Potential impacts of liquid metal plasma facing components on heating and current drive actuators for a Fusion Nuclear Science Facility

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Abstract

This paper addresses the potential impact of liquid metal (LM) plasma facing components (PFCs) for the heating and current drive actuators (H&CD) on the Fusion Nuclear Science Facility (FNSF) fusion reactor. Fulfilling the high neutron fluence mission of the FSNF requires steady-state operation for extremely long pulses (months to years) between maintenance opportunities. The use of liquid metal as a surface material is one strategy for extending the lifetime of the PFCs for long pulse operation in a high heat flux, high neutron flux environment like that of the FNSF. Liquid metal PFCs provide possible pathways forward on many difficult aspects of a fusion reactor, however the LM PFCs also bring new challenges and unknowns with respect to the H&CD actuators needed to provide steady-state operation. The development of LM compatible materials for RF antennas will be critical, as well as strategies for minimizing contamination of antenna surfaces and the
core plasma. Successful deployment of LM PFCs on the FNSF will require operational experience with RF in a liquid metal environment both on test stands and in an integrated toroidal environment.

**Keywords:** liquid metal, RF actuator, FNSF

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**1. Introduction**

The Fusion Nuclear Science Facility (FNSF) [1] is designed with the goal of qualifying fusion reactor-relevant materials and technologies in an integrated environment, serving as a bridge between the first burning plasmas (e.g. ITER [2] or SPARC [3]) and a commercial fusion reactor. The FNSF is a large \( R = 4.8 \) m, \( a = 1.2 \) m, high field \( B_T = 7.5 \) T tokamak with considerable current drive requirements \( I_p = 7.87 \) MA at \( f_{BS} = 0.52 \). The FNSF will require extremely long pulses (steady-state for \( \sim \) months between maintenance periods) to achieve its mission of high neutron fluence of the first wall and breeding blanket.

Steady-state operation will require non-inductive heating and current drive (H&CD) actuators that are powerful, efficient, and able to survive the extreme particle and energy fluxes of the tokamak environment [4]. The baseline design [5] for the FNSF study includes all of the non-inductive H&CD actuators used routinely on present-day tokamaks: neutral beam injection (NBI, 50 MW), electron cyclotron range of frequency (ECRF, 20 MW), lower hybrid range of frequency (LHRF, 30 MW), and ion cyclotron range of frequency (ICRF, 20 MW). All of these H&CD actuators have a proven experimental physics basis on present-day tokamaks with solid metal walls.

The introduction of liquid metal (LM) plasma facing surfaces (PFCs) in the FNSF design [6] provides a possible solution to several issues related to the first wall in a fusion reactor, namely erosion/reconstitution of solid PFCs, removal of heat load from the surface of PFCs, nuclear damage and transmutation of the PFCs, and reduction in gradients (temperature, stress, lattice displacements) in the PFCs. The addition of LM PFCs also brings additional challenges to the design and safe operation of a fusion reactor. These benefits and challenges of LM PFCs are discussed in accompanying papers from the FNSF Liquid Metal study [7, 8, 9, 10, 11, 12, 13].

This paper will address the potential impact of LM PFCs on the H&CD actuators for the FNSF. A discussion of port allocations and the interaction between ports and flowing LM surfaces is contained in Section 2, followed
by the impact of LM walls on the physics of wave propagation in Section 3. Materials compatibility, impurity generation, and antenna operation are covered in Sections 4, 5, and 6, respectively. The paper concludes with a discussion of findings and pathways forward in Section 7.

2. Ports

The FSNF design includes ports allocated for diagnostics and H&CD actuators as shown in Table 1. The ports are built into the sixteen toroidal blanket/first-wall sectors and assembled inside the vacuum vessel to form a nearly axisymmetric plasma facing first wall [14]. Most of the ports are located near to the mid-plane of the tokamak with the exception of divertor diagnostics and gas injectors, which are located at $± \sim 90^\circ$. Two coverage options were considered for the LM FNSF study: an all LM PFC design and a design with a LM divertor and solid PFCs elsewhere. More detailed descriptions and illustrations of these LM PFC options are available in [6, 13]. For the purpose of this section we will consider the all LM first wall as it will have the larger impact on the ports.

The ports in the first wall will interrupt the flow of LM for flowing or jet based first wall concepts and will require special consideration in the design of the flow channels; capillary wetted concepts do not have flowing LM and consequently the port penetrations will be less disruptive to the LM systems of that type. The flow path of the liquid metal is roughly poloidal for flowing LM first walls that have insulating barriers between toroidal segments. The poloidal flow of LM will need to either (a) divert around the port penetration (i.e. toroidal displacement with subsequent increase in flow velocity and/or thickness) or (b) behind the port (i.e. poloidal flow changing to radial flow away from the plasma at the top of the port, with a feeding manifold at the bottom of the port). Ports in most tokamaks are either circular/elliptical (to improve stress distribution and vacuum integrity) or rectangular (to maximize useful area within the port and to ease manufacturing) in cross section. These shapes also naturally lend themselves to certain applications, such as circular for ECRF and NBI ducts, or rectangular for endfire waveguide arrays commonly used in LHRF antennas. Rectangular ports are well suited for option (b), while circular/elliptical ports are better suited for option (a). Hydrodynamically favorable port shapes such as a teardrop or lozenge oriented parallel to the flow to minimize eddies should be considered as well for option (a). Ports could also be aggregated into a smaller number of toroidal
Table 1: Port allocations for the FNSF.

<table>
<thead>
<tr>
<th>System</th>
<th># of ports</th>
<th>Individual plasma facing area $[\text{m}^2]$</th>
<th>Total plasma facing area $[\text{m}^2]$</th>
<th>Poloidal angle $[^\circ]$</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICRF</td>
<td>2</td>
<td>2.04</td>
<td>4.08</td>
<td>0</td>
<td>1.2m×1.7m per port</td>
</tr>
<tr>
<td>LHRF (LFS)</td>
<td>2</td>
<td>1.4875</td>
<td>2.975</td>
<td>42.5</td>
<td>0.85m×1.75m per port</td>
</tr>
<tr>
<td>LHRF (HFS)</td>
<td>4</td>
<td>0.75</td>
<td>3</td>
<td>225</td>
<td>0.75m×1m per port</td>
</tr>
<tr>
<td>ECRF</td>
<td>1</td>
<td>0.675</td>
<td>0.675</td>
<td>-20</td>
<td>0.5m×1.35m per port</td>
</tr>
<tr>
<td>NBI</td>
<td>2</td>
<td>1.43</td>
<td>2.86</td>
<td>4</td>
<td>2m×0.715m per port</td>
</tr>
<tr>
<td><strong>Total H&amp;CD</strong></td>
<td><strong>11</strong></td>
<td><strong>13.59</strong></td>
<td><strong>13.59</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pellets</td>
<td>1</td>
<td>0.01</td>
<td>0.01</td>
<td>225</td>
<td>0.1m×0.1m per port</td>
</tr>
<tr>
<td>Diagnostics,</td>
<td>3</td>
<td>0.9</td>
<td>2.7</td>
<td>0</td>
<td>0.9m×1.0m per port</td>
</tr>
<tr>
<td>midplane</td>
<td>1</td>
<td>0.25</td>
<td>0.25</td>
<td>0</td>
<td>0.5m×0.5m per port</td>
</tr>
<tr>
<td>Diagnostics,</td>
<td>2</td>
<td>0.15</td>
<td>0.3</td>
<td>90, -90</td>
<td>0.5m×0.3m per port</td>
</tr>
<tr>
<td>midplane (small)</td>
<td></td>
<td>2</td>
<td>0.02</td>
<td>90, -90</td>
<td>0.1m×0.1m per port</td>
</tr>
<tr>
<td>Diagnostics,</td>
<td>2</td>
<td>0.04</td>
<td>0.08</td>
<td>0</td>
<td>0.2m×0.2m per port</td>
</tr>
<tr>
<td>divertor</td>
<td>2</td>
<td>0.04</td>
<td>0.08</td>
<td>0</td>
<td>0.2m×0.2m per port</td>
</tr>
<tr>
<td>Gas injection, divertor</td>
<td>2</td>
<td>0.04</td>
<td>0.08</td>
<td>0</td>
<td>0.2m×0.2m per port</td>
</tr>
</tbody>
</table>
sectors with perhaps a few “dry” sectors recessed radially relative to the adjacent LM surface sectors to minimize the number of sectors impacted by ports.

For flowing LM first walls without toroidally insulating dividers the flow direction will be helical from the top to the bottom of the tokamak with both the poloidal and toroidal magnetic field acting upon the conducting fluid. If gravity and resistivity are neglected the flow pattern will closely follow the helical magnetic field lines, similar to plasma flows in the scrape-off-layer (SOL). The relatively high mass density of liquid metals (0.516 g/cm$^3$ for liquid Li, the least dense of all liquid metals) results in significant gravitational forces, and when combined with finite resistivity of liquid metals yields flow patterns that deviate from strictly following magnetic field lines but still contain significant toroidal and poloidal components due to magnetohydrodynamic forces. In this situation the ports at different poloidal locations can be arranged such that they line up along the flow, thereby minimizing the perturbation to the overall flow pattern. Again, reconfiguring ports from circular/rectangular to teardrop/lozenge form factors will reduce the size of eddies formed by ports introduced into the flowing liquid metals.

Another consideration is whether both the high field side (HFS) and low field side (LFS) walls will have LM PFCs. The SOL on the HFS is much more quiescent than the LFS, which means that the heat/particle fluxes and concomitant plasma material interactions (PMI) are significantly reduced as compared to the LFS [15, 16]. If the HFS wall uses conventional solid metal PFCs, then moving some ports from the LFS to the HFS will reduce the impact of LM on the ports. Some ports can be moved from the LFS to the HFS (RF actuators, for example [17]), but others such as neutral beams will always need to be located on the LFS due to geometrical constraints.

Ports will need to be kept free of liquid metals during operation. Capillary type LM PFCs rely on wetting of the LM on the substrate to coat the surface, however this wetting behavior should not extend into the port or any components within the port. This could be achieved through use of a non-wetting “frame” surrounding each port, or a recessed “trench” that removes liquid metal from the perimeter of the port in case of flowing liquid metal walls.
3. Impact on heating and current drive physics

Liquid metal PFCs, particularly liquid Li, can have a dramatic effect on the plasma scrape-off-layer. The electron temperature and density profiles in the SOL determine the propagation characteristics of RF waves, particularly in the LHRF and ICRF. These waves require the local density exceed the “cutoff density” for propagation when the parallel index of refraction, \( n_i \equiv c k_||/\omega \), is greater than one (as is typically the case for ICRF and LHRF). Figure 1 shows the slow wave dispersion relation for waves at 5 GHz. The value of \( n_i^2 \) crosses zero (switches from evanescent to propagating) at \( n_e = n_{\text{cutoff}} = 3.1 \times 10^{17} \text{ m}^{-3} \) for waves at 5 GHz. The density at the antenna must be maintained close to the cutoff density for efficient coupling of slow LHRF waves into the plasma [18]. For fast waves in the ICRF, the cutoff (typically of order \( 10^{18} \text{ m}^{-3} \)) must be kept in proximity to the antenna [19]. Although the cutoff density for ICRF fast waves is higher than for LHRF slow waves, the longer evanescent decay lengths for ICRF fast waves allow for efficient tunneling to the propagating region.

In general, liquid metal walls (particularly liquid lithium) are observed to reduce the density and increase the temperature in the SOL by reducing recycling from the wall [20]. Profiles on the LFS and HFS mid-plane for both metal and liquid lithium divertors (with an otherwise solid metallic wall) are plotted in Figure 2. In the case of predicted SOL profiles for the FNSF, the difference between the liquid and solid divertor is inverted, with the liquid Li divertor case having somewhat higher density in the SOL, particularly on the LFS.

From the perspective of RF actuator performance there is only a small difference between the solid W and liquid Li divertors when considering the profiles of Figure 2. Both cases show densities above (for LHRF) or similar to (for ICRF) the cutoff density in the far SOL. From a coupling perspective the small differences in density between the solid and liquid divertors is inconsequential. Figure 3 shows reflection coefficient (\( \Gamma^2 \)) and directivity curves for the launcher design in [4]. The optimal launched \( n_i \) values of 1.7 (HFS) and 1.9 (LFS) from the previous study are plotted. Both reflection coefficient curves exhibit a broad minimum at densities in the mid-\( 10^{17} \text{ m}^{-3} \) range. This density is achieved at a distance from the last closed flux surface (LCFS) of at least 5 cm, as determined by extrapolating from the curves in Figure 2. The density at the antenna mouth can be adjusted by moving the plasma towards or away from the wall at the proper poloidal location,
an adjustment of several cm for a plasma of several meters in radius. This small perturbation (of order 1%) in plasma position is easily achieved with feedback control on existing tokamaks.

Another aspect of the SOL to consider is parasitic losses due to collisions. Liquid metal walls typically increase the temperature and decrease the density, and indeed “collisionless” SOL parameters are reported in LTX [20]. Figure 4 compares simulations of driven current profile for LHRF for the liquid and solid divertors discussed above. The small difference in the peak current density profile is attributed to a slight increase in collisional absorption in the SOL with the higher density liquid Li divertor SOL profiles. A full liquid metal wall with a collisionless SOL is approximated by turning off SOL collisions in the model. The resulting current profile is nearly identical to that of the solid metal divertor case.

4. Materials compatibility

Liquid metals are known to be extremely corrosive to many solid metals [6]. The structural material for RF antenna components inside the nuclear
Figure 2: Simulated SOL density profiles on the LFS and HFS mid-plane for FSNF designs with solid PFCs [21] and with a liquid lithium divertor [7] as a function of distance from the LCFS.
Figure 3: Simulated reflection coefficients (top) and directivity (bottom) for the antenna described in [4] with a density scale length of 7 mm. The two launched $n_{||}$ values shown are optimized for HFS (1.7) and LFS (1.9) antenna locations. A 1 mm vacuum gap between the antenna and plasma is assumed in this model, consistent with a local protection limiter mounted proud of the waveguide apertures by that distance.
Figure 4: Simulated current density profile calculated by GENRAY/CQL3D [22, 23] for the FNSF HFS LHRF system [4] with solid W (red) and liquid Li divertor (green) SOL profiles. The blue curve uses the same SOL profiles as the liquid Li divertor case, but turns off SOL collisions in the model, approximating a “collisionless” SOL corresponding to a full liquid Li wall.
island will likely be a reduced activation ferritic-martensitic (RAFM) steel alloy due to the mechanical and nuclear properties required for this application. A high conductivity coating of several skin depths (skin depth $\delta \sim 0.15 \mu m$ in the ECRF, $1 \mu m$ in the LHRF, $6 \mu m$ in the ICRF) on the surface of the RAFM will likely be needed to reduce RF losses in the antenna and thus improve overall engineering gain [4]. Copper is a primary candidate for this application due to it’s high conductivity (both electrical and thermal) and established industrial techniques for applying thin coatings on top of metal substrates. Many liquid metals, particularly liquid Li, are incompatible with Cu on the basis of accelerated corrosion [24, 25], which when considered in the context of a few $\mu m$ thickness would not require prolonged exposure to have a detrimental effect on the coating. If Cu is used as a coating on antenna components, extreme care must be taken to avoid contact between the liquid metal and the coated surfaces. The corrosive effect of liquid Li vapor on thin Cu coatings has not, to the author’s knowledge, been studied.

Other high conductivity metals such as Au, Ag, and Al are ruled out on the basis of transmutation in a high neutron flux environment, leaving W as the likely coating of choice for a liquid metal environment. Corrosion of W by liquid metals is considerably reduced as compared to Cu, and has the side benefit of having a much higher resistance to plasma erosion and melting, hence it is selected as the plasma facing armor in most solid wall fusion reactor designs. The conductivity of W is roughly three times lower than Cu, which will increase RF losses and require a thicker coating (approximately $1 \mu m$ for ECRF, $5 \mu m$ for LHRF, $30 \mu m$ for ICRF), however the conductivity of W remains an order of magnitude higher than that of steel.

5. Core impurity accumulation

Impurity influx from the wall is a known issue for solid metal wall tokamaks with ICRF heating [26, 27, 28]. Impurities in the plasma core dilute the DT fuel mixture and increase core radiation leading to lower energy confinement and decreased fusion performance. The source of these impurities is attributed to physical sputtering by ions accelerated through the DC sheath generated by the oscillating parallel RF electric field at the plasma-wall interface. The mechanism is described in detail by Perkins in [29]. Figure 2 in [30] gives a schematic representation of how the oscillating RF electric field results in a DC sheath potential to oppose the current governed by the I-V curve.
Physical sputtering is the main source of impurity influx for solid metal walls. Physical sputtering is also an important phenomenon for liquid metals in addition to ad-atom losses. Accumulation of a low $Z$ impurity in the plasma will have a much lower impact on reactor performance, and thus impurity generation caused by RF sheaths is likely to be less of an issue for Li ($Z = 3$). Lithium fractions of order 1% in the fusion core are allowable in the FNSF [6]. Higher $Z$ liquid metals such as Sn ($Z = 50$) and its alloys have high sputtering yields (an order of magnitude higher than W [31, 32]) and high enough $Z$ to contribute significantly to core radiation, thus reducing fusion core performance. A core Sn fraction of 0.06% is the maximum allowable in the FNSF, only a factor of 2.3 larger than the maximum allowable W fraction (0.026%). Thus control of impurity radiation from Sn PFCs is likely to be more difficult than for W PFCs.

6. Power handling

Reliable operation of H&CD actuators requires that antenna surfaces remain smooth and free of contamination. Contamination by condensation, drips, or splashes of liquid metal on antenna surfaces may cause operational issues. Condensation of liquid metal vapor on the antenna can be avoided by operating the antenna at a temperature higher than the boiling point of the relevant liquid metal (generally greater than 600°C), but this will increase the resistive RF losses in the antenna significantly. The resistivity of Cu, for example, more than doubles between 300°C and 600°C.

Loosely attached material on the surface of antenna components causes two problems: sharp edges or points, and ejection of material from the surface. Sharp edges and points locally concentrate electric fields and may cause arcing at reduced power levels as compared to a smooth surface. The surface tension of liquid metals will cause small droplets to form if the underlying surface is smooth and polished as is generally the case on antennas (to reduce RF surface current losses), and thus the liquid metal does not wet the surface.

A buildup of solidified liquid metal (if the antenna components are operated below the melting point of the liquid metal), or the impurity slag left behind after the liquid metal vaporizes (if the antenna components are operated above the boiling point of the liquid metal) may come loose from the surface due to thermal expansion/contraction or electromagnetic forces, thus causing an injection into the plasma. Procedures must be in place for clean-
ing any contamination from the antenna surfaces, either through a yet-higher temperature bake or by utilizing robotic cleaning technology [33].

Multipactor can also limit the power handling capability of antenna structures in the ICRF [34] and LHRF [35]. Free electrons accelerated in the presence of the RF electric field will impact material surfaces if a component of $\vec{E}_{RF}$ is parallel to $\vec{B}$ at the surface of the antenna. If the secondary emission coefficient of the material exceeds unity and the RF electric field is sufficiently strong, then the number of electrons liberated from the surface during each wave cycle will increase exponentially until an arc develops. Secondary emission coefficients for pure Li, Sn, and Pb are near unity [36, 37, 38], but increase to 1.5 for Sn-Li alloys [39] and over 4 when impurities are present in Li [40]. For comparison the secondary emission coefficient for Cu is 1.5. In this regard liquid metals may reduce the risk of multipactor so long as they are free of impurities.

Liquid metals may also be an issue for high power neutral beams, which require extensive use of cryopumps to prevent gas in the neutralization chamber from escaping into the main torus. Care must be taken to avoid excessive deposition of the liquid metal vapor on the neutral beam cryopump panels. Furthermore, the relatively high pressure hydrogenic gas would form hydrides aggressively with any Li that finds its way into the beam neutralization chamber.

7. Discussion and Pathways Forward

At the present time there is little experience in the use of RF H&CD actuators in the presence of liquid metal walls. Many of the impacts discussed in the paper thus far are speculative based on relevant experience with H&CD actuators on solid wall tokamaks. If a steady-state liquid metal device such as FNSF is to be realized, then experience should be developed first on smaller-scale experiments.

Near term research and development might focus on the addition of liquid metals to an RF test stand experiment. Several such test stands exist, but an upgraded or new test stand would be needed to accommodate the use of liquid metals. Independent temperature control of the liquid metal and RF components should be specified to allow for testing in multiple regimes (e.g. RF components below boiling point of Li with a high temperature Li to simulate a hot “vapor box” type divertor).
Test stand experiments can inform some aspects (material compatibility, power handling), while other aspects (overall actuator performance, impurity accumulation) will likely need to be assessed in an integrated tokamak environment. Small footprint flowing liquid Li limiter experiments on EAST [41] and liquid LI divertor experiments on NSTX-U [42] in the near term may provide some feedback on how liquid metal interactions with H&CD actuators in an integrated environment. An all liquid metal wall tokamak would likely be required to verify the potential physics benefits of extremely low recycling wall conditions.

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