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Advancements in SMBI Technology for Fusion Reactor Fueling Framework: AI - Driven Innovations and Physical Insights

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In magnetic confinement fusion devices, gas injection is crucial for fueling. Despite the challenges of achieving core fueling through gas injection in fusion reactors, it remains a significant supplementary fueling method. Among gas injection techniques, supersonic molecular beam injection (SMBI) is recognized as an optimized approach, offering distinct advantages in terms of directionality, distribution control, and rapid response[1]. It is anticipated to make substantial contributions to edge particle control, heat load management[2], and supplementary fueling in fusion reactors. This report highlights the reactor - oriented advancements in SMBI technology, focusing on tritium - compatible fueling system, edge particle control, and heat load mitigation for next generation devices.

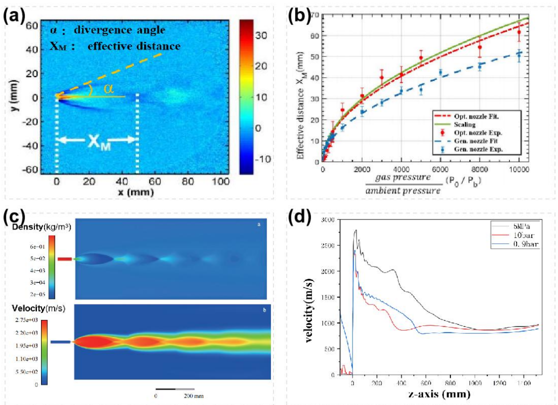

Figure 1. Experimental database of SMB. (a) beam structure measured by schlieren system,(b) scaling relation between gas pressure ratio and the effective distance of fueling beam, (c) simulation of beam profiles, (d) beam velocity profiles along the flow direction with different gas pressure

Recent technical advancements, particularly in beam detection and performance optimization, have been achieved through refined injector geometry and multi-phase gas condensation. These improvements have further enhanced the capabilities of the SMBI technique, as illustrated in Figure 1. A comprehensive database and corresponding scaling laws for beam parameters have been developed, integrating both simulation and experimental results. A key finding is that the inlet gas pressure has minimal impact on beam velocity within an effective operational distance. This observation provides a foundation for the development of low-pressure SMBI strategies. The latest research on low-pressure tritium injection strategies, using deuterium as an analog, has been conducted in anticipation of upcoming deuterium-tritium (D-T) operations on HL-3. These studies offer valuable insights for enhancing future tritium fueling and edge particle control in fusion reactors. Fueling experiments and BOUT++ simulations suggest that a low-pressure SMB strategy can improve fueling efficiency by softening the density gradient and promoting mild outward turbulence convection. This finding indicates that tritium fueling strategies for ITER and HL-3 could benefit from lower gas source pressures, achieving higher fueling efficiency while ensuring tritium safety. However, further in-depth research is still required.

In addition, a U-Net deep learning model has been employed for beam-integrated profiling, accurately predicting the velocity profiles of SMB. This enhances the accuracy of experimental and simulation analyses of the gas source. Further development of models driven solely by gas pressure for specific injectors enables rapid prediction of beam profiles, significantly amplifying the potential for feedback control of edge density profiles using SMBI systems. Ongoing research on SMBI technology and its applications is expected to continue driving the development of fueling systems for fusion reactors.

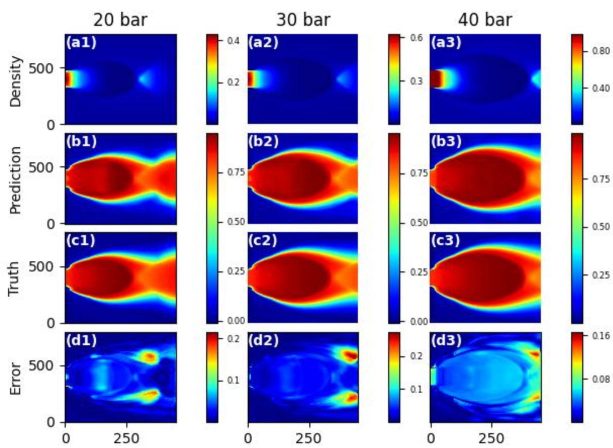

Figure 2. Velocity distribution prediction of 20 bar,30 bar and 40 bar gas source pressure by U-net deep learning model. (a1-a3) is the density distribution under the three different gas source pressure, (b1-b3) is the predicted velocity distribution under the three different gas source pressure, (c1-c3) is the actual velocity distribution under the three different gas source pressure, (d1-d3) is the error between predicted velocity distribution and actual velocity distribution.

References

[1] G.L. Xiao, W.L. Zhong, X.R. Duan et al *Reviews of Modern Plasma Physics* (2023) 7, 2

[2] G.L. Xiao, H.L. Du, D.M. Fan et al *Nuclear Fusion*