Mitigation of scrape-off layer power flow with lithium plasma-facing surfaces

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Technology to be assessed. The technology to be assessed is, for a reactor, the use of liquid lithium plasma – facing surfaces to *mitigate* localized power loading in the divertor. Liquid metal surfaces have been proposed as a replacement for solid plasma facing components (PFCs), in order to cope with erosion, and permit higher power loading. For the replacement of solid PFCs, a few liquid metals, notably tin, lithium, tin-lithium eutectics, and gallium, have been proposed. Here the emphasis is specifically on the use of liquid lithium, in order to strongly modify the scrape-off layer (SOL) plasma. The properties of lithium which uniquely suit it to this application include low recycling, low Z, high solubility of hydrogenics (good retention of D and T), low secondary electron emission, and a low first ionization potential.

Near-term assessment of SOL modifications can be performed in present-day tokamaks with solid or liquid lithium coatings on nonreactive substrates, such as metals or silicon carbide.

Application in tokamaks and stellarators. Flowing liquid lithium PFCs are required for this application for either tokamaks or stellarators. The rate of flow can be fast (1 – 10 m/s), in which case the plasma heat load will be removed with the flowing wall or divertor surface, or slow (a few cm/sec), in which case the substrate over which the liquid lithium flows must be cooled to prevent the surface temperature from exceeding approximately 400 °C, in order to maintain a low recycling surface. Within the requirements that the surface temperature be controlled, and that flow be sufficient to transport dissolved hydrogen from the tokamak or stellarator before excessive amounts of lithium tritide or deuteride (which are high melting point solids) are formed, the effects of lithium walls on the SOL are not dependent on the rate of flow, or the techniques used to induce flow. Additionally, some core fueling technique which avoids neutral gas injection in the edge is required. The low recycling SOL approach is not compatible with gas injection to induce high edge radiation; low edge neutral pressure is required.

It has now been shown experimentally that a low recycling lithium wall will produce very high edge temperatures, with $T_{e,i}(r=a) \sim T_{e,i}(r=0)$;[1,2] this consequence of lithium plasma-facing surfaces has been predicted for some time.[3] The flux of ions to the wall in a very low recycling confinement device will therefore consist of a low density, low collisionality population of very high energy particles, rather than the relatively dense, collisional, low temperature flux typical of high recycling devices. The expectation here is that all surfaces which intercept plasma losses will be liquid lithium. A liquid metal is not susceptible to surface damage, the sputtering coefficient of lithium is strongly reduced at high ion impact energies,[4] secondary electron emission is low for lithium at high (electron) energies,[5] and of course lithium is low recycling, all of which make liquid lithium suitable for contact with a hot edge plasma.

Although it is likely not possible to radiate away any significant fraction of the power flowing across the separatrix and maintain low recycling conditions, the scrape-off length for power flow is increased by virtue of the larger ion poloidal gyroradii in a hot edge plasma. With $T_{e,i}(r=a) \sim T_{e,i}(r=0)$, the scrape-off length for density will be approximately an order of magnitude greater than for a high recycling machine with a cold edge. The scrape-off length for temperature with a low recycling wall, and flat temperature profiles, is effectively infinite. As a result, the power scrape-off length is increased in a low recycling device by an order of magnitude or more, and the peak power loading in the divertor is reduced by a similar factor.

The SOL will be nearly collisionless, with $\boldsymbol{\nu}^*_{i,e} < 0.1$. Since the trapped particle fraction will not vary significantly just outside the last closed flux surface (LCFS), compared to just inside the LCFS, most of the particle population in the near-midplane, low field side, SOL of a low recycling device will be mirror trapped. Trapped particles can only be lost to the divertor if they are pitch angle scattered into the loss cone. Since the 90° pitch angle scattering time is much shorter for electrons than for ions, one consequence of a mirror trapped population in the SOL is the development of a Pastukhov (ambipolar) potential.[6] The ambipolar potential in the SOL will serve a purpose similar to the sheath potential in a more collisional, fluid SOL – constraining the electron loss rate to equal the ion loss rate. However, unlike the sheath potential in a collisional SOL, the ambipolar potential is not localized to the divertor target, but will vary along the SOL magnetic field line, generating a significant electric field in the SOL. In mirror machines, the electric field arising from the ambipolar potential served to eject high-Z impurities from the mirror plasma,[7] and a similar effect should occur for any lithium sputtered from the wall, or helium ash re-emitted from the lithium PFC, as long as the impurities are ionized near the wall. Impurity screening should be very effective.

Mirror trapping of the plasma in the SOL increases the impact of radial transport. For a collisional SOL, radial turbulent (or blobby) edge transport must be rapid enough to increase the density scrape-off length on the same time scale as the parallel loss time to the divertor (~the connection length/sound speed = L_{conn}/C_s). In a hot, nearly collisionless SOL, plasma is confined for a 90° pitch angle scattering time, which is $>>L_{conn}/C_s$. If turbulence levels are similar in both cases, then the scrape-off length for density will be much more strongly affected for a collisionless, than for a conventional collisional, SOL. Line-tying to the divertor targets may prevent development of flute instabilities, but the SOL will likely be peeling-ballooning unstable, leading to radial plasma losses. Particle drifts may also contribute to transport. Importantly, a number of kinetic codes are already available which can effectively address the collisionless regime for the SOL, and can be used to assess the heat flux to the walls.

Critical variable; design variables. Power deposition profiles in the divertor and on the (presumably liquid lithium) wall are not yet known for a nearly collisionless, partly confined SOL. Inner vs. outer divertor loading for either lower single null or double-null configurations has not been explored. The fraction of mirror-trapped particles in the low field side SOL will vary with aspect ratio – the trapped fraction in a spherical tokamak (ST) will be especially high, which may be advantageous for the ST. Consequently, wall loading in the ST may be significant.

A hot SOL would cause surface damage to solid PFCs, so this concept requires that liquid lithium constitute all plasma-facing surfaces. A hot edge cannot be sustained with high recycling surfaces, which rules out the use of alternative liquid metals. In addition, sputtering of high Z

liquid metals by the hot edge would likely be unacceptable. Sputtering is greatly reduced at high energies for D,T incident on lithium. [4]

Control of the edge and SOL temperature may be possible through edge gas puffing; puffing is seen to clearly reduce the edge temperature in LTX.[1,2] In a reactor, however, puffing D,T in the edge will result in more tritium uptake in the liquid lithium, and increase requirements for tritium processing. A more elegant solution would be to control D,T retention with the temperature of the liquid lithium. Direct reflection is always low for incidence of moderately energetic D,T on lithium, but retention of hydrogenic species drops significantly if the temperature of the lithium exceeds 400°C.[8] For slowly flowing capillary systems, temperature control would require varying the cooling of the underlying substrate. For a fast flowing divertor target, it would only be necessary to vary the flow speed. Since the surface heating of a fast flowing liquid lithium divertor target, for constant heat exposure, varies as $(1/v_{flow})^2$, less than a 30% reduction in flow speed is required to produce a factor of two increase in the surface temperature. Further reductions in the lithium flow speed to increase the surface temperature to 400° - 500°C would also increase lithium evaporation and consequently SOL radiative losses. The time response for this approach to control of the recycling level would primarily depend on the (flow path length)/(flow speed). For a divertor target a few tens of cm in radial extent, and for flow speeds in the range of a few - 10 m/sec, response times of <100 msec should be readily achievable. Note that this approach to recycling control would certainly affect core plasma confinement as well, if energy confinement is a strong function of recycling.[9]

Risks and uncertainties. Even if all plasma-contacting surfaces are liquid, solid structures remote from the plasma will still be subject to damage from charge exchange neutrals. Core fueling is required here, and the absence of edge gas puffing will greatly reduce the flux of charge exchange neutrals to solid wall components, but the charge exchange flux must still be modeled. Estimates of the maximum surface temperature for liquid lithium divertors and PFCs have been made, based on impurity influx limits, but not for the very hot, broad SOL discussed here. Helium pumping efficiency has not been assessed. Although puffing of a radiating gas for radiative cooling is clearly not compatible with a hot edge, ionization of sputtered lithium will re-introduce radiative losses, which must be characterized. It remains to be seen if the lithium influx can be limited to acceptable levels with a very hot SOL. Finally, the use of low recycling lithium walls and divertors to modify the SOL, and mitigate divertor power loading, requires the successful development of reactor-relevant flowing liquid lithium PFCs, which is clearly a significant uncertainty.

Technology development. The generation of a low recycling, nearly collisionless, hot SOL requires the use of flowing liquid lithium plasma-facing surfaces, but is not sensitive to variables such as the flow speed, so long as the surface temperature of the moving lithium does not exceed the levels at which excessive evaporation takes place. The technical readiness level (TRL) of flowing lithium plasma-facing surfaces varies from low for self-cooled fast flowing systems (TRL~2), to higher for slowly flowing capillary porous systems, which have already been partially demonstrated in tokamaks (TRL~3-4).

For any flow speed, it will be necessary to develop a system to efficiently remove pumped tritium from the liquid lithium. Tritium removal will be ex-situ, via a process loop which exits the breeding blanket. A process loop must service the entire lithium inventory (100-200 kg of liquid lithium) within approximately 12-24 hours, in order to provide fuel and limit the in-vessel

tritium inventory. A promising candidate for tritium removal is solid-state electrolysis,[10] which can be carried out in a lithium buffer tank, part of the external process loop. Solid-state electrolysis makes use of lithium ion conducting ceramic electrolytes such as lithium lanthanum zirconate (LLZO). The LLZO ceramic membranes are stable in the presence of molten lithium metal. The decomposition LiD to Li metal and D_2 has been demonstrated using the solid lithium conducting electrolytes at the lab scale (TRL~2). Techno-economic analysis indicates that achieving ionic conductivity of 5 mS/cm and reducing electrolyte thicknesses to the 50 micron range would allow LiT electrolysis with energy input of less than 100 W for processing 1 tonne/hr, for an LiT concentration of 10 ppm. The energy input will scale with the T, D concentration, but the electrolyzer power requirement is clearly low. Electrolyte development is ongoing and improved synthesis techniques for the LLZO electrolyte membranes have assisted in making more uniform grain sizes that lead to higher conductivity and material stability. The effect of additives such as Ga are also being investigated to improve the electrolyte properties.

For fast flowing liquid lithium PFCs, the flow speed requirement is largely determined by the power loading profile. For slowly flowing PFCs, power loading determines the substrate cooling requirement. Kinetic modifications to the SOL which may reduce peak divertor power loading, and increase distributed wall loading, will strongly affect the technical design requirements, such as flow speed, for flowing liquid lithium walls.

References

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[9] See R. Majeski, et al., "Recycling reduction for control of anomalous transport," white paper submitted to the FESAC TEC, Rockville, MD, 30 May – 1 June 2017.
[10] See L. Olson, et al., from the Fall 2015 meeting of the Tritium Focus Group, https://energy.gov/em/downloads/electrolytic-tritium-extraction-molten-li-lit. Process developed at Savannah River National Laboratory; a patent (application US20160122881A1) has been submitted.