The need and development of liquid metal plasma facing components and blanket using TEMHD for an IFE device

Daniel Andruczyk and David N. Ruzic
Department of Nuclear, Plasma and Radiological Engineering (NPRE)
University of Illinois at Urbana-Champaign (UIUC)

I. Liquid-Surface Verses a Solid-Surface Wall?

Future inertial fusion energy (IFE) concepts will look operate continuously with pulsed discharges. No matter the situation the deuterium-tritium (DT) reactions will be generating helium and neutrons, two main by-products of the fusion reaction that need to be dealt with. Also, any residual D and T that is not burned up will also need to be removed. In particular, the T will need to be removed and re-used. This is a situation that magnetic confinement fusion (MCF) concepts are already thinking about. Solid surfaces, though easier to handle can potentially cause problems in that they will retain tritium with no way to get it out without shutting down the machine and helium can cause several issues with surface damage. The overall heat flux to the surface will need to stay below 10 MWm^{-2} and this means that the overall vessel will be large. Liquid metals (LM), especially lithium potentially can provide the means to protect the surface as well as provide a means to absorb tritium, deuterium and helium, transport it out of the main vessel and extract at least the tritium for further use. For fusion is to become an economically competitive energy source, the envisioned future device must cost significantly less. These technologies can lead to overall smaller devices which will bring down the overall costs.

II. Advantages of Lithium as a PFC Surface

Liquid lithium as PFC surface has several unique advantages over solid surfaces. The first being that liquids are essentially self-healing systems, and with lithium the lowest-Z material possible, allows higher impurity concentrations overall. Lithium has the unique property of absorbing or reacting with isotopic hydrogen species which are incident upon its surface, *as long as the lithium is clean* **[1]**. This produces a low-recycling surface, where cold isotopic-hydrogen are ***not*** returned to the plasma. In the high-recycling regime, wall-temperature molecules leave the surface in equal numbers to the hotter ion flux impinging on the wall surface. Such a return of recycled isotopic-hydrogen species cools the edge fusion device and will impact the background vacuum in a IFE chamber, and therefore can potentially impact the plasma which reaches temperatures high enough for fusion. A device operating in the low-recycling regime can reduce the background pressure therefore lessening the impact on the fusion plasma. A low-recycling flowing lithium-surface machine could *cost an order-of-magnitude less* and still produce the same electricity output **[2,3]**. While the average heat flux to the surface would be higher in a smaller machine, liquids also allow the possibility of tolerating that flux since they are already melted! One of the other big issues in fusion is how to remove the helium ash that is

Figure 1: Hybrid Illinois Device for Research and Applications (HIDRA) a tokamak/stellarator hybrid, formerly WEGA, now at UIUC.

generated from a fusion reaction. In 2005 it was demonstrated at UIUC that flowing liquid helium can indeed trap and flow helium **[4, 5]**. This was performed in the FLiER device and used a helium ion beam incident on a flowing lithium surface **[6]**. This forms a seal between two chambers so the only way He could enter the second chamber was by being transported by the lithium. More recently lithium experiments in a helium plasma in HIDRA **[7-9]** have shown a reduction in the recycling rate by over 90% **[10]**. Here "cold helium" from the HIDRA walls was the recycling atom and helium was flowed at a constant rate during the whole discharge. Figure 1 shows HIDRA as it currently operates. When helium was introduced, the cold helium disappeared while the lithium was present. Once the lithium source (~100 mg) was exhausted and left the plasma, then the recycling helium atoms returned. All this was observed over a 600 s HIDRA plasma discharge. When the helium recycling was low plasma performance increased dramatically from 15 eV to 55 eV. This along with the FLiER results shows that lithium is an effective was to pump and remove helium from the device.

III. Liquid Metals in Blanket Design

An IFE device, just like any MCF device, will need to have a way to generate the electricity. This will be done via the blanket. The blanket will use a lead-lithium (PbLi) eutectic, where the lead is a neutron multiplier and lithium will breed tritium. With this as well the blanket will heat up, and a heat exchange system will be required to remove this. As of now there is no clear cut way that a blanket will be designed and thus much work needs to be done. IFE devices potentially offer a simpler solution since there are no magnetic fields to cause MHD drag in flows. In the past UIUC has been able to produce a similar eutectic liquid metal for PFCs, tin-lithium (SnLi) **[11]**, and could use its facilities to produce PbLi and indeed intend on doing this in the near future. This combined with developed flowing LM concepts could provide a way forward to the development of a viable blanket for ICF.

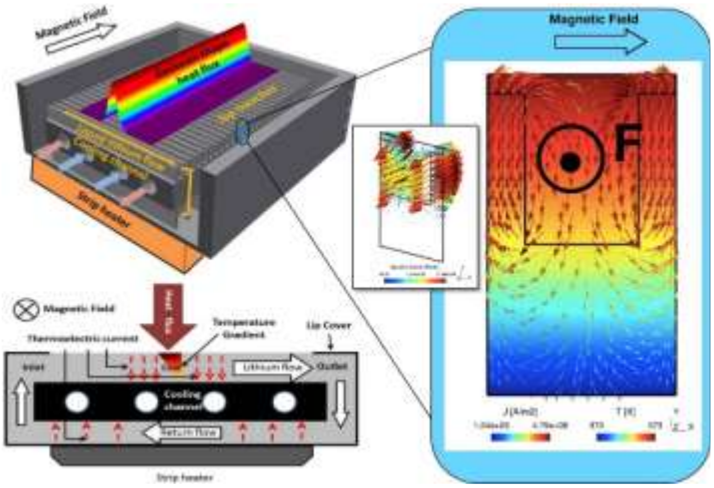

Figure 2: LiMIT works by a thermopower difference between the top and bottom of the trench structure. The current generated when "crossed" with the toroidal magnetic field causes a force on the molten lithium propelling along the trench.

IV. Challenges for Liquid Metals?

Liquid metals, and in particular lithium, have their own engineering challenges that need to be solved or taken into account. Lithium will become contaminated or saturated with "impurity" atoms it absorbs. To counteract this problem liquid metal surface must be ***both molten and flowing***. This allows a constantly clean surface to be exposed to the incident ions/atoms. One way to do this is using LiMIT (Liquid Metal Infused Trenches) **[12]** which utilizes the TEMHD effect, the plasma/particle heat flux onto the surface, and a perpendicular magnetic field, to self-pump molten material across the surface as shown in figure 2. This was first demonstrated at Illinois in laboratory experiments **[13]**, and subsequently in other devices such as Magnum-PSI to determine heat flux limits **[14]**, placed in HT-7 to illustrate its compatibility with tokamak relevant fields **[15]**, in DeVEX to show how droplet emission could be eliminated by proper spacing of the trench components **[16]** and more recently in EAST as a flowing PFC for plasma operations

[17]. Other flowing lithium concepts are also possible such as FLiLi **[18]** and CPS **[19]**, as long as continuous replenishment and removal of the lithium takes place.

In a fusion reaction, not all the tritium will be used up and will go to the wall. This means that the flowing lithium will absorb all the unburned tritium and potentially all the tritium in the World **[3]**. Thus. a low recycling wall solution requires prompt tritium removal and re-injection. This is possible, much of the hydrogen stays in solution with molten lithium **[6]** as opposed to forming hydrides. A fast-distillation of the hydrogen-filled lithium will need to be done, see figure 3. It has been demonstrated in a static systems **[20]**, but integrated into fully-flowing lithium-loop is yet to be demonstrated. This could easily be done on HIDRA, where a full accounting of isotopic-hydrogen recycling, removal and recovery can be done. Liquid lithium is limited to the types of substrate materials that can eb used. Liquid lithium is corrosive and difficult to handle, however the fortunate fact is that may of the fusion materials being considered, for, example tungsten, is resistant to Li attack. But this still means that an active technology program is essential for looking at other materials such as low activation RAFM steels. Handling lithium safely is paramount, but quite possible.

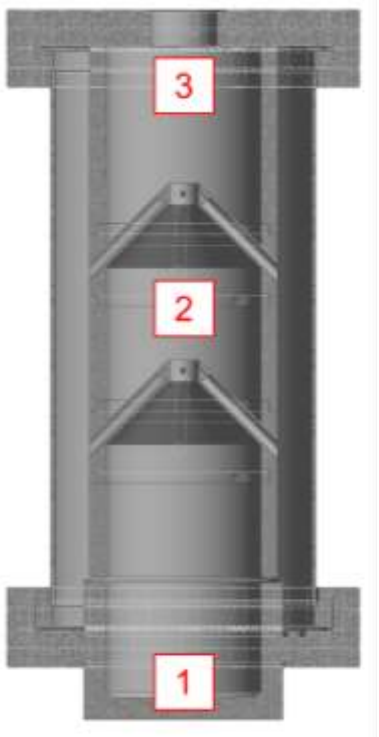

Figure 3: Pilot-scale lithium/lithium hydride distillation column displayed effective hydrogen recovery, while evaporated lithium was captured within the column

To this end a complete integrated systems with molten lithium need to be tested under realistic conditions before they can be adopted in larger-scale machines. Since HIDRA can serves as a liquid metal / lithium technology testbed, where the actual lithium-containing structures will are being tested shows that they all fit and will be hit by a realistic edge plasma. As well an understanding of the lithium with a plasma and background gas can be done using a dedicated material analysis tool (HIDRA-MAT) **[21]** where the chemistry can be studies with *in-vacuo* diagnostics including LIBS, LIDS, TDS and RGAs. This allows a surface to be studies temporally since vacuum does not have to be broken and a surface can be exposed to a plasma several times. Also a lithium injector can place a clean drop of liquid lithium onto the surface for exposure **[22]**.

IV. Conclusions

Future fusion reactor devices and power plants based on the IFE design need to be thinking about the impacts of neutrons and helium that is generated by the reactions and how they will be removed and used. Liquid metals offer an alternate approach to PFCs that is superior to the demanding challenges in a reactor. They also are crucial in the breeding of tritium in the blanket as well as generating the thermal heat for driving electrical generators. The low-recycling wall, if it can be made to work, could reduce the size and cost of fusion energy reactors. To realize this, further innovative technology development is still required in IFE. The US is the present leader in this field of using liquid metals as a PFC. It is important to the future of fusion energy that such programs exist in the IFE. Liquid-lithium surfaces are an innovation which could fulfill the promise of fusion energy.

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