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H-mode fueling optimization with supersonic deuterium jet in NSTX

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Abstract

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A conventional gas injection (GI), and its variant, a supersonic gas injection (SGI), are candidate fueling techniques for the initial plasma density build-up and local SOL density control, e.g. in front of radio-frequency antennas or in the divertor region, in future large tokamaks, such as ITER. On NSTX, long-pulse 0.7-0.9 MA 6 MW NBI-heated small ELM H-mode plasma discharges have been developed as prototypes for extrapolation to future spherical tori. It is envisioned that innovative lithium coating techniques for density pumping and H-mode fueling with SGI will be used in these discharges to achieve the low pedestal collisionality and low n_e/n_G fractions (0.3-0.6), essential to maximize the non-inductive (bootstrap and beam driven) current fractions. Experiments with SGI fueling on NSTX have demonstrated to date reliable H-mode access and a high fueling efficiency η. The low field side SGI on NSTX consists of a Laval nozzle, capable of producing a Mach 4 deuterium jet, and a piezoelectric gas valve, capable of multipulse ms-scale injection at reservoir gas pressure up to 0.67 MPa, and gas flow rates of up to $\sim 10^{22}$ particles/s. Using integrated electron and carbon inventory analyses, η was estimated to be in the range 0.1-0.4 in divertor configurations. The H-mode pedestal density increased by 5-40 % concomitant with SGI pulses, suggesting that particles are deposited and accumulated mainly in the pedestal region. A reduction in H-mode density rate of rise was accomplished by reducing the flow rate of the uncontrolled high field side gas by up to 90 % and replacing it with the SGI. The DEGAS 2 neutral transport code was used to study the impact of a directed gas velocity on η. It was found that while the SGI does focus the molecules towards the core, there is a reduction in the number of dissociation product atoms that provide much of the transport for the conventional GI, resulting in similar SGI and GI η values. Although the high-pressure gas jet is not fully described by the "single particle" DEGAS 2 model, the results suggest that adding a directed velocity does not guarantee an increase in fueling efficiency η. This work is supported by U.S. DoE in part under contracts DE-AC52-07NA27344 and DE-AC02-76CH03073.

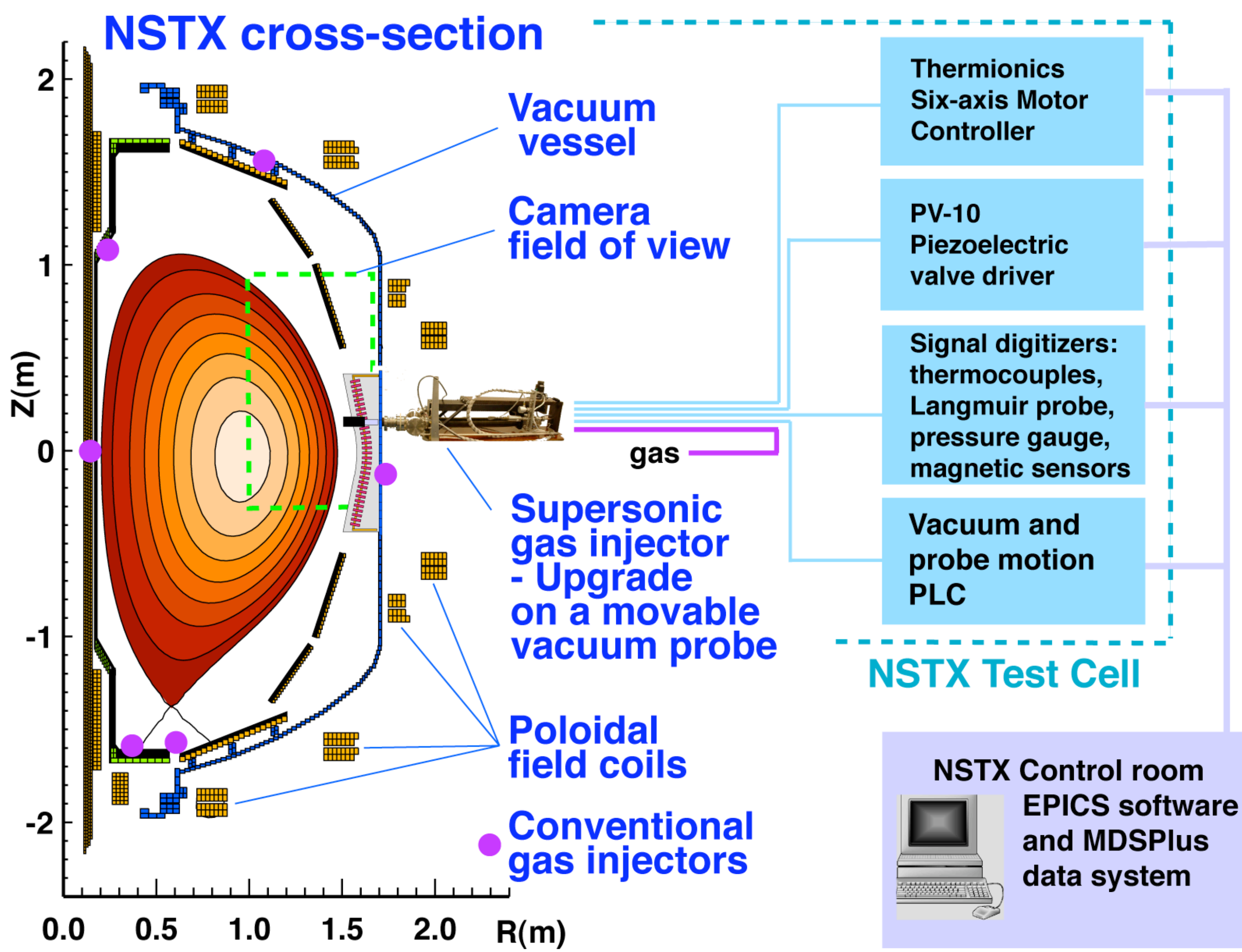
Summary

- High-pressure supersonic deuterium jet is used for fueling optimization in 6 MW NBI-heated H-mode discharges on NSTX
- Supersonic jet fueling efficiency is high (0.1-0.3)
- Jet is ionized in scrape-off layer, electron density increases in H-mode pedestal region
- Small X-point MARFE is formed during supersonic jet fueling
- In the future, low density / low collisionality H-mode scenario will be developed using innovative lithium techniques for density pumping, and supersonic gas jet for controlled fueling

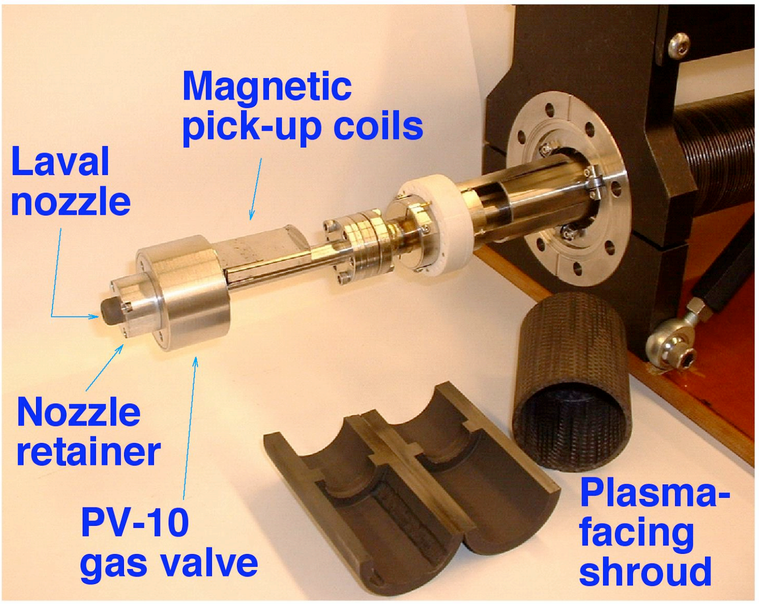
Supersonic gas jet fueling is a unique technique studied on NSTX

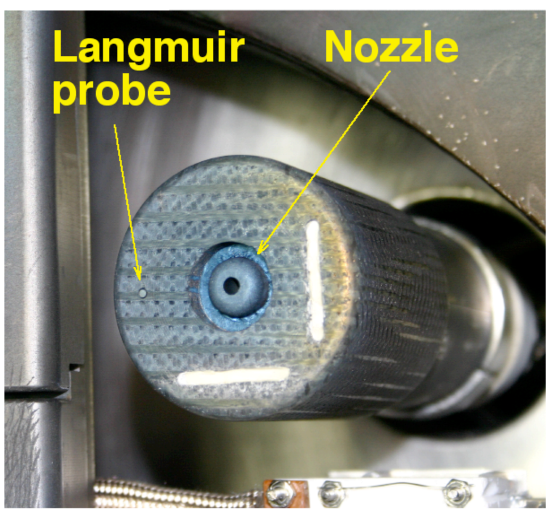
- Future large tokamaks will still use gas injection for sustaining local density and density control
  - in front of RF antennas
  - in SOL and divertor
- Supersonic gas injector (SGI)
  - was installed on NSTX in 2004, experiments conducted in 2005-2006 in ohmic, L- and H-mode discharges
- **Supersonic gas injector - Upgrade (SGI-U - this poster)**
  - Upgraded to 5000 Torr plenum pressure capability and multi-pulse capability in 2007
- Supersonic gas jet fueling has been studied in other plasma devices
  - Limiter tokamaks (HL-1M, Tore Supra)
  - Divertor tokamaks (ASDEX-Upgrade, JT-60U, HL-2A)
  - Divertor Stellarator (W7-AS)

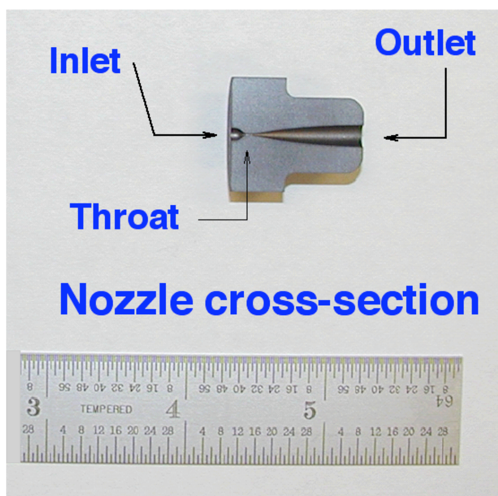
Supersonic gas injector is a complex computer-controlled high gas pressure apparatus



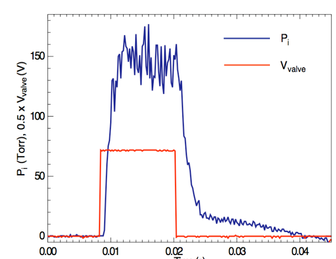
Supersonic gas injector consists of Laval nozzle and piezoelectric valve

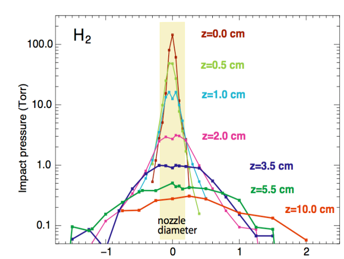






- SGI-U is operated at flow rates 20-130 Torr l /s ($1.5 - 9.0 \times 10^{21}$ s^{-1})
- Supersonic deuterium jet properties:
  - Jet divergence half-angle: $6^o - 25^o$ (measured)
  - Mach number $M = 4$ (measured)
  - Estimated: T ~ 60 - 160 K, $n < 5 \times 10^{23}$ m^{-3}, $v_{flow} = 2.4$ km/s, $v_{therm} \sim 1.1$ km/s
  - Nozzle $Re = 6000$





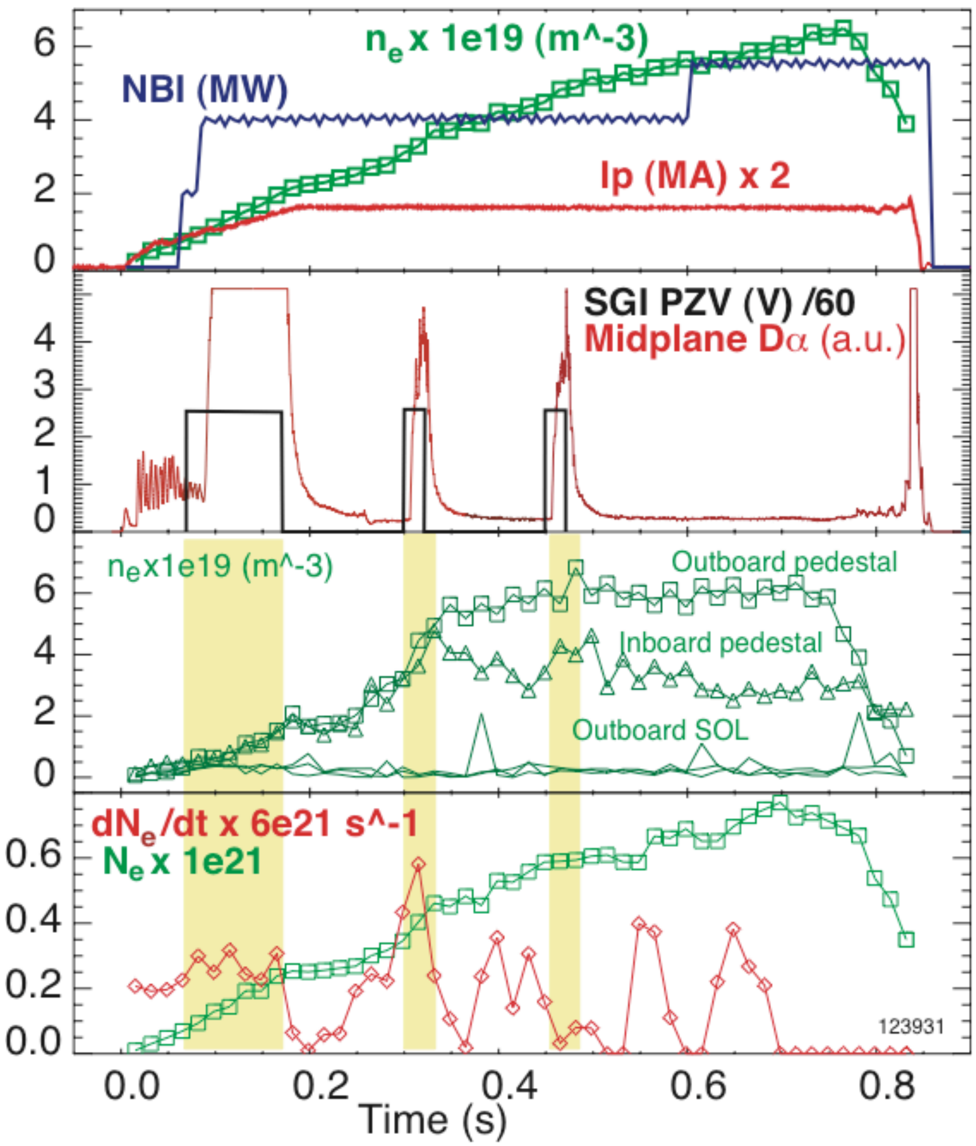
Reduced density / collisionality high-performance H-mode scenarios are developed

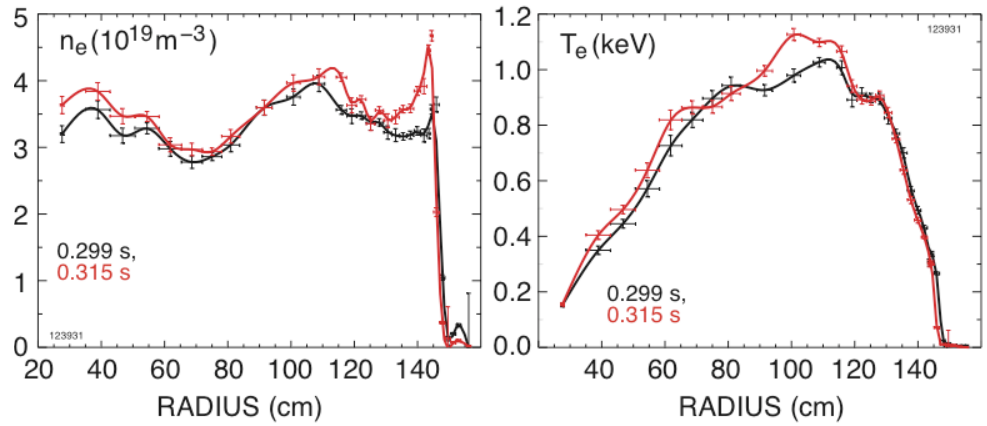
- All present NBI-heated H-mode discharge scenarios on NSTX use uncontrolled high-field side (HFS) deuterium injection
  - Reliable H-mode access obtained
  - However, uncontrolled fueling, detached inner divertor, MARFEs, leading to uncontrolled density rise

- Techniques for reduced density / collisionality H-mode discharge
  - Density pumping with innovative lithium coatings (R. Kaita et. al, Poster P1.009, This conference)
  - Supersonic gas jet for controlled fueling

- Previous results obtained with SGI at lower jet pressure
  - H-mode access reliable
  - H-mode scenario with SGI fueling and reduced (by up to 95 %) HFS fueling
  - SGI-fueled double-null H-mode plasmas demonstrate different ELM regime (type III ELMs vs small and type I ELMs with HFS fueling)
  - Measured fueling efficiency 0.1 - 0.3

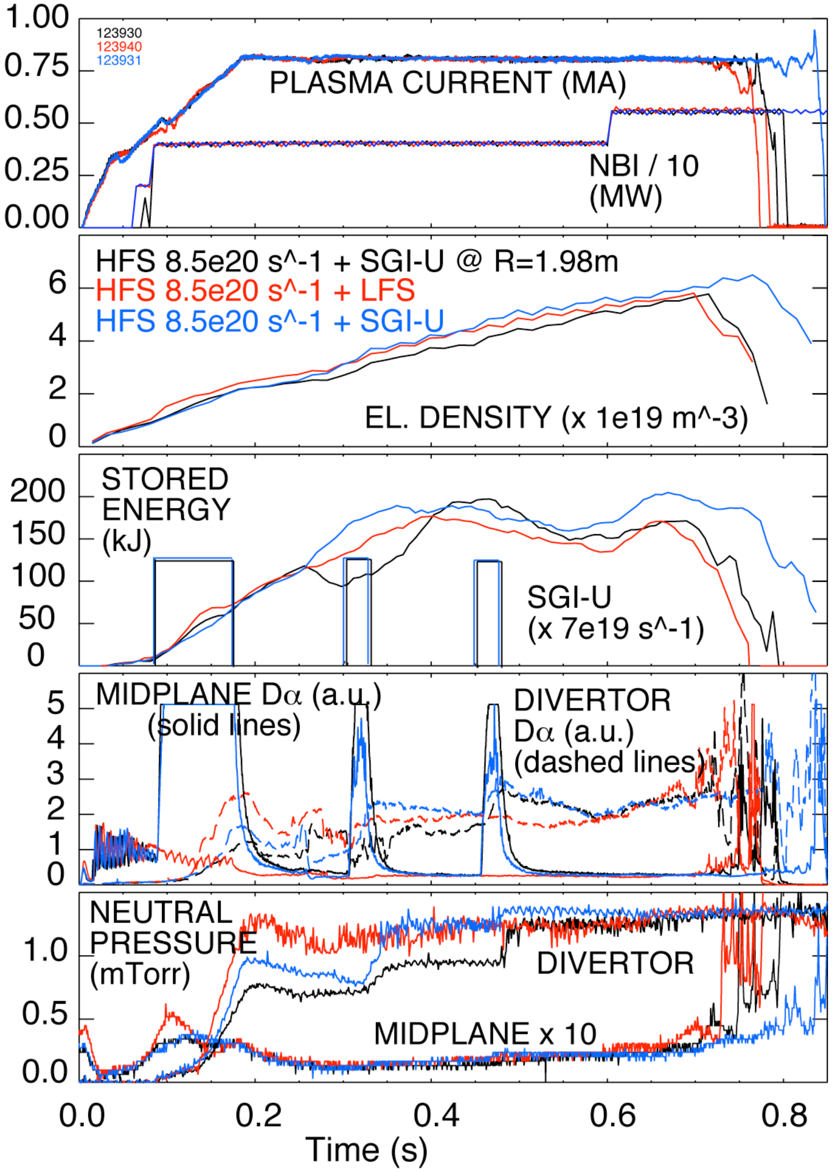
Supersonic gas jet ionizes in SOL, deposits ions in H-mode pedestal region





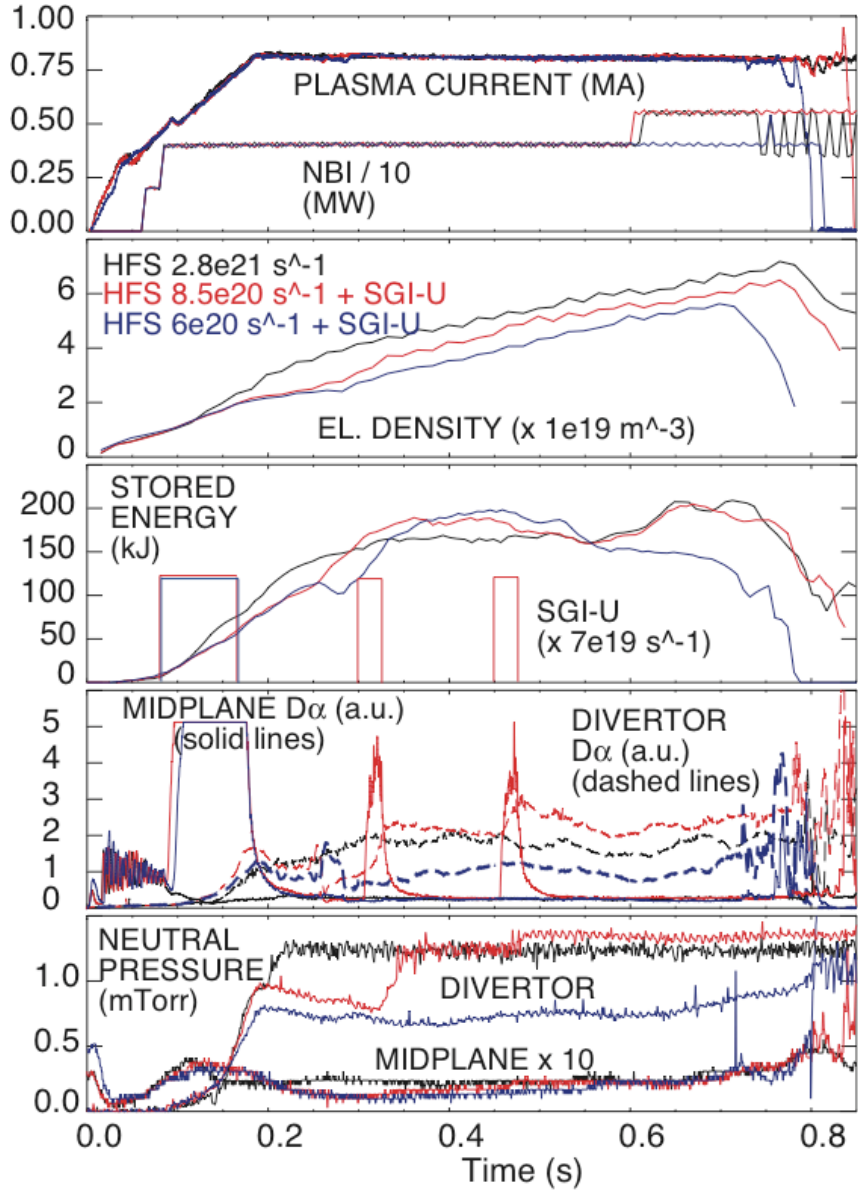
- In H-mode plasmas, n_e "ear" height and width increase, edge / pedestal and/or core T_e decrease by 10-15 %
- Supersonic gas jet does not penetrate beyond separatrix (typically stops at 0.5-6 cm from separatrix)

SGI-U fueling favorably compares to conventional gas injection fueling



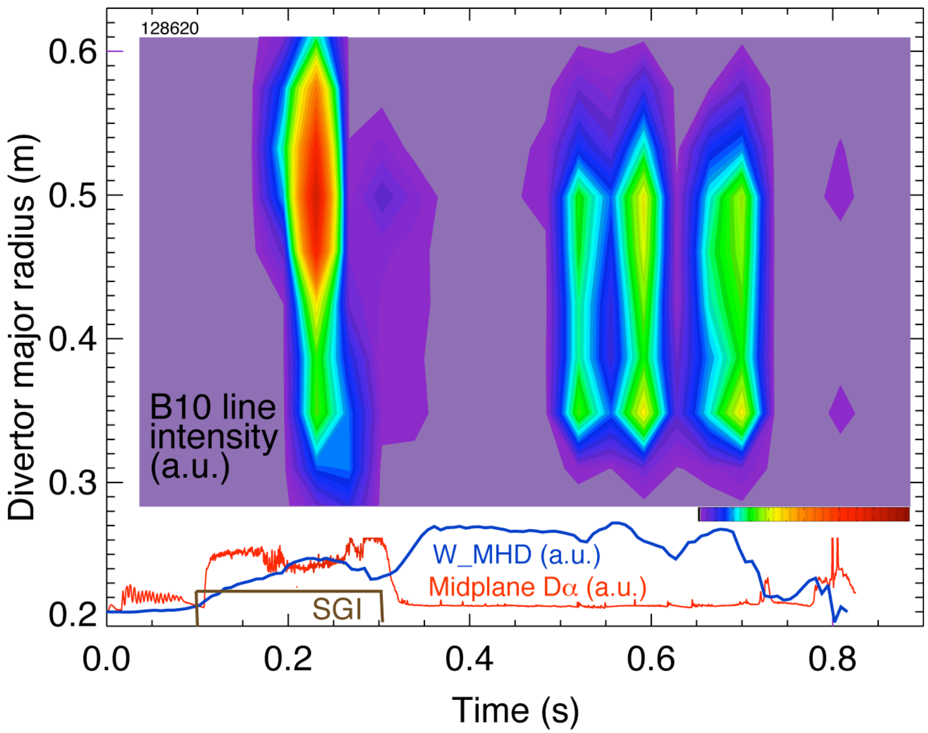
- Three discharges with different fueling are compared:
  - reduced HFS rate + LFS similar to SGI-U
  - reduced HFS + SGI-U at R=1.57 m
  - **reduced HFS+SGI-U at R=1.98 m**
- In the SGI-U-fueled discharges
  - divertor pressure lower
  - divertor recycling lower
  - midplane pressure lower
- When SGI-U is closer to separatrix (R=1.57 m vs **R=1.98 m**) - higher plasma density is obtained
- However, all fueling methods result in high divertor ionization source, and monotonic density rise : need active pumping for mitigation

Reduced density H-mode plasmas with complementary SGI-U fueling are obtained

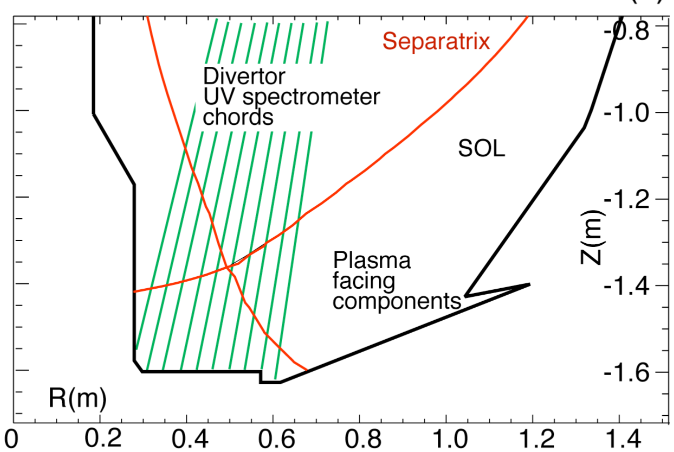


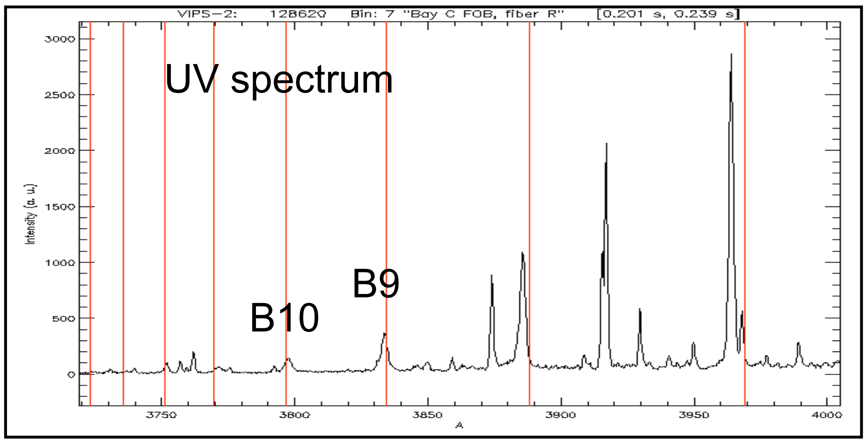
- Three discharges with different fueling are compared:
  - reduced HFS rate + SGI-U
  - more reduced HFS + SGI-U
  - **high HFS rate**
- Best fueling scenario - reduce HFS rate to the lowest possible, and add SGI-U

X-point MARFE forms during SGI-U fueling, leading to weak degradation in confinement

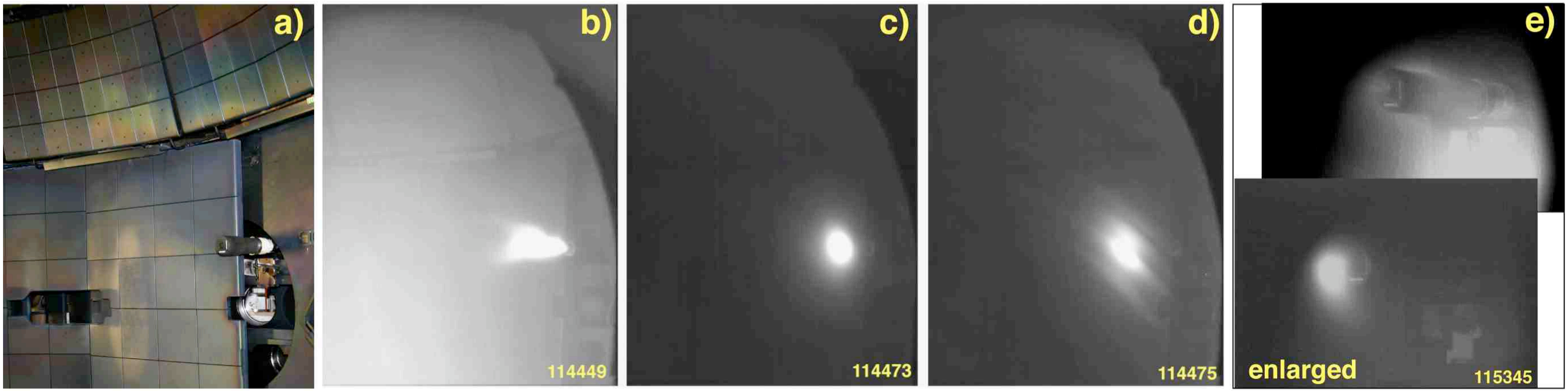


- X-point MARFE appears during SGI-U injection
- Weak impact on confinement
- MARFE is detected by spatially and temporally resolve spectra of divertor Balmer series (B9, B10, B11 lines)

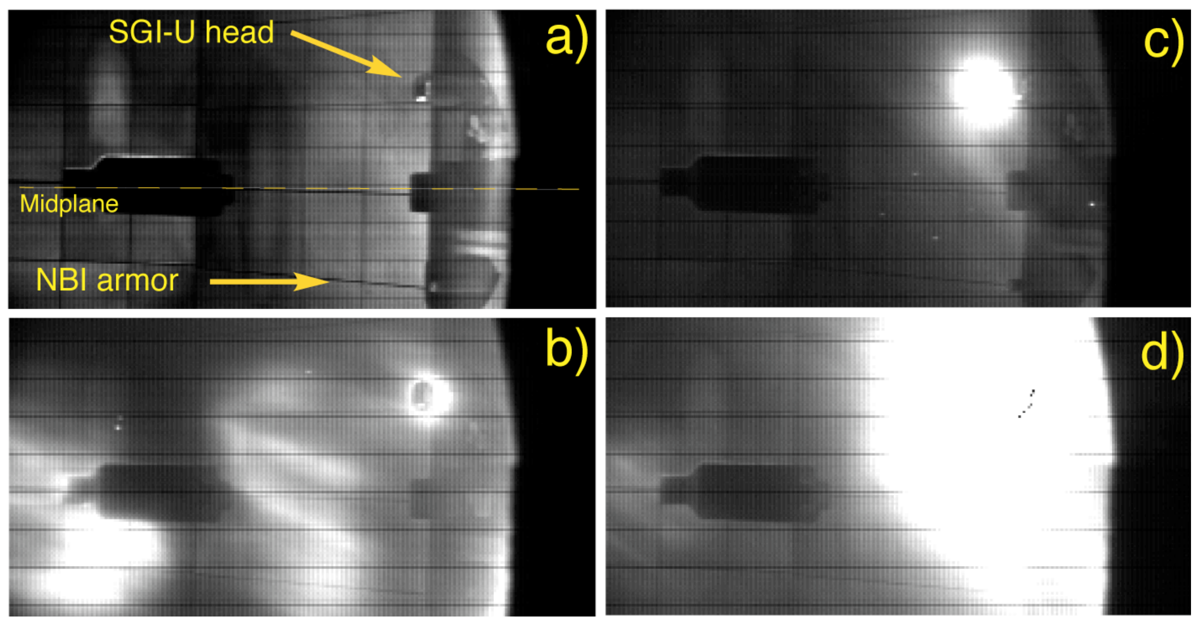




Fast camera shows localized supersonic deuterium jet interaction with SOL plasma

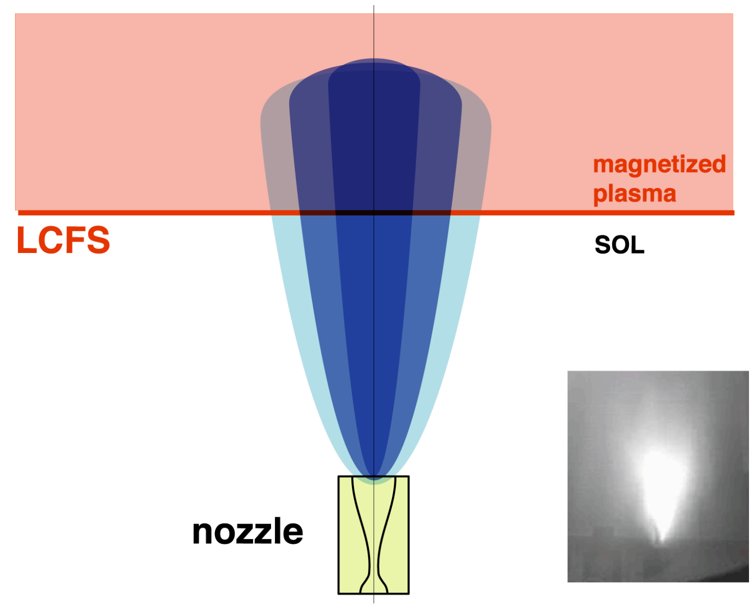


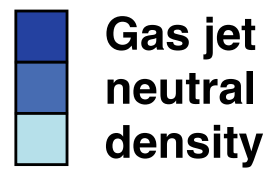
- Plasmoid located 0.5-6 cm from separatrix, - ionization source in SOL
- Size of Dα light-emitting region consistent with low jet divergence



High-density deuterium jet penetration through SOL relies on self-shielding from plasma

- 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
- Depth of penetration is determined by jet pressure and plasma kinetic and magnetic pressure
- High density plasmoid blocks jet from deep penetration into magnetized plasma
- Desirable for fueling are molecular clustering and/or droplet formation in jet achieved at very high pressure and cryogenic temperatures





References:
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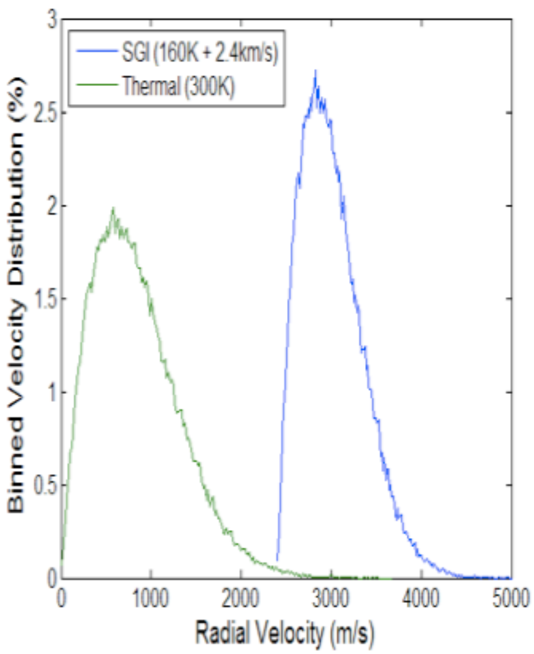
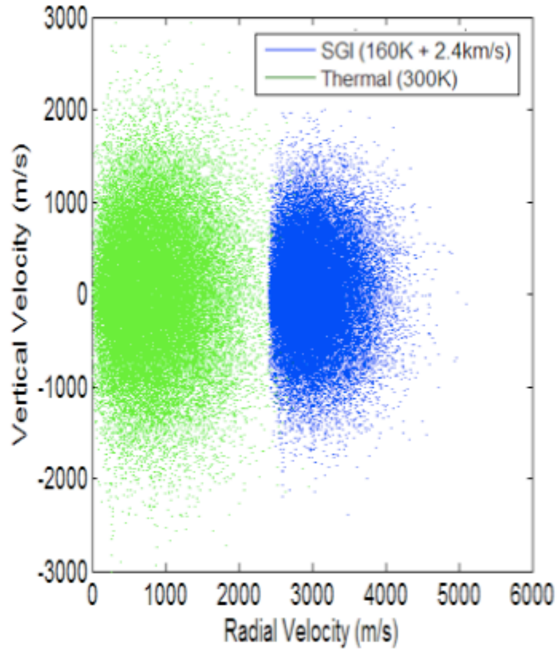
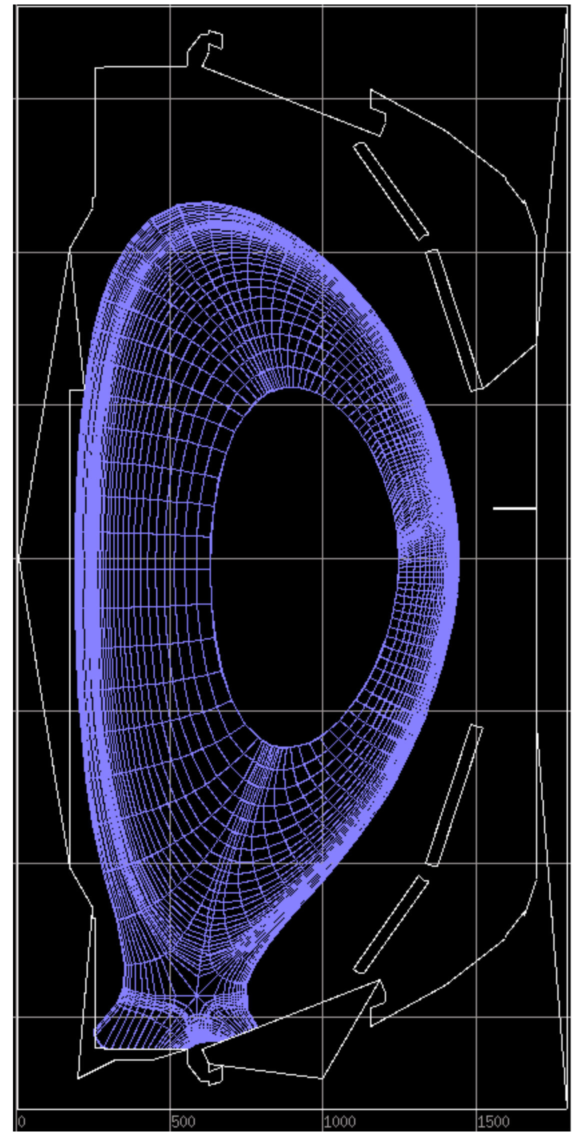
DEGAS 2 neutral transport code is used to simulate supersonic and conventional gas injection

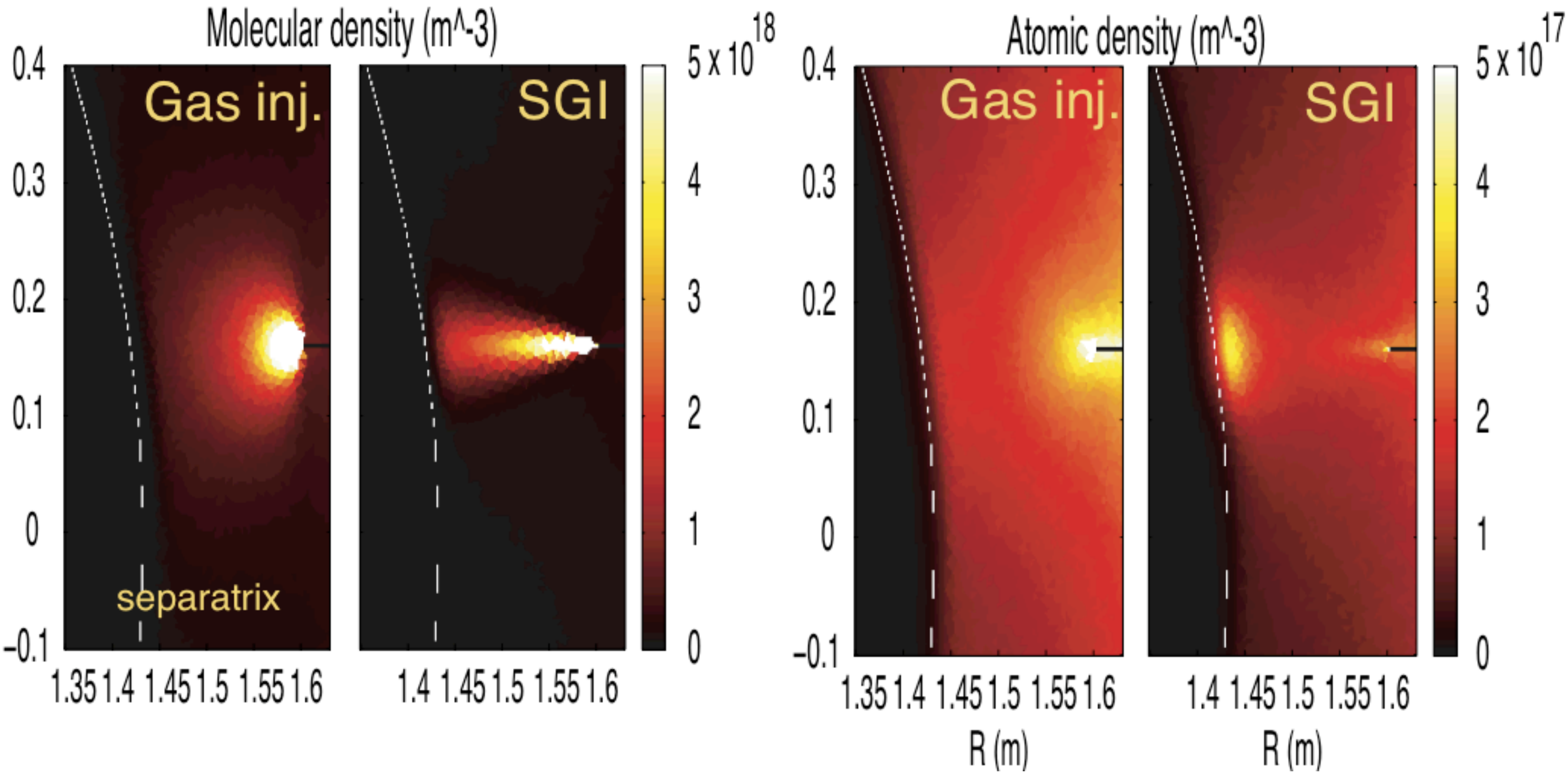






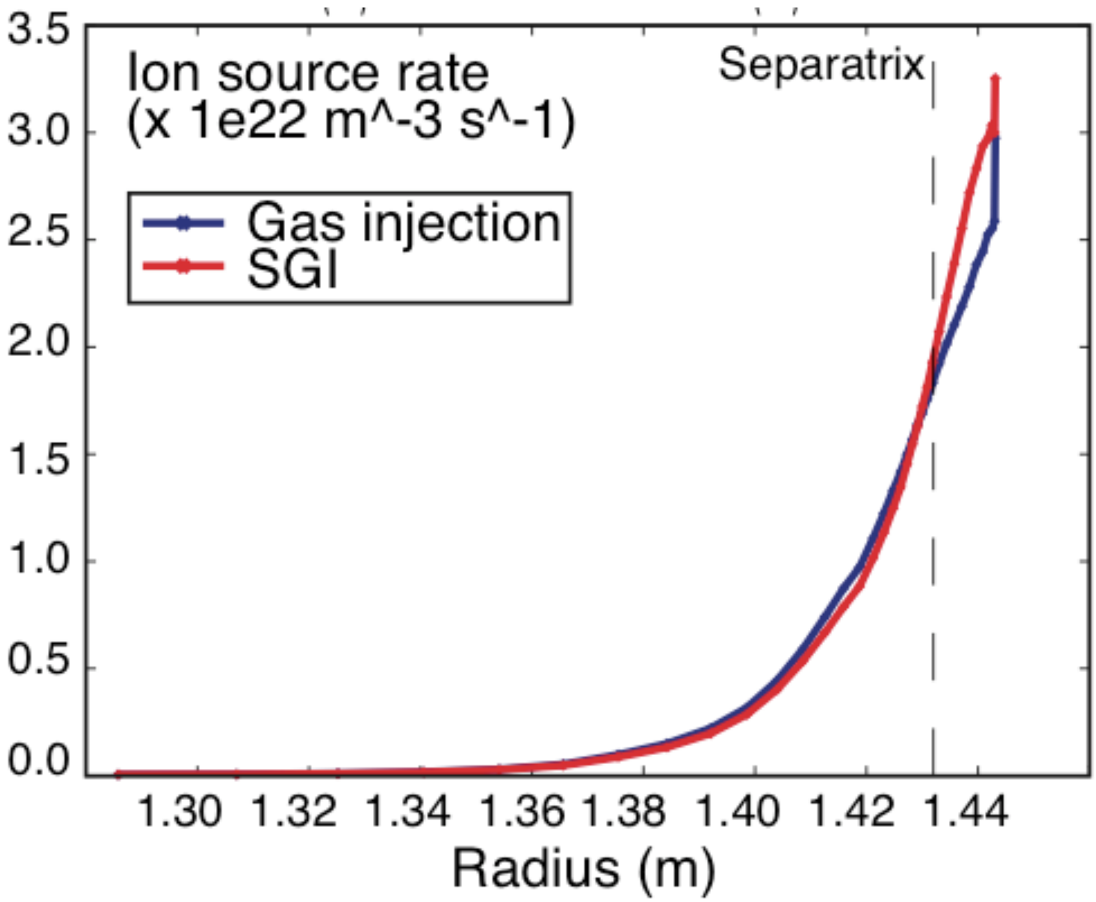
- DEGAS 2 - Monte Carlo neutral transport code
- Plasma background T_e, n_e and equilibrium-based mesh from real SGI-U fueled H-mode discharge
- “Single-particle” tracking model, not self-consistent with plasma model - assumes the SGI is in “low-flow” regime
- Supersonic D_2 jet velocity is Maxwellian at T=160 K + shift 2.4 km/s, thermal gas injection at T=300 K

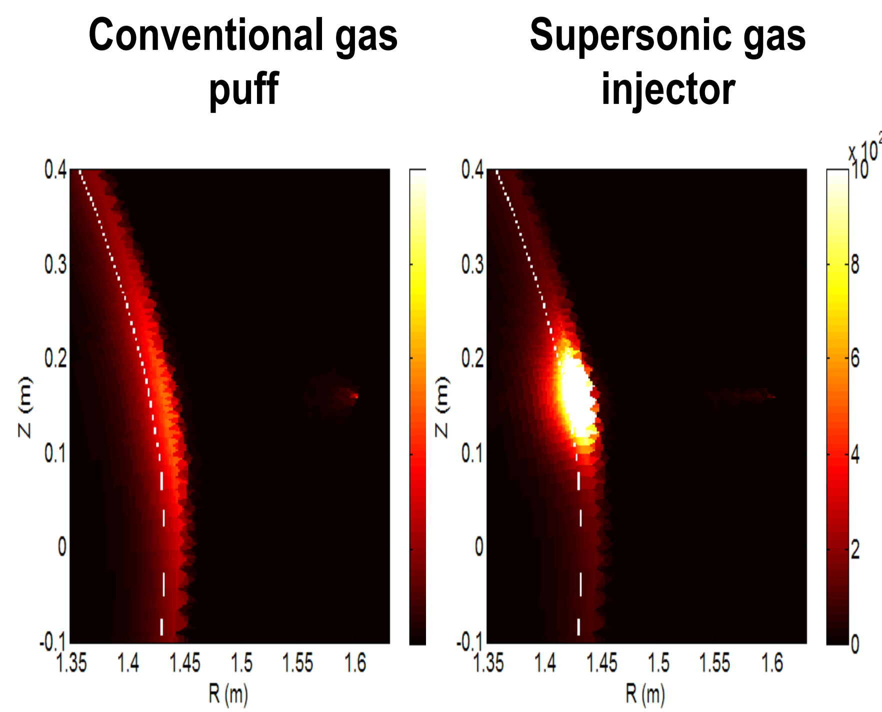
In simulations supersonic gas jet molecular and atomic densities are highly localized



- Molecules dissociate in far SOL, Frank-Condon atom transport is important
- Thermal gas injection produces larger D^0 population than SGI

Ionization rates and fueling efficiencies of SGI and gas injection are nearly equal in simulations





D^+ Source Rate (m^{-3} s^{-1})

- Ion source rate is flux surface averaged
- Fueling efficiency of gas injection and SGI in H-mode 0.35-0.39
- **Conclusion: directed velocity does not necessarily lead to higher fueling efficiency and deeper penetration**

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