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ORIGINAL RESEARCH

A Domestic Program for Liquid Metal PFC Research in Fusion

D. Andruczyk[1] · R. Maingi[2] · Chuck Kessel[3] · D. Curreli[1] · E. Kolemen[2] · J. Canik[3] · B. Pint[3] · D. Youchison[3] · S. Smolentsev[4]

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Abstract

While high-Z solid plasma-facing components (PFCs) are the leading candidates for reactors, it is unclear that they can survive the intense plasma material interaction (PMI). Liquid metals (LM) PFCs offer potential solutions since they are not susceptible to the same type of damage, and can be "self-healing". Following the Fusion Energy System Study on Liquid Metal Plasma Facing Components study that recently was completed by Kessel et al. (Fusion Sci Technnol 75:886, 2019) a domestic LM PFC design program has been initiated to develop reactor-relevant LM PFC concepts. This program seeks to evaluate LM PFC concepts for a Fusion Nuclear Science Facility (FNSF) or a Compact Pilot Plant via engineering design calculations, modeling of PMI and PFC components and laboratory experiments. The latter involves experiments in dedicated test stands and confinement devices and seeks to identify and answer open questions in LM PFC design. The new national LM PFC program is first investigating lithium as the plasma facing material for a flowing divertor PFC concept. Several flow speeds will be evaluated, ranging from $\sim$ cm/s to m/s. The surface temperature will initially be held below the strongly evaporative limit in the first design; higher temperatures with strong evaporation will be considered in future concepts. Other topics of interest include: understanding of the hydrogen and helium interaction with the liquid lithium; single effect experiments on wetting, compatibility and embrittlement; and prototypical experiments for control and characterization of flowing LM. A path to plasma and future tokamak exposure of these concepts will be developed.

Keywords Plasma · Fusion · Liquid metal · Lithium · PFC · Divertor

Introduction

At the moment solid plasma facing components (PFCs) are the leading candidates for future fusion reactors, of which tungsten is the leading solid PFC candidate for future devices. The accepted heat flux limit for tungsten can be quite high, $\sim$ 5–15 MWm^{-2}. Tungsten also has substantial resilience to physical sputtering and little to no chemical sputtering with hydrogenic species. Finally, tritium retention in tungsten is acceptably low [1, 2]. The divertor in ITER is designed with tungsten monoblock tiles, along with beryllium on the first wall [3]; the designed divertor steady heat flux limit in ITER is 10 MWm^{-2}.

Despite the attractive properties of tungsten, the fusion environment is challenging for any PFC material. Tungsten's properties degrade moderately, less than most other solid material, such that 5 MWm^{-2} is the projected acceptable upper bound for steady heat flux removal in devices with strong neutron fluence [4]. Tungsten generally embrittles under neutron irradiation and the ductile-to-brittle transition temperature is a little higher than desired for natural tungsten, and increases with neutron fluence [2, 5]. In addition, tungsten can develop nano-structures, i.e. "fuzz", bubbles, or dust [6, 7]. Research continues to explore tungsten alloys, composites, and laminates to allow its use as a fusion reactor PFC.

While ITER's scenarios are designed to work with tungsten and beryllium PFCs, the power exhaust challenge for reactors the size of ITER is substantially harder, requiring substantially higher amounts of core and divertor

✉ D. Andruczyk
andruczy@illinois.edu

1 University of Illinois Urbana-Champaign, Urbana, IL, USA

2 Princeton Plasma Physics Laboratory, Princeton, NJ, USA

3 Oak Ridge National Laboratory, Oak Ridge, TN, USA

4 University of California Los Angeles, Los Angeles, CA, USA

radiation [8]. Studies performed in the last 10 years since the ReNeW study [2009 "Research Needs for Magnetic Fusion Energy Science", Report of the Research Needs Workshop (ReNeW) report, June 9–13, 2009] have shown that both steady and transient heat exhaust is more challenging than previously thought, owing in part to the narrowness of the scrape-off layer power flux footprint with increasing midplane poloidal magnetic field [3, 9–16]. These results pertain to an "attached" divertor, which is not considered a viable plasma operating mode in ITER or power plants, and some form of radiative dispersal of steady state power is largely understood to be required. Both solid and liquid divertor concepts benefit from radiative dispersal, from hydrogen and impurity radiation or evaporated liquid and impurity radiation, respectively.

If plasma transient events cannot be avoided or mitigated, the peak particle and heat loads will challenge current solid materials beyond their capabilities. Liquid metal (LM) PFCs hold the promise to be a self-healing boundary against surface damage from transients that could handle large heat and particle fluxes. LMs also offer the ability to control hydrogenic species [17]**.** An extensive Fusion Energy Systems Study (FESS) [18] of liquid metals for fusion devices was recently completed. In that study issues common to LM PFCs and issues related to individual LM choices (e.g. Li, Sn, or Sn-Li) were highlighted. This FESS study became the base for a three-year liquid metal PFC development and research initiative. The LM PFC development program brings in experts from four institutions, Princeton Plasma Physics Laboratory (PPPL), Oak Ridge National Laboratory (ORNL), the University of Illinois at Urbana-Champaign (UIUC), and the University of California Los Angeles (UCLA).

Approach for the Program

With the uncertainty of the performance of solid PFCs in the harsh reactor environment, particularly with the renewed U.S. focus on compact systems, it is prudent and timely to consider alternative PFC solutions, such as LM. The FESS study [18] that was stated in the previous section listed four expected benefits:

- To eliminate plasma degradation of a solid PFC (erosion, reconstitution) as a lifetime limit
- To remove comparable or higher heat fluxes than solid PFC
- To reduce the nuclear damage and transmutation that would happen with a solid PFC
- To reduce the largest gradients (damage, temperature, stress) that would happen with a solid PFC

There are a number of potential benefits with respect the use of LM PFCs [19, 20]; this PFC development initiative partly seeks to determine if these potential benefits can be realized in a reactor environment:

- Very high steady, and transient heat exhaust can be removed: steady 50 MWm^{-2} and pulsed 60 MJm^{-2} in 1 μs [21]**.**
- Eroded material from the main chamber is transported to the divertor as 'slag' [22]; this slag may removable via flowing liquids.
- Substrates below the LM can be protected from PMI.
- Liquid lithium, specifically, offers access to low recycling, high confinement regimes in a certain surface temperature range within a few hundred degrees of its 180.5 °C melting point [23–27].
- Li-coated PFCs, real-time lithium powder injection, and flowing liquid lithium PFCs can mitigate and even eliminate ELMs in present devices [28–33].

US researchers have been the leaders in liquid metal PFC research and technology development, mainly focused on lithium. Elsewhere, Europe (and Japan) are focusing on liquid tin PFCs, and are complementary to the US program. The Chinese capabilities for flowing liquid lithium PFCs have been growing steadily, based on experiments on the HT-7 and EAST tokamaks; indeed, the US and Chinese have made joint advances by collaborating on flowing liquid lithium limiters on EAST [34]. The present domestic initiative is to evaluate reactor-relevant flowing liquid Li PFC designs with full toroidal coverage.

As stated above, the established team of ORNL, PPPL, UIUC and UCLA will examine the science and technology associated with a liquid Li flowing divertor and corresponding issues in a fusion nuclear device. PPPL has overall management responsibility, with PPPL, ORNL, UIUC and UCLA sharing technical program responsibilities. These including planning, organizing work and national meetings, and reporting. More specifically the LM PFC program will be examining the engineering design, plasma interface description, single effect experiments, and basic prototypical (flowing LM in magnetic fields) experiments in support of the liquid Li flowing divertor concept.

Several initial selections have had to be made to help focus the program on a LM PFC. First, the LM has been chosen to be lithium due to the expertise in the US program. Second, a divertor PFC concept will be designed first, before considering the design of a full liquid wall. Finally, a flowing LM concept with flow rates including ($\sim$ 0.1–1 cm/s), medium ($\sim$ 10 cm/s), and fast ($>$ 100 cm/s) will be investigated first. Initially the emphasis will be on temperature ranges below the evaporative limit ($<$ 400 – 450 °C); higher temperatures with evaporative cooling will be evaluated in future years. Some of these design activities will be briefly elaborated on more in the following sections.

Design Activities

The engineering design activity will include a wide range of analyses. LM flow analysis and plasma equilibrium geometry will provide a base for the flow surface geometry that will allow for a parametric study in a wide range of flow parameters with the goal to minimize the MHD drag and enhance heat transfer. Thermo-mechanics and computational fluid dynamics (CFD) be important tools used to help determine the substrate design. To begin with, the numerical simulations will utilize simplified computational models of reduced dimensionality for rapid engineering operating space determination, such as 2D (see Fig. 1), Q2D (quasi-two-dimensional) and 2.5D models. Later, full 3D models based on Navier–Stokes–Maxwell equations with appropriate source terms and boundary conditions be used for a more detailed study.

Also, the high effectiveness of reduced LM MHD flow models has recently been demonstrated for an integrated LM PFC design [35]. Two simplified models, Q2D and 2.5D, were successfully used [36, 37] to predict LM flows and heat transfer and eventually optimize several LM divertor options (see Fig. 2). Similar models will be utilized in this new project.

The main goal of the initial parametric study using these models, is to first establish a stable flow configuration for which the flow doesn't experience high MHD drag leading

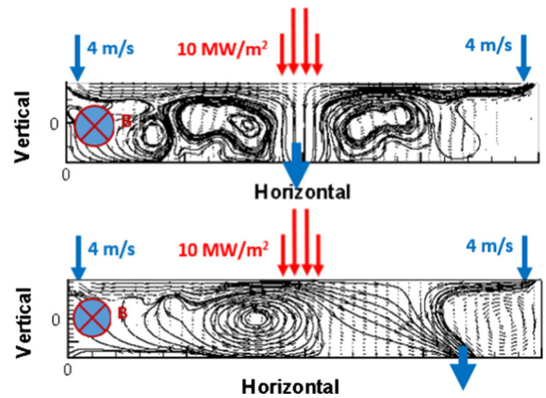

Fig. 2 MHD/heat transfer analysis for the shallow tub-like Li divertor based on the Q2D flow model [37]. The figure shows the locations of the incoming IB and OB jets, drain orifice, applied heat flux and the computed flow field in the liquid for two configurations: **a** the drain is at the middle of the pool, and **b** shifted in the radially outward direction to $x = 1$ m

to thickening and hydraulic jumps that can lead to "dry spots" due to dry out. Further characterization of the temperature rages in the LM structure that is below the vapor limit of 450 °C.

Plasma Interface Modeling

An accurate determination of the particle and heat fluxes reaching the LM surface requires to account for the dynamic, nonlinear interactions of the near-surface plasma with the surface. This region is interested by a number of physical and chemical processes such as ion implantation,

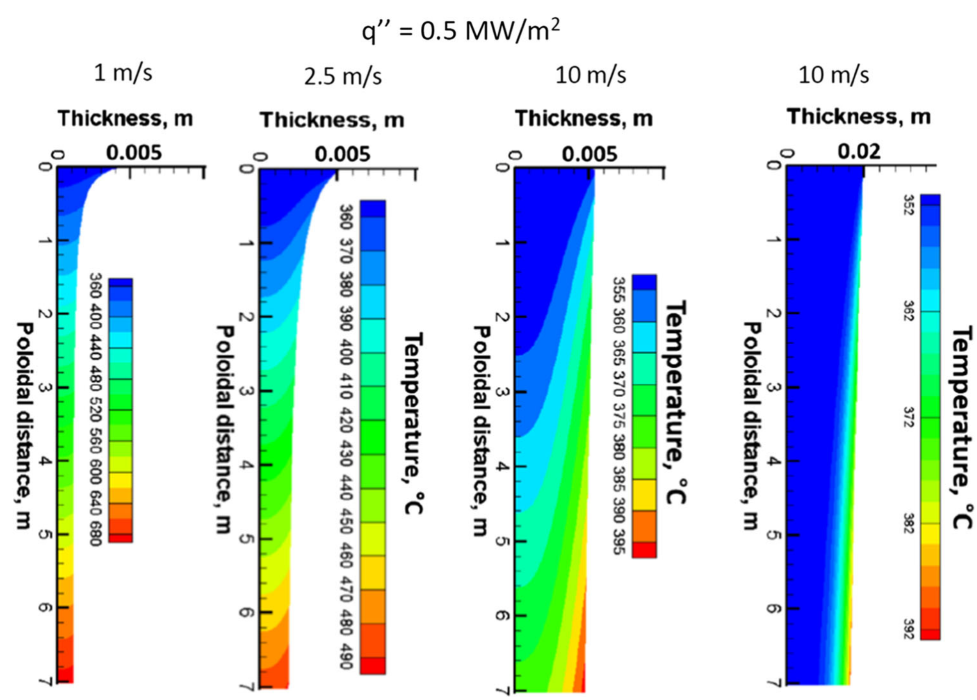

Fig. 1 Example of 2D LM flow simulations for a give heat flux and varying flow speed and LM layer thickness, indicating a range of substrate participation in heat transfer [37]

material sputtering, evaporation, deriving from the interaction of an accelerating ion flow toward a material surface. A detailed quantitative understanding of the near-surface physics is thus necessary for the correct quantification of the fluxes impinging on the liquid metal and of the vapor cloud formed in front of the surface and screening a fraction of the plasma heat flux.

2D SOL/divertor (including plasma and neutrals) simulations with SOLPS are performed to establish plasma solutions that are consistent with a chosen geometry, appropriate boundary conditions, pumping, and impacts on the core plasma. The Scrape-Off-Layer densities, temperatures, and flow velocities are used as an input to kinetic models of the near-surface region. The ions accelerating through the magnetic presheath and the electrostatic sheath cause sputtering, ad-atom, evaporation. The material impurities emitted by the surface are transported into the divertor and the SOL, and are either redeposited at a different location or they can cross the separatrix and contaminate the plasma core. A fraction of the impurities is ionized close to the surface, where a vapor cloud can form and shield a fraction of the incoming heat flux via inelastic collisions.

Currently there is no single code that can handle the multi-physics Plasma-Material Interaction problem on a region spanning from the SOL to the bulk material surface. The problem can be split into four regions described by different models (and corresponding codes), as shown in Fig. 3: (1) bulk material region, (2) material surface, (3) plasma sheath, and (4) scrape-off layer. Figure 4 shows the breakdown and flow-chart of the plasma-surface modeling effort required for such a problem and computational codes able to tackle this problem. An effective code coupling strategy is necessary, operating the transfer of input/output between the different codes.

The bulk material zone codes look at the evolution of the implanted plasma ions below the surface. Although this is important for LM and for tritium handling and extraction, it is considered beyond the scope of this project. The surface regions can be handled properly using the Fractal-TRIDYN [38] code**,** which can handle the interaction of low energy ions with the first few atomic layers, determining the ion implantation profiles and the distributions of sputtered and reflected particles. The code has been developed and is used extensively at UIUC to look at the surface interaction with the incoming plasma [38]. The magnetized sheath formed above the material surface largely affect the energy-angle distributions of the the ions arriving at the surface, which in turn affect sputtering, evaporation, particle and energy reflection and backscattering. The Particle-in-Cell code hPIC [39], 40 was specifically designed to tackle this problem, and it was

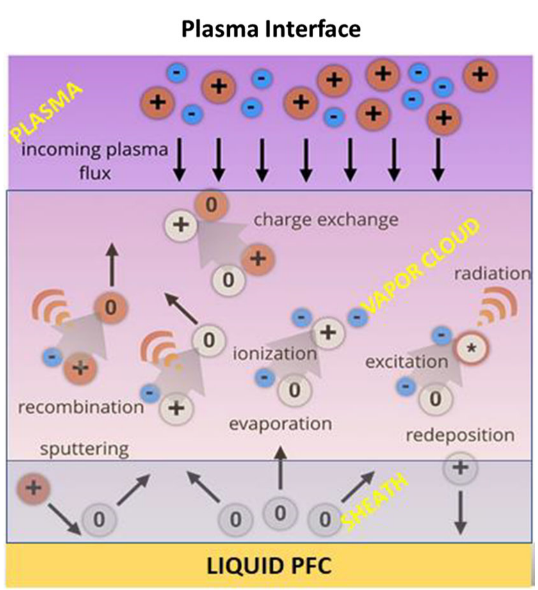

Fig. 3 Behavior of ions and neutrals at the Liquid Metal / Plasma / Gas interface is important to accurately predict losses and ability to dissipate heat, etc. Graphic shows physics processes that need to be considered, e.g. sheath formation, sputtering, evaporation, adatom effects, ionization, re-deposition, migration, surface contamination, etc

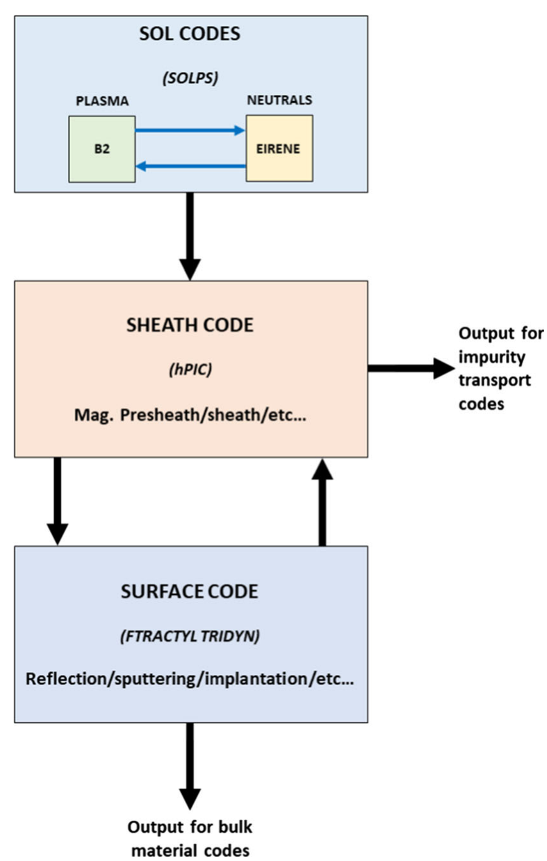

Fig. 4 Flow chart of the plasma-surface modelling effort that will be used for plasma-interface modelling

used extensively for simulations of near-surface plasmas in strongly magnetized conditions [41]**.** hPIC is coupled to the F-TRIDYN sputtering code [42] and it used as part of this project for erosion and redeposition studies of liquid lithium exposed to divertor fluxes.

The SOL, divertor plasma and neutral physics is treated with a 2D plasma transport solver B2 and the 3D Monte Carlo neutrals solver EIRENE, coupled within the SOLPS package. With a given wall geometry, core plasma definition, impurity definition, and boundary conditions (sources and sinks, perpendicular transport), the SOLPS code determines the species densities, temperatures, heat and particle fluxes in the main chamber and divertor surfaces and lead to finding results for the heat fluxes on the LM surface, the LM density upstream in the main chamber, radiative power dissipation, and particle fluxes and energies to the LM surface. Code integration will require data transfer from the multiple codes, including the SOL model, the sheath, and the surface models. In particular, a detailed analysis of the vapor cloud formed in the sheath region is critical to building up a quantitative picture of the LM-plasma interaction.

Single Effect and Flowing Experiments

Several important LM behaviors have been identified for their critical impact on the feasibility of a LM PFC to be possible. The engineering and plasma analysis described in previous sections provides the operating parameter space and description of the LM PFC system, however the detailed characteristics of certain phenomena are still not known and require experimental determinations. Examples of these include wetting:

Wetting

Wetting is the adherence [43] of the LM to the solid substrate, and its tendency to spread and cover a surface fully. This can be important where surface coverage and capillary forces are relied upon. Experiments at UIUC will use MEME and other facilities such as MCATS or SLIDE to determine the conditions for wetting and for understanding how to restart flow and wetting after the lithium cools and solidifies. We seek to answer: *what are the requirements for wetting in flowing LM systems with thin and thick layers (*$\sim$ *1 cm)? What governs the long-term wetting behavior in a large scale LM flowing system? Under what conditions does dry out occur, and how can it be mitigated.*

Compatibility/Erosion

The compatibility of lithium with stainless and ferritic steels is found to be good (T $<$ 500 °C) [44, 45], but its precise behavior is needed to be known to make reliable projections for components. Flow speeds can be high ($>$ 10 m/s) with some designs, erosion must also be examined. Experiments will involve exposing metal samples in high velocity liquid lithium and determining the compatibility and erosion behavior through mass loss and SEM measurements. We seek to answer: *does prolonged exposure of steels to liquid lithium affect compatibility and erosion, and what role does flow rate play?*

Liquid Metal Embrittlement

LM embrittlement (LME) [46] and failure mechanisms of substrate materials, or other materials that the LM can contact in off-normal situations, must be assessed to guarantee such an interaction does not occur. We will examine tensile stress, temperature, and other properties of the LM and substrates to qualify them, since theories do not exist that can explain the phenomena. Time to failure is also an important factor that needs to be studied and there is a need to know how this changes as a function of temperature, tensile load, exposure time, and composition. *We seek to answer: Will lithium cause LME in any of the candidate substrate, or fusion core materials it could potentially contact, under the anticipated operating conditions? This activity will establish the LME qualification procedures and approaches for lithium, and subsequently for other liquid metals.*

Hydrogen Uptake and Hydriding

The uptake (implantations, absorption and retention) of hydrogen by the lithium flows in the divertor is a complex topic that is governed by the flux of hydrogen to the lithium surface, the particle energies, the LM temperature, and near surface physics. Once the amount of hydrogen retained is determined an extraction system will seek to measure the actual retention for comparison. We seek to answer: *under what conditions (e.g. temperature windows, fluxes) does lithium retain hydrogen, and what is the role of surface impurities.*

Helium Pumping

Helium exhaust must be removed from the plasma region at the same rate or greater that it is produced or the plasma will be extinguished due to dilution of the plasma. Helium particles are expected to impinge onto the lithium flows in the divertor, with some particle flux and energy distribution. The ability of lithium to retain the helium, before it diffuses back to the surface, is still uncertain based on modeling and measured diffusion coefficients. Helium removal rates will need to be looked at through a flowing

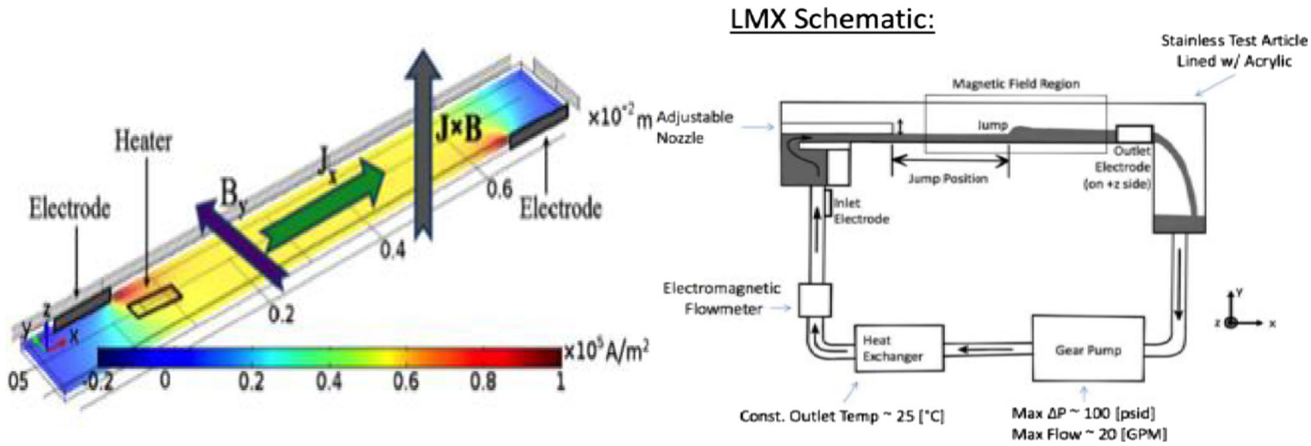

Fig. 5 Schematic of the LMX, showing the capability to apply various electromagnetic fields and heat. The flow loop (galinstan) is shown in the panel on the right

liquid lithium system where a helium plasma will be incident on the surface. We seek to answer: *under what conditions does flowing liquid lithium pump helium?*

With the LM PFC concept being a flowing system, the basic prototypical experiment is a linear chute (or similar) for LM to flow in the presence of various magnetic field components. Initially a surrogate LM, i.e. galinstan (GaInSn), will be used which is very weakly reactive, compared to lithium which requires a vacuum enclosure. Ultimately, lithium would be the preferred LM and as the experiment integrates more features and compares to simulations. We will conduct chute (i.e. open channel flowing LM) experiments and delivering results on the Liquid Metal Experiment (LMX) needed for the PFC engineering design activity. Figure 5 shows a schematic of LMX, showing its capabilities. The flow loop (galinstan) is shown in the panel on the right.

The LMX at PPPL is one prototypical linear chute (open-channel) experiment, with galinstan flowing in applied magnetic fields [47–50]. Magnetic fields can easily be applied as well flow obstructions can also be added to agitate the flow for turbulence enhancing and to improve heat transfer. The LMX can be used to answer many of the questions related to LM flow and MHD effects and the effects on liquid Li can be computed via extrapolation of dimensionless magnetic parameters [51].

Summary

The materials that make up the first wall and divertor of fusion devices have a substantial impact on the performance of the plasma. There are no obvious candidates that can readily scale to *steady-state* conditions. High-Z materials such as W have received much of the attention, and many major fusion devices have begun transitioning towards W PFCs. If plasma transient events cannot be avoided or mitigated, the peak heat and particle loads will challenge current solid materials. LM PFCs hold the promise to be a self-healing boundary against surface damage from transient events and may handle large heat and particle fluxes. LM also offer the potential ability to control hydrogenic species within the PFCs. With all this in mind and the results from the FESS study, a three-year liquid metal PFC development research initiative has been initiated in the U.S. This initiative consists of 3 parts: Engineering design activity including plasma interface calculations with SOL and divertor codes, single effect lab experiments to identify and answer basic LM questions, prototype tests of flowing LM in applied magnetic fields in experiment test stands. Several down-selections have already been made and other choices have been identified and will be investigated in the future. The LM has been chosen to be lithium, a divertor PFC concept will be designed first, a flowing LM concept with flow rate as a design choice will be investigated and temperature ranges below the strongly evaporative < 400–450 °C will used.

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