

Supersonic gas injector for fueling and diagnostic applications on the National Spherical Torus Experiment

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A prototype pulsed supersonic gas injector (SGI) has been developed for the National Spherical Torus Experiment (NSTX). Experiments in NSTX will explore the compatibility of the supersonic gas jet fueling with the H-mode plasma edge, edge localized mode control, edge magnetohydrodynamic stability, radio frequency heating scenarios, and start-up scenarios with a fast plasma density ramp up. The diagnostic applications include localized impurity gas injections for transport and turbulence experiments and edge helium spectroscopy for edge T_e and n_e profile measurements. Nozzle and gas injector design considerations are presented and four types of supersonic nozzles are discussed. The prototype SGI operates at room temperature. It is comprised of a small graphite Laval nozzle coupled to a modified commercial piezoelectric valve and mounted on a movable vacuum feedthrough. The critical properties of the SGI jet—low divergence, high density, and sharp boundary gradient, achievable only at $M > 1$, have been demonstrated in a laboratory setup simulating NSTX edge conditions. The Mach numbers of about 4, the injection rate up to 10^{22} particles/s, and the jet divergence half angle of 6° have been inferred from pulsed pressure measurements. © 2004 American Institute of Physics. [DOI: 10.1063/1.1787579]

I. INTRODUCTION

An advanced method of refueling the high temperature fusion plasma with a supersonic gas jet has been developed on the HL-1M tokamak¹ and later reproduced on several nuclear fusion plasma facilities.^{2,3} The demonstrated advantages over a conventionally used gas injection into the plasma edge through a fast valve⁴ are a higher fueling efficiency and a reduced interaction of injected gas with in-vessel components. The concept looks particularly attractive for a continuously operated tritium fusion reactor. The underlying physics mechanism of the supersonic high density gas jet penetration in the plasma, however, is yet to be put on a firm theoretical ground,⁵ and its compatibility with advanced plasma regimes is to be demonstrated. This article describes design considerations and characterization experiments with a prototype of a supersonic gas injector (SGI) being developed for the National Spherical Torus Experiment (NSTX). The NSTX Boundary Physics program presently focuses on edge power and particle flow optimization and control in high performance $t \leq 1$ s plasmas with auxiliary heating up to 12 MW.⁶ The initial fueling of plasmas is achieved by injecting deuterium or helium through several fast piezoelectric valves with injection rates of up to 10^{22} particles/s, and a fueling efficiency of about 0.1.^{7,8} The fueling efficiency is defined as $\eta = (dN_i/dt)\Gamma_{\text{gas}}^{-1}$, where N_i is the confined particle inventory, and Γ_{gas} is the gas injection rate. Experiments in NSTX will explore the compatibility of the supersonic gas jet fueling with the H-mode plasma edge, edge localized mode control, edge magnetohydrodynamic stability, radio frequency heating scenarios, and start-up scenarios with a

fast plasma density ramp up. The diagnostic applications will include localized impurity gas injections for transport and turbulence experiments and edge helium spectroscopy.

II. NOZZLE DESIGN CONSIDERATIONS

Physics and engineering aspects of making and diagnosing supersonic gas jets for various applications have been extensively studied and are fairly well understood and developed (for example, Refs. 9 and 10). An isentropic expansion of gas through a nozzle produces a supersonic flow if the pressure in the reservoir is adequate. The supersonic jet velocity is $u = Mc = M\sqrt{\gamma kT/m}$, where M is a Mach number, c is a local speed of sound, and γ is the specific heat ratio. The static temperature T in a compressible flow, however, is reduced according to $T/T_0 = (1 + (\gamma - 1)M^2/2)^{-1}$, where T_0 is the stagnation temperature, so that the terminal velocity is $u_{\text{max}} = \sqrt{2\gamma kT_0/(m(\gamma - 1))}$. The particle velocity distribution in the jet is described by a drifting narrowed Maxwellian distribution with the drift velocity u . The thermal gas velocity is of the same order of magnitude. It is the particle velocity (energy) that determines the neutral penetration length λ_n in accordance with the ionization, charge exchange and molecular reaction rates with plasma electrons and energetic neutrals. The significance of a high Mach number for the discussed applications is in two associated phenomena: Mach focusing and clustering and condensation of gas molecules. The Mach focusing provides a low divergence high intensity jet. The molecular clustering, conventionally characterized by an empirical Hagen parameter, may increase the jet density by orders of magnitude.¹¹ Lastly, the SGI op-

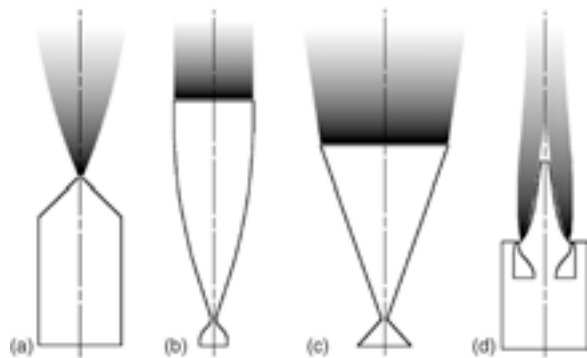


FIG. 1. Schematic view of the nozzle geometries: (a) converging nozzle, (b) converging-diverging Laval nozzle, (c) converging-diverging 20° conical nozzle, (d) aerospike (plug) nozzle.

erates in a pulsed regime, whereas any nozzle design relies on an established flow with steady-state parameters. The finite flow settle time limits the minimal SGI pulse length. The flow rate of the SGI is dependent on the nozzle geometry and valve parameters, and is usually defined by the plasma refueling requirements. These considerations demonstrate that the choice of proper nozzle geometry is critical. Shown in Fig. 1 are four axisymmetric nozzle shapes used for producing high quality supersonic gas jets: the converging sonic nozzle, the converging-diverging Laval nozzle, the converging-diverging conical nozzle, and the aerospike (plug) nozzle. The advantage of the converging nozzle is its simplicity. Free jets produced by the converging nozzle, however, suffer from the axial barrel and normal Mach disk shocks. The ratio of the reservoir stagnation pressure to the background pressure P_0/P_{bg} must be very high to avoid the Mach disk from being too close to the nozzle exit.⁵ In contrast, the contoured nozzles produce highly uniform flows with constant Mach number, temperature, and density—the desirable conditions which also favor the molecular condensation. A much higher jet intensity can be obtained with a lower pressure ratio in a contoured nozzle. The Laval nozzle shape must be properly calculated to 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.¹⁰ Simple alternatives to the Laval nozzle are the aerospace “standard” conical nozzle with a $\theta=15\text{--}20^\circ$ half angle, and the aerospike nozzle with an important property of self-adjusting the flow to the background pressure. Both these nozzles avoid complications associated with the fabrication of the Laval nozzle.

We have chosen the Laval nozzle geometry for initial evaluation in the NSTX SGI. The geometry was obtained by scaling down a large wind tunnel $M=8$ nozzle¹² 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 (Fig. 2). It was critical to evaluate the performance of the nozzle with hydrogen at the background pressure similar to the NSTX edge neutral pressure as the s of the jet core and the boundary layer do not scale similarly.¹³

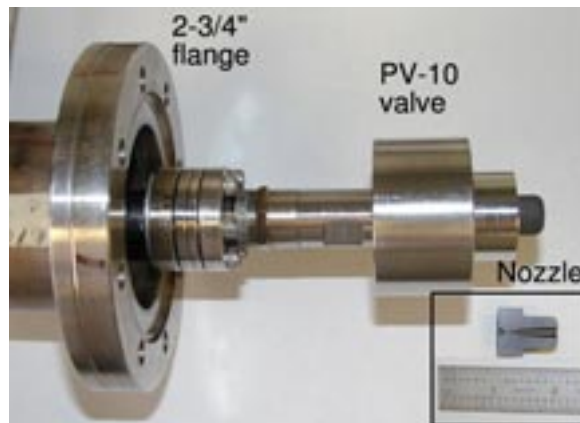


FIG. 2. (Color online) Photograph of the prototype supersonic gas injector. The inset shows a cross section of the Laval nozzle.

III. RESULTS AND DISCUSSION

A prototype SGI has been built for off-line optimization work. The goal of the characterization experiments is to measure the gas injection rates, and to evaluate the gas jet profile, the flow Mach number and the flow velocity. A local Mach number is obtained under the assumption of isentropicity from the Rayleigh–Pitot law using the pressure measurements upstream and downstream the shock formed at the transducer immersed in the flow. The impact (stagnation) pressure P_t is measured on axis and the flow static pressure P_0 is measured in the SGI plenum.¹⁰ The apparatus is shown in Fig. 3. A $V\approx 50$ l vacuum tank is evacuated by a turbomolecular 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 feedthrough (Fig. 2). The setup is equipped with a variety of ionization, Baratron and Sensotek pressure gauges to measure the background pressure P_{bg} and the reservoir pressure P_0 . We use an Entran EPX absolute piezoresistive transducer with a response time of $\tau < 1$ ms for the impact pressure

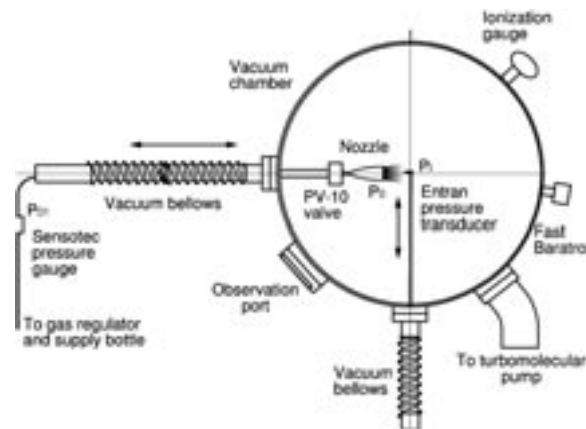


FIG. 3. Schematic view of the experimental setup for supersonic gas injector characterization.

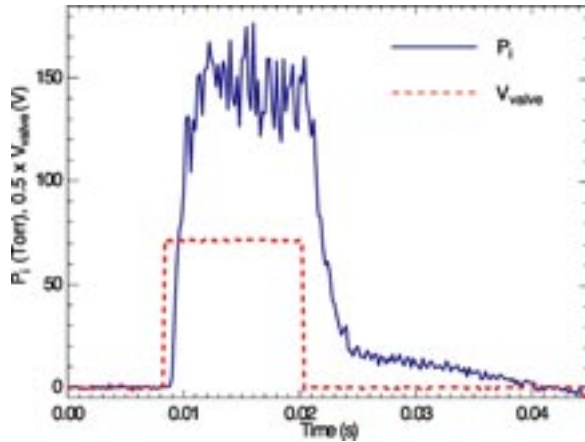


FIG. 4. (Color online) Time traces of the valve control wave form and on-axis impact pressure for a $\tau=12$ ms SGI pulse and $P_0=1000$ Torr, $P_{bg}=10^{-4}$ Torr.

measurements. The transducer is mounted on a vacuum feedthrough probe movable in the transverse direction to the SGI. A sharp “snout” tip with an opening of 1 mm is used on the transducer to increase its spatial resolution without reducing its sensitivity. 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.¹⁴ The jet profile was found to be insensitive to the background pressure in the range $10^{-5} < P_b < 100$ Torr, consistent with the notion that the optimal background pressure for a supersonic expansion is equal to the static flow pressure. The usable pulse length was limited to 40 ms by thermal shocks induced by a gas pulse in the piezoresistive transducer. Shown in Fig. 4 are the time traces of the control voltage applied to the PV-10 valve and the transducer response. By varying the plenum pressure P_0 in the range from 300 to 2300 Torr, the injection rates from 40 to 120 Torr 1/s have been measured. Shown in Fig. 5 is the measured gas jet profile obtained at $P_0=1000$ Torr cor-

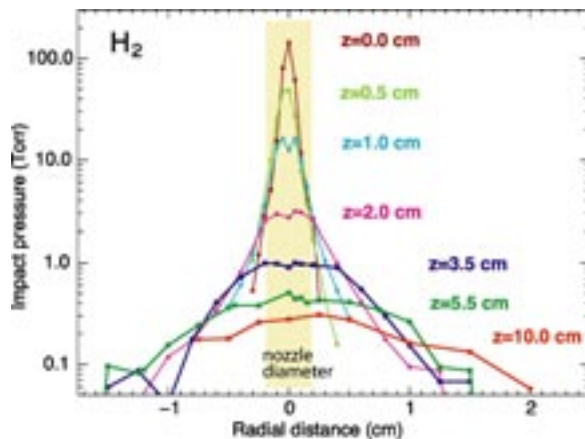


FIG. 5. (Color online) Jet pressure profile measurements at different axial locations.

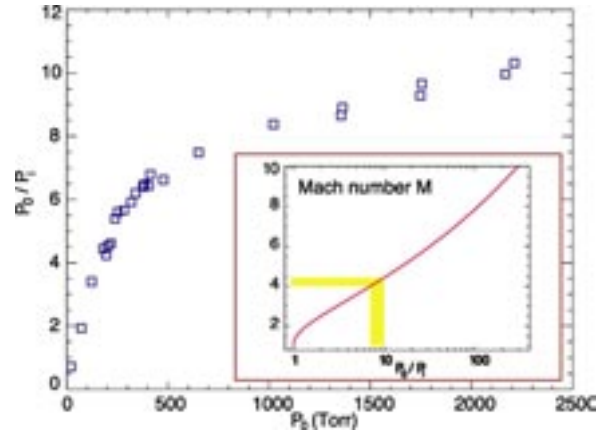


FIG. 6. (Color online) Measured ratio of the impact and static flow pressures. The inset shows the P_0/P_i dependence on Mach number according to the supersonic Rayleigh–Pitot formulas.

responding to the injection rate of $S=65$ Torr 1/s. The pressure sharply decreases at about 10 mm from the nozzle exit, however, a sharp pressure gradient defining the jet can be measured up to 120 mm from the nozzle. The jet divergence half angle is $\theta_{1/2}=6^\circ$. Shown in Fig. 6 is the P_0/P_i ratio measured as a function of the plenum pressure P_0 . The supersonic Rayleigh–Pitot formula is used to estimate the jet Mach number from the P_0/P_i ratio.¹³ The deduced Mach number at the nozzle exit is 4–4.5 for $500 < P_0 < 2300$ 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 quantities¹⁰ 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 $Re \approx 6000$.

Based on the high density and collimation of the supersonic jet, and the expected higher penetration into the plasma edge, several plasma diagnostic applications that utilize conventional gas injectors can be much improved. These are the helium line ratio spectroscopy,¹⁵ the gas puff imaging for turbulence studies,¹⁶ and gas injections for impurity transport experiments and cold pulse propagation measurements for heat transport studies.

In summary, we have developed a prototype pulsed supersonic gas injector for fueling and diagnostic applications on NSTX. The SGI utilizes a contoured Laval nozzle with the measured Mach number 4 for a range of plenum pressures, a well defined density profile, and the divergence half angle of 6° . The prototype SGI rate is up 120 Torr 1/s. Future SGI development work will explore the applications of contoured nozzles specifically designed for the NSTX conditions.

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- ¹L. Yao *et al.*, Nucl. Fusion **41**, 817 (July 2001).
- ²B. Pegourie *et al.*, J. Nucl. Mater. **313–316**, 539 (2003).
- ³J. Miyazawa *et al.*, Nucl. Fusion **44**, 154 (2004).
- ⁴S. C. Bates and K. H. Burrell, Rev. Sci. Instrum. **55**, 934 (1984).
- ⁵J. Yiming, Z. Yan, Y. Lianghua, and D. Jiaqi, Plasma Phys. Controlled Fusion **45**, 2001 (2003).
- ⁶R. Maingi *et al.*, Nucl. Fusion **43**, 969 (2003).
- ⁷V. A. Soukhanovskii, R. Maingi, R. Raman, H. W. Kugel, B. P. LeBlanc, A. L. Roquemore, and C. H. Skinner, J. Nucl. Mater. **313**, 573 (2003).
- ⁸H. W. Kugel *et al.*, in *NSTX High Field Side Gas Fueling System*, Proceedings of the 20th IEEE/NPSS Symposium on Fusion Engineering (IEEE, San Diego, CA, 2003).
- ⁹*Molecular Beams and Low Density Gasdynamics*, edited by P. P. Wegener (Dekker, New York, 1974).
- ¹⁰M. A. Saad, *Compressible Fluid Dynamics* (Prentice-Hall, Englewood Cliffs, NJ, 1993).
- ¹¹O. F. Hagena, Rev. Sci. Instrum. **63**, 2374 (1992).
- ¹²M. L. Baumgartner, Ph.D. thesis, Princeton University, 1997.
- ¹³G. Dupeyrat, J. B. Marquette, and B. R. Rowe, Phys. Fluids **28**, 1273 (1984).
- ¹⁴R. Raman, H. W. Kugel, T. Provost, R. Gernhardt, T. R. Jarbo, and M. G. Bell, Rev. Sci. Instrum. **74**, 1900 (2003).
- ¹⁵A. R. Field, P. G. Carolan, N. J. Conway, and M. G. O'Mullane, Rev. Sci. Instrum. **70**, 355 (1999).
- ¹⁶R. Maqueda *et al.*, Rev. Sci. Instrum. **74**, 2020 (2003).