Investigation of Power Balance and Excess Ion Heating in the National Spherical Torus Experiment

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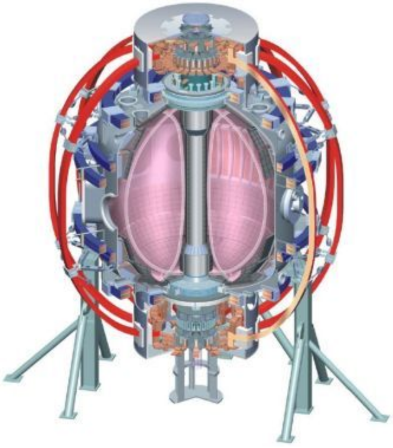

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Abstract

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. Grad-Shafranov reconstructions of the plasma were performed using magnetic, temperature, and MSE measurements as constraints. The input power to the ions was studied using the TRANSP code, which performs time dependent transport calculations. Analysis of TRANSP calculations shows additional heating in the plasma. This excess heating is strongest in the presence of high frequency CAE modes. Full orbit calculations of thermal particles show that the presence of these high frequency modes may be responsible for the excess heating. NPA measurements show almost no fast ions for some discharges but a very strong signal for other discharges, which may indicate a fundamental limitation in the NPA diagnostics. Other power loss terms, such as ripple loss and edge charge exchange show almost no effect on the overall power balance. This work was supported by DoE contract No. DE-AC02-76CH03073

Outline

- Power Balance Overview
- Excess Heating in NSTX
  - Review of heating theory
  - Excess heating observed in NSTX
  - MHD modes might explain the excess heating
  - NPA diagnostic may not show needed information
- Other Power Loss Mechanisms
  - Charge Exchange
  - Ripple Loss
  - Other Loss Mechanisms
- Implications/ suggestions for further study

Power Balance Overview

In its simplest for, power balance can be written as

$$P_{in} = P_{out}$$

where P_{in} is the heat the we apply to the plasma, and P_{out} is everywhere that the heat can go. If we assume that neutral beam heating is the only source of ion heating, we get:

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

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_{loss} -Other loss terms, such as MHD induced power loss, charge exchange, etc.

Power Balance Continued

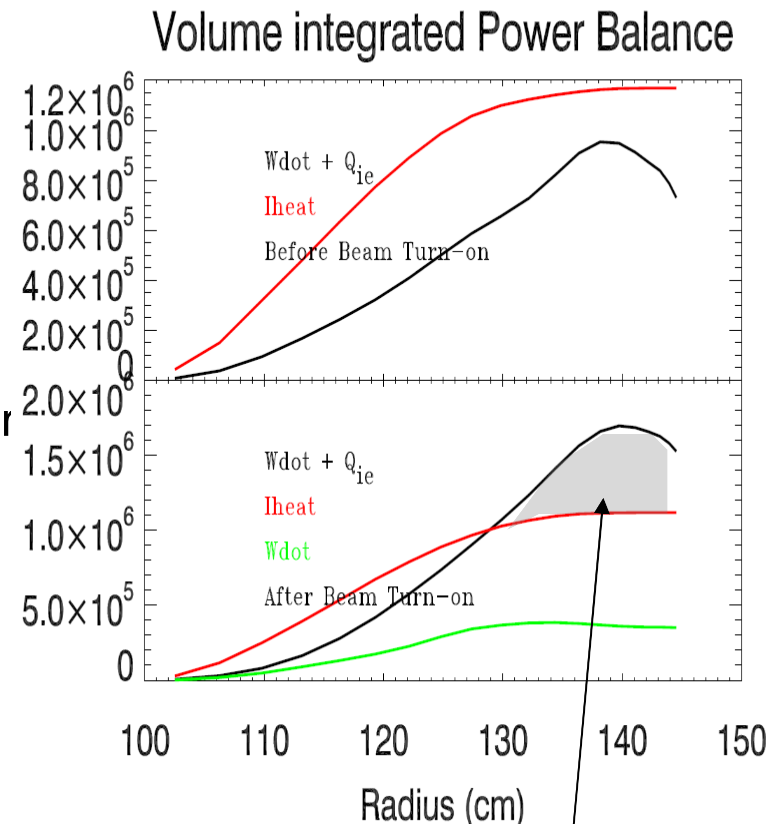
If there is a source of excess heating, then the power balance equation becomes

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

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

Beam Modulation Was Used to Modify Plasma Input Power

Two Modulation Speeds

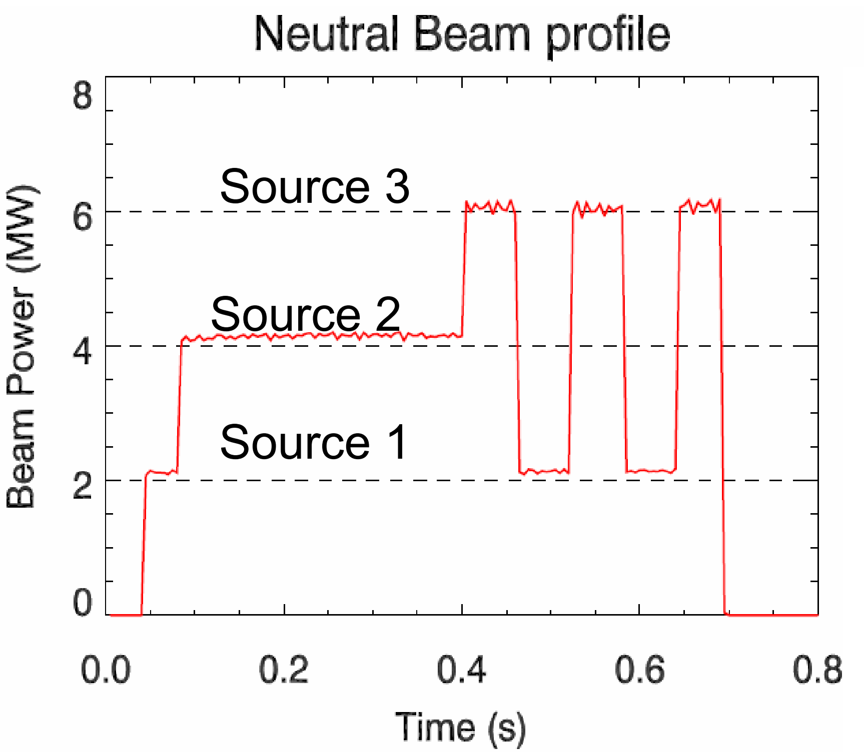
Fast Modulations:

- 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

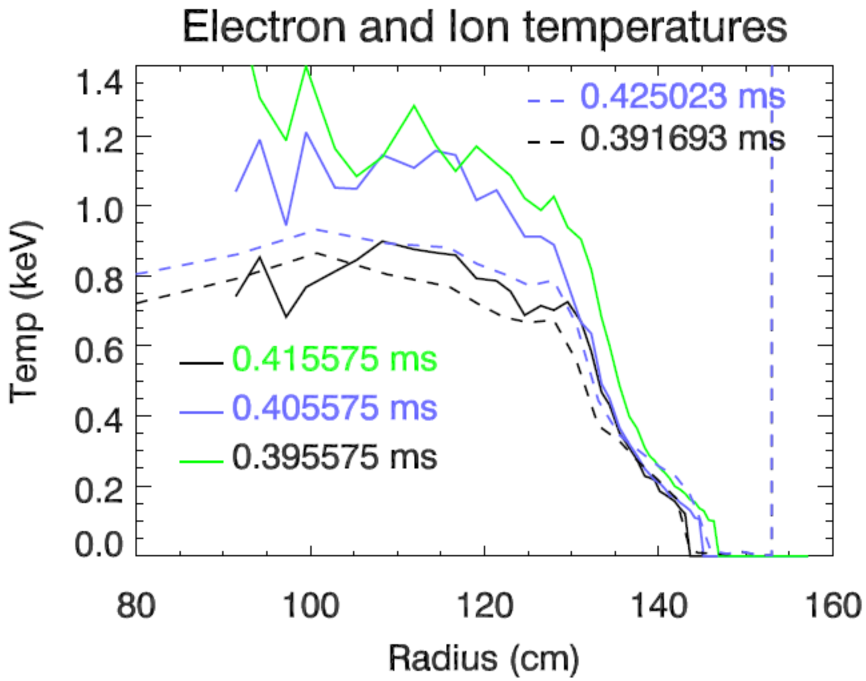
Slow Modulations:

- 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



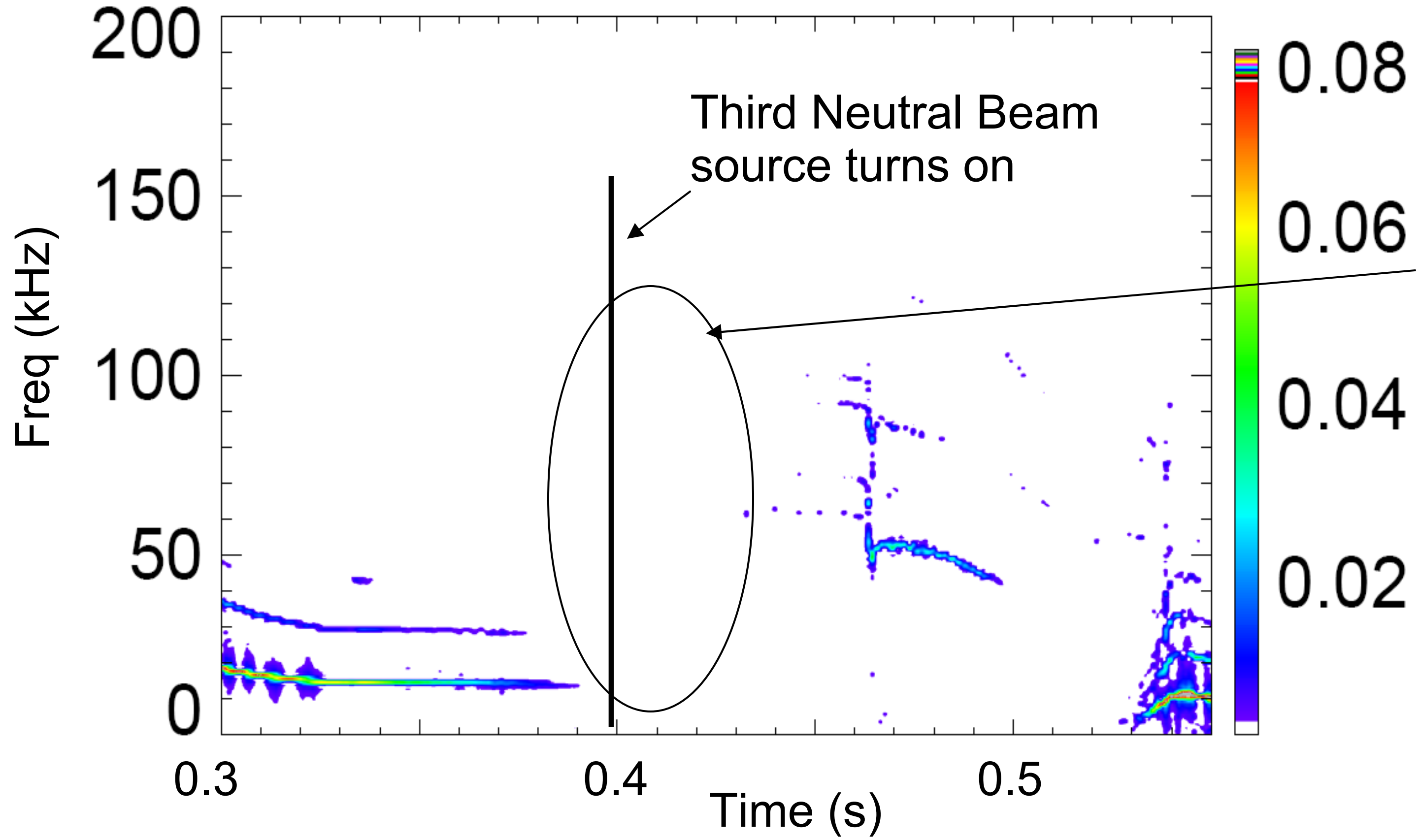
The Neutral Beam profile. The Third beam turns on at 400 ms. This coincides with the MHD free period.



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.

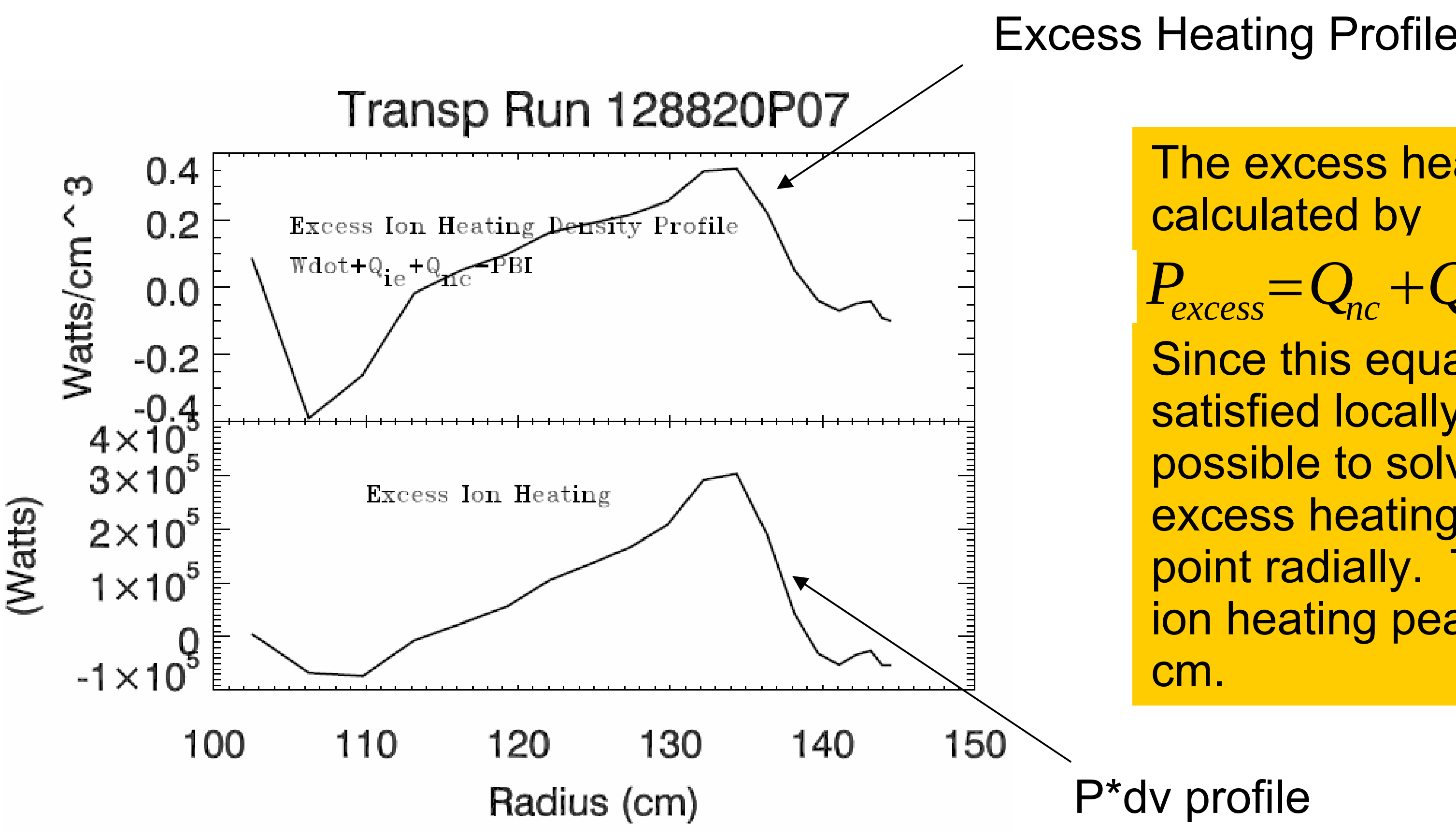
A Quiescent Low Frequency MHD Period Was Necessary to Study Power Balance

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

Excess Heating required peaks around 130 cm



The excess heating is calculated by

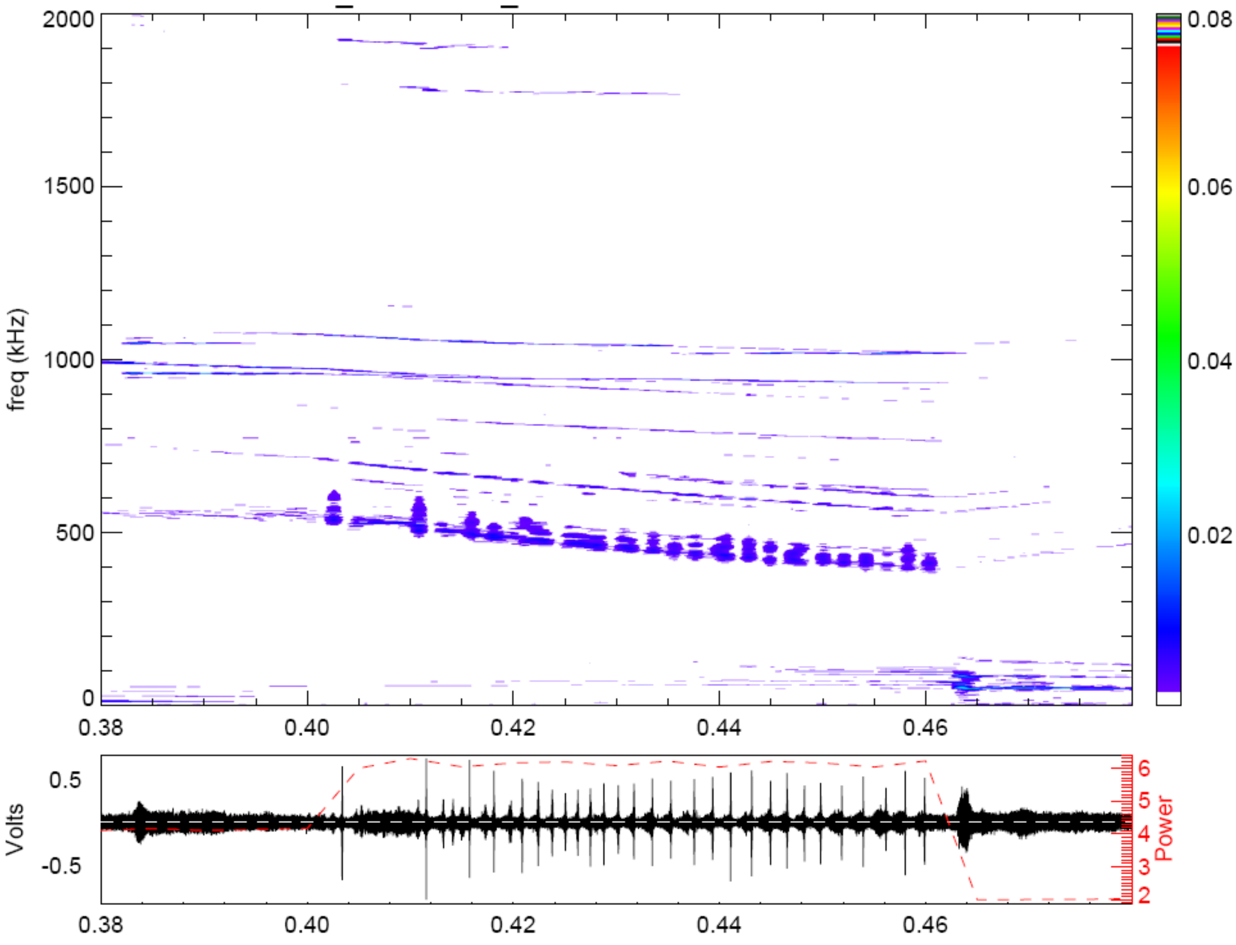
$$P_{excess} = Q_{nc} + Q_{ie} + \dot{W} - P_{nb}$$

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.

Note: Not all discharges require excess heating to satisfy the power balance equation

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. The modes are driven by fast ions, but it is not clear why these modes are bursting.

The Theory of CAE Modes Predicts Eigenfunctions

These MHD modes have been identified as Compressional Alfven Eigenmodes. (Gorilenkov et al, Nuclear Fusion **42** 977 (2002)) By solving the eigenmode equation for CAE's, 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.

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

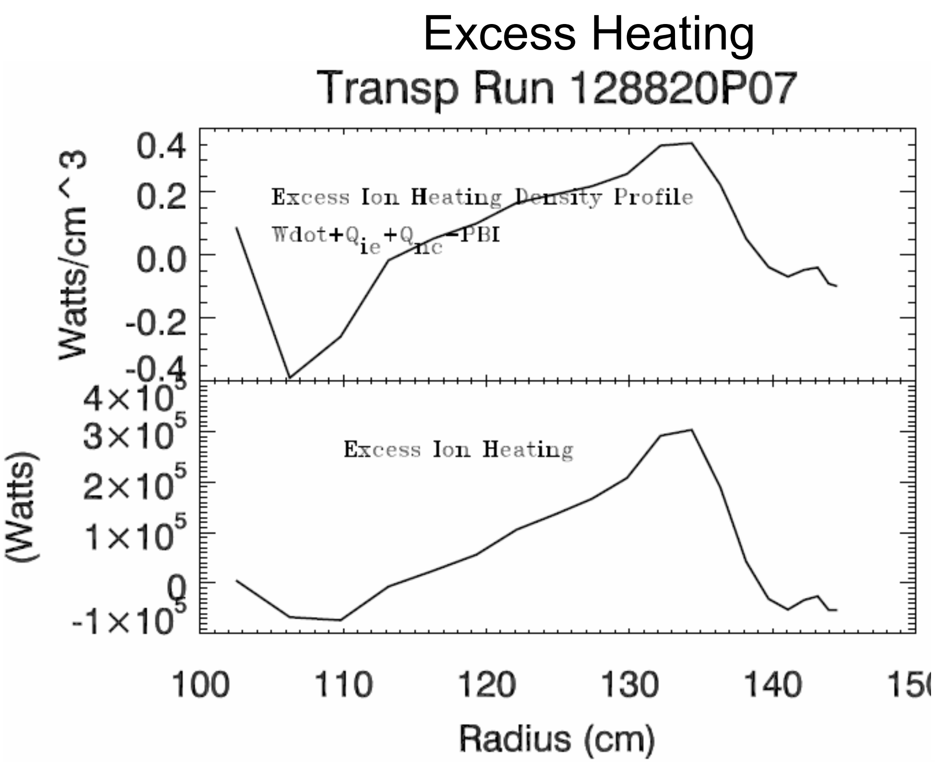
$$E_r = \frac{i\omega_c}{\omega} E_\theta$$

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

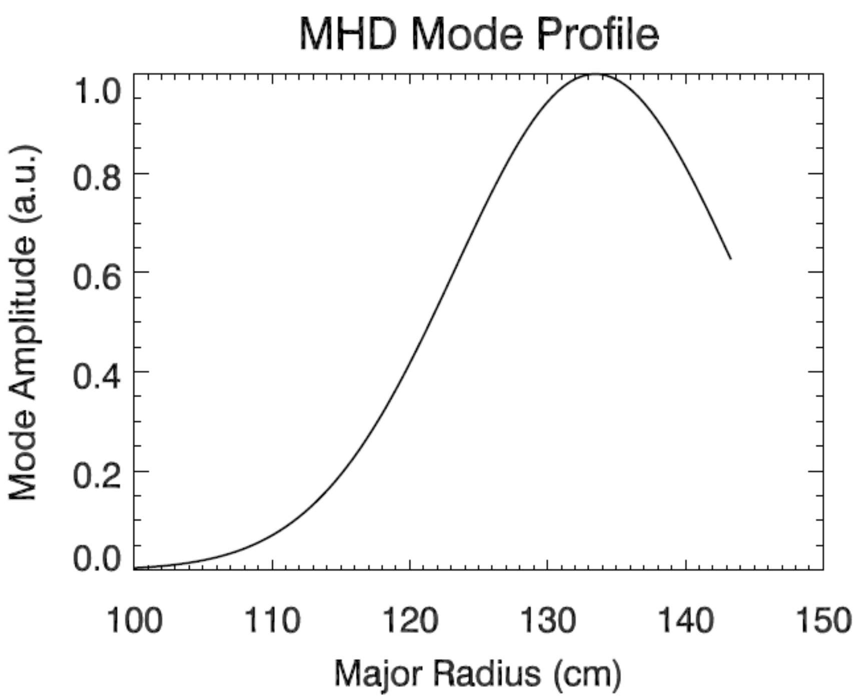
$$\Delta^2 = a^2 \frac{\sqrt{2\sigma_i/(1+\sigma_i)}}{m(1+\sigma_i)(1+\varepsilon_0)}$$

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

Good Spatial Correlation Between Peak in Excess Heating and the Peak in the Radial Eigenfunction of the CAE's



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

To test the theory that these modes could heat the plasma, perturbations similar to CAE modes were made in a slab model geometry and the particle orbits were followed. The heating to the particles was strongly dependent on the mode amplitudes

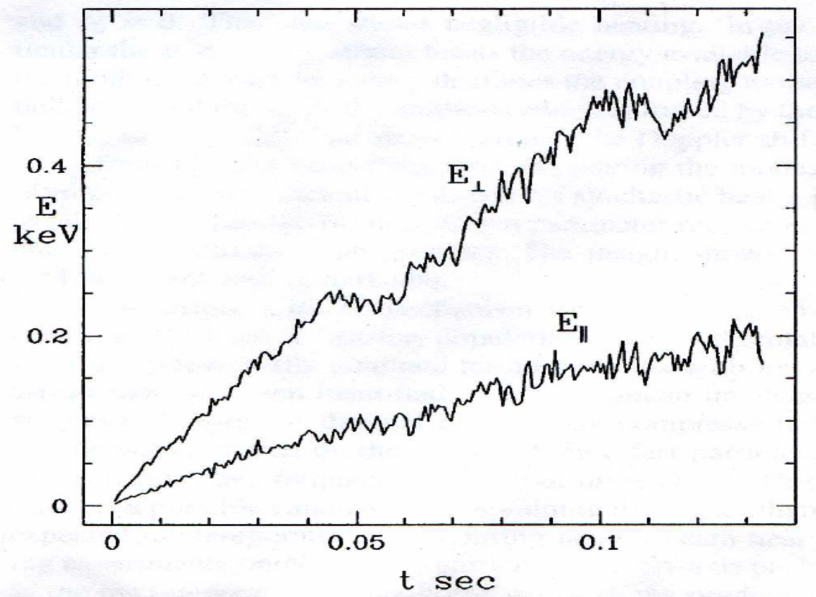


FIG. 1. Ion energy in keV vs time, for $\delta B_y/B = 6.0 \times 10^{-4}$.

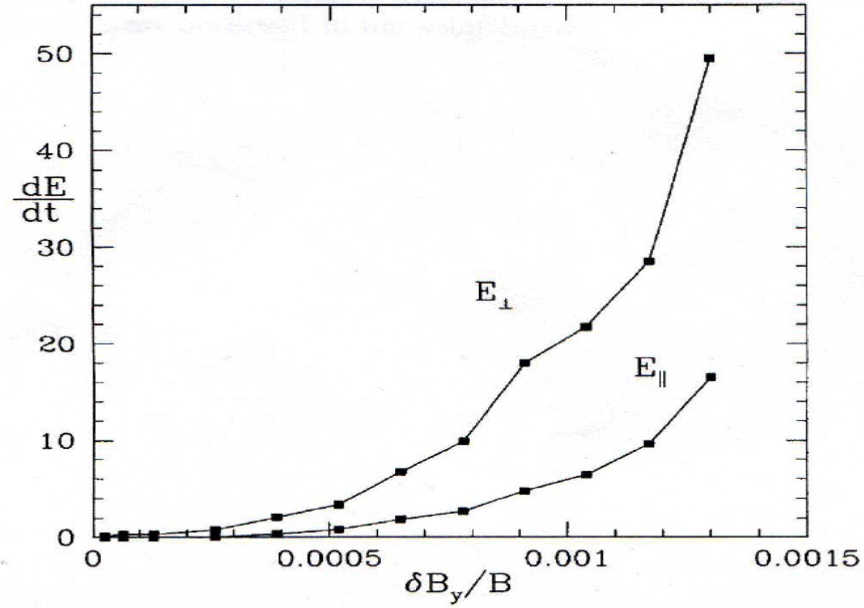
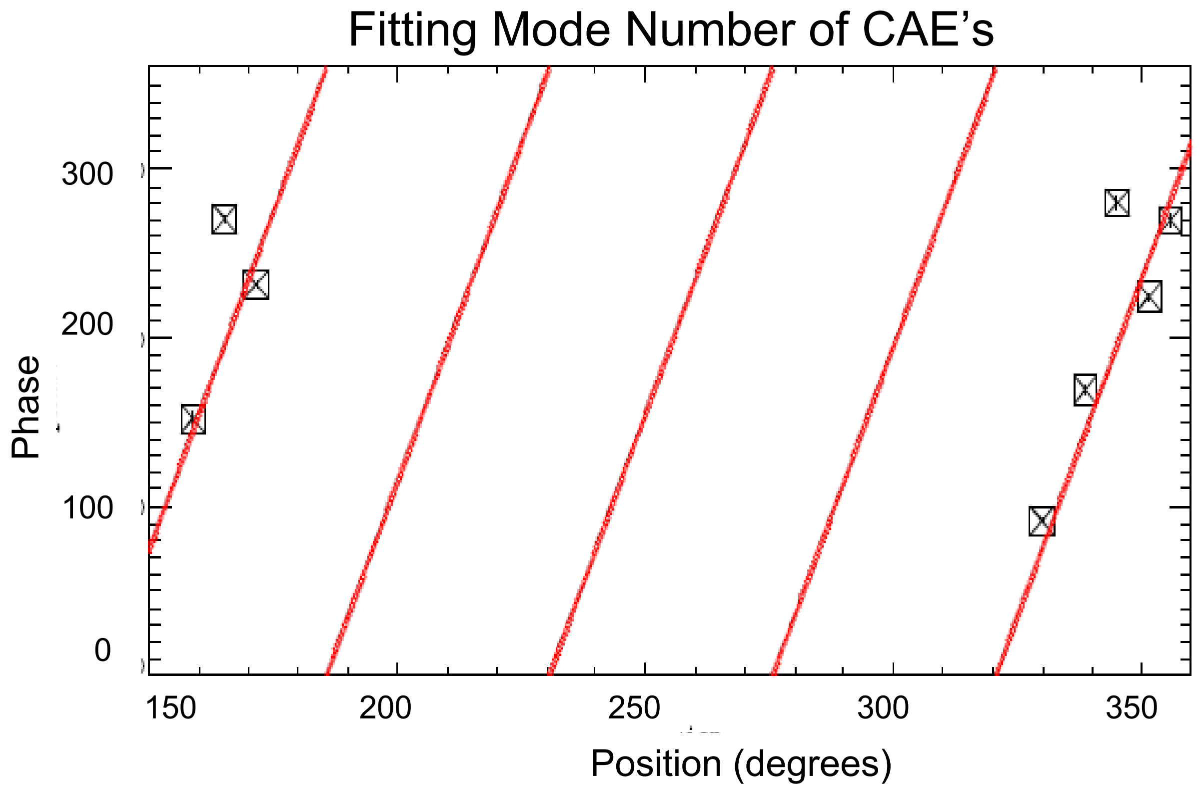


FIG. 2. Heating rate (keV/s) vs $\delta B_y/B$.

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).

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.

$\delta n/n = \delta B_{||}/B$

Start with the continuity equation: $$\tilde{n} = -\xi_r \frac{\partial n}{\partial r} - n\nabla\vec{\xi}$$

Lowest damped modes have $k_{\perp}$>>$k_{||}$, which gives $$\vec{k} \bullet \vec{B} = 0$$

which gives $$\nabla\vec{\xi} = \frac{B_{||}}{B}$$

The displacement is $$\xi_r = \frac{iE_{\theta}c}{B\omega}$$

The continuity equation becomes $$\frac{\tilde{n}}{n} = -\frac{iE_{\theta}}{B\omega}\frac{\partial \ln n}{\partial r} - \frac{\tilde{B}_{||}}{B}$$

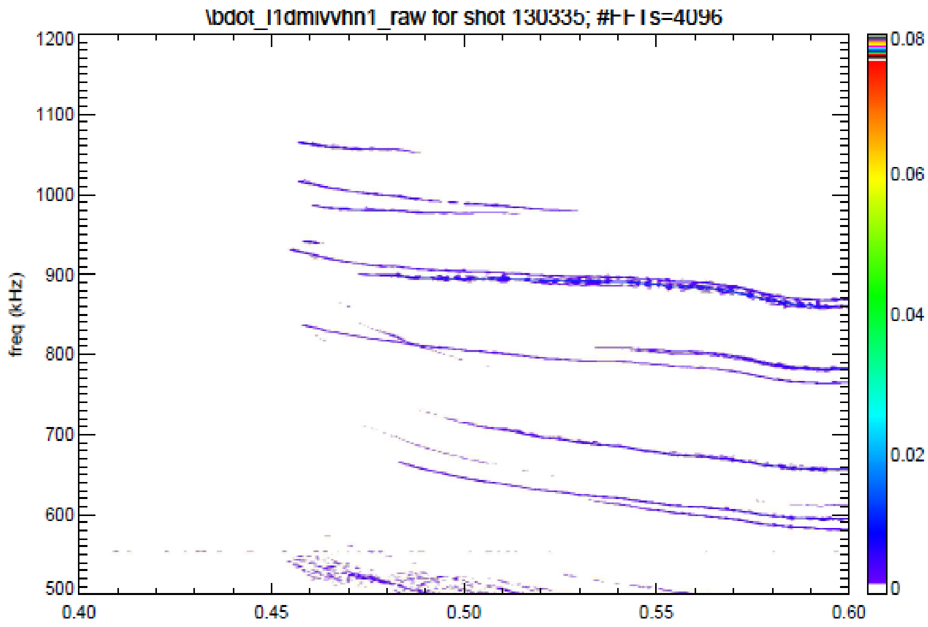
If the mode frequency w<<w_c then only the second term survives, giving

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

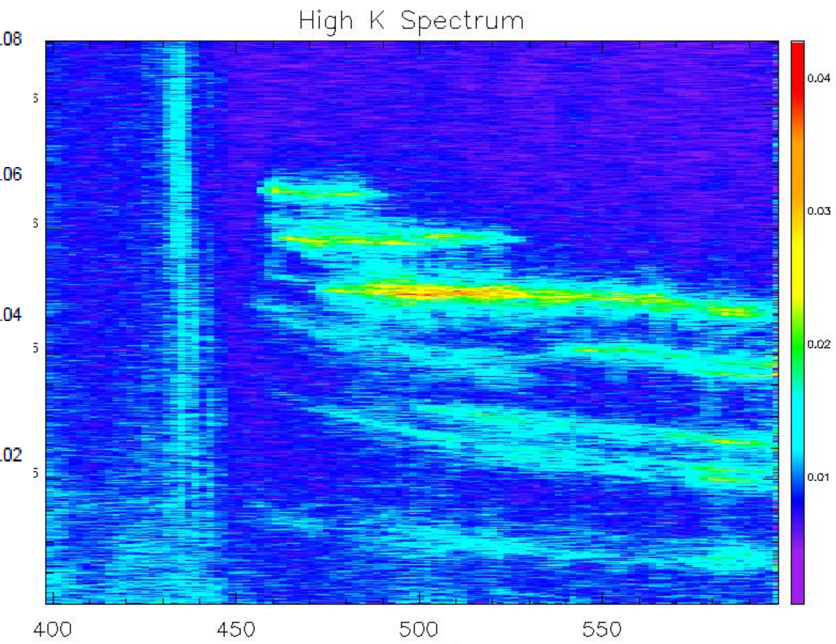
This analysis was reproduced from N. Gorilenkov, 2008 (unpublished)

The High-k diagnostic can get an amplitude for Magnetic Perturbations

FFT of Mirnov Coil Signal

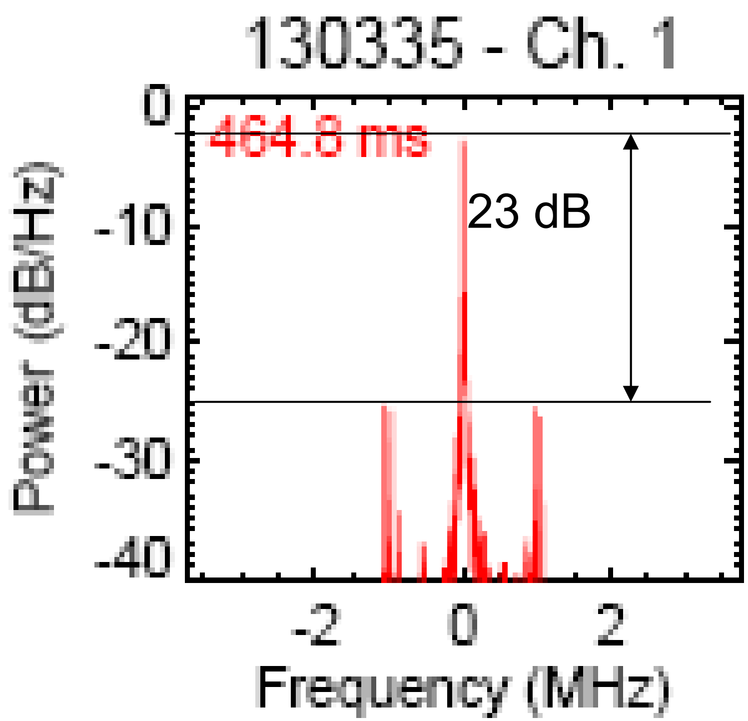


FFT of High-k Channel 1



The high K diagnostic can be used as an interferometer to match perturbation amplitudes with plasma fluctuations

Line Integrated Phase Shift = 7.07e-2



The signal amplitude goes as

$$
\begin{aligned}
e^{i\phi} &= e^{i(\phi_0+\tilde{\phi})} \\
&= e^{i(\phi)} e^{i(\tilde{\phi})} \\
&= A e^{i(\tilde{\phi})} \\
&\approx A(1+i\tilde{\phi})
\end{aligned}
$$

Unshifted Shifted

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.

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

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

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

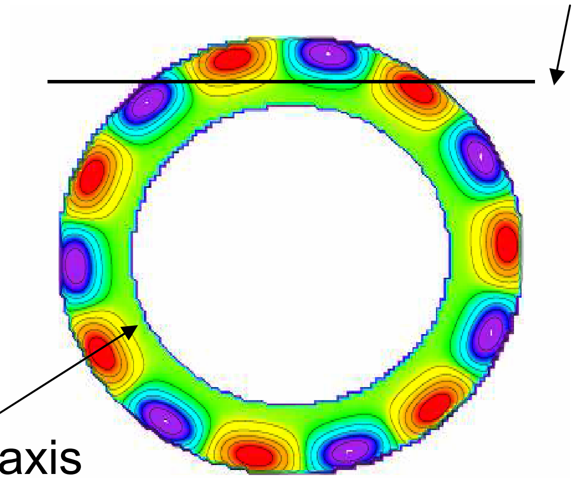
$$\tilde{\phi} = k\int \frac{1}{2}\frac{4\pi e^2}{m(kc)^2}\tilde{n}_e\, dl = 4.48x10^{-15}\int \tilde{n}_e\, dl \Rightarrow \int \tilde{n}_e\, dl = 1.56x10^{13}$$

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

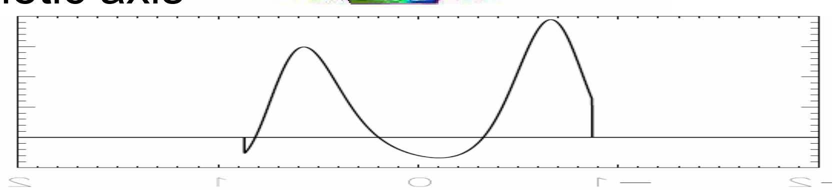
Mode Amplitude δn/n = 7.9e-3

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

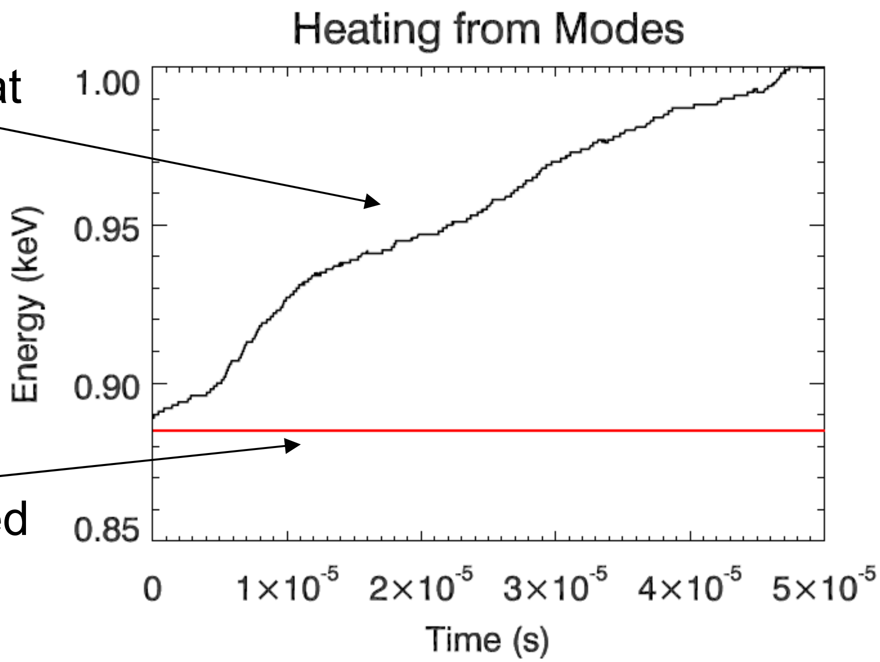
$$\frac{\tilde{B}_{\parallel}}{B} = \frac{\tilde{n}_e}{n_e} = 0.0079$$

Full Gyroorbit Calculations were performed using MHD Perturbations

- The ‘Gyroxy’ Full orbit code was used to test the theory using measured modes amplitudes. The mode amplitudes were measured by scaling the Mirnov coil signal to the High-k amplitude for shot 130335, then applying that scaling to the Mirnov signal for shot 128820. 5000 particles were placed at the location of the peak amplitude of the modes. Energy of the particles was calculated as a function of time.

High frequency MHD modes heat the plasma

Without modes, energy is conserved



Does this explain the excess heating observed?

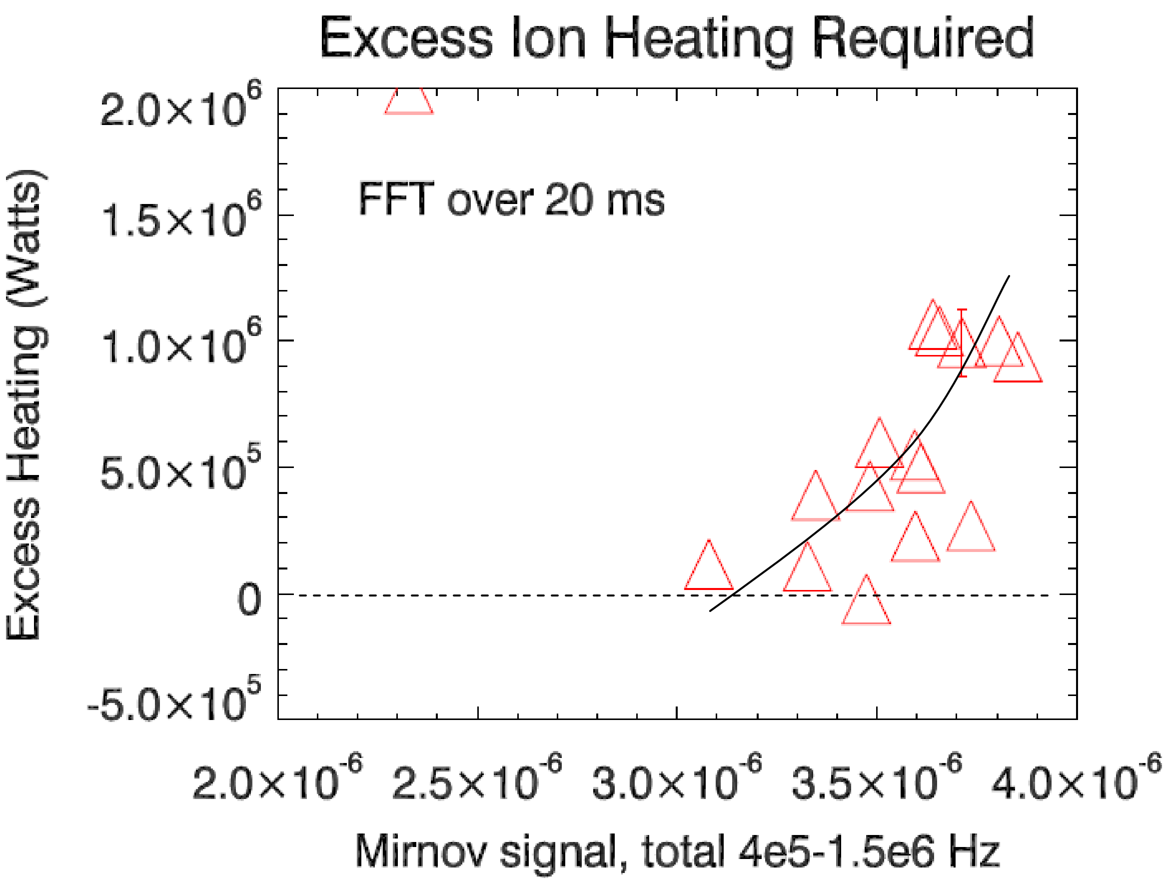
The Calculated Mode Heating Might Match Transp

$$P_{tot} = \frac{Energy}{particle\ sec} * \frac{particles}{m^3} * m^3$$

$$P_{tot} = \frac{0.1\,keV}{5e-5\ sec} * 4e19 = 1.2e7\ \ Watts$$

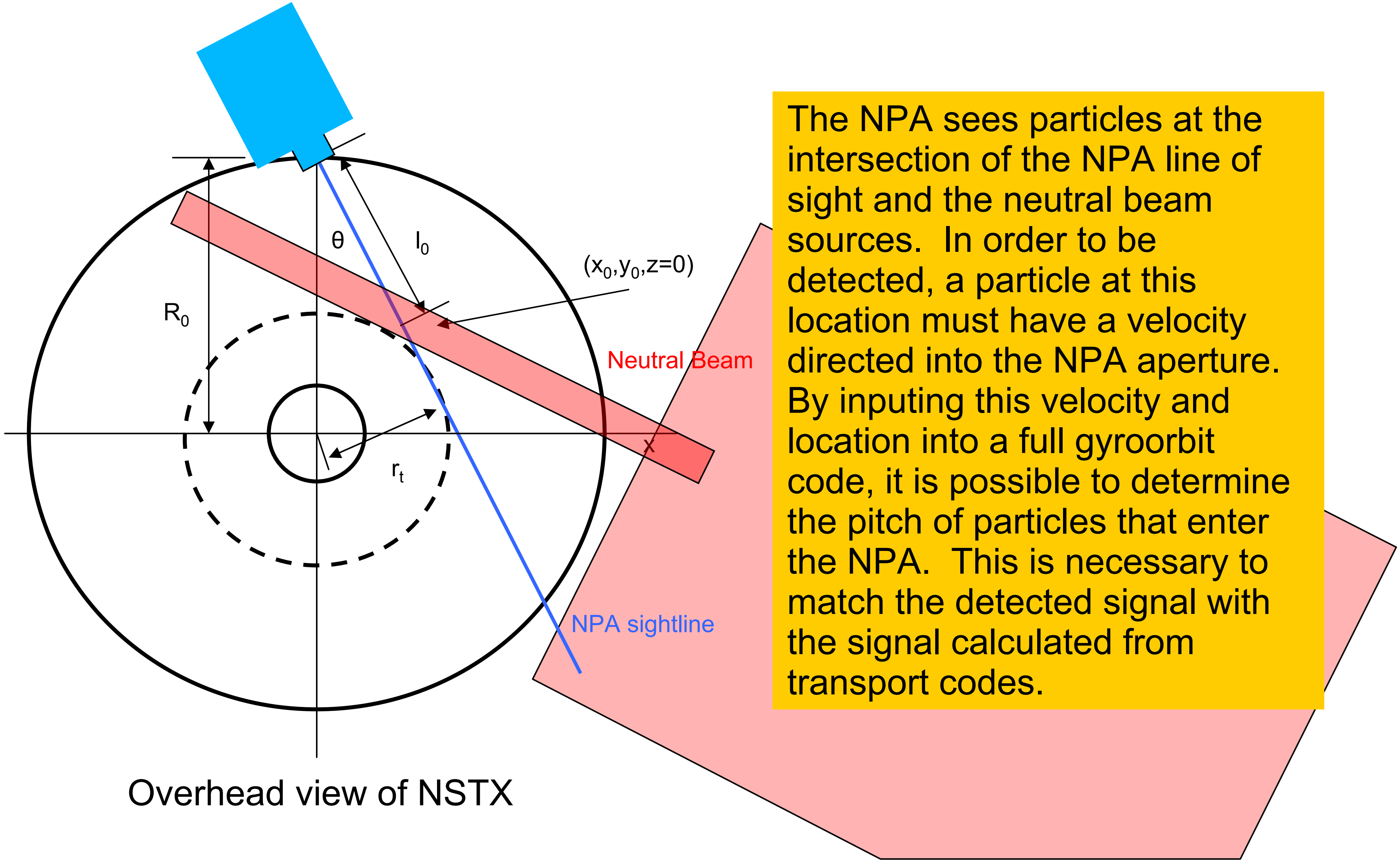
That's more than the Neutral Beam power to NSTX (6 MW). However, the particles were placed at the peak amplitude. Because of the distribution of particles, the density is lower at the location of the peak mode amplitude than it is at the peak density. Since the heating power seems to scale strongly with mode amplitude, the location with the highest density would not heat nearly as much. Also, different poloidal mode number (m numbers) heat different amounts, and diagnostics are not currently available to measure m number. Further study is needed to confirm that the actual heating by these modes is reasonable. Nonetheless, it shows that heating by these high frequency MHD modes is possible.

High Frequency MHD Amplitude Correlates with Observed Excess Heating



By taking the FFT of the Mirnov coil signals and then summing over the CAE frequency band, it is possible to show a correlation between the RMS amlplitudes and the excess heating as calculated by TRANSP. The shape of the plot is similar to that computed in a slab geometry.

NPA measures fast particle slowing down spectrum at one spatial point and a specific pitch

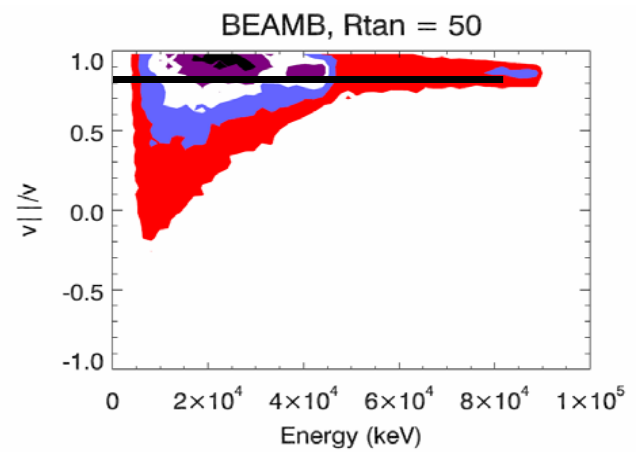


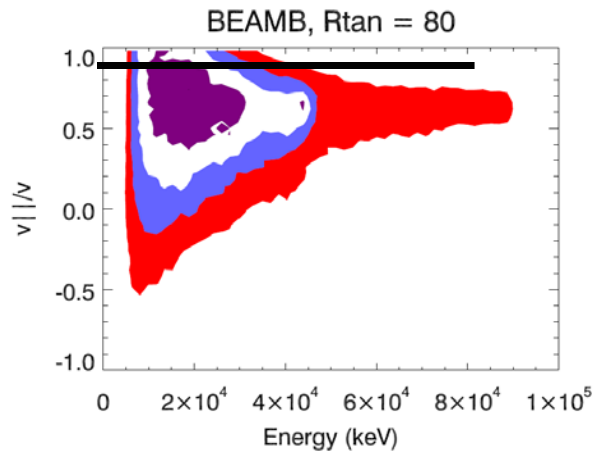
Overhead view of NSTX

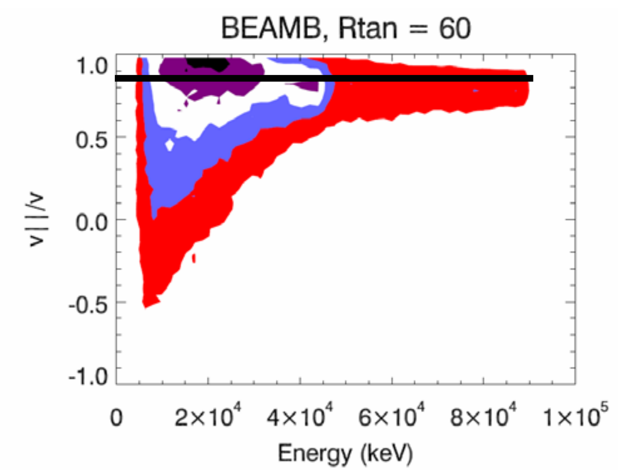
The NPA sees particles at the intersection of the NPA line of sight and the neutral beam sources. In order to be detected, a particle at this location must have a velocity directed into the NPA aperture. By inputing this velocity and location into a full gyroorbit code, it is possible to determine the pitch of particles that enter the NPA. This is necessary to match the detected signal with the signal calculated from transport codes.

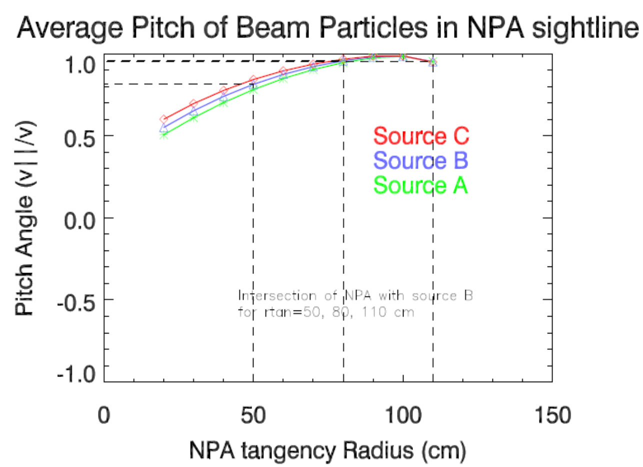
FLR Correction to TRANSP NPA Distribution Function Correction Required to Correctly Predict Optimum NPA Sightline

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





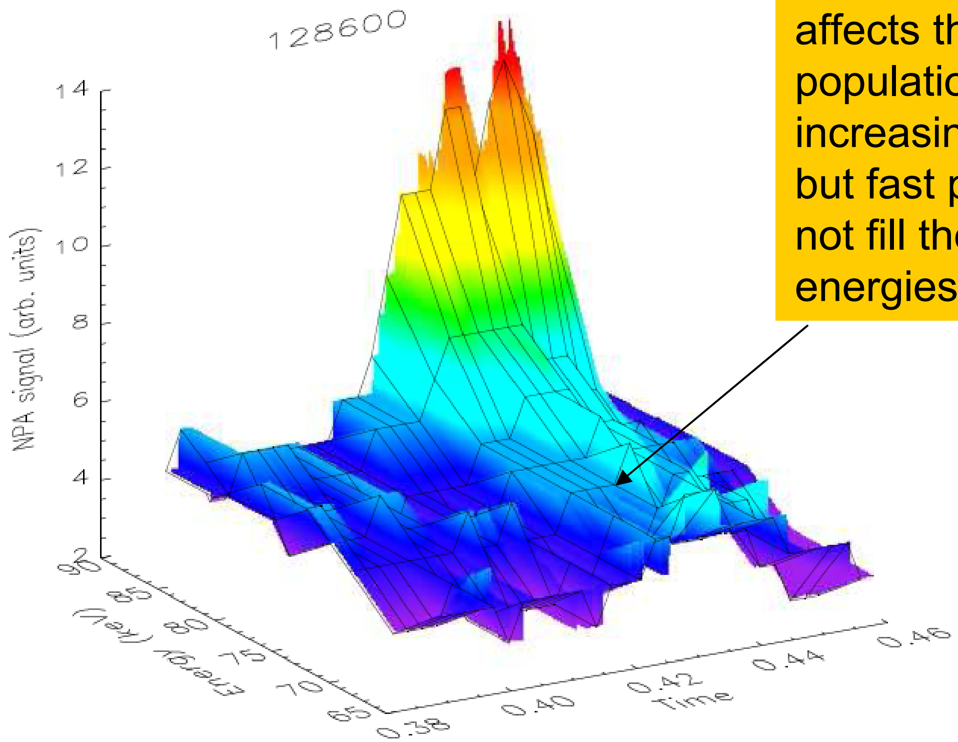




When the TRANSP calculations of NPA signals are corrected the large Larmour radius on NSTX, it is shown that the spatial intersection of the NPA with the exiting neutralized bean ions is much narrower than previously thought

Measured NPA signal Does Not Show Expected Slowing Down Spectrum

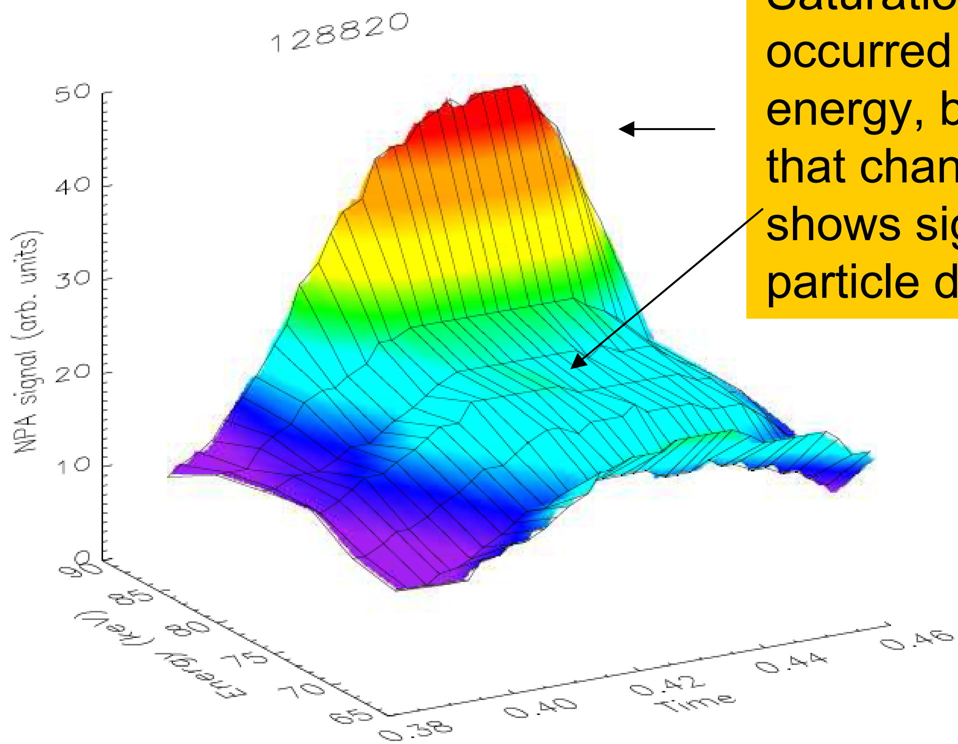
The beam turn-on and turn-off are visible at the full energy, but the data does not show the classical slowing-down spectrum that is expected. This was true at a variety of tangency radii.



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, fast particle spectrum deviates significantly from expectations

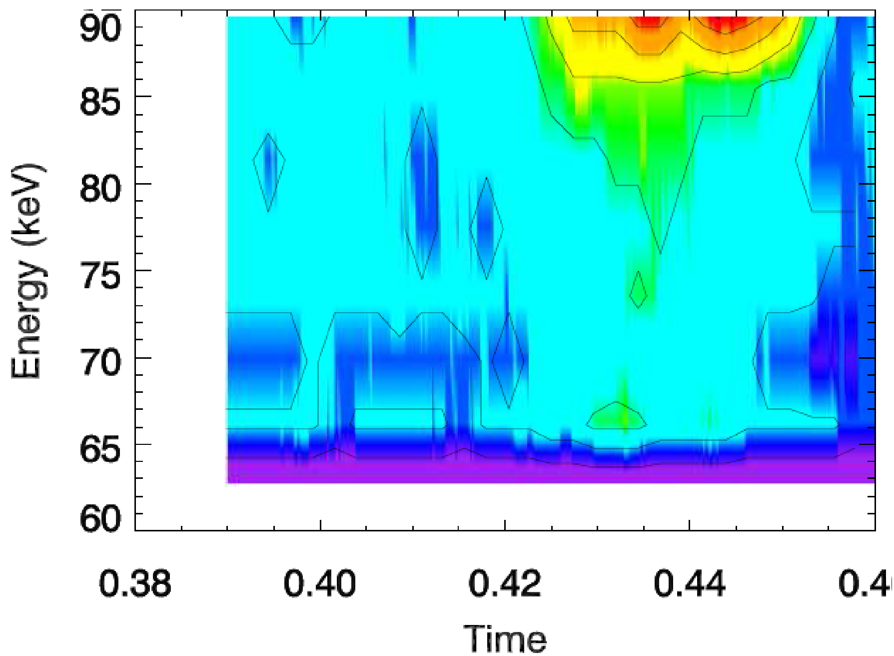


Saturation has occurred at full energy, but ONLY that channel shows significant particle density.

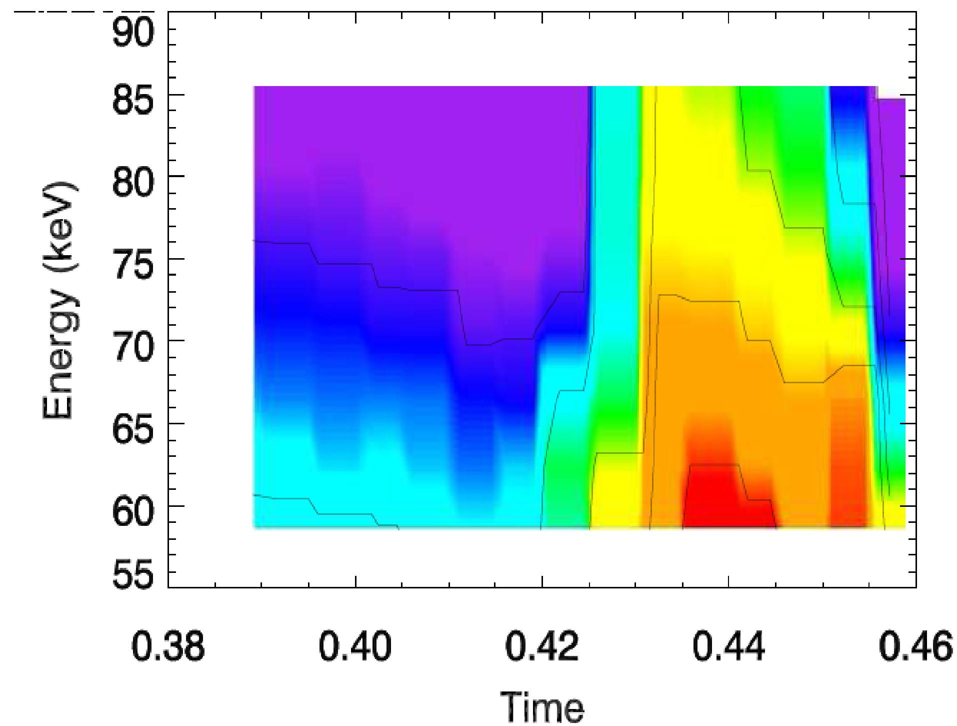
Where did the fast ions go?

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.

Correction: NPA has limitations, but not a “Fundamental Flaw” as originally stated

- The NPA measures particles at a particular location with a particular pitch.
- The NPA is not able to fully measure the fast ion distribution at the desired locations.
- If fast ions are being moved in phase space by losing energy to the MHD modes, they may completely escape the NPA line of sight.

Other Loss term

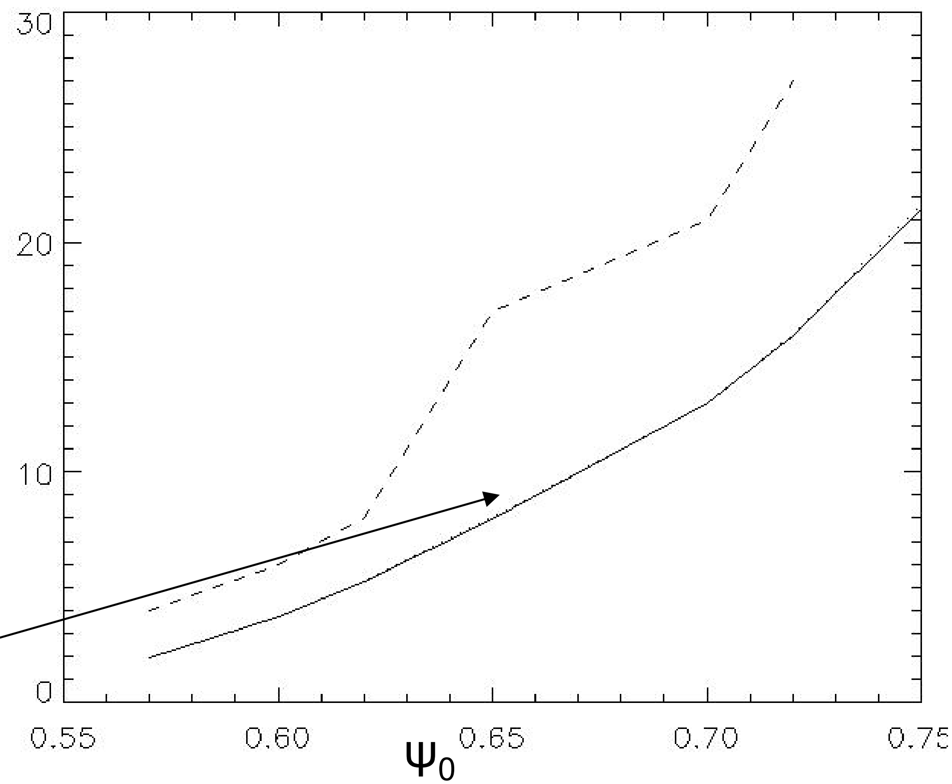
- The equation $P_{excess} = Q_{nc} + Q_{ie} + \dot{W} - P_{nb}$ represents a lower bound on the excess heating. In reality, other loss machansims are present which increase the need for heating. These include
  - Charge Exchange
  - Ripple loss
  - MHD induced losses

- Fortunately, these loss terms are small compared to those discussed above.

Ripple Loss Does Not Play a Significant Role in Energy Loss

- ORBIT (Guiding Center) code show smalls ripple loss (~2% of the particles at any given flux surface)
- Ripple loss is dominated by collisional effects
  - At ψ_0=0.75, ripple loss ~ 0.1%, while collisional diffusion resulted in ~60% particles lost
- Significantly increasing the ripple causes the loss to become stochastic

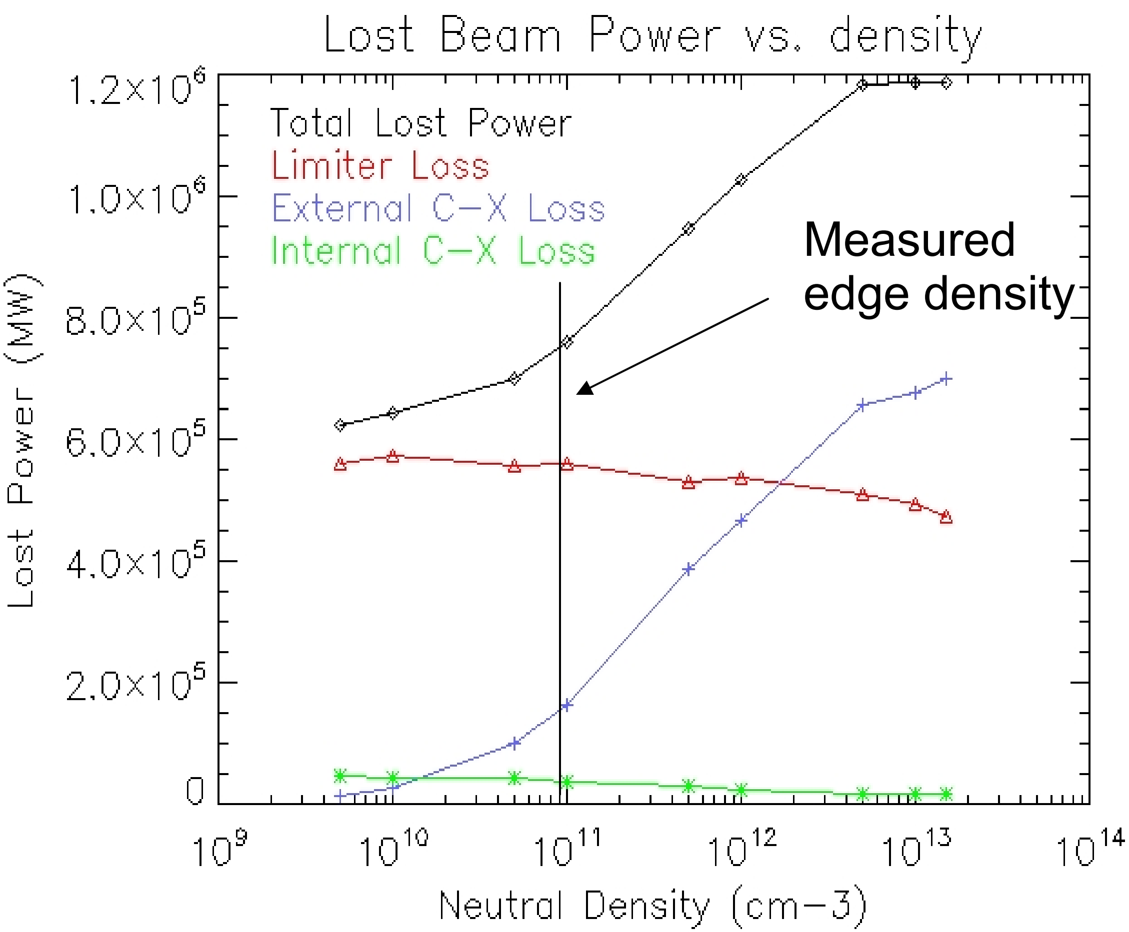
Percentage of 50 keV particles lost for cases at various flux surfaces.



Solid and dotted lines completely overlay, indicating that NSTX ripple does not play a signifcant role.

Solid line shows no-ripple cases. Dotted line includes ripple effects with NSTX calculated ripple. Dashed line shows with 10x ripple.

Charge Exchange Loss is not significant in NSTX.



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 (1-1.5e11), the total lost power is about 10% of the total input power.

Conclusions

- Beam modulations were successfully used to investigate Power Balance in NSTX.
- During some discharges, excess heating was required to match the power balance equation. This was not true for all discharges or all times during the discharge. It was most noticeable with the turn on of a third neutral beam source.
- During these discharges, the neutral beam modulations excited high frequency MHD modes.
- The profile of the CAE eigenfunctions matches the profile of the excess heating.
- High-k data has been used to connect the MHD mode amplitudes to the observed density perturbations.
- The excess heating follows the beam modulations and does not appear to be a transient artifact.

Conclusions (continued)

- Full orbit calculations show that MHD modes can heat thermal ions enough to account for this excess heating. A final step to confirm this will be to put into the code a distribution of particles similar to the density of the plasma to observe the effects.
- The NPA shows an absence of particles below the full energy. However, this may be due to exceeding the limitations of the NPA diagnostic.
- Other loss mechanisms (charge exchange, ripple loss) did not seem to play a significant role in the power balance equation