Fast Liquid Metal Program for Fusion Reactor Divertor

E. Kolemen[1]
[1]Princeton University
Email: ekolemen@princeton.edu

1. Technology to be assessed:

The technology to be assessed is the use of fast flowing liquid metal divertor for a fusion reactor. In a reactor Plasma Facing Components (PFCs) will have to endure a combination high heat, particle and neutron fluxes. At the divertor of a reactor, the challenge becomes even harder with much increased heat flux compared to the rest of the surfaces. While extensive work is underway, it is yet unclear that a solid high-Z metals divertor solution exists for a long pulse D-T fusion reactor that can handle these conditions. However, these divertors suffer from erosion, dust formation, peaked thermal stresses, heat removal issues, confinement degradation, impurity accumulation in the core plasma, and tritium inventory control. Additionally, new research suggests that high-Z impurities may lead to disruption of the plasma [1], which would make materials such as Tungsten unfit for reactor PFCs. Liquid metal surfaces are a possible alternative to solid PFCs, in order to cope with erosion, and permit higher power loading.

Tin, lithium, tin-lithium eutectics, and gallium are the main liquid metals that have been studied experimentally and via simulations. Much of the research is focuses on what we will call “slow” flow liquid metal solutions, as opposed to the “fast” alternative that is the focus of this white paper. The distinction we make between these two regimes is that, “fast” flow takes all (or almost all) the heat flux coming to the PFCs while the “slow” flow is mainly for PCFs erosion protection and requires a heat removal system similar to the solid alternatives. The distinction is dependent on the reactor and divertor design, and liquid metal choice. However, for a generic reactor divertor “fast” flow generally requires ~1-20 m/s range speed with approximately mm to cm thickness while the “slow” options considered are creeping flows held by tension forces to the surfaces. Balancing the heat flow into the divertor and carrying capacity of the liquid metal flow is the main requirement that sets the “fast” flow speed for the divertor.

2. Application of the technology

Fast flowing liquid metal would be flown at multiple m/s speeds over a stainless metal surface at the divertor of a tokamak or stellarator. Fast liquid metal divertor has many advantages compared to solid and slow flow systems:

- Previous studies showed that Hydrogen isotope particles are likely to be trapped in the liquid metal surface (e.g., lithium) due to the high chemical solubility of hydrogen. It is also expected that adequate helium self-trapping can be achieved in flowing lithium as PFC getting rid of the active pumping requirement [2]. This simplified the divertor design.
- Taking all the particle and heat flux makes the divert material behind the liquid to be designed only for neutron fluxes. This permits the use of neutron-tolerant, low thermal conductivity, steels as guide walls or substrates – an innovation which would greatly reduce the need for materials development for fusion. Demonstration of a fast flowing liquid metal wall system could provide a key enabling technology for this approach.
- Faster flow allows lower liquid metal temperatures by reducing the exposure time to the hot plasma. This may allow achieving low recycling surface (for lithium) and reduced evaporation and impurity diffusion into the plasma.

- Getting rid of the piping requirement for heat removal helps with simplifying the engineering of the divertor compared to slow flows.
- Possibly the most important benefit would come in the fusion reactor design flexibility. As the size of the reactor gets smaller for a given power level the reactor generally becomes cheaper but the divertor heat flux issue becomes even more complicated. Thus, reactor designs currently optimize the plasma not only for optimal fusion energy gain but heat flux requirements to the divertor. Generally, high radiative fraction and less aggressive core plasma parameters are chosen to alleviate this issue. Advanced divertors such as X-divertor, snowflake divertor are also considered, diminishing the cost and space savings. If the heat flux were not a concern, compact economical reactors would be much easier to achieve. Fast flow development gives us this possibility.
- Plasma enhancing properties of liquid metals is descried in detail in another whitepaper [3].

3. Critical variable(s) – variable that determines or controls the output of the technology

- Avoidance of free-surface instabilities that can lead to splashing of the LM into the plasma
- Enhanced convective heat transport form the top layer of the LM to handle the plasma heat flux, which would reduce the requirements for LM speed and volume.
- Achievement of enough propulsion to flow the LM through the divertor via hydraulic and electro-magnetic means. Since a high magnetic field is already available a jxB pumping system the most likely option. This system would run a vertical current through the LM in the return path. Another highly likely system to be employed is the magnetic propulsion concept suggested by Zakharov [4]. This concept uses the fact that the magnetic field in a tokamak is 1/R dependent, leading to a pressure gradient in the LM form the higher field side to higher field side.

4. Design variables:

- Type of LM: Lithium, Tin, Gallium, Eutectics of different metals
- The material of the plate surface that the LM flows: Steel, Tungsten, …
- Length of the divertor flow plate: For a given total heat exhaust the angle with respect to the magnetic fields is a free parameter that can adjust the heat flux per area
- Surface shape of the divertor plate: Flat plate, bend plate with a specific profile, groves and channels
- Surface properties of the divertor plate: Roughness, possible engraving on the surface using laser for better wetting, vortex generators for enhanced advection
- LM height: Inlet height, height as a function of position on the divertor (can be adjusted by proper design)
- LM velocity: Spatial profile of the velocity, variation of the velocity in time (e.g. sinusoidal variation)
- Nozzle design: Dimensions, shape, controllability (e.g. the nozzle be adjustable during operations)
- Current injection in the LM scheme: Level of the current (Amps), Temporal variation of the current (e.g. AC current on top of DC for ponderomotive effect), direction of the current (e.g. along, perpendicular to field lines), spatial variation of the current field, location and shape of the positive and negative leads
- Perturbative control of LM: Possibly electromagnets can be under the divertor to control the flow

- Plasma induced current on the LM: ELM free vs ELMy (type of ELMs), scrape-of-layer current

5. Risks and uncertainties:

- It is possible that the yet to be understood physics of liquid metal instabilities does not allow free surface flows at the fusion reactor conditions
- Currents needed for control of the LM may prove infeasible to implement in a reactor
- Non-toroidal magnetic field effects may make the LM flow unstable in a way that can not be overcome by good system design or control
- The effect of temperature induced thermocurrents on the LM needs to investigated in more detail
- Cost of the LM system can be prohibitively high
- Tritium separation from the LM may be cost prohibitive or may cause safety issues
- Plasma-LM interaction may lead to flow instabilities
- Penetration of the ionized LM in the core may lead to dilution level inconsistent with high fusion gains needed for economical reactors
- Penetration of the ionized LM in the core may lead to too much radiation and reduce the plasma performance to a level that is inconsistent with high fusion gains needed for economical reactors (mainly a problem for high-Z LM)
- Safety concerns with using lithium flow may cause issues
- Issues related to the recirculating flow of LM such as corrosion of the pipes
- Technical issues with using LM that freezes under room conditions such as pipe bursting

6. Maturity:

The current state of the fast free surface LM flow technology is roughly at technical readiness level of 2 (~TRL2). There were a few LM flowing concepts that were tested in a preliminary fashion but no fast free flow system yet has been implemented on a tokamak.

There have been some studies of the liquid metal wall concepts. However, most these are focused on the stationary or creeping flow mainly relying on surface tension with limiter and capillary-pore system (CPS). Results from these studies listed below are generally positive for liquid metal surface interaction with the plasma.

- T-11M showed that CSP system is stable under high heat loads and plasma conditions were not degraded [5].
- NSTX studied the Liquid lithium divertor with thin layer of lithium and FTU is currently studying various LM limiter options [6].
- LTX showed that the liquid lithium wall produces very high edge temperatures and beneficial for fusion reactor design [7].

However, the focus of this whitepaper is on fast open surface flow. Open channel fast flow system is much less studied area. The studies can be separated into two groups, first one fast LM flow in magnetic fields without plasma, and the second fast open channel LM flow LM in tokamaks.

Plasma free studies:

- Liquid metal studies at UCLA with MTOR looked at fluid instabilities under magnetic field conditions with up to ~0.5 T [8]. One option considered was the high-speed droplets formed from a jet at the divertor. Experimental findings indicated that a steady transverse magnetic field stabilizes a LM jet flow - reducing turbulent disturbances and delaying jet breakup. For the film flow, the magnetic field changes the surface wave structures from hydrodynamic wave at low B to 2D column-type surface disturbances high B.

- Experimental studies at Liquid Metal eXperiment (LMX) showed that application of poloidal current through the liquid metal is able to restrain the LM to the wall, decreases its height and increase the velocity and hydraulic jump location can be pushed out of the divertor [9,10]. Laminarization of the flow with increased magnetic field was also observed.

Free surface LM studies in tokamak conditions:

- Russian TM-3 tokamak in 80s showed that under fast B_t ramp (1 Tesla in 10s of milliseconds) liquid metal flow stopped and there was splashing. Details of this old experiment such as velocity, pressure, thickness are not well documented. However, it is know that such high temporal B_t variation induces strong MHD drag and would lead to stopping of the flow. Thus, this experiment does not give insight to the realistic LM operation in a superconducting tokamak/stellarator in which the magnetic field is constant or varying orders of magnitude slower. Unfortunately, this result has been sometimes cited incorrectly as non-existence proof for free LM flow in magnetics fields. [11]
- CDX-U utilized large-area (34 cm Radius and 10 cm width) ~6 mm thick free-surface liquid metal limiter tray and improved performance with lithium limiter [12]. Though this was a free surface experiment, lithium was stationary not moving.
- FLiLi (Flowing Liquid Lithium) is a plate with flowing thin film lithium at EAST which is currently being tested. Initial tests showed the engineering concept for flowing lithium works in tokamak conditions. The physics results are to be available soon [13]
- ISTOK looked at the effect of gallium droplets as they pass through plasma and showed that the droplets drift and shape of the droplet changes as it moves through the magnetic field [14].

Numerical and analytical studies:

- Conditions for ejection of droplets from a liquid metal surface under magnetic fields was analytically studied by Jaworski et al. [15]. The analysis shows that the particles will eject when the total out of plane jxB force is larger than the surface tension and fits reasonably well to experimental results. The total current is the total of the self-induced and imposed currents such as current from ELMs. Thus, running appropriate poloidal currents through the LM can avoid ejection.
- Numerical simulation of open surface flows is a challenging task even for regular water flows (non-MHD conditions). Thus, quantitatively reliable open surface MHD flow are not available at this point in time. However, there have been studies that give qualitative insight. HIMAG code was developed at UCLA to study 3D open channel mhd flow [16]. Simulations showed that the application of magnetic propulsion current was useful in stabilizing the surface shape and propelling the liquid through the magnetic gradient region.

7. Technology development path for fusion applications

- A device to study the flow stability of fast LM under realistic tokamak/stellarator conditions is necessary at the initial technology development path to prove the feasibility of running the LM in relevant MHD conditions without instabilities. This device should have sufficiently high magnetic field (~1 T) in fully toroidal and poloidal flow path (unlike a channel flow test facility).
- jxB pump for fusion reactors should be developed.

- The developed system should be installed on a tokamak/stellarator with high heat flux (~10 MW/m^2) to prove the compatibility of the fast flow with fusion plasma.
- A feasible process for separation of Hydrogen isotopes from the LM (detailed in the whitepaper by Majeski, Kolemen, et al. [2]) should be developed.

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