Particle Transport and Density Fluctuations in HSX

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Abstract

- Perturbative particle transport study in the quasi-helically symmetric stellarator, HSX, are carried out using a multichannel interferometer system. Density perturbations are produced by modulating the gas fuelling and the particle source is measured by a multi-channel H_α system. Diffusion coefficient D and convection velocity V are modeled by solving the continuity equation. Preliminary estimates indicate a diffusion coefficient D_e~2 m^2/s. The high-frequency density fluctuations in the range of 25-120 kHz were observed in quasi-helically symmetric plasmas in HSX. . These fluctuations have an m=1 mode nature. These fluctuations may be driven by gradients in the plasma pressure.

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Outline

1. **Equilibrium electron density profile for *Quasi-Helically Symmetric* (QHS) and *Mirror Mode* (MM) plasmas**
   Do direct loss orbits play a role in determining $n_e(r)$?

2. **Perturbative studies of particle transport by gas modulation experiments**

3. **High-frequency density fluctuations**

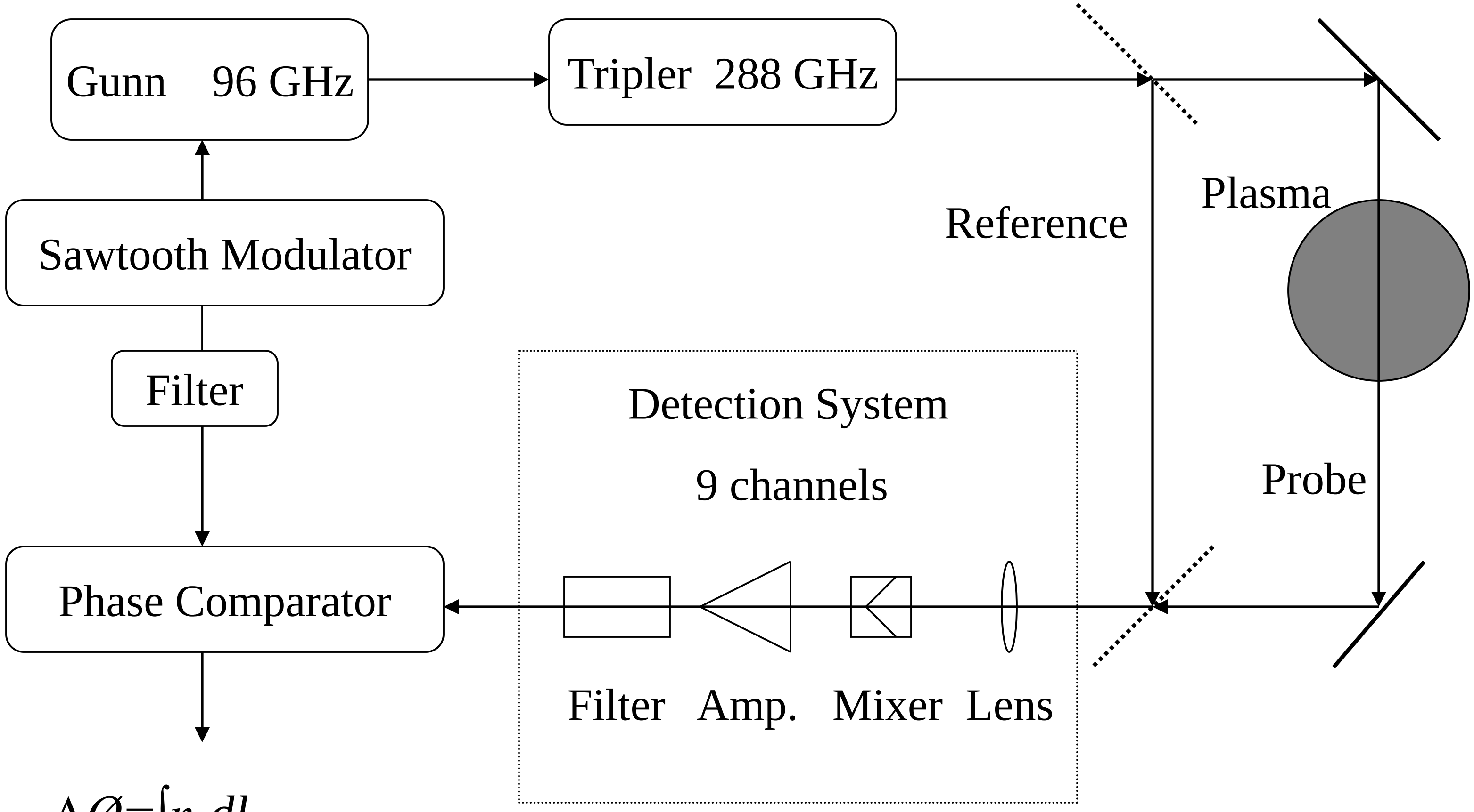
Interferometer Capabilities

- **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°)
  $(\Delta n_e dl)_{min} = 9 \times 10^{11}$ cm^{-2}
  0.4% level density fluctuations can be measured
- **Density fluctuations**: wavenumber resolution
  (i) $k_\perp < 2.1$ cm^{-1}, (ii) $k_{||} < 0.07$ cm^{-1}

Solid State Source

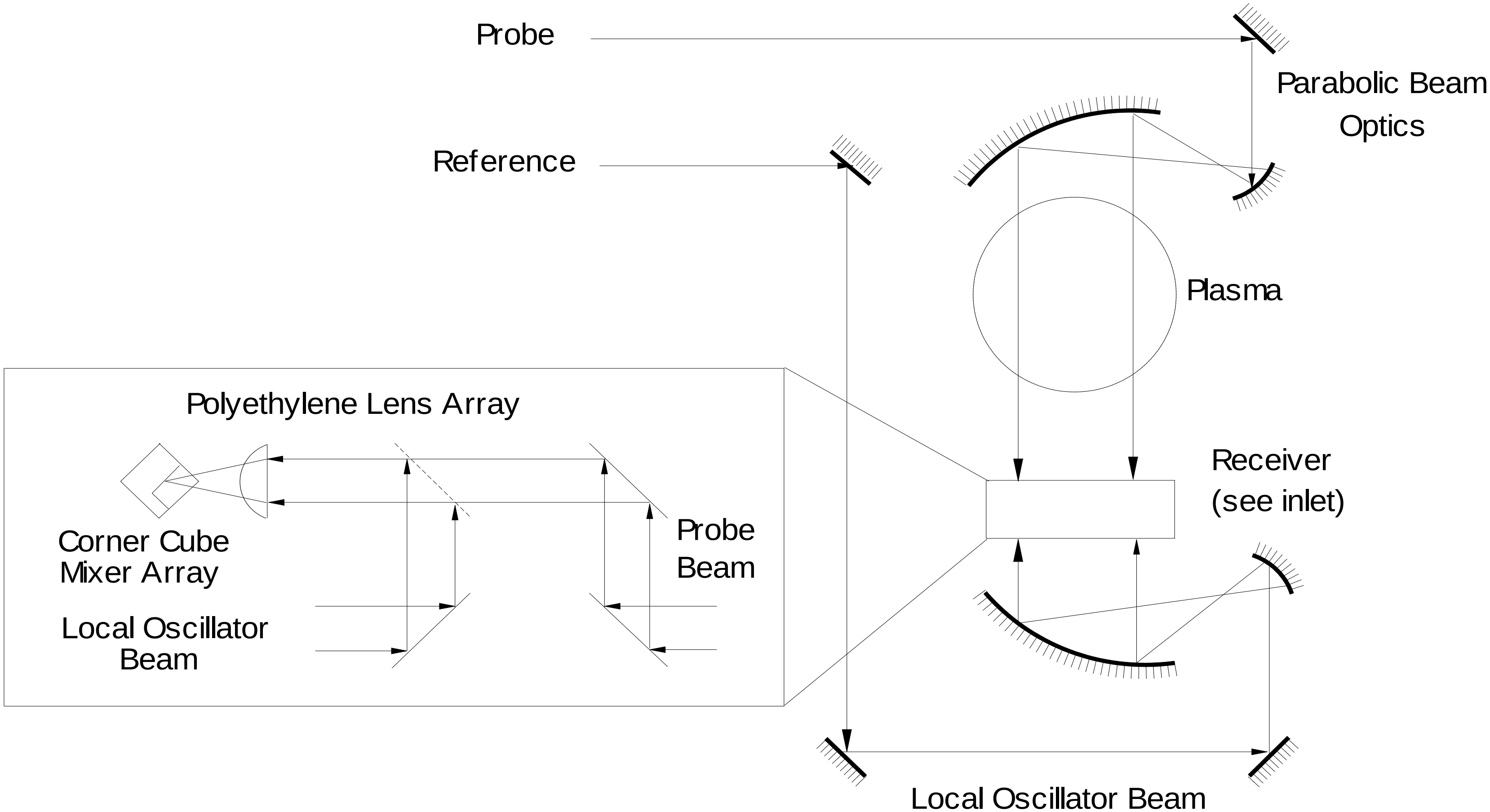
- **Solid State Source**:
  - bias-tuned Gunn diode at 96 GHz with passive solid-state Tripler providing output at 288 GHz (8 mW)
- **Support of Optical Transmission System**:
  - 2.5 meter tall, 1 ton reaction mass, mounted on structure independent of HSX device. Reduces structure vibration and minimizes 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

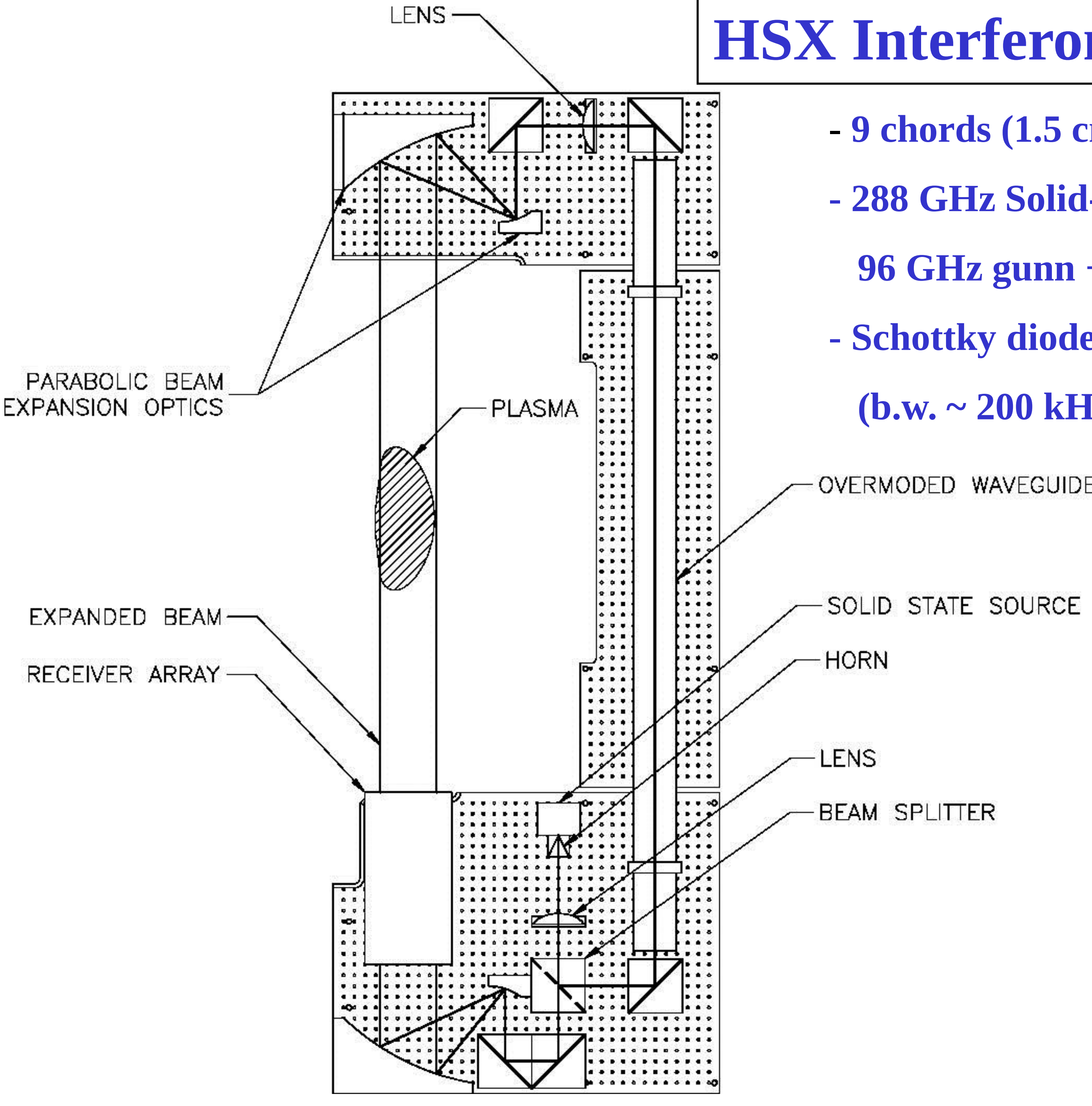


$\Delta\varnothing = \int n_e dl$

Beam Expansion Optics and Receiver Array



HSX Interferometer System

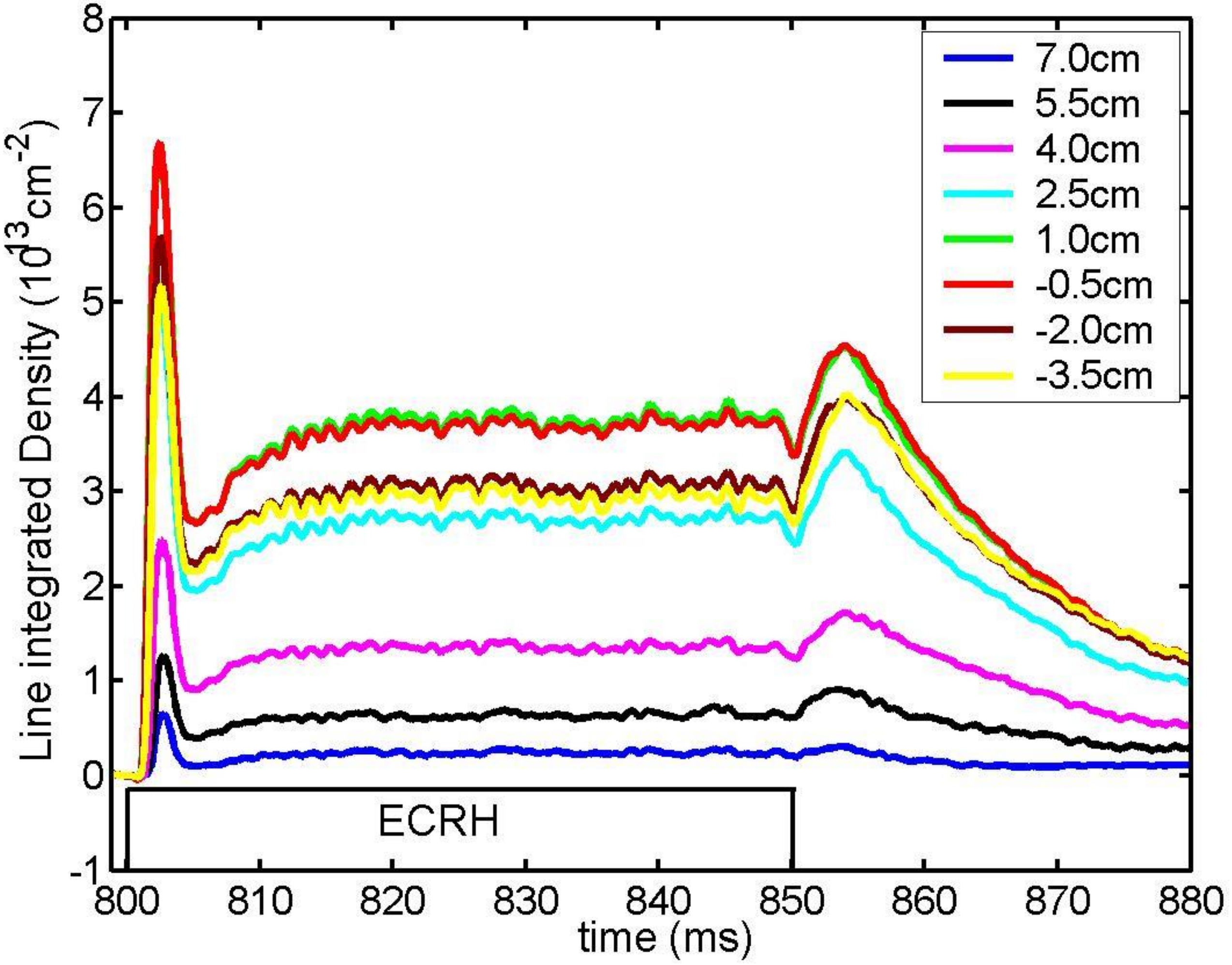


- 9 chords (1.5 cm width)
- 288 GHz Solid-State source

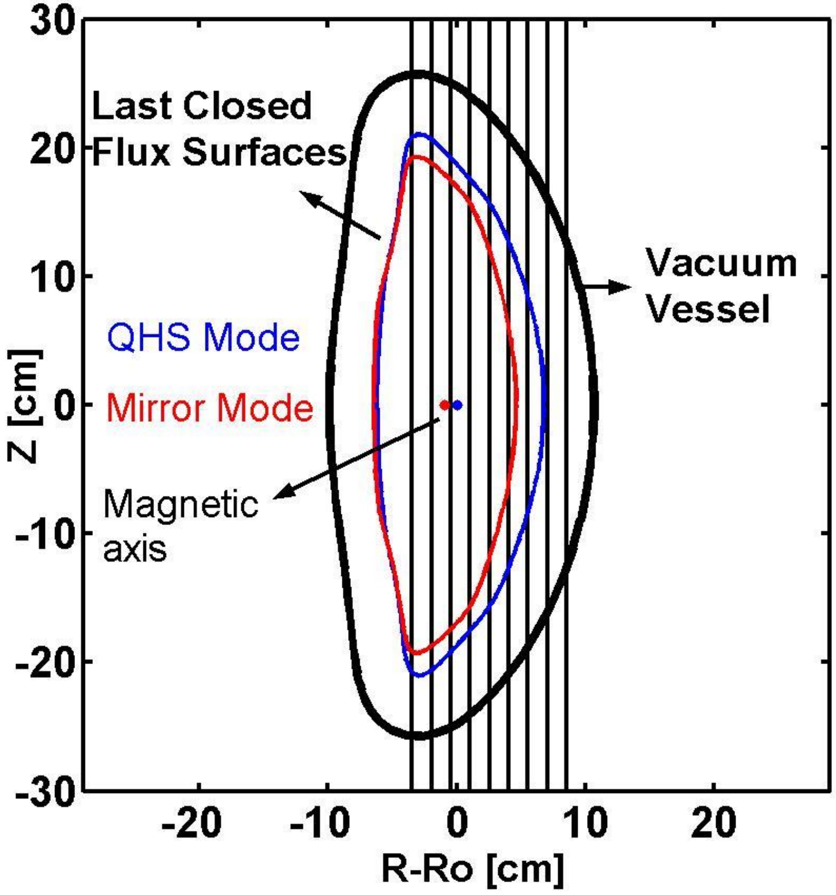
  96 GHz gunn + tripler; ~ 3 mW
- Schottky diode detectors

  (b.w. ~ 200 kHz)

Density Evolution for QHS Plasma



Flux Surfaces and Interferometer Chords



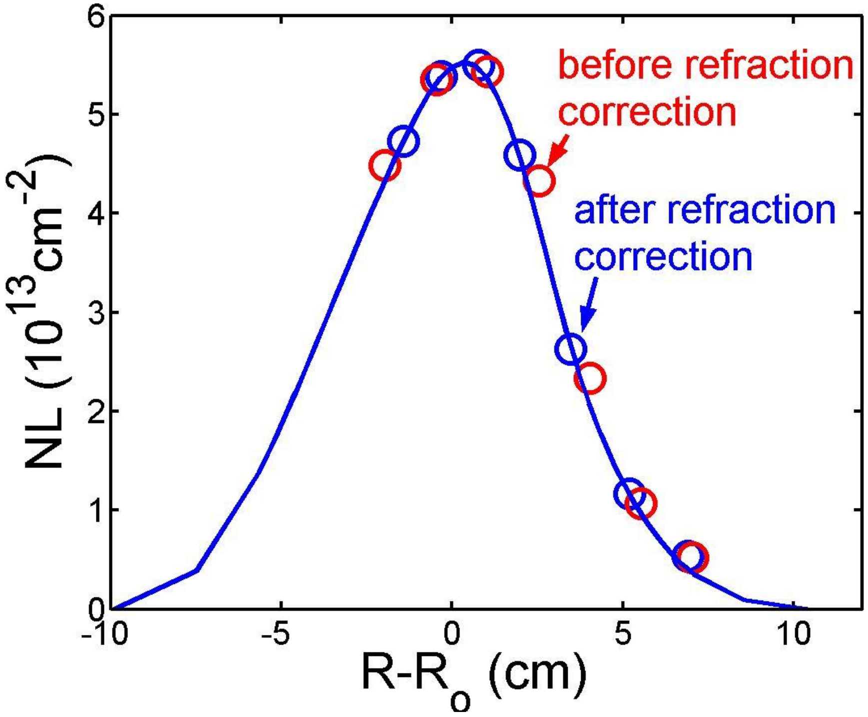
Inversion Process:

1. spline fit $\Phi = n_e dl$
2. construct path length matrix

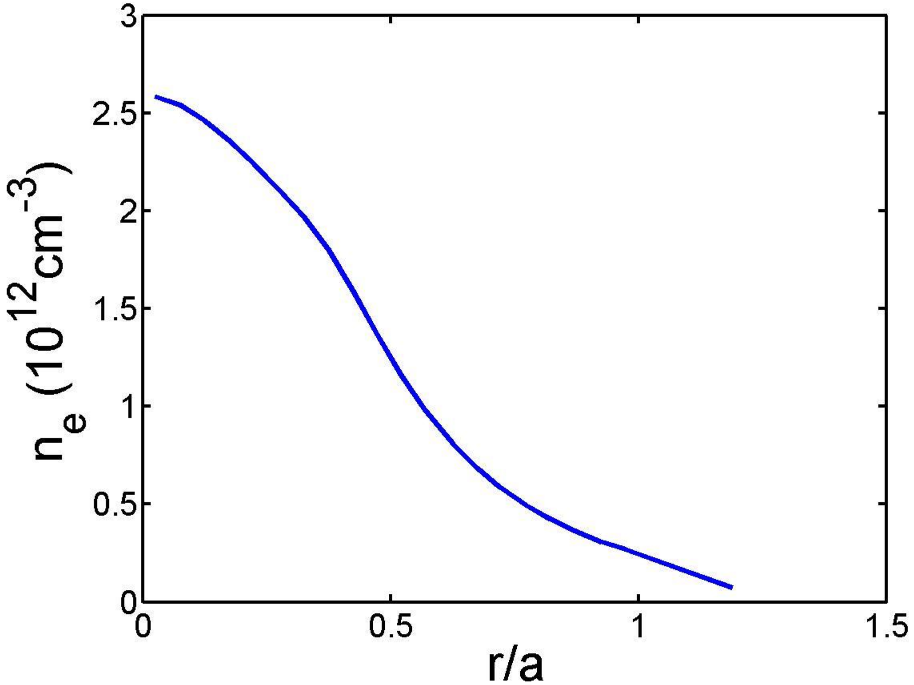
   $L \cdot n = \Phi \ (= n_e dl)$
3. solve using SVD

HSX Density Profile (QHS)

Measured Line-Integrated Density Profile and fitting

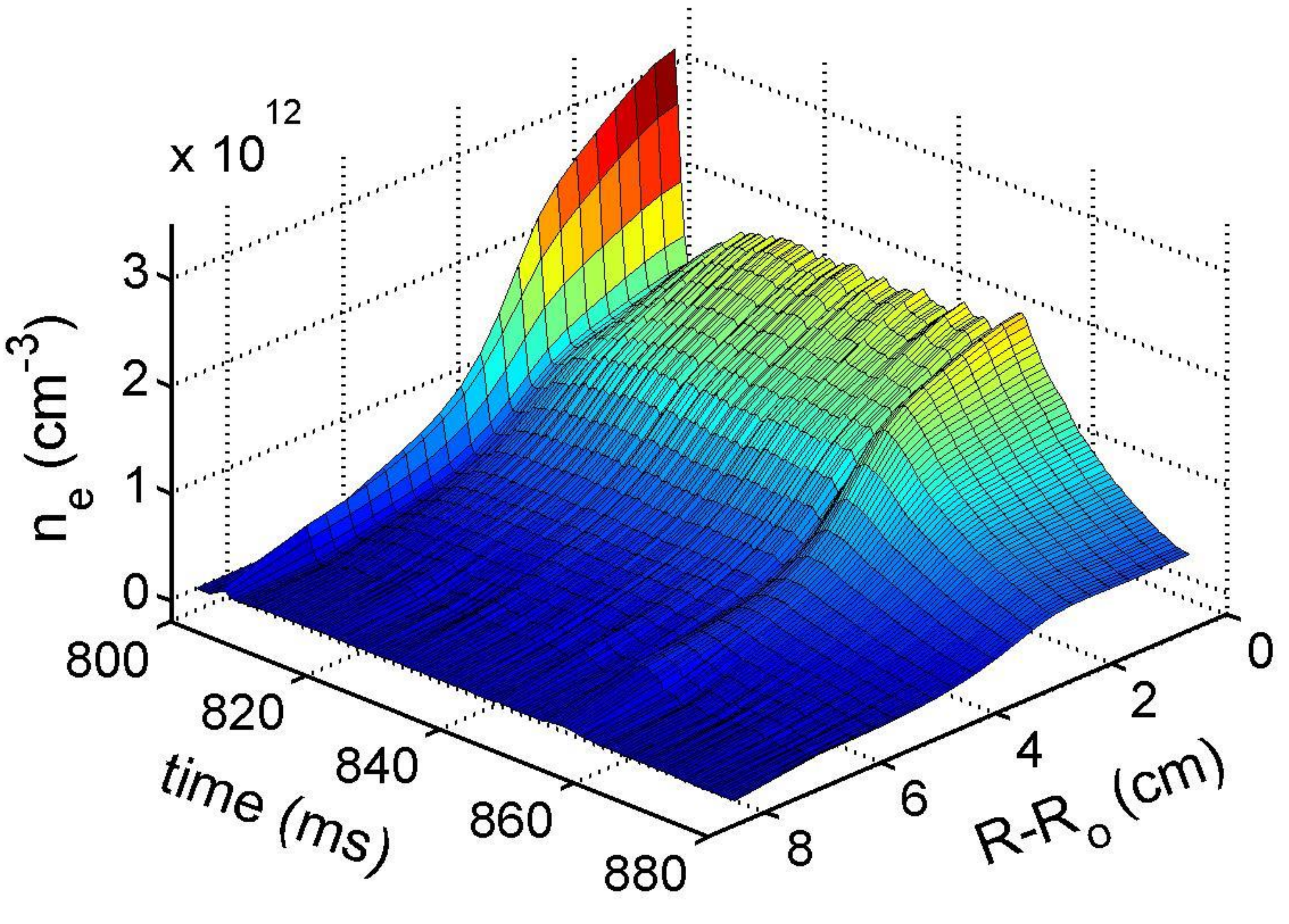


Inverted Density Profile



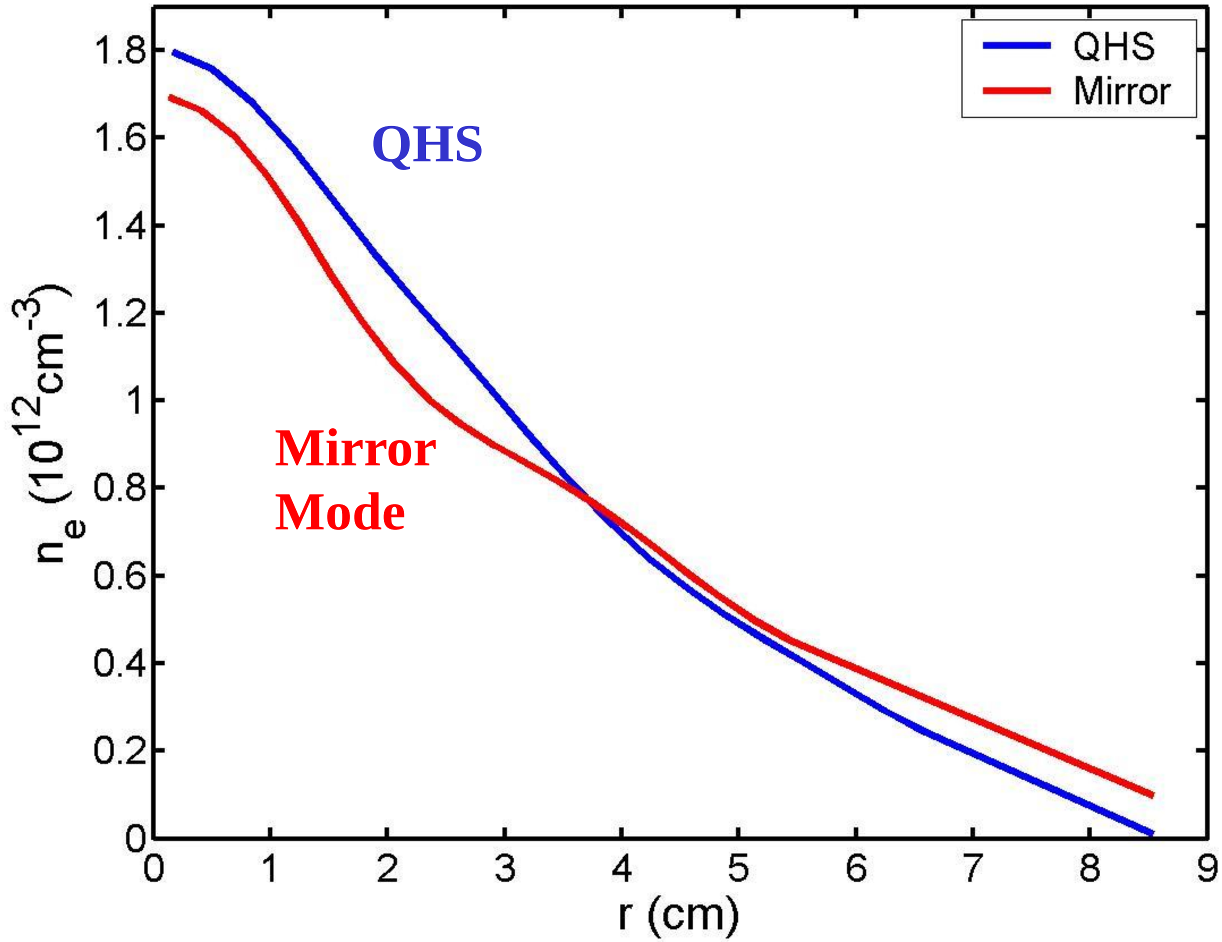
t=840 ms

Density Evolution for QHS Plasma



QHS and Mirror Mode Density Profiles

$n_e \sim 1 \times 10^{12}\ cm^{-3}$



$W_{QHS} = W_{MM} \sim 20\ J$

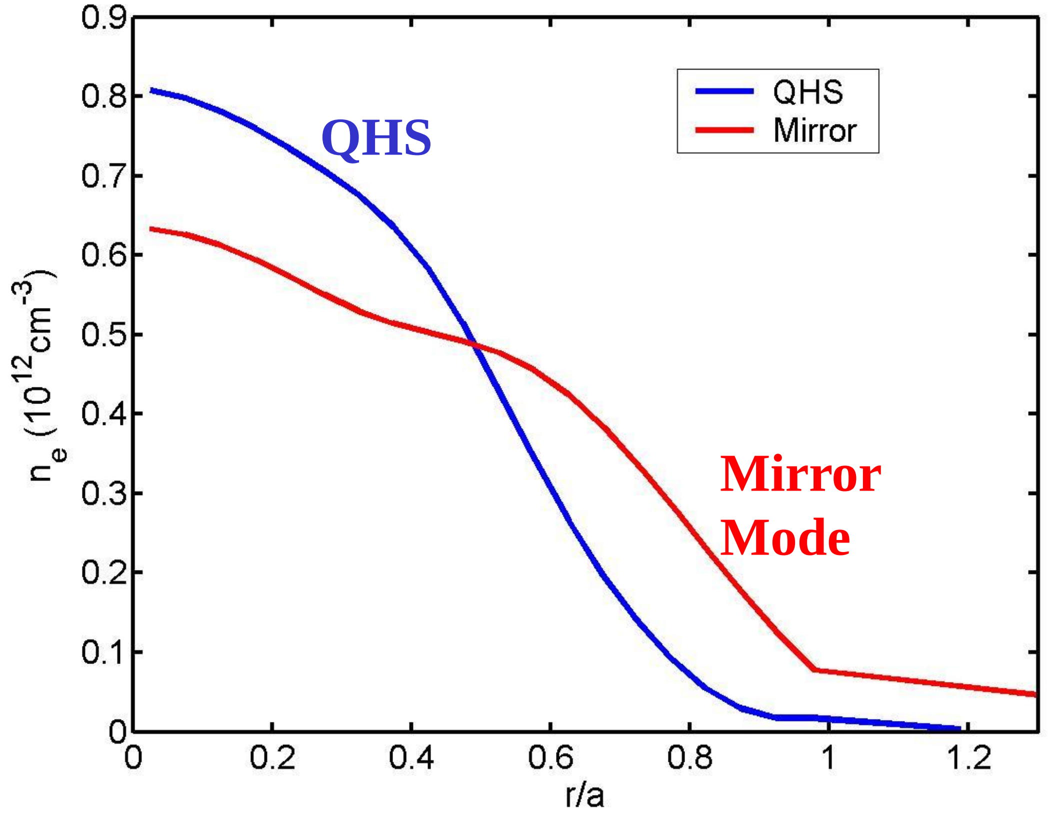
Profile shapes are

(1) centrally peaked

(2) similar shape

QHS and Mirror Mode Density Profiles

$n_e \sim 0.4 \times 10^{12}\ cm^{-3}$



$W_{QHS} \sim 30$ J

$W_{MM} \sim 7$ J

Profile is broader for Mirror Mode

Perturbative Particle Transport Study

Density perturbation: obtained by gas puffing modulation

Transport coefficients D and V: obtained by comparing measured amplitude and phase of density perturbation with the results of the modeling, which gives the best fit.

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.

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

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

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

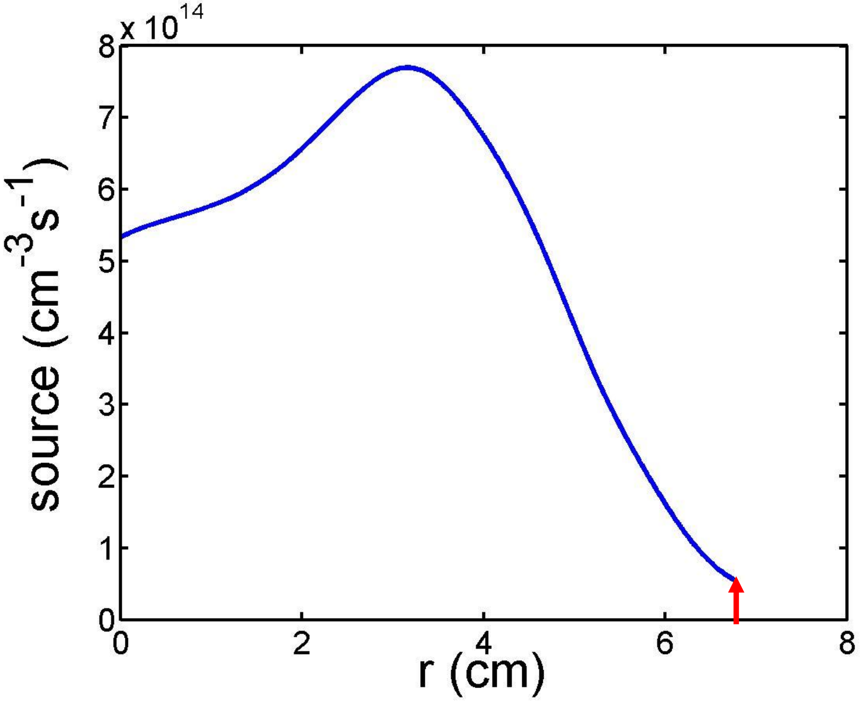
The boundary conditions are:

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

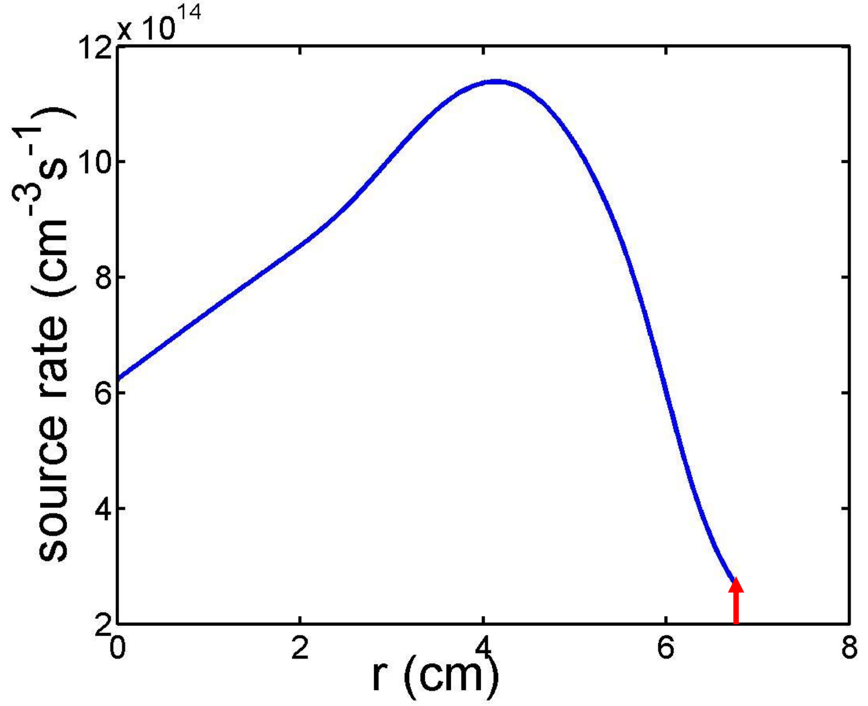
at r=a. $\tilde{n}_{re} = 10^9 cm^{-3}; \tilde{n}_{im} = 0$ (7)

DEGAS code and H_α Measurements used to estimate the neutral particle distribution in HSX

(1) peaked in the core (2) broad



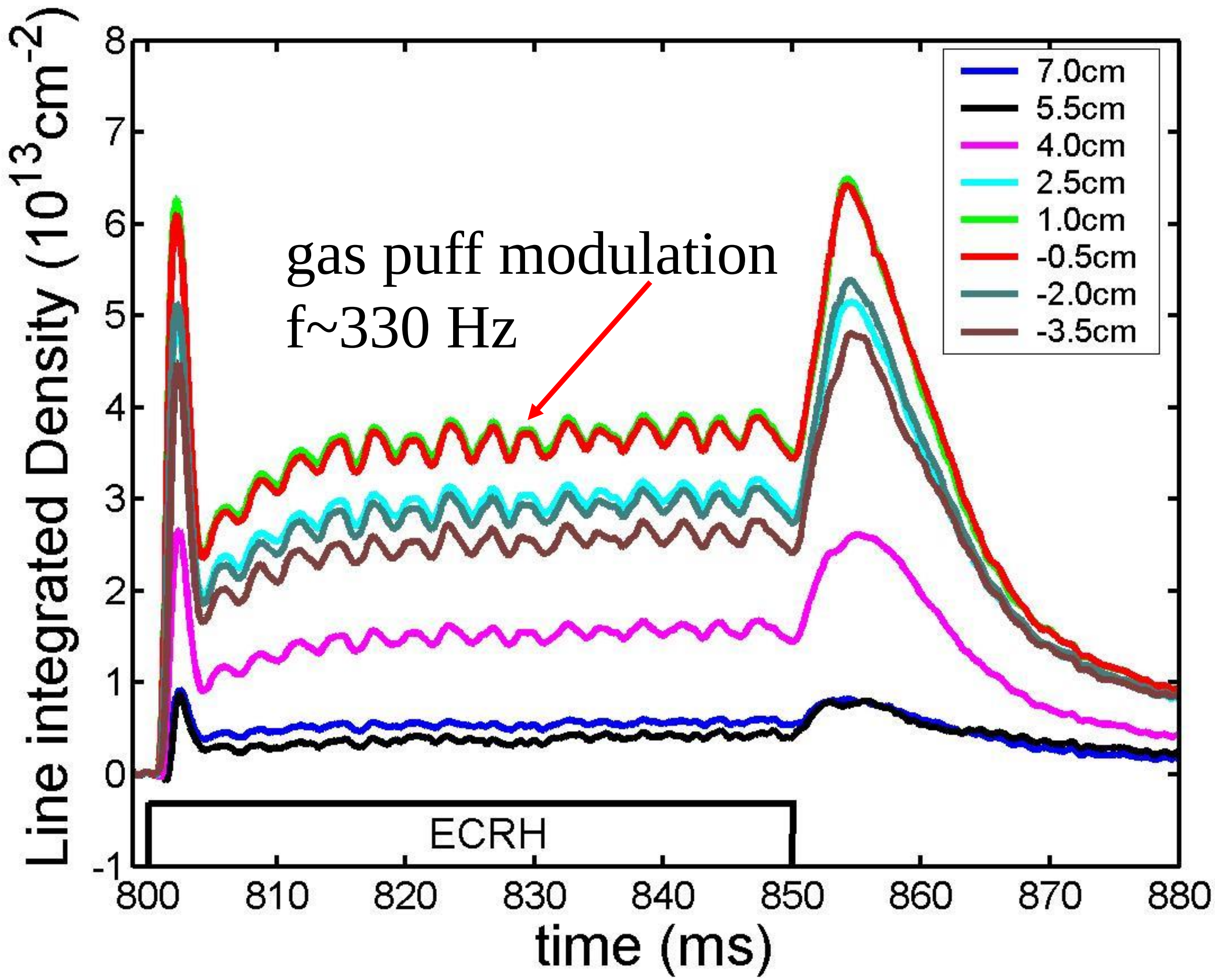
$n_e \sim 0.4 \times 10^{12}\ cm^{-3}$



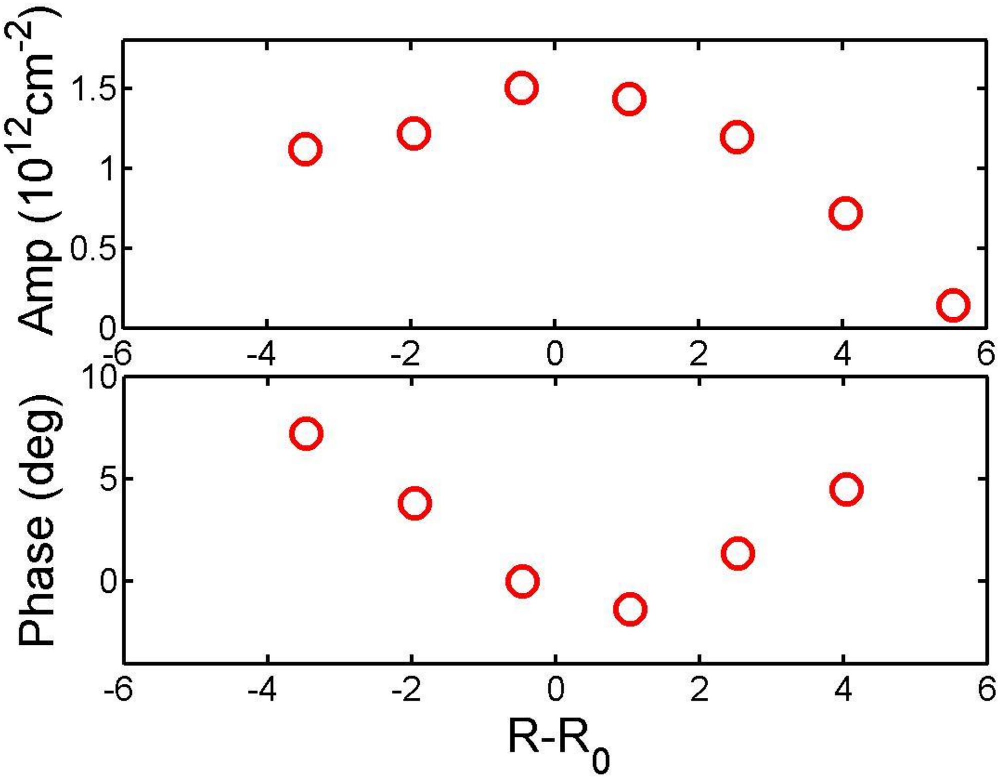
$n_e \sim 1 \times 10^{12}\ cm^{-3}$

Source details: see J. Canik poster

Perturbative Transport



Density Perturbation Amplitude and Phase



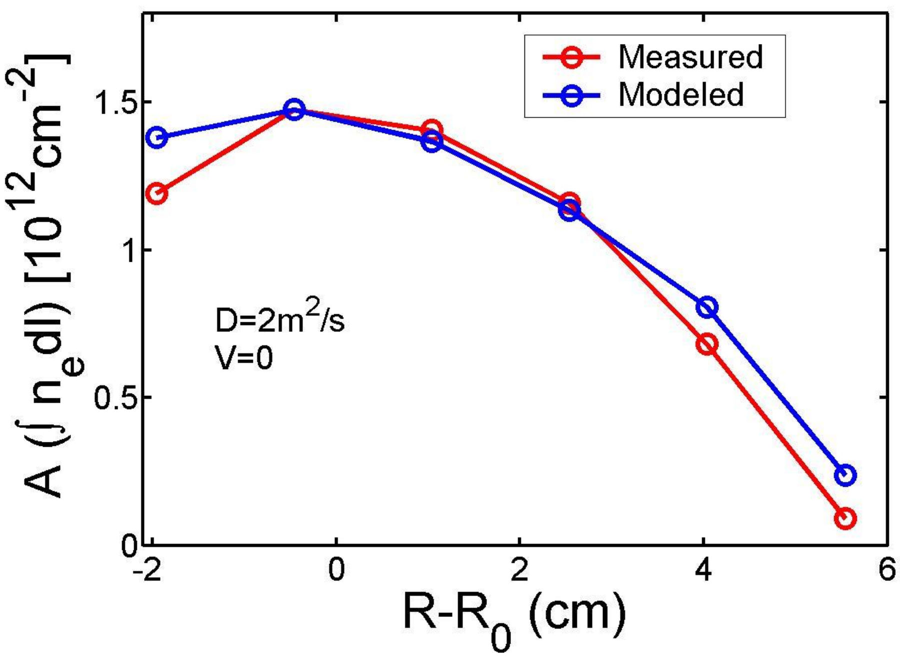
- Analysis approach computes Fourier coefficients of the line integral $\tilde{n}_e = \int \tilde{n} dl$

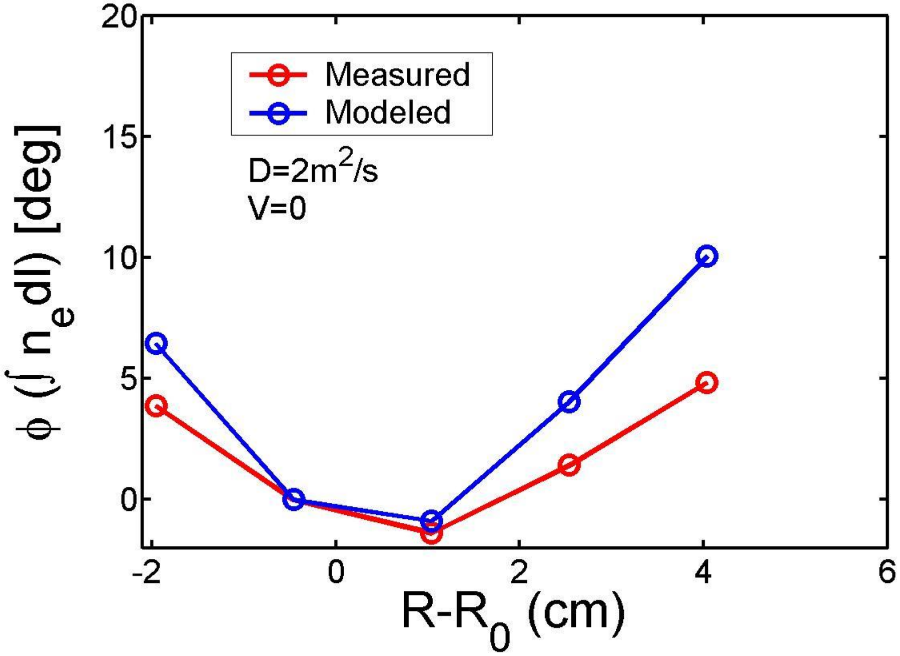
- Linearize the continuity equation for small density perturbations, model $\Gamma(= -D\nabla\tilde{n}_e)$, and solve for amplitude and phase.

- Use ~10 cycles (f~200-400 Hz), $\tilde{n}/n_e \leq 10\%$

Reasonable Fit (to amplitude) using D_{mod}=2 m^2/s

Ne~ $1.0*10^{12}cm^{-3}$

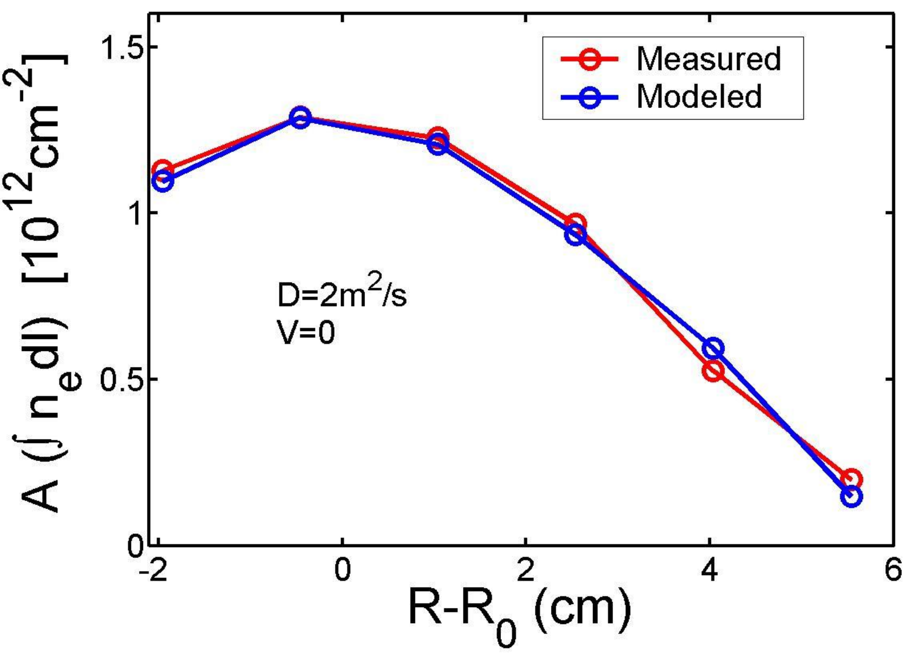


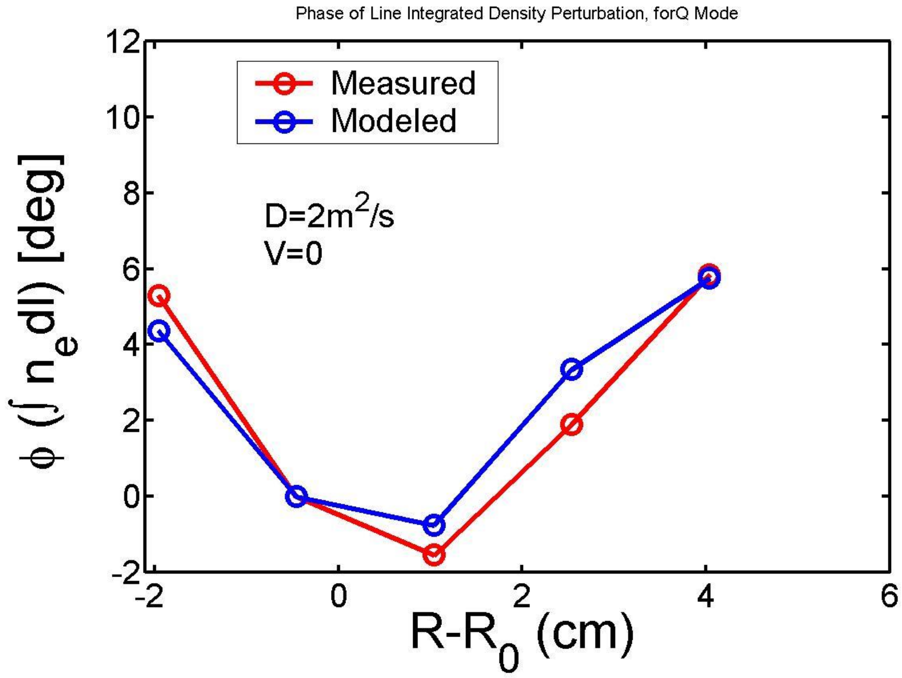


- By making modest (<30%) changes to source, fits to phase can be improved significantly
- Results very sensitive to source profile,
- No pinch term required

Reasonable Fit (to amplitude) using D_{mod}=2 m^2/s

Ne~ $0.5*10^{12} cm^{-3}$

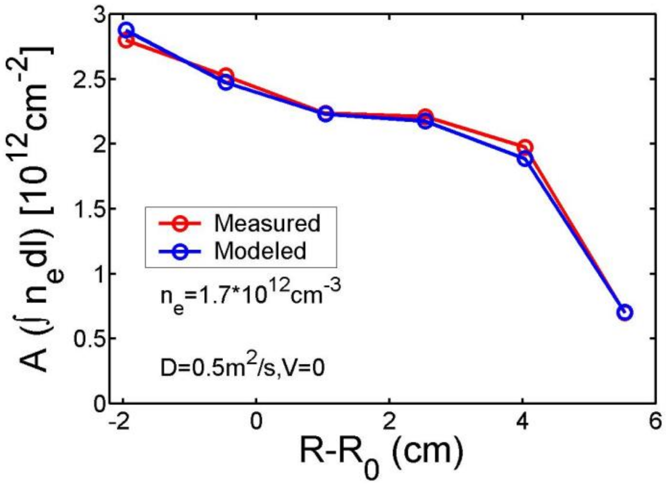


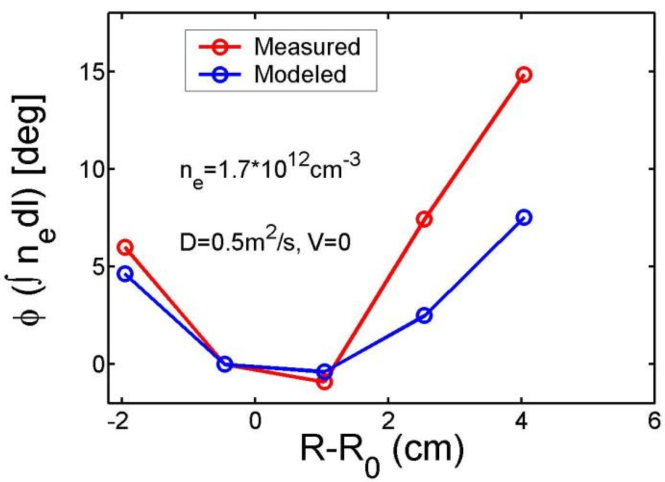


Comparison of QHS plasma and Mirror Plasma

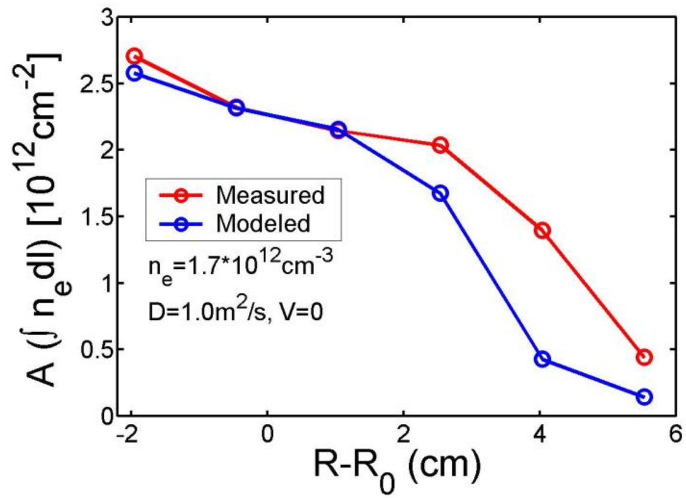
$ne=1.7*10^{12}cm^{-3}$

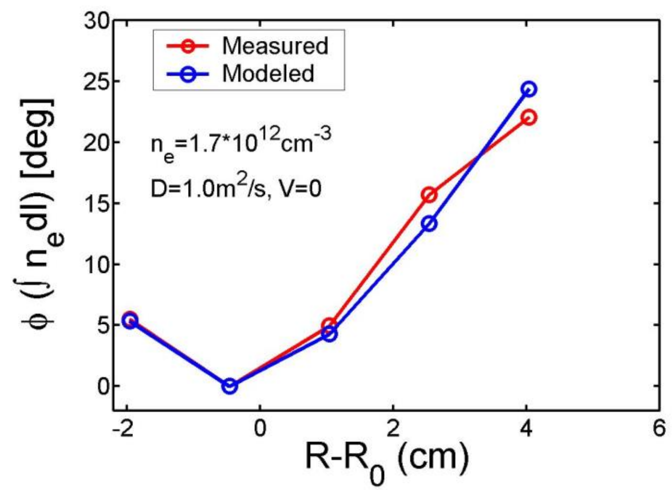
QHS mode, D=0.5m2/s





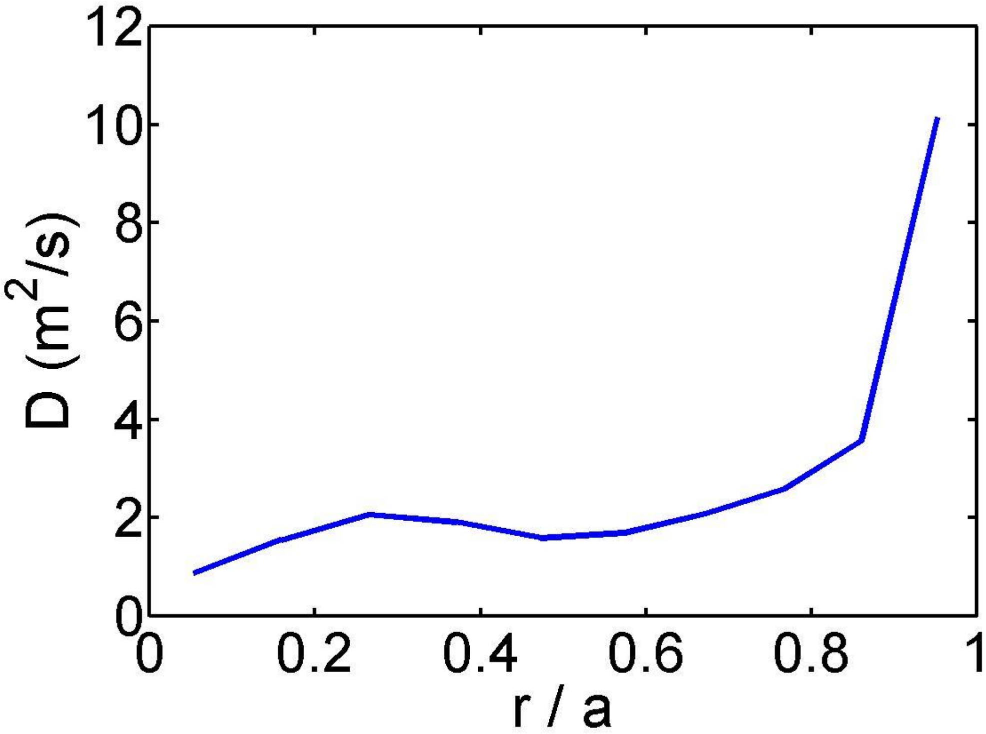
Mirror mode, D=1.0m2/s





Solving the Continuity Eq. for Steady-State Plasma

$$\nabla \bullet \Gamma = S \qquad where \quad \Gamma = -D_o \nabla n_e$$

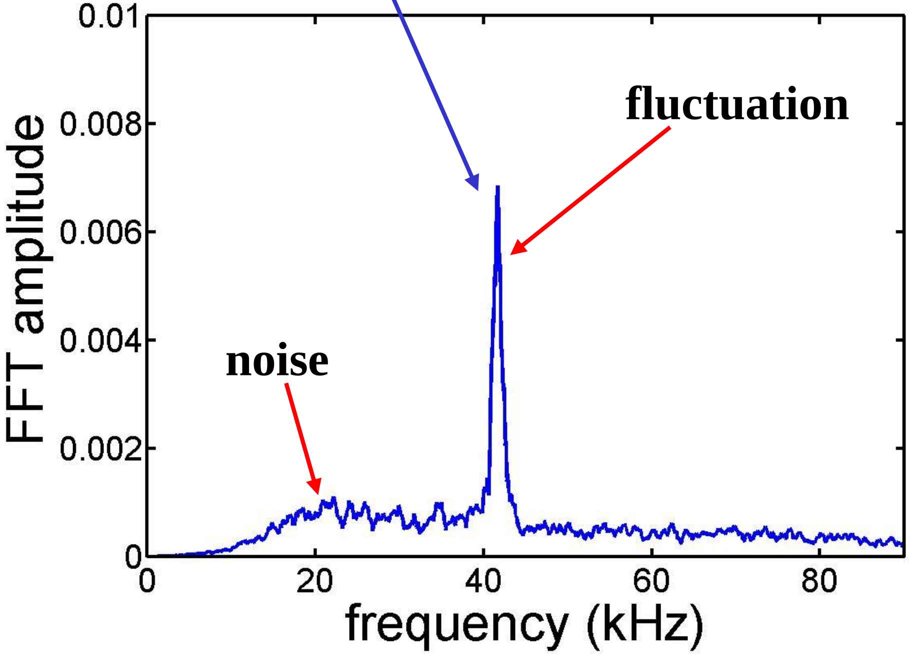


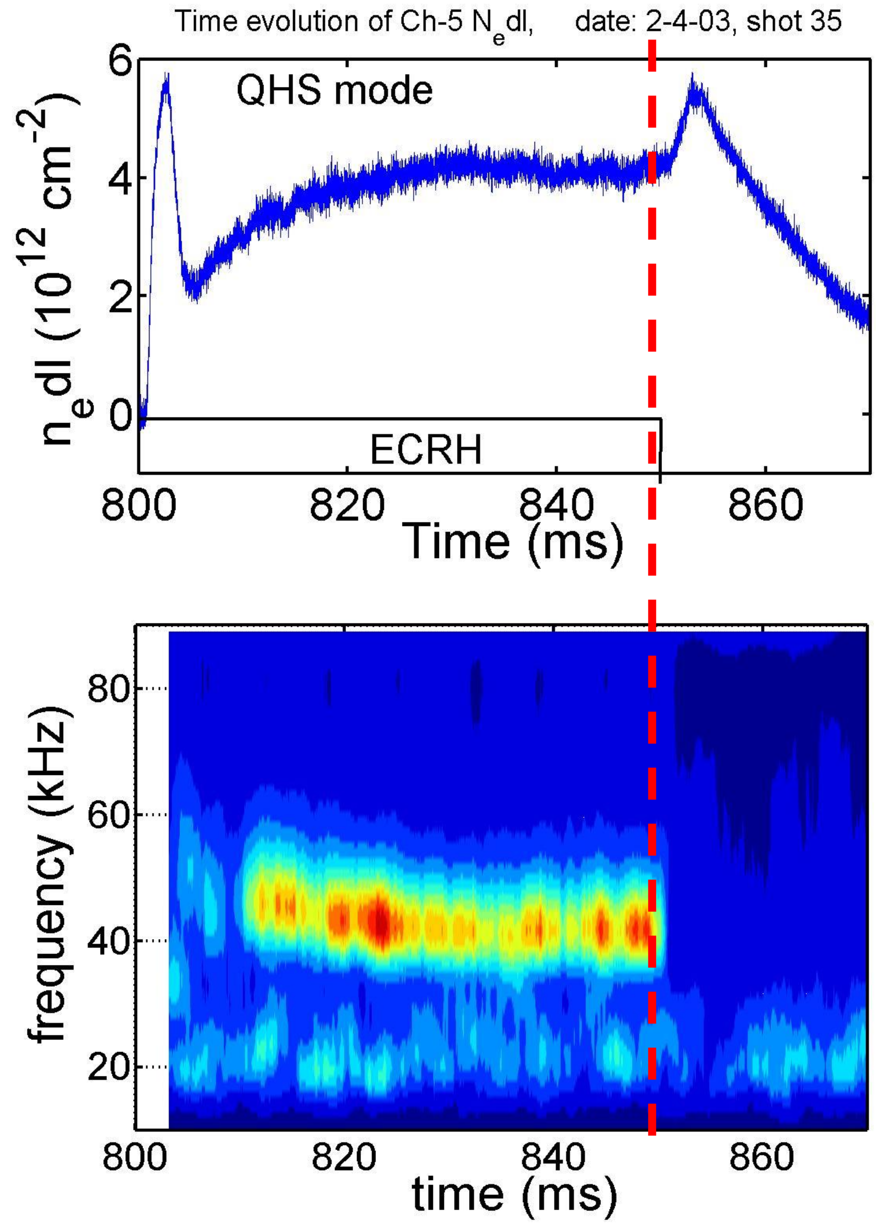
$D_o \sim D_{mod} \sim 2\ m^2/s$

For details, see J. Canik poster on Wed.

Density Fluctuations

mode observed only in QHS plasmas

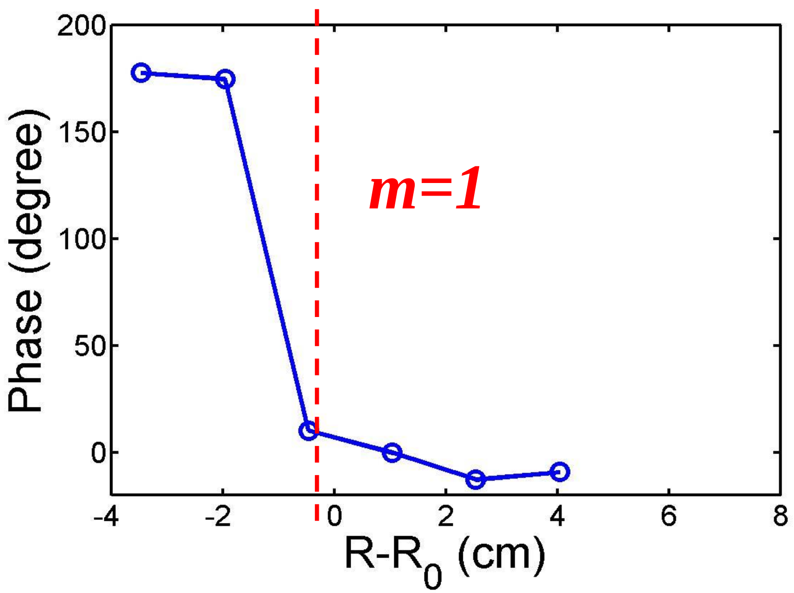




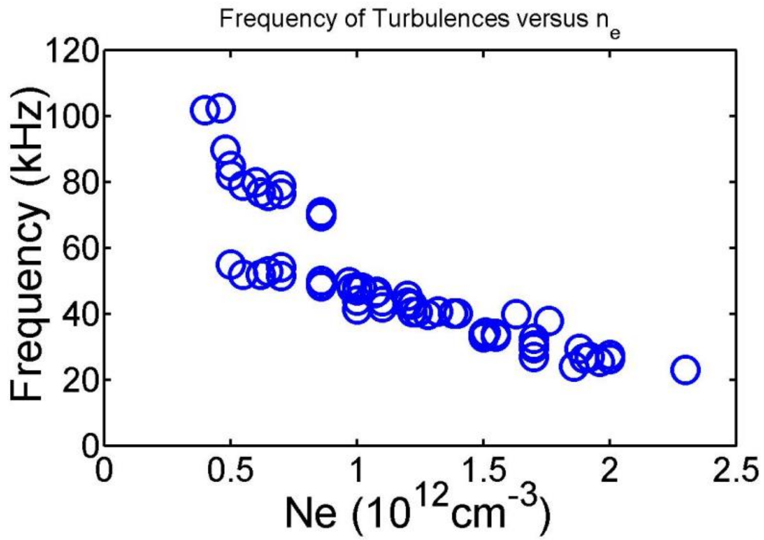
Noise: f < 30 kHz

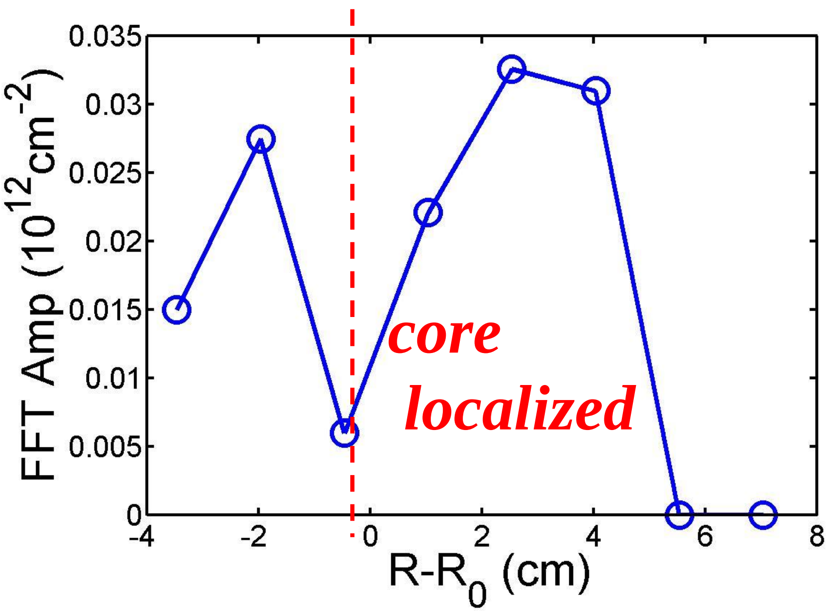
Fluctuation Features

- QHS plasmas
- coherent, m=1
- localized to steep gradient region
- Frequency ~ $1/n_e$; double frequencies, when $ne<0.7*10^{12}cm^{-3}$
- Pressure (temperature) driven but ***no resonant surface***!

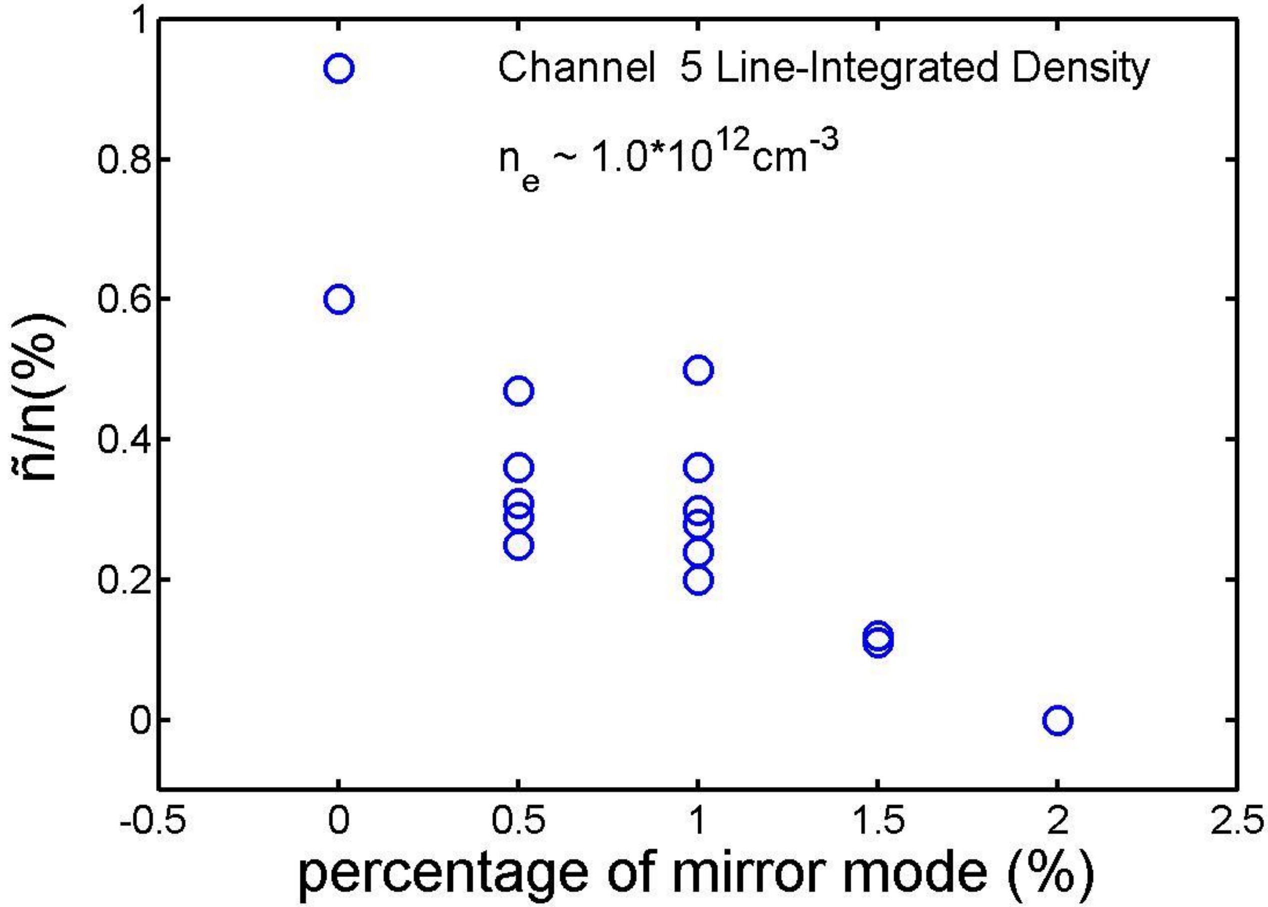


Density Dependence



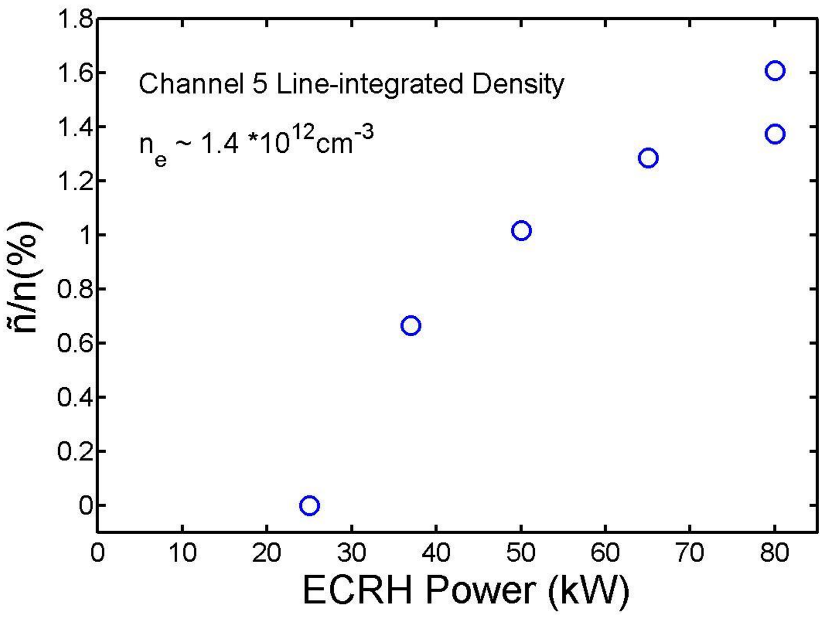


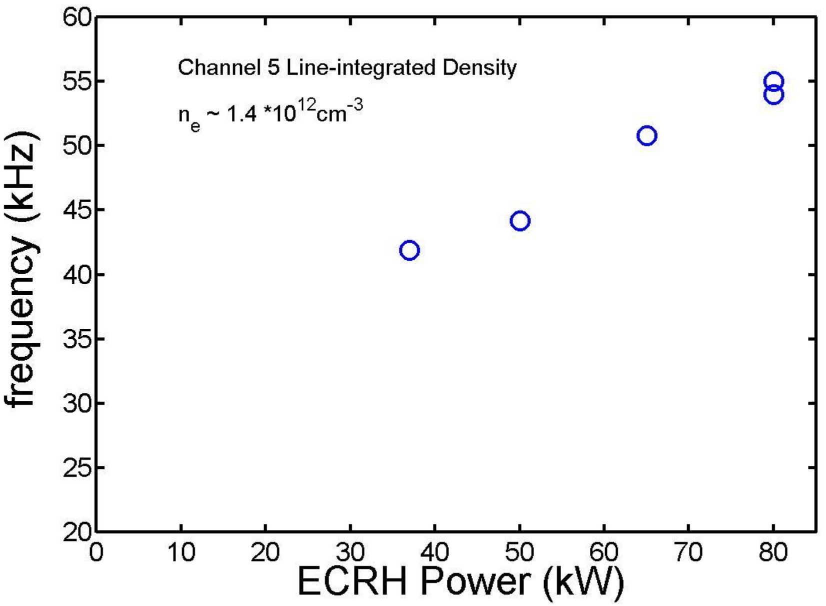
Fluctuations Disappear When Symmetry broke



Fluctuations with ECH Power

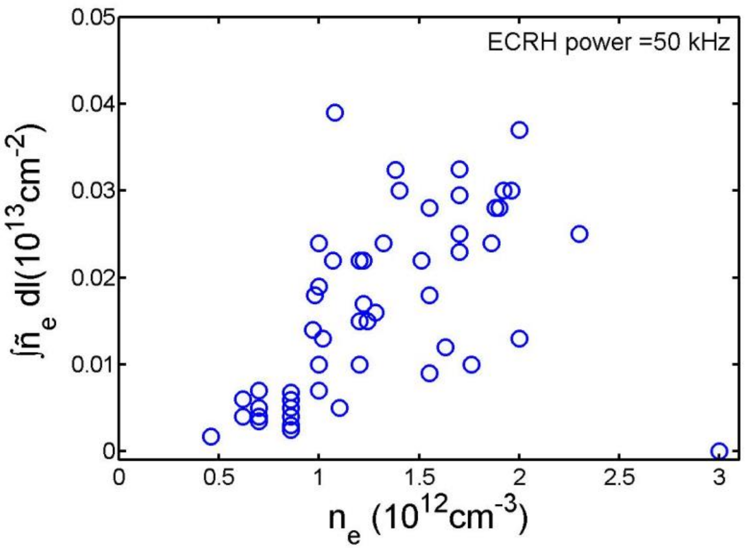
- Amplitudes of Fluctuations increase with ECRH Power
- Frequency of Fluctuations increase with ECRH Power
- T_e measurement shows $T_e(0)$ increase linearly with ECH power
- No fluctuations observed when ECH power lower than 27kW

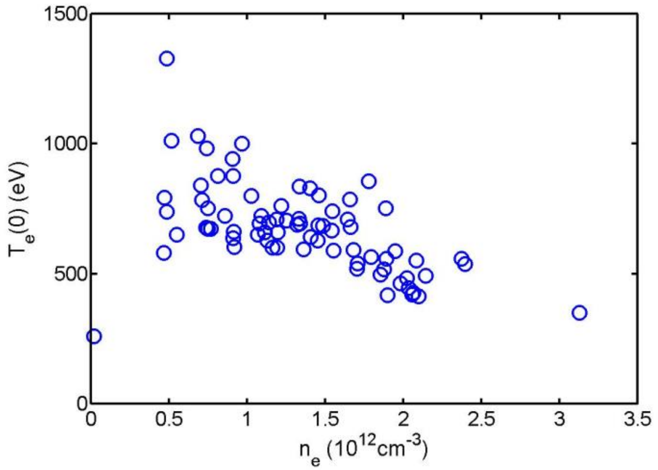


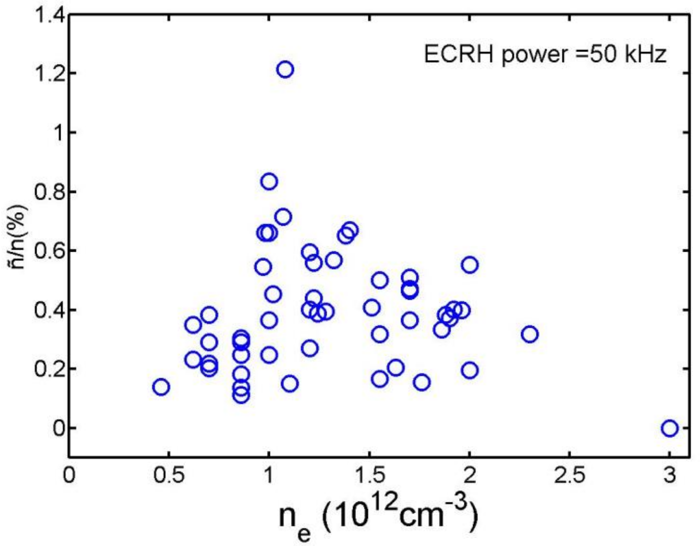


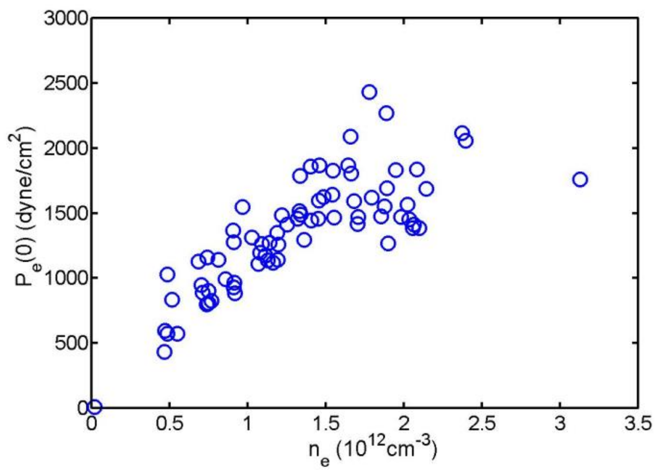
Density windows of the Fluctuations

• When $n_e < 0.5*10^{12}cm^{-3}$ and $n_e > 3.0*10^{12}cm^{-3}$ no fluctuation were observed









Summary

1. **Equilibrium electron density profile is peaked for both the QHS and Mirror Mode configurations (at low density, Mirror Mode plasmas are broader than QHS)**

2. **Peaking on axis likely arises because the source profile is centrally peaked and broad.**

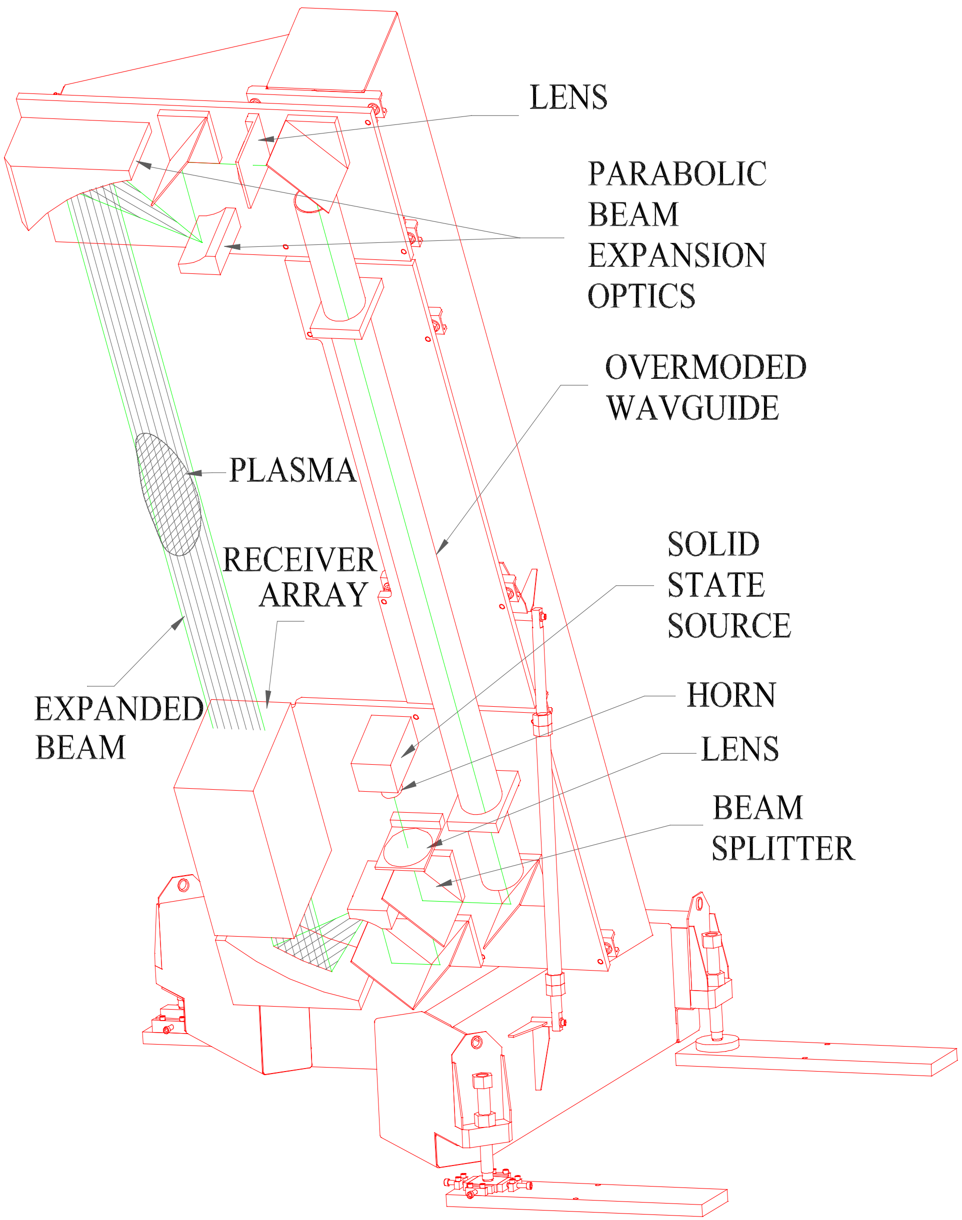
3. **Modulated gas feed studies indicate constant $D_{mod} \sim 2\ m^2/s$. No inward pinch required due to centrally peaked source profile.**

4. **Future operation (53 GHz) at higher density should move the source to the plasma edge allowing particle transport issues to be addressed**

5. **High-frequency density fluctuations (f~25-120 kHz, m=1) are observed for QHS plasmas.**

6. **These fluctuations are clearly associated with temperature or pressure gradients (but no resonant surface).**

HSX Interferometer System



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