Supersonic gas injector for plasma fueling

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Abstract— **A supersonic gas injector (SGI) has been developed for fueling and diagnostic applications on the National Spherical Torus Experiment (NSTX). It is comprised of a graphite converging-diverging Laval nozzle and a commercial piezoelectric gas valve mounted on a movable probe at a low field side midplane port location. Also mounted on the probe is a diagnostic package: a Langmuir probe, two thermocouples and five pick-up coils for measuring toroidal, radial, vertical magnetic field components and magnetic fluctuations at the location of the SGI tip. The SGI flow rate is up to 4 x 10²¹ particles/s, comparable to conventional NSTX gas injectors. The nozzle operates in a pulsed regime at room temperature and a reservoir gas pressure up to 0.33 MPa. The deuterium jet Mach number of about 4, and the divergence half-angle of 5° - 25° have been measured in laboratory experiments simulating NSTX environment. In initial NSTX experiments reliable operation of the SGI and all mounted diagnostics at distances 1-20 cm from the plasma separatrix has been demonstrated. The SGI has been used for fueling of ohmic and 2-4 MW NBI heated L- and H-mode plasmas. Fueling efficiency in the range 0.1 - 0.3 has been obtained from the plasma electron inventory analysis.**

I. INTRODUCTION

Because of its technical simplicity, gas injection at the plasma edge is universally used for fueling of high-temperature plasmas in present day magnetically confined fusion (MCF) devices. Its well-known shortcomings are the low fueling efficiency, in the range 0.01 - 0.2, and gas loading of in-vessel surfaces leading to uncontrolled fueling of plasma by out-gassing and recycling. The fueling efficiency is defined as $\eta = (dN_i/dt) \; \Gamma_{gas}^{-1}$, where N_i is the confined particle inventory, and Γ_{gas} is the gas injecton rate. Despite the shortcomings the gas injection technique is likely to complement other presently utilized fueling techniques - the high velocity cryogenic pellet injection and compact toroid injection - in future long-pulse experimental reactors, such as ITER [1]. A variation of the gas injection technique had been developed on the HL-1M tokamak [2], and later reproduced on several high-temperature MCF devices [3]–[6]: a high-pressure low-divergence supersonic gas jet, also referred to as a supersonic molecular beam, is used for fueling the edge plasma. The gas jet is formed by a nozzle attached to a fast gas valve. A higher fueling efficiency of 0.3-0.6 and a reduced gas-wall interaction and therefore a lower wall saturation limit have been observed in L-mode plasma experiments in limiter tokamaks [7], [8]. In divertor tokamak experiments with the supersonic gas jet, a fueling efficiency of 0.1-0.3 has been reported [6], [9].

A supersonic gas injector (SGI) has been developed on the National Spherical Torus Experiment (NSTX) [10], [11] to study the supersonic gas jet fueling and optimize long-pulse high-performance spherical tokamak plasmas. The SGI is a part of the NSTX particle control program which explores various wall conditioning techniques and active density control tools, such as cryopumping and low-recycling lithium surfaces. Plasma fueling is achieved in NSTX by injecting deuterium or helium through several piezoelectric valves with injection rates up to 10^{22} particles/s, and a fueling efficiency of about 0.1 [12], [13]. The NSTX SGI was designed to operate in a long pulse steady-state mode, injecting gas at a flow rate similar to conventional gas injectors, typically $N_{pulse} \simeq (0.1-0.5) \times N_i$. This distinguishes it from the other supersonic injectors [3]–[6] designed to inject gas in massive quantities $\Delta N_{pulse} \simeq (0.2 - 0.9) \times N_i$ in milliseconds, leading to localized cooling of the plasma edge [14] or confinement degradation [6]. Experiments conducted in NSTX to date focused on characterization of the gas jet and its impact on the plasma edge.

II. SUPERSONIC GAS INJECTOR DESIGN AND CHARACTERIZATION

The SGI design incorporates several engineering and physics requirements: operational and vacuum autonomy, least interaction with NSTX machine operation and maintenance cycle, radial translation capability, gas throughput and diagnostic needs. For these reasons the SGI and several edge diagnostics are placed on a radially moving remotely controlled probe. The probe is mounted on a standard 4" diameter vacuum vessel port. The port is equipped with a machine vacuum interface valve and located at a distance 0.16 m above the midplane (Fig. 1). A ceramic break is used to isolate the probe electrically from the NSTX vacuum vessel potential. The SGI includes a nozzle, a valve and gas-handling hardware. The diagnostic package is comprised of a Langmuir probe, two thermocouples, and an Edge Magnetic Sensor (EMS) with five magnetic pick-up coils. The diagnostics and the valve with the nozzle are enclosed in a probe head covered by a protective shroud. The shroud is made of carbon fiber composite and ATJ graphite because of their low sputtering coefficient. All materials used in the SGI are ultra high vacuum compatible and bakeable to 125 °C. The head is mounted on a Thermionics ZC-450 movable probe as shown in Fig. 2. The probe stroke is 24", with a step size 0.0005" and a travel rate
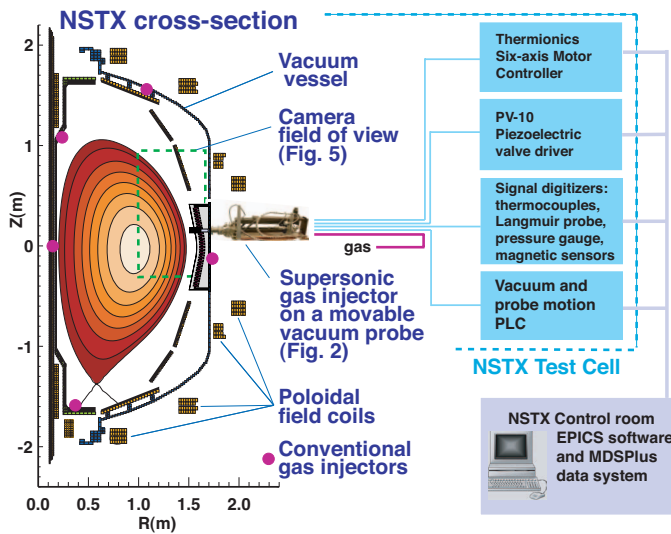
Fig. 1. Schematic of supersonic gas injector placement on NSTX and a block diagram of SGI control elements.

up to 15 in/sec. A 0.5" flexible gas line, a 0.25" OD gas line and electric cables are routed along the stand and connected to the SGI through vacuum electrically isolated feed-throughs. A 0.5" OD gas line and cables are mounted in vacuum inside the flexible probe bellows. The gas delivery lines are designed to handle flowing gas in a viscous regime with minimum boundary layer effects for a typical SGI deuterium pressure $P_0 \leq 0.33$ MPa. The gas delivery system includes a Sensotek Model TJE 5821-01 absolute pressure transducer for plenum pressure measurements before and after an injection and a fill isolation valve actuated by compressed air. The SGI gas line is connected to the NSTX Lower Dome and Inner Wall gas system [13] which uses standard gas bottles with a maximum regulator pressure of 0.33 MPa imposed by hardware limits. The electric cables mounted inside the probe bellows are low-voltage signal cables with an exception of a SGI piezoelectric valve driver cable. A Veeco PV-10 piezoelectric precision leak valve with a throat diameter 0.02" is used in the SGI. The valve characteristic opening time is 1-2 ms. Whereas the flow rate is proportional to the applied voltage in the range between 60 and 150 V, we always operate the valve at 150 V. The SGI plenum pressure variation is used to alter the flow rate. Several
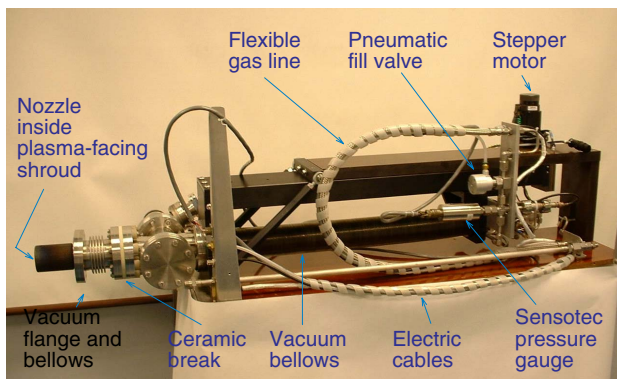
diagnostics are densely packed under the protective shroud around and behind the gas valve (Fig. 3). Integrated into the front surface of the shroud are a single Langmuir probe, a thermocouple, and two magnetic pick-up coils. The Langmuir probe is a flush-mounted type graphite tip probe 0.069" in diameter. It is similar to the NSTX divertor tile probes used to determine the scrape-off layer (SOL) plasma potential, particle flux and with proper analysis, plasma temperature and density. The probe saturation current I_{sat} value in the tens of milliampers is obtained when the probe power supply voltage is swept between -50 V and 50 V. The thermocouples are used to monitor the shroud and the gas valve temperature during plasma operations. Two pick-up coils are mounted in slots on the front surface of the CFC shroud. Their spatial orientation enables measurements of the B_z and B_t components with a proper calibration. Three pick-up coils are mounted in a small shielded box behind the gas valve. Two of them are designed to measure radial and vertical magnetic field components B_r, B_z while the third, Mirnov, coil is for edge magnetic fluctuation measurements.

The Thermionics probe is equipped with an encoder and a 6-axis stepper motor controller (SMC). EPICS software is used to communicate with the vacuum programmable logic control elements, such as the probe limit switches, vacuum and gas valves, and control the SMC remotely using its RS-232 port. The software is executed on an NSTX Engineering Network computer safeguarded by a firewall computer, and run from a terminal in the NSTX Control Room. The SGI head position has been calibrated in respect to the tokamak major radius R. The probe is usually parked at $R = 1.98$ m when unused, at $R = 1.75$ m in the glow discharge cleaning mode, and at $R = 1.52 - 1.60$ m (several cm from plasma) during plasma operations.

The SGI operation principle is based on diverse physics fields: gas-dynamics, compressible fluid mechanics, neutral gas transport, and magnetized plasma physics. An expansively cooled supersonic gas jet is obtained by expanding gas from a high pressure reservoir into vacuum through a nozzle. The jet penetrates through the plasma scrape-off layer perpendicular to the magnetic field, ionizes in the separatrix region and creates a localized high pressure plasma region. This plasmoid region expands along field lines, locally cooling

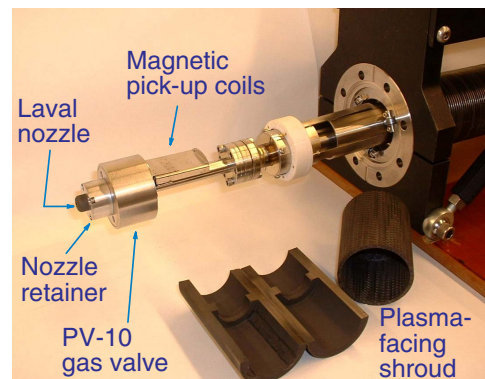Fig. 2. Photograph of the SGI probe on a mounting stand.
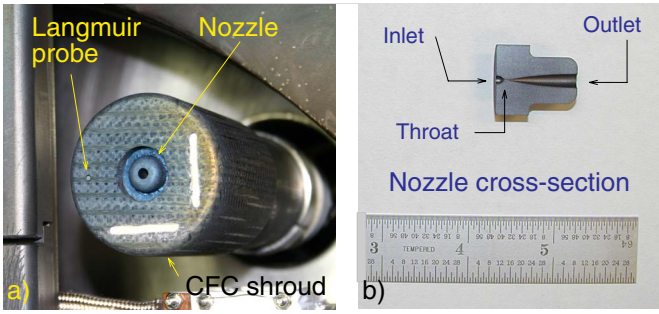

Fig. 3. Photograph of the SGI head assembly.

Fig. 4. Photographs of the SGI probe head inside the NSTX vacuum vessel (a) and the Laval nozzle (b). A flush-mount Langmuir probe tip and magnetic pick-up coil slots are visible on the SGI head.

Fig. 6. Fast camera imaging of gas jet interaction with edge plasmas: (a) collapsing plasma with a wide $T_e = 3$ eV, $n_e = 2 - 2.5 \times 10^{18}$ m^{-3} scrape-off layer, (b) 6 MW NBI-heated L-mode plasmas and (c) 4 MW NBI-heated H-mode plasmas.

and fueling the edge plasma. The SGI operates in a pulsed regime whereas any nozzle design relies on an established flow with steady-state parameters. The finite flow settle time limits the minimum SGI pulse length. The nozzle geometry determines supersonic jet properties, particularly the Mach number M and the degree of clustering (and condensation) of gas molecules - two properties believed to be crucial for fueling applications. A low divergence high pressure jet is formed because of the Mach focusing of gas flow, while molecular clustering may increase the jet density by orders of magnitude. The jet terminal velocity $u_{max} = \sqrt{\frac{2\,\gamma}{\gamma-1}\frac{kT_0}{m}}$ is only a factor of 2 - 3 greater than the thermal gas velocity $v_{th} = \sqrt{3kT_0/m}$ (γ is the gas specific heat ratio, T_0 is the stagnation temperature). Four axisymmetric nozzle shapes are commonly used for making high quality supersonic gas jets: a converging nozzle (free jet), a converging-diverging Laval nozzle, a converging-diverging conical nozzle, and an aerospike (plug) nozzle [10]. In comparison with a simple converging nozzle, a shaped Laval nozzle produces a highly uniform flow with constant Mach number, temperature, and density - the conditions favorable for molecular condensation. A higher flow intensity can be obtained with a lower pressure ratio in a contoured nozzle avoiding problems associated with normal Mach disk shocks. The Laval nozzle shape must be
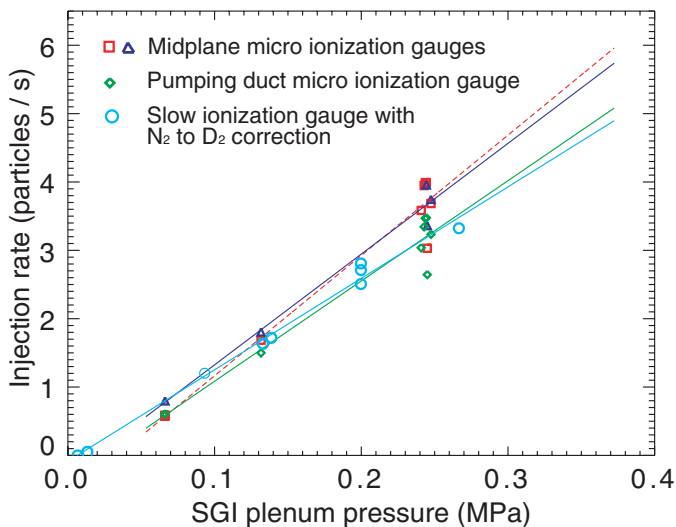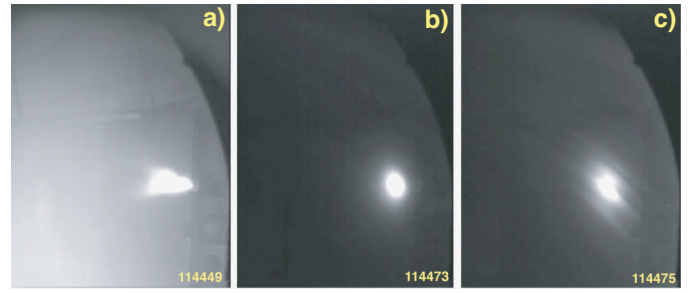
properly calculated to optimize the isentropic flow core and minimize the thickness of the boundary layer. This is usually done using the method of characteristics or computational fluid dynamics methodology based on numerical solution of the Navier-Stokes equations. A converging-diverging de Laval geometry (Fig.4) is presently adopted in the NSTX SGI. The nozzle is mechanically machined from graphite with dimensional tolerance of ± 0.0025". The nozzle throat diameter is $d = 0.01$", the inlet diameter is 0.087", and the exit diameter is 0.015". The nozzle is 0.92" long. Nozzle performance in a pulsed regime has been evaluated in a simulated tokamak environment: the SGI injected gas pulses of 1 - 50 ms duration into a 50 liter vacuum tank with a background pressure $P_b = 10^{-4}$ Torr, similar to the neutral pressures measured in NSTX [10], [11]. The deduced Mach number at the nozzle exit is about 4 for D_2 or H_2. The jet divergence half-angle is $\theta_{1/2} \simeq 6 - 12^o$. 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 $T \geq 70$ K. The nozzle Reynolds number is $Re \simeq 6000$. These parameters indicate that the NSTX gas jet is not in the regime favorable for molecular cluster formation. Flow rates have been also calibrated on a laboratory stand and *in-situ* on NSTX using neutral pressure gauges (Fig. 5). The scatter of the measured flow rate is due to ionization gauge location proximity to the pump duct, calibration, and different plenum pressure differentials ΔP for gas pulse lengths 5 - 300 ms used in the tests. The effective plenum volume of NSTX SGI is about 125 cc. Longer pulses lower the plenum pressure and reduce the effective flow rates up to 10 %: for example, a 200 ms pulse causes a 5 % decrease, whereas a 600 ms pulse causes a 15 % decrease in the plenum pressure. A larger plenum will be installed in order to reduce this effect.

III. PERFORMANCE ON NSTX

Initial NSTX experiments focused on commissioning the SGI and the diagnostics, and studying the interaction of the supersonic gas jet with edge plasmas. Deuterium pulses of 50-500 ms duration have been injected in ohmic and NBI-heated L- and H-mode plasmas. In ohmically heated plasmas the SGI head was brought as close as 1 cm to the plasma separatrix without any disruptive effects on the plasma or SGI head overheating. However, in NBI-heated plasmas the SGI head interacted with lost orbit energetic particles as soon as

Fig. 5. Measured SGI rate as a function of SGI plenum pressure. Lines represent linear fit to the data.

it cleared the radio-frequency antenna limiter. The resulting recycling and carbon flux from the SGI head caused a confinement degradation (H-L transitions) in H-mode plasmas and disruptive MHD activity. In subsequent NBI-heated discharges the SGI was always positioned in the shadow of the limiter at a distance 6-12 cm from plasma separatrix. To monitor gas jet formation, evolution, and the SGI head and jet interaction with the SOL plasma fast camera imaging has been used. Shown in Fig. 6 are photographs of visible light from the supersonic gas jet interacting with different types of plasma taken by the Canadian Photonics camera with 1 ms frame rate and a line of sight 48° with SGI axis. Gas jet divergence of 40-60° degrees and the formation of a high-density region are inferred from the images confirming that the SGI operates in a supersonic regime. Shown in Fig. 7 are waveforms from a representative 2-4 MW NBI-heated H-mode plasma discharge fueled by the inner wall gas injector. An SGI pulse of 0.20 s duration is added starting at 0.18 s with a flow rate $\simeq 3.9 \times 10^{21}$ s^{-1}. The SGI remains at a distance 8 - 13 cm from the plasma throughout the pulse duration. The SGI injection is clearly visible on the D_α emission waveform. Two inflections are seen on the line-integrated density $\bar{n}_e$ and total electron inventory N_e time traces: the first one occurs at the inner wall gas injection onset time, and the second at the time of the SGI gas injection and an L-H transition onset. In order to calculate the SGI fueling efficiency $(d\ \Delta N_e/dt)\Gamma_{SGI}^{-1}$, fueling contributions from other gas injectors, recycling and impurities must be accounted for. Present analysis uses a difference between the total electron inventories ΔN_e of two consecutive discharges with and without an SGI pulse. The total electron inventory N_e is obtained by volume-integrating the flux surface averaged Thomson scattering n_e profiles for each time point. Fueling efficiency between 0.1 and 0.3 has been inferred in this manner, demonstrating high-density H-mode plasma fueling with the supersonic gas jet. The SGI diagnostic package has been commissioned and used in several experiments to study the SGI performance and edge plasma characteristics. Shown in Fig. 7 are signal traces from the SGI probe diagnostics. Both thermocouples usually measure room temperatures throughout a plasma pulse. The Langmuir probe saturation current I_{sat} time trace does not show any increase in SOL particle flux during the SGI pulse. The EMS has been used in the poloidal field (PF) only start-up experiments to monitor PF null formation, and during SGI pulses to monitor edge magnetic field perturbations, and edge MHD activity. The EMS signal traces shown in Fig. 7 use preliminary magnetic calibration factors.

IV. FUTURE WORK

In summary, we have developed a pulsed supersonic gas injector for fueling and diagnostic applications on NSTX. Experiments to date have demonstrated the SGI fast time response, fueling efficiency in the range 0.1 - 0.3, and compatibility with H-mode plasmas. Future NSTX experiments will focus on development of high-performance plasma scenarios with supersonic gas jet fueling. Laboratory work will include testing of other nozzle geometries in an effort to optimize the SGI flow rate and gas jet divergence.
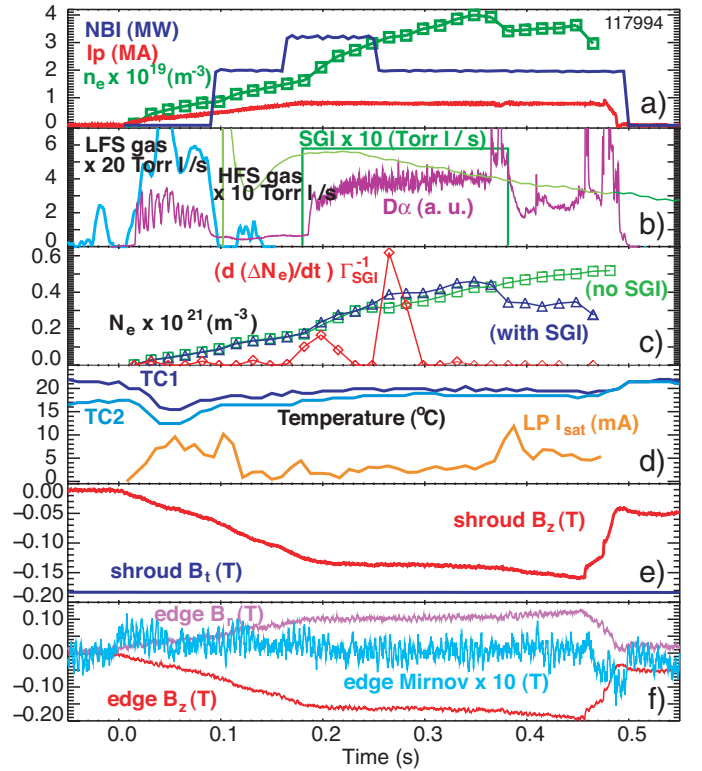

Fig. 7. Time traces of a representative SGI-fueled H-mode discharge. (a) Plasma current I_p, NBI power, line-averaged density $\bar{n}_e$, (b) Midplane D_α emission, gas flow rates for the low field side (LFS), high field side (HFS) injectors and SGI, (c) Total electron inventories for this shot and a shot without SGI, and the SGI fueling efficiency, (d) Shroud TC1 and gas valve TC2 thermocouple temperatures and Langmuir probe I_{sat}, (e) Shroud coil sensor traces of B_t and B_z, (f) edge coil sensor traces of B_r, B_z and magnetic fluctuations (Mirnov).

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