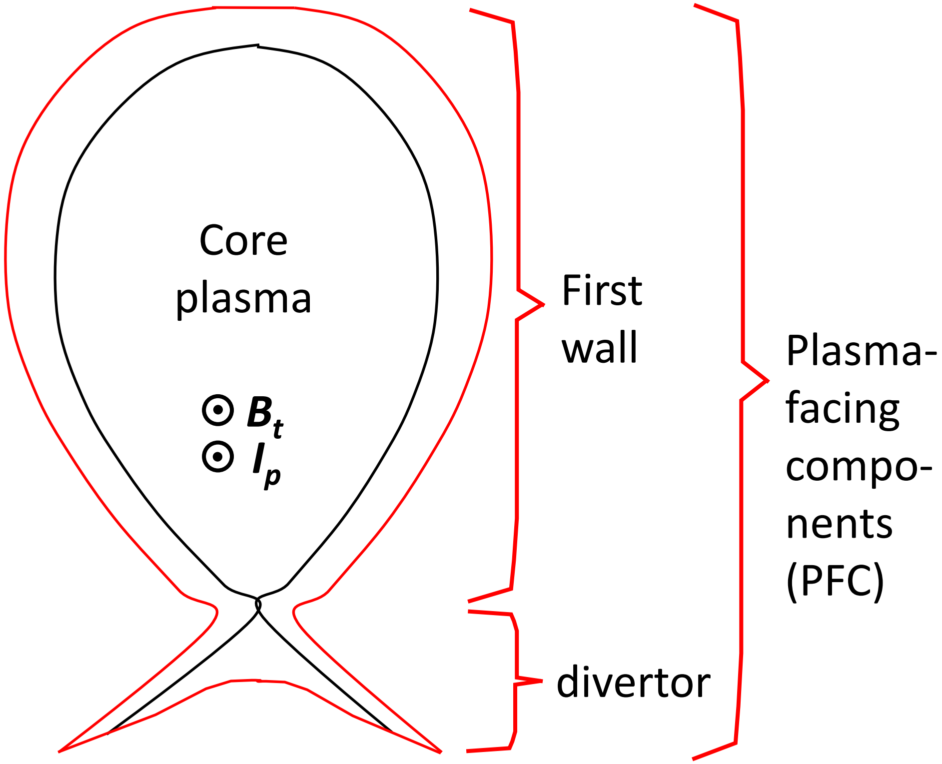
Magnetically-guided liquid metal divertor (MAGLIMD) with resilience to disruption and ELMs

Michiya Shimada
michiya.shimada@gmail.com

10th Anniversary QUEST Symposium
20 July 2018

Table of contents

Background-1

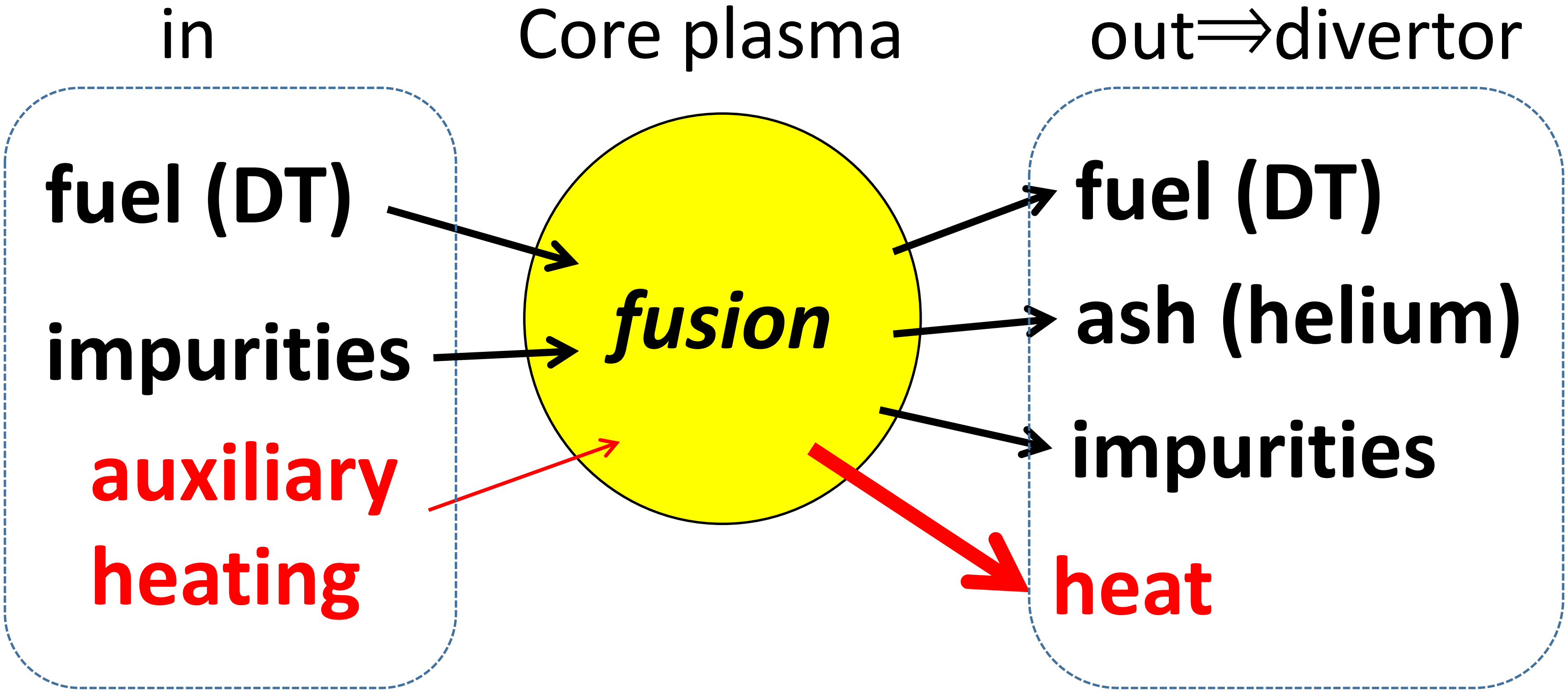


Goals of fusion research:

- Power-generating core plasma
  - High density (high Ip)
  - Good confinement (high Ip)
  - High purity (low impurity density)
- Stability
  - ***Hard to avoid disruption and ELMs***
  - ***Mitigation of consequences***
- Steady state (current drive (CD))
  - CD poses limits in Ip and density
  - Particle control is a key
- PFC compatible with the core
  - Limits in impurity ingression
  - Controlled surface temperature
    - Radiative cooling (impurity)
  - No melting or evaporation
  - Forgiving of transient heat load
  - Continuous wall conditioning
  - Long life

Function of divertor

The divertor "diverts" the power and particles coming out from the core plasma to a volume separated from the core. The divertor handles significant portion of the power and particles.



in

Core plasma

out⇒divertor

fuel (DT)

impurities

auxiliary heating

fusion

fuel (DT)

ash (helium)

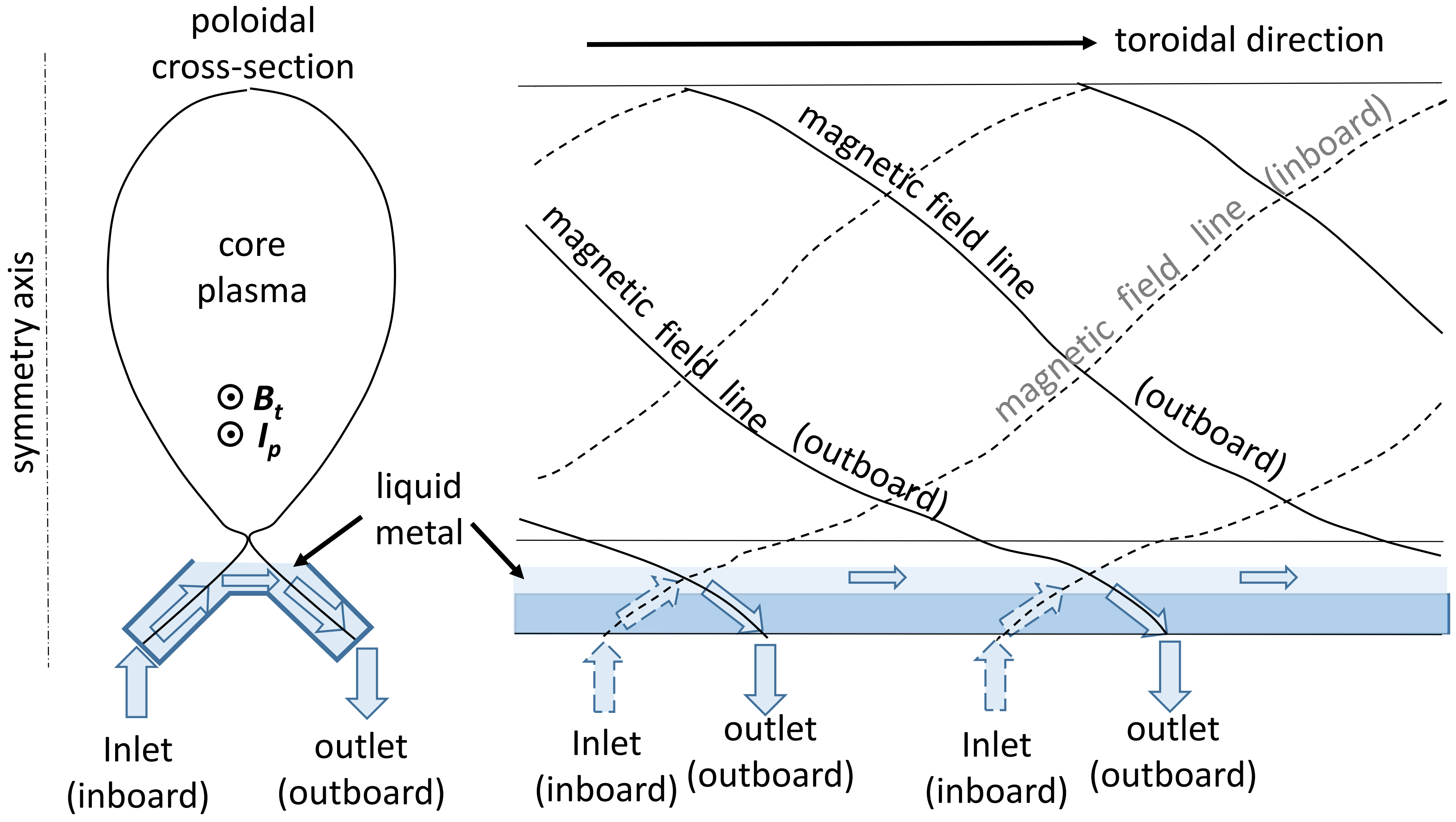
impurities

heat

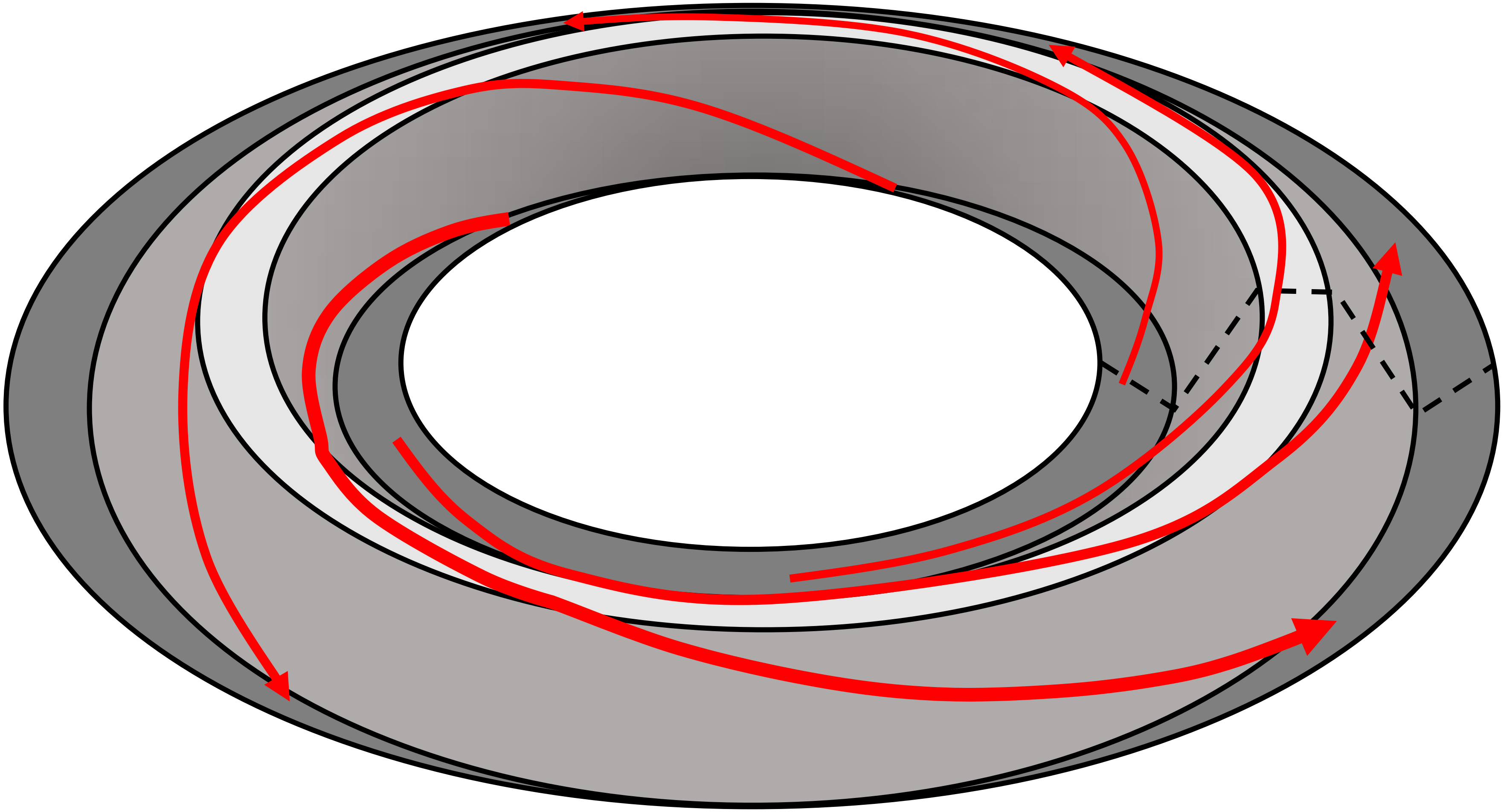
Background-2

- ***Power handling is a major issue*** in a fusion reactor
  - Much more serious in DEMO than in ITER because:
    - x 3–6 more power but a similar device size
- Concerns on tungsten:
  - DBTT˜400° C becomes higher with neutron irradiation and hydrogen implantation (cracking?)
- Disruption control, particularly **runaway electron suppression**, is a ***crucial and unresolved*** issue.
- Under the heat load of unmitigated disruption and ELMs, tungsten targets would melt and the rough surface after resolidification would deteriorate heat handling capability.
- Disruption prediction requiring learning process is difficult to implement, since **failure of disruption prediction during the learning process would lead to unacceptable consequences**; furthermore, ***ingress of first–wall debris is difficult to predict.***
- ***Strongly mobilized Liquid metal divertor** could provide a solution to some or all of the issues above*

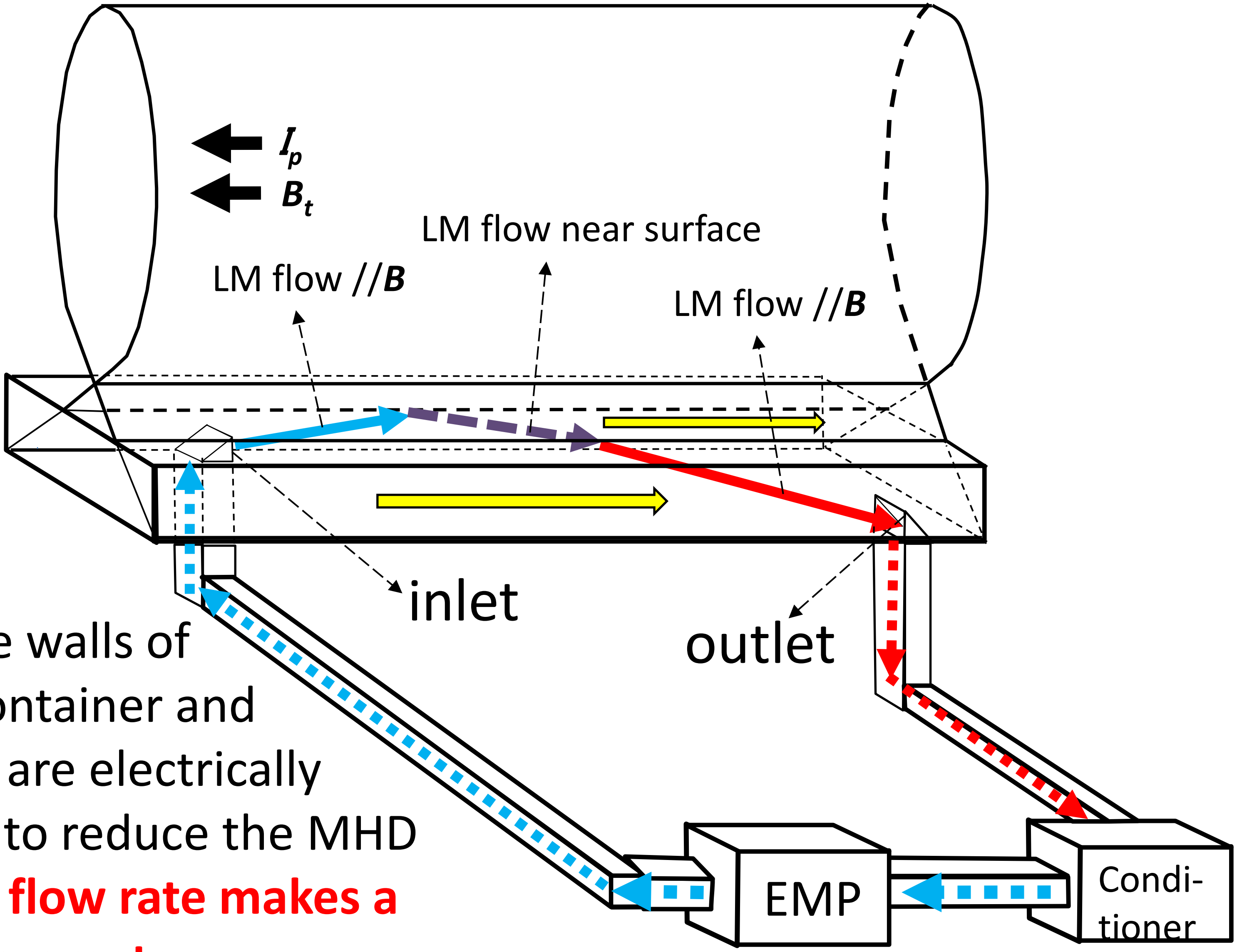
A tokamak with MAGLIMD (Magnetically-guided liquid metal divertor)



Bird’s eye view of MAGLIMD and flow pattern



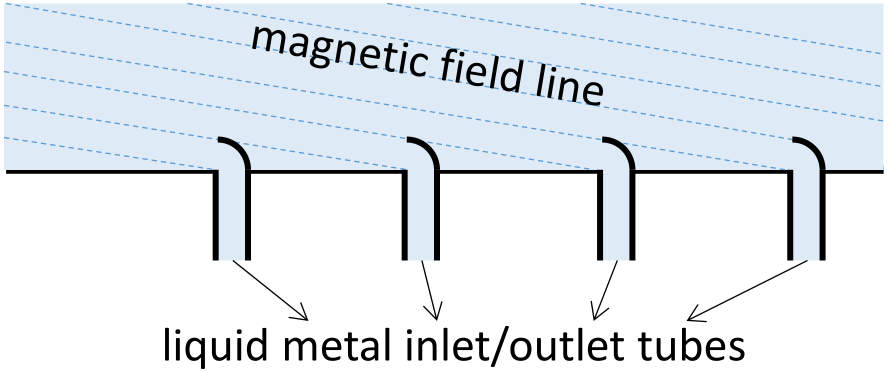
Magnetically-guided liquid metal divertor (MAGLIMD)



The inside walls of the LM container and the ducts are electrically insulated to reduce the MHD drag. **The flow rate makes a control parameter.**

EMP: electromagnetic pump

Toroidal uniformity



In a fusion reactor, where the divertor configuration is fixed and the field line in the LM divertor forms a grazing angle to the surface, inlet/outlet openings can be arranged in such away that there appears no toroidal gap on the LM surface despite the openings installed only discretely in the toroidal direction.

LM flow rate 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:

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

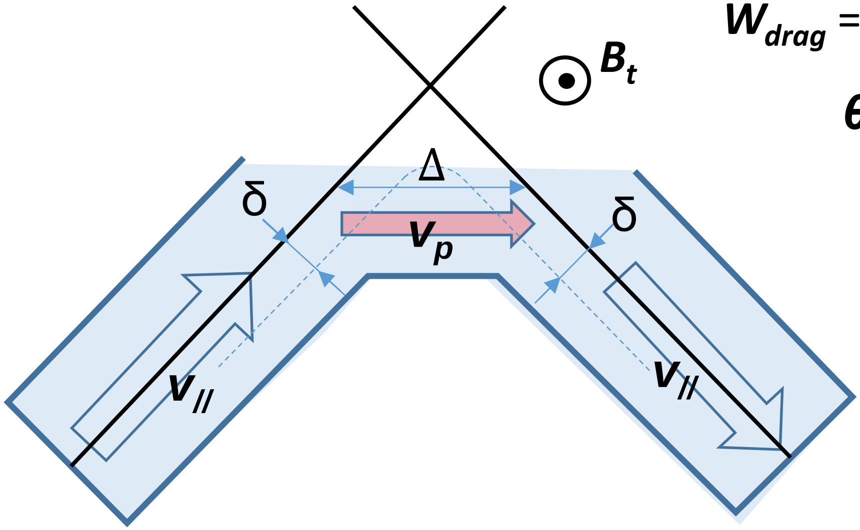
e.g. With P = **400 MW**, ρ = 7 x 10^3 kg/m^3, C = 228.4 J/kg/deg, T_{out} = 400 ° C, T_{in} = 300 ° C: **f = 2.5 m^3/s**

With an effective surface area of ~10 m^2 (50 m(toroidal) x 0.2 m(poloidal)), and the pitch of the field line $\boldsymbol{\theta}$ of 0.05, the parallel flow velocity $\boldsymbol{v}_{//}$ ~5 m/s.

The power $\boldsymbol{P_{drive}}$ required to drive the LM flow $\boldsymbol{f}$ against the gravitation force is given by: $\boldsymbol{P_{drive}} = \boldsymbol{\rho g h f} \sim 2$ MW

for $\boldsymbol{g}$ = 9.8 m/s^2 (gravitation) and $\boldsymbol{h}$ = 10 m (height of the divertor LM surface measured from the EMP). This power is negligible compared with the power the LM divertor will handle.

With all the insulated walls contacting LM, the remaining MHD drag stems from the $\boldsymbol{j_{toroidal}}$ x $\boldsymbol{B_p}$ force ($\boldsymbol{j_{toroidal}}$ is driven by the toroidal component of the ***v*** x ***B*** EM force)



The work done by the MHD drag W_{drag} can be estimated like:

$$W_{drag} = j_{toroidal} \times B_p\, 2\delta = \sigma\theta v_{\square} B \times \theta B\, 2\delta = \sigma v_{\square}\theta^2 B^2\, 2\delta$$

$$\theta = B_p/B, \text{ if we assume } v_{\square} \sim v_{//}\,\theta,$$

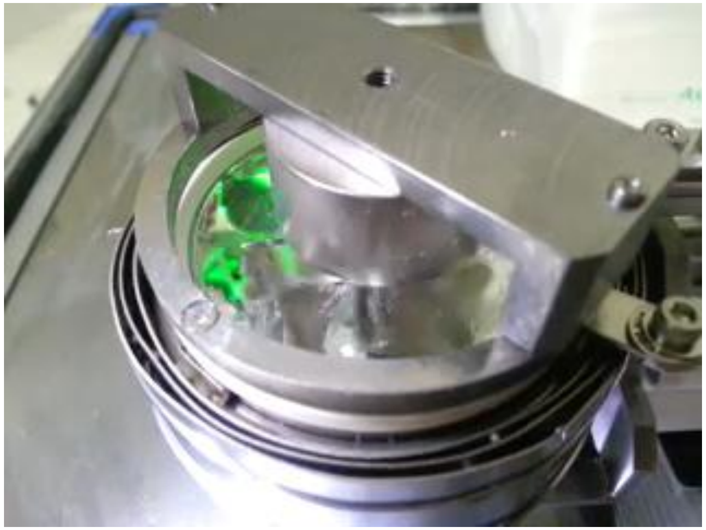
$$W_{drag} = \sigma\, v_{//}\, \theta^3 B^2\, 2\delta$$

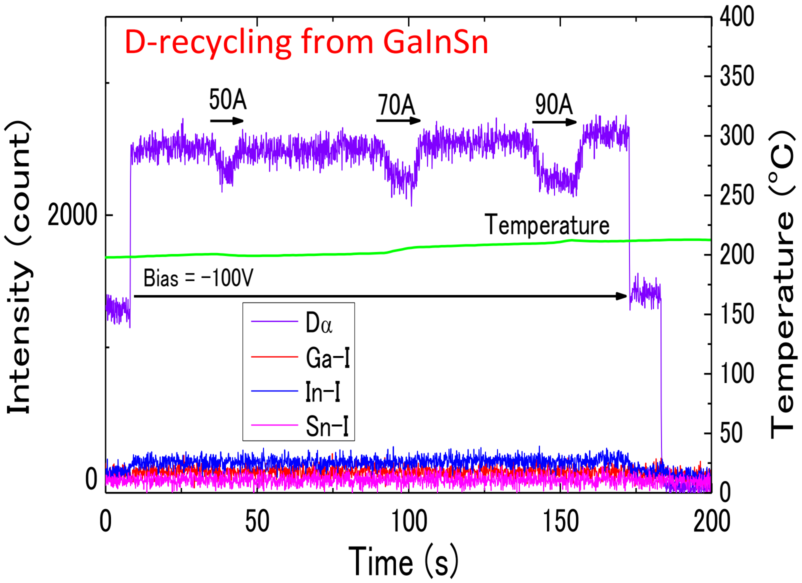
The work done by the centrifugal force W_{cf} can be made ***<u>stronger</u>*** than W_{drag}

$$W_{cf} = \rho\, v_{//}{}^2/R\ \ \Delta$$

$$\frac{W_{cf}}{W_{drag}} = \frac{\rho v_{//}\Delta/R}{\sigma\theta^3 B^2\, 2\delta} \sim \frac{7\text{x}10^3\text{x}5\text{x}0.2/8.5}{2\text{x}10^6\text{x}0.05^3\text{x}6^2\text{x}2\text{x}0.02} \sim 2$$

Particle control and wall conditioning





Hirooka, Fusion Eng. Design 117 (2017) 140

hydrogen removable with a flow rate of 2.5 m^3/s

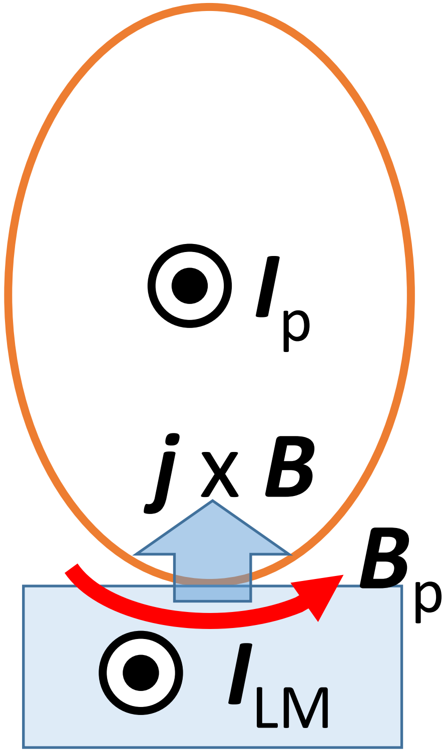
0.47×10^{-4} H/Sn x 2.5 m^3/s x 7 x 10^3 kg/m^3 /(0.119 kg/mol) x 6 x 10^{23}/mol /(5.3 x 10^{20}/Pam^3)= 7.8 x 10^3 Pam^3/s

(Particle exhaust rate in a reactor:100-200 Pam^3/s)

In JET-ILW experiments, wall conditioning was done every 200 shots（GDC）(Douai (2013))
⇒Steady state operation requires continuous wall conditioning ⇒MAGLIMD

Start-up and shutdown (1)

Limiter configuration



At the discharge start-up with limiter configuration, LM would be ejected if ***j*** x ***B*** force exceeds the gravitation.

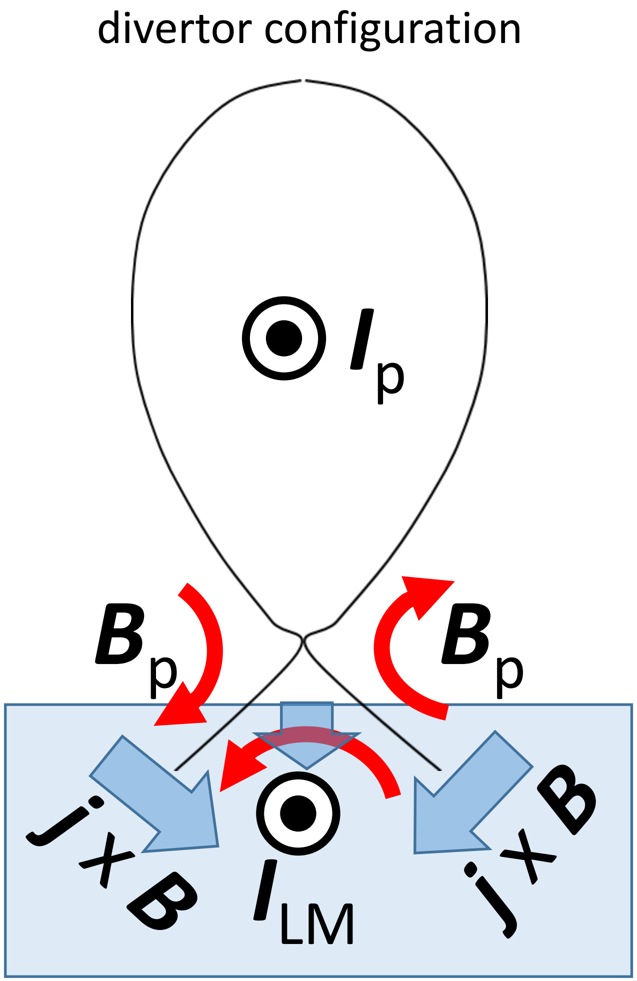
$$jB_p > \rho g,\ j \sim \sigma E$$

$$E > \frac{\rho g}{\sigma B_p}$$

$$E > \frac{7\times10^3\cdot9.8}{2\times10^6\cdot0.2} = 0.17\ \mathrm{V/m}$$

$B_p \sim 0.2$ T is assumed. At the discharge start-up, the minimum toroidal electric field is estimated to be ~0.3 V/m. At the start-up with limiter configuration, the divertor might have to be empty of LM. LM should be supplied into the divertor after the toroidal ***E*** field decreases below this level.

Start-up and shutdown (2)



At the discharge start-up with *divertor* configuration, current will be induced in LM in the same direction as the plasma current, but LM would *not* be ejected toward the core.

The induced LM current and the poloidal field from it would ***not*** disturb plasma operation.

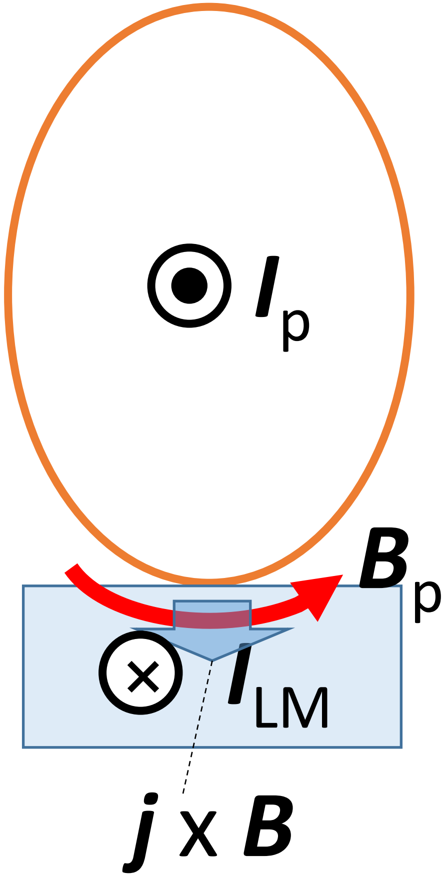
$$I_{LM} \sim \frac{\sigma V_l}{2\pi R} \cdot A_{LM}$$

$$I_{LM} \sim \frac{2\times10^6\cdot1}{2\pi\cdot8.5} \cdot 0.1 \sim 4\ \mathrm{kA}$$

Note that a typical poloidal coil current of a reactor is 10 MA-turn. One-turn loop voltage of 1 V and a poloidal cross section of the LM tray of 0.1 m^2 (e.g. 0.5 m wide and 0.2 m deep) are assumed.

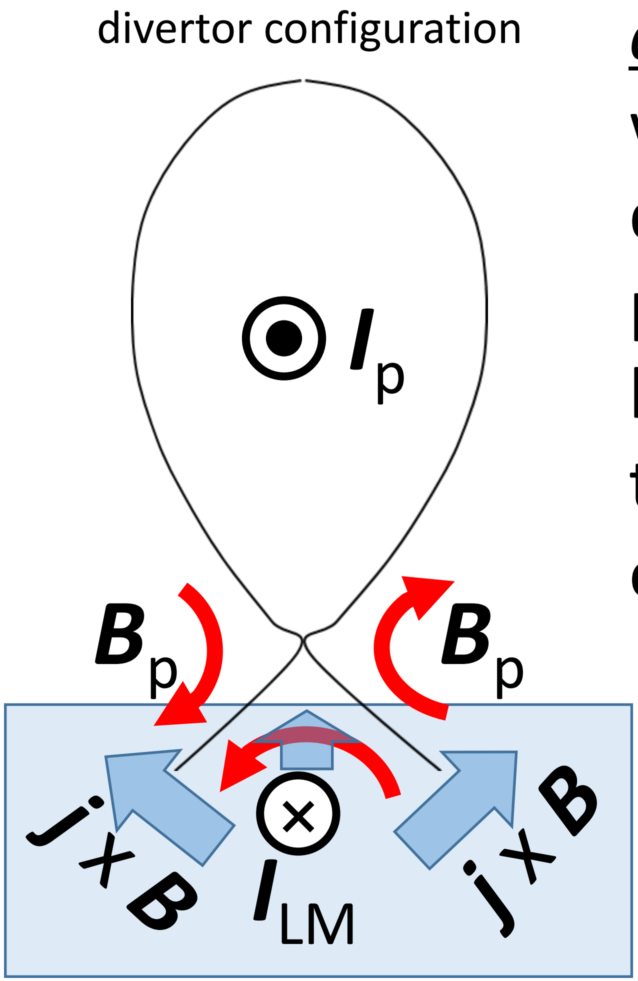
Start-up and shutdown (3)

Limiter configuration



At the discharge shutdown with *limiter* configuration, current is induced in the LM in the direction ***opposite*** to the plasma current. LM will ***not*** be ejected.

Start-up and shutdown (4)



At the discharge shutdown with *divertor* configuration, current will be induced in LM in the direction opposite to the plasma current. LM would *not* be ejected toward the core if the loop voltage does not exceed the following value.

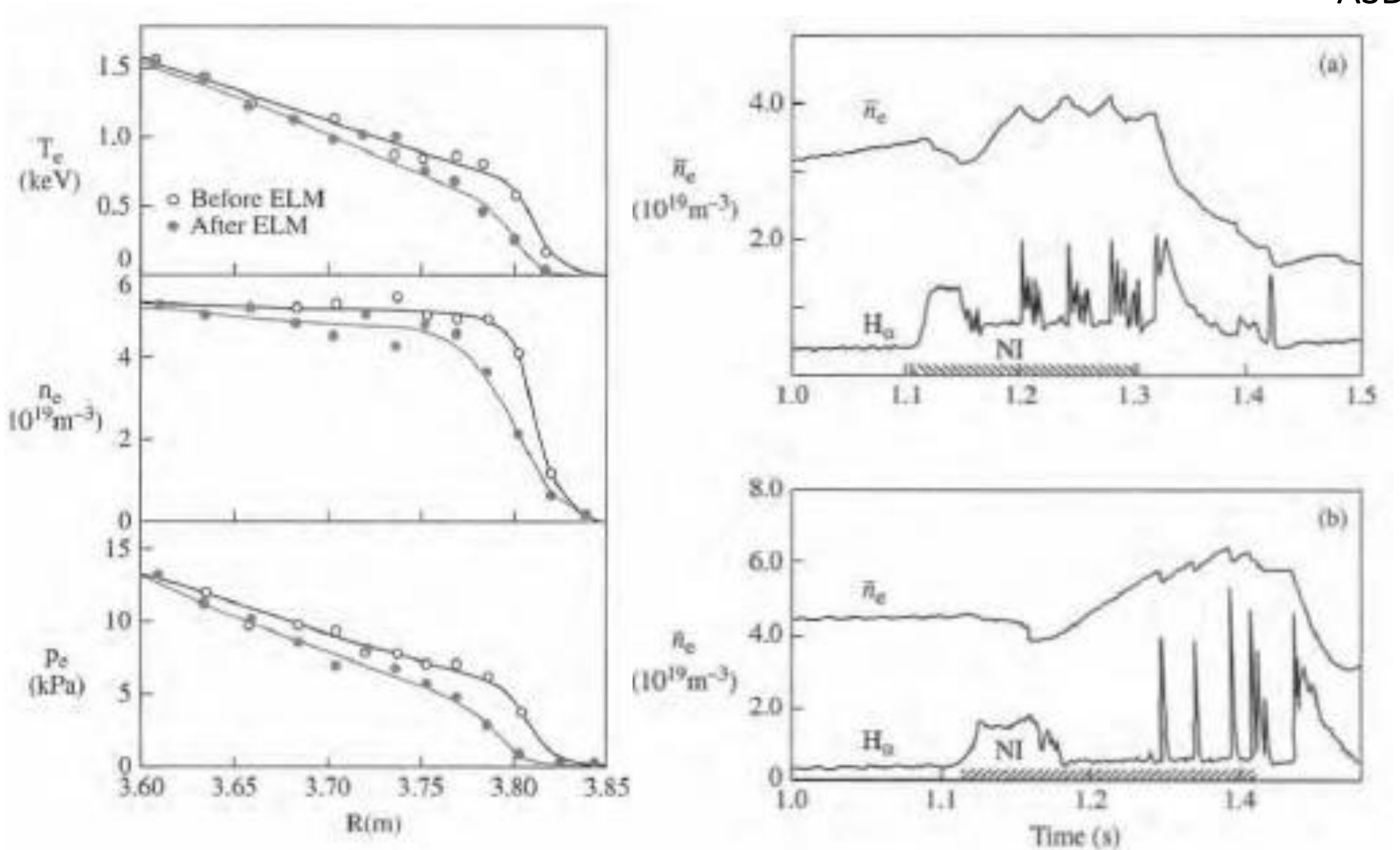
$$j\,B_p < \rho g,\ j \sim \sigma E \sim \sigma \frac{V_l}{2\pi R}$$

$$V_l < \frac{2\pi R \rho g}{\sigma B_p}$$

$$V_l < \frac{2\pi \cdot 8.5 \cdot 7\times10^3 \cdot 9.8}{2\times10^6 \cdot 0.2} = 9.2\ \mathrm{V}$$

Edge localized mode (ELM)

ASDEX

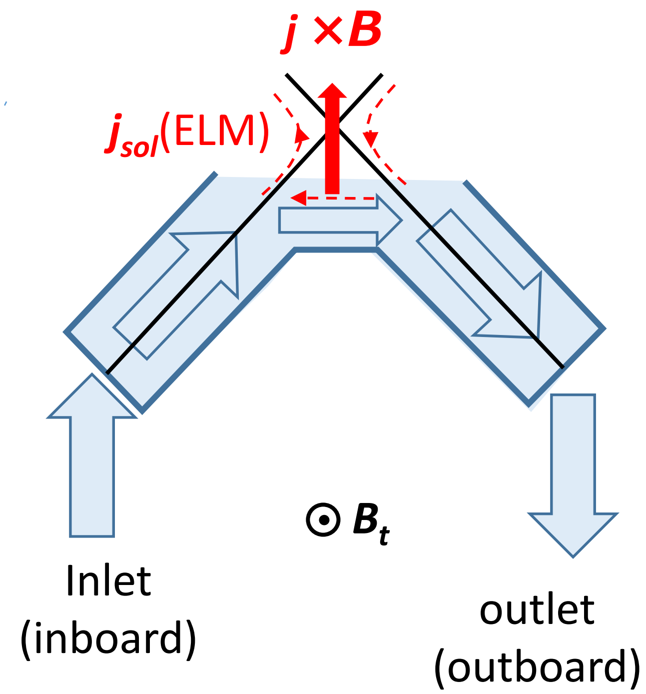


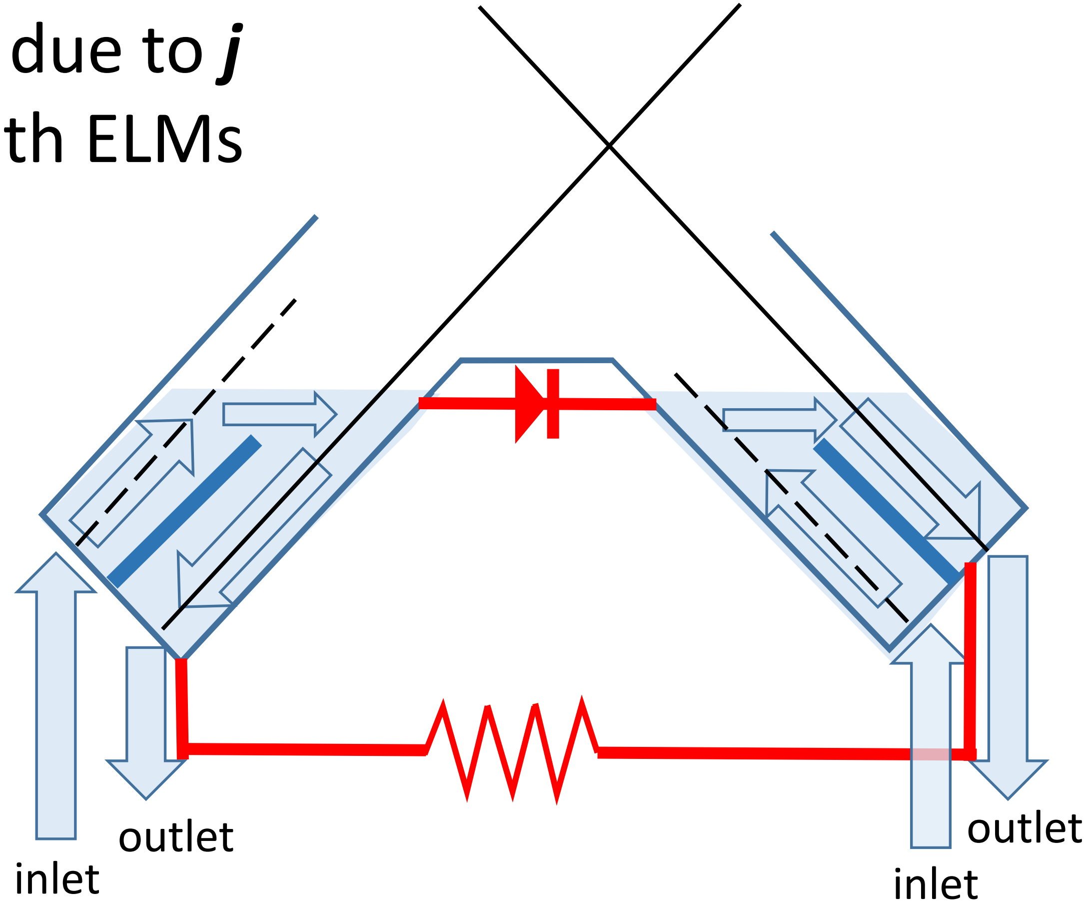
ELM can be triggered at the edge pedestal region, with a steep gradient of density, temperature and pressure, releasing a large amount of energy, which causes a large transient heat load on the divertor

Wesson Tokamaks

Electrically separating the inner and outer channels could make MAGLIMD **resilient to ELMs**

The original scheme might be vulnerable to splashes due to ***j*** x ***B*** force associated with ELMs



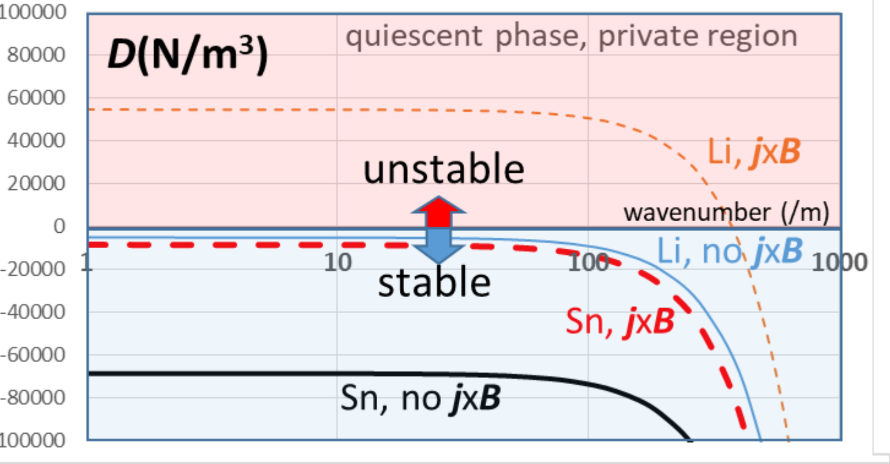


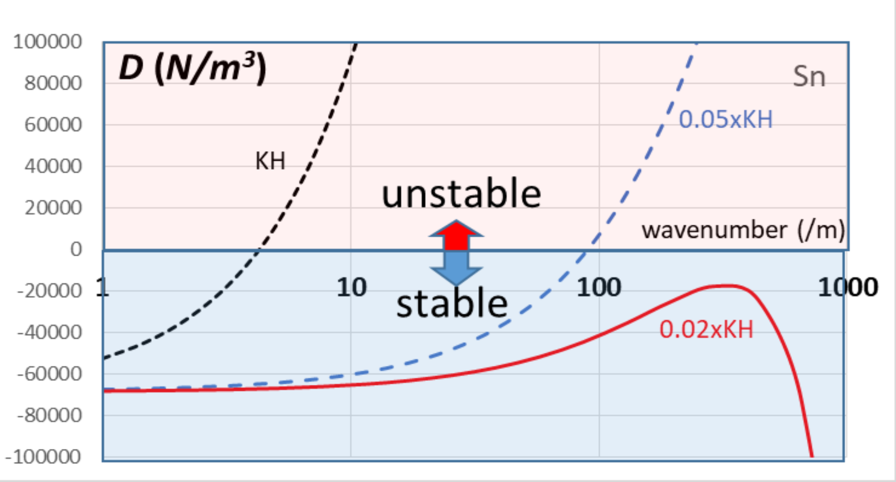
Rayleigh-Taylor and Kelvin-Helmholtz instabilities

$$D = -\rho g + (j \times B)\cdot n - \gamma k^2 + p_p k$$

D>0: unstable, D<0: stable. The first term: gravitation force. The second: ***j*** x ***B*** force (vertical component). The third: surface tension. The last: KH driving term. $\boldsymbol{p_p}$ is plasma pressure at the sheath. ***k*** is the wavenumber perpendicular to B (most unstable).

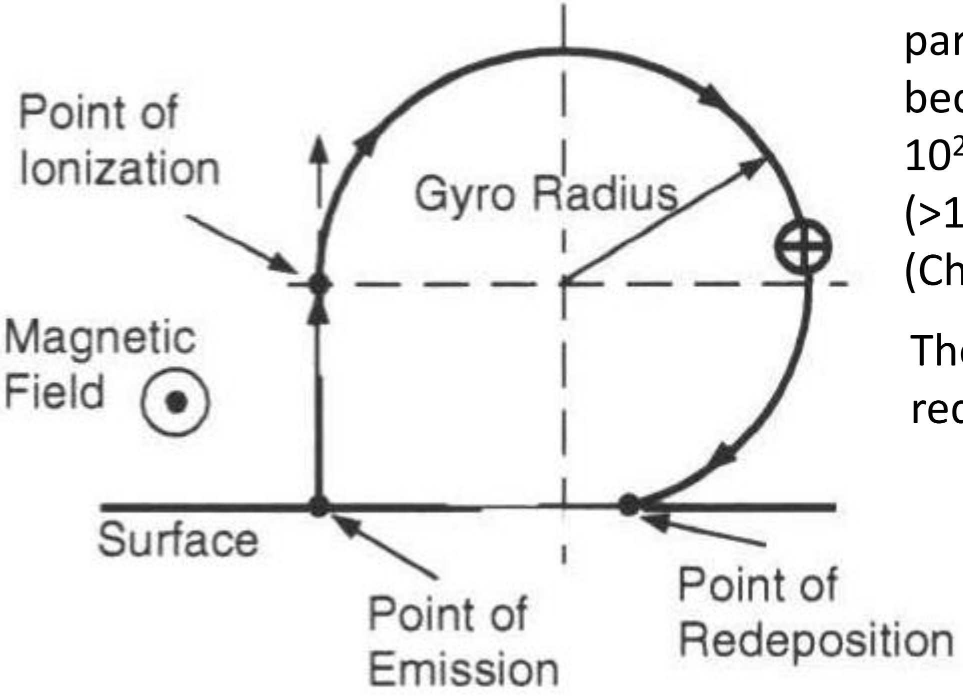
Li is stable for RT instabilities at ~10^3/m, requiring capillary pore structure(CPS) with sub-mm mesh. CPS makes convective transport extremely difficult.





High mass density of Sn makes it much more stable. Separation of the two divertor channels and ELM mitigation make Sn surface stable.

Prompt Redeposition



The prompt redeposition of W has a particularly large effect in ITER ELMs because of the high plasma density (>1 x 10^{21} m^{-3}) and high electron temperature (>100 eV) near the divertor targets (Chankin (2014))

The formula for the fraction of non-redeposition (Dux (2011)):

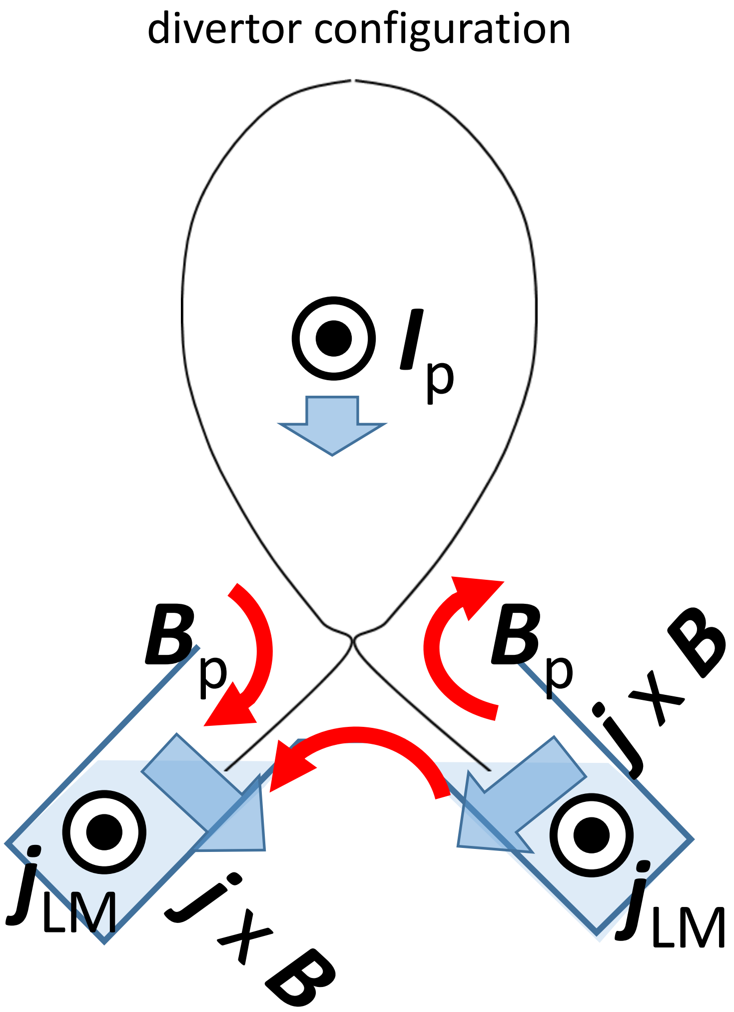
$$f_{non-redep} = \frac{p^2}{1+p^2}$$

$$p = \tau_{ion}\omega_{gyro} = \lambda_{ion}/\rho_{W_{max}^+}$$

At the ELM condition, $p \ll 1$, $f_{non\text{-}redep} \sim p^2 \ll 1$. The electric field in the magnetic pre-sheath (MPS) prevents the W ions from entering the main plasma beyond MPS (Chankin (2014)).

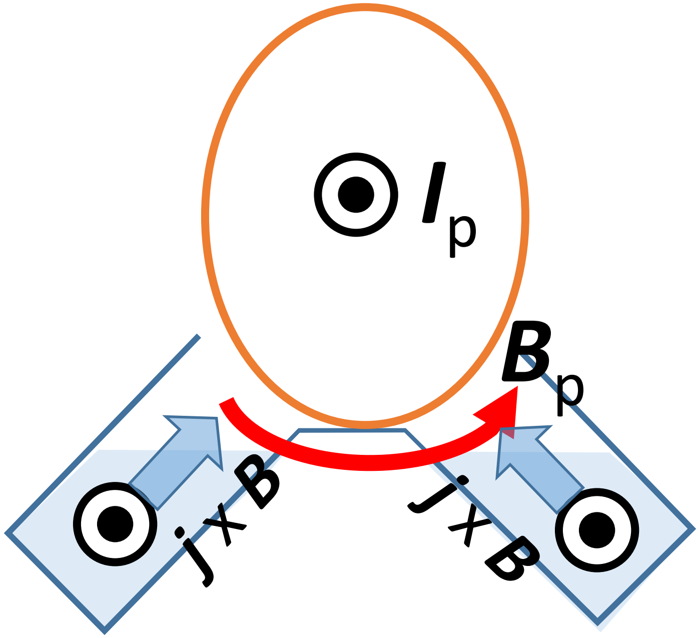
For the case of Sn at the **ELM** condition:1 x 10^{21} m^{-3} and 100 eV, $p \sim 0.01$:
Almost complete prompt redeposition of tin, similar to W, is expected.

Disruption (toroidal current at CQ)



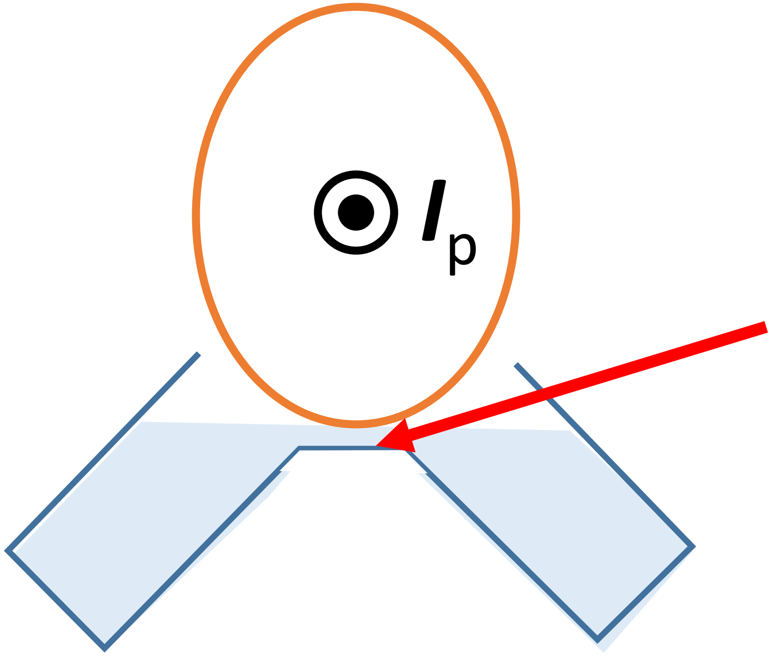
At the current quench (CQ) of a disruption with *divertor* configuration, current will be induced in LM in the same direction as the plasma current. LM would *not* be ejected toward the core but the core plasma would be attracted toward the divertor (***benign VDE***), which will eventually result in limiter configuration (next slide).

Disruption (toroidal current at CQ)



VDE will eventually lead to limiter configuration, then the ***j*** x ***B*** force due to the toroidal current induced in LM and the poloidal field will eject the LM into the core (***automatic disruption mitigation***). The ***j*** x ***B*** force during the current quench would be much stronger than the gravitation force.

Disruption (VDE)



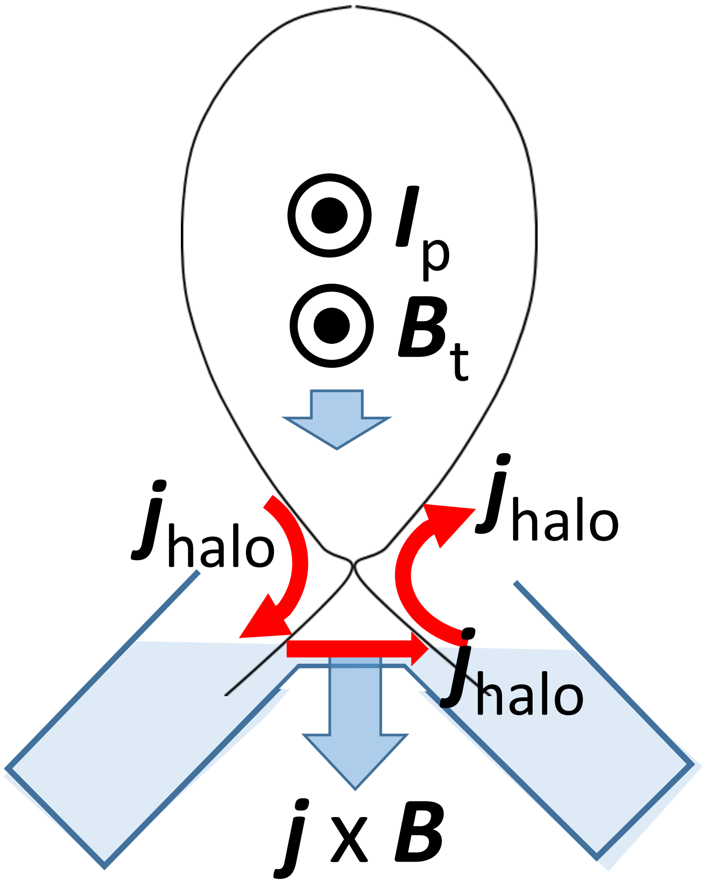
Since the vertical speed of VDE is slow (~0.5 s), the level of LM can be heightened so that the top of the dome will be protected.

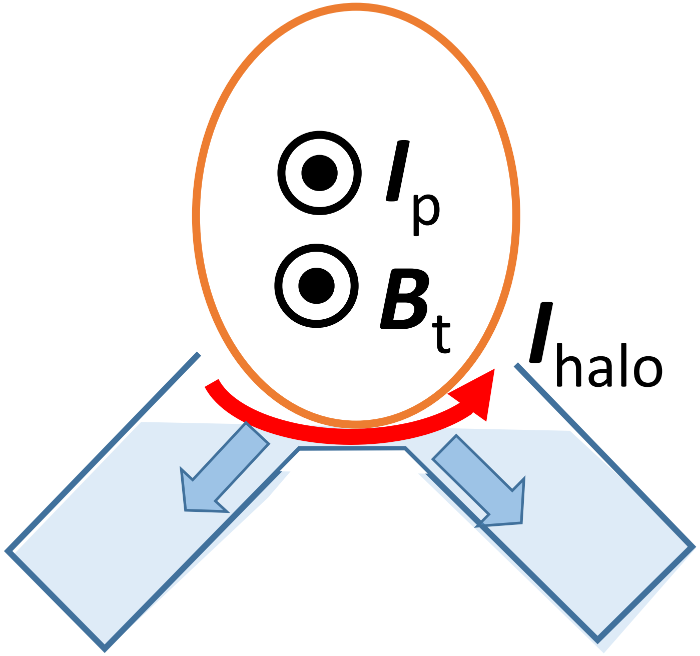
The level of the liquid metal surface can be increased at a rate of:

$$dh/dt \sim f/(2\pi Rw) \sim 2.5/(2\pi \cdot 8.5 \cdot 0.5) \sim 0.1 \text{ m/s}$$

Disruption (halo current)

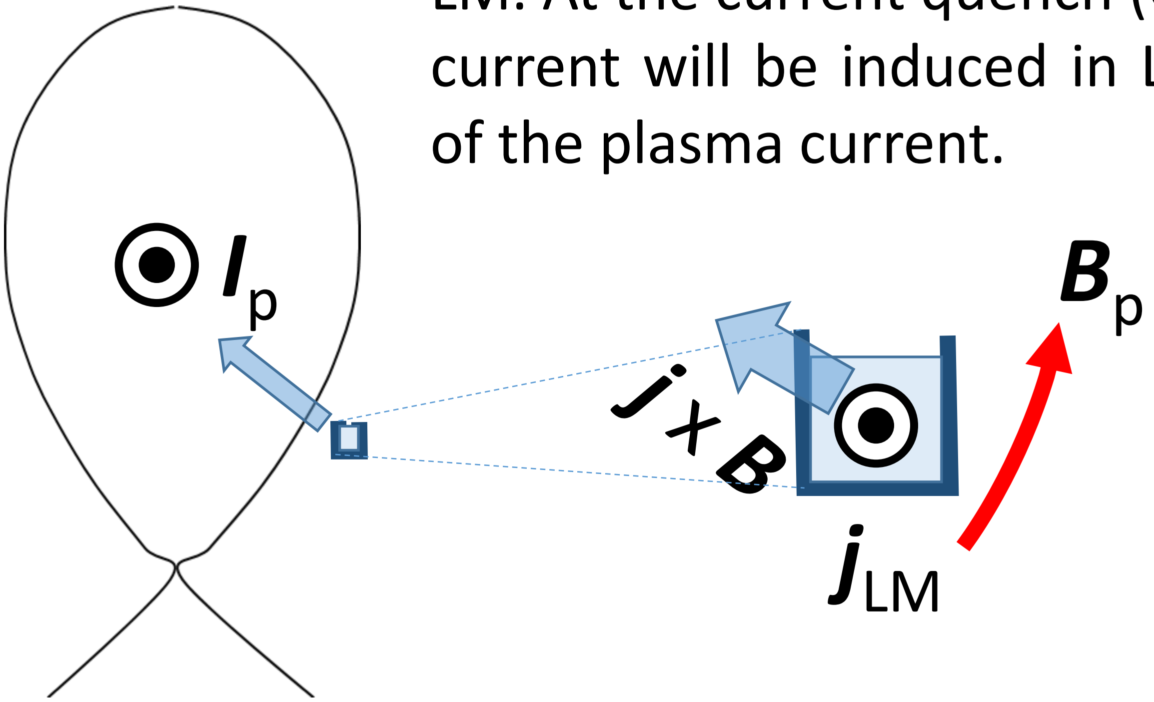
The ***j*** x ***B*** force due to halo current and the toroidal field does *not* eject the LM toward the core.





automatic disruption mitigator

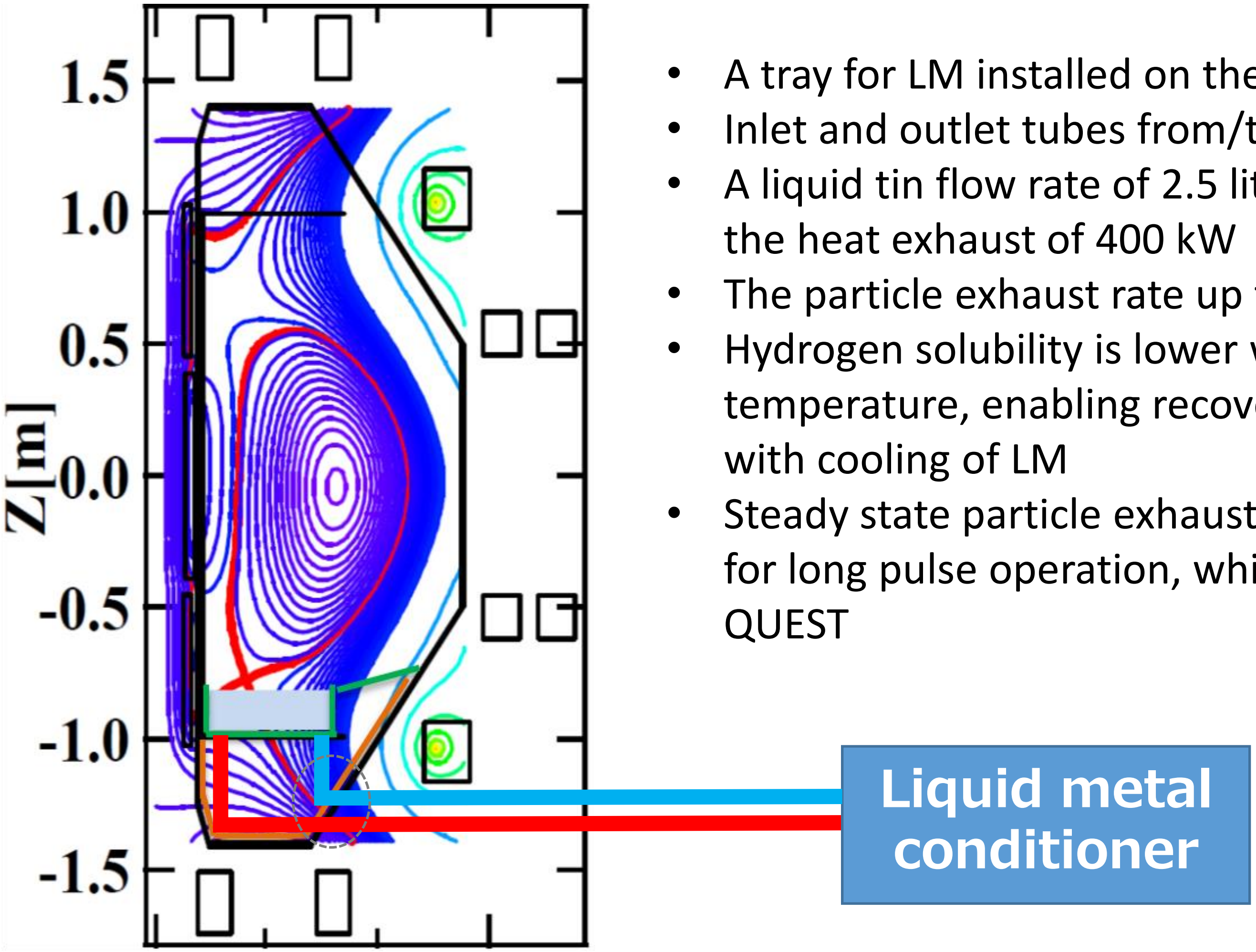
A toroidally continuous tube, installed at the lower midplane with its top open, is filled with LM. At the current quench (CQ) of a disruption, current will be induced in LM in the direction of the plasma current.



The resulting ***j*** x ***B*** force will eject the LM toward the core, providing ***automatic disruption mitigation***.

A tube of 1cm (***w***) x 1cm (***h***), 50 m long, will hold liquid tin of 35 kg, to be ejected at ~5m/s, sufficient to quench runaway electron.

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

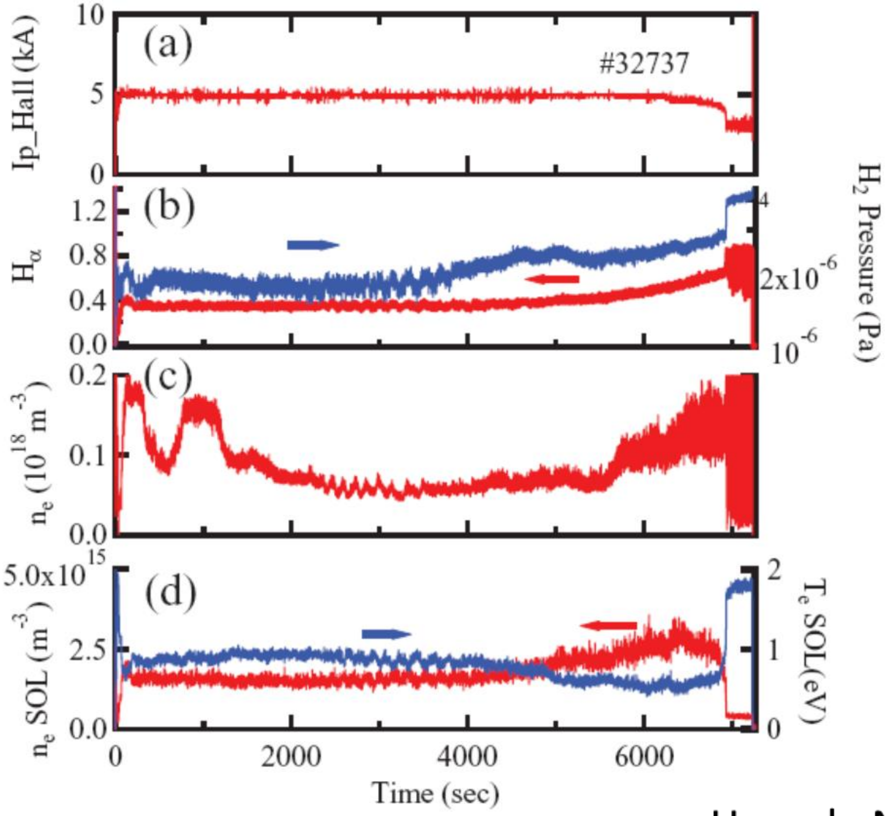


Liquid metal conditioner

- A tray for LM installed on the bottom part of VV
- Inlet and outlet tubes from/to LM conditioner
- A liquid tin flow rate of 2.5 litre/s will suffice for the heat exhaust of 400 kW
- The particle exhaust rate up to 8 Pam^3/s
- Hydrogen solubility is lower with low temperature, enabling recovery of hydrogen with cooling of LM
- Steady state particle exhaust would be essential for long pulse operation, which is a goal of QUEST

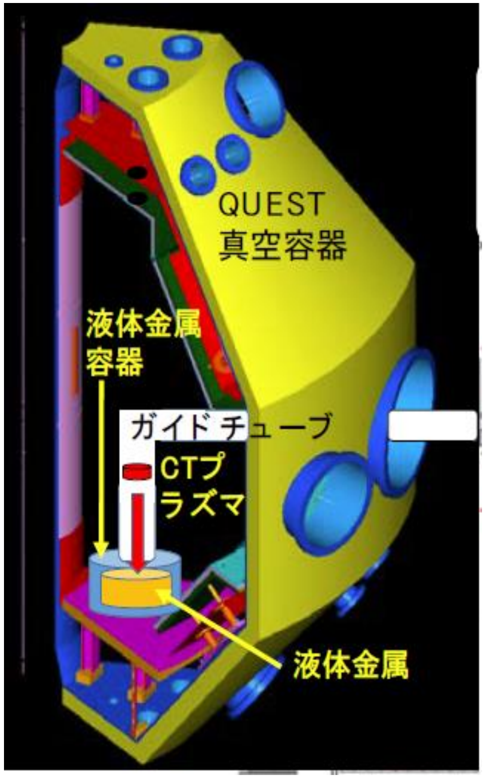
M. Shimada and K. Hanada “Conceptual Design of Manetically-Guided Liquid Metal Divertor on QUEST” Proc. Plasma Conference (2017) 22P-101.

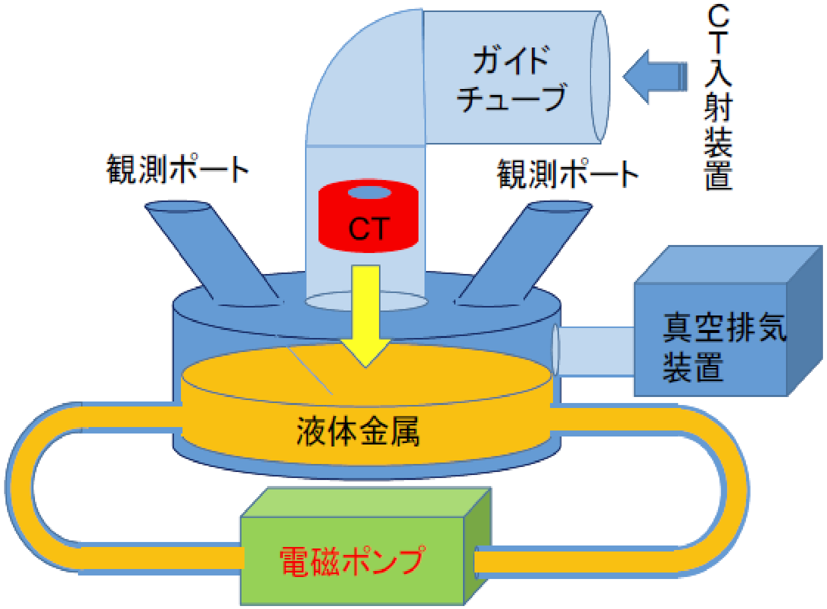
In the long pulse operation of QUEST, wall saturation increases particle recycling and discharge characteristics, which are expected to improve with active pumping



Hanada Nucl. Fusion (2017)

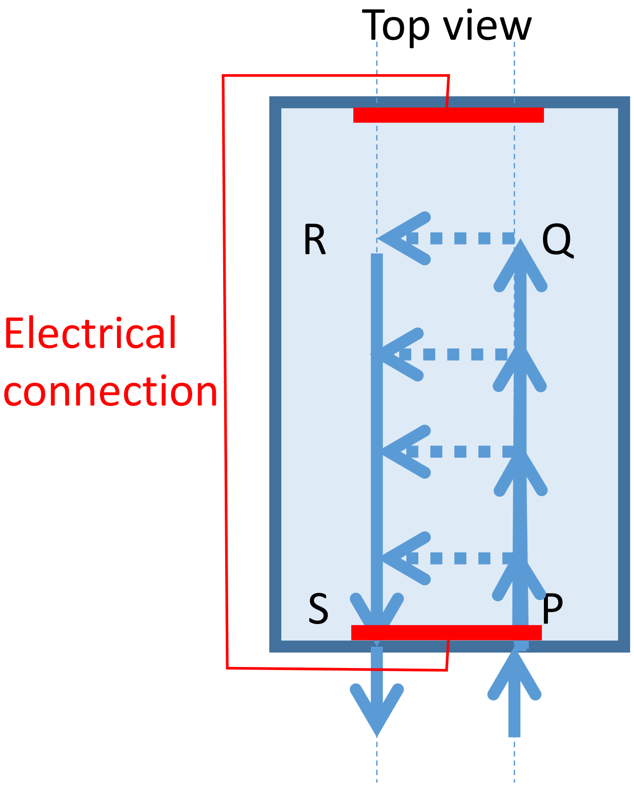
Preliminary experiment in QUEST (under discussion)



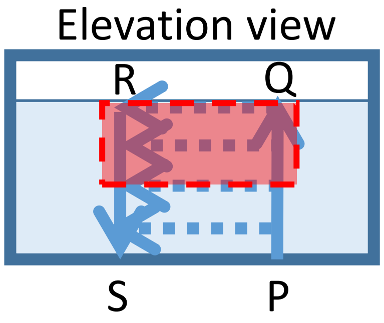


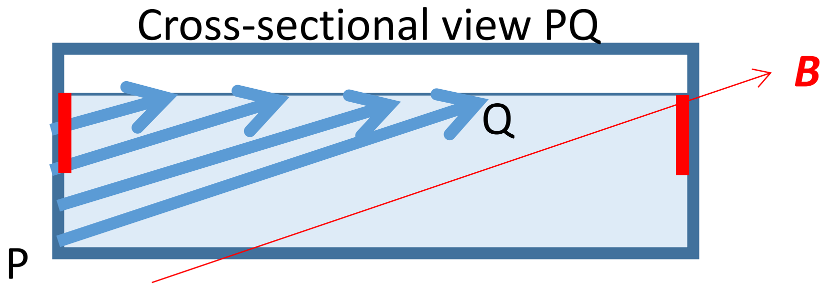
A LM container will be installed in the QUEST VV. The flow of LM pumped by EMP will be diagnosed and compared with CFD calculation. The behaviour of LM with CT injection will also be investigated.

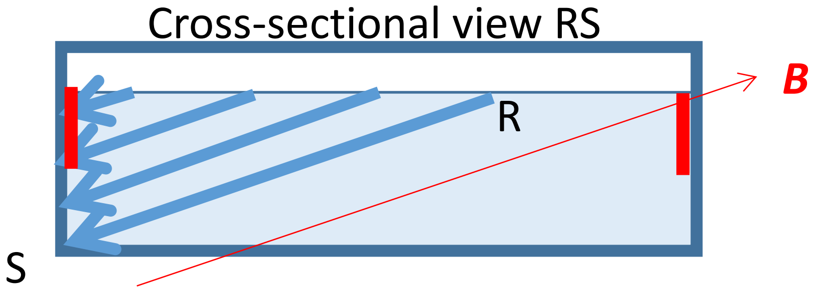
Proof-of-Principle experiment (1)


Top view

An acrylic casing is installed the QUEST vacuum vessel. A combined magnetic field (toroidal and vertical) is applied. Injection of liquid metal (Galinstan) from P and exhausted from S creates a flow pattern as illustrated. Cross-field flow from Q to R would suffer from MHD drag, which is compensated by a step on the liquid metal surface. Measurement of velocity and step is compared with CFD calculation.


Elevation view


Cross-sectional view PQ


Cross-sectional view RS

Proof-of-Principle experiment (2)

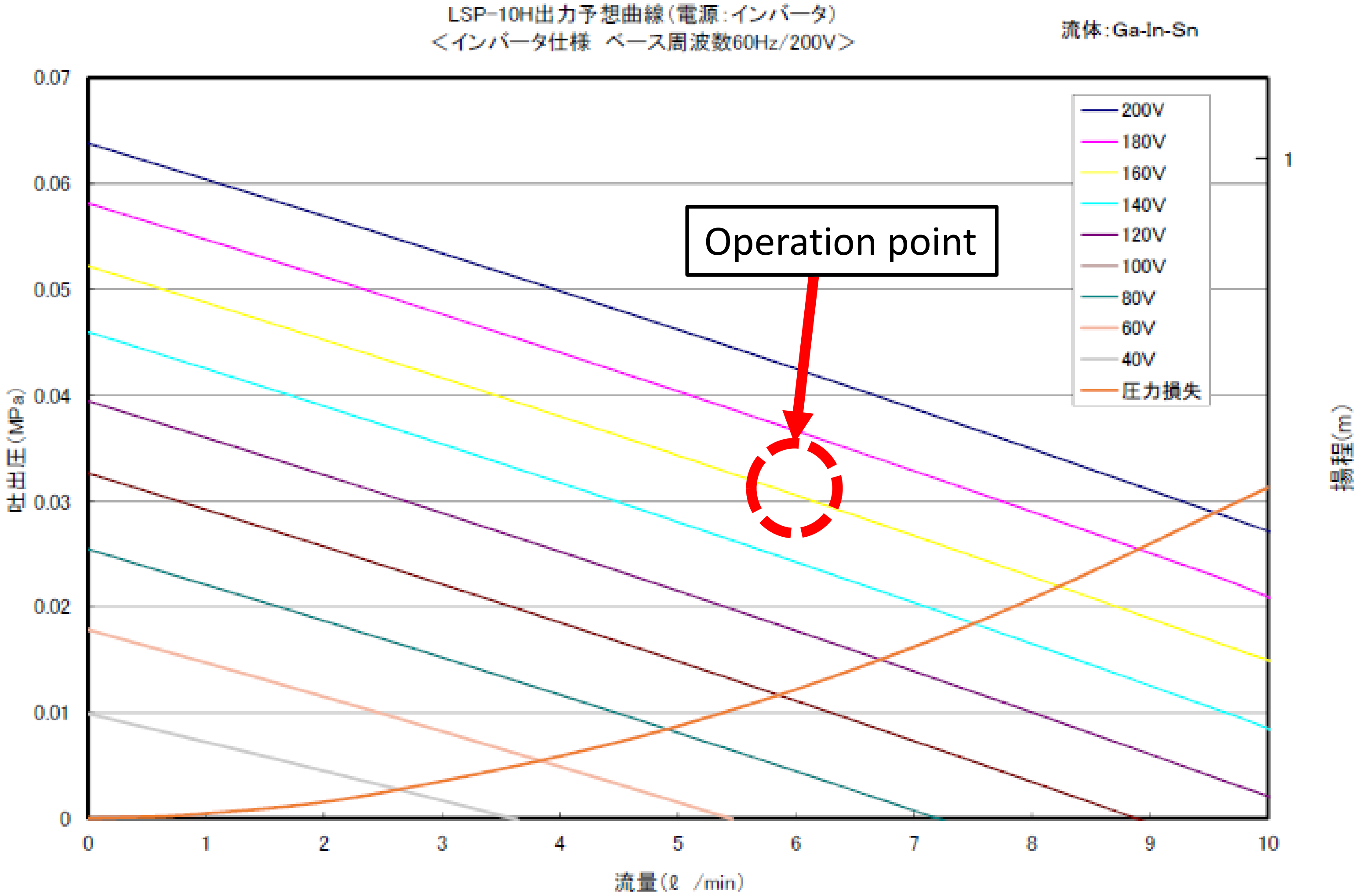
LM volume = 0.1m(w) x 0.2m(l) x 0.05m(h) = 1 litre
Replacement in e.g. 10 s → 0.1 litre/s or 6 litre/min.
For Inlet/outlet tube cross section 4cm^2,
v(LM velocity) = 25 cm/s
dynamic pressure = $\frac{1}{2}\rho v^2 \sim \frac{1}{2} \cdot 6.4 \times 10^3 \cdot 0.25^2 \sim 200$ Pa

MHD drag = $vB\vartheta \cdot \sigma \cdot B\vartheta \cdot \delta = 0.25 \cdot 0.5 \cdot 0.1 \cdot 3 \times 10^6 \cdot 0.5 \cdot 0.1 \cdot 0.05$
=94 Pa → 1.4 mm step on LM surface (e.g. larger ϑ?)

Elevation =0.5 m → static pressure: $\rho gh = 3.1 \times 10^4$ Pa
Total pressure ~ 3.1×10^4 Pa

Electromagnetic pump on loan to RIAM from NIFS

The parameters of PoP exp. are within the capability of the electromagnetic pump

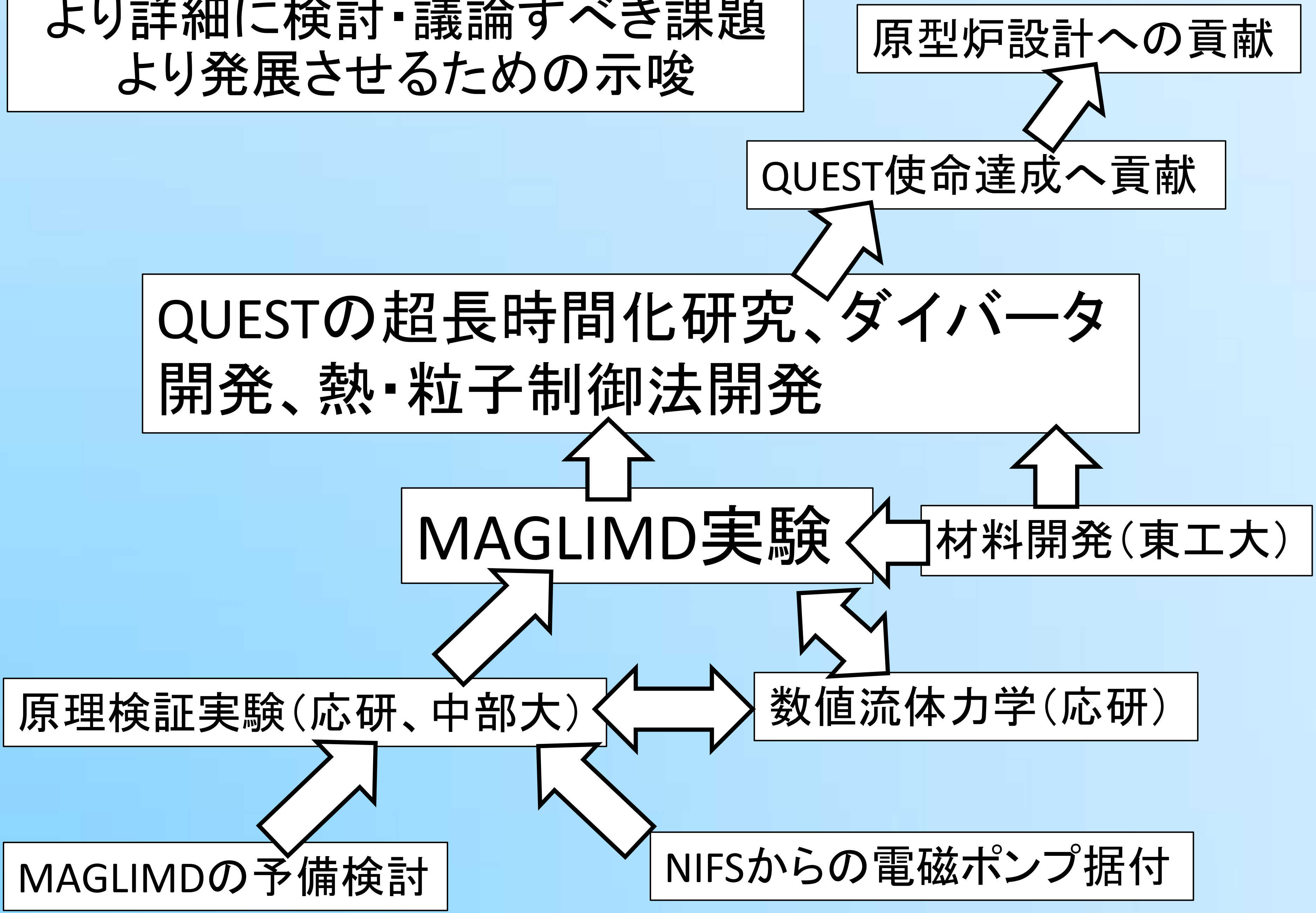


Operation point

Summary

1. An innovative concept of divertor power and particle control is proposed and discussed. This new concept could provide a simple and compact scheme for power and particle control of fusion reactors with easy maintenance and high reliability.
2. ***Centrifugal force*** is expected to be significant, driving the poloidal flow in the private region.
3. Electrical separation of the two divertor channels could enhance ***resilience to ELMs***
4. During current quench in a disruption, toroidal current is induced in the liquid metal divertor, in the same direction of the plasma current. The resultant EM force pulls the main plasma toward the divertor (benign VDE) or splash LM toward the main plasma. (***Automatic disruption mitigation***)
5. PoP experiments are being discussed.

より詳細に検討・議論すべき課題
より発展させるための示唆



原型炉設計への貢献

QUEST使命達成へ貢献

QUESTの超長時間化研究、ダイバータ開発、熱・粒子制御法開発

MAGLIMD実験

材料開発（東工大）

原理検証実験（応研、中部大）

数値流体力学（応研）

MAGLIMDの予備検討

NIFSからの電磁ポンプ据付