ADVANCING TRITIUM FUELING FOR DT FUSION IN HL-3: INNOVATIONS IN SMBI TECHNIQUES AND PHYSICS-BASED TRITIUM FUELING STRATEGIES

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Deuterium (D) and tritium (T) burning plasma can produce nuclear fusion power when these hydrogen isotopes fuse into helium, as demonstrated in D-T experiments at JET[1] and TFTR[2] , which is expected to be very soon under investigation at HL-3 and ITER. The fusion power from the D-T reaction scales with the square of the plasma electron density. However, the torus-shaped magnetic topology confining the plasma makes high-density core plasma fueling challenging, particularly for large tokamaks like ITER. In fusion devices, fueling can be achieved through several methods, including fueling pellet injection[3], gas injection[3,4], neutral beam injection (NBI) [5], and compact torus[6]. Among these, tritium gas injection remains a significant challenge, despite the maturity of deuterium injection technology. Tritium pellet injection has yet been commissioned in few tokamak devices, and results from tritium NBI at JET suggest that it is pretty far from an attractive option. The primary reasons are the large quantity of tritium required, the burden of fuel recycling, and tritium safety concerns. On the other hand, tritium gas injection is more developed and, as such, does not generate T waste during the injection process. Therefore, improving tritium gas injection performance has a much better perspective. For this purpose, supersonic molecular beam injection (SMBI), which is well known for its high gas beam performance compared to conventional gas puffing, is under consideration to inject tritium into large devices. Recent SMBI developments and initial studies concerning tritium injection strategy for future DT operation in HL-3 open a very positive perspective for better tritium fueling and edge particle control of next-generation fusion devices

This paper discusses recent progress on SMBI techniques and potential strategies for tritium injection in upcoming HL-3 D-T plasma operations. Two common approaches to enhance SMB performance for fueling are to achieve a more convergent beam structure or more condensed density and higher speed of beam particle. Recent experiments on beam parameter dependence have provided relations of some typical beam characteristics, such as effective distance and divergence angle, to injector parameters. Those results base the beam structure optimization toward a more converging beam and higher particle velocity, limiting the ideal velocity close to it. A schematic of beam structure and parameter dependence is detailed in Figure 1(a). Besides, an ideal velocity limit—determined by the gas species and temperature, is independent of gas pressure—could be approached through the optimization of the injector structure. Another complementary technique is the condensation of gaseous particles to create a multiphase mixture with a cooling system. Figure 1(b) shows the design of this cooled injector and the testing results obtained using a schlieren system. Further developing beam-integrated profiling and machine learning-based predictions, which expand the potential role of SMBI systems, has already hinted at possibilities regarding the density control of the edge profile.

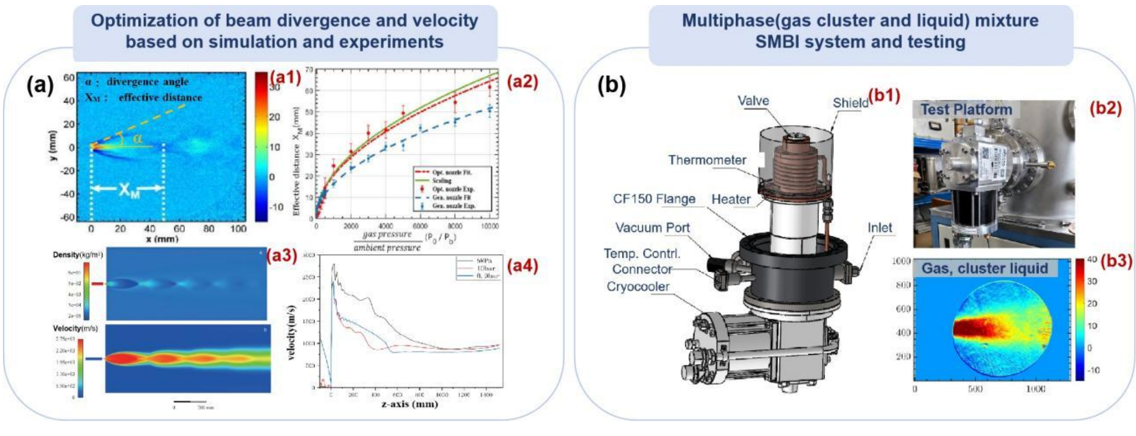

Fig.1 Innovations of SMBI techniques aiming for tritium injection strategy. (a) optimization of SMB. (a1) beam structure measured by schlieren system,(a2) scaling relation between gas pressure ratio and the effective distance of fueling beam, (a3) simulation of beam profiles, (a4) beam velocity profiles along the flow direction

with different gas pressure; (b) Multi-phase mixture SMBI techniques. (b1) design of the Multi-phase SMBI cooler injector, (b2) Testing platform,(b3) schlieren image of Multi-phase SMB.

In ITER, the gas pressure for tritium fueling is limited to below 0.9 bar for safety reasons.However, in HL-3, small-scale tritium injection allows for localized high gas pressure. Various fueling strategies developed for different gas pressures in ITER and HL-3 have been studied, and D2 SMBI fueling experiments have been compared with HL-3. Figure 2 presents the main physical analyses of the fueling strategies, focusing on edge profile evolution, edge turbulence, and fueling efficiency. Preliminary statistics from HL-2A and HL-3 both indicate that fueling efficiency increases as the gas source pressure decreases. Profile analyses across different gas pressures reveal that high-pressure gas injection leads to the rapid formation of steep edge density profiles. The same particle velocity but steeper density profiles and larger edge density fluctuations in high-pressure beam cases can enhance particle transport and create a barrier for the inward propagation of edge neutral gas particles.

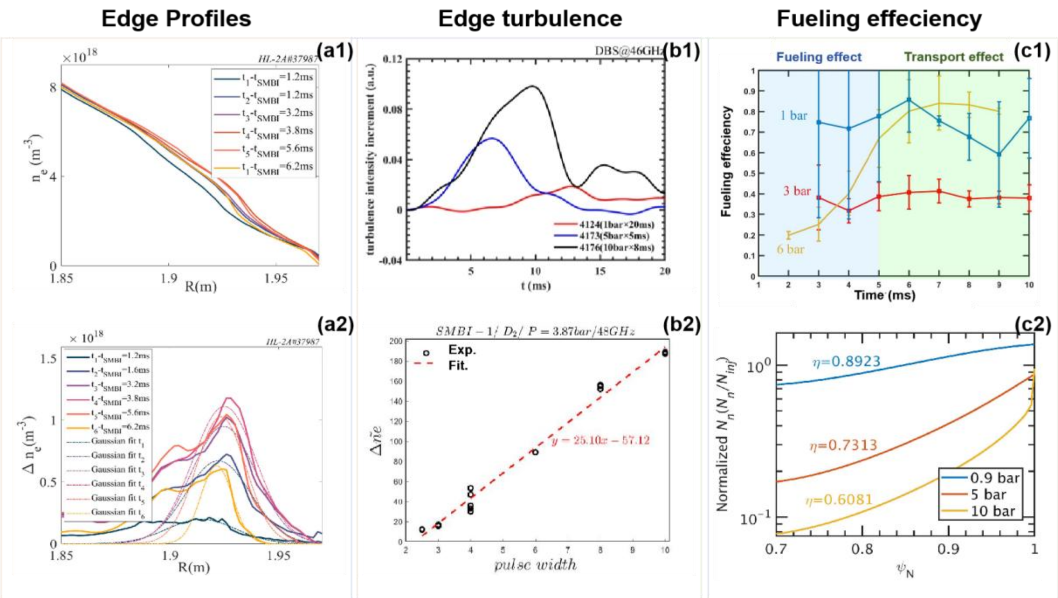

Fig.2 pre-investigation of tritium fueling strategies using D_2 for HL-3. (a) Effect of SMBI fueling on edge density profiles,(a1) edge density profiles by microwave reflectometry, (a2) density profile increment after SMBI; (b) Effect of SMBI fueling on edge turbulence detected by Doppler reflectometry,(b1) effect of gas pressure on edge turbulence, (b2) effect of gas duration on edge turbulence; (c) Analysis of relation between fueling efficiency and gas pressure,(c1) fueling efficiency from experimental data,(c2) neutral particle profiles and fueling efficiency from BOUT++ simulation result.

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