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Supersonic gas jet fueling (XP 516)

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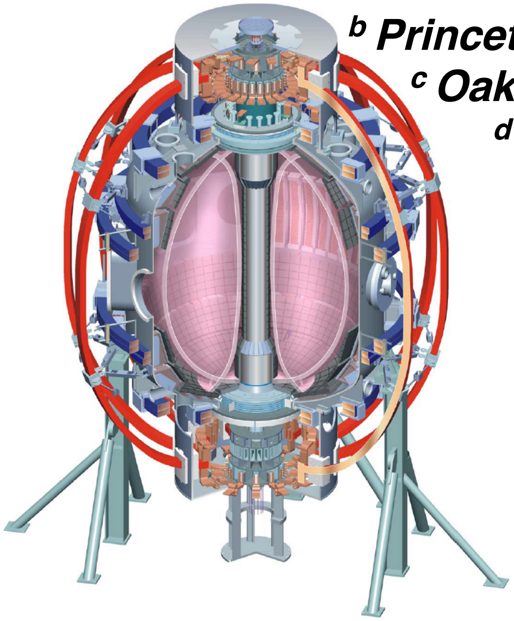


NSTX FY05 Results Review
12 December 2005
Princeton, NJ

Supersonic gas jet is a unique fueling technique studied in NSTX

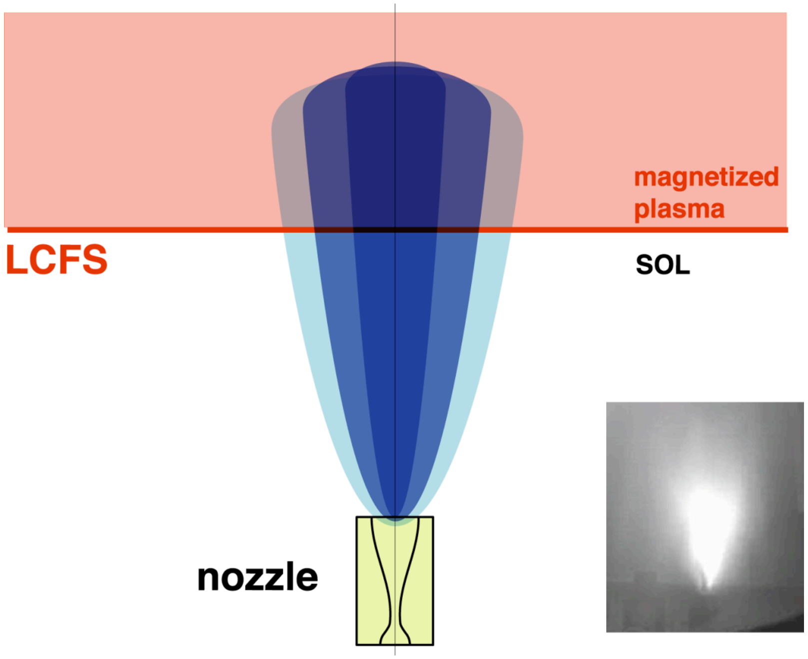
- **Improve / optimize gas fueling**. ITER will rely on central fueling (pellet, compact toroid), but plasma start-up and edge fueling will use gas puffing. SGI is viewed as supplemental approach for ITER. Unique contribution of NSTX to novel fueling techniques.

- Supersonic gas jet fueling results to date
  - limiter tokamaks (HL-1M, Tore Supra): injects 0.2-0.9 of total plasma inventory in several ms, perturbative, fueling efficiency 0.3-0.6
  - divertor tokamak (AUG), divertor stellarator (W7-AS): similar gas jet parameters, but FE ~ 0.1-0.3

- Implemented in NSTX in FY04, started XP 516 in FY05

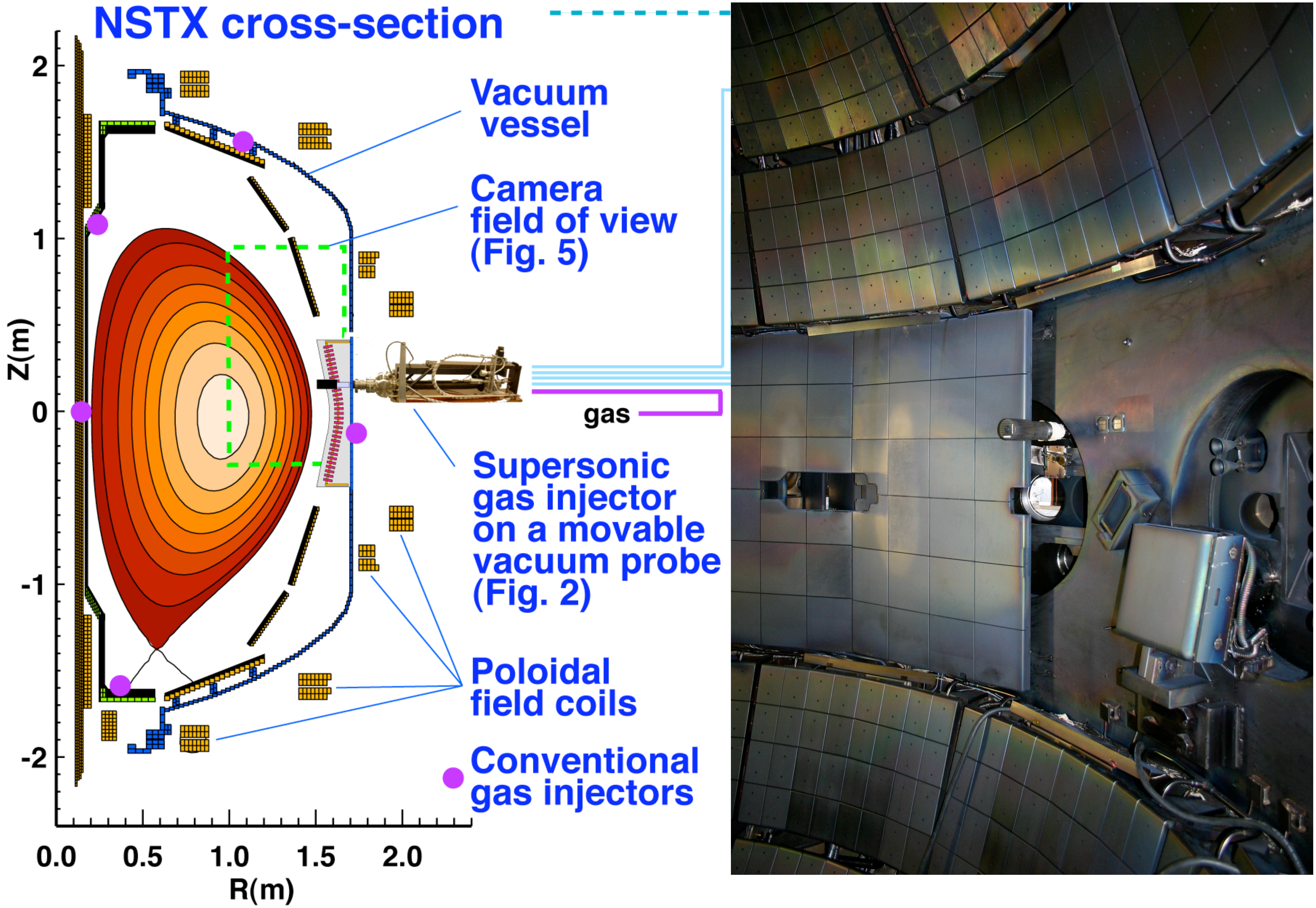
Supersonic gas jet penetration mechanism

- Gas jet retains low-divergence shape (compressible fluid gasdynamics)
- 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)

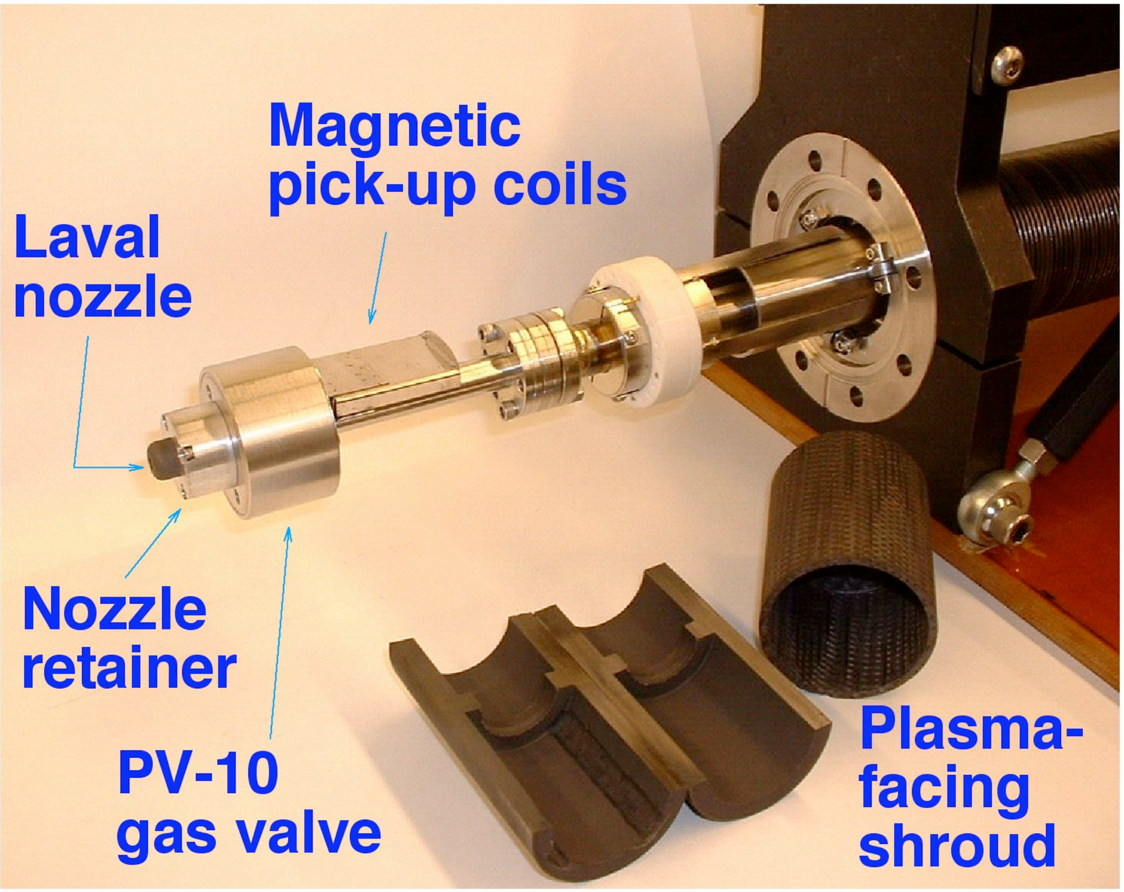


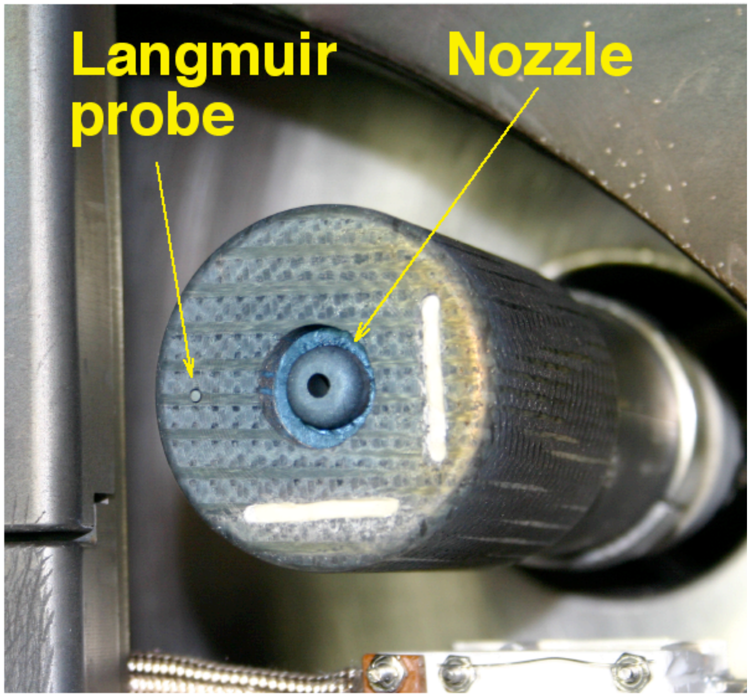
- Velocity distribution function is drifting narrowed Maxwellian with $u_{drift} = u_{flow}$
- $u_{flow} = M c = M \sqrt{\gamma kT/m} > v_{therm}$

SGI on NSTX: placement and control elements



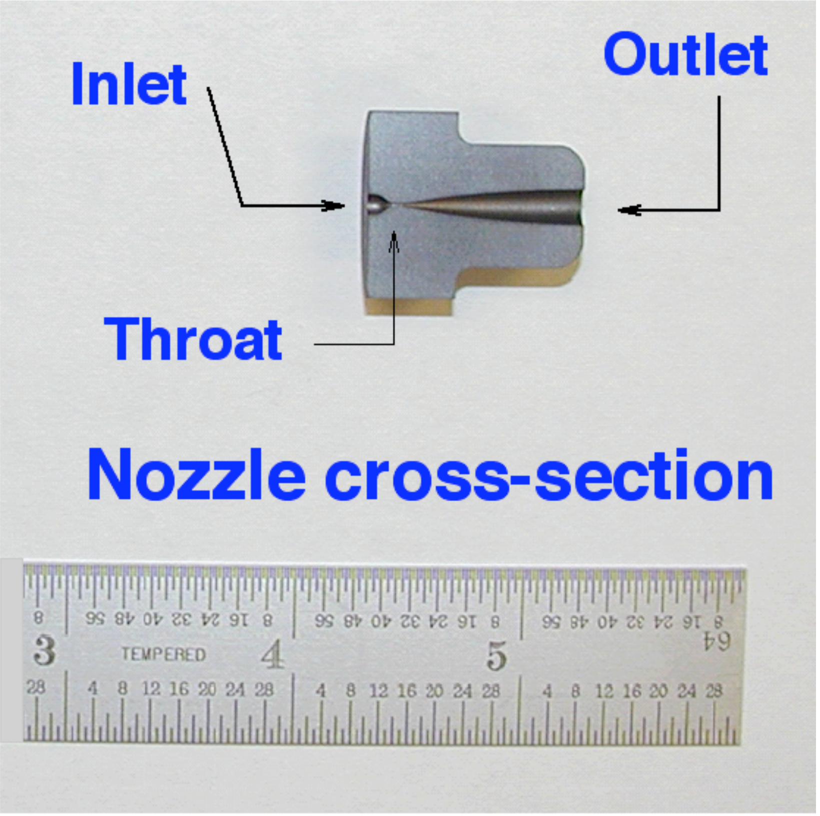
SGI head is a densely packed apparatus



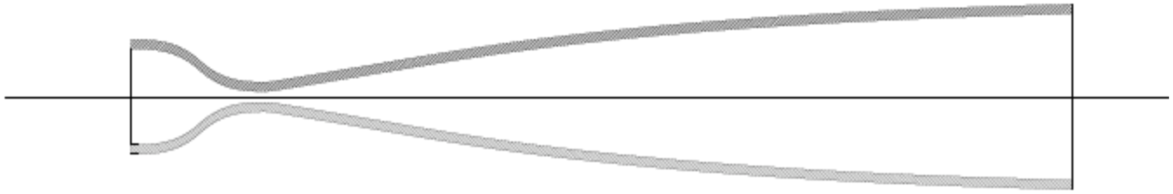


- Veeco PV-10 gas valve: d_{throat}=0.02”, typical opening time 1-2 ms, driving voltage150 V
- Thermocouples in shroud and in gas valve
- Two magnetic pick-up coils on shroud front surface for B_z, B_t measurements
- Three magnetic pick-up coils in shielded box inside shroud for B_z , B_r and magnetic 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

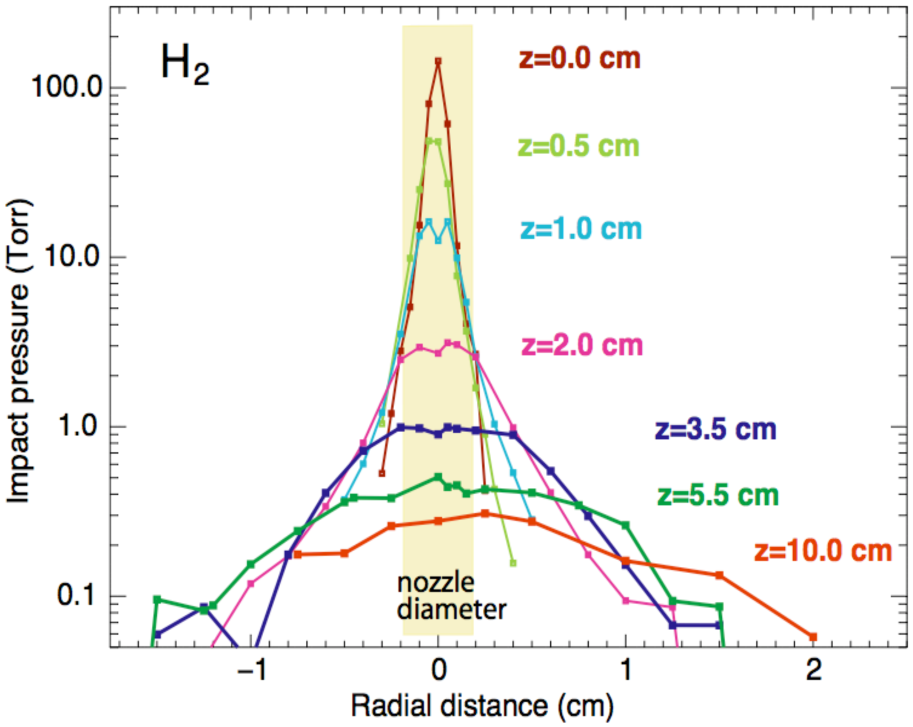


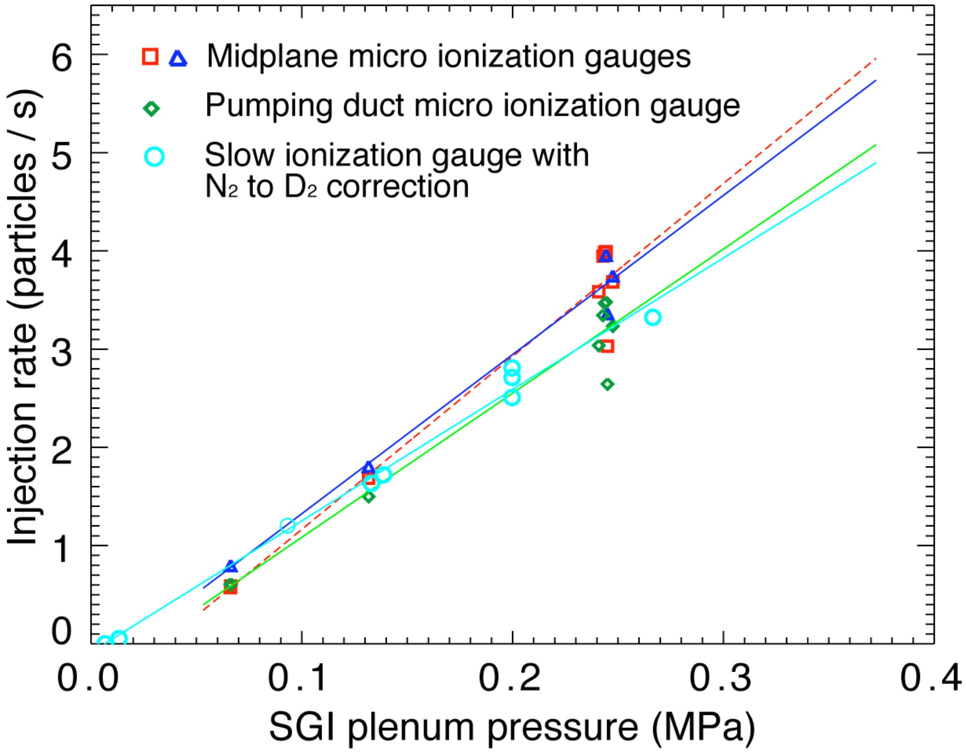
- Graphite nozzle L = 23.4 mm
- True Laval geometry calculated for air at P=1 atm, designed for $M = 8$, linearly scaled down to obtain $d_{throat} = 0.01$” (throughput requirement)
- Compressible fluid theory: isentropic core and boundary layer scale differently!
- Nozzle is made by mechanical machining 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.)

SGI parameters characterized off-line and *in situ*





- NSTX SGI is operated at 45-60 Torr l /s (~ (3.2 - 5) x 10^{21} mol/s)
- NSTX gas injector rates: HFS: 10 - 50 Torr l /s, LFS: 20 - 120 Torr l /s
- Jet divergence half-angle: 6^{o} - 25^{o}
- Hydrogen / Deuterium: $M = 4$, $T \sim 60 - 160$ K, $\rho \sim 5 \times 10^{17}$ cm^{-3},

  $Re = 6000$, $v_{therm} \sim 1100$ m/s, $v_{flow} = 2400$ m/s

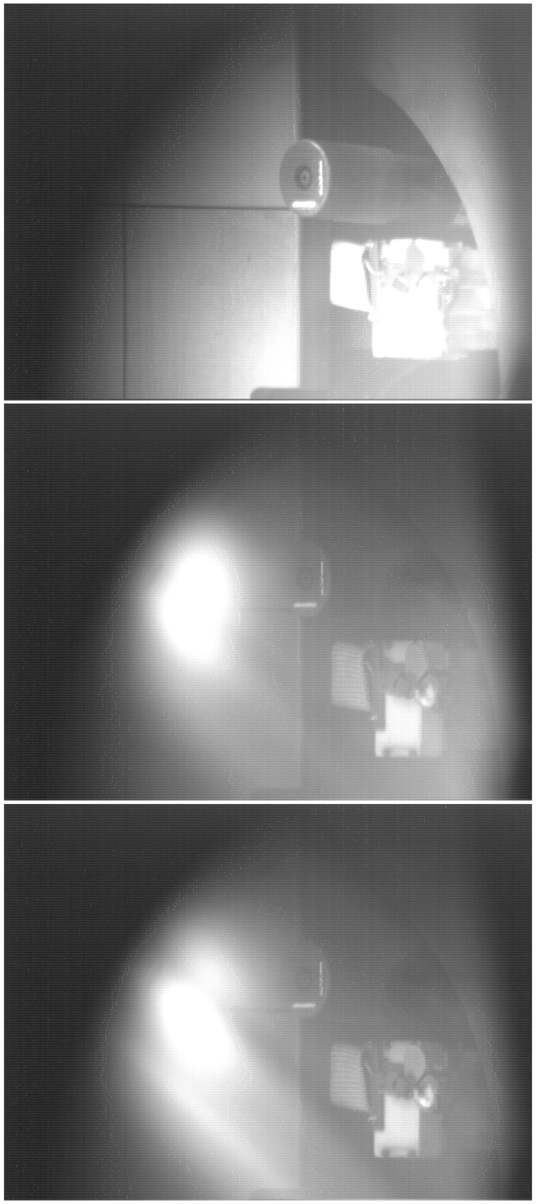
XP-516: Supersonic gas jet fueling

- Goals of XP:
  - Determine fueling efficiency (FE), penetration characteristics
  - Determine feasibility of fueling of H-mode plasmas
  - Study effects on edge plasmas
  - Develop model for high-pressure gas jet interaction with magnetized plasma

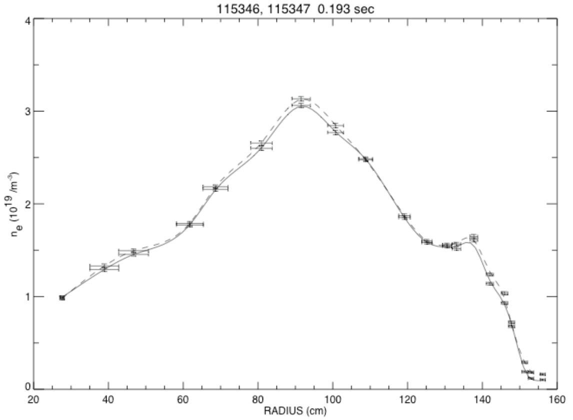
- SGI and “payload” diagnostics worked well in FY05:
  - Motorized SGI probe and PLC worked well
  - Diagnostic package (“payload”) commissioned and operated
  - Thermocouples measure room temperatures
  - Langmuir probe I_{sat} routinely obtained, T_e analysis in progress
  - Edge Magnetic Sensor: B_z, B_r, B_t coils and Mirnov coil signals routinely obtained, initial calibration completed, signals used in Poloidal Field only Plasma Start-up Experiment

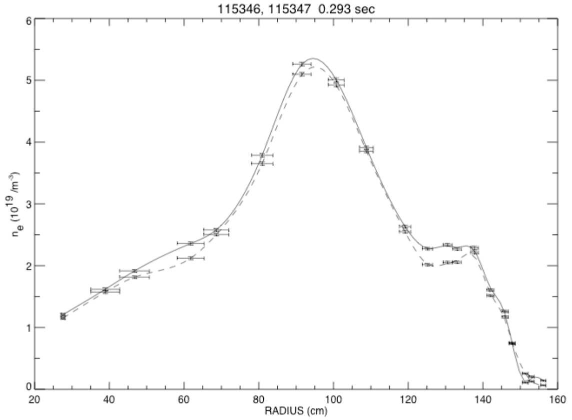
XP 516 results

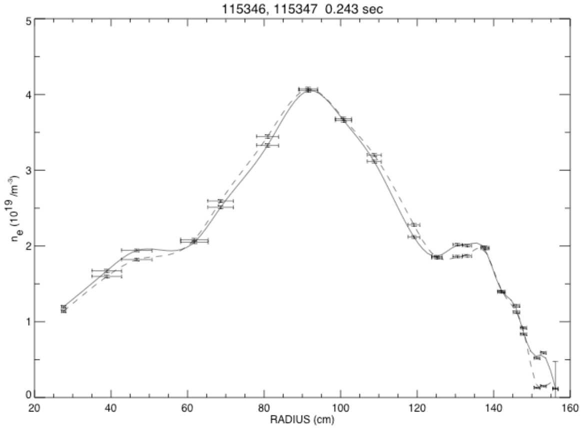
- LCFS - SGI distance scan in ohmic plasmas demonstrated that “closer is better”
- Cannot go closer than RF limiter in NBI-heated plasmas due to interaction with energetic particles
- Compatible with H-mode up to Inj. rate of 60 Torr l /s (conventional gas injection is not)
- FE is between 0.1 and 0.3
- SGI used gas pulses 70-300 ms
- Injected 0.1 - 1.0 of total plasma inventory
- Due to localization SGI gas pulse is not seen as pulse on MPTS or interferometry n_e traces
- Need to improve FE analysis: Present analysis for N_e only, need to exclude carbon contribution to particle inventory (using N_i from CHERS)

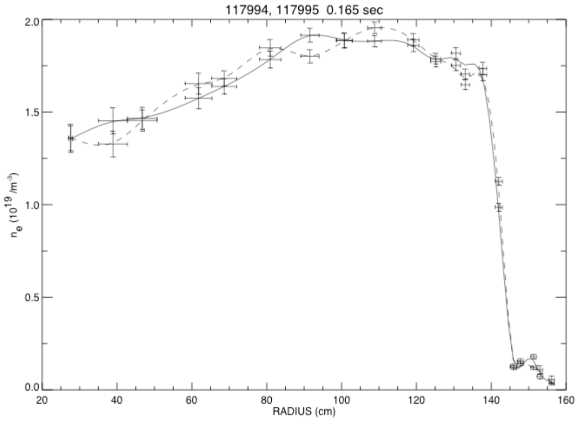


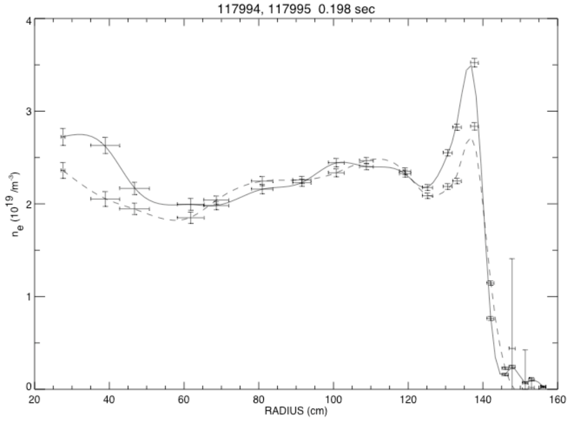
Particles from SGI are deposited at the edge

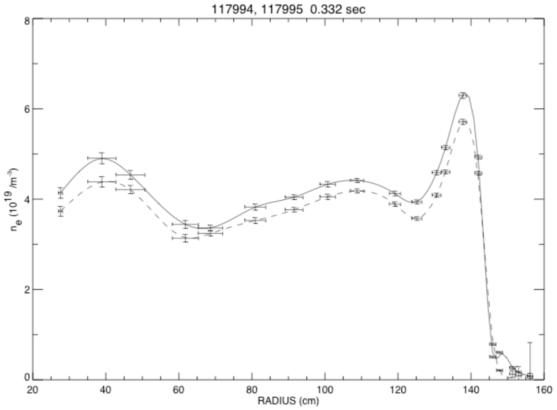








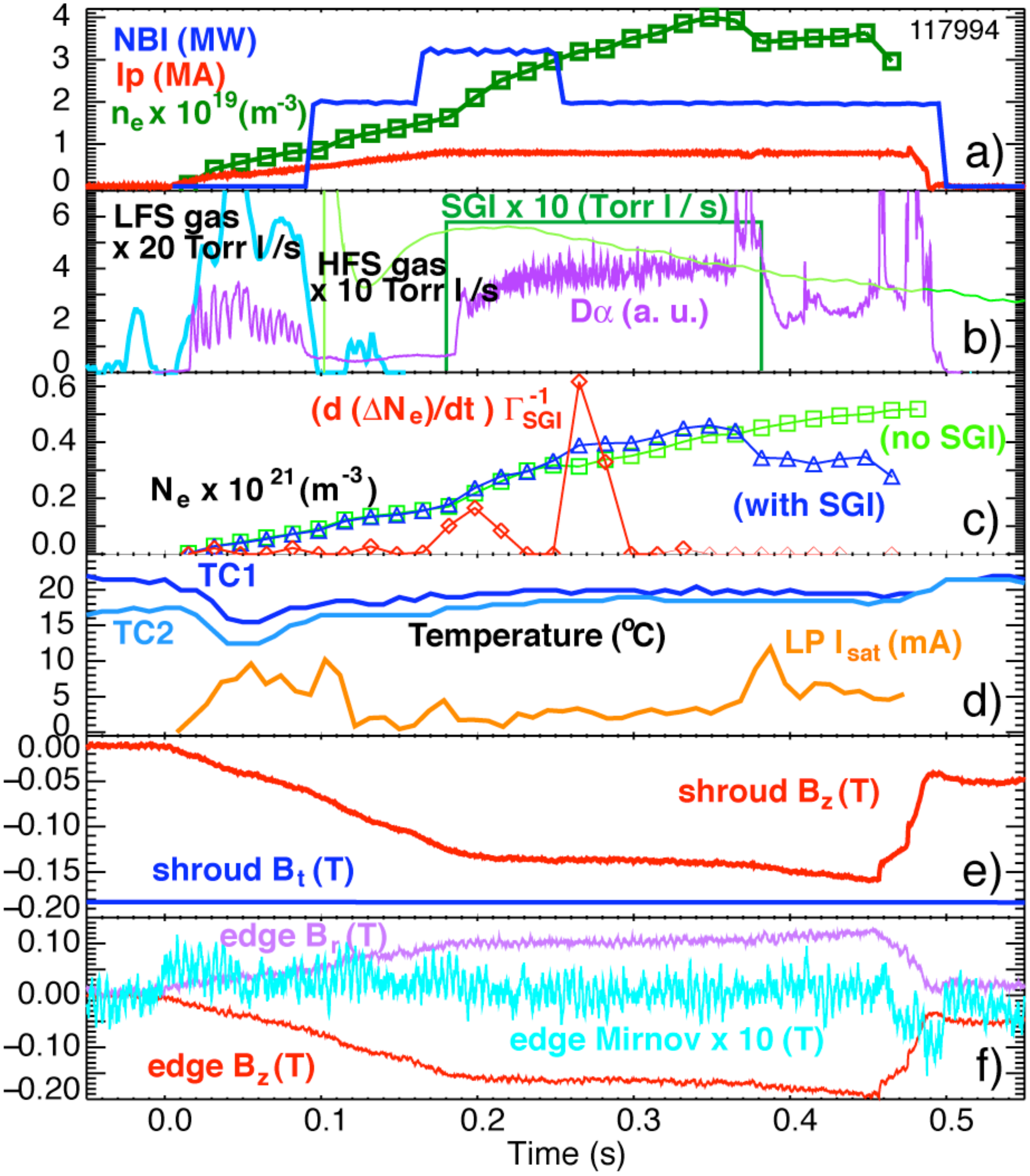




- SGI increases edge density (in H-modes, “ears” density)
- Effect is not always large -> need to look at total particle inventory
- Edge MHD and ELMs affect fueling

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
- Good diagnostic signal
  SNR



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. Compatibility with H-mode pedestal has been demonstrated.

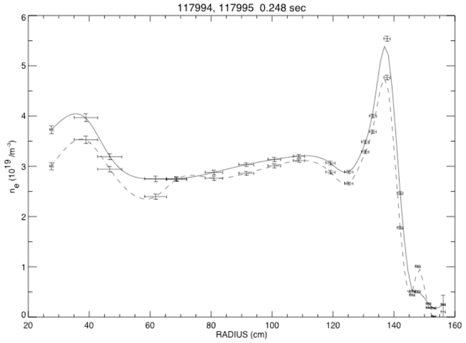
- Measured fueling efficiency 0.1 - 0.3

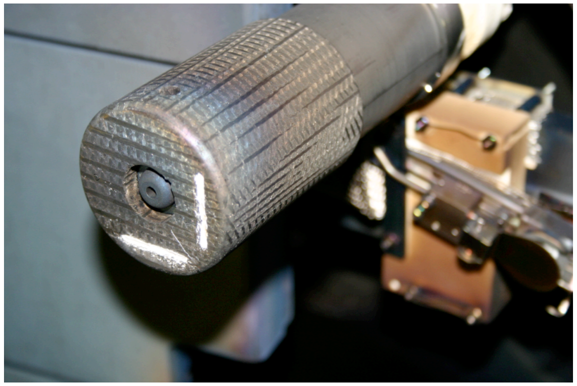
- Supersonic gas jet does not perturb plasma edge

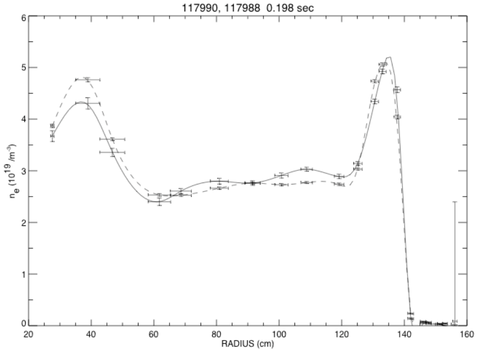
- Need to finish XP 516 (fueling during plasma start-up, H-mode access with SGI, …)

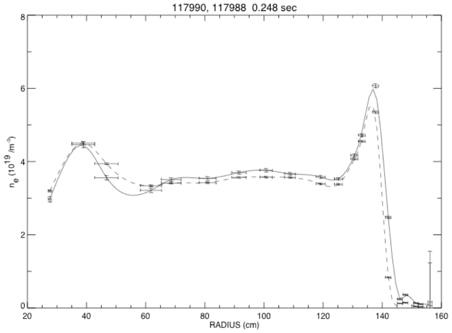
- Expected to be an important tool in lithium experiments

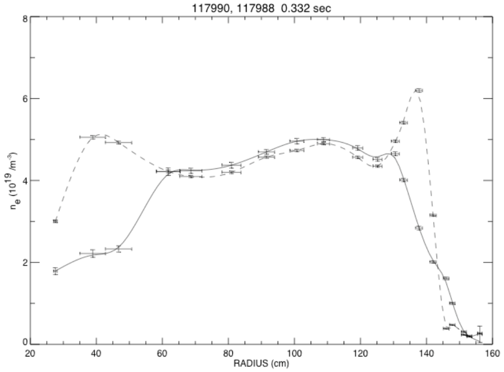
Backup slides

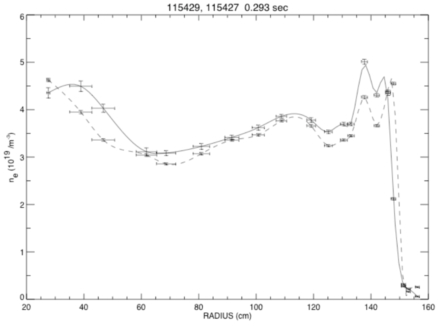


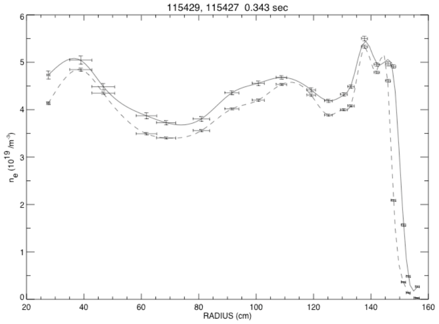


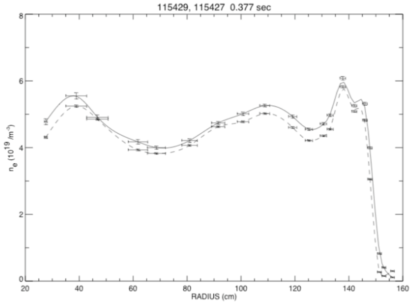












NSTX reference data

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

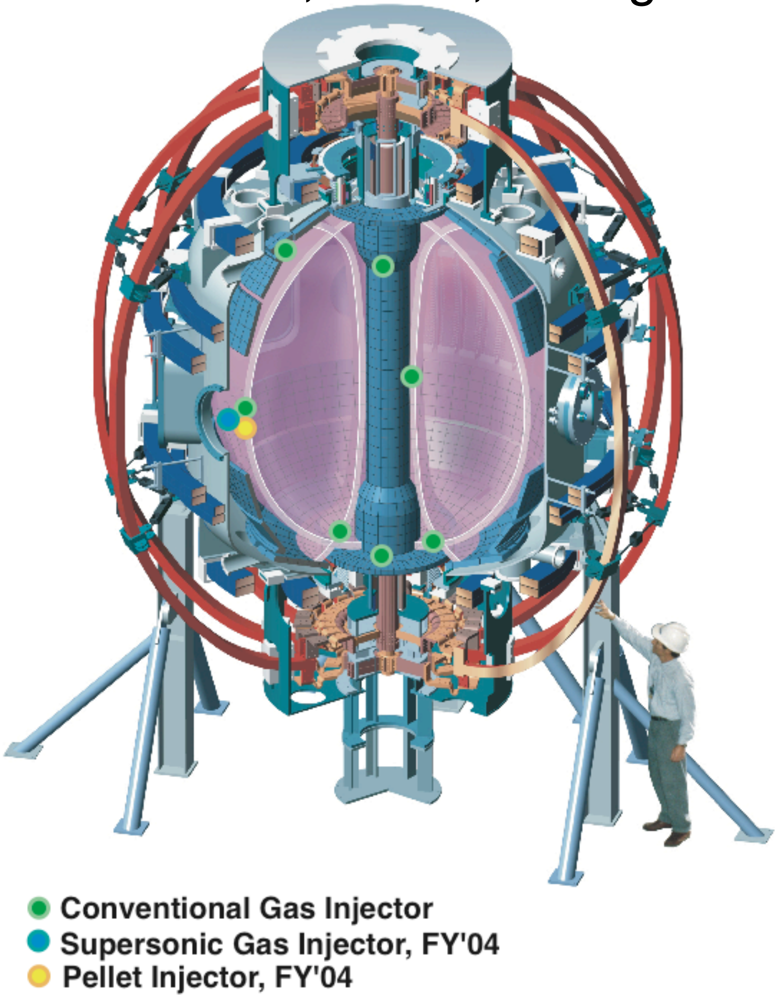
- Between shots He GDC
- He conditioning plasmas
- TMB and Plasma TMB

NSTX pumping

- Turbomolecular pump (3400 l / s)
- NBI cryopump (50000 l / s)
- Conditioned walls

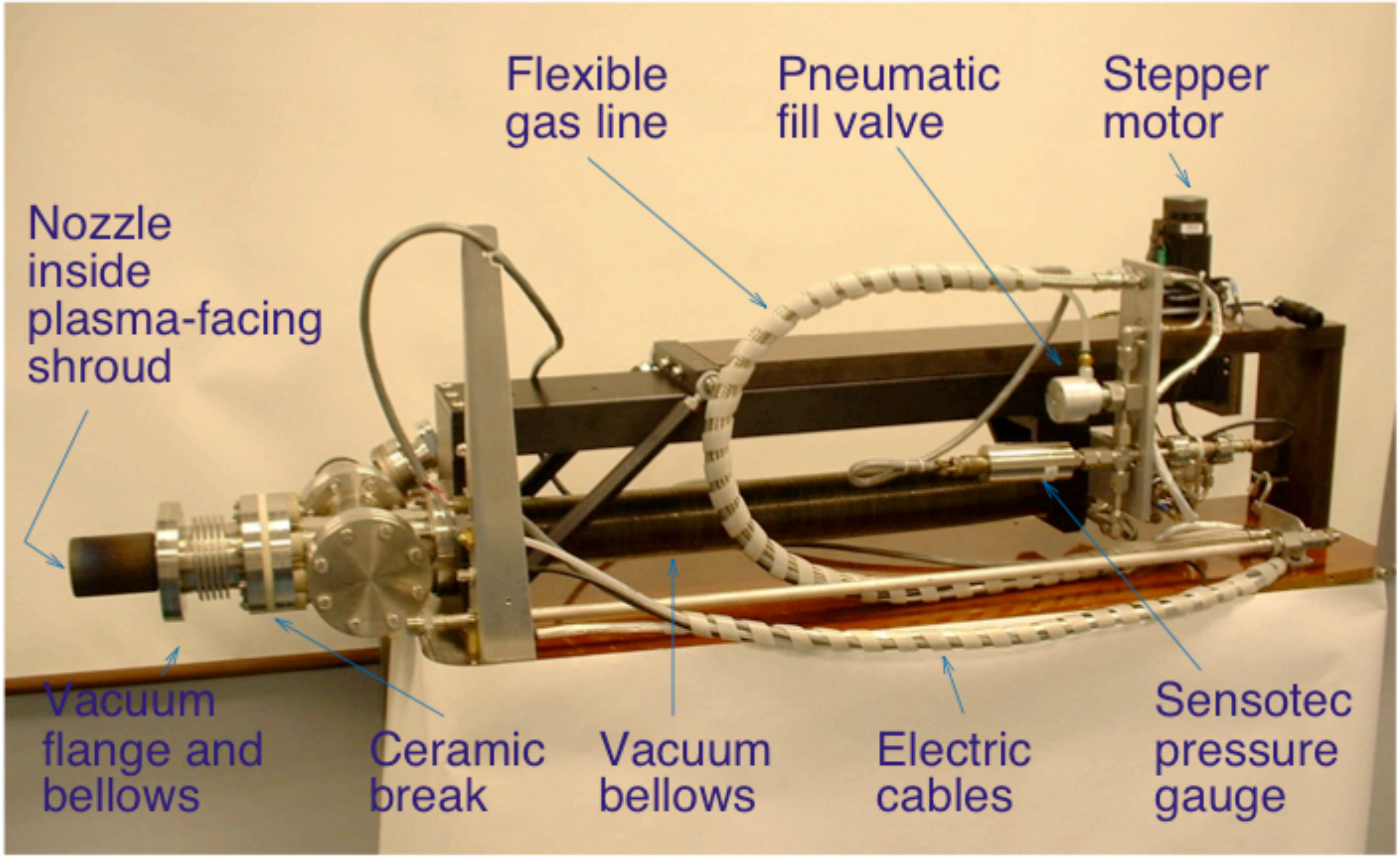
PFC

- ATJ graphite tiles on divertor and passive plates
- ATJ and CFC tiles on center stack
- Tile thickness 1” and 2”



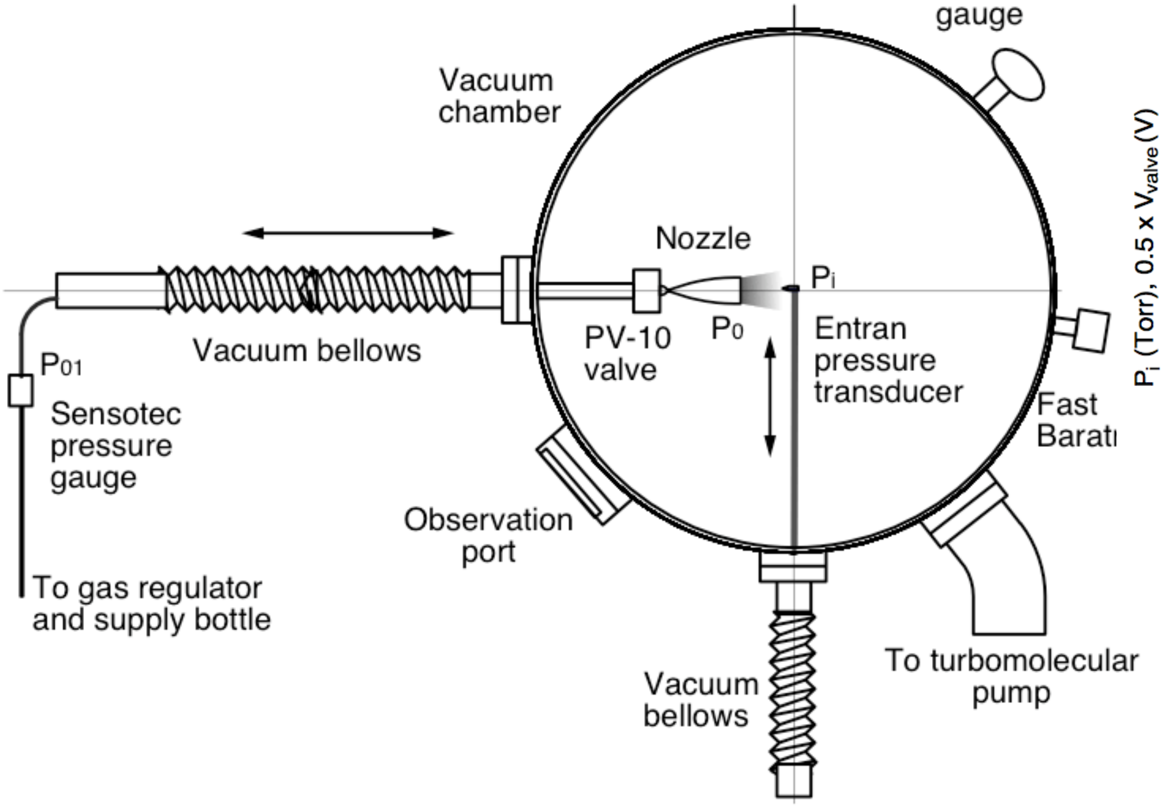
🟢 Conventional Gas Injector
🔵 Supersonic Gas Injector, FY'04
🟡 Pellet Injector, FY'04

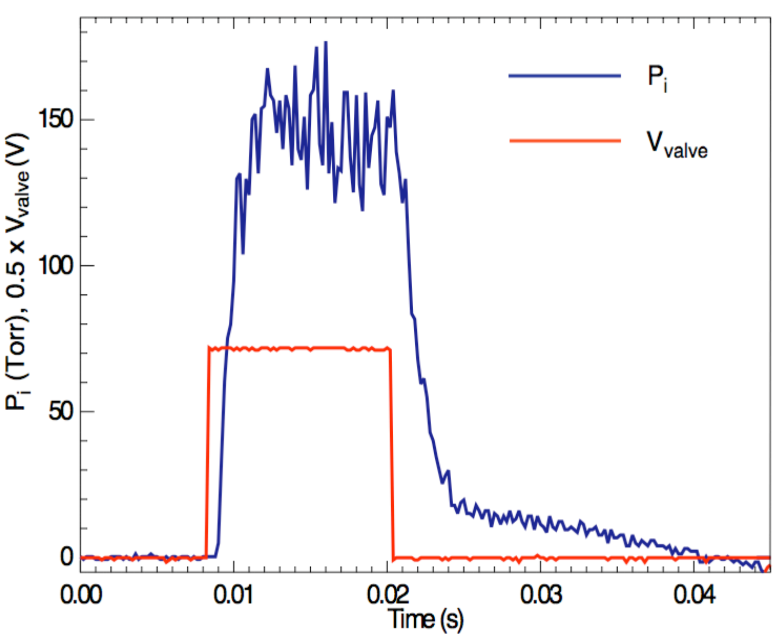
SGI: fueling and diagnostic packages on a probe



- 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

Laboratory tests designed to evaluate SGI

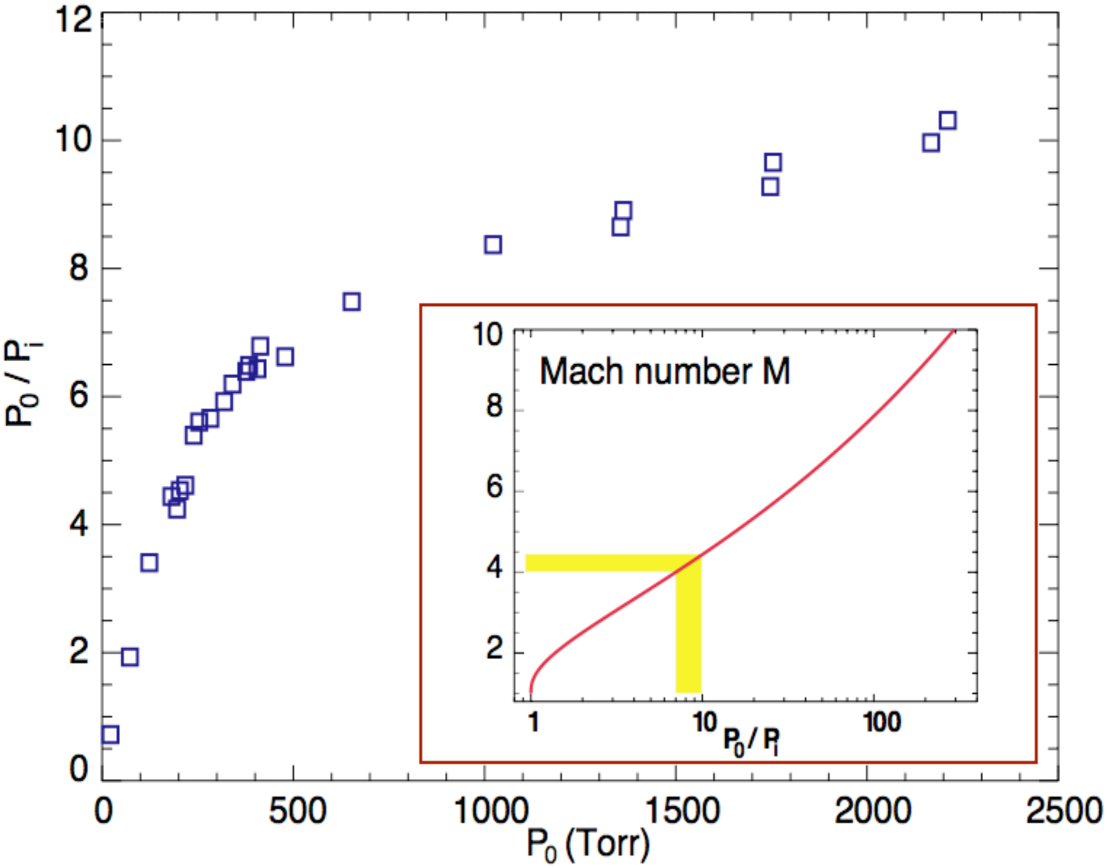




- Any nozzle must be tested to enable comparison with calculations - real nozzles often do not perform as expected
- Flow parameters diagnostic methods: Shadowgraphy, Schlieren photography, Laser induced fluorescence, Electron beam fluorescence, Laser scattering, Dust imaging, and others are either too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

⇒ 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

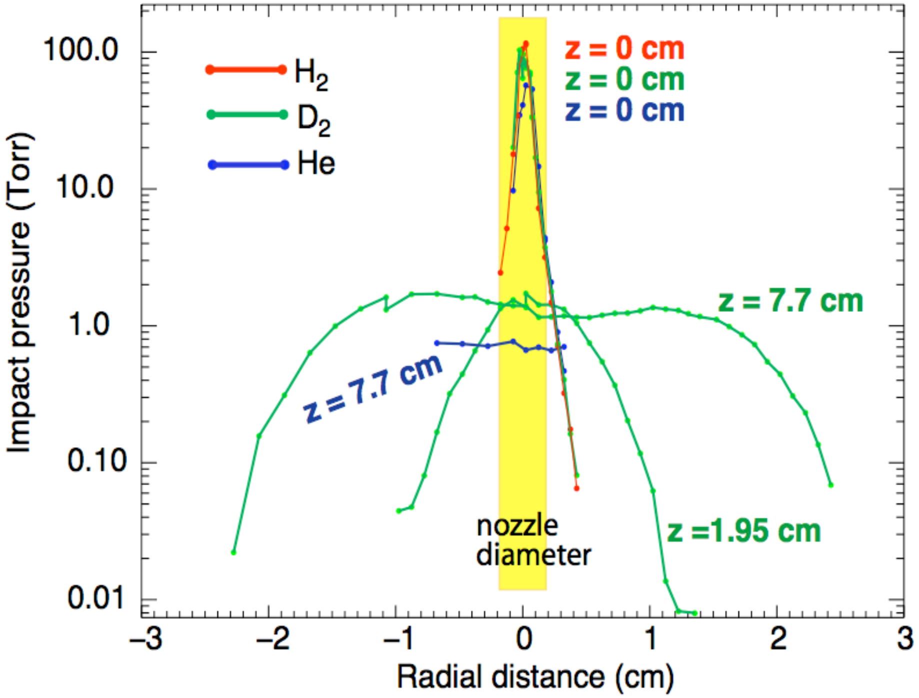


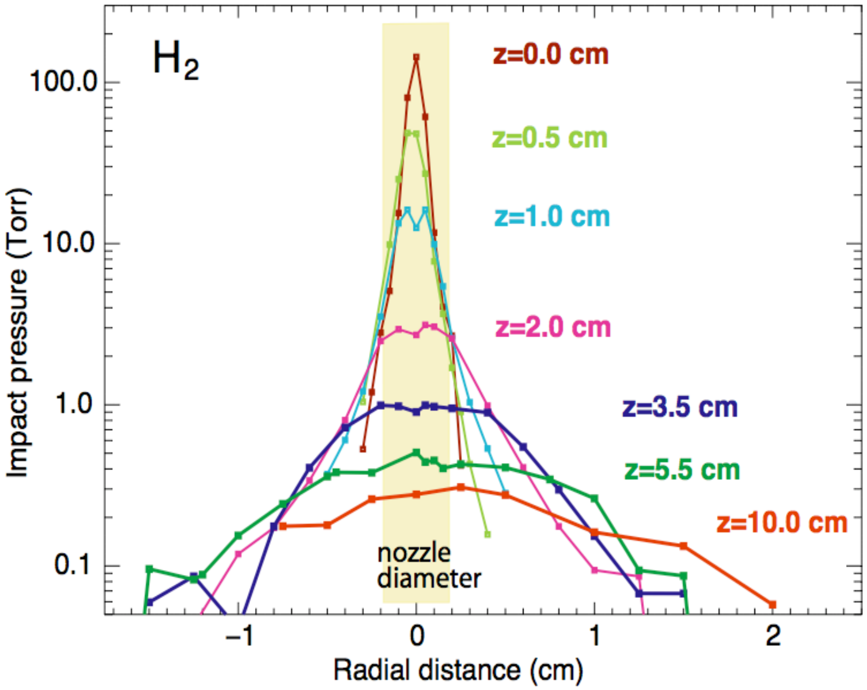
(gauge)

- 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^o - 25^o

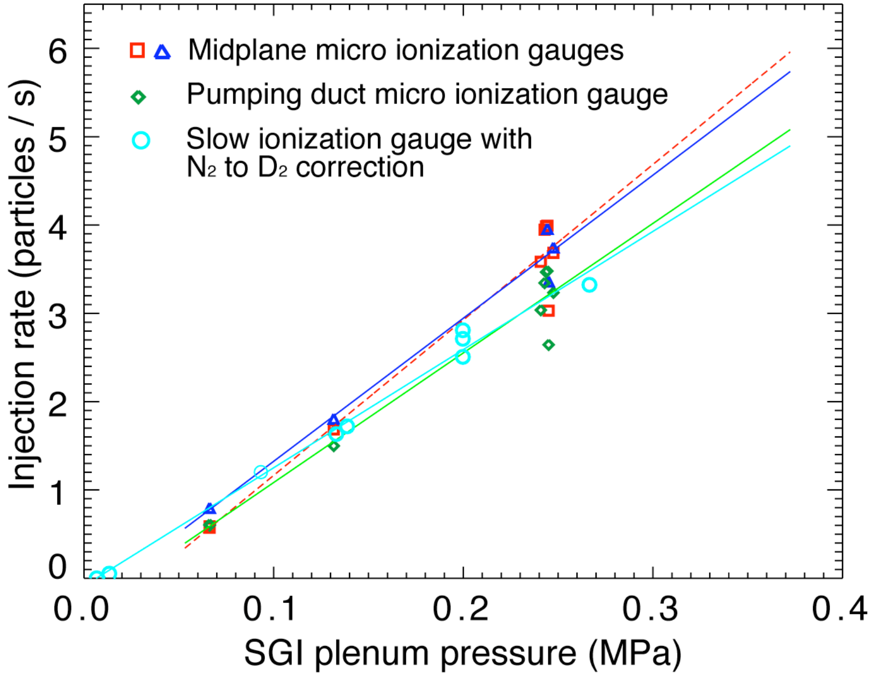
D$_2$: $M = 4$, $T \sim 60 - 160$ K, $\rho \sim 5 \times 10^{17}$ cm^{-3}, $Re = 6000$

D$_2$: $v_{therm} \sim 1100$ m/s, $v_{flow} = 2400$ m/s

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

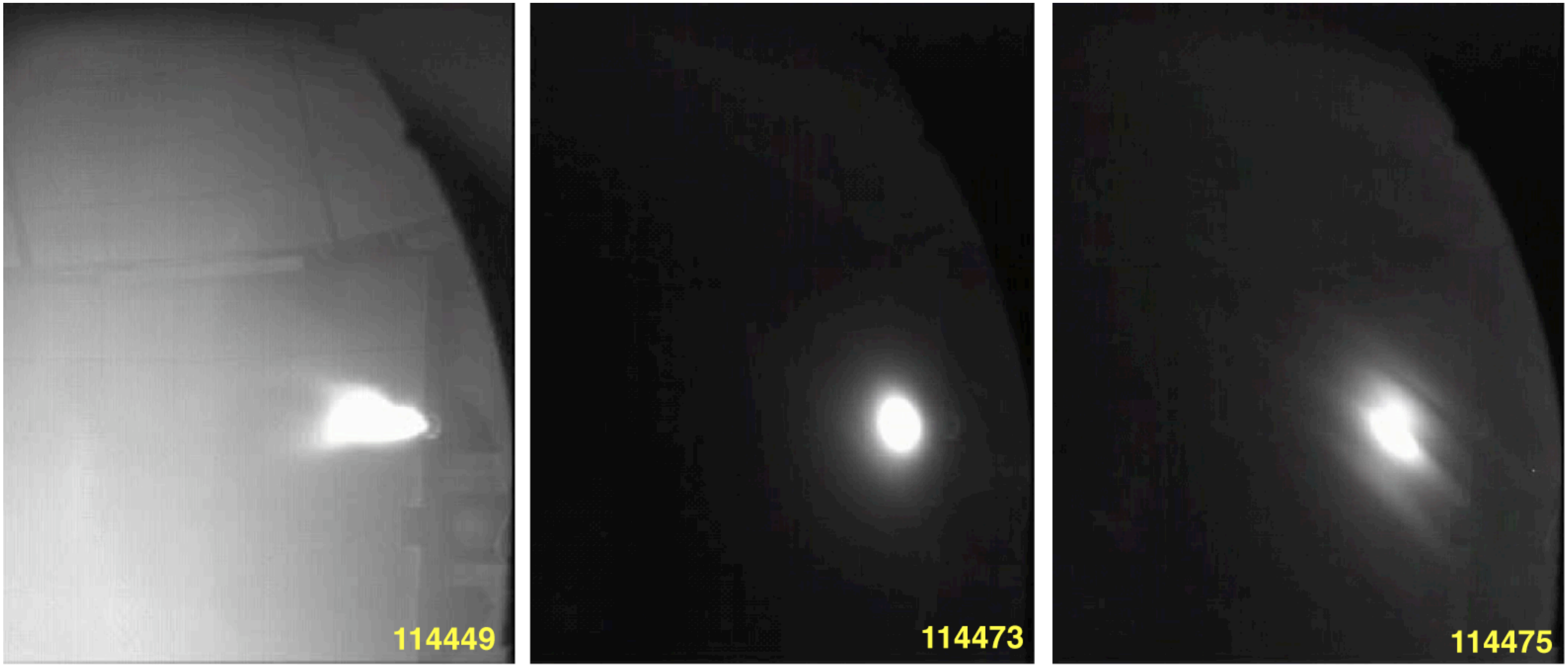
For comparison: divergence half-angle of viscous sonic flow - 30^o,
molecular effusion from orifice - 60^o

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

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