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Supersonic gas jet fueling in NSTX (XP 626)

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Acknowledgements:

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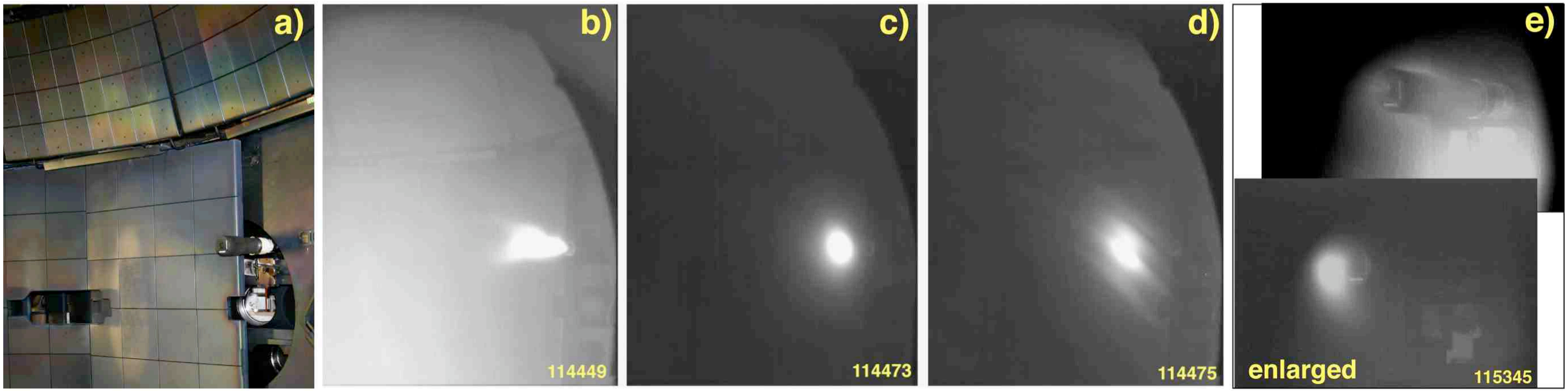
XP 626 summary

- 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 x 20 high field side (HFS) fueling rate 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 $\Gamma < 5 \times 10^{21}$ particles/s in quantities 0.1 - 0.3 of NSTX plasma inventory in a multi-pulse, continuous fashion with measured fueling efficiency 0.1 - 0.3
- SGI has been used “commercially” in several XPs

Supersonic gas jet does not perturb plasma edge



- Used Canadian Photonic camera with 0.5-2 ms framing rate
- Example frames above: (a) SGI in NSTX vacuum vessel, (b) SGI injecting gas into collapsing plasma with a wide T_e = 3 eV, n_e = (2-2.5) x 10^{18} m^{-3} scrape-off layer, (c) 6 MW NBI-heated L-mode plasmas, (d) 4 MW NBI-heated H-mode plasmas, (e) ohmic plasmas at 3 cm distance from LCFS
- Plasma filaments (“blobs”) are often observed to traverse through gas jet

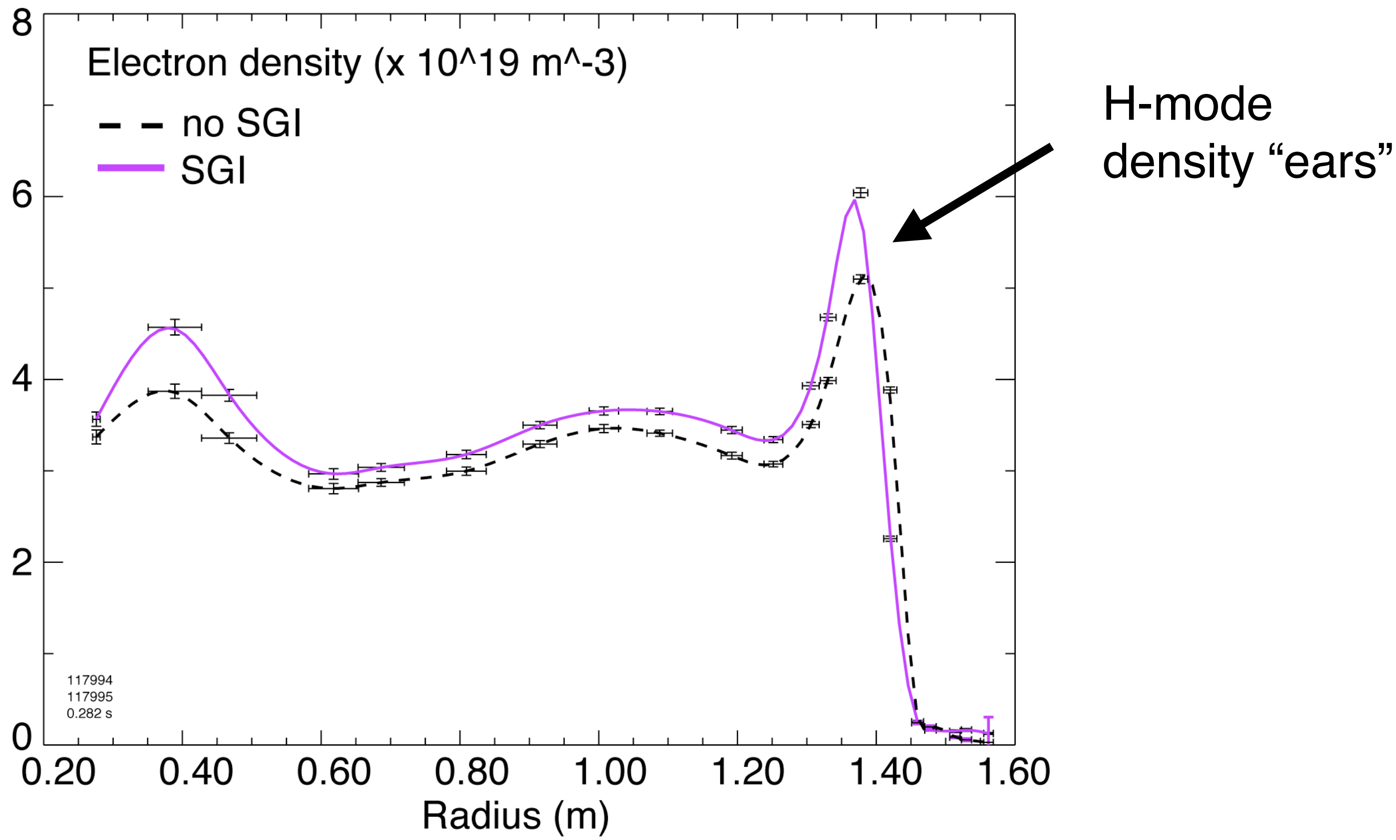
- During supersonic gas injection
  - SGI Langmuir probe does not typically show T_e reduction or I_{sat} increase
  - Magnetic sensors do not show any EM perturbations

SGI-fueled H-mode plasmas demonstrate different properties (low power threshold, type III ELMs)

I_p (MA)	P_{NBI} (MW)	Magnetic configuration	Fueling	Power threshold (MW)	ELM type	Comment
0.7-1.0	2-6	LSN, $\delta=0.4$, $\kappa<2.2$	HFS	1-2	I, small	**Uncontrolled density rise due to HFS fueling**
0.7-1.0	2-6	DN, $\delta=0.8$, $\kappa<2.2$	HFS	1-2	I, small	
0.7-1.0	2-4	LSN, $\delta=0.4$, $\kappa<2.2$	HFS + SGI	< 2	small	**HFS fueling can be reduced or eliminated**
0.8-1.0	4-6	DN, $\delta=0.8$, $\kappa<2.2$	HFS + SGI	< 2	small, III	

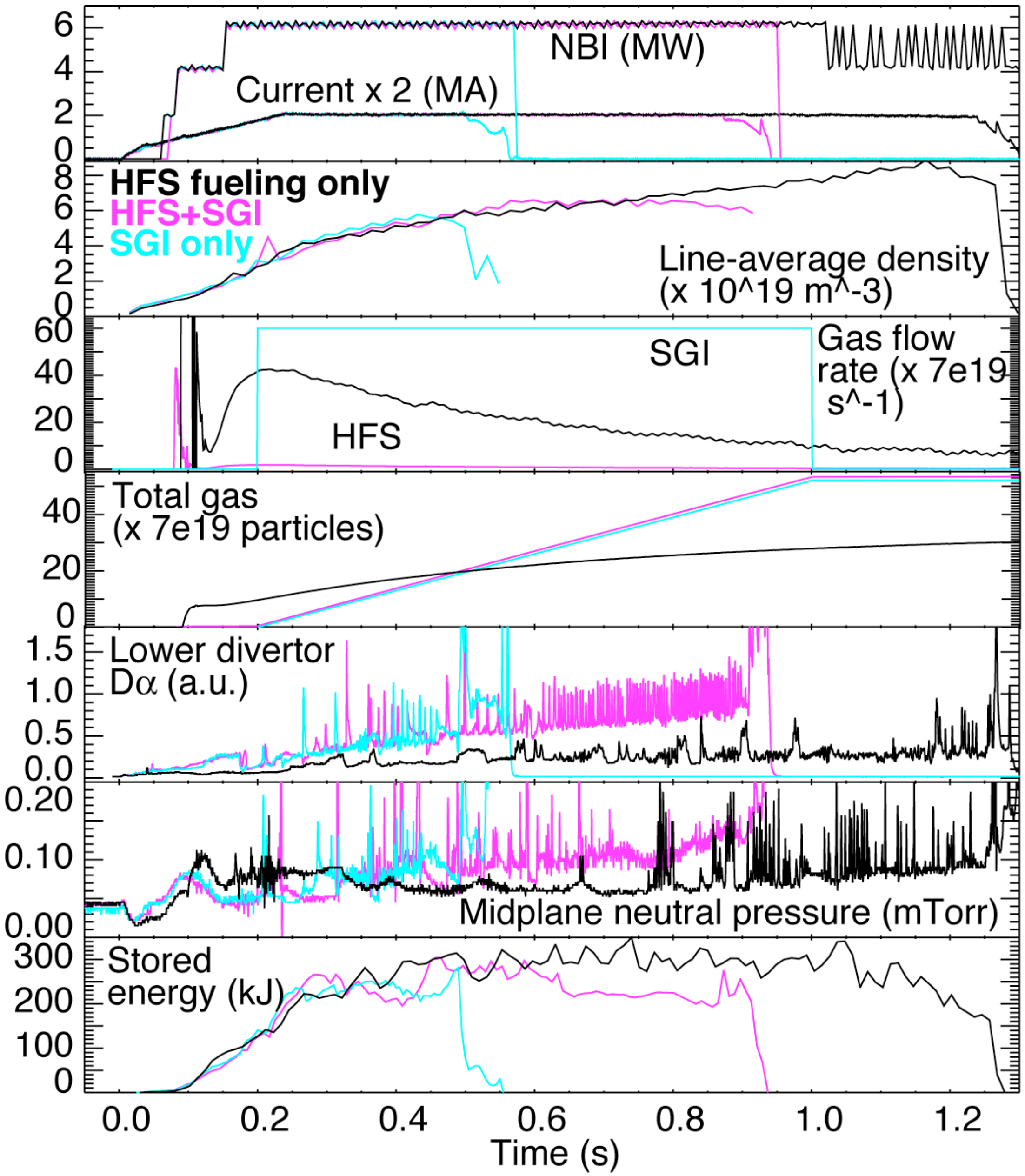
- Purpose of H-mode fueling experiments: eliminate uncontrolled density rise observed in HFS-fueled H-mode plasmas
- H-mode power threshold is low with LFS SGI fueling (high with LFS gas)
- With SGI fueling - transition from type I to type III ELMs in Double Null
- H-mode references: R. Maingi et al. PPCF 46 (2004) A305, NF 43 (2003) 969

In H-mode plasmas supersonic gas jet deposits particles in SOL and edge



- Supersonic gas jet does not penetrate further than 1-4 cm from separatrix
- Density rise is often seen in H-mode density profile "ears", often "ears" width increases. Pedestal width/height analysis in progress…
- T_e profiles indicate pedestal and core reduction by up to 10-15 %

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



- Shown three discharges with full 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

Future work

- Hardware improvements under consideration:
  - Independent gas handling system
  - Increased plenum pressure (presently limited to 2500 Torr)
  - New supersonic nozzles
  - Density feedback with SGI using Plasma Control System

- Experiments under consideration
  - Low density H-mode plasma development
  - H-mode density control with SGI
  - ELM regimes characterization - power and gas injection scan
  - ELM control with SGI

Supersonic gas jet is a unique fueling technique studied on NSTX

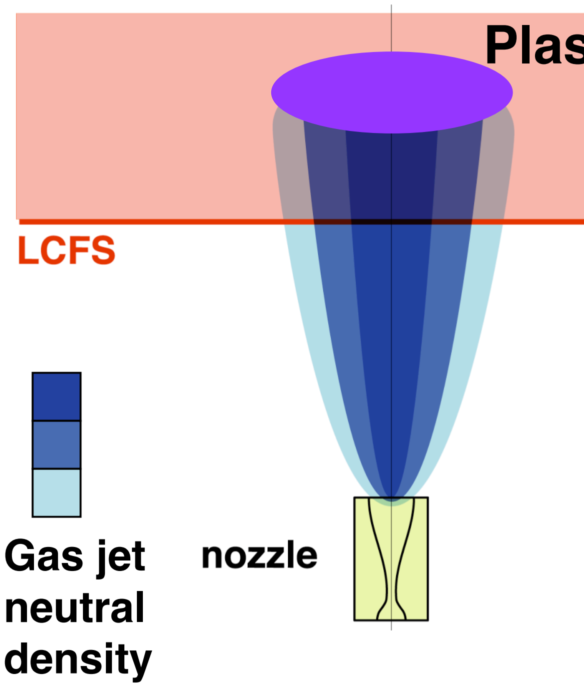
- **Improve and optimize gas fueling**
  - ITER will rely on central fueling (pellet, compact toroid), however plasma start-up and edge fueling will use gas puffing

- Supersonic gas injector installed on NSTX in 2004, experiments conducted in ohmic and NBI H-mode plasmas in 2005-2006

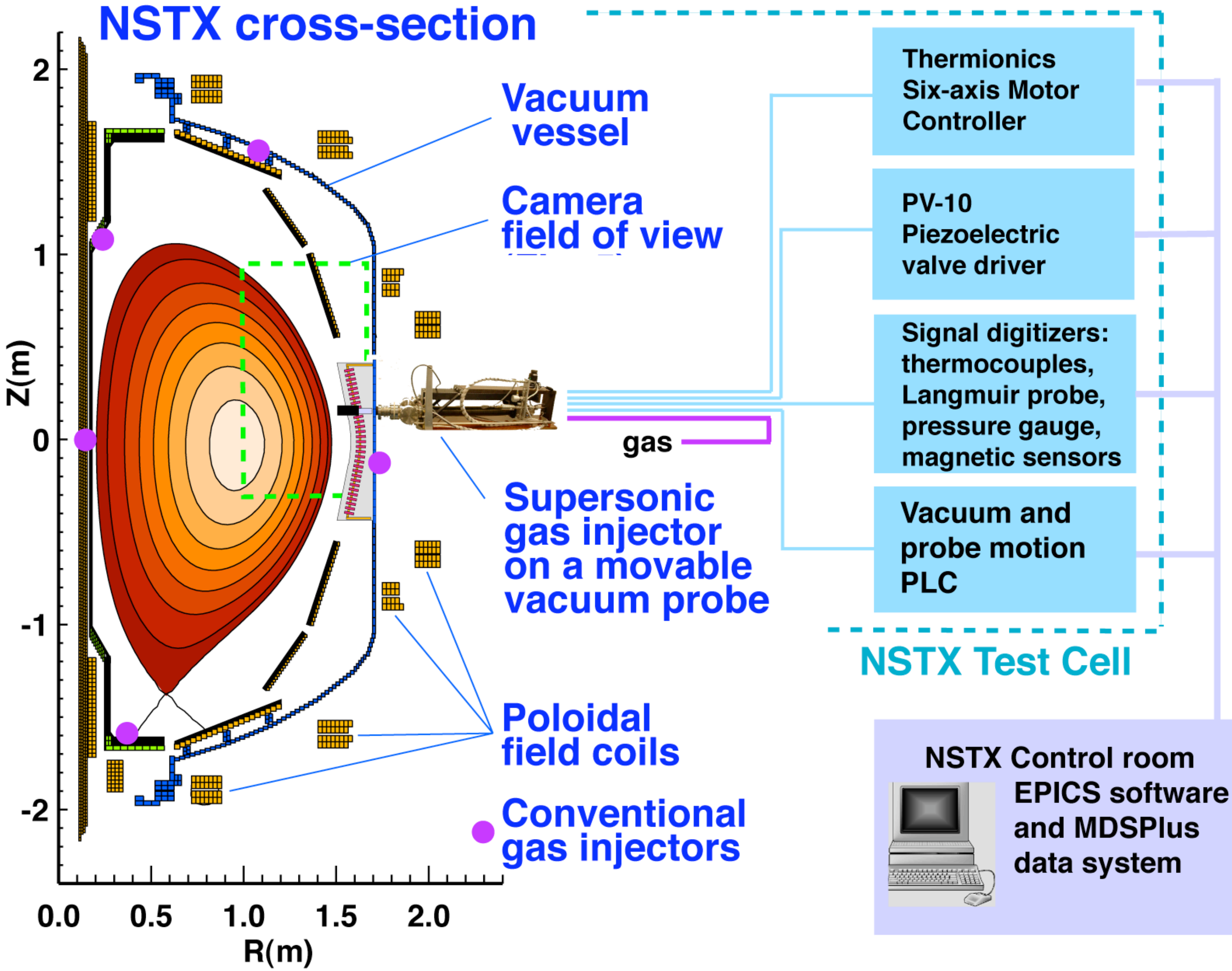
- Supersonic gas jet fueling was studied on other facilities
  - limiter tokamaks (HL-1M, Tore Supra): injected 0.2-0.9 of total plasma inventory in several ms, perturbative, fueling efficiency 0.3-0.6
  - divertor tokamak (AUG), divertor stellarator (W7-AS): similar gas jet parameters, but fueling efficiency ~ 0.1-0.3

Supersonic gas jet penetration mechanism

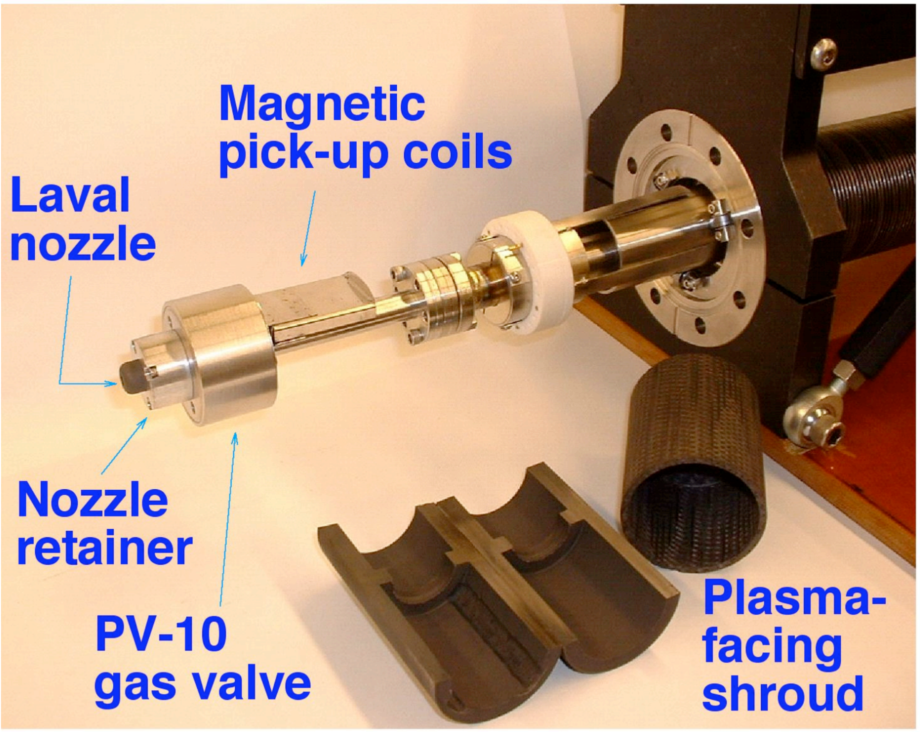
- Supersonic gas jet is a low divergence high pressure, high density gas stream
- Velocity distribution function is drifting narrowed Maxwellian with $u_{drift} = u_{flow}$
  $u_{flow} = M\,c = M\sqrt{\gamma\,kT/m} > v_{therm}$
- SOL/edge electrons with low T_e do not fully penetrate gas jet, gas jet retains neutral (molecular-atomic) -ion structure, eventually ionizes and creates a plasmoid
- High density plasmoid blocks jet from deep penetration into magnetized plasma
- Depth of penetration is determined by jet pressure (density) and plasma kinetic and magnetic pressure
- Single particle ionization / charge exchange penetration model is inapplicable
- Modeling must include continuity, momentum, energy balance (Braginskii) equations with detailed reaction rates and neutral transport

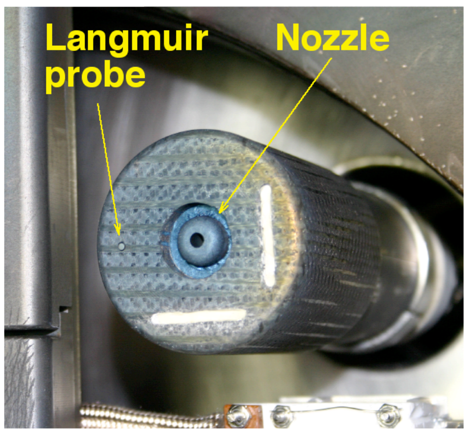


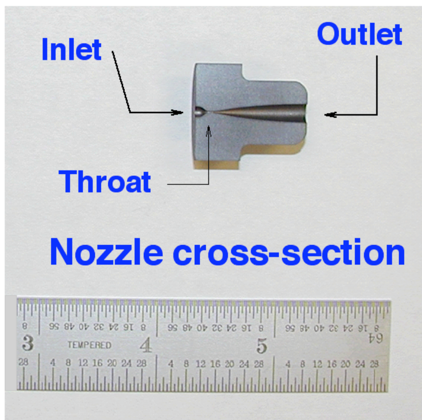
SGI on NSTX: placement and control elements



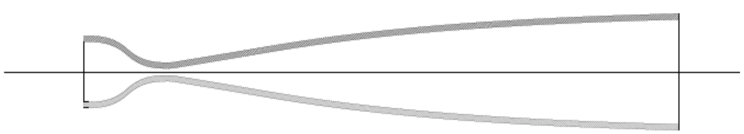
SGI head is a densely packed apparatus



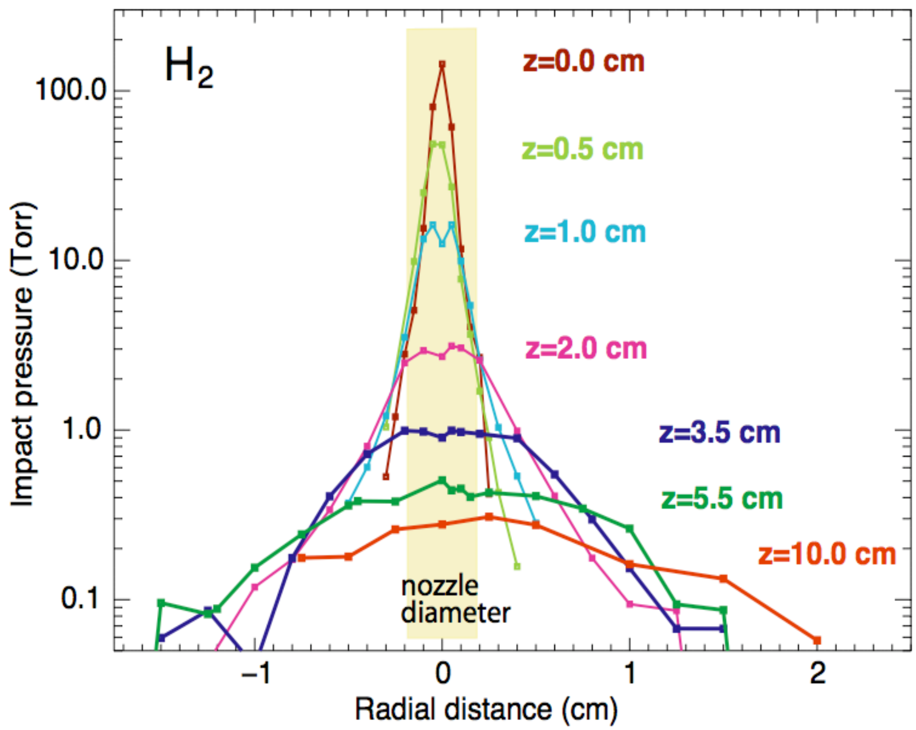


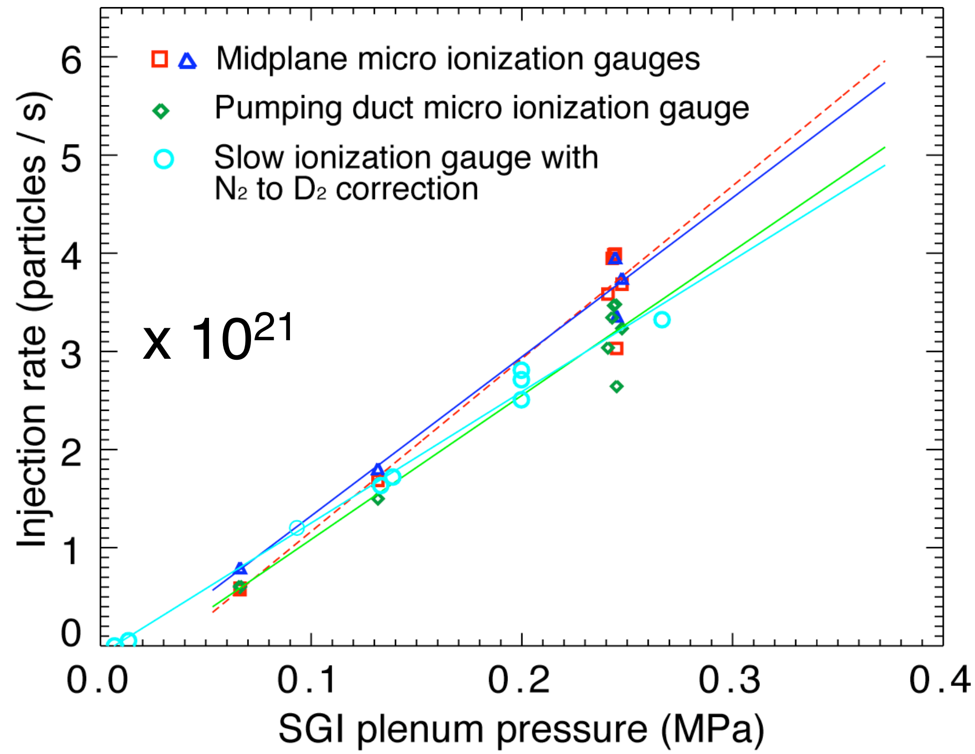


- Shroud: CFC and ATJ graphite
- Gas valve: Veeco PV-10 piezoelectric type, d_{throat}=0.02", typical opening time 1-2 ms, driving voltage 150 V
- Thermocouples in shroud and in gas valve
- Two magnetic pick-up coils on shroud front surface for B_z, B_t measurements
- Three magnetic pick-up coils in 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 Laval geometry, L = 23.4 mm, d_{throat} = 0.01"



SGI parameters characterized off-line and *in situ*





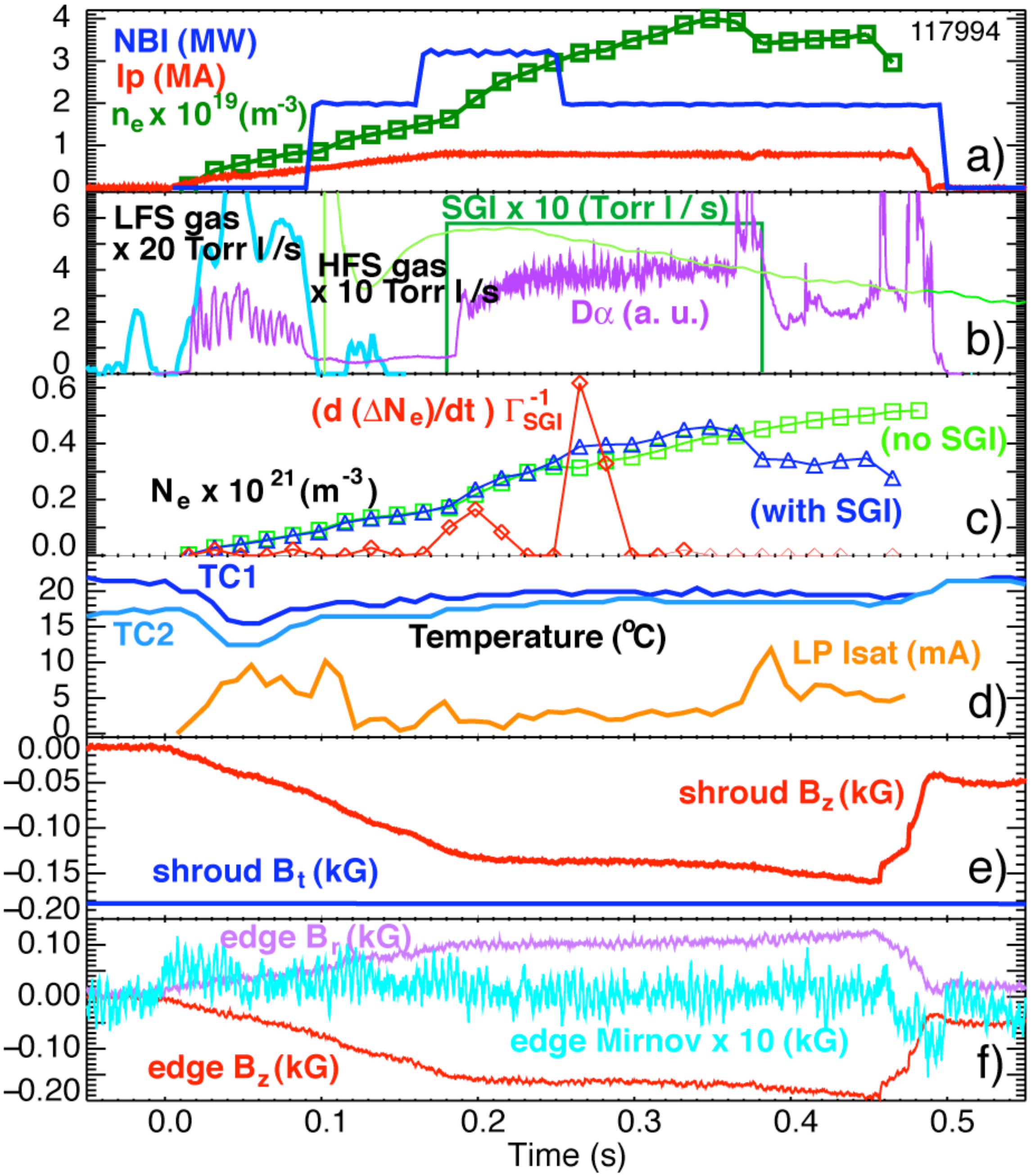
- NSTX SGI is operated at 45-60 Torr l /s (~ (3.2 - 5) x 10^{21} mol/s)

- Jet divergence half-angle: 6^o - 25^o

- Hydrogen / Deuterium: $M = 4$, $T \sim 60 - 160$ K, $\rho < 5 \times 10^{17}$ cm^{-3},

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

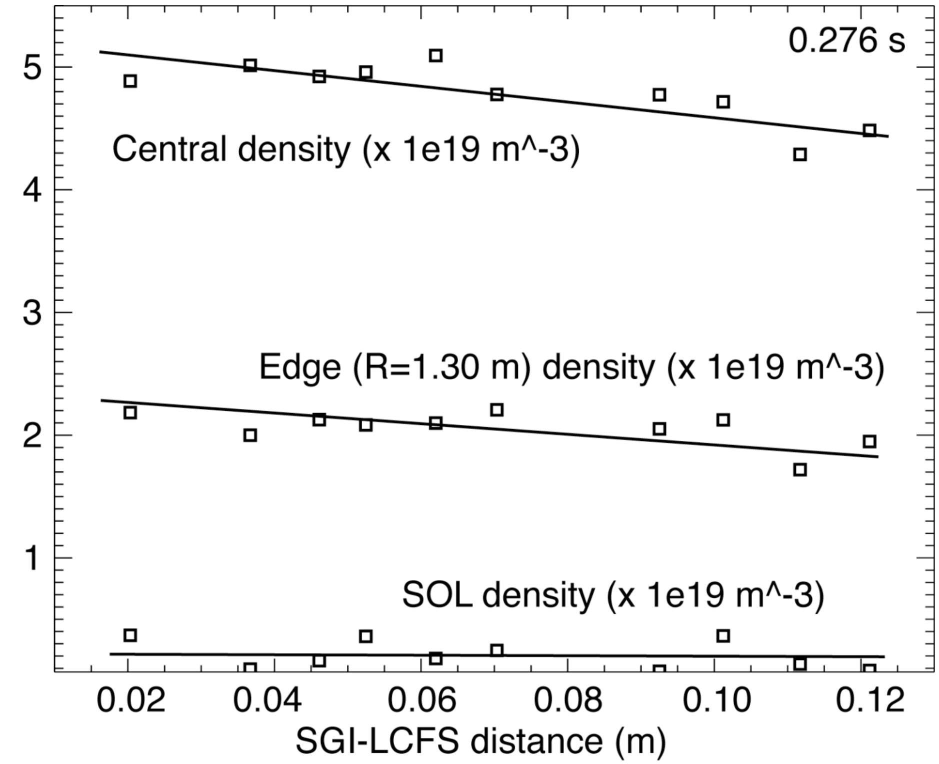
SGI H-mode fueling efficiency 0.1-0.3

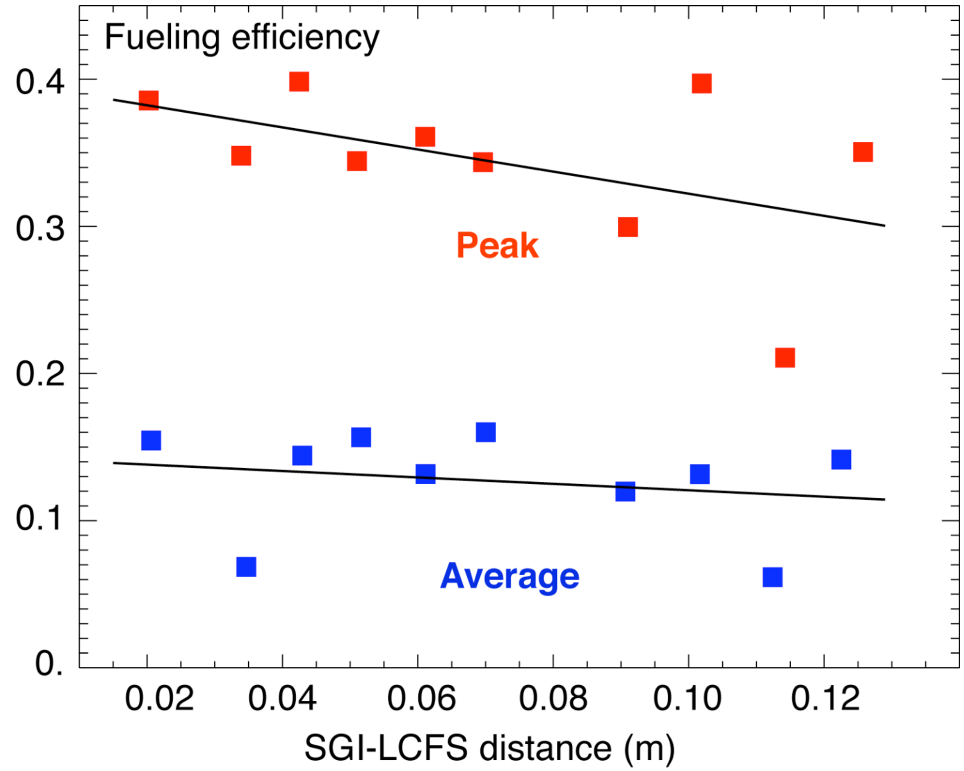


- Example of 2-3 MW NBI HFS and SGI fueled LSN H-mode plasmas
- Density approaching Greenwald scaling limit
- SGI turns on at 0.180 s
- Supersonic gas jet does not perturb plasma edge

- (a) I_p, P_{NBI}, n_e
- (b) Gas injection rates, Dα
- (c) Electron inventory N_e, fueling efficiency
- (d) SGI thermocouples, Langmuir probe I_{sat}
- (e) and (f) - various SGI magnetic field and magnetic fluctuation sensors

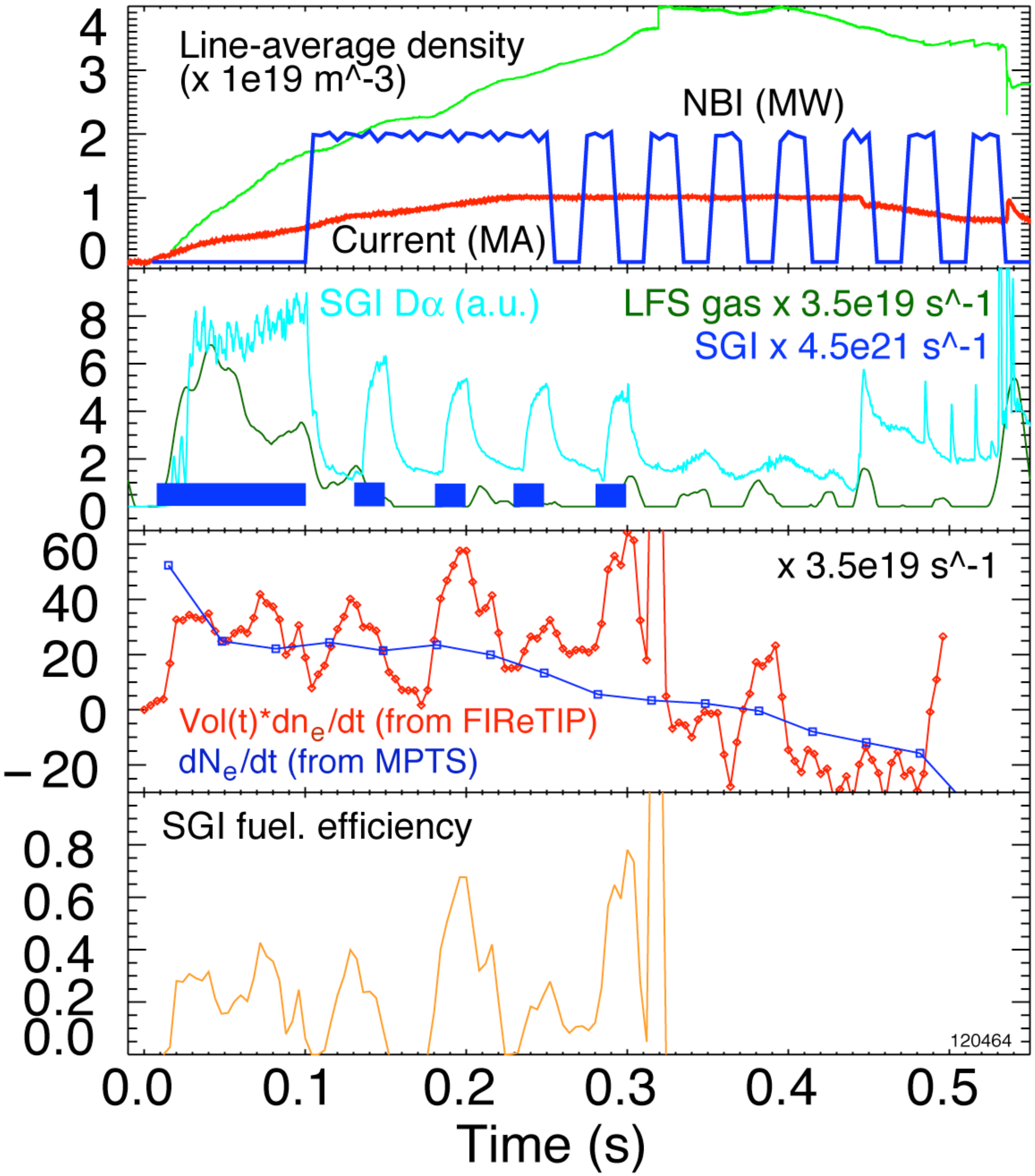
Fueling efficiency is a function of SGI plenum pressure and distance to plasma





- Experiments in ohmic plasmas were conducted at reduced Γ_{SGI}=2.8 x 10^{21} s^{-1}
- Calculated instantaneous fuelling efficiency (dN_e/dt) * Γ_{SGI}, then averaged over Γ_{SGI}
- Plasma density and fueling efficiency is a weak function of SGI-separatrix distance
- Need to run SGI at highest plenum pressure (presently 2500 Torr) and as close as possible to plasma

Fueling efficiency higher in inner-wall limited plasmas



- Example of NBI-heated inner wall limited L-mode plasma
- Pulsed SGI fueling
- Fueling efficiency 0.1 - 0.4
- Result important for using SGI during start-up when plasma is limited
- Instantaneous fueling efficiency is calculated using plasma volume *Vol(t)* and *dn_e/dt* from FIReTIP interferometer
- SGI at Γ~4.2 x 10^{21} s^{-1}

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 < 65 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)

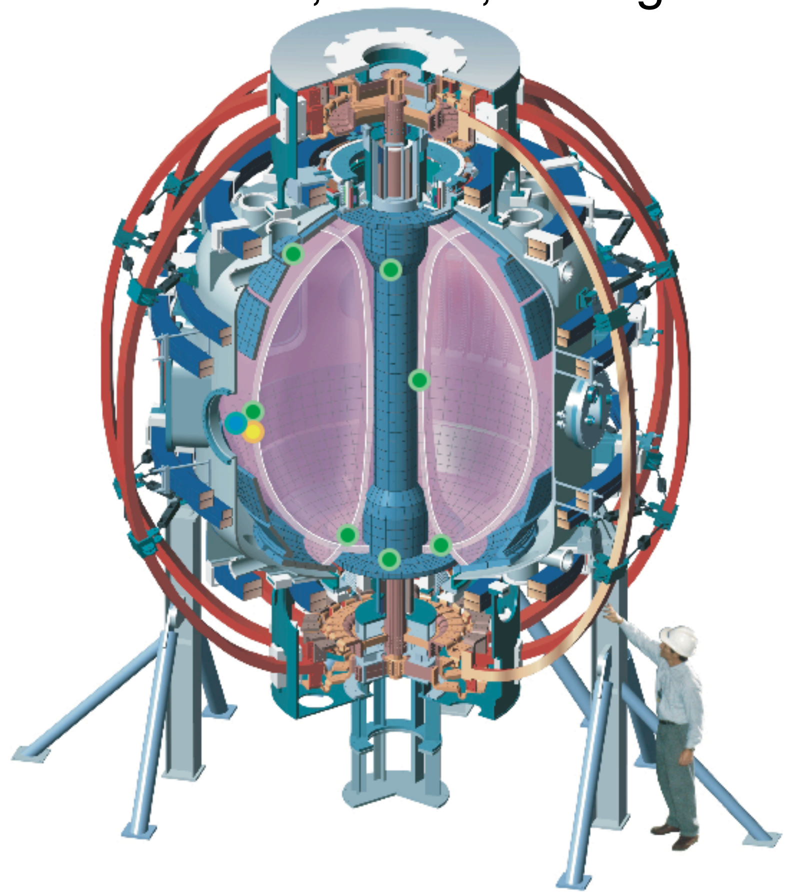
• Conditioned walls

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