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NSTX

Supersonic gas jet fueling efficiency studies in NSTX

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Abstract

Electron and carbon inventory analysis is used to infer the fueling efficiency (FE) of a pulsed high-pressure supersonic D_2 jet, produced by a low field side supersonic gas injector (GI) at a flow rate 3-9x10^{21} s^{-1} at distance 5-15 cm from the plasma. In ohmic and 2-6 MW NBI-heated L- and H-mode plasmas, the FE of the Mach 4 jet is found to be in the range 0.1-0.4, higher than FE of a conventional GI. During supersonic GI pulses, the pedestal density increases by 5-40% suggesting that particles are deposited mainly in the pedestal region.

A "single particle" model of lower-end pressure supersonic GI fueling is developed using the DEGAS 2 neutral transport code. Details of a high-pressure jet interaction with background plasma are not included in the model. The modeling suggests that adding a directed velocity does not guarantee a FE improvement. While the supersonic GI does focus the molecules towards the core, there is a reduction in the number of dissociation product atoms that provide much for the transport for the conventional puff, resulting in comparable FE's of a supersonic and a conventional GI's.

Summary

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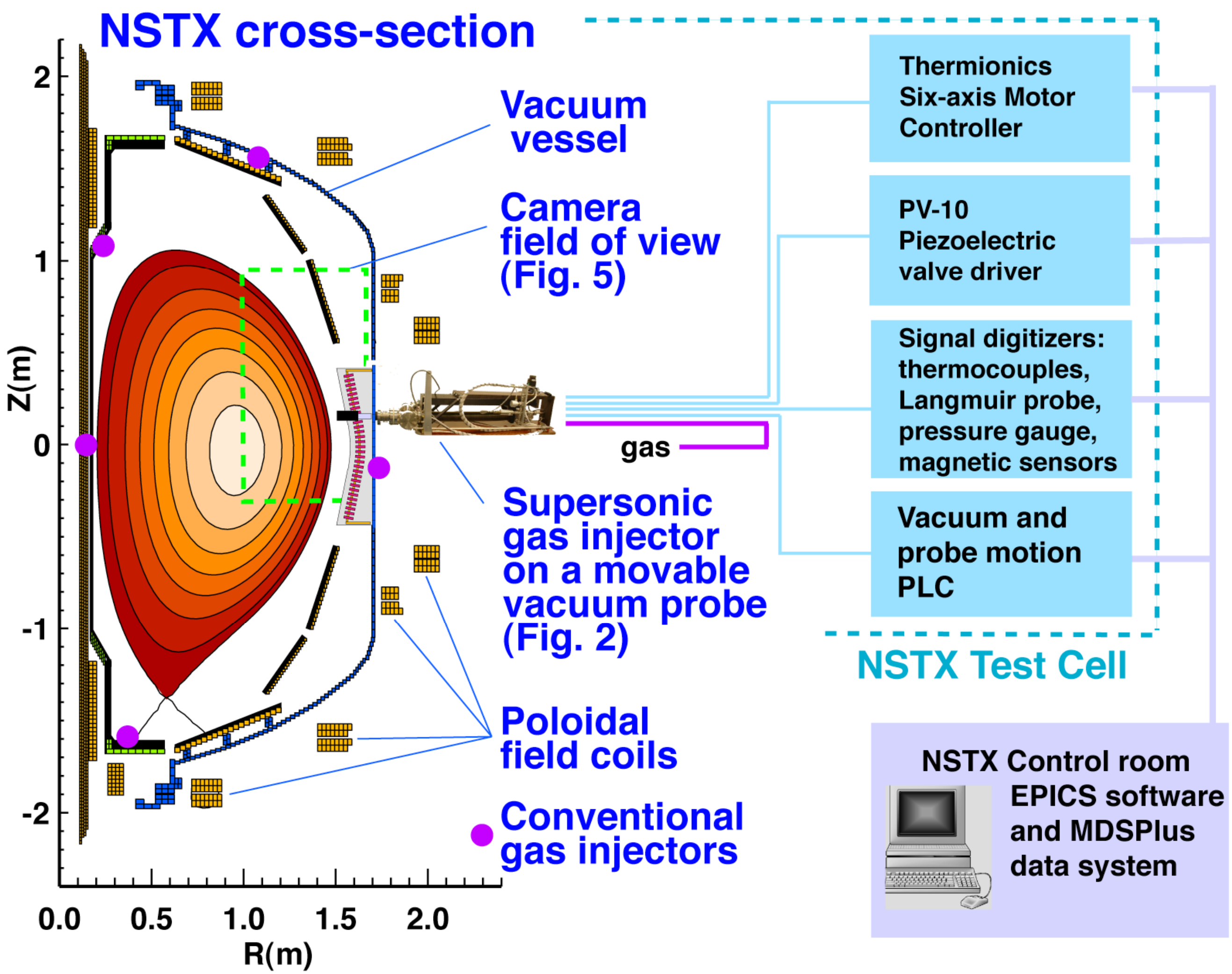
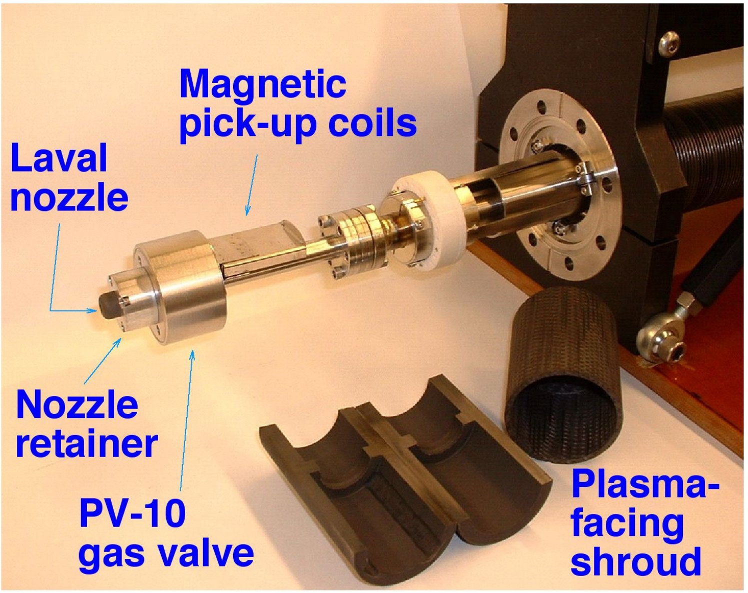
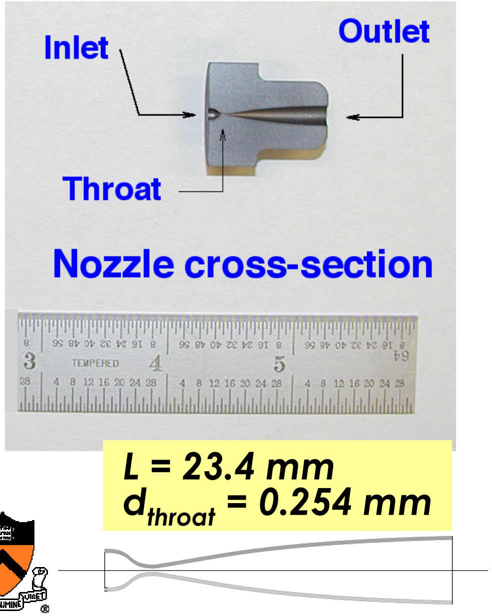
- Low field side (LFS) supersonic gas injector (SGI) has been used for fueling of ohmic and 2-6 MW NBI-heated L- and H-mode plasmas
  - SGI-fueled H-mode power threshold low (< 2 MW NBI), H-mode access reliable
  - SGI injects deuterium at G < 5×10^{21} particles / sec in quantities 10-30% of NSTX plasma inventory in a continuous fashion, with measured fueling efficiency 0.1-0.3
- DEGAS 2 simulations indicate SGI fueling efficiencies of 30-35%, which roughly agree with the measured NSTX values
- In the "low-flow" regime of the DEGAS 2 code, including the large directed velocity of the SGI does not guarantee an improvement in fueling efficiency over a conventional gas puff

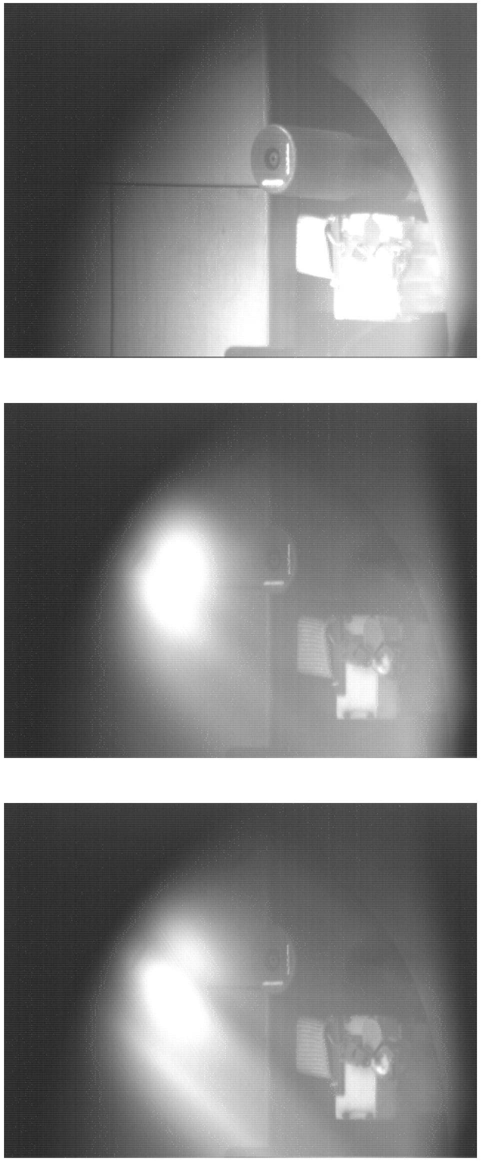
Supersonic gas injector is a complex multi-diagnostic package on a moveable probe



Supersonic gas injector uses de Laval shaped nozzle and *ms*-response piezo valve







- NSTX SGI is operated at flow rates 20-65 Torr l /s (1.5 - 4.5 x 10^{21} s^{-1}) - unique fueling tool
- Supersonic deuterium jet properties:
  - Jet divergence half-angle: 6° - 25° (measured)
  - Mach number M = 4 (measured)
  - Estimated: T ~ 60 - 160 K, n < 5 x 10^{23} m^{-3}, Re = 6000 v_{flow} = 2400 m/s , v_{therm} ~ 1100 m/s

Only very high pressure supersonic gas jet penetrates plasma

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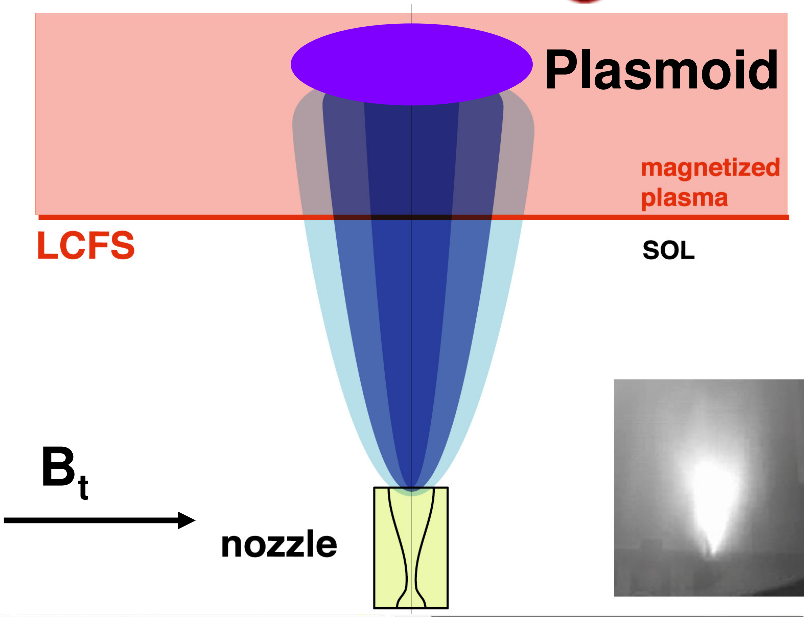
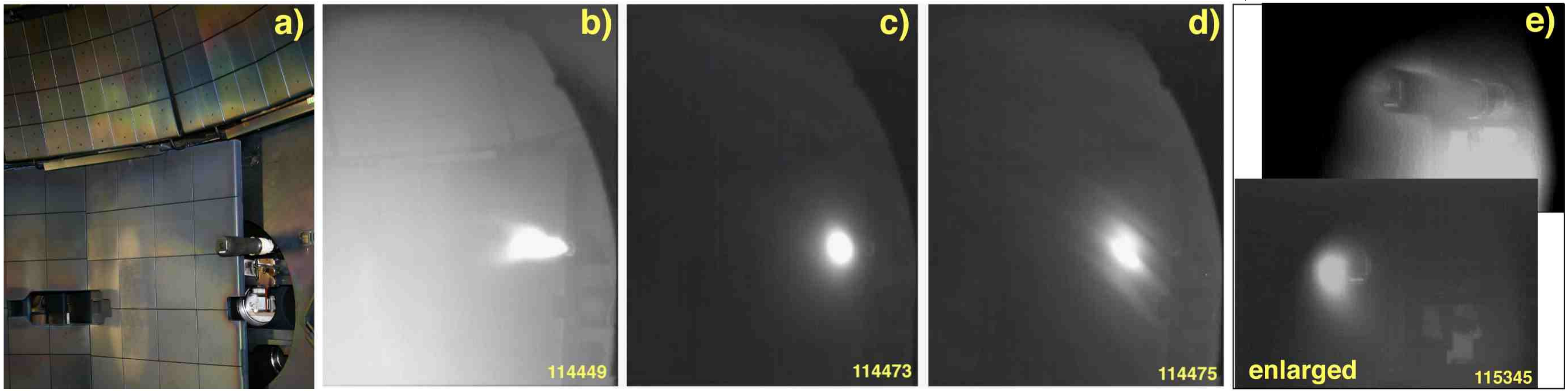
- Supersonic gas jet is a low divergence, high pressure, high density gas stream with low ionization degree - bulk edge/SOL electrons do not fully penetrate gas jet
- Depth of penetration is determined by jet pressure and plasma kinetic and magnetic pressure





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

Supersonic gas jet deposits particles at the edge

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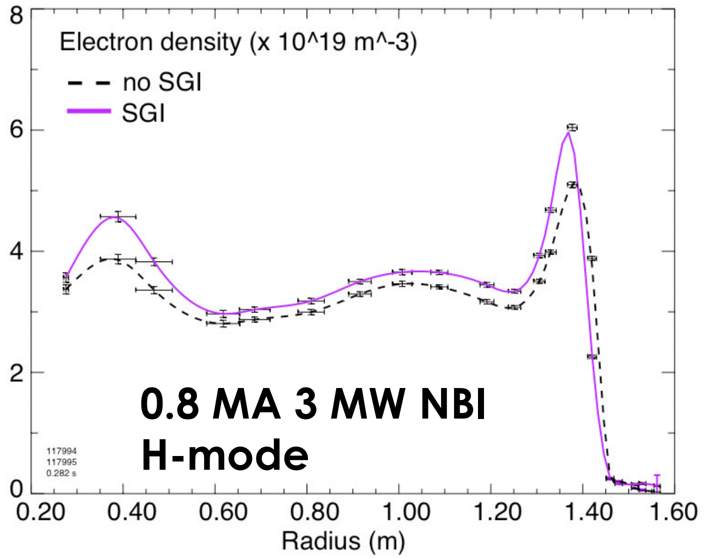
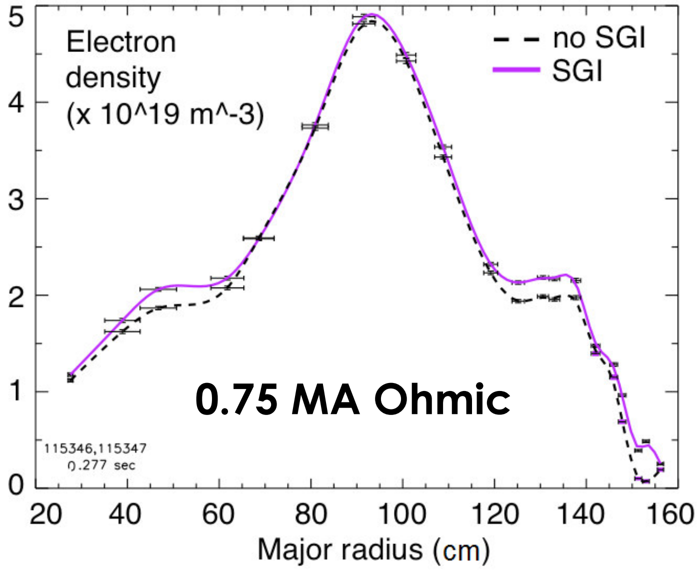
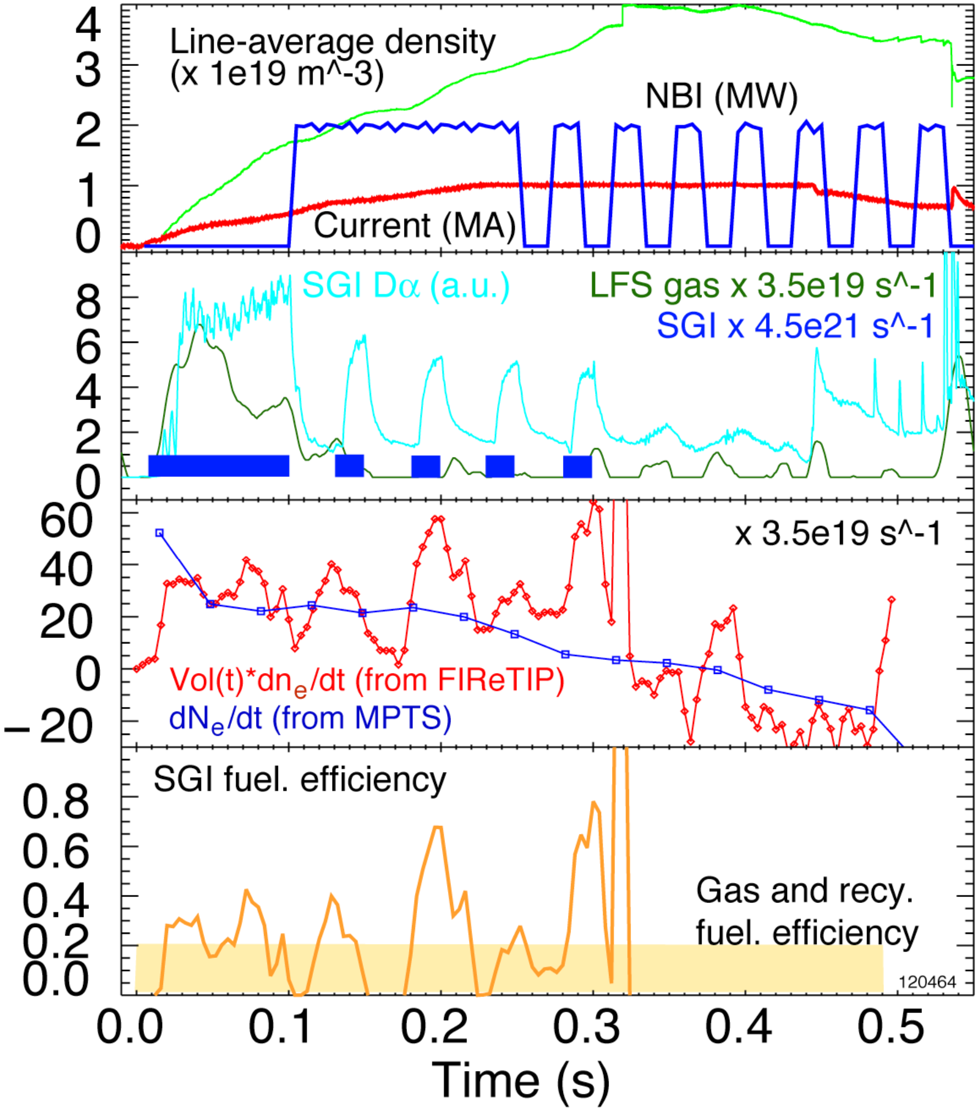
- In H-mode plasmas, n_e “ear” height and width often increase, edge/pedestal and/or core T_e decrease by < 15 %
- In Ohmic plasmas edge density rise is often observed
- Supersonic gas jet does not penetrate further than 1-4 cm from separatrix





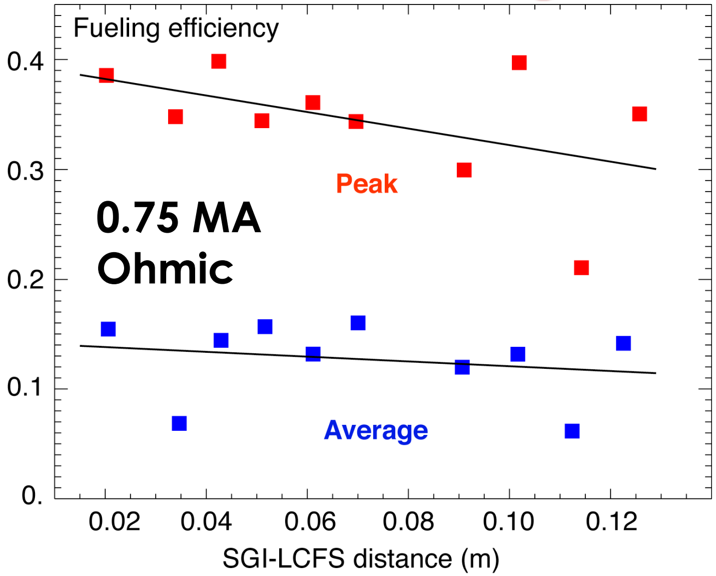
Fueling efficiency is higher in inner wall limited plasmas

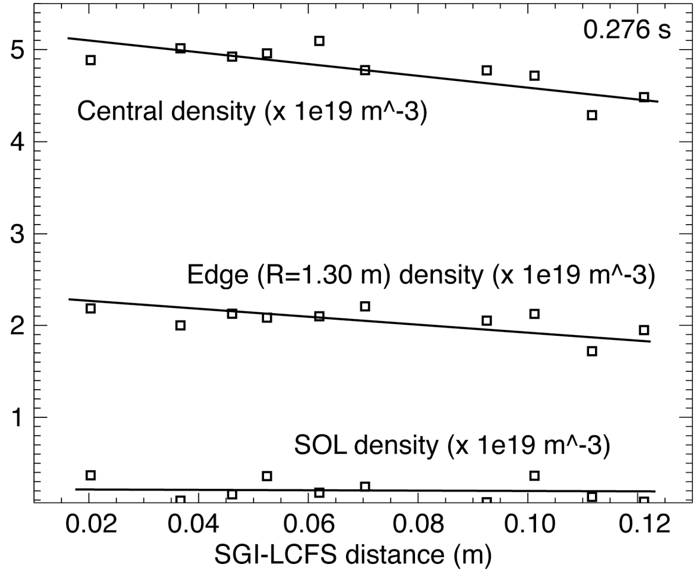
- Instantaneous fueling efficiency (FE) is calculated as $dN_e/dt * \Gamma^{-1}$
- In Ohmic plasmas, FE is a function of SGI-LCFS distance (SGI at Γ~40 torr-l/s) in LSN configuration
- FE in inner wall-limited plasmas higher than in diverted configurations
- FE in LSN H-mode plasmas is 0.1-0.3 (SGI at Γ~65 torr-l/s ~ 4.3×10^{21} s^{-1})



Gas jet fueling efficiency in low flow regime is a weak function of distance to plasma

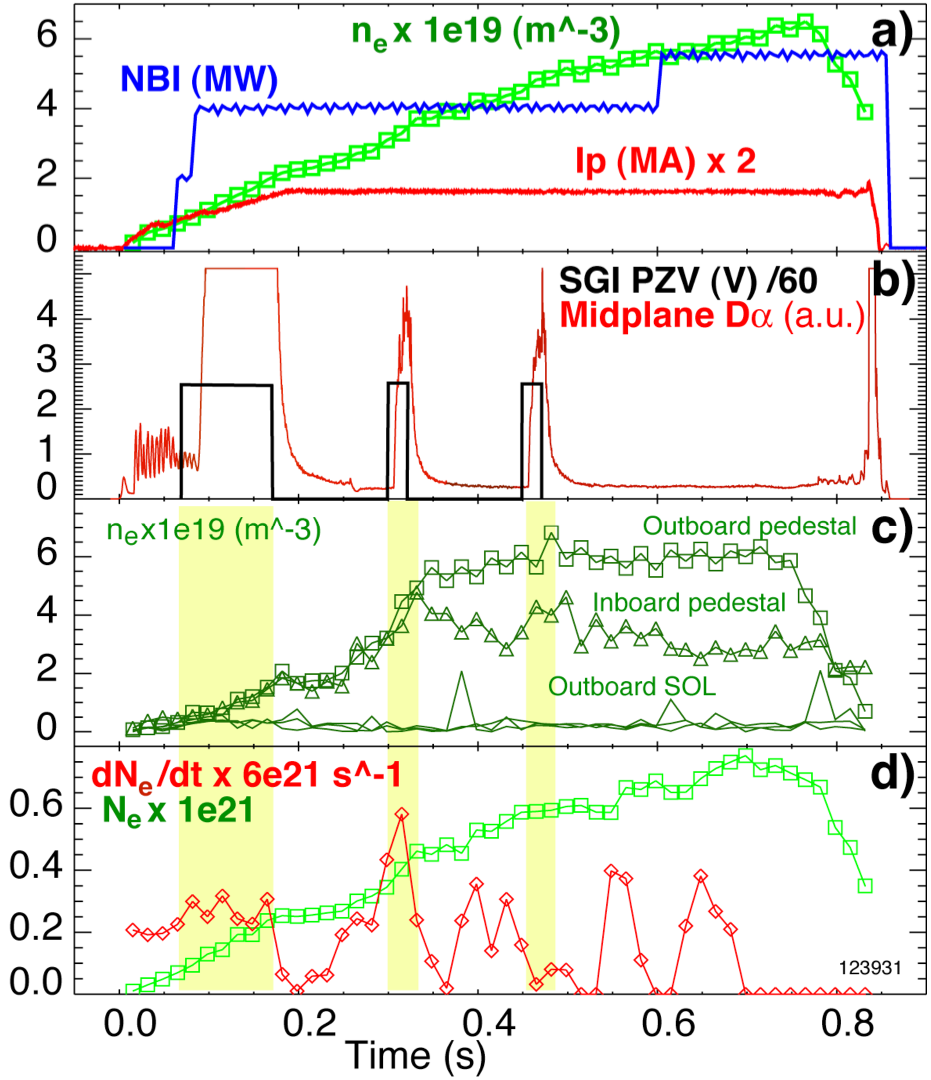
- Experiments in ohmic plasmas were conducted at reduced Γ_{SGI}=2.8 x 10^{21} s^{-1}
- Calculated instantaneous fueling efficiency (dN_e/dt) * Γ_{SGI}, then averaged over Γ_{SGI}
- Plasma density and fueling efficiency is a weak function of SGI-separatrix distance in this regime





High-pressure SGI-Upgrade appears to have same fueling efficiency

- 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



Simulation Goals

- Model the SGI on NSTX with available computational tools
- Compare simulated fueling efficiency with measured values on NSTX
- Is there an improvement over a conventional puff in a low-flow regime?
- Can we understand the behavior of the SGI without including the complex physics of a high-pressure jet?

DEGAS 2 – A Monte Carlo Neutral Transport Code

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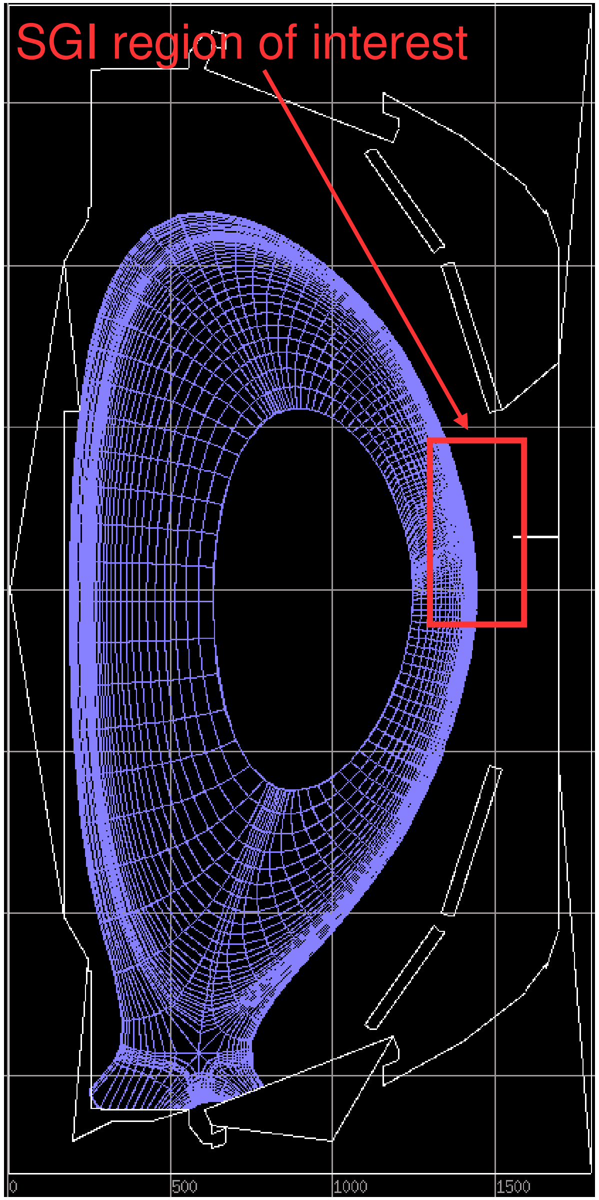
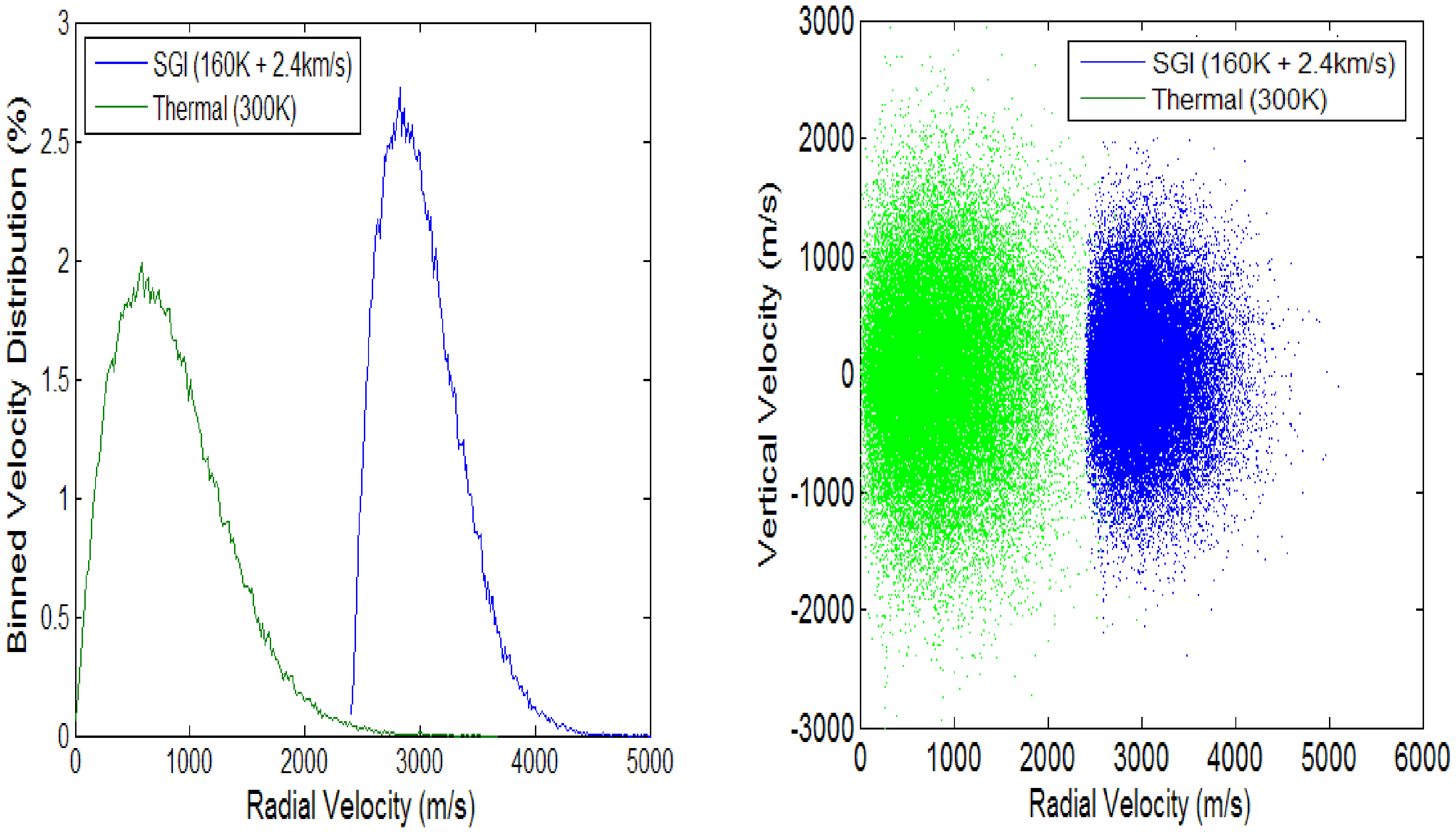
- Monte Carlo neutral transport code
  - Problem geometry can be irregular and complex
  - Allows an arbitrary level of atomic physics detail
- Uses externally specified geometry, plasma profiles and neutral source distribution
  - Plasma profiles from past NSTX shots used for these simulations
- Propagates neutral particle paths from the source, tallying interactions with the plasma until only ionized products remain
- Outputs include neutral density and reaction rate profiles
  - Ion source and D_α emission profiles are of particular interest for SGI studies

NSTX Simulation Parameters

- 2-D plasma mesh constructed with EFIT equilibrium
  - Separatrix location is important to accurately calculate fueling efficiency, so ~1mm mesh used
  - Remaining volume filled with triangles
- D_2 source is 1mm wide, at a radius of 1.5-1.7m
  - $4x10^{21}$ particles / second source rate
  - SGI: 2.4 km/s directed velocity,160K temperature
  - Puff: 300K temperature
- Simulations are time independent
  - n_e, T_e from a single Thomson Scattering time point
- Three NSTX shot profiles used:
  - 115346 – Ohmic with SGI
  - 115347 – Ohmic with no SGI (reference shot)
  - 117994 – NBI heated H-mode



SGI modeled by imposing a large directed velocity on the distribution



DEGAS 2 – Physics Limitations

- "Single Particle" model
  - Shielding of inner jet by outer neutrals not included
  - Neutral-neutral scatters not calculated for these simulations
- Assumes neutrals do not have an appreciable effect on background quantities (n_e, T_e)
  - Simulations are not "self-consistent"
  - Local plasma cooling from the high density jet not modeled
- More exotic phenomena such as molecular clustering and an ExB drift of the jet plasmoid are also not in the model
- But DEGAS 2 provides a reasonable approximation to SGI experiments previously done on NSTX in a "low-flow" regime
- Transport stops at ionization, so "all ions are treated equally" for calculating fueling efficiency

Addition of a directed velocity does not guarantee an improvement in fueling efficiency!

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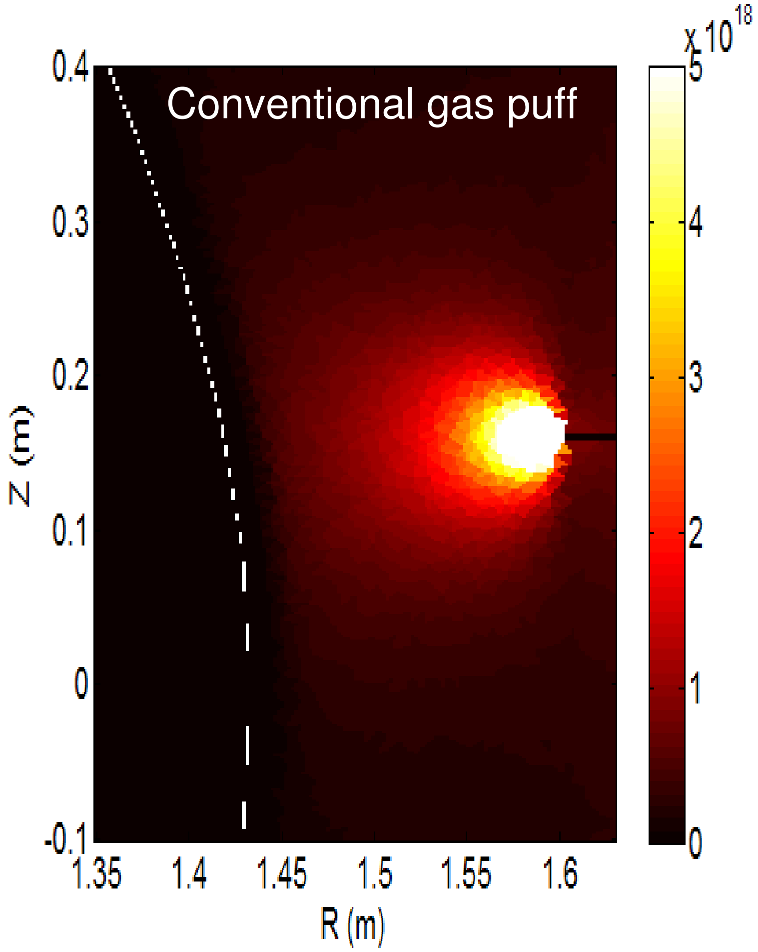
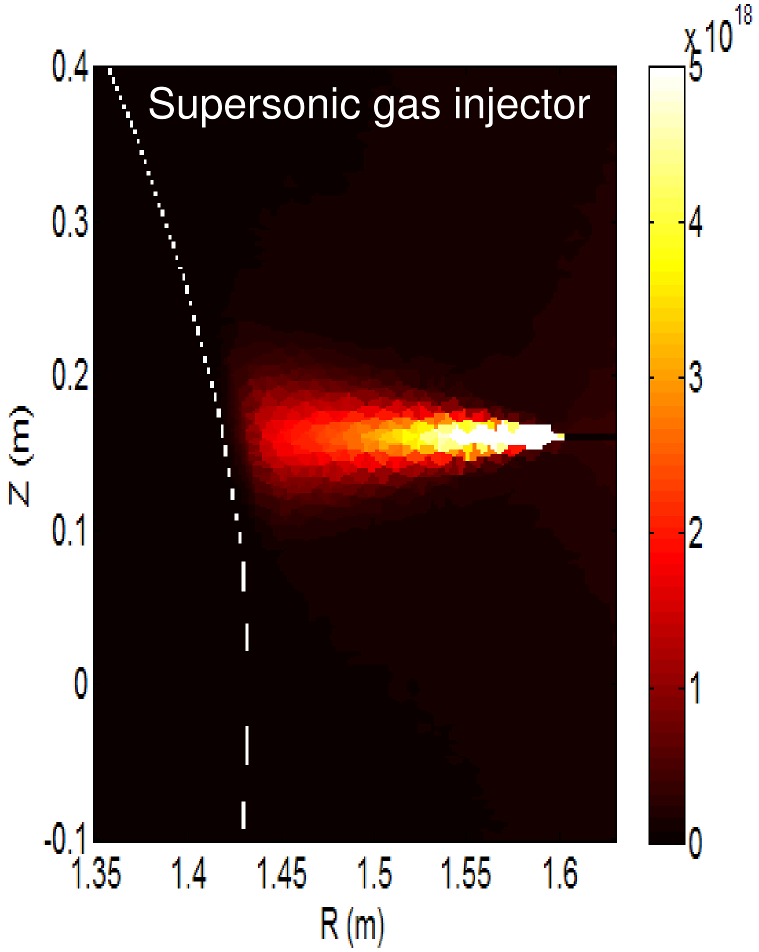
- FE = η = D^+ source inside separatrix / Particle injection rate
- SGI fueling efficiencies roughly agree with experiments (~30-35%)
- But they are not higher than the FE of a simulated gas puff
  - Example: for an H-mode with the injector located at 1.6m, a thermal puff yielded a fueling efficiency of 38.1%, the SGI 35.8%

Injector Type	Profile	Injector Radial Location	η
Puff	H-mode	1700mm	39.2%
Puff	Ohmic	1700mm	33.7%
Puff	Ohmic Reference	1700mm	32.5%
Puff	H-mode	1600mm	38.1%
Puff	Ohmic	1600mm	32.7%
Puff	Ohmic Reference	1600mm	32.0%
Puff	Ohmic	1560mm	31.9%
SGI	H-mode	1600mm	35.8%
SGI	Ohmic	1600mm	32.2%
SGI	Ohmic Reference	1600mm	32.0%
SGI	H-mode	1560mm	35.1%
SGI	Ohmic	1560mm	31.7%
SGI	Ohmic Reference	1560mm	31.8%

Molecules do not penetrate the separatrix, so secondary transport of product atoms is important

Molecular Density D_2 (m^{-3})





SGI D_2 is ionized near, but mostly outside of the separatrix Puff molecular ionization rate is smaller

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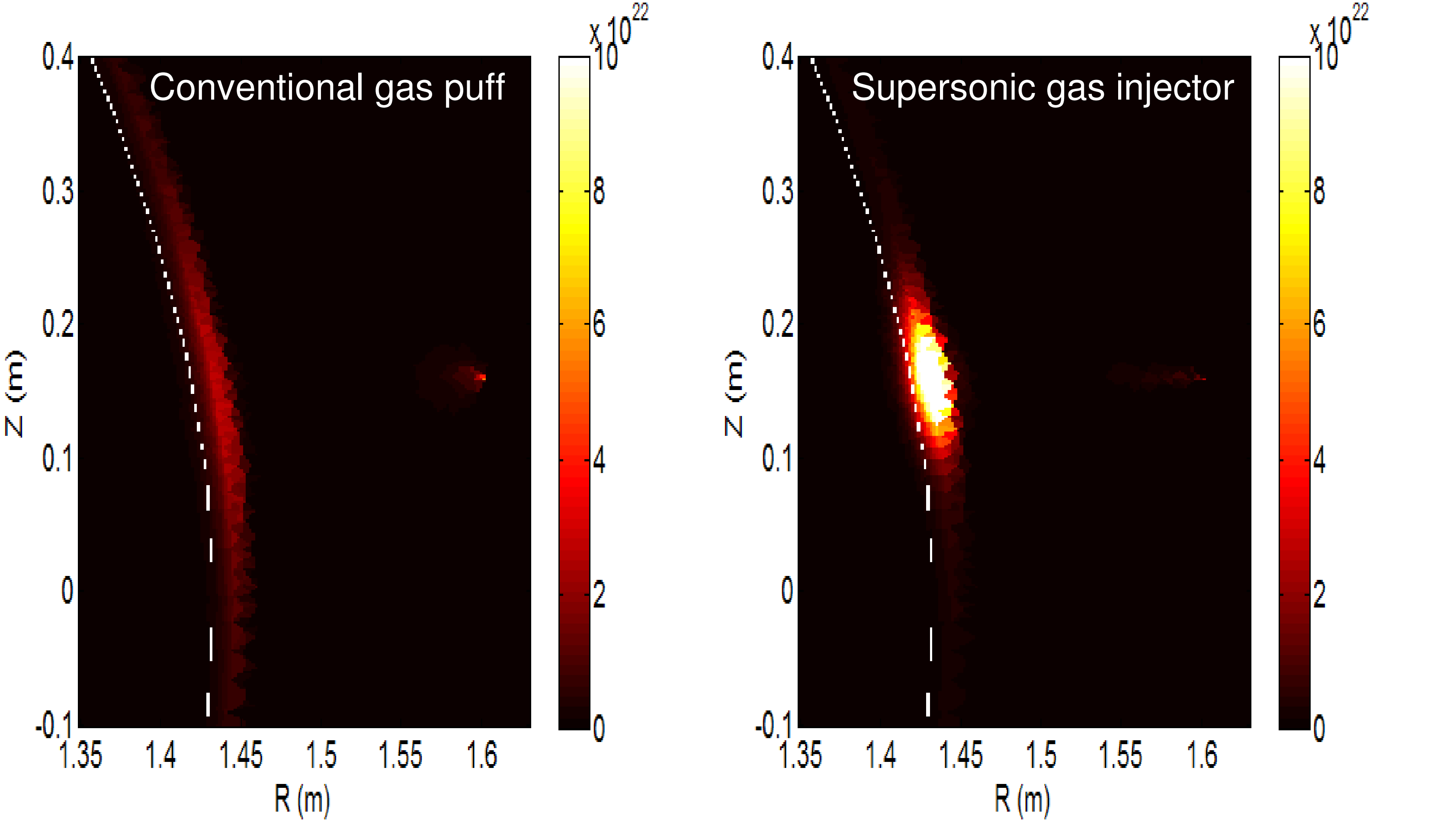
Molecular Ionization Rate ($m^{-3}\ s^{-1}$)



A larger fraction of the gas puff D_2 dissociate
Product atoms have ~2-3eV and can transport a significant additional distance

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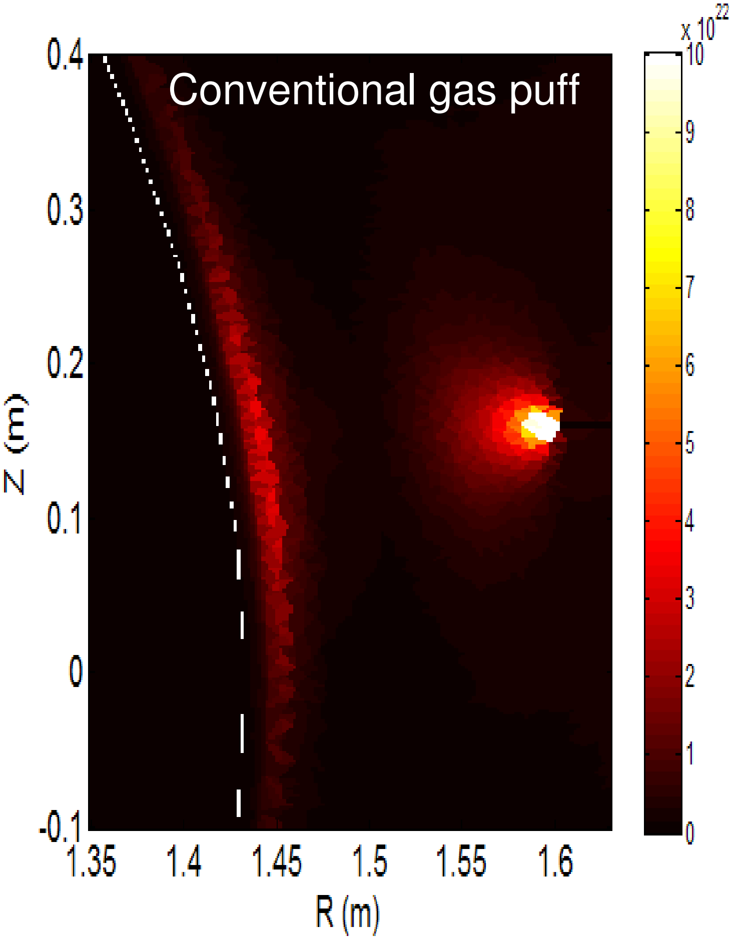
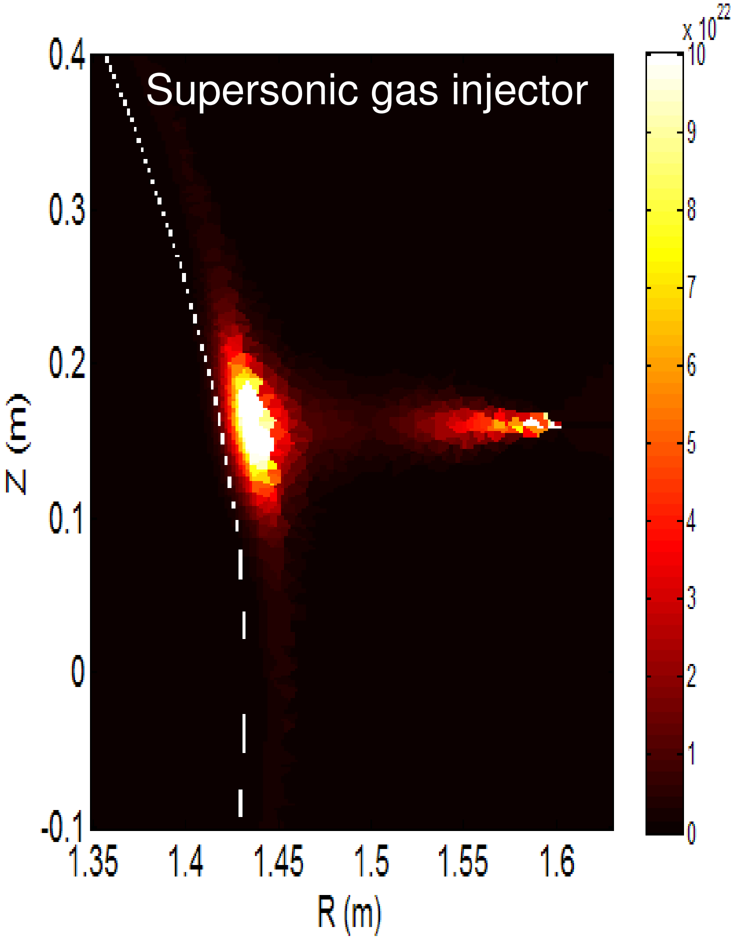
Molecular Dissociation Rate ($m^{-3}\ s^{-1}$)





Puff produces a significant D° population

The SGI D° density is localized, and the flux-surface averaged density is smaller

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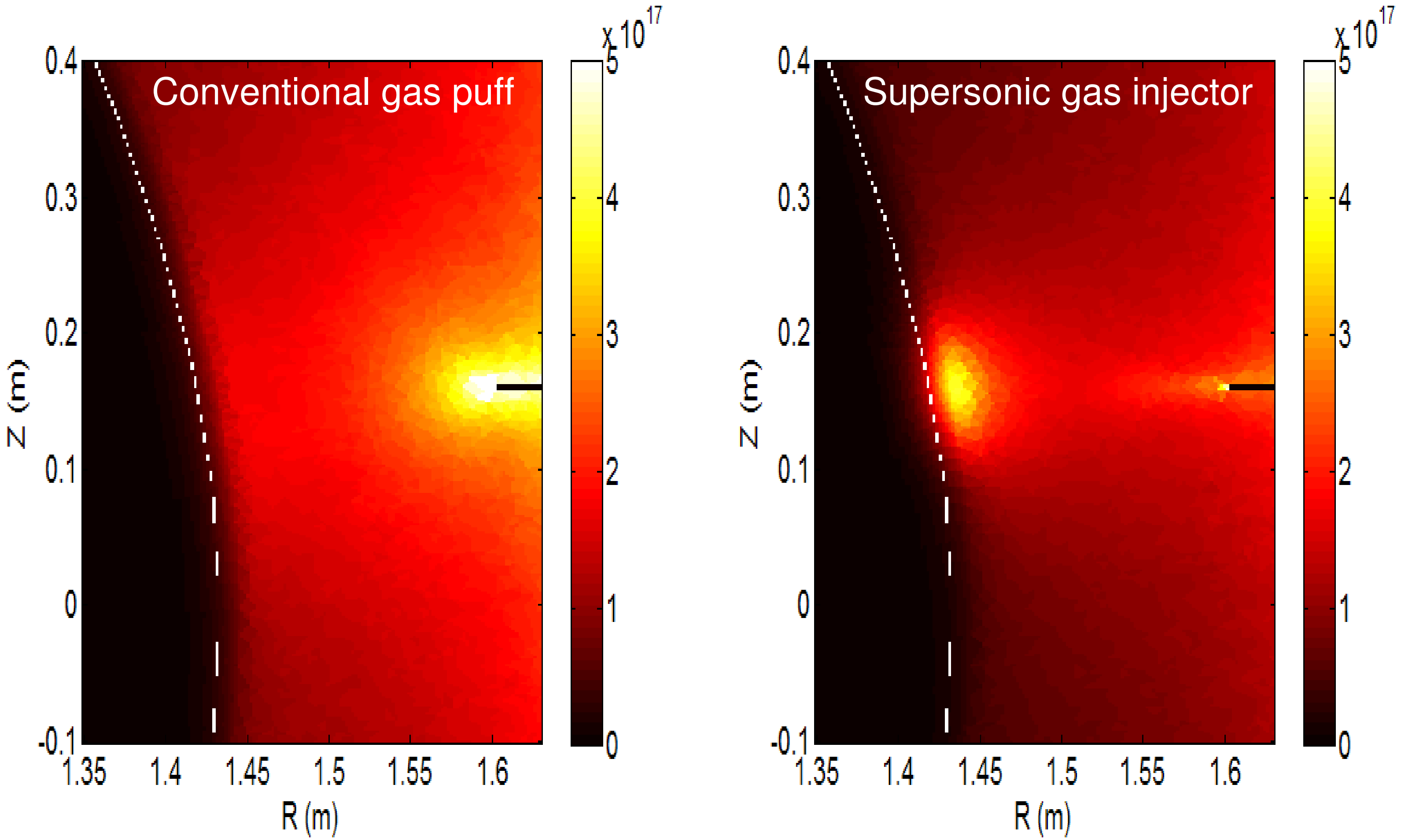
D° Atomic Density (m^{-3})



The SGI D^+ source is intensely localized near the separatrix
A modest increase in the penetration should significantly improve fueling efficiency

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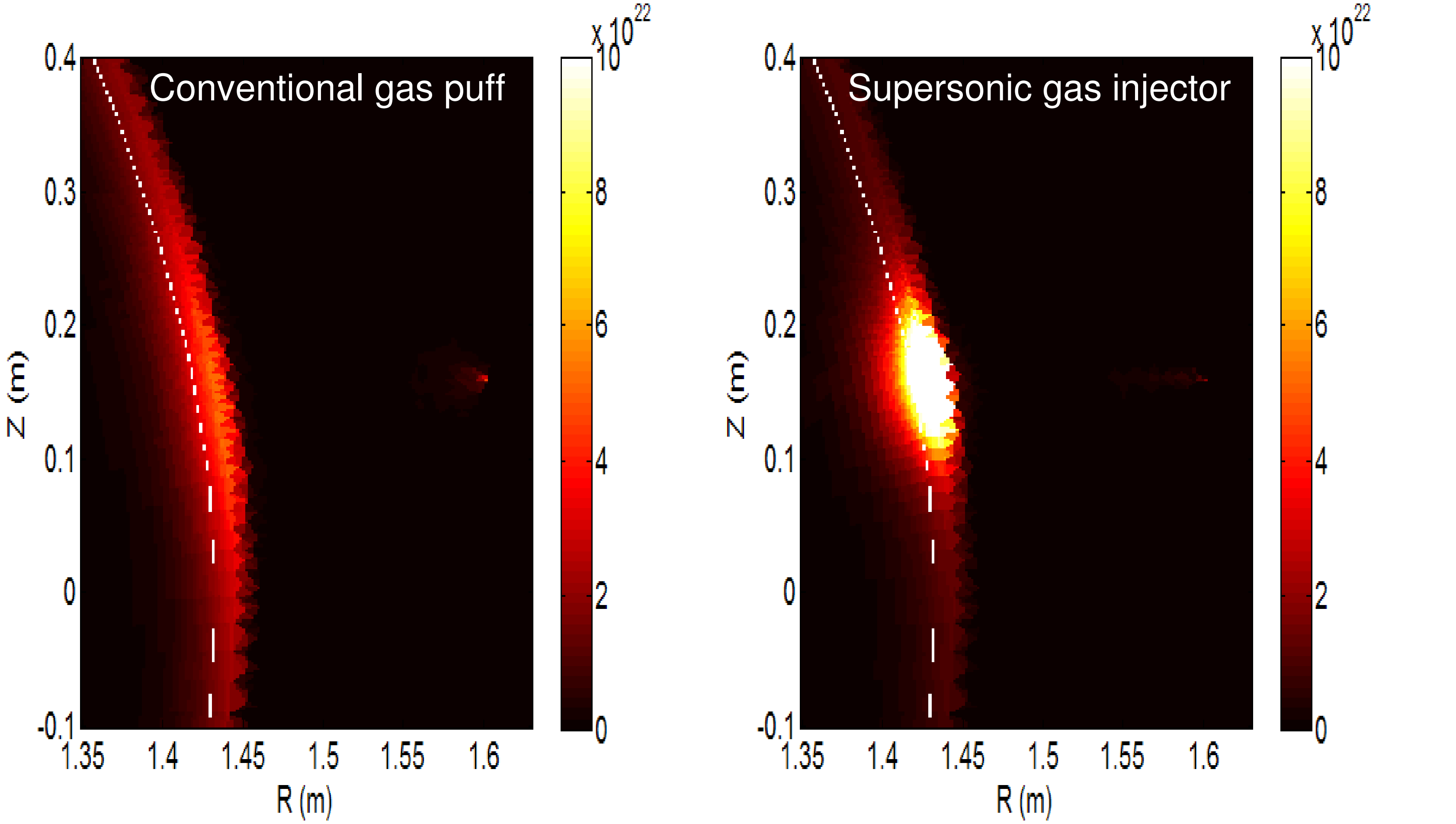
D^+ Source Rate ($m^{-3}\ s^{-1}$)



The conventional puff sources more ions than the SGI inside the separatrix

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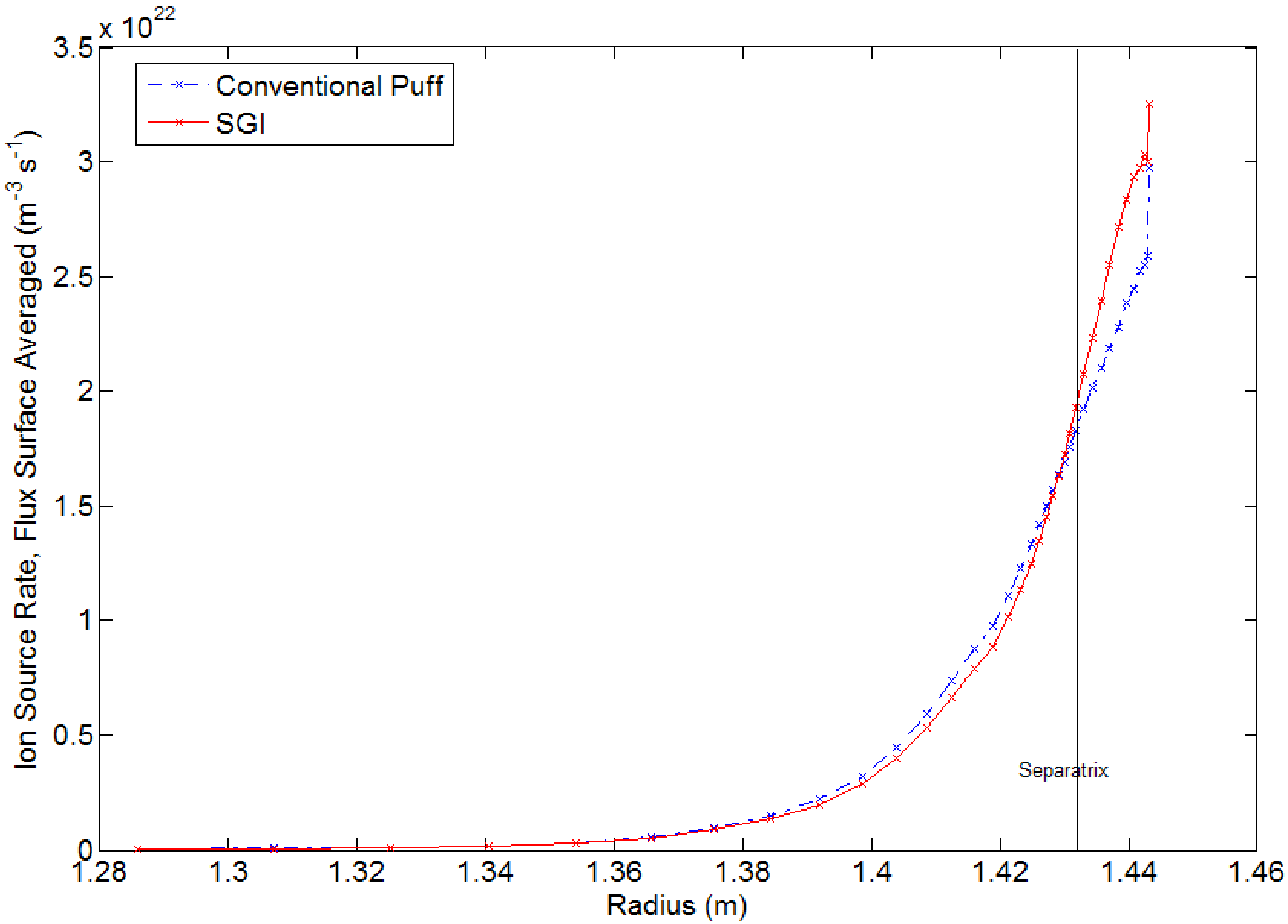

Conclusions

- 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 injects 10-30% of NSTX plasma inventory in a continuous fashion, with measured fueling efficiency 0.1-0.3
- The directed velocity of the SGI is not the primary factor in enhancing penetration over a gas puff
  - Collective effects are necessary to improve fueling efficiency
- Future SGI experiments should deviate significantly from the DEGAS 2 results as higher pressure regimes are reached