

## Liquid Metal Technologies for Next-Generation Tokamak Applications

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**Abstract**

*Nuclear fusion holds the promise of providing an almost limitless and clean energy source; however, realizing a sustainable and commercially viable fusion reactor remains a formidable challenge. A major limitation lies in the thermal performance of plasma-facing components (PFCs) in tokamaks. While solid plasma-facing materials (PFMs) have been extensively studied, their inherent constraints under extreme fusion conditions have prompted growing interest in liquid metal PFMs. Among these, liquid lithium has emerged as a particularly promising candidate due to its low atomic number and excellent thermal properties. This review traces the development of liquid lithium PFC concepts, with a focus on the Lithium Metal Infused Trench (LiMIT) system. It examines the complex interactions between liquid lithium and magnetic fields, highlighting the resulting magnetohydrodynamic (MHD) and thermoelectric magnetohydrodynamic (TEMHD) phenomena. Both experimental and computational studies reveal the potential of liquid lithium systems, as well as the associated challenges, including dryout under high heat flux and the need for optimized channel designs. This review provides a comprehensive overview of tokamak liquid metal technology and identifies critical areas for future research, with the ultimate goal of enabling the practical deployment of liquid lithium-based PFCs in fusion reactors.*

**Keywords:** Nuclear fusion, Plasma-facing components (PFCs), Liquid lithium, Magnetohydrodynamics (MHD), Tokamak, Heat flux, Lithium Metal Infused Trench (LiMIT), Thermoelectric magnetohydrodynamics (TEMHD).

**Introduction**

The pursuit of a sustainable and clean energy source has positioned nuclear fusion as a promising alternative to conventional energy generation. Unlike nuclear fission, fusion has the potential to provide an almost limitless energy supply without producing long-lived radioactive waste. Despite significant advances in fusion research over recent decades, achieving a stable, self-sustaining fusion reaction under terrestrial conditions remains a formidable challenge. A major obstacle to the realization of functional fusion reactors is the development of materials capable of withstanding the extreme conditions of fusion plasmas. Plasma-facing components (PFCs) serve as the first line of defense, directly exposed to the intense heat and particle flux generated during fusion. Traditionally, solid plasma-facing materials (PFMs), such as tungsten and carbon, have been extensively studied due to their high melting points and ability to tolerate substantial thermal loads. However, these materials present notable limitations, including sputtering, erosion, and the introduction of high atomic number impurities into the plasma, which can degrade performance and reduce fusion efficiency. In recent years, liquid metal based plasma-facing units (PFUs) have emerged as viable alternatives to solid materials due to their unique properties, including self-healing capabilities, high thermal conductivity, and the ability to absorb and release large amounts of energy through phase transitions. Among these, liquid lithium has gained particular attention owing to its low atomic

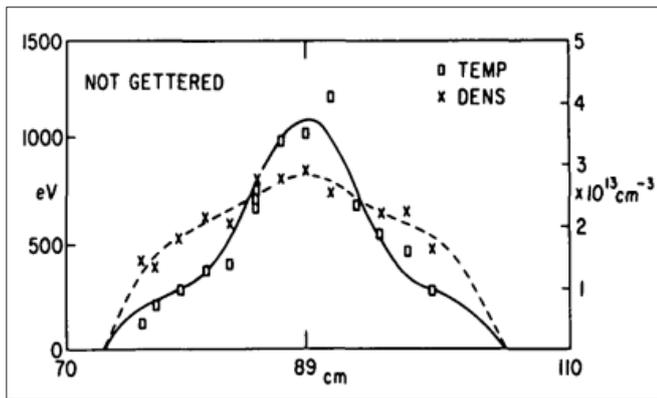
number which minimizes radiation losses and its effective trapping of hydrogen isotopes, enhancing fuel recycling while reducing plasma contamination. Liquid metals have enabled the development of innovative concepts, such as the Lithium Metal Infused Trench (LiMIT) system, in which liquid lithium is circulated by thermoelectric magnetohydrodynamic (TEMHD) forces.

This review provides a comprehensive overview of tokamak liquid metal technology, emphasizing fundamental principles, experimental findings, and computational modeling that have advanced our understanding of these systems. It addresses key challenges associated with liquid lithium, including dryout under high heat flux and complex interactions with magnetic fields. Additionally, it highlights critical gaps in current research and identifies promising directions for future investigation, with the ultimate goal of facilitating the successful integration of liquid lithium PFUs into next-generation fusion reactors.

**Review**

Nuclear fusion has been studied for more than half a century, yet achieving sustainable fusion energy remains a formidable challenge. One of the key obstacles limiting the development of practical fusion devices is the selection of suitable materials for plasma-facing components (PFCs) (Federici et al., 2002; Khan et al., 2024; Shakir et al., 2024; Ahmed et al., 2020).

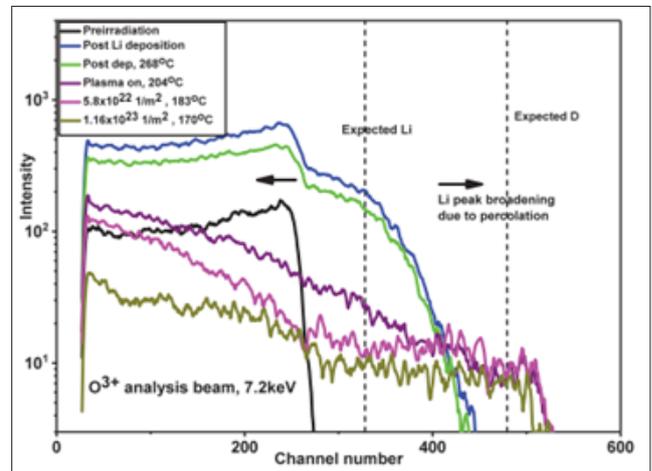
Historically, significant effort has been devoted to identifying the most appropriate solid plasma-facing materials (PFMs), with a range of high- and low-atomic-number elements evaluated and tested (Philipps et al., 2000; Javid et al., 2024; Khan et al., 2019; Khan et al., 2012). A critical consideration in material selection is the recycling phenomenon in tokamaks (Pitts, et al, 2013; Abdullah et al, 2024; Khan et al, 2023; Ahmed et al, 2021), where plasma particles escape the hot core plasma and move to the cooler edge plasma, interacting with PFCs or the vacuum vessel wall. These particles transfer energy and may form surface monolayers, while some, predominantly hydrogen, are dislodged and re-ionized into the plasma, helping maintain plasma density but incurring energy losses (Stott et al., 1975; Alam et al., 2023; Khan et al., 2018; Gao et al., 2014) see fig.1. In addition to hydrogen, atoms from PFCs themselves can enter the plasma as impurities. Low-Z impurities from low-Z PFMs are easily ionized, causing relatively minor energy loss, whereas high-Z impurities require substantial ionization energy and contribute to bremsstrahlung radiation, which further dissipates energy from the plasma. Conversely, low-Z materials typically have lower melting points than high-Z materials, limiting their thermal resilience (Oliver, 2023; Elqahtani et al., 2023; Khan et al., 2022; Khan et al., 2020; Khan et al., 2014).



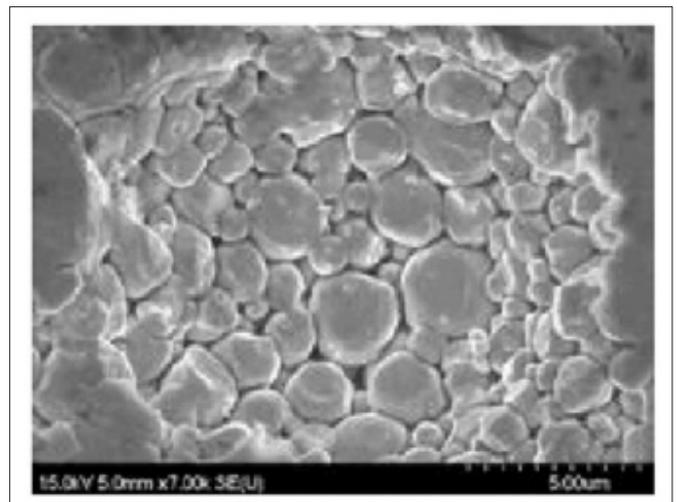
**Figure 1:** Density and electron temperature profile (Stott et al., 1975)

To balance structural integrity with the benefits of low-Z PFMs, liquid metals have been explored as plasma-facing units (PFUs). Liquid metal PFUs offer enhanced thermal handling capabilities through conduction, convection, and evaporative heat transfer, alongside self-healing surface properties due to surface tension and simplified maintenance (Allain, 2019; Khan et al., 2021; Khan et al., 2020) see fig.2 & 3. Extensive studies over the past decade have identified lithium as a particularly suitable liquid metal, owing to its high hydrogen isotope retention efficiency, large latent heat of vaporization, high heat capacity, reduction of residual gases such as oxygen and water vapor, and compatibility with steel across a wide temperature range (Jaworski et al., 2016; Tabarés, 2015; Khan et al., 2017; Khan et al., 2017; Khan et al., 2020). When deployed in tokamaks, liquid metals interact with magnetic fields and the charged particles within the metal (Meng et al., 2022; Wang et al., 2017; Shi et al., 2015). The motion of these charged particles generates induced electric currents, which in

turn interact with the applied magnetic field to produce Lorentz forces that drive the liquid metal flow (Khan et al., 2016; Khan et al., 2015; Khan et al., 2016). Additionally, thermoelectric magnetohydrodynamic (TEMHD) effects arise from the Seebeck effect: thermal gradients across interfaces of different metals cause electron diffusion, creating electric fields that interact with the magnetic field and further drive liquid lithium motion (De Castro et al., 2021; Khan et al., 2015; Zheng et al., 2015; Khan et al., 2015; Khan et al., 2018).



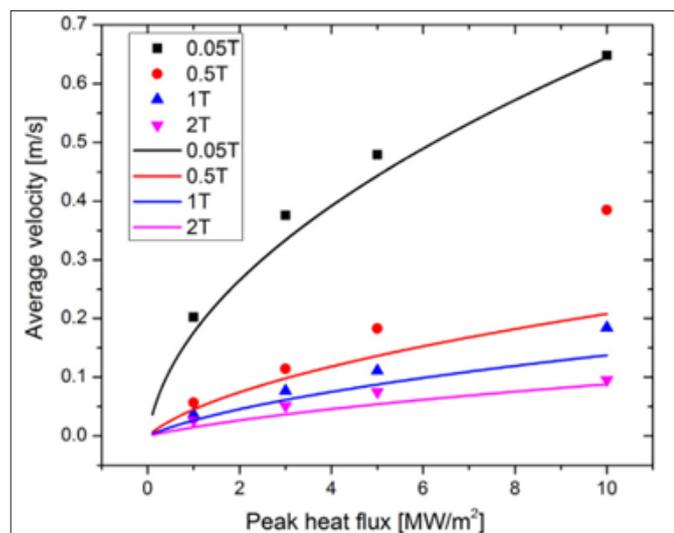
**Figure 2:** Li deposition after deuterium irradiation (Allain, 2019)



**Figure 3:** via SPS W with LiSn NPs (Allain, 2019)

Over the past decade, multiple liquid lithium PFU concepts have been proposed and tested, with the Lithium Metal Infused Trench (LiMIT) system, developed in 2011 at the University of Illinois at Urbana-Champaign (UIUC), being one of the most prominent (Xu, 2015). The LiMIT design features open stainless-steel trenches wetted with liquid lithium, where narrow channels on the plasma-facing side and wider channels on the backside facilitate heat transfer. Lithium flow is driven not by pressure gradients but by Lorentz forces, while a resistive heater maintains lithium above its melting point. A critical operational requirement is to prevent dryout, where the stainless steel becomes exposed due to excessive lithium evaporation or localized depression and pileup at high heat flux

regions (Xu et al., 2014; Ruzic et al., 2017; Khan et al., 2016; Khan et al., 2012) see fig.3.



**Figure 4:** Peak heat flux and velocity of lithium trenches (Xu et al., 2014)

Experimental studies have further explored LiMIT performance. Fiffis et al. (2015) investigated thermal behavior in the Magnum PSI linear plasma simulator, using air-cooled stainless-steel trenches of  $1 \times 2$  mm cross-section and 5 cm length carrying liquid lithium. Under an absorbed heat flux of  $3 \text{ MW/m}^2$ , lithium velocities and surface temperatures were measured, revealing that local depression and pileup could lead to dryout and trench damage. Geometry modifications and wire mesh integration were explored in ANSYS Fluent simulations, demonstrating that maintaining the lithium above  $230 \text{ }^\circ\text{C}$  prevents dryout, with maximum steel temperatures remaining below  $435 \text{ }^\circ\text{C}$  under  $3 \text{ MW/m}^2$  heat flux (Xu, 2015; Shaukat et al., 2021; Shahzad et al., 2020; Shahzad et al., 2020). Szott et al. (2020) performed 2D simulations with moving mesh modules in COMSOL to determine dryout conditions in open-surface trenches. The TEMHD-driven volumetric forces, obtained from 3D analyses, were applied in 2D as a Gaussian distribution, and ledge height optimization was found to mitigate dryout effectively. In summary, despite decades of research, the development of sustainable nuclear fusion remains a complex challenge, with the selection of PFCs playing a critical role. The limitations of solid PFCs, including susceptibility to surface damage and plasma contamination, have driven interest in liquid metals as promising alternatives. Liquid lithium, in particular, offers exceptional thermal properties, efficient hydrogen isotope retention, and self-regenerating capabilities. Recent innovations, such as the LiMIT system, have demonstrated significant progress in addressing dryout and improving thermal regulation under extreme heat fluxes. While challenges remain particularly regarding interactions with magnetic fields and localized dryout ongoing research and computational modeling offer viable solutions, advancing the performance and longevity of PFCs and bringing practical nuclear fusion closer to realization.

## Conclusion

The development of plasma-facing components remains one of the most critical challenges in achieving practical and sustainable nuclear fusion. Solid PFCs, such as tungsten and carbon-based materials, have demonstrated the ability to withstand high thermal loads and particle fluxes, yet their limitations including erosion, sputtering, high-Z impurity generation, and susceptibility to cracking under cyclic thermal stresses restrict their long-term applicability in next-generation tokamaks. Advanced solid designs, including tungsten-coated carbon substrates and optimized monoblock geometries, have improved thermal performance, adhesion, and structural resilience, but challenges related to residual stress, crack propagation, and fabrication complexity persist. Liquid metal PFUs, particularly those based on lithium, offer a promising alternative by leveraging self-healing properties, high thermal conductivity, and effective hydrogen isotope retention. Concepts such as the Lithium Metal Infused Trench (LiMIT) system have demonstrated significant advancements in thermal regulation, MHD-driven flow control, and mitigation of dryout under high heat flux conditions. Experimental and computational studies have highlighted both the potential and the challenges of liquid lithium systems, including interactions with magnetic fields, localized depression and pileup, and operational safety limits. In conclusion, the integration of advanced solid PFCs and liquid metal PFUs represents a complementary approach to addressing the extreme thermal, mechanical, and particle flux requirements of future fusion reactors. Continued research into material optimization, innovative cooling strategies, and predictive modeling is essential to enhance the durability, reliability, and performance of plasma-facing components. These advancements are critical for enabling the practical deployment of next-generation fusion reactors, bringing the goal of sustainable and clean nuclear fusion energy closer to reality.

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