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Design and Integration of SMBI System for SST-1 Tokamak

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Abstract. Supersonic molecular beam injection (SMBI) is one of the most effective fuelling methods for injecting neutral particles at very high velocity into the plasma core. Due to higher speed and lower divergence, the beam penetrates several centimetres into the plasma and hence increases the fuelling efficiency. For SST-1 Tokamak, two types of SMBI systems are proposed. One will be installed in the low field side (LFS) while other will be integrated in the high field side (HFS). This paper describes the design, fabrication and implementation of SMBI system in SST-1 Tokamak.

1. Introduction

The currently adopted fueling techniques in Tokamak devices includes conventional gas puffing (GP), supersonic molecular beam injection (SMBI) and pellet injection (PI) etc. Among these methods SMBI is better compared to GP and is technically simpler in comparison to PI. The fueling efficiency of SMBI is around 30 ~ 60 %, about three to four times higher than the conventional gas puffing (GP) [1-3]. SMBI can also enhance the penetration depth and the fueling efficiency. A higher fueling efficiency and a reduced gas-wall interaction and therefore a lower wall saturation limit have been observed in L-mode plasma experiments in limiter tokamaks. In divertor tokamak experiments with the supersonic gas jet, a fueling efficiency of 10-30% has been reported [4,5].

Through a Laval nozzle, stagnation gas (P_0, T_0) is accelerated by imposing pressure difference so that it enters into vacuum chamber with a definite speed. When the background pressure (P_b) of vacuum chamber is low enough and the ratio (P_0/P_b) exceeds a critical value (G) which is less than 2.1 for all gases, the flow reaches a sonic speed or Mach number equals to 1 at the nozzle throat. The critical value is expressed as

$$G = ((\gamma + 1)/2)^{\gamma / (\gamma - 1)} \tag{1}$$

where γ is the ratio of heat capacity, C_p and C_v.

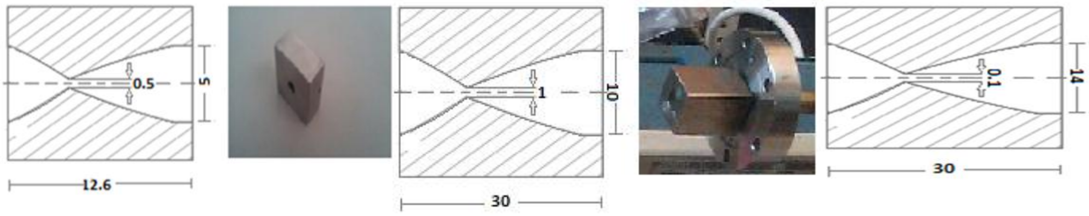
Beyond the nozzle throat, an isentropic expansion can produce a supersonic gas flow and the Mach number increases. The characteristic dimension of the supersonic area (X_M) i.e. the axial length from the nozzle to the position of Mach disk, measured in terms of nozzle diameter (d) is given by [6]

$$X_M/d = 0.67\,(P_0/P_b)^{1/2} \tag{2}$$

SST-1 Tokamak [7] is a medium size superconducting tokamak with major radius 1.1 m, minor radius 0.2 m having toroidal field of B_t = 3T at the center. Recently SST-1 machine has been upgraded [8] with graphite first wall for divertor experiment. This machine is designed for double-null D-shaped plasma operation of 1000 s duration. In order to maintain such long plasma duration and hence to enhance the plasma density, SMBI system is designed and installed in SST-1 machine. The design, experimental validation and the implementation of SMBI system is discussed in the subsequent sections.

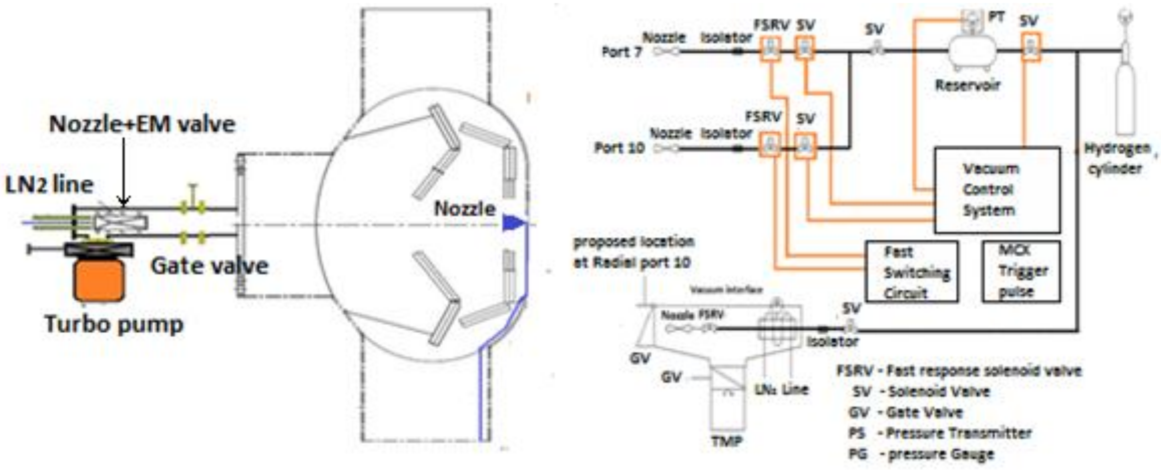
2. Nozzle design and parameters

In SST-1 machine, two Laval nozzles made up of SS 304L with throat diameters of 0.5 mm and 1 mm were installed at HFS side at the port locations 7 and 10 respectively. The taper angle is 12°–15° for these two exit diameters of 5 mm & 10 mm with the lengths of 12.6 mm and 30 mm respectively as shown in figure 1(a) and (b). The plenum gas pressure P_0 can be varied from 0.5–1MPa. If the background pressure P_b is 10^{-3} Pa, then the corresponding X_M is 7.5–10.5 m and 15–21 m respectively. The ratio of reservoir stagnation pressure to the background pressure P_0/P_b must be very high to avoid the Mach disk from being too close to the nozzle exit. To avoid the emergence of Mach shock and guarantee the beam convergence, the distance from the nozzles to edge plasma should be as short as possible. The schematic of SMBI inside the vacuum vessel as well as its PID is shown in figure 2. A Series-99 (Parkar) solenoid valve is used as a fast response valve (FSRV) with a response time of 1 ms which can be operated up to 5 MPa. To avoid the influence of toroidal field, this solenoid valve is mounted outside the toroidal filed coils.



(a) (b) (c)

Figure 1. Nozzle design having throat diameters (a) Ø 0.5 mm, (b) Ø 1.0 mm, (c) Ø 0.1 mm.



(a) (b)

Figure 2. (a) Schematic of SMBI nozzle inside SST-1 vacuum vessel, (b) PID of SMBI system.

Similarly, at LFS side, a nozzle of 0.1 mm diameter with the plenum gas temperature at 80 K, maintained using liquid nitrogen (LN_2) as shown in figure 1(c) shall be used during next experimental campaign. The onset of clustering can be described by an empirical scaling parameter referred as the Hagena parameter [9] which is given by

$$\Gamma^* = k\ \frac{(d/tan\alpha)^{0.85}}{T_0^{2.29}}\ P_0 \tag{3}$$

where d is the nozzle diameter in μm, α is the expansion half angle (α = 45˚ for sonic, α < 45˚ for supersonic), P_0 is the backing pressure behind the valve in mbar, T_0 is the pre-expansion temperature in K, and k is a constant related to bond formation (for hydrogen k = 184). Clustering generally begins for Γ^* > 100–300. For the both type of nozzles, Γ^* ~ 200 for high plenum pressure operation and hence onset of cluster may occur. The distance between the nozzle and the plasma column is maintained at ~ 1.2 m for LFS side while it is maintained at 70 mm from HFS side.

3. Experimental set-up

The initial characterization of the nozzle for flow rate and injection rate was carried out in the laboratory using a chamber of 50 mm diameter and 400 mm length. The cylinder is connected to a turbo-molecular pump having an effective pumping speed of 150 ls/. The pressure inside the chamber was maintained at ~ 1.0 × 10^{-2} Pa. A laser source (405 nm, 5 mW) was mounted horizontally with a fast imaging camera mounted perpendicular to the line of sight of laser as shown in figure 3.

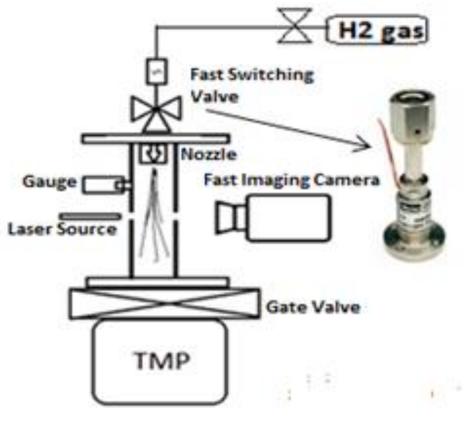


Figure 3. Schematic of experimental set-up.

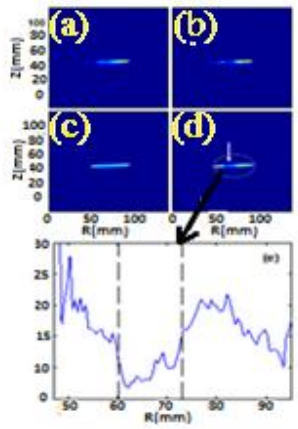


Figure 4. Fast imaging data.

3.1. Flow rate measurement

The flow rates (Pa m^3s^{-1}) of both the nozzles were determined at plenum pressure ranging from 0.25 MPa to 1 MPa as shown in table 1. Particle flux measured for nozzle with throat diameter Ø 0.5 mm and Ø 1 mm at plenum pressure 1 MPa is 2.6 × 10^{22} and 8.0 × 10^{22} particle/s respectively.

Table 1. Hydrogen gas flux (Pa m^3/s) measured for nozzle at different plenum pressure.

Sr. No.	Plenum pressure (MPa)	Flux (Pa m^2/s)	
		Throat diameter (0.5 mm)	Throat diameter (1.0 mm)
1	0.25	34	133
2	0.50	49	200
3	0.75	67	266
4	1.00	110	334

3.2. Beam divergence measurement

The divergence of beam for the nozzle with throat diameter 1.0 mm is measured from scattering of light using a fast imaging camera as shown in figure 4. Figure 4(a) and figure 4(b) are the raw images before and after the firing of supersonic molecular beam nozzle. Clear gradient in intensity can be seen along the laser path as light intensity gets attenuated along the path as laser is fired from left to right. Figure 4(c) and figure 4(d) are the intensity calibrated images corresponding to figure 4(a) and figure 4(b) showing the uniform intensity before firing the nozzle. A clear discontinuity in intensity after SMBI firing is shown by white solid arrow in figure 4(d) while figure 4(e) is the portion of laser path circled by white broken oval. The two vertical black broken lines denotes the actual beam width at the location. Actual beam width at laser path location is 12.88 mm at a distance of 130.45 mm from the nozzle.

3.3. Injection rate per pulse

The injection rates for both the nozzles have been determined at different plenum pressure ranging from 0.25 MPa to1.0 MPa) for the pulse lengths of 3 ms and 4 ms respectively. The measured injection rate per pulse of nozzle with throat diameter Ø 1.0 mm is shown in figure 5.

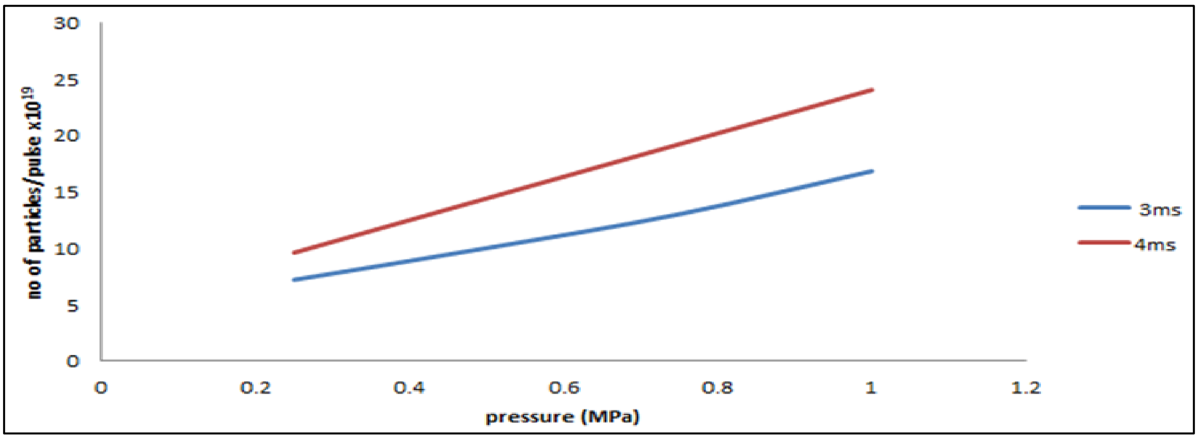


Figure 5. Injection rate per pulse measured for nozzle with throat diameter Ø 1.0 mm at different plenum pressure.

4. Implementation of SMBI system in SST-1 tokamak

The SMBI system will be used for gas puffing alongside conventional GP system. Also it will be used for density control as shown in figure 6. The pulse length can be varied from 1-20 ms. Pulse duration and pulse numbers will be controlled from main control system and can be adjusted according to the experimental requirement. Heterodyne radiometry will be used as a feedback for density control. The feedback system will start when the plasma current reaches 80% and the plasma density reaches to 6.0×10^{12} /cm^3 with 1 ms on-time and 20 ms off-time. Output of control will be amplified and applied to SMBI solenoid valve. Once the plasma density reaches a maximum value of 2.4×10^{13} /cm^3 or the plasma current start decaying, the feedback system will accordingly stop the pulse for gas puffing.

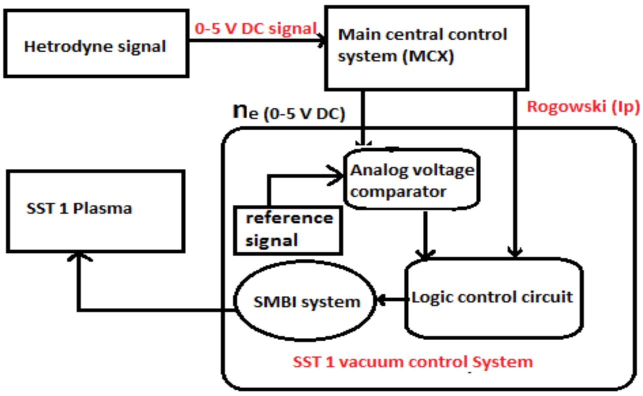


Figure 6. Schematic of density control system for SST-1 tokamak.

5. Conclusion

The SMBI system for SST-1 machine has been successfully characterised experimentally for its flow rate and injection rate. Two nozzles of different diameters has been successfully installed in SST-1 tokamak at two locations near HFS. In next experimental campaign, the same type of nozzles will be mounted in LFS with 80 K Plenum temperature and will be used for gas fuelling with density feedback control.

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