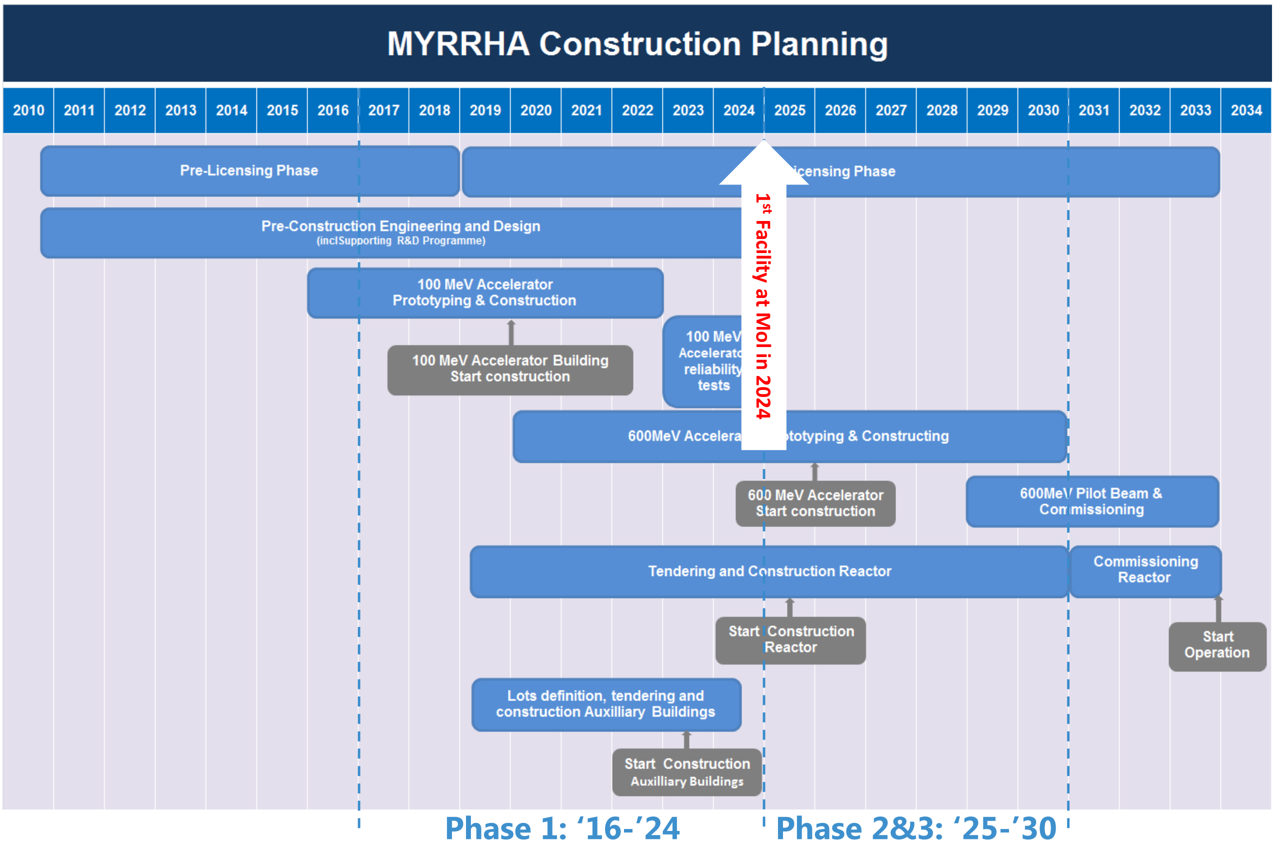
- Reducing technical risk
- Spreading investment cost
- First R&D facility available in Mol end of 2024



Source:SCK•CEN MYRRHA Project Team

Phased implementation plan MYRRHA Project (2016-2030)

> Implementation High-Level overview



Source: SCK•CEN MYRRHA Project Team

MYRRHA is embedded in an international R&D network

Source: SCK•CEN MYRRHA Project Team

A jump in the future for pioneering innovation in Belgium
For sustainable nuclear energy in Europe and the world

SCK•CEN
Studiecentrum voor Kernenergie
Centre d'Etude de l'Energie Nucléaire
Belgian Nuclear Research Centre

Stichting van Openbaar Nut
Fondation d'Utilité Publique
Foundation of Public Utility

Registered Office: Avenue Herrmann-Debrouxlaan 40 – BE-1160 BRUSSELS
Operational Office: Boeretang 200 – BE-2400 MOL

3.3.2 D-T neutron sources (including HINEG, SORGENTINA, etc): Y. Wu (FDS)

Institute of Nuclear Energy Safety Technology, CAS
Key Laboratory of Neutronics and Radiation Safety, CAS

Better Nuclear Energy Technology, Better Life!

www.fds.org.cn

D-T Neutron Sources

Presented by Yican Wu

Contributed by FDS Team

Key Laboratory of Neutronics and Radiation Safety

Institute of Nuclear Energy Safety Technology (INEST)

Chinese Academy of Sciences

www.fds.org.cn

Outline

I. Background

II. Research & Development

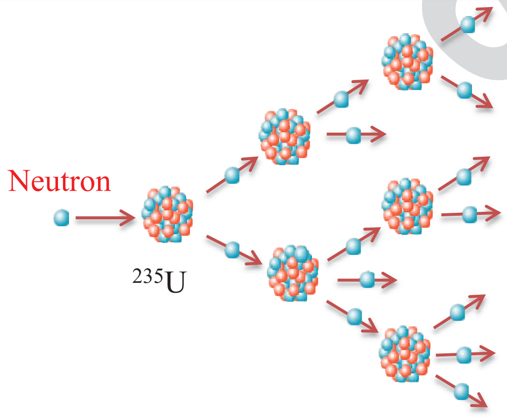
III. Application

IV. Summary

Neutron is the Root of Nuclear Energy and Technology

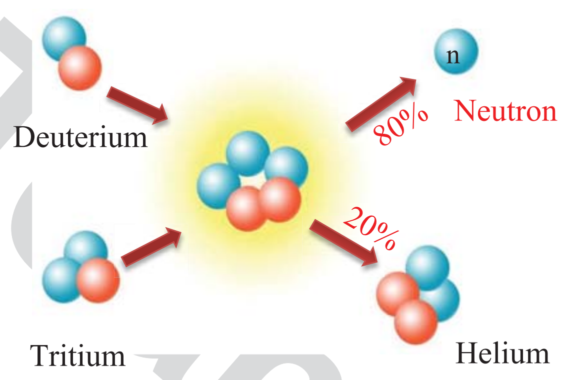
——The essential element for safe operation ('soul')

Fission: Trigger and Medium



$$^{235}U + n \rightarrow {}^{A1}X + {}^{A2}Y + \nu n + 200MeV$$

Fusion: Main Energy Carrier

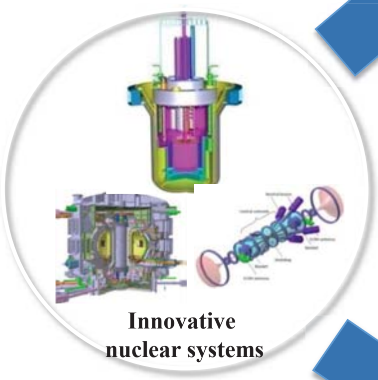


$$D + T \rightarrow He + n + 17.6MeV$$

FDS Team

Neutron is the Root of Nuclear Energy and Technology

——Neutron physics in advanced nuclear systems



Technological Objectives

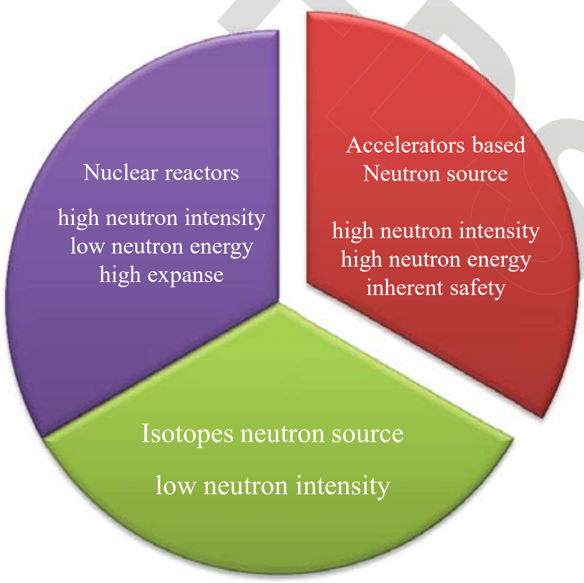
- Safety
- Economic efficiency
- Sustainability

System Features

- Complex structure and materials
- Complex neutron spectrum
- Spanning multiple scales

Neutron :
New properties
New challenges
?

Characteristics of Common Neutron Sources



- Spallation neutron source
- D-Li neutron source
- D-Be neutron source
- **D-T neutron source**
- …

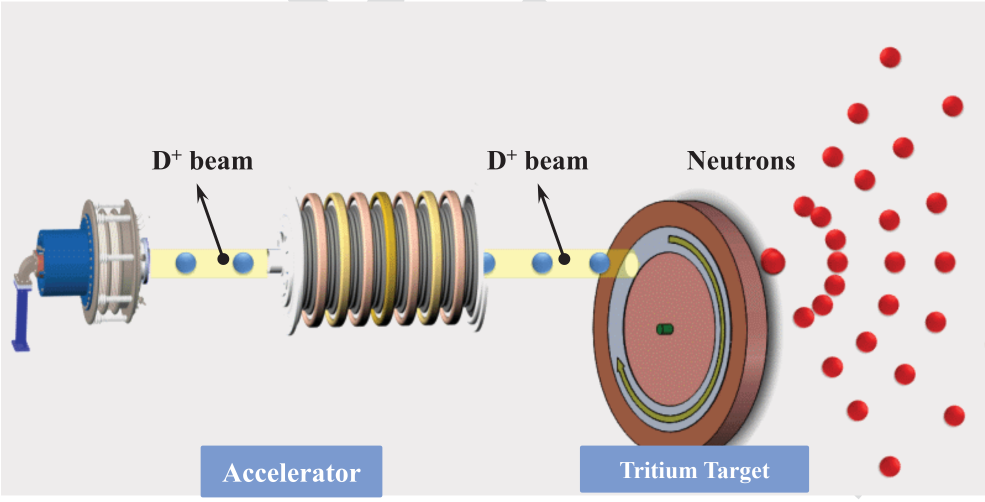
Mono neutron energy, Actual D-T spectrum

Principle of D-T Neutron Source

Accelerated high intensity deuterium ions hit tritium (deuterium) targets to produce 14.1 MeV (2.45 MeV) mono-energetic neutrons:

$$D + T \rightarrow n\ (14.1MeV) + {}^{4}He$$

$$D + D \rightarrow n\ (2.45MeV) + {}^{3}He$$



Outline

I. Background

II. Research & Development

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Outline

I. Background

II. Research & Development

- INEST (China)
- ENEA (Italy)
- PNL (USA)

III. Application

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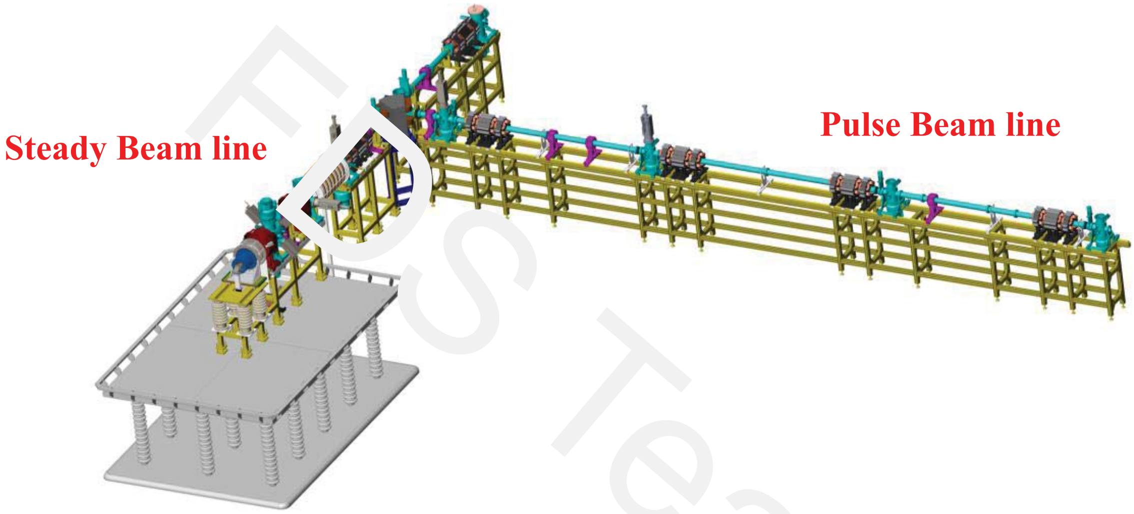
Overview of HINEG-I

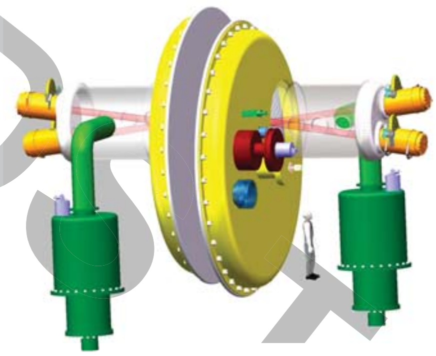


Fusion neutrons with yield of 6.4$\times 10^{12}$n/s have been generated

FDS Team

Preliminary Scheme of HINEG-II

- Neutron Yield: 10^{15}-10^{16} n/s



Conceptual Design Option

- Key Technology of HINEG-II

Ultra-High Power Rotating Target	High Heat Flux Removal Technology
Ion Accelerator	Ampere Level Ion Source & Accelerator Technology

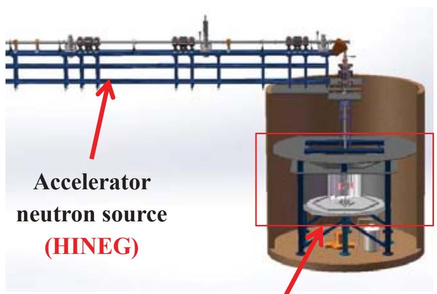
R&D for key components of HINEG-II are on-going

Institute of Nuclear Energy Safety Technology,CAS
Key Laboratory of Neutronics and Radiation Safety,CAS

Lead Based Zero-Power Sub-critical /Critical Reactor CLEAR-0

HINEG Extraneous Driving→ ADS-0 / FDS-0

- **The experimental platform for the integrated validation of lead based reactor neutron and safety control in China**
  - Physical design and analysis method, program and database verification of lead based reactor
  - Integrated test of physical plan and control technology of lead based reactor
- **The test equipment for physical and engineering validation of lead base reactor core**
  - The energy spectra are similar to that of CLEAR-I core（similar coolant, similar fuel and similar structure）
  - The core arrangement is flexible and other small and medium sized metal cooled fast reactor core can be simulated in full-scale
- **Taking into account the development requirements of ADS subcritical lead reactor technology**
  - Can be coupled with the external neutron source to achieve subcritical operation
  - Can provide necessary nuclear physics data support for applying for permits of CIADS construction



Zero-Power reactor (CLEAR-0)

Experimental Hall of HINEG

Outline

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- ENEA (Italy)
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The FNG neutron source

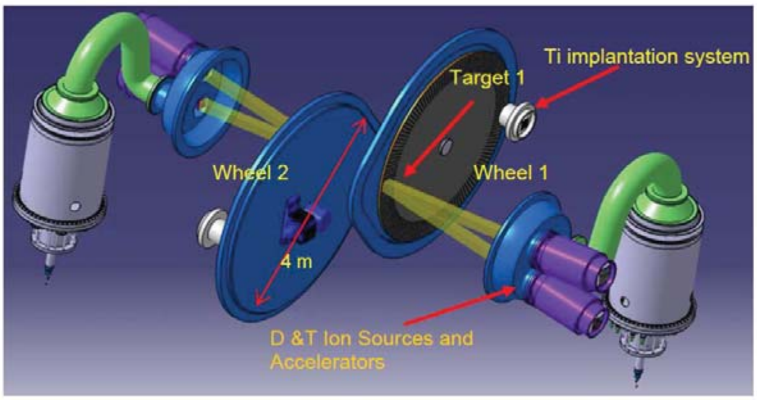
Parameter	Value
Neutron Yield	1×10^{11}n/s
Beam Energy	230keV
Beam Current	1mA
Beam Spot Size	Φ1.5cm

Institute of Nuclear Energy Safety Technology,CAS
Key Laboratory of Neutronics and Radiation Safety,CAS

The Sorgentina Project

- **Two ion beams of 25 A (D^+) + 25 A (T^+) accelerated at 160 keV impinging on a spot of 10×20 cm^2 surface**
- **D-T neutron source is made of 2 facing wheels, 2 m radius**
- **In-between the wheels high neutron flux irradiation zone is available**

High flux Irradiation Zone
~ 50 cm^3
1×10^{13} n/cm^2/s
2 dpa/fpy



Mario Pillon, Maurizio Angelone, Aldo Pizzuto, Antonino Pietropaolo. Feasibility study of an intense D–T fusion source:"The New Sorgentina". Fusion Engineering and Design, 2014, 89:2141-2144.

Outline

I. Background

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- INEST (China)
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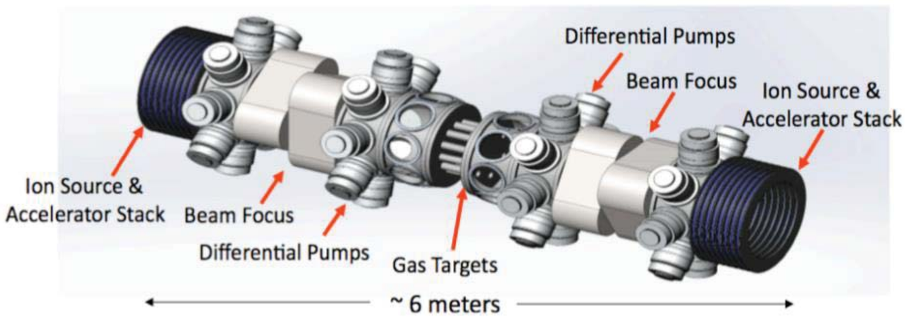
PNL Neutron Source

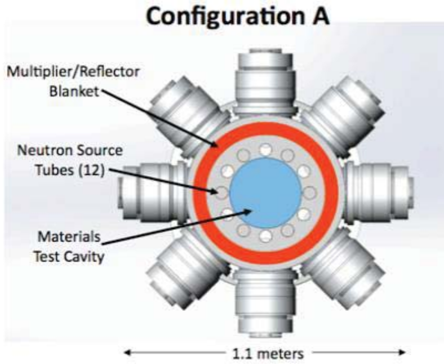
- HV Power supply
- Microwave Ion Source
- Electrostatic Accelerator
- Focus Element
- Differential Pumping
- Gas Target

Measured D-D neutron yield of 3×10^{11} n/s

Design of 14 MeV Fusion Neutron Irradiation Facility

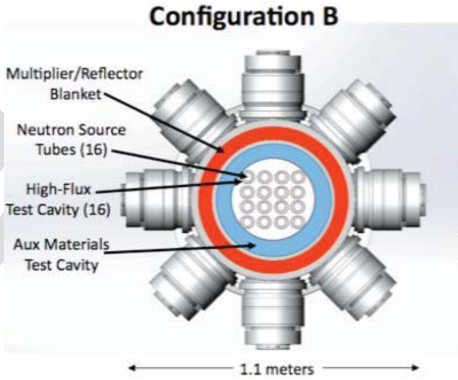


Configuration A



Parameter	Value
Peak Displacement Damage Rate	4 dpa/fpy
Peak Helium Production Rate	40 appm/fpy
Useful Irradiation Environment	2 Liters
Projected Operating Time/Year	90%

Configuration B



Gerald L. Kulcinski, Ross F. Radel, Andrew Davis. Near term, low cost, 14 MeV fusion neutron irradiation facility for testing the viability of fusion structural materials. Fusion Engineering and Design, 2016, 109-111:1072-1076.

Outline

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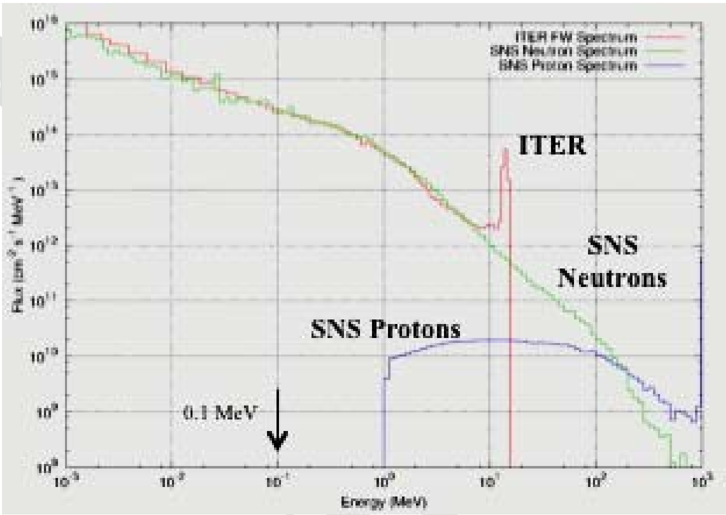
Applications of D-T neutron sources

- Materials irradiation damage mechanism
- Neutronics theory and software validation
- Nuclear data measurement and validation
- Neutronics performance of blanket/reactor
- Nuclear technology applications

Mechanism of Materials Irradiation Damage

- **Existing neutron sources can not meet the demand**
  - **Fission reactor, large spallation neutron energy gap**
  - **Electron, ions and other radiation is hard to equivalent**
- **High intensity D-T fusion neutron source**
  - **Energy spectrum**, **He /dpa ratio** and other key performance is the same as the fusion reactor
  - **$10^{15\text{-}16}$n/s neutron source** radiation displacement damage is up to **4 dpa/fpy**
  - Flexible experimental space, and **magnetic, thermal, force and other physical environment can be coupled**



Spallation VS Fusion

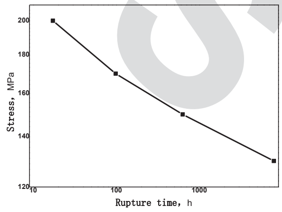
D-T neutron sources can reproducing "first wall" irradiation spectrum

Development of Structure Materials for Advanced Reactor

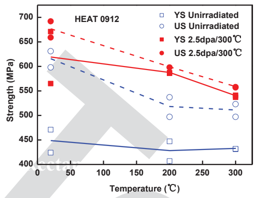
CLAM (China Low Activation Martensitic steel)

- **Nominal composition: 9Cr-1.5W-0.2V-0.15Ta-0.45Mn-0.1C**
- **~18 ton smelting with good control of main composition**

~ 6 ton ingot during forging



creep test ~10000hrs



2.5dpa neturon Irradiation

Nuclear Reactor Material Database (NRMD)

- **High-dose neutron irradiation experiments**

(Spallation source ~ 21dpa) (High Flux Engineering Test Reactor ~3 dpa)

Properties of CLAM steel is comparable with Eurofer97 and F82H, and CLAM steel has been selected as the candidate structural material for CN ITER TBM

Q. Huang, FDS Team. Development Status of CLAM Steel for Fusion Application. Journal of Nuclear Materials, 2014, 455:649-654.

FDS
Institute of Nuclear Energy Safety Technology,CAS
Key Laboratory of Neutronics and Radiation Safety,CAS

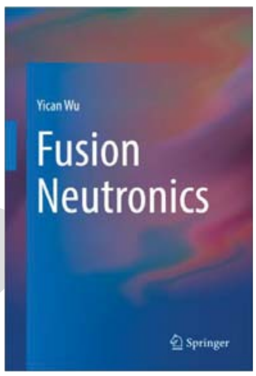
Accurate Modeling Theories and Calculation Methods

with multi-processes direct coupling for neutron transport in complex systems

Provides a leap forward from isolated solutions to whole-process and multi-scale simulation for neutron transport and makes the accurate and efficient three-dimensional nuclear design and safety evaluation of complex nuclear systems realistic

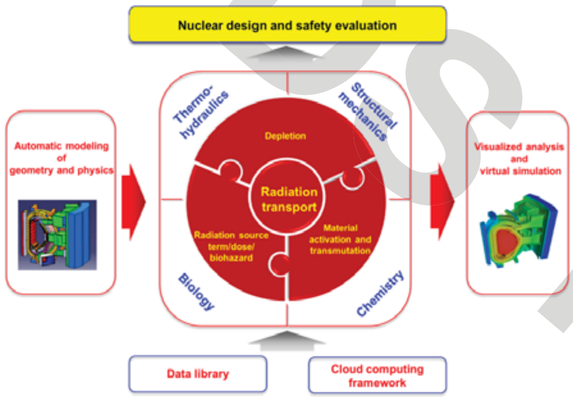
- **Innovative idea** — Integrated accurate irregular modeling (geometry, material, source…)
- **Physical model** — Directly coupling multiple processes (→ Stochastic + Deterministic)
- **Advanced approach** — Efficient stochastic approach based on feature pre-judgment | Discrete ordinates nodal transport method

7 ESI Top1% papers
NO.1 in nuclear software area
The first monograph "Fusion Neutronics"



Super Monte Carlo Program for Nuclear and Radiation Simulation SuperMC

The first comprehensive neutronic simulation program in the world



- Internal coupled **comprehensive** neutronic simulation
- **Irregular** boundary and **complete** physics modeling
- High calculation efficiency (600+ times acceleration for ITER machine)

- Applied in 50+ nations, 30+ major international nuclear projects
- ITER reference code. Publicly distributed by OECD/NEA
- The first fusion neutronics monograph in the world

Measurement and Validation of Nuclear Data

Nuclear Data Evaluation and Validation

- Neutron multiplication, new-type nuclear fuel , etc

Nuclear data measurement

- Materials' Service Properties and Life

  (n,p), (n,^{3}He) and (n,α) of Cu, Fe, W, Ni etc.

- Shielding and Activation

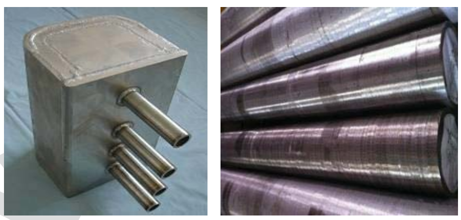
  (n,γ) of Fe, Li, Pb etc.

Neutronics properties of materials Evaluation

- Tritium Breeding, Shielding, Neutron Multiplication, etc.
- Lead-based Coolant: PbLi, PbBi, Pb
- Structural Material of CN ITER TBM: CLAM steel

Challenges for nuclear data *

- Lack of experimental data
- Precision not enough
- Evaluations inconsistent



TBM blanket and CLAM steel

*: http://www-nds.iaea.org

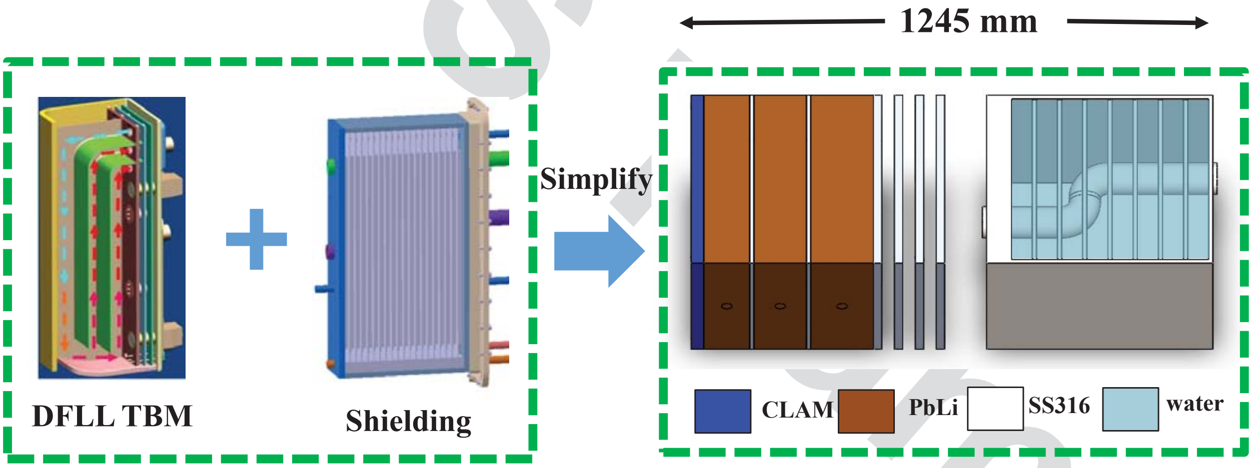
D-T neutron sources are the important method for nuclear data measurement and validation

Neutronics Performance of Fusion Blanket

——Experiment for DFLL (Dual Functional Lithium-Lead) TBM

Goal: Verify Tritium Breeding → TBM: CLAM + PbLi + SS

Research Deep Penetration → Shielding: SS + Water



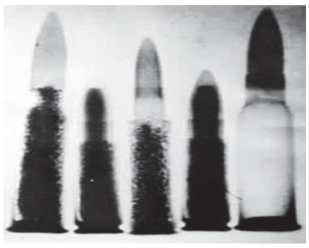
Experiment mock-up

D-T neutron sources are experimental verification tool for neutronics performance of fusion blanket

Institute of Nuclear Energy Safety Technology,CAS
Key Laboratory of Neutronics and Radiation Safety,CAS

Research on Nuclear Technology Applications

- **Fast neutron radiography**
  - Good metal penetration, detect internal structure
  - Analyze the internal structure of high density big scare material
  - Miniaturization neutron source is used in easy moving detect for drug and explosive



- **Isotope production**
  - ^{99m}Tc is widely used (80%) in medical isotope
  - D-T fusion neutron source can produce ^{99m}Tc via low enriched uranium, avoid the using of highly enriched uranium

- **Proton/neutron radiotherapy**
  - Strong penetrability, strong cancer cell killing ability
  - Suitable for malignant tumor, which can tolerate normal radiation.

D-T neutron sources have obvious advantages in related nuclear technology applications

Outline

I. Background

II. Research & Development

III. Application

IV. Summary

Summary

- Neutron is the essential element of nuclear energy system and nuclear technology application, D-T fusion neutron source can serve in fission/fusion energy and also other nuclear technology application;

- R&D of D-T neutron sources with neutron yield of 10^{15}-10^{16}n/s are on going, e.g. HINEG-II, Sorgentina, PNL;

- D-T neutron sources are useful on neutronics theory, nuclear data and program validation, materials radiation damage in high neutron radiation environment, neutronics performance of blanket/reactor, and also will expand nuclear technology application.

Thanks for Your Attention!

Website: www.fds.org.cn
E-mail: contact@fds.org.cn

3.3.3 Present status of neutron sources development: Y. Kiyanagi (Nagoya Univ.)

Workshop on Advanced Neutron Sources and Its Applications, Aomori, 5 November 2017

Present status of neutron sources development

- Overview of neutron sources -

Y. Kiyanagi

Nagoya University

President of Japanese Society for Neutron Science

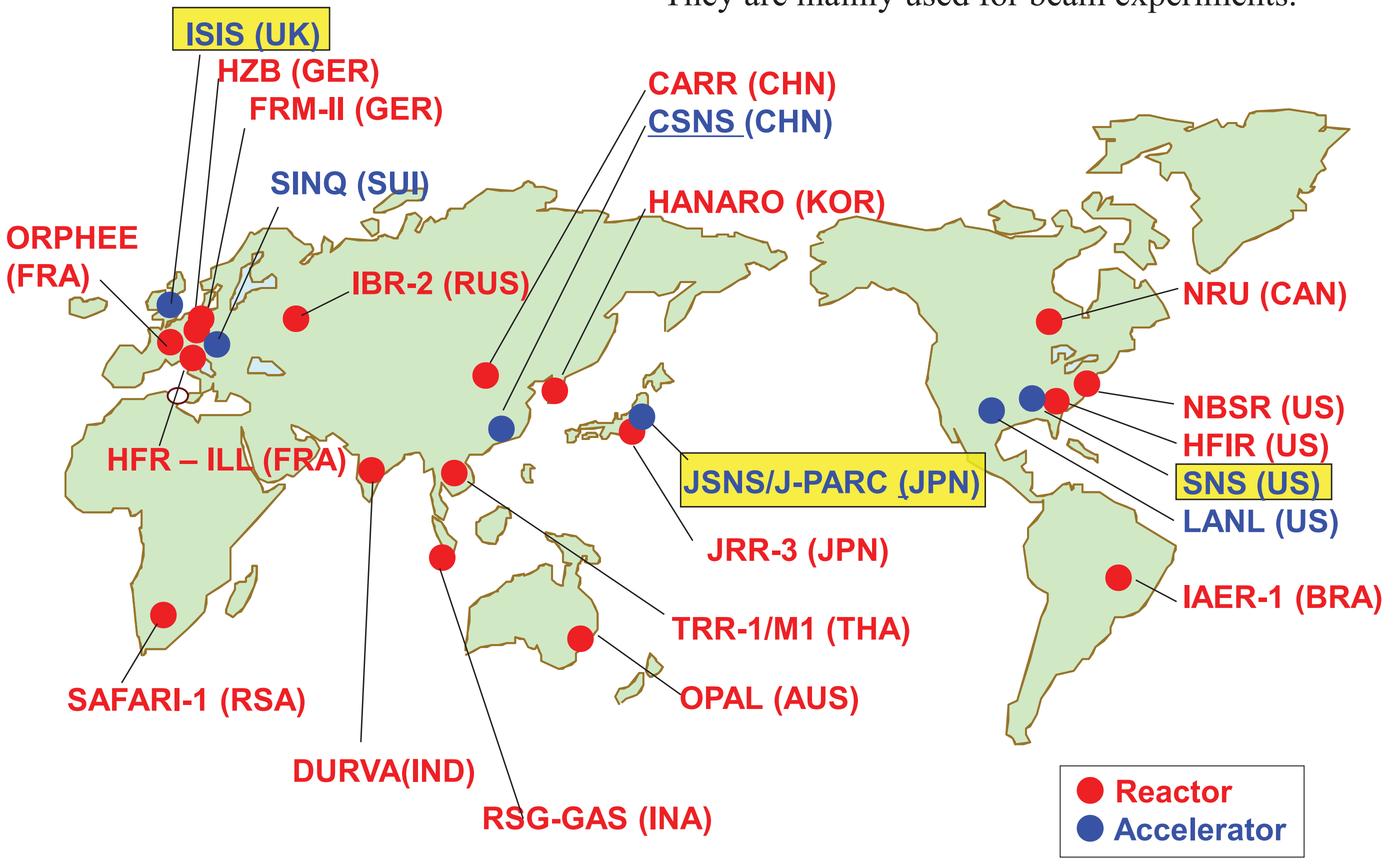
Content

- Neutron sources in the world and Japan
- Activity of Accelerator driven Neutron Sources in Japan
- New neutron source projects
- Summary

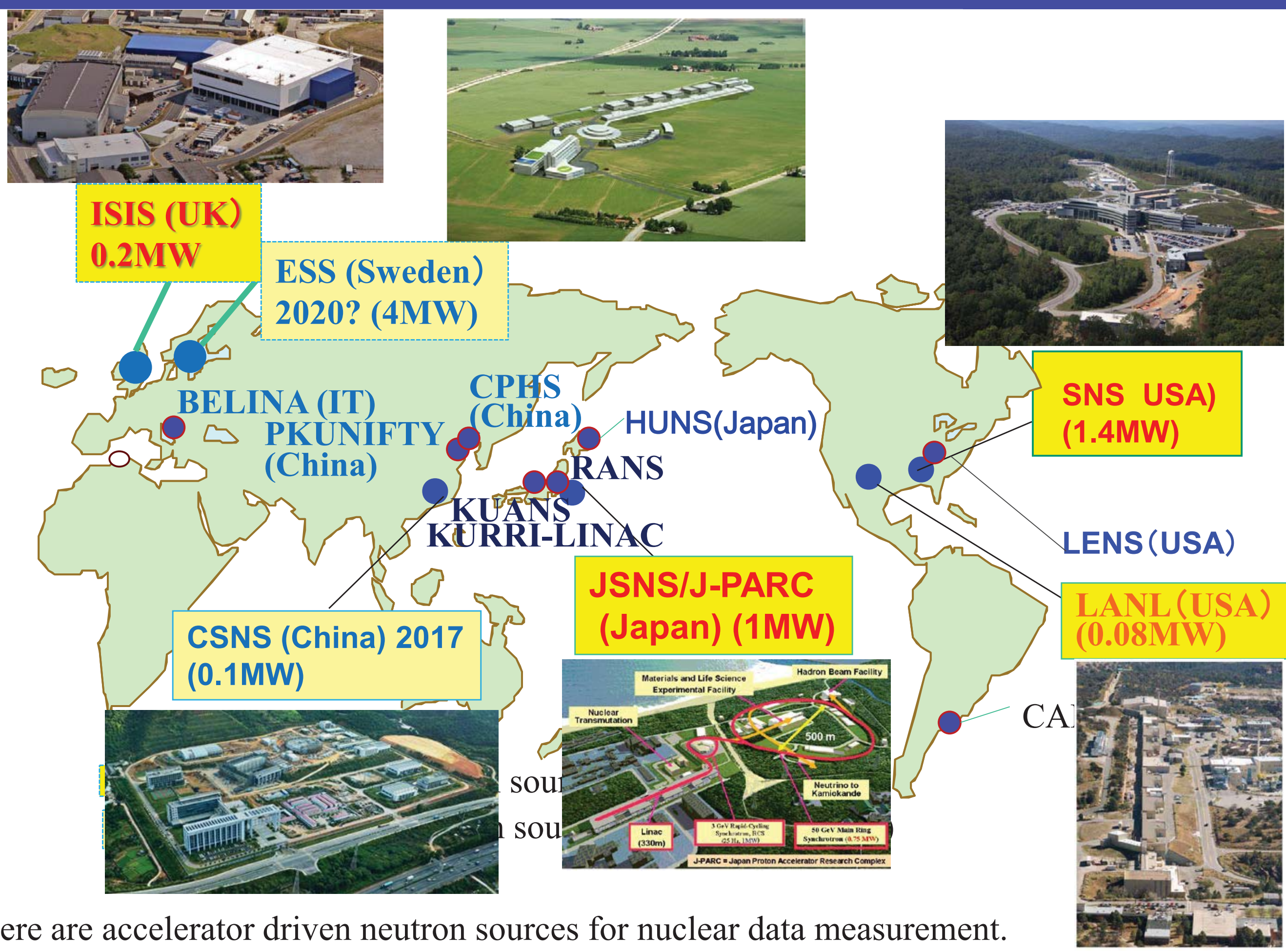
Major Neutron Sources in the World

(Names with underline show facilities in the planning stage or under construction.)

They are mainly used for beam experiments.

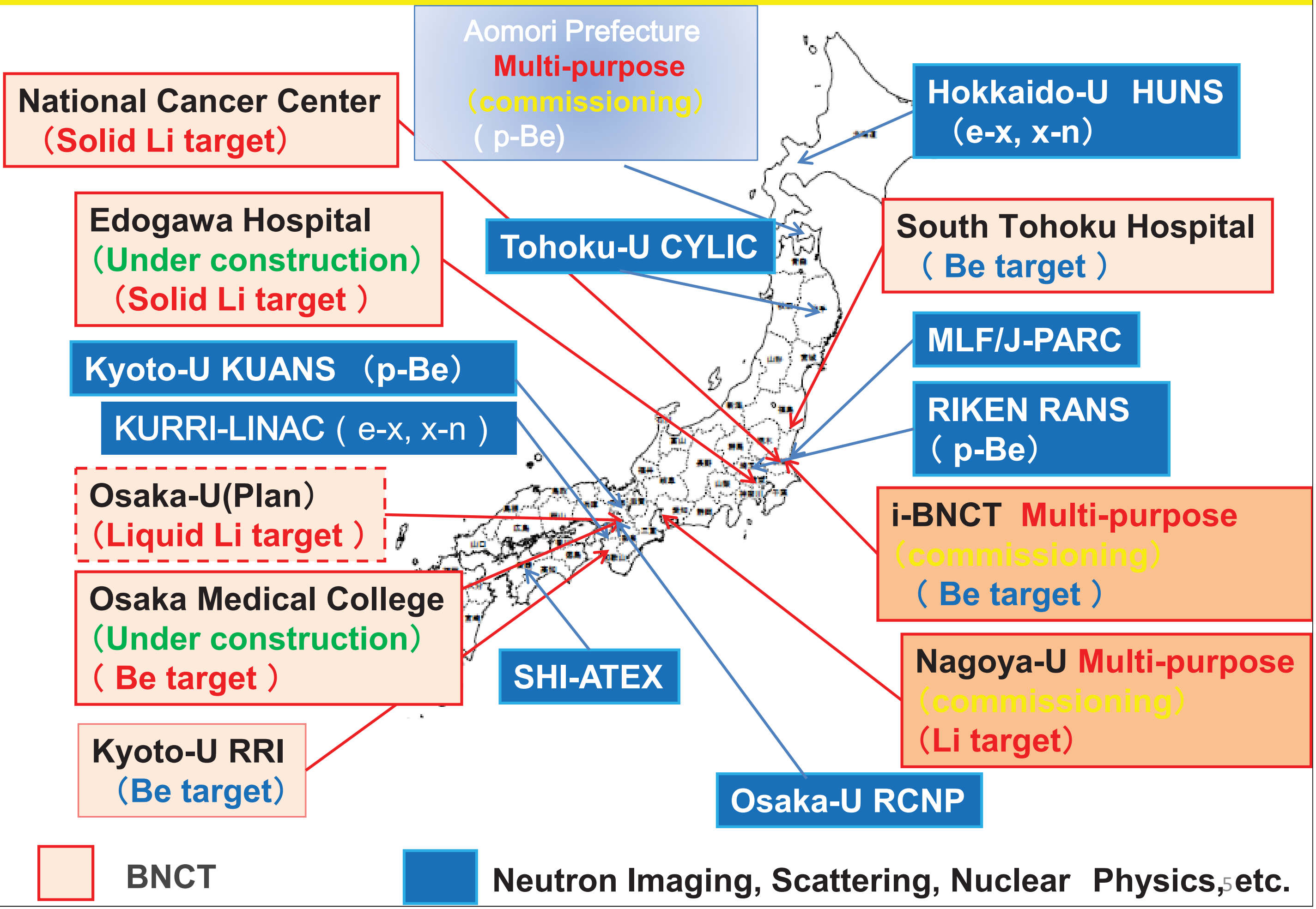


Accelerator driven neutron sources in the world



There are accelerator driven neutron sources for nuclear data measurement.

Accelerator-driven Neutron Sources in Japan



Boron Neutron Capture Therapy (BNCT)

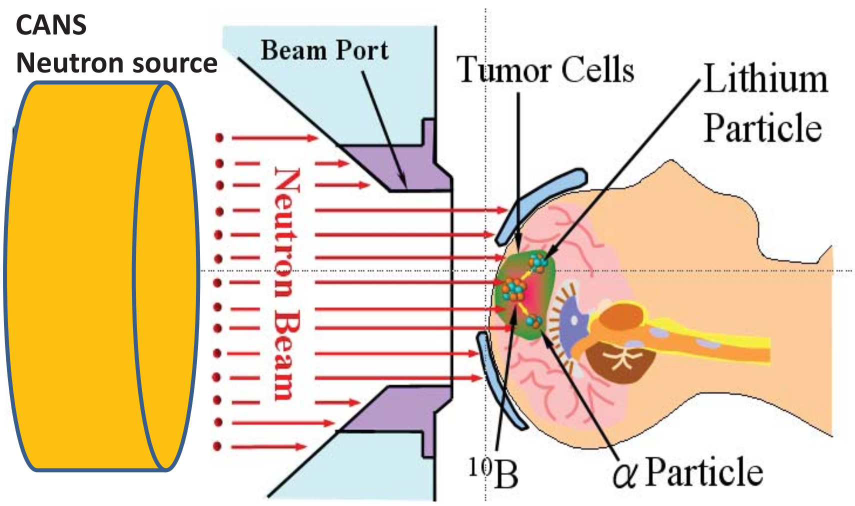
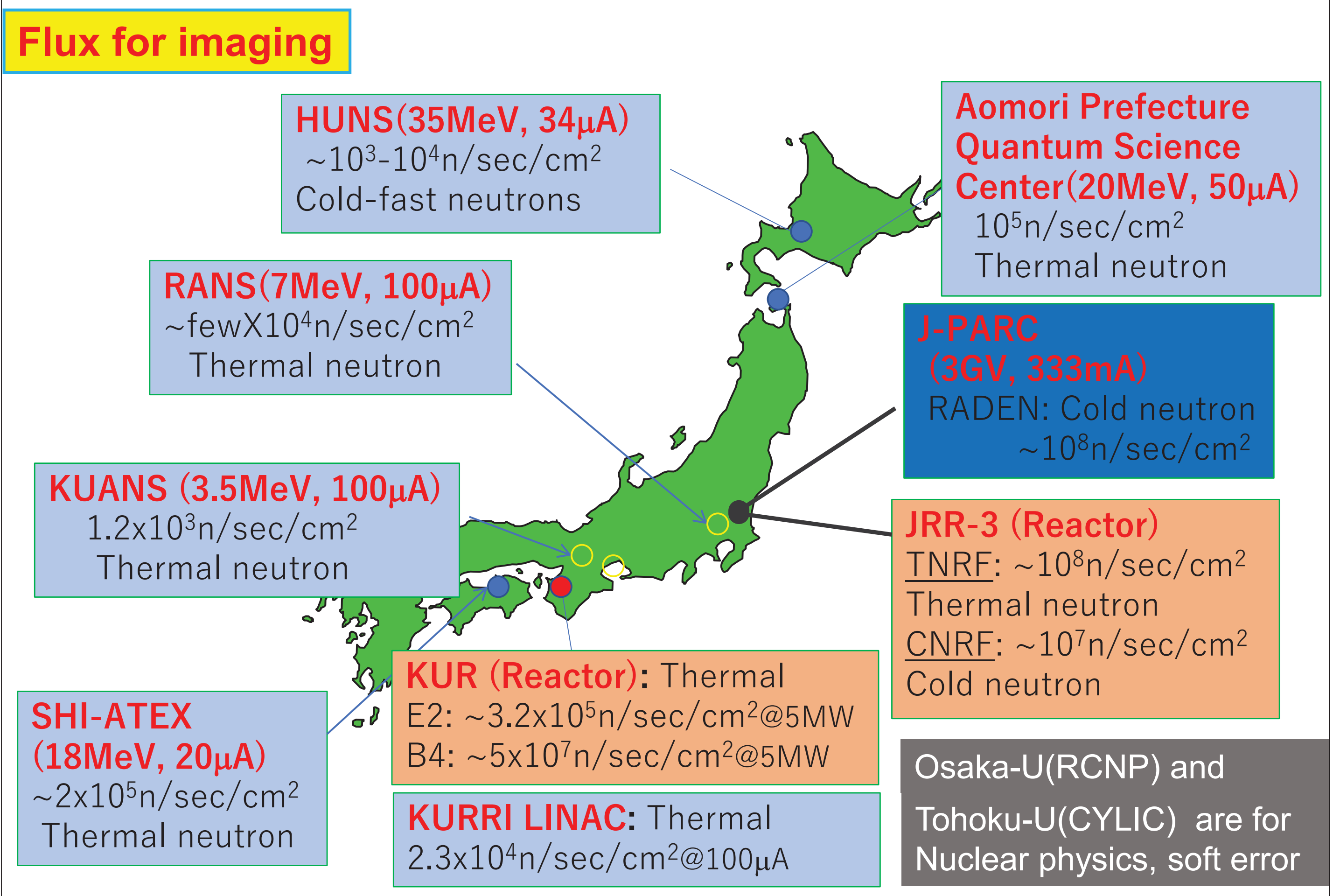


Photo from Osaka University

The first treatment of head and neck cancer.

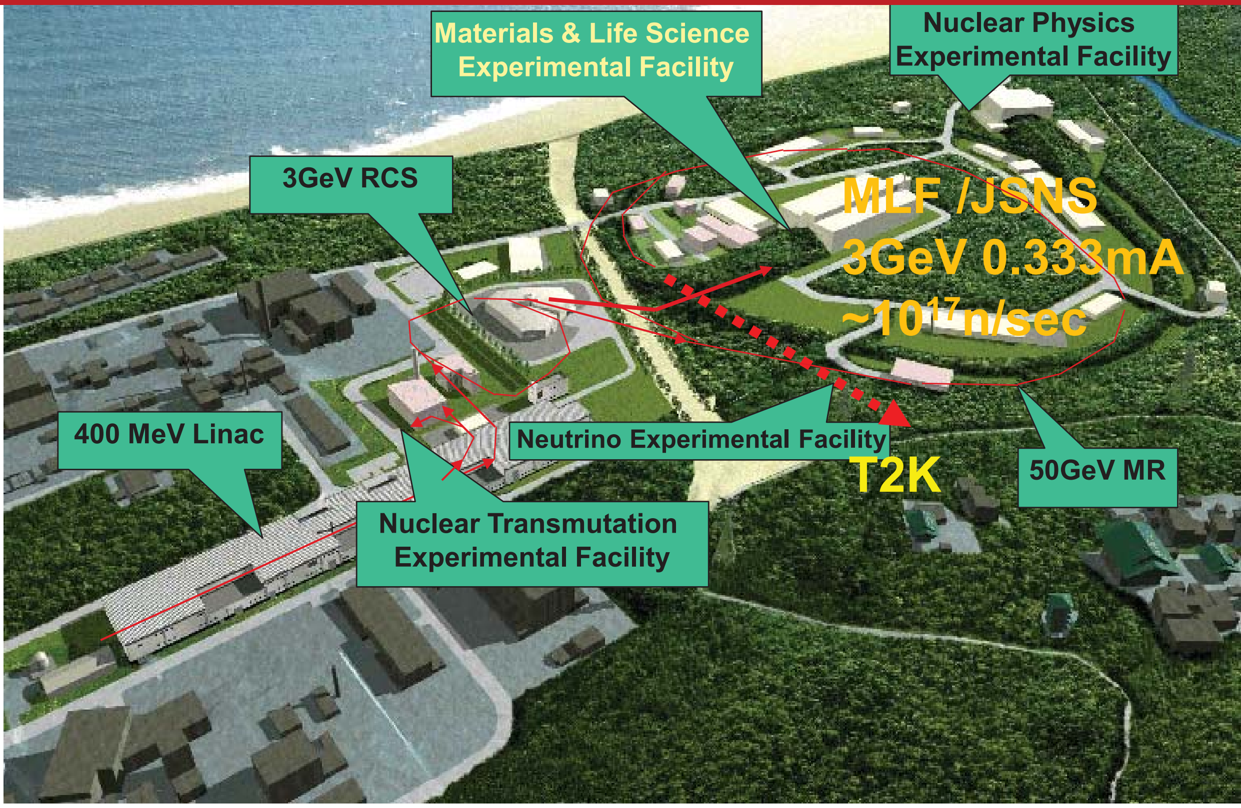
http://www.jsnct.jp/about_nct/deep.html

Accelerator-driven Neutron Sources in Japan



Activity of Accelerator driven Neutron Sources in Japan

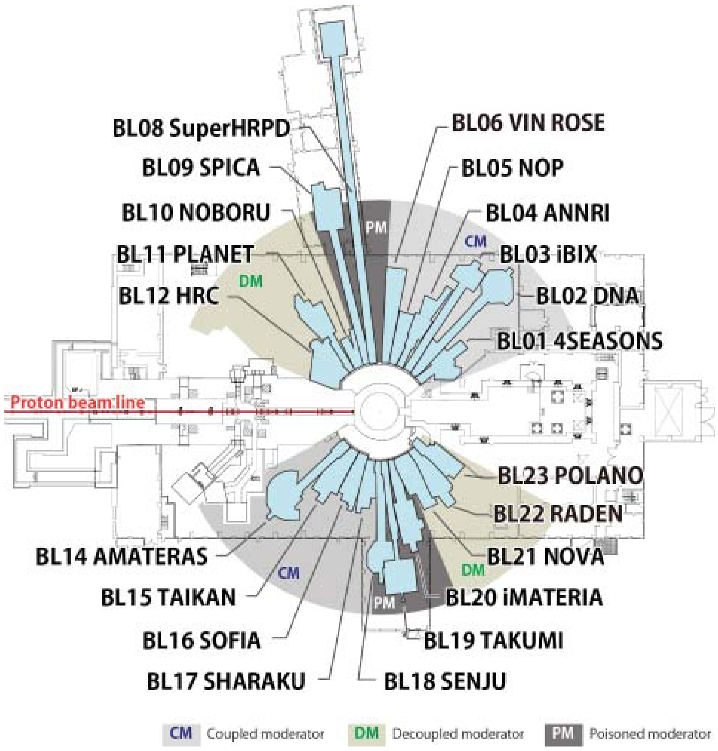
1) J-PARC/MLF



http://j-parc.jp/researcher/MatLife/ja/instrumentation/ns.html

Layout of neutron instruments

- 23beamlines with individual shutters.



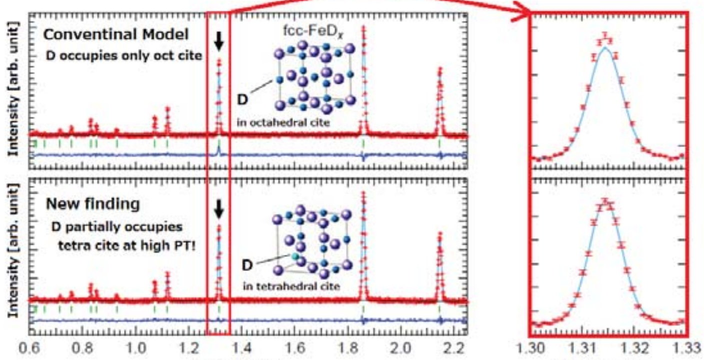
High-pressure Neutron Diffractometer PLANET (BL11)
Hydrogen in Fe lattice under high pressure and high temperature condition

Hydrogen in iron is directly related to hydrogen embrittlement of iron and the possible origin of the deficit in density of the Earth's Core.

Hattori Sano Funakoshi Abe Machida

PLANET measured neutron diffraction from hydrogen (deuterium) in iron at high-*PT* condition (6.3 GPa and 988 K)

Neutron diffraction patterns obtained at 6.3 GPa and 988 K



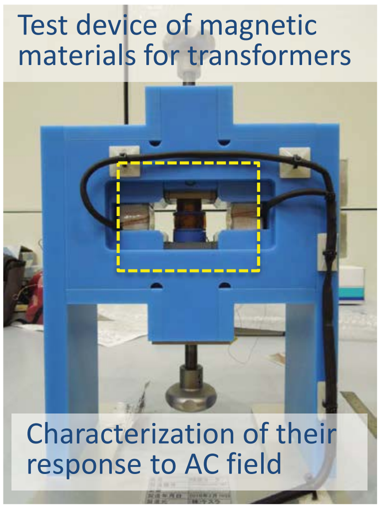
(Upper) Conventional model with no occupancy of D in tetrahedral cite, (Lower) New model with D partly occupied tetrahedral cite. New model showed better fitting.

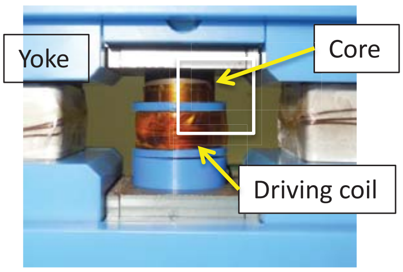
Large press "ATSUHIME"

The structure analysis revealed that small amount of deuterium do occupy the tetrahedral site, contrary to conventional model where all the deuterium occupy the octahedral site.

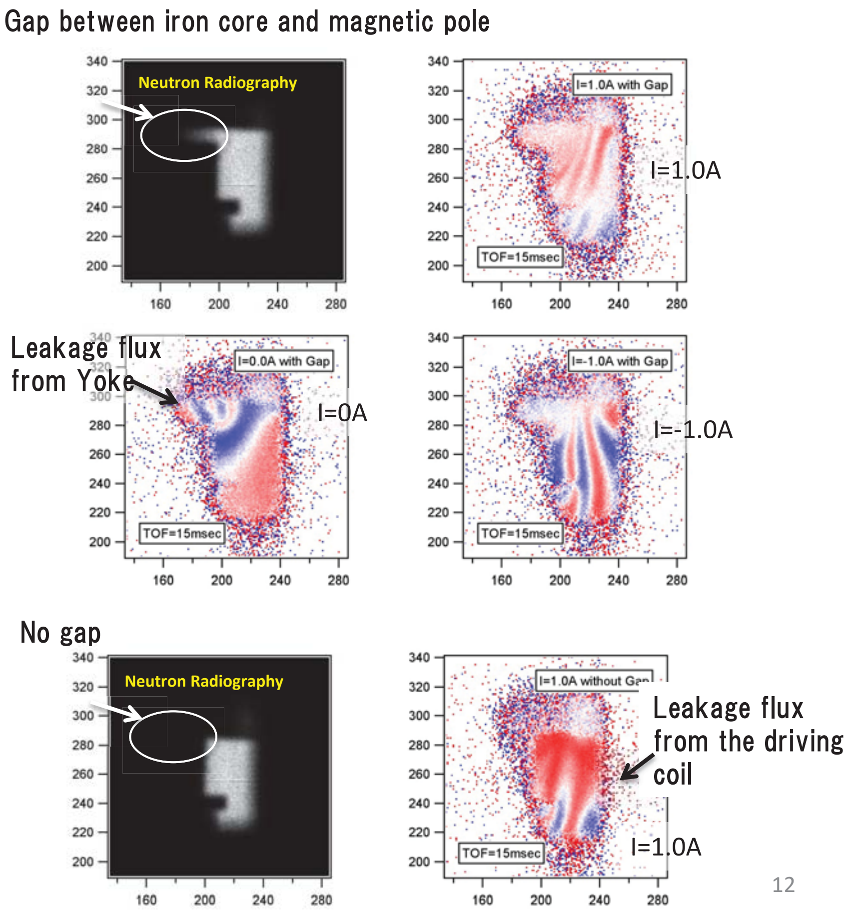
Nature Communications **5**, 5065 (2014).

Leakage magnetic field observation between rotor and motor





Place an iron core with a coil between the poles

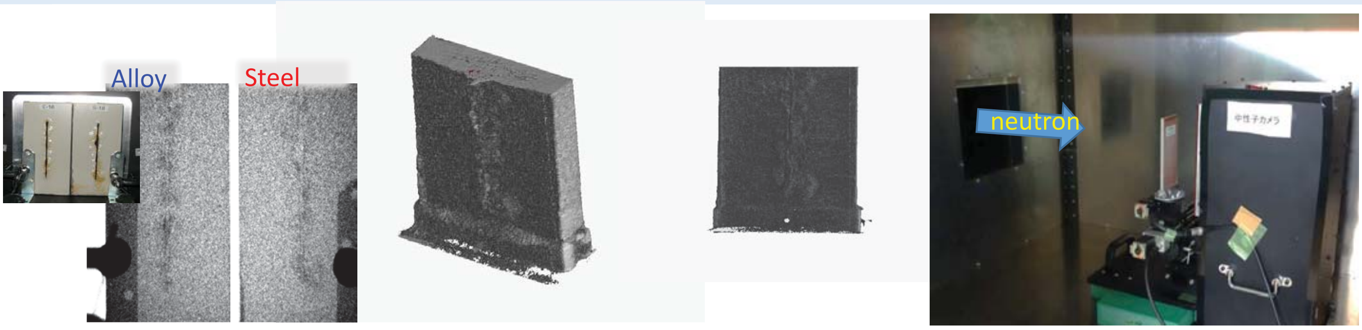


2) RANS (RIKEN Accelerator-driven compact neutron source)
compact neutron source for practical use

Courtesy of Dr. Yoshie Otake

Proton linac, (commercially sold accelerator) (1.5 M.US$)
Ep=7MeV ~10^{12}n/sec
Ip<100 μA maximum averaged current
Δτ : 10-180μs pulse width of proton (30μs→modified)
Fr : 20-180Hz repetition rate of proton

Industrial use –iron and steel-
A) Imaging : Corrosion and water movement



Alloy has higher resistivity than steel.

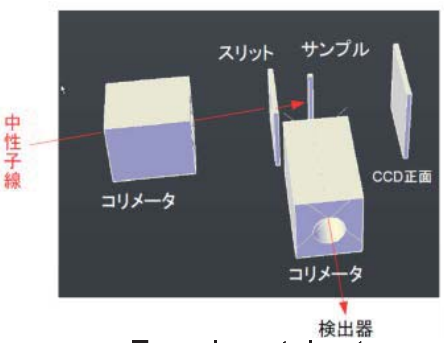
"Atsushi Taketani, et al : ISIJ International Vol. 57, No. 1 (2017)

B) Texture measurement by diffraction

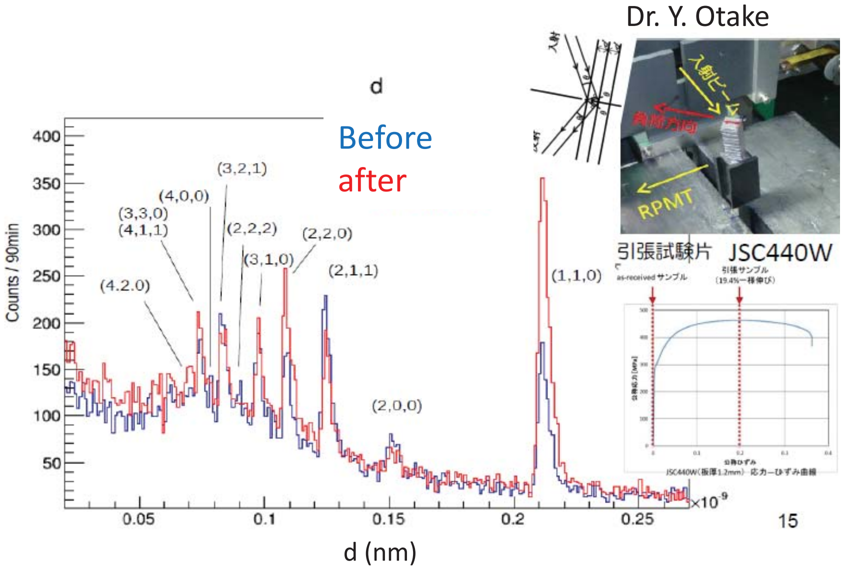
Texture → Crystal plasticity theory → Mechanical characteristics of steel

Dr.H.Suzuki(JAEA), Dr.M.Kumagai (T.C.U)

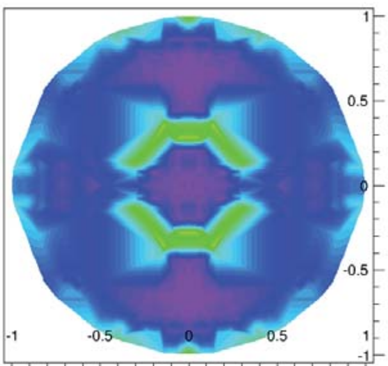
Dr.Y.Ikeda, Dr.M.Takamura Dr. Y. Otake



Experimental setup



15



Polar figure

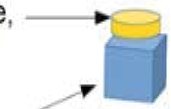
Texture change was successfully observed.

(110) Pole figure (IF steel)

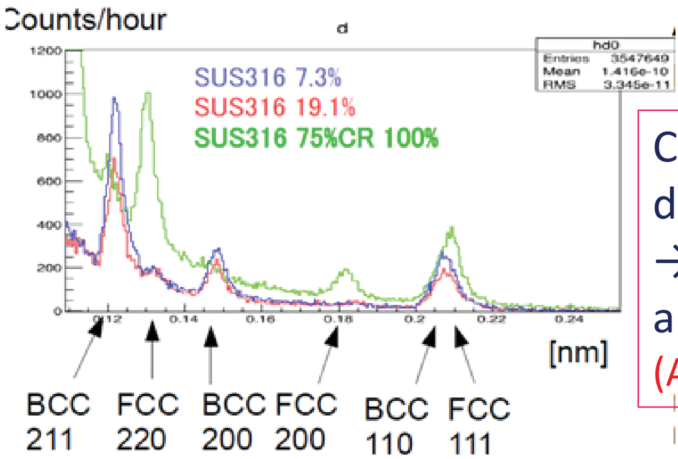
C) Quantitative analysis of austenite of a dual-phase steel (Workability and ductility : High industrial needs)

SUS316 25%CR (FCC, Austenite, φ10mm, w1mm)

Annealed SM440A (BCC, Ferite, 10mm³)



RANS diffraction	Real volume ratio
6.7±0.8%	8.3%
17.4±0.8%	19.1%



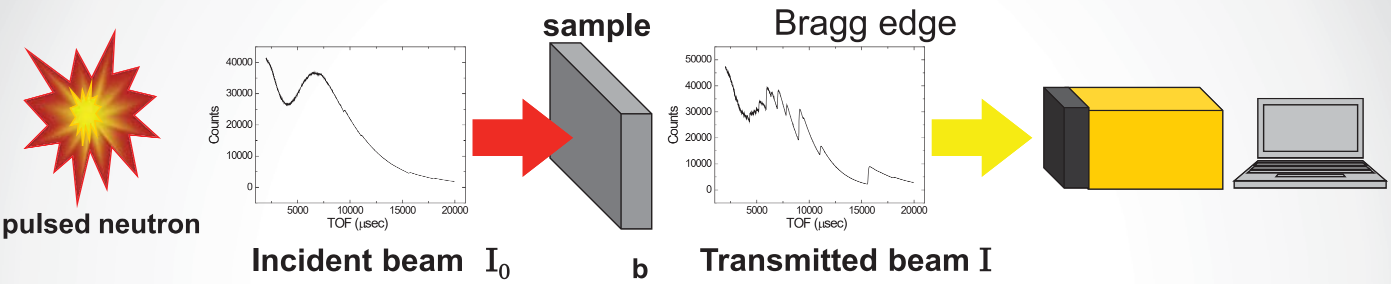
Peaks of both textures are measured

Composition of austenite was determined within 1%
→Compact NS can evaluate residual austenite
(Accelerate the material development)

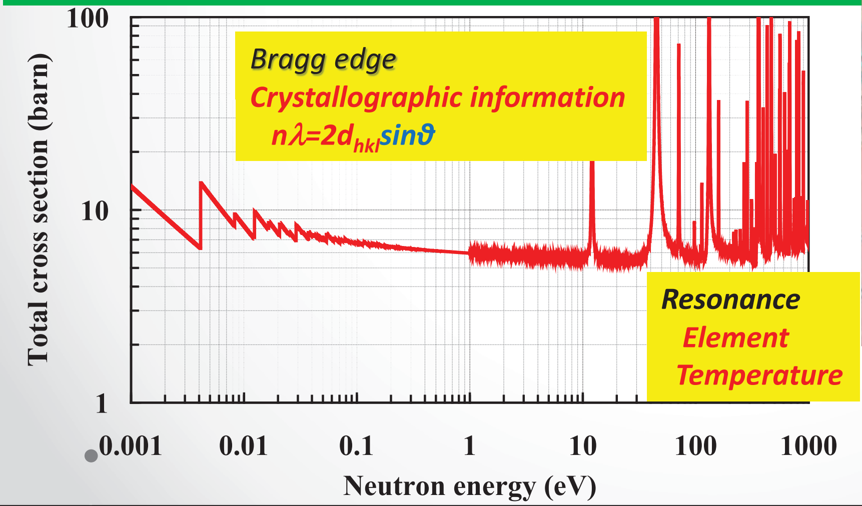
•Rietveld analized with Z-Rietveld
R. Oishi et al, Rietveld analysis software for J-PARC
Nucl. Instrum. Methods, A 600 (2009) 94–96

3) Pulsed neutron imaging @HUNS

HUNS: Hokkaido University accelerator-driven Neutron Source



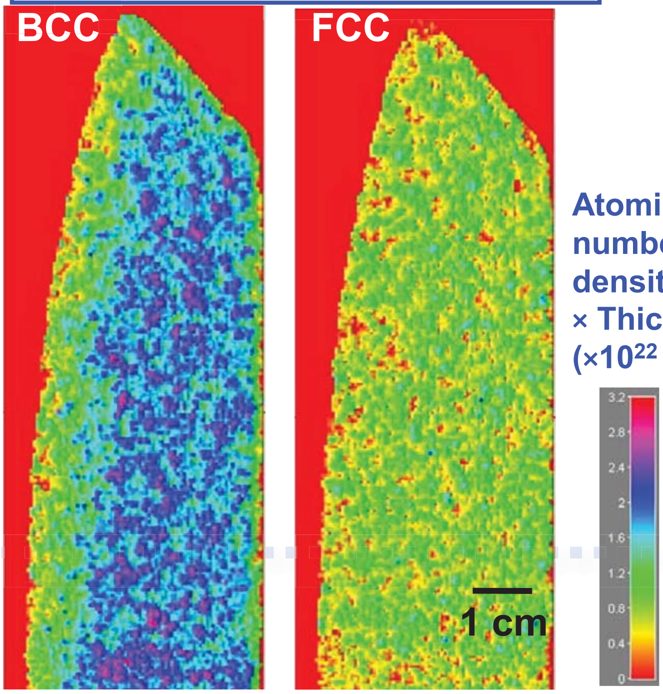
Bragg edge and resonance imaging



A) Bragg Edge Imaging of crystalline phase & microstructure

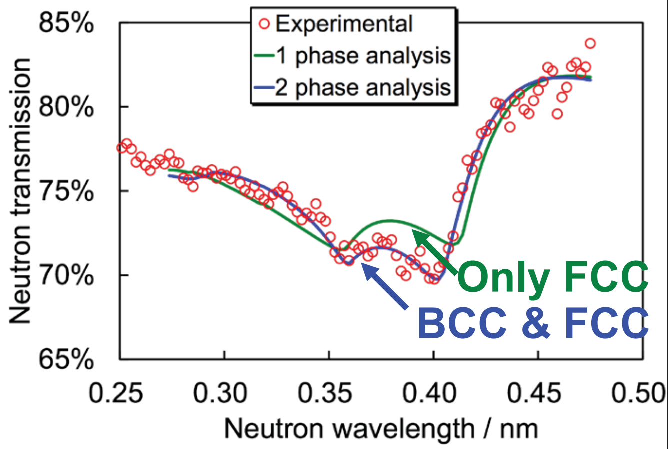
@HUNS

■Phase in a kitchen knife



H. Sato, *et al*, Hokkaido University

■ Two phase analysis

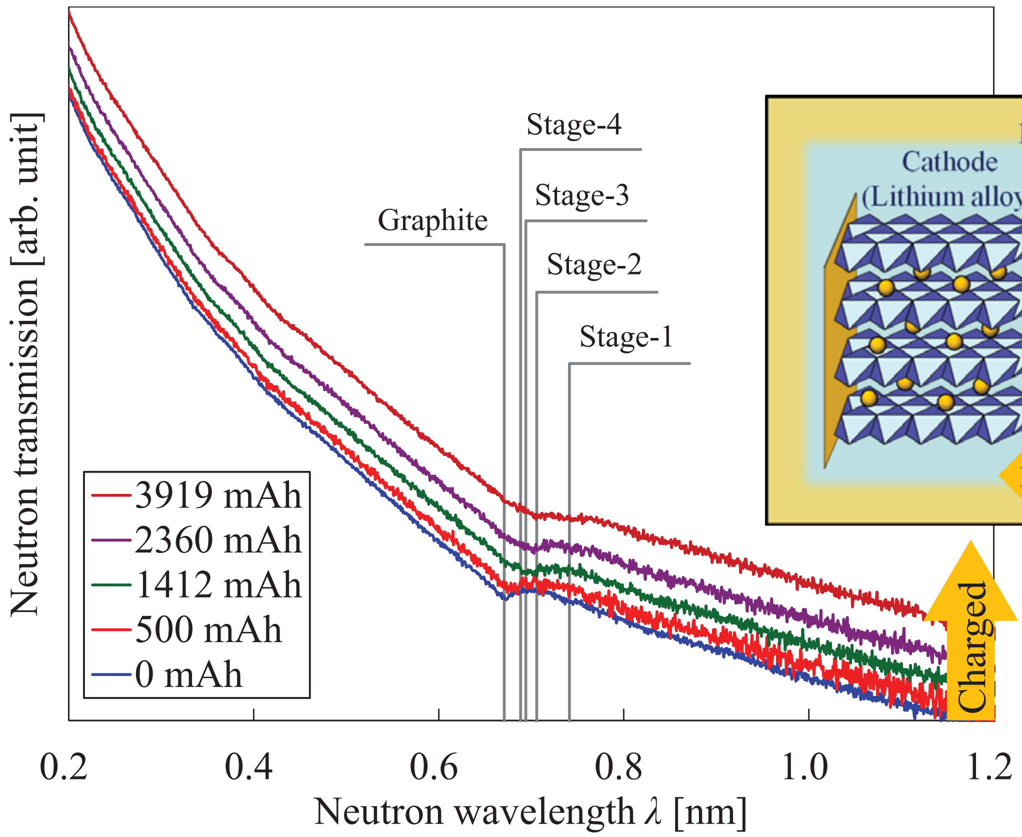


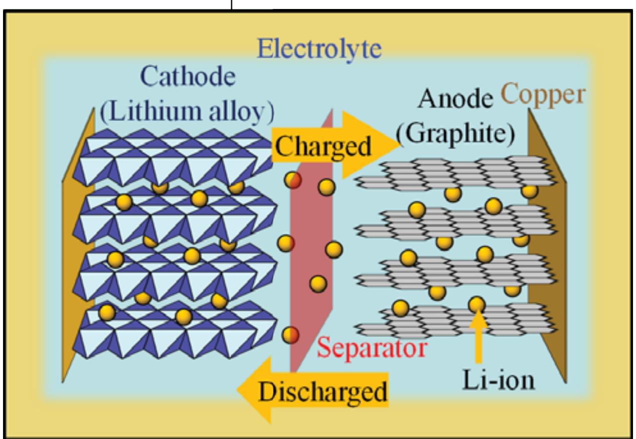
New neutron imager with a TOF function.

B) Spatial distribution of layer space in Li-ion battery

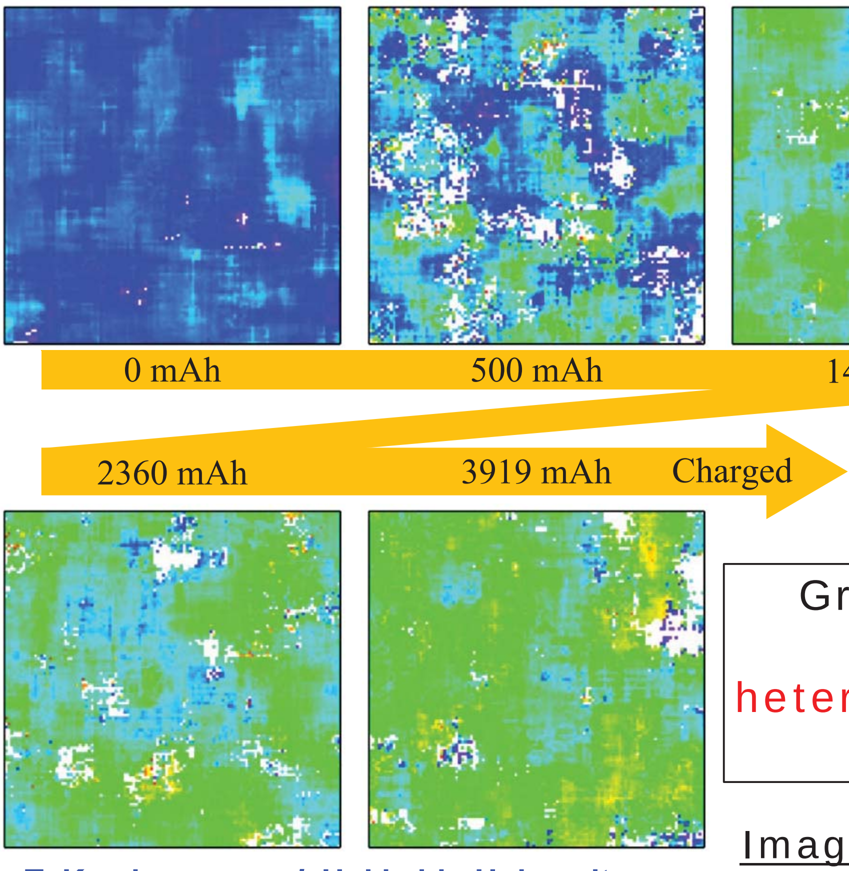
Bragg-edge spectra against charge level

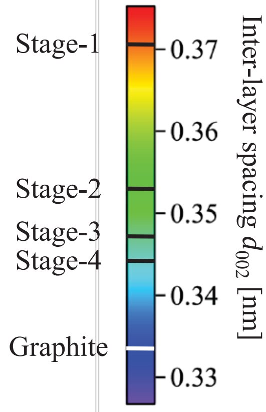
Takashi Kamiyama @Hokkaido University





Layer space distribution





Graphite layer space shows **heterogeneous distribution in mm order.**

Imaging area ~ 9 cm × 9 cm

T. Kamiyama, *et al*, Hokkaido University

C) Medium angle scattering: Lab (SAXS) and Lab(SANS) complementary use @HUNS

Scattering intensity = $(\Delta\rho)^2$ x Number dens. x (Volume x Grain form factor) ^{2}

Composition

Intensity factor
Number density and composition will be separated

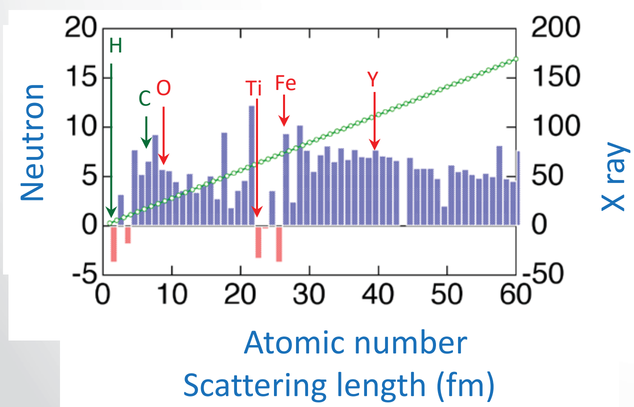
Common in X and N

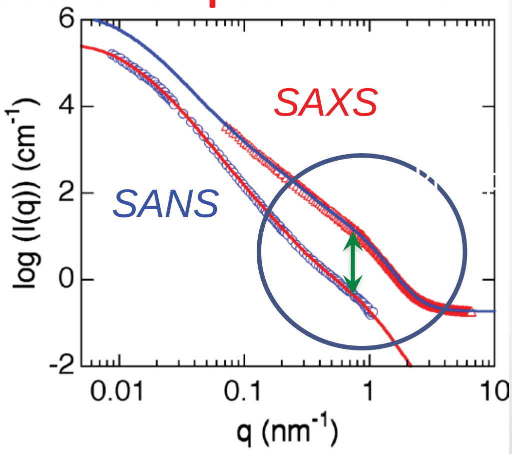
$$\Delta\rho = \rho - \rho_{\text{matrix}} \quad \rho = \sum_i n^a c_i^a b_i$$

N/X cancel out material structure parameter

Different between X and N in the same composition case

Deduce composition information





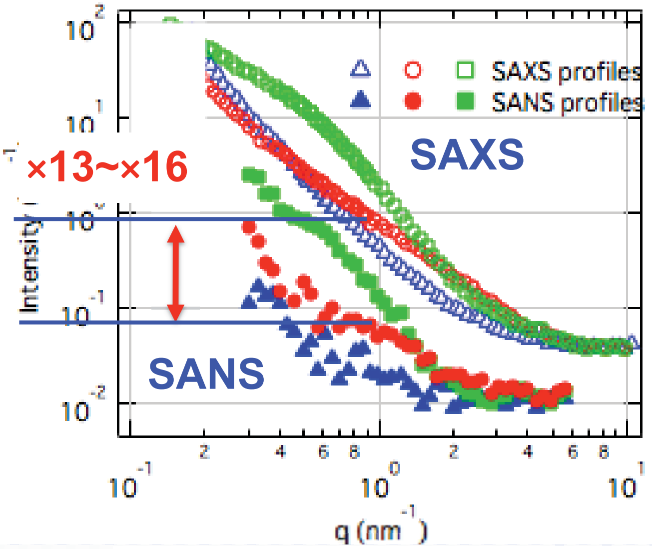
M. Ohnuma and M. Furusaka @ Hokkaido University

Relatively high q region is useful.

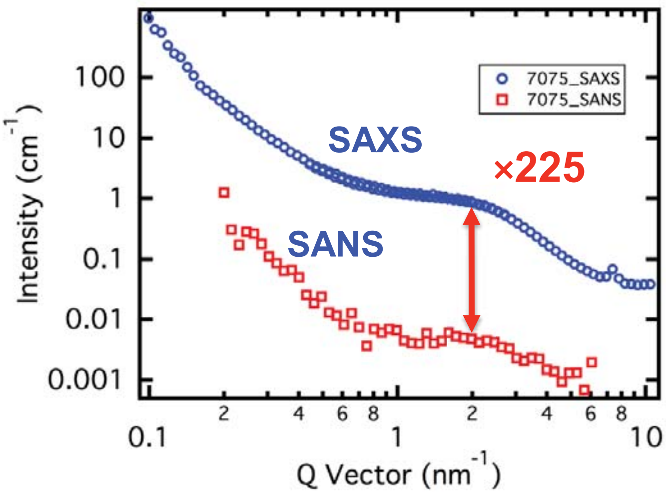
iANS, intermediate-angle neutron scattering instrument

Many others

TiC precipitates in steels



Al alloys : 7000 series



Precipitates are TiC: ×14

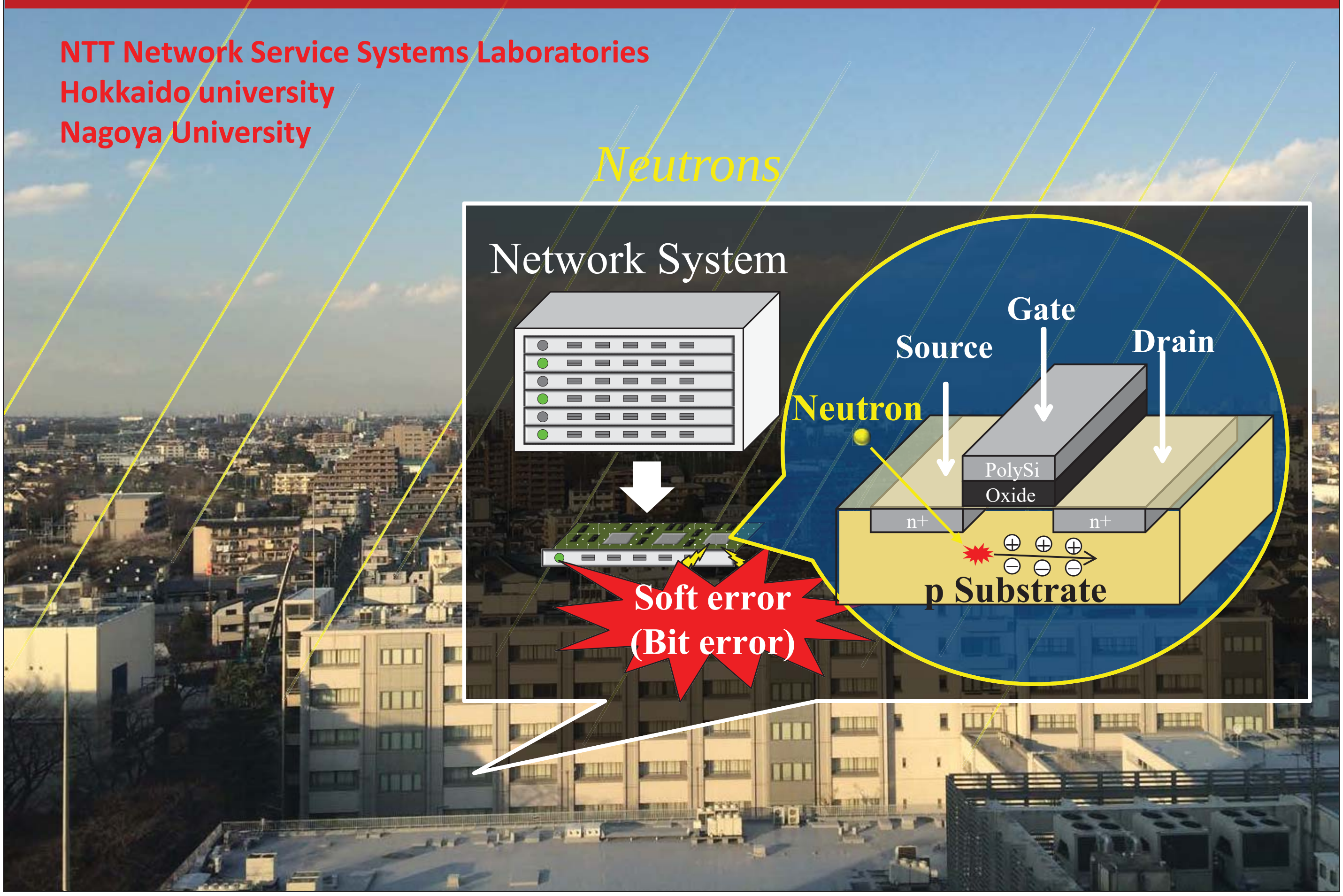
Precipitates are $TiCMgZn_2$: 230

We can identify the precipitates

T ISHIDA, M OHNUMA, B S SEONG and M FURUSAKA, submitted to ISIJ International

D) Soft error acceleration test

NTT Network Service Systems Laboratories
Hokkaido university
Nagoya University

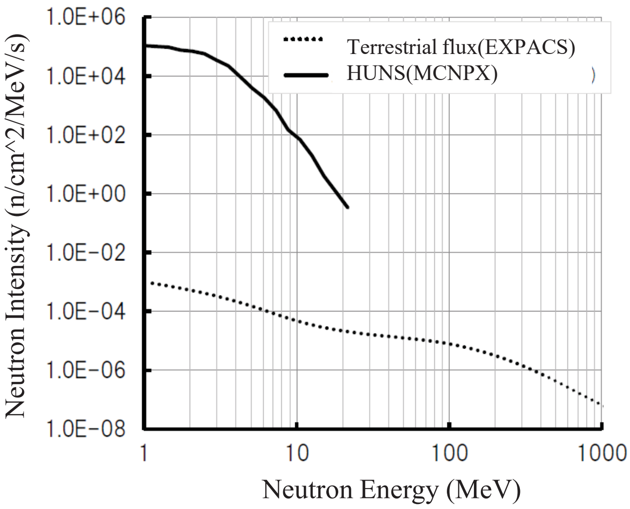


*Soft error test using HUNS

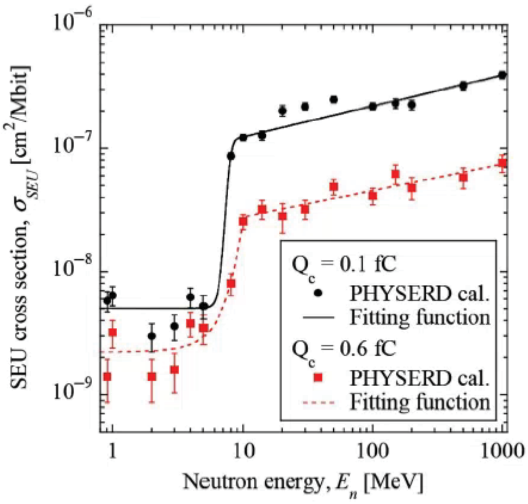
Simulation for the occurrence number of soft error

Innovative R&D by NTT

We designed the neutron source for the soft error test and simulate it.



Neutron Energy spectrum



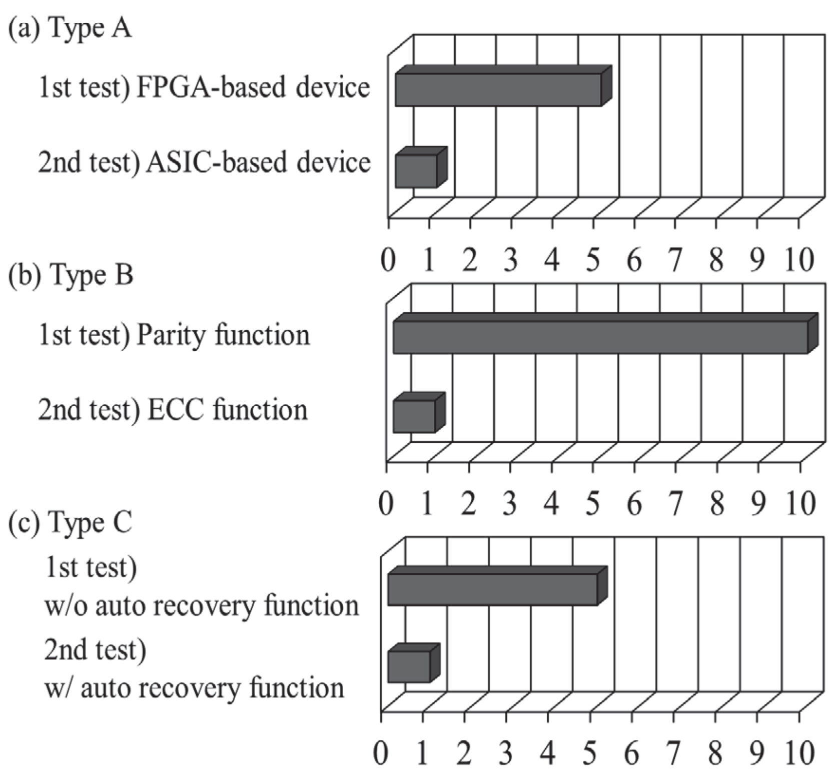
SEU* cross section by neutron energy*

Soft errors occur in a few or ten minutes, and it was proved to be effective.

*SEU (Single Event Upset)

NTT ※ : S.abe and Y.Watanabe, IEEE Transaction on Nuclear Science, 61, 3519-3526(2014)

Examples of neutron soft-error rate reductions after implementing ASIC-based devices, ECC, or auto recovery functions.



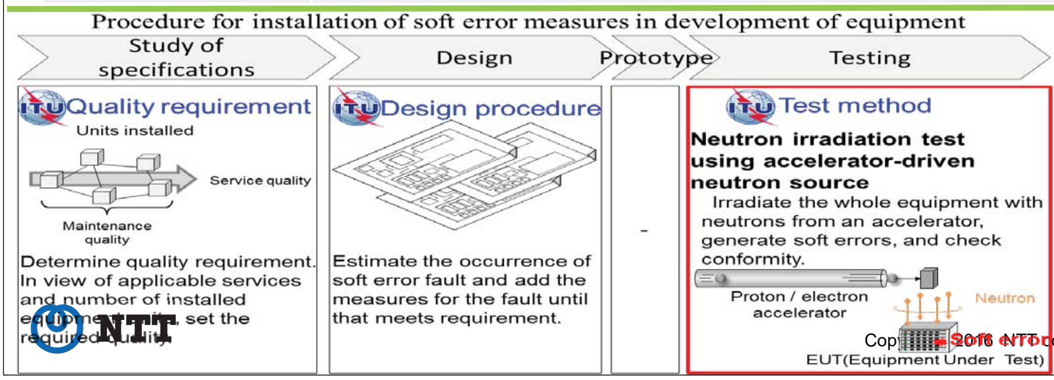
Comparison of neutron soft-error rate

ECC: Error Correction Code

*Standardization for soft error
Proposal to ITU

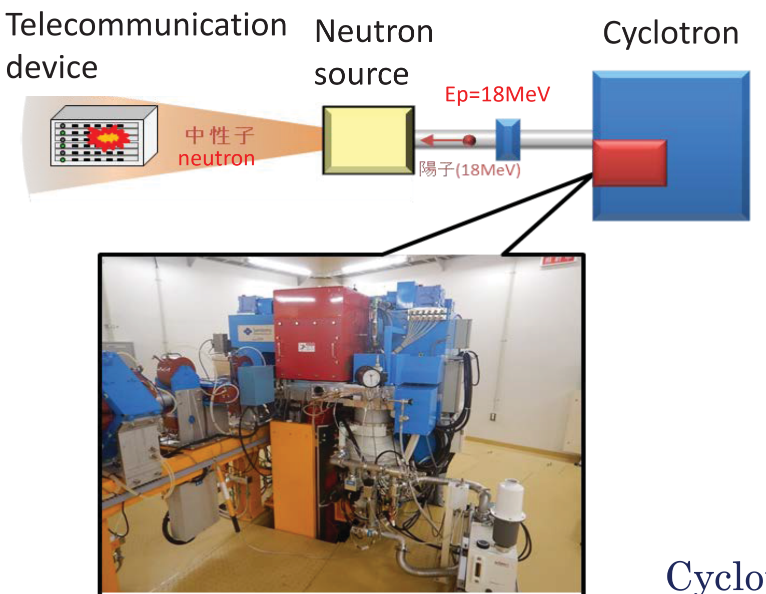
K.124 was already approved.

Recommendation	Title	Status
K.124	Overview of particle radiation effects on telecommunications systems	Approval in 2016
K.soft_des	Design methodologies for telecommunication systems applying soft error measures	Under study until 2017
K.soft_test	Soft error test method for telecommunication equipment	Under study until 2017
K.soft_mes	Quality estimation methods and application guidelines for mitigation measures based on particle radiation tests	Under study until 2018



ITU: United Nations specialized agency for information and communication technologies – ICTs.

Commercial service of acceleration test of the soft error
New step for industrial application



メーカー/型式	住友重機械工業製／CYPRIS370
加速粒子	陽子
加速エネルギー	18MeV
加速器サイズ	2.4m×1.8m×2.0m

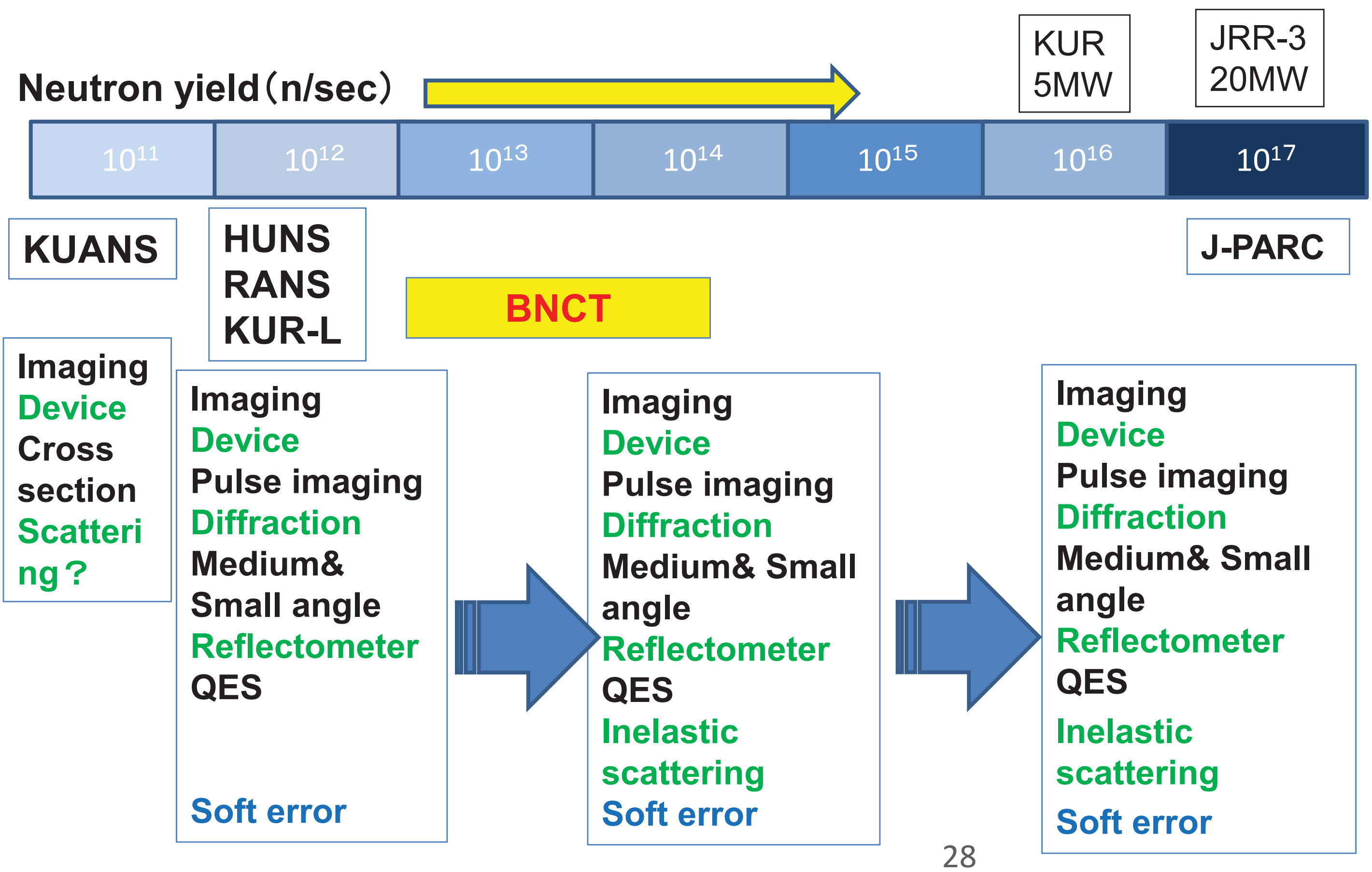
From 19 Dec. 2016

NTT
Nagoya University
Hokkaido University
SHIEI
*NTT Advance Technology
(Responsible for the tests)

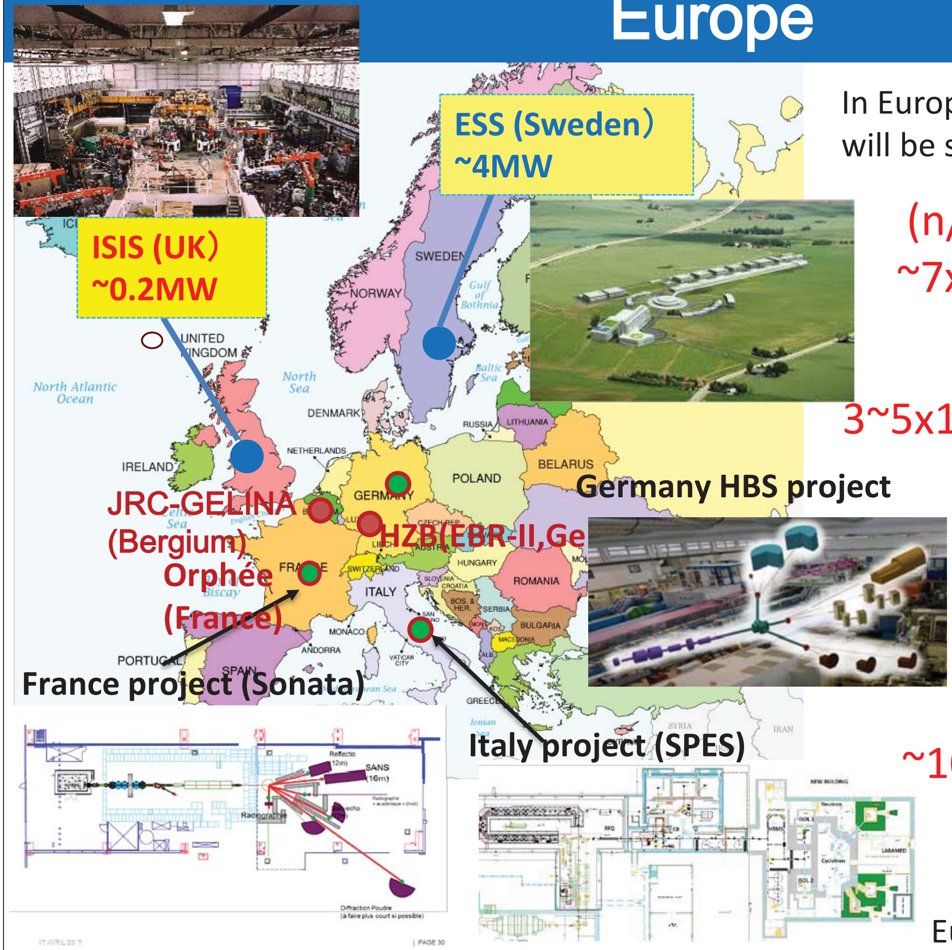
Cyclotron-driven neutron source at SHI-ATEX

New neutron source projects

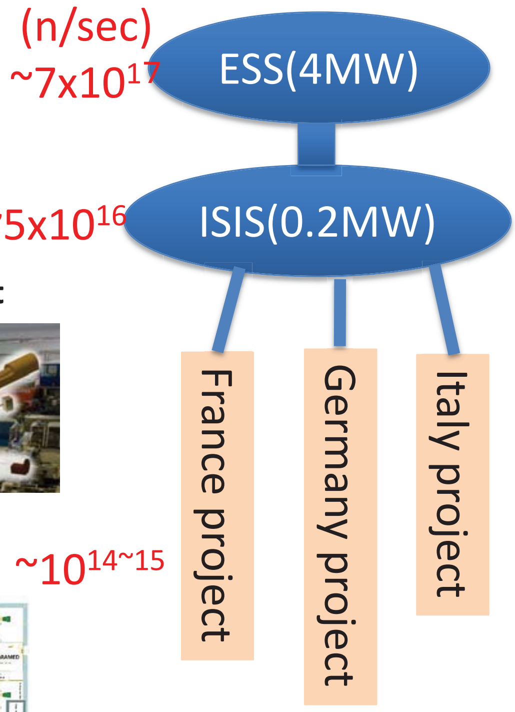
Experiments performed at CANS



Projects of accelerator driven neutron sources in Europe



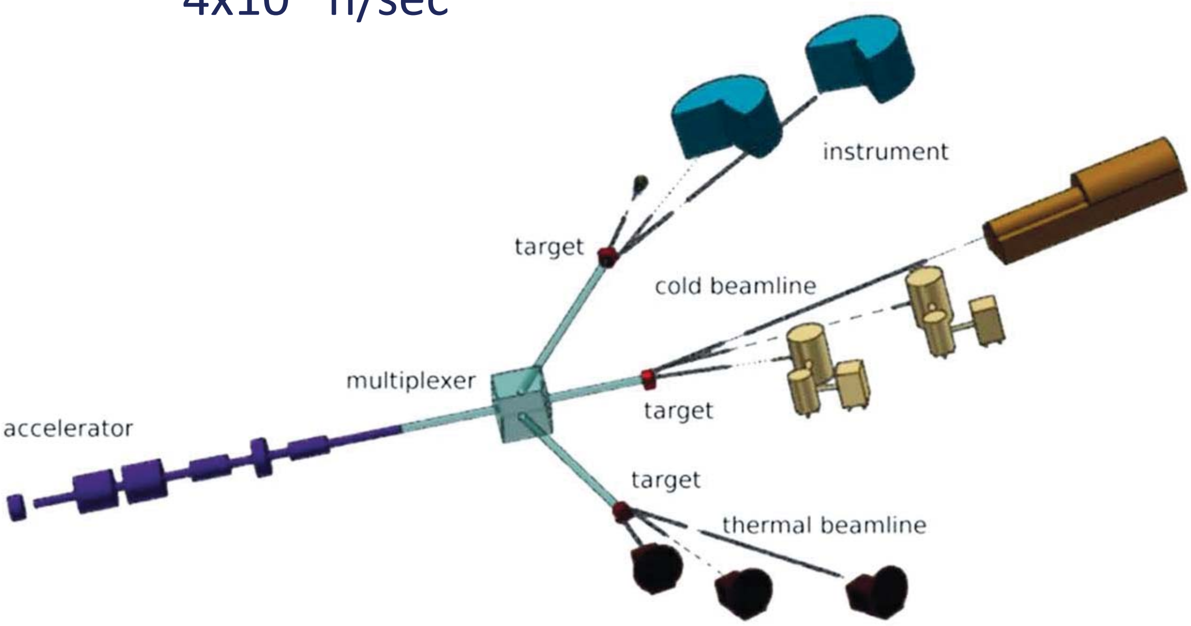
In Europe 2 medium power reactors will be shut down till end of 2019.



Eur. Phys. J. Plus (2016) 131: 72

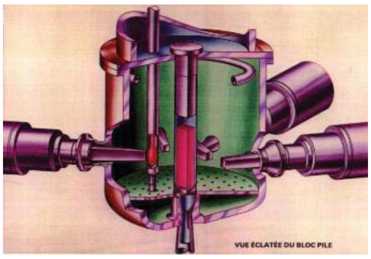
HBS(High Brilliance Source) project in Jülich, Germany

If assume 25MeV 4mA, 100kW, 4×10^{14} n/sec



FRENCH HIGH BRILLIANCE SOURCE, SONATA, ROUGH PERFORMANCES ESTIMATION

From presentation by Alain Menelle, LLB Saclay



Orphée

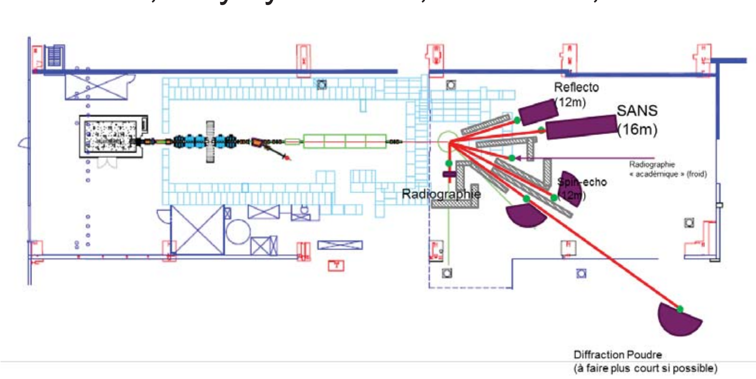
Source volume (core)	~ 5 10^4 cm^3
Moderation volume	~ 8 10^5 cm^3
# neutrons	~ 1 10^{18} $n.s^{-1}$
Mean neutron density	~ 1 10^{12} $n.cm^{-3}.s^{-1}$

Compact source

Source volume (Be)	~ 2 cm^3
Moderation volume	~ 6 10^3 cm^3
# neutrons	~ 2 10^{15} $n.s^{-1}$
Mean neutron density	~ 3 10^{11} $n.cm^{-3}.s^{-1}$

Ep = 20MeV, Ipeak = 100mA, duty cycle = 4%, P = 80kW, fixed Be target.

$3x10^{14}$ to 10^{15} n/s



SPES project at Laboratori Nazionali di Legnaro, Italy

Cyclotron 35-70MeV, 0.75mA

Neutron production (NEPIR) is the delta phase project and not yet financed.
~10^{14}n/sec is expected.

Soft error ANEM

Slow neutron beam (SLOWNE) is also under consideration.

New facilities in Japan

1) Aomori Prefecture Science Center

(Next to LIPAc)

Open on 6 Oct 2017

Multi purpose proton beam applications

Proton: Animal PET

Neutron: Imaging, Animal test for BNCT

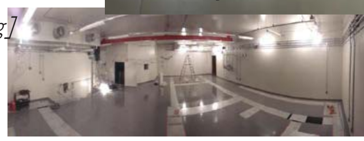
【Dormitory etc…】

Photo taken in January 2017

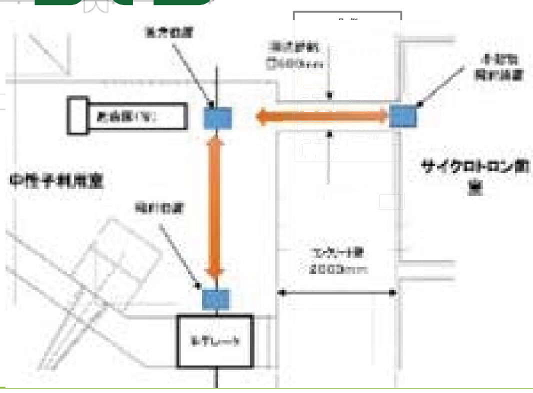
http://www.pref.aomori.lg.jp/soshiki/energy/iter-shien/files/h28-kentoiinkai-shisetsu.pdf

【Research building】

[RI building]



Plane View



Neutron area

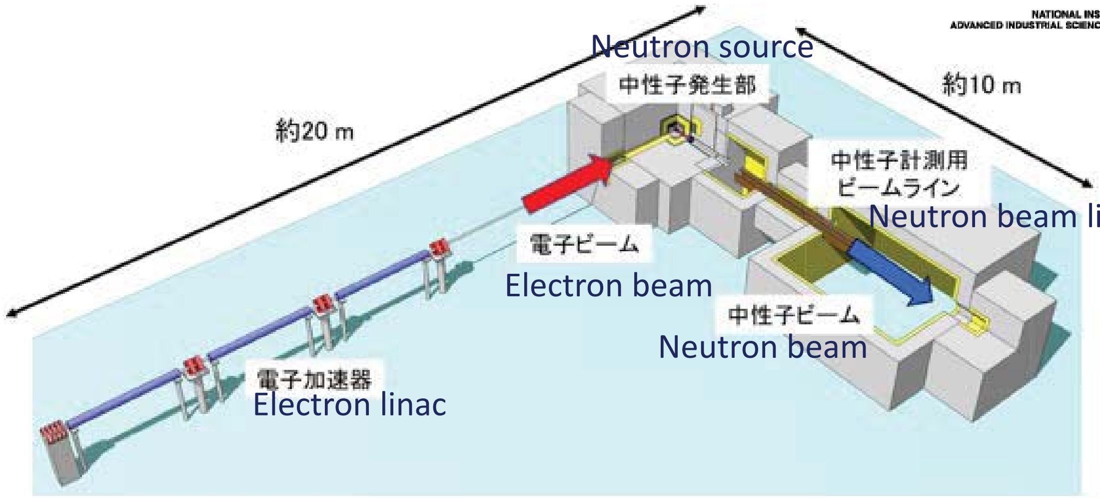
Imaging

BNCT for animal irradiation test

2) National Institute of Advanced Industrial Science and Technology in Tsukuba, Ibaraki

New neutron source (under construction)

10kW power, ~10^{13}n/sec

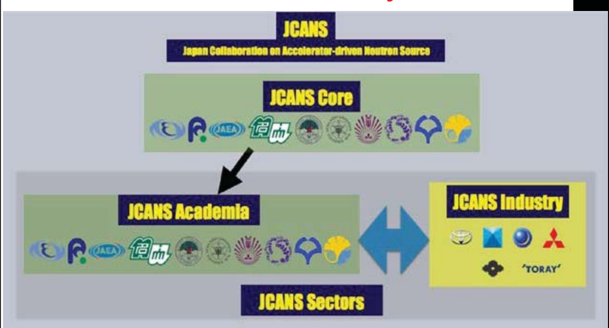


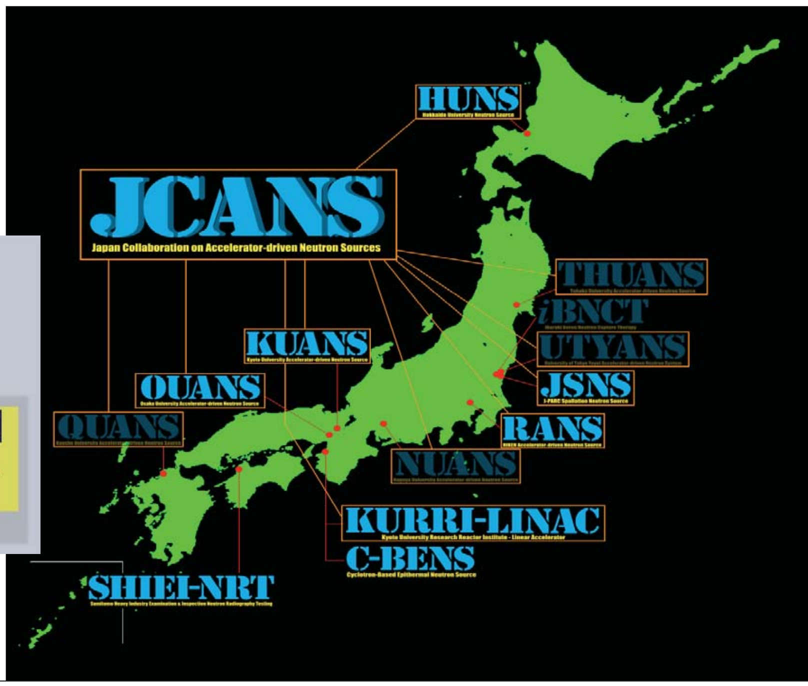
http://www.aist.go.jp/index_en.html

JCANS
Japan Collaboration on Accelerator-driven Neutron Sources

Japan Collaboration on Accelerator-driven Neutron Sources

The JCANS was consolidated on Oct. 20, 2011 at KEK with the starting members: Yoshiaki KIYANAGI and Michihiro FURUSAKA from Hokkaido University, Susumu IKEDA and Hirohiko M. SHIMIZU from KEK, Yoshihisa IWASHITA and Tomofumi NAGAE from Kyoto University, Yutaka YAMAGATA and Katsuya HIROTA from RIKEN, to activate a nation-wide network of individual research activity on neutron source and moderators, and practical neutron beam technologies for the applications in science and industry. .





UCANS: Union for Compact Accelerator-driven Neutron Sources

Summary

- For the neutron beam experiments, the accelerator driven neutron sources have been constructed.
- In Japan, accelerator driven BNCT facilities were constructed.
- In Japan, compact accelerator driven neutron sources, are being used as well as J-PARC/MLF for developing and improving methods for the material study.
- Neutron sources for multi-purpose use (BNCT + Beam experiments) are under commissioning.
- In Europe, medium and small size reactor neutron sources will be closed, and in place of the reactor sources medium power accelerator driven neutron sources are being planed.

Thank you for your attention!

3.4 Technical Session 3: Panel Discussion on development of High/Low power neutron sources

3.4.1Accelerator related issues

3.4.1-i) Comparison of a few schemes of RFQ-based compact neutron sources:

S. Kurokawa (KEK)

Comparison of RFQ-Based Compact Neutron Sources

Shin-ichi Kurokawa
Cosylab/KEK
2017/11/05
Aomori, Japan

Applications of Compact Neutron Sources

- High Intensity
  - BNCT (CW or Pulsed)
- Medium Intensity
  - Thermal and cold neutron production (Pulsed)
  - Radiography (CW or Pulsed)
- Detection of fissionable material, explosive, etc. (pulsed or CW)

Four Types of BNCT Neutron Sources

1. 2.5-3 MeV proton onto Li target
   Ion source + RFQ
   Ion source + DC accelerator

2. (1) ~8 MeV proton onto Be target
   Ion source + RFQ + DTL
   (2) ~5MeV proton onto Be target
   Ion source +RFQ

3. 1.5-3 MeV deuteron onto Be target
   Ion source + RFQ
   Ion source + DC accelerator

4. 30 MeV proton onto Be target (not considered in this talk)
   Ion Sources + 30 MeV cyclotron

Requirements of BNCT (Boron Neutron Capture Therapy)

BNCT starting point ➔ IAEA-TECDOC-1223

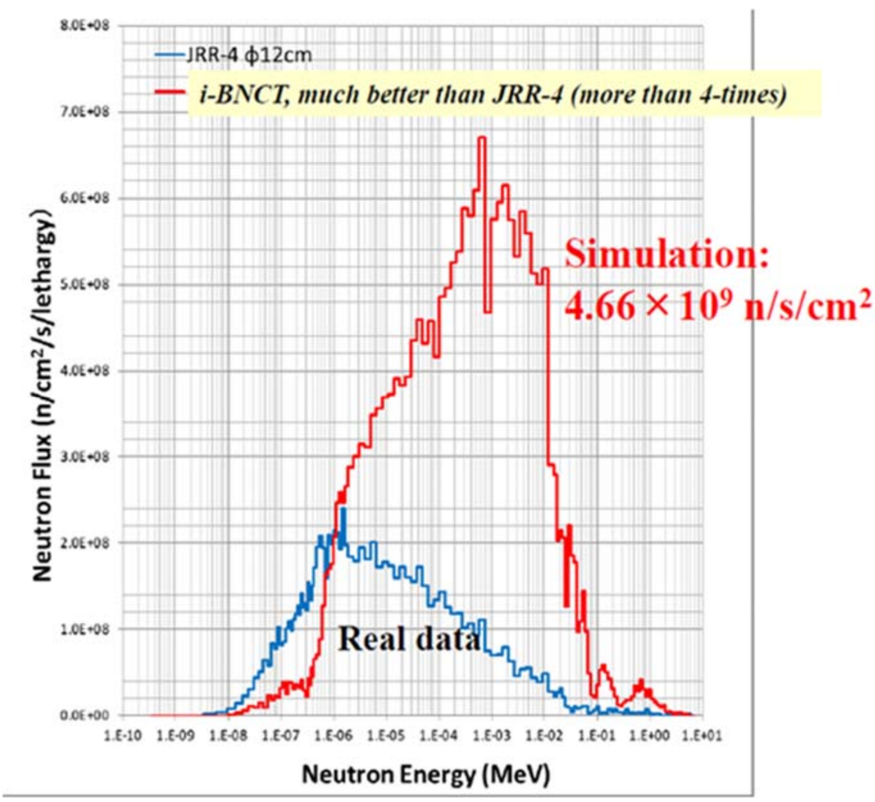
1.2. Epithermal beam intensity

For the purposes of reporting beam intensity, the common definition for an epithermal energy range should be used, namely 0.5 eV to 10 keV. If other energy limits are used, they should be clearly reported.

Current experience shows that a desirable minimum beam intensity would be 10^9 epithermal neutrons cm^{-2} s^{-1}. Beams of 5×10^8 n cm^{-2} s^{-1} are useable, but result in rather long irradiation times.

Energy range of "BNCT epi-thermal"
➔ (0.5 eV ~ 10 keV)"
Neutron flux ➔ > 1 X10^9 n/cm^2/s

Ibaraki BNCT neutron energy spectrum (simulation)



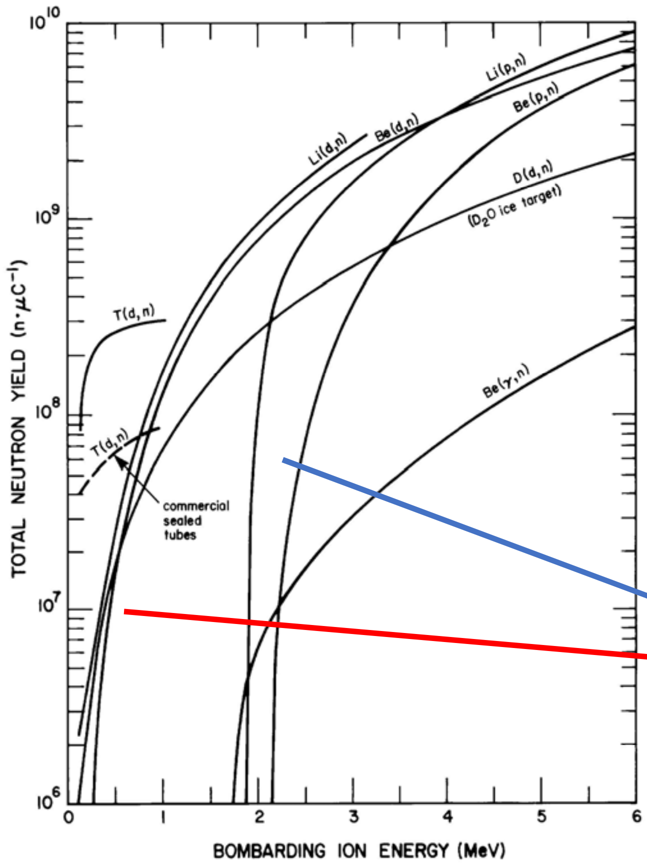


Figure 1. Neutron yields for low energy particle beam reactions.[3]

Comparison of Thick Target Yield of neutrons

Total Neutron Yield wrt Ion Energy onto Target by M.R. Hawkesworth AER 152 (1977)

Two types of Reactions:

Endothermic
Exothermic

Table 3.1 For different neutron-producing reactions, the table lists the threshold and bombarding energy, the total thick target neutron production for different bombarding energies, the percentage for which the maximum neutron energy is less than 1 MeV, and the maximum and minimum neutron energies [17, 22, 39, 40]

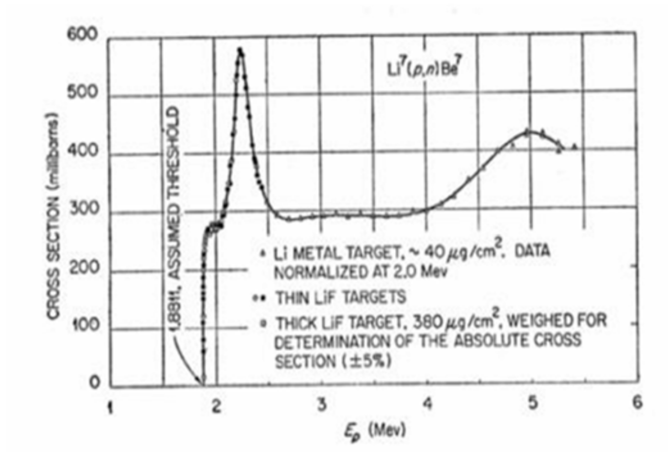
Reaction	E_{th} (MeV)	E_{in} (MeV)	Total production (n/mA s)	Fraction E_n < 1 MeV (%)	$E_{n,max}$ (keV)	$E_{n,min}$ (keV)
^{7}Li(p,n)^{7}Be	1.880	1.880	0	100	30	30
		1.890	6.3×10^{9}	100	67	0.2
		2.500	9.3×10^{11a}	100	787	60
		2.800	1.4×10^{12b}	92	1,100	395
^{9}Be(p,n)^{9}B	2.057	2.057	0	100	20	20
		2.500	3.9×10^{10}	100	574	193
^{9}Be(d,n)^{10}B	0	0	0	50	3,962	3,962
		1.500	3.3×10^{11}	50	4,279	3,874
^{13}C(d,n)^{14}N	0	0	0	75	4,974	4,964
		1.500	1.9×10^{11}	70	6,772	5,616
^{12}C(d,n)^{13}N	0.327	0.327	0	100	4	3
		1.500	6.0×10^{10}	80	1,188	707
d(d,n)^{3}He	0	0	0	0	2,451	2,451
		0.120	3.3×10^{8c}	0	2,898	2,123
		0.200	1.1×10^{9}	0	3,054	2,047
t(d,n)^{4}He	0	0	0	0	14,050	14,050
		0.150	4.5×10^{10}	0	14,961	13,305

[a] Average between the values reported in Colonna et al. [17] and Lee and Zhou [39, 40]
[b] Allen and Beynon [2]
[c] Ganda et al. [22]

Endothemic

Exothemic

Comparison between Lithium and Beryllium ${}^{7}Li(p,n){}^{7}Be$ ${}^{9}Be(p,n){}^{9}B$



Li

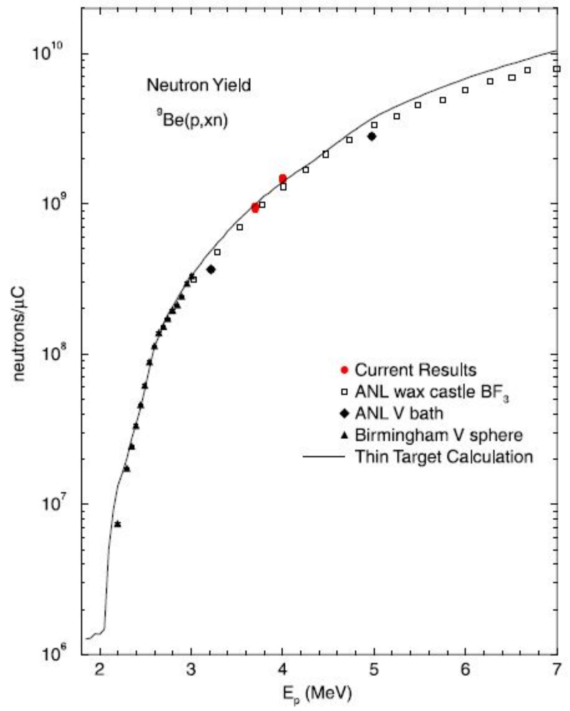


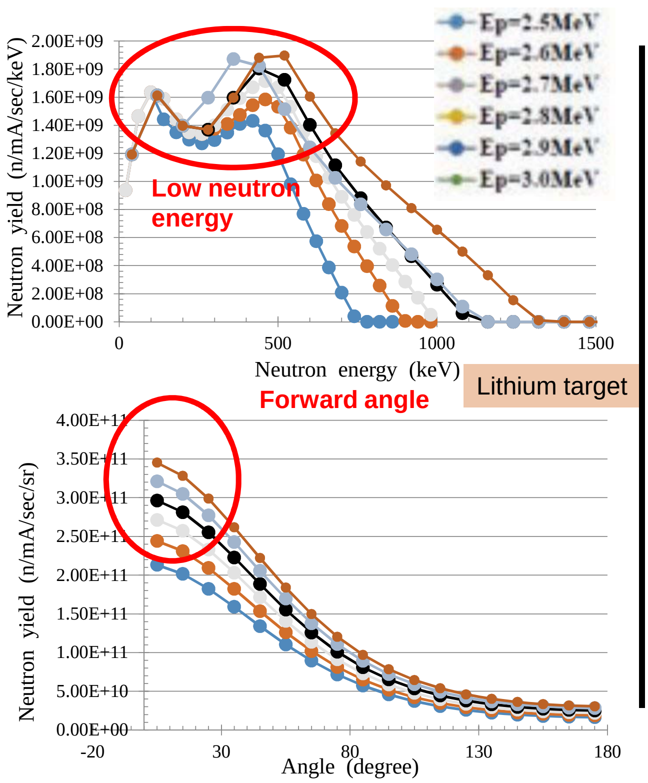
Fig. 16. Calculated and experimental thick-target neutron yield. The neutron yield was calculated using the evaluated cross section in Fig. 1. The ANL and Birmingham total neutron yields are uncorrected for leakage of high-energy neutrons.

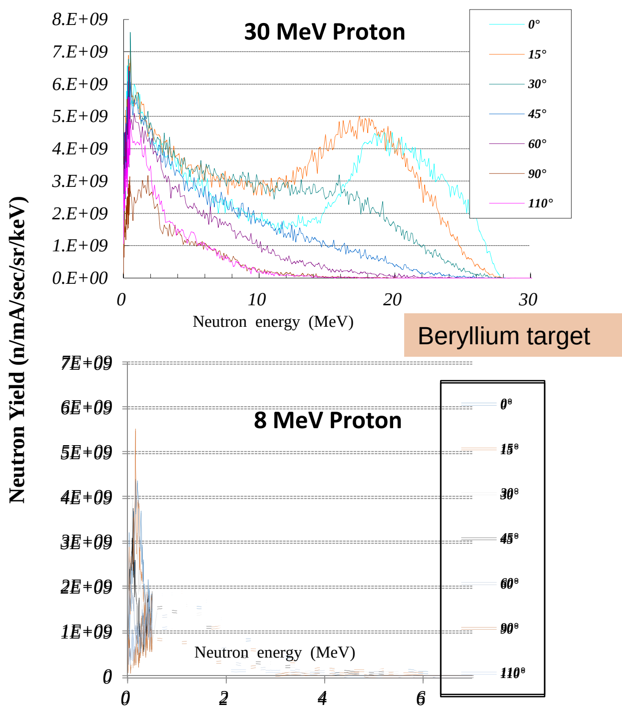
ICABU16

NEUTRON ENERGY SPECTRUM

OIST

Various production angle





Selection of Target Material

- Li(p,n)Be reaction seams quite attractive; however, Li target is rather difficult to make, especially, for high current incident beam.
- Also Li changes to radio active Be7 by Li(p,n)Be7 reaction, and the half lifetime of ~50 days of Be7 becomes an issue.
- It is worthwhile to think about the use of Be target, impinged not by proton but by deuteron.

Compact Neutron Sources with Low-Energy Deuterons onto Be Target

(Li target is relatively difficult to make and use compared to Be target if the beam power is high. Why not to try to find a possibility of compact neutron source using Be target ?)

The neutron emission for E_d = 0.9 MeV is characterized by a stripping process leading to a hard neutron spectrum with an average neutron energy in excess of 2.8 MeV.

The dramatic change in the neutron spectral shape occurs when deuterons are accelerated above 1 MeV due to appearance of neutrons corresponding to the excitation of one or more of the 5.11 MeV, 5.16 MeV and 5.18 MeV levels in ^{10}B residual nucleus. This considerably increases the yield and softens the neutron spectrum.

J. Guzek, et al.,
Characterisation of the 9Be(d,n)10B reaction as a source of neutrons employing commercially available radio frequency quadrupole (RFQ) linacs, SPIE Vol. 2867, pp 509 – 512 (1997)

This means that even though Be(d,n)B reaction is exothermic, if the energy of d^+ exceeds ~1 MeV, this reaction becomes endothermic, Be(d,n)B*.

Table 10.27 from (2004TI06): Levels of ^{10}B from ^{9}Be(d, n) and ^{9}Be(^{3}He, d) [a]

E_x (MeV ± keV) [a]	^{9}Be(d, n) [b]		^{9}Be(^{3}He, d) [c]		$J^\pi; T$ [a]
	l_p	S_{rel}	l_p	$(2J+1)C^2S$	
0	1	1.0	1	3.30	$3^+; 0$
0.72	1	1.97	1	2.76	$1^+; 0$
1.74	1	1.36	1	1.20	$0^+; 1$
2.15	1	0.41	1	0.82	$1^+; 0$
3.59	1	0.10	1	0.29	$2^+; 0$
4.77	(≥ 2)		$1 + (3)$ [d]	0.10 ≤ 0.82	$3^+; 0$
5.11	0	0.14	$0 + 2$	0.34, 0.14	$2^-; 0$
5.16 5.18	1	0.43	1	0.86	$2^+; 1$ $1^+; 0$
5.92	1	0.49	1	2.05	$2^+; 0$
6.03			(3) [d]	≤ 0.20	4^+
6.13	(2)		(2) [e]	3.04	3^-
6.56	(3)		(2) [e]	2.01	$(4)^-$
6.89 ± 15	(1)				$1^-; 0+1$
7.00 ± 15	(1)				$(1, 2)^+; (0)$
7.48 ± 15	[f]				[g]
7.56 ± 25	[f]				$0^+; 1$
(7.85 ± 50)	[f]				1^-
(8.07 ± 50)	[f]				$(2^-; 0)$
(8.12 ± 50)	[f]				

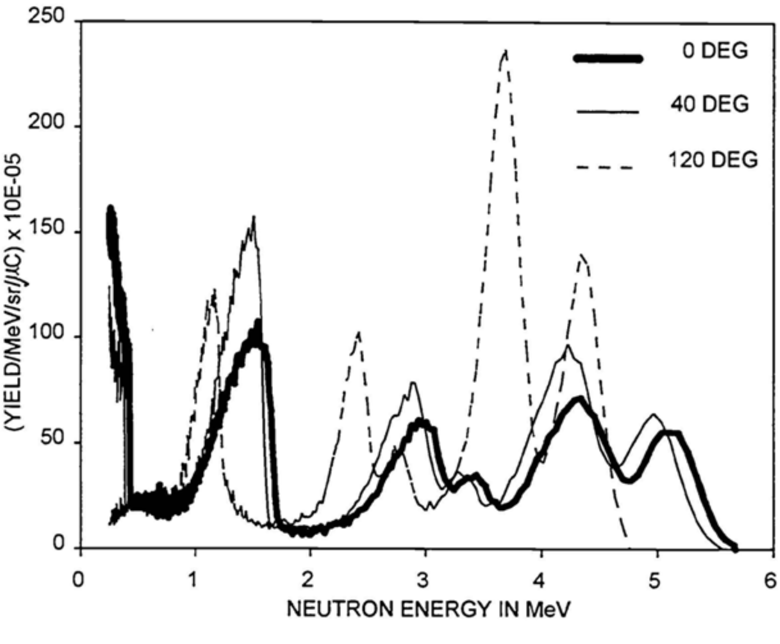


Fig. 2a. Neutron energy spectra obtained at 0°, 40° and 120° from bombarding a thick ^{9}Be target with deuterons of 0.9 MeV.

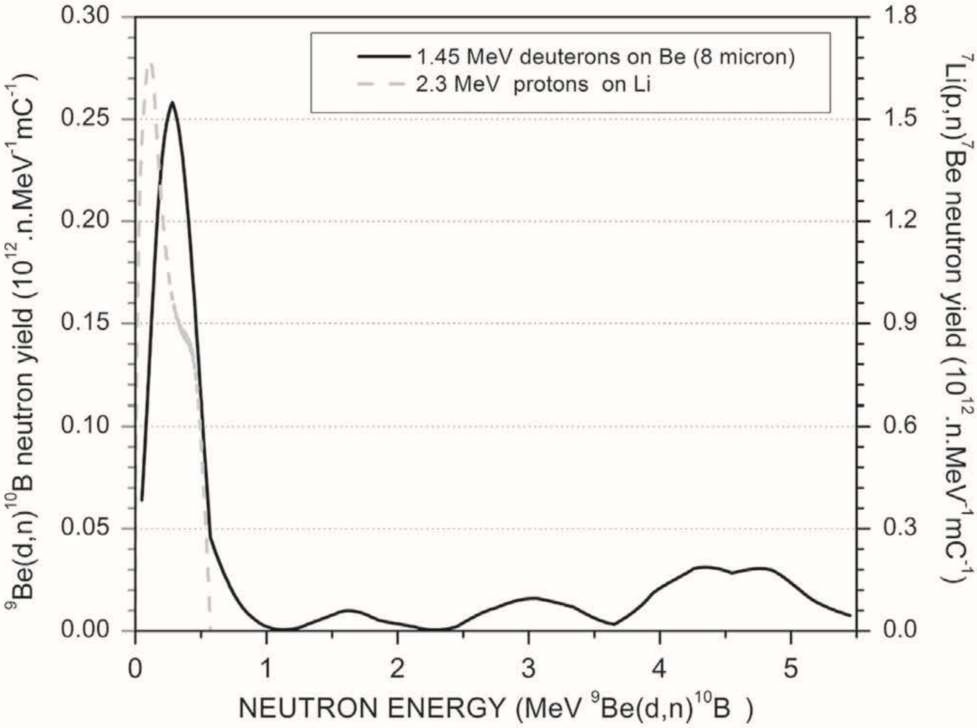


Fig. 1. Neutron spectra produced by 1.45 MeV deuterons on a 8 μm-thick Be target (left scale) and by 2.3 MeV protons on Li (right scale).

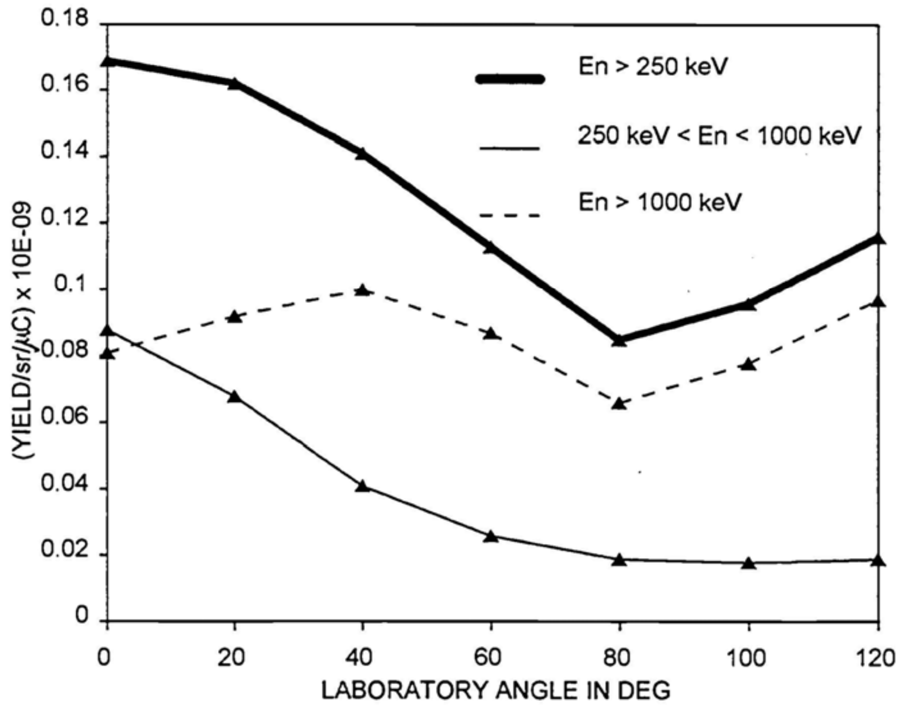


Fig. 3. Neutron angular distribution for the thick target $^{9}Be(d,n)^{10}B$ reaction at E_d = 1.5 MeV.

Comparison of Yields

- Yield of neutrons <2.5 MeV by 3 MeV Be(d,n)B reaction is x ~8 of that of 1.5 MeV d case (1.7×10^8 neutrons/uC)

  - 1.4×10^9 neutrons/uC

- Yield of neutrons < 1 MeV by Li(p,n)Be with 2.5 MeV p

  - 9.3×10^8 neutrons/uC

- Taking into account of the efficiency of moderation, 3 MeV Be(d,n) and 2.5 MeV Li(p,n) is equivalent in terms of number of neutrons.

- Yield of neutrons by Be(p,n)B with 5 MeV p is ~40% of that of 8 MeV case, but the maximum energy of neutrons is 3 MeV in the former and 6 MeV in the latter. If we take into account the efficiency of moderation this ratio changes to about 2 : 3.

- This means that 10 mA CW 3 MeV deuteron on Be target can produce almost equal number of neutrons to 10 mA CW 2.5 MeV proton on Lithium target and 10 mA CW 8 MeV protons on Be target.

- 15 mA CW 5 MeV protons on Be target can also produce the same number of neutrons.

A Few Comments on Be(d,n)B

- IS + RFQ suffices. This scheme will make the system simpler, easier to operate, and more robust.
- In order to reduce the higher energy neutron production, the thickness of the Be target should be finely controlled to make deuterons with lower than 1 MeV energy not to stop within the target. The thickness of the target will be ~20 um.
- The study on this scheme is still rudimental. More detailed study has yet to be done.

Lessons from Deuteron RFQ and Deuteron Ion Source at LiPAC in Rokkasho

1. LiPAC has shown that higher than 100 mA CW deuteron beam is produced by its ion source with 100 KV extraction voltage. ~20 mA d ion source (~ 70 kV extraction voltage) will be of no problem.
2. LiPAC also has shown that 175 MHz 5 MeV deuteron CW RFQ can be made, although real beam operation has yet to be done. In this frequency TETRODEs can be used and we do not need to have any modulators even in the case of pulsed operation.
3. By decreasing the frequency down to ~175 MHz, the shunt impedance of RFQ has become more than doubled, and CW operation of RFQ for compact neutron sources will be within the reach of hospital and universities.

Summary

- Discussion on neutron source on the basis of d(Be, n)B is still rudimental. The remaining main issues are: (1) exact estimation of neutron yield , (2) detailed design of RFQ and Ion Source, (3) development of thin (~20 um) Be target, and (4) design of the moderator.

- CW 10 mA Be(p,n)B with 8 MeV p, CW 15 mA Be(p,n)B with 5 MeV p, CW 10 mA Li(p, n)Be with 2.5 MeV p, CW 10mA Be(d,n)B with 3 MeV d can produce about the same number of available neutrons for BNCT.

- Except for the case of 8 MeV protons, IS + RFQ suffices, which make the system simpler and easier to operate.

- Strong point is that we can learn much from LIPAc experiences, especially those of ion sources and CW RFQ.

Thank you for your attention!

3.4.1-ii) High power linacs: J. Knaster (IFMIF/EVEDA)

High Power Linacs

3.5 MW beam power

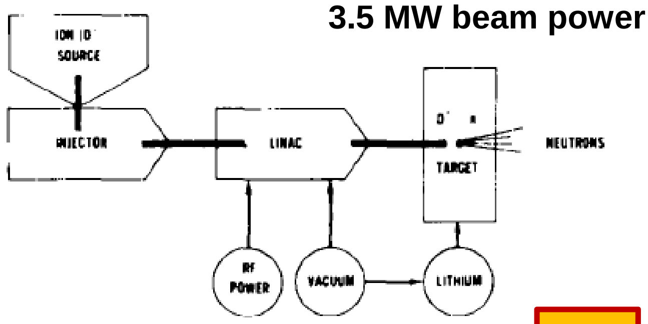


Fig. 1. Principle of FMIT operation.

1979

Journal of Nuclear Materials 85 & 86 (1979) 463–465
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THE FUSION MATERIALS IRRADIATION TEST FACILITY AT HANFORD*

E. W. POTTMEYER, JR.
Westinghouse Hanford Company, Hanford Engineering Development Laboratory, Richland, WA 99352, USA

What do we call as High Power Linac?

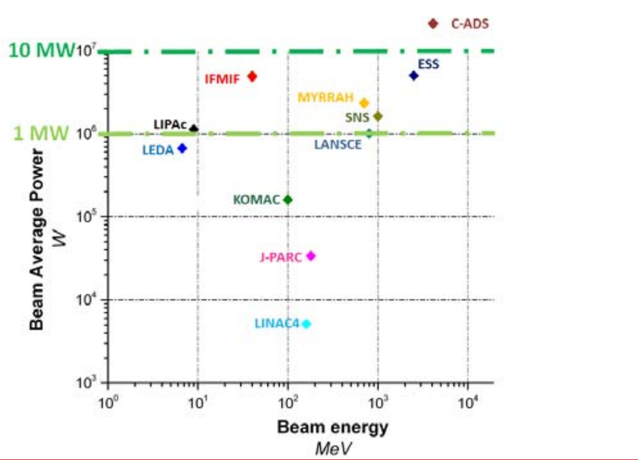
Beam power vs Beam average power

I x E x duty cycle

but energy is measured in **eV**

thus the energy gives the voltage that the particle undergoes

P = I x V



Proton Linacs have exhibited basically same structure since the invention of the RFQ in 1969 in the URSS

its invention led to an enormous enthusiasm

A LINEAR ION ACCELERATOR WITH

SPATIALLY UNIFORM HARD FOCUSING

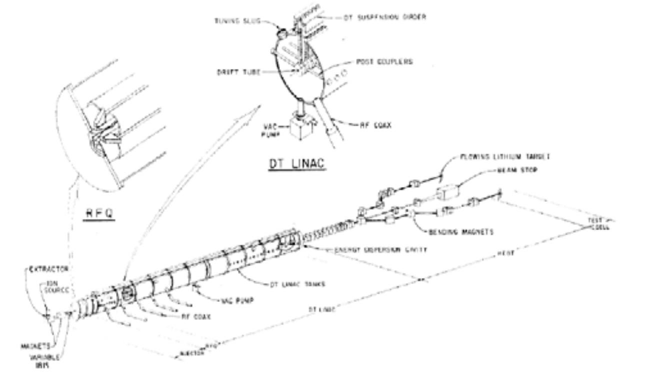
by

I.M. Kapchinskiĭ
GKAE* Institute of Theoretical and Experimental Physics

and

V.A. Teplyakov
GKAE* Institute of High-Energy Physics

The authors propose a linear ion accelerator in which the focusing and acceleration are achieved with a high-frequency electric field produced by a long four-conductor line. The accelerator contains no drift tubes. The advantages of this accelerator are its relative simplicity of design, small transverse dimensions, and possibility of substantially reducing the injection energy while maintaining the accelerated beam at a high intensity.



Journal of Nuclear Materials 85 & 86 (1979) 463–465

THE FUSION MATERIALS IRRADIATION TEST FACILITY AT HANFORD*

E. W. POTTMEYER, JR.

Westinghouse Hanford Company, Hanford Engineering Development Laboratory, Richland, WA 99352, USA

The Fusion Materials Irradiation Test Facility (FMIT) is a high-energy, high-flux neutron source for fusion materials development. The FMIT linear accelerator will produce a 35 MeV beam of deuterons that generates high-energy neutrons by a nuclear stripping reaction with flowing liquid lithium targets. The targets will be located in two identical irradiation test cells, either of which will provide an irradiation volume of 10 cm^3 at a neutron flux of 10^{15} n/cm^2-s and 500 cm^3 at a flux of 10^{14} n/cm^2-s. FMIT has been authorized by the US Congress and will be constructed and operated by the Hanford Engineering Development Laboratory (HEDL) at Richland, Washington, in collaboration with the Los Alamos Scientific Laboratory (LASL) which is providing the accelerator design. The project is currently entering the detailed design phase, targeting for start of construction in early 1980 and operation in 1983-84. Research and development programs are underway at both HEDL and LASL to resolve uncertainties in the lithium target and accelerator designs.

About FMIT

it was cancelled in 1985

IFMIF

Received November 16, 1975
Accepted for Publication January 16, 1976

INTRODUCTION

The needs of the Controlled Thermonuclear Reactor (CTR) program related to radiation damage in fusion reactor materials are becoming critical to the development of the planned Experimental Power Reactor. The 14-MeV neutron sources with high enough fluxes [$>10^{14}$ n/(cm^2 sec)] in large volumes (~1 liter) do not exist. Neutron sources being constructed or pro-

NUCLEAR TECHNOLOGY VOL. 29 JUNE 1976

Note that these parameters can be met utilizing state-of-the-art, proven technology in the accelerator field, and liquid-metal handling area to achieve a viable and reliable neutron radiation test facility, and that this facility could be made operational as early as 1981.

AN INTENSE Li(*d*,*n*) NEUTRON RADIATION TEST FACILITY FOR CONTROLLED THERMONUCLEAR REACTOR MATERIALS TESTING

MATERIALS

KEYWORDS: *neutron sources, lithium-6, deuteron reactions, materials testing, thermonuclear reactor materials, test facilities, lithium-7*

P. GRAND, K. BATCHELOR, J. P. BLEWETT, A. GOLAND, D. GURINSKY, J. KUKKONEN, and C. L. SNEAD, Jr.
Brookhaven National Laboratory, Upton, New York 11973

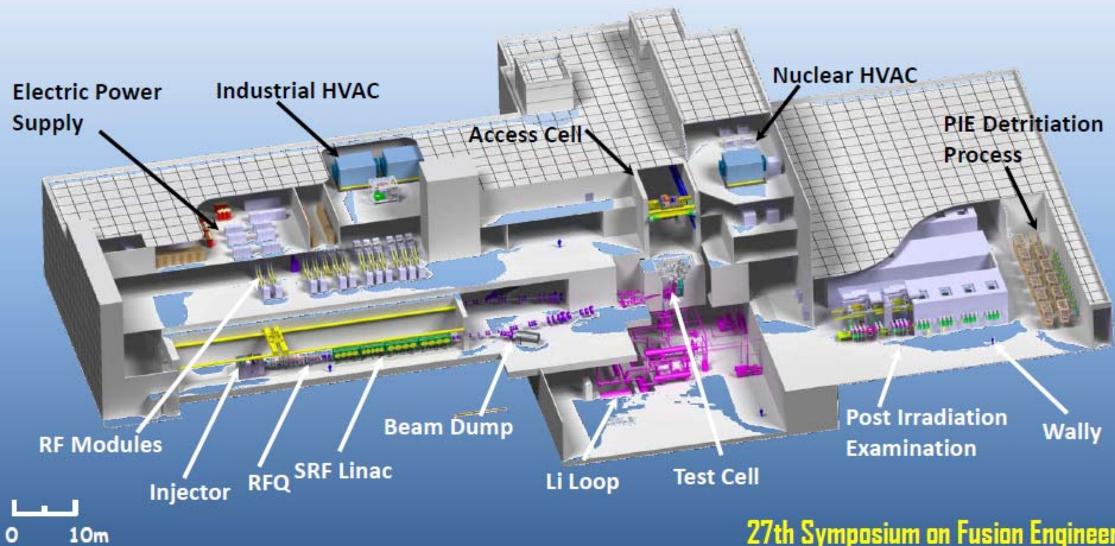
Received November 16, 1975
Accepted for Publication January 16, 1976

World accelerators technology
was not ready in the 70s
for a high current accelerator in CW mode

Liquid metal technology
was not ready in the 70s
for a massive lithium target

Status of IFMIF Project

is it still talking about IFMIF like talking of Alice in Wonderland?



We are, and Alice is not present

Fusion materials research have historically boosted ADS developments

J. Knaster & Y. Okumura, *Accelerators for fusion materials testing*. **Reviews of Accelerator Science and Technology Vol. 8 , 115-142 (2016)**

1981

FMIT

First attempt of constructing
a high current proton linac was in the 80s
an accelerator of **100 mA in CW at 35 MeV** was required

G. Boicourt et al, *Analysis of the deuteron distribution emerging from the FMIT RFQ*, **IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, (June 1981)**

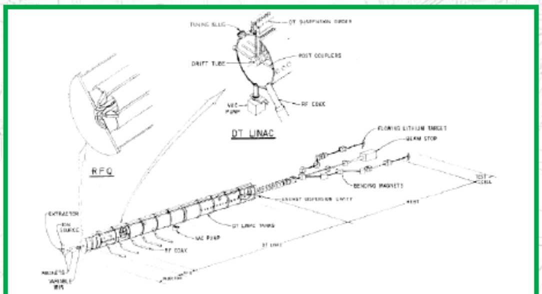
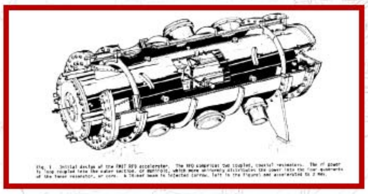


Fig. 7. Layout of the FMIT accelerator.

A validating prototype was constructed in Los Alamos
a **100 mA in CW H_2^+ at 2 MeV** linac
that would be upgraded with a 5 MeV DTL in CW

CW operation was achieved briefly
but the RFQ swiftly damaged
'Beam halo' was discovered the rough way

W.D. Cornelius, *CW operation of the FMIT RFQ accelerator*, **Nucl. Instr. Meth. Phys. Res. B10/l1 859-863 (1985)**



and the project cancelled in 1985

with strong recommendations to pursue an international collaboration

We don't need to operate with H_2^+
to learn how D^+ would behave

1st concern: D+ accelerator of 125 mA CW at 40 MeV

IFMIF

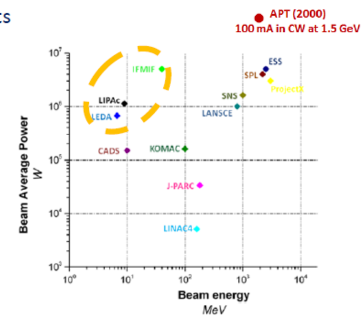
Space charge issues play a relevant role at high currents
being are severe at low-β
they cancel in relativistic regions

Space charge induced emittance growth
limits high currents

The perveance
figure of merit for space charge issues
is world highest in LIPAc

$$K = \frac{eI}{2\pi\varepsilon_0 m_0 v^3 \gamma^3}$$

Deuterons present high inelastic cross sections
commissioning would be difficult
if done with deuterons
but
protons at half energy and half intensity behave
as deuterons at nominal conditions



F. Scantamburlo et al., *LIPAc, the 125 mA/9 MeV CW deuteron IFMIF's prototype accelerator: what lessons have we learnt from LEDA?*, **IPAC 2014**

We can operate in far better conditions with H^+

Injector → RFQ → DTL → RF cavities

~100 keV ~ 5 MeV > 100 MeV

High current accelerators face space charge phenomena
intra-beam non-linear repulsive forces lead to beam losses

Beam losses on high power linacs can be very damaging
1 W/m when talking of MW beam power is challenging

Acceleration can only be done in stages with specific hardware
all hardware has its operational limits

Injector needs to provide very high quality beam

in FMIT it was cathode based

DTL exhibits limits at high currents

drift tube linacs

Narrow tubes spaced a given distance

that the particle travels in phase with the RF power

Problems for low energies

Problems for high energies

Problems for high currents

Beam halo is enhanced by misaligment in interfacing equipment

FMIT targeted 200 μm alignment precision

In LIPAc we are aligning within 30 μm precision

For high currents Linacs

DTL is replaced by the novel concept of SC cavities

IFMIF

The possibility of using SC cavities at low β
is a **technological breakthrough** for high current accelerators
since beam losses limitation is severe in DTL structures

SC cavities advantages

High accelerating gradients lead to lower const.&oper. costs

Lower RF losses lead to more efficient RF power transfer

XUHV conditions minimizing beam-gas interactions

High reliability architecture

Higher apertures

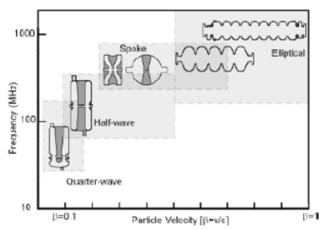


Fig. 1. Practical superconducting cavities spanning the full range of low and intermediate values of beta.

M. Kelly, *Superconducting Radio-Frequency Cavities for Low-Beta Particle Accelerators*, **Reviews of Accelerator Science and Technology Vol. 5 (2012) 185–203**

Technological breakthroughs to say goodbye to Alice

T. Taylor and J.S.C. Wills, *A high-current low-emittance dc ECR proton source,* **Nucl. Instr. Meth. Phys. Res. A309, (1991)**

The 1st attempt to run a RFQ in CW was in Los Alamos (LANL) for FMIT accelerator validation exercise

The 'beam halo' was discovered the rough way

80s

W.D. Cornelius, *CW operation of the FMIT RFQ accelerator,* **Nucl. Instr. Meth. Phys. Res. B10/l1 (1985) 859-863**

90s

Beam quality injected in RFQ was poor

ECR approach was technologically validated for H^+ in Chalk River

L.M. Young et al., *High power operations of LEDA,* **LINAC 2000, Monterey**

1999

LANL successfully operated LEDA

100 mA in CW at 6.7 MeV

with a dual electrodes capacitive/inductive part cooling RFQ tuning

and unraveled beam halo physics the following years

2001

C.K. Allen et al., *Beam-Halo Measurements in High-Current Proton Beams,* **Phys. Rev. Lett. 89, Number 21, 18 Nov. 2002**

M. Kelly, *Superconducting Radio-Frequency Cavities for Low-Beta Particle Accelerators,* **Reviews of Accelerator Science and Technology 5:185 (2012)**

Alvarez type accelerating structure (DTL) for beam energies within $0.2<\beta<0.6$ is a difficult challenge for high currents in CW

the feasibility of superconducting resonators for low-β was demonstrated in LANL in 2002

2001

T. Tajima, et al., *Evaluation and Testing of a Low-β Spoke Resonator,* **PAC 2001, Chicago**

2013

Operation of superconducting HWR cavities in CW

SARAF has operated 176 MHz HWR cavities in CW in 2013

J. Knaster and Y. Okumura, *Accelerators for fusion materials testing,* **Reviews of Accelerator Science and Technology 8, 115142 (2015)**

A. Kreisel at al., *Phase-I proton/deuteron linac beam operation status,* **Proceedings of LINAC2014, Geneva**

IFMIF

Half-Wave Resonators in CW

2013

SARAF operated protons at 4 MeV

1.6 mA CW

176 MHz HWR SC cavities

Figure 2: Phase-I 4 MeV protons and 5 MeV deuterons linac in the 4.5 m W, 5 m H and 25 m long beam corridor.

A. Kreisel at al., *Phase-I proton/deuteron linac beam operation status,* **Proceedings of LINAC2014, Geneva**

2014

IHEP operated protons at 2.2 MeV

10 mA in CW

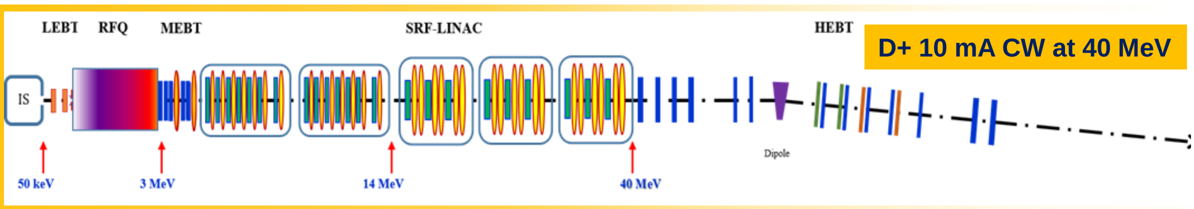
162.5 HWR SC cavity

framed by C-ADS project

10 mA protons at 1.5 GeV

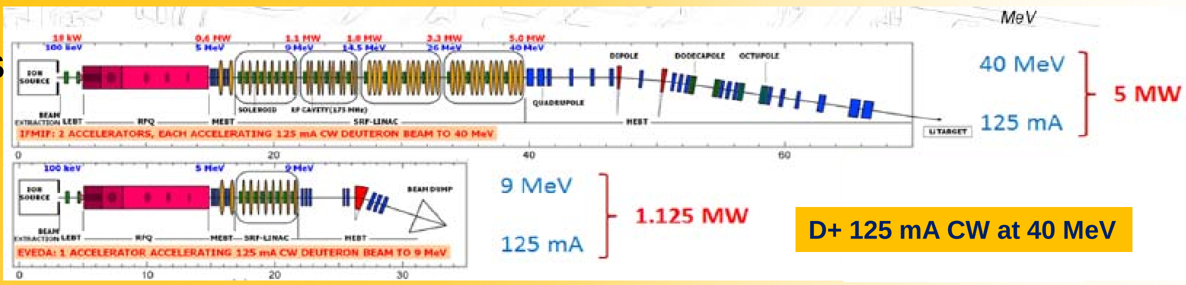
W. Pan and J. Dai, *ADS based on Linear Accelerators,* **Reviews of Accelerator Science and Technology Vol. 8 (2015) 55-76**

BISOL

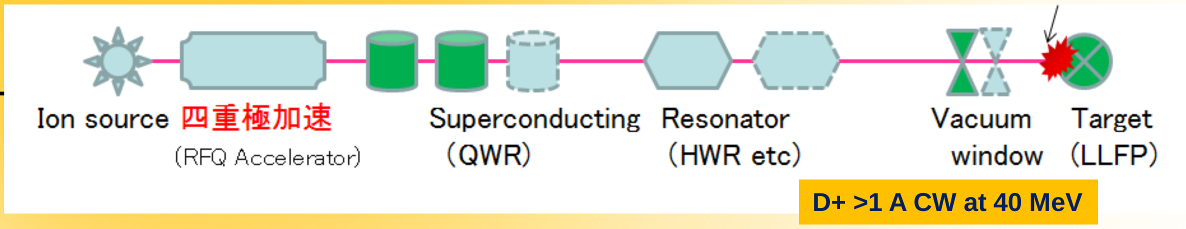


DONES
A-FNS

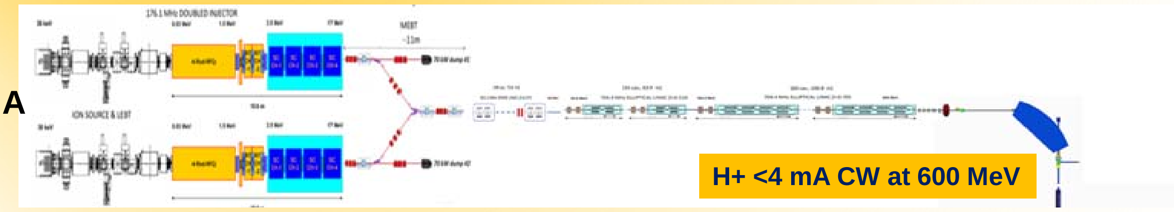
LIPAc



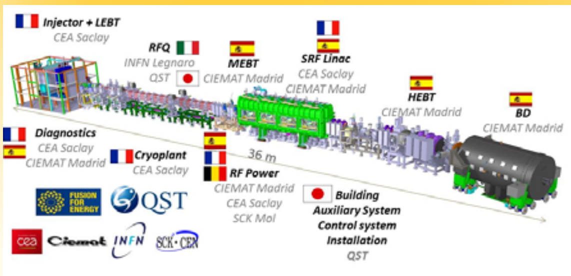
ImPACT

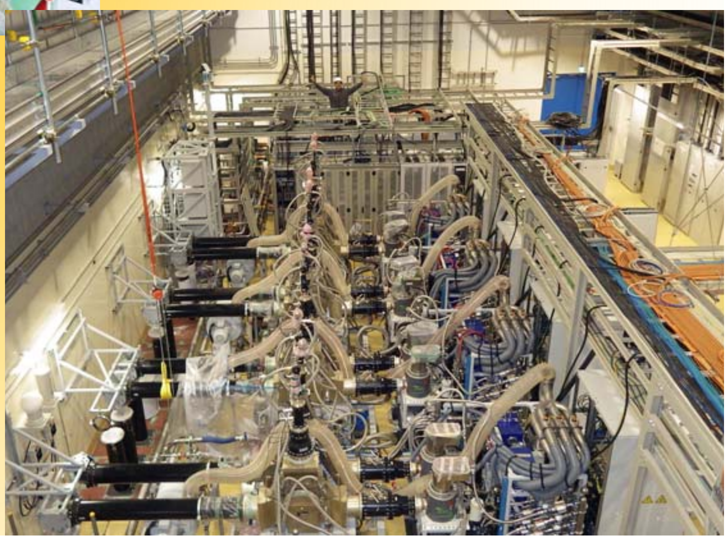


MYRRHA



LIPAc is reality to test 125 mA in CW at 9 MeV through 175 MHz HWR





Yesterday there were two questions

Why ImPACT is pursuing QWRs?

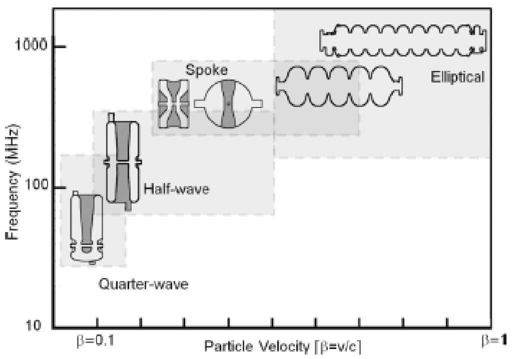


Fig. 1. Practical superconducting cavities spanning the full range of low and intermediate values of beta.

M. Kelly, *Superconducting Radio-Frequency Cavities for Low-Beta Particle Accelerators*, **Reviews of Accelerator Science and Technology Vol. 5 (2012) 185–203**

Has been properly assessed in BISOL injecting D^+ at 50 keV for higher currents tan 10 mA?

Actually,

the lower the energy, the space charge drawback is more severe

$$K = \frac{eI}{2\pi\varepsilon_o m_o v^3 \gamma^3}$$

Another question raised
about availabilities

ADS dream with challenging availabilities
IFMIF has a careful RAMI analysis

Table 1. Inherent availability requirements for the facilities at the IFMIF facilities.

IFMIF facilities (and systems)	Inherent availability (%)
AF	87
LF	94
TF	96
CFs (excluding central control system and common instrumentation)	98
Central control system and common instrumentation	98
TOTAL (product)	75

J. Knaster et al, *Overview of IFMIF/EVEDA project*, **Nuclear Fusion 57 (2017) 102016**

A topic not addressed
but challenging
is beam instrumentation

High powers
prevent interceptive diagnostics

Low energies
makes challenging non-interceptive diagnostics

High power & Low energy beams
becomes an entertaining scenario

Where is the limit of currents in CW through a HWR?

We now know that is at 10 mA

LIPAc will show that 125 mA is feasible

Why not dreaming >1 A?

Anyhow,
don’t forget what means 1 MW beam power flying
at few cm of structures at 4 K

3.4.2 Target-related issues

3.4.2-i) Design and technical challenges of Li target for IFMIF-based neutron sources: D. Bernardi (ENEA)

1st Workshop on Advanced Neutron Source and its Application

Design and technical challenges of Li target for IFMIF-based neutron sources

Davide BERNARDI (ENEA)

4-5 November, 2017 Aomori-city, Japan

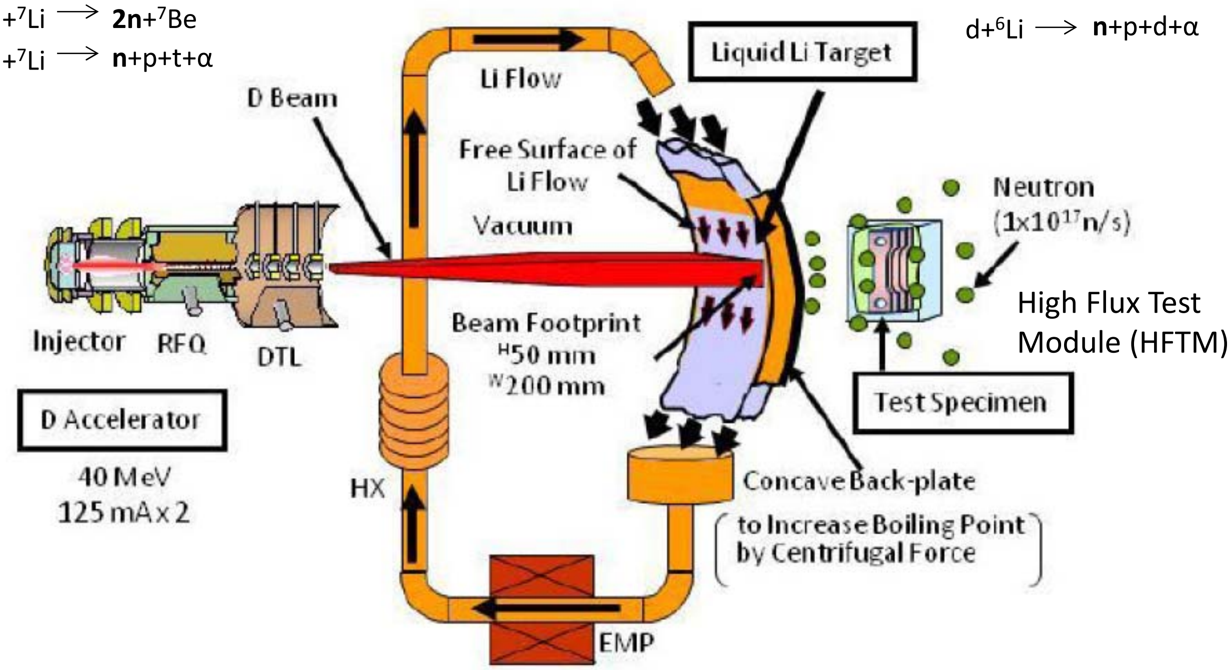
Outline

- ❑ IFMIF Li target concept
- ❑ TA design basis
- ❑ TA lifetime-related issues:
  - ➢ Irradiation embrittlement
  - ➢ Erosion/corrosion
  - ➢ Loss of gaskets performance
  - ➢ Other phenomena
- ❑ Summary and conclusions

IFMIF Li target concept

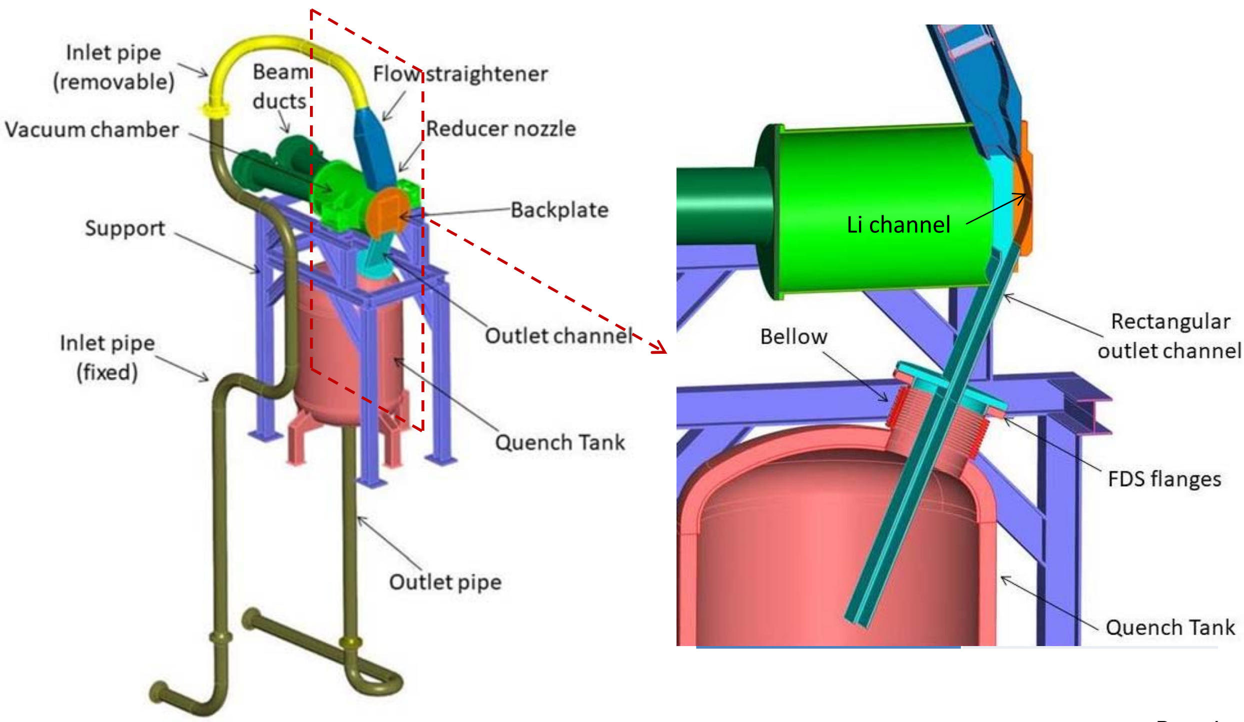
$d+^{7}Li \longrightarrow \mathbf{n}+2\alpha$
$d+^{7}Li \longrightarrow \mathbf{n}+^{8}Be$
$d+^{7}Li \longrightarrow \mathbf{n}+p+^{7}Be$
$d+^{7}Li \longrightarrow \mathbf{2n}+^{7}Be$
$d+^{7}Li \longrightarrow \mathbf{n}+p+t+\alpha$

$d+^{6}Li \longrightarrow \mathbf{n}+^{7}Be$
$d+^{6}Li \longrightarrow \mathbf{n}+\alpha+^{3}He$
$d+^{6}Li \longrightarrow \mathbf{n}+p+^{6}Li$
$d+^{6}Li \longrightarrow \mathbf{n}+p+d+\alpha$



TA design basis /1

- maintain a stable high-velocity, free surface flow of liquid lithium in front of the D+ beam
- produce the adequate neutron flux to properly irradiate the test modules
- remove the high thermal power deposited in the lithium jet by the D+ beam

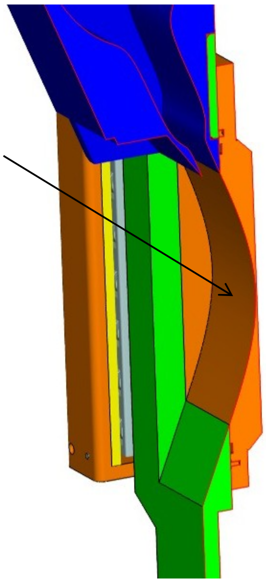


TA design basis /2

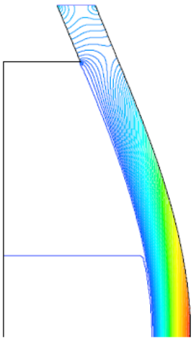
Li channel profile developed by ENEA

- Avoid Li boiling
- Create smooth pressure distribution

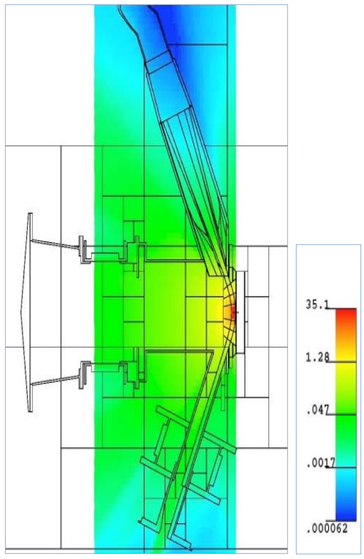
Variable curvature profile allowing for gradual pressure increase to limit flow disturbances



Pressure distribution

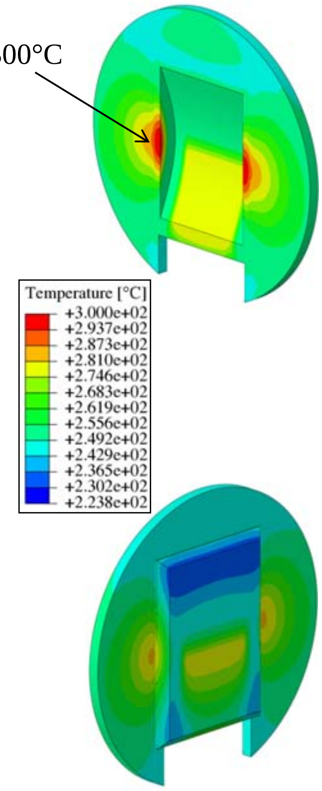


Damage rate [dpa/fpy] (DONES)



Backplate thermal field (DONES)

$T_{max} = 300°C$



Successfully tested in ELTL (Oarai, Japan) within IFMIF/EVEDA

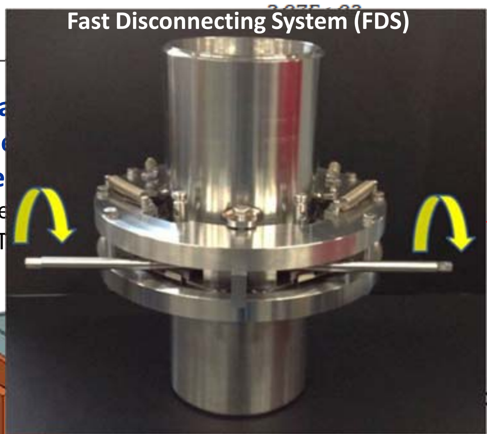
TA design basis /3

Average nuclear responses on the BP footprint volume

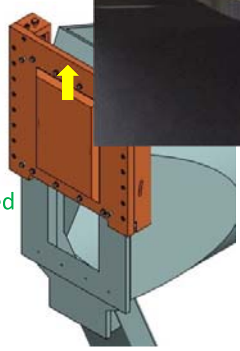
IFMIF conditions (two accelerators – 10 MW beam)

Neutron flux ($n/cm^2/s$)	1.36E+15
Photon flux ($\gamma/cm^2/s$)	3.92E+14
Neutron heating (W/cm^3)	1.66E+01
Photon heating (W/cm^3)	1.55E+01
Displacement per atom (DPA/fpy)	5.67E+01
Hydrogen production (appm/fpy)	[illegible]
Helium production (appm/fpy)	[illegible]

M. Frisoni et al. "*Nuclear analysis of the IFMIF European lithium target assembly system*, Fusion Engineering and Design, 89 (2014), 1959-1963



- **The BP is the TA most critica**... nd harsh working conditions
- **BP lifetime is expected to be**... performance and maintenance
- **Replacement of BP/TA is ne**...
  - ✓ Bayonet concept: only the...
  - ✓ Integral concept: all the T...

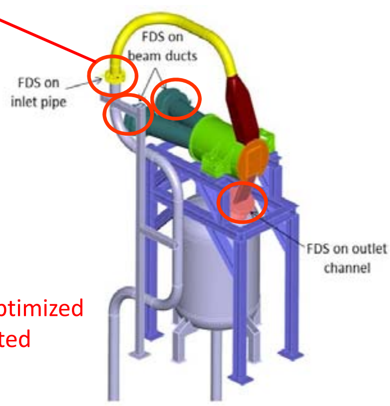


Bayonet BP concept

- Low activated waste
- Maintenance optimized
- Sealing gasket needed
- Complex design

...pt

- No gasket needed
- Simplified design
- Maintenance not optimized
- More waste generated



TA lifetime related issues

Main life-limiting factors for the Li target:

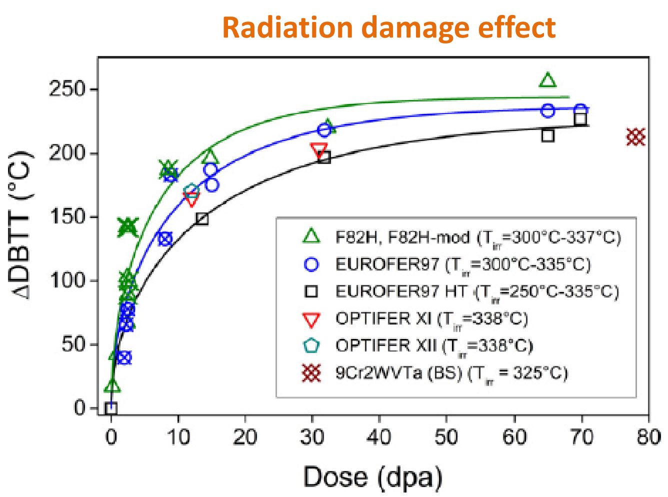
- ❑ Irradiation embrittlement (L_{emb})
- ❑ Erosion/corrosion by high-speed Li flow (L_{corr})
- ❑ Loss of sealing gaskets performance (L_{gask})
- ❑ Other phenomena (swelling, creep,…)

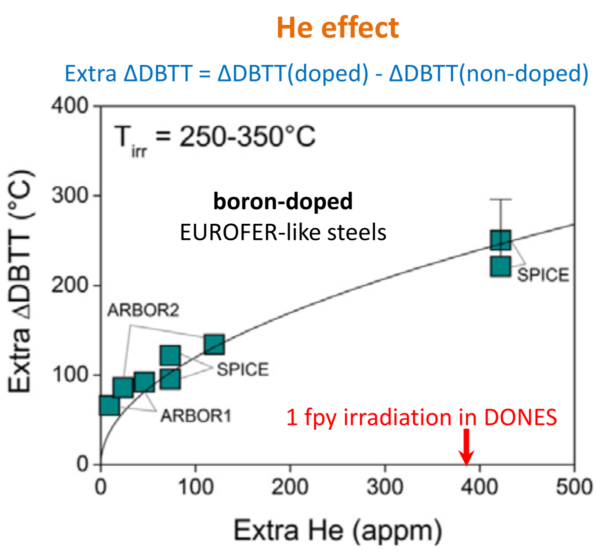
TA lifetime = min (L_{emb}, L_{corr}, L_{gask}, ...)

Irradiation embrittlement /1

Irradiation in Fast spectrum Reactors (HFR, BR2, BOR60) within different EU programmes (SPICE, ARBOR,…)

E. Gaganidze, J. Aktaa, *Assessment of neutron irradiation effects on RAFM steels*, Fusion Engineering and Design 88 (2013) 118–128



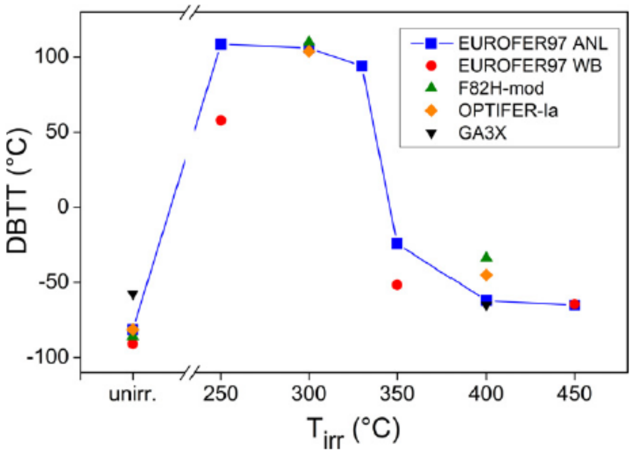


- Strong DBTT increase at low doses, saturation beyond 15 dpa, slow increase up to ~70 dpa
- Large scatter of DBTT (unirrad.) but always lower than -50 °C
- DBTT ~120°-125°C@30dpa (DONES), ~140°C-150°C@60 dpa (IFMIF)
- He effect strongly enhances embrittlement in the concerned T range
- Neutron irradiation of **B-doped steel technique probably largely overestimates He embrittlement**

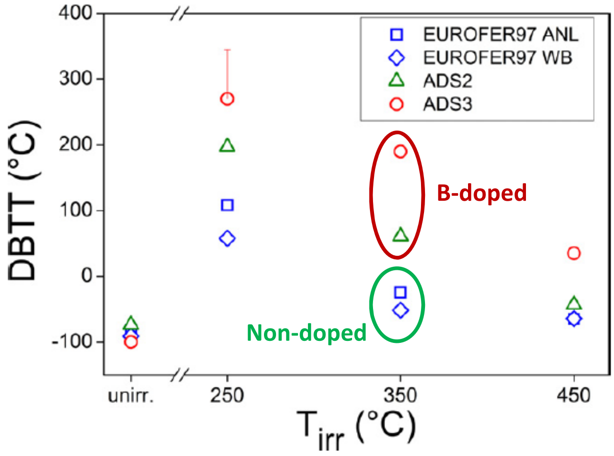
Irradiation embrittlement /2

Influence of temperature on DBTT shift

dpa-induced DBTT shift



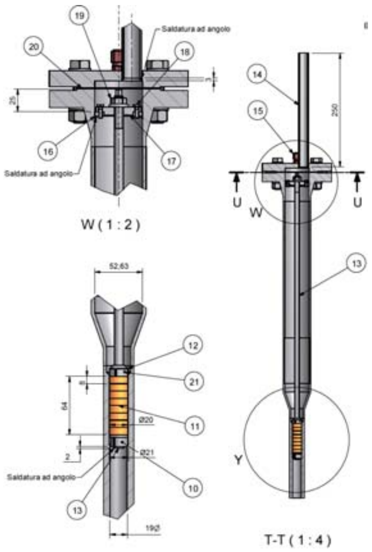
He-induced DBTT shift



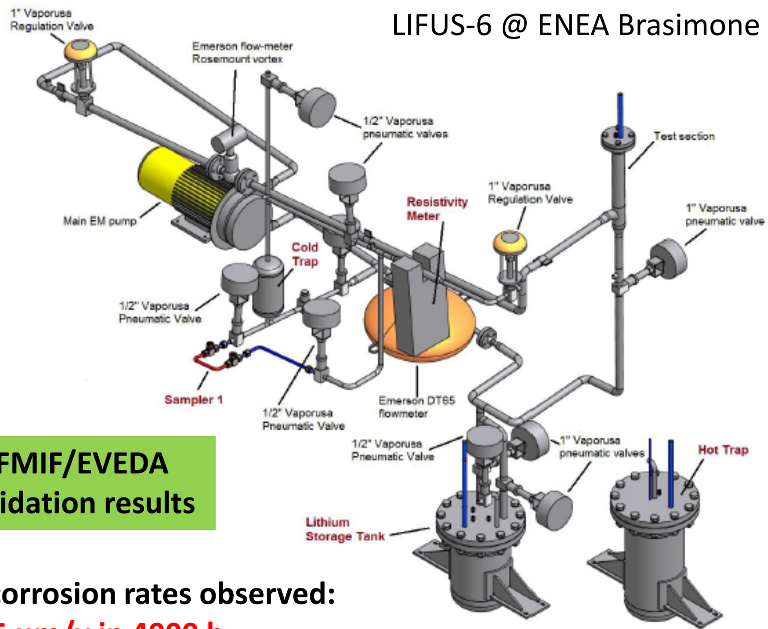
E. Gaganidze, J. Aktaa, *Assessment of neutron irradiation effects on RAFM steels*, Fusion Engineering and Design 88 (2013) 118– 128

- DBTT shift much more sensitive at lower temperatures (< 350 °C)
- Possible mitigating actions:
  - increase TA operating temperature to ~350-360°C (limited by swelling)
  - Thermal annealing at high temperature (550°C/3 h)

Erosion/corrosion



LIFUS-6 @ ENEA Brasimone



IFMIF/EVEDA validation results

Recent LIFUS-6 results:

- Material: EUROFER 97
- Li speed = 15 m/s
- T = 330 °C
- N concentration ~**30 wppm**
- duration: **4000 hours**

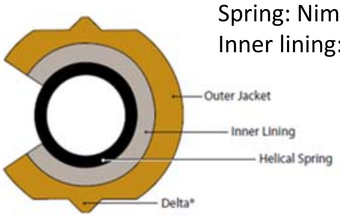
Max corrosion rates observed:
~0.25 μm/y in 4000 h

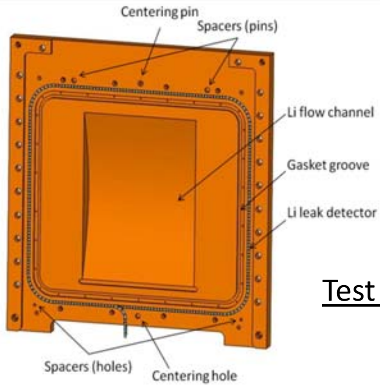
Erosion/corrosion is seen to play no role on the BP lifetime

Loss of sealing gaskets performance

Helicoflex HNV 200 sealing gasket

Outer jacket : soft iron
Spring: Nimonic 90
Inner lining: AISI 304





Exposure tests to stagnant Li were performed **up to 7000 h** at ENEA Brasimone **within IFMIF/EVEDA** validation activities

Test conditions:

T=350 °C
N conc. in Li < 300 wppm
(certified by supplier)

Post-test analysis after 7000 h exposure

Test results:

Test @ 5500 h: no leakage
Test @ 7000 h: leakage observed

Suitability of the gasket proved only up to 5500 h

but…suspect of some uncontrolled conditions in the 7000 h test → **more long-term tests are needed**

Other phenomena

- **Thermal creep**

  According to RCC-MRx (Tome 6), for temperatures below 375°C EUROFER thermal creep is negligible whatever the holding time, thus **at the TA operating temperature this effect is not significant**

- **Swelling**

  For temperatures below 360 °C the Japanese RAFM steel F82H irradiated with heavy ion beams shows a negligible swelling up to 50 dpa. EUROFER is also reported to show long swelling incubation times at low temperatures (*Material Property Handbook*, EUROfusion WPMAT) and therefore **this effect is expected to be not relevant for the TA**

- **Irradiation creep**

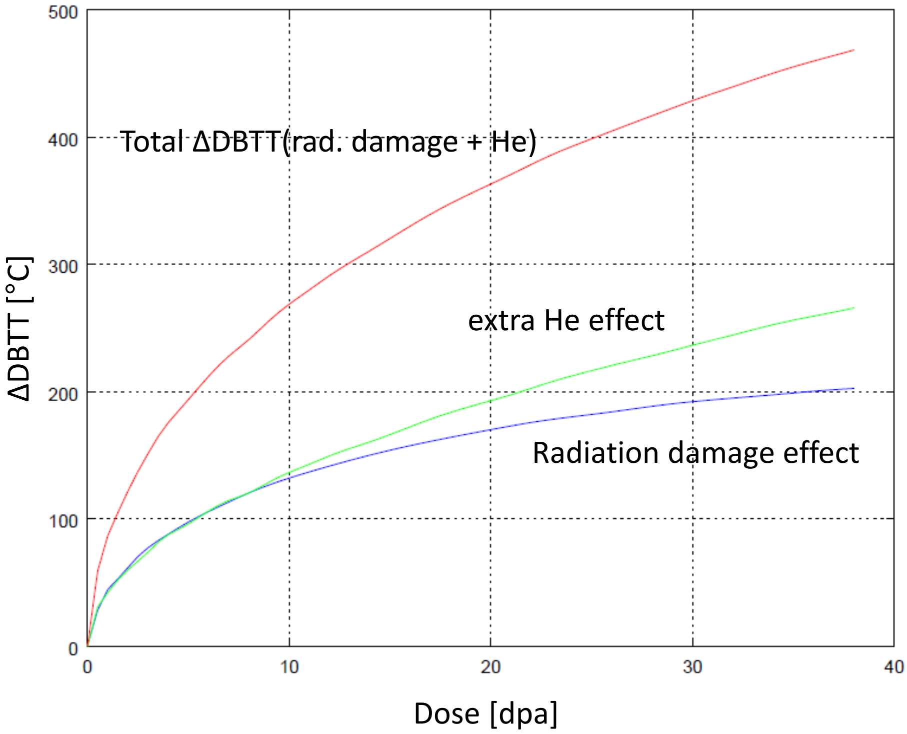
  EUROFER presents **a very low irradiation-creep deformation (less than 1%) after irradiation for 63 dpa at 325°C** (A. Alamo, *Post-Irradiation Examinations (PIE) of materials irradiated in BOR60 at 325°C up to 42 dpa* Final Report - TW2-TTMS-001-D02)

Summary and conclusions

- A rough **assessment of the factors limiting the TA lifetime has been carried** out based on available literature and experimental data
- Two issues seem to be the most critical: **irradiation embrittlement** of F/M steel and **loss of gasket performance**
- In the concerned temperature range, **strong DBTT shift is expected even at low doses** due to both displacement damage and He production effects
- As a possible countermeasure, an **increase of the TA operating temperature** (up to ~350°-360 °C) or a **thermal annealing** could be considered to partially overcome or recover the irradiation embrittlement
- **Gasket integrity** has been **proved only until 5500 h**
- However…gasket exposure test @ 7000 h may have been jeopardized by some unexpected event (air entrance, oxidations,…) → **a more extensive test campaign is needed for the full qualification of the gasket** (possibly taking into account also irradiation)

Thank you

Irradiation embrittlement /3



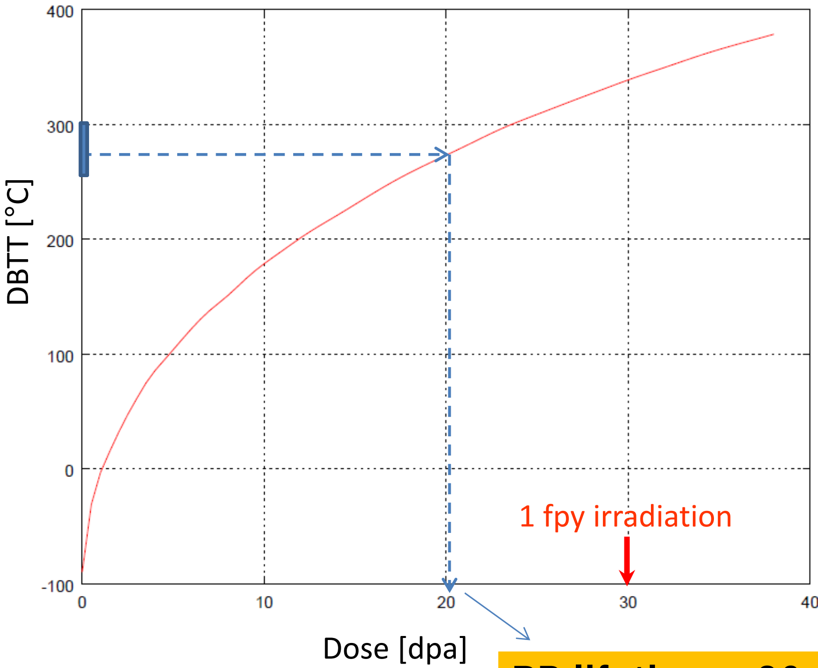
Based on **13 appm He/dpa** (evaluated from nuclear analysis of TA under DONES conditions)

Irradiation embrittlement /4

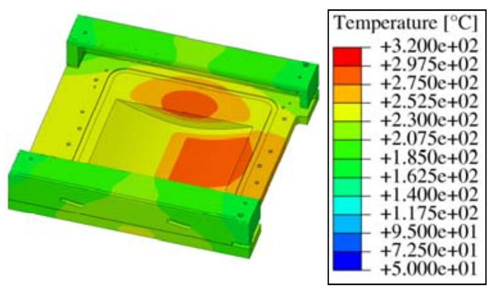
Lifetime estimation due to dpa+He embrittlement

DBTT of unirradiated EUROFER

DBTT = -90 °C + ΔDBTT total



BP thermal field under DONES conditions (5 MW beam)



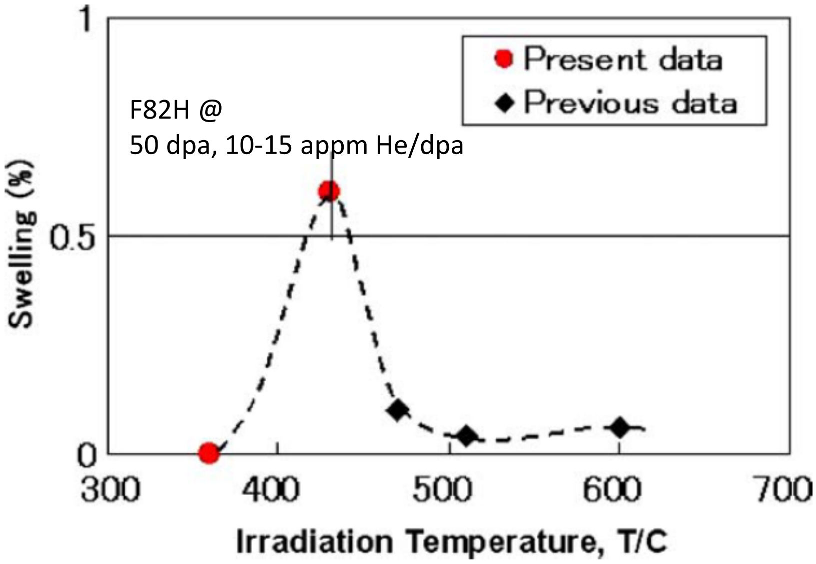
BP operating temperature: ~250-300 °C

BP lifetime ~20 dpa → 20/30*12 ~ 8 months

Rather conservative due to probable overestimation of He-induced effect in B-doped steel

Swelling

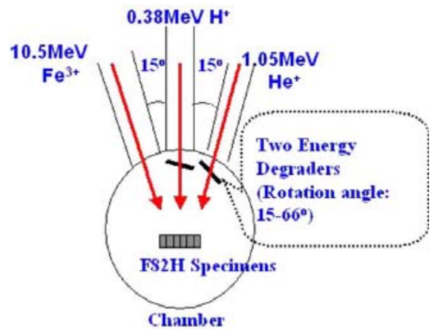
E. Wakai et al., *Effect of gas atoms and displacement damage on mechanical properties and microstructures of F82H*, Journal of Nuclear Materials 356 (2006) 95–104



- Swelling negligible below 360 °C
- Max. volumetric swelling @ 430 °C (~0.6%)

Since BP operating T is < 360 °C swelling is not expected to be an issue

Literature data not available for EUROFER (only for F82H)



Dual-beam ion irradiation was performed:

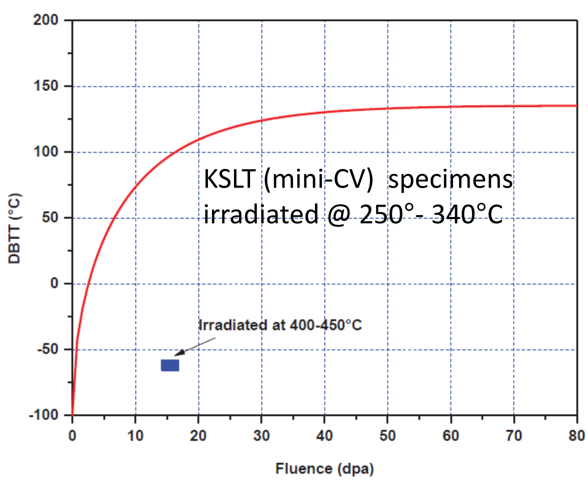
- Fe3+ ions @ 10.5 MeV
- He+ ions @ 1.05 MeV
- 50 dpa
- 10-15 appm He/dpa (controlled by energy degraders)

Irradiation embrittlement /1

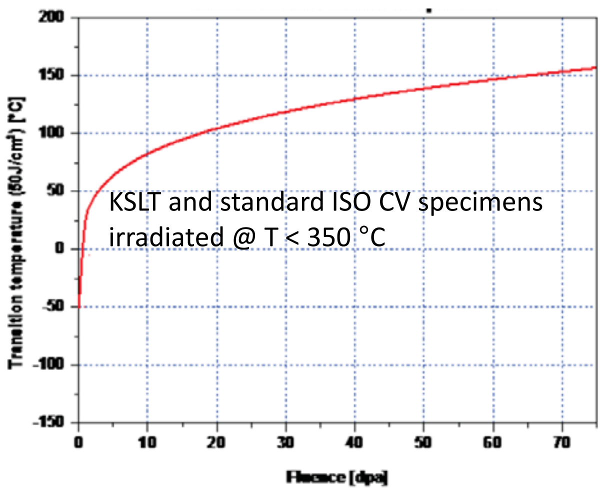
Irradiation-induced DBTT shift of EUROFER 97

EUROfusion WPMAT, *Material Property Handbook*

CHARPY tests - criterion: 50% of USE



CHARPY tests - criterion: 50 J/cm^2



3.4.2-ii) Target challenge for High power compact accelerator based neutron source; as status of the iBNCT: T. Kurihara (iBNCT)

Target challenge for High power compact accelerator based neutron source; as status of the iBNCT: the heat issue and blistering

High Energy Accelerator Research Organization(KEK)
Toshikazu Kurihara
toshikazu.kurihara_AT_kek.jp

On the other hand, low flux and medium or low energy neutron sources are being developed world wide, but still some issues in stable operation has not been fully solved. It would be very beneficial...
*(**Information of** Workshop on Advanced Neutron Source and its Application)*

- Accelerator-based neutron source available intensity ~ 10^7 n/s/cm^2
- Neutron intensity for BNCT IAEA-TecDoc-1223

  1 x 10^9 n/s/cm^2 @(0.5eV-10keV) ~100 times
- Factor to satisfy demanded intensity

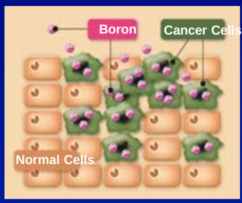
  problem heat issue and blistering
- Solution latent heat, nucleate boiling cooling and anti-blistering

Boron Neutron Capture Therapy, BNCT

iBNCT Project

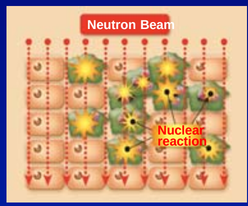
Mechanism of the treatment

Administer boron -containing drug:



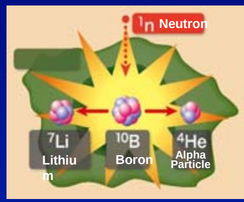
A boron-containing drug that selectively accumulates in cancer

Neutron irradiation:



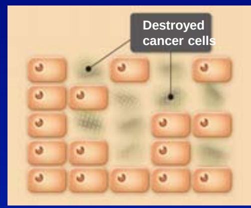
The affected site is irradiated with an energy-adjusted neutron beam.

Neutron react with boron:



Emitted alpha particles and lithium particles destroy cancer cells

Cancer cells are destroyed:



These particles only travel a distance of one cell width (about 10μm), allowing for cell-level

Features of BNCT

- **Pinpoint treatment at cell level**
  Alpha particles and lithium particles, with energy three times higher than regular radiation, selectively destroy the DNA helixes of cancer cells.
- **New treatment of refractory cancer**
  Including invasive cancer, multiple cancer, recurrent cancer, radiation-resistant cancer, cancer patents not indicated for surgery or radiation therapy, etc.
- **Causes minimal stress and provides high quality of life to patients**
  Treatment is completed in only one session of 30 minute irradiation without incision.
  Indication for medication can be determined in advance.

Development status of accelerator-based BNCT in the world

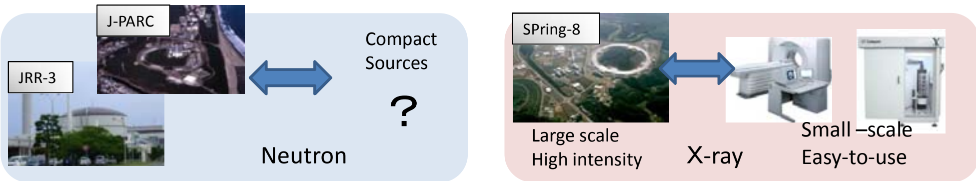
iBNCT Project

	Location	Machine (Status)	Target & reaction	Beam Energy (MeV)	Beam current (mA)
	Neutron Therapeutics Inc. (USA)	Electrostatic Proton Accelerator	Solid ^{7}Li(p, n)	2.6	30
	Budker Institute (Russia)	Vacuum insulated Tandem (Ready)	Solid ^{7}Li(p, n)	2	2
	iPPE-Obninsk (Russia)	Cascade generator KG- 2.5 (Ready)	Solid ^{7}Li(p, n)	2.3	3
	Birmingham Univ. (UK)	Dynamitron (Ready)	Solid ^{7}Li(p, n)	2.8	1
	Soreq (Istael)	RFQ-DTL (Ready)	Liquid ^{7}Li(p, n)	4	1
	Legnaro INFN (Italy)	RFQ	Be(p, n)	4-5	30
	CNEA Buenos Aires (Argentina)	Single ended Tandem Electrostatic Quadrupole (TESQ)	Be(d, n)	1.4	30
			Solid ^{7}Li(p, n)	2.5	30
Japan	**KURRI**	**Cyclotron (Clinical Trial) (SHI)**	**Be(p, n)**	**30**	**1**
Japan	**University of Tsukuba**	**RFQ-DTL (MHI)**	**Be(p, n)**	**8**	**10**
Japan	NCCenter, CICS	RFQ (CICS)	Solid ^{7}Li(p, n)	2.5	20
Japan	Fukushima South Tohoku Hospital	**Cyclotron (Clinical Trial) (SHI)**	Be(p, n)	30	1
Japan	Osaka Medical College	Cyclotron (SHI)	Liquid ^{7}Li(p, n)	~2.5	-
Japan	Nagoya University	Dynamitron (IBA)	Solid ^{7}Li(p, n)		
Japan	Planning and designing : Osaka University (Osaka), Edogawa Hospital (Tokyo), Kyoto Prefecture University of Medicine (Kyoto), OIST (Okinawa) ,				

Accelerator-based neutron source available intensity ~ 10^7 n/s/cm^2 for BNCT

Need for compact neutron sources

- There are large-scale neutron sources (reactor-based, spallation neutron sources) with very high intensity



Compact neutron sources will play important role to expand neutron user community and industrial applications.

7MeV proton Linac
Avr. Current: 100uA
Peak Current: 10mA
Pulse width: 20-200us
Rep. Freq. : 20-200Hz
Neutron yield: 10^{12}n/s
Thermal neutron flux: 10^4n/cm^2/s

700W

RIKEN Accelerator-driven compact Neutron Source (RANS)

Yutaka YAMAGATA et al. 2015

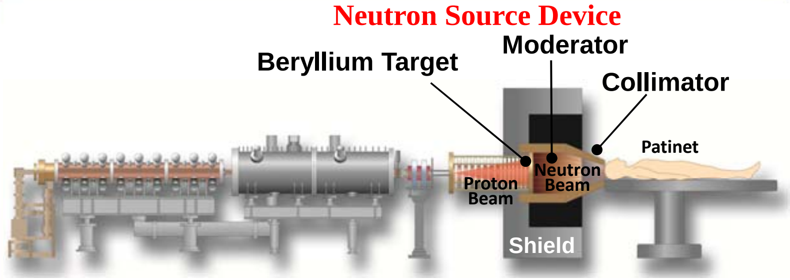
キーテクノロジー①：BNCT用小型大電流陽子線加速器

J-PARC Linac

R

40~80kW (4.5MW/m^2)

IAEA Tec Doc
Intensity 1x10^9 n/s/cm^2



Accelerator Type	RFQ＋DTL Type Linac
Proton Energy	8MeV
Peak Current	50mA
Average Current	> 5mA （Max. 10mA）
Beam Width	1msec
Beam Duty	20%
Power to Target	> 40kW （Max. 80kW）
Dimension	Length: <7m, Footprint: <50m^2

Target challenge for High power compact accelerator-based neutron source (HPCANS) - the heat issue and blistering -

* Neutron intensity for BNCT, 100 times stronger than available accelerator-based neutron source
* Technical issue to overcome

  Heat issue and blistering

* Solution latent heat, nucleate boiling cooling and anti-blistering

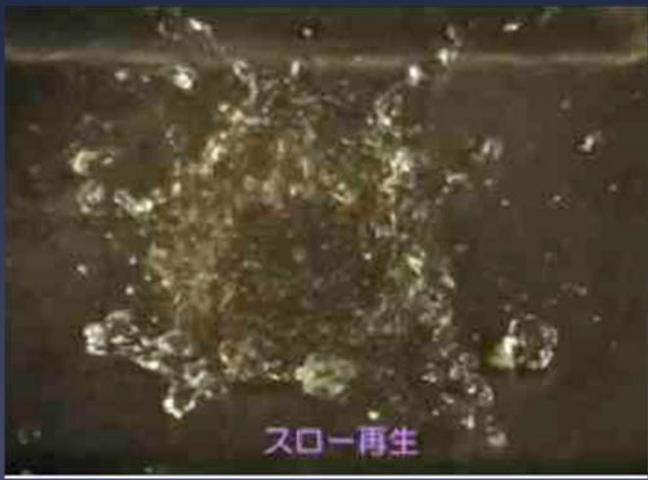
heat issue

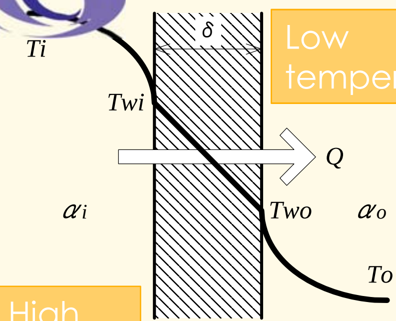
* How to deal with 80kW (4.5MW/m^2) heat?
* Solution latent heat, nucleate boiling cooling and anti-blistering

Special thanks to http://apej.org/archives/ちょっとした工夫(井上健)/kuhuuinoue.html

Heat Transfer Leidenfrost dance

Pan and water





Low temperature

Heat transfer

Nukiyama curve
In 1930s
S. Nukiyama, "Maximum and Minimum Values of Heat Transmitted from Metal to Boiling Water Under Atmospheric Pressure," Journal of the Japanese Society of Mechanical Engineers, 37, pg 367 (1934).

High temperature

Bubbles.
Blistering phenomenon comes out,
it also affect thermal conductivity

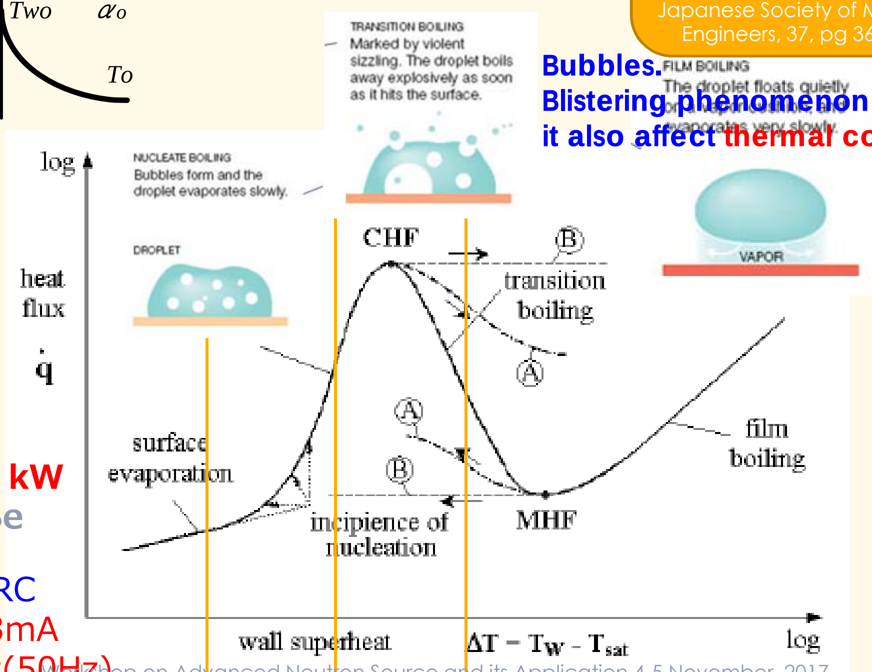


Fig. 1: The Nukiyama curve.

- **8MeV** proton
- **50mA** peak; 10mA ave. **80 kW**
- **0.5mm** thin Be

	i-BNCT	J-PARC
I ave.	10mA	0.33mA
Rep.	200Hz	25Hz(50Hz)

heat issue

MODELING THE NUKIYAMA CURVE FOR WATER-COOLED FUSION DIVERTOR CHANNELS

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II. HEAT TRANSFER CORRELATIONS

A. Bare Channel Mockup

1. Forced Convection. For the forced convection regime, Sieder-Tate [2] was the selected correlation. This selection was based upon: (1) a thorough review of the forced convection literature for fusion-relevant conditions [3],[4],[5] and (2) the correlation's excellent agreement with previous heat transfer experiments at Sandia National Laboratories [6]

The correlation demonstrates the correct trends for the heat transfer coefficient response and generally has very good agreement with experimental data. It is written as:

$$h_{fc} = \left(\frac{k}{D_h}\right)\cdot\left[0.027\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{1/3}\left(\frac{\mu_b}{\mu_w}\right)^{0.14}\right] \quad (1)$$

$$\mathrm{Re} = D_h\cdot\left(\frac{v_b\rho_b}{\mu_b}\right) \qquad \mathrm{Pr} = \frac{C_p\mu_b}{k} \quad (2)$$

3. Partially Developed Nucleate Boiling. The Bergles-Rohsenow [7] partial nucleate boiling correlation was selected based on three factors: (1) the correlation's good agreement with data from non-uniform heating experiments at fusion-relevant water conditions [4], (2) the logic of the correlation's graphical approach, and (3) the continuity of the correlation with Bergles-Rohsenow's onset to nucleate boiling correlation. The correlation is written as:

$$\Phi_{pb} = \Phi_{fc}\sqrt{1+\left[\frac{\Phi_{fdb}}{\Phi_{fc}}\left(1-\frac{\Phi_{bi}}{\Phi_{fdb}}\right)\right]^2} \quad (4)$$

Φ_{bi} = incipient boiling flux (W/m²)
Φ_{fc} = forced convection flux (W/m²)
Φ_{fdb} = fully developed nucleate boiling flux (W/m²)
Φ_{pb} = partially developed nucleate boiling flux (W/m²)

4. Fully Developed Nucleate Boiling. The Araki [9] correlation was selected based on three factors: (1) the correlation's good agreement with data from non-uniform heating experiments at fusion-relevant water conditions [6], ...ental data envelopes the ...he mockup was highly ...eticulously performed.

(5)

...te boiling flux, (MW/m²)
... (°C)

...e Tong-75 [10] critical ... selected because it (1) ...mal and hydrodynamic ... progression of CHF, (2) ... recommended for fusion ...mpares well with data ...as:

(6)

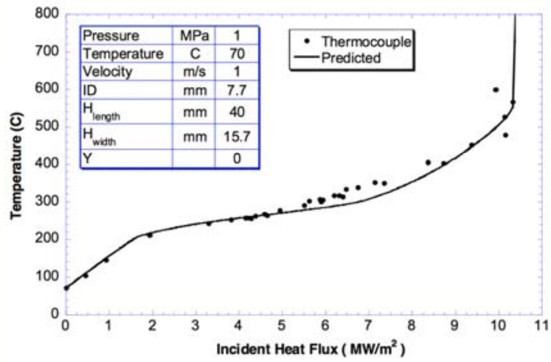


Figure 2: Experimental and predicted thermocouple temperatures for bare channel mockup.

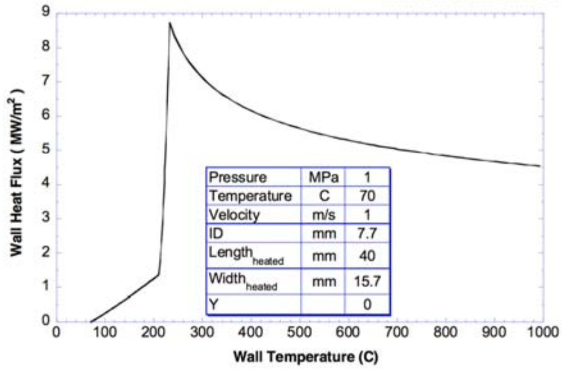
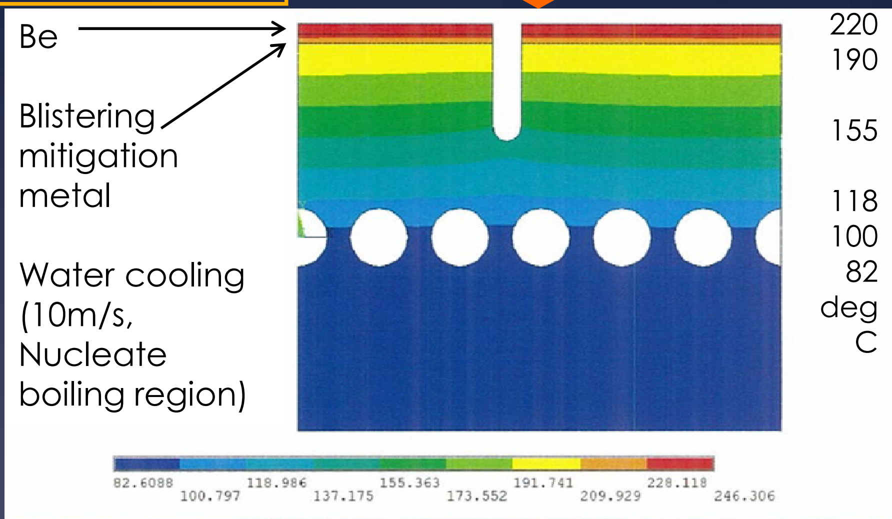


Figure 3: Predicted Nukiyama curve for bare channel mockup.

Steady state temperature of three tier design

8MeV Proton beam
80kW, 4.5MW/m²

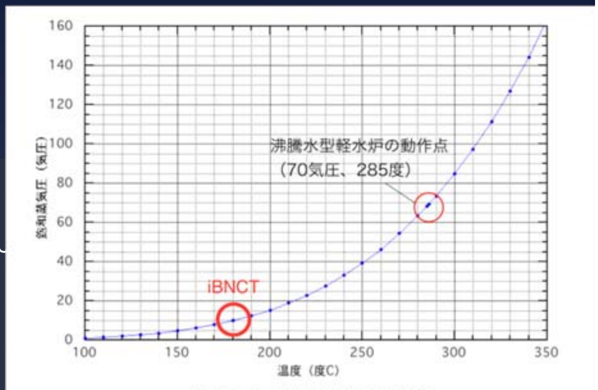


Simulated with CST studio

Design heat density :4.5MW/m²
Water cooling of nuclear boiling region is crucial condition
Surface temperature of Beryllium layer > 220℃

heat issue

- [Cooling system]
- Darcy–Weisbach Equation
- http://www.m-setsubi.jp/examination/kankouji/fou
- In case of BNCT
- Pressure loss form
-   Δp = λ (L * ρ v^2) / (d * 2)
- Reynolds number
-   Re = Vd/ν
- Turbulent Regime For Reynolds number greater than 4000, the flow is turbulent; the resistance to flow follows the Darcy–Weisbach equation
-   When the pipe surface is smooth (the "smooth pipe" regime), the



温度と水の飽和蒸気圧の関係

TARGET冷却検討2.3_110909.xlsx

項目	単位	EX1	EX2	EX2 1.6MW/m2	EX2-2 流速	EX3	EX3 100L	EX3 150L	EX3 L=0.2m	EX4	EX4 150L	EX5
ドリル孔寸法呼び		Dia.1mm	Dia.2mm	Dia.2mm	Dia.2mm	Dia.3mm	Dia.3mm	Dia.3mm	Dia.3mm	Dia.4mm	Dia.4mm	Dia.5mm
ドリル孔内径	m	0.001	0.002	0.002	0.002	0.003	0.003	0.003	0.003	0.004	0.004	0.005
ドリル孔長さ	m	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.2	0.15	0.15	0.15
流体密度	kg/m3	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
流体動粘度	m2/s	8.01E-07	8.01E-07	8.01E-07	8.01E-07	8.01E-07	8.01E-07	8.01E-07	8.01E-07	8.01E-07	8.01E-07	8.01E-07
ドリル孔内流速	m/s	10	10	10	12	10	10	10	10	10	10	10
Re数（計算）		12484	24969	24969	29963	37453	37453	37453	37453	49938	49938	62422
ドリル孔内面摩擦係数（計算）		0.030	0.025	0.025	0.024	0.023	0.023	0.023	0.023	0.021	0.021	0.020
摩擦損失水頭（計算）	m	22.93	11.45	11.45	16.49	7.62	7.62	7.62	10.17	5.71	5.71	4.56
11:Weston, 12:Hazen-Williams		28.79	12.79	12.79	17.93	7.96	7.96	7.96	10.62	5.69	5.69	4.38
ドリル孔内圧力損失（計算）	kPa	224.5	94.4	94.4	129.9	56.9	56.9	56.9	75.8	39.7	39.7	30.0
ドリル孔１本当りの流量(計算)	l/min	0.471	1.884	1.884	2.261	4.239	4.239	4.239	4.239	7.536	7.536	11.775
TARGET通過流量	l/min	50	50	100	100	50	100	150	150	50	150	50
ドリル孔数（計算）	本	106.16	26.54	53.08	44.23	11.80	23.59	35.39	35.39	6.63	19.90	4.25
ドリル孔合計伝熱面積(計算)	m2	0.050	0.025	0.050	0.042	0.017	0.033	0.050	0.067	0.013	0.038	0.010
単位面積当りパワー(80kW時)(計算)	MW/m2	1.60	3.20	1.60	1.92	4.80	2.40	1.60	1.20	6.40	2.13	8.00

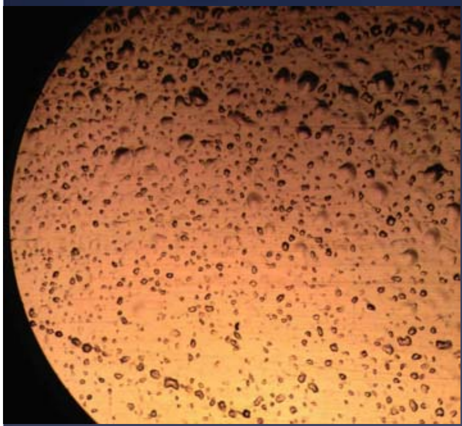
Target challenge for High power compact accelerator-based neutron source (HPCANS) - the heat issue and blistering -

- Factor to satisfy demanded intensity

  problem heat issue and blistering

- Solution latent heat, nucleate boiling cooling and anti-blistering

Neutron target with 8MeV p+ is impossible ?

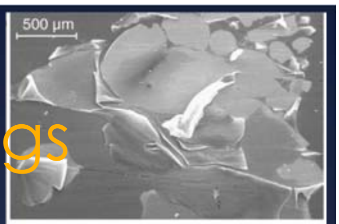


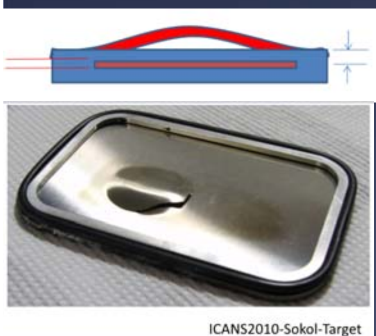
Oct.2012,Prof.Ono of Kyoto Univ. who started clinical practice phase I with 30MeV cyclotron commented BNCT target with low energy proton beam accumulates protons in target metal and the blistering cannot be avoided.

Result after the in-situ observation of Cu sample done at Cockcroft-Walton, KEK. Blisterings are observed by optical microscope. (Mirror grade Cu)

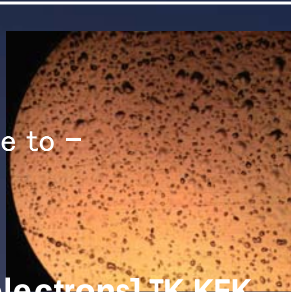
新医療 2012年12月号(72)

Radiation damage, blisterings





p+
 |
p+ + e− [H atom] thermal equilibrium, diffuse to −
 | vacancies, lattice defects
H molecule [expansion of volume]



[Protons stop in Be target and catch electrons] TK,KEK

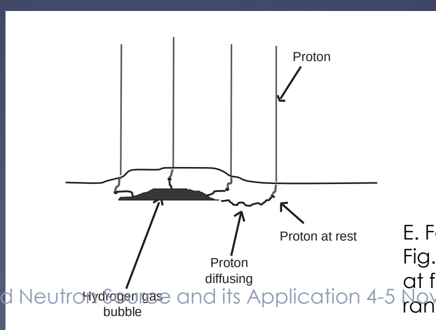


Fig. 4. Principle of blistering. Heavy hydrogen implantation in the target creates bubbles and cracks.

E. Forton et al. ARI 67 (2009) S262. Fig.4. This phenomenon appears at fluences in the 10^{18} 1/cm² range for most materials. => Iron

Blistering

- Solution anti-blistering
- How does the blistering occur? =>The in situ blistering observation system is developed and introduced into accelerator irradiation beam line.
- What kind of materials have endurance toward blistering? =>Search for anti-blistering material

Experimental results of the blistering threshold (BINP)

Experimental Studies of Blistering of Targets Irradiated by Intense 200 keV Proton Beam[1]

S.V. Polosatkin*,**, V.T. Astrelin*,**, A.V. Burdakov*,***, P.V. Bykov*, I.A. Ivanov*,**, Y. Jongen****, S.G. Konstantinov*, A.M. Kudryavtsev*, K.N. Kuklin*, K.I. Mekler*, V.V. Postupaev*,**, A.F. Rovenskikh*, S.L. Sinitskiy*,**, and E.R. Zubairov*

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Phone: +7(3833) 29-47-73, Fax +7(3833) 30-71-63, E-mail: s.v.polosatkin@inp.nsk.su
**Novosibirsk State University, Novosibirsk, Russia
***Novosibirsk State Technical University, Novosibirsk, Russia
****Ion Beam Applications SA, Louvain-la-Neuve, Belgium

9th International Conference on MODIFICATION OF MATERIALS WITH PARTICLE BEAMS AND PLASMA FLOWS

Blistering of the selected materials irradiated by intense 200 keV proton beam

V.T. Astrelin[a,b], A.V. Burdakov[a,c], P.V. Bykov[a], I.A. Ivanov[a,b], A.A. Ivanov[a,b], Y. Jongen[d], S.G. Konstantinov[a], A.M. Kudryavtsev[1], K.N. Kuklin[a], K.I. Mekler[a], S.V. Polosatkin[a,b,*], V.V. Postupaev[a,b], A.F. Rovenskikh[a], S.L. Sinitskiy[a,b], E.R. Zubairov[a]

[a] Budker Institute of Nuclear Physics, Lavrent'eva 11, Novosibirsk 630090, Russia
[b] Novosibirsk State University, Novosibirsk, Russia
[c] Novosibirsk State Technical University, Novosibirsk, Russia

Element	Yield point, 10^7 Pa	Diffusion activation energy E_D, eV	Dissociation energy E_S, eV	Blistering threshold, 10^{18} cm^{-2}
Cu	20–50	0.4	0.37	0.4–0.1
W	50–90	0.39	1.03	2–4
Fe	12–15	0.05	0.27	80–150
Pd	20	0.23	–0.11	200–300
V	31	0.045	–0.34	not observed up to 120
Ta	57	0.14	–0.35	not observed up to 230

Compared with Cu,Be, Pd,V,Ta have 1000times longer lifetime

Very short lifetime for Cu

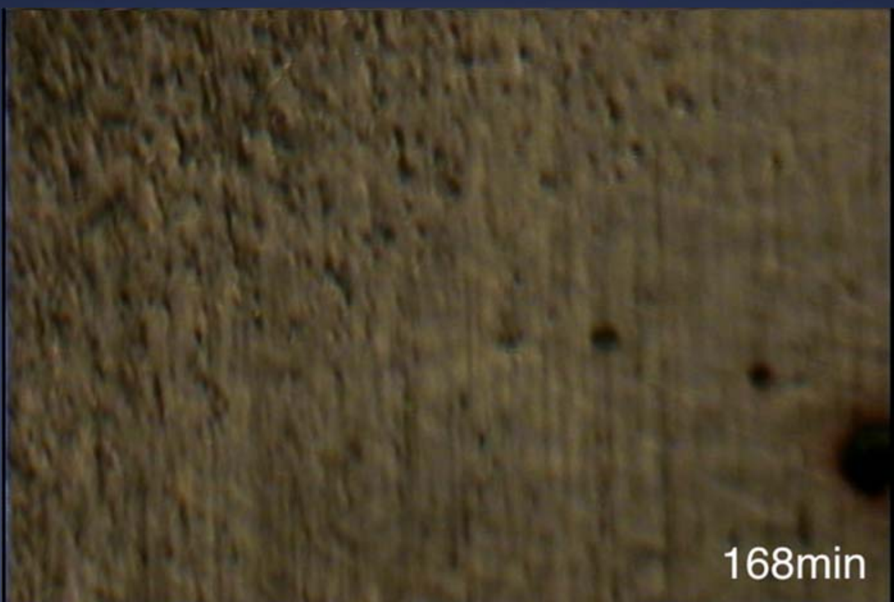
Hydrogen absorbing alloys

Ta good?

Blistering observation system PLDM

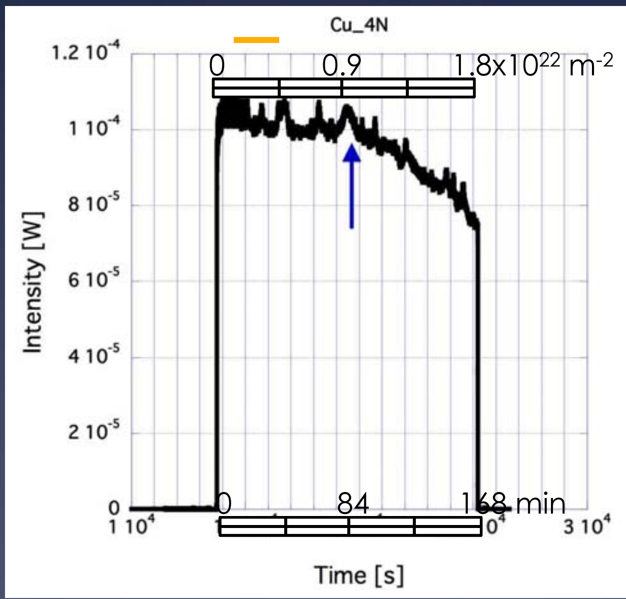
J Radioanal Nucl Chem (2015) 305:935-942

照射中の試料表面の偏光顕微鏡像
PLDM of the Cu surface under irradiations



Pure Cu irradiated by 750keV H- ~10^18/cm^2
FOV 1mm based on 1/3'' Sensor

照射中の銅表面のレーザー光反射強度変化
Difference of laser light reflection from Cu surface

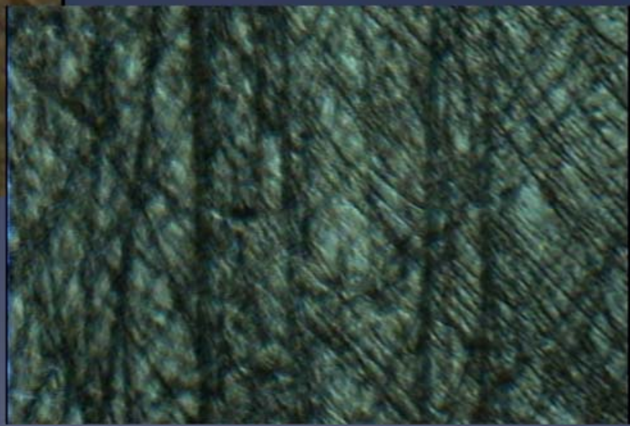


Blistering phenomeon here is not only the puncture mechanism but the evaporation from solid phase.

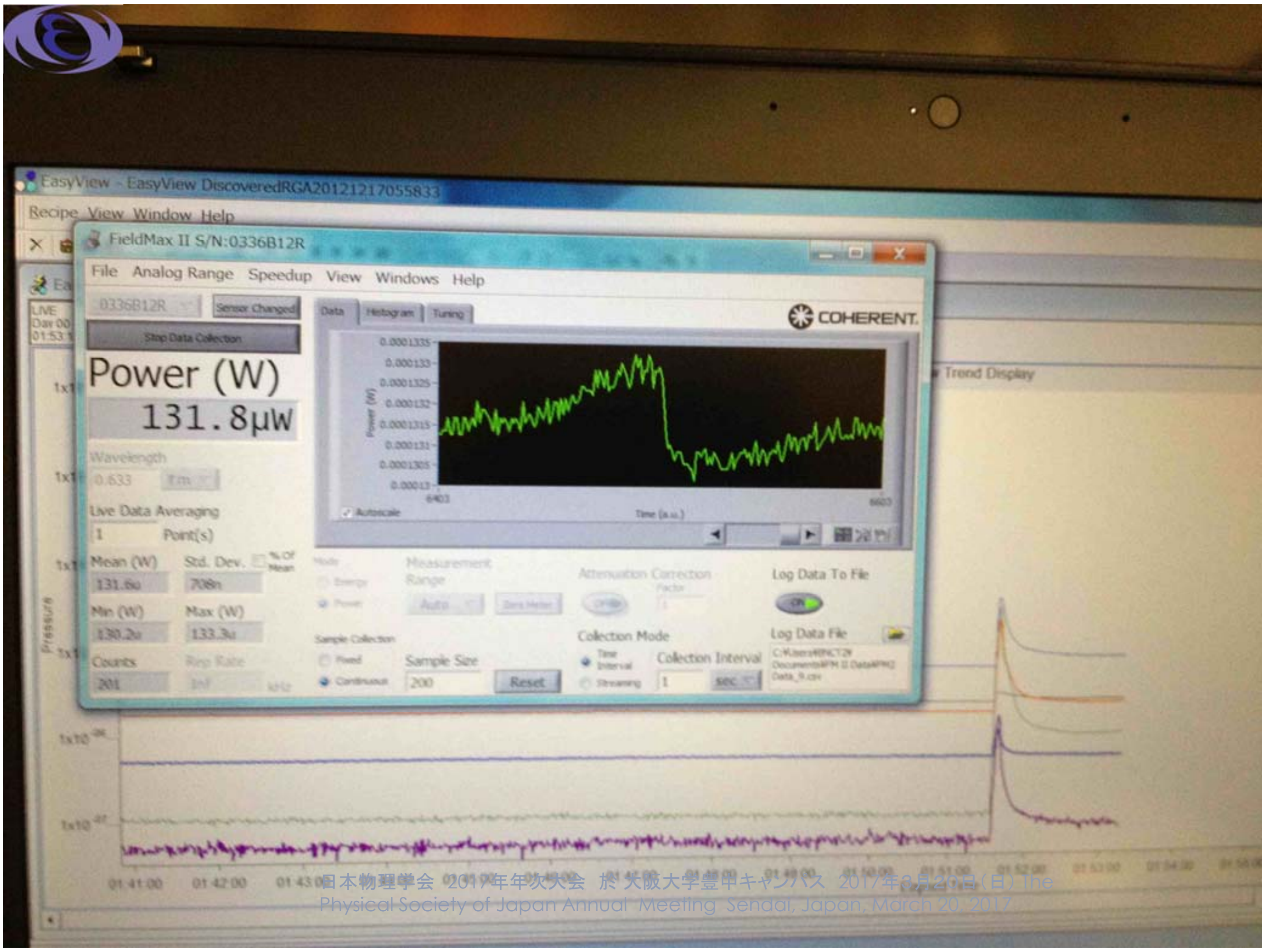
-PLDM- 12.17 22:20 05:30:00-06:10:00

W PLDM, LRM, RGA

Cu 25uA ~168min

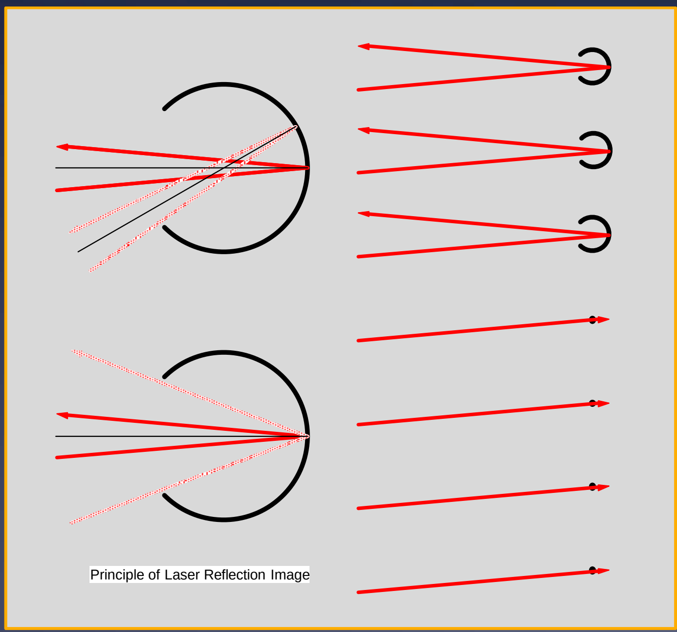


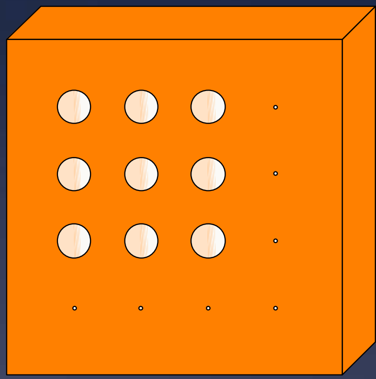
W 25uA ~14hrs

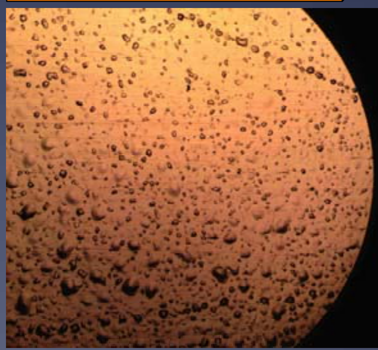


日本物理学会 2017年年次大会 於 大阪大学豊中キャンパス 2017年3月20日（日）The Physical Society of Japan Annual Meeting Sendai, Japan, March 20, 2017

レーザー反射顕微鏡(LRM)法 -原理-

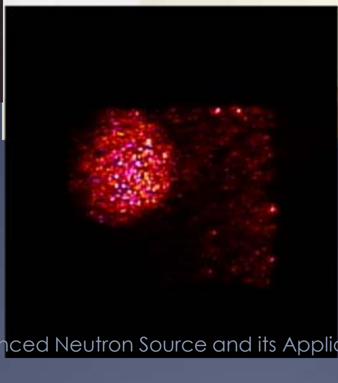






Blistering observation system
Laser Reflection Image (LRI) WD~ few meters

To be published in full later



8-MeV Target

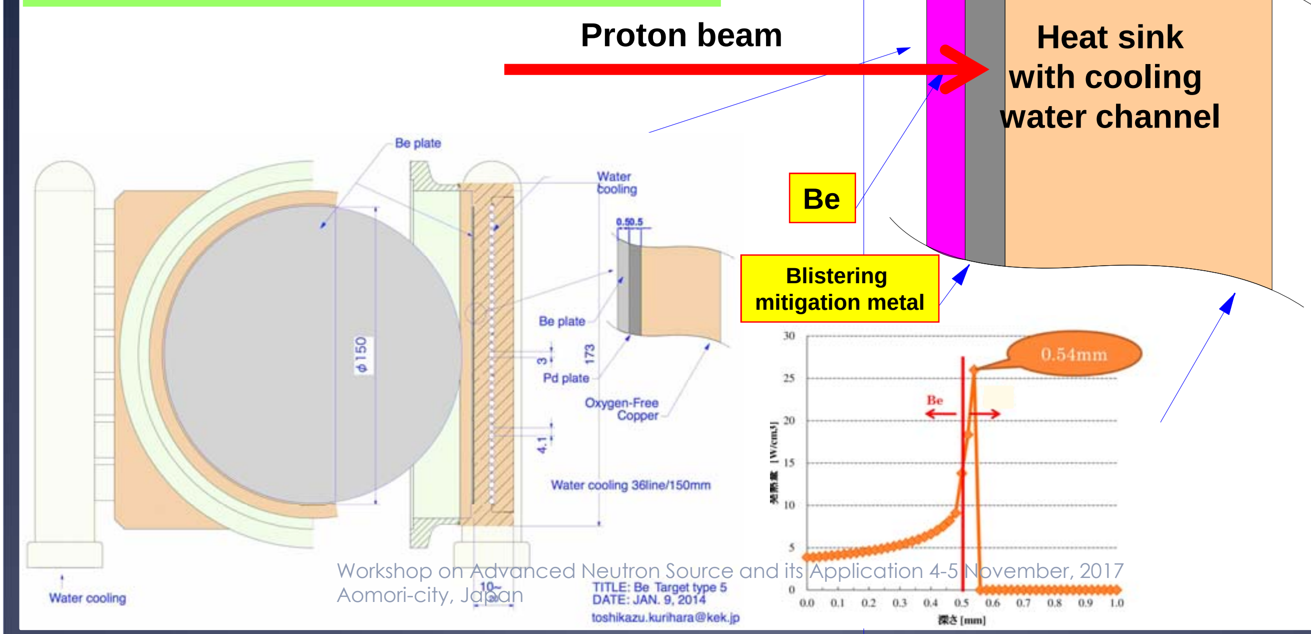
- Separated function target
- top: neutron production
- middle: beam stop and blistering mitigation
- back: heat sink (water cooling)
- Joinig dissimilar metals by diffusion bonding
  - Anti-blistering
  - 4.5MW/m² high power target

Three tier target

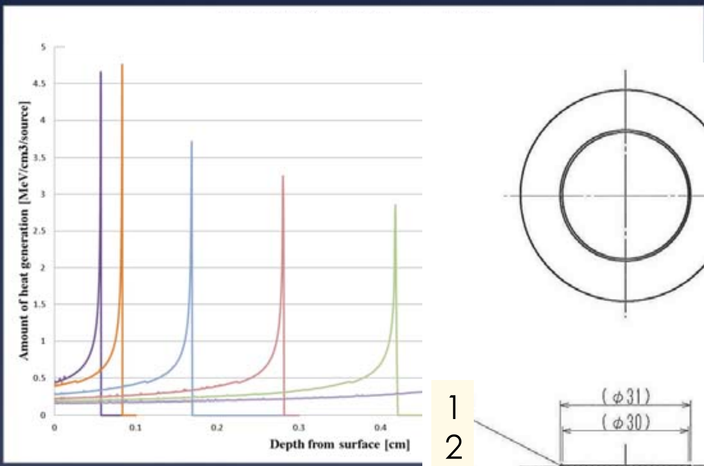
Patent 特開2014-81211

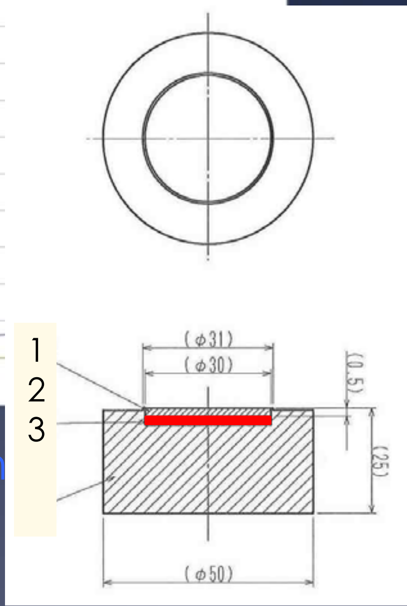
Design of the blistering tolerant neutron target

Ibaraki target (separated function)
Target thickness is 0.5mm
needs backup plate for beam window



Three tier bonding test for First Generation Neutron Target





Test piece

Bragg peak > Thickn

Neutron produced at 1st layer Be

Proton stops at 2nd layer

Candidate for 2nd layer

Ta,Nb,Pd,Ti

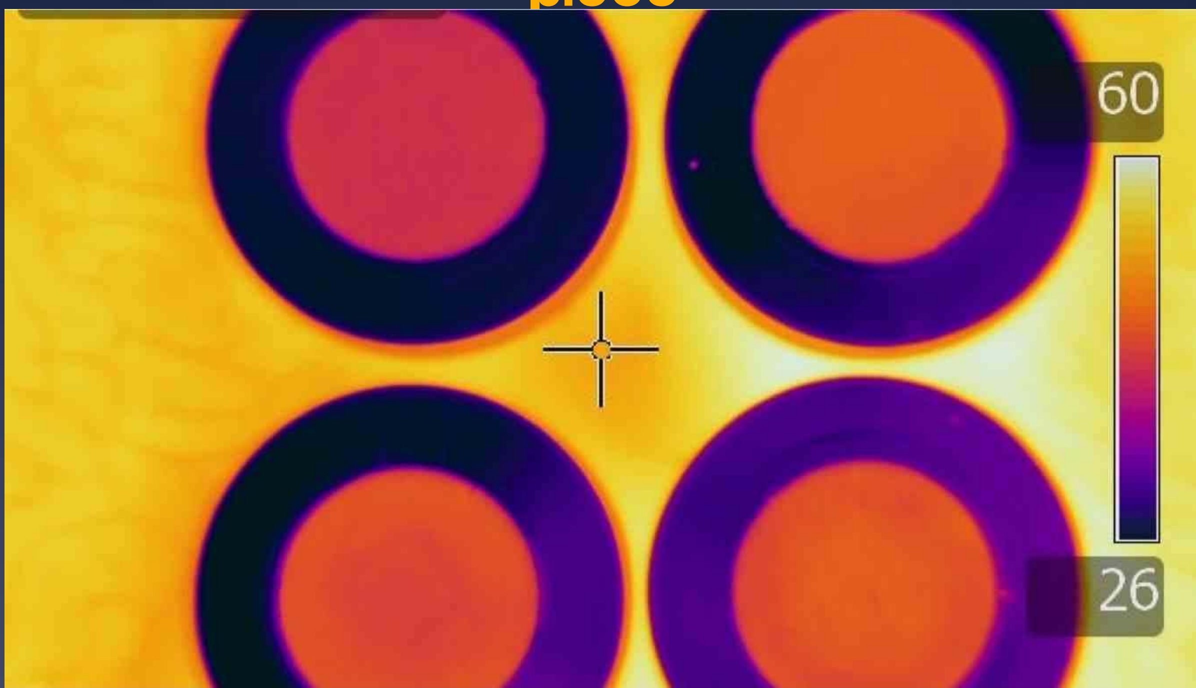
(hydrogen storage alloys)

Cooling for 3rd layer

(Cu with Nucleate boiling region cooling)

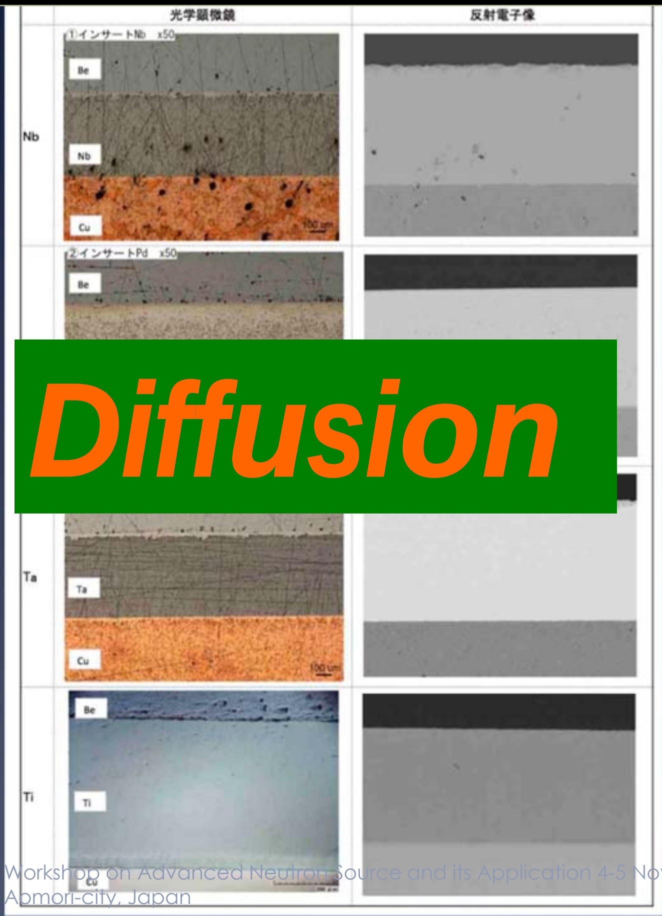
HIP; METHOD FOR JOINING DISSIMILAR METALS by MTC

Thermographic observation of HIP test piece



Thermal diffusivity, Bonding of interface, Tensile testing

Structure observation by optical and electron microscope



Diffusion

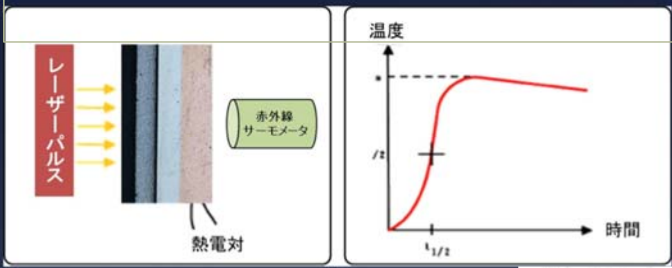
Be metal supply, structure observation by NGK

Structure observation by optical and electron microscope

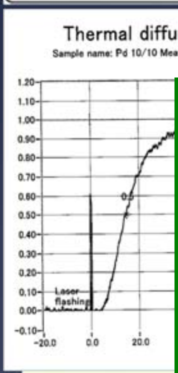
Diffusion

Be metal supply, structure observation by NGK

Thermal diffusivity measurements of three tier blistering tolerant neutron target



Spec. of laser
Pulse width: 0.4ms
Pulse energy: 10Joule/pulse
Wave length: 1.06um
Diameter of laser: 10Φ



熱伝導率測定

測定温度:25℃

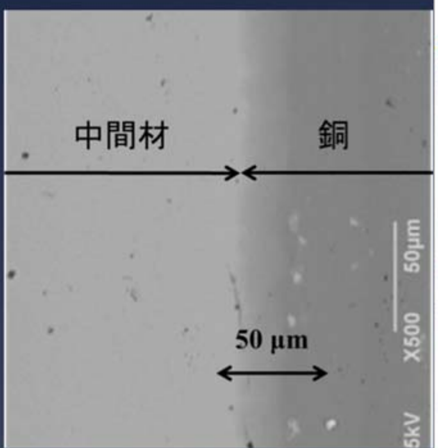
Heat thermal diffusivity

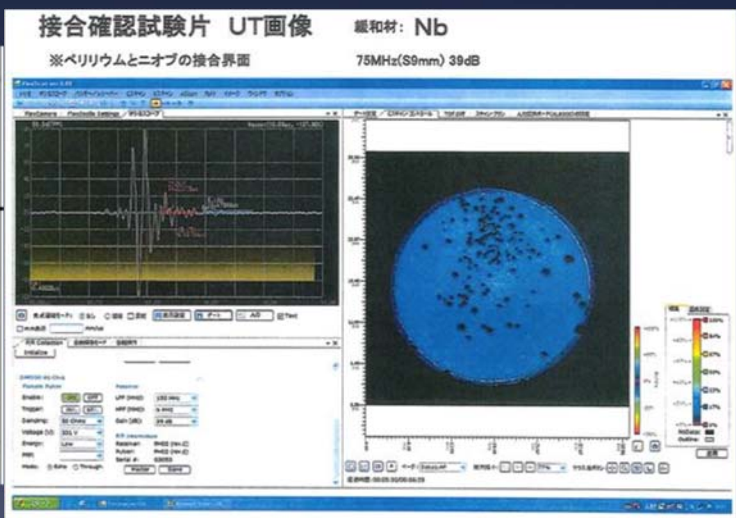
測定温度:25℃

試 料	熱拡散率 cm^2/sec	密 度 g/cm^3	比 熱 J/(g·K)	熱伝導率 W/(m·K)
HIP温度 ref	0.591	8.302	0.397	195
HIP温度 低	0.599	8.277	0.404	200

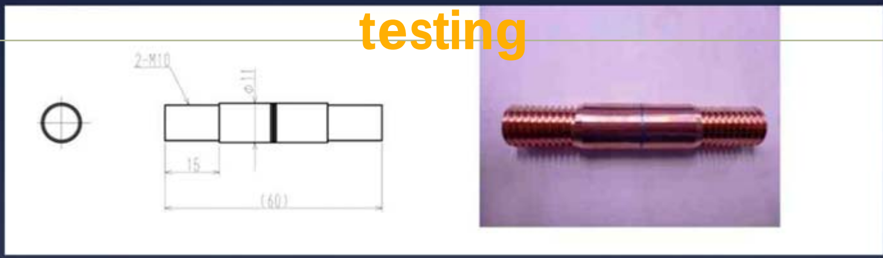
Direct measurement of heat conductivity with laser-flash method
→200 W/(m/K)
→Good enough for the practical use

Observation of interface, bonding layer by electron microscope and ultrasonic testing





Heat treatment temperature and tensile testing



Tensile testing conditions

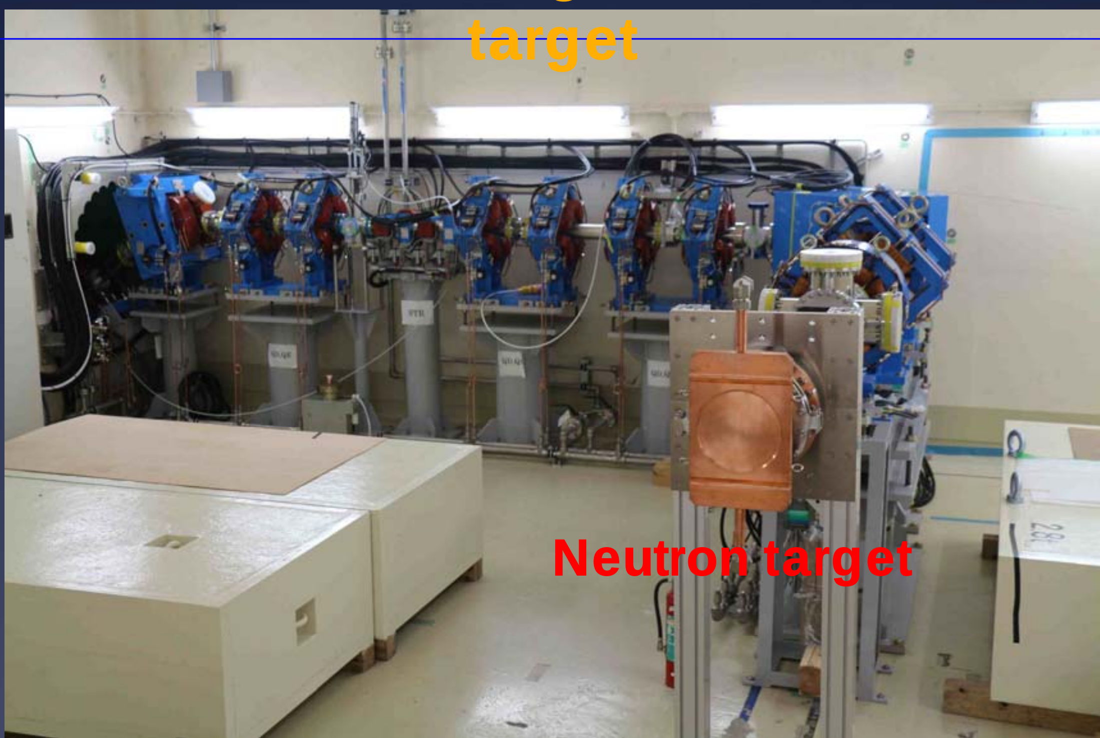
Loading velocity	0.5mm/min

Tensile testing results

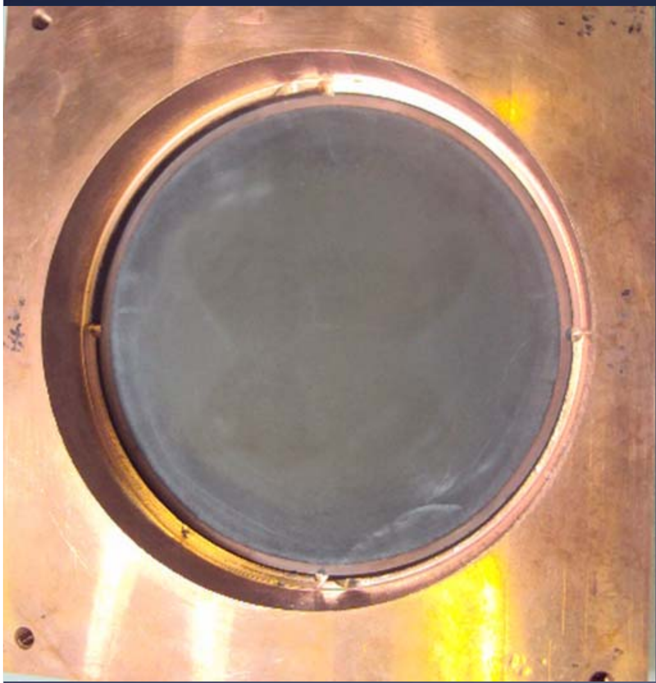
Sample No.	Heat Treatment Temperature(℃)	Maximum Load(N)	Tensile Strength(MPa)
1	low	2362	24.6
2	high	1166	12.1
3	high	2050	21.3
4	low	3285	34.4
5	low	2980	37.4
6	low	2620	34.4

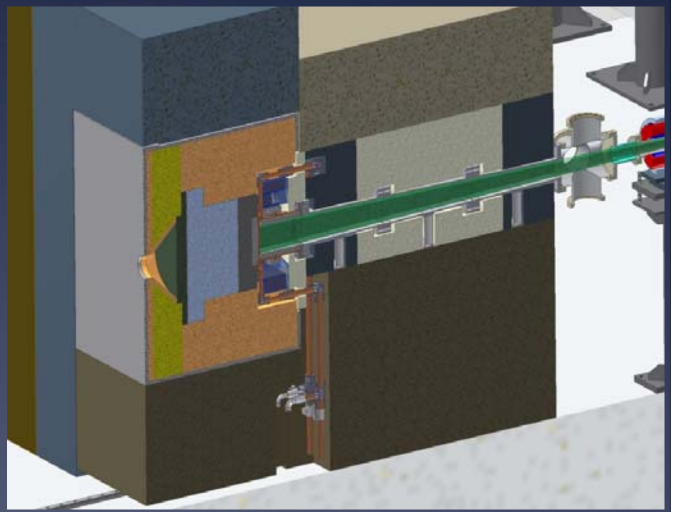
特開2014-81211

Three tier blistering tolerant neutron target



Target manufacturing

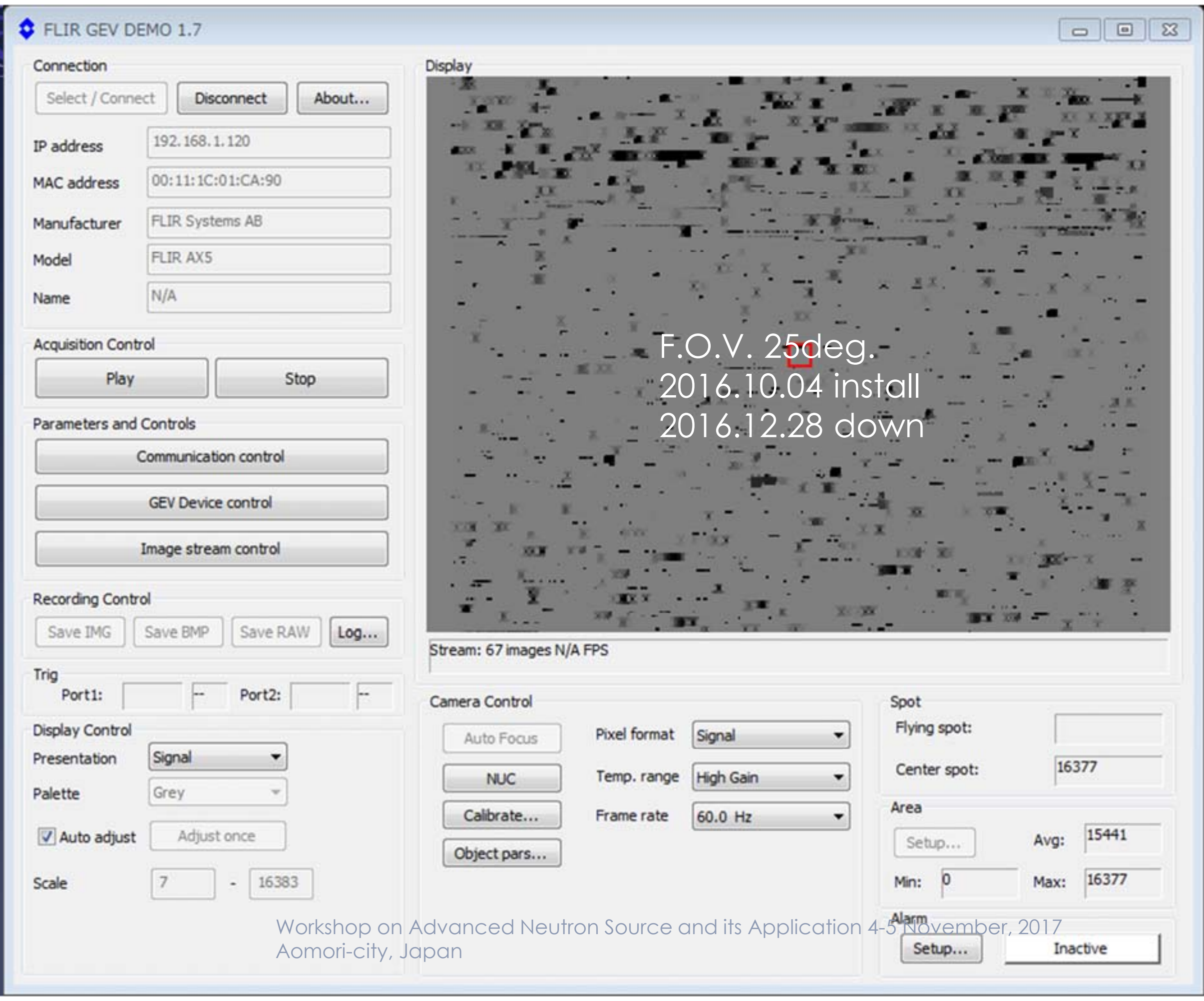


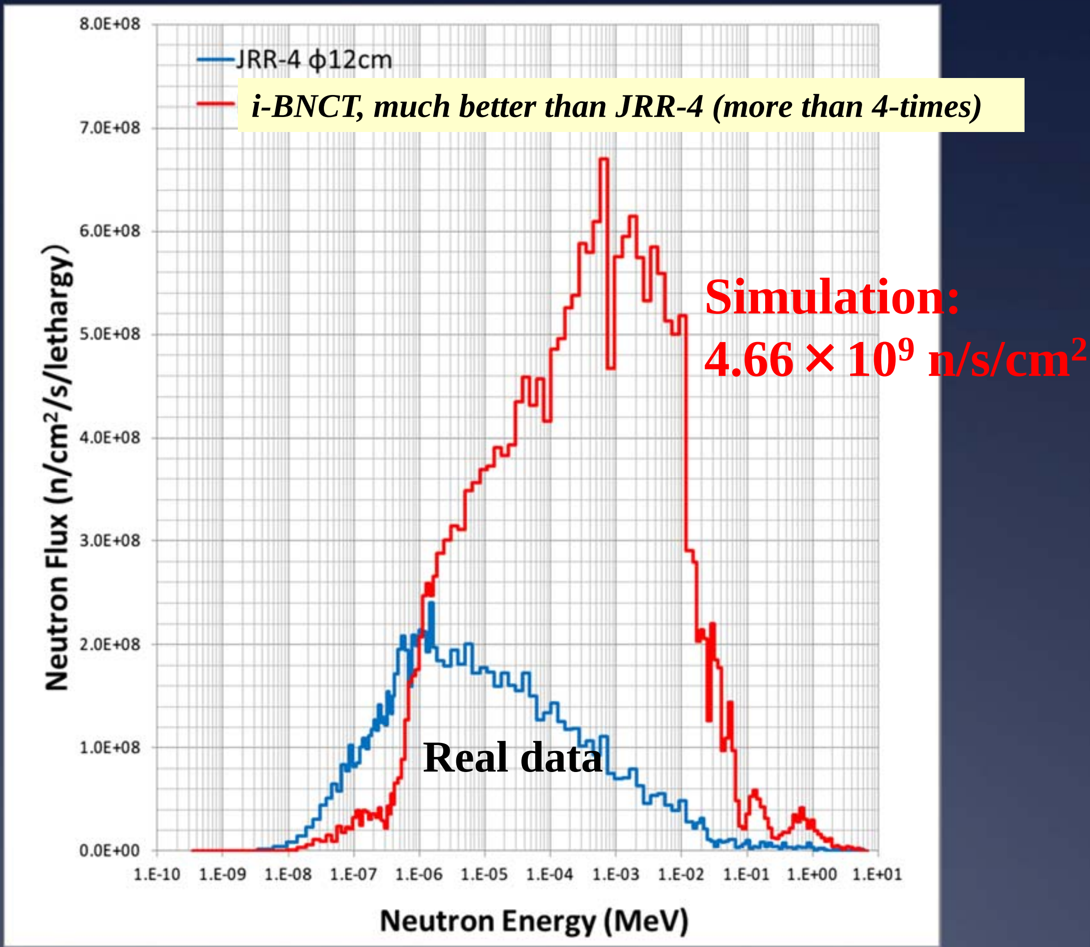


特開2014-81211

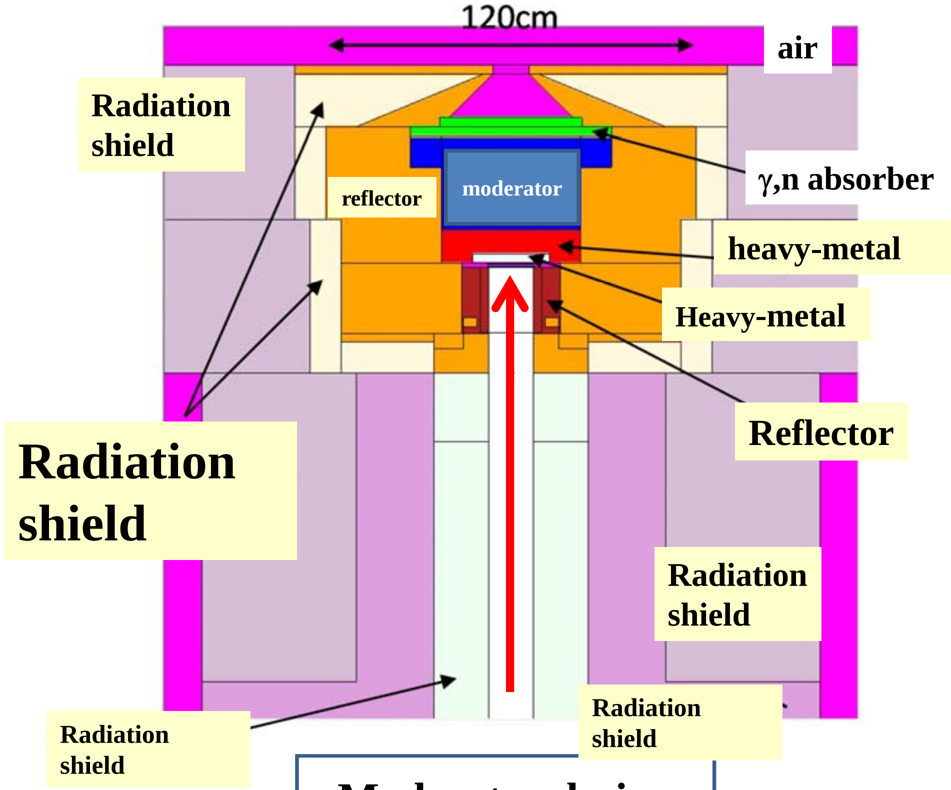
Three tier target

Target and moderator





	Beam energy MeV	Beam power kW	Beam current mA	Epi-thermal Energy Range	Flux n/s/cm^2	Flux Ratio	Flux/Power aribitrary unit	Efficiency Ratio
Ibaraki-1	8	10	80	0.5eV˜10keV	4.3×10^9	3.52	0.053	1.43
Ibaraki-2	8	10	80	0.5eV˜40keV	4.66×10^9	3.82	0.058	1.58
Kyoto	30	1.1	33	0.5eV˜40keV	1.22×10^9	1	0.037	1



Moderator design (Plan view)

Team Organization of Ibaraki BNCT

- **Univ.of Tsukuba:** Medical, Total coordination
- **KEK:** Accelerator, Target, Maintenance Strategy of target and moderator system
- **JAEA:** Radiation Safety, Radiation shield, Neutron measurement, many experiences of JRR-4
- **Hokkaido Univ.:** Design of Moderator and Shield, Simulation & Design of required Neutron field
- **Ibaraki prefecture:** Building for BNCT, Established the Ibaraki Neutron Medical Research Center

Special thanks to

* R. Fukatsu, K. Nojiri, H. Hiramitsu NGK INSULATORS, LTD., Handa 475-0825, Japan
* M. Okuwaki, Y. Nagasawa, M. Tsuchiya Metal Technology Co. Ltd., Sanami 370-1132, Japan
* K. Tsumagari, T. Sugano, Mitsubishi Heavy Industries, LTD., Mihara 729-0393, Japan
* H. Kumada, University of Tsukuba, Tsukuba 305-0005, Japan
* 科学研究費助成事業 課題番号23340080 平成23年—平成25年 基盤研究(B) 8-10MeV陽子ビームを用いた医療産業用小型中性子源標的の開発
* 科学研究費助成事業 課題番号26293136 平成26年—平成28年 基盤研究(B) 次世代低放射化医療用中性子標的の開発

Target challenge for High power compact accelerator-based neutron source (HPCANS)
- the heat issue and blistering -

* Accelerator-based neutron source available

Thank you for your attention.

* Neutron intensity for BNCT IAEA-TecDoc-1223

  1 x 10^9 n/s/cm^2 @(0.5eV-10keV) ~100 times

* Factor to satisfy demanded intensity

  problem heat issue and blistering

* Solution latent heat, nucleate boiling cooling and anti-blistering

3.4.2-iii) Present status of neutron target on J-Parc Presentaer: T. Naoe (JAEA/J-Parc)

Workshop on Advanced Neutron
Source and its Application
4 - 5 Nov. 2017

Present status of neutron target on J-PARC

Takashi Naoe

Hiroyuki Kogawa, Takashi Wakui
Katsuhiro Haga, Eiichi Wakai, Hiroshi Takada

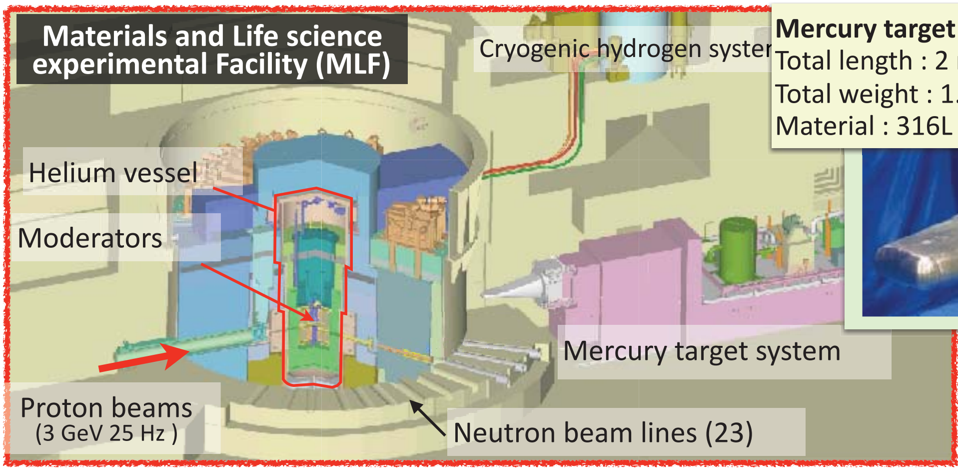
Mercury target group, Neutron Source Section,
Material and Life Science Division,
J-PARC Center, JAEA

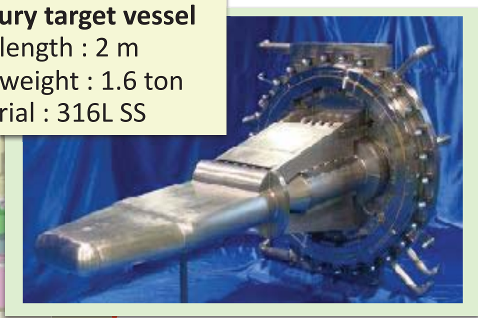
Contents

- **Background**
  - *Outline of J-PARC spallation neutron source*
  - *Mercury target, pressure waves*
- **For achieving 1MW stable operation**
  - **Cavitation damage mitigation technologies**
    - *Gas microbubbles injection into mercury*
    - *Multi-walled beam window, etc*
  - **Improvement of target vessel design**
  - **Fatigue strength up to gigacycle**
- **Summary**

Spallation neutron source in J-PARC

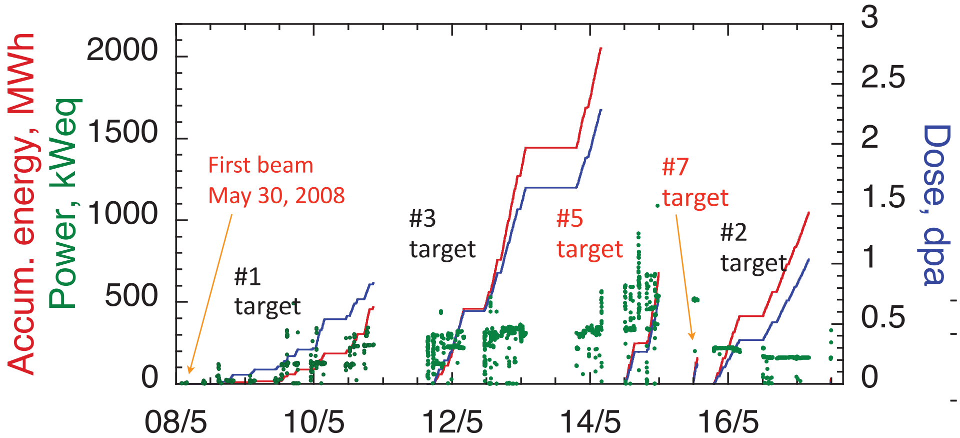
Japan Proton Accelerator Research Complex in JAEA Tokai-site

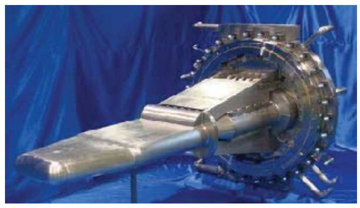




Provides neutron beams for materials and life science and industrial use

Operation histories for J-PARC mercury targets

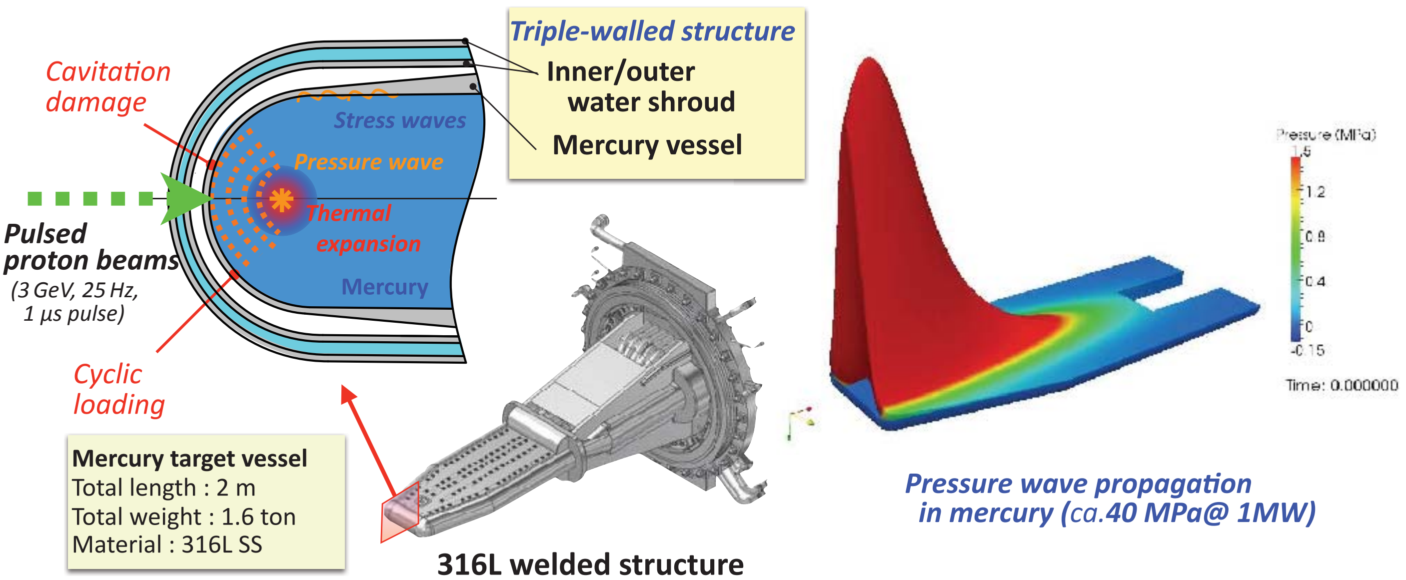




- Target ID is fabrication number
- Operation time calculated from the number of pulses at 25 Hz
- kWqq denotes power/pulse

	From	Due	Operation time, h	Average beam power, kW	Accumulated energy, MWh	Accumulated dose, dpa	Remaks
#1	2008/5	~2011/11	3713	127	471	0.84	Pneumatic bellows failed by earhquale
#3	2011/12	~2014/6	7537	272	2050	2.28	
#5	2014/10	~2015/4	1672	400	670	0.73	Water leak from outer water shroud
#7	2015/10	~2015/11	308	516	159	0.17	Water leak from inner water shroud
#2	2016/2	2017/7	5801	181	1048	1.04	
#8	2017/10~	in service		300			

Proton beam-induced pressure waves in mercury



Irradiation damage	3 Gev proton and neutron irradiation
Cavitation damage	Proton beam-induced pressure waves in mercury causes cavitation
Fatigue damage	Loading cyclic with high strain rate stress in service life (~4.5×10^8) TIG welded multi-walled structure (back bead)

Factors to decide lifetime of target

Radiation damage (incl. water shroud)

- Depending on beam power and operation time (8 dpa@5000MWh)
- Designed lifetime:1 MW 2500 h

  Tentative dose : 5 dpa (10 dpa allowable)

Damage inside mercury vessel

- **Cavitation damage**

  Depending on beam power & operation time
- **Measures**

  1st : Surface modification

  3rd: Gas microbubbles injection

  5th: Bubbling and double walled structure

  Prediction and measurement of damages for lifetime estimation

Fatigue by pressure waves

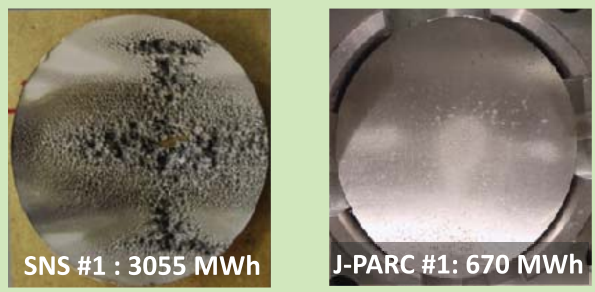
- Very high-cycle fatigue
- Induced by beam injection

  4.5×10^8 cycles for 5000 hours (1Y)

Fatigue by thermal stress

- Low cycle fatigue
- caused by beam trip

  ca.10^4 cycles for 5000 hours



SNS mercury target vessel (ORNL)
D. McClintock, et al., JNM 431(2012)

Cavitation damage is dominant factor to decide lifetime in the present situation

Cavitation damage mitigation technologies

Targets
Fabrication number

1st

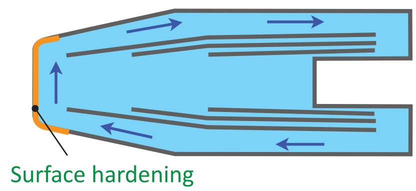
3rd

4th

5th
|
8th

Surface hardening

Reduce cavitation damage
Nitriding & Carburizing, Kolsterising®

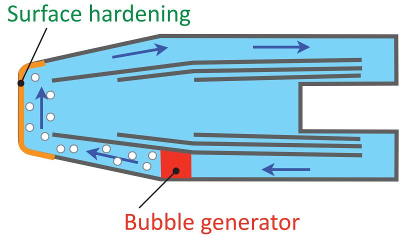


2nd target (Spare) No-bubbling techniques to mitigate pressure waves and cavitation damage

Microbubble injection

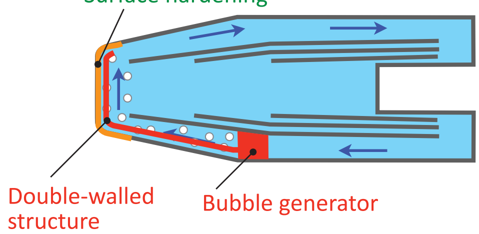
Reduce pressure wave and cavitation damage
Inject helium gas microbubbles (R<50 μm) into flowing mercury (VF:10^{-2} in flow ratio)

3rd target vessel with bubble generator



Double walled structure

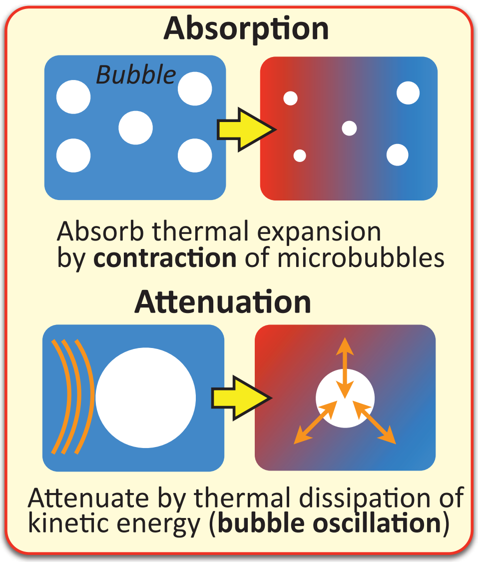
Reduce cavitation damage by high-speed mercury flow and narrow gap



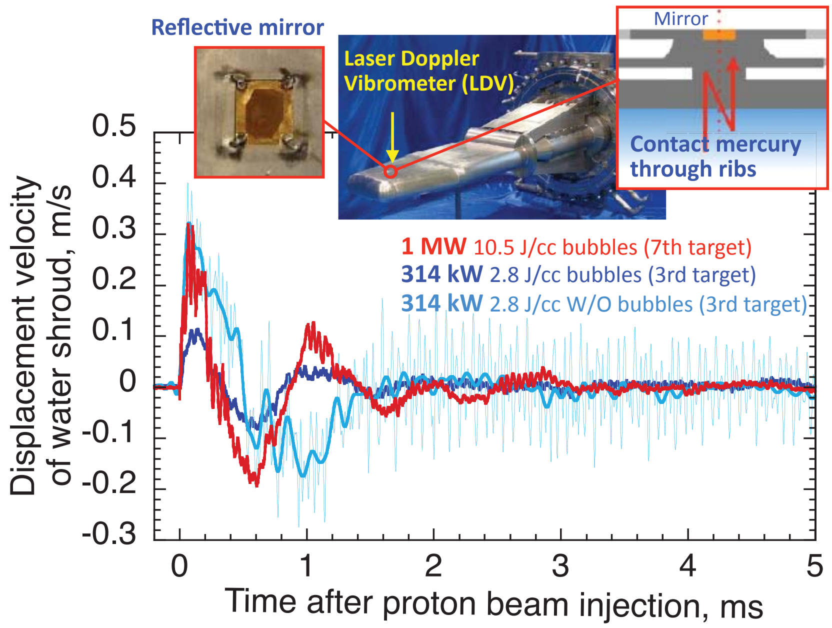
Order of target vessel operation

	1st →	3rd →	5th →	7th →	2nd →	8th
Year	2008	2011	2014	2015	2016	2017

Effect of gas microbubble injection



Bubbles works on shock absorber

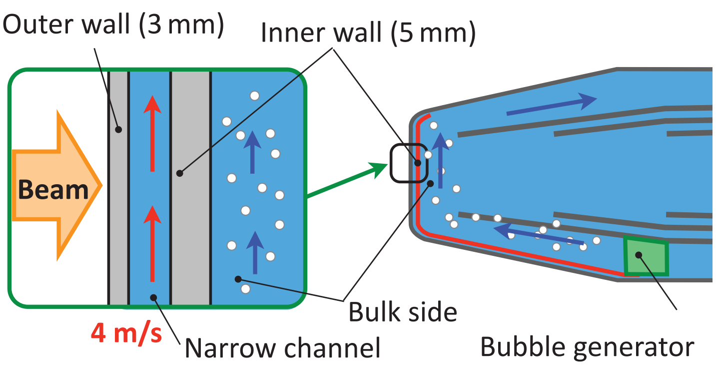


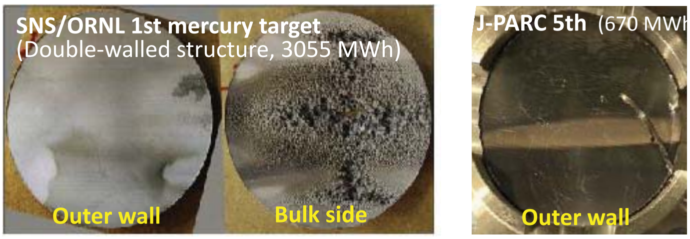
Vibration time responses for 3rd and 7th target

- Target system has the LDV diagnostic system (*LDV, Retro-reflecting corner cube mirror*)
- Peak amplitude of 1 $MW_{equiv.}$ study (OCT. 2015) showed similar amplitude of 300 kW W/O bubble ➡ **Bubbles extremely mitigates pressure waves**
- Peak amplitude of velocity for bubbles case seems to be 1/4 of W/O bubbles cases

Double-walled beam window

5th target ~

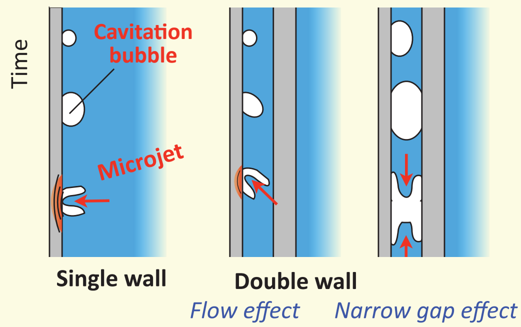




D. McClintock et al., J. Nucl. Mater. 431 (2012) 147–159

T. Naoe, et al., JNM in press

Expected damage mitigation effect

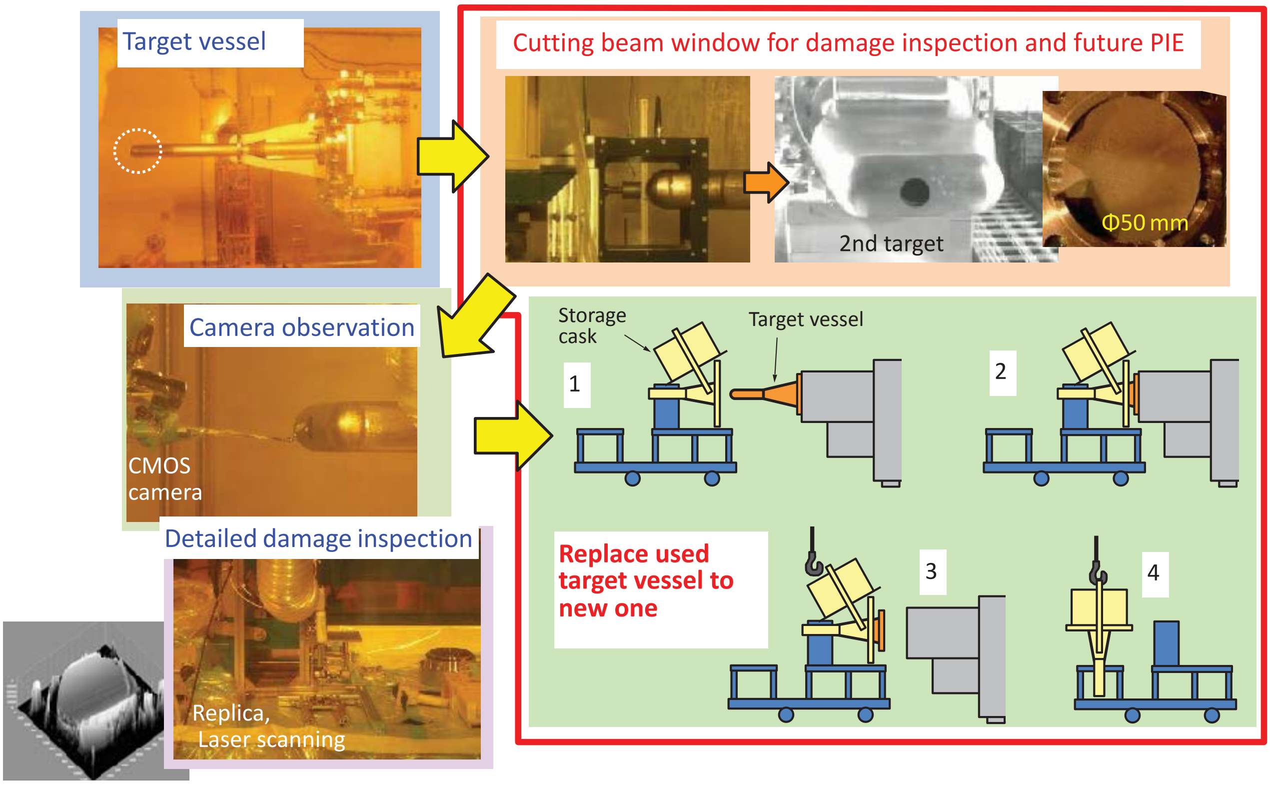


Deform bubble growing/collapsing by high-speed flow
Interrupt bubble growing/collapsing by narrow gap

Direction change of microjet ejection reduces cavitation damage at wall

- Expects damage reduction effects inside narrow channel
  - Flowing effect (increase pressure gradient around surface)
  - Narrow channel effect (asymmetrically bubble collapsing)
- SNS/ORNL target has actual results of damage mitigation effect by double-walled structure

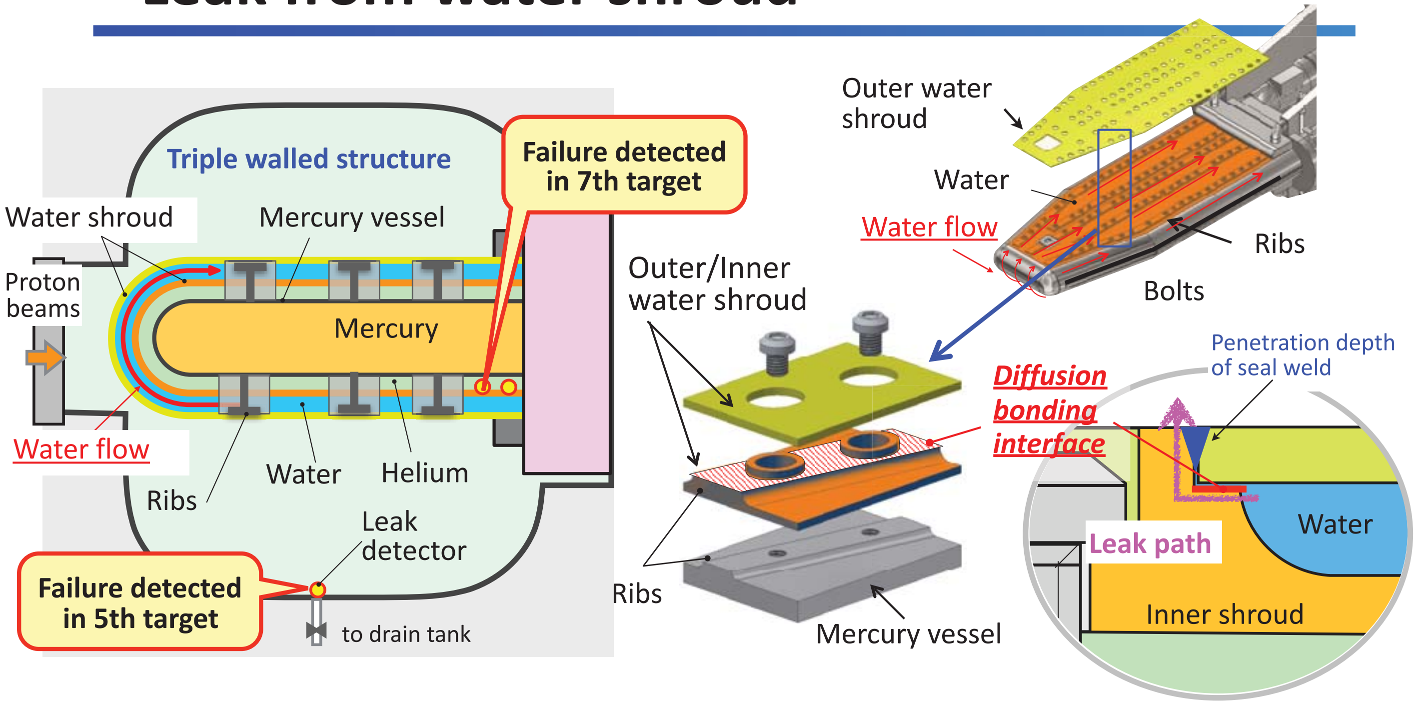
Cutting and replacement of target vessel



- Target vessel replaces every year (Designed lifetime: 5000 MWh)
- Cut beam window for damage inspection and future PIE
- Replace new target by full-remote handling

Leak from water shroud

J-PARC

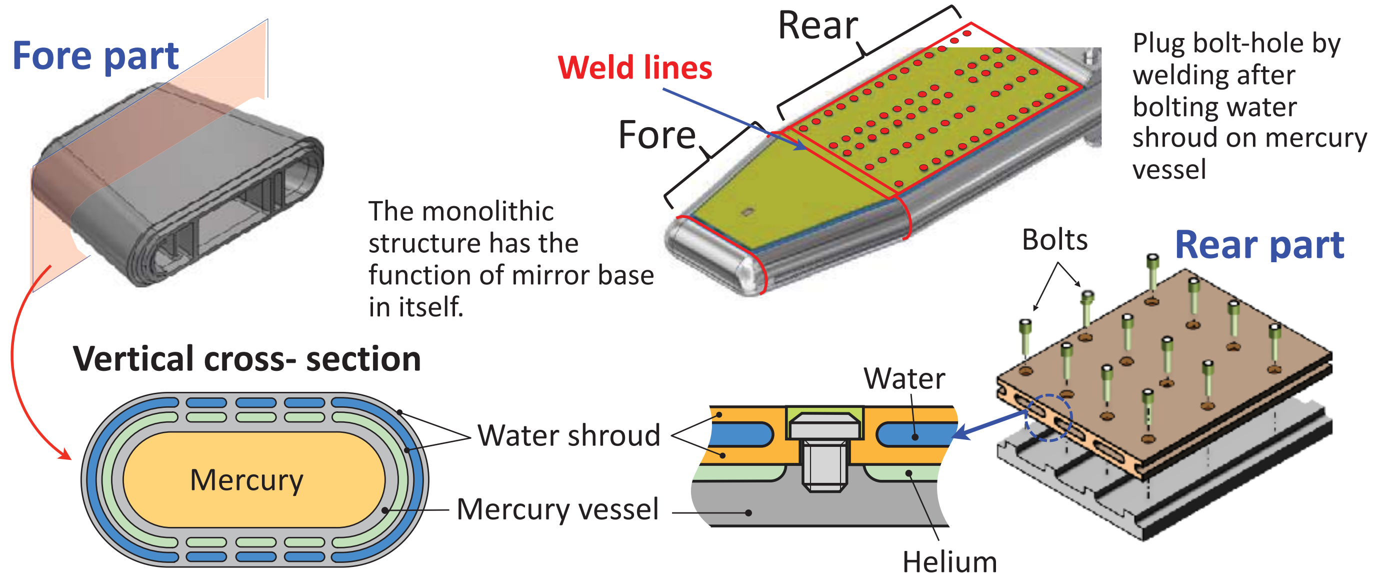


- 5th and 7th targets were failed due to water leak at water shroud
- Water leaked to outside of target vessel (#5), inside of target vessel (#7)
- Bolt head and outer/inner shroud interface was welded by TIG weld
- Lack of penetration depth for seal welding led leakage of water (#5)
  Fatigue crack was propagated thermal cycles by beam trip from weld defect

Lesson and improvement from failures

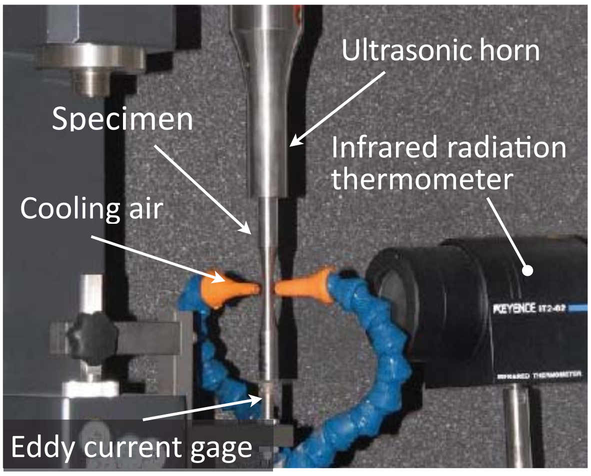
J-PARC

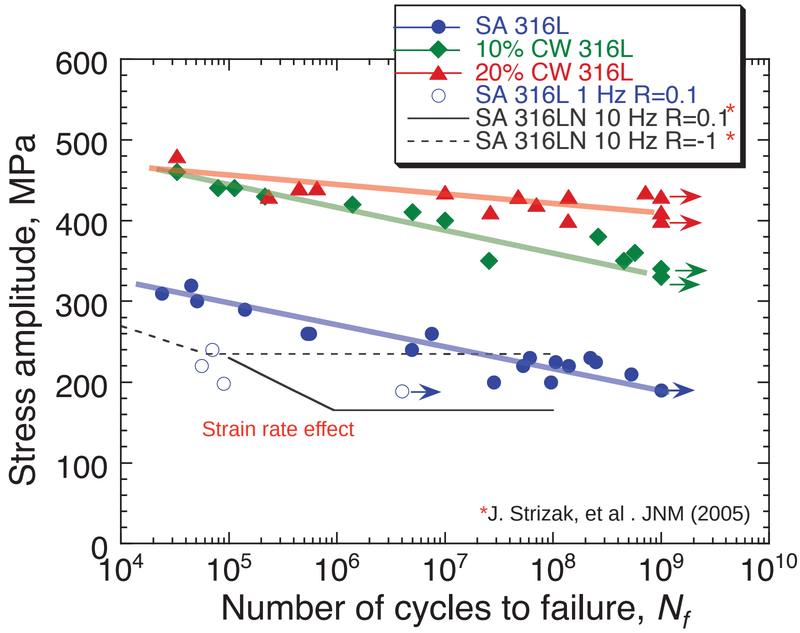
Improvement for 8th target



- Wire EDM was applied to reduce welding line and to eliminate diffusion bonding
- Monolithic structure of LDV mirror base seemed to be induce un-welded region which acts as notch, and fatigue crack propagated by pressure waves
- Strengthen the inspections for weld lines by RT and UT

Gigacycle fatigue

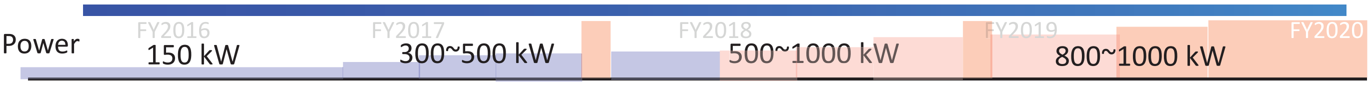




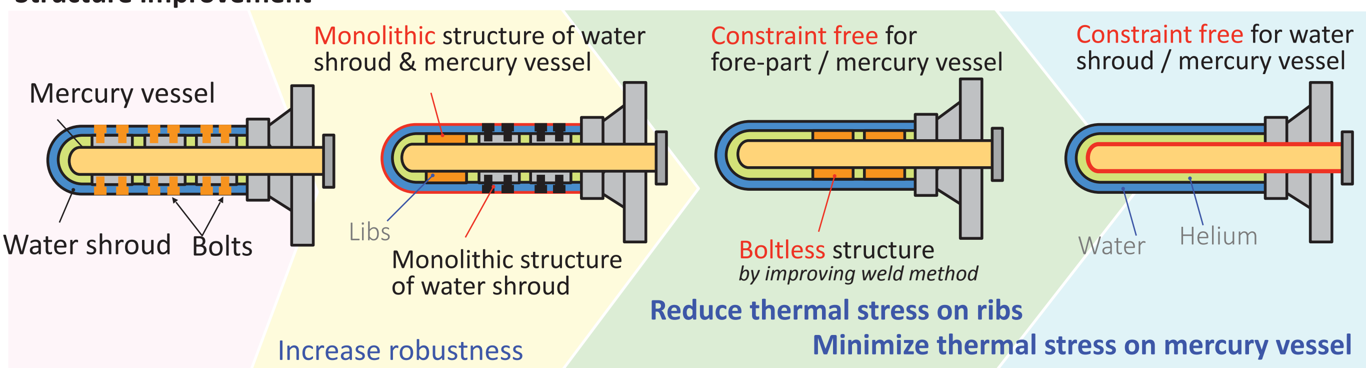
- Cyclic loading (50 1/s, 4.5x10⁸ cycles at 25 Hz) by proton beam-induced pressure waves
- Gigacycle fatigue, non-metallic inclusion, insufficient data for welding
- Stress applied through the ultrasonic resonance of 20kHz (430 Hz for intermittent loading)
- Target vessel (triple walled structure) assembled with TIG weld

→Now we are investigating effect of **welding and weld bead** on gigacycle fatigue

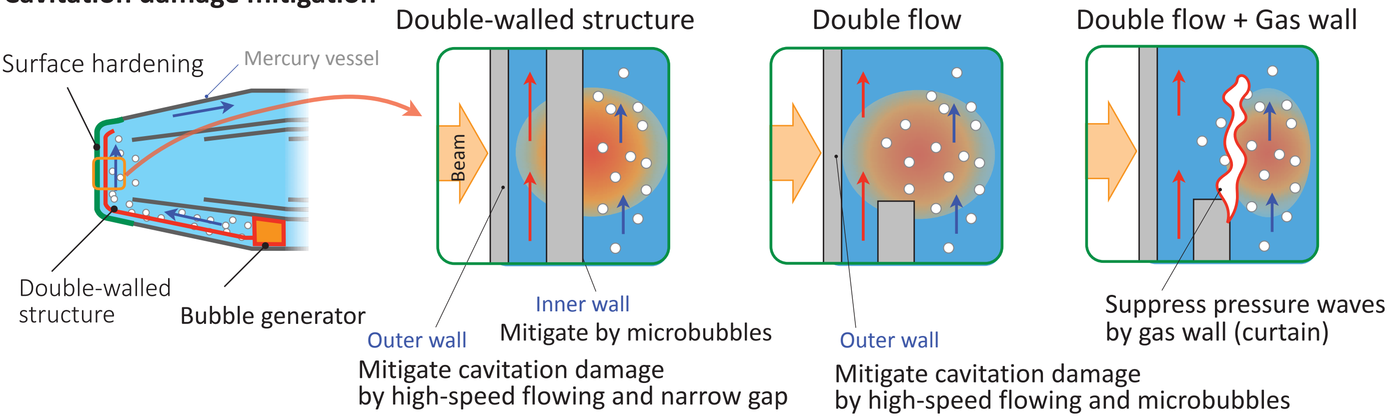
Upgrade scheme to achieve MW stable operation



Structure improvement



Cavitation damage mitigation

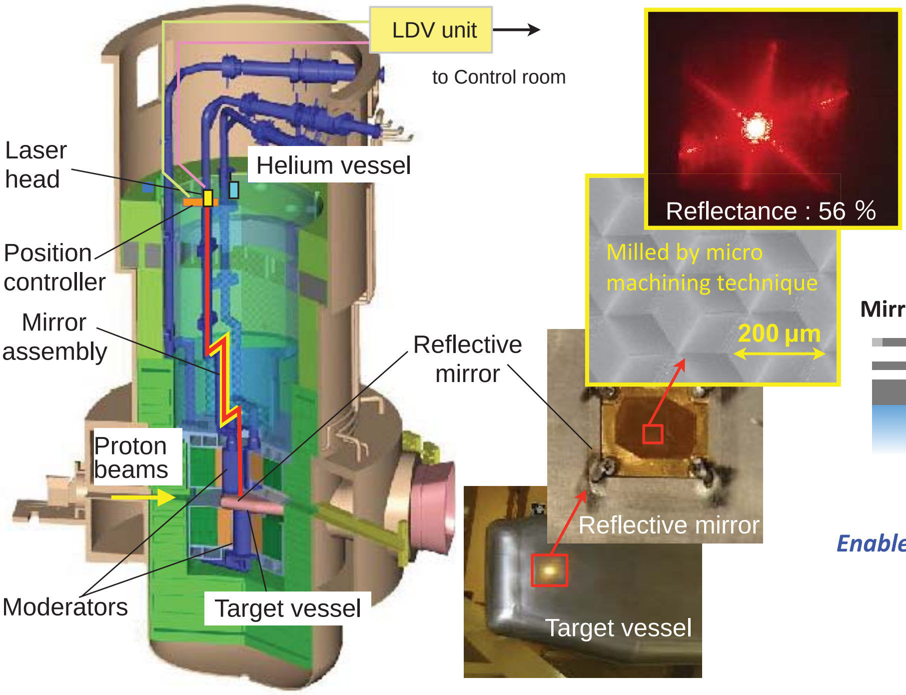


Summary

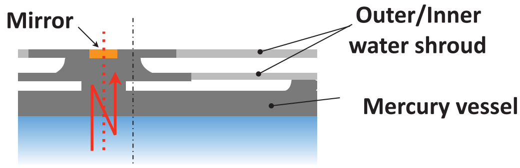
- Cavitation damage in mercury is the critical issue to decide lifetime of target vessel
- 1 $MW_{equiv.}$ beam experiment was achieved in 2015, and confirmed excellent effect of injecting gas microbubbles on pressure wave mitigation by LDV measurement
- Mitigation technologies are developed and demonstrated their effectiveness to reduce cavitation damage
- Effect of microbubbles injection and double-walled structure will be checked by 8th target inspection (2018 summer)
- Target structure is gradually updated for achieving 1 MW stable operation

Backup slides

Target diagnostic system



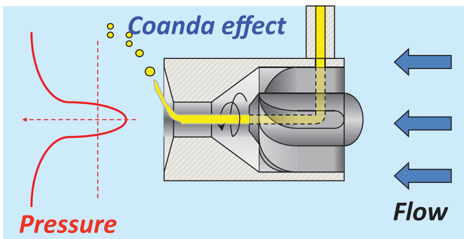
Laser Doppler vibrometer (LDV)
Velocity range: 0.01—10 m/s
Frequency range: 0.3—3 Hz
Data sampling: 1MHz



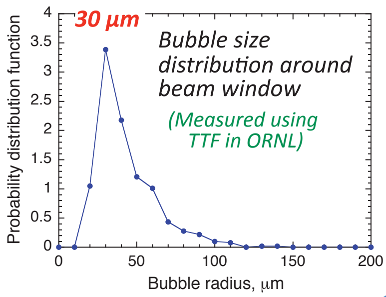
Enable to detect pressure waves in mercury

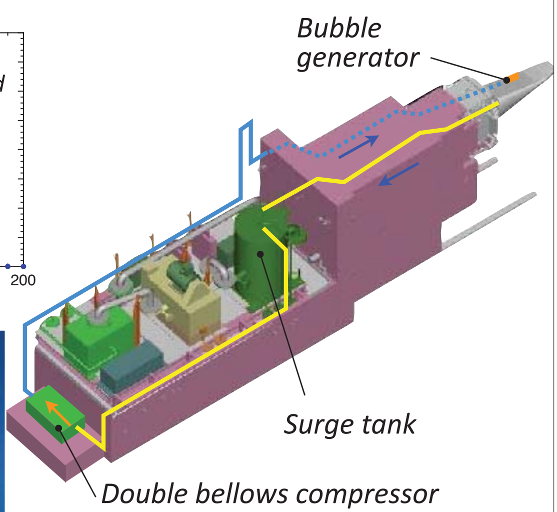
- LDV have been installed for monitoring the vibration of target vessel by proton beam injection
- Corner cube reflector was directly machined on pure gold plate by newly developed micro machining technique (Ni mirror of #1 target corroded)
- Mirror part is directly contacting with the mercury (mono-structure)

Gas microbubbles injection system

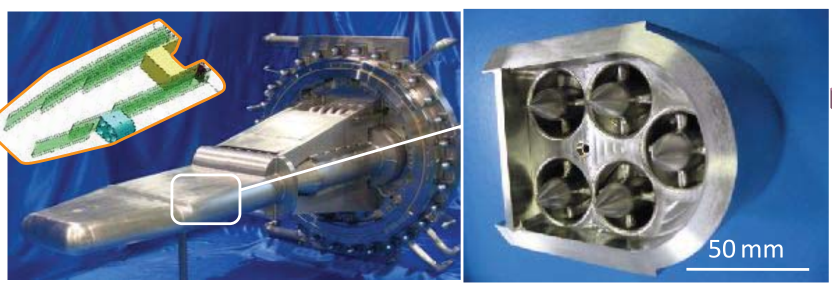


Swirl type bubble generator





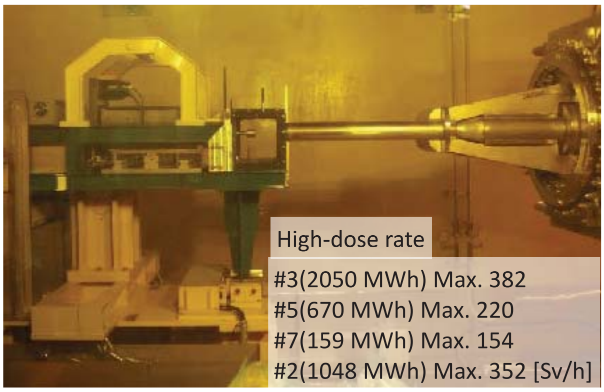
Mercury circulation system
(Closed helium gas loop)

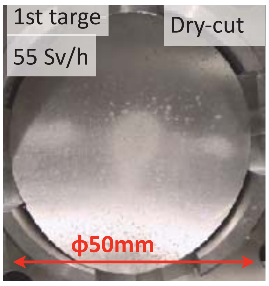


#3 target vessel with bubble generator

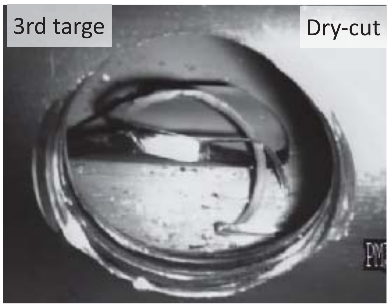
- Swirl type microbubble generator was installed from 3rd target vessel with gas circulation system to mitigate proton beam-induced pressure waves
- Peak bubble radius is 30 μm, void fraction (He/Hg flow ratio) is 10^{-2} at bubble generator

Difficulties in cutting by full remote handling

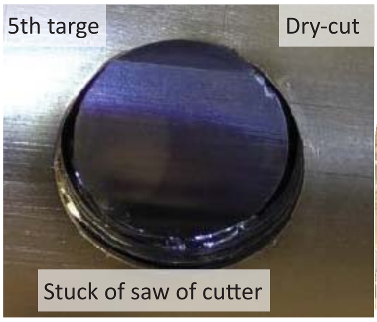


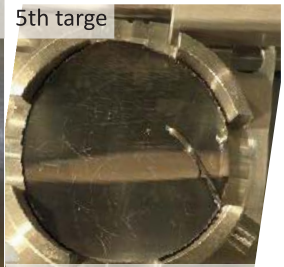


Succeed 1st cut



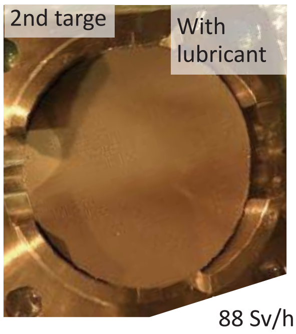
Inner most wall of 3rd target fallen inside vessel





Outer wall facing narrow gap

Narrow gap mitigate damage but not enough for MW stable operation

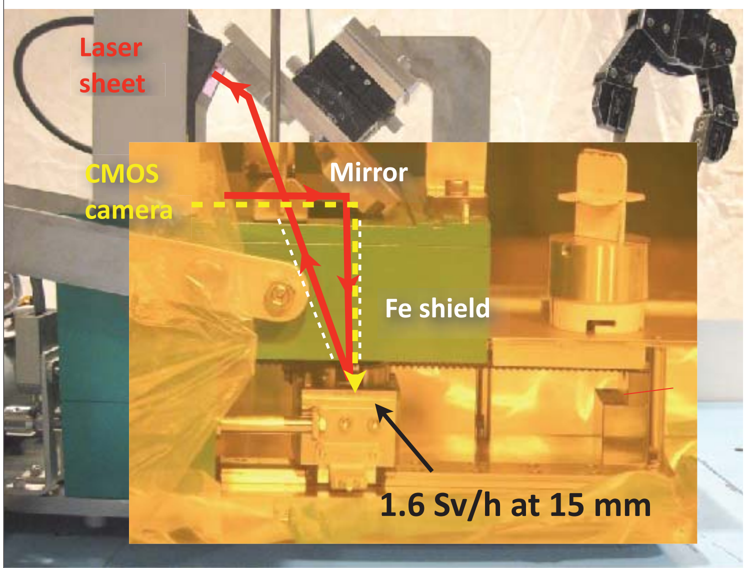


88 Sv/h

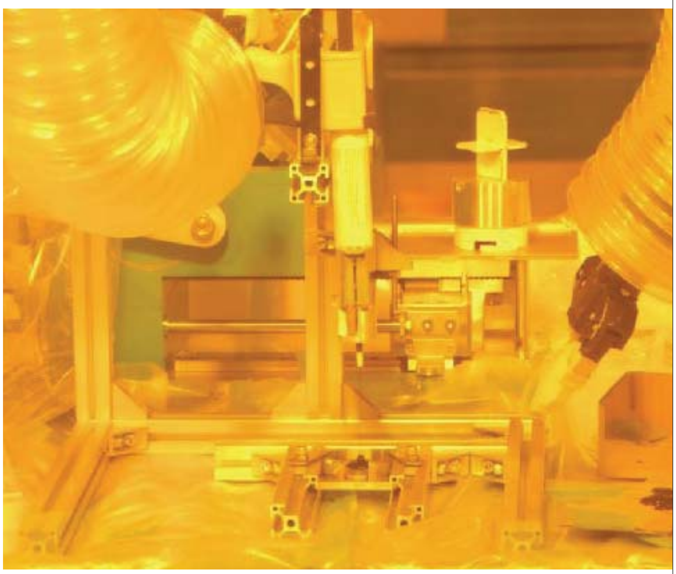
Inner most wall of 5th target remained window

Cutting performed under target fixing on trolley by full-remote handling
Nos. 1,3,5 targets cut without any lubricant —>Failed #3 and #5 cutting
No quantitative information was obtained for bubbling effect —> #8 will cut 2018
Succeeded #2 cut by optimizing cut condition (w/ lubricant)

Damage depth measurement



Laser profilometer

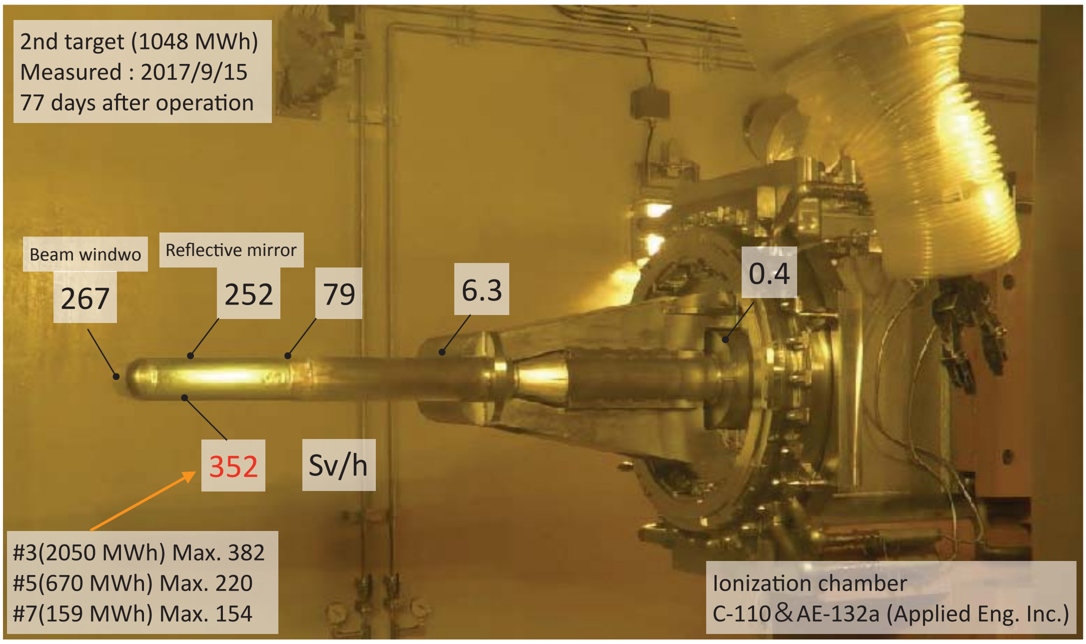


Replicate surface (silicon-rubber) for LSM observation

- **Prepared two types of measurement systems:**

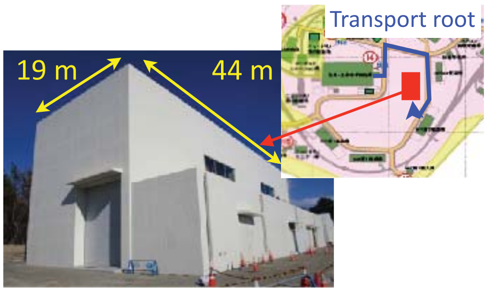
  Laser profilometer for deep damage (0.1 mm~penetrated damage)
  Replica for detail observation (0.1 µm~0.5 mm)

Radiation dose rate of used target vessel



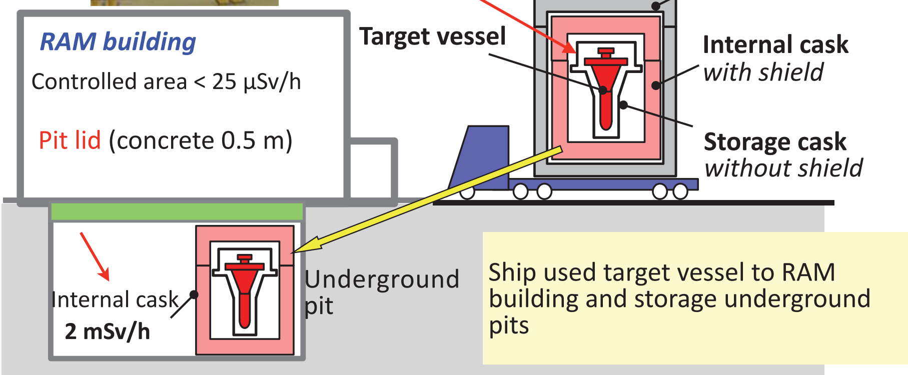
- Beam window is irradiated proton and neutron irradiation
- Difference between top and bottom sides around mirror is affected by moderator and reflector
  (Volume of neutron absorber around top side is larger than bottom side)
- Remaining mercury and radioactive materials are also affected dose rate

Storage building for used components



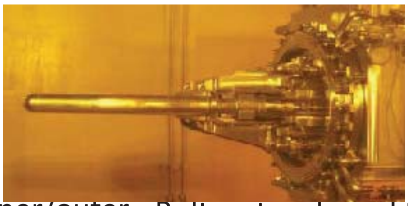
RAM (Radio Active Material) building

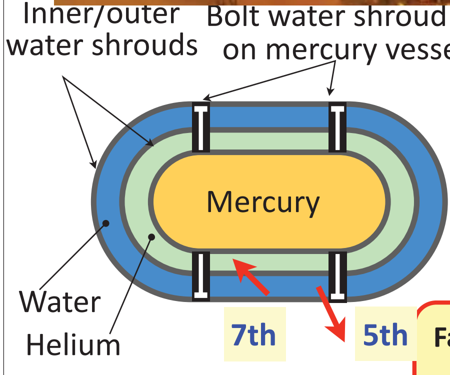
Pits for storage used target



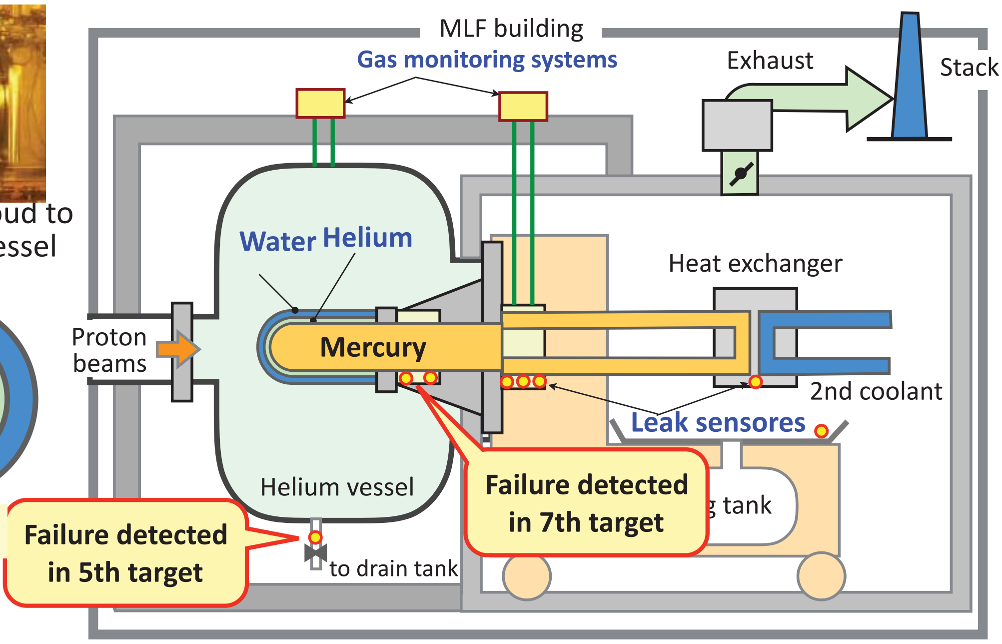
- MLF building has storage room for used targets (capacity:8)
- Not enough for 30 years operation (1 target/year)
- Storage building (capacity:15-20) was completed and will transport in next summer

Troubles in 2015 — 5th and 7th targets —





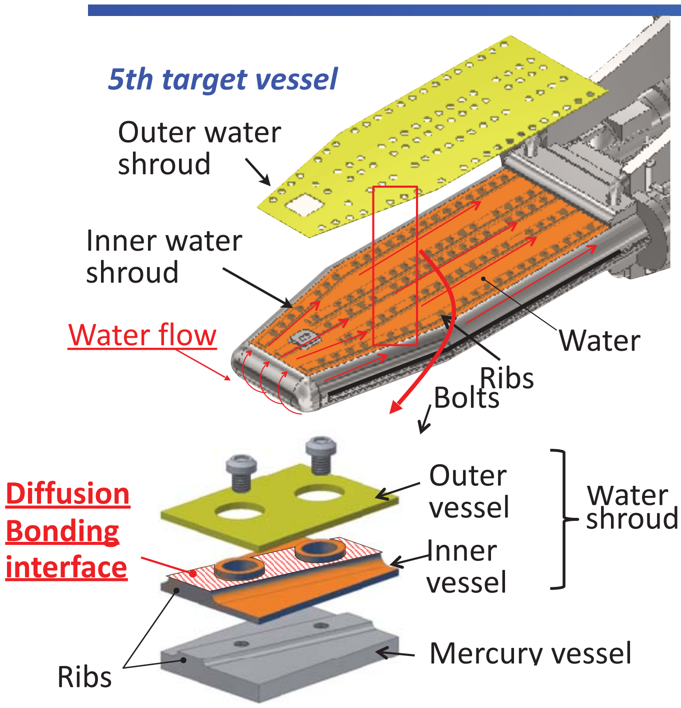
Vertical cross-section of target vessel



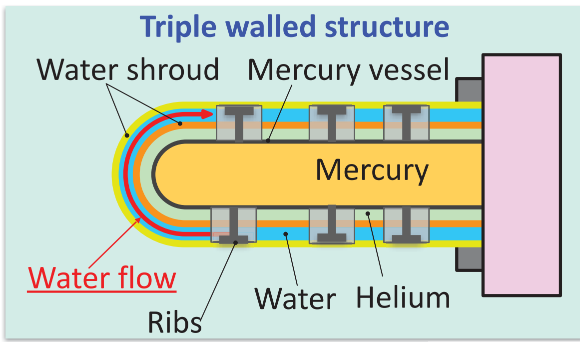
- 5th and 7th targets were failed due to water leak at water shroud
- Leak sensor at the drain tank of helium vessel was detected leak for 5th target
  Water leaked to outside of target vessel
- Leak sensor inside target vessel was detected leak for 7th target
  Water leaked to inside of target vessel

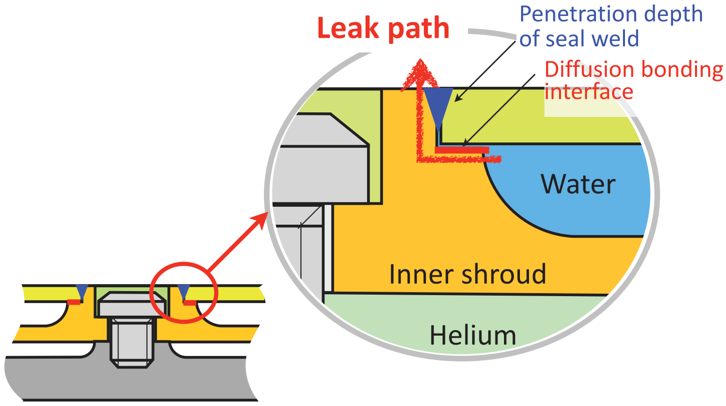
Radioactive gas was not released from stack (Leak occurred in enclosed vessel)

Structure of mercury target vessel (~5th target)



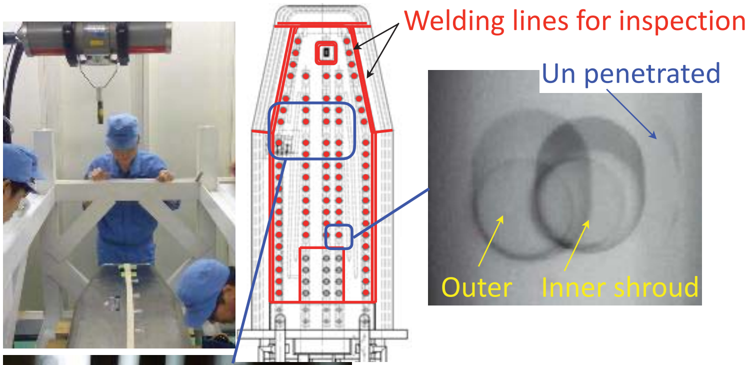
Vertical cross section of the target viewed from the target side





- Target vessel has triple walled structure (Inner/Outer water shroud, Mercury vessel)
- Outer and inner water shroud (diffusion bonded) was bolted to mercury vessel
- Bolt head and outer/inner shroud interface was welded by GTAW

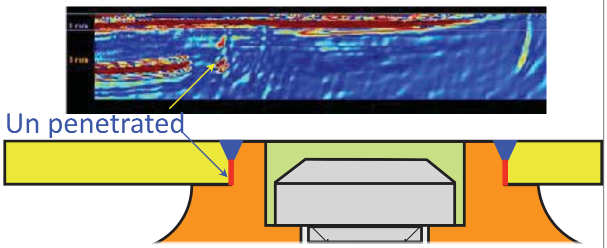
Improvement of inspection



6th target vessel was inspected to investigate inspection processes of RT and UT

Radiographic Testing (RT)

Inspection of mock-up specimen by phased array & Full Matrix Capture (FMC) / Total Focusing Method (TFM)

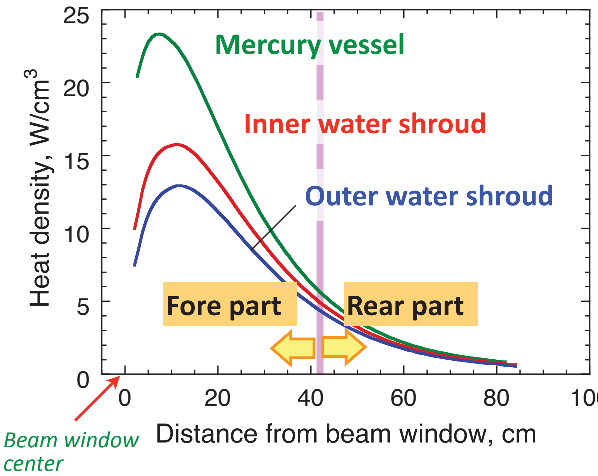


Ultrasonic Testing (UT)

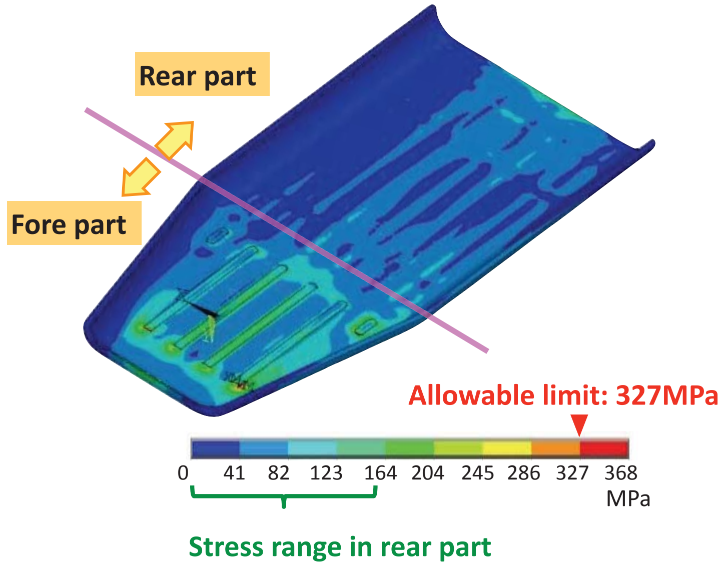
Details of nondestructive inspection for target vessel will be shown in Wakui's poster

- Based on the experiences of target failure, we revised the inspection procedure
  RT : Front part of mercury vessel only (~7th) —> All part including water shroud (8th~)
- UT inspection will be added :
  Nondestructive inspection method: phased alley &FMC/TFM method (GEKKO, Insight)

Heat density and thermal stress



Heat density distribution at 1MW



Thermal stress distribution for inner water shroud at 1 MW

- Heat density in rear part is less than 1/4 of fore part
- Thermal stress is less than half of allowable stress

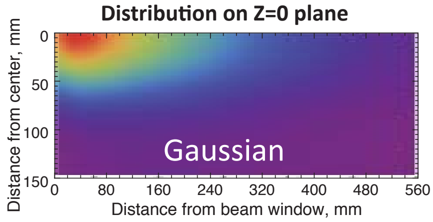
Bolt structure in rear part is enough to withstand thermal stress at 1 MW

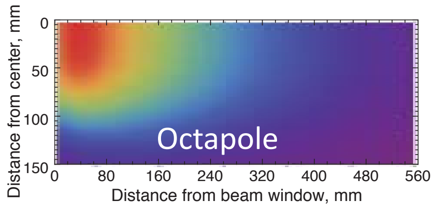
Heat distribution in mercury target

1 MW proton beam condition Half of input beam energy change to heat in mercury

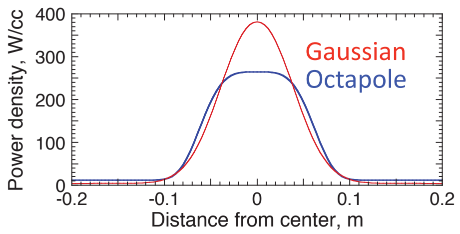
	Gaussian beam profile	Adding Octapole magnet
Total energy in mercury	480 kW	491 kW
Peak energy deposition	Max=381.397 W/cc (15.25 J/cc)	Max=264.73 W/cc (10.58 J/cc)

Distribution on Z=0 plane

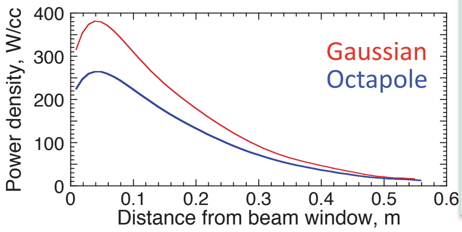




Horizontal direction X=30 mm Z=0 plane



Beam direction Y=X=0



Rise of mercury temperature

$$\Delta T = \frac{\Delta Q}{\rho C_V}$$

Rise of pressure in mercury

$$\Delta P = \beta K_T \Delta T$$

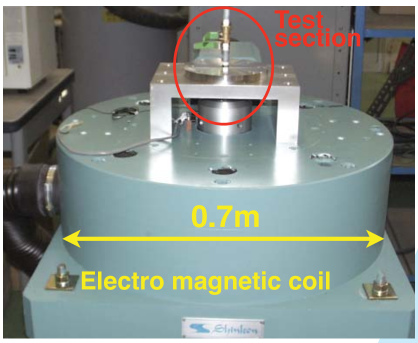
C_V: Specific heat 139 [J/(kgK)]
ρ: Density 13500 [kg/m^3]

ΔT=8.52°C@400 W/cc(16J)

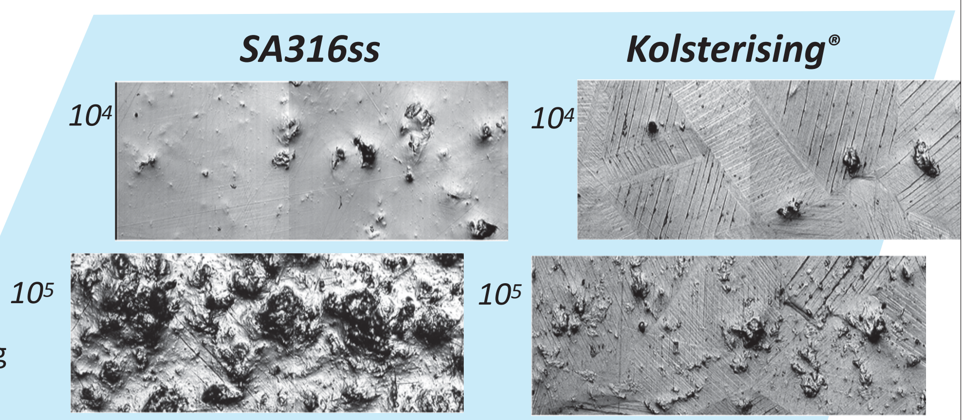
β: Thermal expansion rate 180.99e-6 [1/K]
K_T: Bulk modulus 25.6 [GPa]

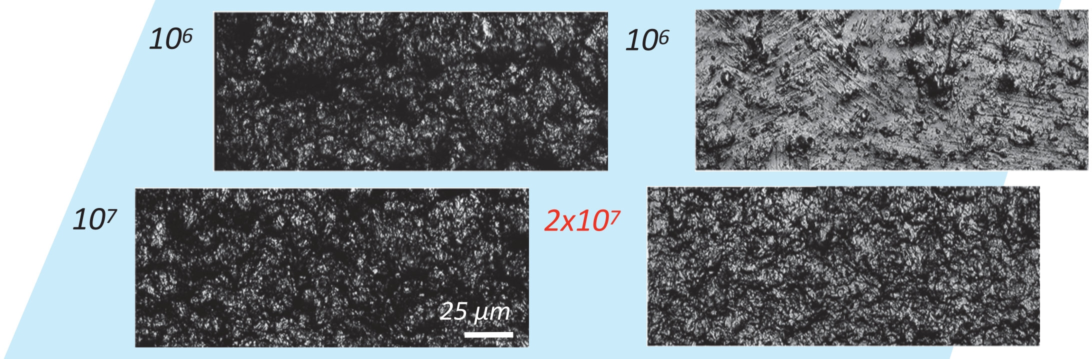
ΔP=40MPa@400W/cc(16J)

Surface hardening treatment



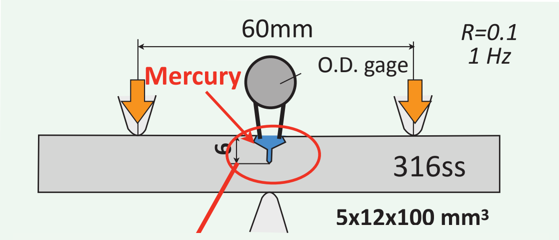
electroMagnetic IMpact Testing Machine (MIMTM)



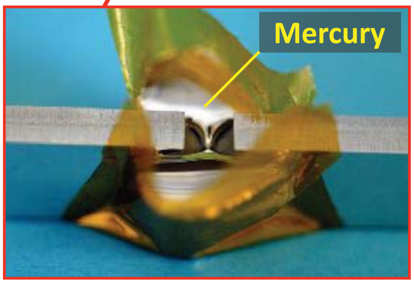


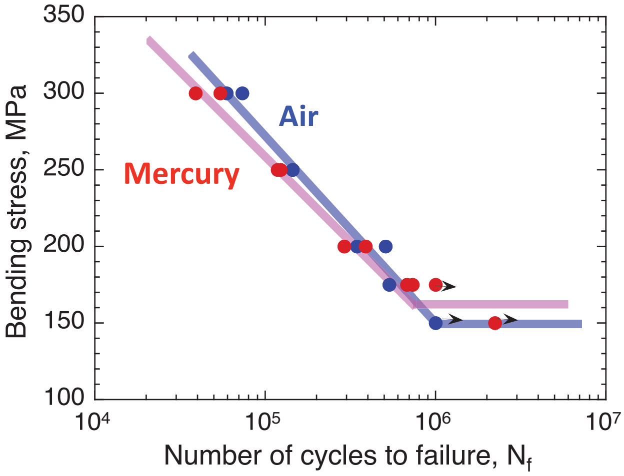
- Cavitation damage tests in stagnant mercury
- Incubation period for erosion damage extends 10 times by Kolsterising®

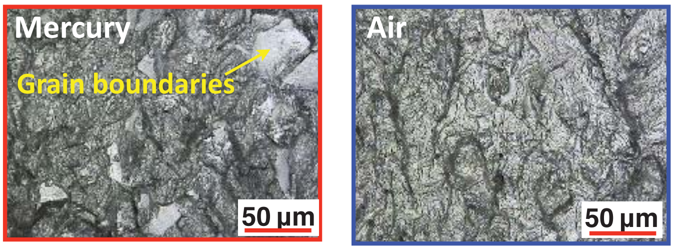
Fatigue behavior in mercury



3-point bending fatigue test with V-notch



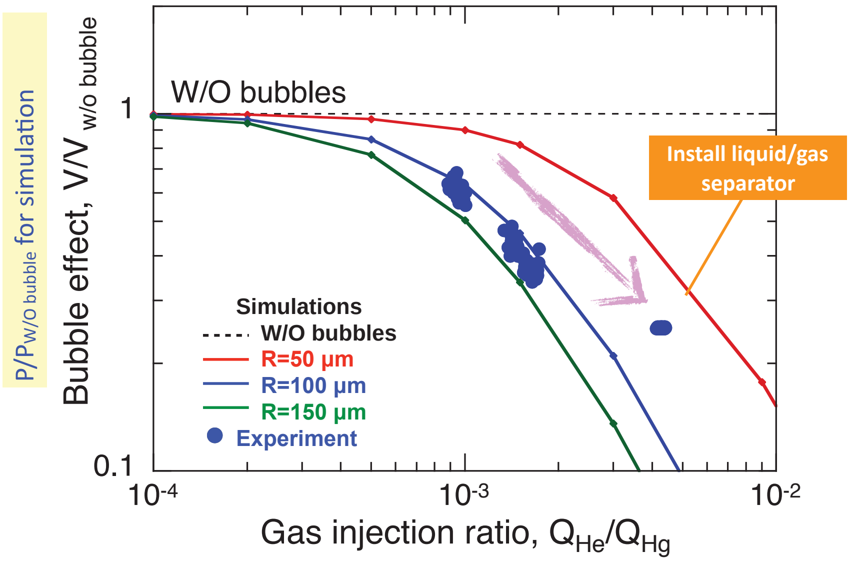


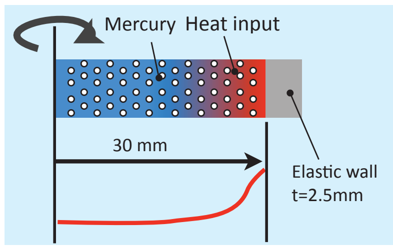


Fracture surface at 300 MPa

- Fatigue strength was degraded by mercury immersion at high stress imposed area
- Fatigue crack propagation accelerates by mercury immersion in the high-stress intensity factor range

Effect of void fraction on pressure wave mitigation





Pressure wave propagation in bubbly mercury (uniform size) obtained from simulation

- Peak amplitude of LDV is correlated with the void fraction
  Peak velocity was normalised at w/o bubble case predicted based on beam experiments
- LDV denotes the same tendency of the numerical simulation

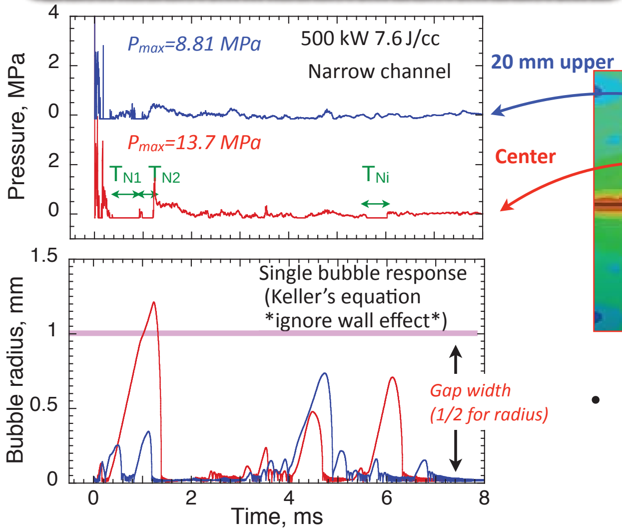
Damage and pressure response in narrow channel

Negative pressure period

Accumulated time of negative pressure period $T_{N_{accum}} = \sum_{i=1}^{n} T_{N_i}$

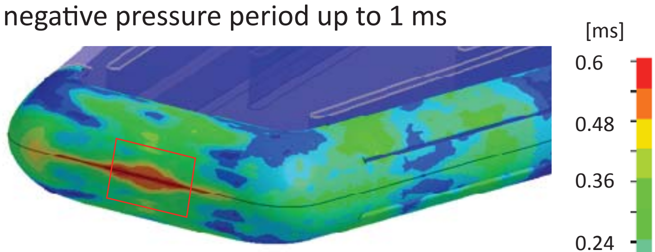
T_N=duration of negative pressure (-0.15 MPa)

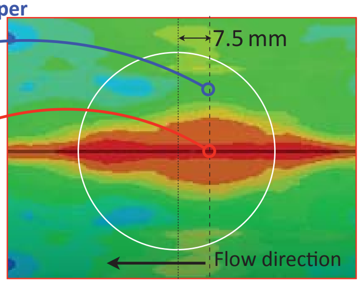
-0.15 MPa -> threshold for cavitation



Time responses of pressure and cavitation bubble in narrow channel at 500 kW conditions

Distribution of accumulated negative pressure period up to 1 ms

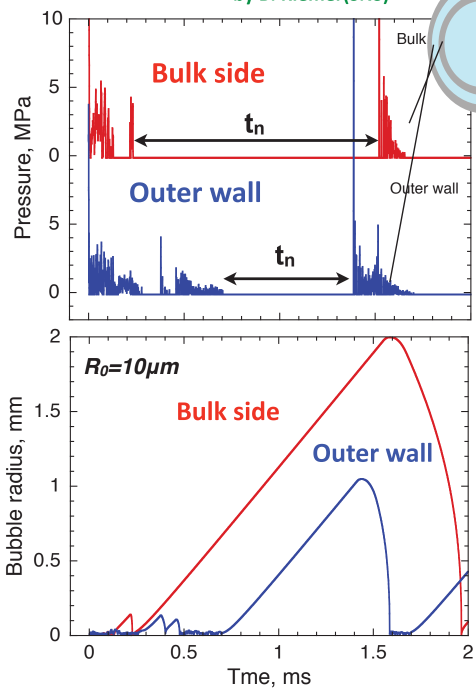


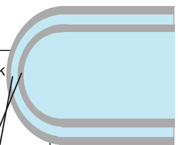


- Distribution of accumulated negative pressure period correlated with observed damage distribution

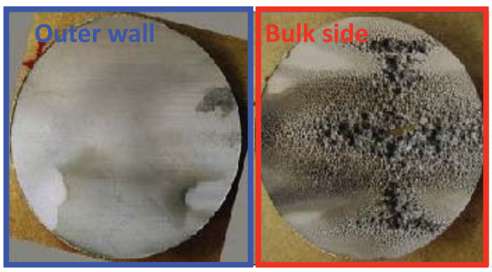
Shorter negative pressure period reduces cavitation damage in narrow channel

Bubble behavior in the narrow channel





(Cutoff model)



D. McClintock et al., J. Nucl. Mater. 431 (2012) 147–159

Keller equation Single bubble

$$\left(1-\frac{\dot{R}}{C_L}\right)R\ddot{R}+\left(\frac{3}{2}-\frac{\dot{R}}{2C_L}\right)\dot{R}^2 = \frac{1}{\rho}\left(1+\frac{\dot{R}}{C_L}\right)\left(P_b[t]-P[t+R/C_L]-P_0\right)+\frac{R}{\rho C_L}\dot{P}_g[t]$$

$$P_g[t]=\left(P_0-P_V+\frac{2\sigma}{R[t]}\right)\left(\frac{R_0}{R[t]}\right)^3+P_v$$

$$P_b[t]=P_g[t]-\frac{2\sigma+4\eta\dot{R}[t]}{R[t]}$$

R: Bubble radius
ρ: Density
σ: Surface tension
P: Pressure
η: Viscosity

- Short interval of negative pressure is not effective to bubble growth
- Maximum bubble size at narrow channel is a half of bulk side
- Insufficient data to explain a significant damage difference

3.4.3 Irradiation area- related issues

3.4.3-i) Irradiation area- related issues: F. Arbeiter (KIT)

EUROfusion

Workshop on Advanced Neutron Source and its Application

Technical Session 3-1 : High Power Neutron Sources

Irradiation-area related issues - introductory slides

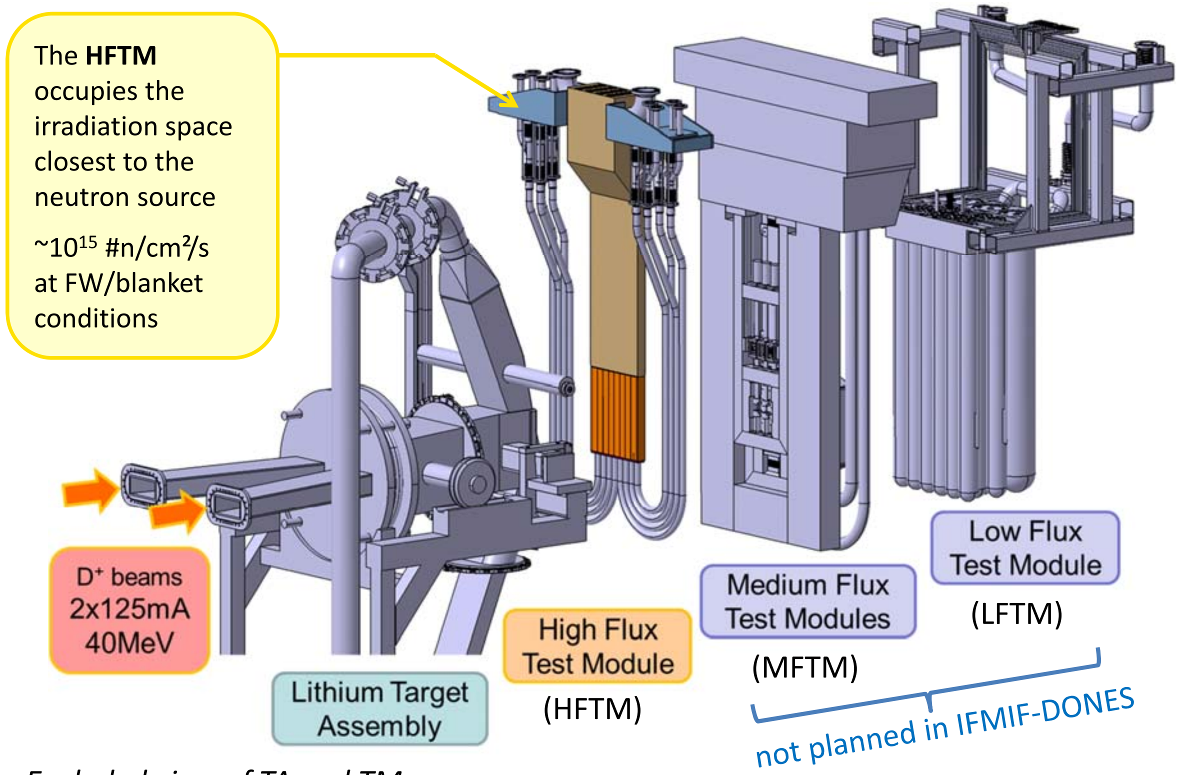
F. Arbeiter (KIT), A. Ibarra (Ciemat), A. Möslang (KIT), M. Serrano (Ciemat)

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 633053.
The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Challenges of high power neutron sources for the irradiation area

- Shielding of the high intensity neutron radiation
  - providing interfaces (cooling, power, signal) through shielding (connectors!)
  - safety of involved alkali metals (if applicable)
  - no moderation of spectrum
- Exploitation of „directed“ limited extent neutron source
  - gradients of nuclear responses
  - shape of irradiation volume (cuboid vs. cylinders)
  - small irradiation volume ➔ small specimens
- Handling of high volumetric heating in the specimens
  - limitation of specimen stack size
  - application of heat transfer media
- Lifetime of involved structural and functional materials
  - lifetime (creep, fatigue) of pressure vessel components
  - lifetime of electrical heaters and instrumentation (n detectors)
- Priorization of functions / test matrix
  - Irradiation of specimens for PIE
  - In-situ test experiments (creep fatigue, tritium release, ...)
  - general nuclear physics applications, isotopes production etc.

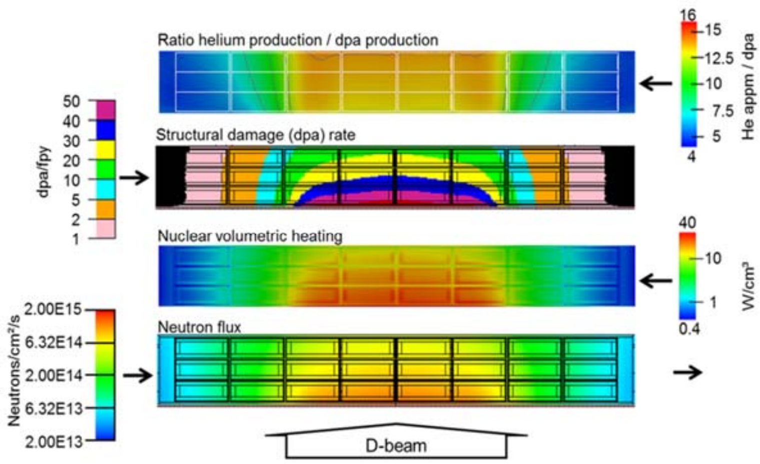
Example: Irradiation experiments in the IFMIF Test Cell

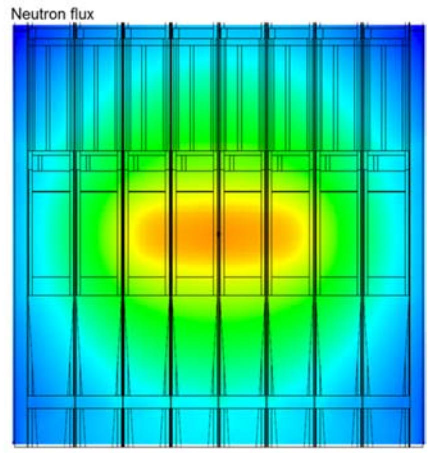


Exploded view of TA and TMs

Example: IFMIF HFTM irradiation performance

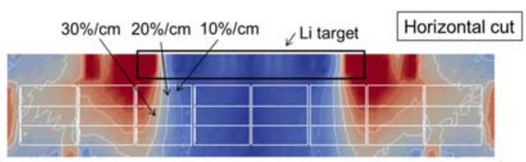
As developed 06/2013 (IFMIF/EVEDA DDD-III for 2x 125mA 40MeV D+

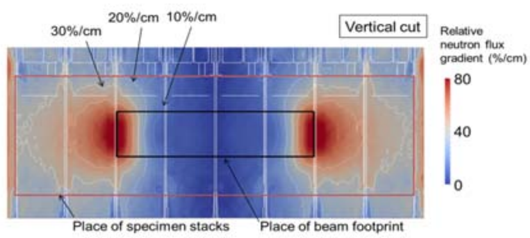




„337 cm³ specimens at > 10dpa/fpy“

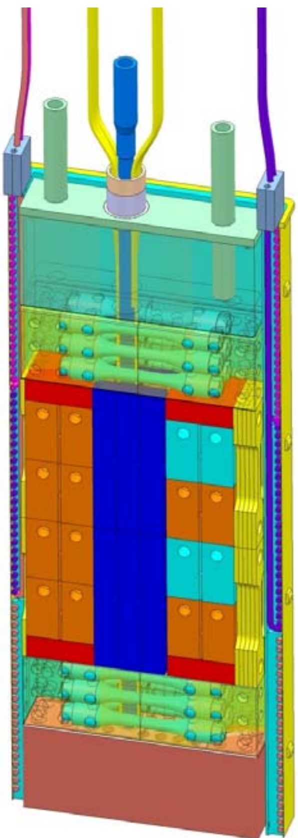
(uniaxial horizontal gradients)

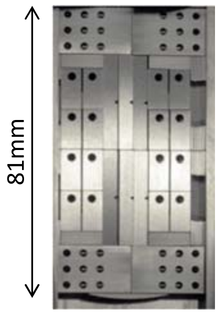




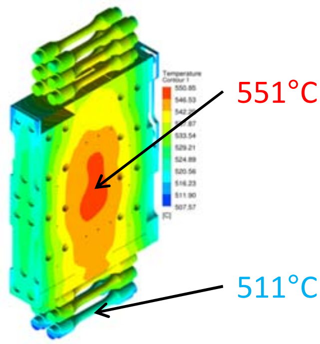
[Keitaro Kondo, IFMIF/EVEDA HFTM DDD-III, 2013]

HFTM specimen payload (working proposal)





[F. Arbeiter et al., ICFRM-17, 2015]



specimen stack
81 x 40 x 9.3 mm³

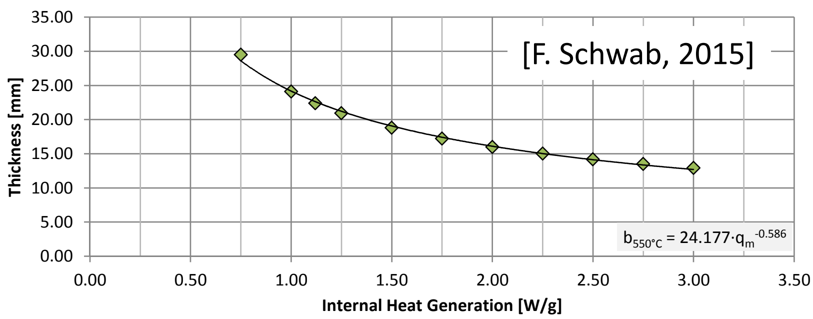
3D temperature map
with resolved specimens

#/caps.	Test type	Bounding box [mm]
2x12	Flat tensile (static)	27 x 4.6 x 0.76
2x2	Fracture toughness (Compact Tension)	11.5 x 11.5 x 2.3
2x12	Bend bar / Charpy impact	27 x 4 x 3
2x6	Cylindrical fatigue	27 x D4 (gauge 9 x D2)
2x3	Fatigue Crack Growth	11.5 x 11.4 x 4.6
2x8	Pressurized creep tubes	27 x D2.5 t0.25
	TEM plates	

[A. Möslang, Final Report on the EFDA Task TW4-TTMI-003 D4, 2006]

Impact of heating intensities

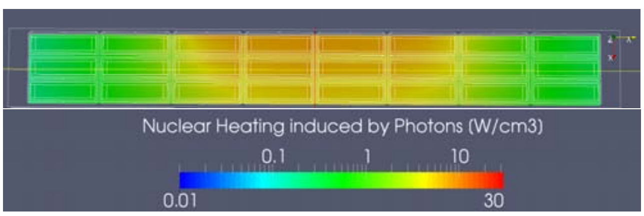
- For allowed max. temperature spread, the maximum thickness of the specimen stack inside the capsule depends on the nuclear volumetric heating intensity:



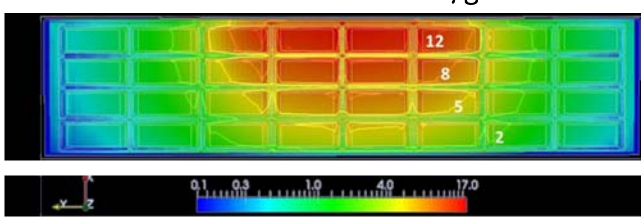
$$\Delta T \propto \frac{q''' \cdot b^2}{\lambda}$$

- Thick capsules allow higher specimen usage fraction vs. „parasitic“ volumes !

IFMIF 2x125mA : ~3 W/g



IFMIF-DONES 1x125mA : ~1.5 W/g



Conclusions

- The *usable* **volume x dpa product** of planned fusion-relevant irr. facilities is limited and neccessitates the use of SSTT
- A certain **spread of nuclear responses** (dpa, He/dpa) within the specimen set and even a gradient within individual specimens gage volume have to be accepted and needs to be accommodated in the SSTT data assimilation procedures
- The spread of temperatures can be limited (on cost of irradiation volume), a few outliers may however occur

Issues to discuss

Proper definition of the requirements for the irradiation experiments/facilities now being designed will maximize their use for fusion materials science and FPP licensing !

- Priorities for the test matrix
  - materials (RAFM steels, W, Cu, ... base/welded/bonded)
  - test types (tensile, fracture toughness, creep, fatigue, ...)
  - Specimen / testing device for in-situ creep
- Technologies and methodologies for data evaluation
  - Small Specimen Test Technique (SSTT)
  - data assimilation from „dispersed“ {T_{irr}, dpa} specimen bases
  - required statistics per test type
- Promising solutions for technical realizations of the irradiation experiments (heating, cooling, structure, instrumentation)

3.4.3-ii) Complementary Experiments at DONES: Wojciech Królas (CIEMAT)

Complementary Experiments at DONES

W. Królas, A. Ibarra, A. Maj, F. Arbeiter

THE HENRYK NIEWODNICZAŃSKI INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCES · Ciemat · KIT Karlsruhe Institute of Technology

- Activities of the WPENS **Early Neutron Source** work package (2015-20) of EUROfusion
- White Book on the **„Complementary Scientific Programme at IFMIF-DONES”** (2016)
- Decision: Extension of DONES scope by adding ***„Complementary Experiments”*** areas

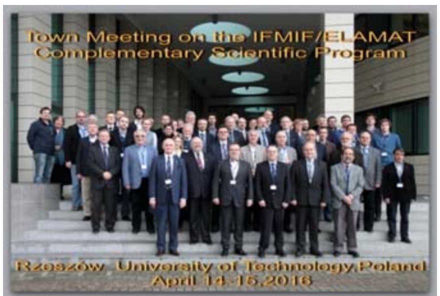
EUROfusion

DONES Complementary Science Program

The **ELAMAT Consortium** which was preparing the bid to site DONES in Poland proposed to extend the objectives of IFMIF-DONES beyond fusion materials studies

ELAMAT PODKARPACKIE

- An international science committee was formed, meetings were held during which various scientific areas were considered as complementary research topics.



DONES Complementary Science Program

The **ELAMAT Consortium** which was preparing the bid to site DONES in Poland proposed to extend the objectives of IFMIF-DONES beyond fusion materials studies

❖ An international science committee was formed, meetings were held during which various scientific areas were considered as complementary research topics.

Applications of medical interest

- Radiopharmaceuticals for therapy (e.g. ^{99}Tc)
- Accelerator-based boron-neutron-capture therapy (BNCT)
- ...

Basic physics studies

- Half-life measurements on long-lived isotopes
- Neutron and neutrino oscillations
- Solid state physics studies

Their feasibility and compatibility with the main DONES role must be evaluated

Nuclear physics and radioactive ion beam facility

- Nuclear Structure & Astrophysics
- Mechanism of nuclear fission
- Cross-section measurements for applied physics (n,γ), (n,xn), (n,lcp)
- ...

Industrial application of neutrons

- Mechanical properties of irradiated materials from small samples
- Computed tomography imaging using fast neutrons
- Transmutation doping of silicon and radiation-damage testing of electronics

DONES Complementary Science Program

The **ELAMAT Consortium** which was preparing the bid to site DONES in Poland proposed to extend the objectives of IFMIF-DONES beyond fusion materials studies

❖ An international science committee was formed, meetings were held during which various scientific areas were considered as complementary research topics.

„A White Book report on on the Complementary Scientific Programme at IFMIF-DONES"

IFJ PAN Report No. 2094/PL, 2016

Eds. A. Maj, M.N. Harakeh, M. Lewitowicz, A. Ibarra, W. Królas

https://www.ifj.edu.pl/publ/reports/2016/2094.pdf

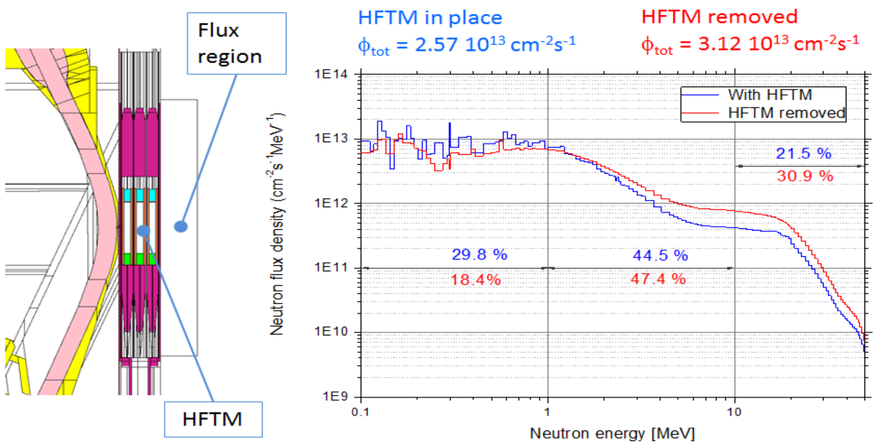
Adapted by the EUROfusion **WPENS** work package as Technical Report *EFDA_D_2MP66K*

Complementary Experiments: Boundry conditions

Main DONES mission: irradiation of fusion materials

Complementary experiments could use:

- **Deuterons** extracted from the accelerator beam but only a small fraction (a few percent)
- **Neutrons** available behind the Irradiation Module either inside the Test Cell or in a dedicated additional experimental hall



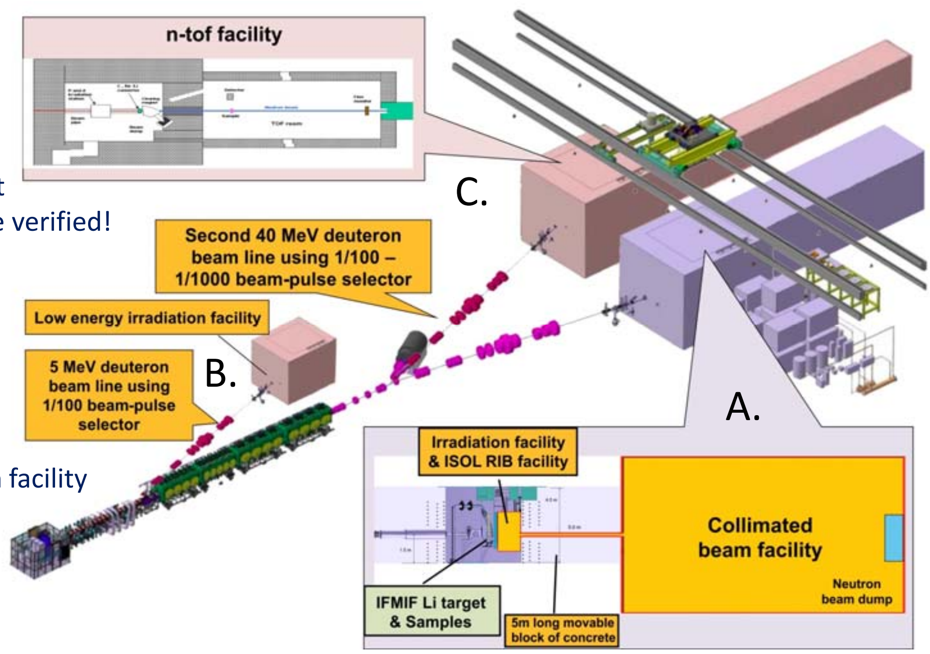
Courtesy of U. Fischer

Flux region behind High Flux Test Module with HFTM in place and removed

Complementary Experiments Areas: White Book proposal

C. A second 40 MeV deuteron beam line using 1/100 to 1/1000 beam-pulse selector to a neutron Time-of-Flight facility – feasibility must be verified!

B. A 5 MeV deuteron beam line using 1/100 beam-pulse selector to a low-energy irradiation facility



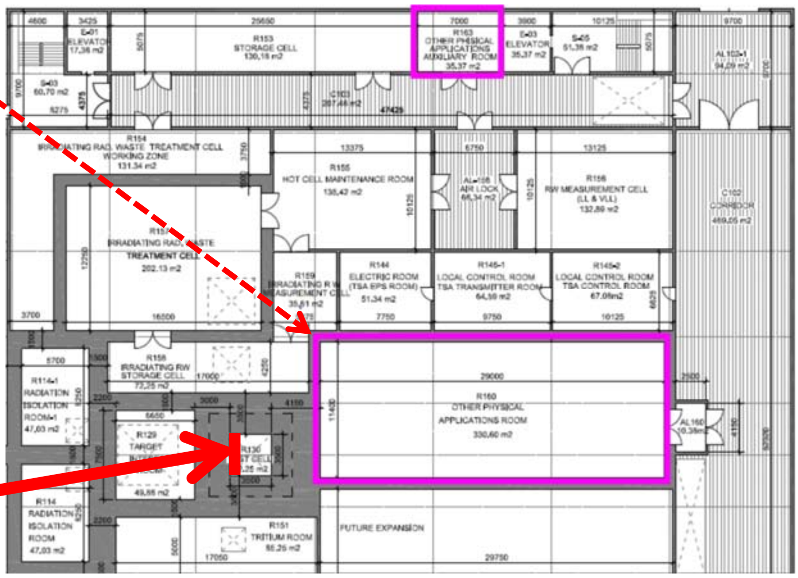
A. Irradiation facility and ISOL RIB facility behind the HFTM; **Collimated beam facility with an 8 m long neutron line**

Complementary Experiments Area (option A) incorporated into the DONES building design

Complementary Exp Area
Room R160
Dimensions
29.00 m x 11.40 m,
height 8.00 m, 330.60 m^2

Auxiliary Room R163
7.00 m x 5.07 m, 35.37 m^2

40 MeV deuteron beam arrives from this direction



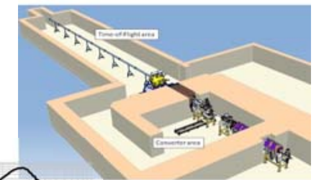
Part of the DONES first floor plan (as in the PEDR)

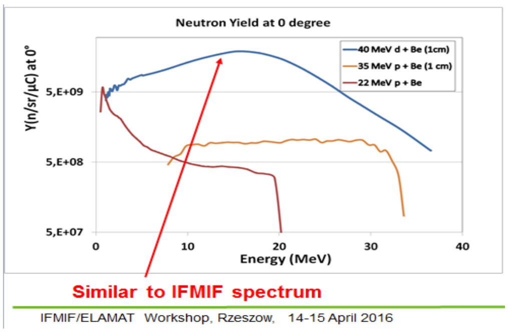
❖ **Ongoing discussion on shielding, arrangement of experimental setups in R160**

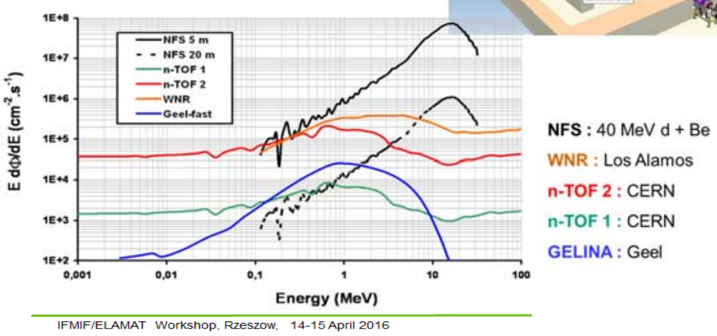
❖ **Other remaining proposals** (deuteron beam kicker at 5 or 40 MeV) **are on-hold** pending feasibility confirmation and external user interest

For comparison: NFS Neutrons for Science facility at GANIL

40 MeV deuteron or **33 MeV proton** beam from LINAG:
I = 50 μA – 5 mA, pulsed beam *T* = 11 ns
40 MeV d + Be, on rotating thick Be target (2000 rpm)







Courtesy of X. Ledoux and the NFS collaboration

A very rich nuclear physics program planned from 2018 onwards:

- Neutron induced reaction studies: (n,xn), activation and prompt spectroscopy
- Fission: distributions, neutron multiplicities, gamma-ray spectroscopy in induced fission
- Measurements of reaction cross sections by activation
- Biology, R&D for the production of isotopes for medicine
- Neutron detector development

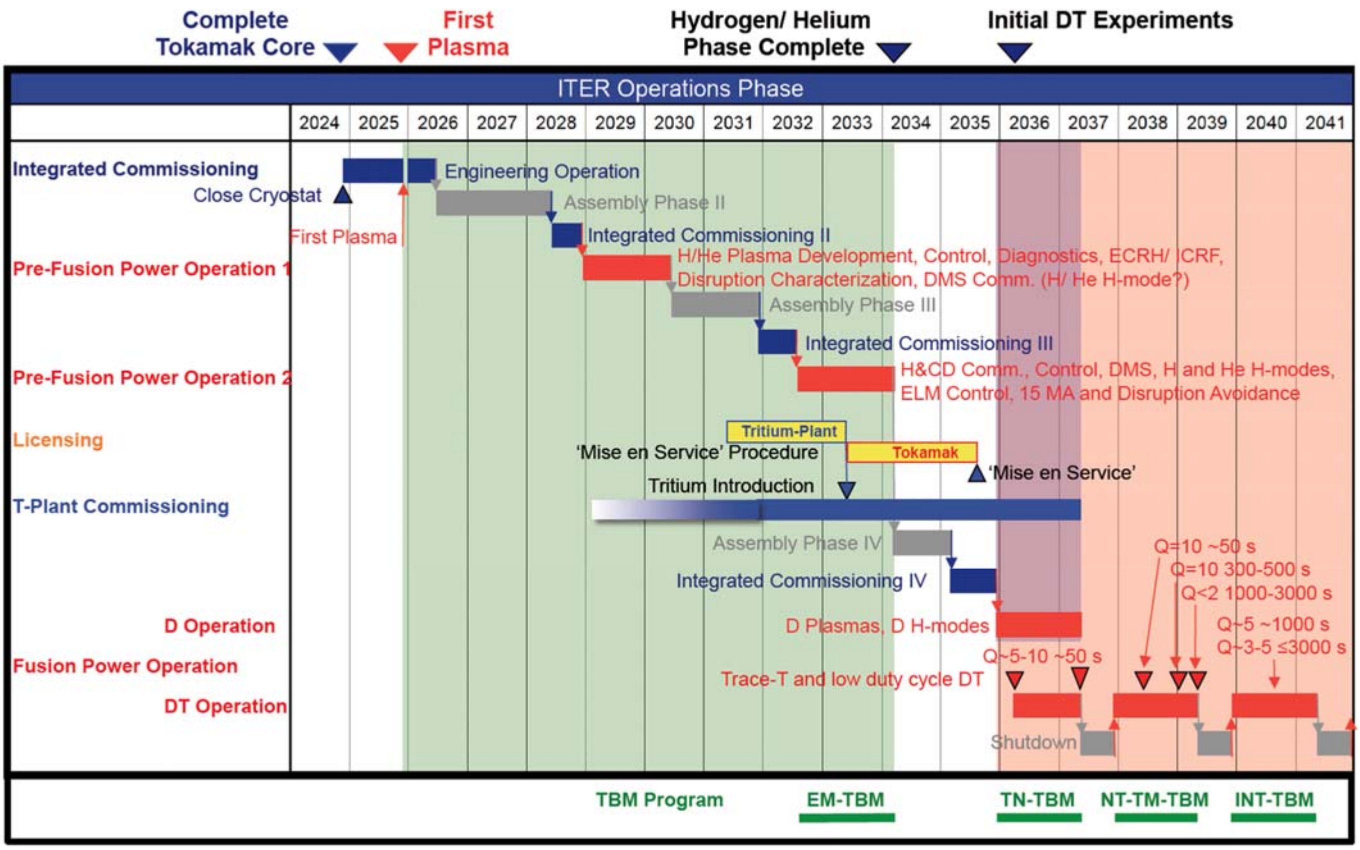
3.4.3-iii) Comment on the middle flux module: Takeo Nishitani (NIFS)

Comment on the middle flux module
- Proposal of the blanket functional tests -

Takeo Nishitani

[1]*National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan*

- **ITER program is delayed. Substantial TMB test is later than 2038.**
- **Nuclear functional test of the blanket is required much earlier.**



● **Tritium Release Test Module (from Intermediate Eng. Design Report)**

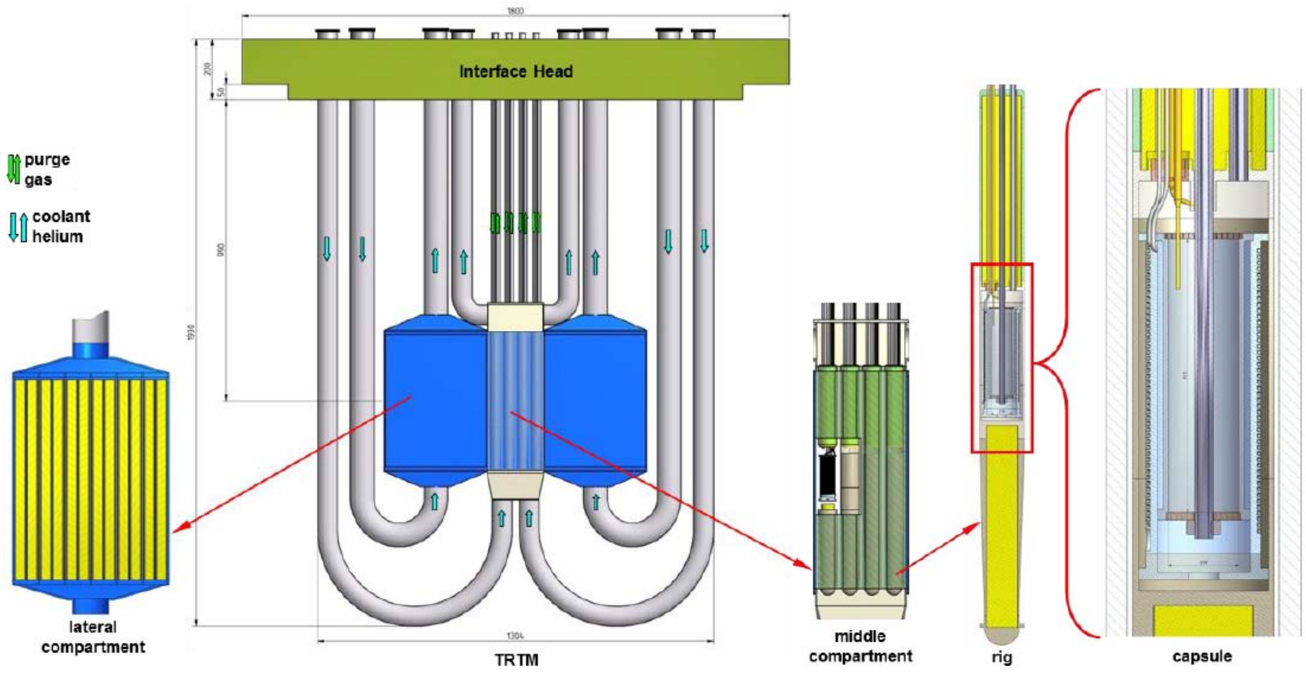


Figure 1: The TRTM system and its main components.

Comment and proposal

Partial model of the blanket or small scale blanket module should be considered.

- **for the blanket functional test, not only tritium release but also nuclear heating.**
- **to assess irradiation effect in the breeding/multiplying materials including impact on the tritium permeation**

3.4.3-iv) Tools and procedures for radiation damage modelling and intercomparison of experiments: Fernando Mota (CIEMAT)

Tools and procedures for radiation damage modelling and intercomparison of experiments

Fernando Mota, Christophe J. Ortiz, Rafael Vila

Laboratorio Nacional de Fusión – CIEMAT, 28040 Madrid, Spain

EUROfusion

Motivation: Calculation and comparison of radiation damage under DONES and Fusion conditions

- Goal of DONES: Test materials under equivalent neutron fusion irradiation conditions
- **Will IFMIF-DONES produce similar radiation damage to DEMO ?**
- Then our main objective is to identify in which conditions two neutron irradiation experiments are equivalent.
- In order to compare the radiation damage induced by neutron irradiation experiments, several issues that affect the damage dose in the materials have to be considered:
  - **Calculation of the atomic displacement induced by neutrons**
    - Calculation of the PKA spectrum induced by different neutron sources (MCNP, NJOY, nuclear data libraries)
    - Calculation of the radiation damage associated to the PKA spectrum
  - **Simulation of thermally-activated processes during irradiation**
    - Identification of atomistic mechanisms and impurities (He, C,…) that play important role
    - Use of adequate kinetic models (diffusion equations, kinetic Monte Carlo, etc…)

- The root cause of the differences between neutron irradiation experiments
  - Total dose
  - Neutron spectrum
    - Gas production (H, He)
    - PKA spectrum - primary damage and clustering
    - Transmutation Impurities could affects to the macroscopic properties

- The root cause of the differences between ion irradiation experiments and neutron irradiation experiments
  - Damage dose rate is different
  - The PKA spectrum is different
  - The volume of irradiation is different (The damage induced by ions is more concentrated than the one induced by neutrons)

- But, the most import issue is to identify why all these previous parameters produce different damage. To find the most important magnitudes to compare.

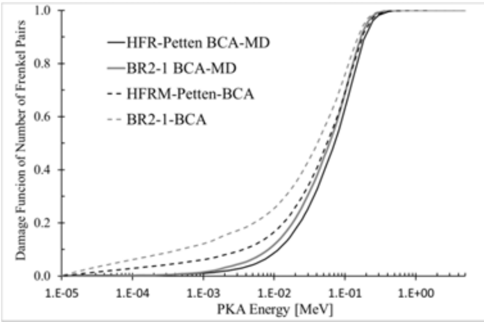
How to compare irradiation experiments

- The dpa is widely used to characterize the primary displacement damage induced by neutron, but currently, there are several concepts of dpa.

  - **dpa_{NRT}**
  - **$dpa_{arc\text{-}dpa}$**
  - **dpa_{BCA}**

  Therefore, we have to be careful when we use them because the comparison of different irradiation experiments using different dpa concepts could give contradictory conclusions.

  In addition, any dpa concepts only give information about point defects



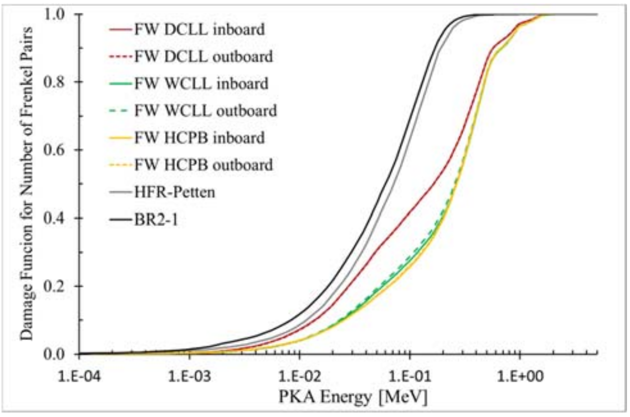
- Therefore, more information about the primary damage would be desirable to compare irradiation experiments
  - In order to give more information to the comparison of irradiation experiment We have developed a methodology coupling BCA-MD (BCAMD-CIEMAT methodology) to compare irradiation experiments in order to compare damages functions taking into account:
    - Number of defects (Frenkel pairs) – $dpa_{BCAMD\text{-}CIEMAT}$)
    - Fraction of defects in clusters
    - Size distribution of clusters

Therefore, this technique will give valuable information which could help to design more reliable nuclear fusion equivalent irradiation experiments to test materials.

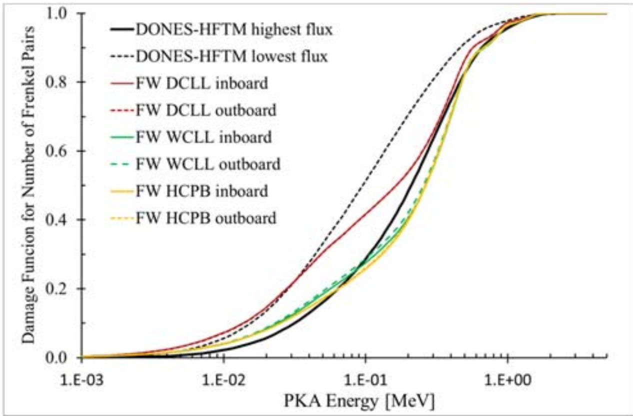
Results with BCAMD-CIEMAT

The damage functions of number of Frenkel Pair for different DEMO concepts (DCLL, WCLL, HCPB), IFMIF-DONES and nuclear fission facilities (BR2, HFR-PETTEN) have been compared using this methodology

Comparison of different DEMO concepts with Fission facilities damage functions for Iron



Comparison of HFTM of IFMIF-DONES with different concept of DEMO (DCLL, WCLL, HCPB) damage functions for Iron



As it is expected, as results of the comparison of the damage function of iron for number of Frenkel pairs is that , DONES-HFTM resulting an excellent facility to reproduce nuclear fusion conditions for structural materials. Contrary to the results obtained for nuclear fission facilities.

Proposal

- Therefore, it is important to make a comparison of the different dpa concepts calculated for different irradiation facilities like fission reactor, spallation neutron sources, fusion facilities and DONES-HFTM in order to quantify how far are from each others.

- But the most important issue is to identify the minimum amount of parameters representative of the damage is needed to compare, with the aim to figure out whether two irradiation experiments are similar or not.

- In addition, to comment that the BCAMD-CIEMAT methodology could give valuable information to try to solve this question, whether two irradiation experiments are equivalent or not, because both, the defect formation calculation is more realistic and information about the clustering is provided.

3.5 Technical Session 4: Summary session

Summary: J. Knaster (F4E)

Summary

1st Workshop on neutron advanced sources and applications

We have had intense expositions of our projects

ADS

Fusion materials

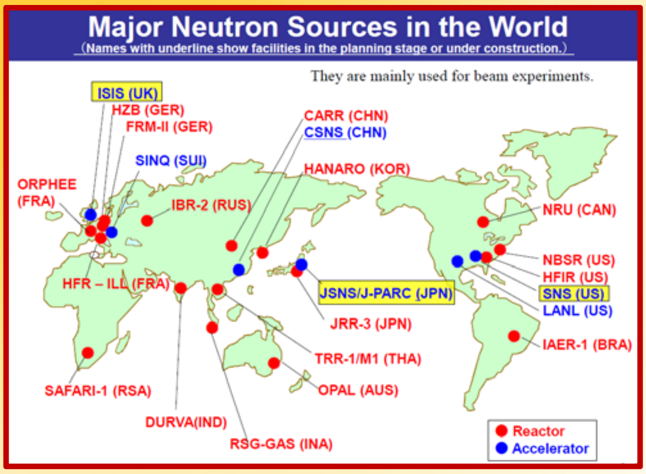
Transmutation

DT sources

BNCTs

we also had a beautiful summary of worldwide scenario

by Kiyanagi-san



We have seen many commonalities

On Accelerators

On Targets

Be, Hg, Li, tritium

Solid, liquid, gas

On Irradiation cells

I also trust that networking has grown

that was one of the objectives

Various issues possibly not properly covered

were grasped

simulations

testing specimens

dpas extrapolation

cavitation phenomena

alternative applications

new ways for beam footprints

additional damage scenarios of targets

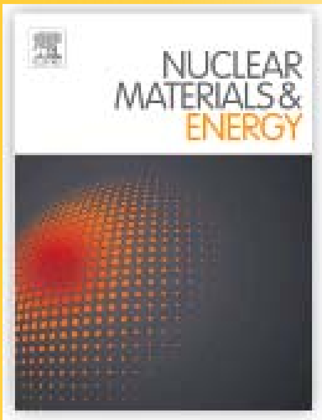
Time seemed short as per the topics addressed

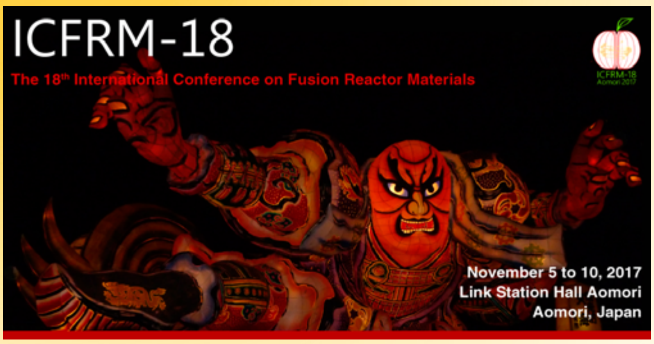
It is my perception that
this initiative should be repeated
and possibly grow in scope

we should also share more and more
not only our concerns
but also
the solutions found

IP matters are always controversial
but sometimes are artificial

We are willing to prepare an article
on the highlights and conclusions of our Workshop in





I have already sent to all of you by e-mail a zipped file
with all the slides
with the exception of
D-T neutron sources by Y. Wu (FDS)

Also we will prepare rapidly a weblink for an easy download

Thanks to
Ochiai-san
O'hira-san
Ibarra-san
Heidinger-san

For the nice initiative

And now Ibarra-san is going to say something…

4. Appendix

Workshop on Advanced Neutron Source and its Application
4-5 November, 2017
Aomori-city, Japan

Saturday, 4 November 2017 (@IFERC site and Festival city Auga)

(Technical tour to LIPAc)

8:30 Departing from Nebuta museum “WA RASSE” nearby Hotel Route Inn Aomori Station (See the detailed information)

10:00 Arriving the IFERC Site and tour to LIPAc

12:00 Departing the IFERC Site (Light meal will be provided at the site for lunch)

13:30 Arriving at Auga

(Main Meeting)

14:00 Opening (A. Ibarra, S. O`hira)

14:15 Technical Session 1: Users' perspective on neutron sources for materials development: T. Muroga (NIFS)

15:00 Technical Session 2-1: Presentations about the neutron sources developed or being developed (30 +10 min x 4 presentations) Chair: Shigeru O'hira (QST)

- DONES: A. Ibarra (CIEMAT)
- A-FNS: K. Ochiai (QST)
  (+ coffee break 15 min.)
- BISOL: Y. Wang (Peking Univ.)
- Neutron sources for transmutation of long-lived fission products: H. Okuno (Riken,)

18:00 Adjourn

19:00 Workshop dinner

Sunday, 5 November 2017 (@Link-Station Aomori)

9:30 Technical Session 2-2: Presentations about the neutron sources developed or being developed (30 min x 3 presentations + discussion) Chair: Juan Knaster (F4E)

- Neutron sources for transmutation applications (including MYRRHA): D. Terentiev, (SCK-CEN)
- D-T neutron sources (including HINEG, SORGENTINA, etc): Y. Wu (FDS)
- Present status of neutron sources development: Y. Kiyanagi (Nagoya Univ.)

11:30 Lunch

12:45 Technical Session 3: Panel Discussion on development of neutron sources

Chair: Angel Ibarra (CIRMAT)

High/Low power neutron sources (4-5 items, 10-15 min. each + discussion)

- Accelerator-related issues. *Promoter: F4E J. Knaster (F4E)*
  - Comparison of a few schemes of RFQ-based compact neutron sources: S. Kurokawa
  - High power linacs: J. Knaster (IFMIF/EVEDA)
- Target-related issues. *Promoter: K. Ochiai (QST)*
  - Design and technical challenges of Li target for IFMIF-based neutron sources by D. Bernardi (ENEA)
  - Target challenge for High power compact accelerator based neutron source; as status of the iBNCT: the heat issue and blistering T. Kurihara (iBNCT)
  - Present status of neutron target on J-PARC Presentaer: T. Naoe (JAEA/J-PARC)
- Irradiation area- related issues. *Promoter: F. Arbeiter (KIT)*

(4-5 items, 10-15 min. each + discussion)

(+ coffee break 15 min.)

16:30 Technical Session 4: Summary session Chair: Kentaro Ochiai (QST)

- From IFMIF users committee: IEA/W-GIFT history and proposal (15 min.)*
  : E. Diegele (EUROfusione)
- Summary: *J. Knaster (F4E)*

17:30 Adjourn

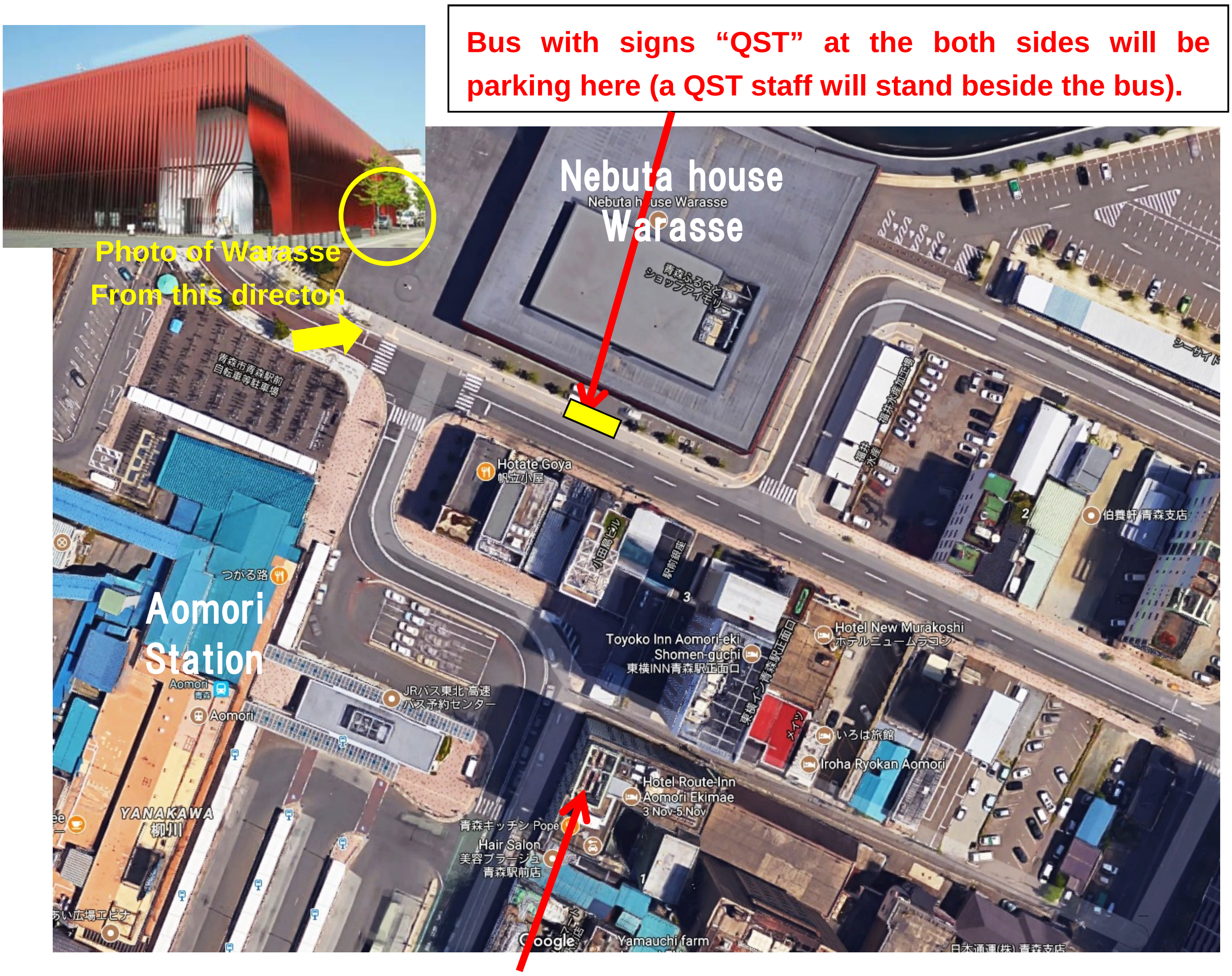
*: This presentation was resigned.

Detailed Information

for Workshop on Advanced Neutron Source and its Application

1. LIPAc Tour on 4th November

Bus for the tour will depart at 8:30 from the place shown in the following picture;



Hotel Route Inn Aomori Station

Tour Schedule:

8:30: Depart Aomori station (Warasse)

10:00 Arrive at the IFMIF/EVEDA Accelerator Building in QST Rokkasho Institute (IFERC site) and start LIPAc tour.

11:20 Lunch at Administration & Research Building (Lunch box)

12:00 Depart QST Rokkasho Institute

13:30 Arrive at Auga (the workshop venue on 4th Nov.)

2. Meeting venue on 4th November

Meeting Room (5F) @ Auga at 14:00-18:00
Workshop Dinner @ “Ichinosuke” at 19:00-21:00

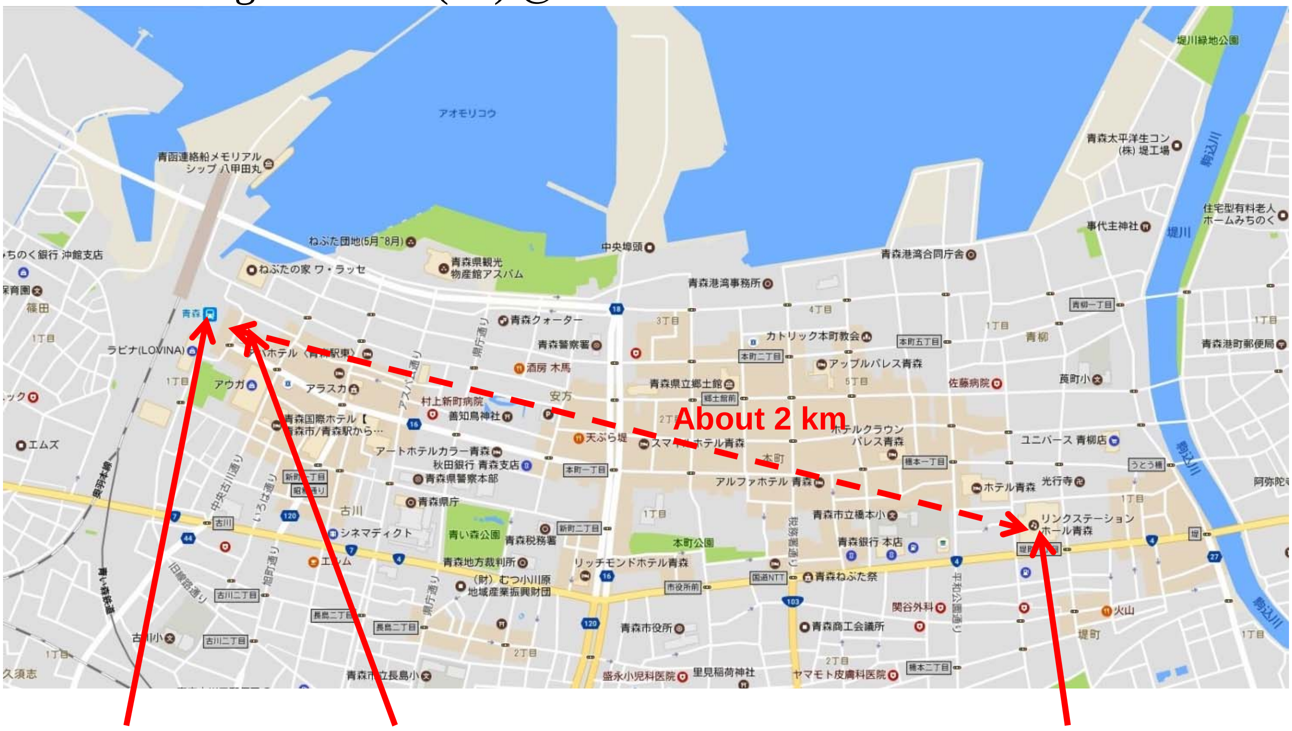
Hotel Route Inn Aomori Station

Enter here and go up to 5th floor by the elevator

Workshop dinner at “Ichinosuke” from 19:00

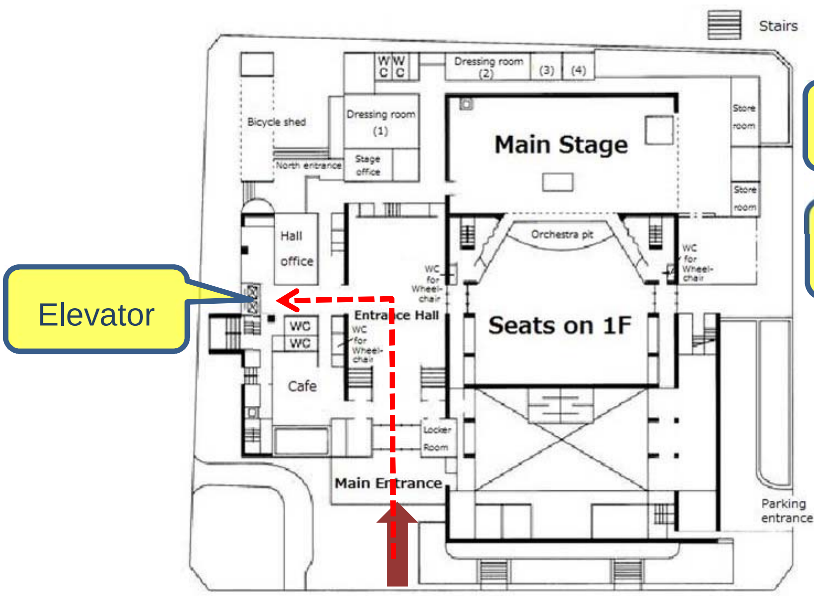
2. Meeting venue on 5th November

Small Meeting Room #4 (3F) @ Link Station Hall Aomori at 9:30-17:30

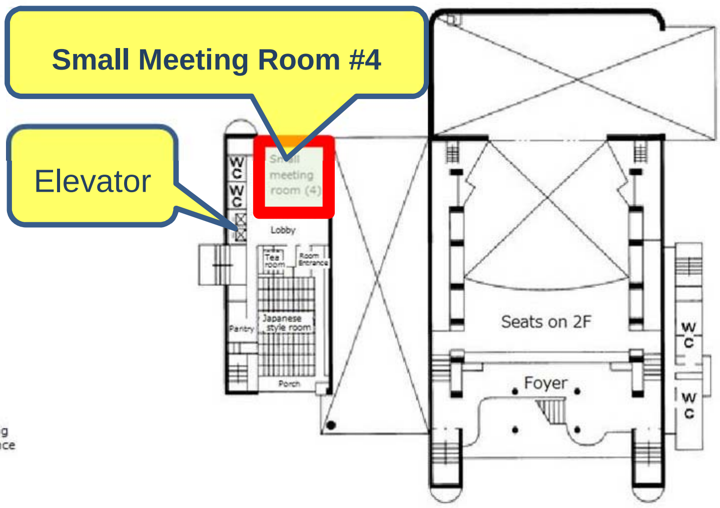


Aomori Station **Hotel Routeinn Aomori Station** **Link Station Hall Aomori**

It will take about 25 min by walk form Aomori Station to Link Station Hall Aomori, about 10 min by a taxi (about ¥1000 Yen) or bus (¥190 from bus stop #2 at the Aomori Station).
For the participants staying at Hotel Route Inn Aomori Station and hotels nearby, QST staff may arrange transportation to Link Station Hall Aomori depending on weather. Please get together at the lobby of Hotel Route Inn Aomori Station at 8:45 if you need that arrangement.
A lunch box will be provided for each participant at lunch time.



Link Station Hall Aomori (1st Floor)



Link Station Hall Aomori (3rd Floor)