Electrode-free Actively circulated liquid metal divertor (EF-ACLMD)

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Plan of the talk

1. Background
2. Original scheme, new scheme without electrode
3. Spontaneous toroidal rotation
4. MHD drag
5. Requirements
6. Particle control
7. Corrosion
8. Possible consequences of MHD instability
9. Discussion of experiments in QUEST
10. Summary

Background

- Power handling is a major issue in fusion reactor
  - Much more serious in DEMO than in ITER because:
    - x 6 more power but similar device size (Slim-CS) ; radiative cooling becomes increasingly difficult at high power:
      - The impurity concentration f_z required to radiate power P scales as P^2 (next slide)
    - RAFM must replace copper
- Concerns on tungsten:
  - Consequences after unmitigated major disruption (power handling, erosion, lifetime, impurity control)
  - DBTT~400° C becomes higher with neutron irradiation and hydrogen implantation (cracking?)
- *Strongly mobilized Liquid metal(LM) can be a better PFC?*

The impurity concentration f_z required to radiate power P scales as P^2

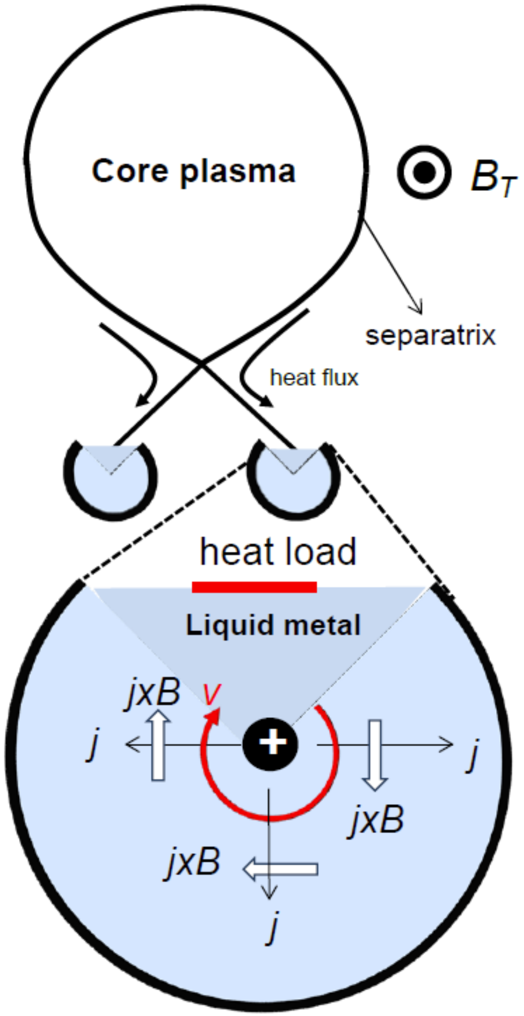
$$q_{//} \sim -T^{5/2}\frac{dT}{dx} \qquad \frac{dq_{//}}{dx} \sim -f_z n^2 L_z(T)$$

($q_{//}$: power density parallel to B)

$$q_{//\mathrm{up}}{}^2 - q_{//\mathrm{target}}{}^2 \sim f_z (nT)^2 \int_{T_{target}}^{T_{up}} \mathrm{T}^{1/2}\, L_z(T)\, dT$$

$\sim P^2$ $\qquad\sim 0$

Original scheme

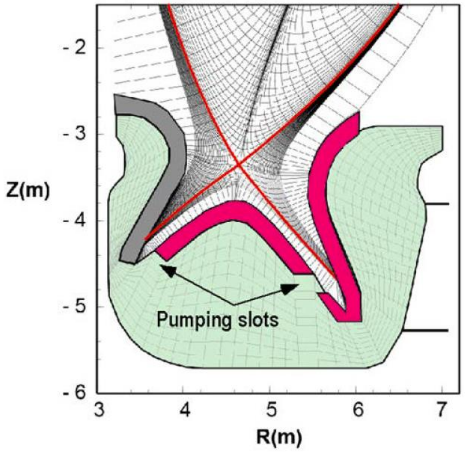


- The divertor plates are replaced with liquid metal (LM) in containers, equipped with electrode(s) and cooling tubes. *j* x *B* force drives the rotation of liquid metal, which distributes the heat to a wide area.
- Probably insulating plates (immersed in the LM) are necessary at multiple toroidal locations to avoid short-circuiting along the magnetic field and to reduce the toroidal current in the LM during the discharge start-up.
- Proof-of-Principle experiments were done (Hirooka's talk)

Shimada and Hirooka, Nucl. Fusion (2014)

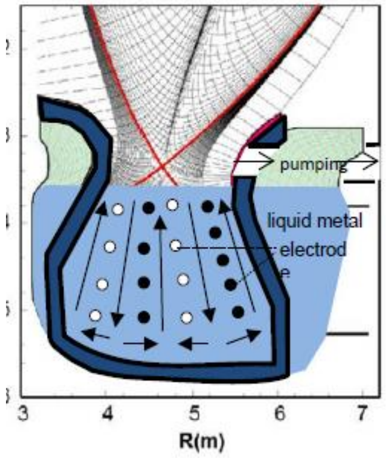
More compact and more simple

Conventional
divertor



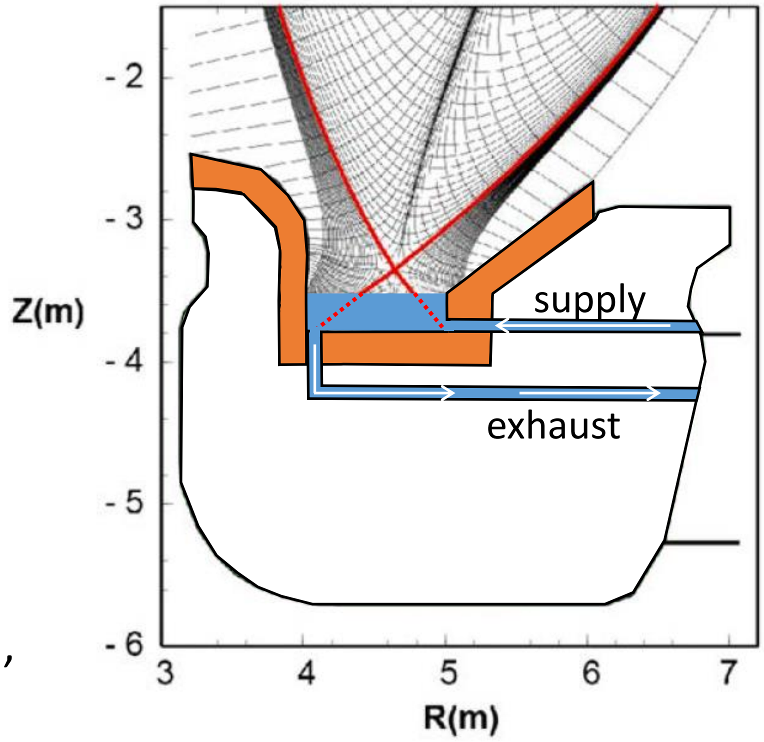
Slim-CS
Tobita, NF 2009

Original
ACLMD



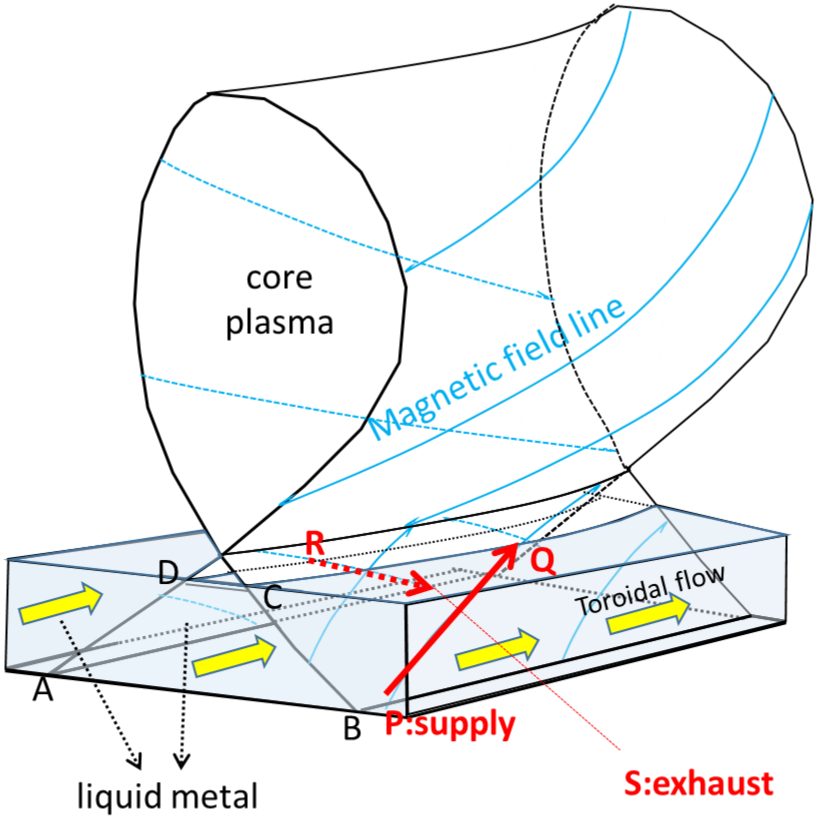
Shimada and Hirooka,
NF 2014

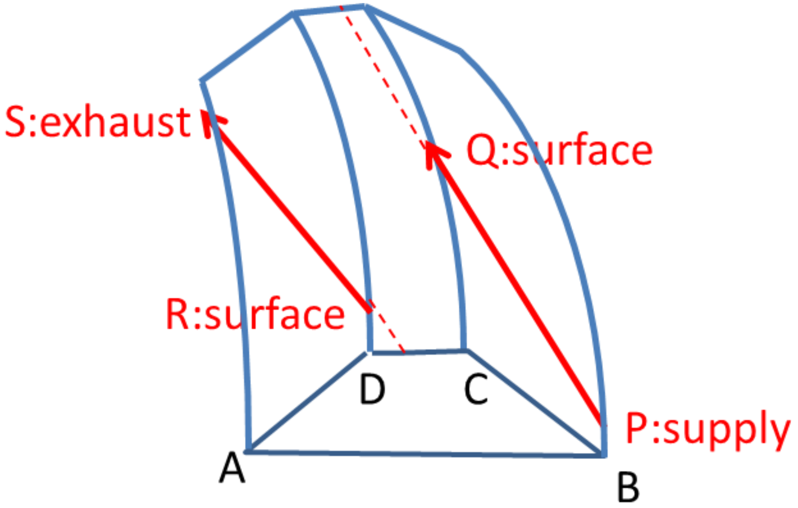
Electrode-free
ACLMD



More compact and more simple divertor could reduce cost, facilitate maintenance and improve reliability

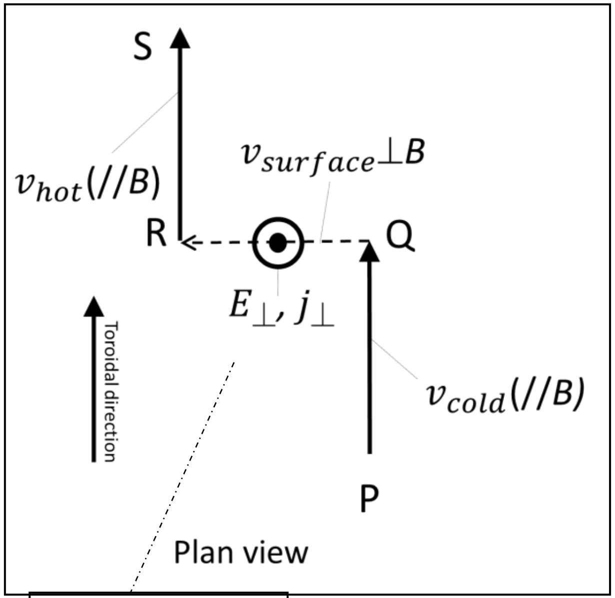
Because liquid metal (LM) tends to follow the magnetic field line, the LM connected to the exhaust line and the LM connected to the supply line flow along the field line, both in the same toroidal direction. As a consequence, viscosity could make the whole LM to rotate toroidally. The toroidal rotation would assure toroidal uniformity of the LM even with the limited number of exhaust and supply lines. The convection between Q and R (C and D) would be enhanced if the bottom plate (floor) of the LM container between A and B is electrically insulated. But some mhd drag would remain due to toroidal current (next slide).





Points A,B,C,D and P,Q,R,S in the right figure correspond to those in the left.

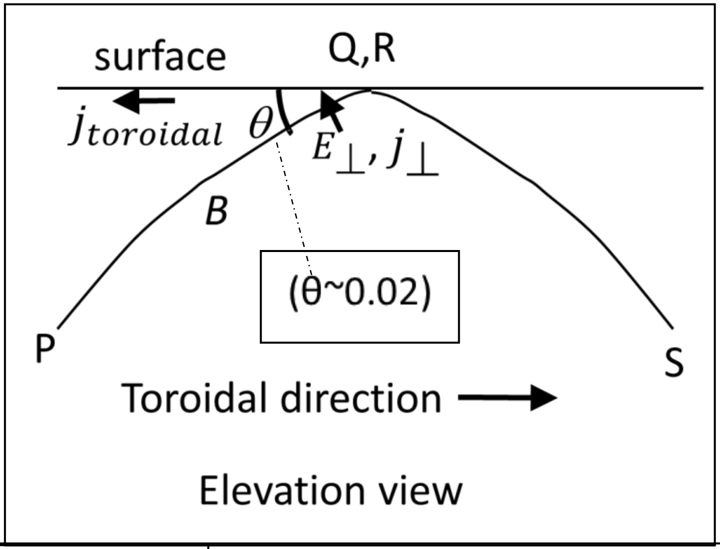
mhd drag due to toroidal current could be acceptable



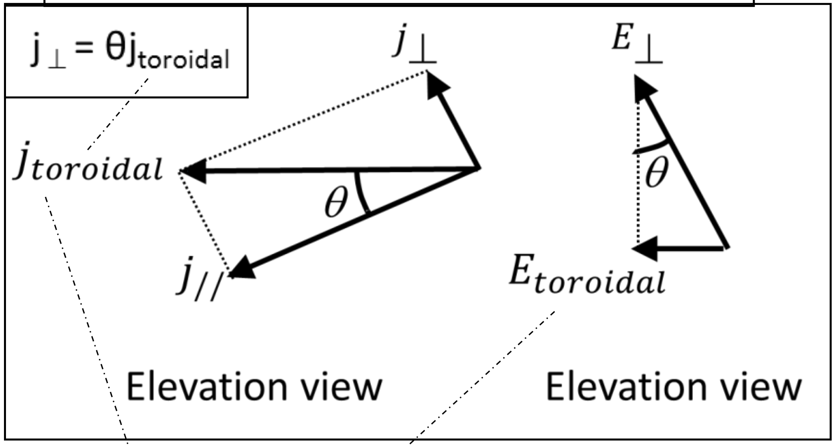
$E_\perp = v_{surface} x B$

$j_{toroidal} = \sigma E_{toroidal}$

$$F = j_\perp \text{ x } B\delta = \theta\, j_{toroidal}\, B\delta = \theta\, \sigma\, E_{toroidal}\, B\delta$$
$$= \theta^2\, \sigma\, E_\perp\, B\delta = \theta^2\, \sigma\, v_\perp \text{ x } B^2\delta$$
$$\sim (0.02)^2 \cdot 10^7 \cdot 0.3 \cdot 5^2 \cdot 0.05$$
$$\sim 1.5 \text{x} 10^3 \text{ Pa} \quad = 0.015 \text{ atm}$$
(δ: cross-field length)



$j_\perp = \theta j_{toroidal}$



$j_{toroidal} = \sigma E_{toroidal}$

LM flux required to remove heat

To remove power P(W) e.g. with **liquid tin** with mass density ρ(kg/m^3), specific heat C(J/kg/deg), flux f(m^3/s), temperature of supplied tin T_{in}(degree C), temperature of exhaust tin T_{out}(degree C),

$$P = \rho C f\,(T_{out} - T_{in})$$

We estimate the LM flux required to remove heat:

$$f = \frac{P}{\rho C(T_{out} - T_{in})}$$

e.g. With P = **500 MW**, ρ = 7 x 10^3 kg/m^3, C = 228.4 J/kg/deg, T_{out} = 400 ° C, T_{in} = 300 ° C: ***f* = 3.1 m^3/s**

If we supply SOLID tin at room temperature
(heat of fusion H_{melt} = 59.2 kJ/kg)

$$P = \rho f\,\{ C\,(T_{out} - T_{in}) + H_{\mathrm{melt}} \}$$

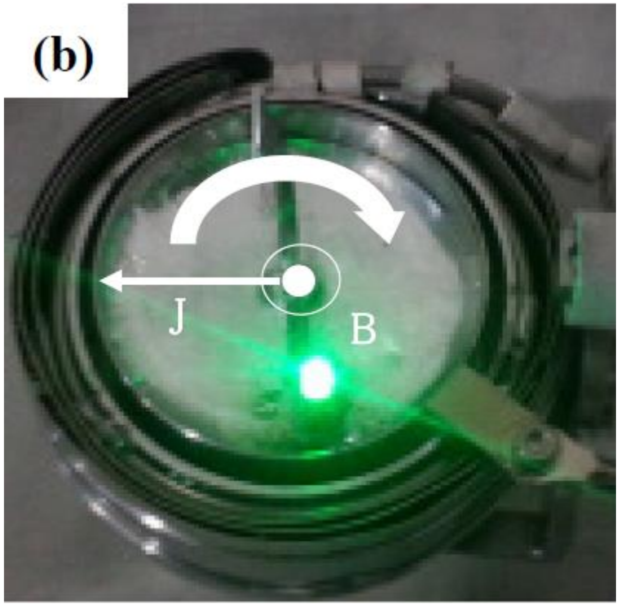
$$f = \frac{P}{\rho\{C(T_{out} - T_{in}) + H_{melt}\}}$$

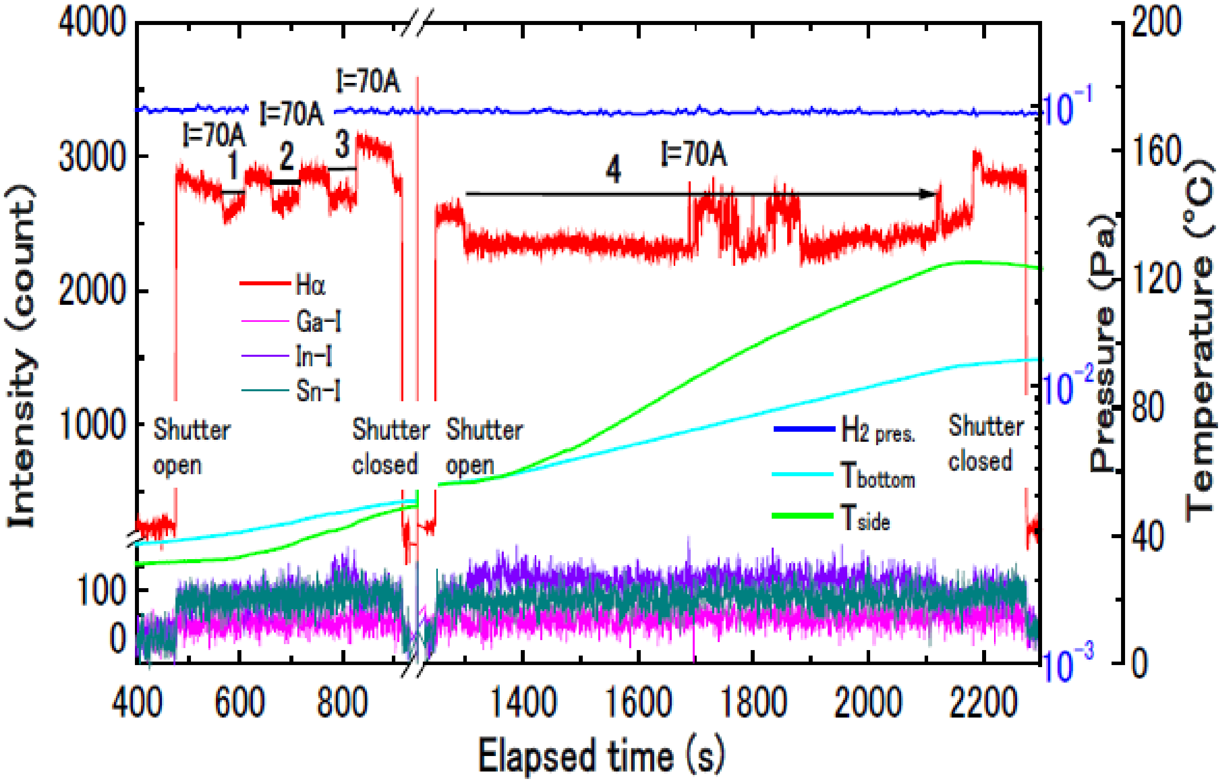
With T_{in} = 30 ° C: ***f* = 0.5 m^3/s**

Particle control with ACLMD is demonstrated

Active convection of LM by JxB force maintained reduced particle recycling condition for 800 s

⇒ ACLMD enables particle recycling control

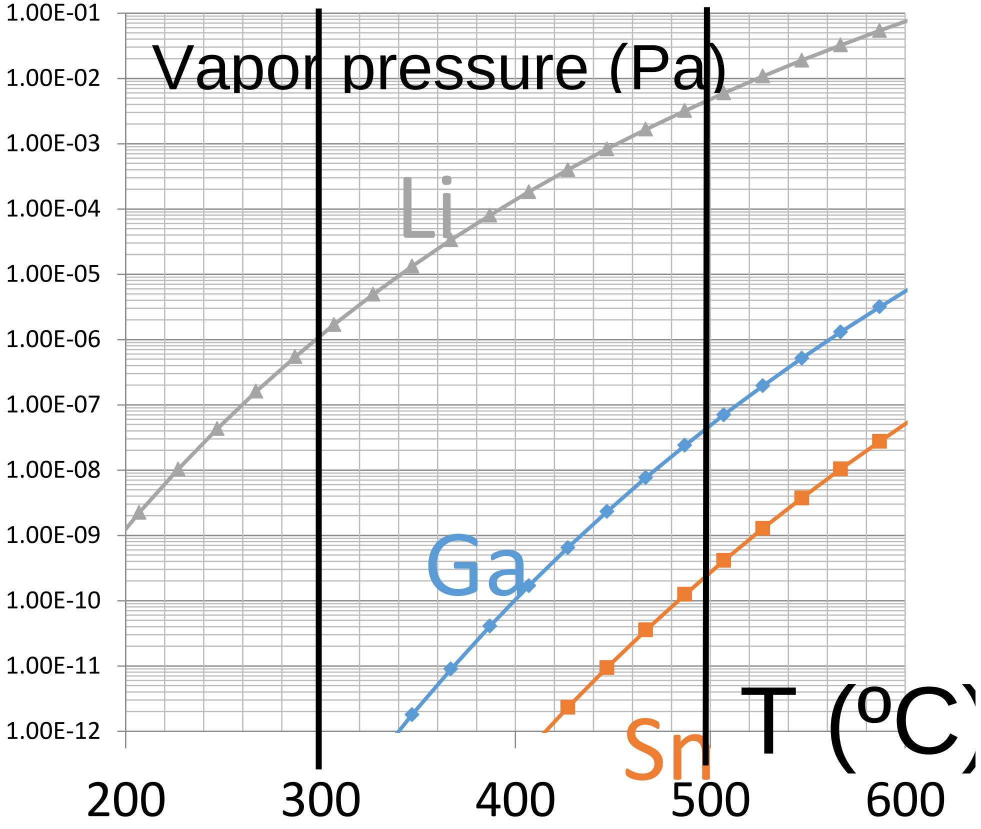




Hirooka, ISLA-4, to be published in FED

Vapor pressure of three liquid metals (Sn, Ga and Li)

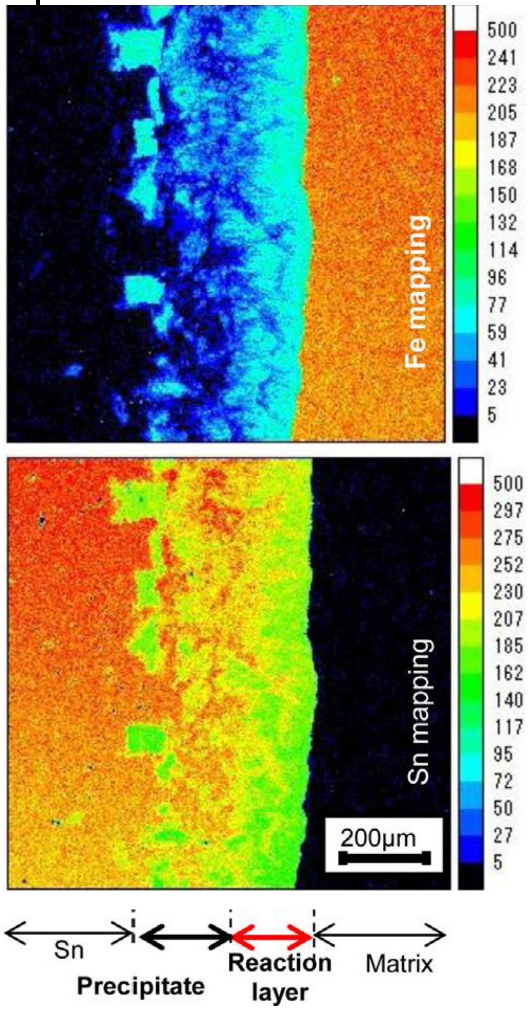
The vapor pressure would not be problematic for Ga and Sn, if the temperature is controlled below 500 ºC.



Michiya Shimada and Yoshi Hirooka, Nucl. Fusion 54 (2014) 122002

Corrosion is a problem at high temperature (600 C)

JLF-1 steel exposed to liquid Sn at 873 K for 250 h.

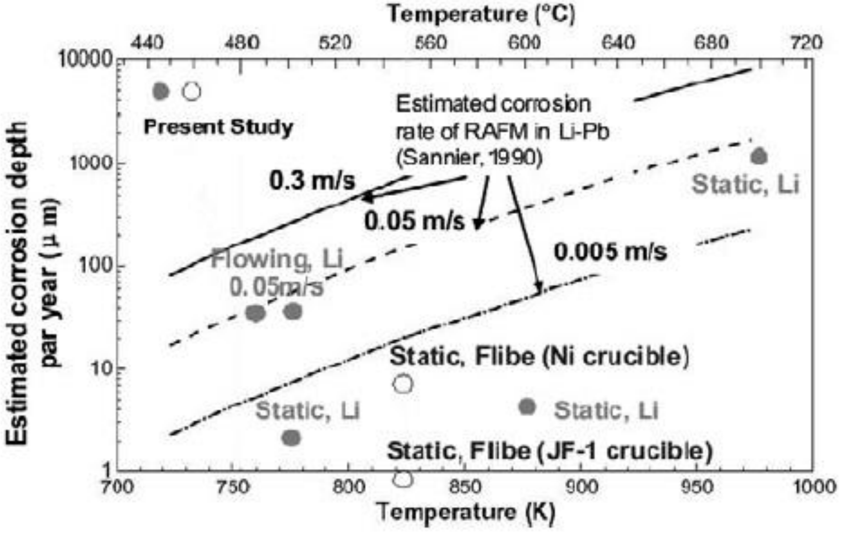


Kondo, FED (2015)

Temperature control is a key.

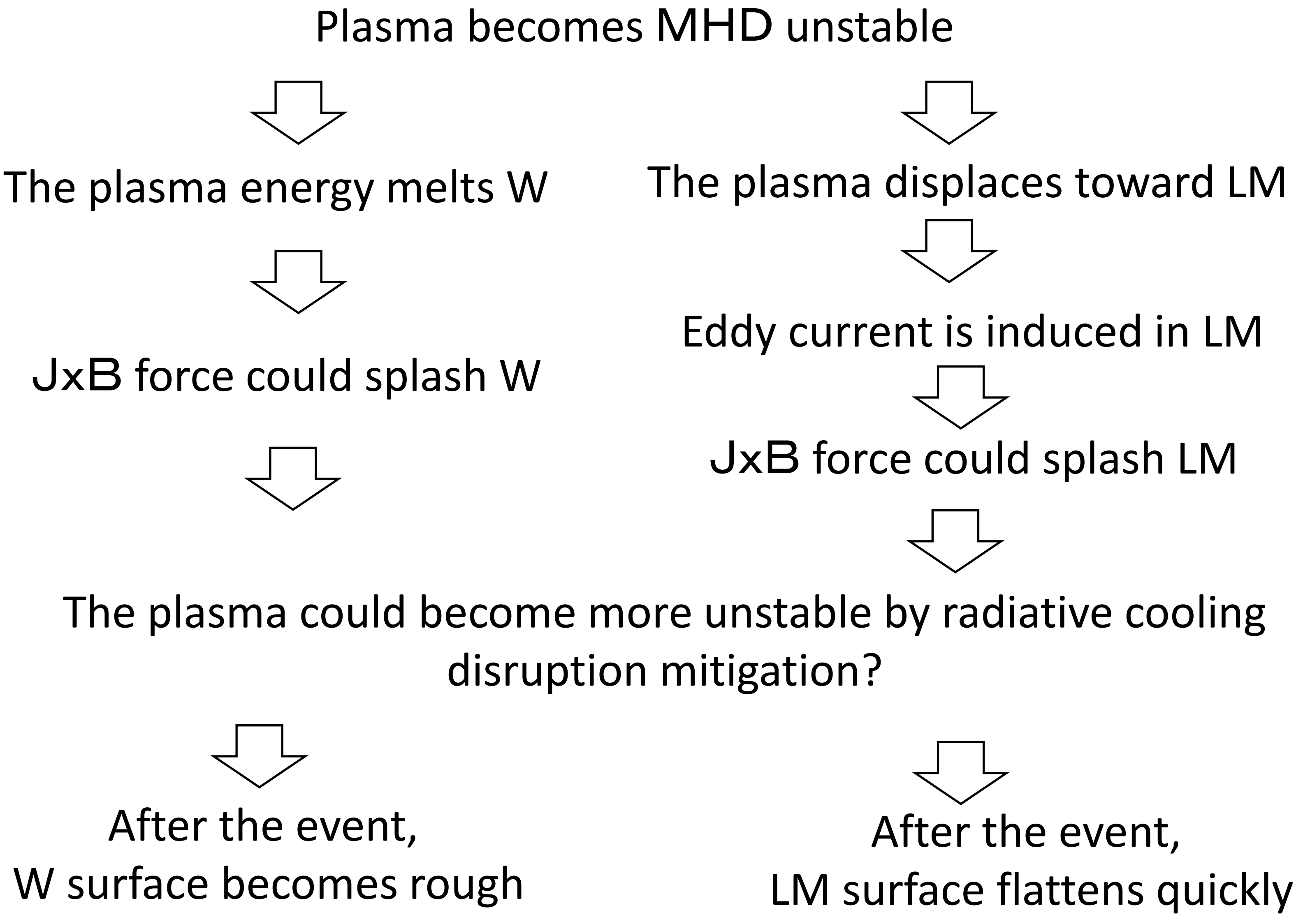
Reduction of corrosion is expected at lower temperature, but yet to be confirmed.

The effects of LM flow and B field are not yet confirmed.



Muroga, IAEA FEC (2008)

Possible consequences of MHD instability



Plasma becomes MHD unstable

The plasma energy melts W

JxB force could splash W

The plasma displaces toward LM

Eddy current is induced in LM

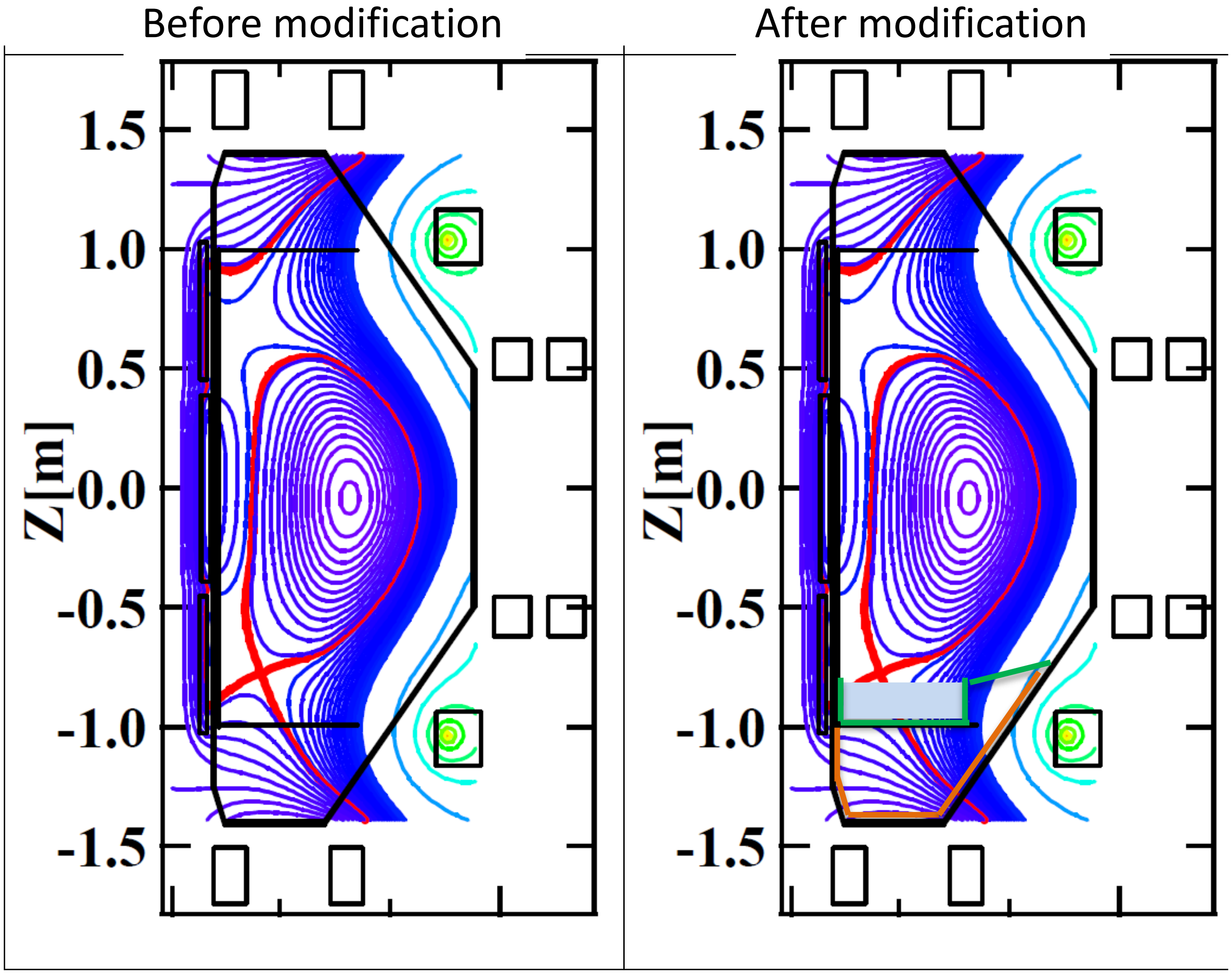
JxB force could splash LM

The plasma could become more unstable by radiative cooling
disruption mitigation?

After the event,
W surface becomes rough

After the event,
LM surface flattens quickly

Experiments in QUEST (RIAM, Kyushu Univ., baking temperature up to 500 °C) are being discussed



Summary

- ACLMD could provide high power handling and particle control in DEMO
- ACLMD is expected to be free from the consequences of disruption
- ACLMD could be made compact, reduce cost, facilitates maintenance and improve reliability
- Corrosion could be problematic at high temperature, making temperature control an important issue
- Experiments in QUEST are being discussed