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沿磁場液体金属PFCコンセプト
Concept of magnetically-guided liquid metal PFC

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1. Introduction

An innovative concept of power and particle removal from the divertor is proposed. This scheme takes full advantage of liquid metal convection, in addition to conduction, to remove heat from the divertor, which is the most difficult issue of fusion reactor design.

2. General scheme

We propose that liquid metal (LM) should replace the solid divertor plates on the bottom of the vacuum vessel (Figs. 1-3). The LM is continuously supplied from openings located at the inner separatrix hit point on the floor of the LM casing on the bottom of the vacuum vessel, and exhausted from openings located at the outer separatrix hit point on the floor of the LM casing, driven by the external electromagnetic pump (Fig. 3). The LM flow is guided basically along the field line to reduce the MHD drag. The LM volumes connected to the inlet openings and those connected to the outlet openings along the field line are kicked in the same toroidal direction. Consequently, the whole LM move in the toroidal direction, making the LM characteristics (e.g. temperature and particle inventory) uniform in the toroidal direction.

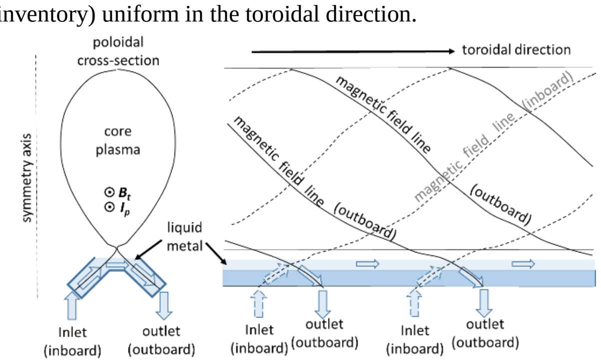

Fig. 1 Poloidal cross-section of a tokamak with MAGLIMD and its side view. The solid lines of the side view indicate magnetic field lines running on the outboard separatrix surface and the broken lines magnetic field lines running on the inboard separatrix surface. These field lines penetrate into the LM divertor and guide the LM flow.

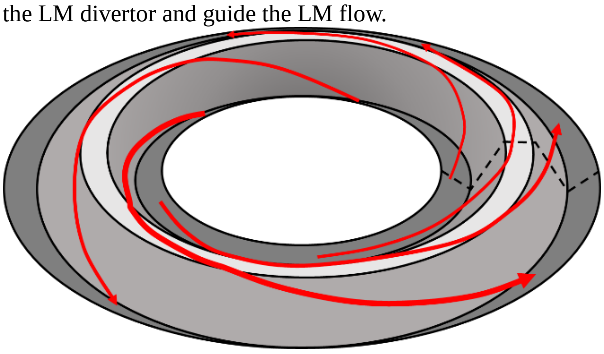

Fig. 2 Bird's eye view of MAGLIMD and the LM flow, which is guided basically along the field line to reduce the MHD drag.

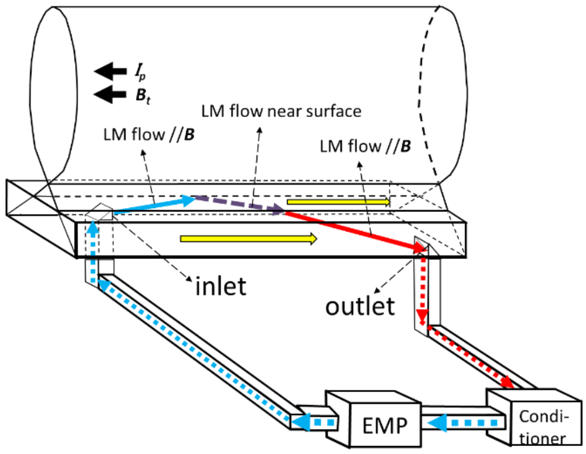

Fig. 3 Schematic of MAGLIMD. The solid arrows indicate LM flows along the field line. LM is injected from the inlets installed on the separatrix hit point on the inboard floor of the LM container, driven by an electromagnetic pump (EMP). The injected LM flows along the field line up to the LM surface. The LM is exhausted from the outlets installed on the separatrix hit point on the outboard floor of the LM container. The LM flows along the field line up to the outlet. The dotted arrows indicate flows across the field line. Insulation of the container wall and inlet/outlet tubes significantly reduces MHD drag. The arrows with a frame indicate LM toroidal flows.

3. Liquid metal flow rate required to remove heat

First, let us discuss the liquid metal flow rate required to remove heat from the divertor. We estimate the LM flow rate required to remove power $\boldsymbol{P}$ (W) with the following formula with liquid tin with mass density ρ (kg/m^3), specific heat $\boldsymbol{C}$ (J/kg/deg), flow rate $\boldsymbol{\Gamma}$ (m^3/s), temperature of supplied tin $\boldsymbol{T_{in}}$ (degree C), temperature of exhausted tin $\boldsymbol{T_{out}}$ (degree C):

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

e.g. With $\boldsymbol{P}$ = 400 MW, ρ = 7 x 10^3 kg/m^3, $\boldsymbol{C}$ = 228.4 J/kg/deg, $\boldsymbol{T_{out}}$ = 400 °C, $\boldsymbol{T_{in}}$ = 300 °C, we obtain $\boldsymbol{\Gamma}$ = 2.5 m^3/s.

The flow speed along the field line $v_{//}$ is estimated as:

$$v_{//} = \frac{\Gamma}{2\pi R w \theta} = \frac{2.5}{2\pi \cdot 8.5 \cdot 0.2 \cdot 0.05} = 5\ m/s$$

Where a major radius $\boldsymbol{R}$ of 8.5 m [1], a tube width $\boldsymbol{w}$ of 0.2 m, and a field line pitch $\boldsymbol{\theta}$ (=B_p/B_t, B_p and B_t are the poloidal and toroidal magnetic field, respectively) of 0.05 are assumed.

4. Disruption

In the event of disruption, the current induced in the LM during the current quench in the same direction of the plasma current, would either attract the plasma toward the LM divertor (making a benign Vertical Displacement Event), or splash the LM toward the core plasma, providing automatic disruption mitigation, not requiring a learning process. The current induced in the LM would significantly reduce the eddy current induced in the blankets and the vacuum vessel. After the disruption, the LM surface quickly recovers the flat surface, ready for operation.

5. MHD drag

The MHD drag, associated with the LM movement perpendicular to the magnetic field near the LM surface in the private region, is expected to be acceptable due to insulation of the wall contacting the LM, and a geometrical effect (the field line takes grazing angle to the LM surface) The effect of the centrifugal force more than compensates for that of MHD drag.

The MHD drag on the LM flowing in the duct perpendicular to the magnetic field is analyzed with a formula derived by Shercliff [2]. With a duct length of 10 m running perpendicular to the magnetic field of 6 T, the MHD drag is $\sim 2 \times 10^5$ Pa, which is within an acceptable range.

6. Rayleigh-Taylor and Kelvin-Helmholtz instabilities

6.1 Theoretical background

The free surface instability of liquid metal was analysed by Hassanein [3], Jaworski [4] and Fiflis [5]. The dispersion relation used for stability analysis considered the gravitation force (stabilising), the electromagnetic force due to the current originating from the sol plasma and the background ***B*** (stabilising or de-strabilising), the surface tension (stabilising), and the driving term of Kelvin-Helmholtz instability due to the plasma mass flow (destabilising). The maximum observed value of sol current density was used for the stability assessment.

6.2 Private region

In the private region i.e. the area between the inner and outer channels, there is no plasma. During the quiescent phase, if the electromagnetic force points upward, the free surface would be unstable for the case of lithium, but stable for the case of tin, due to higher mass of tin (Fig. 4).

Lithium free surface can be stable during the quiescent phase, at high wavenumbers (e.g. 10^3 m^{-1}); that is the motivation of using capillary pore structure (CPS) with sub-mm pore dimension [6], which makes it difficult to implement heat removal by convection. In contrast, tin free surface is stable during the quiescent phase, eliminating the need of CPS and opening up the possibility of efficient heat removal with convection.

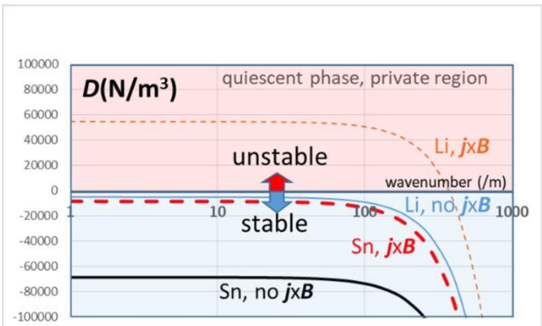

Fig. 4 Stability diagram for Li and Sn during quiescent phase in the private region.

During ELMs, sol currents are enhanced by one order of magnitude in comparison with the quiescent phase, which makes the free surface unstable even for the case of tin (Fig. 5). Separating the two divertor channels and eliminating the current flowing radially inward in the private region should significantly reduce the $\boldsymbol{j} \times \boldsymbol{B}$ force and could enhance stability of the free surface (Fig. 6).

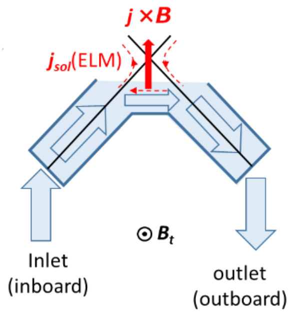

Fig. 5 The broken lines indicate ELM currents in the sol and LM, which flows along ***B*** in the plasma and across ***B*** in the LM. The solid line shows the resultant electromagnetic force, ejecting the LM into the core.

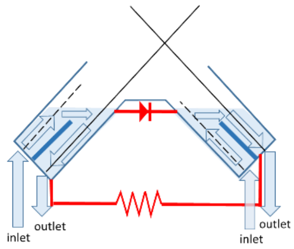

Fig. 6 MAGLIMD with two divertor channels separated electrically.

6.3 LM surface in contact with the plasma

Assuming that the Rayleigh-Taylor instability is suppressed by separating the two divertor channels (Fig. 6), Kelvin-Helmholtz stability was examined. The assumed parameters of the plasma hitting the LM during ELM were $\boldsymbol{n_e} = 1 \times 10^{21}$ m^{-3} and $\boldsymbol{T_e}$ = 100 eV. Even with significant mitigation (a factor of 50 in pressure), lithium surface is unstable for a wide range of wavelength. The tin surface is stable with a mitigation of a factor of 50, indicating the need of ELM mitigation methods, which is under development.

One should note here that the consequence of unmitigated ELM is more serious with tungsten targets. With bombardment of unmitigated ELMs, the surface of tungsten targets would be seriously damaged, requiring replacement. For the case of LM divertor, the surface flatness will be recovered quickly.

4. Prompt redeposition at ELMs

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 [7]. The electric field in the magnetic pre-sheath (MPS) prevents the W ions from entering the main plasma beyond MPS [7, 8]. For the case of Sn, an estimate at the ELM condition indicates almost complete prompt redeposition of tin, similar to W.

Acknowledgement

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