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# Supersonic gas injector for plasma fueling

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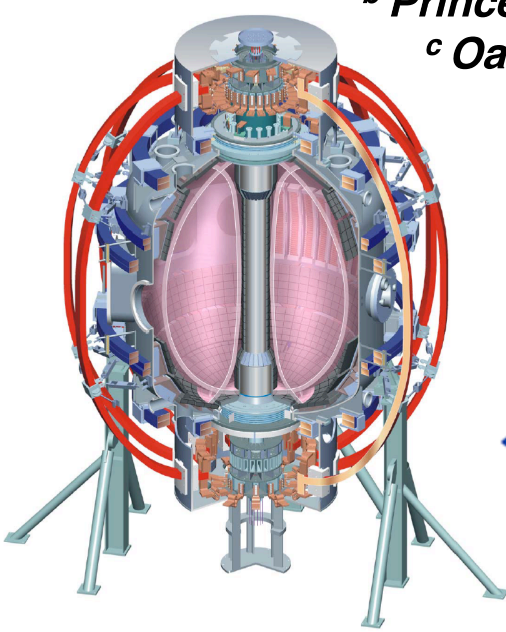

**Poster B14, Session II.b**
Tuesday Afternoon, 3:45 - 5:45 PM
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# Abstract

**SUPERSONIC GAS INJECTOR FOR PLASMA FUELING**

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Gas puffing is a common technique used for plasma density initiation, sustainment and diagnostic gas injection in present day high temperature plasma devices. A supersonic gas injector (SGI) has been developed for fueling and diagnostic applications on the National Spherical Torus Experiment (NSTX) following a successful demonstration of the enhanced fueling efficiency and reduced gas-wall interaction with the SGI on the HL-1M tokamak [1] and other facilities. The SGI design and operation principle are based on diverse physics fields including gas-dynamics, compressible fluid mechanics, neutral gas transport, and magnetized plasma physics. A high density expansively cooled gas jet penetrates through the plasma scrape-off layer perpendicular to the magnetic field, ionizes in the separatrix region and creates a localized plasma region of high pressure. This plasmoid region expands along field lines, cooling and locally fueling the edge plasma. The NSTX SGI is comprised of a nozzle, a modified commercial piezoelectric gas valve, and a diagnostic package mounted on a movable probe at a low field side midplane port location. The diagnostic package consists of a Langmuir probe, thermocouples and pick-up coils for measuring toroidal, radial and vertical magnetic field components at the location of the SGI tip. Supersonic gas jet profiles and SGI parameters have been measured in a laboratory facility, and in-situ in NSTX experiments. The converging-diverging Laval nozzle yields a gas flow rate of up to $4 \times 10^{21}$ particles/s, comparable to the conventional gas injectors. The nozzle operates in a pulsed regime at room temperature, gas pressure up to 0.27 MPa, Mach number of about 4, and deuterium jet divergence half-angle of $5^{o}$ - $25^{o}$. The focus of NSTX experiments is to study SGI fueling characteristics, compatibility of the pulsed supersonic gas jet fueling with an H-mode pedestal, edge localized mode stability, and high harmonic fast wave (HHFW) heating scenarios in high power density long pulse plasma regimes. Laboratory work is aimed at optimization of gas jet fueling parameters by using axisymmetric nozzles of different shapes and operating regimes. This work is supported by U.S. DOE under Contracts No. W-7405-Eng-48 and DE-AC02-76CH03073.

L. Yao, et. al., *Nuclear Fusion* 44, 420, 2004.

# Thesis

- Supersonic gas jet fueling of high-temperature magnetically confined plasmas may offer higher fueling efficiency (FE) and reduced gas-wall interaction

- Potential benefits for $D_2$, $T_2$ fueling of burning tritium plasma in experimental reactor such as ITER

- Improved FE of 0.3-0.6 has been demonstrated on limiter tokamaks HL-1M, HT-7, (PR of China), Tore Supra (France), and 0.2-0.3 on divertor tokamak AUG (Germany)

- Supersonic gas injector has been build, tested and mounted on NSTX. Fueling of 2-6 MW NBI-heated H-mode plasmas with higher efficiency (cf. conventional gas puff) has been demonstrated in initial experiments

# Outline

- Plasma fueling with supersonic gas jet: principle and details
- Supersonic Gas Injector on NSTX: design and parameters
- Off-line characterization of NSTX SGI
- Performance on NSTX: fueling L- and H-mode plasmas
- Summary

# NSTX reference data

**NSTX fueling**

• Gas injection: low field side (LFS, top + side), high field side (HFS, midplane + shoulder), private flux region. $D_2$, He, injected at S = 20 - 120 Torr l /s.

• Neutral beam injection system: three beams, 40 - 100 keV, 6 MW, fueling rate: S < 6 Torr l / s

• Supersonic gas injection: S = 60 Torr l / s

**NSTX wall conditioning**

• Between shots He GDC

• He conditioning plasmas

• TMB and Plasma TMB

**NSTX pumping**

• Turbomolecular pump (3400 l / s)

• NBI cryopump (50000 l / s)

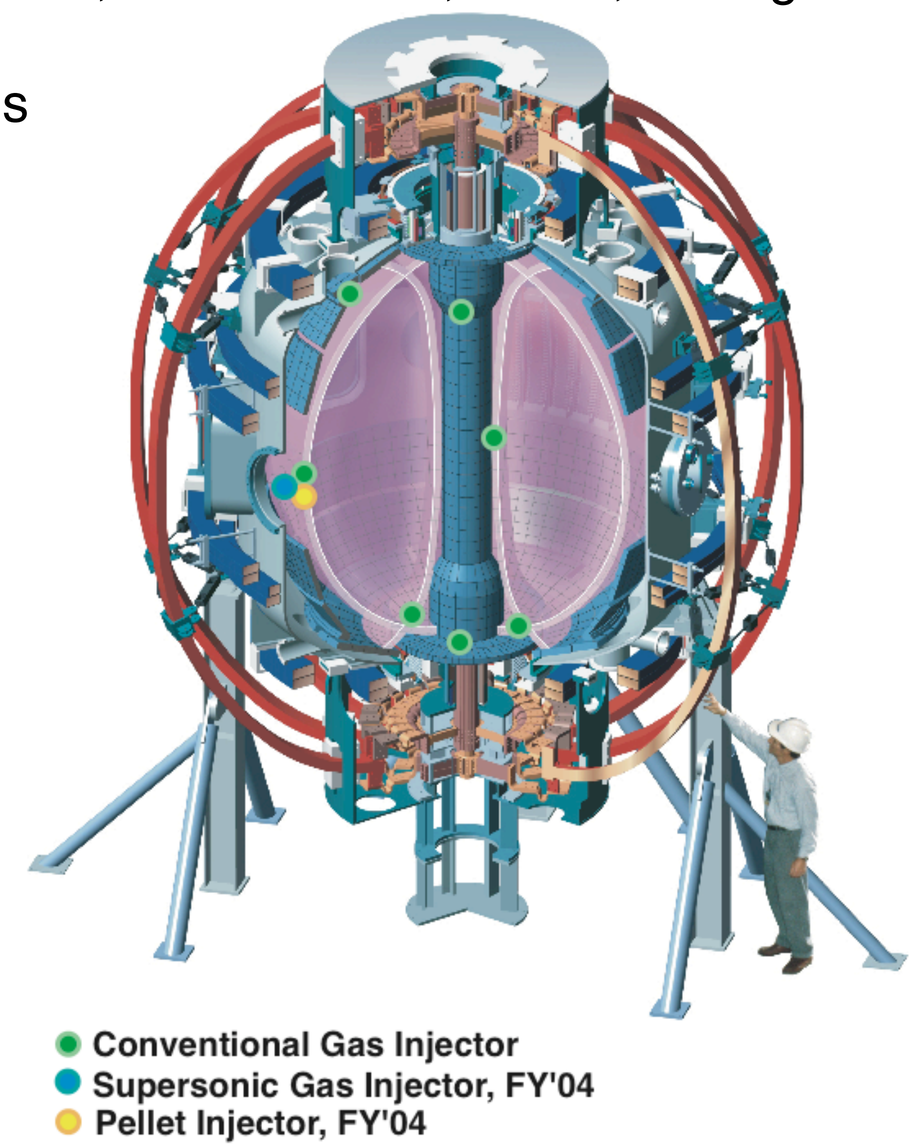
• Conditioned walls

**PFC**

• ATJ graphite tiles on divertor and passive plates

• ATJ and CFC tiles on center stack

• Tile thickness 1” and 2”



# Supersonic gas jet fueling

• Conventional gas puff: low fueling efficiency, saturation of vacuum chamber walls with gas atoms and molecules leading to outgassing and recycling

• Supersonic gas jet - high pressure/density low divergence jet, highly localized

• Demonstrated on HL-1M and Tore Supra limiter tokamaks experimentally, main results: fueling efficiency 0.3-0.6, lower wall saturation limit. However, both inject large inventory per pulse

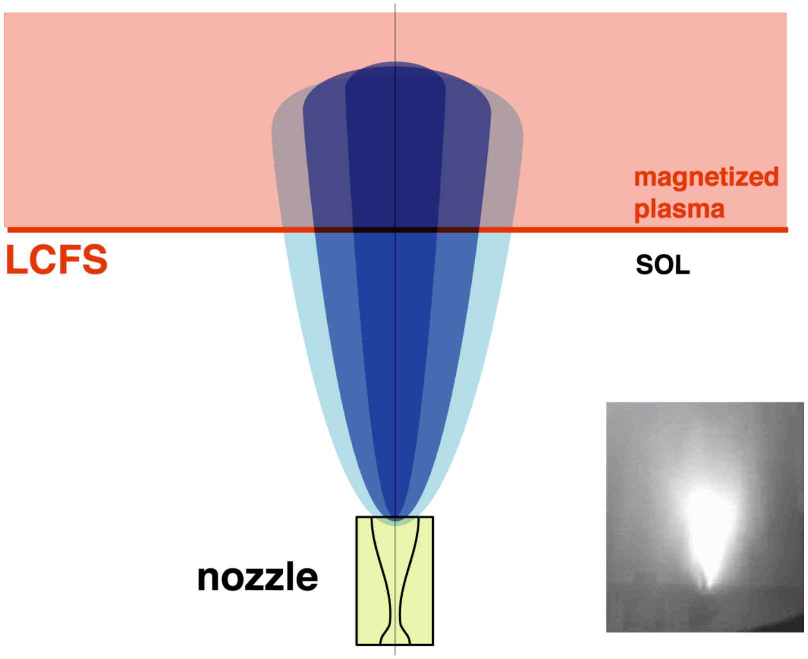
• Velocity distribution function is drifting narrowed Maxwellian with $u_{drift} = u_{flow}$

• $u_{flow} = M c = M \sqrt{\gamma kT/m} > v_{therm}$

**Two main properties of supersonic gas jet are critical for fueling applications: Mach focusing and Clustering**

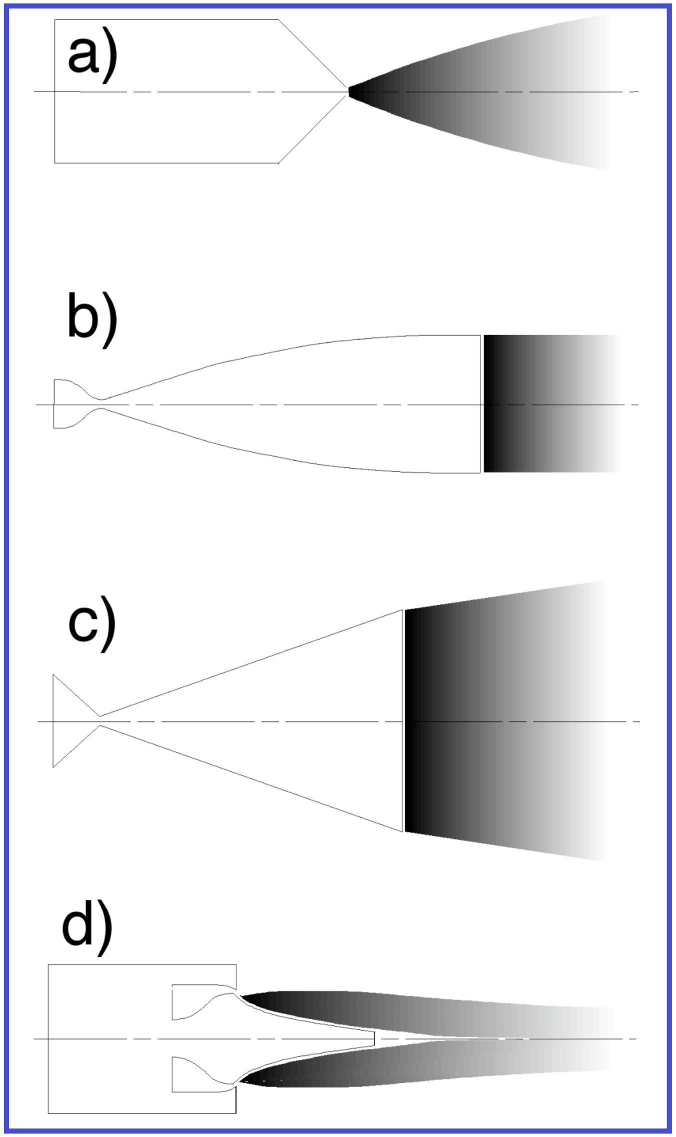
# Supersonic gas jet penetration mechanism

- Gas jet retains shape due to compressible fluid gasdynamics considerations
- Gas jet eventually ionizes and creates a plasmoid
- Gas jet retains cluster-molecular-atomic-ion structure
- SOL/edge electrons with low $T_e$ do not fully penetrate gas jet
- Plasmoid can not penetrate deep into the magnetized plasma due to insufficient velocity and high plasma kinetic and magnetic pressure
- Single particle model is inapplicable
- Modeling must include continuity, momentum, energy balance (Braginskii) equations with detailed reaction rates and neutral transport (such as UEDGE+DEGAS 2)

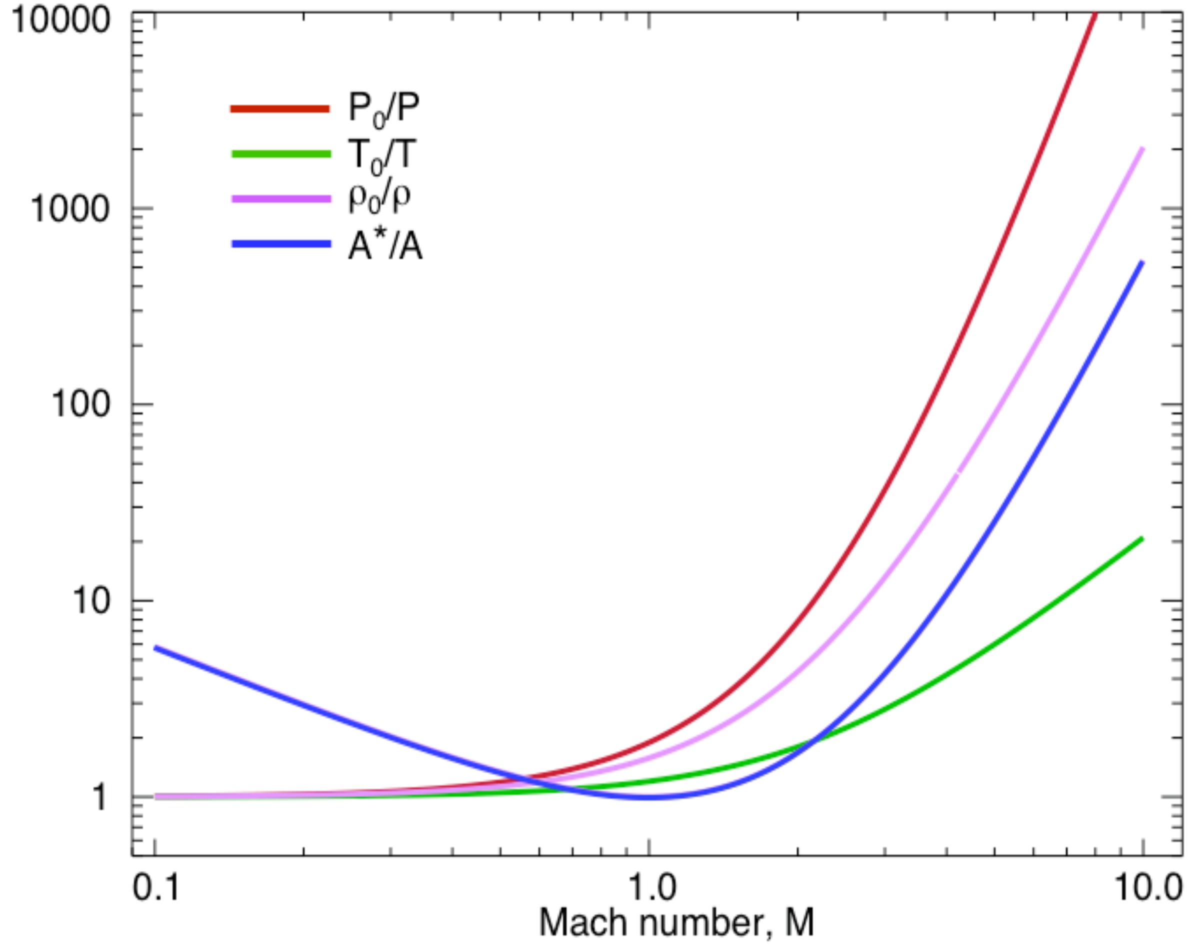


# Nozzle geometry determines flow characteristics

- Converging nozzle (a)
  - Very simple
  - Barel shock and Mach disk (normal shock) interfere with flow
  - Requires very high $P_0/P_{bg}$ to avoid Mach disk
  - Nonuniform M, P, T, $\rho$ in jet
- Laval nozzle (b)
  - Best choice but difficult to fabricate
  - Shape must be calculated properly (CFD or method of characteristics)
  - Uniform M, P, T, $\rho$ in jet - good for clustering
- Conical nozzle (c)
  - Aerospace standard
  - Similar in performance to Laval nozzle
  - Easy to fabricate
- Aerospike (plug) nozzle (d)
  - Quasi-converging jet. Easy to fabricate
  - Self-adjusting to $P_{bg}$
  - Shape must be properly calculated

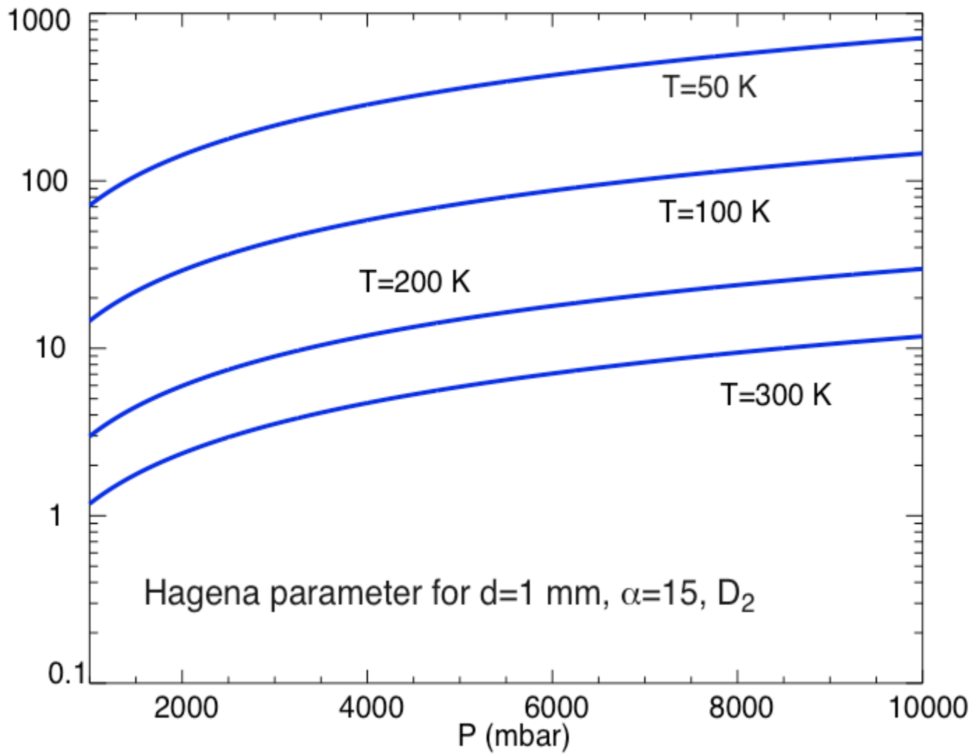


# Proper nozzle operation critical for Mach focusing




Isentropic ratios determine supersonic gas jet properties *P, T,* $\rho$ as a function of Mach number in reference to reservoir parameters $P_0$, $T_0$, $\rho_0$

# Condensation and clustering



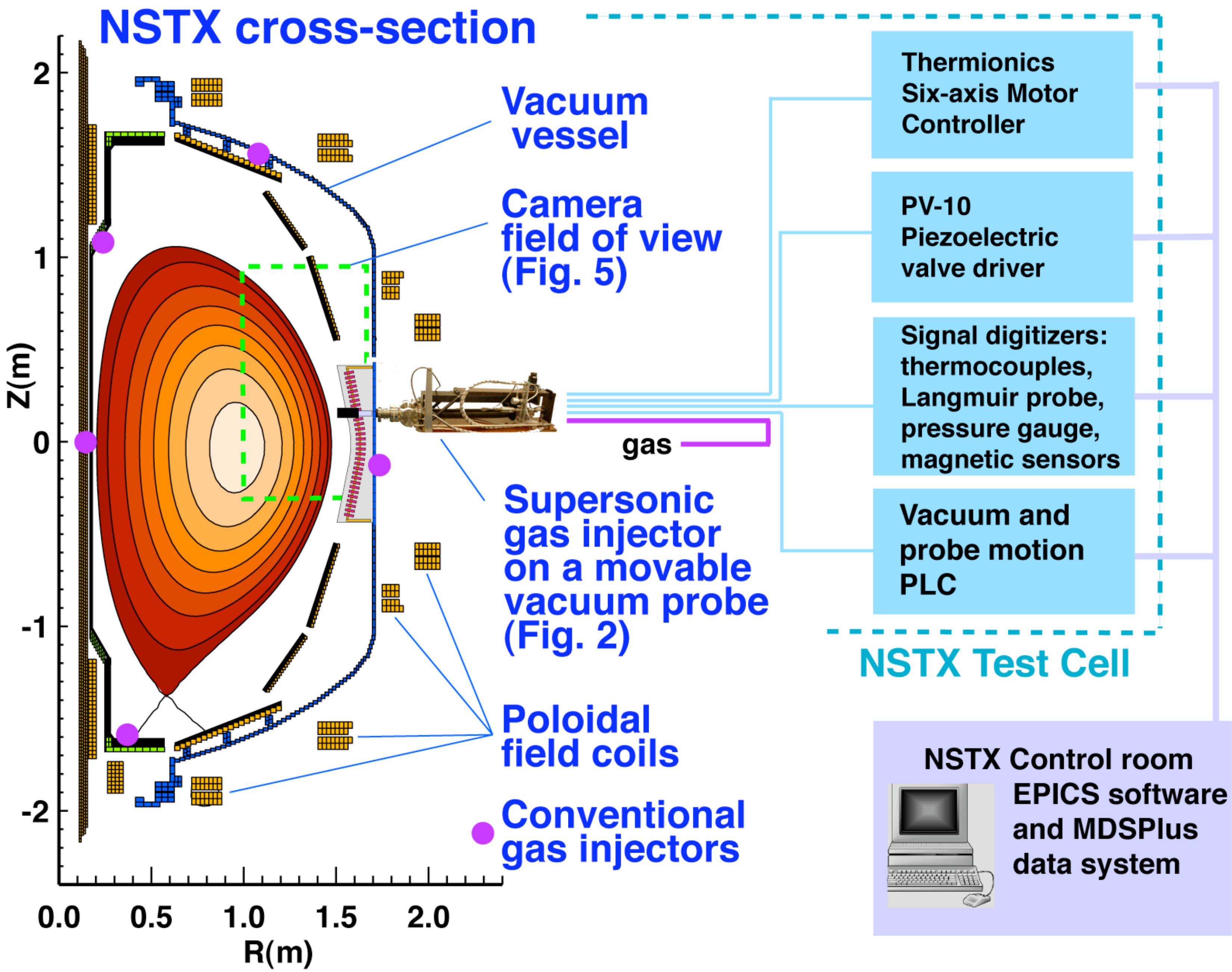

- Molecular clustering increases jet density by order(s) of magnitude
- Condensation / droplet formation in jet is attractive for fueling but may cool edge plasma
- Degree of clustering in jet is estimated through Hagena parameter
- Empirical scaling

$$\Gamma^* = k\frac{(d/\tan\alpha)^{0.85}}{T_0^{2.29}}P_0 = 100 - 300$$

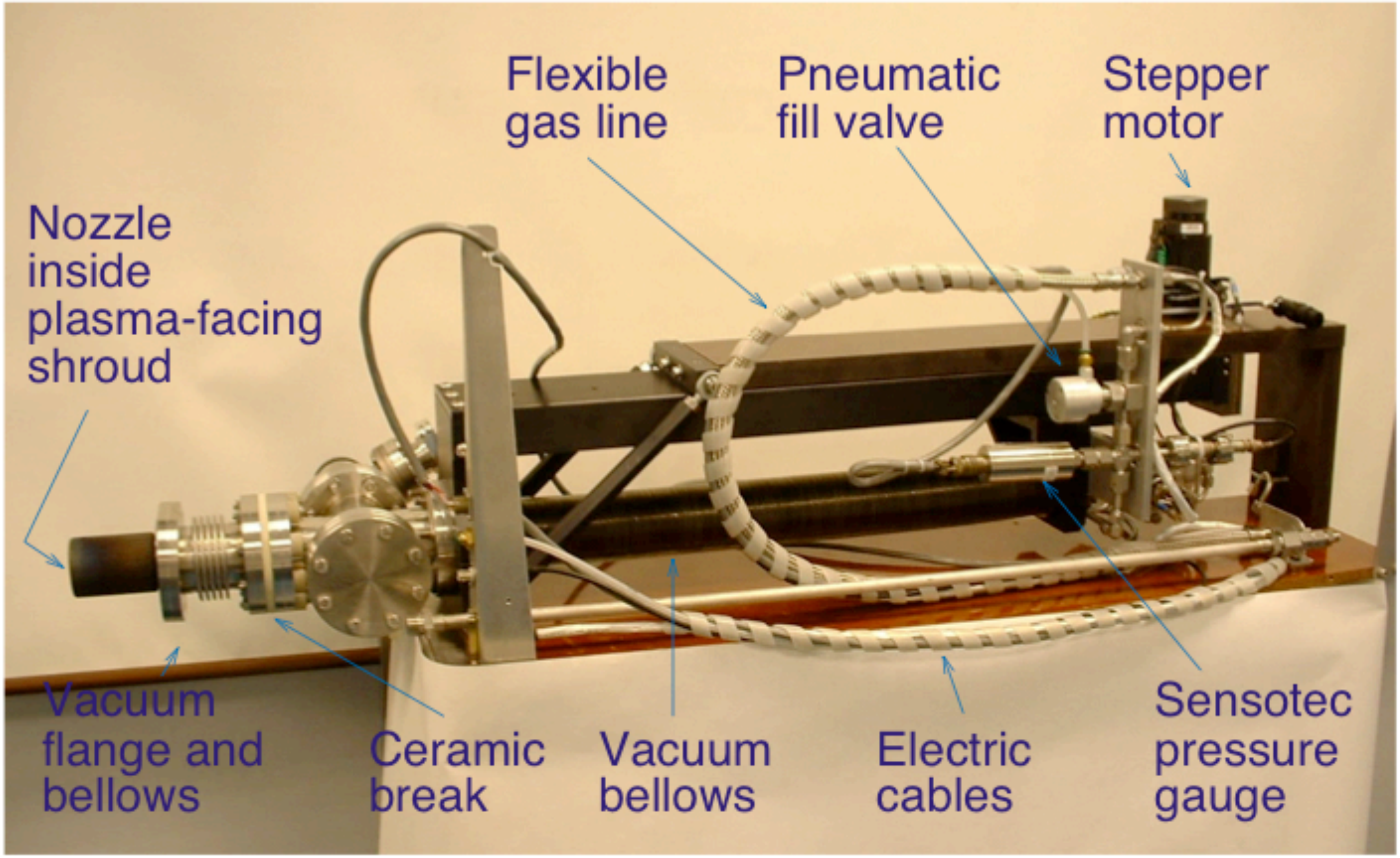
**← Clustering onset**

*d* - nozzle diameter, $\alpha$ - nozzle half angle, $T_0$ and $P_0$ are stagnation temperature and pressure. Cluster bond formation constant k=181 for $D_2$, k=185 for Ne. Number of molecules in cluster $N_c \sim \Gamma^{2-2.5}$

# SGI on NSTX: placement and control elements

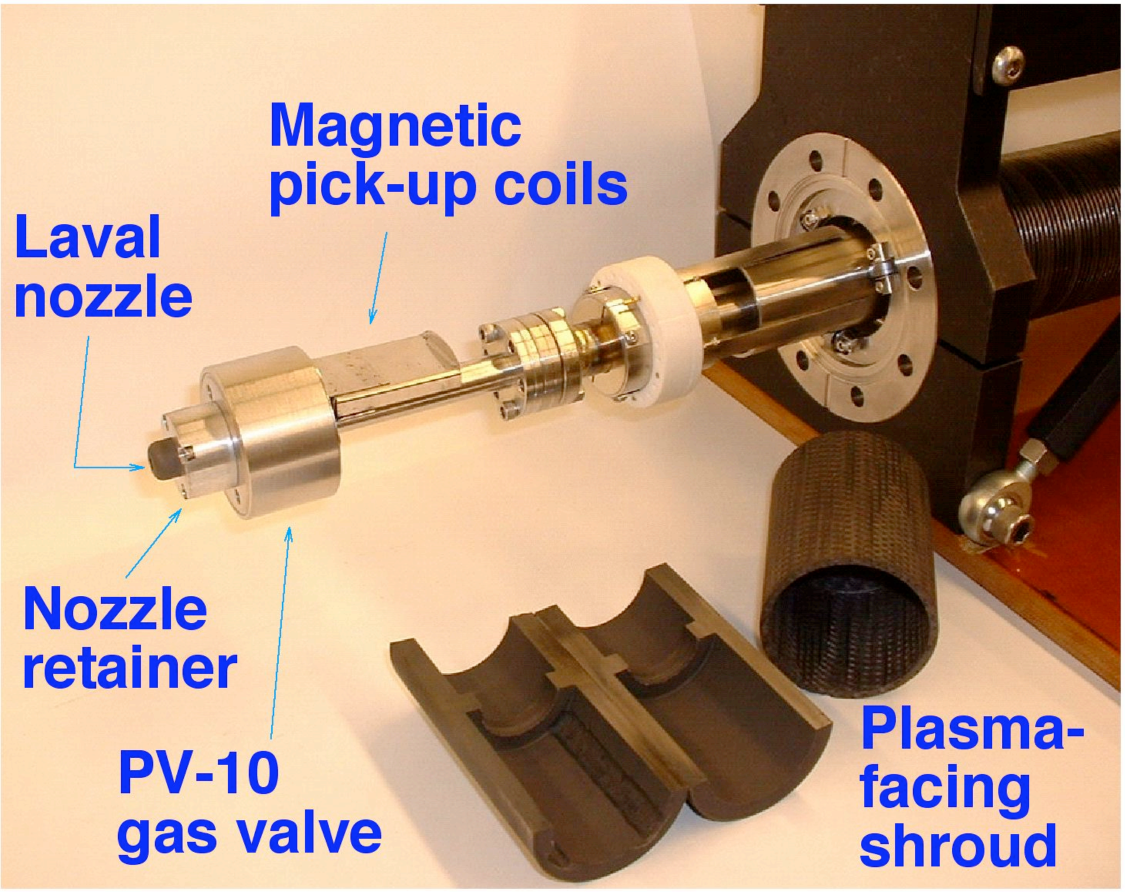


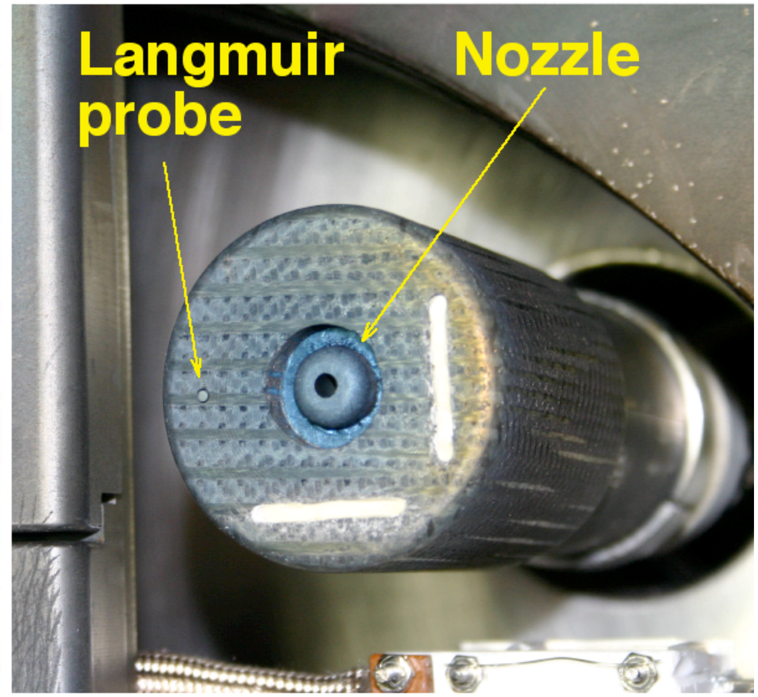
# SGI: fueling and diagnostic packages on a probe




- Thermionics ZC-450 movable probe, stroke 24”, travel rate < 15 in/s
- 6-axis Stepper Motor Controller, controlled using RS-232 port
- EPICS software used for SMC control and communication with Vacuum PLC

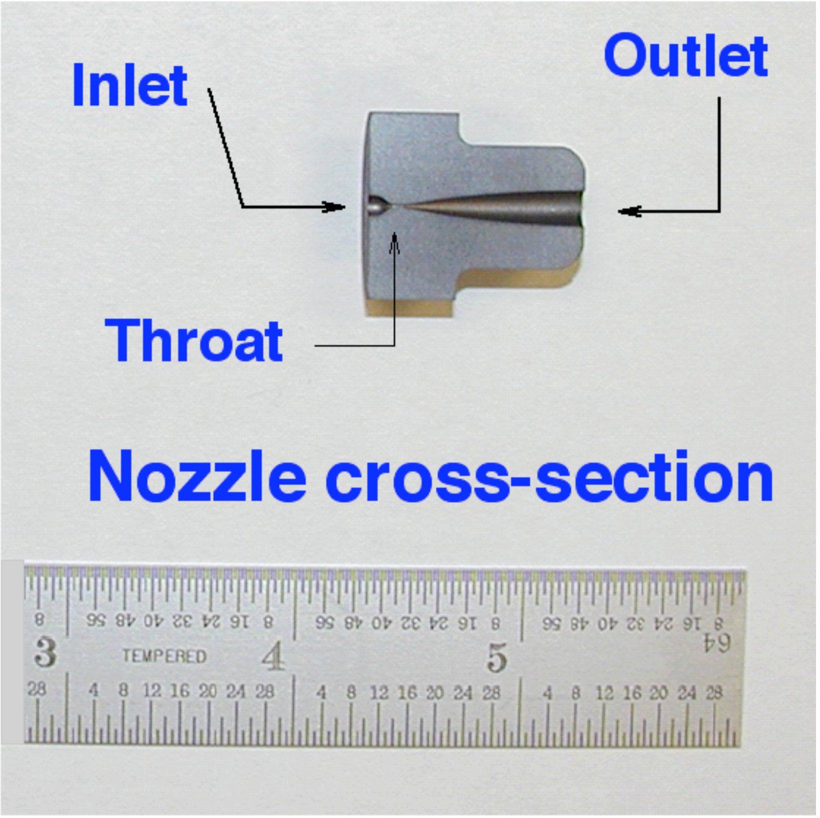
# SGI head is a densely packed apparatus



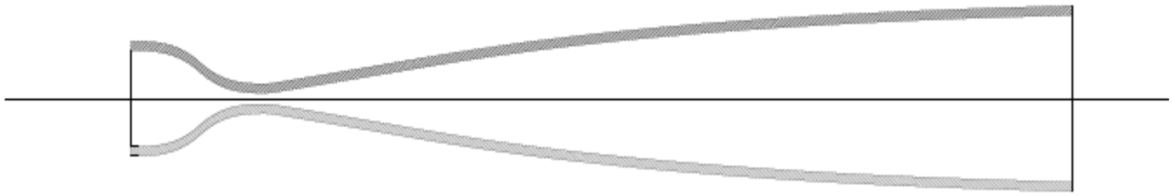




- Veeco PV-10 gas valve: $d_{throat}$=0.02”, typical opening time 1-2 ms, driving voltage150 V
- Thermocouples in shroud and in gas valve
- Two magnetic pick-up coils on shroud front surface for $B_z$, $B_t$ measurements
- Three magnetic pick-up coils in shielded box inside shroud for $B_z$ , $B_r$ and magnetic fluctuations measurement
- Langmuir probe: flush-mounted design, $d_{tip}$= 1.75 mm, *I-V* recorded at 5 kHz, -50 < *V*<50
- Shroud: CFC and ATJ graphite

# Laval contoured nozzle is used in NSTX SGI

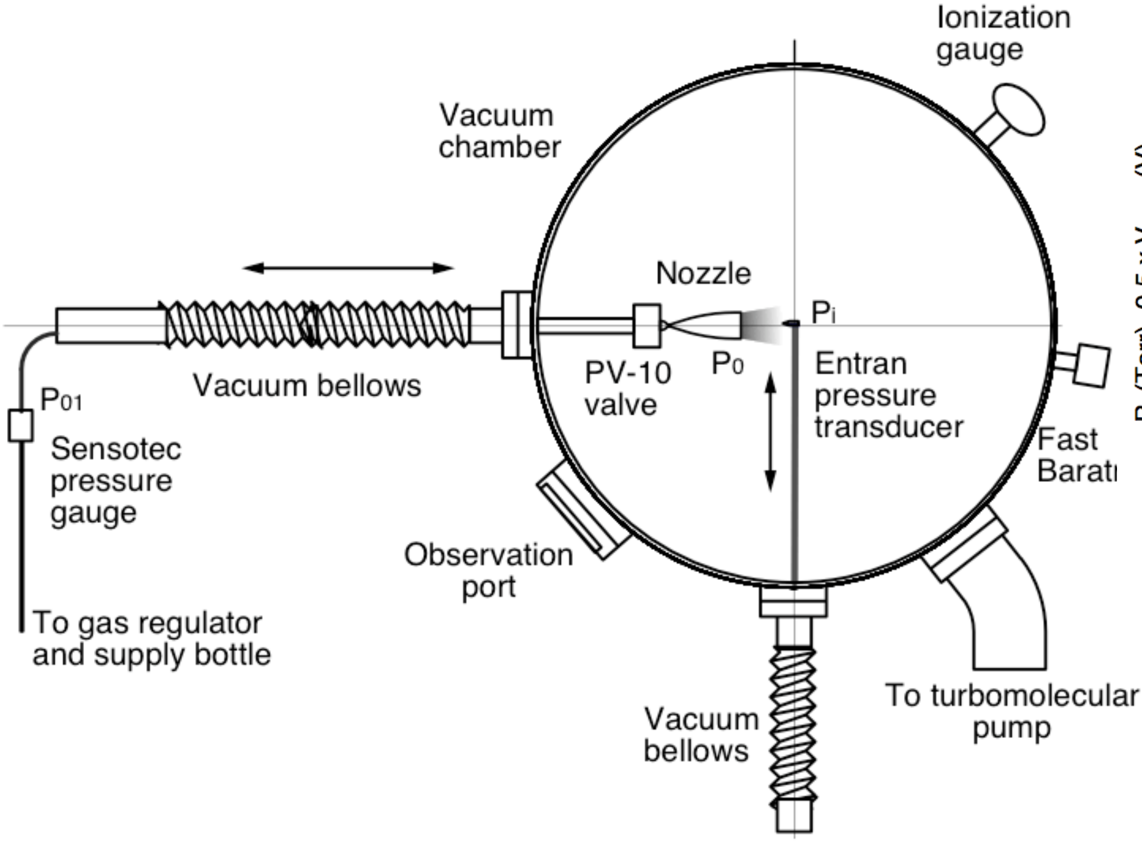


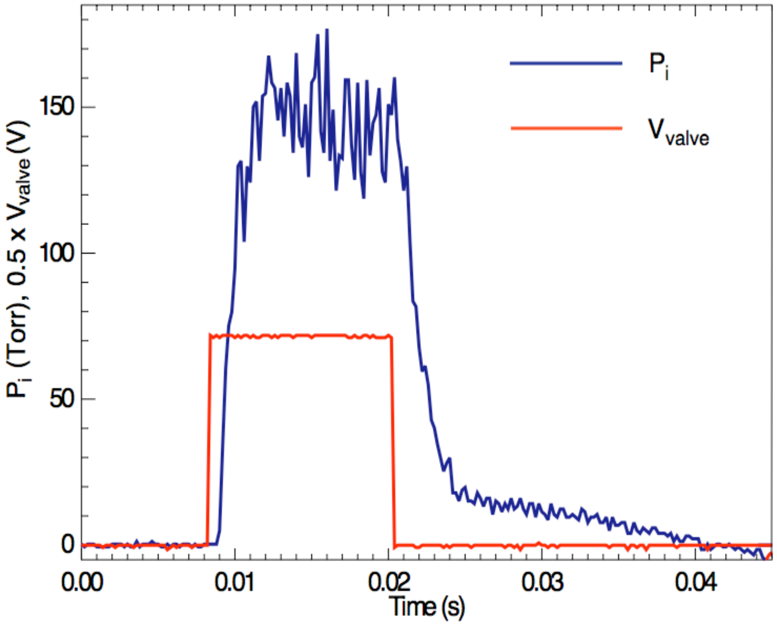

- Graphite nozzle L = 23.4 mm
- True Laval geometry calculated for air at $P$=1 atm, designed for $M$ = 8, linearly scaled down to obtain $d_{throat}$ = 0.01” (throughput requirement)
- Compressible fluid theory: isentropic core and boundary layer scale differently!
- Nozzle is made by mechanical machining using special tool with tolerance +- 0.0025”
- Nozzle attached to valve with a retainer using Viton O-ring



Nozzle design courtesy of Drs A. J. Smits, S. Zaidi (Princeton Univ.)

# Laboratory tests designed to evaluate SGI

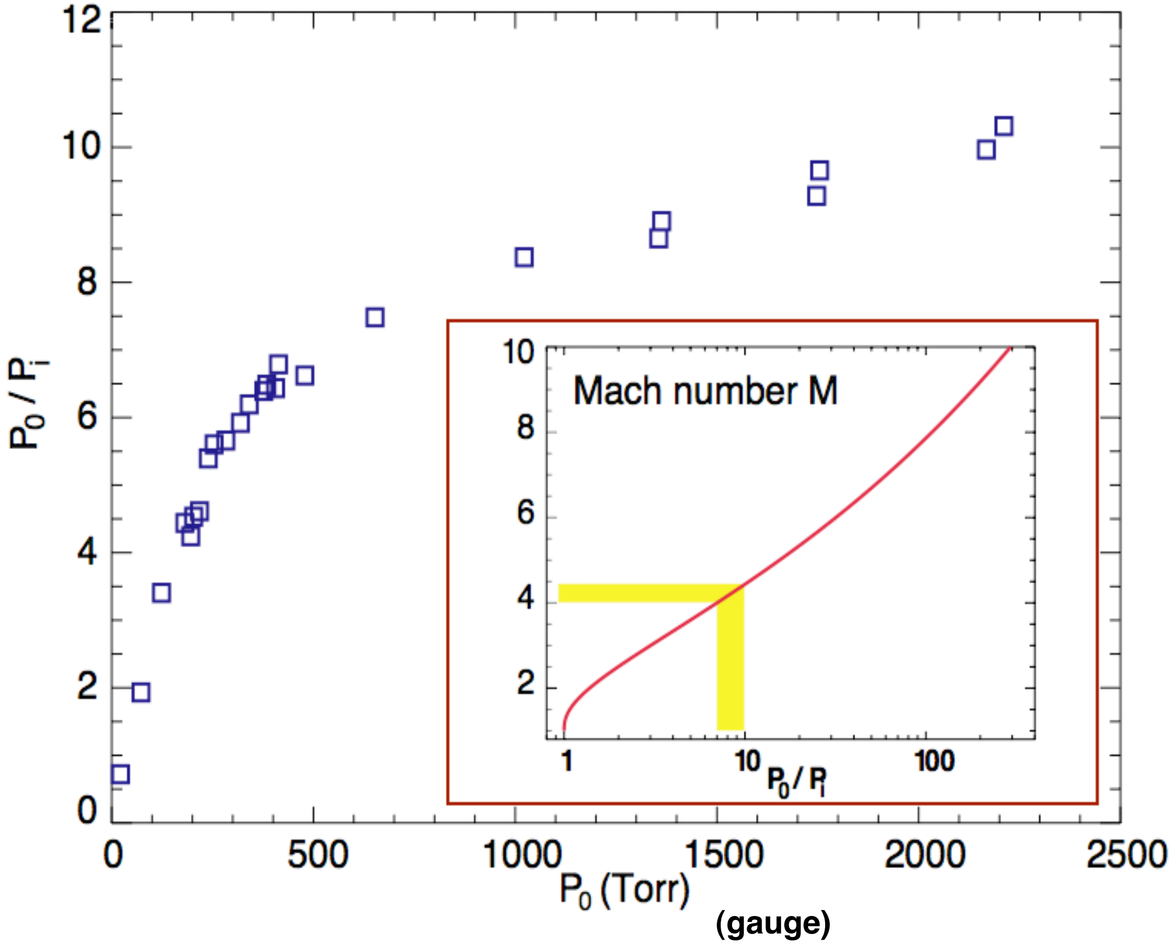



- Any nozzle must be tested to enable comparison with calculations - real nozzles often do not perform as expected
- Flow parameters diagnostic methods: Shadowgraphy, Schlieren photography, Laser induced fluorescence, Electron beam fluorescence, Laser scattering, Dust imaging, and others are either too complicated or would not work in vacuum, in a pulsed regime

$\Rightarrow$ Impact pressure measurement + supersonic Rayleigh-Pitot law for Mach number and jet pressure profile measurements at various distances *z* from the nozzle

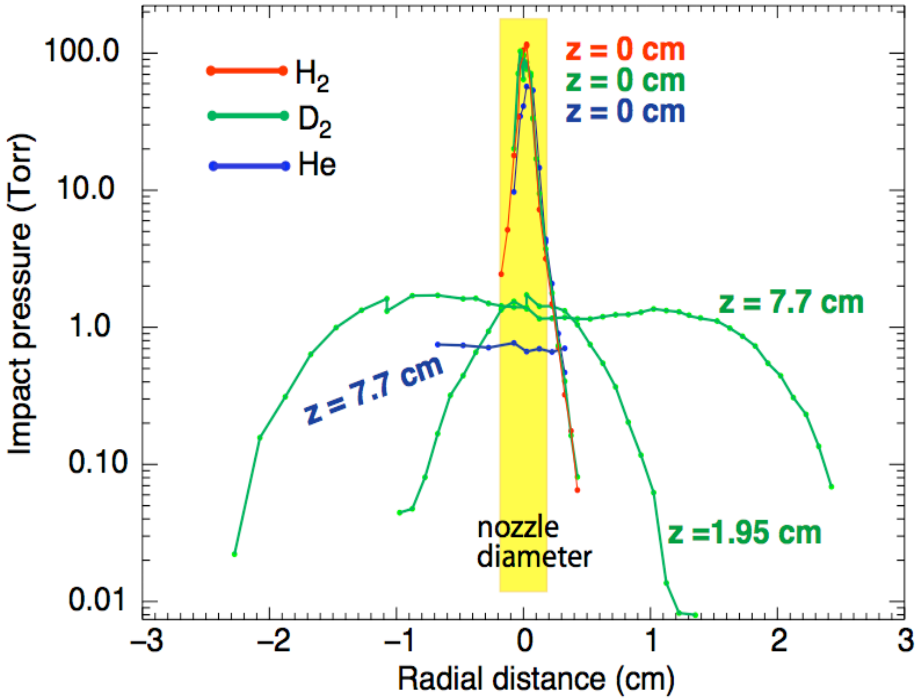
# Laboratory tests confirm high Mach number

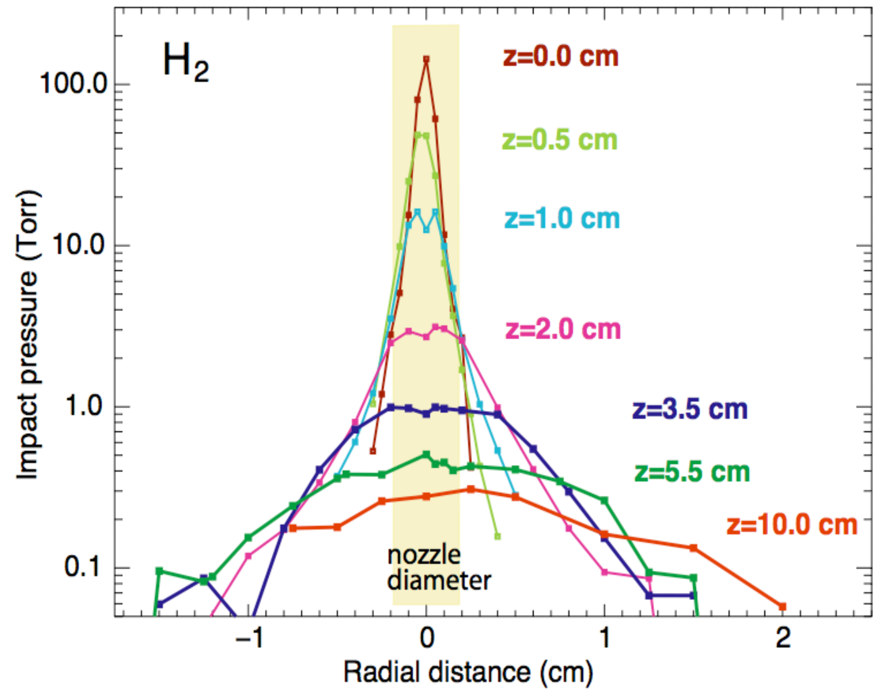



- Supersonic Rayleigh-Pitot law used to infer Mach number *M* from $P_0/P_i$ measurements

$$\frac{P_i}{P_0} = \left(\frac{(\gamma+1)\ M^2}{(\gamma-1)\ M^2+2}\right)^{\gamma/(\gamma-1)}\left(\frac{\gamma+1}{2\gamma M^2-(\gamma-1)}\right)^{1/(\gamma-1)}$$

# Laboratory tests confirm low divergence of gas jet




Jet divergence half-angle: 6° - 25°

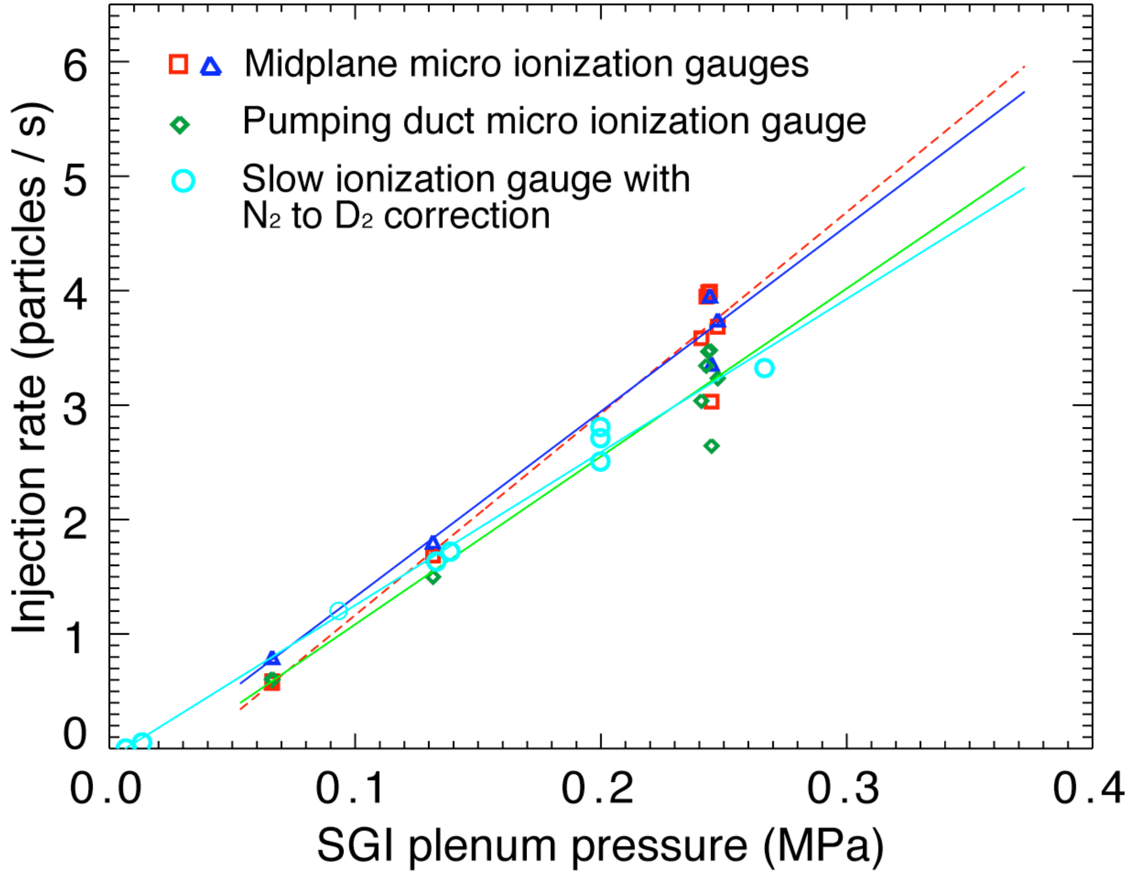
$D_2$: *M = 4, T ~ 60 - 160 K, ρ ~ 5 x $10^{17}$ $cm^{-3}$, Re = 6000*

$D_2$: *$v_{therm}$ ~ 1100 m/s, $v_{flow}$ = 2400 m/s*

$$u_{max} = \sqrt{\frac{2\gamma}{\gamma-1}\frac{kT_0}{m}},$$

For comparison: divergence half-angle of viscous sonic flow - 30°,
molecular effusion from orifice - 60°

# Flow rate is measured *in situ* on NSTX




- Flow rate (Torr l / s): $\Gamma = V_{NSTX}\, dP / dt$
- NSTX SGI is operated at 45-60 Torr l /s (~ (3.2 - 5) x $10^{21}$ mol/s)
- Future SGI may require $P_{plenum} > 2500$ Torr
- NSTX gas injector rates: HFS: 10 - 50 Torr l /s, LFS: 20 - 120 Torr l /s

# SGI and payload diagnostic results from FY05

- Motorized SGI probe and PLC worked well: Probe moved in for plasma fueling and moved out for vessel glow discharge cleaning between plasma discharges.

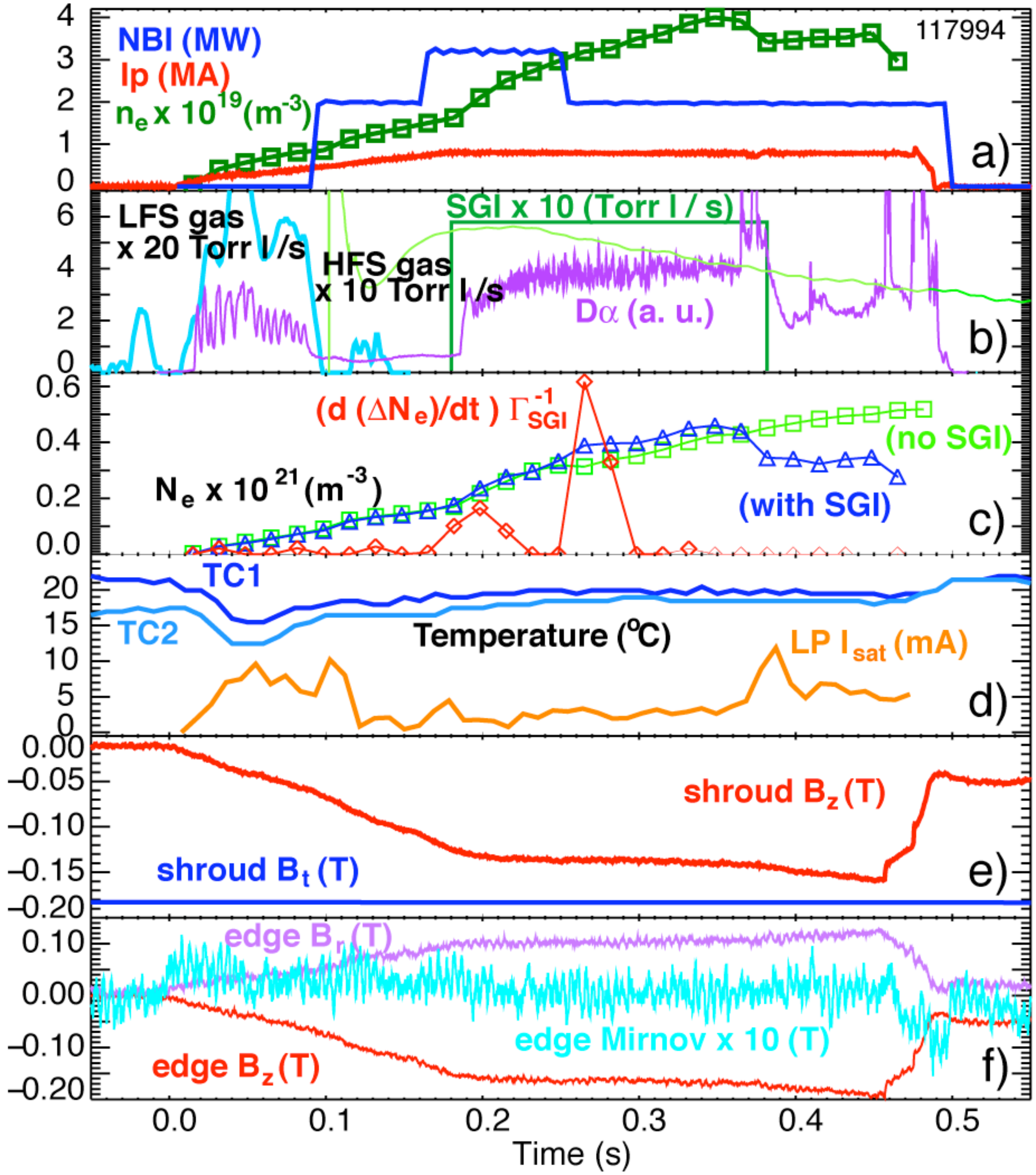
- Diagnostic package ("payload") commissioned and operated:
  - Thermocouples measure room temperatures
  - Langmuir probe $I_{sat}$ routinely obtained, $T_e$ analysis in progress
  - Edge Magnetic Sensor: $B_z$, $B_r$, $B_t$ coils and Mirnov coil signals routinely obtained, initial calibration completed, signals used in Poloidal Field only Plasma Start-up Experiment

- Supersonic gas jet and its impact on edge plasma studied with many NSTX diagnostics, notably fast cameras

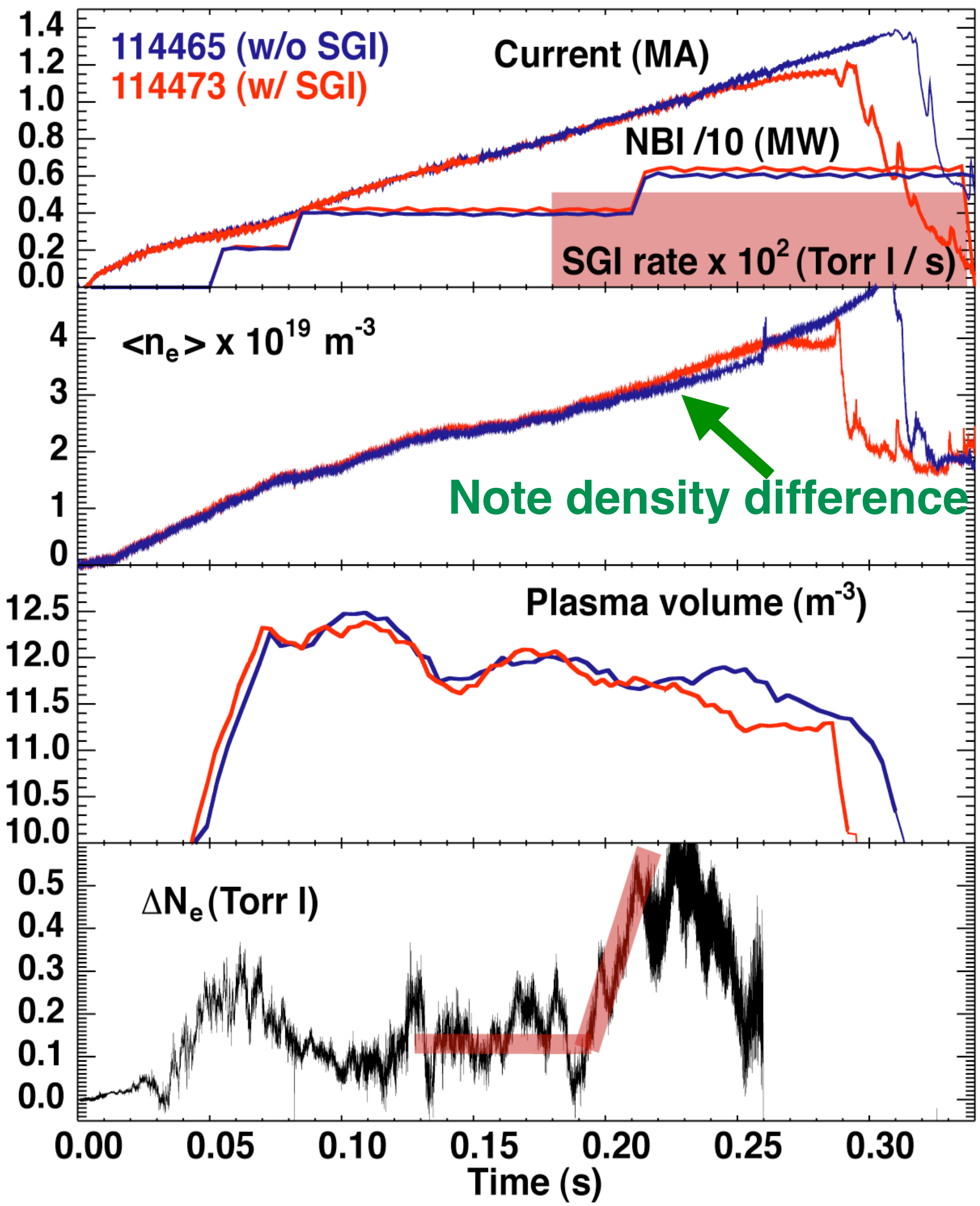
- Fueling of ohmic, 2-6 MW NBI-heated L- and H-mode plasmas has been demonstrated

# SGI and diagnostics perform well in real plasmas

- Example: NSTX 2 MW NBI-heated H-mode plasma
- SGI starts at 0.180 s
- SGI rate ~ 55 Torr l / s
- FE ~ 0.1 - 0.3
- Present analysis for $N_e$ only, need to exclude carbon contribution
- Good diagnostic signal SNR



# Improved SGI fueling efficiency observed




- Compare two 6 MW NBI-heated plasmas

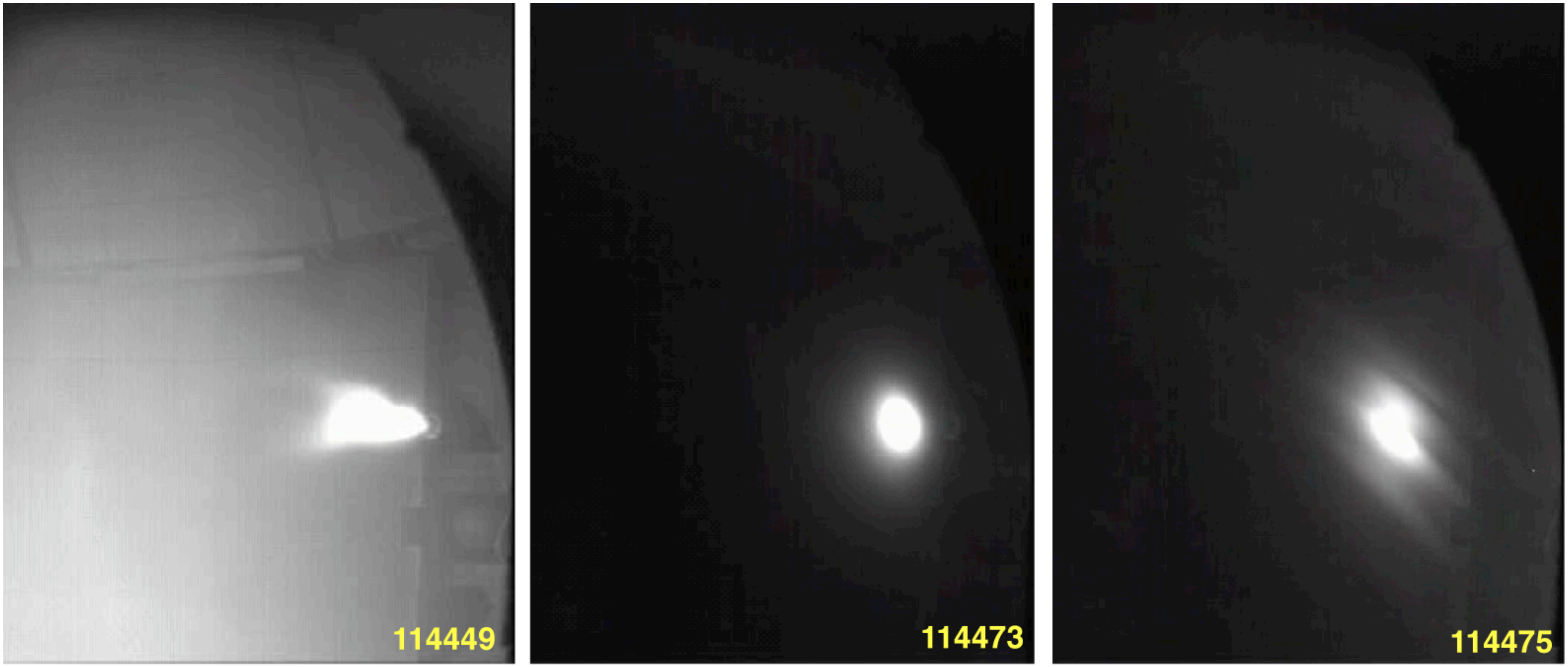
high-β pulses with and without supersonic gas injection

- Fueling efficiency

$$\eta = \frac{dN_i/dt}{\Gamma_{gas}}$$

- $\Gamma_{gas}$~ 50 Torr l / s
- $dN_e/dt$ = 0.4 / 0.025 = 16 T l / s
- η = 0.3-0.4

# Fast imaging of gas jet - plasma interaction




- Used Canadian Photonic camera with 0.5-2 ms framing rate
- Example frames above: (a) collapsing plasma with a wide $T_e$ = 3 eV, $n_e$ = (2-2.5) x $10^{18}$ $m^{-3}$ scrape-off layer, (b) 6 MW NBI-heated L-mode plasmas and (c) 4 MW NBI-heated H-mode plasmas

# Summary

- Supersonic gas injector and diagnostic package on a movable probe commissioned and operated on NSTX in FY04 - FY05
- Supersonic gas jet used to fuel ohmic and 2-6 MW NBI-heated L- and H-mode plasmas
- Supersonic gas jet does not perturb plasma edge
- Compatibility with H-mode pedestal has been demonstrated
- Measured fueling efficiency 0.1 - 0.3
- Fueling scenario with SGI for long high-performance H-mode plasma to be developed

**Visit NSTX SGI homepage at nstx.pppl.gov/sgi**