SUPERSONIC GAS INJECTOR FOR FUELING and DIAGNOSING OF NSTX PLASMA

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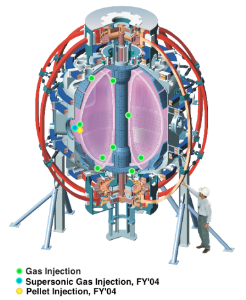
APS DPP 2003
45th Annual Meeting of the Division of Plasma Physics
October 27-31, 2003
Albuquerque, New Mexico

Particle control in NSTX



NSTX fueling

- Gas injection: low field side (LFS, top + side) and high field side (HFS, midplane + shoulder). Fueling gases: D_2, He, injected at S = 20 - 150 Torr l / s. Diagnostic gasses: He, Ne, Ar.
- Neutral beam injection system: three beams, 80 - 100 keV, 6 MW, fueling rate: S < 4 Torr l / s
- Supersonic gas injection (near future)
  S = 10 - 50 Torr l / s
- Pellet injection (edge - near future, core - future)
- Compact toroid injection (near future)

NSTX wall conditioning

- Between shots He GDC (present)
- TMB and Plasma TMB (present)
- Lithium coatings (future)

NSTX pumping

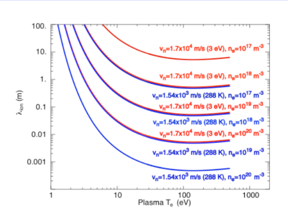
- TM pump (3400 l / s)
- NBI cryopump (50000 l / s, in NBI heated plasmas only)
- Conditioned walls
- Divertor cryo-pump (future)

Requirements for gas injection

NSTX gas fueling:
- Improve gas injectors
- Improve pumping / reduce vacuum vessel conductances.

- High injection rate (S = 5 - 100 Torr l / s)
- High fueling efficiency, close to LCFS or inside
- Localized - minimize contact of neutrals with PFC / leakage
- High jet density ρ
- High neutral velocity v_0
- Time response ~ ms for feedback control
- Minimize undesirable edge plasma effects - cooling, edge MHD

SGI has been implemented on Tore Supra tokamak (France), HT-7 and HL-1M tokamaks (China)



Gas flow regimes

- Viscous flow (Poiseuille) λ << d
- Molecular flow λ >> d
- Knudsen flow(transitional) λ ≈ d
- Compressible flow

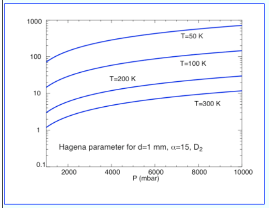
$$Q_{Visc} = \frac{\pi a^4 k}{16hl} P_{av}(P_2 - P_1)$$

$$Q_{Mol} = \frac{4}{3}\frac{\sqrt{\frac{8kT}{\pi m}}}{\int_0^l \frac{H}{A^2}dl}(P_2 - P_1)$$

- FWHM of viscous flow jet - 32 deg,molecular effusion from orifice 60 deg, nozzle < 20 deg

$$\lambda_{ion} = \frac{v_n}{n_e S_{ion}} = \frac{v_n}{n_e \langle \sigma_{ion} v_e \rangle}$$

Condensation and clustering



Molecular clustering increases jet density by order(s) of magnitude

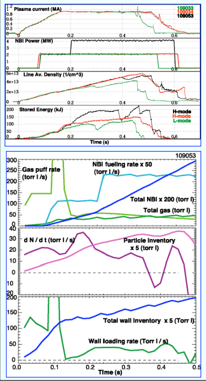
- Condensation / droplet formation in jet is attractive for fueling but may cool edge plasma
- Degree of clustering in jet is estimated through Hagena parameter

$$\Gamma^* = k\frac{(d/\tan\alpha)^{0.85}}{T_0^{2.29}} P_0 = 100 - 300$$

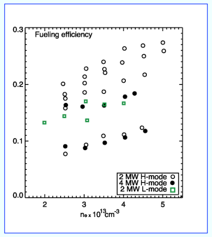
D - nozzle diameter, a - nozzle half angle, T_0 and P_0 are stagnation temp. and pressure

- k=181 for D_2, k=185 for Ne (clust. bond formation constant)
- $N_c \sim \Gamma^{2\text{-}2.5}$

NSTX plasmas fueled by gas injection and recycling



- Observe continuous density rise in LSN and DND plasmas fueled from HFS+LFS or LFS
- Gas fueling efficiency weakly depends on density in one discharge
- Fueling efficiency does not depend on gas inj. rate
- Variability between discharges is due to wall conditions
- Core/edge fueling by impurities may be significant
- Poloidal location of fueling source is unimportant in L-mode plasmas, critical for access to H-mode
- NBI fueling efficiency FE ~ 0.9 (“high”)
- dN/dt is ~ 20 Torr l / s
- NBI rate is ~ 2 - 4 Torr l / s
- HFS gas rate < 50 Torr l / s
- Net result - wall pumping
- LFS fueling only: wall degassing, LFS+HFS: fueling- wall pumping

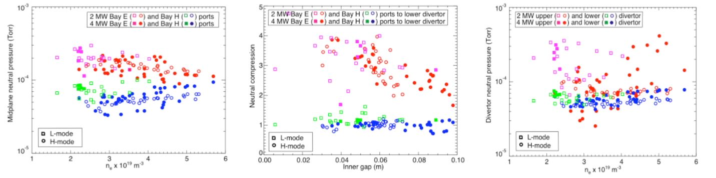


Fueling efficiency

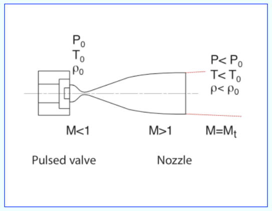
$$\eta = \frac{N_i(t)}{N_p(t)} \quad \text{or} \quad \eta = \frac{dN_i/dt}{\Gamma}$$

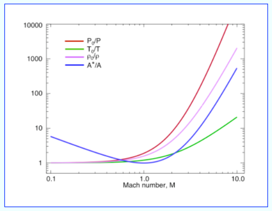
$$\frac{dN_p}{dt} = \Gamma_{gas} + \Gamma_{NBI} + \Gamma_{NBI\_cold} + \Gamma_{NBI\_cryo} + \Gamma_{wall} + \Gamma_{pump} + \frac{dN_n}{dt}$$

Neutral pressure measurements may be indicative of large v. vessel conductances



Isentropic compressible gas flow





Technology is well developed - aerospace and molecular beam research and industry

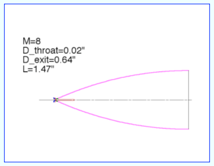
- Molecular beam: simple convergent nozzle with skimmers
- High pressure focused gas jet from contoured nozzle

Sound speed $c = \sqrt{(\frac{\partial p}{\partial \rho})_s} = \sqrt{\gamma RT}$
Mach number $M = V/c$
Reynolds number $Re = \frac{\rho v D}{\mu}$
Isentropic relations: $\frac{p_0}{p} = (\frac{T_0}{T})^{\frac{\gamma}{\gamma-1}}$
$\frac{\rho_0}{\rho} = (\frac{T_0}{T})^{\frac{1}{\gamma-1}}$
$\frac{p_0}{p} = (1 + \frac{\gamma-1}{2}M^2)^{\frac{\gamma}{\gamma-1}}$
Terminal flow velocity: $v_{max} = \sqrt{\frac{2\gamma}{\gamma-1}\frac{kT_0}{m}}$

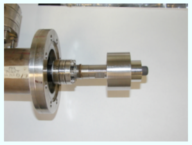
Laval nozzle design

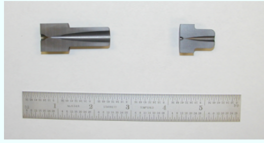
Nozzle of De Laval - convergent-divergent contour

- Method of characteristics
- Algorithms based upon expansion waves



Prototype nozzle injector has been built for evaluation





Characterization experiments in progress:

- Fueling experiments on CDX-U small spherical torus
- Mach number measurement in lab vacuum tank
- Injection rate measurement in lab vacuum tank
- Jet profile measurement in lab vacuum tank
- “Standard” diagnostic methods
  - Schlieren shadowgraphy
  - Mach number Pitot measurements

will not work for pulsed gas experiments in vacuum

Planned NSTX fueling experiments

Ohmic L-mode plasmas

- Determine fueling rate and efficiency in IWL, LSN, DND plasmas
- Determine change in edge plasma conditions (T_e, n_e, n_0, MHD modes, plasma rotation, impurities)
- Determine impact on core plasma performance (τ_e, τ_p, E_{stored})
- Attempt to raise density to n_G
- Monitor divertor detachment

Aux. Heated L- and H-mode plasmas

- All from above +
- Determine compatibility with H-mode operation
- Determine compatibility with HHFW heating

Attractive diagnostic applications to be demonstrated

- Impurity injection (He, Ne)
- Electron transport studies using cold pulse propagation measurements
- He line ratio spectroscopy for edge T_e, n_e profile measurements
- Disruption mitigation potential