

Advances and Future Directions in Tokamak Limiter Technology : Transitioning from Solid to Liquid Metal System

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Submitted: 26 Nov 2025; Accepted: 13 Dec 2025; Published: 27 Feb 2026

Citation: Shafiq, M. et al., (2026). Advances and Future Directions in Tokamak Limiter Technology : Transitioning from Solid to Liquid Metal System. *I J T C Physics*, 7(1):1-6. DOI : <https://doi.org/10.47485/2767-3901.1072>

Abstract

The development of limiters has been central to the advancement of tokamak technology, playing a critical role in plasma confinement and protecting the vacuum vessel during diverse operational phases. As tokamaks evolved toward stronger magnetic confinement and higher power densities, plasma particles incident on limiters became increasingly energetic. Early designs using high-Z materials, such as steel and molybdenum, were replaced by low-Z materials like graphite and beryllium to minimize core plasma contamination. Subsequent advancements introduced pump limiters, helical magnetic limiters, and liquid metal limiters, each addressing specific challenges in plasma-material interactions. Recent research has focused on liquid metal limiters, particularly those based on lithium and tin, owing to their regenerative plasma-facing surfaces and superior thermal management. This paper reviews the historical evolution, technological innovations, and future prospects of limiter designs in tokamaks, emphasizing their vital role in enabling high-performance magnetic confinement fusion.

Keywords: Tokamak, Limiters, Plasma-facing materials (PFMs), Plasma-material interactions (PMI), Plasma confinement, Liquid metal limiters, Lithium, Magnetic confinement fusion.

Introduction

Tokamaks, the most prominent devices for magnetically confined fusion, require precise control over plasma behavior to achieve optimal performance while minimizing damage to in-vessel components. Among these, limiters play a crucial role by defining the plasma boundary, protecting the vacuum vessel, and managing heat flux during non-diverted operational phases. The evolution of limiter technology has mirrored advancements in tokamak design, progressing from early implementations using high-Z materials such as steel and molybdenum to modern solutions employing low-Z materials, including graphite and beryllium (khan et al., 2024; Shakir et al., 2024; Abdullah et al., 2024). The increasing power density and improved confinement capabilities of contemporary tokamaks have driven the development of limiters capable of handling higher heat loads while reducing impurity contamination. This led to innovations such as pump limiters, which facilitate efficient particle removal, and magnetic limiters, which utilize electromagnetic fields to control plasma behavior at the edge. Despite these advancements, solid material limiters still face challenges under extended high-performance operations, including surface erosion, impurity release, and limited thermal resilience (Khan et al., 2023; Alam et al., 2023). Liquid metal limiters have emerged as a promising alternative, offering self-regenerating surfaces and enhanced heat dissipation. Liquid lithium, in particular, has demonstrated the ability to improve plasma performance by reducing impurity levels, enhancing energy confinement, and mitigating recycling. Experimental

applications in devices such as FTU, T-11M, and EAST have shown notable benefits, including improved plasma stability, reduced particle recycling, and increased capacity for handling high heat fluxes (Elqahtani et al., 2023; Khan et al., 2022). This study provides an overview of the evolution, current advancements, and future potential of limiter technology in tokamaks, with a focus on the transition from solid to liquid metal designs. The challenges and opportunities associated with these innovations are examined, highlighting their critical role in advancing tokamak performance and supporting the long-term goal of sustainable fusion energy.

Review

Limiters, one of the most critical in-vessel components of a tokamak, have undergone extensive research and development over the past decades. During normal operation in a diverted configuration, the maximum heat flux is absorbed by divertor target plates specifically designed for this purpose. However, during startup and shutdown phases, before the divertor configuration is fully established, the plasma must be prevented from contacting the vacuum vessel walls. Limiters thus serve a dual purpose: shaping the plasma edge and protecting the vessel from direct plasma impact during both normal and off-normal events, such as disruptions (Stangeby, 2011; Khan et al., 2022; Khan et al., 2021). Global interest in limiters surged following their successful deployment in the Soviet T-3 tokamak in the late 1960s, which resulted in cleaner plasma

and unexpectedly long confinement times. Early limiters were constructed from diaphragms and rails composed of steel and molybdenum, which experienced significant heating under plasma flux. As tokamaks evolved toward stronger magnetic confinement, heat loads increased, raising limiter temperatures and sputtering yields. To prevent contamination of the core plasma with high-Z impurities, limiter materials were subsequently restricted to low-Z elements such as graphite and beryllium (Conn, 1984; Khan et al., 2020). Another approach to reduce impurity influx from sputtering is the use of magnetic limiters, such as helical magnetic limiters. These employ electromagnetic coils to generate a helical field, forming a boundary layer at the plasma edge that limits plasma contact with the first wall. The helical field also spreads plasma particles over a larger volume, enhancing convective cooling. While effective, magnetic limiters are less widely used than physical limiters due to their more complex design and manufacturing requirements (Feneberg & Wolf, 1981; Khan, et al., 2019; Khan, et al., 2018). The need for efficient particle removal led to the development of pump limiters. According to the ideal gas pumping law, $Q=SPQ = S \cdot PQ=SP$, where Q is the particle throughput, S is the pumping speed, and P is the neutral gas pressure at the plasma edge. Increasing neutral pressure is generally more economical and geometrically favorable than increasing pumping speed for achieving higher particle throughput. In this context, the Advanced Limiter Test (ALT-1) program on TEXTOR studied both fixed and variable geometry pump limiters. Fixed geometry limiters feature a stainless-steel head and neutralizer plate providing a constant inlet, suitable for low-recycling regimes, whereas variable geometry limiters, with graphite heads, allow adjustment of the throat length and width for different operational scenarios (Pontau et al., 1984; Khan et al., 2017; Wang et al., 2017; Shi et al., 2015) see fig.1. The ALT-II program, launched in late 1986, extended ALT-I to a complete toroidal belt pump limiter on TEXTOR. The graphite limiter blades, with a total area of 3.4 m², were designed to withstand plasma heating loads up to 4 MW for 3–4 seconds. Equipped with an eight-port plasma exhaust system capable of extracting 5–10% of the core plasma efflux, the system met the requirements for steady-state D–T reactors. The low-field-side blades, constructed from INCONEL 625 and incorporating 28 graphite tiles, intercepted a significant portion of power and particle flow. Power removal was evaluated using infrared thermography, while applied electric fields optimized particle exhaust in the scrape-off layer (SOL). ALT-II thus provided a foundation for achieving high-confinement modes and managing plasma-boundary radiation (Brown et al., 1985; Finken et al., 2005; Khan et al., 2015; Zheng et al., 2015; Khan et al., 2014). Recently, liquid lithium has gained attention as a first-wall material due to its potential to establish non-recycling plasma boundaries, which enable unique tokamak equilibria. In CDX-U, initial rail limiters were replaced with heated stainless-steel trays to increase lithium surface exposure. Injection systems later ensured uniform liquid lithium coverage, improving impurity control and plasma performance. Similar benefits were observed in experiments like DOLLOP in TFTR, though issues such as lithium intercalation into graphite were noted.

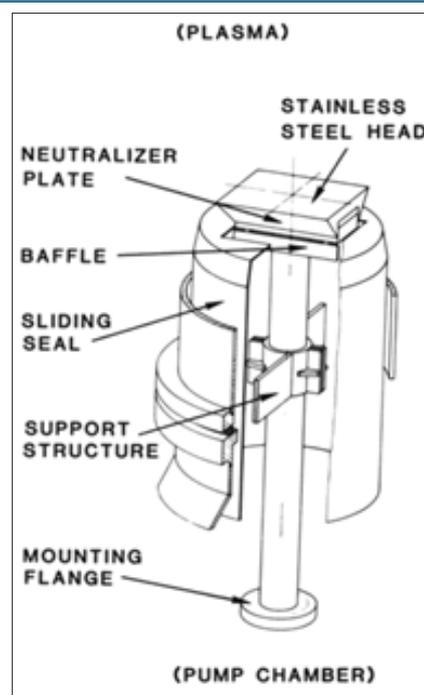


Figure 1: Limiter fix geometry module of ALT-1-FG (Pontau et al., 1984)

Capillary porous rail limiters in T-11M created self-replenishing lithium surfaces, requiring tray temperatures above 300°C to maintain stability during discharges (Majeski et al., 2005; Khan et al., 2015; Khan et al., 2020; Khan & Khan, 2017; Khan et al., 2015) see fig.2. The Frascati Tokamak Upgrade (FTU) further advanced liquid lithium research with a capillary porous system (CPS), reducing recycling and producing exceptionally clean plasmas, where only lithium emission lines were observed. Lithization of the inner wall decreased plasma instabilities and enhanced performance metrics such as energy confinement and stored energy. The LLL system demonstrated resilience to substantial thermal loads, with future plans to incorporate active cooling to extend operational life (Mazzitelli et al., 2011; Khan et al., 2016; Shaukat et al., 2021; Khan et al., 2012). As solid materials like tungsten proved inadequate under expected PFC conditions, research shifted toward liquid metals in CPS designs. The tin liquid limiter (TLL), under development for FTU, is designed to handle incident fluxes up to 10 MW/m² while maintaining temperatures between 300–900°C. Liquid tin offers lower chemical erosion and a higher boiling point than lithium, providing improved operational margins and heat load tolerance. The TLL incorporates a tungsten felt CPS and features in-vessel heating and cooling to maintain the liquid state, with preliminary tests completed by 2015 (Vertkov et al., 2017; Shahzad et al., 2020; Ahmed et al., 2020; Khan et al., 2012). Liquid lithium has addressed challenges such as surface damage, material degradation, plasma contamination, and tritium retention. Comparative analyses of CPS matrix materials indicate that tungsten felt outperforms stainless steel in thermal shock resistance, thermal conductivity, and corrosion resistance. Advanced CPS designs with graded pore sizes and channel structures enhance capillary pressure, ensuring efficient lithium flow (Vertkov et al., 2014; Ahmed et al., 2021; Khan

et al., 2012; Khan et al., 2013; Khan et al., 2013). Successful implementations of lithium PFMs have been reported in TFTR, TJ-II, NSTX, HT-7, and EAST, demonstrating improved energy confinement, lower H-mode power thresholds, reduced hydrogen recycling, and compatibility with strong magnetic fields. Flowing liquid lithium limiters (FLiLi) in HT-7 and EAST have shown higher flow velocities, improved heat flux handling, and maintainable designs, confirming liquid lithium's potential for future fusion applications (Ren et al., 2014; Gao et al., 2014; Khan et al., 2016; Khan et al., 2015; Yang et al., 2017; Khan et al., 2016; Wen et al., 2015; Khan et al., 2017) see fig.3. In summary, limiter technology in tokamaks has evolved from early solid materials to sophisticated liquid metal systems. This progression addresses critical challenges in heat flux management, impurity control, and long-term durability of plasma-facing components. Advanced designs, including magnetic limiters, pump limiters, and capillary porous liquid metal systems, have demonstrated the potential for cleaner plasma, improved confinement, and enhanced operational resilience. These developments provide a strong foundation for future PFC designs, moving the field closer to achieving sustainable and practical fusion energy.

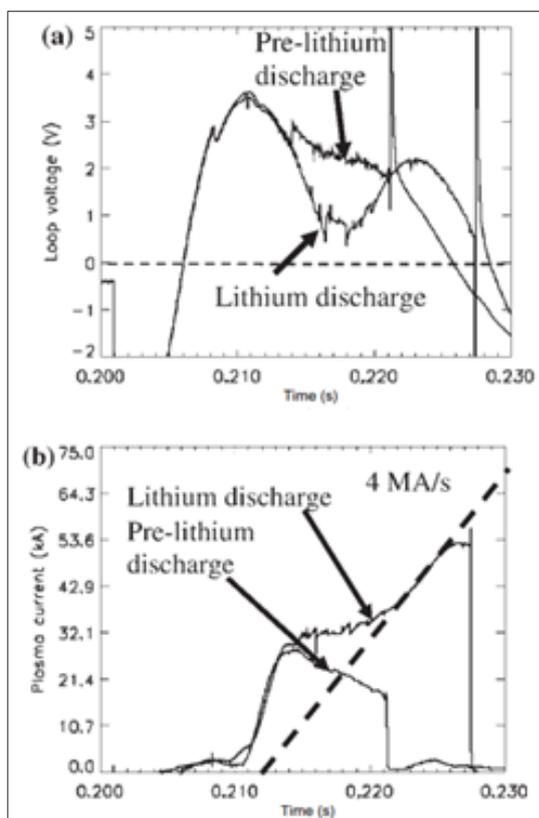


Figure 2: Comparison for pre- and post-lithium discharges (Majeski et al., 2005)

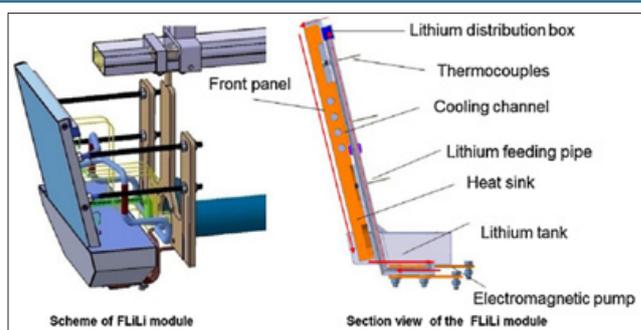


Figure 3: module of latest lithium limiter of EAST (Yang et al., 2017)

Conclusion

The development of limiter technology in tokamaks has undergone a remarkable evolution, transitioning from early solid materials such as steel and molybdenum to advanced low-Z solids like graphite and beryllium, and ultimately to modern liquid metal systems. Limiters play a critical role in shaping the plasma edge, protecting the vacuum vessel, managing heat flux, and controlling impurity influx. Innovations such as magnetic limiters, pump limiters, and capillary porous systems using liquid lithium or tin have addressed many challenges associated with plasma-material interactions, including surface erosion, plasma contamination, and thermal load management. Liquid metal limiters, in particular, offer self-regenerating surfaces, superior heat dissipation, and enhanced plasma performance. Experimental implementations across devices like TFTR, HT-7, EAST, and FTU have demonstrated the viability and advantages of these systems under high heat flux conditions. Moving forward, the knowledge and insights gained from these developments will be instrumental in designing robust, high-performance plasma-facing components, advancing the practical realization of sustainable nuclear fusion.

Acknowledgement

The authors would like to express their sincere gratitude to Hazara University, Mansehra, for its continuous academic support and research facilitation throughout this work. Special thanks are also extended to the Pakistan Tokamak Plasma Research Institute (PTPRI), Islamabad, for providing technical assistance, simulation resources, and valuable guidance related to fusion plasma and divertor technology. Their contributions were instrumental in the successful completion of this study.

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