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High Pressure Supersonic Gas Jet Fueling on NSTX

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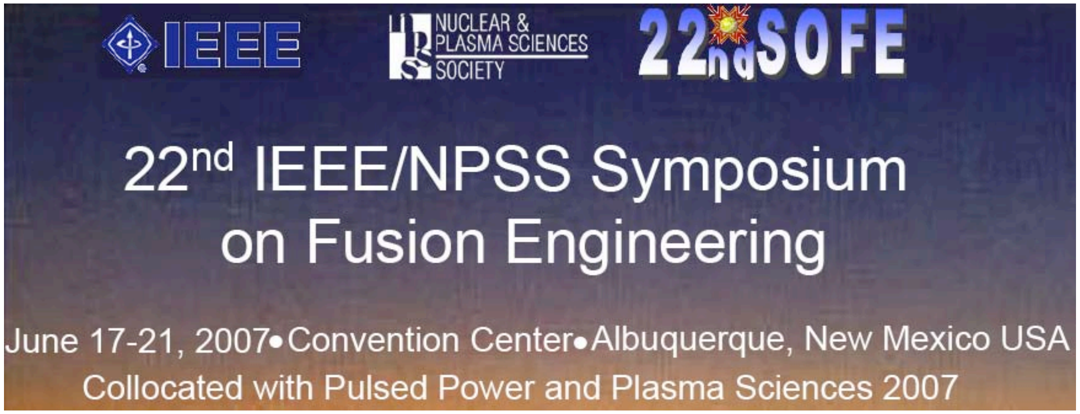
Poster P1-27



Abstract

A supersonic gas injector (SGI) has been used for fueling of ohmic and 2 - 6 MW NBI-heated L- and H-mode plasmas in NSTX. The SGI is comprised of a small de Laval converging-diverging graphite nozzle, a commercial piezoelectric gas valve, and a diagnostic package (Langmuir probe, thermocouples and magnetic pick-up coils), all mounted on a movable probe at a low field side midplane port location. The nozzle operated in a pulsed regime at room temperature, reservoir deuterium pressure up to 0.33 MPa, flow rate up to 4.55e21 particles/s, and a measured Mach number of about 4. The jet divergence half-angle was measured to be between 5 and 40 degrees. It was mainly dependent on the reservoir neutral pressure or background plasma conditions. Reliable H-mode access was obtained with SGI fueling in NSTX. Good progress was also made toward a controlled density SGI-fueled H-mode plasma scenario with the flow rate of the uncontrolled high field side (HFS) gas injector reduced by up to 20. As a result, comparable or slightly higher core and pedestal densities were obtained, with 5 - 15 % reduction of core and pedestal temperatures, and a change in the ELM character from Type I and small, Type V ELMs to Type III ELMs. The SGI fueling efficiency was found to be a function of the jet pressure (density) and the plasma - nozzle distance, typically held at 5 - 15 cm. In these experiments the SGI was operated with deuterium since the original gas delivery configuration was common to the NSTX HFS gas injection system. Typical fueling efficiency values inferred from the plasma electron inventory analysis were in the range 0.1 - 0.35. These results motivated an upgrade of the SGI gas delivery system. The goals of the upgrade were: 1) to increase the available plenum pressure to 0.67 MPa, thus increasing the jet pressure and the flow rate by up to 100 %, 2) to enable multi-pulse capability for better fueling control, and 3) to have the capability to easily allow for injection of various gases, other than deuterium, for particle transport and divertor heat flux mitigation experiments. Details of the upgrade and laboratory high-pressure tests will be presented, along with available initial fueling results from NSTX plasmas.

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Summary

- **Low field side (LFS) supersonic gas injector (SGI) has been used for fueling of ohmic and 2-6 MW NBI-heated L- and H-mode plasmas**
  - ✓ SGI-fueled H-mode power threshold low (< 2 MW NBI), H-mode access reliable
  - ✓ Developed H-mode scenario with SGI fueling and reduced (nine-fold) high field side (HFS) fueling demonstrating the possibility of density control
  - ✓ SGI-fueled double-null H-mode plasmas demonstrate different ELM regime (type III ELMs vs small and type I ELMs with HFS fueling)
  - ✓ SGI injects deuterium at G < 5 x 1021 particles/s in quantities 0.1 - 0.3 of NSTX plasma inventory in a continuous fashion with measured fueling efficiency 0.1 - 0.3
- **Recent SGI upgrades**
  - ✓ Increase plenum pressure from 2500 Torr to 5000 Torr
  - ✓ Multi-pulse capability (from 1 to 10 pulses per plasma discharge)
  - ✓ Plenum volume increase from 120 cc to 250 cc
  - ✓ Independent gas handling system (D_2, other gases, e.g. He, CD_4)
- **These upgrades led to improved SGI performance**

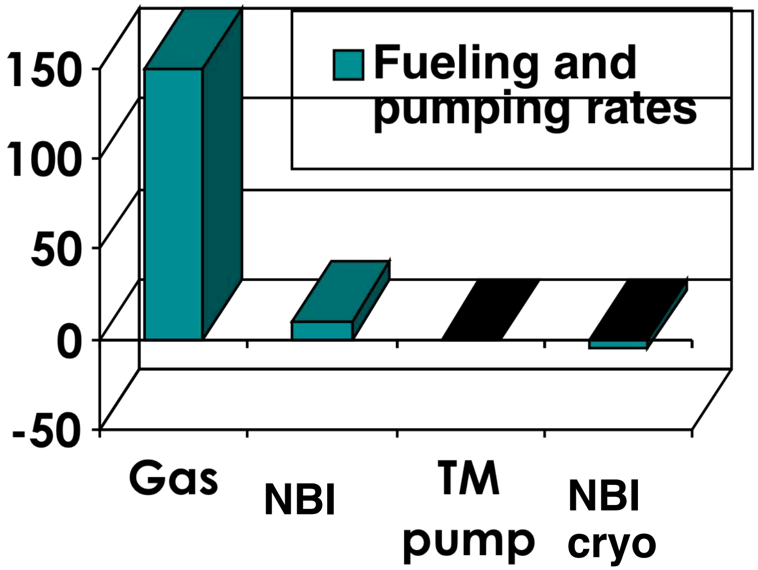
Supersonic gas jet is a unique fueling technique studied on NSTX

- **Improve and optimize gas fueling**
  - » ITER will rely on central fueling (pellet, compact toroid), however plasma start-up and edge fueling will use gas puffing

- Supersonic gas injector installed on NSTX in 2004, experiments conducted in ohmic and NBI H-mode plasmas in 2005-2007

- Supersonic gas jet fueling was studied on other facilities
  - » limiter tokamaks (HL-1M, Tore Supra): injected 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 fueling efficiency ~ 0.1-0.3

Pumping and fueling in NSTX



NSTX pumping

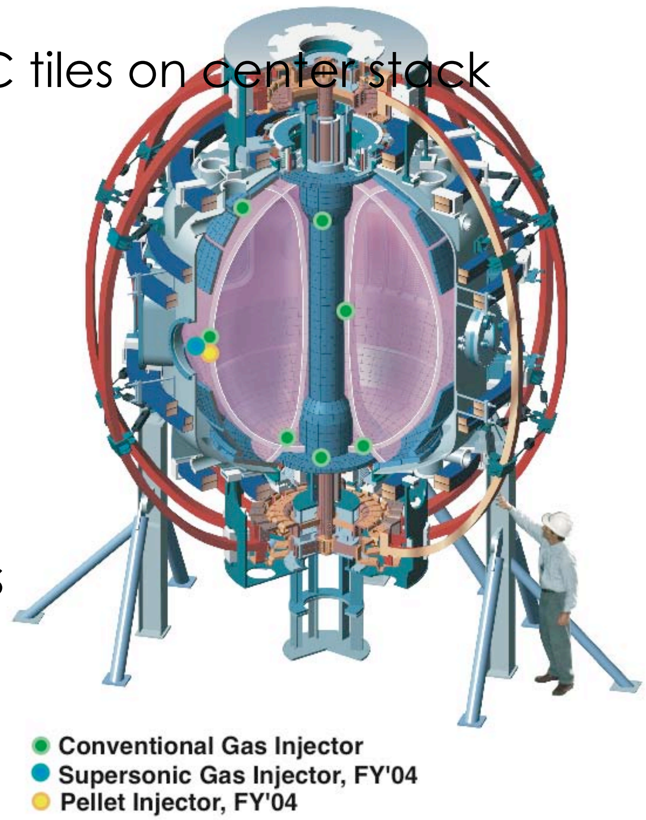
- Turbomolecular pump (S = 3400 l / s)
- NBI cryopump (S = 50000 l / s, in NBI-heated plasmas only)
- Conditioned walls

PFC

- ATJ graphite tiles on divertor and passive plates
- ATJ and CFC tiles on center stack

NSTX fueling sources

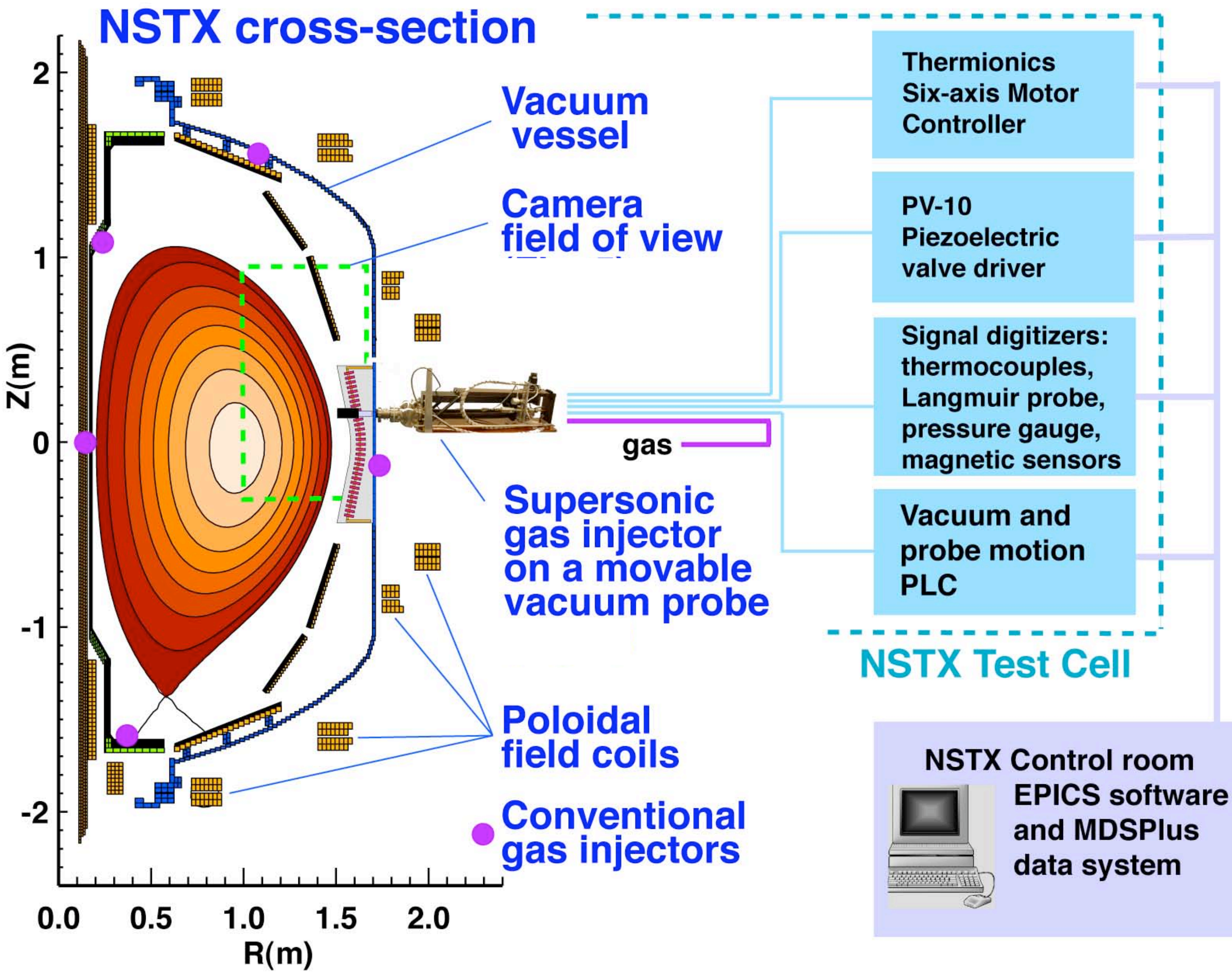
- Gas injection: low field side (LFS, top + side) and high field side (HFS, midplane + shoulder), divertor. D_2, He, injected at S = 20 - 100 Torr l /s.
- Neutral beam injection system: three beams, 60 - 100 keV, 6-7 MW, fueling rate: S < 4 Torr l / s
- Supersonic gas injection S = 30 - 130 Torr l / s
- Wall (and divertor)



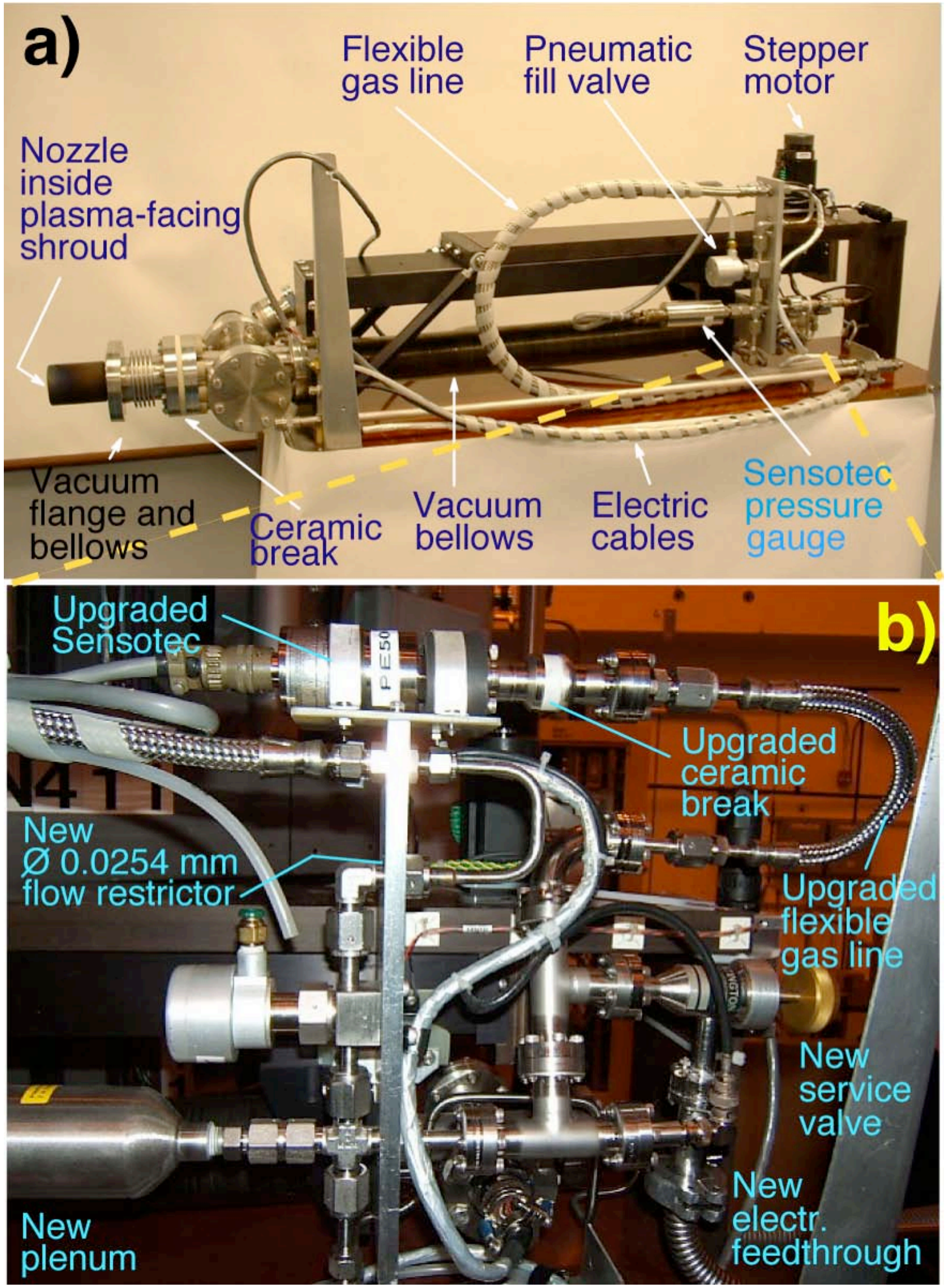
Both physics and engineering benefits are expected from SGI upgrades

Improvements implemented in 2007	Derived benefit
Increased plenum pressure to 100 PSIA (5000 Torr) (previously limited to 50 PSIA (2500 Torr))	**1. Increase flow rate x 2 2. Possibly increase penetration 3. Improve fueling scenario flexibility, density control**
Independent gas handling system	**Inject other than D_2 gases, such as He, N_2 and CD_4**
Upgrade software to multi-pulse capability	**Improve fueling scenario flexibility, density control**
Increase plenum volume (SGI reservoir)	**Reduce flow rate dependence on pressure drop**
Density feedback with SGI using Plasma Control System (future)	Density control with SGI

SGI on NSTX: placement and control elements

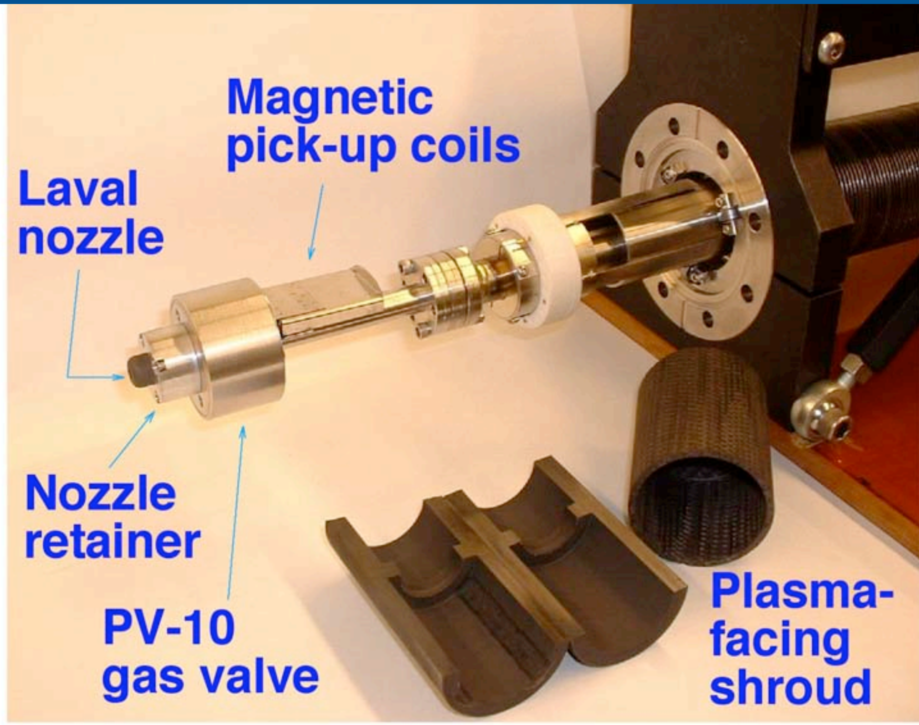


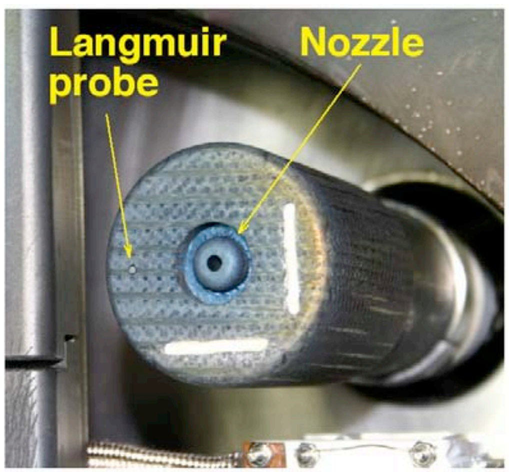
SGI: fueling and diagnostic packages on a probe

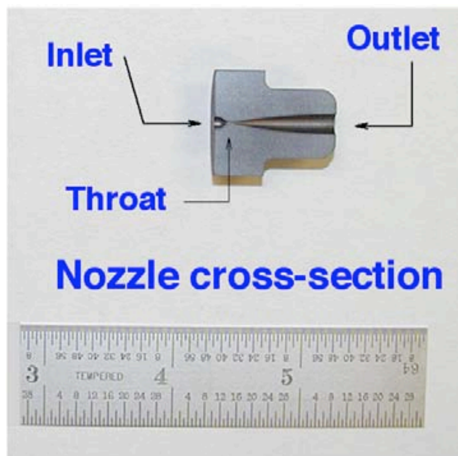


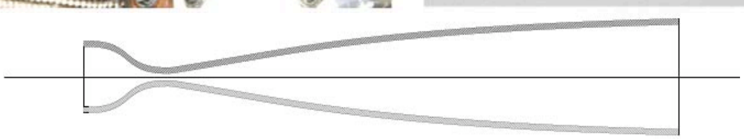
- Thermionics ZC-450 movable probe, stroke 24", travel rate < 15 in/s
- 6-axis Stepper Motor Controller, controlled using RS-232 port
- EPICS software used for SMC control and communication with Vacuum PLC
- **Components added or upgraded to handle 100 PSI (5000 Torr)**

SGI head is a densely packed apparatus





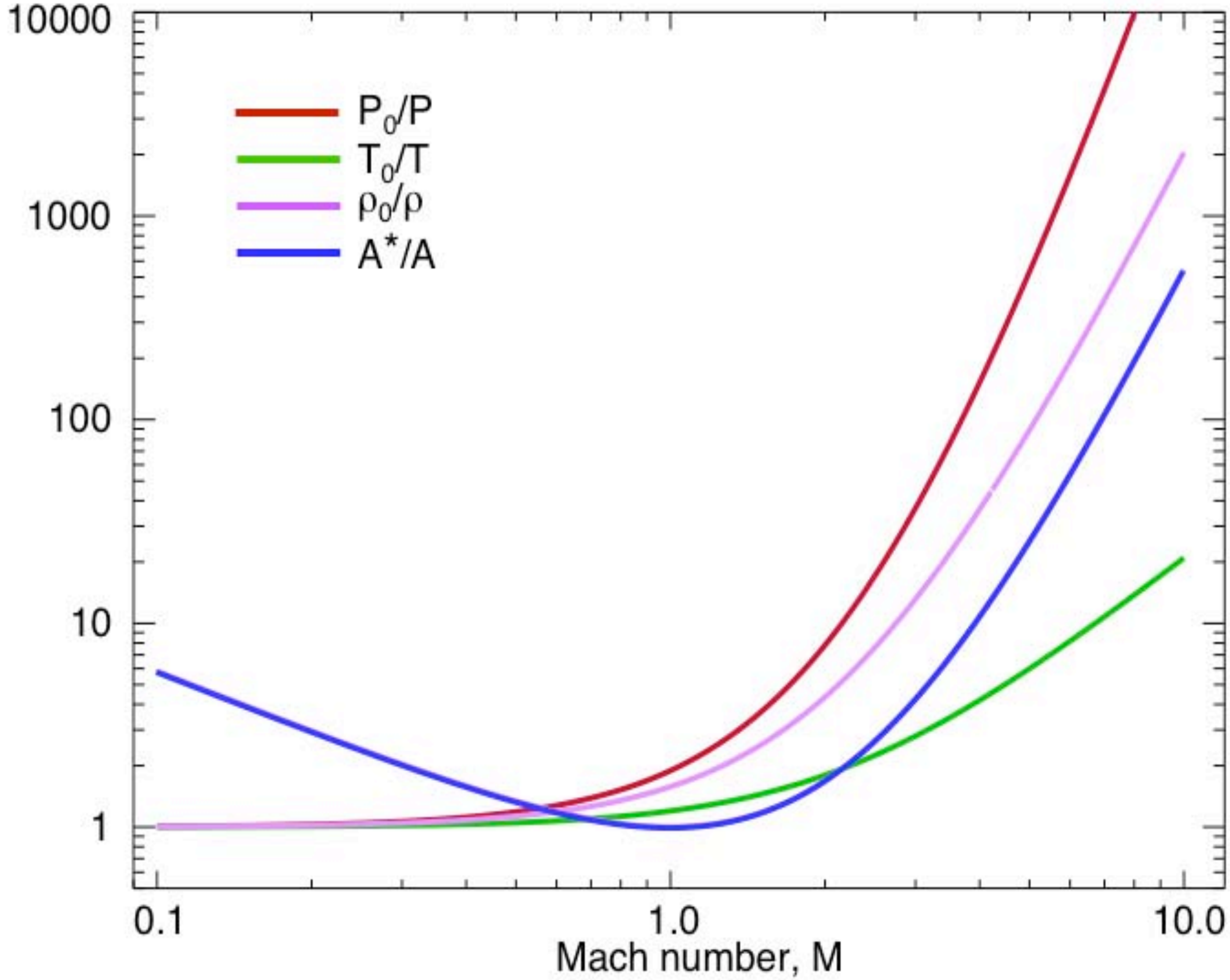




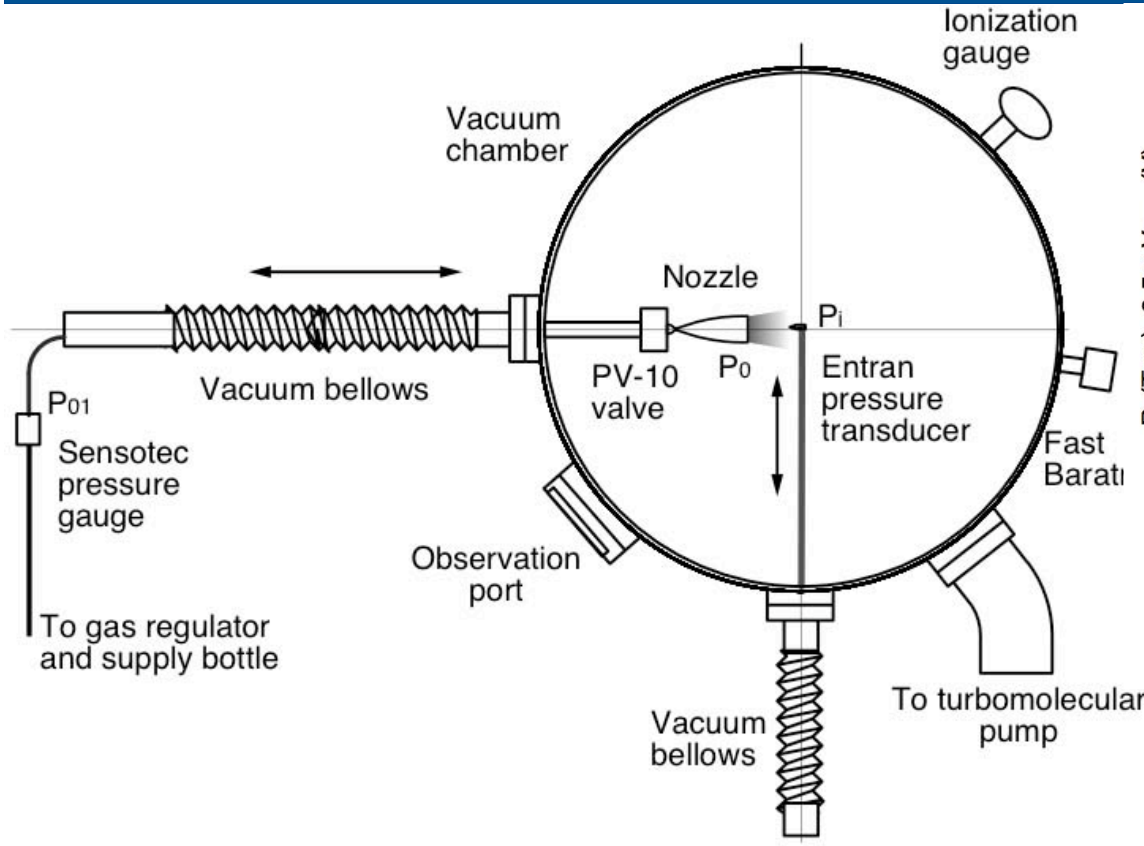
- Shroud: CFC and ATJ graphite
- Gas valve: Veeco PV-10 piezoelectric type, d_{throat}=0.02", typical opening time 1-2 ms, driving voltage 150 V
- Thermocouples in shroud and in gas valve
- Two magnetic pick-up coils on shroud front surface for B_z, B_t measurements
- Three magnetic pick-up coils in 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
- Nozzle: True de Laval geometry, L = 23.4 mm, d_{throat} = 0.01"
- **Can handle 100 PSI (5000 Torr) without change**

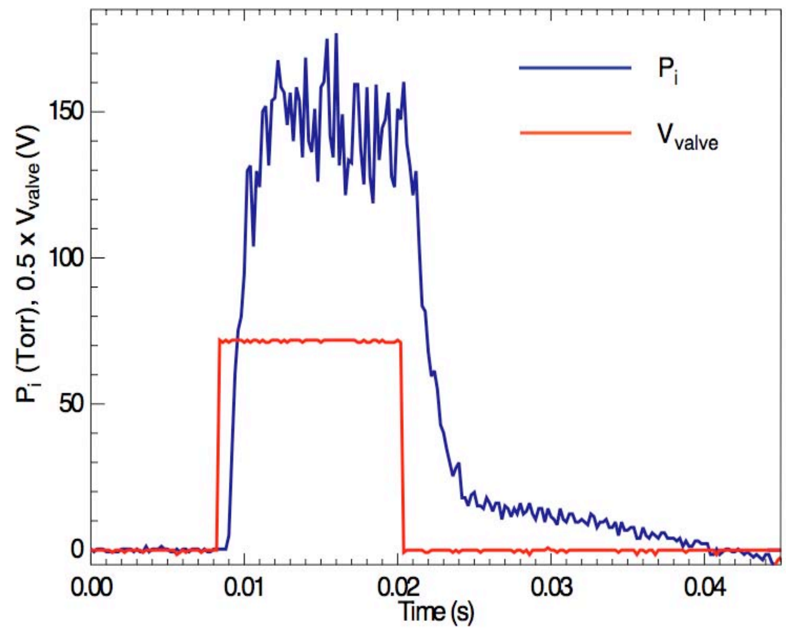
Proper nozzle operation is critical for Mach focusing and gas jet collimation

Isentropic ratios determine supersonic gas jet properties *P*, *T*, ρ as a function of Mach number in reference to reservoir parameters P_0, T_0, ρ_0



Laboratory tests designed to evaluate SGI

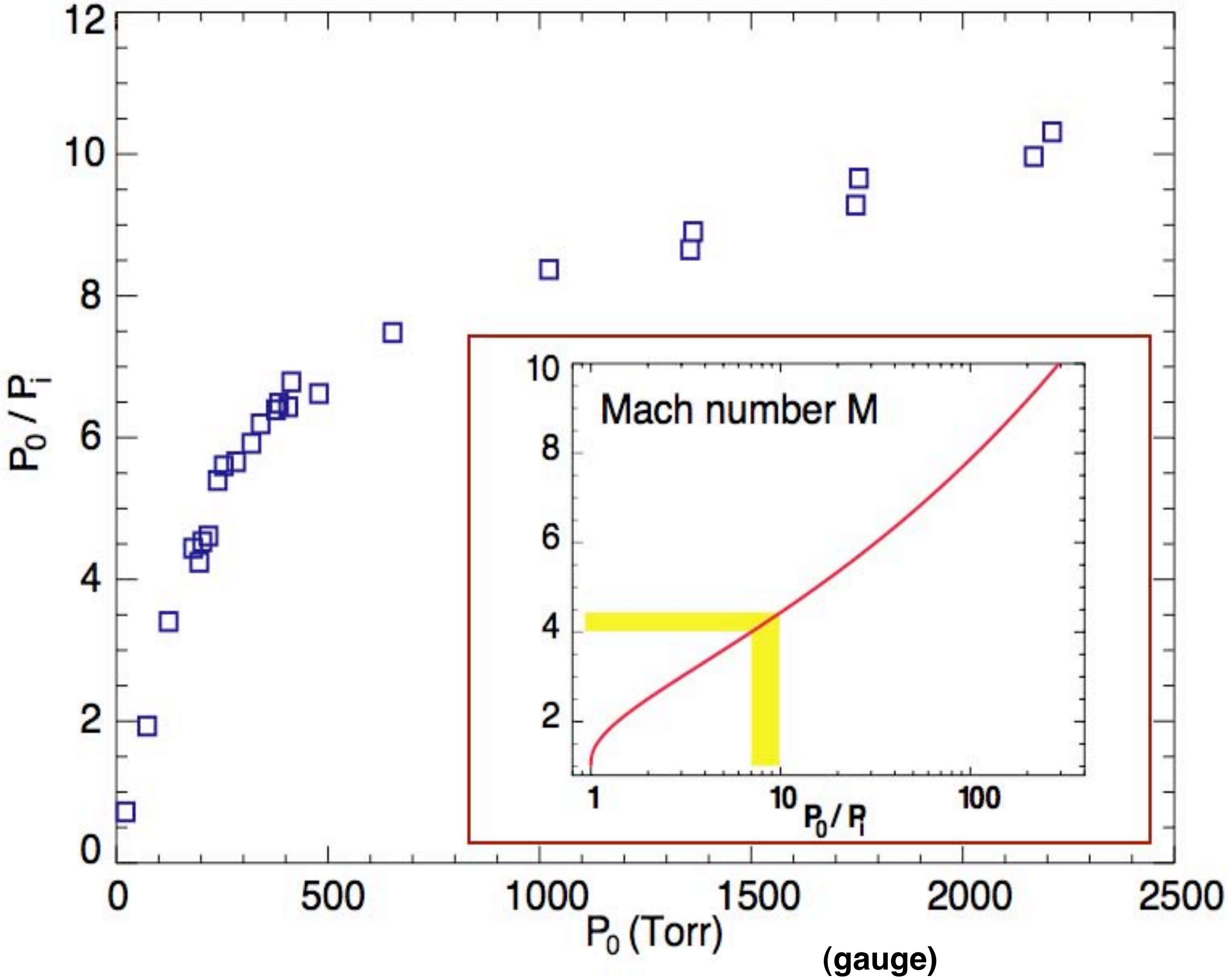




- Any nozzle must be tested to enable comparison with calculations - real nozzles often do not perform as expected
- Flow parameters diagnostic methods: Shadowgraphy, Schlieren photography, Laser induced fluorescence, Electron beam fluorescence, Laser scattering, Dust imaging, and others are either too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

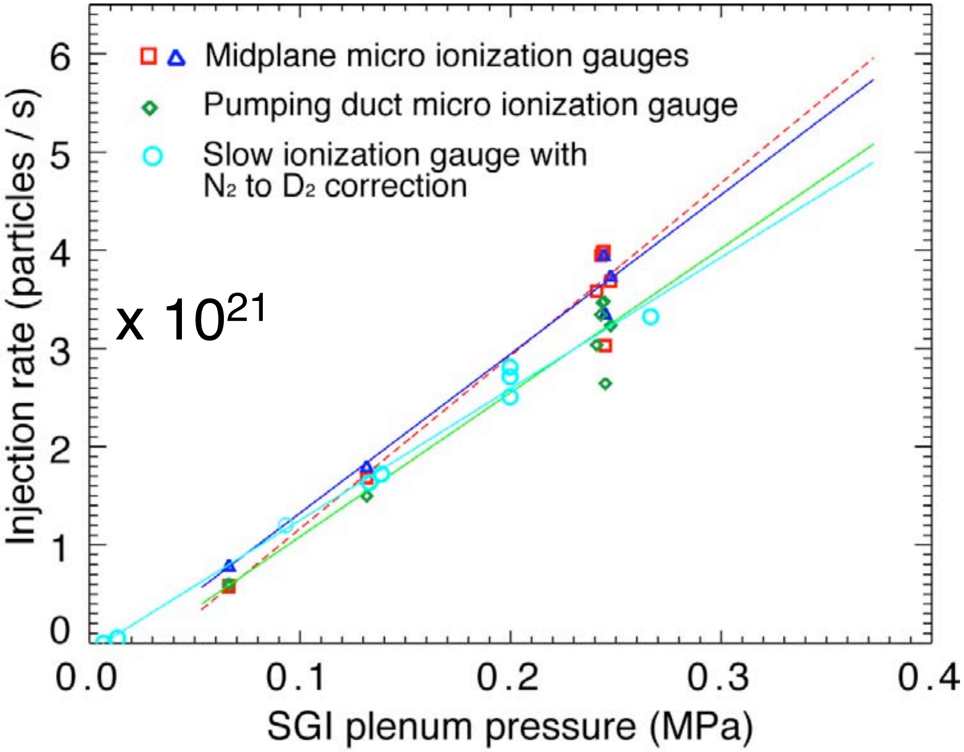
Mach M = 4 is obtained from Rayleigh-Pitot law

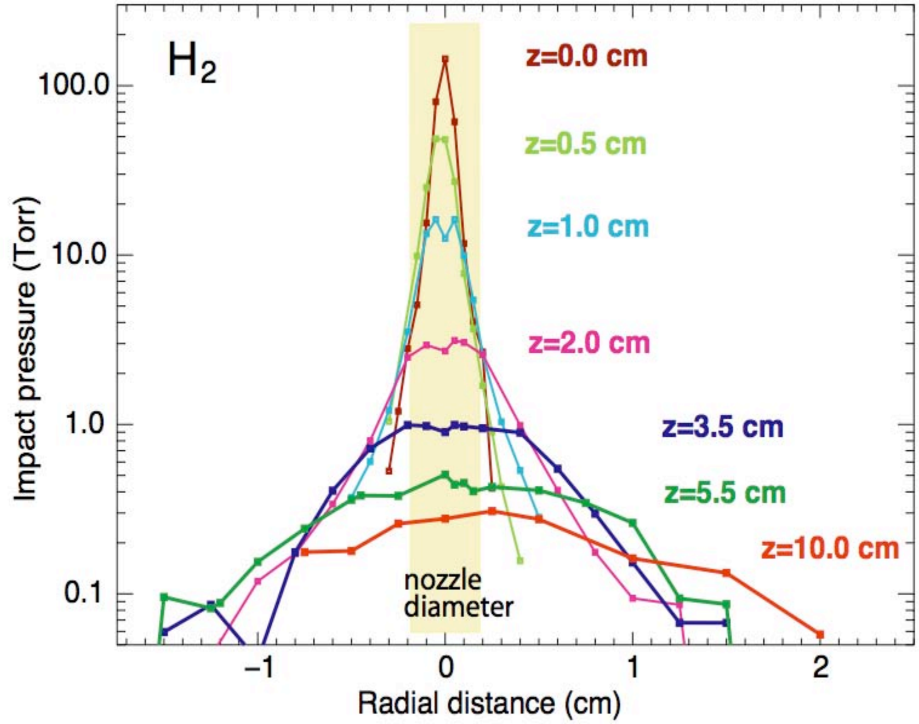


$$\frac{P_i}{P_0} = \left(\frac{(\gamma+1)\, M^2}{(\gamma-1)\, M^2 + 2}\right)^{\gamma/(\gamma-1)} \left(\frac{\gamma+1}{2\gamma M^2 - (\gamma-1)}\right)^{1/(\gamma-1)}$$

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

SGI parameters characterized off-line and *in situ*



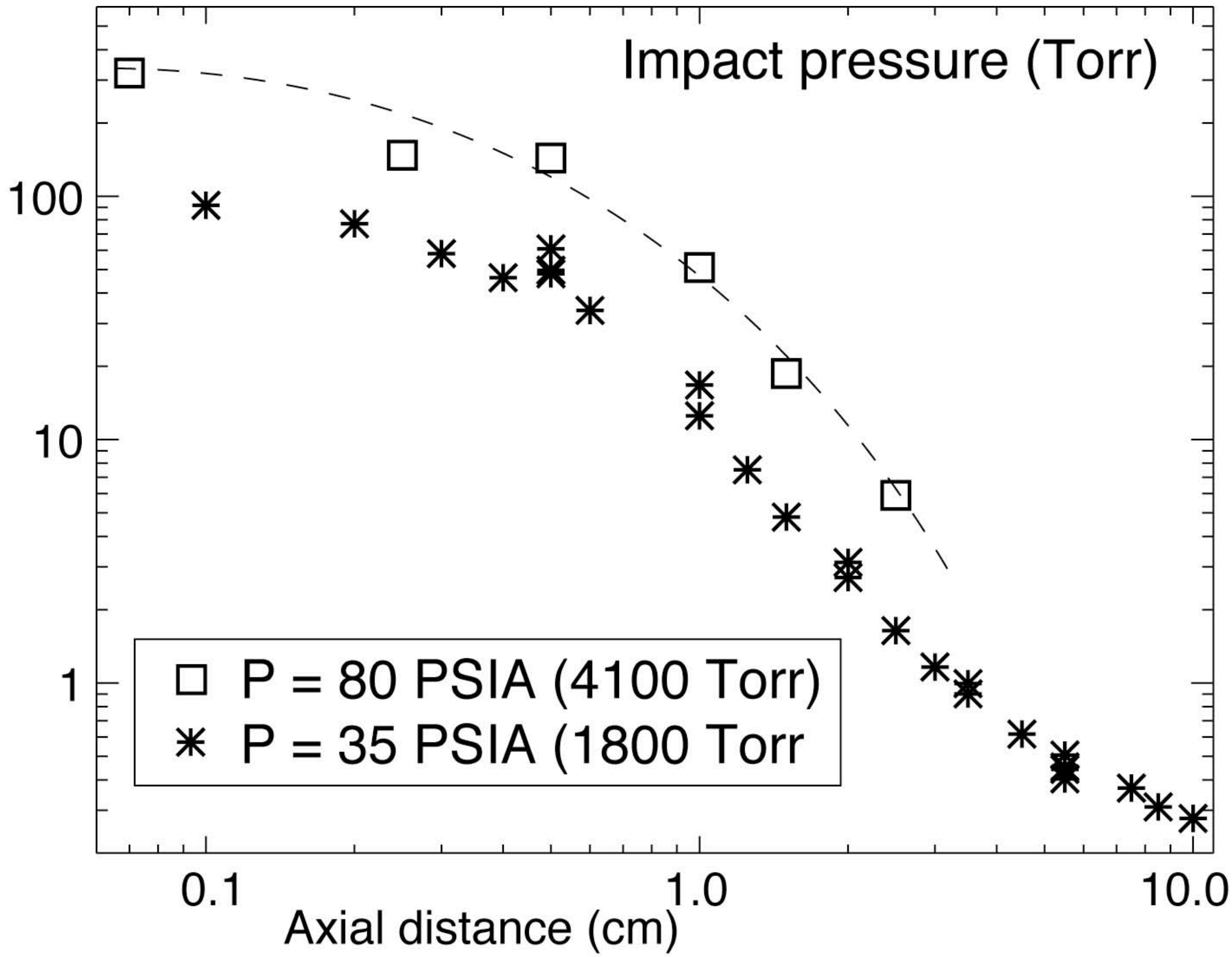


- NSTX SGI is operated at flow rates 20-125 Torr l /s (1.5 - 8.75 x 10^{21} s^{-1})

- Hydrogen or Deuterium jet:
  - ✓ Jet divergence half-angle: 6^{o} - 25^{o} (measured)
  - ✓ M = 4 (measured)
  - ✓ Estimated: T ~ 60 - 160 K, $n < 5 \times 10^{23}$ m^{-3}, Re = 6000, v_{therm} ~ 1100 m/s, v_{flow} = 2400 m/s

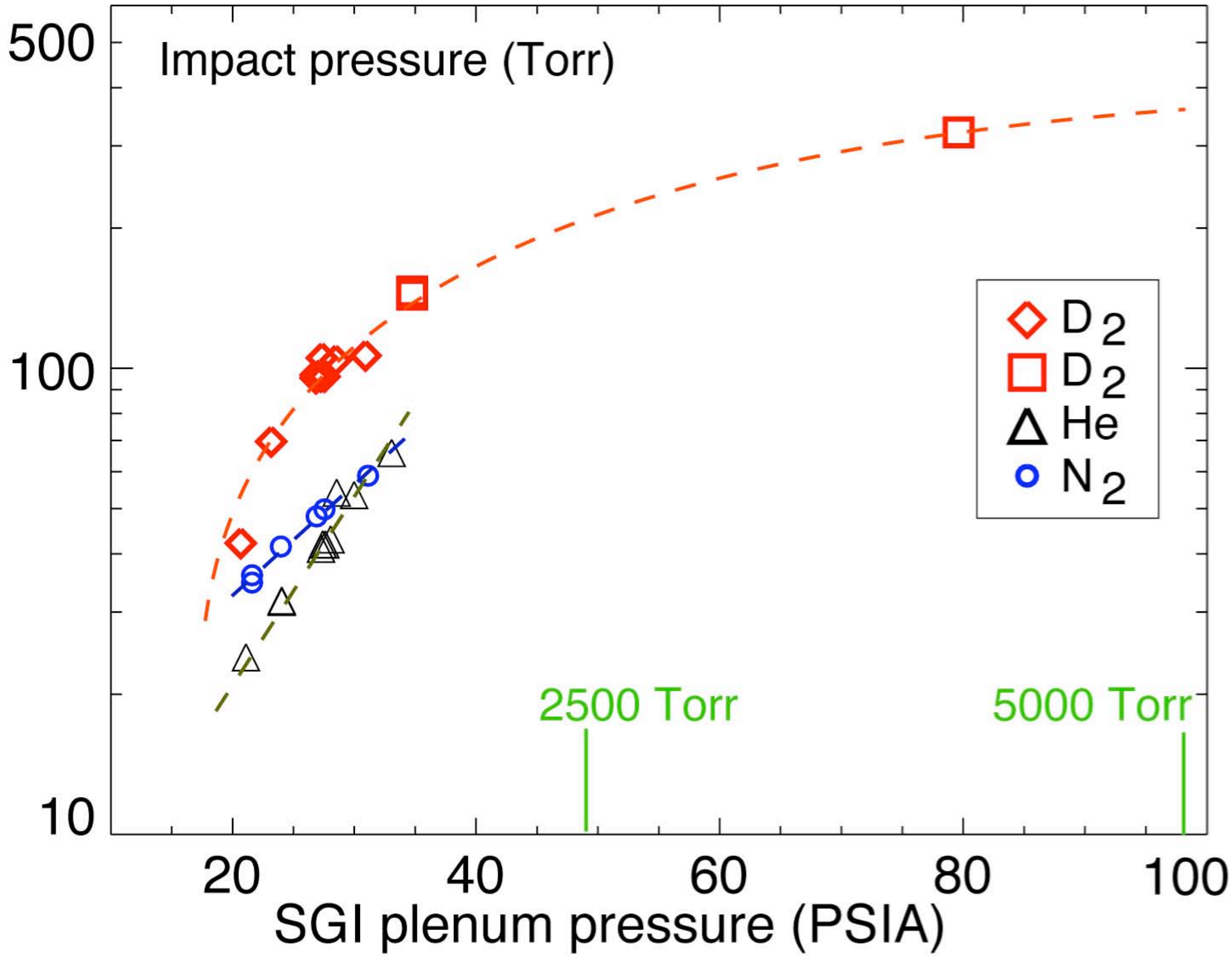
$$u_{max} = \sqrt{\frac{2\,\gamma}{\gamma - 1}\,\frac{kT_0}{m}}$$

Higher plenum pressure leads to proportionally higher supersonic jet pressure



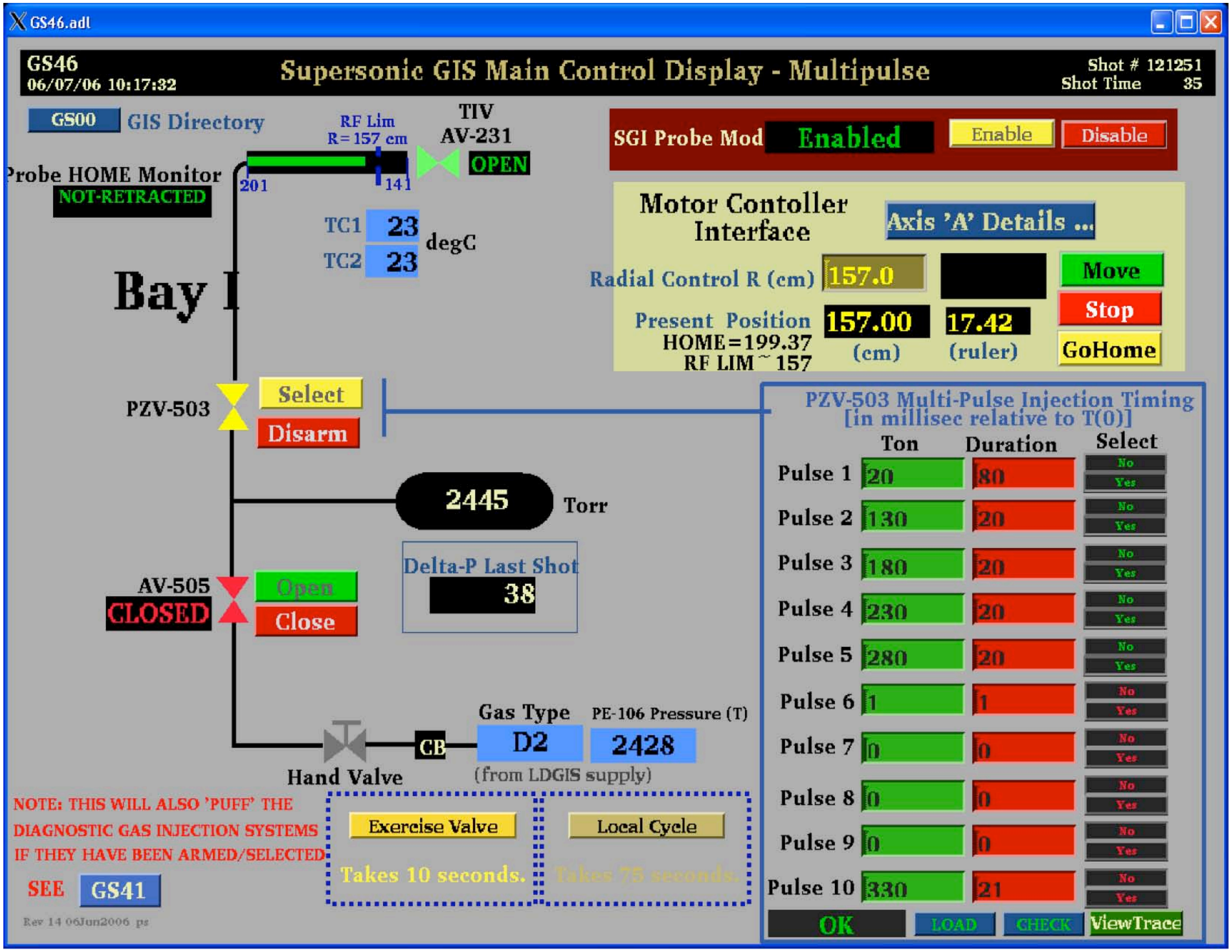
- Measurements done in deuterium by translating pressure probe axially

SGI can produce supersonic gas jets with H_2, D_2, He, and N_2



- Deuterium used for fueling
- Helium, nitrogen can be used for diagnostic purposes (T_e, n_e, transport)
- He, N_2, CD_4 for radiative divertor experiments

Software upgrade enabled multi-pulse capability



- EPICS and MDS Plus are used for SGI controls, PLC and data archiving
- SGI operator specifies SGI head major radius (155 cm < R < 198 cm), plenum pressure (0 < P_0 < 5000 Torr), and timing (t_{start}, $t_{duration}$)

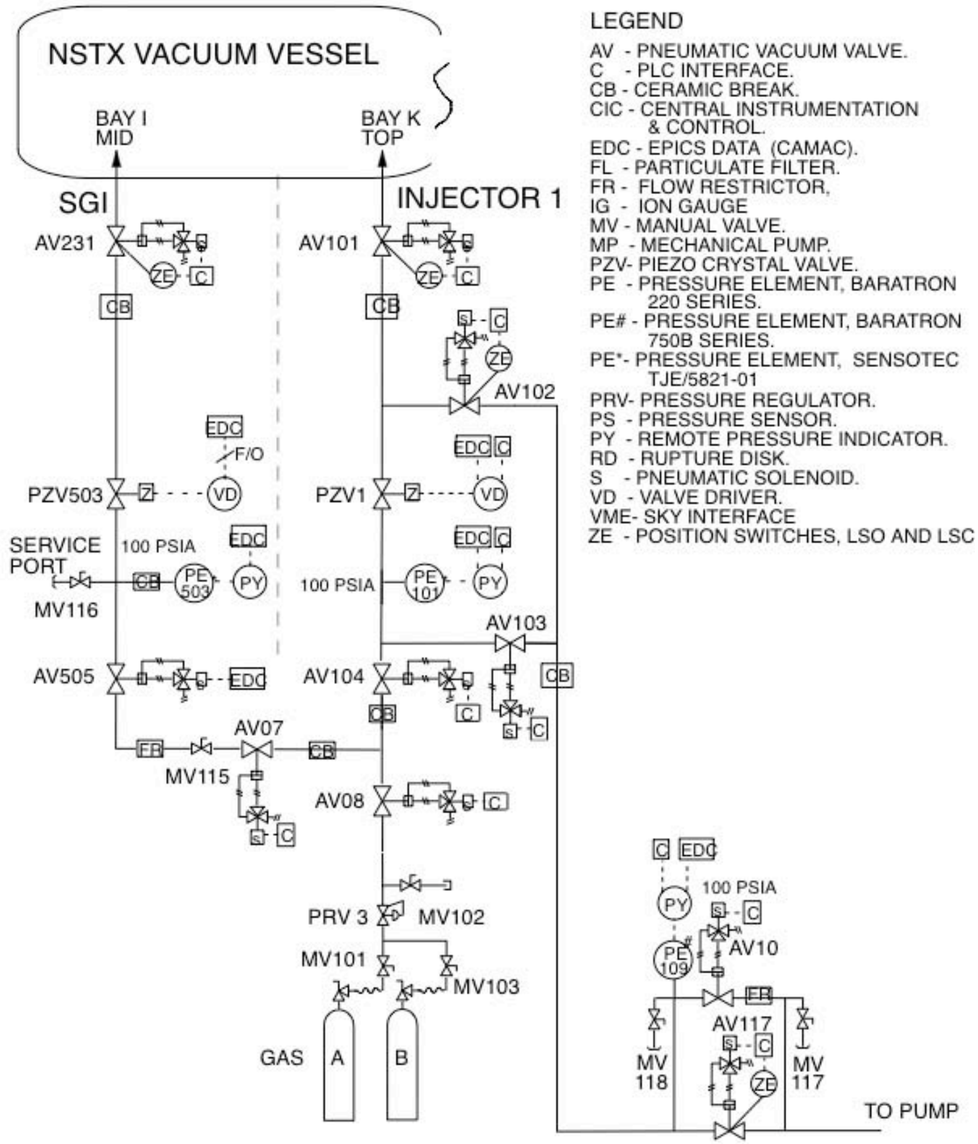
Gas delivery system upgrade made SGI gas system independent from other gas injectors

Hardware components upgraded to handle 100 PSI (5000 Torr):
- ✓ Swagelock joints
- ✓ Ceramic breaks
- ✓ Gas bottle regulators
- ✓ Pressure gauges

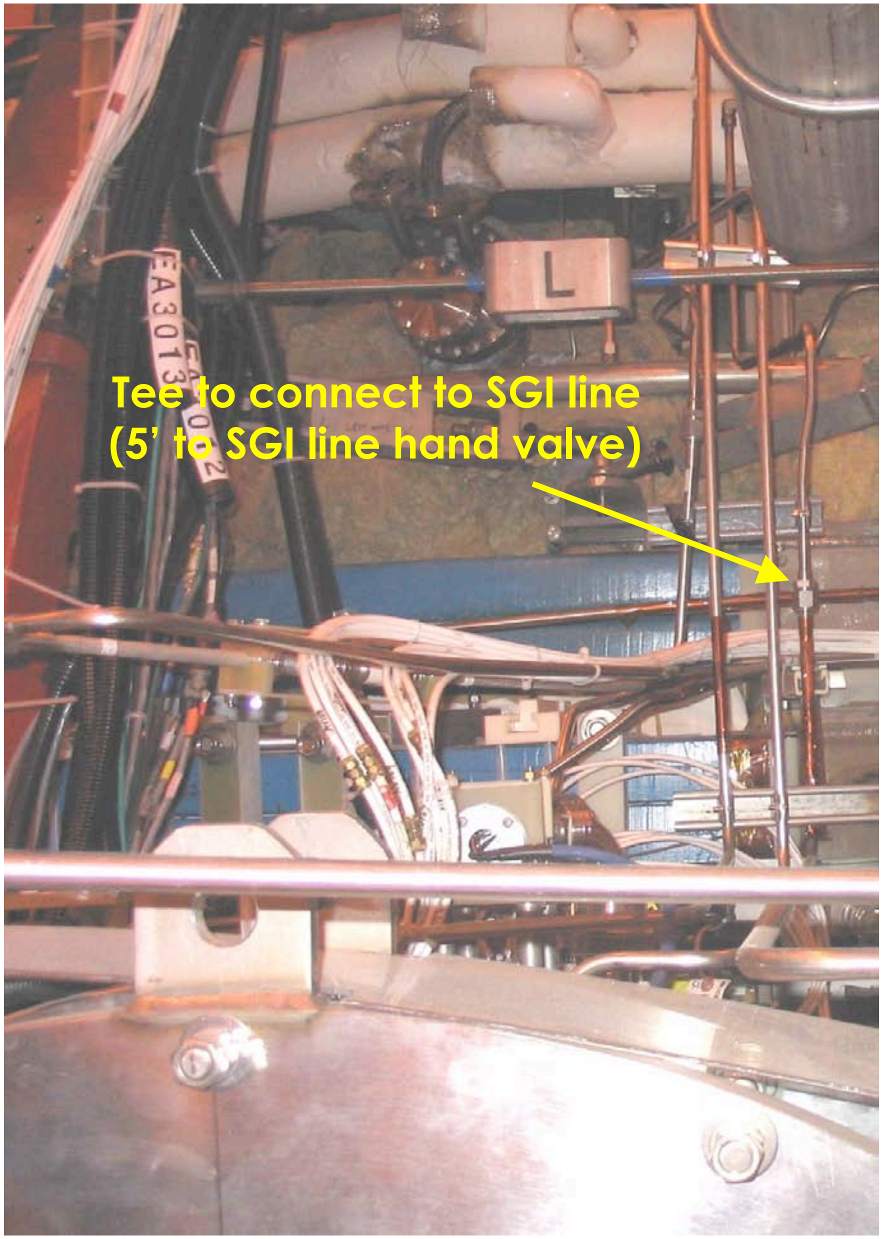
Simplicity
- ✓ Upgrade only few hardware items
- ✓ Minimize needed labor
- ✓ Take advantage of existing infrastructure
  - – Gas delivery system
  - – Pumpout system
  - – PLC control/interlock
  - – Electrical isolation and grounding

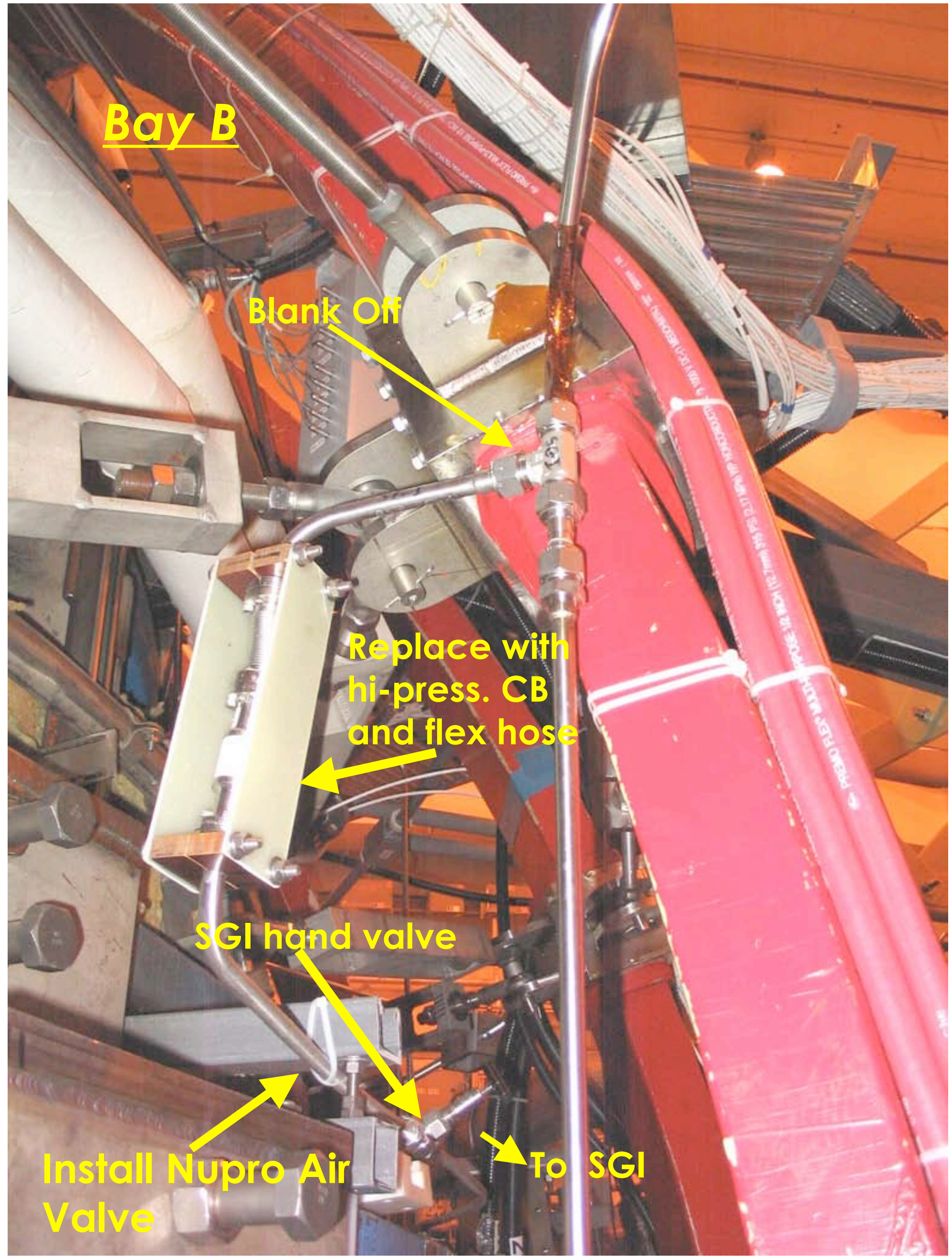
✓ Existing Bay K injector system capability and hardware retained

✓ Bay K system can be used concurrently along with SGI

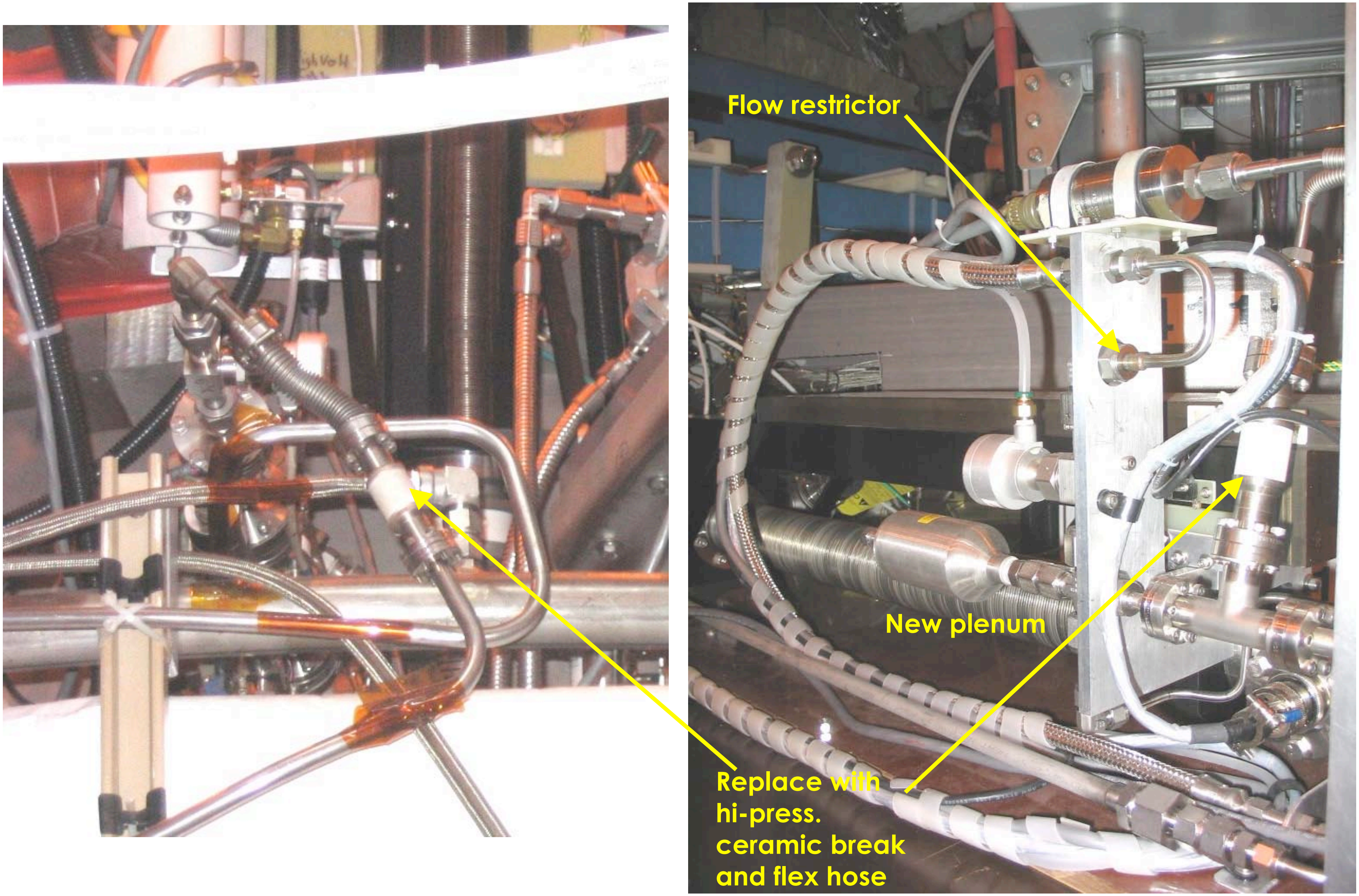


Gas delivery routing for SGI Upgrade

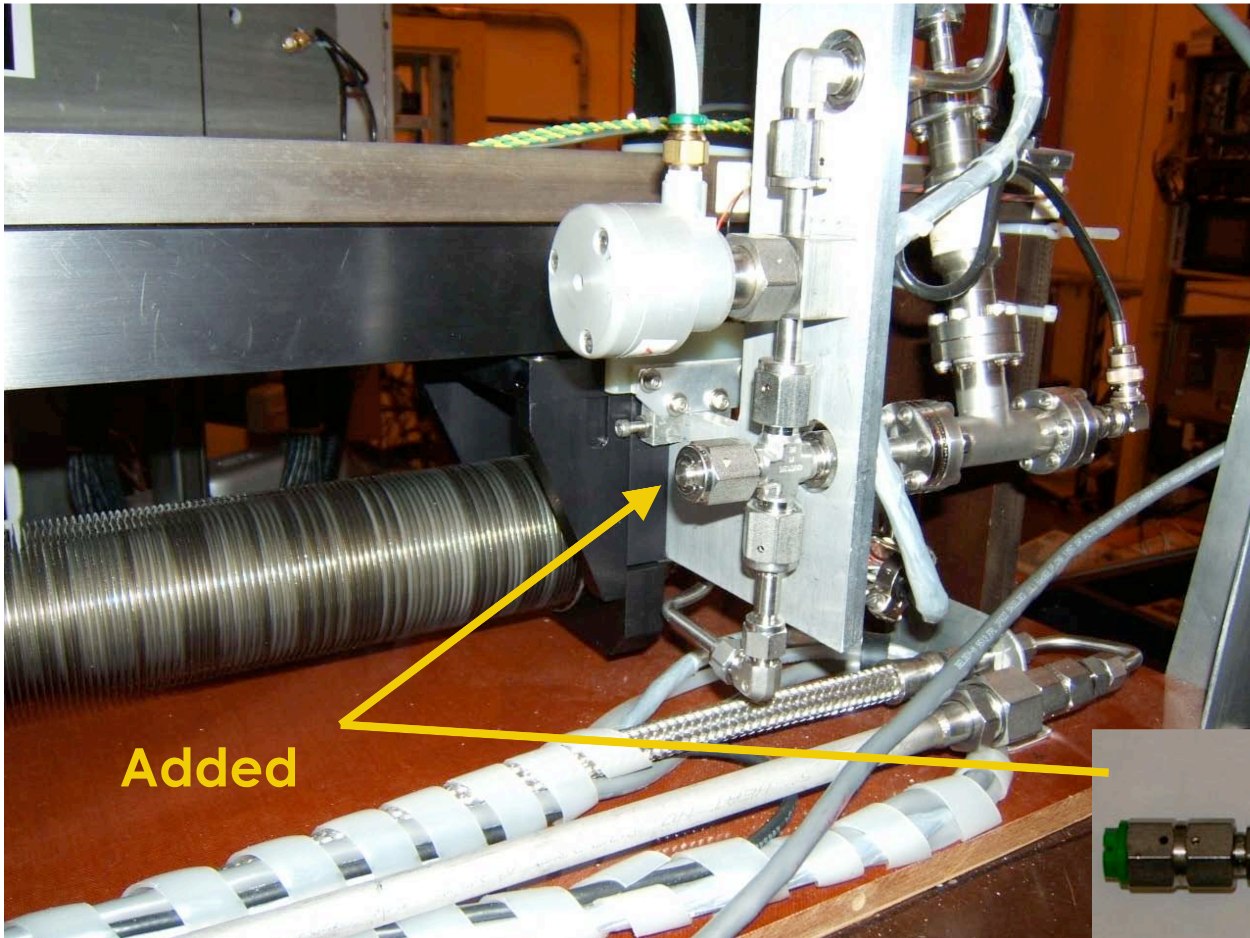




Upgrade hardware components to handle 100 PSI

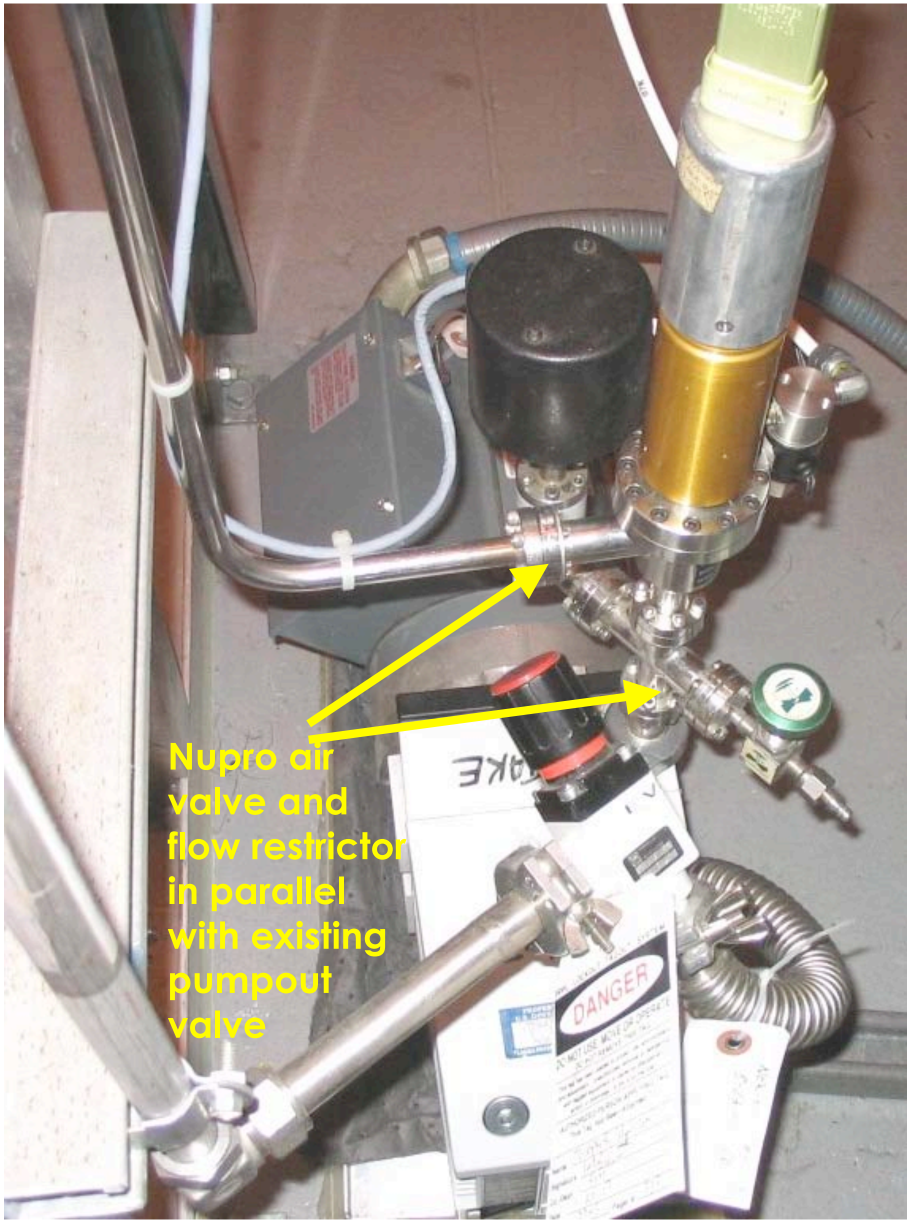


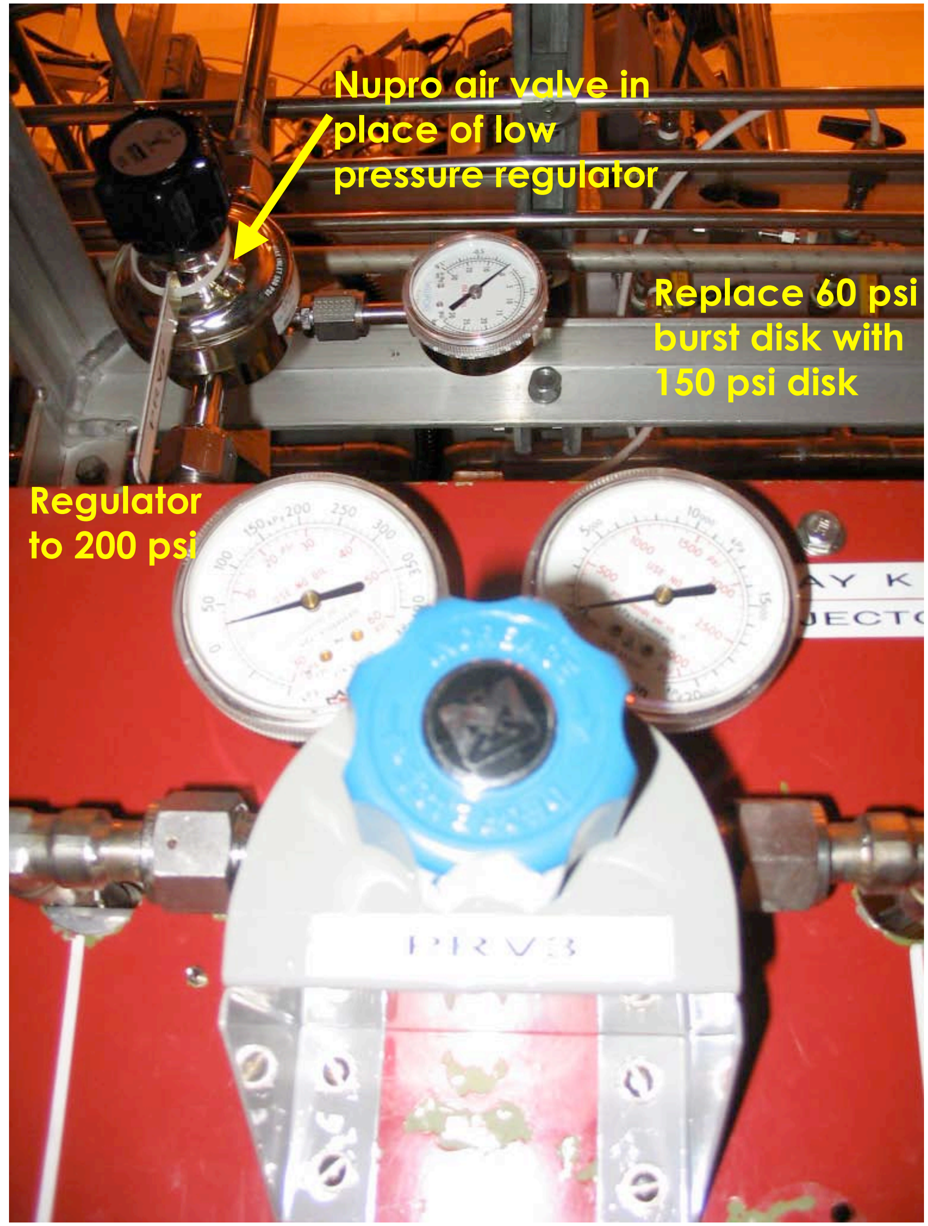
SGI plenum volume increased to reduce flow rate dependence on plenum pressure drop



New calibrated 150 cc volume was added to SGI. Total new volume = 250 cc

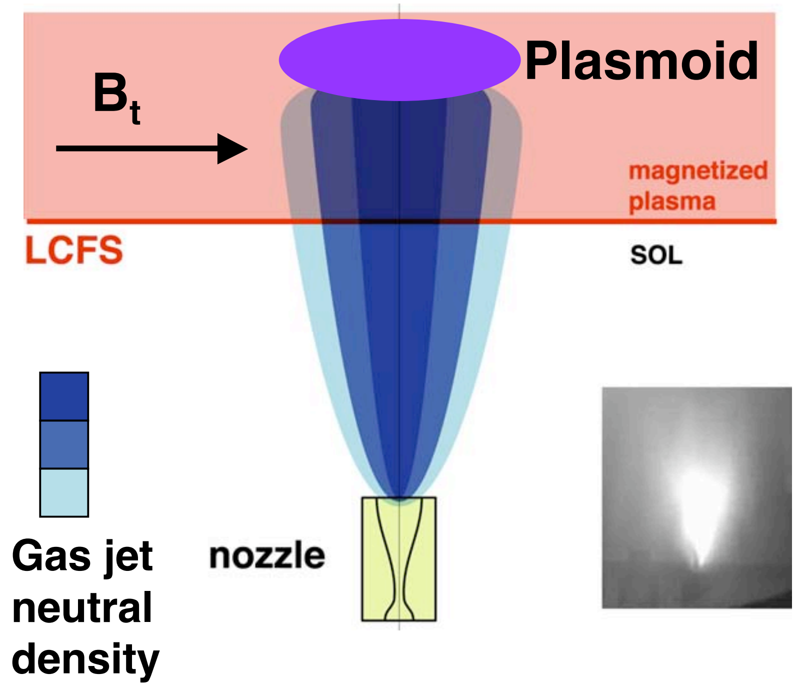
Pump-out and gas bottle system modifications





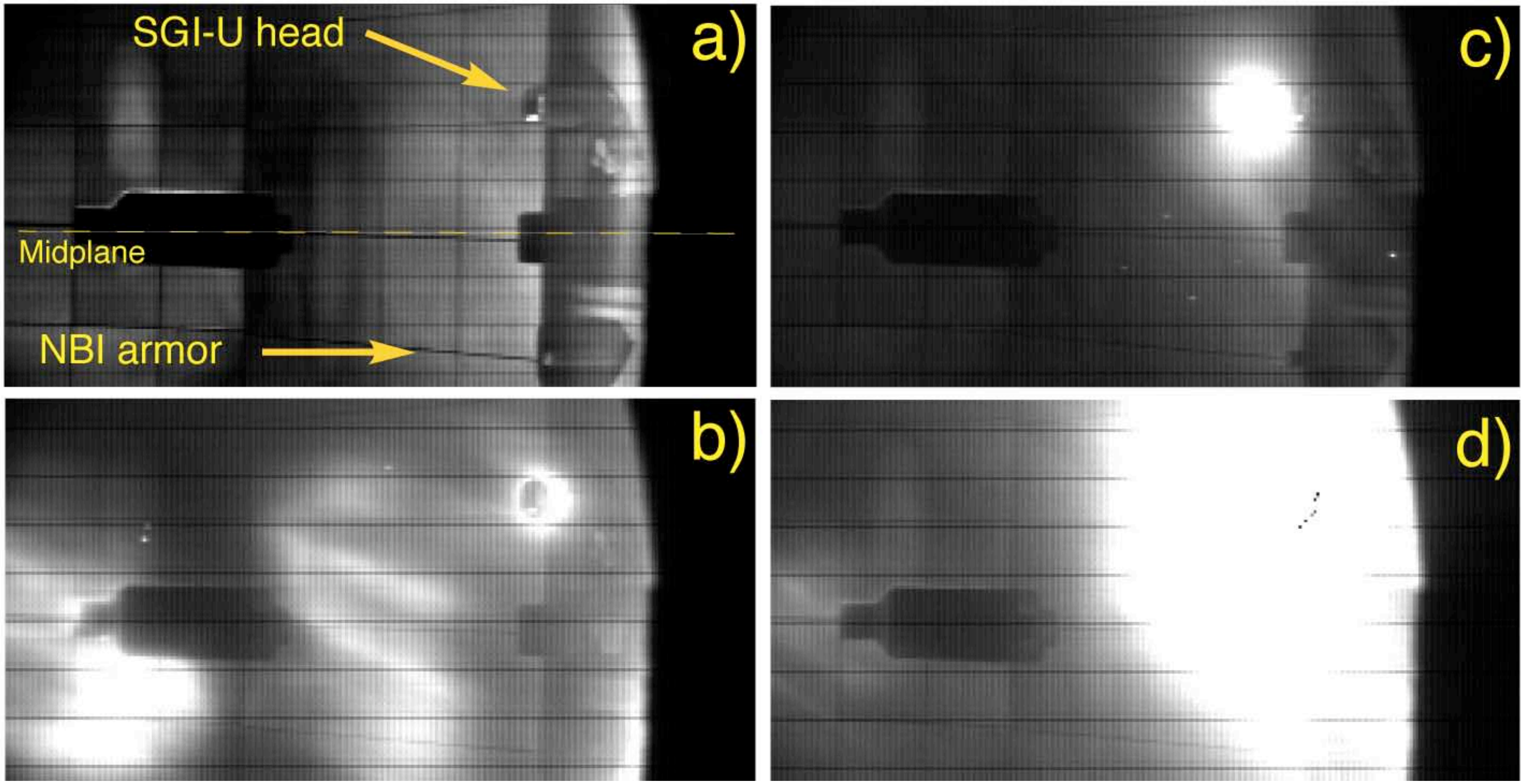
Supersonic gas jet penetration mechanism is different than that of conventional gas injection

- Unlike conventional gas injection, penetration depth of supersonic gas jet cannot be described by single neutral particle ionization / charge exchange penetration model
- Supersonic gas jet is a low divergence high pressure, high density gas stream with low ionization degree - bulk edge/SOL electrons do not fully penetrate gas jet
- High density plasmoid blocks jet from deep penetration into magnetized plasma
- Depth of penetration is ultimately determined by jet pressure and plasma kinetic and magnetic pressure
- Desirable for fueling are molecular clustering and/or droplet formation in jet achieved at very high pressure and cryogenic temperatures



References: Rozhansky et al. NF 46 (2006) 367
Lang et. al. PPCF 47 (2005) 1495

Supersonic gas jet does not perturb plasma edge



- Example frames from fast unfiltered camera movies: (a) SGI-U in NSTX vacuum vessel, (b) SGI-U interacting with edge MHD mode, (c) and (d) SGI-U injecting deuterium into 6 MW NBI-heated H-mode plasma

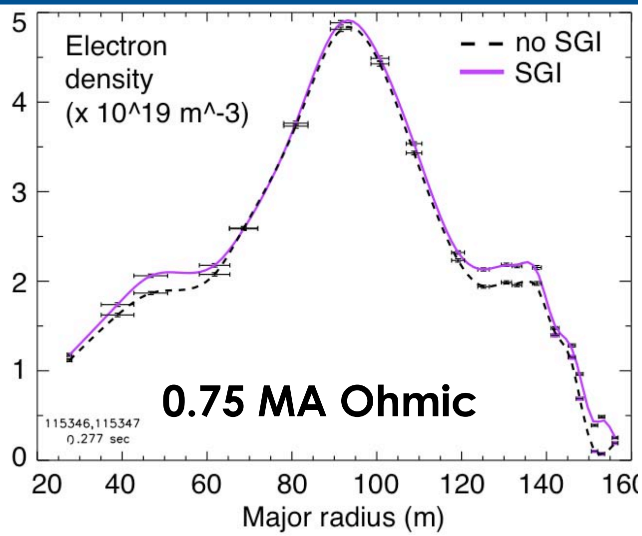
- During supersonic gas injection
  - SGI Langmuir probe does not typically show much T_e reduction or I_{sat} increase
  - Magnetic sensors do not show any EM perturbations

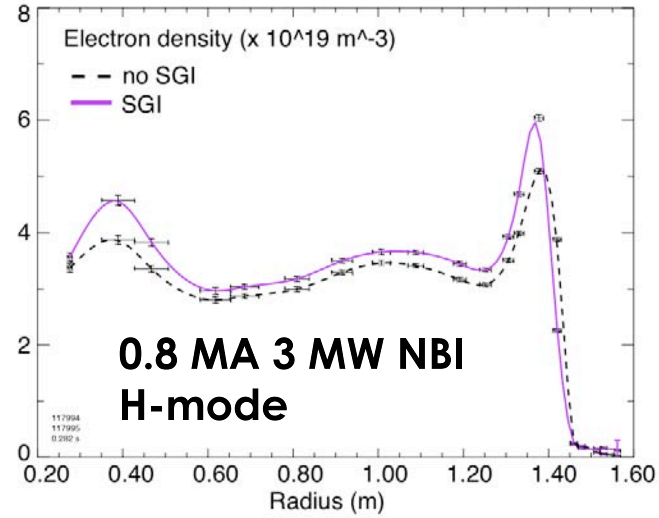
SGI "payload" diagnostics perform well

During supersonic gas injection

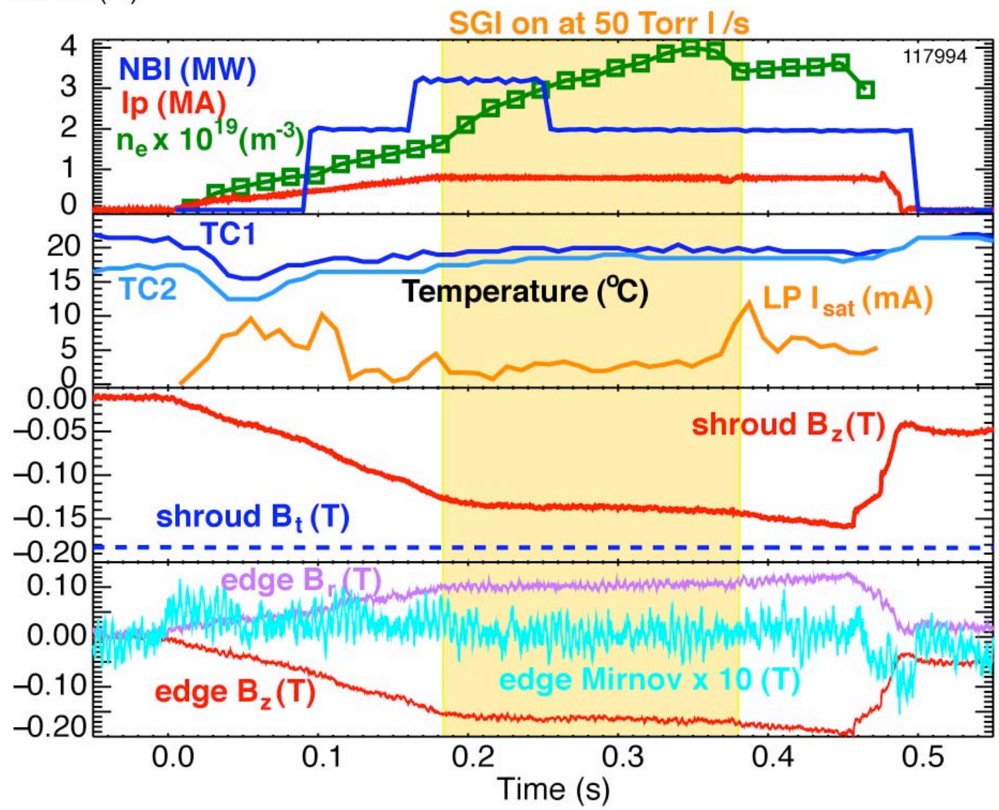
✓ In ohmic plasmas edge density rise is often observed

✓ In H-mode plasmas, n_e "ear" height and width often increase, edge/ pedestal and/or core T_e decrease by < 15 %

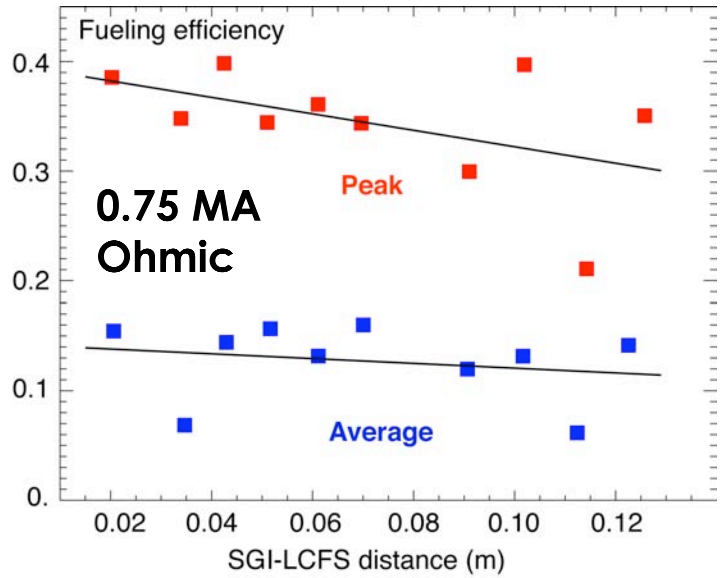




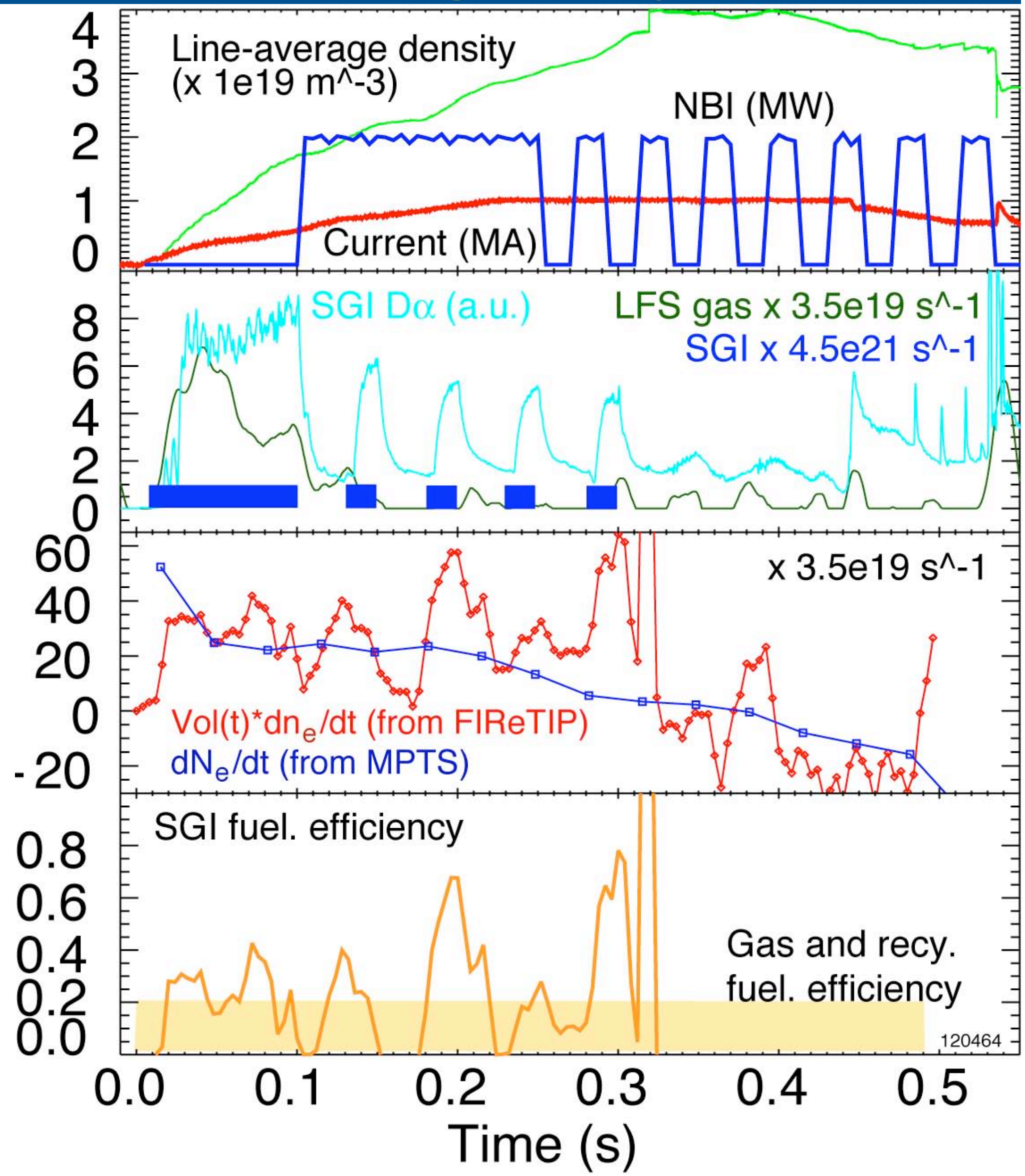
- SGI Langmuir probe does not typically show T_e reduction or I_{sat} increase
- Magnetic sensors on SGI do not show any EM perturbations
- Plasma turbulence filaments ("blobs") or ELM perturbations traverse through gas jet plasmoid
- SGI remains at room temperature
- In ohmic plasmas, SGI-LCFS distance held at 2-15 cm
- In NBI-heated plasmas, SGI-LCFS distance held at 6-8 cm



Supersonic gas jet fueling efficiency is x 2-5 higher than that of conventional gas injection

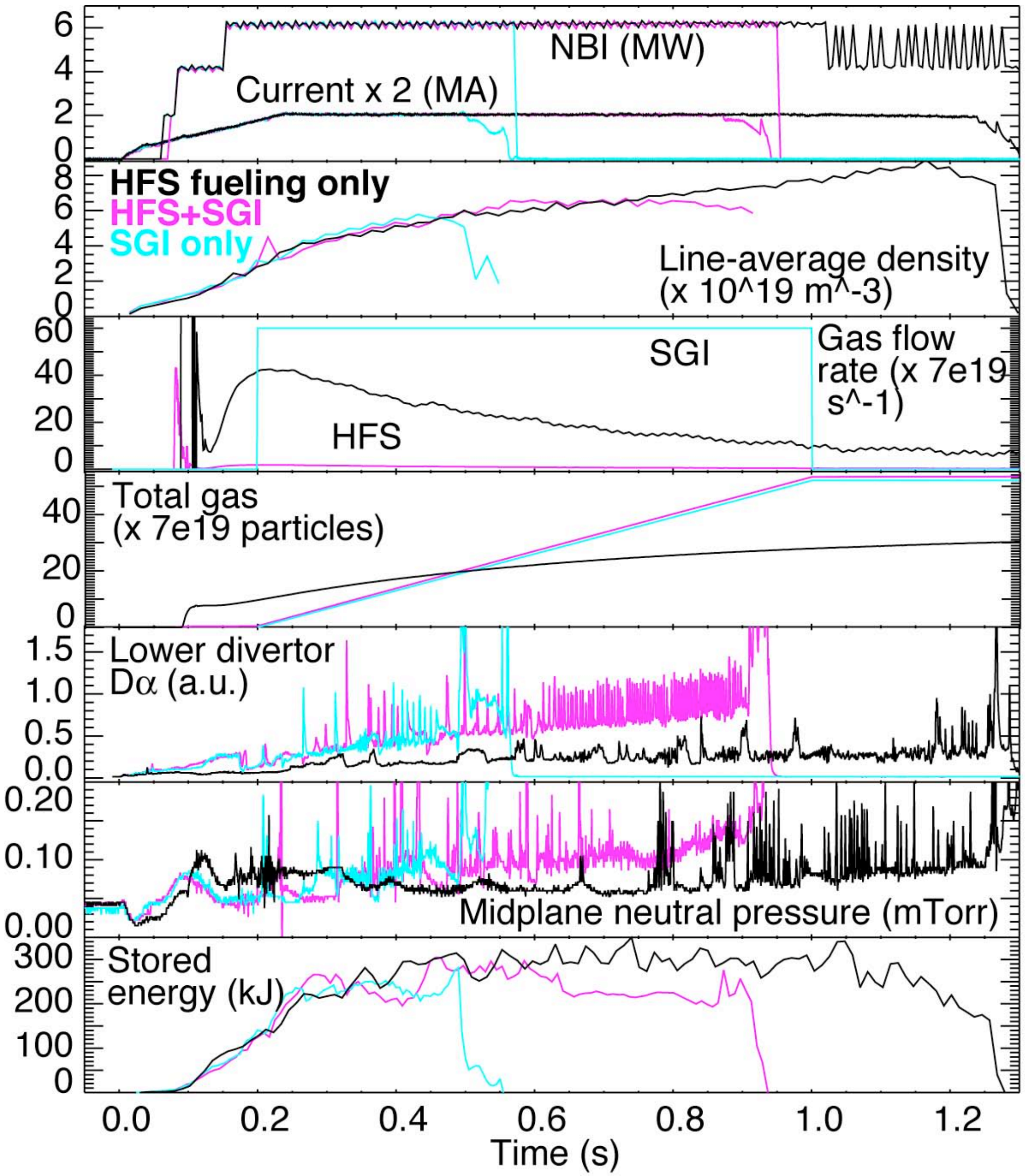


- Instantaneous fueling efficiency (FE) is calculated as $dN_e/dt * \Gamma^{-1}$
- In ohmic plasmas, FE is a function of SGI-LCFS distance (SGI at Γ ~ 40 Torr l /s) in LSN configuration
- FE in inner wall -limited plasmas higher than in diverted config.'s
- FE in LSN H-mode plasmas 0.1-0.4 (SGI at Γ ~ 65 Torr l /s ~ 4.2 x 10^{21} s^{-1}).



IW-limited L-mode target plasma for lithium experiments

HFS fueling can be replaced by SGI fueling without H-mode density reduction



- Shown three discharges with full High Field Side (HFS) fueling, reduced HFS fueling and SGI, and SGI fueling only
- Note **ELM** regime change from small and type I to **type III** in SGI-fueled plasmas
- Total gas input is greater with SGI fueling
- HFS fueling reduced by x 9
- Experiment was run when multi-pulse SGI capability was not yet available

Plasma edge density profiles show clear increase due to high-pressure jet

- ✓ Reduced HFS flow rate by x 3 (plenum pressure from 1100 Torr to 500 Torr
- ✓ SGI-U gas jet operated at 5-7 cm from plasma separatrix
- ✓ Injection pulses result in pedestal density increase, SOL density same
- ✓ Analysis of 2007 data is in progress to determine fueling efficiency of high-pressure SGI fueling