Supported by Office of Science

Supersonic gas jet fueling experiments on the National Spherical Torus Experiment

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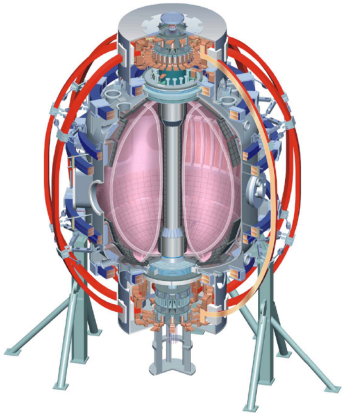
Poster P5.118



33rd EUROPEAN PHYSICAL SOCIETY
Conference on Plasma Physics
Roma, Italy
June 19 - 23, 2006

33rd
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Abstract

Options for fueling future reactor-type tokamaks, such as ITER, include frozen fuel pellets or compact toroids for central and edge fueling, and conventional gas puffing for the initial plasma density build-up and edge density sustainment. A possible improvement to the gas puffing technique - a supersonic gas (SG) jet fueling - is studied in the National Spherical Torus Experiment (NSTX). The NSTX SG injector is comprised of a graphite converging-diverging Laval nozzle, a piezoelectric gas valve, and a diagnostic package (Langmuir probe, thermocouples and magnetic pick-up coils) mounted on a movable probe at a low field side (LFS) midplane port location. The nozzle operates in a pulsed regime at room temperature, reservoir gas pressure up to 0.33 MPa, Mach number of about 4, and a deuterium jet divergence half-angle of 5° - 40°. A high gas jet Mach number is an indicator of its directionality, high density and divergence. The SG jet has been used for fueling of both L- and H-mode plasmas. The injector was located at a distance 2-15 cm from the plasma separatrix in ohmically heated discharges, and 10-15 cm in 2-4 MW NBI-heated discharges to avoid interaction with lost orbit energetic particles. The fueling efficiency in the range 0.1 - 0.3 was inferred from the plasma electron inventory analysis. It was sensitive to the edge plasma pressure and edge intrinsic plasma perturbations, such as MHD modes and small ELMs. The fueling efficiency appeared to be a function of the SG jet pressure. In contrast to a conventional LFS gas injection, steady-state SG injection in the H-mode phase at a rate up to 4.5×10^{21} particles/s did not cause an H to L transition. The density pedestal height increased by up to 20 %, while lower divertor and midplane neutral pressures were obtained. The SG jet fueling is part of the NSTX density control program which also includes wall conditioning tools, in particular, the evaporated lithium coatings planned for the upcoming experimental campaign. This work is supported by U.S. DOE in part under Contracts No. W-7405-Eng-48 and DE-AC02-76CH03073.

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 $\Gamma < 5 \times 10^{21}$ 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

Visit NSTX SGI homepage at nstx.pppl.gov/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

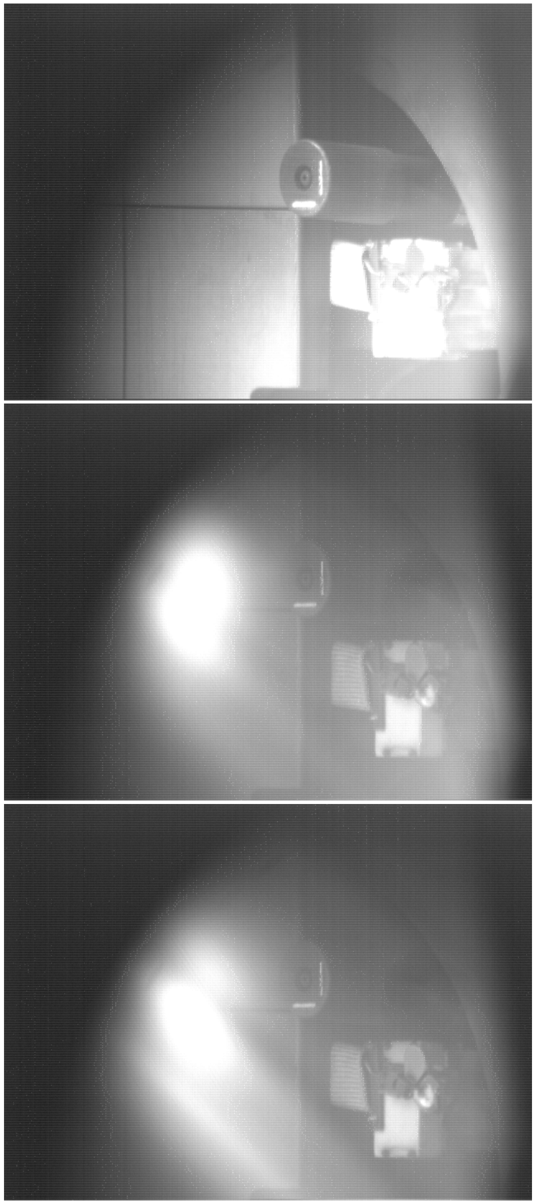
- Supersonic gas injector installed on NSTX in 2004, experiments conducted in ohmic and NBI H-mode plasmas in 2005-2006

- 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 fueling yields promising initial results on NSTX

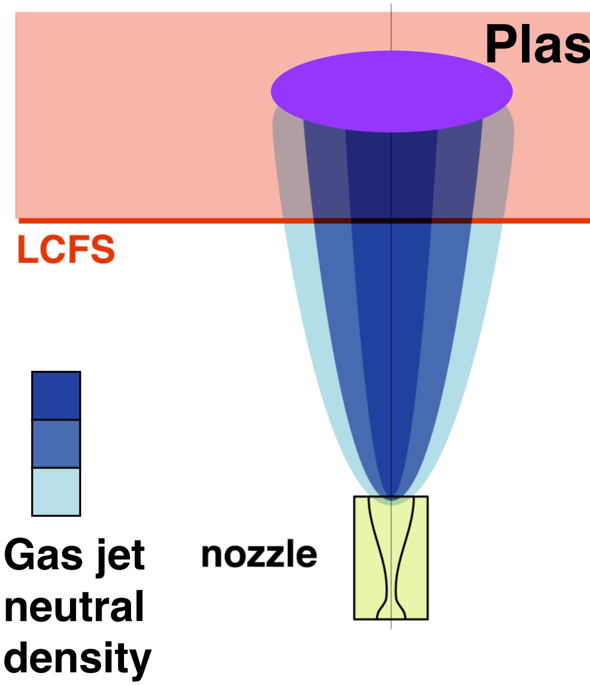
Outline of poster

- Supersonic gas injector and diagnostic package commissioned on NSTX
- Demonstrated possibility of H-mode fueling and substantial HFS fueling reduction
- Studied fueling efficiency and penetration
  - Fueling efficiency is a function of SGI plenum pressure and distance to plasma
  - Present setup does not appear to enable gas jet penetration - need to increase gas jet pressure

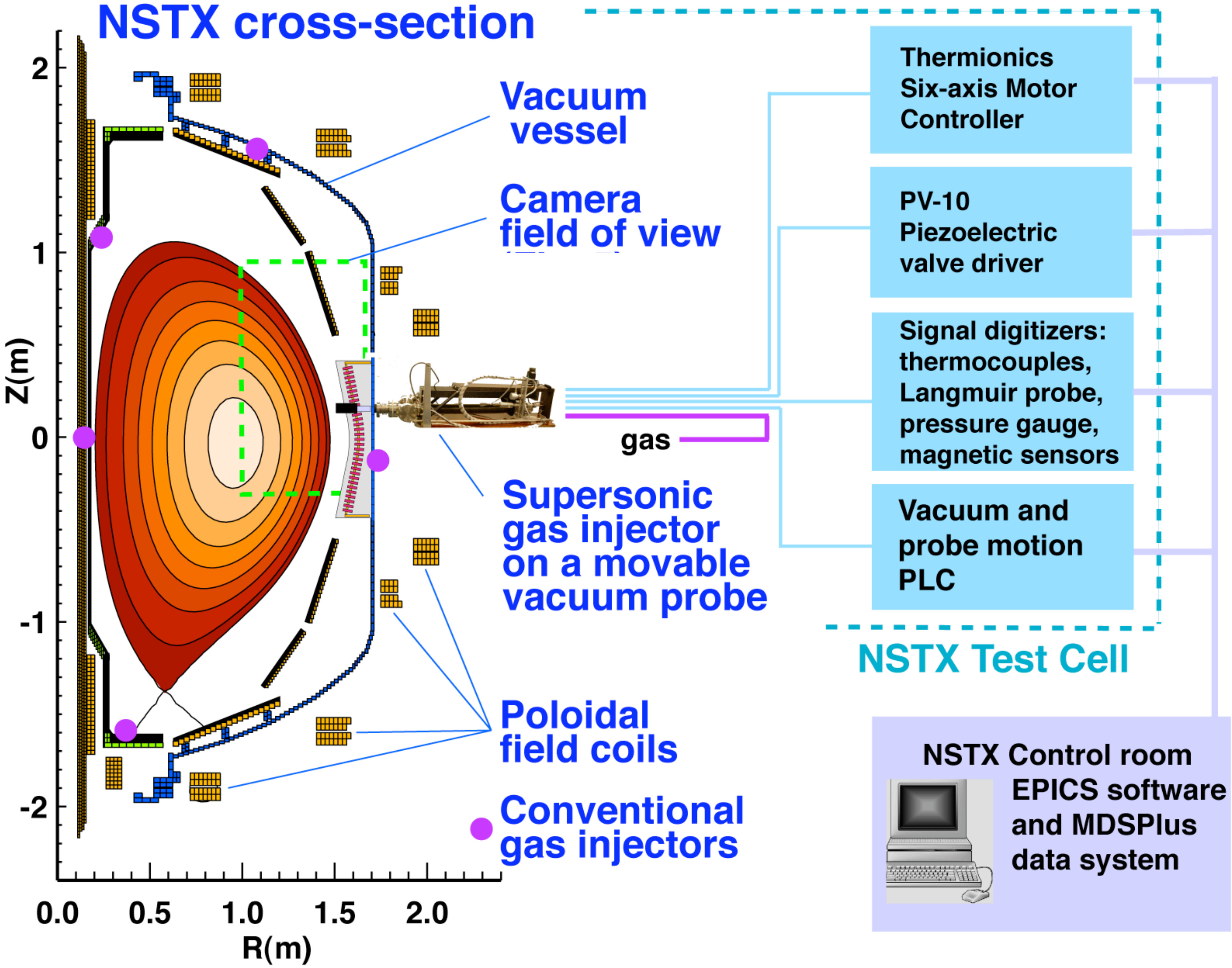


Supersonic gas jet penetration mechanism

- 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



NSTX cross-section

Vacuum vessel

Camera field of view

Supersonic gas injector on a movable vacuum probe

Poloidal field coils

Conventional gas injectors

Thermionics Six-axis Motor Controller

PV-10 Piezoelectric valve driver

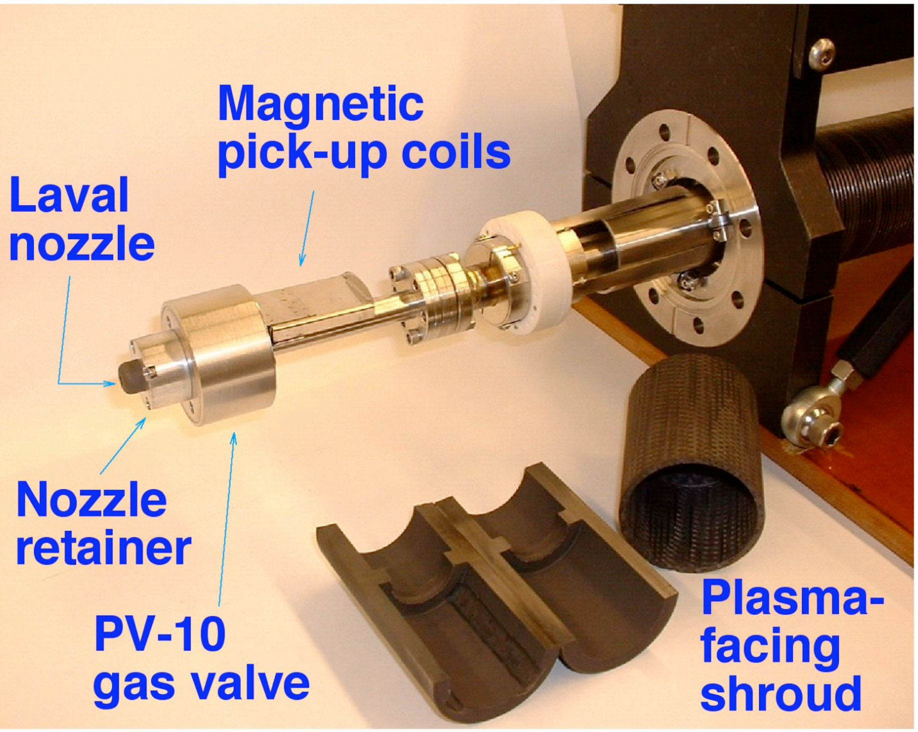
Signal digitizers: thermocouples, Langmuir probe, pressure gauge, magnetic sensors

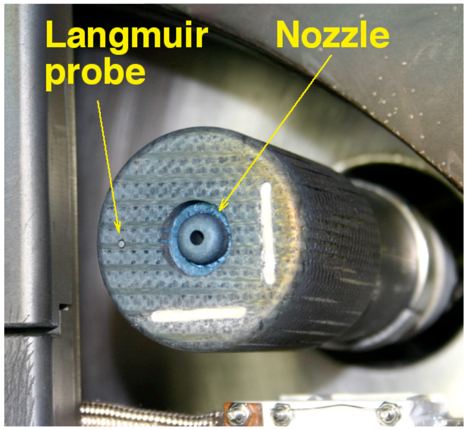
Vacuum and probe motion PLC

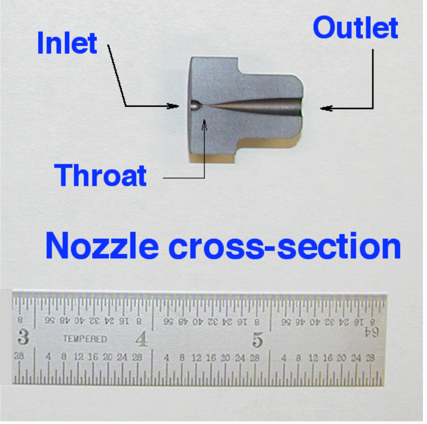
NSTX Test Cell

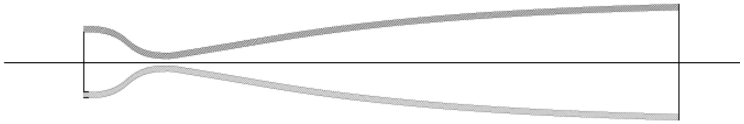
NSTX Control room
EPICS software and MDSPlus data system

SGI head is a densely packed apparatus



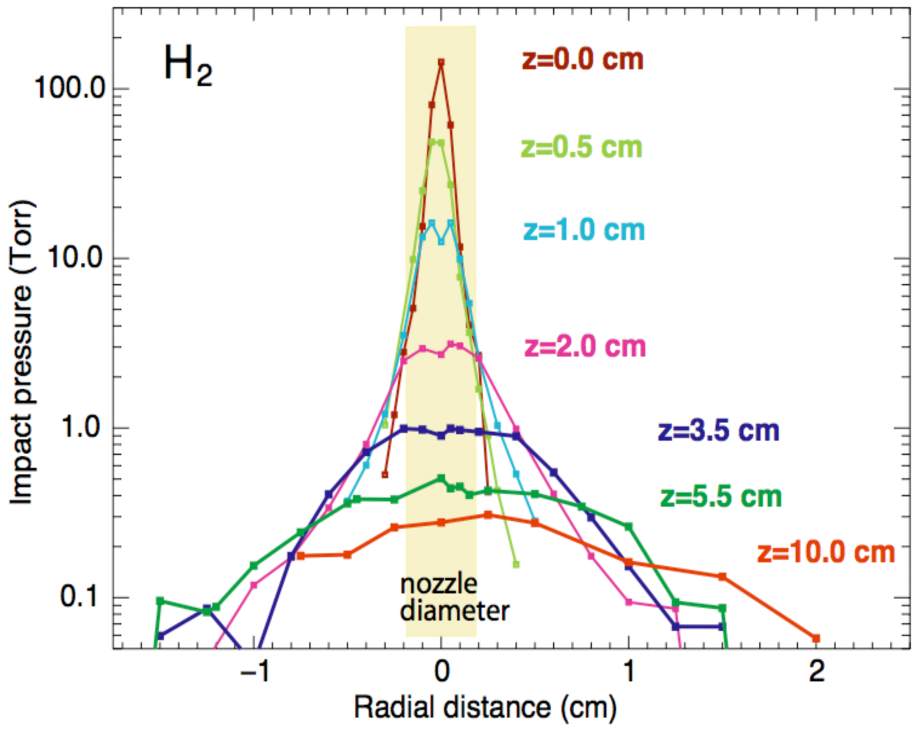


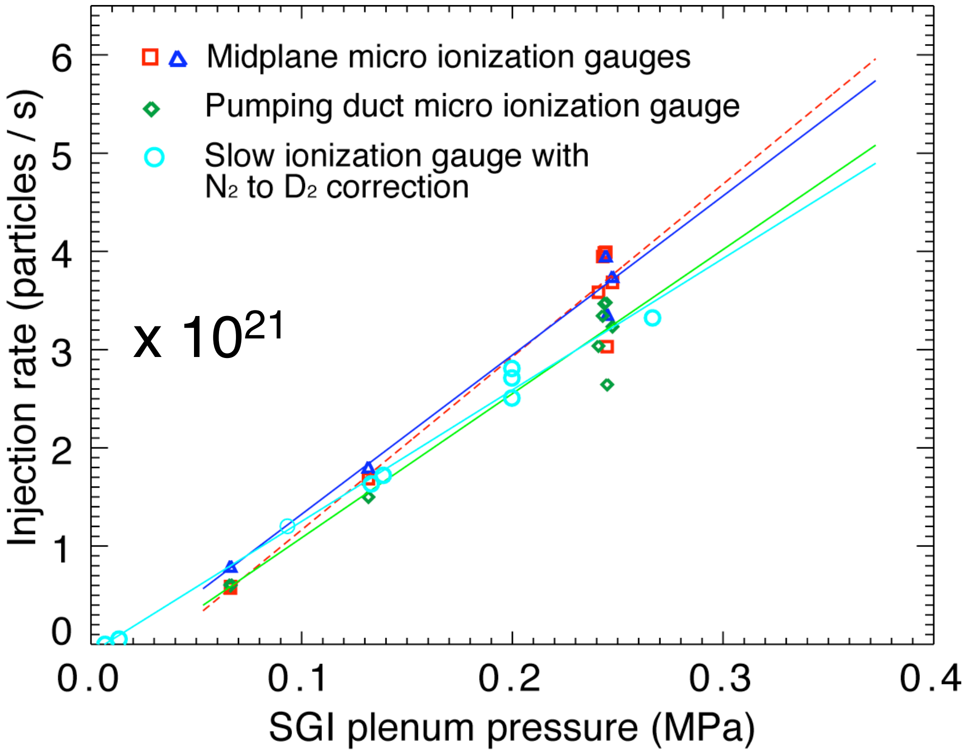




- Shroud: CFC and ATJ graphite
- Gas valve: Veeco PV-10 piezoelectric type, d_{throat}=0.02", typical opening time 1-2 ms, driving voltage 150 V
- Thermocouples in shroud and in gas valve
- Two magnetic pick-up coils on shroud front surface for B_z, B_t measurements
- Three magnetic pick-up coils in 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° - 25°

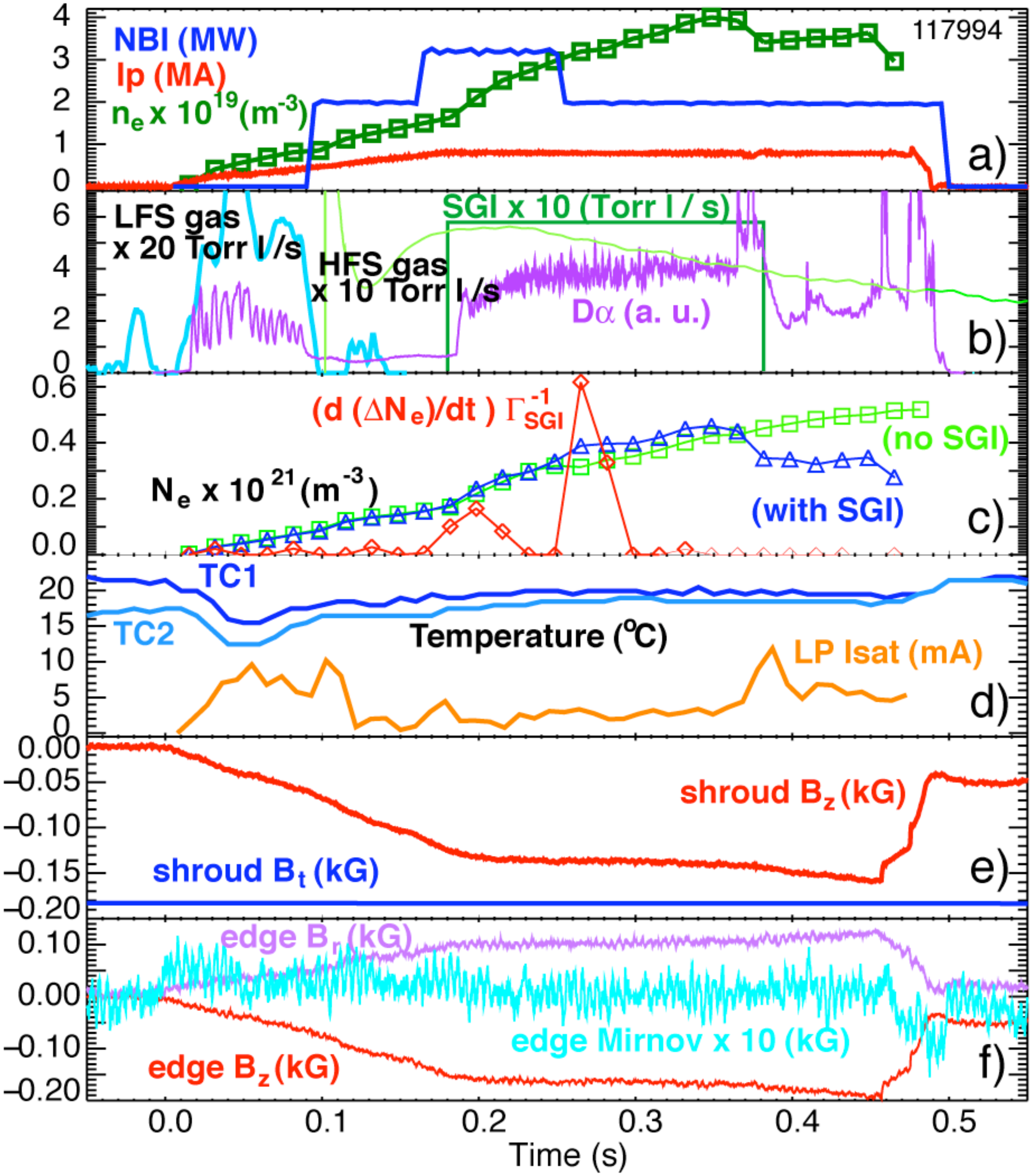
- Hydrogen / Deuterium: $M = 4$, $T \sim 60 - 160$ K, $\rho < 5 \times 10^{17}$ cm^{-3}, $Re = 6000$, $v_{therm} \sim 1100$ m/s, $v_{flow} = 2400$ m/s

SGI-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 SGI fueling H-mode 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

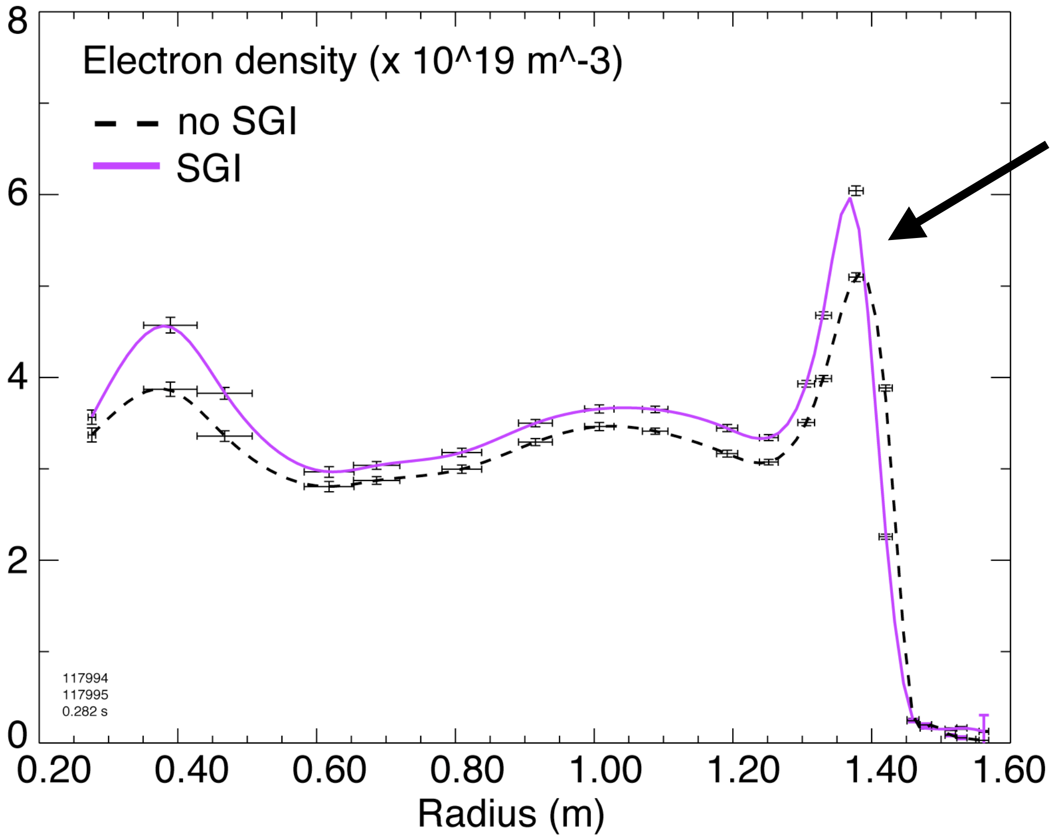
SGI H-mode fueling efficiency 0.1-0.3



- 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

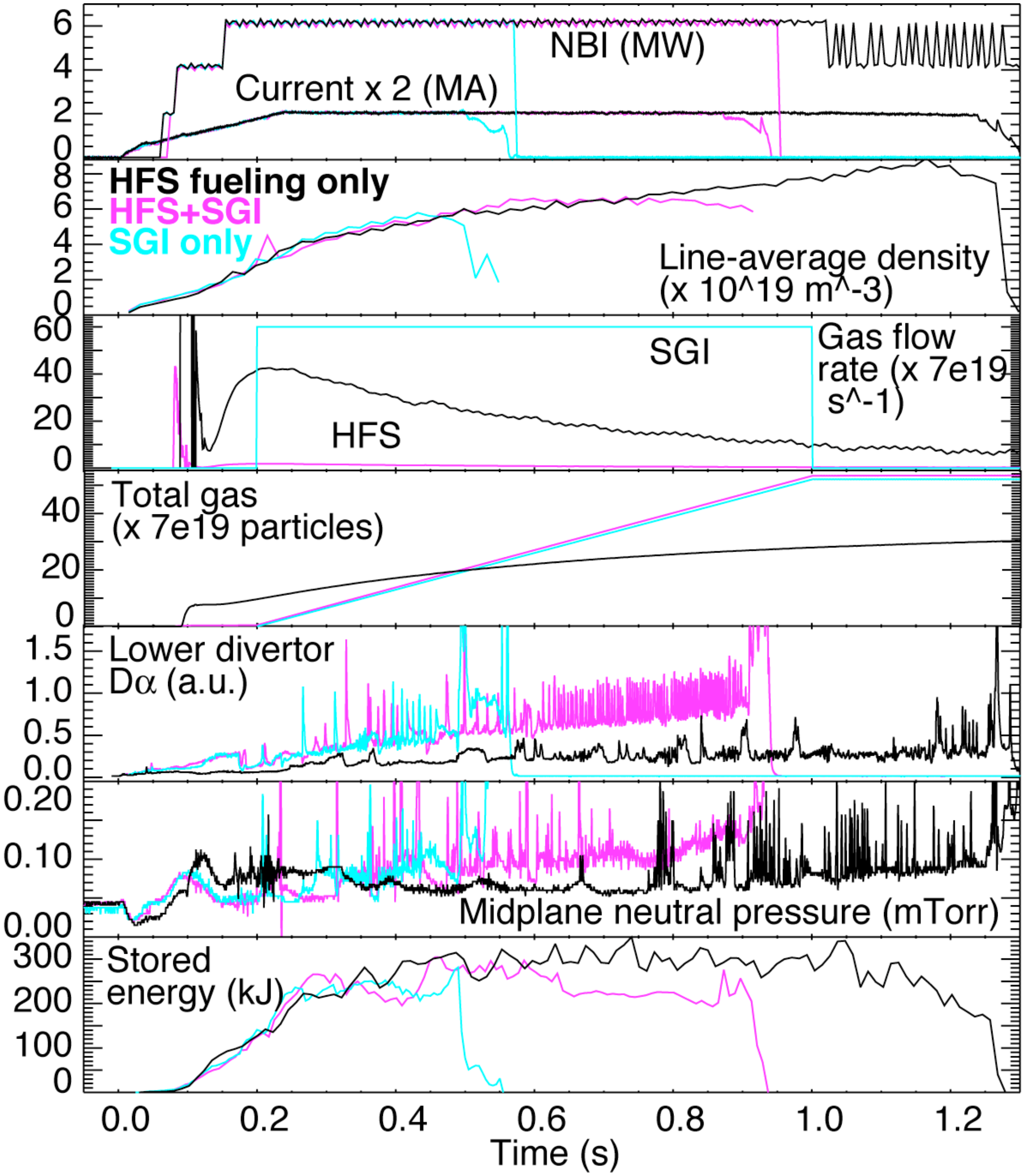
In H-mode plasmas supersonic gas jet deposits particles in SOL and edge



H-mode density “ears”

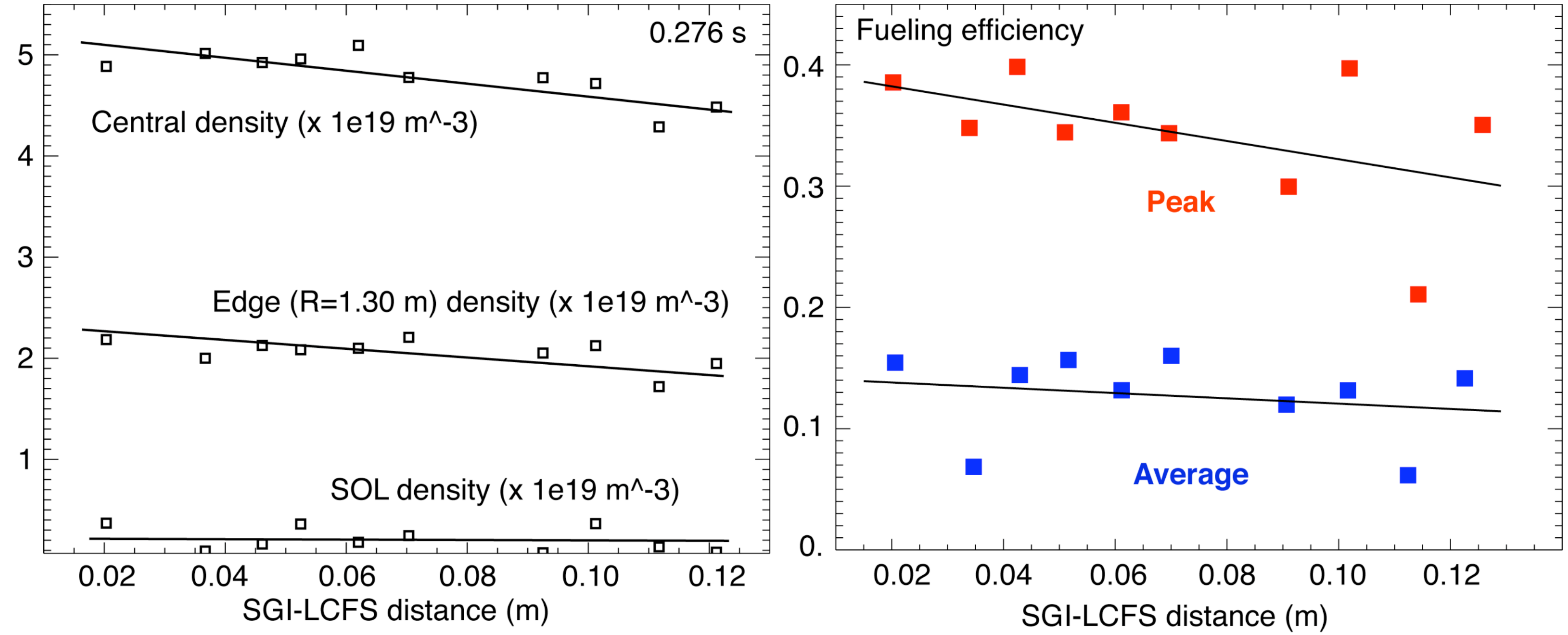
- Supersonic gas jet does not penetrate further than 1-4 cm from separatrix
- Density rise is often seen in H-mode density profile “ears”
- Often “ears” width increases
- T_e profiles indicate pedestal and core reduction by up to 10-15 %

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



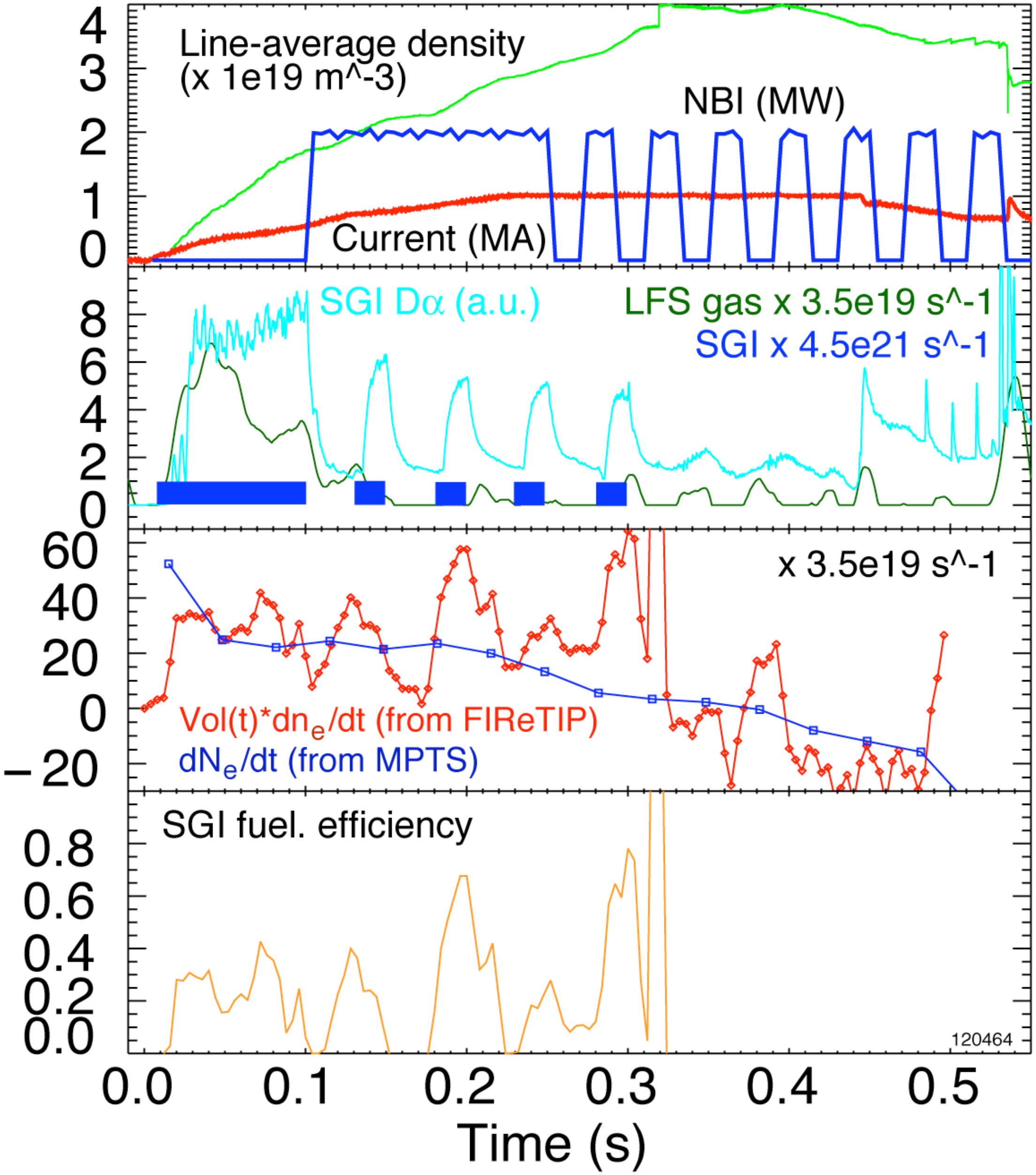
- Shown three discharges with full HFS fueling, reduced HFS fueling and SGI, and SGI fueling only
- Note **ELM** regime change from small and type I to **type III** in SGI-fueled plasmas
- Total gas input is greater with SGI fueling
- HFS fueling reduced by x 9
- Experiment was run when multi-pulse SGI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

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



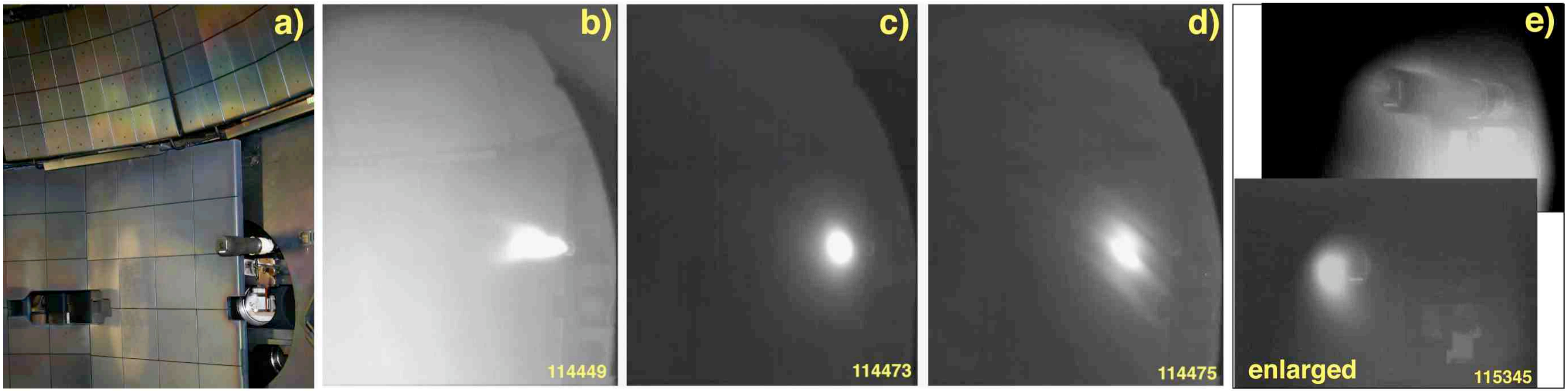
- Experiments in ohmic plasmas were conducted at reduced Γ_{SGI}=2.8 x 10^{21} s^{-1}
- Calculated instantaneous fuelling efficiency (dN_e/dt) * Γ_{SGI}, then averaged over Γ_{SGI}
- Plasma density and fueling efficiency is a weak function of SGI-separatrix distance
- Need to run SGI at highest plenum 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 $\Gamma \sim 4.2 \times 10^{21}$ s^{-1}

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, $n_e = (2\text{-}2.5) \times 10^{18}$ 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 much T_e reduction or I_{sat} increase
  - Magnetic sensors do not show any EM perturbations

Future work

- Hardware improvements under consideration:
  - Independent gas handling system
  - Increased plenum pressure limit (presently limited to 2500 Torr)
  - New more efficient 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

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

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”