Development and Measurements of the Edge Neutral Density Diagnostic

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Abstract

Edge power balance is not well understood in a spherical torus, where large orbits of lost fast particles on the edge can drastically affect the center of the plasma. In order to gain a more precise understanding of power balance, it is important to have an accurate measure of the profile of neutral particles. The development and preliminary demonstration of the Edge Neutral Density (END) Diagnostic are presented. A 2-D CCD with a maximum frame rate of 500 fps was used to image the outboard edge of the National Spherical Torus Experiment (NSTX), using a D_β filter to select an atomic transition. The spatial calibration and absolute photometric calibration are described. The image was Abel inverted assuming toroidal symmetry to obtain a radial profile of the emission intensity. A collisional-radiative model was used in conjunction with electron density and temperature obtained from Thomson Scattering to obtain an absolute radial density profile. Future development of this diagnostic is proposed, including using a 12 bit CCD camera to increase sensitivity and time resolution. Comparison is made between beam heated shots and RF shots.

Motivation for Studying Edge Neutrals

- Ion heating has been observed that does not fit with calculations. In particular, the ions in some beam heated shots are significantly hotter than calculated by TRANSP. This necessitates a study of the power balance, particularly as it relates to the beams.
- Edge Neutrals can have a significant impact on other diagnostics. Neutron diagnostics as well as the Edge Thermal Diagnostics can be affected by neutral populations.
- Understanding the density profile is important in understanding the scrape-off layer flows. This could prove more important for other machines with larger power fluxes, such as ITER.
- This diagnostic will also help in the understanding of Lithium coatings. This diagnostic will help to confirm the reduced recycling due to the lithium, as well as determine how long the lithium coatings affect the plasma.

Fast Ions can Orbit Far into NSTX Plasmas

Gyroradius of Deuterium (on axis):

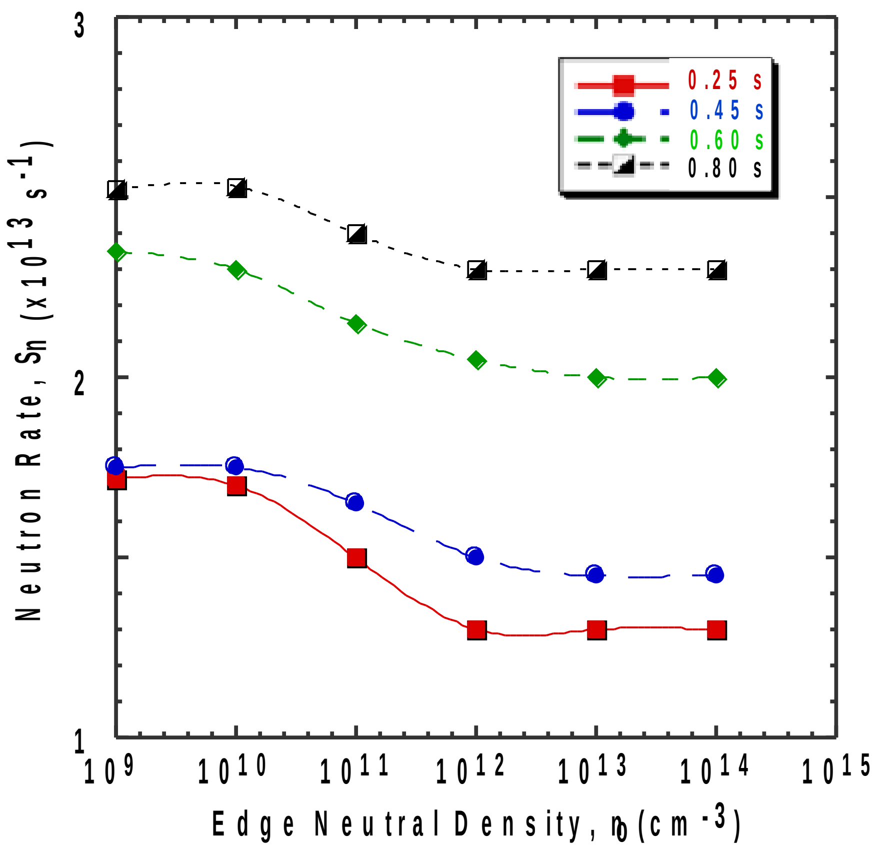
$$\rho_D = \frac{v_{T_i} m_i c}{ZeB}$$

Beam ions in NSTX	Standard Tokamak
Energy ~ 80 keV	Energy ~ 80 keV
B=0.45 T	B=3.0 T
$\rho_D \approx 9\,cm$	$\rho_D \approx 1.3\,cm$
$\frac{\rho_D}{a} \approx 0.15$	$\frac{\rho_D}{a} \approx 0.013$ (assumes a=1 m)

In NSTX, beam ions can cover a significant (15%) portion of the minor radius, while those in a standard tokamak can only reach a much smaller fraction of the way into the plasma. Inside NSTX, this problem is compounded by the banana orbits, which can effectively double the distance into the plasma that can be reached.

Edge Neutral Effects in TRANSP

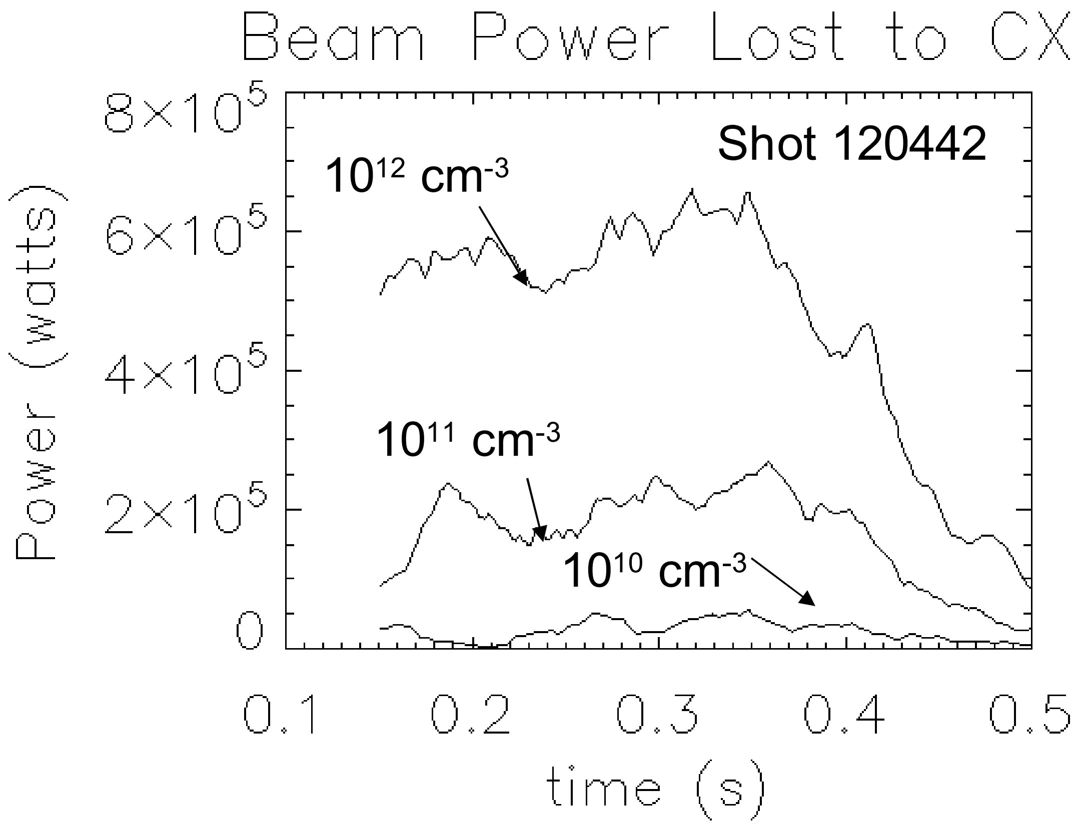
Edge neutral particles can have a significant impact on plasma properties. When the edge neutrals are increased over several orders of magnitude, the neutron rate decreases by ~25%. This is believed to be the result of the loss of neutral beam energy to charge exchange outside the plasma.



As edge neutral density is increased, it can affect the neutron rates by ~25% in the early stages of the plasma.
(S.S. Medley, unpublished)

Beam Power Loss in TRANSP

As the edge neutral density is increased from 10^{10} cm^{-3} to 10^{12} cm^{-3}, the fraction of beam power lost charge exchange outside the plasma increases from less than one percent to nearly 15%. This will have a significant impact in the overall understanding of power balance and heating in NSTX. It may also help to explain the anomalous heating in NSTX.



Total lost power from the neutral beams due to charge exchange outside of the plasma. As the neutral density in the edge is increased, the lost beam power increases to approximately 15% of the total beam power.

Method for Measuring the Edge Neutral Density Profile

1. Measure the absolute emissions from atomic hydrogen using an H_β filter, subtracting out the background.
   - H_α emission would let in more light, but is too near a carbon emission line.
2. Obtain n_e and T_e from Thomson scattering. This data is necessary for the collisional-radiative model to determine the absolute density of neutral hydrogen.
3. Abel-invert the camera image to obtain the emission intensity as a function of major radius.
4. Using the Einstein coefficient (A_{24}) and emission intensity (I), determine the density of the n=4 excited state of hydrogen (n_4) using $I= A_{24}*n_4$
5. Spline the n_e and T_e data onto a table containing the population ratio coefficient (n_4/ n_0), comparing the population fo the n=4 state to the ground state.
6. Determine the absolute density n_0 by $n_0= n_4/ (n_4/ n_0)$ at each pixel of the camera, giving a profile of the edge neutral density.

Calibrating the Edge Neutral Density Diagnostic

- A Labsphere calibrated light source was used to photometrically calibrate the CCD camera for the H_β wavelength (486 nm) outside the vacuum vessel.
- The calibrated camera was used to calibrate the H_β emissions of a whiteplate, which emits a lambertian distribution of light.
- The whiteplate was placed in the vacuum vessel along the line of sight of the camera. This in-vessel calibration of the camera is necessary in order to take into account all of the optics (lens, window) and geometry in the calculation.
- A relative calibration was obtained for the camera view using the whiteplate. The absolute calibration of the whiteplate was then used to determine an absolute calibration of the camera's view.
- This emission is used with the collisional-radiative model above to determine the absolute density of neutral hydrogen.

Abel Inversion Algorithm

Abel inversion is the process of inverting the integrated brightness signal along several lines of sight in order to obtain a radial profile. This can be expresses as a matrix operation.

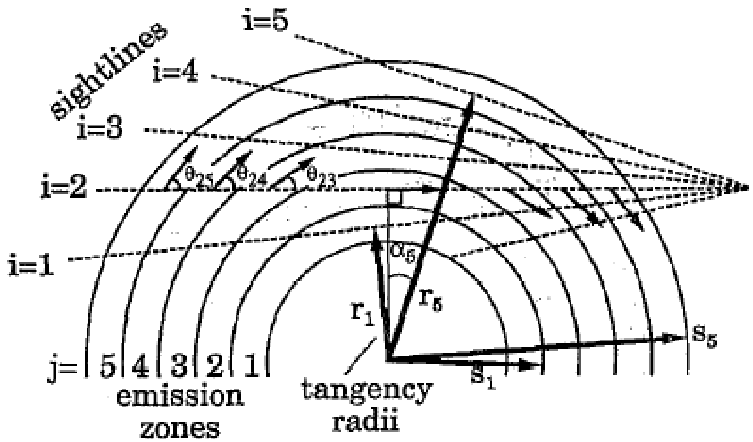
$$B(r_T) = \int \sqrt{R_{\max}^2 - r_T^2}\, E(R)\, dl$$

becomes

$$B_i = \sum_j L_{ij} E_j$$

Inverting this gives

$$E_j = \sum_i L_{ji}^{-1} B_i$$



Cartoon showing contours of equal emissivity and tangency radii for sightlines. The brightness along any sightline is the sum of the emission angle θ times the path length for all intersected zones.

Reproduced from: R.E.Bell, Rev. Sci. Instrum. 66 (1), 1995, p558.

This matrix is applied to a single pixel line. The pixel line is spatially calibrated, and the matrix is computed using the code LINV_NSTX, written by R. Bell. The matrix relies on the signal going to 0 at the outside edge. If the signal does not go to 0, the matrix will give incorrect results. (see R.E.Bell, Rev. Sci. Instrum. 66 (1), 1995, p558.)

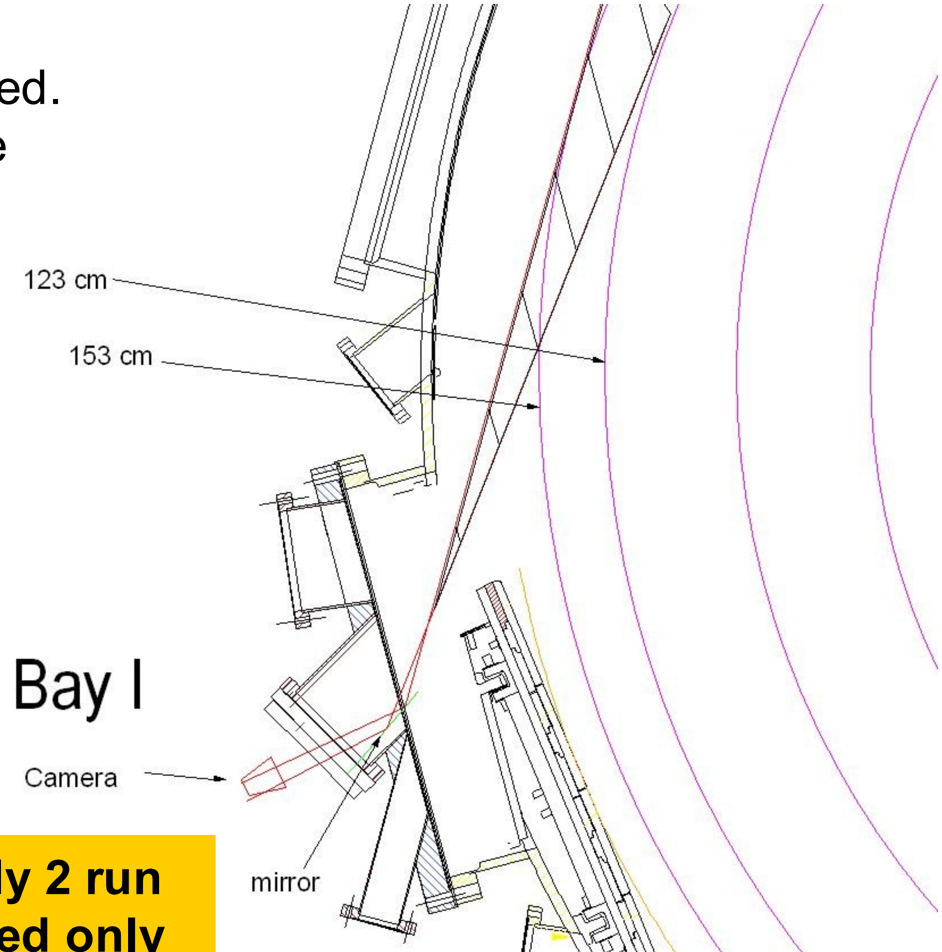
Hardware Requirements for the END Diagnostic

- A tangential view of the edge of the plasma was needed in order to get a profile of the edge neutral emissions. In order to get an effective Abel inversion, the view must see out to where the emissions go to zero.
- Bay I was chosen for this diagnostic. Since a tangential view was not immediately available, a mirror system was designed and welded to the flange to create a tangential view.
- The camera chosen for the initial stages of this diagnostic was an 8 bit CCD camera with 512x480 pixels.
- The lens chosen was a variable focus lens, with the field of focus set to 140-160 cm, corresponding with the distance from the camera to the tangential point of the plasma.
- The filter is an H_β filter (λ=486 nm, fwhm=1.5 nm)

Mirror System

In order to see tangentially into the plasma, a mirror system was designed. The mirror was welded onto a flange cover and bent to an angle of 5°.

In order to protect the mirror and the window, a shutter system was designed which can be closed to protect the mirror during lithium coatings



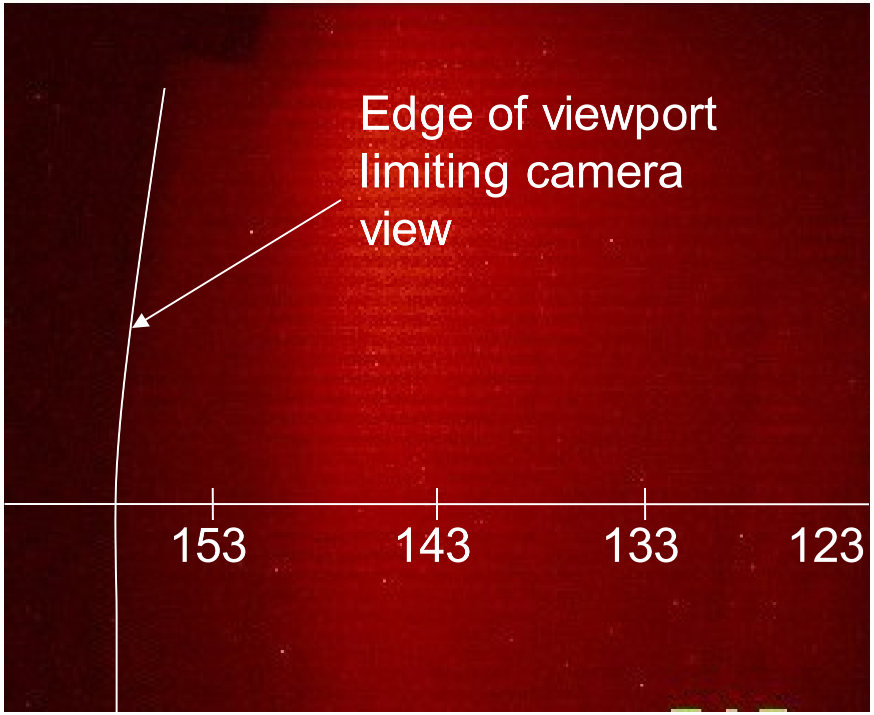
The camera was operable for only 2 run weeks this past year, and obtained only limited data.

Camera view

Shot 121541, time=383 ms.

The camera is situated on the midplane bay I port of NSTX. Using a mirror the camera views the plasma tangentially from a radius of approximately 123 cm-155 cm.

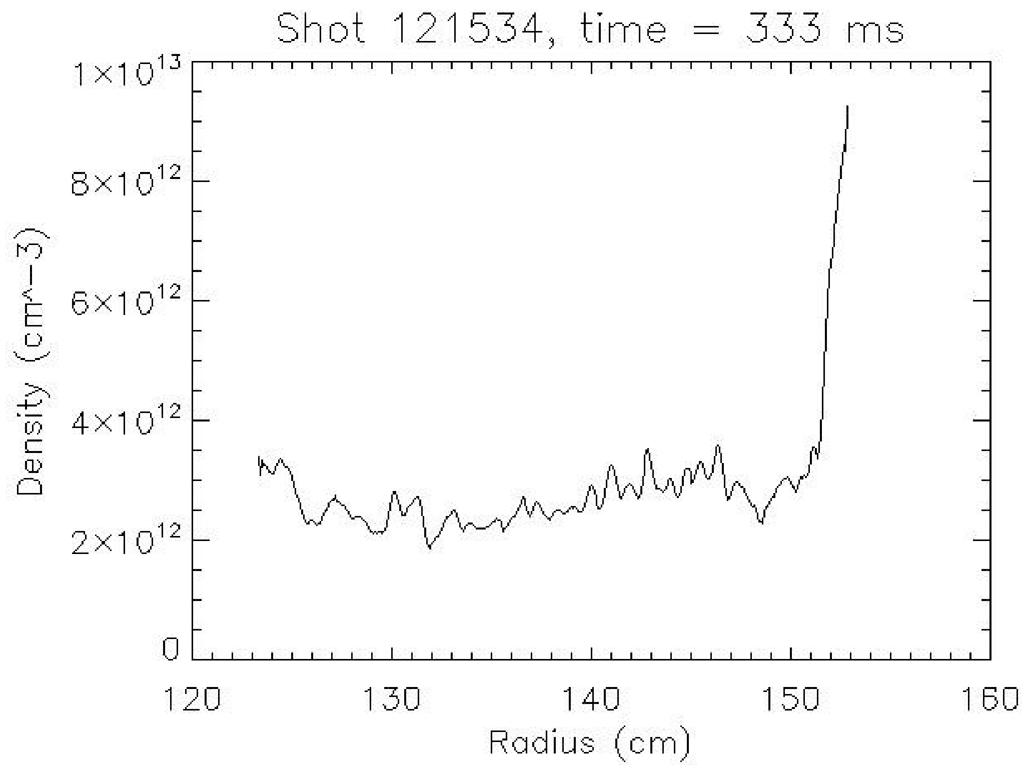
This can create problems if some of the light is emitted by the plasma beyond the 155 cm zone of the plasma. The Abel inversion will give incorrect results unless the signal goes to 0 inside the field of view.



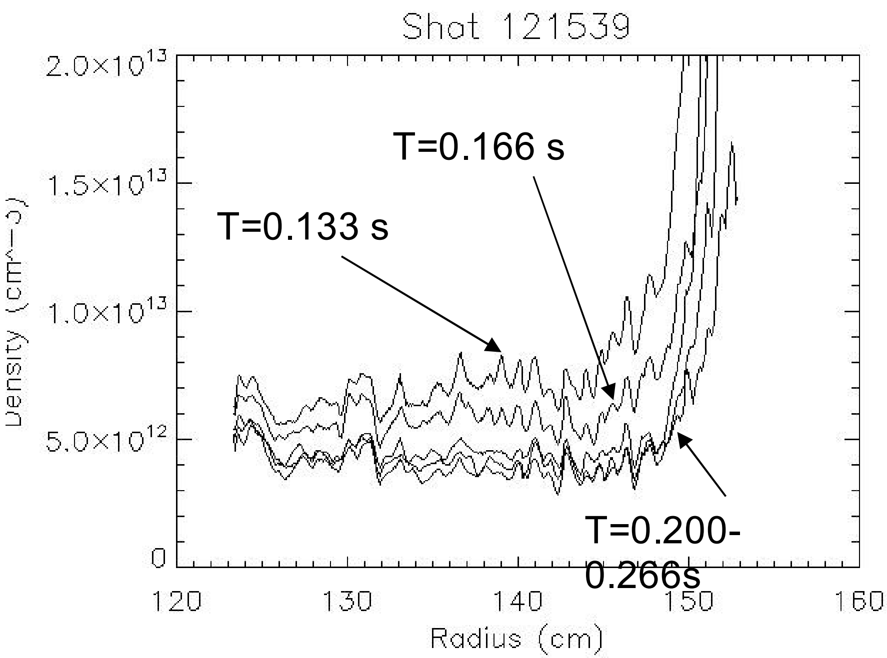
For most RF plasmas and some beam heated plasmas, the seperatrix is outside the line of sight of the camera.

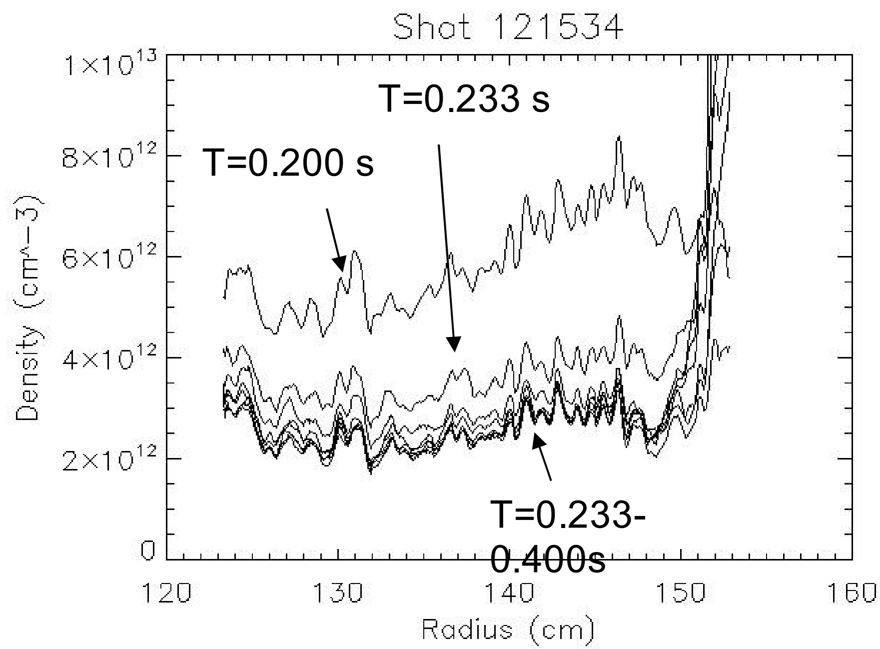
Preliminary Results of the Absolute Neutral Hydrogen Density

The profile exhibits the expected behavior. The center of the plasma contains the lowest density, with increasing density toward the outside. However, it is not yet clear if the steep increase is due to a real effect or if it is an artifact of the inversion matrix or some other effect.



Time evolution of Neutral Density





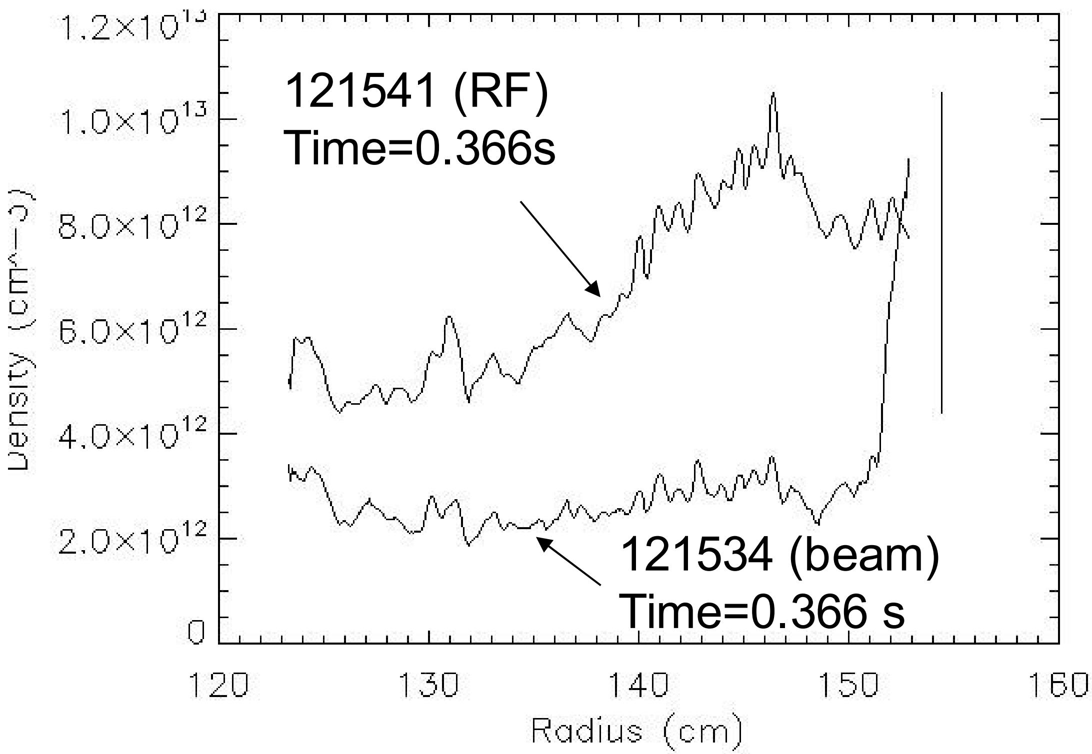
RF shot 121539. This plot shows the neutral density at different time slices from time=0.133-0.266 s. The density drops with consecutive time slices, though it appears to be stablizing by around 0.200 s. This could be a sign of the neutral density reaching an equilibrium.

Beam shot 121534. Although the initial absolute neutral density is approximately equal to that in RF shots, the equilibrium value in beam shots appears to be about half of that in RF shots.

Both shots initially have a large edge neutral density, which quickly decreases to a stable value

Comparing RF and Neutral Beam Shots

The RF plasma seems to have a larger central neutral density, while the beam heated plasma increases significantly in density at the outside edge. This could be a result of the increased radius of the seperatrix in RF plasmas, placing them closer to the RF antenna for maximum coupling.



Comparing RF and beam heated plasmas

Error Analysis

- Errors come from several potential sources:
  - Edge data points from Thomson Scattering data is sparse and has large error bars in the plasma edge.
  - Fluctuations in the electron density and temperature could create errors because the END diagnostic integrates over a much larger time than the Thomson Scattering diagnostic.
  - Abel-inversion can cause problems due to the limitation in the view. If light is emitted by a region of plasma outside of the radius of the field of view of the camera, it can lead to a false signal near the edge. This may be the cause of the sharp increase in density viewed at the edge. The field of view of the END Diagnostic is limited to <153 cm, which is near the seperatrix in RF shots.
  - The field of focus of the lens is approximately 20 cm. Things outside this focus area will not be in focus. This is probably the reason why the central neutral density does not reach 0.
  - Reflections from the back wall could contribute to the overall errors. We hope to minimize this by painting the background black.

Conclusion

- Preliminary data shows neutral densities in the around $2*10^{12}$. The profiles are relatively flat, before sloping sharply at the edge, beyond the seperatrix. This coincides with the expected profile, though the increase is much sharper than expected.
- TRANSP calculations show a decrease in central ion temperature of about 5% as a result of increasing the neutral density from 10^{9}-10^{12} cm^{-3}.
- RF and neutral beam heated shots show very different neutral density profiles. RF shots are more difficult to get good data on, possibly because of the location of the seperatrix. They may in fact exhibit the same behavior as Beam-heated shots, with the sharp rise being out of the viewing range of the camera.
- The 12-bit CCD camera will provide greater resolution in the emission spectrum. It will cause a loss of resolution in the spatial direction, but this should have minimal effect.

Continuing Work

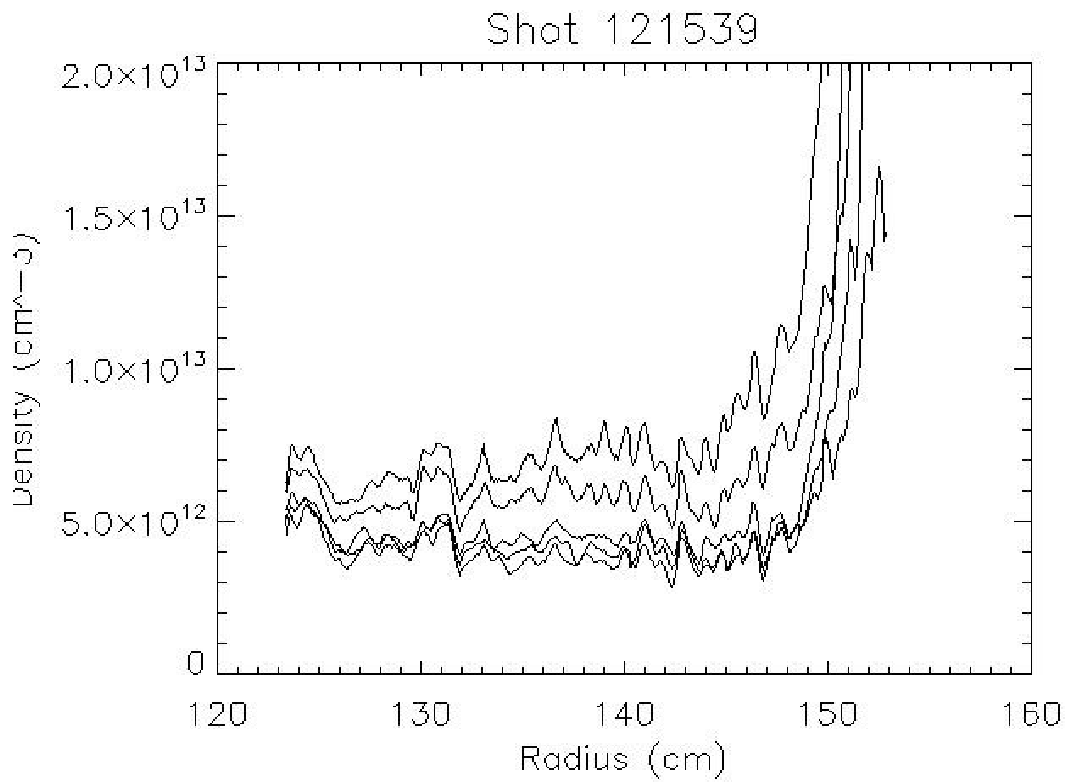
- The 8-bit CCD camera is currently being replaced with a 12-bit CCD camera. This should provide much greater intensity resolution.

	8-Bit camera	12-Bit camera
Resolution	512x480	256x256
Speed	30-250 Hz	30-500 Hz

- Although the number of pixels is decreased, the spatial resolution of the camera lens should still provide adequate data
- The new camera will be in operation for the 2007 run year.
- The density calculation will be verified using the Degas2 code.

Continuing Work-Improving the background shot

The background image from the camera is insufficient to eliminate features that recur from frame to frame. An improved background image should eliminate these peaks. More care will be taken with the 12-bit CCD to ensure that the false peaks are eliminated.



Continuing Work-Error Reduction

- The error in the Abel inversion can be reduced by two methods.
  - First is to alter the angle of the mirror. While it is not possible to extend the mirror, adjusting the angle to ~10° will help us to see farther toward the edge of the plasma.
  - Second, the camera could be moved to increase the angle at which it looks at the mirror. Between these two methods, it is estimated that the camera field of view can be increased to 158 cm.
- In order to reduse the error due to Thomson Scattering data at the edge, the fast probe data will be incorporated as well.
- The background of the camera view will be painted black in order to minimize reflections from the vessel wall. Reflections off near walls have not been a problem.
- It may be possible to get a lens with a greater field of focus. This would reduce the effect of light emitted outside the field of focus, which would also help the Abel inversion.

Reprints

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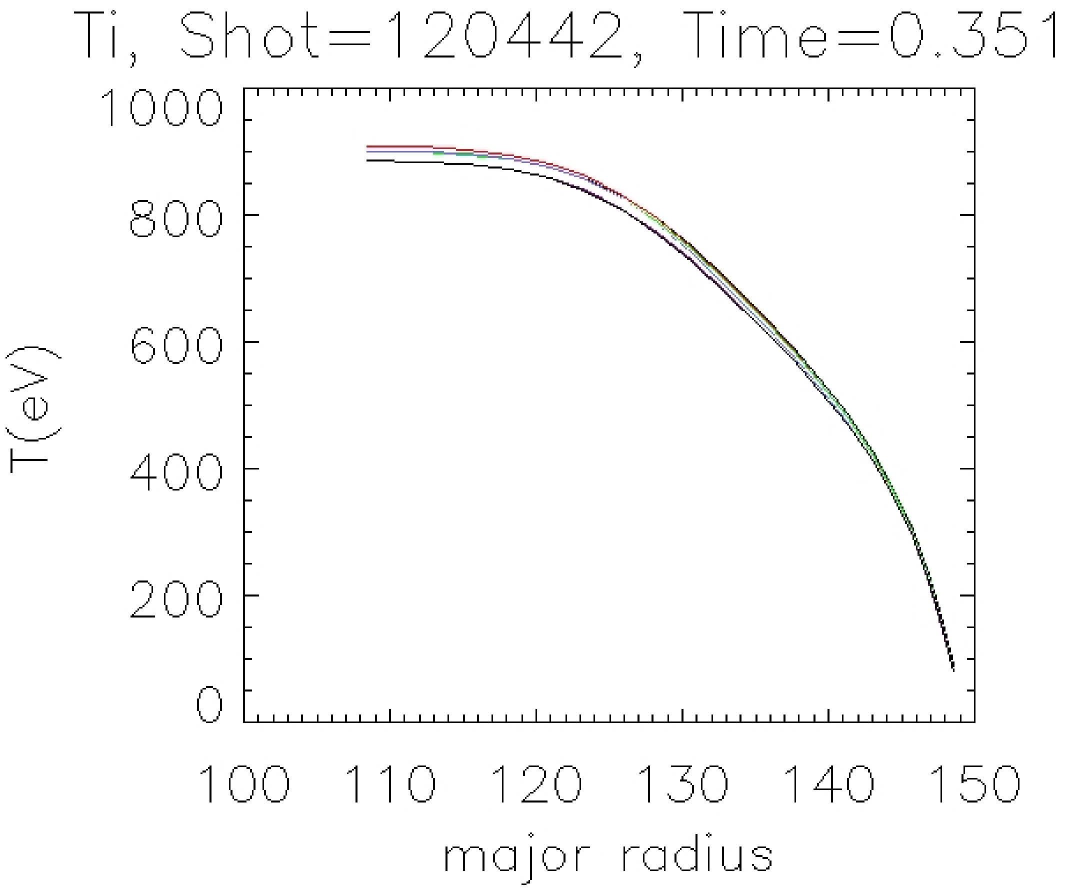
Edge Neutrals in Transp



TRANSP calculations show a minor variation in the ion temperature due to the edge neutral density. Over 3 orders of magnitude, the Ti in the center of the plasma changes by ~5%.

Transp calculations of ion temperature for varying edge neutral densities. The top curves are calculations using lower edge neutrals, with increased neutrals resulting in lower temperatures