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Supersonic Gas Injection Fuelling in Tokamaks

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Abstract: *Fusion power or the requirements for more energy to be created than is put in, relied on the triple product of three vital quantities temperature (T), density (n) and confinement time (τ), (nτT) according to Lawson's criterion. To increase the plasma density Gas Puffing and Pellet injection methods have been significantly studied and compared in regards of their efficiency, cost and complexity. Supersonic Gas Injection method gives high-speed and high-directive gas deeper into the core plasma injection because of higher plenum pressure compared to the conventional gas puffing and it can inject neutral particles. It is economical to develop and to maintain. This method has been tested around the world in many fusion reactor tokamaks by researchers for example, NSTX, Tore Supra, KSTAR, HL-1M, ADITYA, etc. After reviewing many experiments on all these tokamaks we have concluded that Supersonic molecular beam injection (SMBI) is suitable for small and medium sized tokamaks for plasma fuelling.*

Key Words:*Tokamak, Gas Puffing, Pellet Injection, Confinement time, Plasma density, Supersonic flow*

I. INTRODUCTION

In a fusion reactor there will be a steady loss of alpha particles and neutrons so, plasma requires with a corresponding influx of deuterium and tritium for external fuelling to supply their initial particle inventory and to replace particles lost. Fuelling is mainly required to provide hydro genic fuel to maintain the plasma density profile for the specified fusion power, to replace the deuterium-tritium (D-T) ions consumed in the fusion reaction.There are mainly three methods of plasma fuelling used for various tokomaks, Gas Puffing, Pellet injection and Supersonic Molecular Beam injection. Gas puffers produce a diffuse, undirected flow. Due to the low density of the gas, penetration is determined by the single particle mean free path. This results in poor fuelling efficiency, where only 10% or less of the particles penetrate past the plasma edge [1]. Pellet injection system for steady fuelling are complex and expensive, making them ill-suited for medium and small experiments. Furthermore, the pellet system would need to pulse with a frequency that matches the plasma's effective particle confinement time (τ) [1, 2].As an intermediate fuelling source, supersonic gas injectors were developed which consists of a fast pulse valve and supersonic nozzle. In a supersonic expansion, gas is moved from a region of high pressure and hydrodynamic flow, through an orifice or nozzle, into a low pressure or vacuum region where it exhibits molecular flow.

II. LITERATURE REVIEW

A. H. W. Kugel, R. Kaita, et al. -NSTX tokamak-USA[3,4]:

For SGI they have chosen the Laval nozzle geometry for initial evaluation in the NSTX SGI. The geometry was obtained by scaling down a large wind tunnel *M*=8 nozzle operated in air at atmospheric pressures. The nozzle throat diameter is *d*=0.254 mm, the inlet diameter is 2.20 mm, and the exit diameter is 3.78 mm. The nozzle is 23.37 mm long.

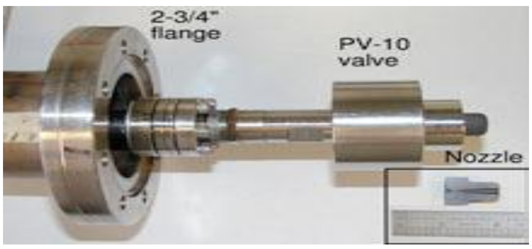

Figure 1: Prototype of supersonic gas injector [4].

Results and Discussion:

The impact or stagnation pressure $P_i$is measured on axis and the flow static pressure P_0 is measured in the SGI plenum. A vacuum tank is evacuated by a turbomoleculer pump to 10^{-6} Torr and filled with hydrogen to a desired background pressure $P_b$in the range $10^{-4}-10^{-1}$ Torr. The SGI operates at room temperature. It is comprised of a graphite Laval nozzle and a modified Veeco PV-10 piezoelectric valve mounted on a movable vacuum feed through.

The measurements were designed to simulate the tokamak environment: the SGI injected hydrogen gas pulses of 1–50 ms duration into the vacuum tank at the background pressure P_b=10−4 Torr, similar to the neutral pressures measured in NSTX. The pressure sharply decreases at about 10 mm from the nozzle exit, however, a sharp pressure gradient defining the jet canbe measured up to 120 mm from the nozzle. The jet divergence half angle is 1/2=6°. The deduced Mach number at the nozzle exit is 4–4.5 for $500 \leq P_0 \leq 2300$ Torr. At lower pressures the ratio P_0 /$P_i$sharply decreases as the flow approaches sonic conditions. Using the isentropic relations between stagnation and static quantities the density at the jet exit is estimated to be $\rho \leq 10^{18}$ cm^{-3}, and the temperature to be T ≥70 K.

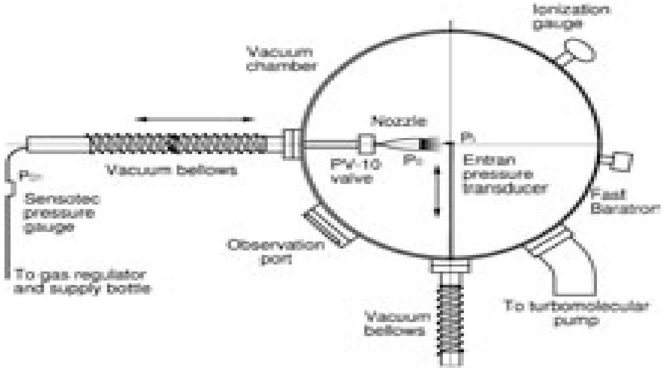

Figure 2: Experimental setup for supersonic gas injector characterization [4].

B. B. Pegouri, E. Tsitrone Frigioneet al. -Tore Supra tokamak-France [5]:

SGI was tested on Tore Supra during the 2001 experimental campaign, demonstrating a fuelling efficiency three to four times higher than for conventional gas puff (GP).

Experimental results:
A supersonic gas injector has been installed in the equatorial plane of Tore Supra allowing to reach a Mach number up to 5, and to inject 0.4 Pa-m^3 of D_2 molecules within 2–4 ms. This corresponds to injection rates up to 5 x 10^{22} part s^{-1}. The total number of particles injected being identical in both cases, GP and SGI. Two successive injections were performed during the same L mode ohmic discharge, with no active pumping and with an average density of 1.6 and 1.8 x 10^{19} m^3, respectively. The increase of density is moderate for GP, while for SGI, a strong density rise is observed, with a first spike followed by a slower decay.

C. Young Ok Kim et al.-KSTAR tokamak-South Korea[6]:

The supersonic molecular beam injection system (SMBI) was installed at median C port of the vacuum vessel for mitigation. The injected gas is cooled down to near 100 K by liquid nitrogen in order to increase its density. The pulse valve (Parker series 099) is used as actuator of the gas flow control. This pulse valve shows a fast response time of 160 µs. The SMBI valve includes pulse valve and its cooling channel. The confined gas in the valve is cooled down by its enclosing cooling channel.

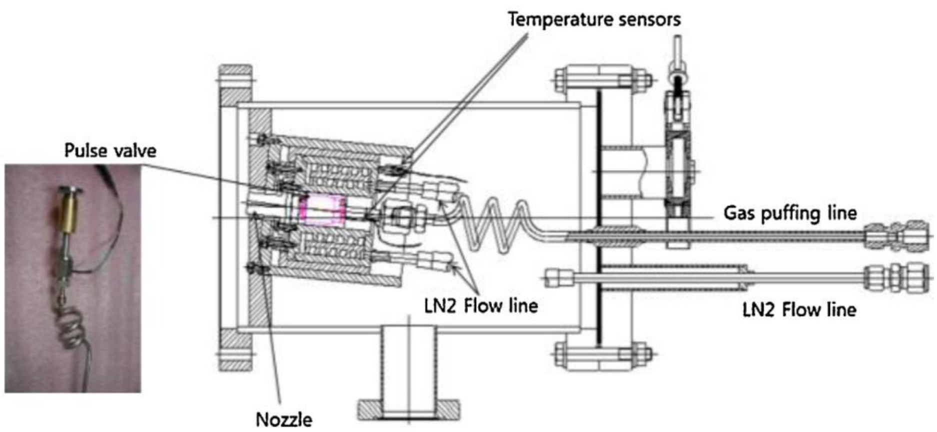

Figure 3: Cross section of SMBI valve of KSTAR [6]

The performance test for SMBI system was carried out at the fuel temperature of near 100 K. A rectangular pulse train with a pulse width of 2 ms and an interval of 500 ms was applied to the valve. The valve inlet was pressurized at 10 bar with deuterium. The pressure difference is linearly proportional to the pulse number. In the KSTAR tokamak, successful experiments of the SMBI fuelling and ELM mitigation have been operated in 2011. The gas pressure range of SMBI system in KSTAR was from 4 to 22 bar. 8 ms SMBI pulse duration was used for ELM mitigation experiment in KSTAR.

D. Lianghua YAO et al. -HL-1M tokamak-China[7,8]:

The parameters of the pulsed molecular beam source and its arrangement are: nozzle diameter of the electromagnetic valve is 1.5 mm, skimmer orifice diameter is 3 mm and distance from the nozzle to the skimmer *d*s is 26.5 mm. The distance between the pair of parallel platesis 20 mm, the limiter diameteris 20 mm and the beam flight distance from the skimmer to the ion gauge detector dis 1 m. About 6 x 10^{19} molecules from the gas source at a pressure of 1 x 10^{5} Pa have passed through the nozzle and entered the beam source chamber at a pressure of less than 1 x 10^{-3} Pa.

The measured mean velocity of the hydrogen molecular beam at a distance of 1 m is about 500 m/s, the local sonic velocity along the particle flying path is about 260 m/s and the Mach number of the beam M = 2. In the experiment on SGI fuelling with helium into hydrogen plasma, τ_E increases with increasing plasma density until $n_e = 6\times10^{19}$ m^{-3}.

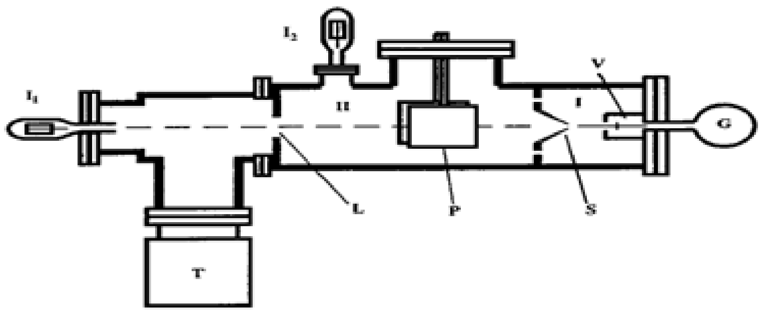

Figure 4: Schematic diagram of the measurement device for pulsed molecular beams [7]: I1, ion gauge 1 for beam detection; I2, ion gauge 2 for background pressure measurement; T, 450 L/s turbomoleculer pump; L, limiter; P, parallel electrodes; S, skimmer; V, fast electromagnetic valve; G, gas source; I, beam source chamber; II, collimator chamber.

This result is over 30% larger than that of previous GP results in the density range of (3.5-6) x 10^{19} m^{-3}.

E. S.B. Bhatt, Ajai Kumara, K.P. Subramanian , P.K. Atrey , Aditya Team-ADITYA Tokamak-INDIA[9]:

A supersonic molecular beam injection (MBI) system for Aditya tokamak is developed in house by modifying a piezoelectric gas inlet valve and using 400µm diameter nozzle at 2–5 kg/cm2 gas pressure. A modified Veeco (model PV10) piezoelectric leak valve along with sonic nozzle was used to form supersonic beam of the fuel gas. The sonic nozzle of diameter, 0.4 mm aperture was mounted on valve sealing surface. Aditya Tokamak is a medium size ohmically heated tokamak having major radius, 0.75m and minor radius, 0.25 m. The volume of the vessel is $\sim 2.0 m^3$. The hydrogen gas is filled in the vessel up to about 1.0×10^{-4} mbar pressure using a piezoelectric gas leak valve. Beyond the exit of nozzle the gas flow expands isentropically. For Aditya tokamak, d = 0.4mm and $P_0/P_b \approx 4\times 10^7$.

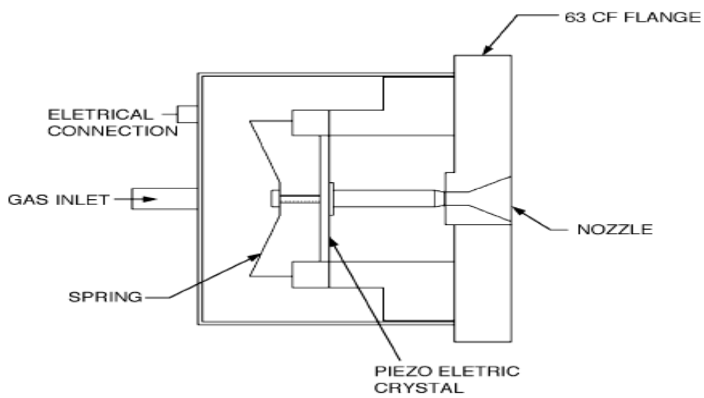

Figure 5: Piezoelectric valve for SGI fuelling [9]

Experiment was done to check the rising electron density, change in temperature, potential fluctuations in the Edge plasma with different pulse width and different number of pulses. (a) For two pulses of gas at 42 and 54 ms of 2.5 and 1.5 ms pulse width density rise rate $d(n_e)/dt$ for MBI is found to be $\sim 3.5\times10^{20}$ m^3/s. (b) for 5ms pulse width, plasma density rises at much faster rate $d(n_e)/dt \approx 1.2\times10^{21}$ m^3/s.

III. CONCLUSION

After reviewing above papers we can say that density of plasma core rise significantly by Supersonic Gas injection fuelling.
It gives high-speed and high-directive gas deeper into the core plasma injection because of higher plenum pressure compared to the conventional gas puffing and it can inject neutral particles and it is also economical to develop and to maintain. In few experiments from above literature we have observed fuelling efficiency of Supersonic Gas Injection 3 to 4 times than conventional Gas Puffing method. It has very simple construction and less controlling requirements which makes it less complex than Pellet Injection. Due to this we can also conclude thatSupersonic molecular beam injection (SMBI) is suitable for small and medium sized tokamaks for plasma fuelling.

IV. ACKNOWLEDGMENT

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