Characterization of Fast Ion Power Absorption of HHFW in NSTX

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NSTX

Introduction and Motivation

- Ion absorption critically important to assessing viability of HHFW to heat and drive current in STs

- Experimental evidence of HHFW interaction with NBI
  - Neutral Particle Analyzer (NPA) scannable at midplane
  - neutron rates, Fast Lost Ion probes

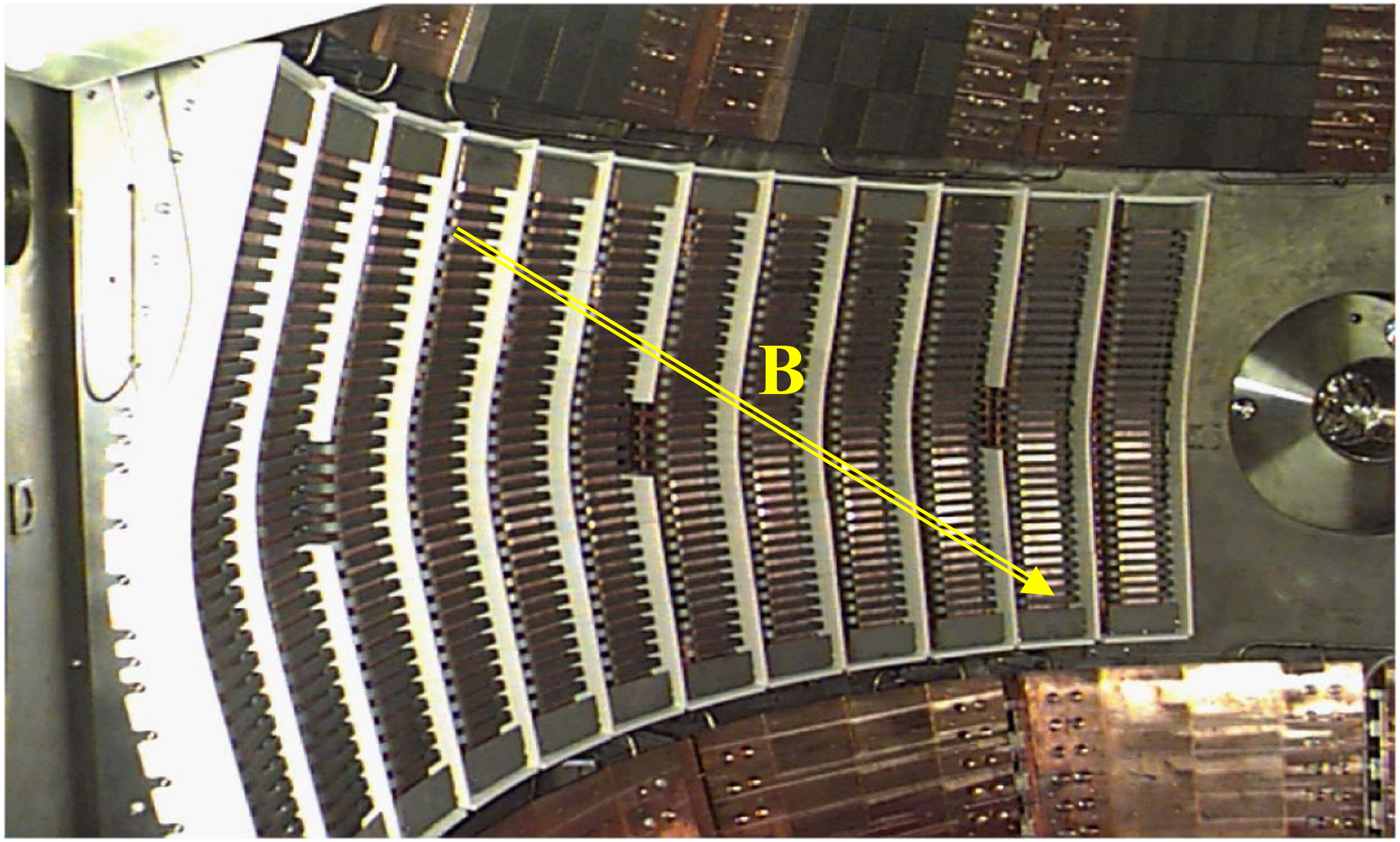
- Thompson scattering measures T_e, n_e profiles
  - X-ray Crystal Spectroscopy measures peak T_i

- Computational evidence
  - HPRT, TRANSP, CURRAY, AORSA, METS

NSTX Utilizes the TFTR ICRF system

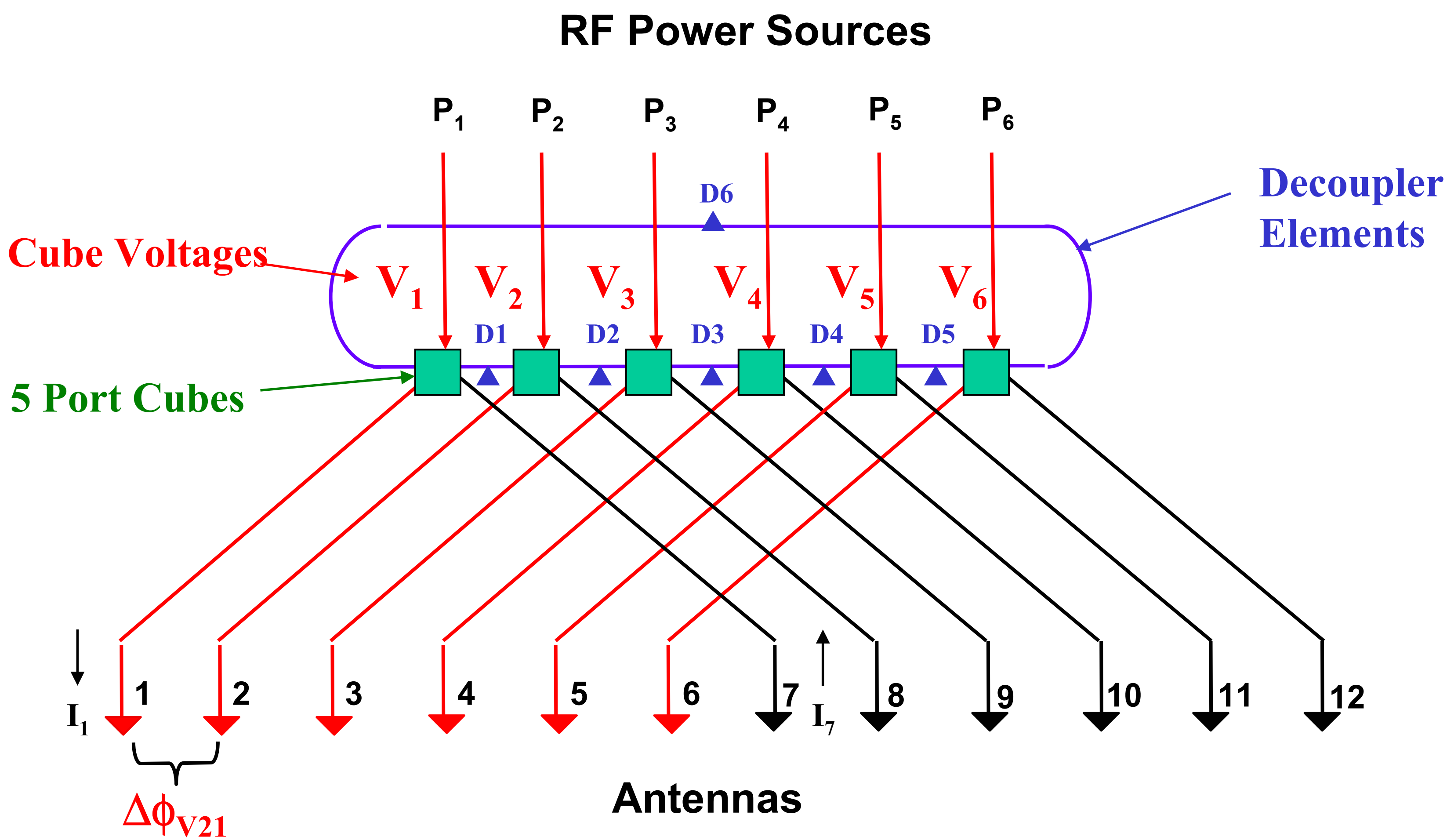
- 30 MHz Frequency corresponds to ω/Ω_D = 9-13
- 6 MW from 6 Transmitters for up to 5 s
- 12 Element antenna with active phase control allows wide variety of wave spectra
  - $k_{||} = \pm$ 3-14 m^{-1}

HHFW 12 element antenna array



- Antenna takes up almost 90° toroidally
- Provides high power capability with good spectral selectivity

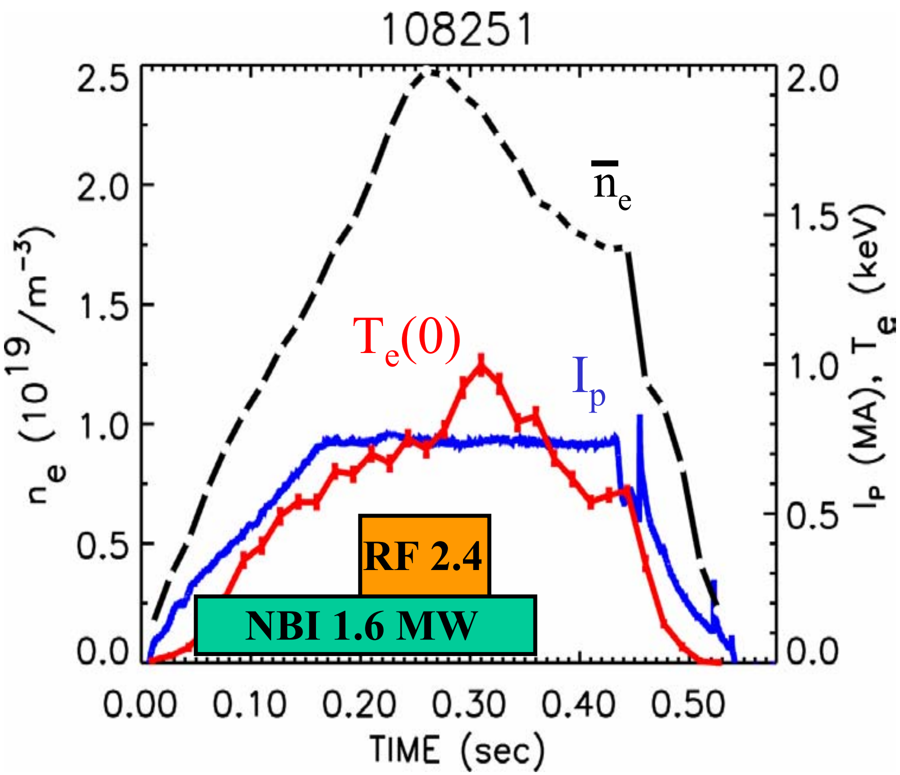
Phase Feedback Control Configuration



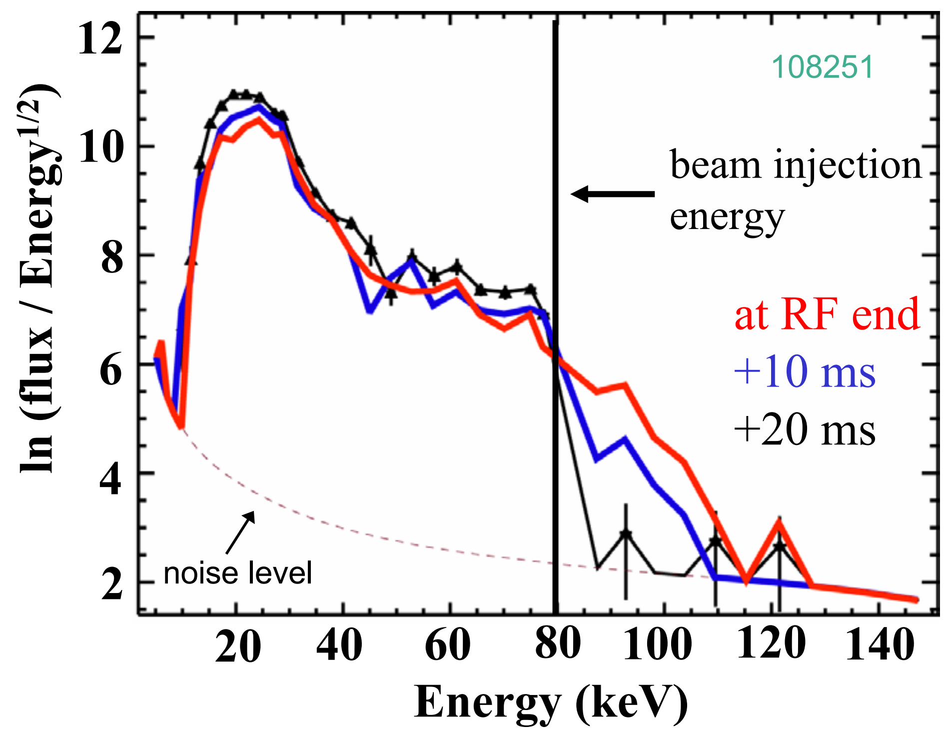
- Digital based phase feedback control is used to set the phase between the voltages of antenna elements 1 through 6
- Decouplers compensate for large mutual coupling between elements and facilitate phase control

HHFW can generate a fast ion tail with NBI

- Typical shot



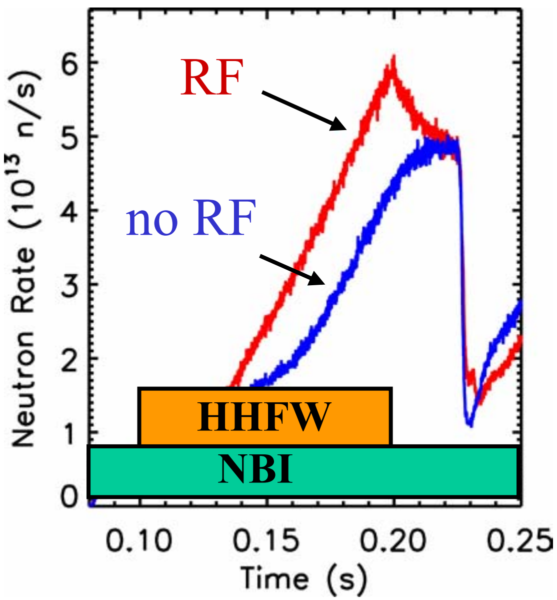
- D^+ tail extends to 130 keV
- Tail saturates in time during HHFW



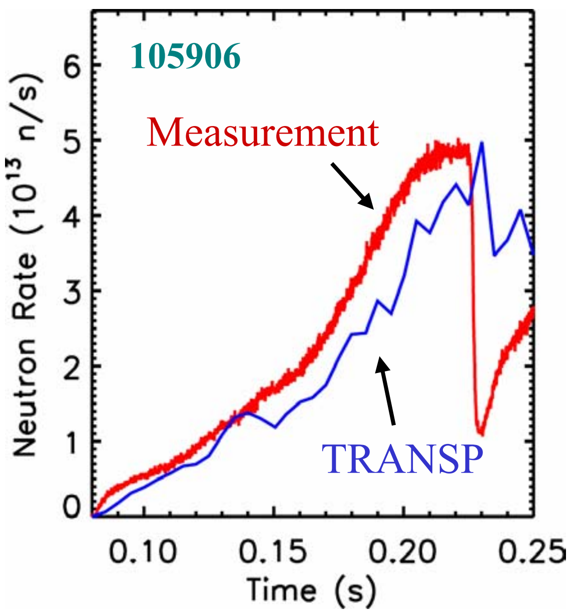
- Tail decays on collisional time scale

HHFW enhances neutron rate

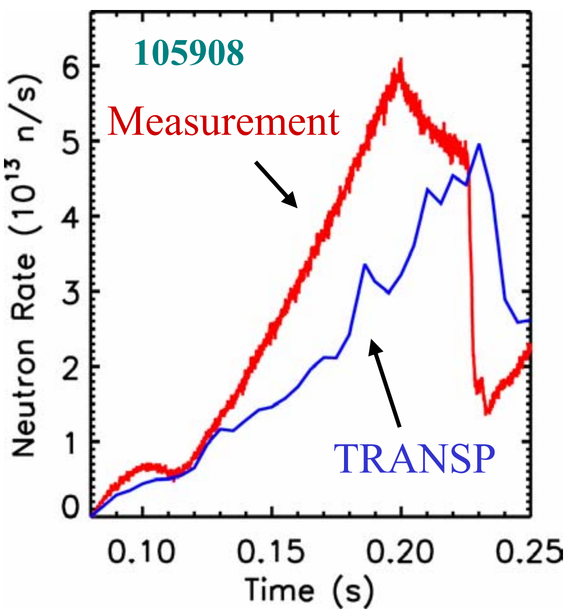
Measured RF vs. no RF



No RF

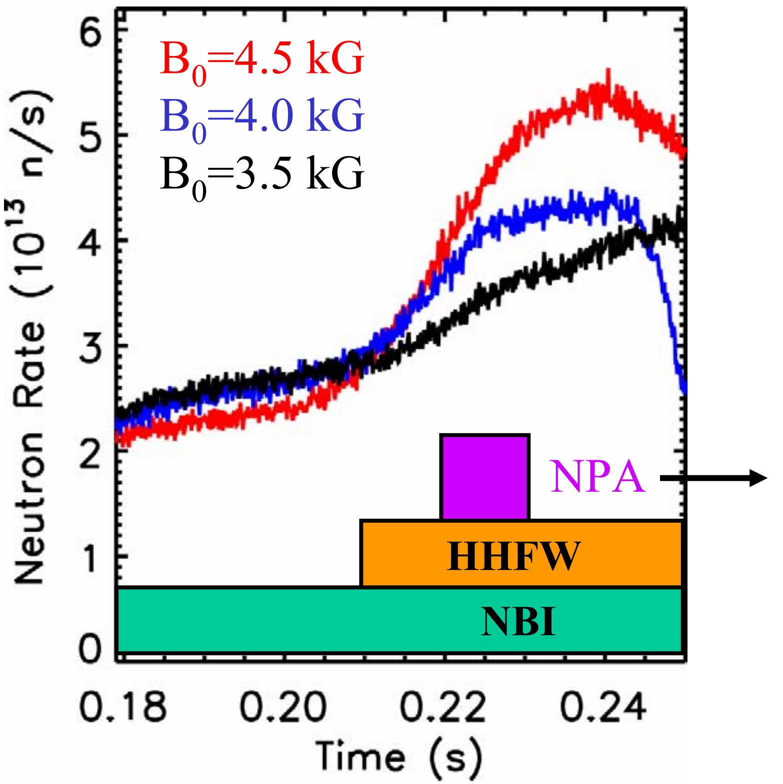


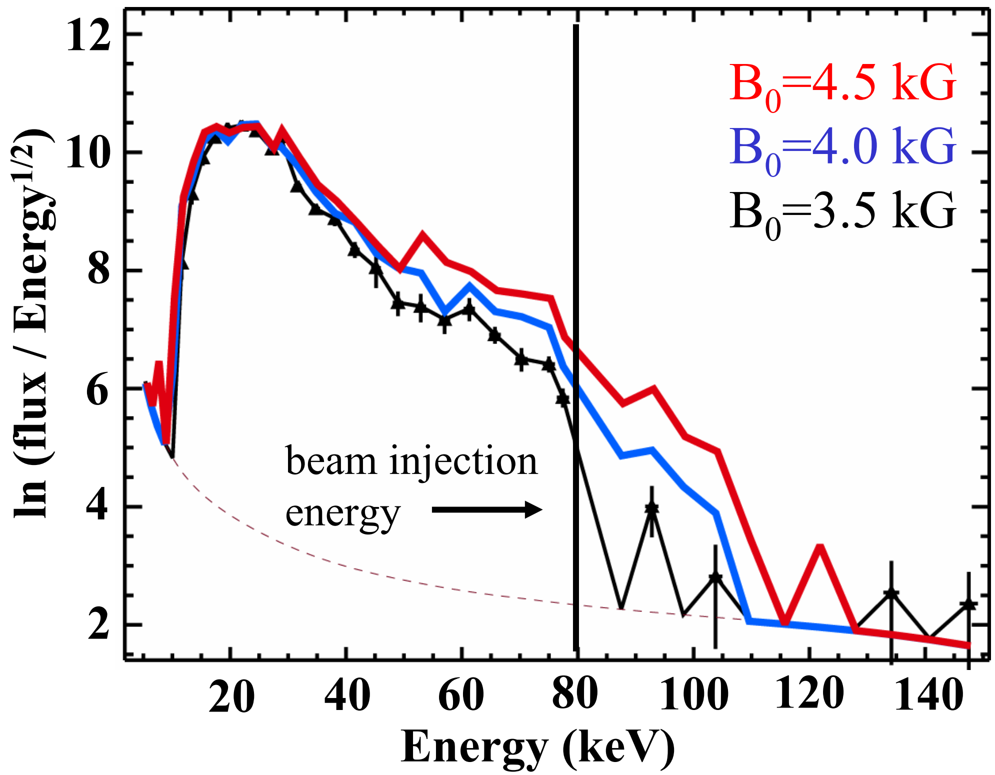
RF



- After RF turnoff, rate decays close to measured and predicted no RF value
- TRANSP neutron rate predictions without RF input fall shorter than measured rate for RF shot

Tail reduced with lower B-field, higher β_t



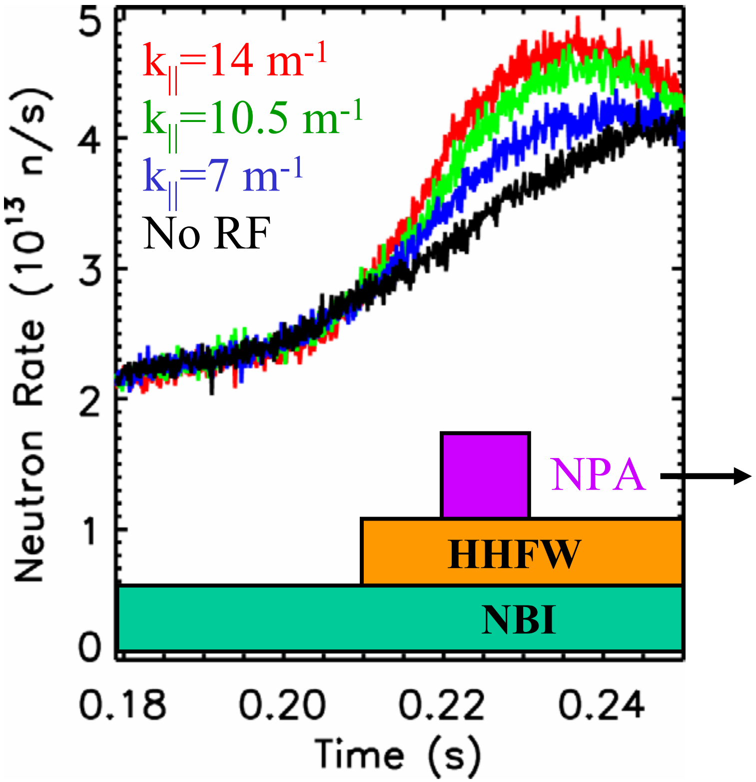


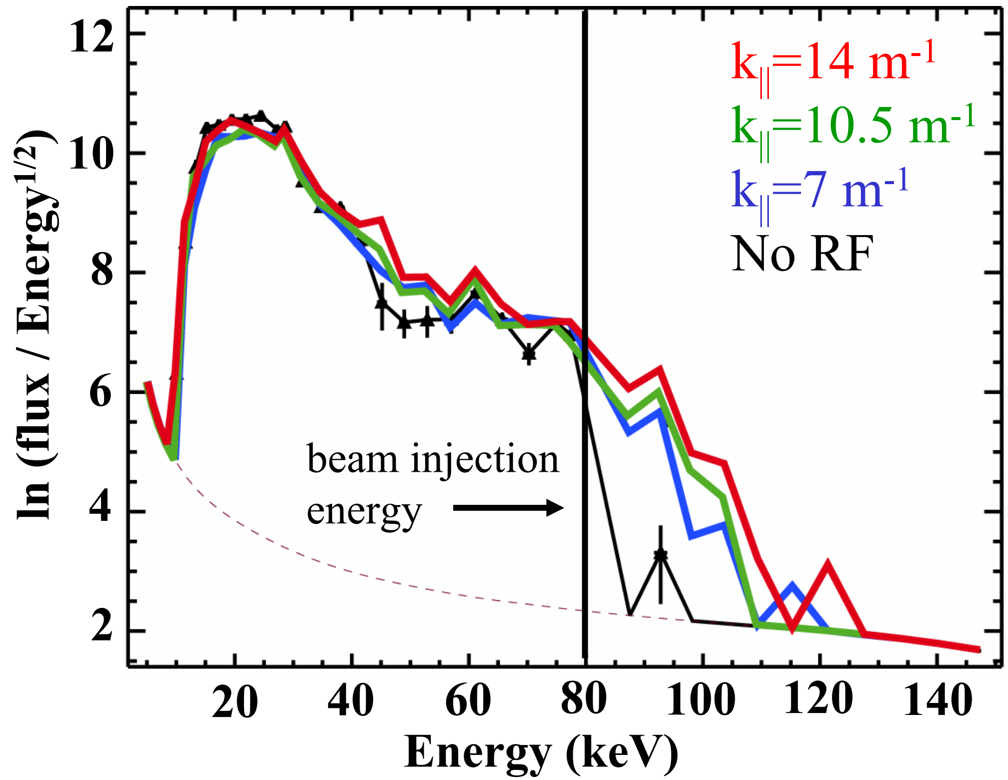
- Larger β_t promotes greater off-axis electron absorption
- Reduces fraction of power available to core fast ion population

Ion loss with lower B-field can't account for reduction in tail

- Two codes used to check ion loss at B_0=4.5 kG vs. 3.5 kG for 80-120 keV ions
- CONBEAM – Egedal (MIT-PSFC)
  - Loss fraction at 120 keV B_0 = 4.5 kG: 21%
    B_0 = 3.5 kG: 25%
- EIGOL – Darrow (PPPL)
  - Loss fraction at 120 keV B_0 = 4.5 kG: 17%
    B_0 = 3.5 kG: 23%
- Small change in loss fraction insignificant compared to major tail reduction
  - More likely an RF effect

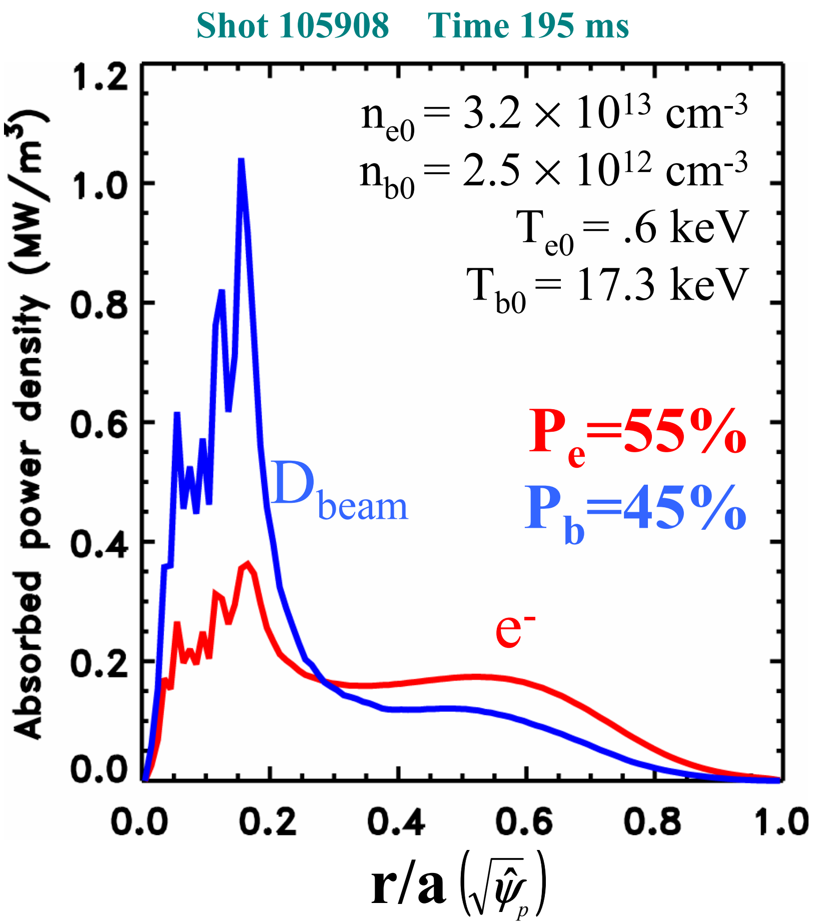
$k_{||}$ has little observed effect on fast ions





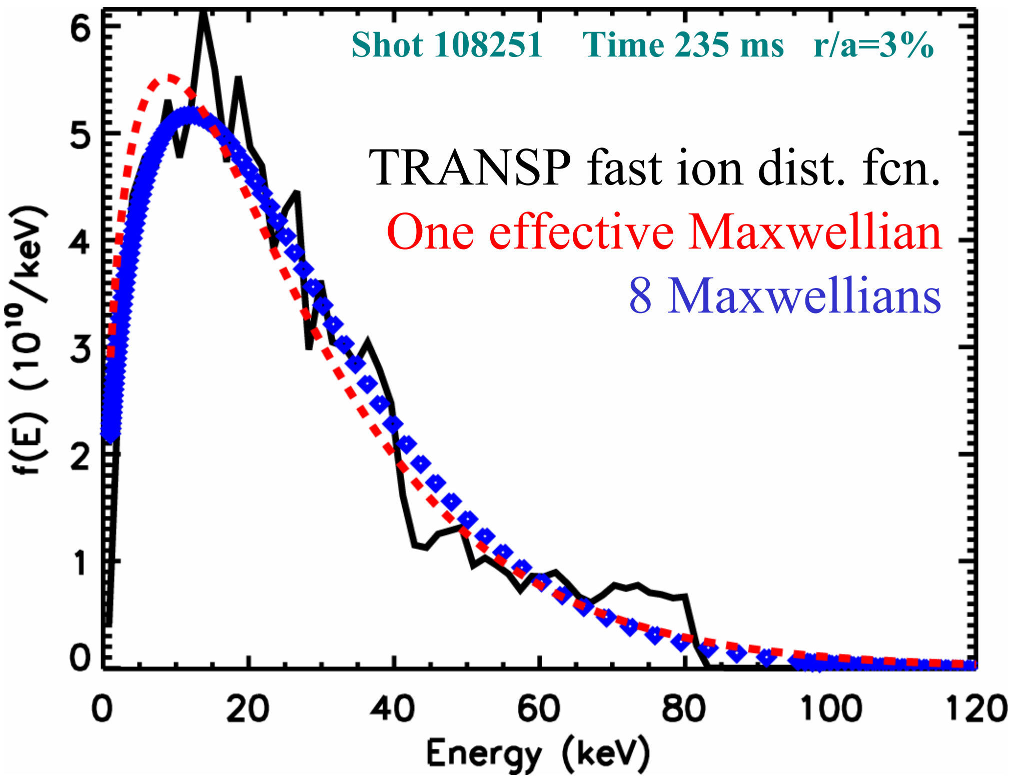
- Greater ion absorption predicted with lower $k_{||}$, but surprisingly little variation in tail, small neutron enhancement with higher $k_{||}$

Ray tracing predicts fast ion absorption competitive with electrons



- HPRT computes hot plasma absorption over cold ion/hot electron ray path
- 25-50 rays used
- TRANSP output used as input for fast ion temp and density distribution
- Fast ions dominate central absorption, electrons further off-axis
- $T_{i,th} = 2\ T_e$ (XCS), no thermal ion absorption

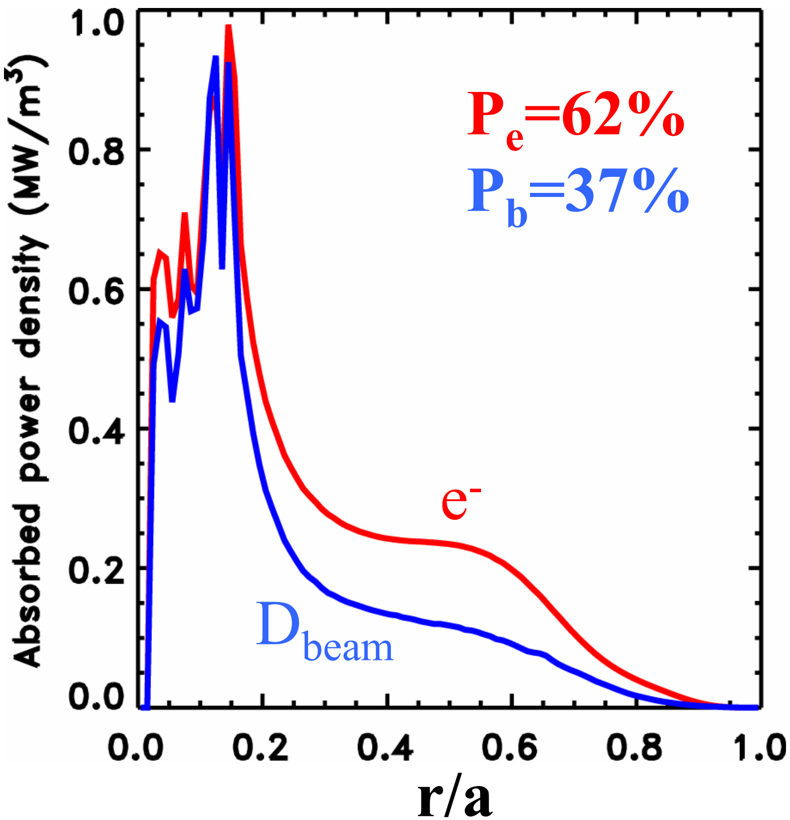
Effective Maxwellian a good approximation for fast ions



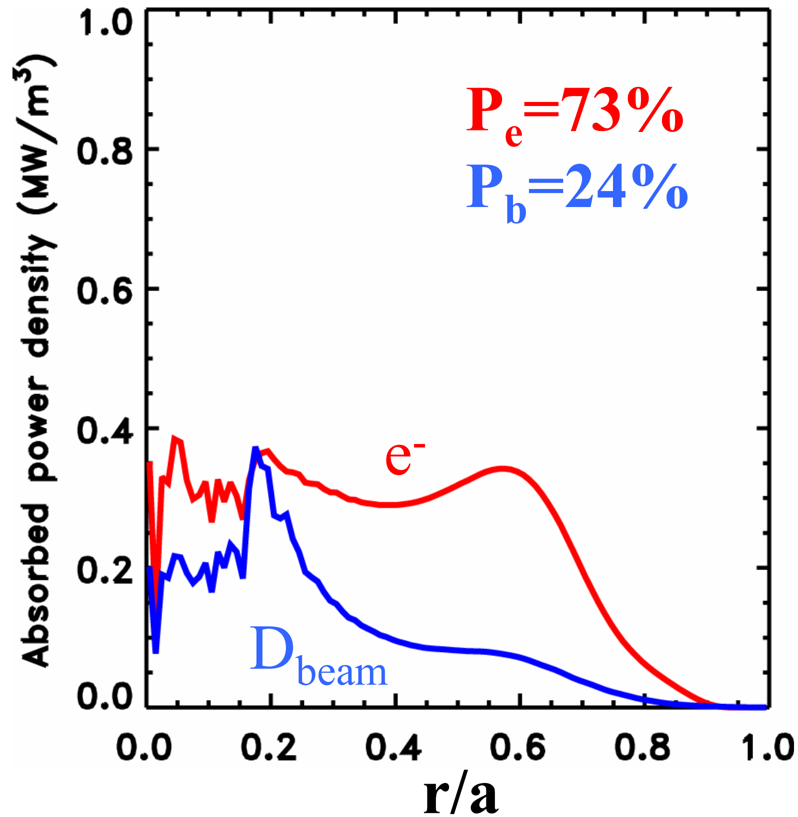
- One effective Maxellian, exactly matching TRANSP energy density and temp., fits f(E) well, though neutron rate off +20%
- More Maxwellians (including negative) can match all moments

Observation of less fast ion absorption at higher β_t consistent with theory

β_t=5%, B_0=4.5 kG



β_t=9%, B_0=3.5 kG



- Lower on-axis absorption for lower B, higher β_t predicted

HPRT Power Absorption

- Energy moment of Vlasov eq. + vector identities leads to [Menard, RF 1999]:

$$\frac{\partial}{\partial t}\int \mathbf{d}^3\mathbf{v}\,\frac{\mathbf{m}_s v^2}{2} f_s + \nabla\cdot\int \mathbf{d}^3\mathbf{v}\,\frac{\mathbf{m}_s v^2}{2}\mathbf{v}\, f_s = \mathbf{E}\cdot q_s\int \mathbf{d}^3\mathbf{v}\,\mathbf{v}\, f_s$$

- The first non-vanishing terms of this are:

$$\frac{\partial W_{ps}}{\partial t} + \nabla\cdot\mathbf{T}_s = \mathbf{E}\cdot\mathbf{j}_s$$

- Kinetic flux term is necessary if one uses the full hot, complex dielectric tensor

Clarifying Kinetic Flux

NSTX

- In Stix (4-15) $$\frac{\partial W}{\partial t} = \frac{1}{8\pi}\left[\omega\,\mathbf{E}^{*}\cdot\left(\mathbf{k}_{i}\cdot\frac{\partial}{\partial \mathbf{k}}\boldsymbol{\varepsilon}_{h}\right)\cdot\mathbf{E} + \ldots\right]$$

- In Stix (4-17,19) $$\frac{\partial W}{\partial t} = -2\mathbf{k}_{i}\cdot\mathbf{T} + \ldots \qquad \mathbf{T} = -\frac{\omega}{16\pi}\mathbf{E}^{*}\cdot\frac{\partial}{\partial \mathbf{k}}\boldsymbol{\varepsilon}_{h}\cdot\mathbf{E}$$

- 1st important note – Stix, p. 75: "In expression for **T**, the dot products are between $\mathbf{E}^{*}$ and ε_h, and ε_h and **E**."

- So, *unambiguous* **T** is: $$\mathbf{T} = -\frac{\omega}{16\pi}\frac{\partial}{\partial \mathbf{k}}\left(\mathbf{E}^{*}\cdot\boldsymbol{\varepsilon}_{h}\cdot\mathbf{E}\right)$$

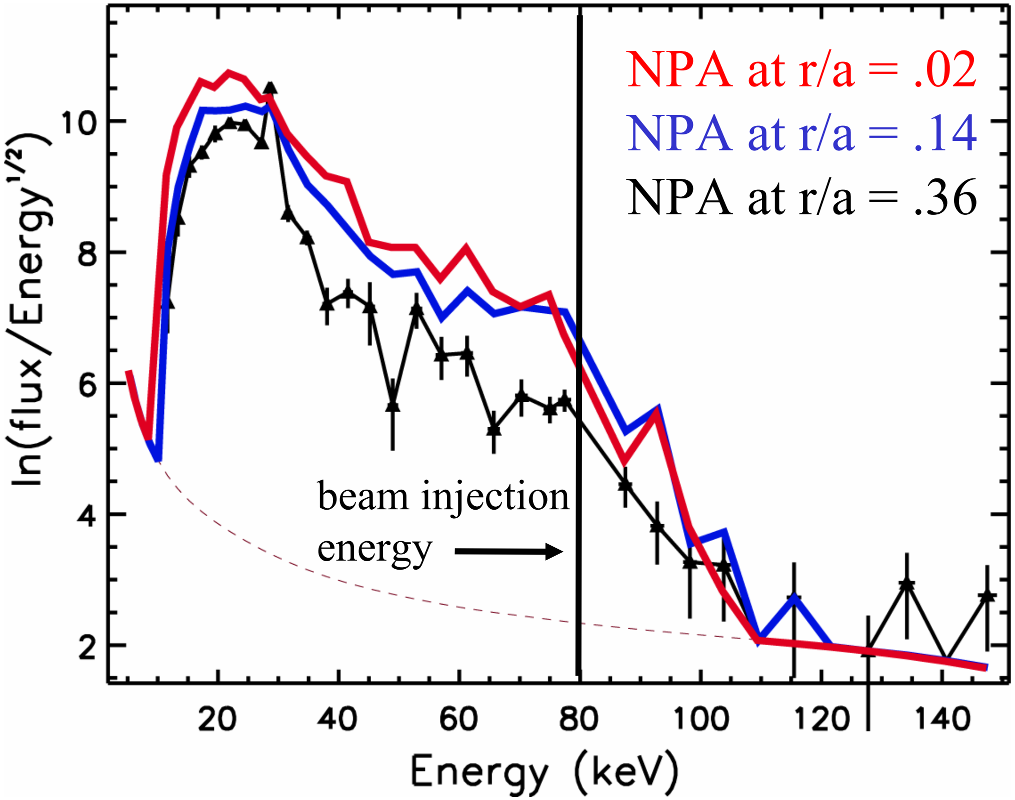
- Does (4-15) = (4-17)? Yes! However…

Only $\nabla\cdot\mathbf{T}$ is unique

$$\mathbf{E}^* \cdot \left(\mathbf{k}_i \cdot \frac{\partial}{\partial \mathbf{k}} \boldsymbol{\varepsilon}_h \right) \cdot \mathbf{E} \quad \text{also equals:} \quad \mathbf{k}_i \cdot \left[\frac{\partial}{\partial \mathbf{k}} \left(\mathbf{E}^* \cdot \boldsymbol{\varepsilon}_h \cdot \mathbf{E} \right) + \mathbf{k}_i \times \boldsymbol{anything} \right]$$

- So expression for **T** is *not unique*; only $\nabla\cdot\mathbf{T}$ well-defined
- Common loss-free plasma approximation of group velocity: $\mathbf{v}_g = \dfrac{\mathbf{P}+\mathbf{T}}{W}$ is invalid, as is any expression which uses **T** in this form.
- 2nd important note: $\mathbf{E}^* \cdot \left(\mathbf{k}_i \cdot \frac{\partial}{\partial \mathbf{k}} \boldsymbol{\varepsilon}_h \right) \cdot \mathbf{E} \neq \mathbf{k}_i \cdot \left(\mathbf{E}^* \cdot \frac{\partial}{\partial \mathbf{k}} \boldsymbol{\varepsilon}_h \right) \cdot \mathbf{E}$
- RHS gets wrong cross derivatives wrt **k**

NPA scan indicates induced tail well off-axis



- Depletion in particle flux with NPA R_{tan} further off-axis
- Tail extends to same energy range
- Future: scan over wider range of r/a

Summary

- Clear RF-induced fast ion tail observed with NBI
- Neutron rate and modeling support interaction
  - Good agreement between HPRT, AORSA, CURRAY
- Tail formation suppressed with higher β_t
- Little effect with $k_{||}$ observed
- Effective Maxwellians can represent fast ion f(E)
- Kinetic flux clarified