Beam Modulation Effects on Ion Power Balance

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Abstract

The coupling between the beam particles and the thermal ions is poorly understood. To examine the coupling, the beam powe was modulated. The fast particles were then measured using a variety of diagnostics. The neutron rate from beam-target interactions shows the expected behavior, with the signal decreasing to a new steady state value in <10 ms. The Neutral Particle Analyzer (NPA) shows a presence of fast ions at various pitch angles, but not at others. The NPA measurement is compared to other fast ion diagnostics including the Fast Ion D Alpha (FIDA) diagnostic, the Solid State Neutral Particle Analyzer (SSNPA) and the Scintillator Fast Loss Ion Probe (SFLIP) diagnostic. Comparison is also made between measured NPA signals and TRANSP calculations. The ion anc electron temperature were also measured and compared befor and after the start of the modulation, and conclusions are draw about the coupling between the beam and the plasma.

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Outline

- Motivation
- Ion Temperature and MHD Activity
- Edge Neutrals and ENDD analysis
- ENDD and Lithium Effects
- Beam Modulations and Fast Ion Population
- TRANSP Calculations and NPA Analysis
- SSNP, FIDA Observations of Beam Modulatior

Ion Power Balance

The ion power balance equation is given by

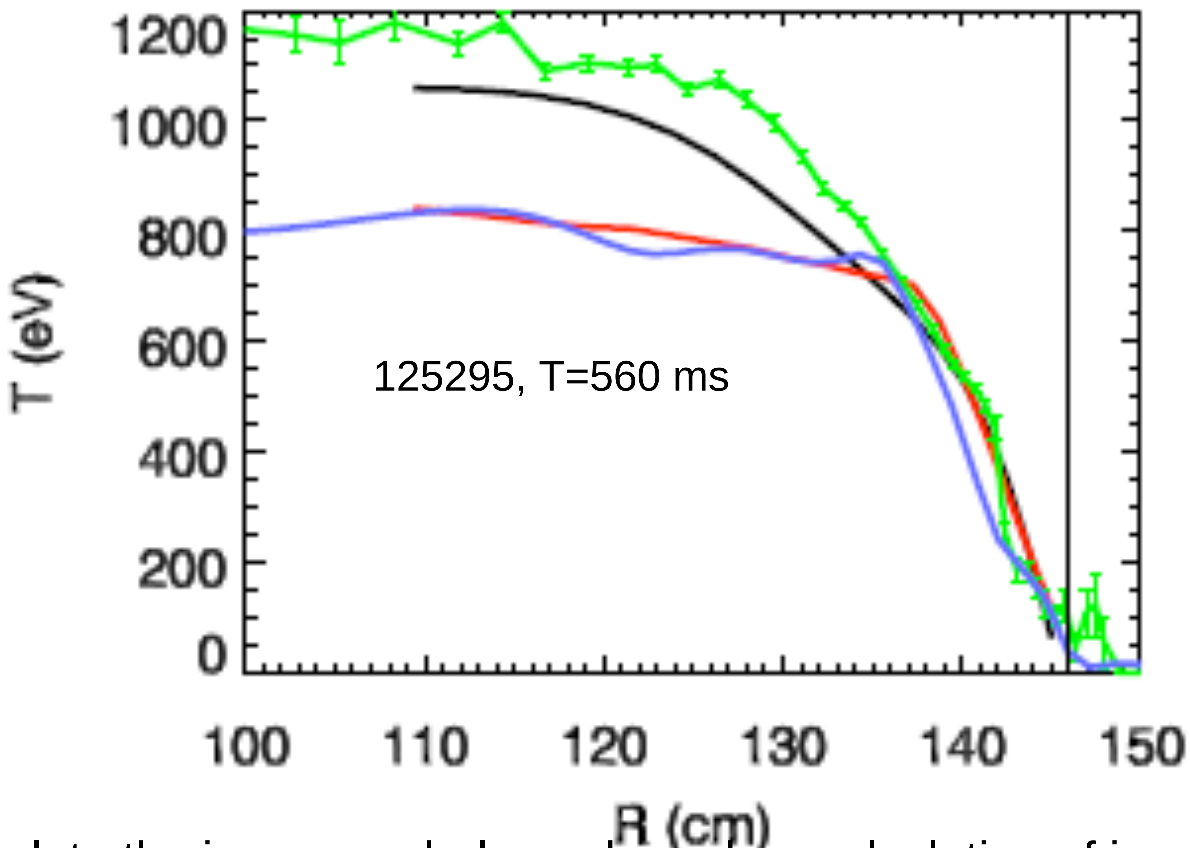
$$P_{beam} + Q_{ie} + \chi_i \nabla T + = \frac{dW_i}{dt}$$

- Q_{ie}, $\chi_i \nabla T$, are calculated in the TRANSP code.
- dW/dt is measured directly by measuring the ion temperature and density.
- P_{beam} is also modeled in TRANSP.

By modulating the neutral beams injected, it is possible to test the beam power deposition model used in TRANSP. It is hoped that we can determine the time scale of the beam interacting with the ions and understand the high ion temperature.

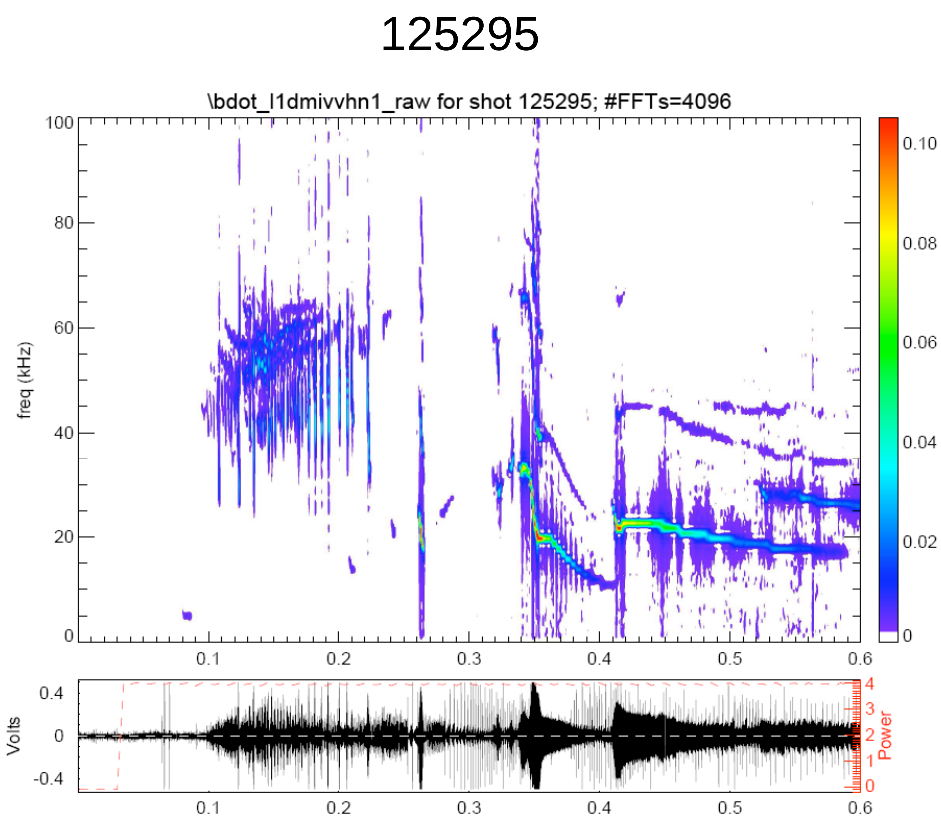
Ion Temperature Does Not Match TRANSP Calculated Temperature Using Neoclassical Diffusion

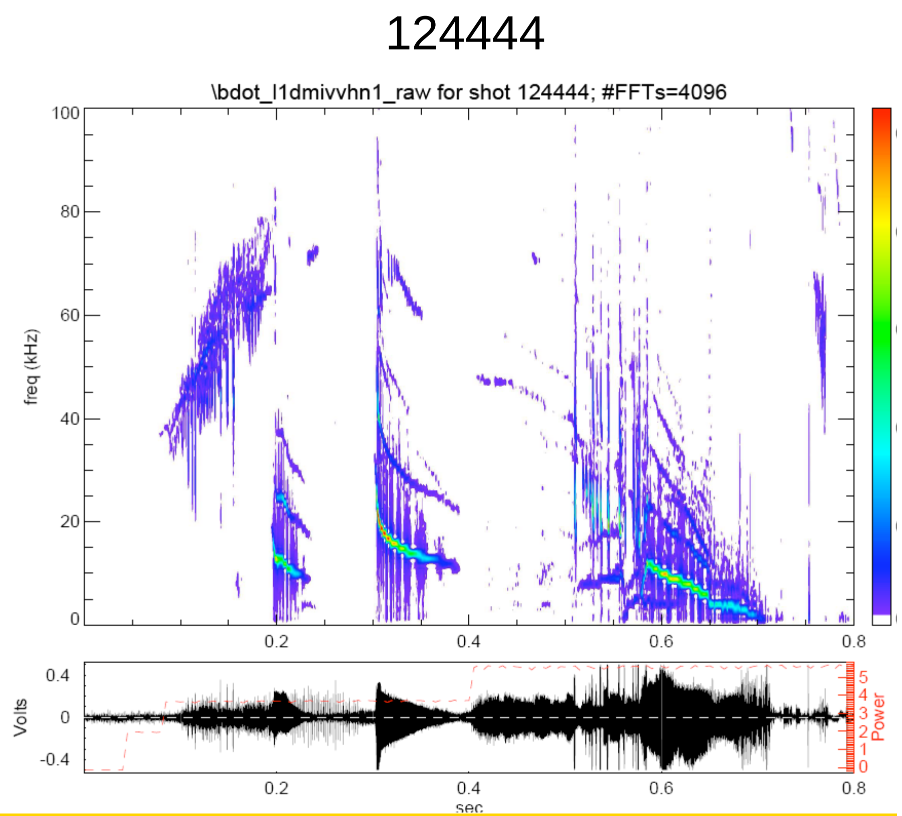
Green=measured T_i
Black=calculated T_i
Blue=measured T_e
Red=T_e fit



TRANSP attempts to calculate the ion power balance based on calculation of input po from beams, and coupling with the electrons. However, for certain shots, the ion temperature is higher than is estimated, even assuming neoclassical diffusion.

MHD Does Not Drive Anomalously High T_i





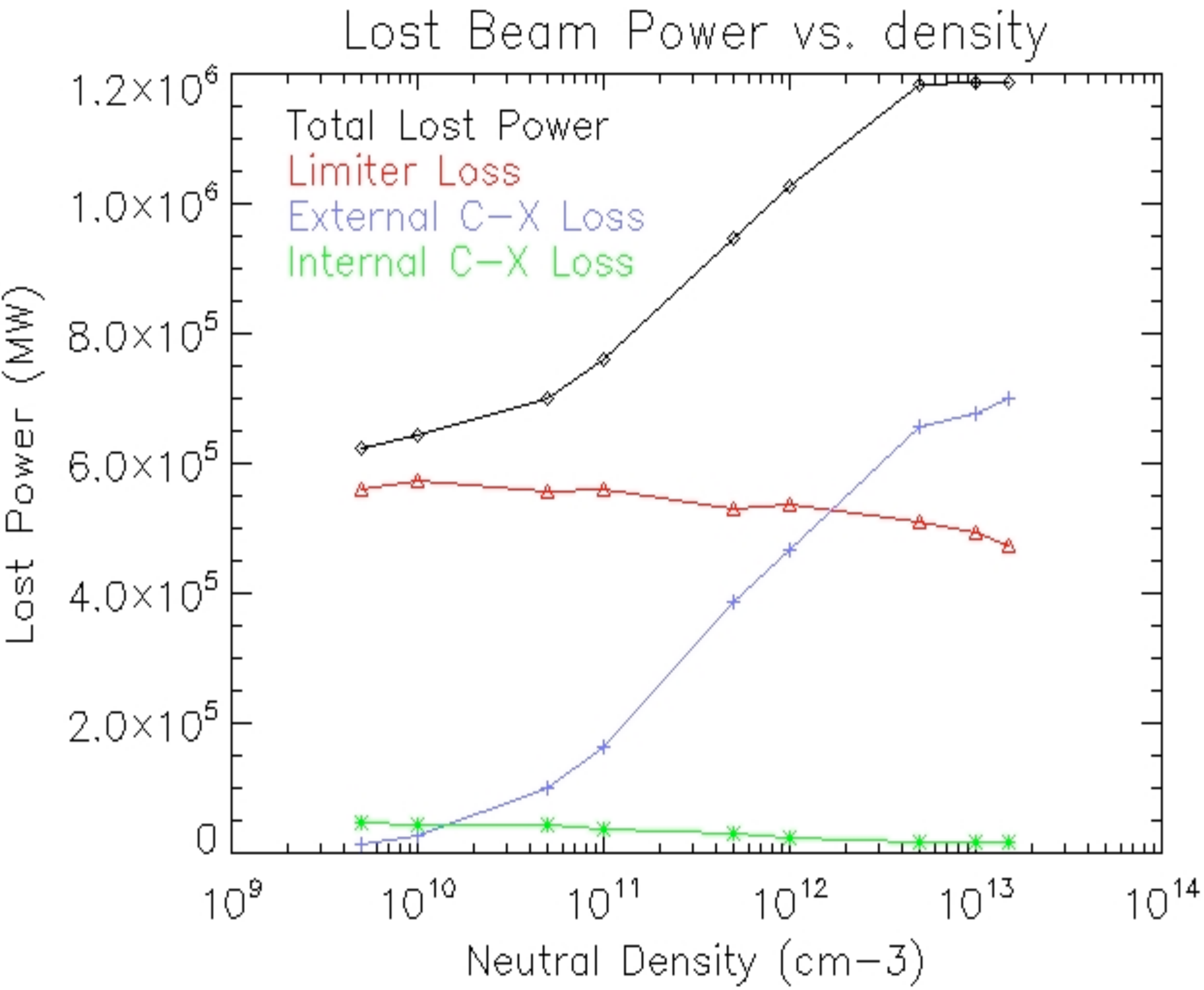
MHD measurements from shots 125295 and 124444. The anomalously high Ti in 1252
corresponds with the onset of some MHD activity (n=2 mode?) near 500 ms, while the
high Ti in shot 124444 occurs during a relatively quiet MHD period near 400 ms.

Ion Power Balance and Neutral Beams

The goal was to study the ion power balance and the coupling between the injected neutral beam and the thermal ions

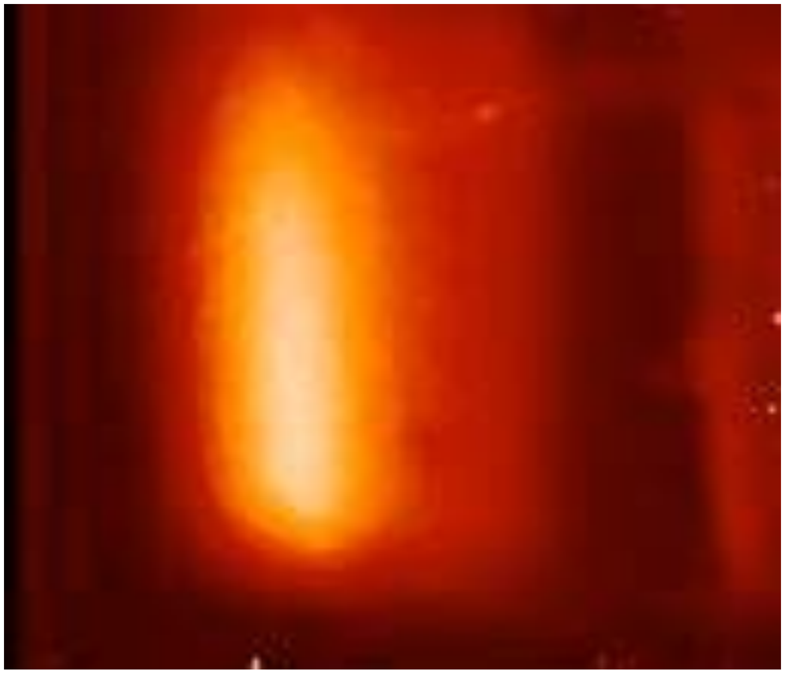
- Modulate Beam power, modulate 3→2 beams
- Evaluate the NPA signal, along with SSNPA, FIDA, and SFLIP
- Compare NPA signal to calculated TRANSP signal
- Determine effects of edge neutrals on beam power balance
- Compare ion temperature and MHD signal with simila shots without modulations

Beam Power Loss to Edge Neutrals



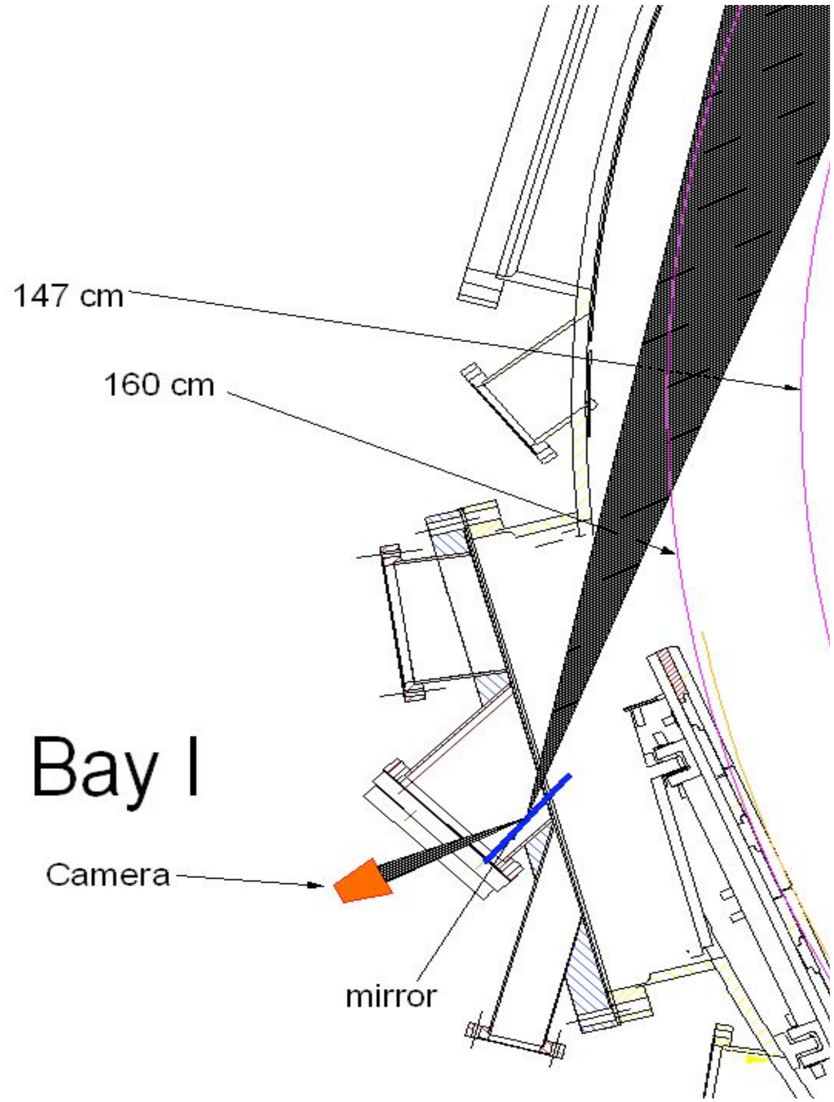
TRANSP calculations show the loss of beam power due to interaction with the edge neutrals. The increase in power lost by external charge exchange leads to a significant increase in the overall loss of beam power. At the edge neutral density measured by the ENDD (1-1.5e13), the total lost power is about 20% of the total input power, a 100% increase over the default TRANSP value of 1e10. Also, it is noteworthy that the lost beam power seems to saturate at 20% of the beam power

Edge Neutral Density Diagnostic (ENDD) measures light emitted by the plasma edge



Inboard Outboard

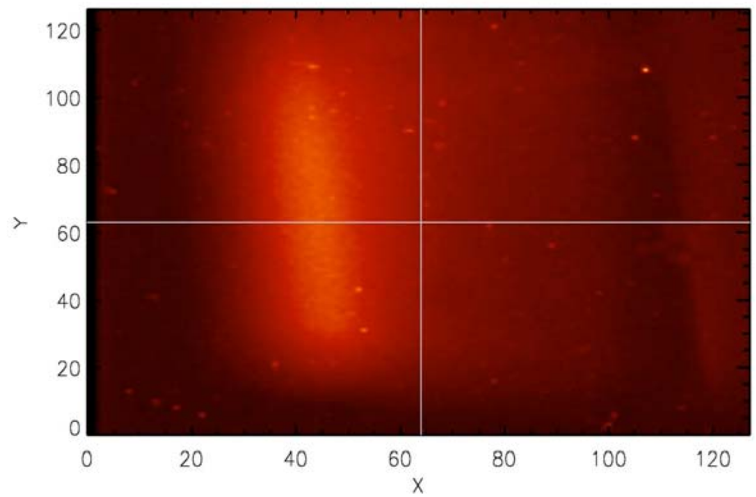
The ENDD uses a 2-D CCD camera to measure D_β emissions. The emission profile is then Abel-inverted to provide a radial profile.

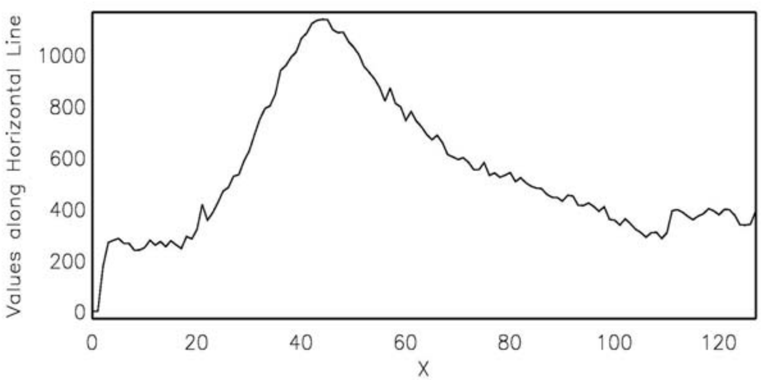


Description of the Edge Neutral Density Diagnostic

- CCD camera with a D_β filter measures emissio of the plasma
- The camera is calibrated to provide the absolute emission
- Toroidal symmetry is assumed and the image i Abel-inverted
  - This ignores bays and injectors on NSTX, which may alter the analysis.
- The profile is calculated using a collisional radiative model

ENDD Analysis





The ENDD camera takes an image of the Dβ emissions of the plasma during discharge. The light obtained by a pixel is determined by

$$p_{ij} = E\frac{\Omega}{4\pi}\eta\theta_{ij}\varphi$$

where

p_{ij} = pixel count

E = plasma emissivity

$\Omega/4\pi$ = the solid angle

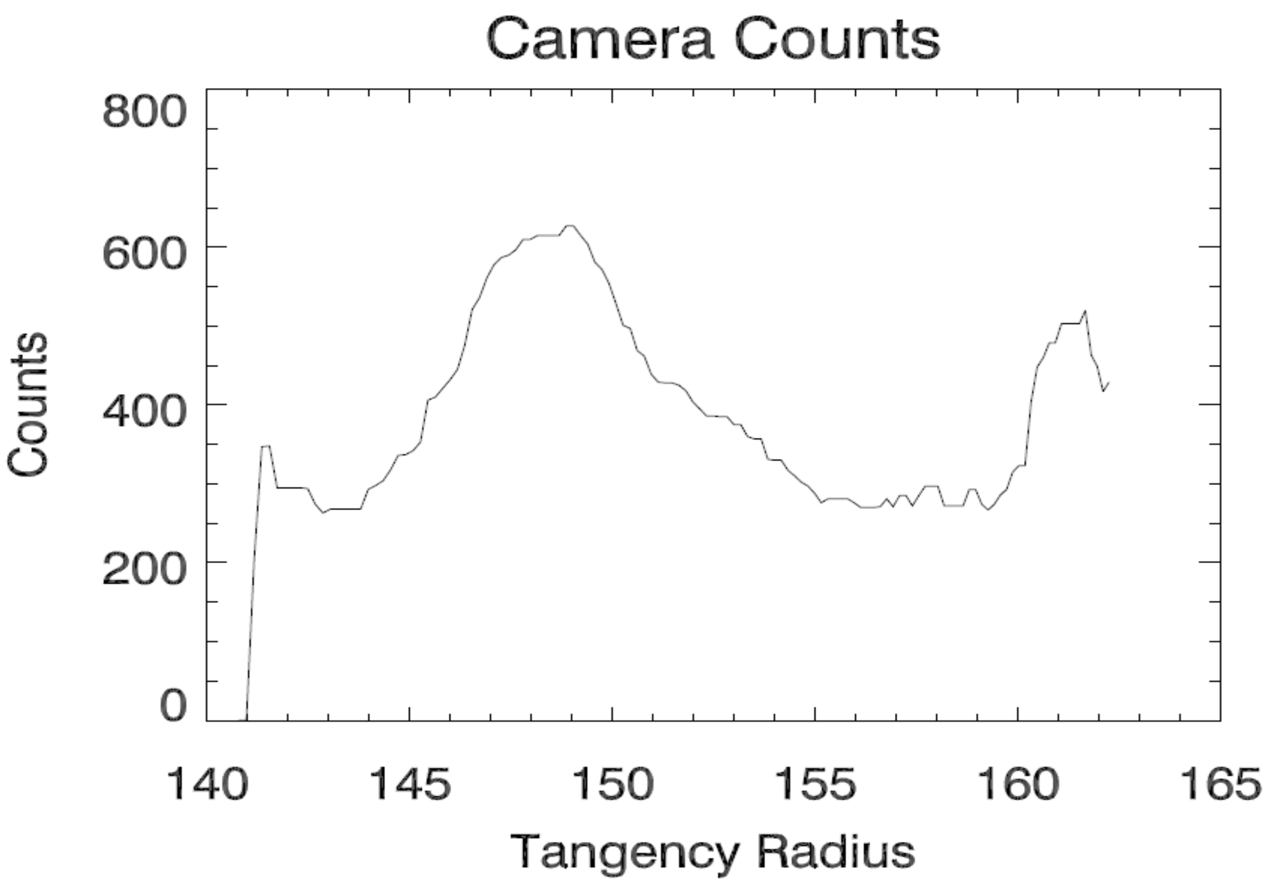
η = the geometric effects, including camera lens

θ_{ij} = the pixel sensitivity

φ = filter effects

By using a calibrated source, we can find η, θ_{ij}, and φ. We can then solve for E in the plasma to solve the neutral density

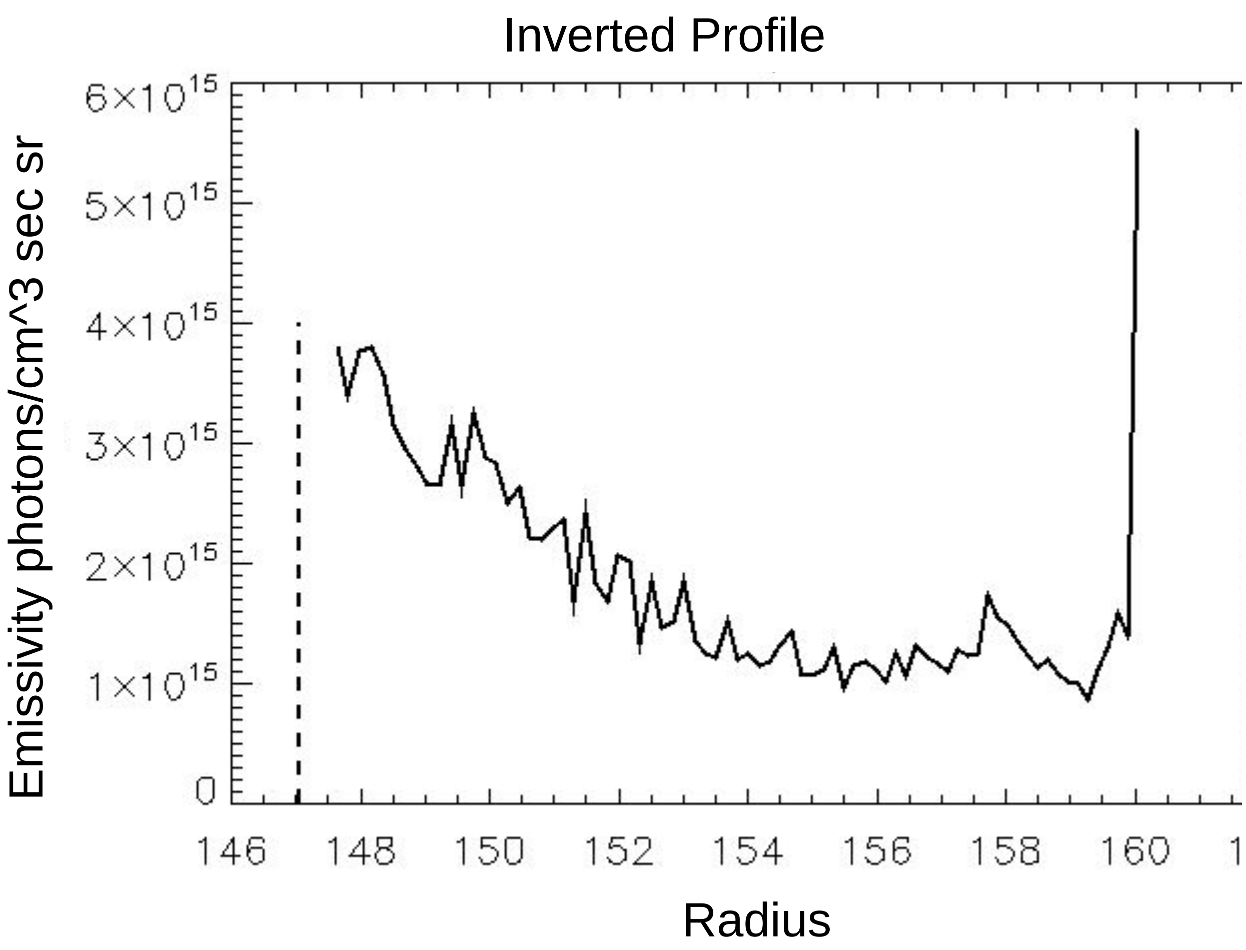
ENDD Analysis



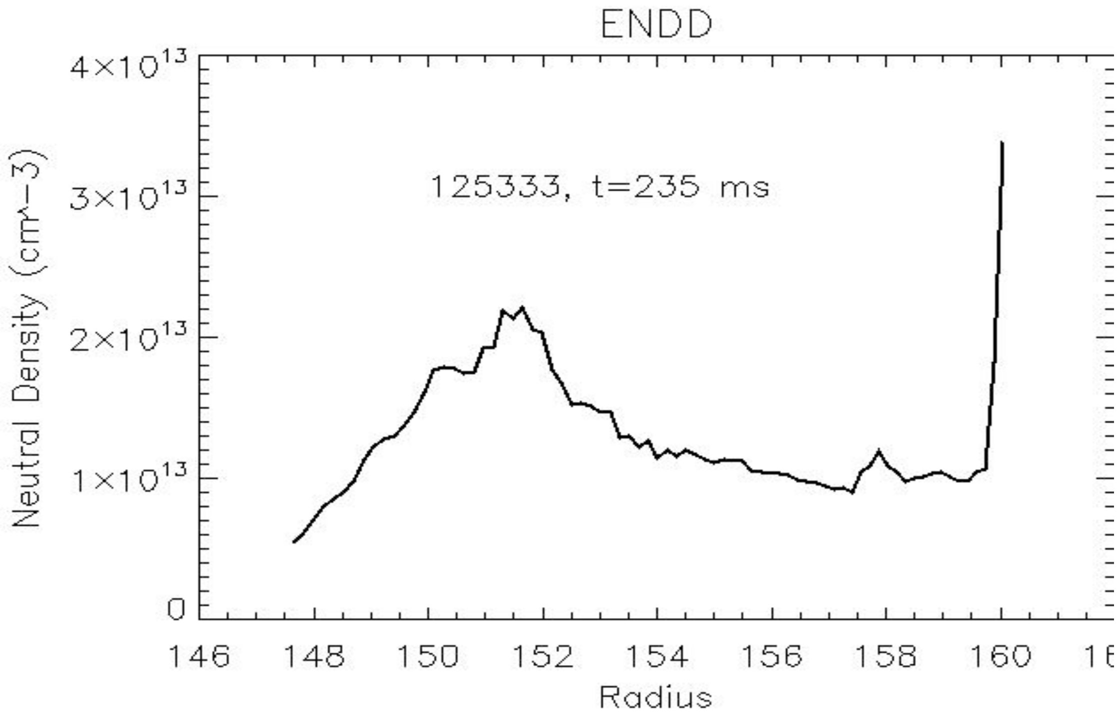
Raw signal. The
12 bit CCD came
records plasma
emission which i
converted into th
emissivity. The
plasma emissivit
is then Abel-
Inverted and use
to calculate the
neutral density

Abel Inversion Shows Intense Light near Separatrix

The inverted spectrum shows a trend in the intensity which indicates the presence of neutrals inboard, and tapering off toward the outboard edge. This is most likely the result of the poor T_e fit and may require the use of other diagnostics in getting a better fit.

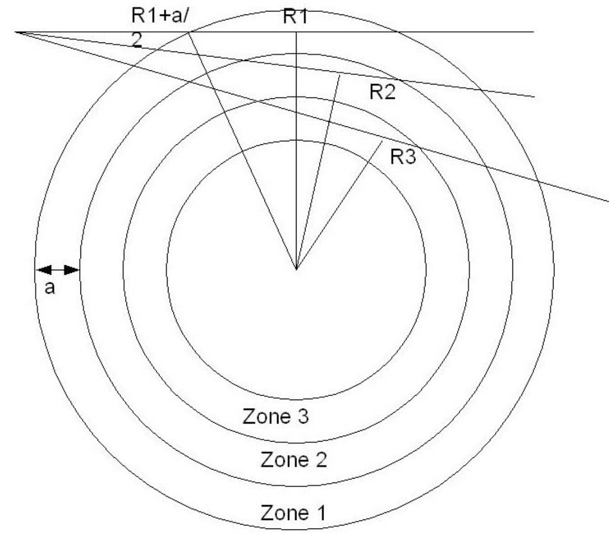


ENDD shows densities from 1e12 - 5e13



The Edge Neutral Density Diagnostic measures the neutral density in the edge of the plasma. Typical densities range from 1e12 to about 5e13.

ENDD Analysis (cont.)
Abel Inversion



Abel Inversion:
Assume each zone emits with a certain intensity, I_n. Starting at the outside edge, the integrated intensity E_m is:

$$E_1 = 2I_1\sqrt{(R_1+\frac{a}{2})^2 - R_1^2}$$

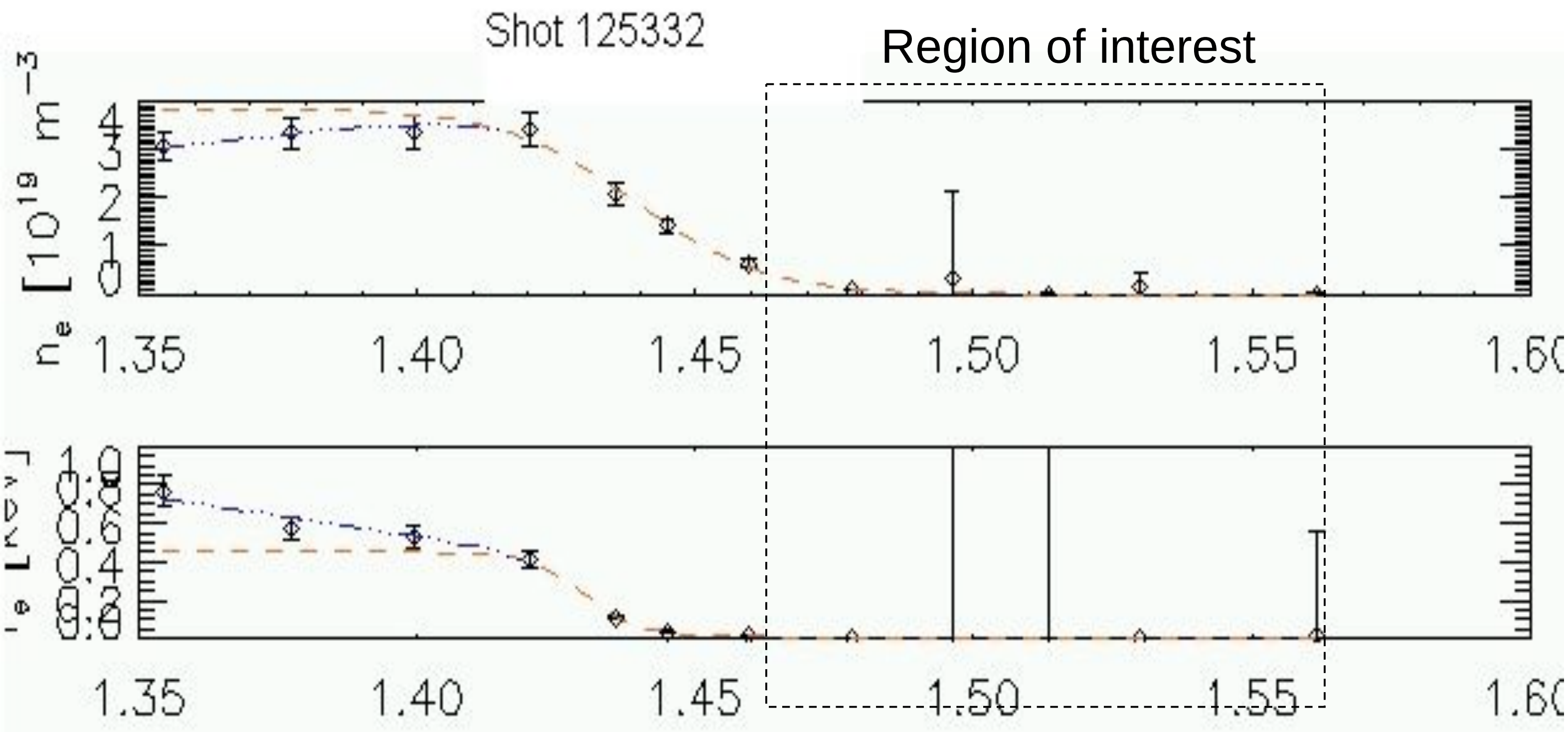
$$E_2 = 2I_2\sqrt{(R_2+\frac{a}{2})^2 - R_2^2} + 2I_1\left(\sqrt{(R_1+\frac{a}{2})^2 - {R_2}^2} - \sqrt{(R_2+\frac{a}{2})^2 - R_2^2}\right)$$

$$E_m = 2I_m\sqrt{(R_m+\frac{a}{2})^2 - R_m^2} + \ldots 2I_1\left(\sqrt{(R_1+\frac{a}{2})^2 - {R_m}^2} - \sqrt{(R_2+\frac{a}{2})^2 - R_m^2}\right)$$

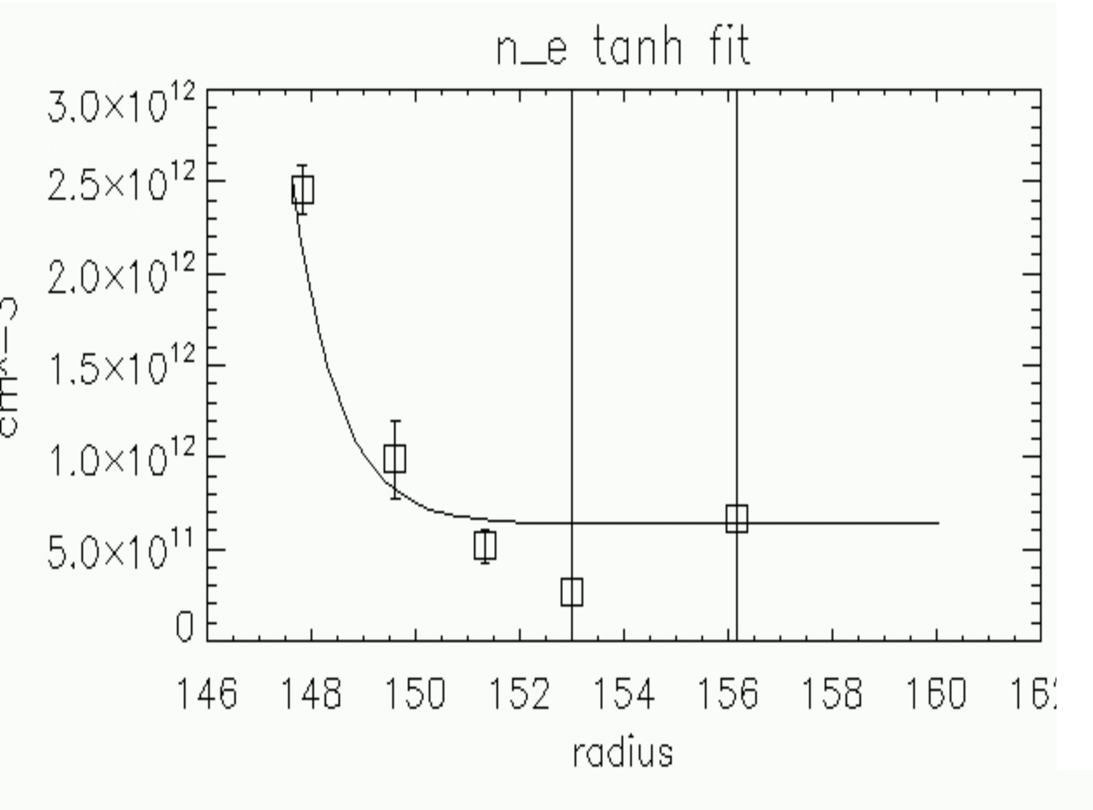
This can be written as a matrix *A*, which is lower triangular, and whose inverse *A* also triangular and represents the Abel inversion, from which, I_1, I_2,…I_m can be solved.

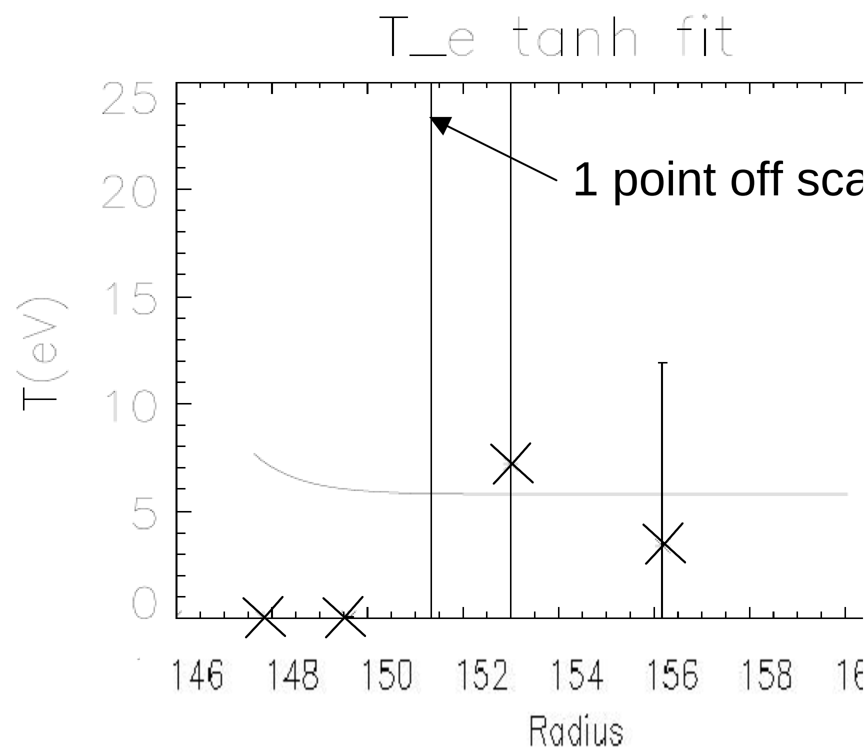
ENDD Analysis (cont.)
Density and Temperature fits

Hyperbolic tangent functions are fit to the temperature and density data obtained by Thomson Scattering to analyze the data in the ENDD diagnostic which covers radius that only contains 5 Thomson Scattering data points.



Density and Temperature Fits (cont.)

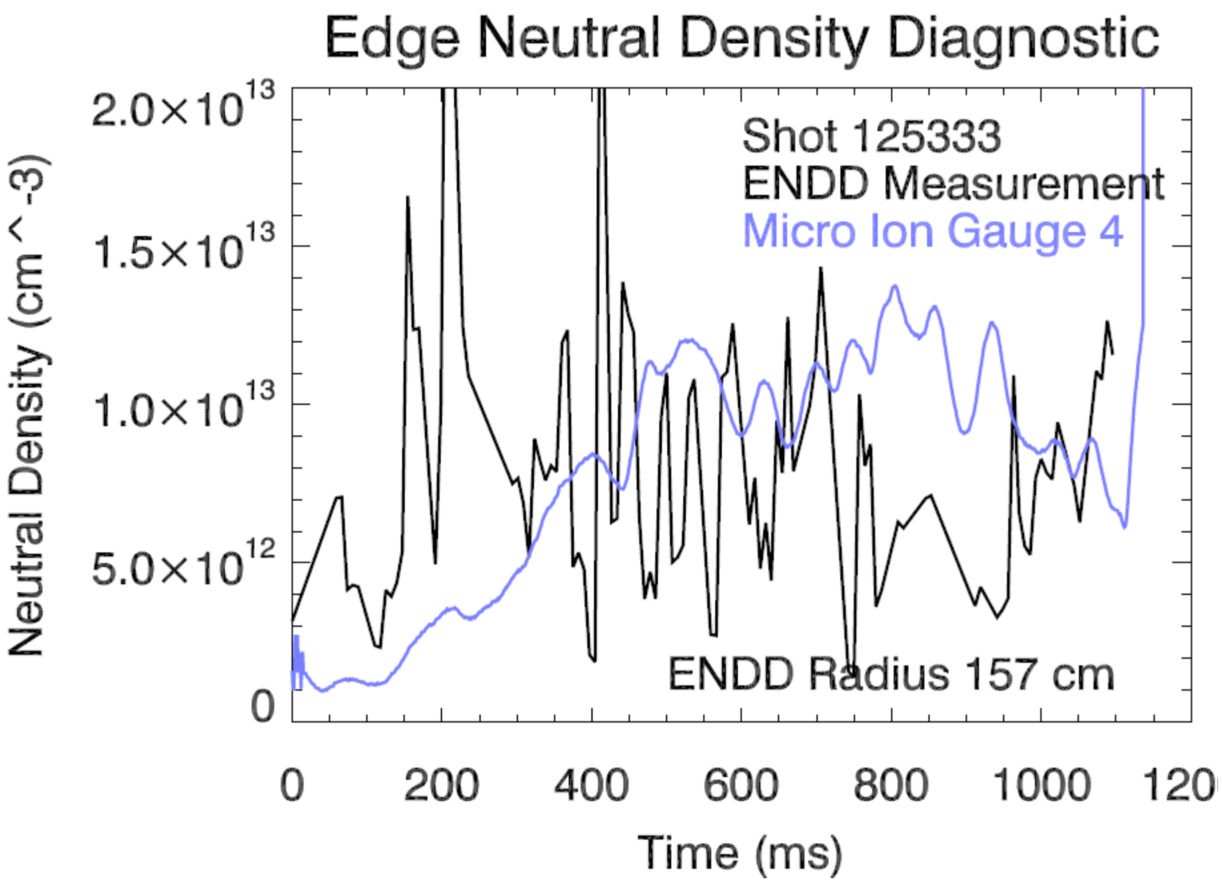




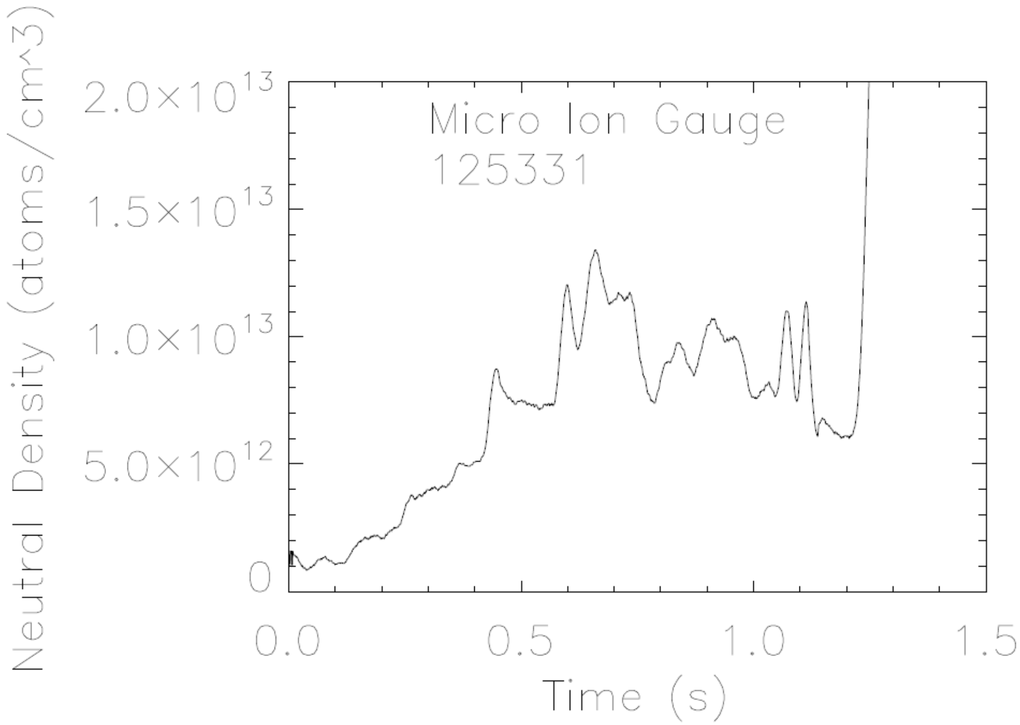
The hyperbolic tangent fits the Thomson Scattering density fairly well. The temperature fit is not as good, and may require using another diagnostic, such as the Fast Probe to get a better fit to the temperature.

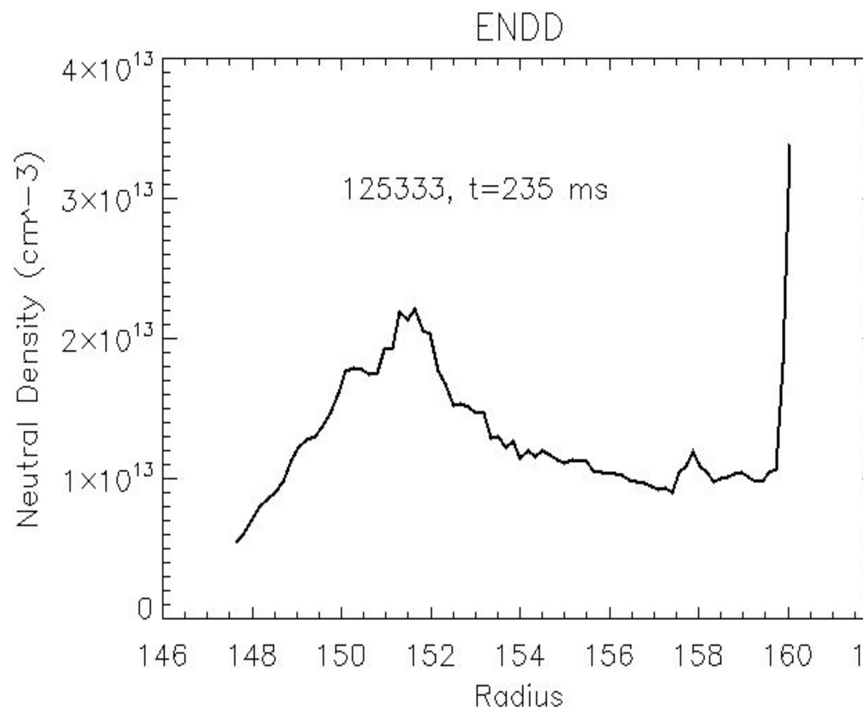
ENDD vs. Neutral Pressure Gauge

The density measured by the ENDD is on the same order of magnitude as the density measured by the micro ion gauge. It is worth noting that other gauges are also within 1-2 orders of magnitude. However, these other gauges are protected from the plasma.



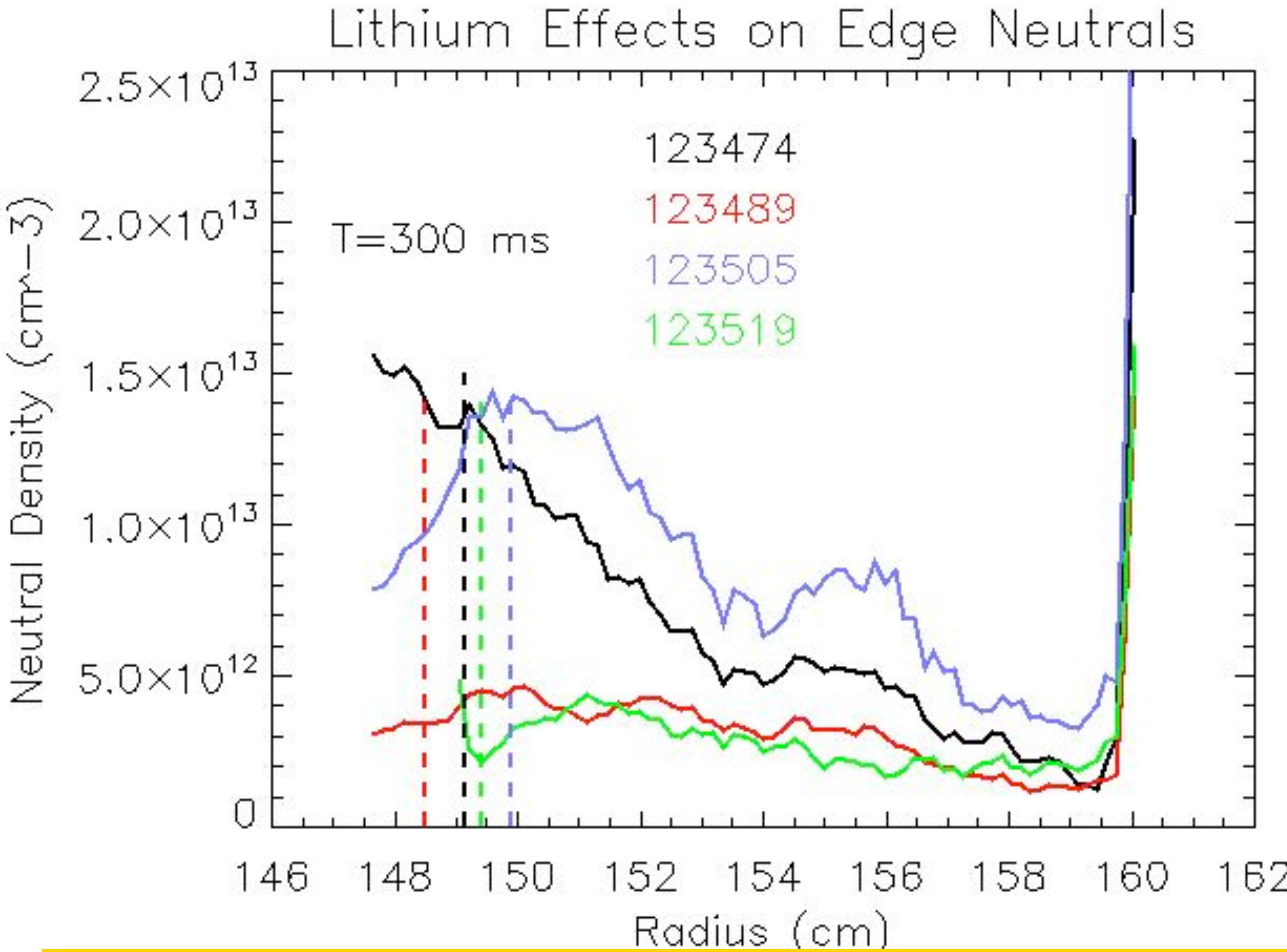
ENDD vs Neutral Pressure Gauge





Note that the two measurements differ by a factor of approximately 1-2 orders of magnitude. The micro ion gauge is located on bay E behind the RF antenna. The pressure measured by the gauge increases as the plasma comes on. However, it is likely that the RF antenna provides shielding from the creation of secondary electrons by the plasma.

Lithium effects on Edge Neutral Density



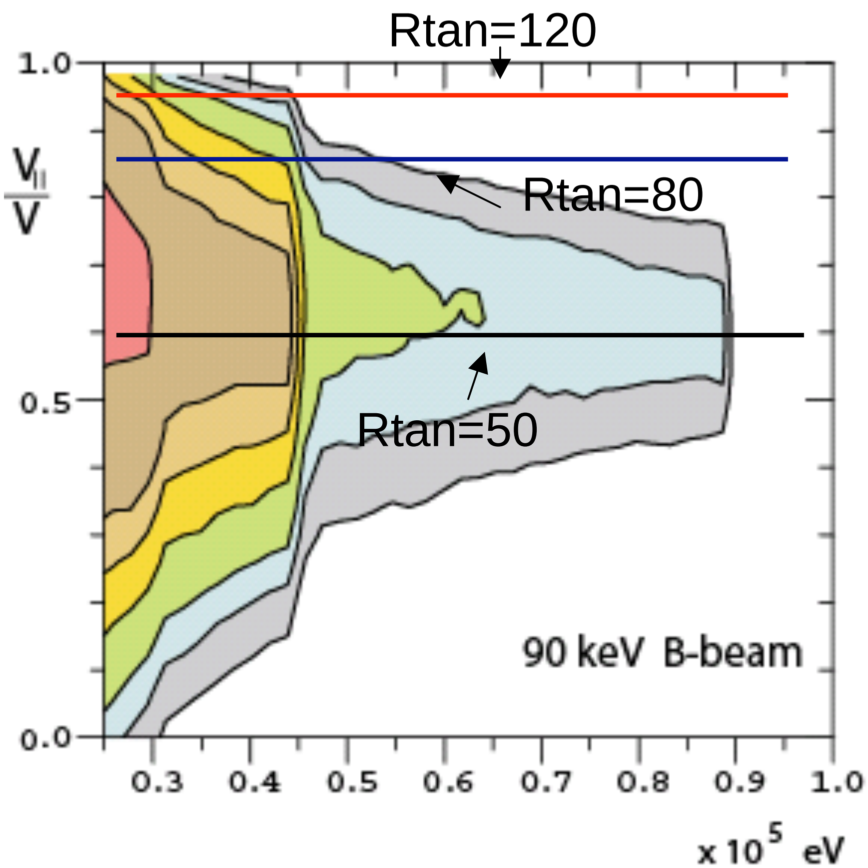
The reference shots from day 1 to day 2 are very similar, even though more than 1.8 grams of Lithium was deposited into NSTX during Day 1 operation. The lithium effects are seen in the final shot of Day 1 (shot 123489), but have completely disappeared by the reference shot of Day 2 (123505).

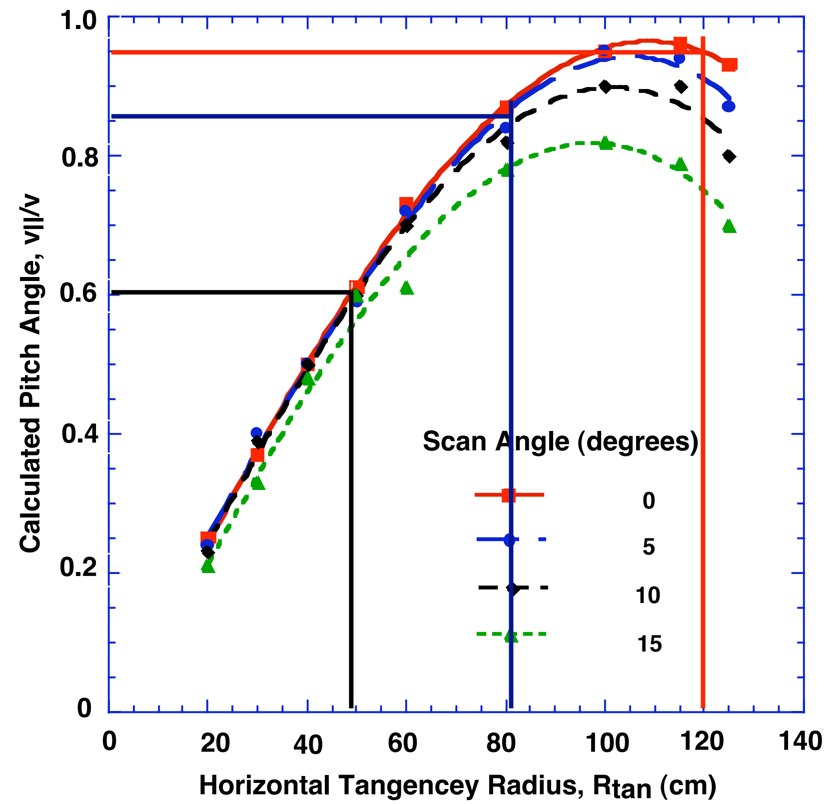
Lithium deposited in NSTX (in mg)

Shot	Lithium	total
123474	0	0
123489	260	1876
123505 (Day2)	0	0 (1876
123419	516	6473 (8349

Lithium deposited in NSTX during XP 719. The center column indicates lithium deposited immediately preceding the shot. Numbers i parentheses are running totals, including past deposits.

Source B does mostly deposits particles in the 50-70c tangency radius

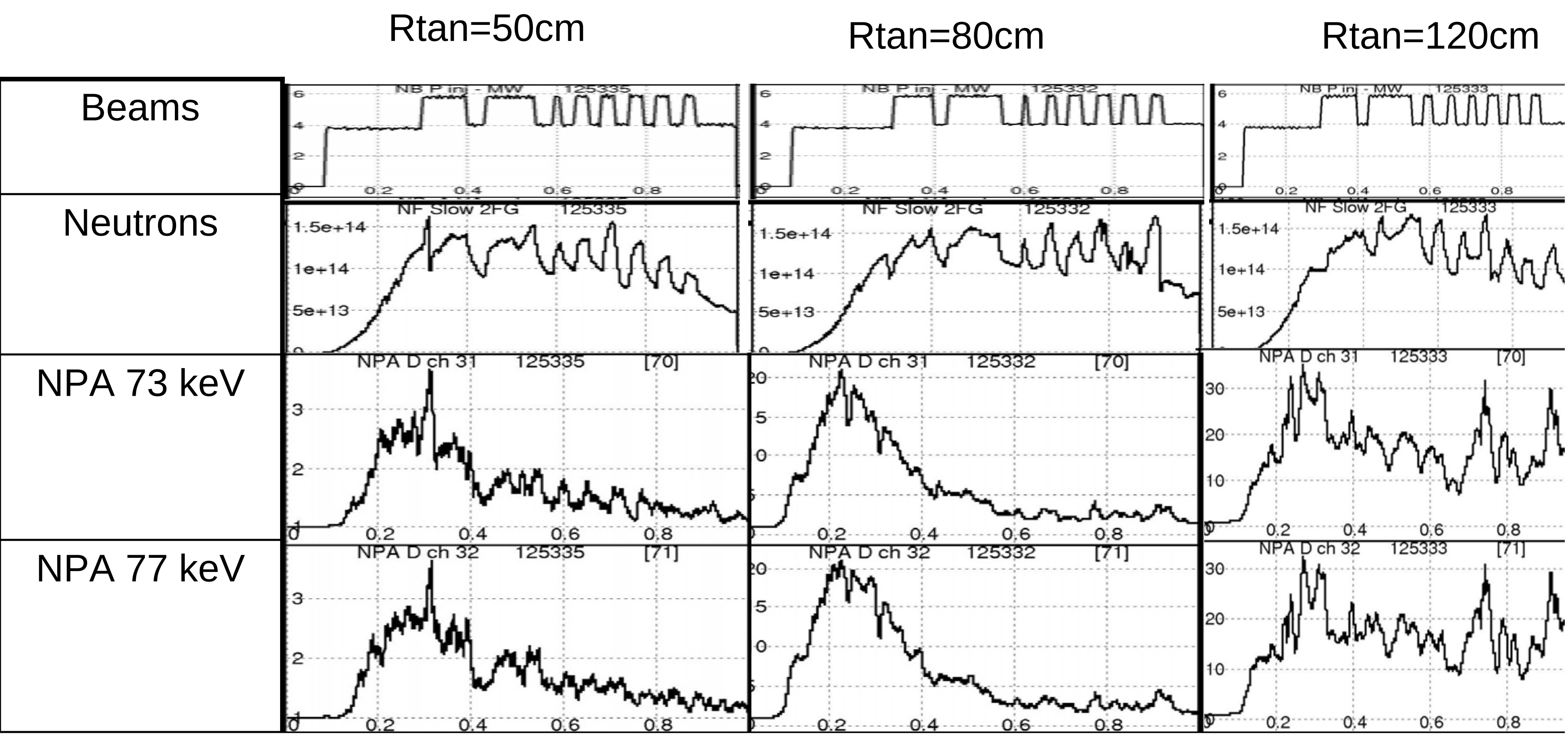




Source B was modulated to explore the power balance issue. However, source B deposits most of its beam neutrals in the 0.4-0.7 pitch angle, which corresponds to an NPA line of sight tangency radius of 40-70

- **Data is from TRANSP simulation of NPA scanning**

NPA signal shows lack at certain pitch angles

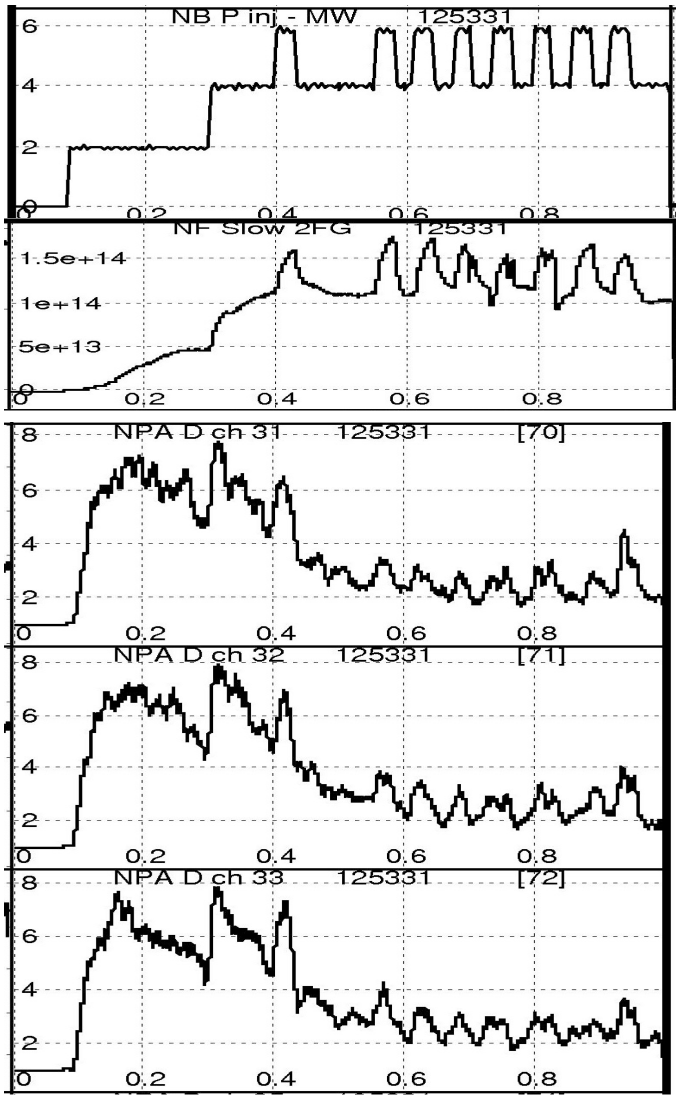


The NPA shows no modulations at Rtan=80 and Rtan=120. At Rtan=50, it appears that there are small modulations which seem to correlate with the beam modulation and neutron measurements. This fits with the calculations of the pitch angles deposited from source B.

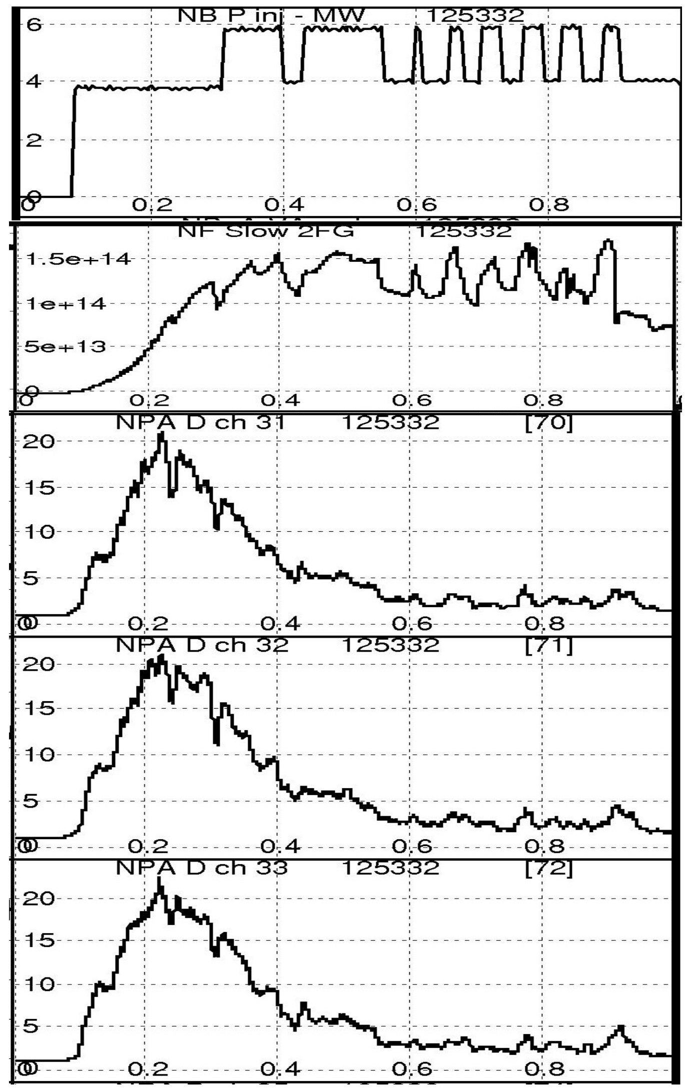
NPA signal dependent on Beam Timing

Rtan=80

- Shot 125331

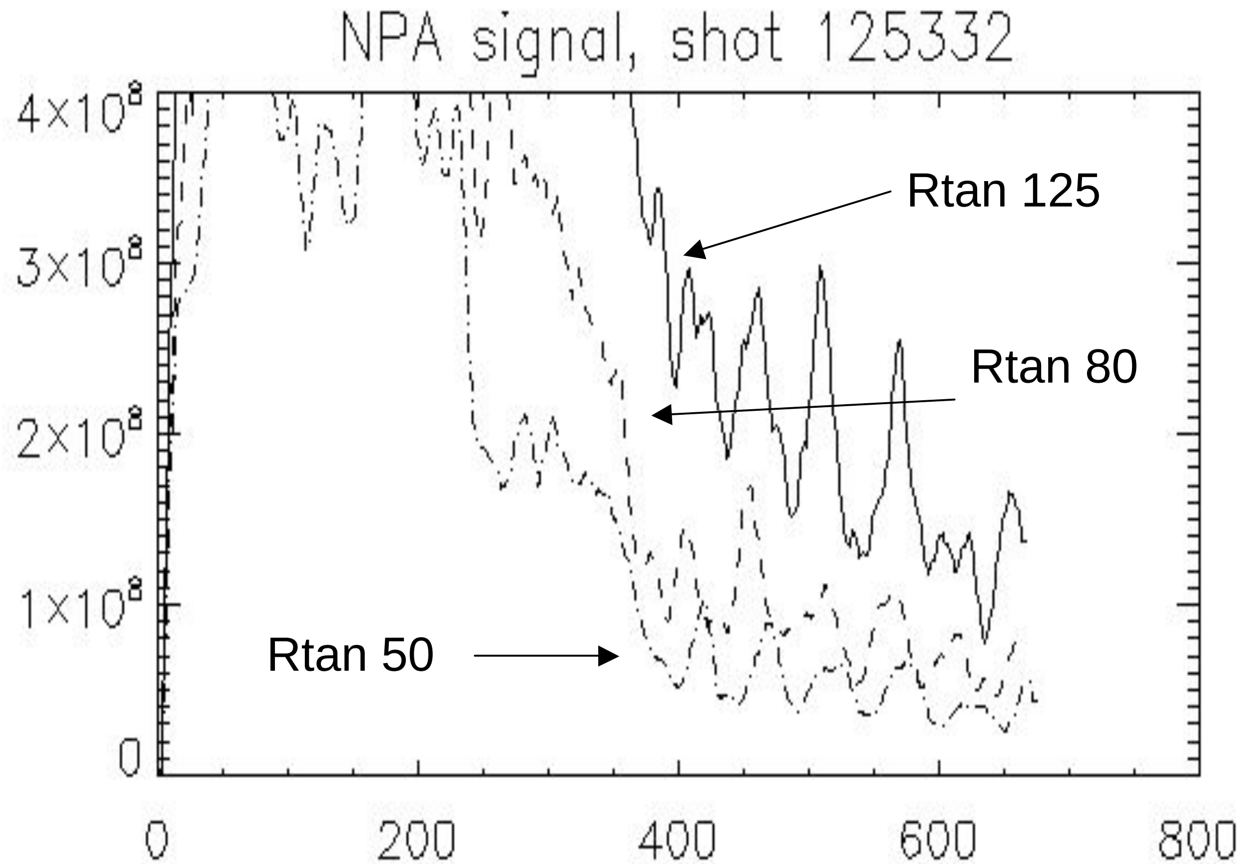


- Shot 125332



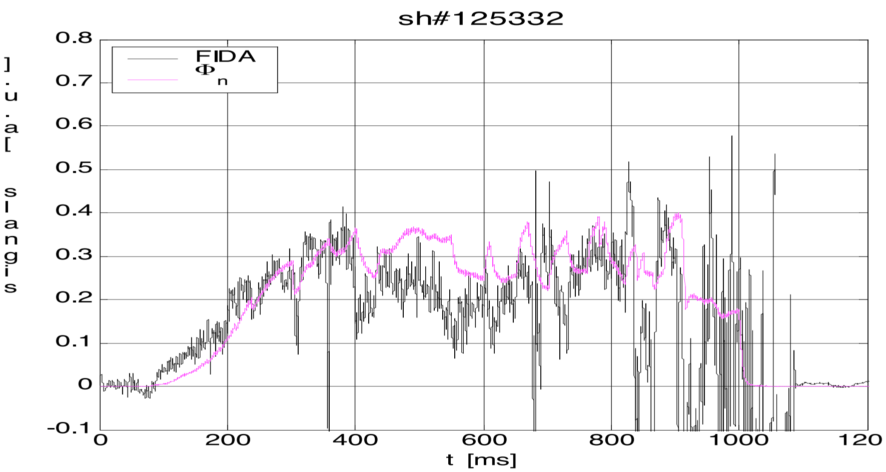
These shots we
very similar. Th
beam timing on
shot 331 was a
mistake, but it
showed how the
beam timing
affects the NPA
signal. We are
sure what plasm
parameters wer
changed by the
changing the be
timing

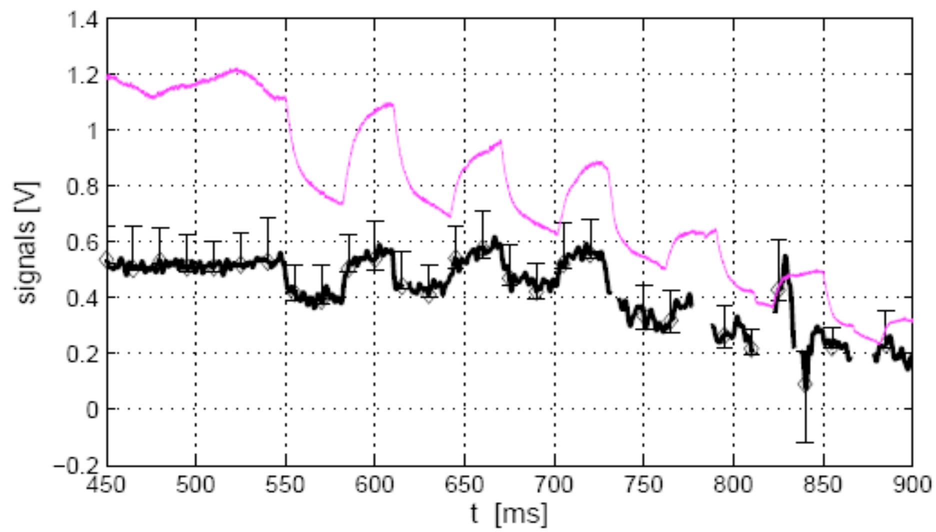
TRANSP shows NPA modulations at all pitch angles



TRANSP shows modulations all tangency radii that match beam modulations. This is n seen in the measured NPA signal, particularly for Rtan 8 near the magnetic axis. (The measured NPA signal is not shown)

FIDA shows similar behavior to NPA



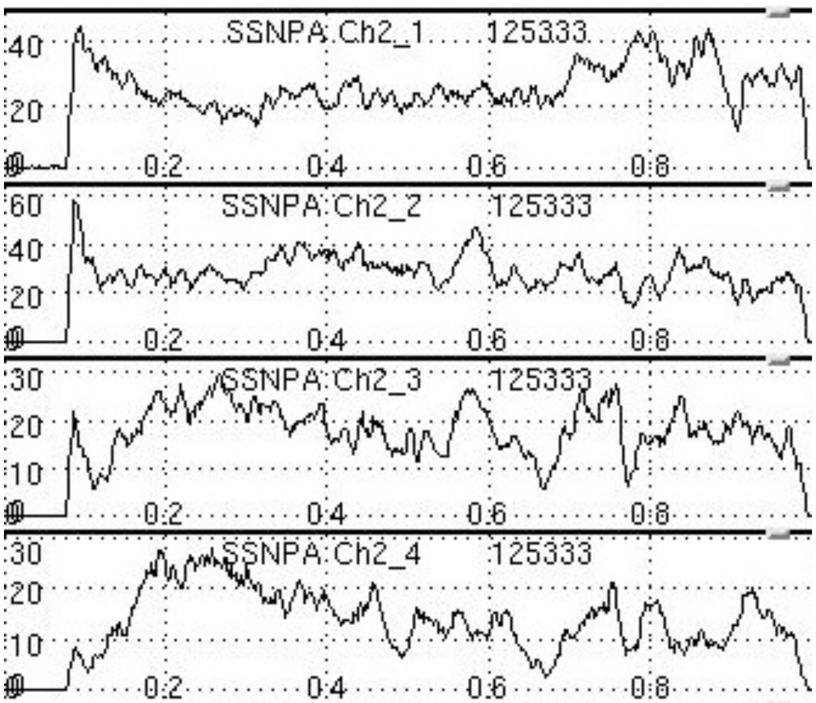


Shot 125332 showed no distinct signal on the NPA and shows a similar lack of signal on the FIDA diagnostic with the beam modulation (Neutron signal in red, FIDA in black)

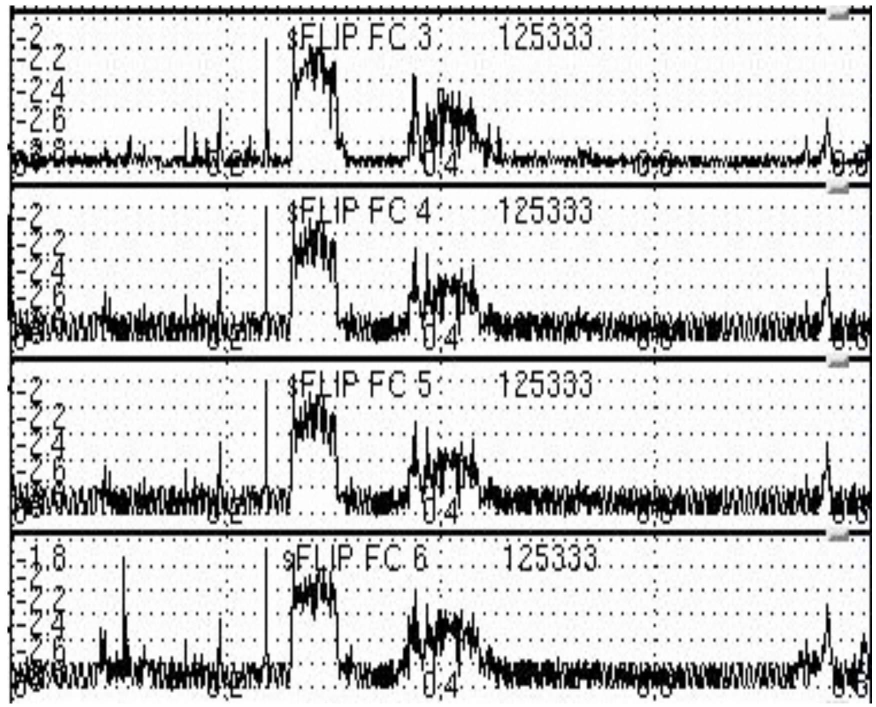
This is the overlay of 5 shots with identical beam timing and plasma parameters. Individual shots were too noisy to detect a correlation. When several signals are overlaid from repeated shots, a small modulation is seen. A similar effect may be possible with the NPA and other diagnostics

SSNPA and SFLIP Add to the Confusion

SSNPA signal at various energies. No obvious signal matches beam modulation



SFLIP probe shows loss associated with MHD activity, but does not show any activity associated with the beam modulation.



SSNPA data was not available for the shot with only 2 early beams (125331), and SFLIP data showed a similar lack of fast ion losses.

Conclusions and Further Analysis

- The ENDD provides a measurement, along with a rough profile shape of the edge neutrals.
- The ENDD was compared with neutral pressure gauges. The two measurements a similar for some gauges but differ by an order of magnitude for others. This can be attributed to proximity to the plasma.
- TRANSP calculations show that beam loss is significantly affected by the edge neutral density. Thus knowing the edge neutral density is important to understandi ion power balance.
- The fits to the Thomson Scattering data fit well for electron densities, but not well fo edge electron temperatures. It may be necessary to use another diagnostic, such a the fast probe, to evaluate the edge electron temperature.
- XP 737 highlighted the lack of understanding of the presence or absence of a stron NPA signal, particularly as related to beam modulations
- Shots with 3 beams early have a significantly higher absolute NPA signal, but lack the large modulations that are apparent in shots without 3 beams early
- SSNPA, FIDA and SFLIP confirm lack of large modulations in fast ion population, although overlaying several shots/performing a Fourier transform may show low amplitude signals. This was not done for the NPA because it was moved for each successive shot

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