NSTX

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Ion Power Balance in NSTX

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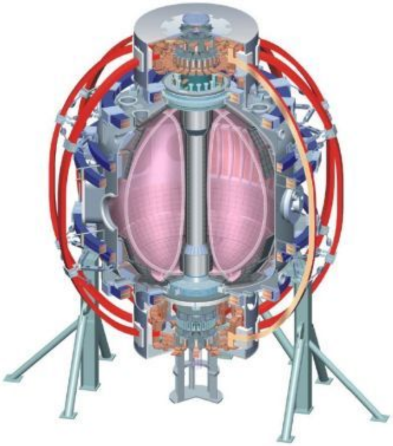

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Abstract

Experiments and simulations have been performed to investigate power balance of thermal ions in NSTX discharges. The neutral beam sources were modulated to affect the input power into the plasma. The modulations occurred on two time scales. For some discharges, the modulations lasted 30 ms which is approximately the thermalization time of beam ions. In other discharges, the modulations lasted for 60 ms, or slightly longer than the energy confinement time. The faster time scale was used to determine the deposition profile of the fast ions, and the slower time scale was used to study the effects of the beam ions on the thermal ions. Grad-Shafranov reconstructions of the plasma were performed using magnetic, temperature, and MSE measurements as constrains. The input power to the ions was calculated using the TRANSP code, which performs a time dependent transport analysis. For the longer modulation time, the inferred confinement in some cases appears to be better than neoclassical, while the shorter modulation time fit better with theoretical predictions. NPA measurements show almost no fast ions for some discharges but a very strong signal for other discharges. Comparison of the fast particle drive MHD spectrum is made between discharges with the longer and shorter modulation times. This work was supported by DoE contract No. DE-AC02-76CH03073.

Background

- Ion transport in tokamaks can be as good neoclassical predictions. Because of high flow shear, NSTX almost allways meets this criterion. NSTX offers a unique opportunity to study ion transport in this new regime. Heating has been observed that appears to be greater than the heating of ions by neutral beam particles. Simultaneously, high frequency MHD modes have been observed. (Gorilenkov, et al., Nucl. Fusion, **42**, 977 (2002).) The super-Alfvenic beam particles (v/v_A>>1) provide a source of free energy that may be used to excite modes that stochastically heat the plasma. The modes have a profile which matches the profile of the observed extra heating. Further, future machines would likely want to take advantage of such a heating mechanism.

Beam Modulation Was Used to Modify Plasma Input Power

Two Modulation Speeds

Fast Modulations:

•Used to observe "Transient" behavior (behavior not related to fast particles slowing down)

•On the order of the beam particle slowing down time

- •Modulations: 30 ms
- •Slowing down: 30 ms
- •τE = 50 ms

•Should not significantly impact thermal ion population unless excess heating is present

Slow Modulations:

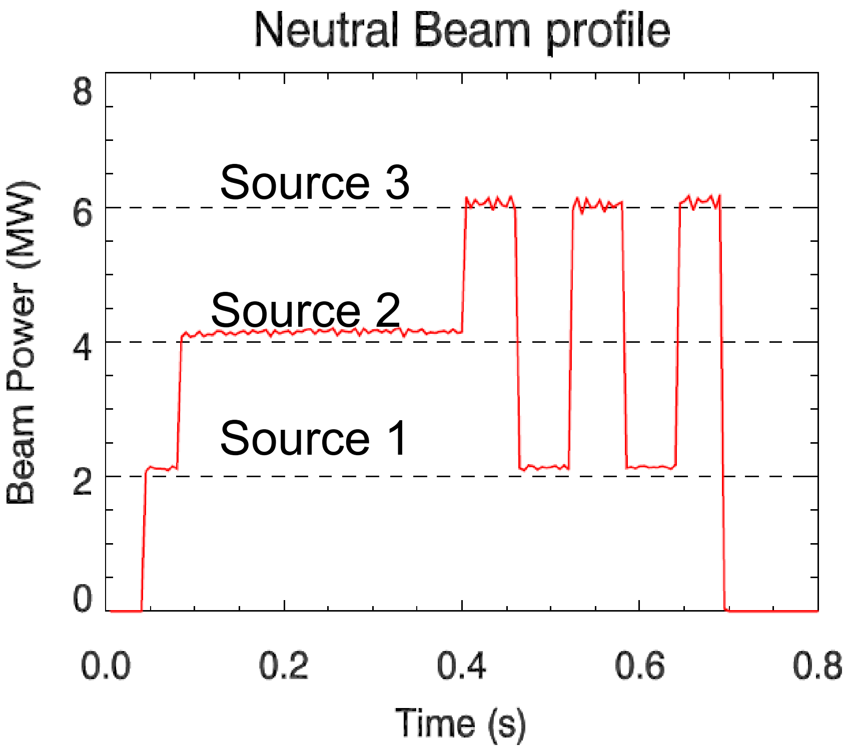
•Used to observe global behavior changes due to power loss

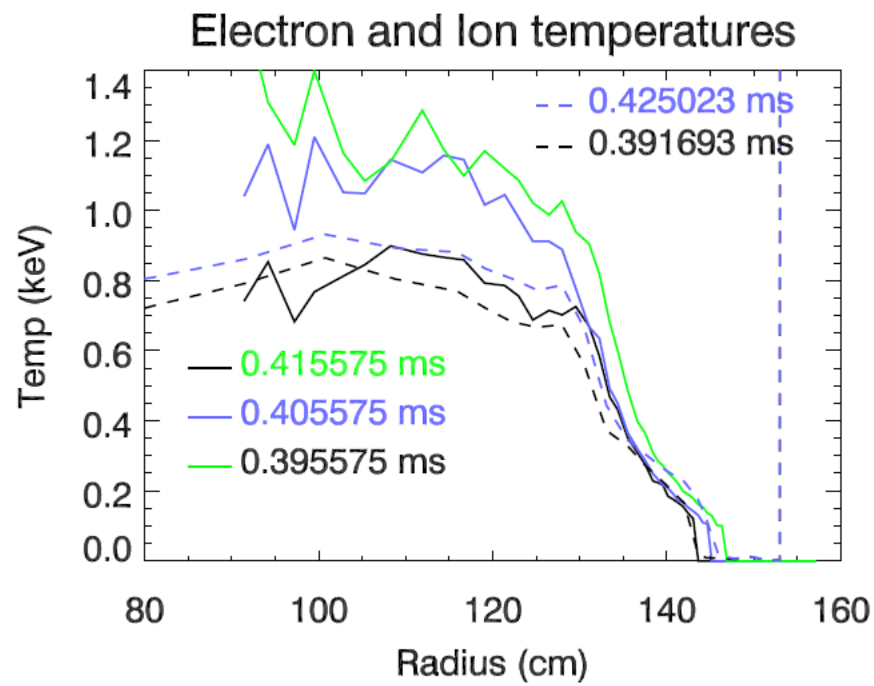
•On the order of the energy confinement time

- •Modulations: 60 ms
- •Slowing down: 30 ms
- •τ_E = 50 ms

•By the end of the modulation, the thermal population should show changes due to fast ion population

The Third Beam significantly heats the Ions, but does not heat the Electrons as much



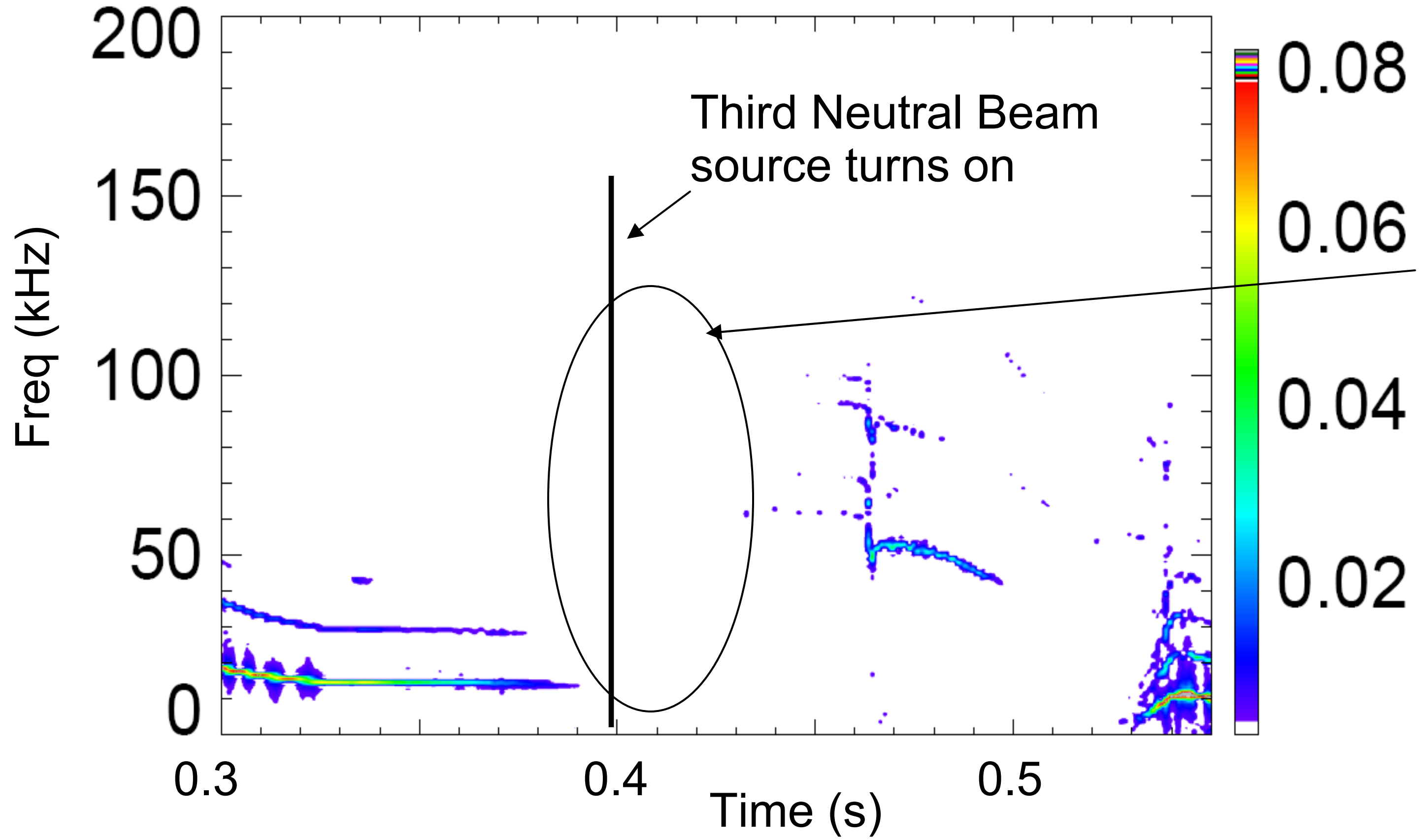


The Neutral Beam profile. The Third beam turns on at 400 ms. This coincides with the MHD free period.

Electron (dashed) and ion (solid) temperatures. The ion temperature rises quickly after the beam turn on at 400 ms. The electron temperature rises only slightly.

A Quiescent Low Frequency MHD Period Was Necessary to Study Power Balance

Low frequency MHD is associated redistributions of beam ions. In order to accurately measure the fast ion distribution, The modulation was performed in a quiescent low frequency MHD period.



The modulations were timed to coincide with the MHD free window

Power Balance Equations

The power balance equation can be written as

$$P_{nb} = Q_{nc} + Q_{ie} + \dot{W} + P_{MHD}(+other\,losses)$$

P_{nb} - Power Deposited from neutral beams

Q_{nc} - Neoclassical Heat transport

Q_{ie} - Heat transfer from Ions to electrons

$\dot{W}$ - Thermal heating of the ions

P_{MHD} - MHD induced power loss

MHD loss and other losses are frequently difficult to quantify. However, the remaining terms can be determined from measurements and theory. NSTX has measurements of temperature profile, the current profile, density profiles and magnetic fields. In terms of what is known,

$$P_{nb} > Q_{nc} + Q_{ie} + \dot{W}$$

Power Balance Continued

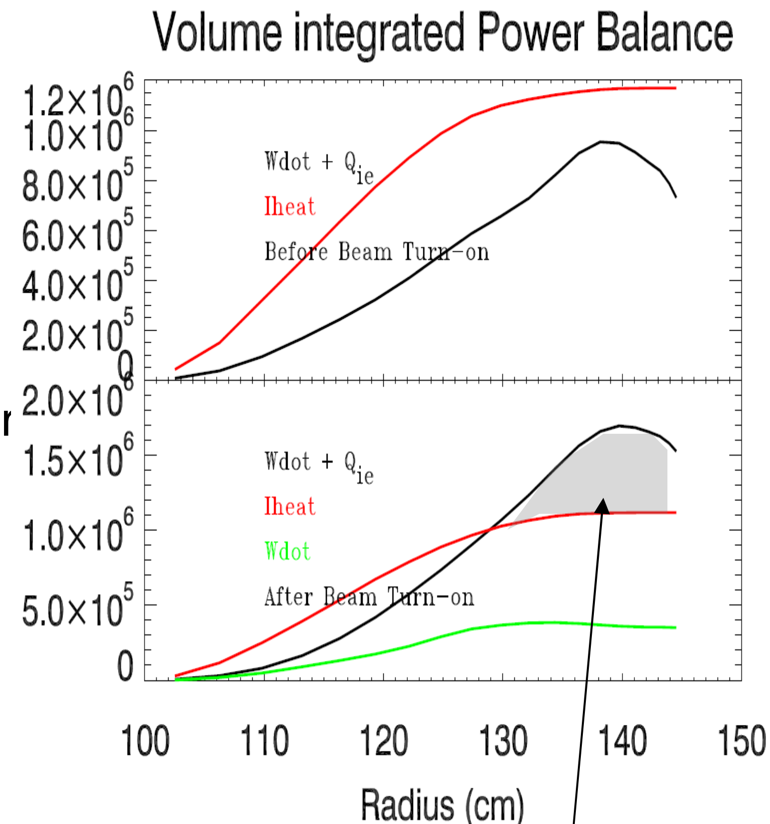
If there is a source of excess heating, then the power balance equation becomes

$$P_{nb} + P_{excess} = Q_{nc} + Q_{ie} + \dot{W}$$

To determine the excess heating of the plasma, we subtract the neutral beam power from the other terms.

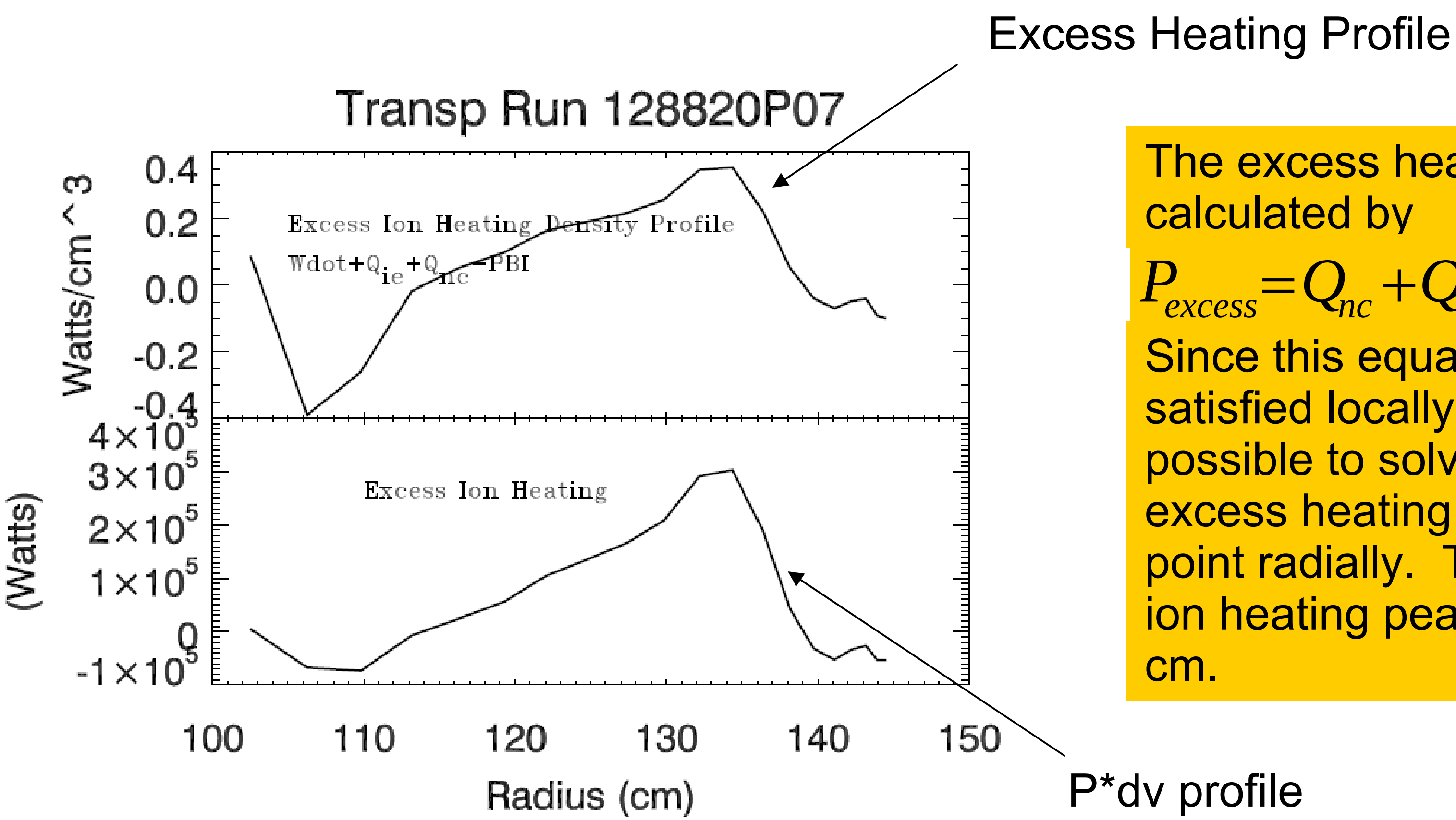
$$P_{excess} = Q_{nc} + Q_{ie} + \dot{W} - P_{nb}$$

This determines a lower bound on the excess heating. If other loss mechanisms are included, the excess heating will increase.



Before the 3rd beam turns on, the heating power is above the loss. After the 3rd beam turns on, the loss dominates the heating, implying an excess heating mechanism

Excess Heating required peaks around 130 cm

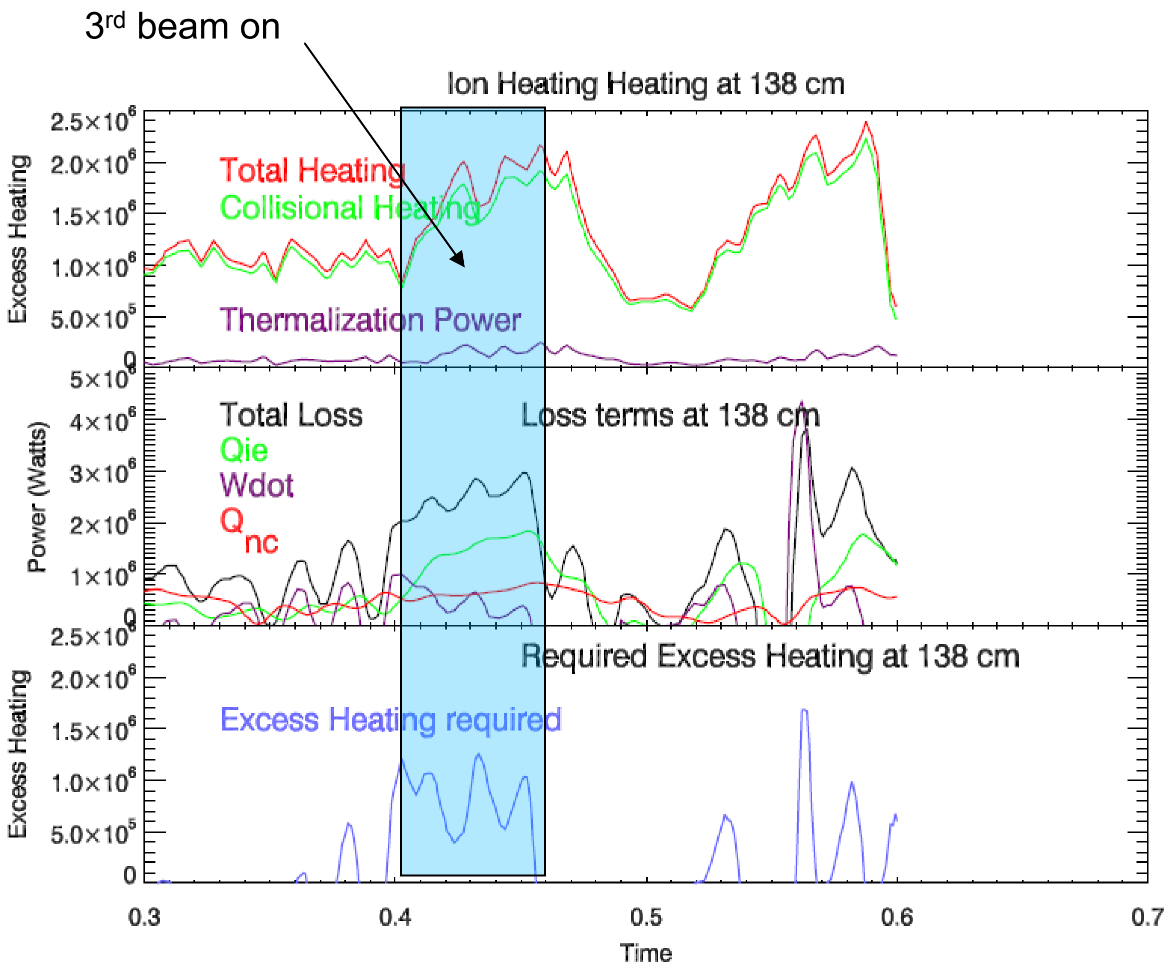


The excess heating is calculated by

$$P_{excess} = Q_{nc} + Q_{ie} + \dot{W} - P_{nb}$$

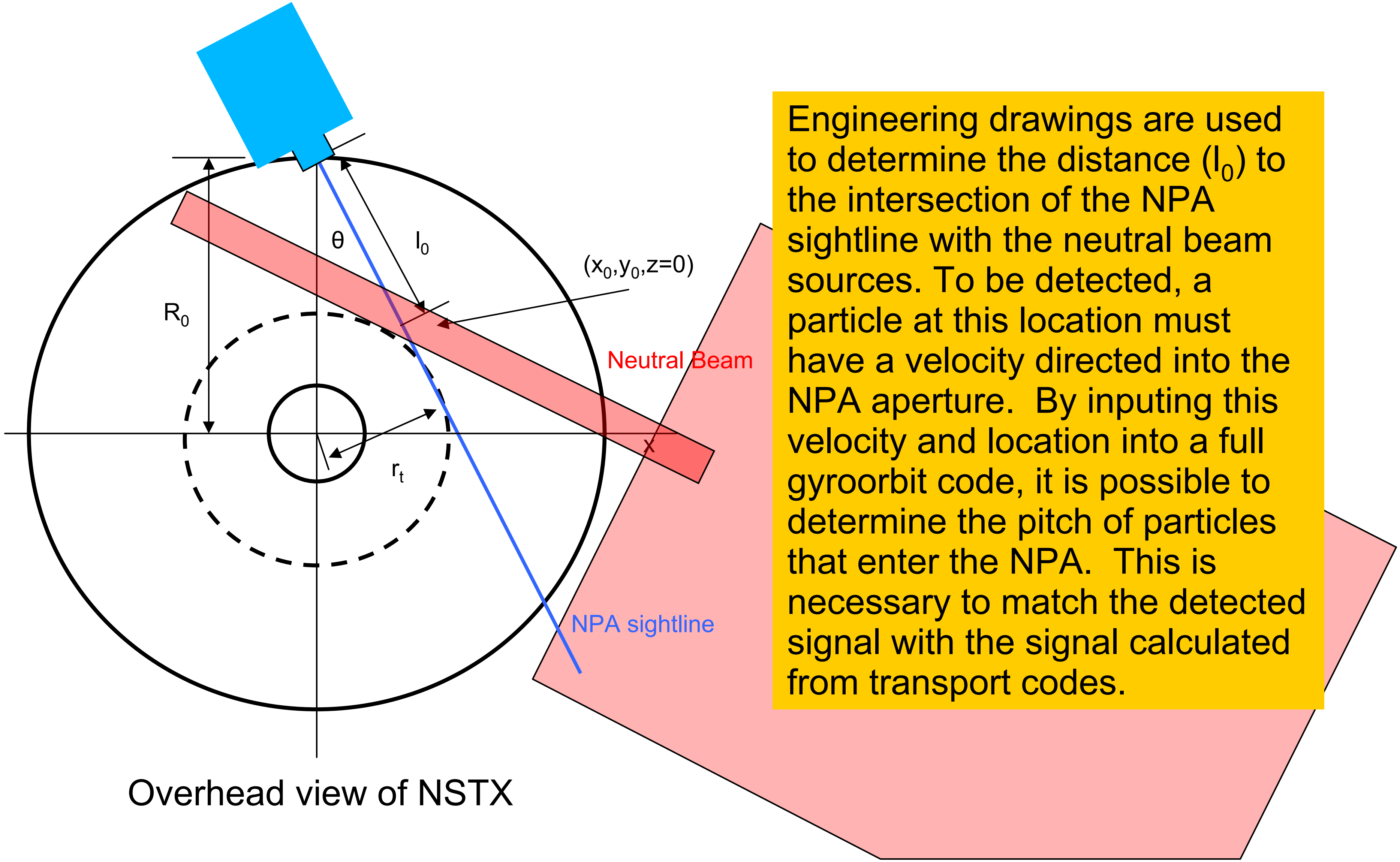
Since this equation is satisfied locally it is possible to solve for the excess heating at each point radially. The total ion heating peaks at 134 cm.

Longer Modulations show similar heating behavior



Longer modulations show a saturation in the excess heating required. This verifies that the modulations are not a result of computational error, but actually demonstrate an additional heating mechanism

NPA Only Sees Beam Particles

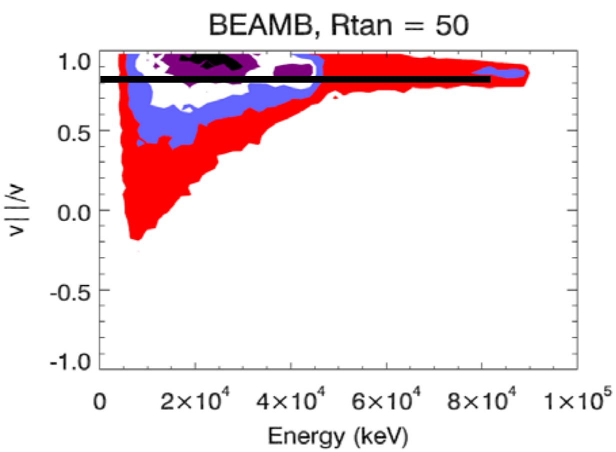


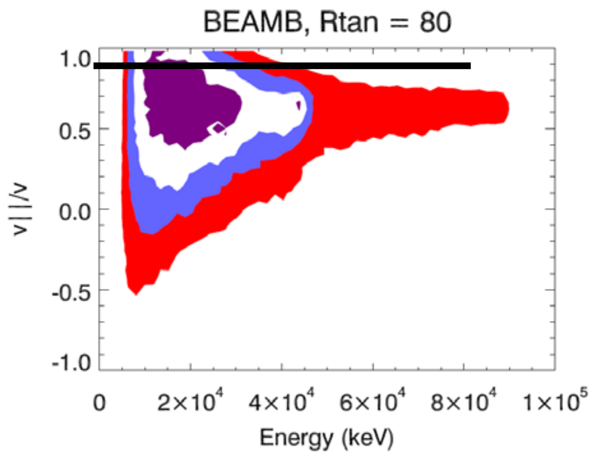
Overhead view of NSTX

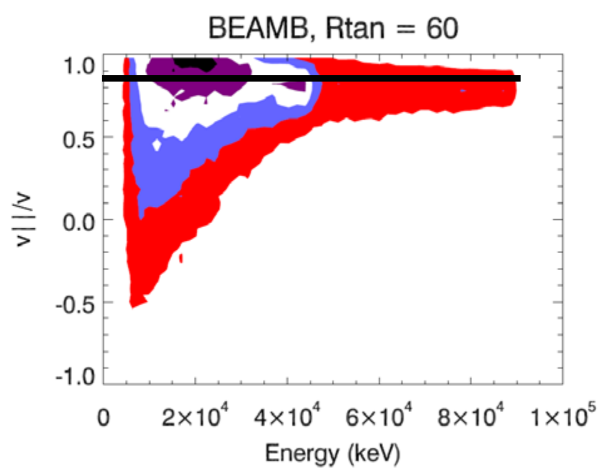
Engineering drawings are used to determine the distance (l_0) to the intersection of the NPA sightline with the neutral beam sources. To be detected, a particle at this location must have a velocity directed into the NPA aperture. By inputing this velocity and location into a full gyroorbit code, it is possible to determine the pitch of particles that enter the NPA. This is necessary to match the detected signal with the signal calculated from transport codes.

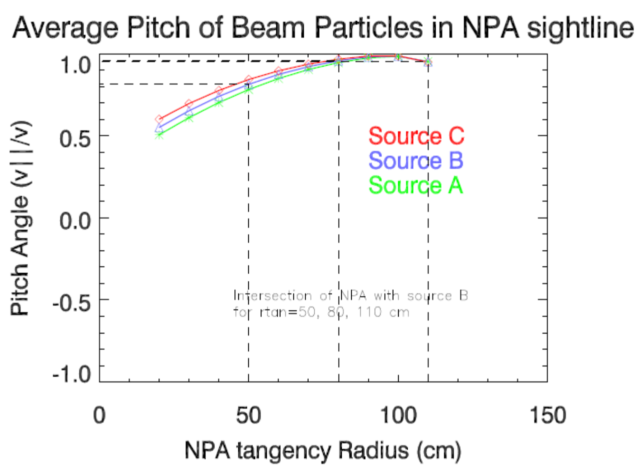
FLR Correction to TRANSP NPA Distribution Function Correction Required to Correctly Predict Optimum NPA Sightline

Plots of the Fast Ion Distribution Function $f(x_{gc}, v_{||}/v, E)$





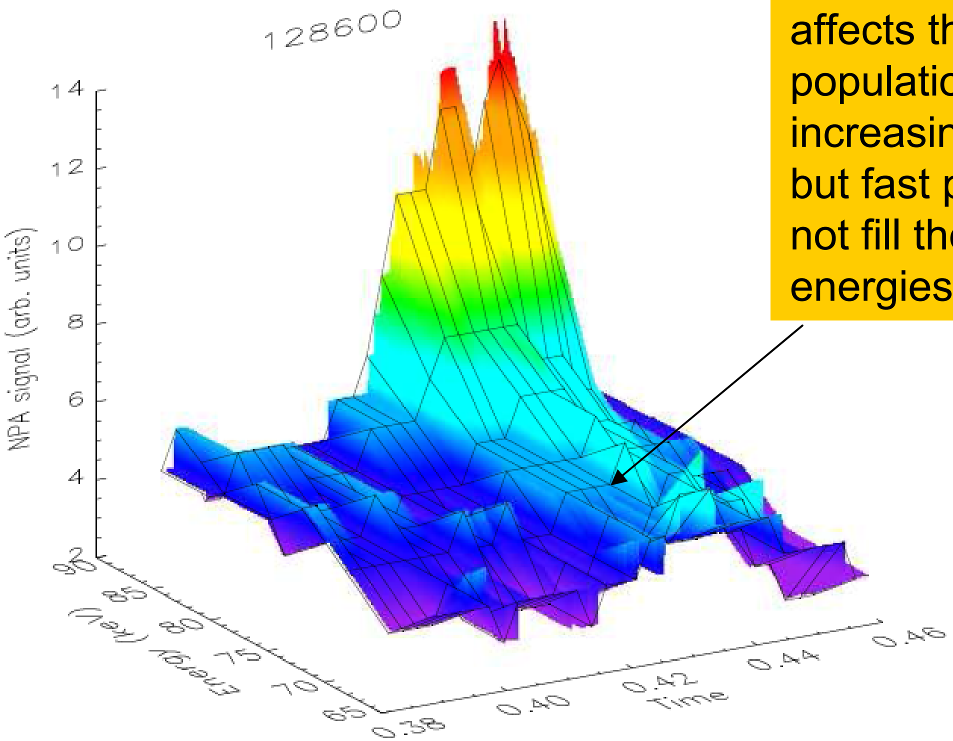




When the TRANSP calculations are modified for finite Larmour radius corrections, it is shown that the NPA does not always see the peak of the distribution function of fast ions.

Measured NPA signal Does Not Show Expected Slowing Down Spectrum

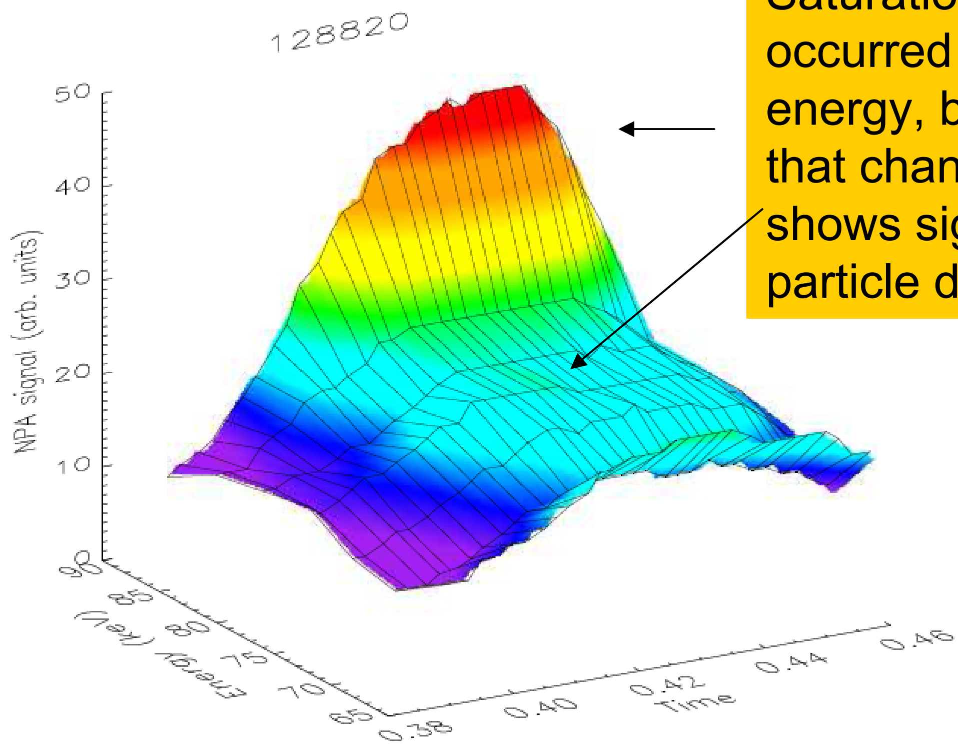
The beam turn-on and turn-off are visible at the full energy, but the data does not show the classical slowing-down spectrum that is expected. This was true at a variety of tangency radii.



Beam turn on affects the neutral population, increasing all signal, but fast particles do not fill the lower energies

Even Long Modulations Showed No Slowing Down Spectrum

Even when the modulation lasted significantly longer than the slowing-down time, no evidence of slowing-down is seen in the NPA spectrum.

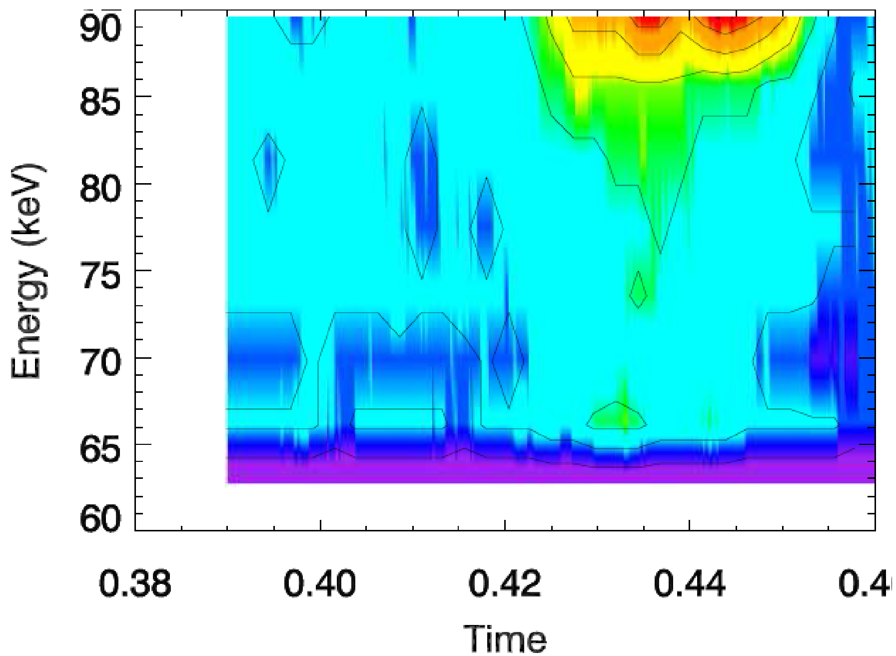


Saturation has occurred at full energy, but ONLY that channel shows significant particle density.

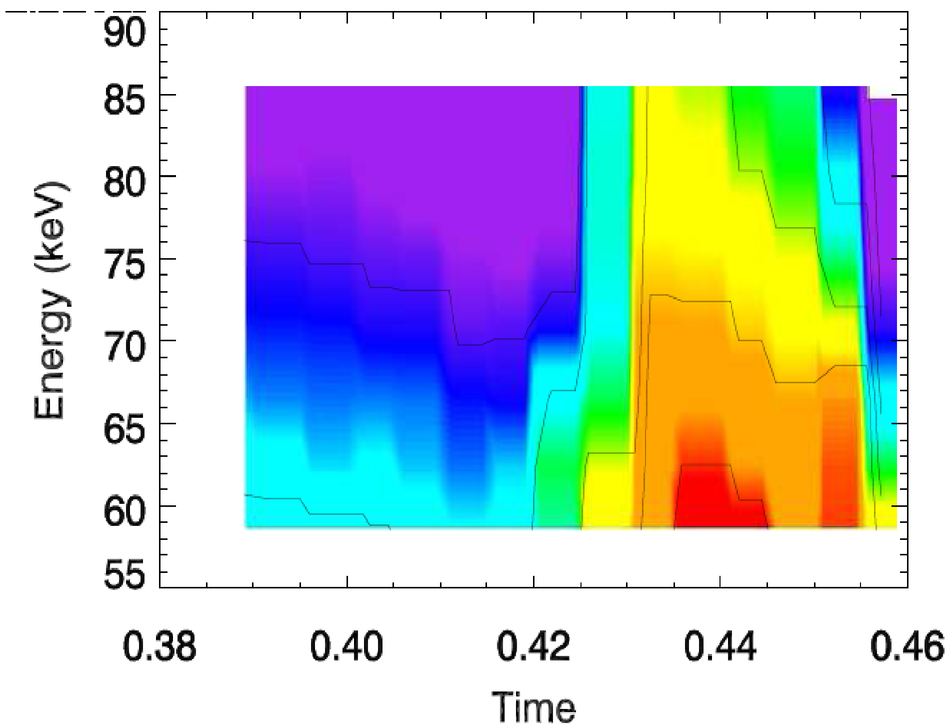
Where did the fast ions go?

TRANSP Simulation Shows Expected Slowing Down Spectrum

NPA Spectrum of shot 128600

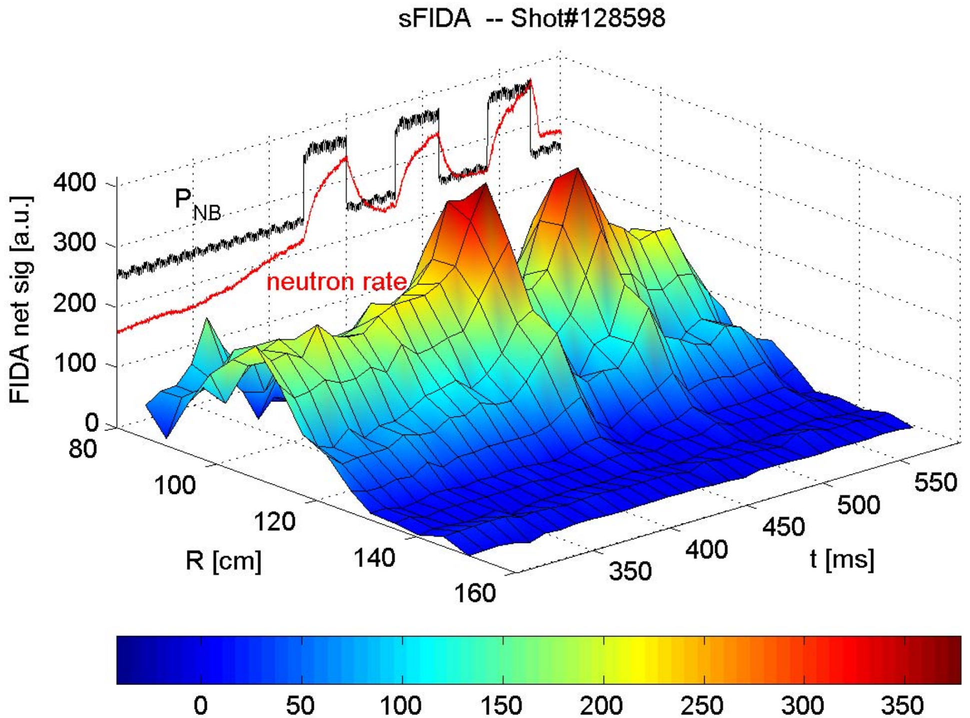


TRANSP Simulation of NPA Spectrum



TRANSP simulations show the expected slowing down spectrum. The beam turn-on is clearly visible, and the lower energies fill up with 30 ms of the beam turn on. This fits well with classical slowing-down theory.

FIDA Data Does Not Indicate Redistribution



(Profile for longer modulations look similar)

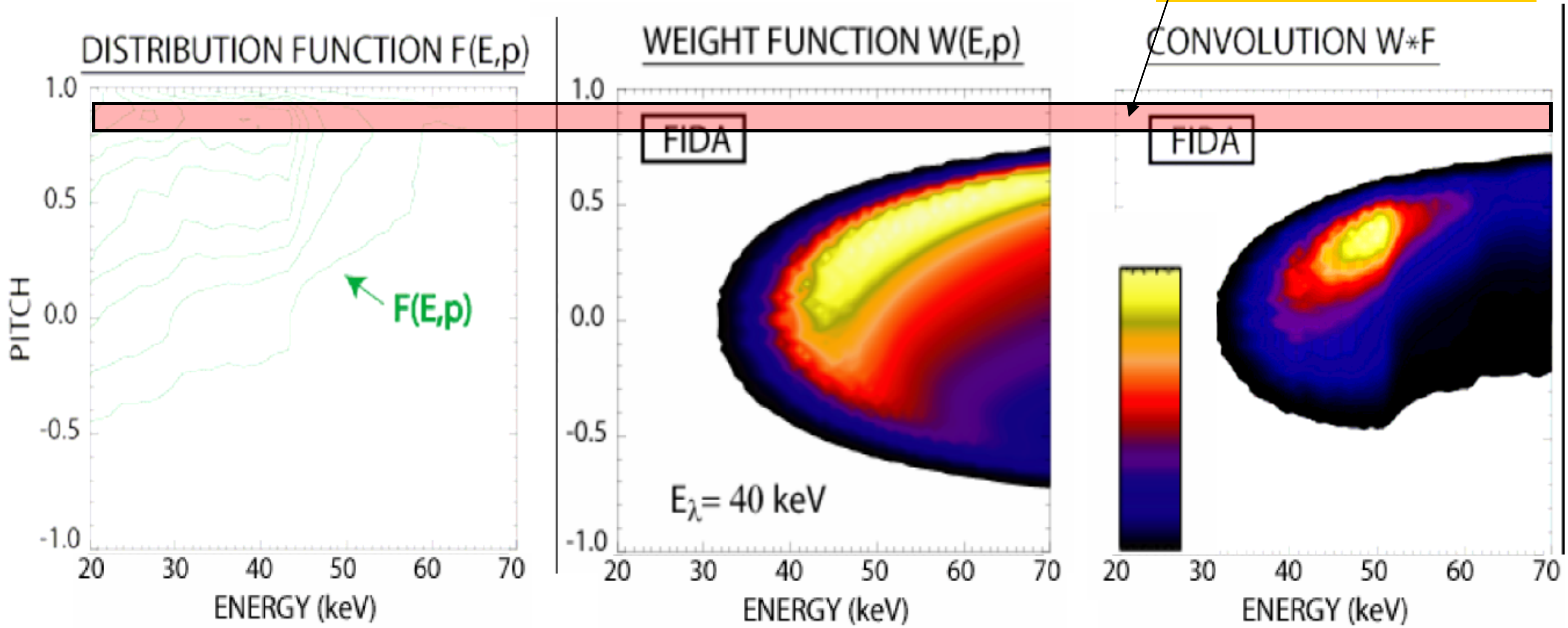
FIDA profile data shows a peaked density function in the core of the plasma. Since the FIDA averages over a wider pitch angle window (unlike the NPA), a redistribution would be visible on FIDA only if the particles still have an appropriate pitch angle.

Present FIDA System Heavily Weighted to Only Show Particles with a Pitch between -0.6 and 0.6.

Measured photons with E_λ=40keV result from fast ions with

$E \geq$ 40keV, pitch $\leq$ 0.5

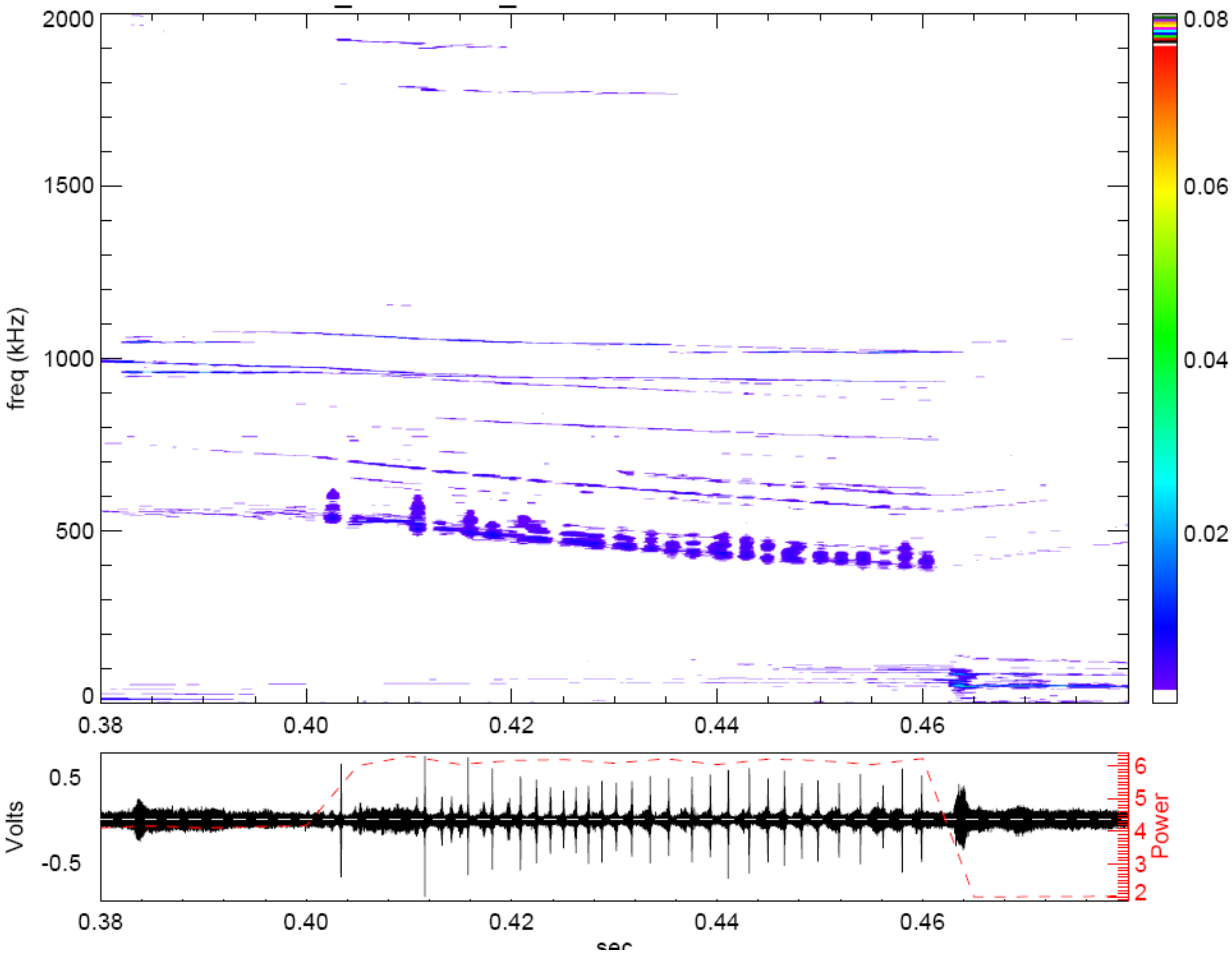
Beam particle pitch



The FIDA diagnostic does not see the peak of the fast ion distribution. If the fast ions are not being seen by FIDA, redistributions could occur without being detected. An upgrade to the FIDA system has been proposed which may rectify this problem. (Podesta, EP SFG 09/09/08.)

Bursting High Frequency MHD Appears with 3rd Source

High Frequency MHD shows Bursting Modes



When the 3rd source turns on, some mid frequency MHD 'bursting' activity occurs. It is not clear what causes the bursting modes, though they may be related to the fast ion population.

The Theory of CAE Modes Predicts Eigenfunctions

By solving the eigenmode equation for Compressional Alfven Eigenmodes (CAE), it is possible to obtain a formula relating the magnetic field to density fluctuations. We can then use the line integrated high-K signal can be used as an interferometer. By calculating the line integral, we can obtain an estimate for the size of the MHD fluctuations.

$$E_\theta = E_0 \phi_m \left(\frac{\sqrt{2}\theta}{\Theta} \right) \phi_s \left(\frac{\sqrt{2}(r - r_0)}{\Delta} \right) e^{i(n\phi - \omega t)}$$

$$E_r = \frac{i\omega_c}{\omega} E_\theta$$

$$\phi_s(x) = \frac{e^{\frac{-x^2}{2}} H_s(x)}{\sqrt{s! 2^s \sqrt{\pi}}}$$

$$\Delta^2 = a^2 \frac{\sqrt{2\sigma_i / (1 + \sigma_i)}}{m(1 + \sigma_i)(1 + \varepsilon_0)}$$

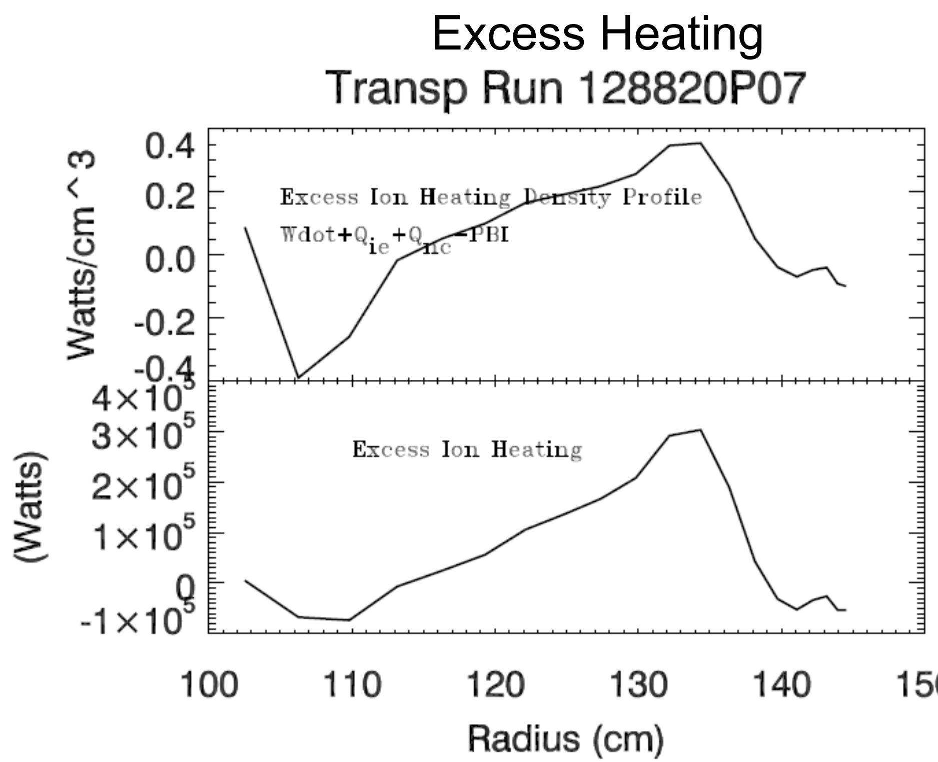
See Gorelenkov, Cheng, Fredrickson, *Phys. Plasmas*, **9**, 3483 (2002).

Using ideal MHD, it is possible to solve the continuity equation and connect the density perturbations to magnetic perturbations. Assuming w<<w$_c$, we get

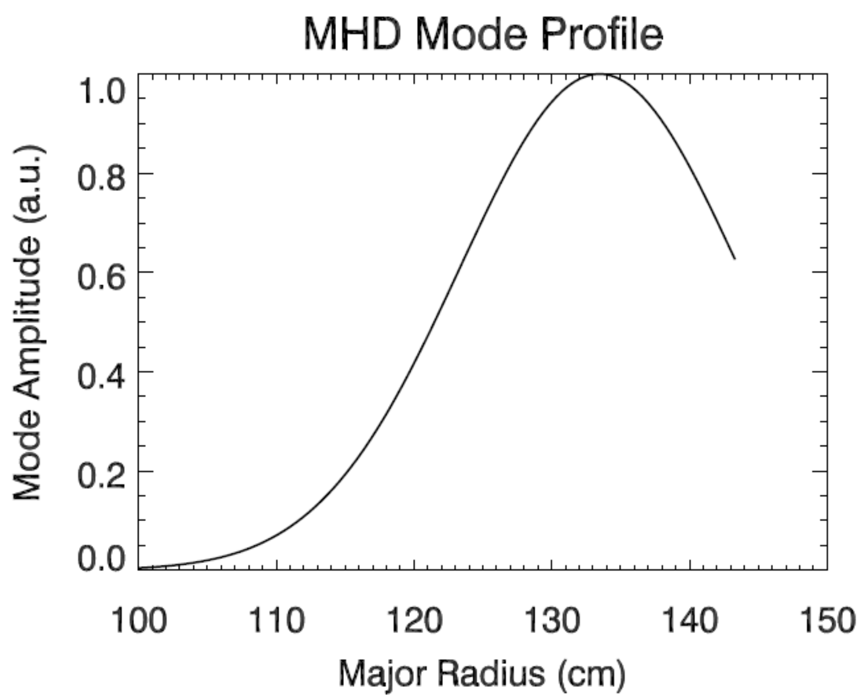
$$\frac{\tilde{n}}{n} = -\frac{\tilde{B}_{\parallel}}{B}$$

(Gorelenkov, unpublished.)

Excess Heating Peaks Near where Alfvén Modes Peak



Excess heating as calculated by Transp. (Top is heating density, bottom is total heating)



High frequency Alfvén modes (radial mode = 0)

The required excess heating peaks around 134 cm, which is near the peak amplitude of the high frequency Alfvén modes.

CAE modes can Stochastically Heat Thermal Particles

These plots were computed in a slab geometry

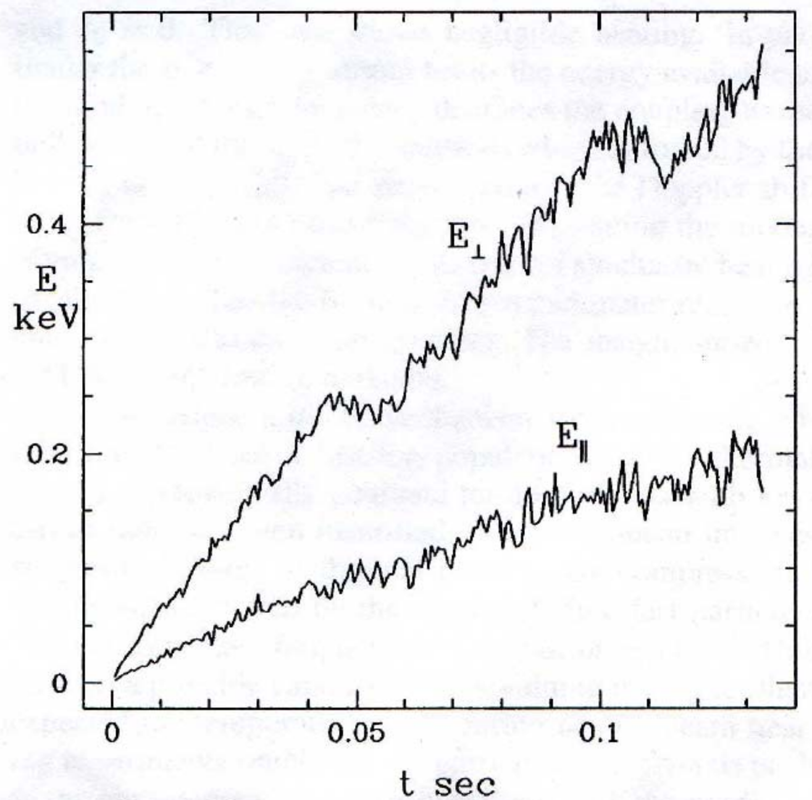


FIG. 1. Ion energy in keV vs time, for $\delta B_y/B = 6.0 \times 10^{-4}$.

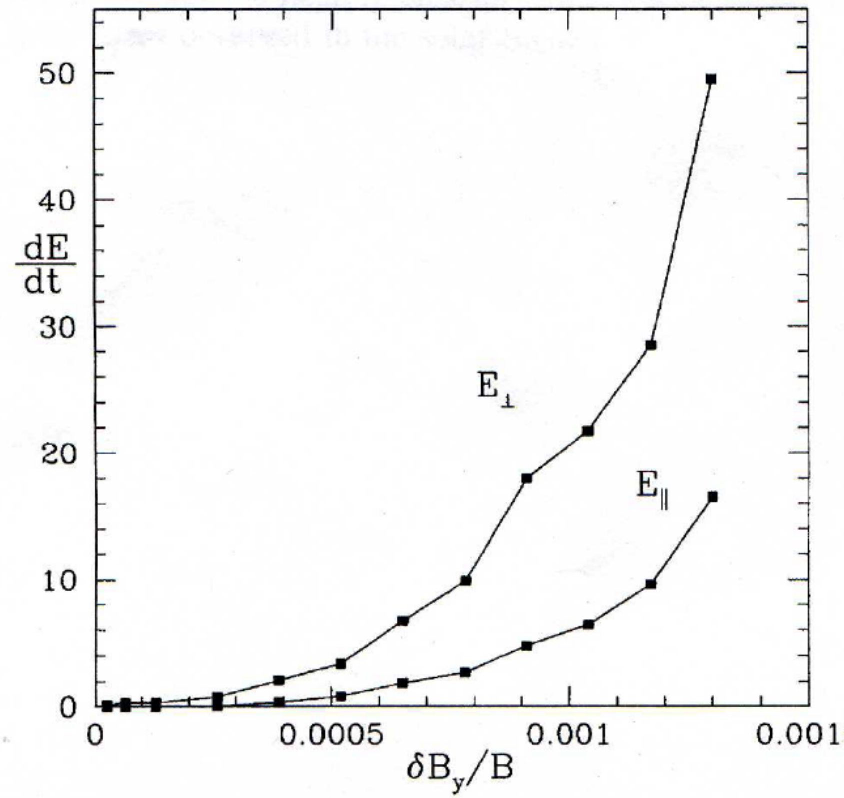
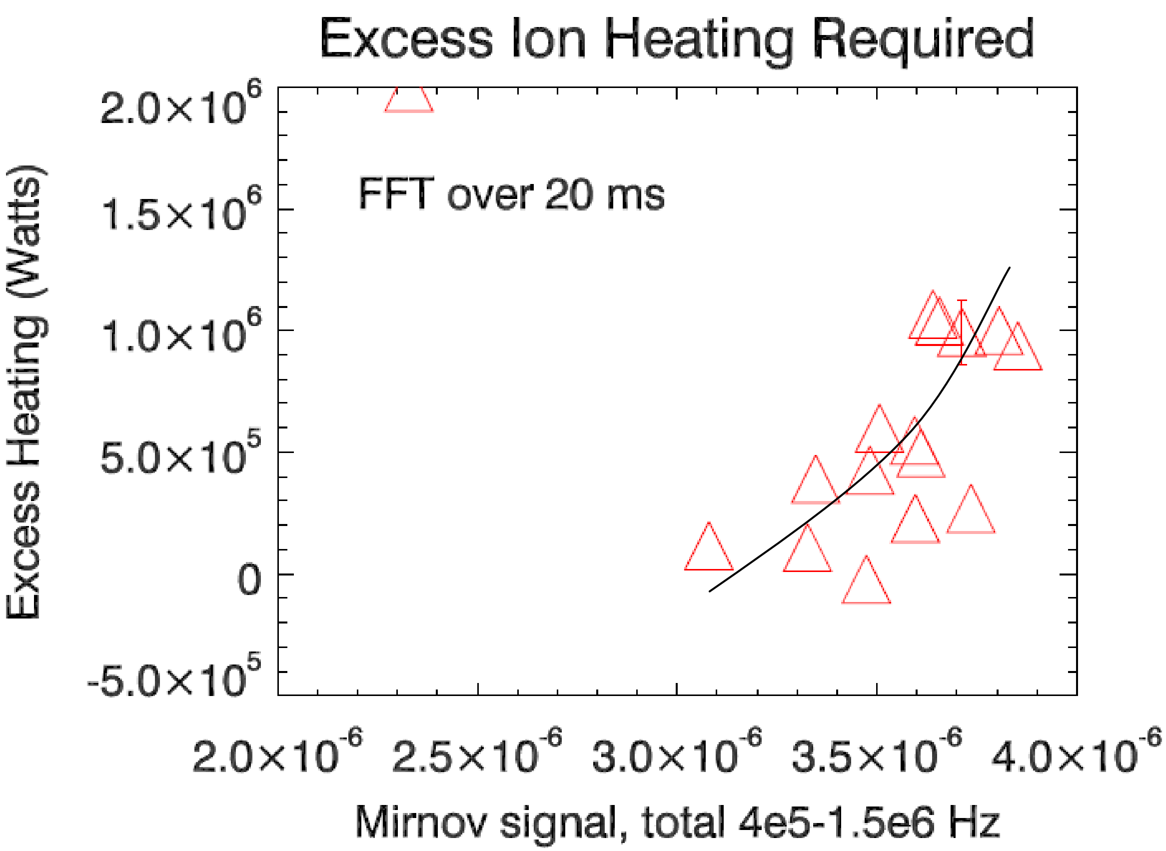


FIG. 2. Heating rate (keV/s) vs $\delta B_y/B$.

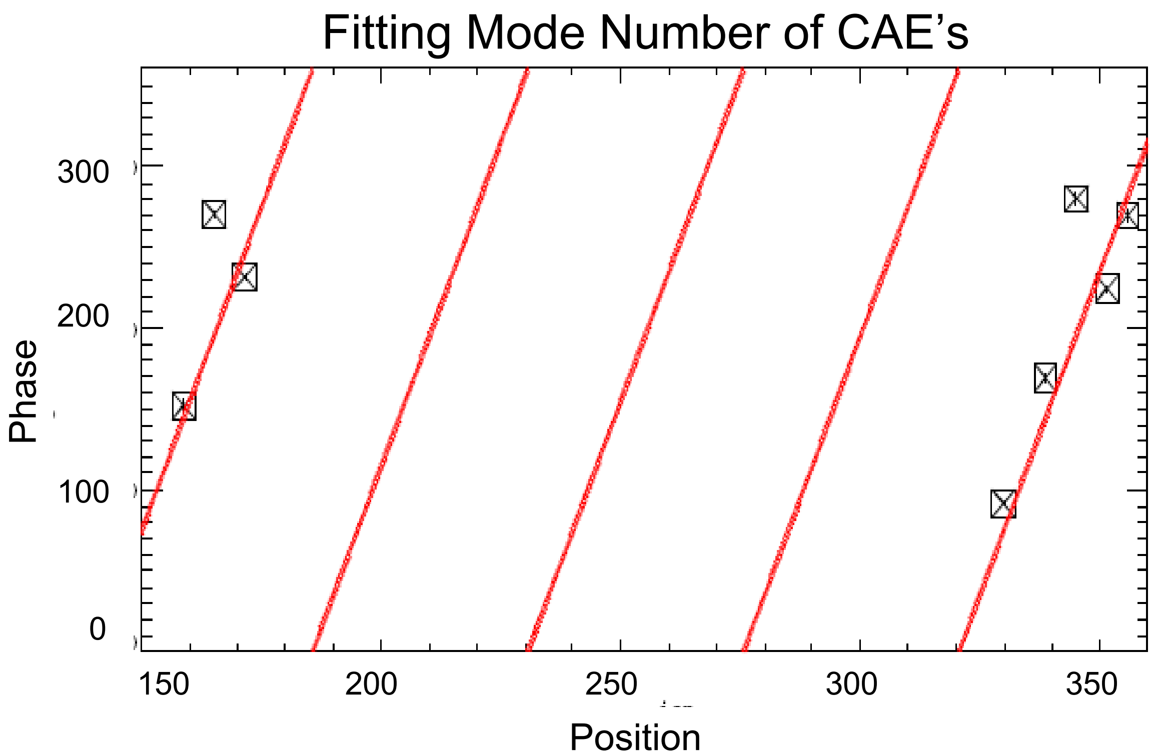
The MHD modes heat the thermal ions perpendicularly. In the absence of collisions, the perpendicular energy saturates. Increased δB leads to increased heating rates. (Gates, et al, Phys. Rev. Lett. **87**, 205003 (2001).

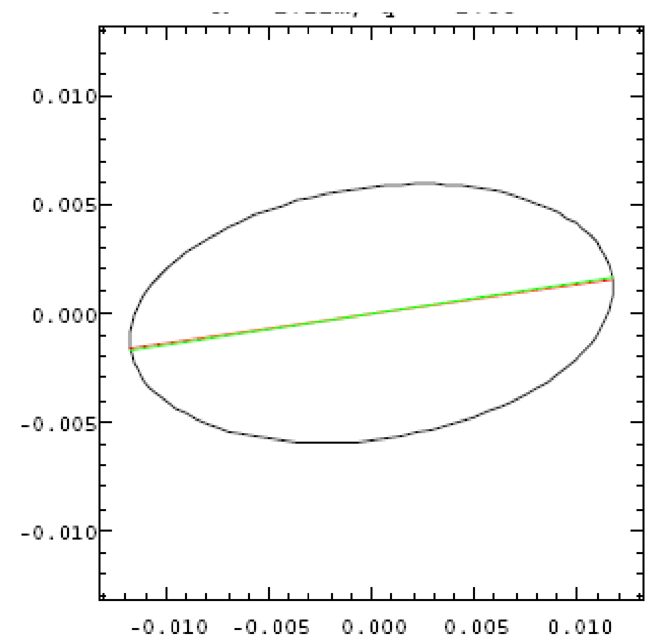
High Frequency MHD Amplitude Correlates with Observed Excess Heating



By taking the FFT of the Mirnov coil signals, it is possible to show a correlation between the amplitude of the MHD modes and the excess heating as calculated by TRANSP. The shape of the plot is similar to that computed in a slab geometry.

Toroidal Mode Numbers of CAE's Can Be Determined by Fitting the Phase of Mirnov Coils





High frequency modes normally have toroidal mode numbers in the range of 7-9. Each mode must be analyzed specifically to determine mode numbers.

By plotting the polarization, it is possible to determine the high frequency modes as CAE's

Integrated Density Perturbation ~1.6e13

$$\tilde{\phi} = k\int \tilde{N}\, dl$$

Where N is the index of refraction, and k is the wave number of the beam.

For an electromagnetic wave in a plasma,

$$N = \sqrt{1-\frac{\omega_p^2}{\omega^2}} \sim 1-\frac{1}{2}\frac{\omega_p^2}{\omega^2} = 1-\frac{1}{2}\frac{\omega_p^2\lambda^2}{(2\pi c)^2}$$

where ω_p is the plasma frequency, and ω is the frequency of the beam. This assumes $w_p \ll w$

$$N = 1-\frac{1}{2}\frac{4\pi e^2}{m(kc)^2}\langle n\rangle - \frac{1}{2}\frac{4\pi e^2}{m(kc)^2}\langle \tilde{n}\rangle$$

The first 2 terms relate to the phase shift of the unperturbed beam through the plasma. The perturbation is only related to the third term. Thus

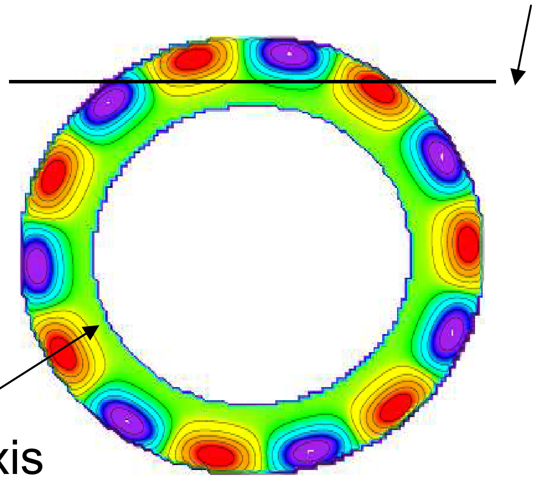
$$\tilde{\phi} = k\int \frac{1}{2}\frac{4\pi e^2}{m(kc)^2}\tilde{n}_e\, dl = 4.48x10^{-15}\int \tilde{n}_e\, dl \Rightarrow \int \tilde{n}_e\, dl = 1.56x10^{13}$$

$$\frac{\int \tilde{n}_e\, dl}{\int n_e\, dl} = \frac{1.56x10^{13}}{6.0x10^{15}} = 2.6x10^{-3}$$

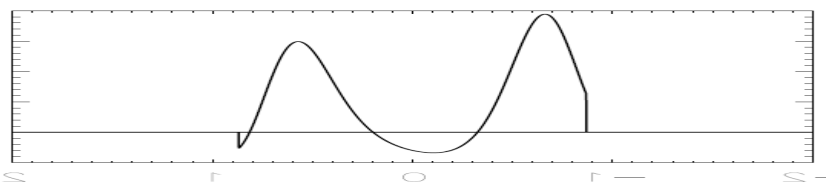
Mode Amplitude δn/n = 7.9e-3

Using the CAE mode profile above, a line integral was performed to determine the amplitude of the CAE. The mode is assumed to vary toroidally as cos(nθ).

High k line of sight



Magnetic axis



Mode amplitude along sightline

Integrating an MHD mode with amplitude “A”, and n=8 gives

$$\int \tilde{n}_{norm}\, dl = 0.33A$$

To calculate the amplitude of the MHD mode in the plasma, we divide the integrated density by this integration factor

$$\frac{\int \tilde{n}_{measured}}{\int \tilde{n}_{calculated}} = \frac{0.0026}{0.33} = \frac{\tilde{B}_{\parallel}}{B} = 0.0079$$

This gives

$$\frac{\tilde{B}_{\parallel}}{B} = \frac{\tilde{n}_e}{n_e} = 0.0079$$

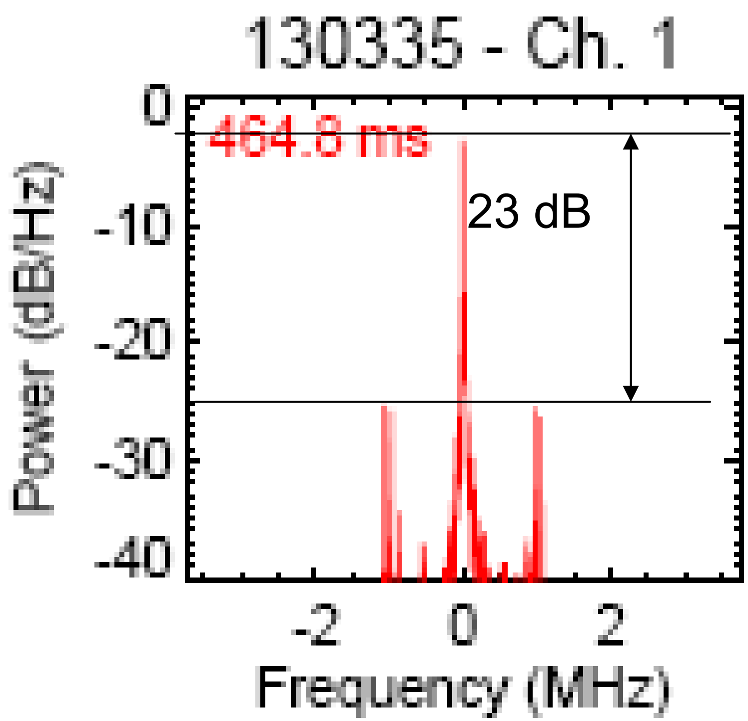
Conclusions

- Beam modulations were successfully used to investigate Power Balance in NSTX.
- The modulations excite high frequency MHD modes.
- The profile of the CAE eigenfunctions matches the profile of the excess heating.
- The excess heating follows the beam modulations and does not appear to be a transient artifact.
- The NPA shows an absence of particles below the full energy. Improvements may need to be made to get a complete picture of the fast ion distribution.
- The upgraded FIDA diagnostic will hopefully be able to observe a redistribution of the main beam ions.
- The High-K data has been used to connect the MHD mode amplitudes to the observed density perturbations.

Future Work

- Complete Error analysis of Heating vs. MHD mode amplitude. This involves funning the TRANSP code adjusting the temperature profiles to the error limits.
- Run full gyroorbit simulations using the mode MHD mode amplitudes to see if the stochastic heating rate matches the calculated excess heating rate of the observed spectra.
- Change the view of the NPA by viewing off axis to observe the full fast ion distribution function.
- Write Thesis.

Line Integrated Phase Shift = 7.07e-2



The signal amplitude goes as

$$
\begin{aligned}
e^{i\phi} &= e^{i(\phi_0+\tilde{\phi})} \\
&= e^{i(\phi)}e^{i(\tilde{\phi})} \\
&= Ae^{i(\tilde{\phi})} \\
&\approx \underbrace{A}_{\text{Unshifted}}(1+i\underbrace{\tilde{\phi}}_{\text{Shifted}})
\end{aligned}
$$

The phase shift is then the ratio of the shifted to unshifted amplitudes. To avoid phase problems, we use power and take the square root.

$$\tilde{\phi}^2 = -23dB = 5e-3$$

$$\boxed{\tilde{\phi} = 7.07e-2}$$