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Review Article

Evolution and Future Prospects of Limiter Technology in Tokamaks: From Solid Materials to Liquid Metal Innovations

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KEYWORDS

ABSTRACT

The development of limiters has been pivotal in the evolution of tokamak technology, significantly contributing to plasma confinement and protection of the vacuum vessel during various operational phases. As tokamaks progressed towards achieving stronger magnetic confinement and higher power densities, increasingly energetic plasma particles were incident on limiter. Initial designs, such as steel and molybdenum limiters, were replaced by low-Z materials like graphite and beryllium to reduce core plasma contamination. Advancements in limiter technology included the development of 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 liquid lithium and tin, due to their potential to offer regenerative plasma-facing surfaces and superior thermal management. This paper reviews the historical progression, technological advancements, and future prospects of limiter designs in tokamaks, highlighting their critical role in the advancement of magnetic confinement fusion.

1. Introduction

Tokamaks, the most prominent devices for magnetically confined fusion, require precise control over plasma behavior to achieve optimal performance and minimize damage to in-vessel components. Among these components, 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 limiters has paralleled the advancements in tokamak technology, from early designs utilizing high-Z materials like steel and molybdenum to contemporary solutions employing low-Z materials such as graphite and beryllium [1-3].

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The increasing power density and improved confinement capabilities of modern tokamaks necessitated advancements in limiter technology to handle higher heat loads and reduce impurity contamination. This led to the development of pump limiters, which enable efficient particle removal, and magnetic limiters, which employ electromagnetic fields to control plasma behavior at the edge. However, as tokamaks continue to evolve toward longer pulse lengths and higher performance regimes, solid material limiters face challenges such as surface erosion and impurity release [4, 5].

Liquid metal limiters have emerged as a promising alternative, offering self-regenerating surfaces and enhanced heat dissipation capabilities. Liquid lithium, in particular, has shown potential to improve plasma performance by reducing impurity levels and enhancing energy confinement. Recent experiments with liquid metal limiters in devices like FTU, T-11M, and EAST have demonstrated significant benefits, including reduced recycling, improved plasma stability, and the potential for higher heat flux handling [6, 7].

This study examines the evolution, present advancements, and future potential of limiter technology in tokamak systems, with a focus on the transition from solid to liquid metal limiters. The challenges and opportunities associated with these advancements are discussed, emphasizing their critical role in the ongoing pursuit of sustainable fusion energy.

2. REVIEW

One of the most critical in-vessel components of a tokamak being limiter has gone through extensive research and development in the past decades. During the normal operation i.e., diverted configuration maximum heat flux is handled by the divertor target plates specifically designed for this purpose. However, during the startup and shutdown phase, until diverter configuration is achieved the plasma must refrain from coming into contact with the walls of vacuum vessel. Limiters in tokamaks thus serve the purpose of shaping the plasma edge as well as preventing direct contact of plasma with walls of vacuum vessel during normal and off normal events such as disruptions [8-10].

Global interest in the limiter spiked after its successful operation in Soviet T-3 tokamak in late 1960’s leading to cleaner plasma with unexpectedly long confinement time. During that period, limiters were constructed from diaphragms and rails composed of steel and molybdenum, with their plasma-facing surfaces experiencing significant heating due to the applied heat flux. However, as the tokamak progressed towards stronger and more stable magnetic confinement the corresponding heat loads also increased. Higher heat loads resulted in higher limiter temperature and also higher sputtering yield. Consequently, to prevent core plasma contamination from high-Z impurities, the limiter materials were restricted to low-Z elements like graphite and beryllium [11, 12].

Another method of lowering the impurity content resulting from sputtering is by using magnetic limiters such as a helical magnetic limiter. This limiter employs electromagnetic coils to generate a helical magnetic field, which interacts with the edge plasma to form a boundary layer, effectively inhibiting the further movement of the edge plasma towards the first wall. Moreover, the helical magnetic field spreads the plasma particles over a larger volume, thereby promoting convective cooling. The boundary layer thus produced prevents ingress of impurities into the core plasma. Nevertheless, the limiters using physical material boundaries remained of grater interest as compared to magnetic limiters mainly because of simpler design and easier manufacturing [13-15].

The need to efficiently removal particles from the plasma lead to the development of pump limiter. The ideal gas pumping law states that, Q = S*P. Where Q is the gas throughput representing the amount particles being removed from the system per unit time, S is the pumping speed indicating how quickly the pumping system can remove gas and P is the neutral gas pressure injected at the edge of the plasma. Increasing the pressure means there are more neutral gas particles available for interaction with plasma. Based on this law, increasing neutral pressure is determined to be economically and geometrically favorable as compared to increasing pumping speed for higher gas throughput. In this context, a pump limiter under Advanced Limiter Test (ALT-1) program was comprehensively studied on TEXTOR. The study utilized a fixed as well as variable pump limiter. The fixed geometry limiter utilizes a fixed stainless-steel head and neutralizer plate proving a fixed inlet for the particles. While variable geometry limiter uses a graphite head and allows for changing the throat length and width of pumping duct. Thus, the fixed geometry limiter is utilized for low recycling regime only while variable geometry limiter can be adjusted for different operation regimes [16-19].

In late 1986, ALT II program extending the ALT I concept to complete toroidal geometry through a toroidal belt pump limiter was initiated on TEXTOR tokamak [20]. The graphite limiter blade, having an area of 3.4 m^2, was specifically designed to withstand plasma heating loads of up to 4 MW for durations of 3 to 4 seconds. It was equipped with an eight-port plasma exhaust system, designed to extract 5-10% of the core plasma efflux, meeting the specifications required for steady-state D-T reactors. Positioned at the low field side (LFS), the eight adjustable blades intercepted a significant fraction of the power and particle flow, constructed from INCONEL 625 and incorporating 28 graphite tiles. Power removal was quantitatively assessed using infrared thermography, while electrical fields were applied to optimize particle exhaust in the scrape-off layer (SOL). Ultimately, the ALT-II configuration provided a critical foundation for achieving high confinement modes and effectively managing neon radiation at the plasma boundary [21-24].

Recently liquid lithium has gained popularity as the first wall material. Research indicates that a non-recycling liquid lithium boundary could provide access to unique tokamak equilibria. In CDX-U, initial experiments utilized a rail limiter, which was later replaced by a heated stainless-steel tray to expose a larger lithium surface to the plasma. The tray was specifically designed to mitigate inductive currents by ensuring alignment with the magnetic field, thereby optimizing plasma performance. Following preliminary tests with solid lithium, a new injection system was implemented to deliver liquid lithium uniformly across the preheated tray, resulting in complete coverage and marked improvements in impurity levels and plasma behavior. The benefits of surfaces with low or non-recycling conditions were also demonstrated in experiments like DOLLOP in the TFTR, though complications such as lithium intercalation into graphite were observed. Later investigations in the tokamaks such as T-11M used a capillary porous rail limiter, which established a 'self-replenishing' liquid lithium surface. To minimize lithium evaporation and undesirable coatings, it was found that maintaining the tray at temperatures of 300°C or higher during discharges is essential for stable tokamak operation [25-29].

The Frascati Tokamak Upgrade (FTU) launched experimental programs utilizing a liquid lithium limiter (LLL) with a capillary porous system (CPS) to explore the potential of liquid metals as plasma facing materials. This approach led to reduction in recycling, producing exceptionally clean plasmas where only lithium emission lines were detected in the UV spectra. Furthermore, lithization—applying a thin lithium layer to the inner wall—reduced plasma instabilities and enhanced performance metrics, such as energy confinement time and stored energy. The LLL demonstrated its resilience to significant thermal loads, with future plans aiming to incorporate actively cooled systems to enhance its operational lifespan [30-33].

As solid materials like tungsten have proven inadequate for PFCs under expected conditions. Recent research has concentrated on the potential of liquid metals, particularly within CPS, as promising candidates for PFCs. The tin liquid limiter (TLL), currently under development for the FTU tokamak, aims to operate at incident fluxes of up to 10 MW/m² while maintaining a stable temperature range of 300–900 °C. Liquid tin (Sn) emerged as a promising alternative to liquid lithium due to its lower chemical erosion and higher boiling point, allowing for greater operational limits and heat load resistance. This design of TLL incorporated a CPS made from tungsten felt and featured an in-vessel plasma-facing element equipped with heating and cooling systems to maintain the liquid state of Sn. Preliminary testing was successfully completed till 2015, marking a significant upgrade in FTU's experimental capabilities [34-37].

The use of liquid lithium has addressed several challenges associated with the long-term use of PFCs in tokamaks, including surface damage, material degradation, plasma contamination, and tritium retention. A comparative analysis of matrix materials for lithium-based capillary porous systems (CPS) showed that tungsten fiber materials, particularly felt, were preferable due to their superior thermal shock resistance, thermal conductivity, and corrosion resistance compared to stainless steel. The development of an advanced CPS design incorporated an outer layer with pore sizes ranging from 20 to 100 µm and an inner layer containing 200 µm channels, increasing capillary pressure and facilitating efficient lithium flow [38-42].

Successful applications of lithium as a PFM were reported in several devices, including TFTR, where lithium pellet injection enhanced energy confinement and D-T fusion power, and in TJ-II and NSTX, where lithium coatings improved performance and reduced the H-mode power threshold. In HT-7, experiments initiated in 2009 utilized various lithium limiter designs, culminating in the autumn 2012 campaign that employed flowing liquid lithium limiters. These experiments marked a significant advancement toward developing a flowing liquid lithium (FLiLi) system for long-pulse plasmas. The tests demonstrated compatibility with strong magnetic fields and achieved lower hydrogen recycling and impurity levels, resulting in improved plasma confinement. Techniques for liquid lithium injection were refined, with one approach utilizing a distributor driven by argon pressure to manage flow speed. However, challenges such as lithium wetting, and emissions needed addressing for further optimization [43-46].

Up till recently liquid lithium experiments have been conducted on various tokamaks, demonstrating its advantages over solid lithium, such as surface regeneration capabilities. Based on experiences gained from HT-7, the FLiLi limiter was developed and tested for EAST tokamak in 2014, featuring a higher lithium flow velocity and improved heat flux resistance. Designed for easy maintenance, the FLiLi limiter included an exchange box for convenient assembly and outgassing. The system specifications targeted a mass flow rate exceeding 2 cm^3/s and a compact design for maintainability. The updated EAST FLiLi limiter system, which enhanced safety and performance, was successfully installed and tested during the 2016 campaign, confirming the potential of liquid lithium for future fusion applications [47-50].

In summary, the research and development of limiters in tokamaks have undergone significant advancements, evolving from early solid materials like steel and molybdenum to modern liquid metal systems. This progression has been driven by the need to address challenges related to heat flux management, plasma contamination, and long-term sustainability of plasma-facing components. Various designs, including magnetic limiters, pump limiters, and capillary porous systems using liquid lithium and tin, have demonstrated the potential for enhanced plasma performance, cleaner confinement, and better durability under extreme conditions. As fusion technology progresses, the knowledge gained from these advancements will play a pivotal role in the design of future PFCs, thereby contributing significantly to the realization of fusion as a sustainable energy source

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