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NSTX

Progress in Measuring RF Power Deposition Profiles on NSTX

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Abstract

In early 2003 preliminary experiments were carried out on NSTX in which the high-harmonic fast wave power was modulated with a 100-Hz square wave. The goal was to measure the deposition profile of the HHFW power in the plasma. The primary diagnostic available to determine this was an ultra-soft x-ray array. Initial analysis of the data will be presented and compared with calculations of the expected deposition profile and the resulting temperature modulation.

<u>OUTLINE</u>

- EXPERIMENTAL SETUP
- DATA ANALYSIS
- RESULTS FROM THEORY

EXPERIMENTAL SETUP

RF modulation experiments were done on NSTX

Plasma conditions:

- $B_0 = 0.45$ T
- $I_p = 600$ kA
- Lower-single null, diverted
- He plasma

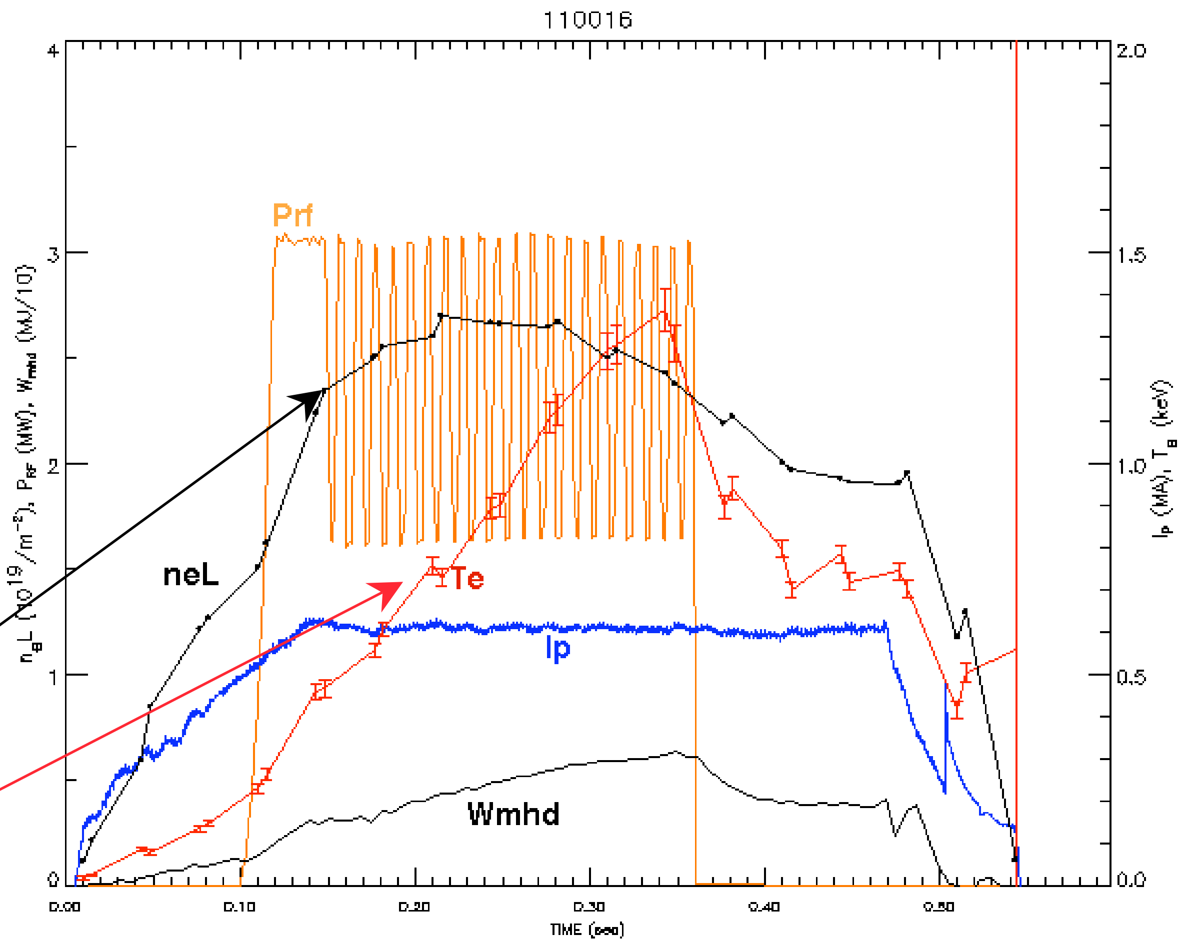
RF:

- Co-current drive phasing
- Max rf power ≈ 3 MW
- Modulation ≈ 50%, 100-Hz square-wave

Note:

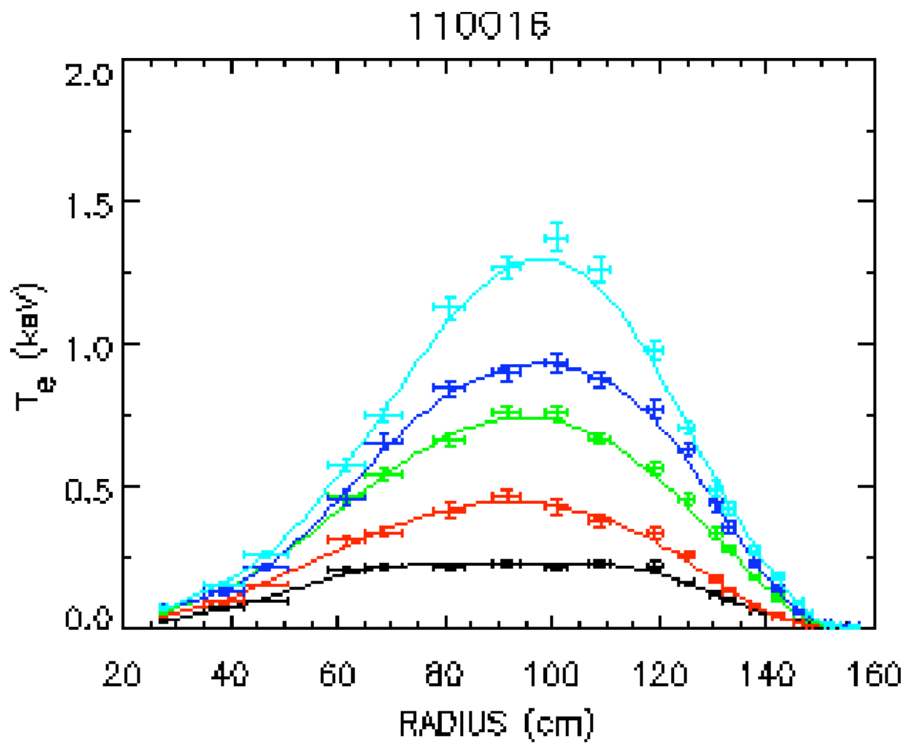
- Relatively flat density vs. *t* during rf modulation
- Monotonic increase in $T_e(0)$ during rf pulse.

Plasma current, T_e, n_eL, RF Power, and Stored energy

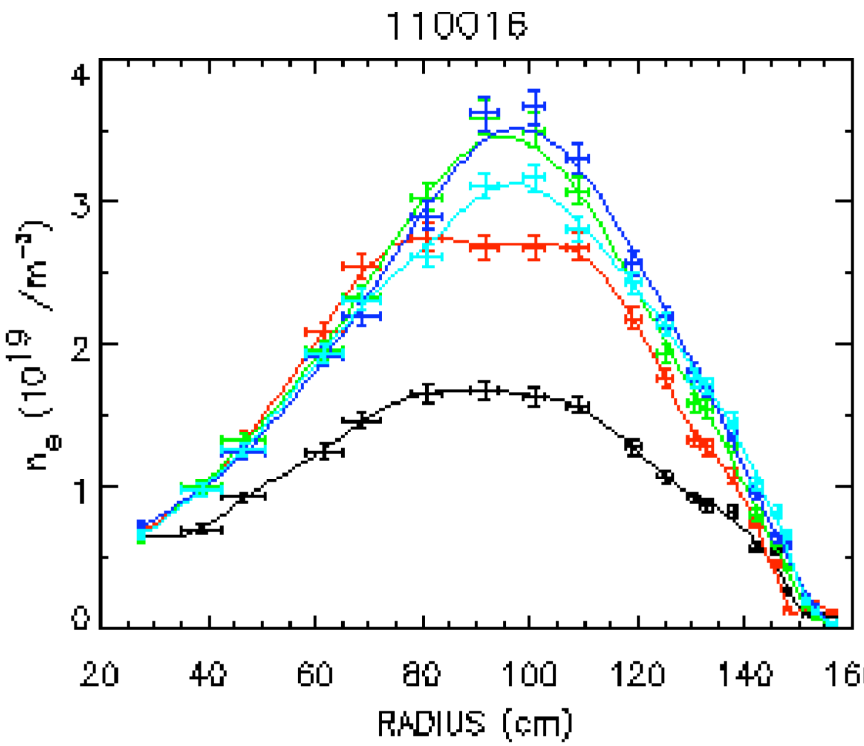


Thomson scattering profiles: T_e rises, $n_e \approx$ constant during rf

T_e and n_e profiles at 100 ms, 150 ms, 200 ms, 250 ms, 300 ms
RF modulation begins at 150 ms



Temperature profile increases slowly with time



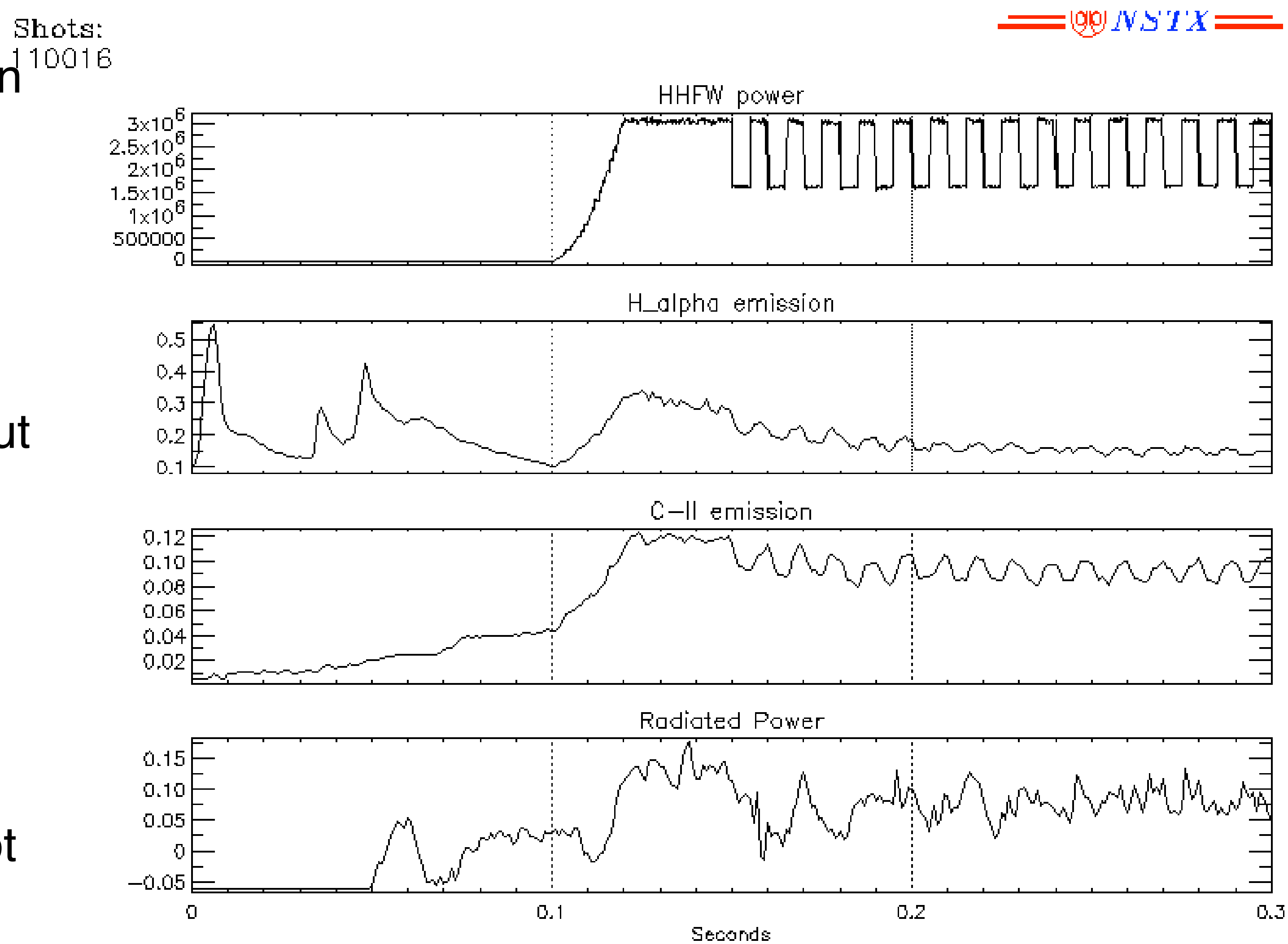
Density profile relatively constant from 200-300 ms

Modulation seen on *some* diagnostics, not on others

Moderate modulation seen on
- H-[?] emission
- C-II emission

Total radiated power *may* have a little modulation, but masked by other fluctuations

Modulation *not* seen on FIR interferometer density chord measurements (not shown)



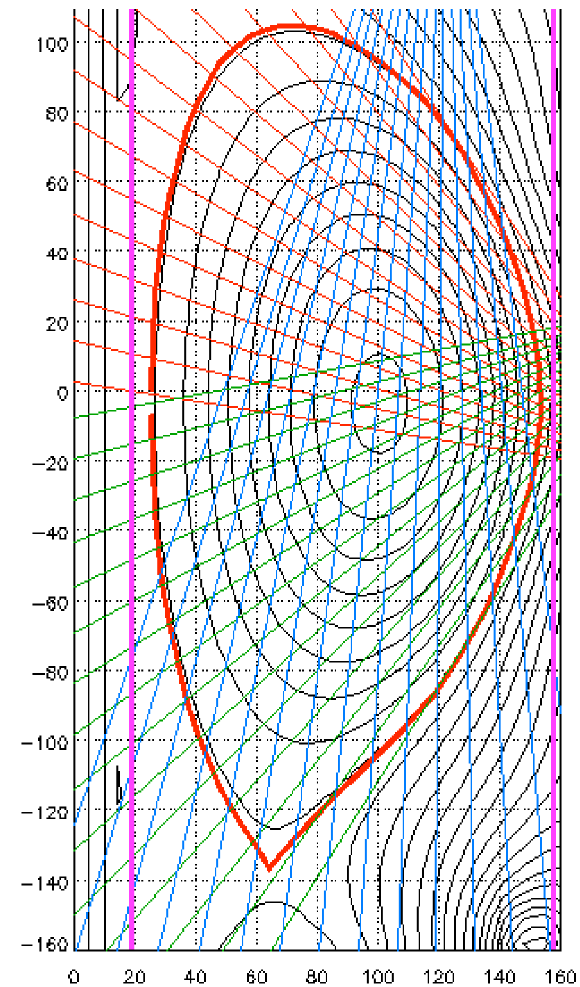
DATA ANALYSIS

USXR array analysis

Stutman et al. have installed 3 ultra-soft x-ray arrays on NSTX. Each has a different energy filter:

- Vertical array (blue lines)
  - 3 μm Ti filter
  - Sensitive to low-energy (0.3 – 0.4 keV)
  - Sensitive to C impurity line radiation, density changes
- Horizontal up array(green lines)
  - 5 μm Be filter
  - Sensitive to x-rays with E ≥ 0.4 keV
  - Relatively insensitive to core or edge T_e changes
- Horizontal down array (red lines)
  - 100 μm Be filter
  - Sensitive to x-rays with E ≥ 1.4 keV
  - Good sensitivity to core T_e changes

Flux surfaces at t = 200 ms



Data from arrays show very different behavior

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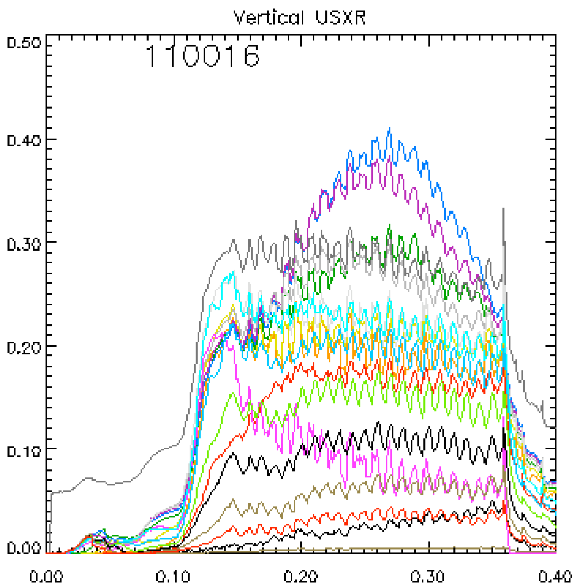
Low-energy array shows clear evidence of response to modulation
Other arrays show little modulation.

Vertical array
(low-E, density or imp.)

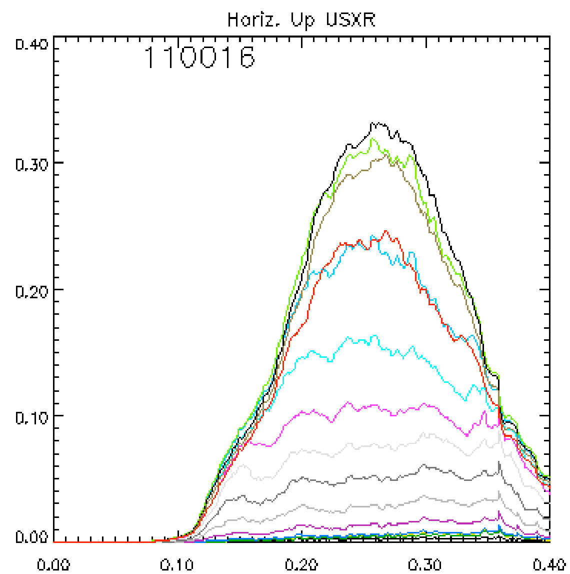
Horiz. down array
(med-E, density or imp.)

Horiz. up array
(high-E, T_e)

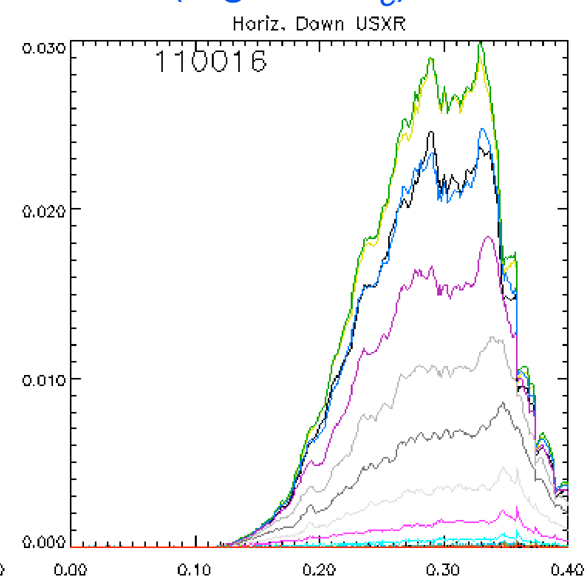
USXR
signal
(a.u.)



t (s)



t (s)

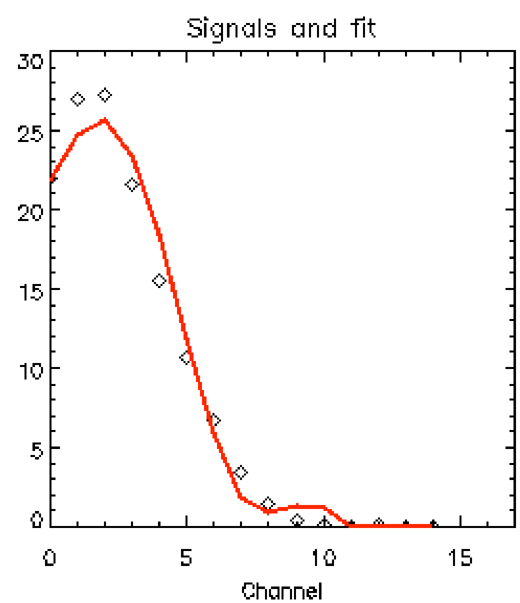


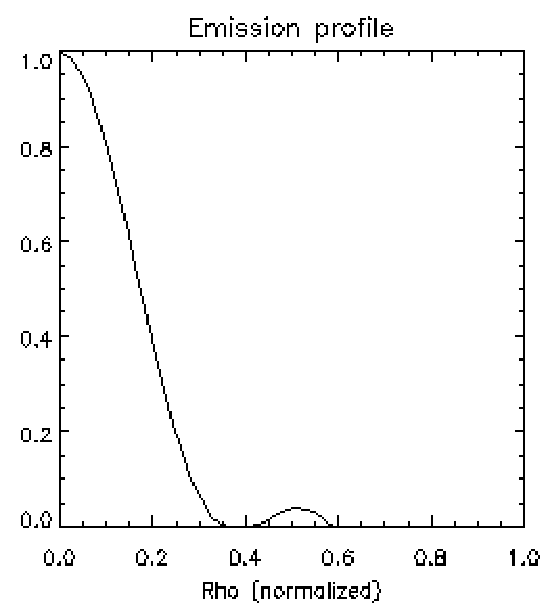
t (s)

Signals from each array can be inverted to get emission vs. ρ

Numerical inversion procedure:

- Assume emission constant on a flux surface
- Assume functional form for emission profile *I(ρ)* (4-term Bessel function series)
- Numerically integrate profile *I(ρ)* along measurement chord for each detector, using equilibrium from EFIT
- Evaluate coeff. in functional form to give best fit to chord-integrated measured signals





Calculation of array sensitivities show big differences to changes in T_e

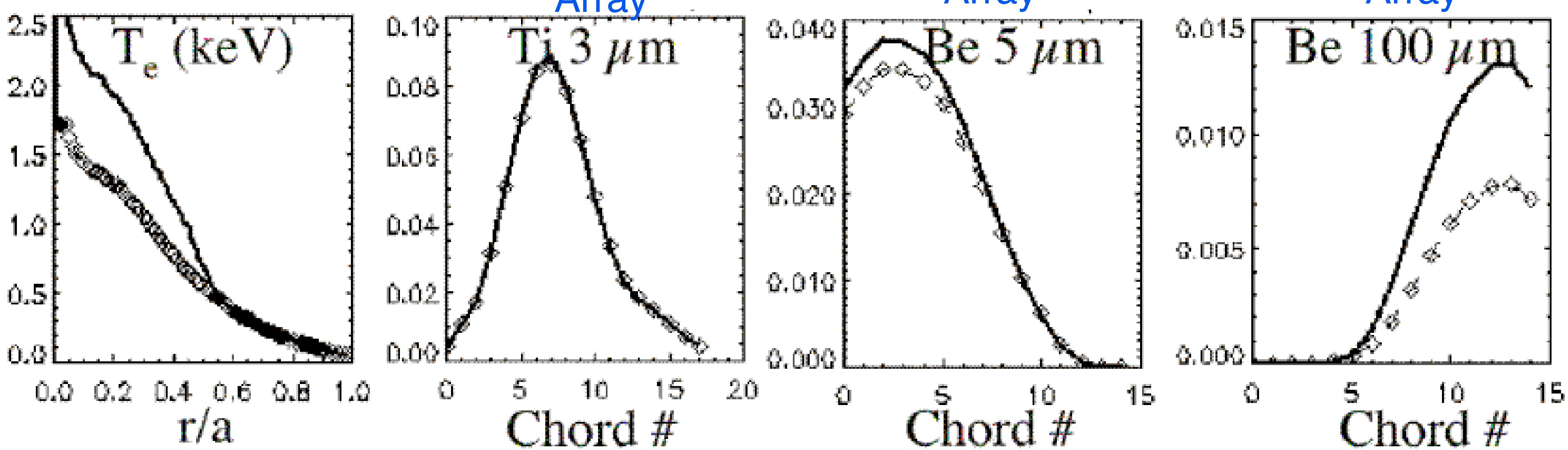
1. Assume two Te profiles

2. Calculate signals in each channel from the 2 profiles

Low-E Array

Medium-E Array

High-E Array



Low-E array *insensitive* to changes in T_e, but will see changes in n_e or density

Med-E array slightly sensitive to central T_e change; insensitive to edge T_e

High-E array very sensitive to central T_e change; insensitive to edge T_e

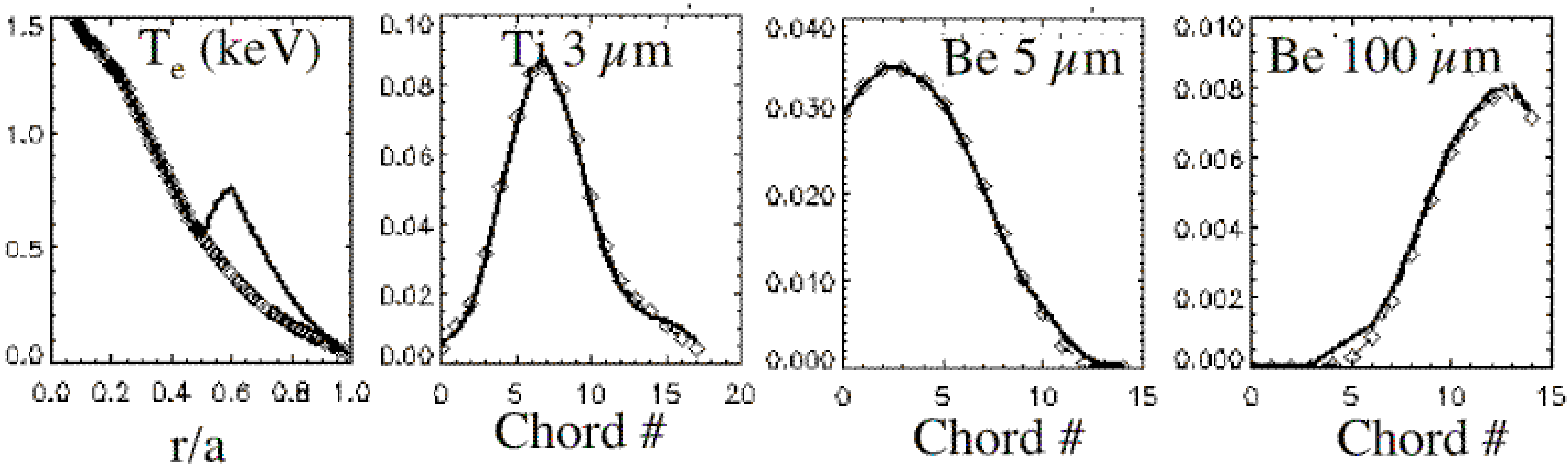
Arrays *insensitive* to a change in T_e in outer part of plasma

Change in *edge* T_e

Low-E Array Response

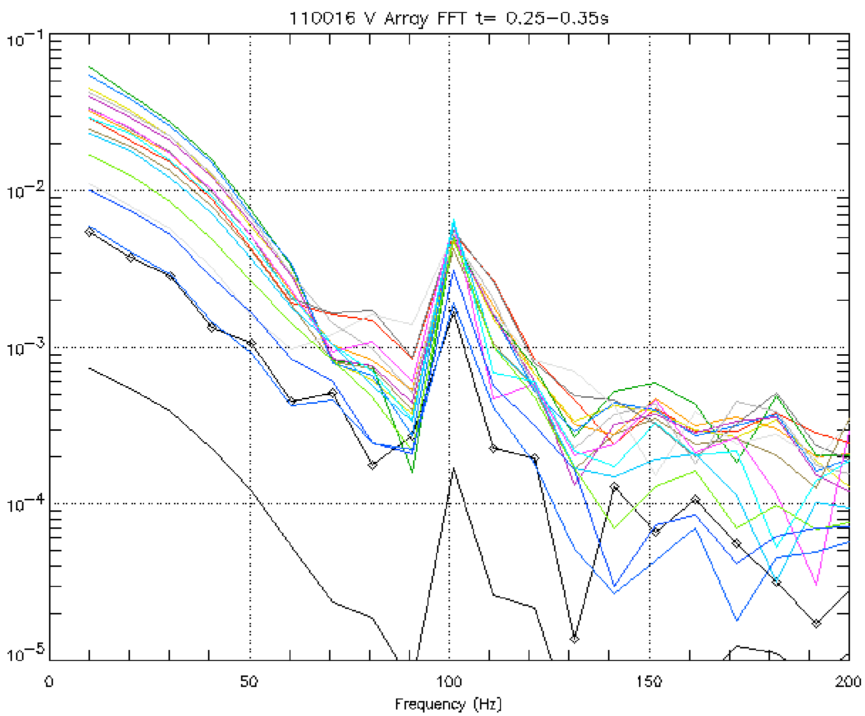
Medium-E Array Response

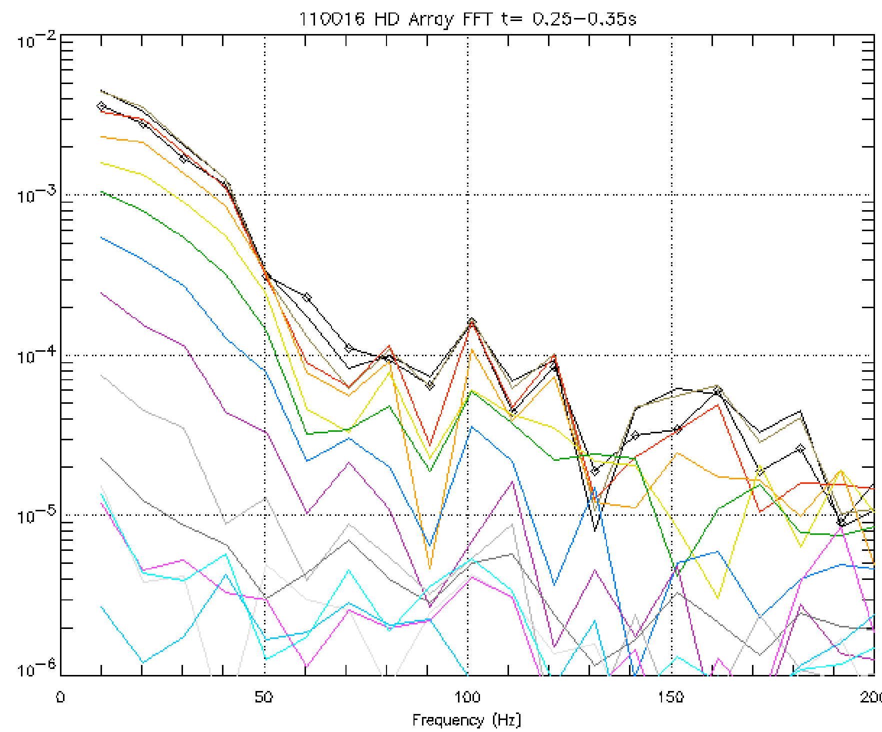
High-E Array Response



How do array signals respond to 100-Hz modulation?

Took Fourier transform of all signals for 0.25 s ≤ t ≤ 0.35 s, giving a data point in frequency-space every 10 Hz





Low-E array signals have significant 100-Hz component

High-E array signals have *S/N* of ≈ 1 – is signal really there?

100-Hz signal components show very different radial dependence

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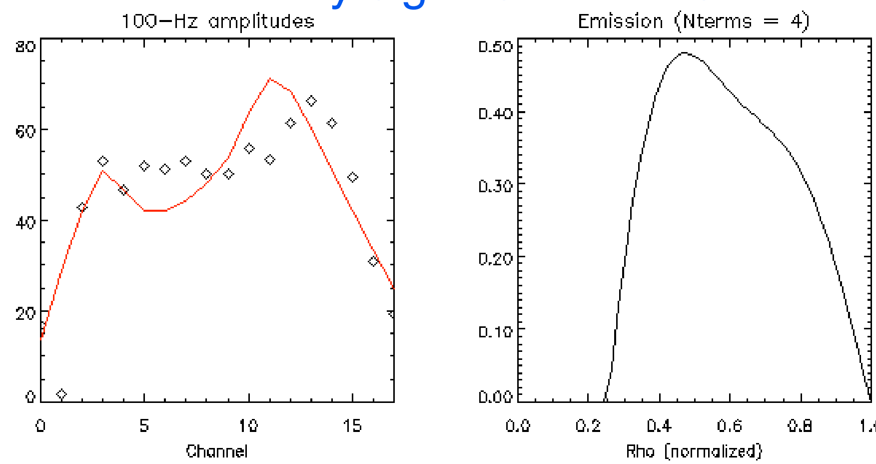
Took 100-Hz component of signal on each channel, inverted to get $S_{100\mathrm{Hz}}$ (□)

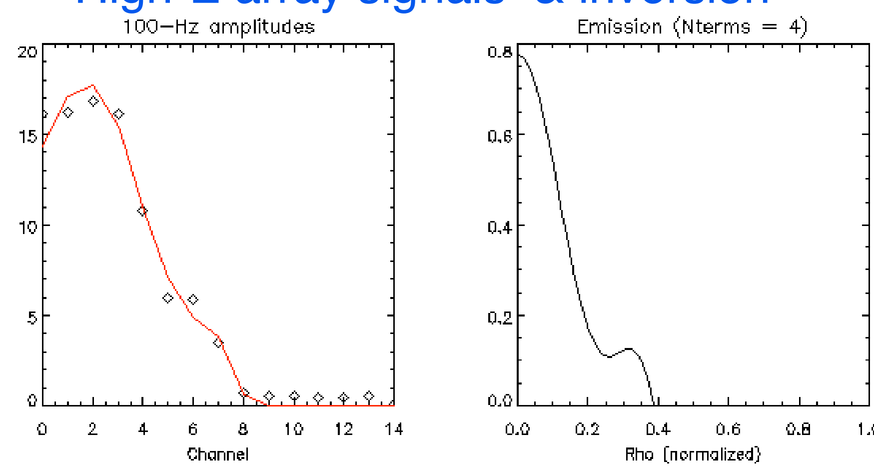
- Low-E array signal is highest in outer half of plasma

Low-E array signals & inversion



- High-E array signal is peaked near the center

High-E array signals & inversion



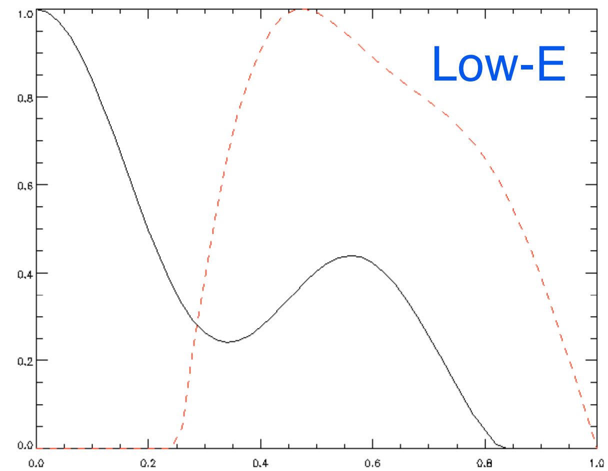
4-parameter inversion gives *reasonably* good fit to signal data.

Modulation of low-E signals near outside; modulation of high-E signals near center

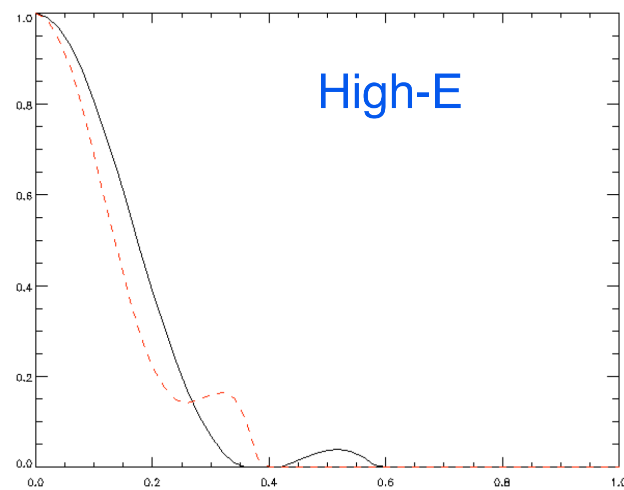
Black curves: inversion of total signals at $t = 0.3$ s

Red curves: inversion of 100-Hz component of signals for $0.25 \leq t \leq 0.35$ s

Curves normalized to unity



100-Hz on low-E channels show significant difference from total signal



100-Hz on high-E channels have ≈ same modulation dependence as total signal.

- Because of low signal level near outside (T_e too low to give a signal), it wouldn't be possible to see edge modulation near edge.

From high-E data, $\square T_e$ very small near center

Observations:

- 100-Hz component has radial profile identical (to within error bars) to unmodulated signal
- Peak-to-peak amplitude of largest channel signal appears to be only about 2% of the total signal amplitude
- Cross-correlation coefficient (*r*) of this signal with rf modulation is low, ≈ *0.2*

Signal amplitude should be very sensitive to changes in T_e

- Near center, $S \sim n^2 Z^2 T_e^{2.3}$

Conclusion:

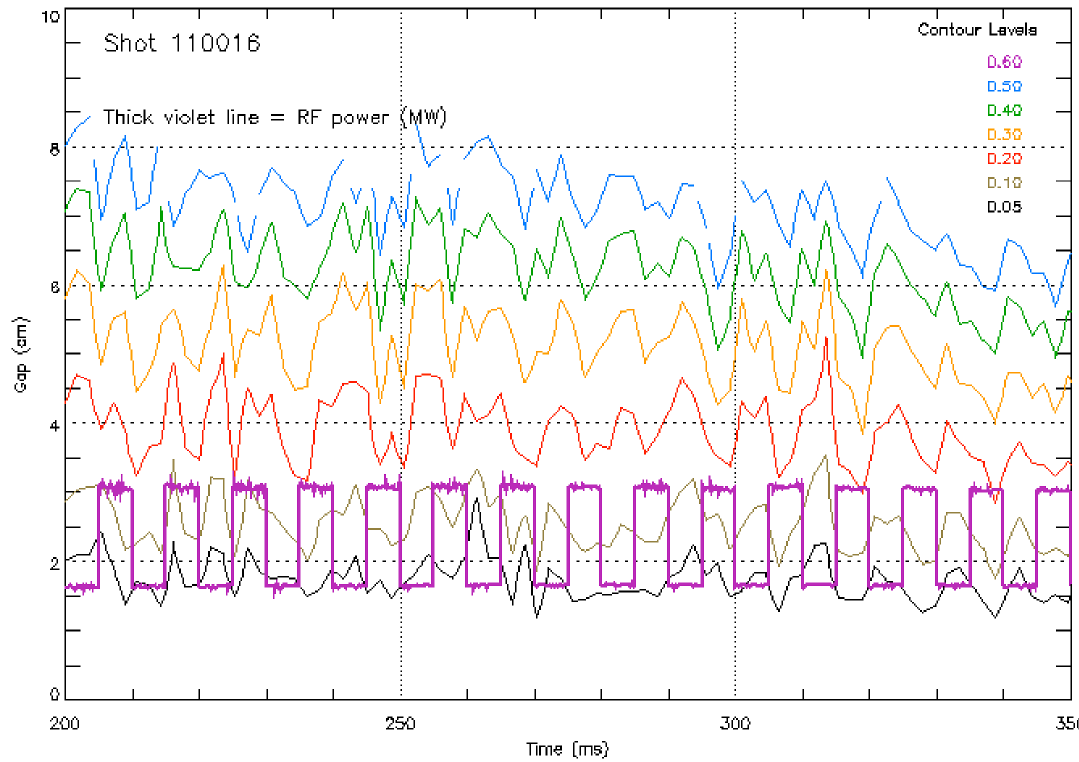
- Upper bound on $\square T_e/T_e$ caused by the modulation is ≤ 1% in central part of the plasma ($\square$ ≤ 0.3)

Edge modulation of low-E signal probably density modulation

Modulation of density profile seen near outer edge.

Could be changes in impurities also; can't sort out one from the other.

Contour plot of edge density(t) from ORNL edge reflectometer.



Magenta trace is rf power(t) [in MW]

RESULTS FROM THEORY

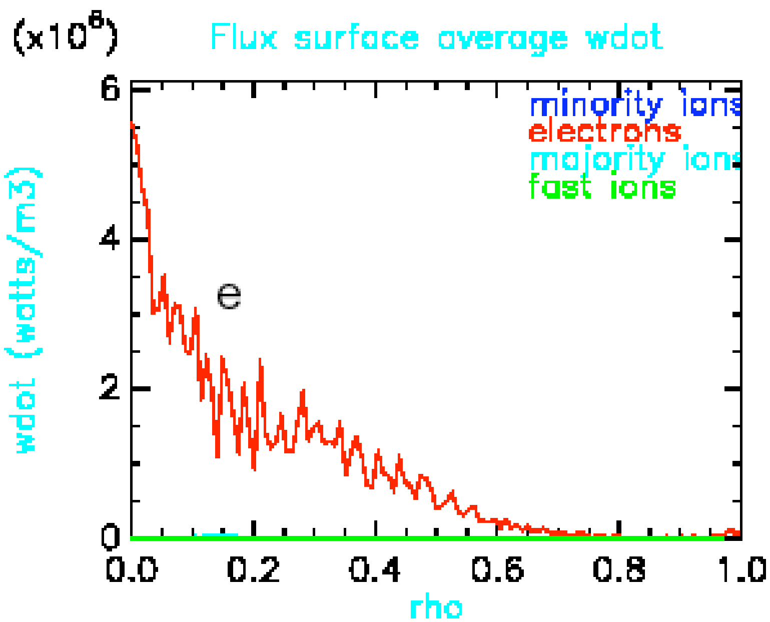
What should we expect to see?

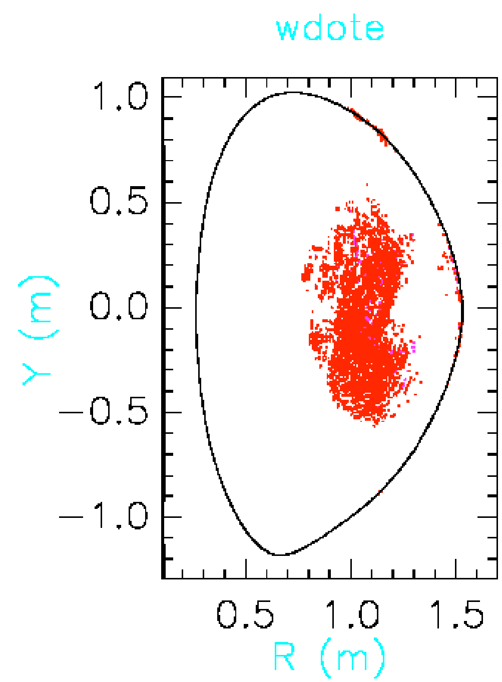
For experimental plasma conditions, calculated power deposition using the AORSA 2D code

- Single toroidal mode [n_{ϕ} = -12, co-current drive direction]

Results:

- Almost all the power should be absorbed by electrons
- Power deposition is centrally peaked
- These results are *not* very sensitive to assumptions on plasma conditions



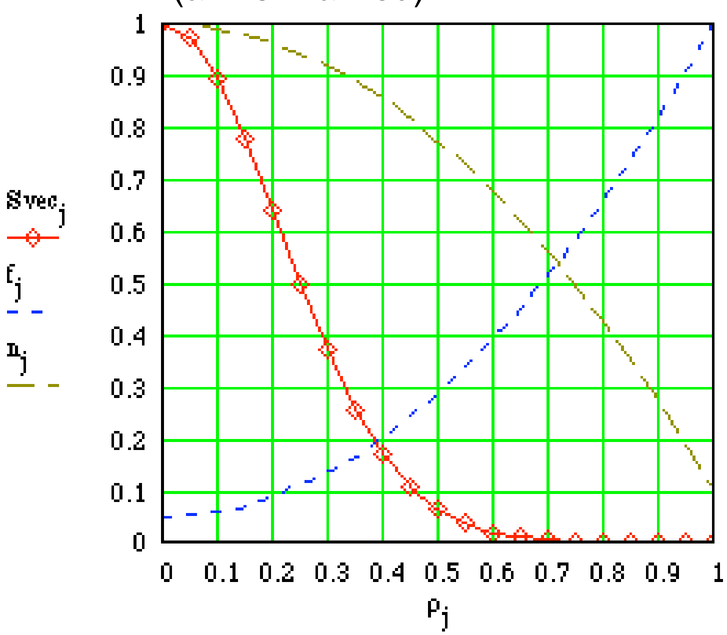


Centrally-peaked power deposition, should give 10-20% $\delta T_e/T_e$

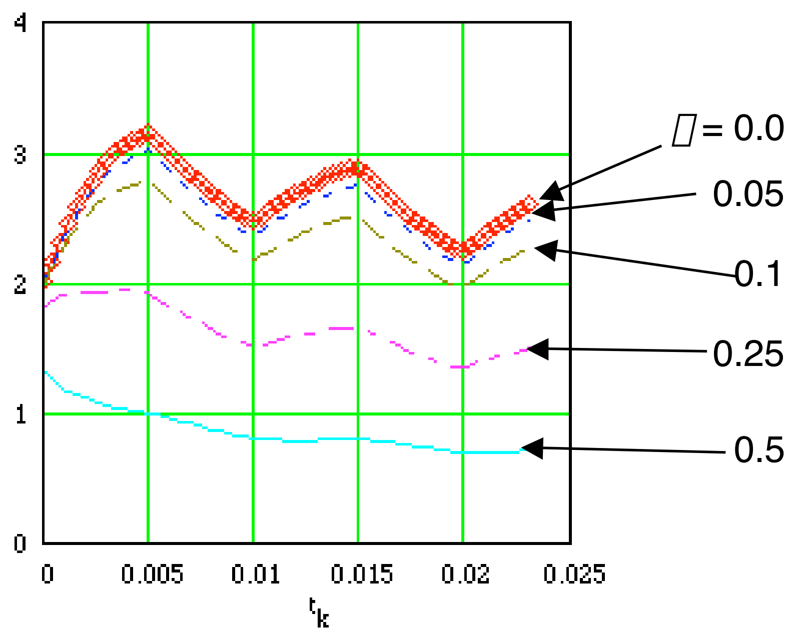
1D model

- Specified constant density profile
- χ_e profile *shape* specified [$\chi(\rho) = \chi(0) + (\chi(1) - \chi(0))\rho^{\alpha}$] magnitude adjusted to give experimental $\tau_e \approx 12$ ms
- Gaussian power deposition profile to electrons, approx. same as from AORSA

Power deposition profile
Density profile
χ_e profile [$\chi(0)/\chi(1) = 0.05$, $\alpha = 2$]
(all normalized)



$T_e(t)$ for different χ values
with 50% modulation
(arb. units)



Changing χ_e profile still gives significant T_e change

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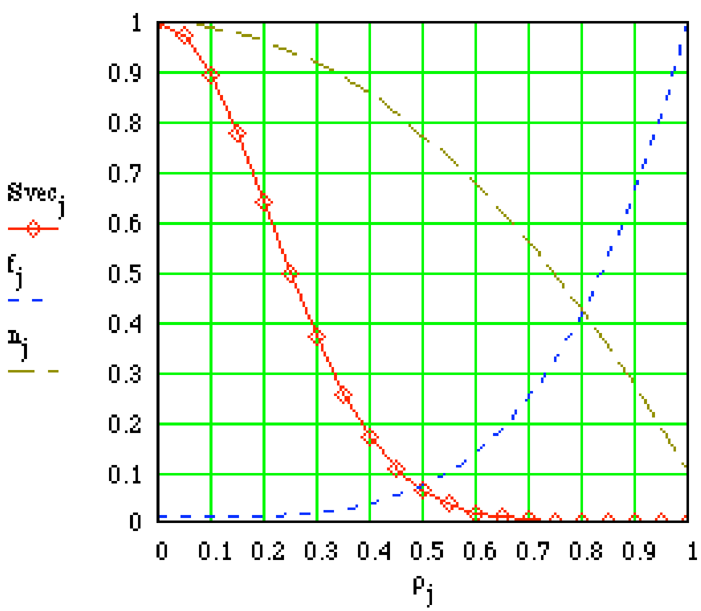
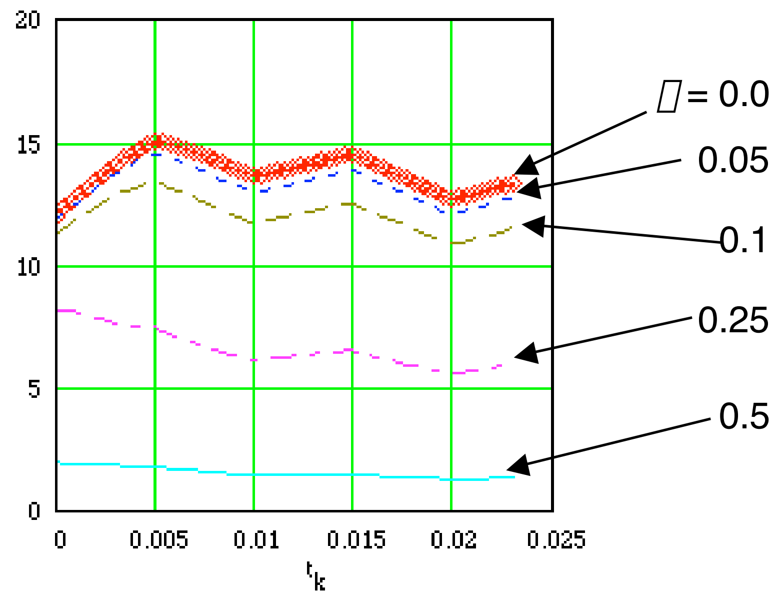
Changing χ_e profile shape can alter $\delta T_e/T_e$ some, but still get ≥ 10% peak-to-peak change during modulation

- Changed $\chi_e(0)/\chi_e(1)$ and shape (≈ ρ^4 instead of ρ^2)
- Adjusted magnitude to keep τ_e ≈ 12 ms

Power deposition profile
Density profile
χ_e profile [$\chi(0)/\chi(1) = 0.01$, $\alpha = 4$]
(all normalized)



$T_e(t)$ for different α values
with 50% modulation
(arb. units)

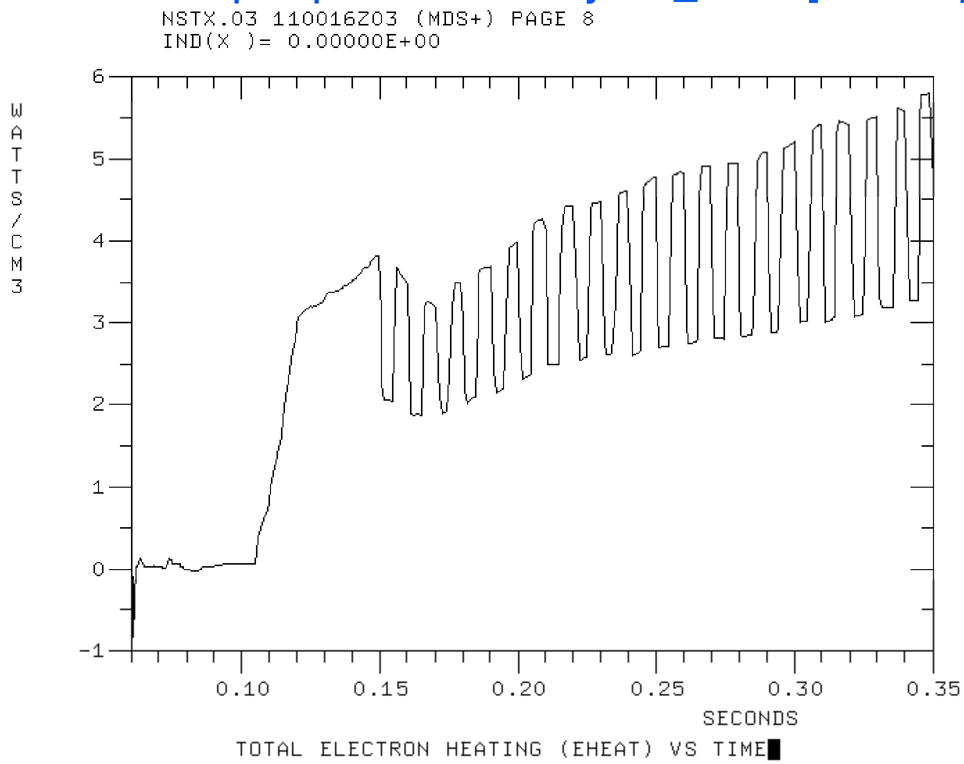


TRANSP simulation

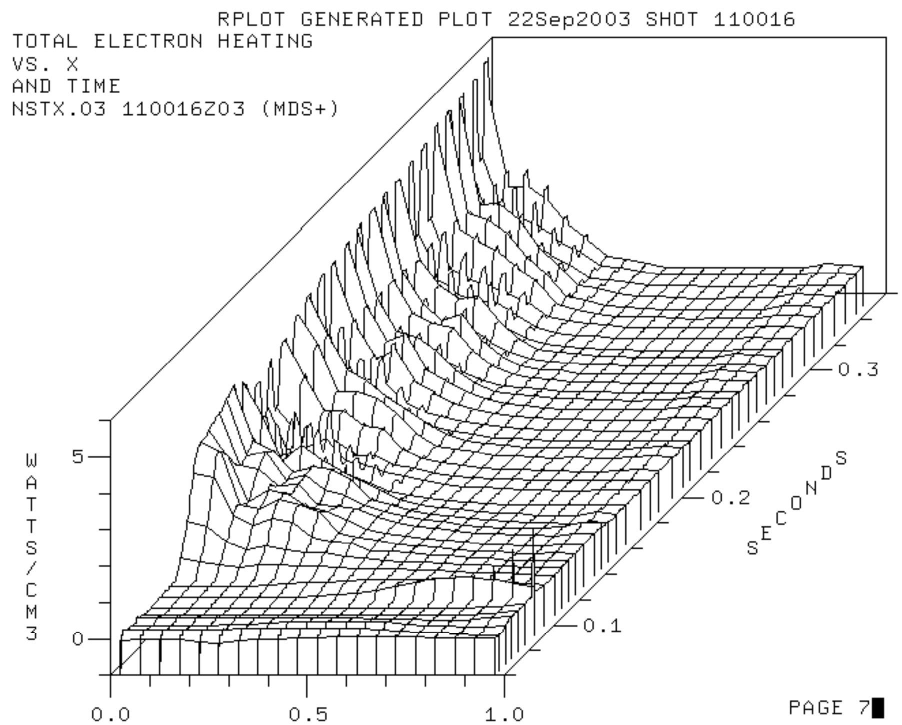
TRANSP run with experimental data to see what might explain results

HHFW power input to TRANSP used (constant) AORSA profile, with total rf power modulated

Total input power density at = 0. [W/cm³]



Total input power density vs. and *t*



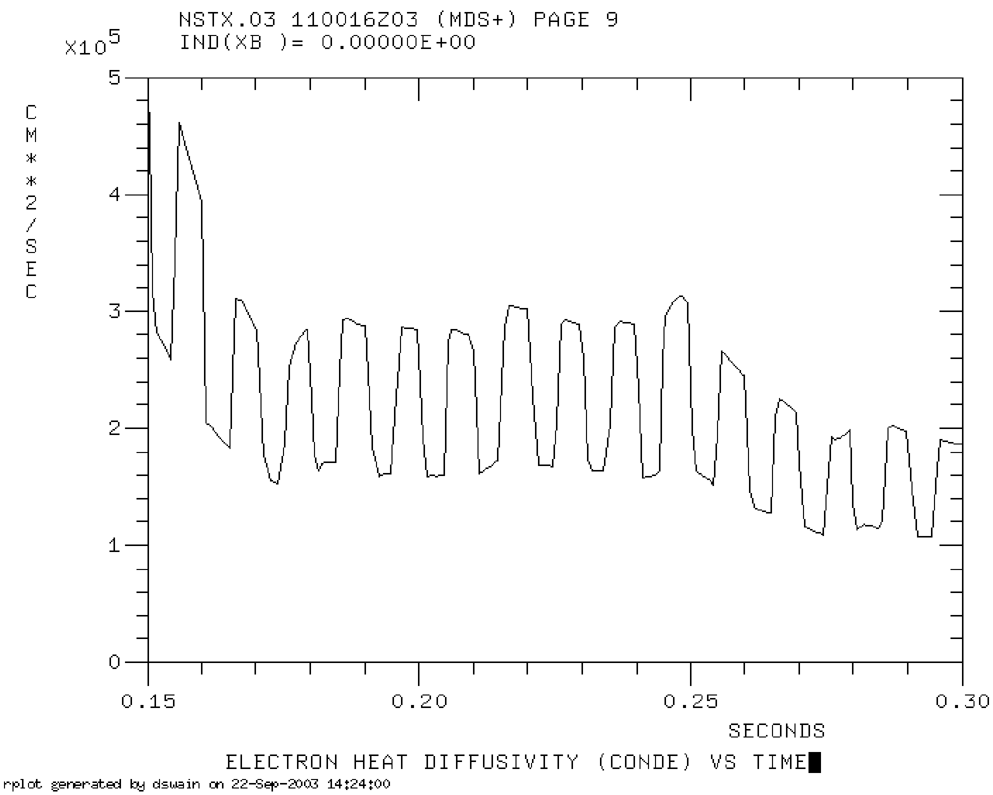
The assumption of no T_e modulation yields time-varying χ_e

TRANSP input:

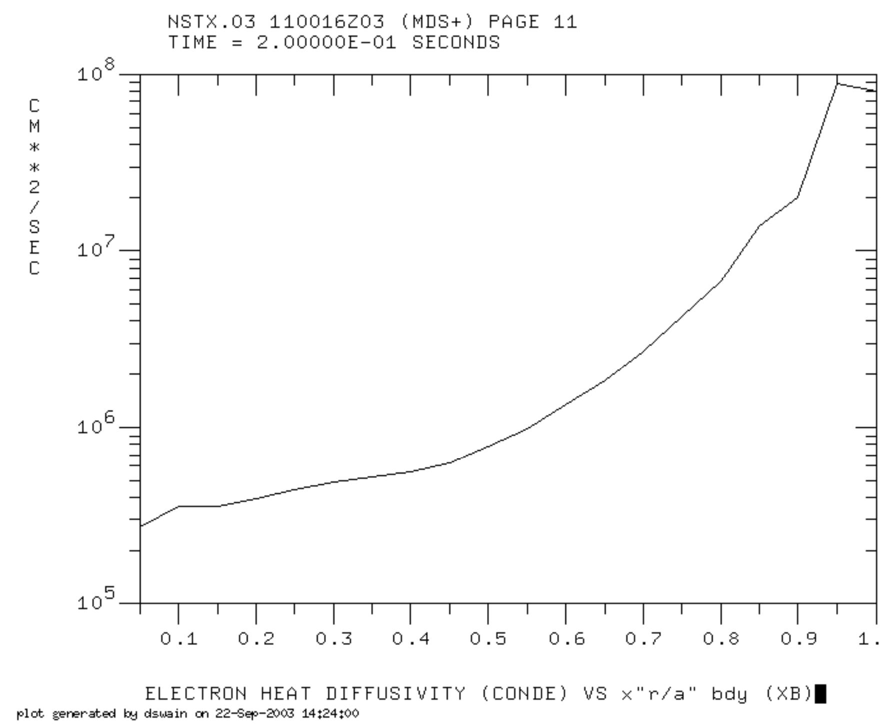
- T_e (R) from Thomson scattering (data every 17 ms)
- Assumed *smooth* transition between TS data points (i.e., no modulation)

Results give peak-to-peak variation in $\Delta\chi_e/\chi_e$ > 50%

$\chi_e(0)$ vs t [cm^2/s]



$\chi_e(\rho)$ at t = 0.20 s [cm^2/s]



Summary

Initial HHFW modulation experiment carried out in NSTX

- Sees very small change (≤ 1%) in T_e during modulation
- *BUT* - definite electron heating (with approx. expected confinement time) observed *over a longer time period*

Calculations indicate that $\Delta T_e/T_e$ in the 10 - 20% range should be seen

Possible explanations are:

- Significant change in central value of electron thermal conductivity during modulation?
- Off-axis power deposition?
- Off-setting density and temperature changes? (i.e., when T_e increases, n_e drops)
- Other?

More experiments and calculations are needed to understand this very interesting result.