Electron Density Distribution in HSX

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Abstract

A multichannel interferometer system is now routinely operating on the new quasi-helically symmetric stellarator, HSX, to measure the equilibrium profile and electron density dynamics. The interferometer system has 9 viewing chords with 1.5 cm spacing. The density spatial distribution is reconstructed from the measured line-integrated density. At high density [$\bar{n}_e > 2\times10^{12}\,cm^{-3}$], an m=1 density oscillation with frequency of (1-2) kHz is observed. Perturbative particle transport studies will be carried out using modulated gas puffing. The particle source will be measured by a multi-channel H_α system. By using the continuity equation, the total radial particle flux Γ_r can then be estimated. The diffusion coefficient D and convection velocity V will also be modeled.

**Supported by USDOE under grant DE-FG03-01ER-54615, Task II and DE-FG02-93ER54222.*

Interferometer Capabilities

- **Spatial resolution**: 9 chords, 1.5cm spacing and width.

- **Fast time response**: analog: 100-200 μsec, real time
  digital: <10 μsec
  maximum bandwidth 250 kHz [with 2 MHz sampling]

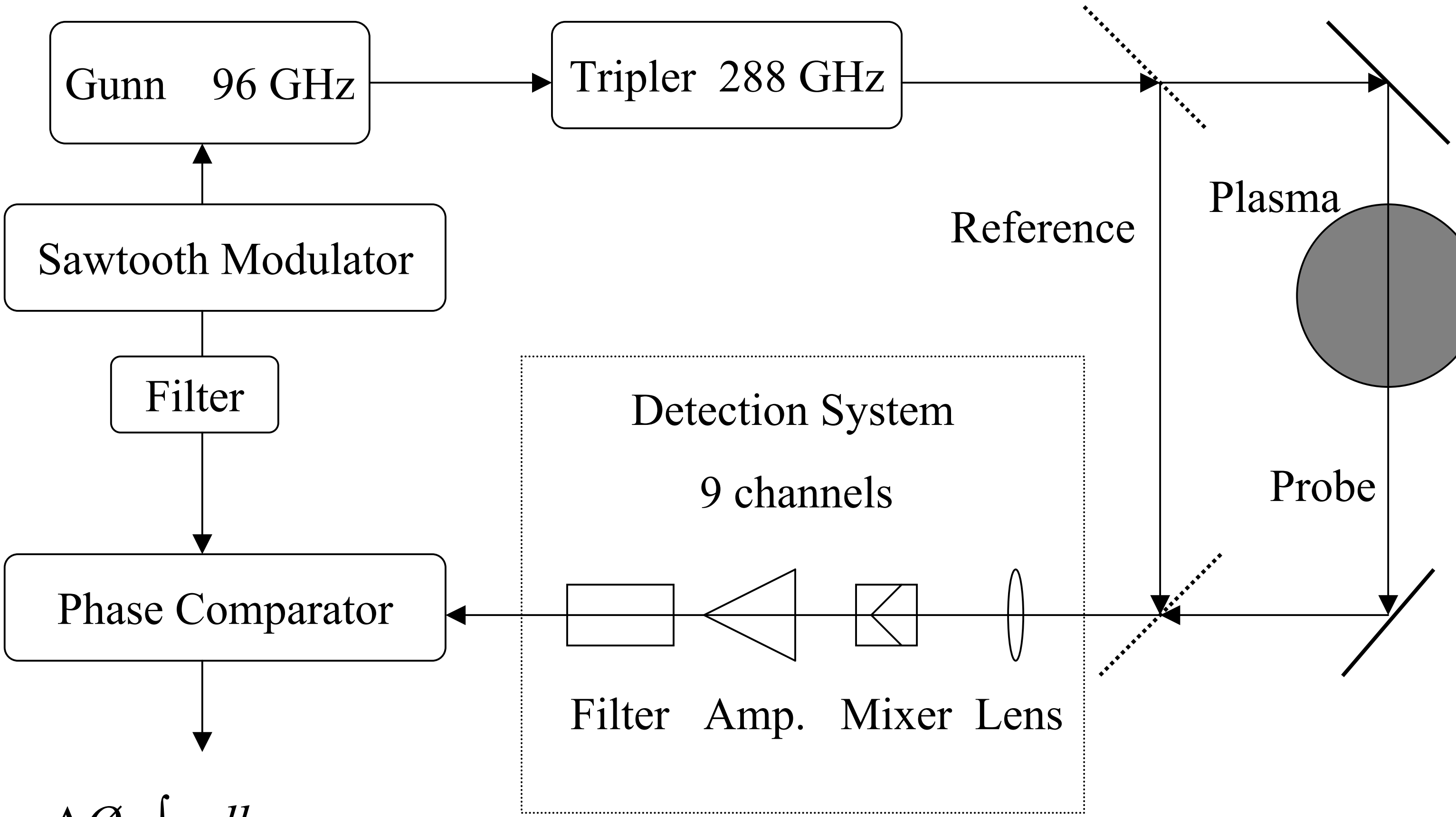
- **Low phase noise**: 24 mrad (1.6°)
  $(\Delta n_e dl)_{min} = 9 \times 10^{11}\ \mathrm{cm}^{-2}$
  0.4% level density fluctuations can be measured

- **Density fluctuations**: wavenumber resolution
  (i) $k_\perp < 2.1\ \mathrm{cm}^{-1}$, (ii) $k_\| < 0.07\ \mathrm{cm}^{-1}$

Solid State Source

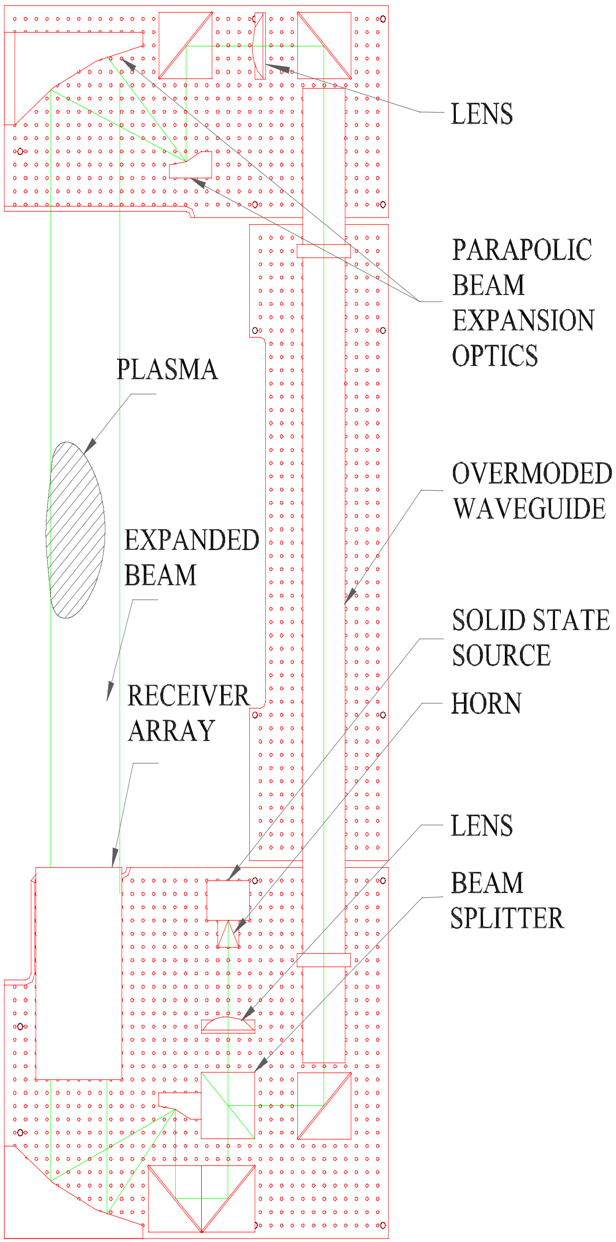
- **Solid State Source**:
  - bias-tuned Gunn diode at 96 GHz with passive solid-state Tripler providing output at 288 GHz (8 mW)
- **Support of Optical Transmission System**:
  - 2.5 meter tall, 1 ton reaction mass, mounted on structure independent of HSX device. Reduces structure vibration and minimizes phase noise.
- **Dichroic Filters**:
  - mounted on port windows to shield interferometer from 28 GHz gyrotron radiation
  - Cut-off frequency: ~220 GHz
  - ~ 10% loss
  - attenuation ranging from 92db at 28 GHz to 68 db at 150 GHz.
- **Edge Filters**:
  - mounted inside port windows to reduce diffraction of the window

Interferometer Schematic

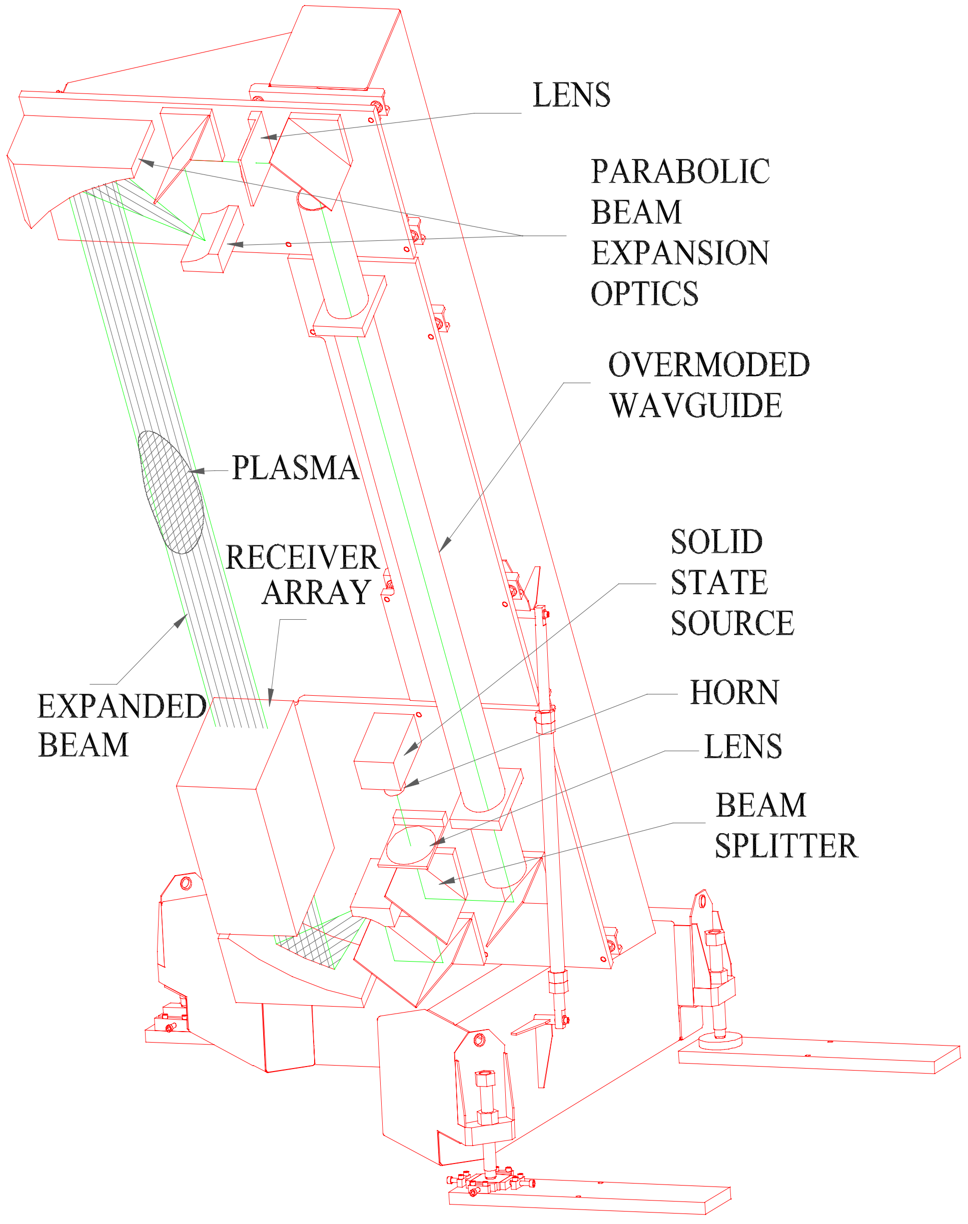


$\Delta \varnothing = \int n_e dl$

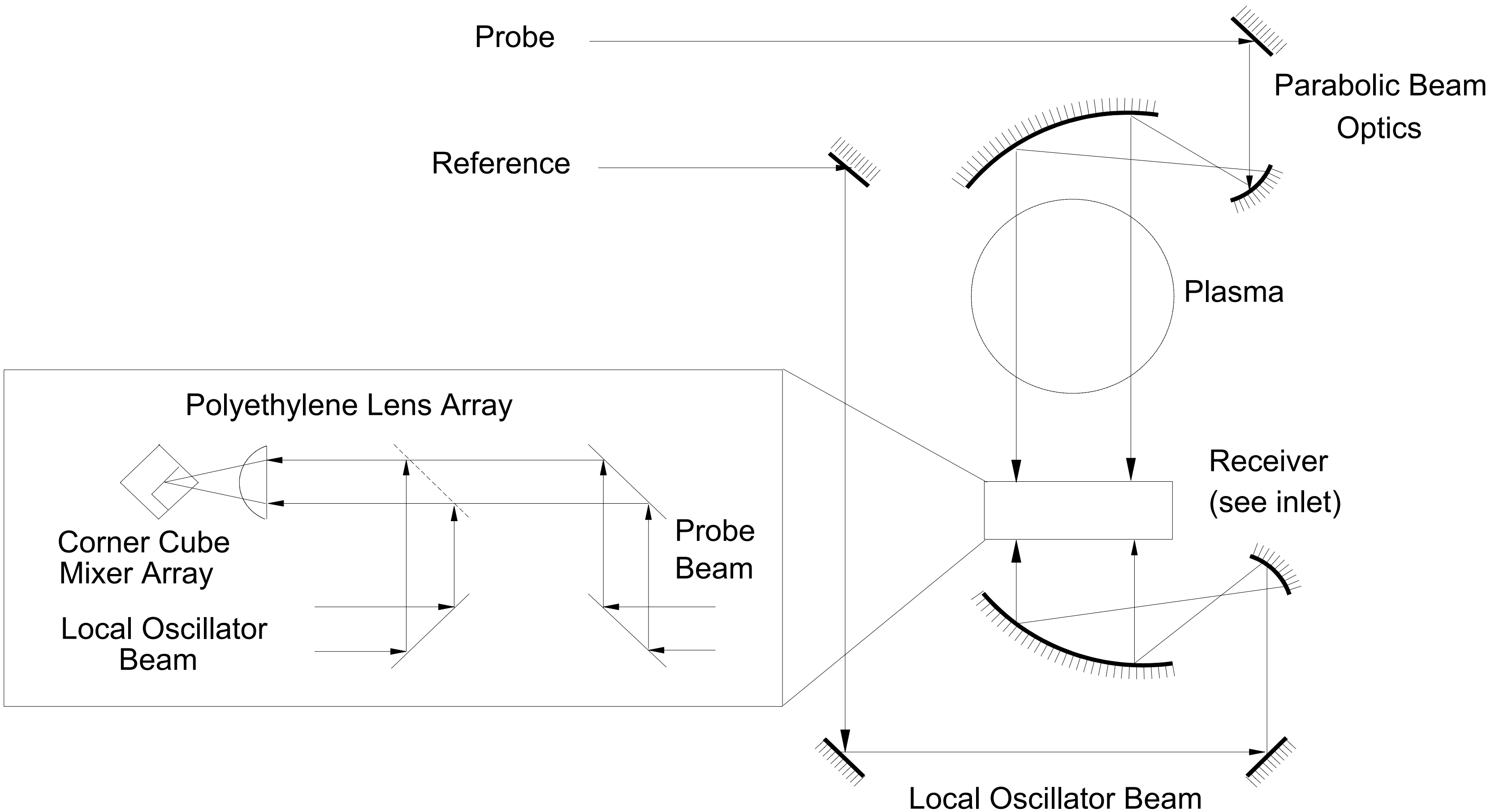
HSX Interferometer Layout



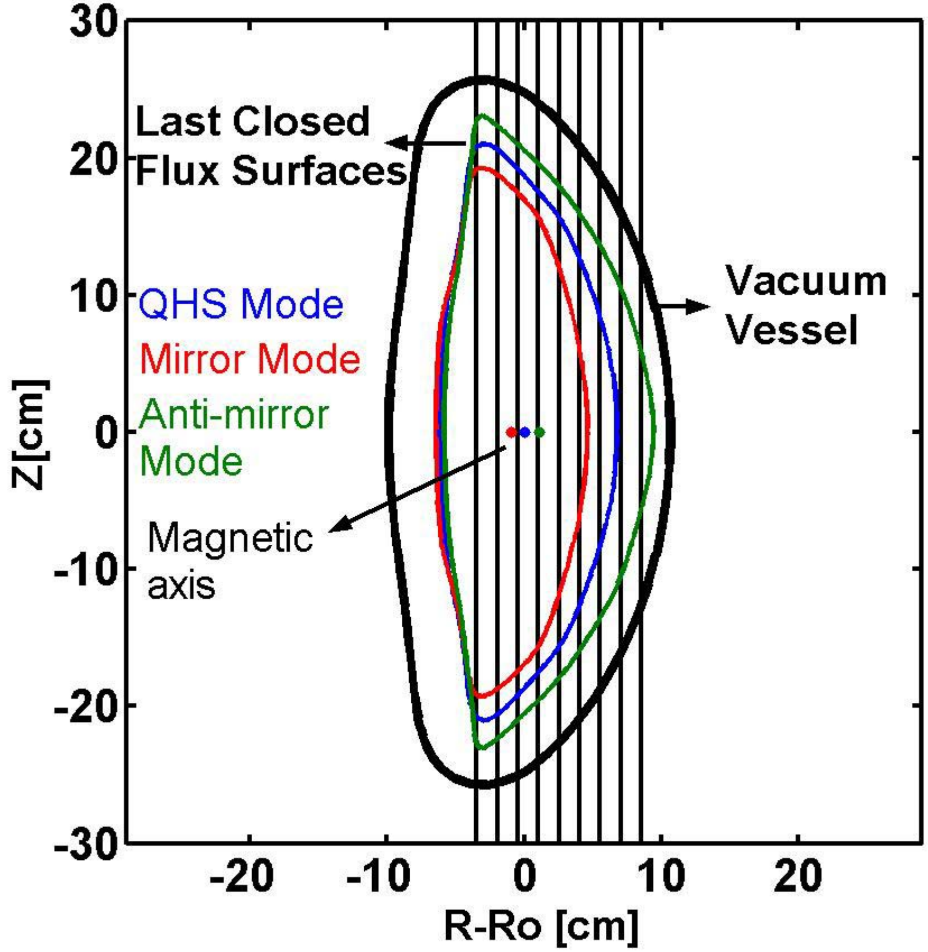
HSX Interferometer System



Beam Expansion Optics and Receiver Array



Flux Surfaces and Interferometer Chords



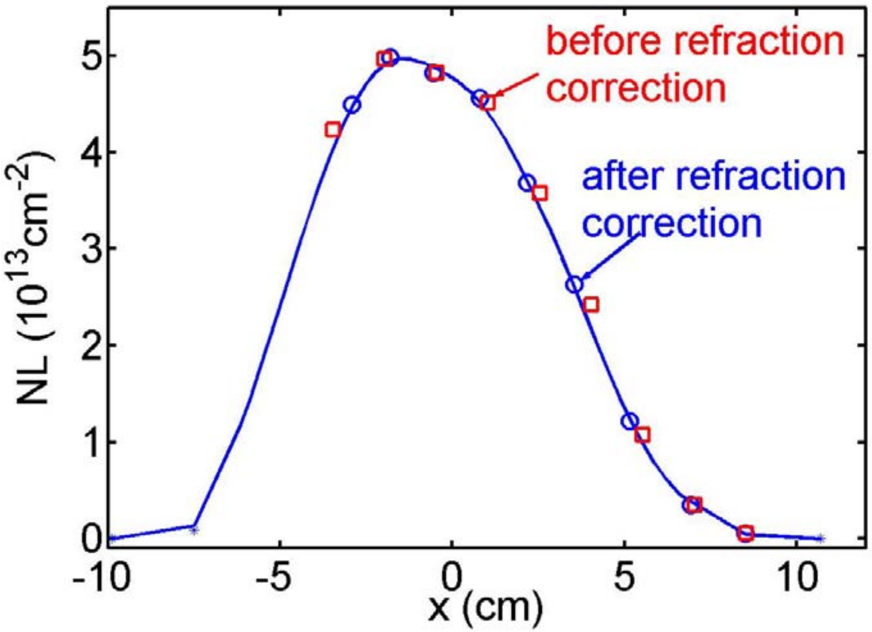
Density Profile Inversion

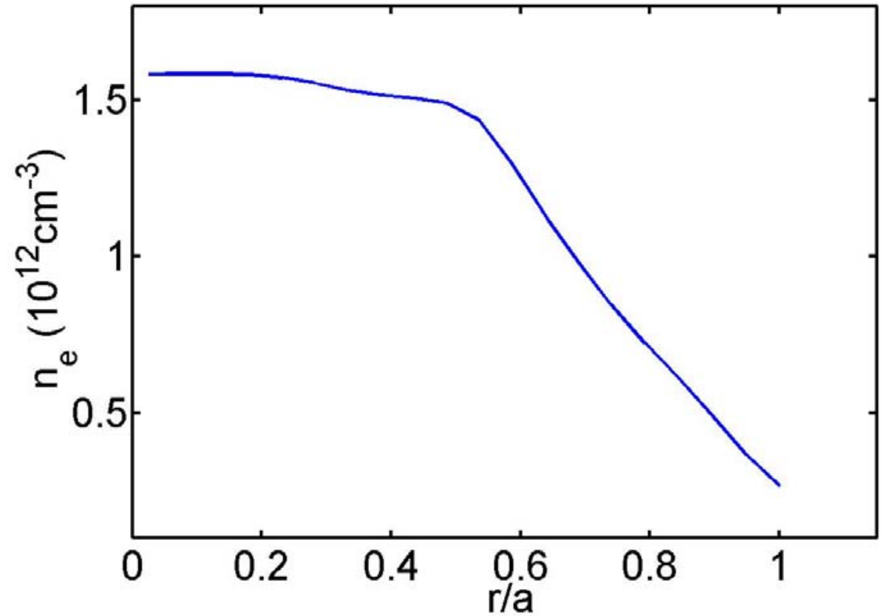
- **Method:** Abel inversion; Singular Value Decomposition
  - flexible boundary conditions
  - non-circular geometry
  - plasma scrape-off-layer SOL estimate
- **Model:** spline fit to 9 channel line-density profile
  - no Shafranov Shift
- **Path lengths:** calculated for twenty vacuum flux surfaces,
- **SOL plasma contribution:** One viewing chord is outside the separatrix. This provides information on the SOL contribution.
- **Refraction correction:** necessary for chord length and position

HSX Density Profile (QHS)

Measured Line-Integrated Density Profile and fitting

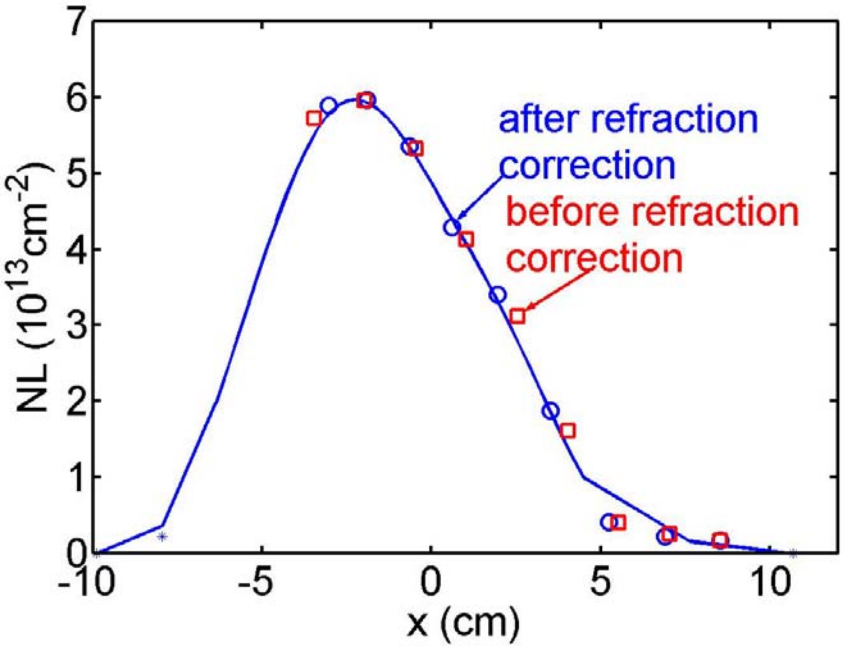
Inverted Density Profile



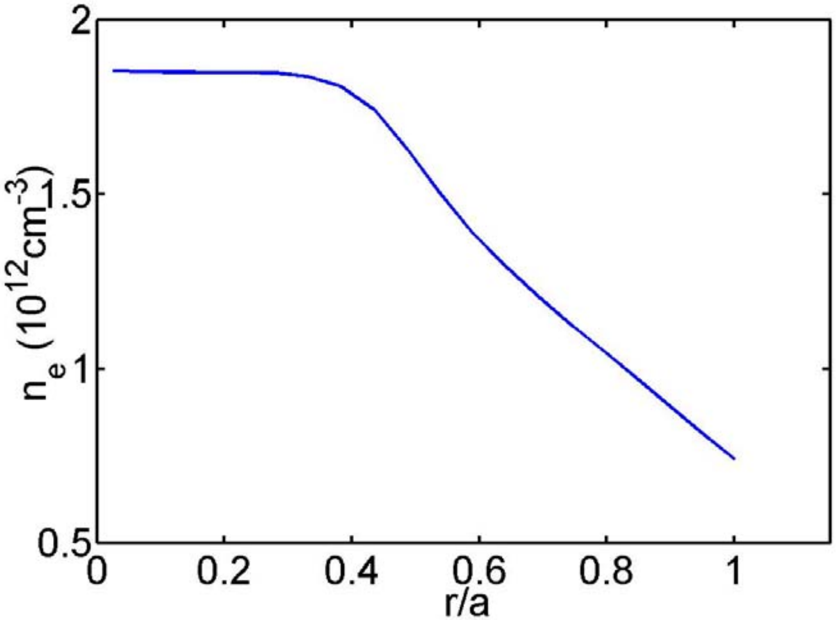


HSX Density Profile (Mirror)

Measured Line-Integrated Density Profile and fitting

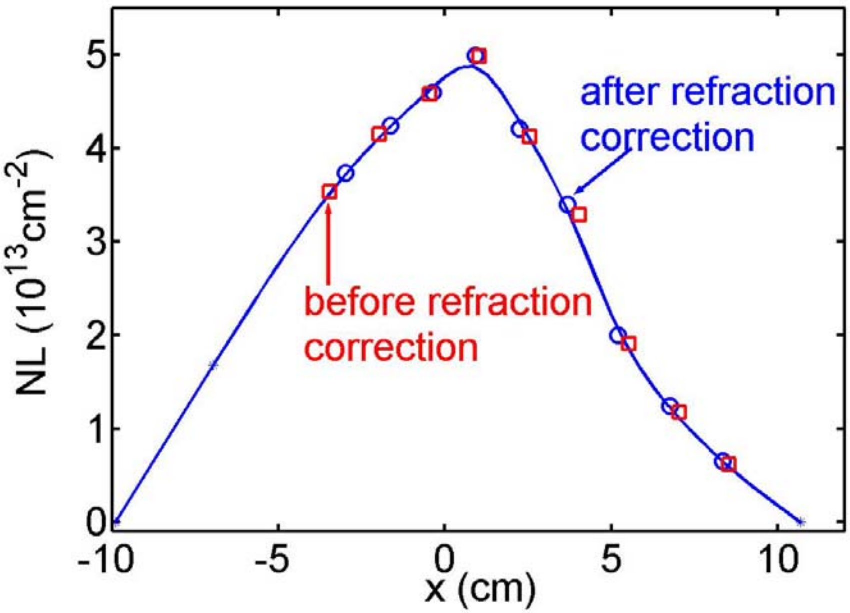


Inverted Density Profile

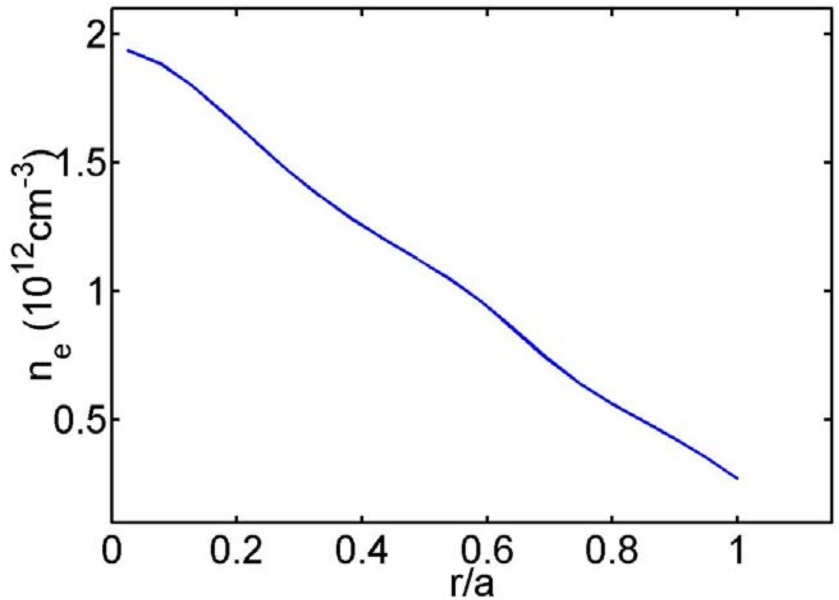


HSX Density Profile (Anti-Mirror)

Measured Line-Integrated Density Profile and fitting



Inverted Density Profile



Perturbative Particle Transport Study

Density perturbation obtained by gas puffing modulation provide a good tool for particle transport study. Previous successful experiments on TEXT, ASDEX, W7-AS

Diffusive and convective effects can be obtained by analyzing profile time evolution:

Sinusoidal wave is ideal for this analysis, which give higher accuracy of the analysis. And a few cycles will be needed to obtain certain accuracy. The amplitude will be around less than 10% to reduce the effects of plasma parameters dependency.

Continuity Equation

The electron density can be constant on magnetic flux surfaces. We use cylindrical geometry transport Equation:

$$\frac{\partial n}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r} r\left(D(r,t)\frac{\partial n(r,t)}{\partial r} - V(r,t)n(r,t) \right) + S(r,t) \qquad (1)$$

Parameters n and S can be separated into two part: (1) stationary part n_0 and S_0, and (2) perturbed part $\tilde{n}$ and $\tilde{S}$.

$$n = n_0 + \tilde{n}\, e^{i\omega t} \qquad S = S_0 + \tilde{S}\, e^{i\omega t} \qquad (2)$$

where ω is the frequency of the density perturbation generated by modulating the gas feed. Also assume D and V are independent of time. Linearizing equation (1) leads to:

Linearized Equations

$$i\omega\tilde{n}(\omega,r) = D(r)\frac{\partial^2\tilde{n}(\omega,r)}{\partial r^2} + \left((\frac{D(r)}{r} + \frac{\partial D(r)}{\partial r} - V) \right)\frac{\partial\tilde{n}(\omega,r)}{\partial r}$$
$$-\left((\frac{V(r)}{r} + \frac{\partial V(r)}{\partial r}) \right)\tilde{n}(\omega,r) + \tilde{S} \qquad (5)$$

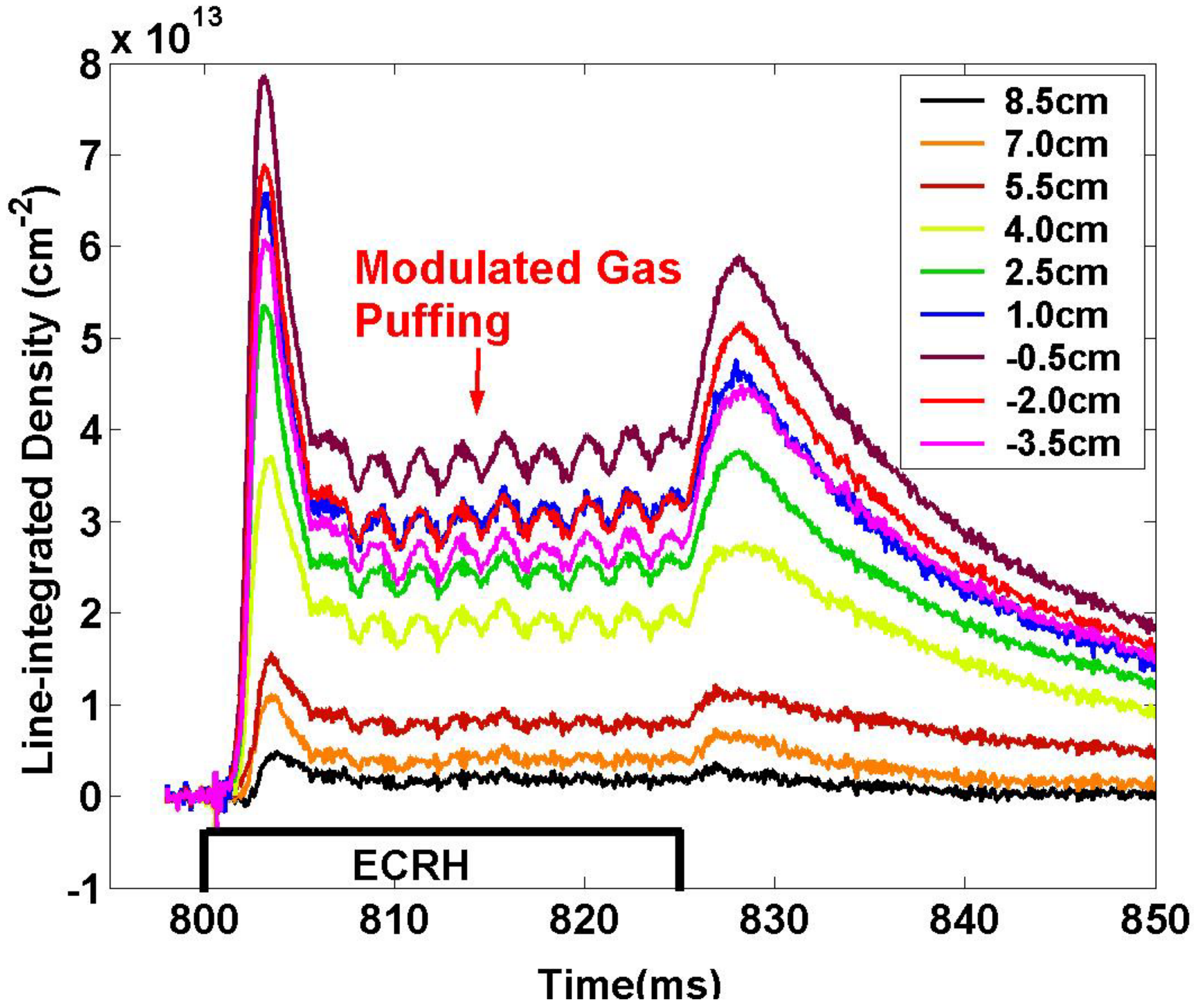
$$\tilde{n} = \tilde{n}_{re} + i\,\tilde{n}_{im}$$

The boundary conditions are:

at r=0 ; $\partial\tilde{n}_{re}/\partial r = \partial\tilde{n}_{im}/\partial r = 0$ (6)

at r=a. $\tilde{n}_{re} = 10^9 cm^{-3}; \tilde{n}_{im} = 0$ (7)

modulated gas feed



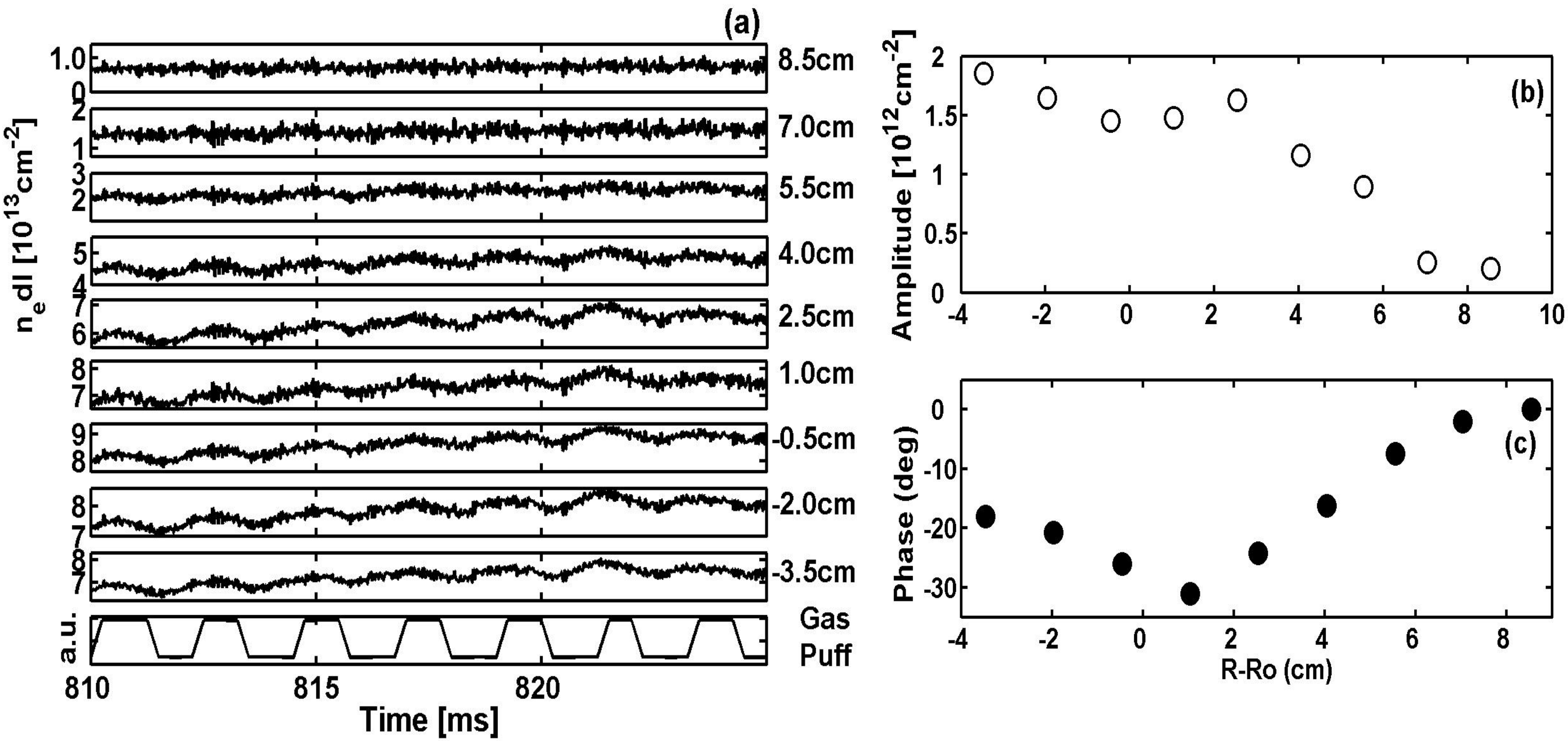
Fourier coefficients

The Fourier coefficients of the line-integrated density were obtained by fitting the following function to the measured data:

$$\tilde{I} = \tilde{N}_{re,1}\cos(\omega t) + \tilde{N}_{im,1}\sin(\omega t) + \tilde{N}_{re,2}\cos(2\omega t) + \tilde{N}_{im,2}\sin(2\omega t) + (a_0 + a_1 t + a_2 t^2)$$

Here $\tilde{N}_{re,i}$ and $\tilde{N}_{im,i}$ are the real and imaginary parts of the Fourier coefficients at the *i*th Harmonic of the modulation frequency. The a0,a1 and a2 correspond to constant, linear and quadratic time dependence and take into account a possible slow time evolution.

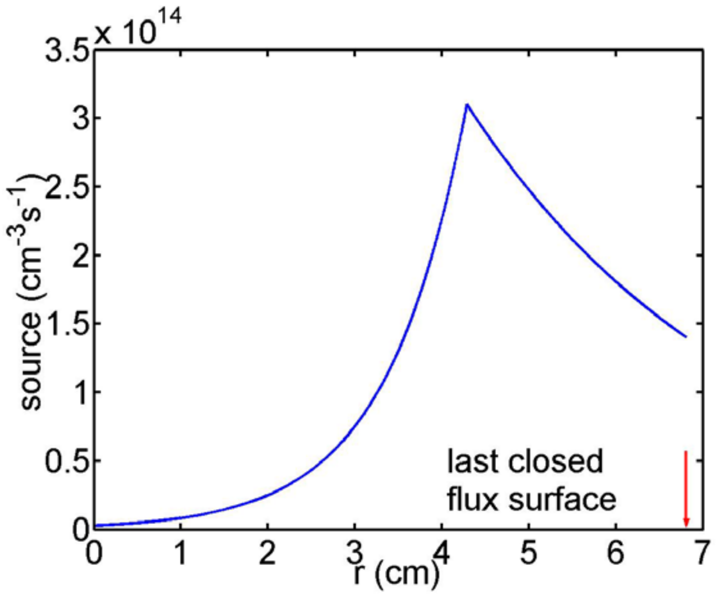
Density Perturbation Amplitude and Phase

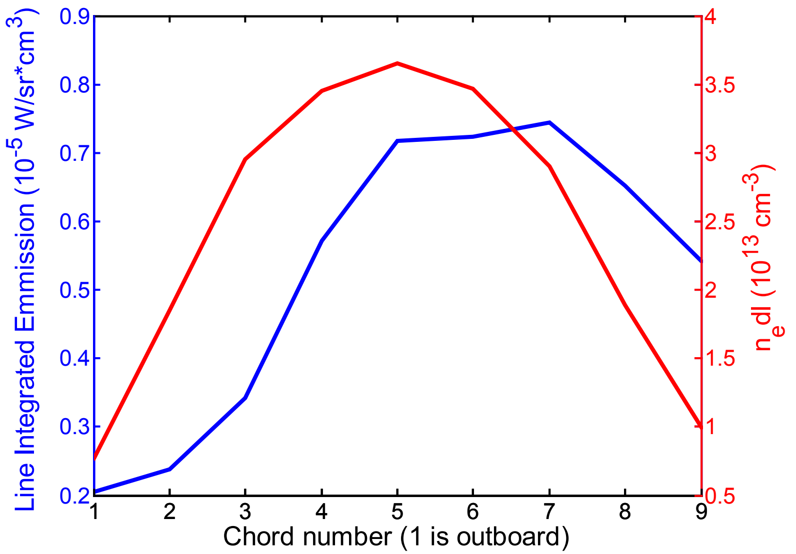


- Amplitude and phase of the first harmonic of the modulation frequency for the line-integrated densities

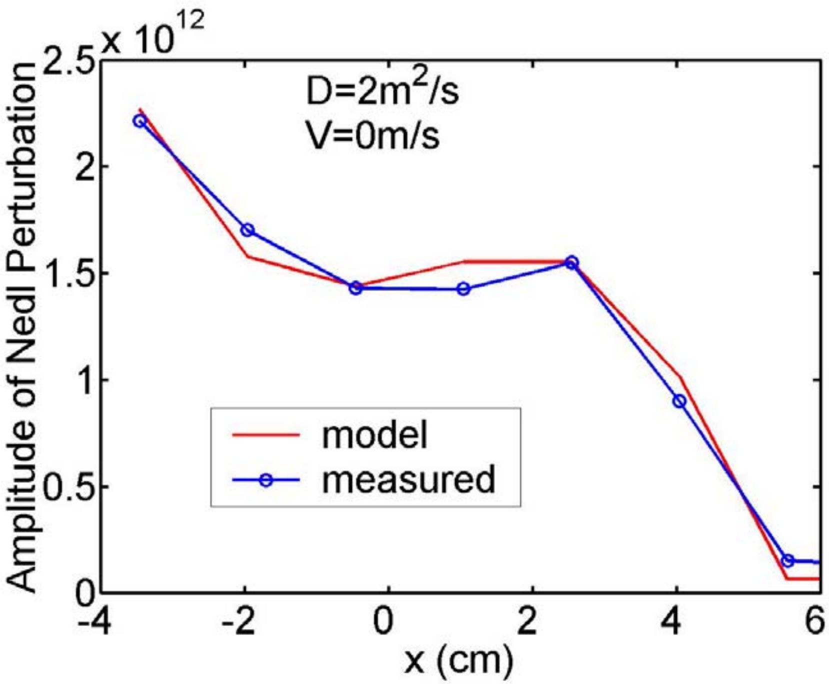
Estimated Source

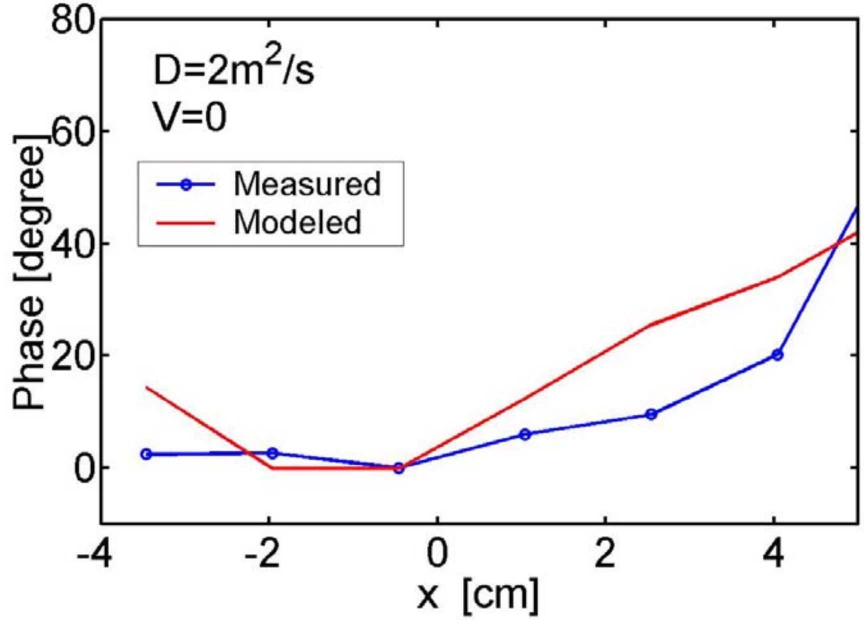
- **At this moment, electron source profile unknown.**
- **Assume source profile has exponential fall-off.**
- **Amplitude and position of the Source were chosen (roughly) according to the Hα measurement.**





Results for D=const. and V=0

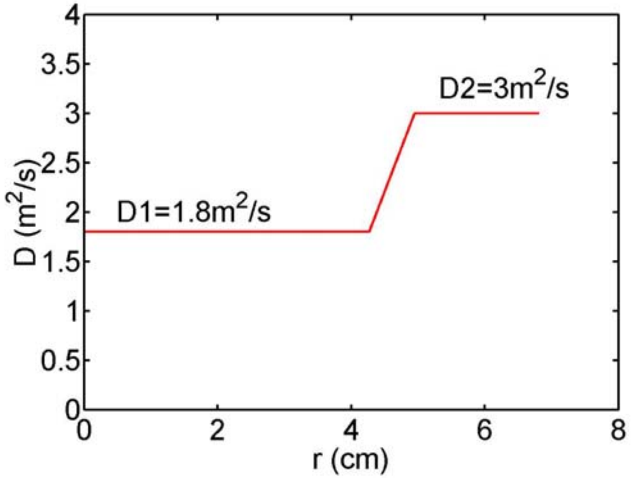




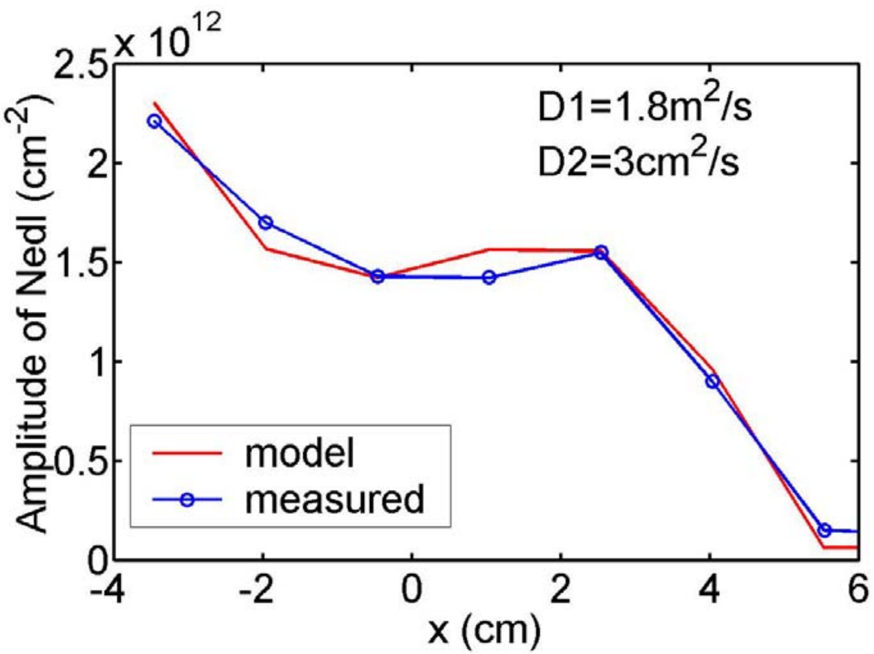
A rough estimate of D from measured particle confinement time, $\tau_p = \frac{\overline{n_e}}{\overline{S}}$

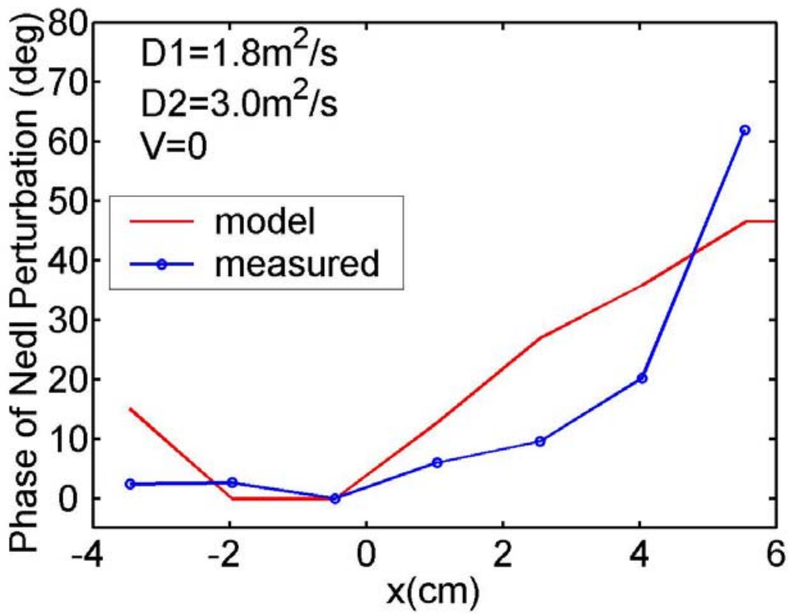
gives ~ 3ms, $D_{est}=a^2/(6\,\tau_p) \sim 1.0 m^2/s$

Results for stepped D, with V=0

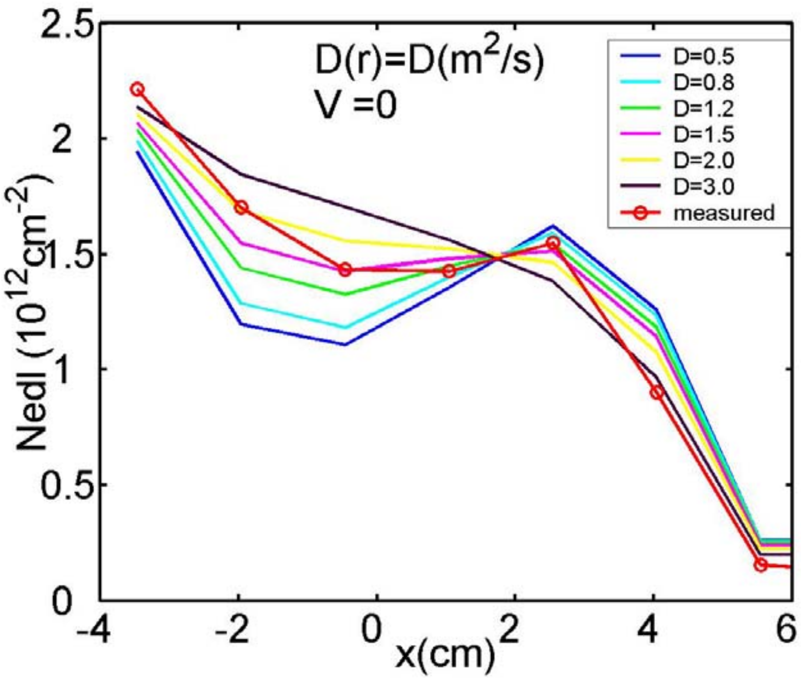


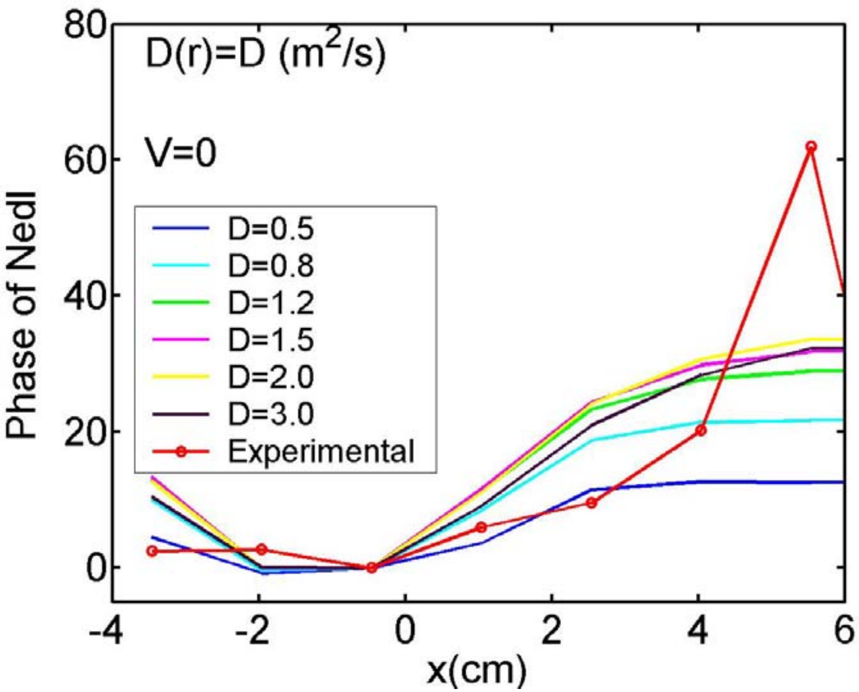
The modeling is not sensitive to the detailed structure of D





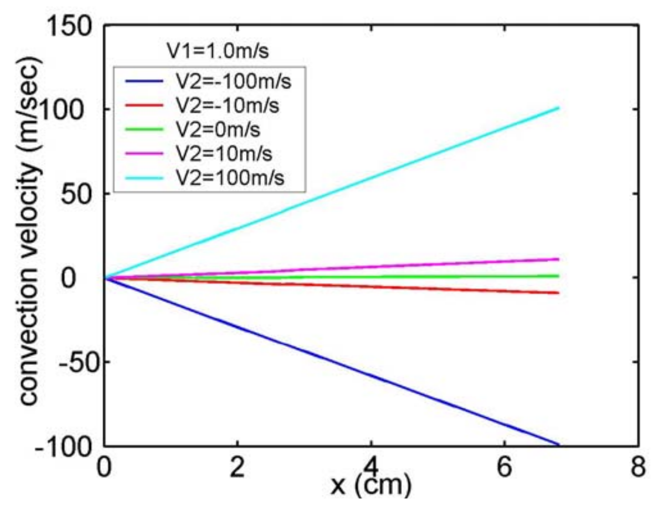
Sensitivity of Modeling to D

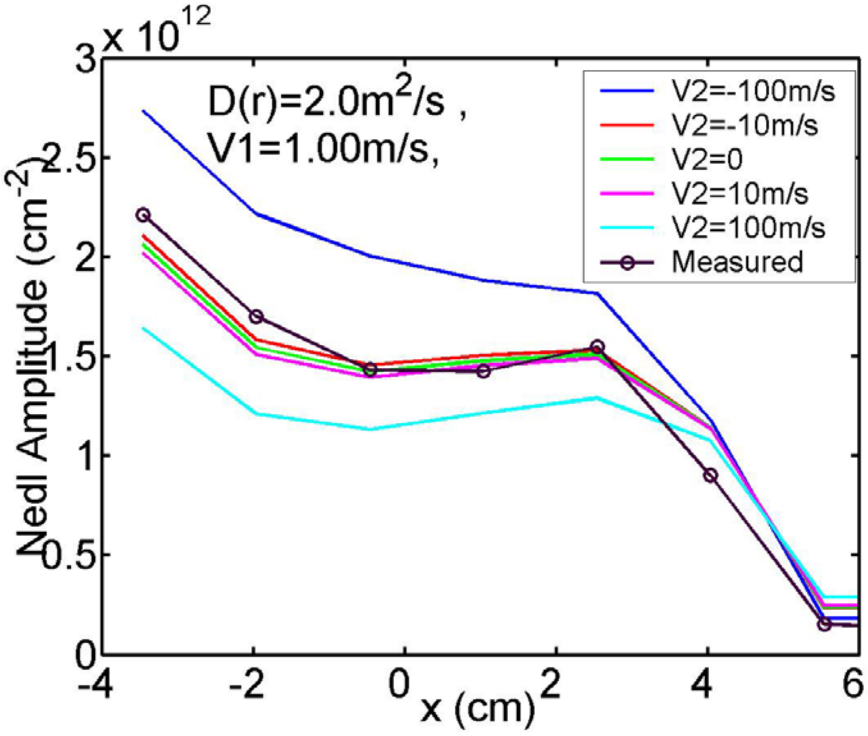


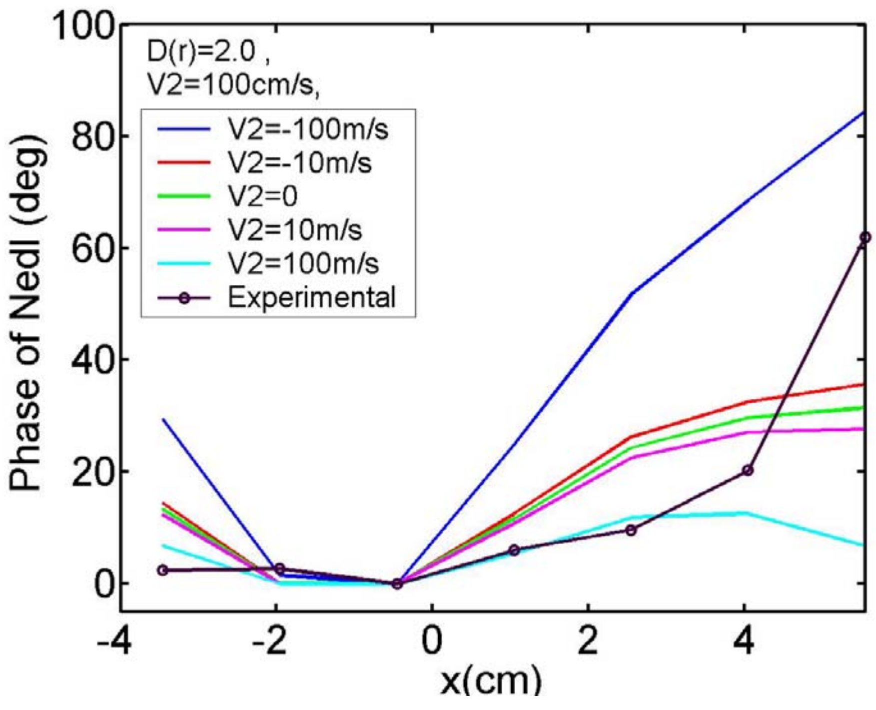


Sensitivity of Modeling to V

$$V = \left(\frac{V_1}{1 + \exp(-(r - r_v)/\Delta)} + V_2 \right)\left(\frac{r}{a} \right)$$



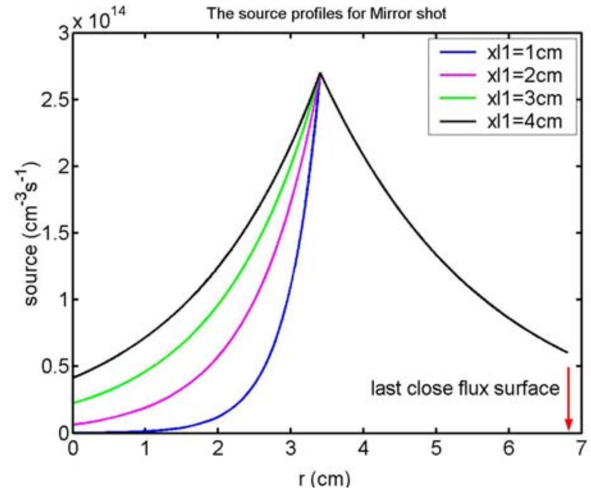


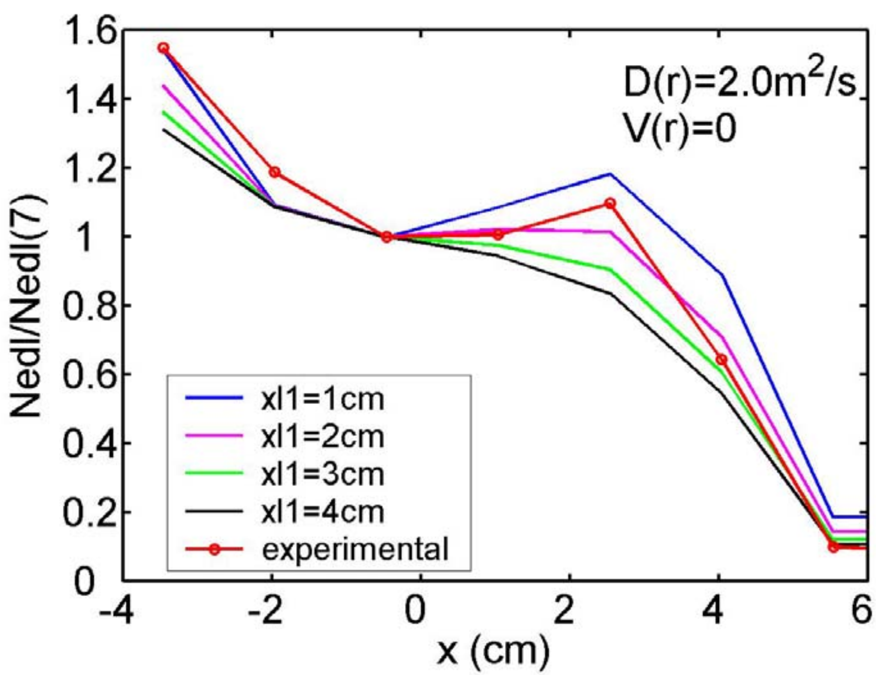


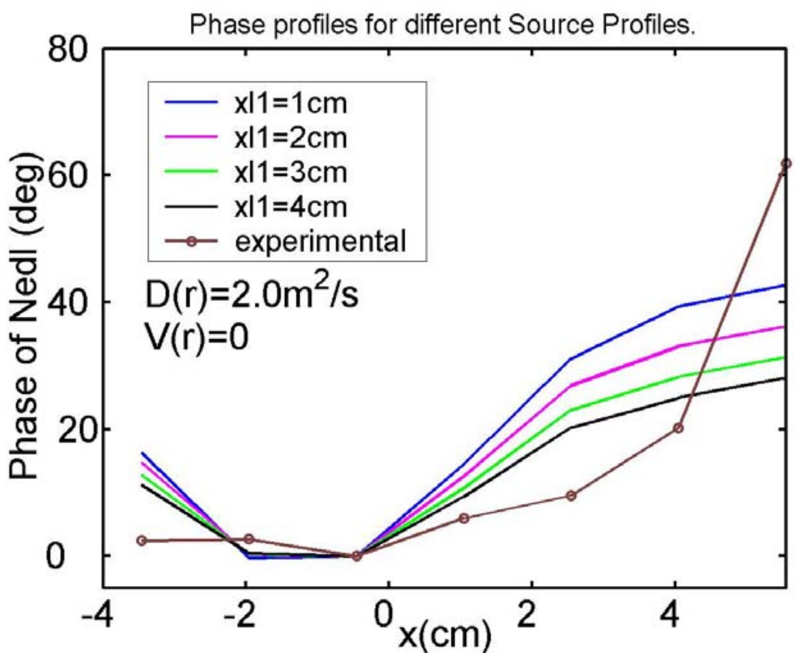
Sensitivity of Modeling to Source Profile

if x<xc

S=no*exp(-abs(x-xc)/xl1);
if x>xc
 S=no*exp(-abs(x-xc)/xl2);
xl2=5cm
Peak position: xc=3.4cm

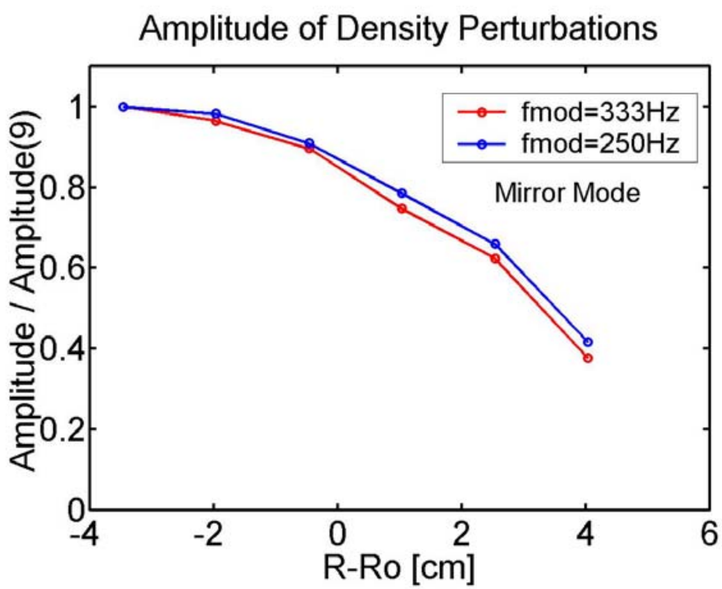


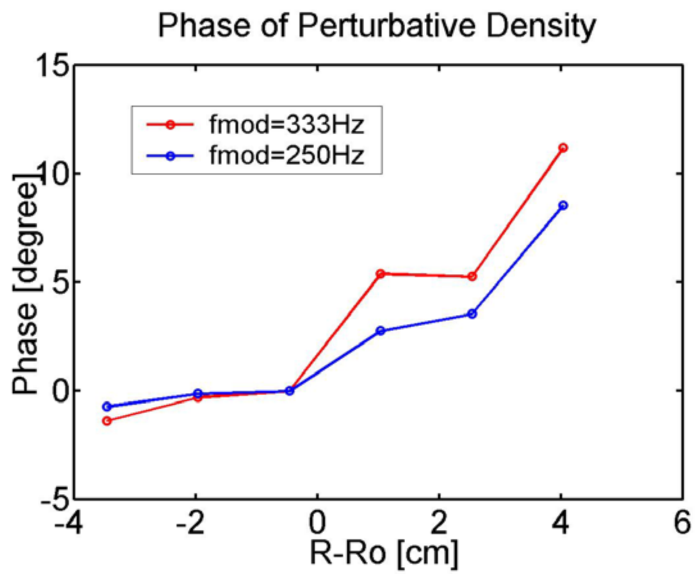




Density Perturbation at different frequencies

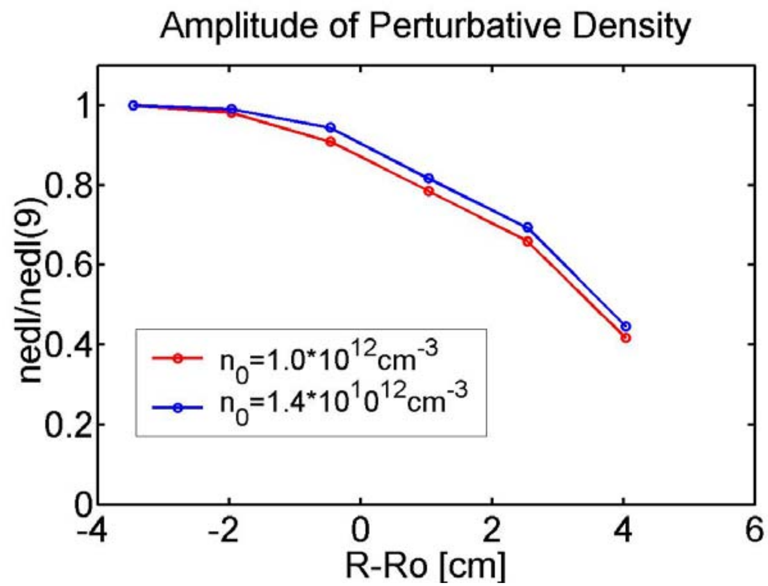
The Particle transport is unchanged with the frequency of gas feed modulations

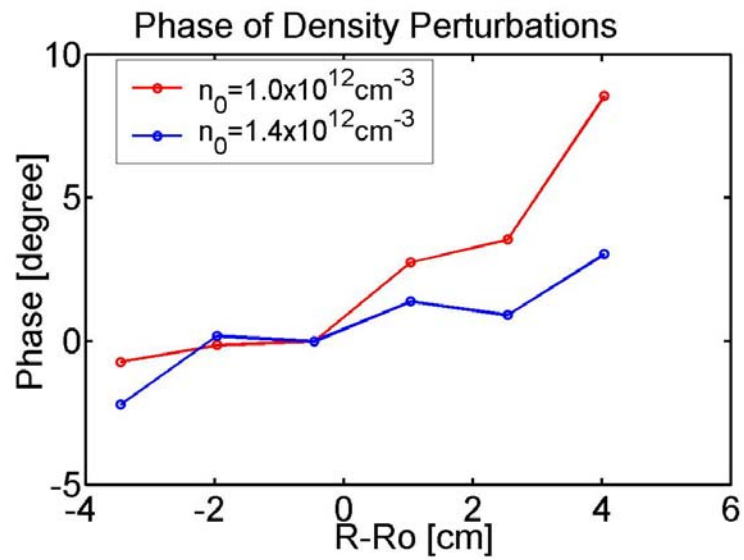




Density Perturbation with different Densities

The Particle transport changes a little with density, which would give smaller D at higher density.

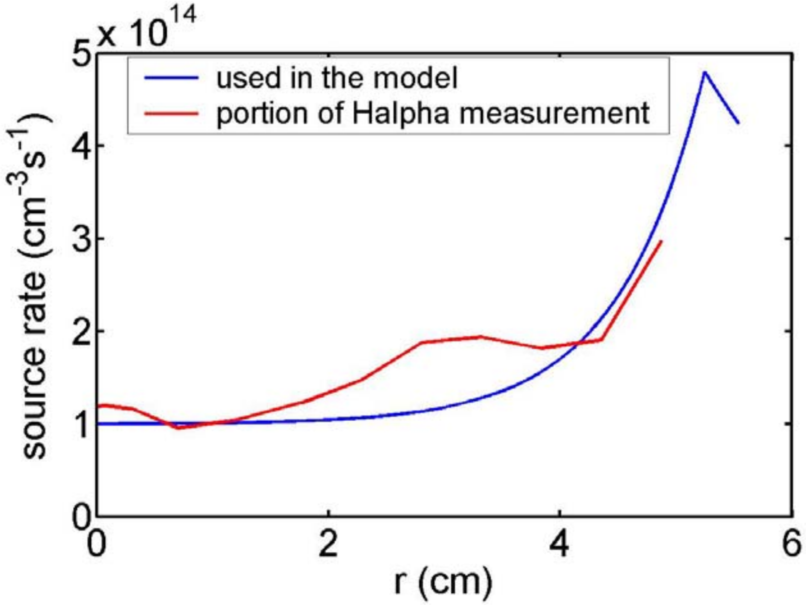


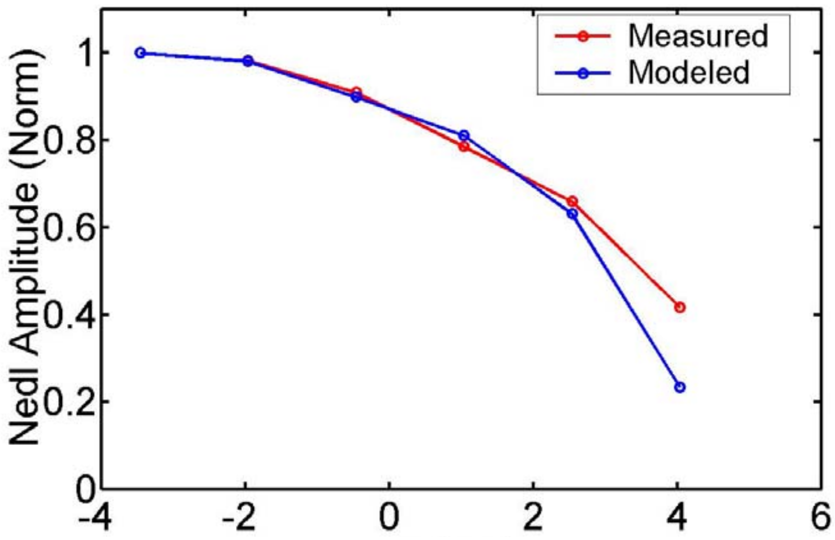


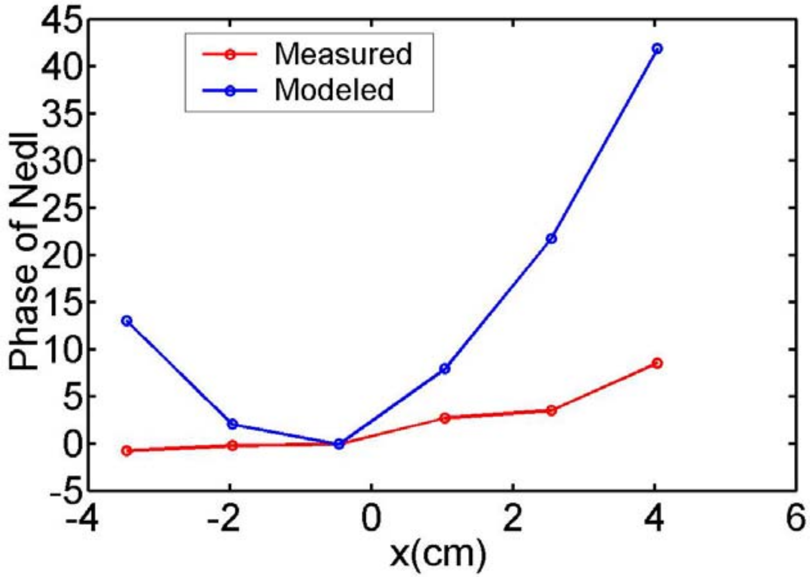
Modeling of the recent experiment

$D=2.0 m^2/sec$

$V=0 m/sec$

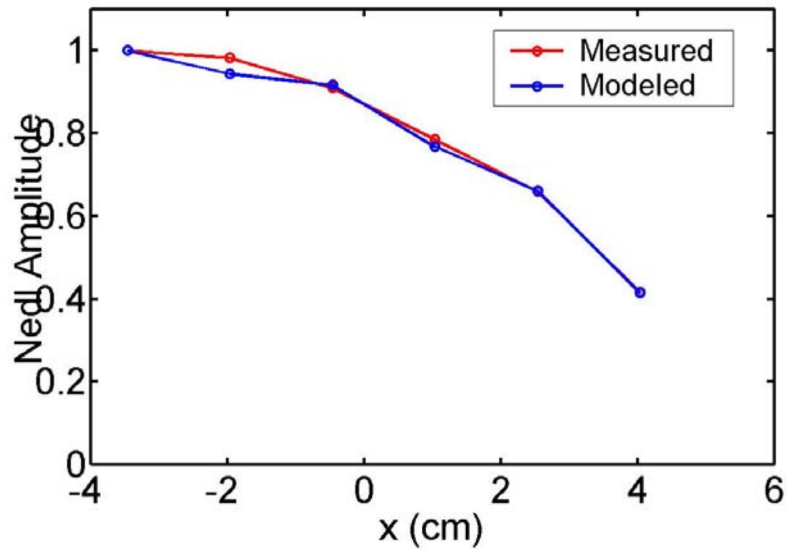


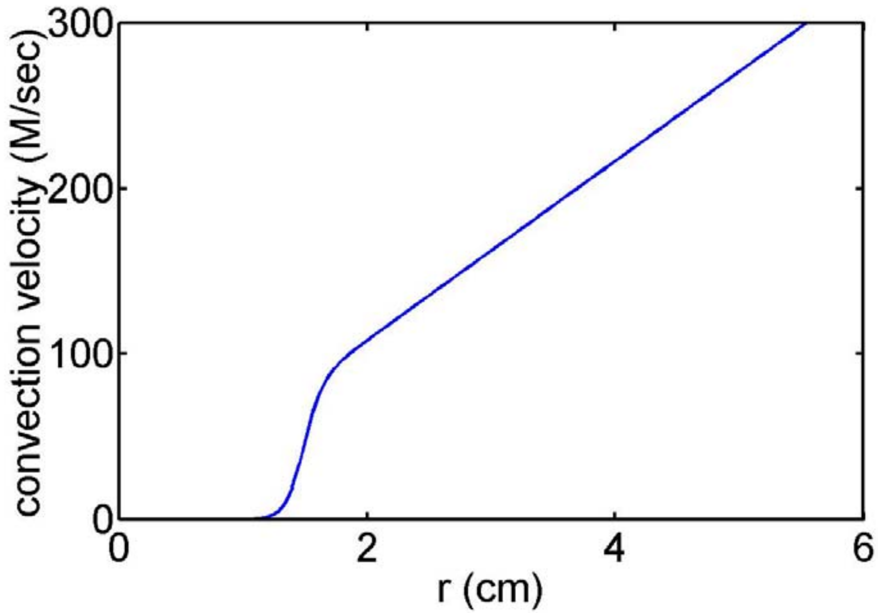


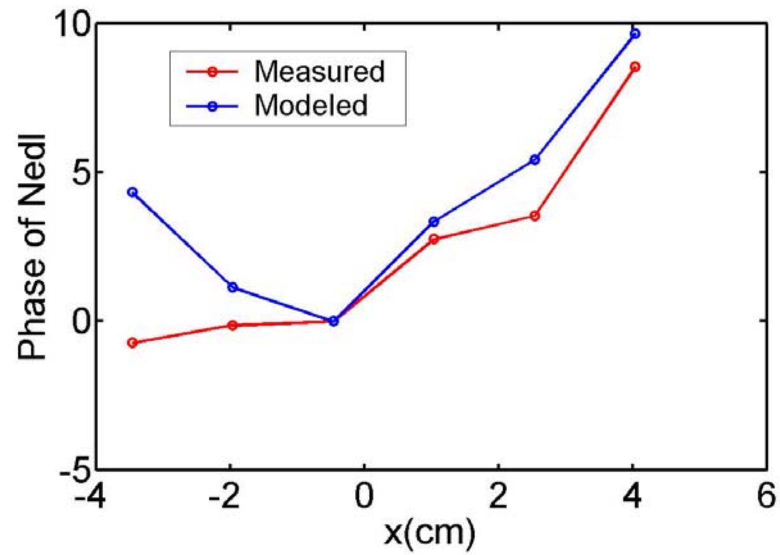


Better fit with outward convection

D=2.0m^2/sec
V=300m/sec
Source same as last slide







Summary

- Equilibrium Density Distributions for QHS, Mirror, Anti-mirror modes were obtained.

- The preliminary measurement and analysis shows the possibility of perturbative particle transport study on HSX,the modeling shows the D around 1-2m^2/s.

- Improved Electron source measurement (or modeling) required to determine D and V which provide best fit to interferometer data.