CONFERENCE PRE-PRINT

ADVANCING TRITIUM FUELING FOR D-T FUSION IN HL-3: INNOVATIONS IN SMBI TECHNOLOGY AND PHYSICS-BASED TRITIUM FUELING STRATEGIES

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Abstract

Deuterium-tritium (D-T) fusion requires effective fueling of high-density plasmas, but tritium fueling presents significant challenges. This study explores the potential of supersonic molecular beam injection (SMBI) as an fueling technology for future D-T operations on the HL-3 tokamak. We present recent advancements in SMBI hardware, including a vector injection system for directional particle and momentum control, and a multi-phase system for producing a denser, more collimated beam. We also introduce machine learning–based predictive models that enable real-time analysis of beam profiles for feedback control. Furthermore, comparative experiments on divertor heat flux mitigation demonstrate that SMBI provides a faster response and superior heat load control compared to conventional gas puffing. Fueling efficiency studies and simulations reveal that efficiency decreases with increasing gas source pressure due to enhanced edge turbulence and outward particle transport. Our findings suggest a strategic approach for tritium injection: employing low source pressure with short pulse durations to maximize fueling efficiency. This work confirms that SMBI offers a promising pathway for achieving robust fueling and enhanced particle control in next-generation fusion devices.

1. INTRODUCTION

Deuterium (D) and tritium (T) plasmas can generate substantial nuclear fusion power when these hydrogen isotopes fuse into helium, as demonstrated in D−T experiments at JET [1] and TFTR [2]. The fusion power from the D−T reaction scales with the square of the plasma electron density. However, achieving efficient fueling of the high-density core plasma remains challenging in toroidal magnetic confinement systems, particularly in large devices such as ITER.

Several methods are available for plasma fueling, including pellet injection [3], gas injection [3,4], neutral beam injection (NBI) [5], and compact torus injection [6]. Among these, tritium fueling is still a significant challenge, despite the maturity of deuterium fueling technologies. Tritium pellet injection has only been tested in a limited number of devices, and results from tritium NBI experiments at JET indicate that this approach is far from attractive. The main difficulties arise from the large tritium inventory required, stringent material compatibility issues, the complexity of fuel recycling, and overall safety concerns. By contrast, tritium gas injection is comparatively well developed and, when implemented in a closed-loop system, minimizes tritium losses during operation. Consequently, improving the performance of tritium gas injection presents a promising pathway. Supersonic molecular beam injection (SMBI), known for its superior performance relative to conventional gas puffing, is being actively considered for tritium fueling in large-scale devices. Experiments have shown that SMBI achieves higher fueling efficiency due to its higher injection velocity and deeper particle penetration. Moreover, long-pulse operation studies indicate that SMBI reduces wall recycling, requires fewer injected particles, and is less likely to trigger density-limit disruptions [7].

In this work, we present recent progress in SMBI technology and discuss strategies for tritium fueling in preparation for future D−T operation on HL-3. These developments highlight the potential of SMBI to provide improved tritium fueling and enhanced edge particle control for next-generation fusion devices. The remainder of this paper is organized as follows: Section 2 introduces advances in SMBI technology, including parameter dependencies, improvements in beam directionality and convergence, and beam profile predictions for plasma profile control. Section 3 describes the application of SMBI to divertor heat load mitigation and its advantages over conventional “puff-and-pump” radiative divertors. Section 4 analyzes the physics of the fueling process and outlines strategies for tritium injection. Section 5 provides the conclusion and discussion.

2. ADVANCEMENT ON SMBI TECHNOLOGY

2.1 Basic parameters of beam injection

The supersonic molecular beam (SMB) is formed through an adiabatic expansion process, characterized by a distinct pressure drop from the nozzle inlet to the outlet. In this process, molecules convert internal energy into translational energy with a directed velocity, enabling them to propagate freely and form a Mach disk shock structure. The particles eventually collide with background neutrals, which reduces their velocity, as illustrated in Figure 1.

The effective distance X_M represents the length of the "zone of silence," where particle velocity exceeds the local sound speed (Mach number M>1). Another key parameter is the half divergence angle α, which characterizes beam convergence. For plasma fueling, a smaller divergence angle—corresponding to stronger convergence—is desirable. These two parameters are commonly used to describe SMB structure.

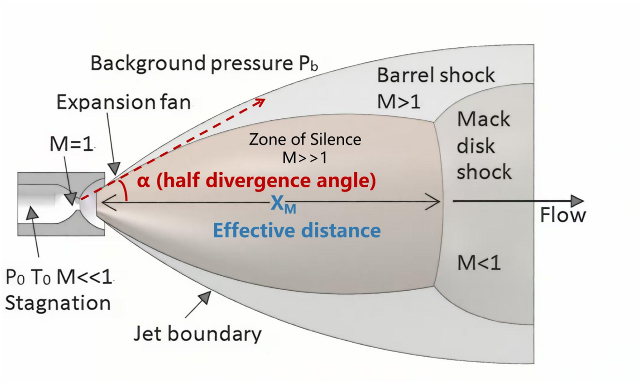

Figure 1. The schematic figure of the SMB structure

On the SMBI testing platform, several diagnostic systems have been developed, including a schlieren system [8], a glow-discharge system equipped with Langmuir probes, and a Rayleigh scattering system, which together provide measurements of beam structure, density, and velocity profiles. Based on these diagnostics, the dependencies of effective distance and half divergence angle on nozzle geometry and operating conditions have been established. They can be expressed by the following scaling relations [9]:

$$X_M = 0.67d\sqrt{\frac{P_0}{P_b}} \tag{1}$$

$$\alpha \propto d^{0.15} \times L^{-0.82} \times \theta^{-0.83} \times P_0^{0.21} \times P_b^{-0.12} \tag{2}$$

Where d is the diameter of the nozzle throat, L is the length of the nozzle divergence section, θ is the cone angle of the nozzle, P_0 and P_b is the pressure of the gas source and the pressure of the background at the nozzle outlet. Base on the scaling formulas, the beam parameters can be predicted and adjusted by the nozzle structure parameters and the working conditions. The optimization such as smaller divergence angle can also be achieved based on the formulas.

2.2 Recent development on SMBI hardware techniques

A vector SMBI system has been developed and tested for directional particle injection and momentum studies. This injector can be rotated in either the poloidal or toroidal direction, with maximum rotation angles as shown in Figure 2(a). Rotation tests, carried out using the schlieren system on the SMBI platform, are presented in Figures 2(a2–a5). This system is scheduled for deployment in the next experimental campaign on HL-3. Moreover, recent theoretical analysis indicates that toroidal or poloidal momentum injection will be accompanied by a radial particle pinch, consistent with the conservation of generalized Kelvin circulation [10]. Such a system may play a key role in high-density fueling experiments near the opacity limit.

In addition, a multi-phase SMBI system has been developed to produce a denser and more collimated particle beam, reducing the fraction of divergent gaseous particles through a finely tuned cooling device. Figure 2(b) shows the design of this cooled injector, together with schlieren test results. Gas clusters and liquid content can be distinguished from density measurements using the schlieren system, while cluster size can be determined via Rayleigh scattering diagnostics. This concept has also been applied in disruption mitigation experiments with impurity gas injection on HL-2A. In the future, such multi-phase SMBI systems are expected to further suppress wall recycling during gas injection—a feature already observed as an advantage of SMBI over conventional gas puffing during long-pulse operation [7].

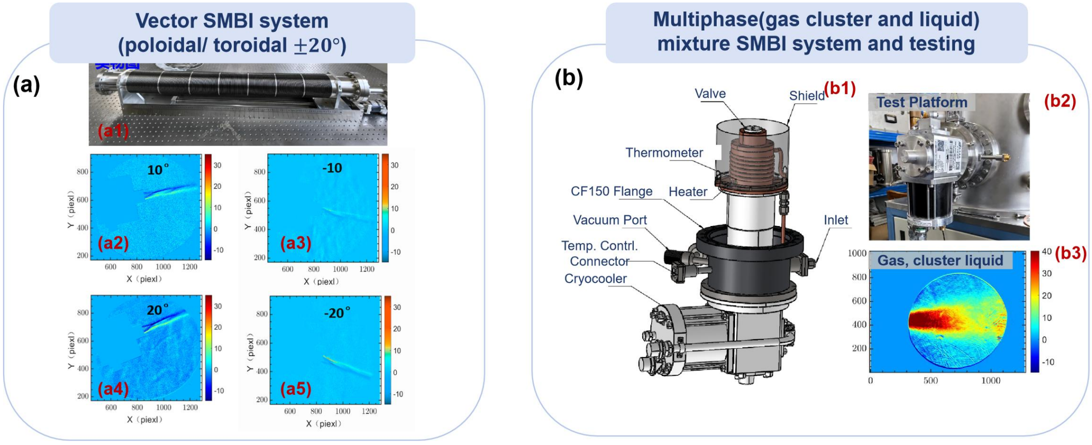

Figure 2. Recent innovations of SMBI techniques. (a) vector SMBI system. (a1) photography of the rotation actuator of the vector SMBI system, (a2)-(a5) is the testing result of the vector SMBI system by schlieren system with the rotation angles at + 10° , - 10° , + 20° and - 20° . (b) Multi-phase mixture SMBI techniques. (b1) design of the Multi-phase SMBI cooler injector, (b2) photography of the cooler on testing platform,(b3) schlieren image of multi-phase SMB.

2.3 Developments on the SMB prediction methods

Recent efforts have focused on developing beam-integrated profiling and machine learning–based prediction methods, which expand the potential role of SMBI systems and open new possibilities for edge density profile control. Direct measurement of multidimensional beam properties in high-vacuum environments is both technically challenging and costly. However, beam profiles evolve continuously and systematically with operating conditions, suggesting that predictive models can be established to infer unmeasured parameters.

To this end, deep learning strategies have been introduced to simplify integrated analysis and achieve high-precision predictions. Figure 3(a) illustrates a neural network model based on the U-Net architecture, designed to infer beam velocity profiles from experimentally measured density data. This approach leverages the practical advantage that density profiles are relatively straightforward to obtain using the schlieren system. Notably, the reverse process—inferring density profiles from velocity data—is also feasible. To enhance predictive fidelity, different attention mechanisms were tested, and results indicate that the convolutional block attention module (CBAM) provides the most significant improvement. Figure 3(b) demonstrates the robust generalization capability of this model, showing accurate predictions at gas source pressures of 20, 30, and 40 bar which are the values outside the training dataset.

Real-time acquisition of fueling beam profiles is essential for millisecond-level response and the implementation of feedback control algorithms aimed at plasma profile regulation. To meet this requirement, we have further developed a neural network - based approach that directly predicts SMB parameter profiles from gas source pressure inputs. As shown in Figure 4(a), the model takes gas source pressure as input and outputs both velocity and density profiles. Figure 4(b) presents an example prediction at 26 bar, demonstrating excellent agreement with experimental measurements. The first row compares predicted and measured velocity profiles, while the second row shows density profiles.

The model successfully captures key structural features, including the silence zone and the complex interface between the silence zone and Mach disk. Error maps confirm strong quantitative agreement, with maximum errors below 10% and mean errors around 1%. These results highlight both the accuracy and efficiency of the model, making it highly suitable for feedback control applications. More broadly, the demonstrated ability to preserve structural fidelity while maintaining predictive accuracy across varying pressures suggests that such models could provide critical real-time data support for plasma profile control in future SMBI applications.

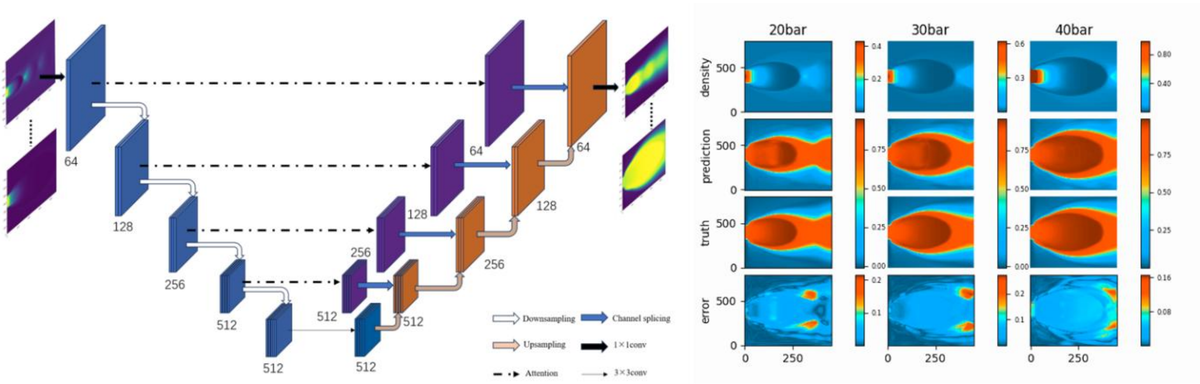

Figure 3. (a) the neural network model based on the U-Net architecture for the beam profiles integrated analysis. (b) prediction results under gas source pressures of 20 bar, 30 bar, and 40 bar, which are outside the training dataset's range [11].

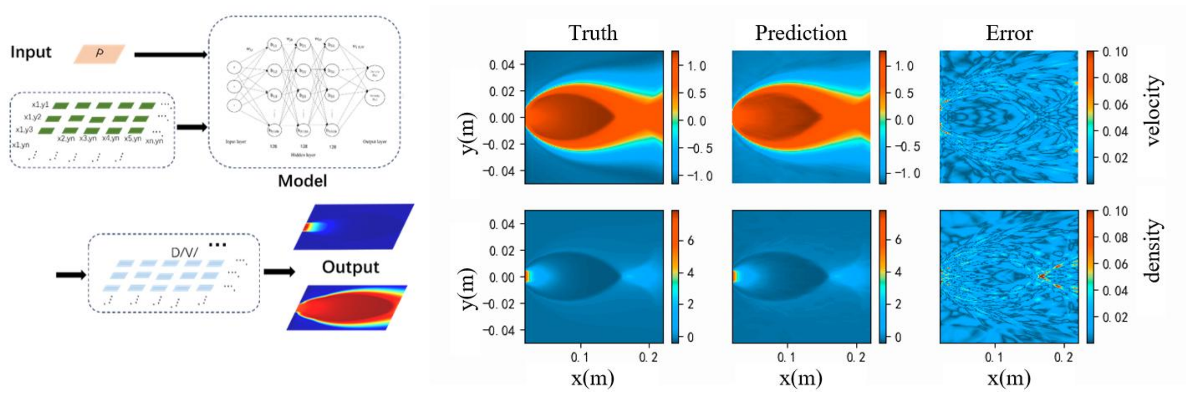

Figure 4 (a)Neural network structure with gas source pressure as input and the velocity and density profiles as output (b) the prediction of gas source pressure of 26 bar. The first line is the comparison of the velocity profile between the prediction values to the truth values, and the second line is the comparison of the density profile between the prediction values to the truth values.

3. APPLICATION ON DIVERTOR HEAT CONTROL

Divertor heat flux mitigation remains a critical challenge for long-pulse, high-performance plasma operation. On HL-2A/3, the implementation of a divertor supersonic molecular beam injection (SMBI) system has demonstrated significant advantages over conventional divertor gas puffing (GP), particularly in terms of response speed and heat flux control effectiveness. These improvements are primarily attributed to the much higher particle velocity and injection rate of SMBI compared with GP.

Comparison experiments clearly show that SMBI achieves a substantial reduction in response time relative to GP. The overall time response can be divided into two stages: (i) the flight time of particles through the injection pipeline, and (ii) the function time required for cold neutrals to cool the divertor plasma after arrival. Platform tests indicate that the flight time of SMBI particles is about 2.7 ms for the pipeline length used in the HL-3 divertor configuration, whereas the corresponding value for GP particles exceeds 50 ms. In divertor heat load control experiments, the difference is even more pronounced: the time delay between injection and the onset of divertor electron temperature reduction is approximately 10 ms for SMBI, compared with more than 100 ms for GP under otherwise similar conditions. This marked contrast arises from the two processes described above—fast neutral transport and the subsequent plasma response. The high velocity of SMBI particles shortens flight time by nearly an order of magnitude, while its large injection rate reduces the function time by producing stronger local cooling. Consequently, SMBI offers a much faster capability for active divertor heat load regulation, which is particularly valuable for mitigating transient thermal events in next-step devices.

In addition to its rapid response, SMBI also provides superior mitigation of peak divertor heat flux. Simulation studies using EMC3-EIRENE (Figure 5) demonstrate that the higher velocity of SMBI neutrals enables them to cross open magnetic field lines and penetrate more deeply into the divertor plasma. This deeper deposition promotes stronger localized radiation and more effective redistribution of parallel heat flux. As shown in Figure 5(a), different source locations were compared, with location #3 corresponding to SMBI, characterized by deeper penetration. The results in Figure 5(b) indicate that SMBI reduces the peak heat flux on the outer divertor target to nearly half of the values obtained for GP cases (#1 and #2). These findings confirm that deeper fueling by SMBI enhances the overall efficiency of divertor heat flux control. The combined advantages of fast response and enhanced heat flux mitigation establish SMBI as a highly attractive technique for future high-performance plasma operations.

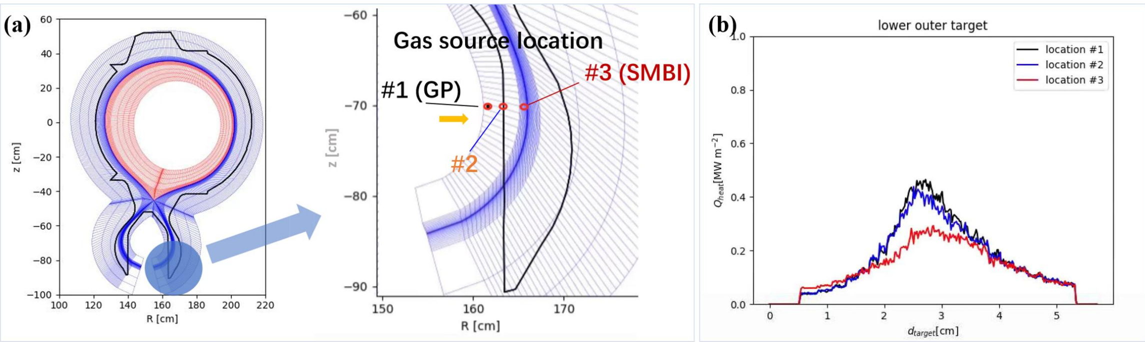

Figure 5. (a) Slice through the 3D computational mesh (with different gas source locations marked with red circles) for EMC3-EIRENE simulations. (b) The heat flux profiles on the outer divertor target for different gas source locations [12].

4. PHYSICS-BASED FUELING STRATEGIES AIMING FOR TRITIUM INJECTION

In ITER, the gas pressure for tritium fueling is required to remain below 0.9 bar for safety reasons. In conventional gas puffing (GP) systems, the injected particle number is typically controlled by the valve opening degree and the pulse duration at nearly constant source pressure. In contrast, in SMBI systems, the injected particle number is determined by the gas source pressure and pulse duration. For high-performance operation on HL-3 and other large devices preparing for D−T campaigns, tritium pellet fueling is not yet a mature option. Thus, tritium injection on HL-3 will rely on SMBI systems, and a feasible fueling strategy — particularly concerning source pressure and pulse duration—requires careful exploration.

4.1 Effect of gas source on the fueling efficiency

Fueling experiments with deuterium have been carried out on HL-3 to guide tritium fueling strategies. Different SMBI source pressures were applied under comparable plasma conditions, and the fueling efficiency was primarily evaluated using microwave reflectometry. Figure 6(a) shows density profiles before and after SMBI injection. The density increment relative to the pre-injection profile is shown as raw data (green line) in Figure 6(b), while a Gaussian fit (red line) is used to characterize the deposition profile. The integration of this Gaussian curve yields the total deposited particle number. This method is valid provided that the pulse duration remains short (≤ 20 ms), which is well below the characteristic transport timescale (tens of seconds).

The fueling efficiency η is defined as the ratio of deposited particle number N_{dep} to injected particle number N_{inj}, where N_{inj} is obtained from offline calibration.

$$\eta = \frac{N_{dep}}{N_{inj}} \tag{3}$$

The deposited particle number N_{dep} is given by the integration of the Gaussian particle deposition curve which is described as following:

$$N_{dep} = \int_{r_1}^{r_2} \Delta n_e(r) \cdot 2\pi r \cdot 2\pi(R + r)\, dr \tag{4}$$

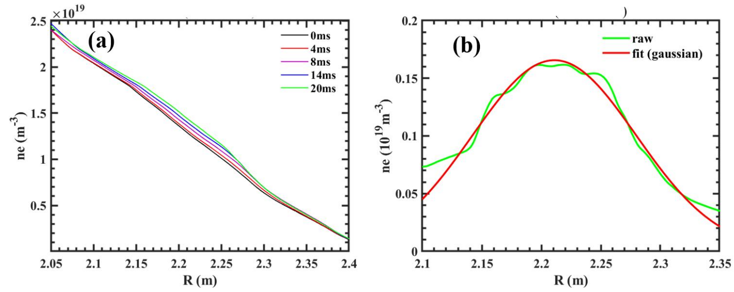

Figure 6. (a) Density profiles before and after SMBI by reflectometry. (b) the raw data of density increment after SMBI(green line) and its Gaussian fit curve (red line)

The time evolution of fueling efficiency for different source pressures is presented in Figure 7. For a 2 ms injection, the fueling efficiency is about 80% at 1 bar, 45% at 5 bar, and 25% at 10 bar, indicating that efficiency decreases with increasing gas pressure. Moreover, efficiency also declines with longer pulse durations, though eventually it approaches a steady level, likely reflecting the balance between deposition and transport effects.

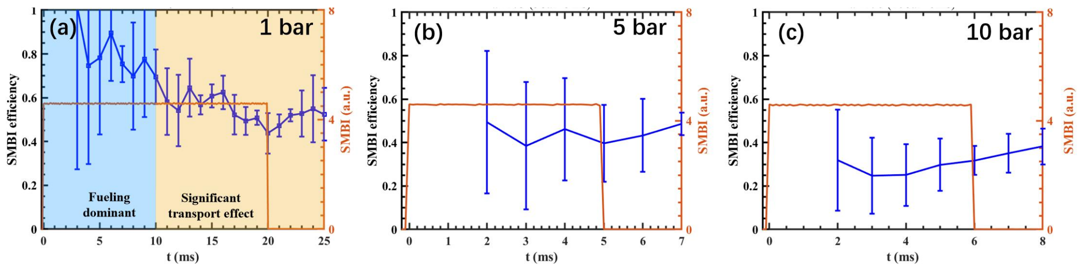

Figure 7. The time evolution of fueling efficiency of different gas source pressure at (a) 1 bar, (b) 5 bar and (c) 10 bar

4.2 Effect of gas source on turbulence and transport

The fueling process is strongly influenced by turbulence transport. Edge density fluctuations were measured by Doppler reflectometry, as shown in Figure 8, for cases with low (1 bar, red), medium (5 bar, blue), and high (10 bar, black) source pressures. The integrated turbulence intensity increases with higher source pressure, indicating enhanced fluctuation-driven transport.

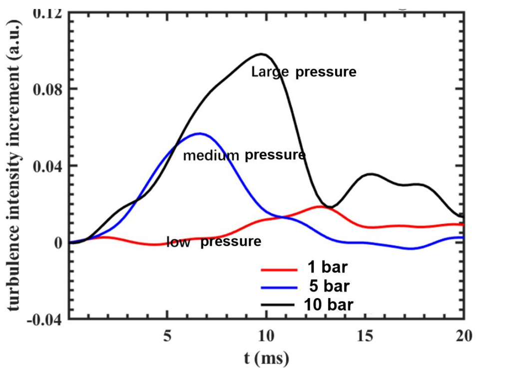

Figure 8. The turbulence intensity measured by the same channel of Doppoer reflectrometry for different gas source pressure

Further spectral analysis (Figure 9) reveals that turbulence characteristics differ between pressure regimes. For the low-pressure case, high-frequency fluctuations are enhanced after SMBI, while for the high-pressure case, low-frequency modes dominate. Previous experiments suggest that SMBI can reduce the edge shear rate immediately after injection. A plausible mechanism is that high source pressure leads to a sharp increase in the edge density gradient while simultaneously reducing the shear rate, thereby driving strong turbulent transport and reducing fueling efficiency.

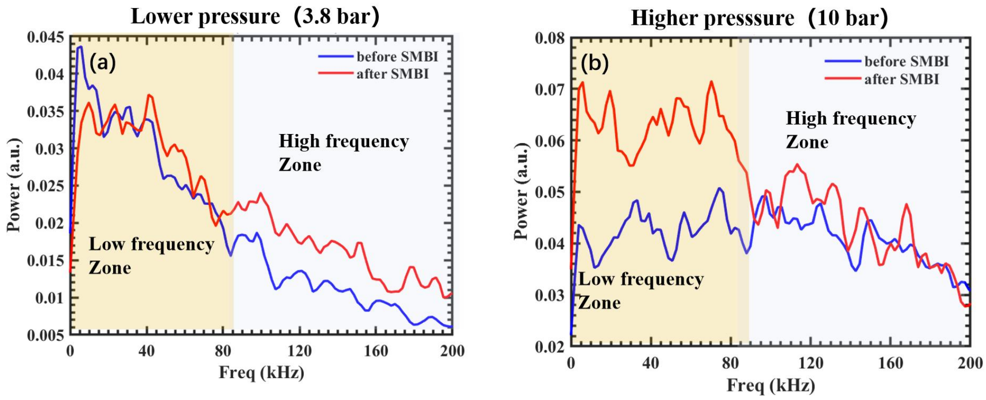

Figure 9. The characteristics of the turbulence power spectrum for (a) the low pressure case and (b) the high pressure case.

4.3 Simulation of the fueling process

To further interpret the experimental observations, simulations of SMBI fueling were conducted using BOUT++. In the model, the initial beam parameters are set by density and velocity. Earlier assumptions that higher pressure corresponds directly to higher velocity need to be reconsidered, especially when optimized nozzles produce beams close to the ideal supersonic structure.

Figure 10 (simulation) shows the hydrogen beam velocity distribution along the flow direction for different gas source pressures (0.9, 2, and 5 bar) with a fixed background pressure of 1×10^{-2} Pa. According to the scaling formulas in Section 2, the effective distance for each case can be derived, as marked in the figure. In practice, the working distance is shorter than the effective distance, ensuring that the beam remains supersonic. The results indicate that beam velocity is nearly independent of source pressure, consistent with the expectation that the ideal beam velocity depends primarily on gas temperature and species. Time-of-flight measurements, based on the delay between SMBI valve signals and edge Dα emission, further support the simulation results. Thus, in BOUT++ simulations, only the density profile varies with source pressure.

The simulated neutral particle distributions and corresponding fueling efficiencies are shown in Figure 11. Fewer normalized neutrals are deposited at higher source pressures, consistent with lower fueling efficiency observed experimentally. The simulations reveal that high-pressure injection produces steep edge density gradients, which amplify fluctuations and enhance outward particle loss. Long pulse durations produce a similar effect when parallel transport is insufficient. Both simulations and experiments therefore indicate that low source pressure combined with short pulse duration maximizes fueling efficiency, and is thus the preferred strategy for tritium injection.

5. CONCLUSION AND DISCUSSION

This work has examined the recent progress of SMBI technology and its application to fueling and divertor heat load control with a focus on tritium injection strategies. Compared with conventional gas puffing, SMBI shows faster response and deeper penetration, which provide clear benefits for both plasma fueling and power exhaust management. Fueling experiments and supporting simulations indicate that fueling efficiency decreases as the source pressure and pulse duration increase. High-pressure injection enhances edge turbulence and outward transport, leading to a loss of injected particles. In contrast, low source pressure combined with short pulse duration consistently gives higher fueling efficiency and thus represents a more effective strategy for future tritium injection on HL-3 and other large-scale devices. Nevertheless, the interaction between SMBI fueling and edge turbulence is not yet fully understood. Further studies are needed to clarify the changes in turbulence characteristics after SMBI, and to quantify outward transport fluxes under different source pressures. Such investigations will be important for refining fueling strategies and ensuring reliable tritium operation in next-step fusion experiments.

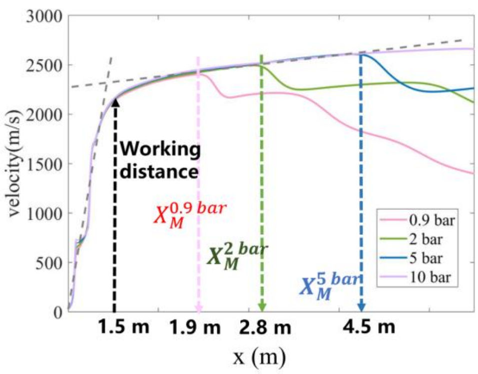

Figure 10. The simulated hydrogen beam velocity distribution in the flow direction with different gas source pressure 0.9 bar, 2 bar, 5bar and fixed background pressure at 1× 10^{-2} Pa

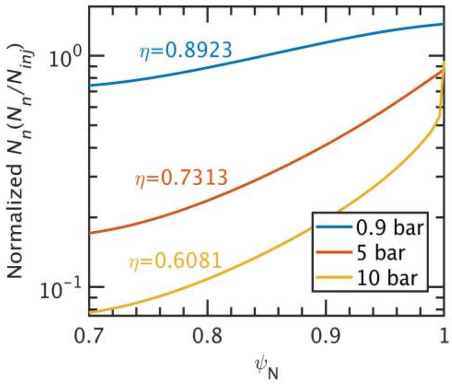

Figure 11. the neutral particle profiles and corresponding fueling efficiency with different gas source pressure.

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