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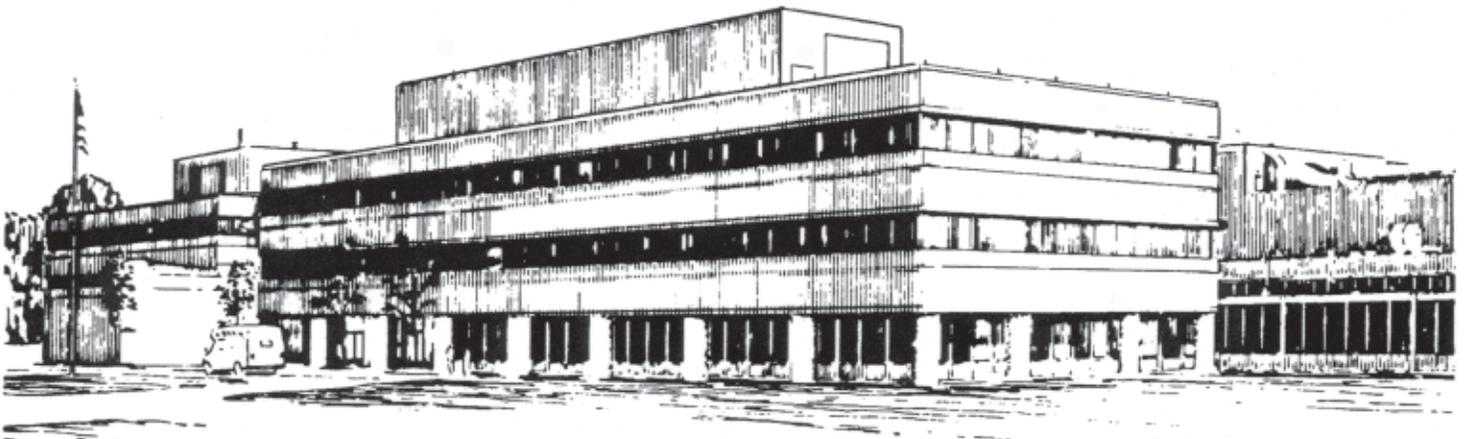
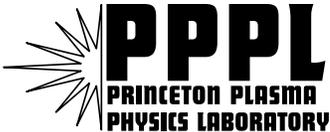
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**Characterization of Fast Ion Absorption  
of the High Harmonic Fast Wave  
in the National Spherical Torus Experiment**

by

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# Characterization of Fast Ion Absorption of the High Harmonic Fast Wave in the National Spherical Torus Experiment <sup>1</sup>

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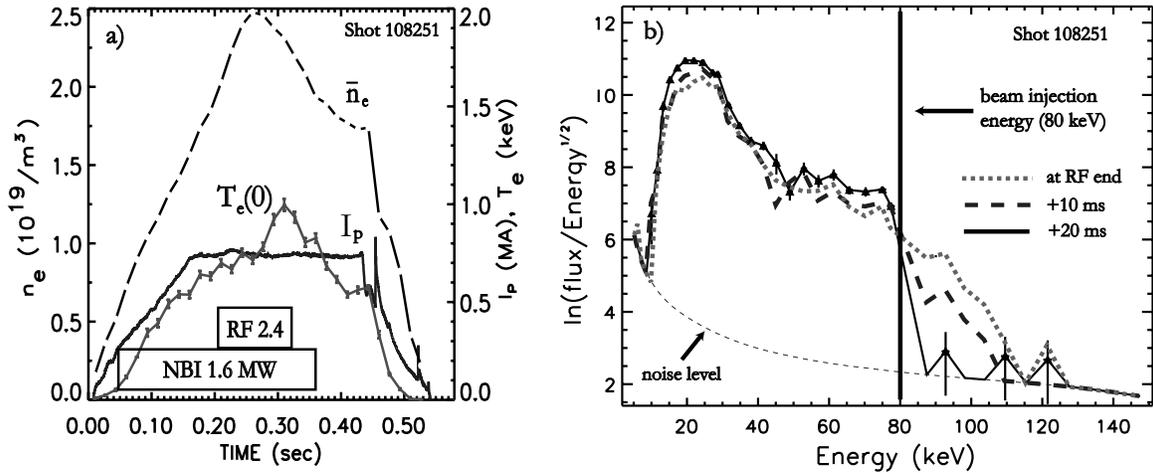
**Abstract.** Ion absorption of the high harmonic fast wave in a spherical torus is of critical importance to assessing the viability of the wave as a means of heating and driving current. Analysis of recent NSTX shots has revealed that under some conditions when neutral beam and RF power are injected into the plasma simultaneously, a fast ion population with energy above the beam injection energy is sustained by the wave. In agreement with modeling, these experiments find the RF-induced fast ion tail strength and neutron rate at lower B-fields to be less enhanced, likely due to a larger  $\beta$  profile, which promotes greater off-axis absorption where the fast ion population is small. Ion loss codes find the increased loss fraction with decreased B insufficient to account for the changes in tail strength, providing further evidence that this is an RF interaction effect. Though greater ion absorption is predicted with lower  $k_{\parallel}$ , surprisingly little variation in the tail was observed, along with a small neutron rate enhancement with higher  $k_{\parallel}$ . Data from the neutral particle analyzer, neutron detectors, x-ray crystal spectrometer, and Thomson scattering is presented, along with results from the TRANSP transport analysis code, ray-tracing codes HPRT and CURRAY, full-wave code and AORSA, quasi-linear code CQL3D, and ion loss codes EIGOL and CONBEAM.

## INTRODUCTION

Interaction between the high harmonic fast wave (HHFW) and energetic particles in a spherical torus (ST) [1] is a new and important research area. A fast ion population of fusion-born alpha particles will be found in a reacting plasma, along with energetic ions from neutral beam injection (NBI) in some scenarios. HHFW is currently being

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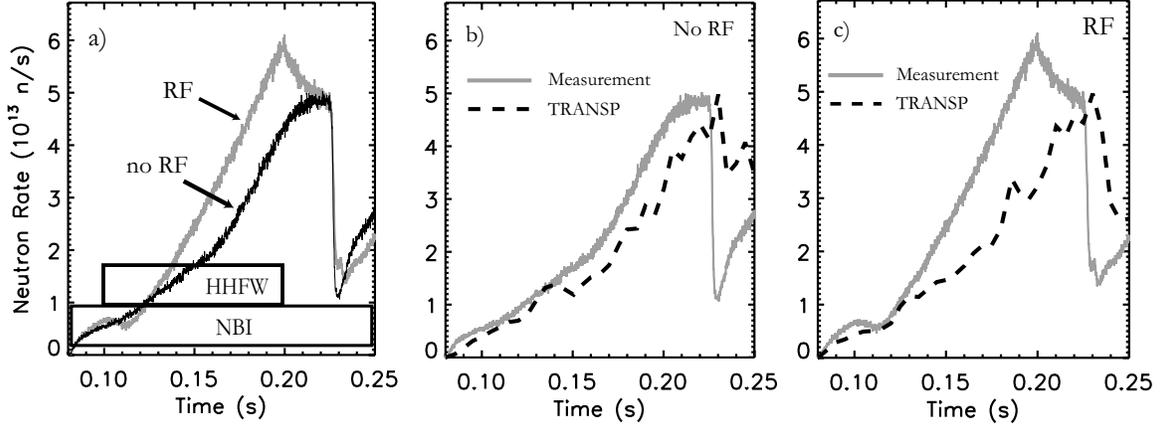
**FIGURE 1.** a) Typical line-averaged density, temperature, plasma current, NBI, and RF power profiles for scans in recent experiments. b) Neutral particle analyzer data for NSTX shot 108251, launched  $k_{\parallel} = 14 \text{ m}^{-1}$  (heating phasing), after RF turns off at  $t = 320 \text{ ms}$ . Fast ion population above 80 keV beam injection energy collapses to a typical no-RF distribution within 20 ms.

explored as a means of heating and driving plasma current. In NSTX's most recent campaigns, a clear fast ion tail was observed on the neutral particle analyzer (NPA) when HHFW and NBI were active simultaneously. Neutron detector and ion loss probe signals provided further evidence for interaction. This occurred for nearly every shot there was a significant overlap in RF and NBI power traces. Ray-tracing was used to analyze these shots, and found absorption by fast ions to be competitive with electron absorption. Measured neutron rates for similar RF and no-RF shots were also compared with predicted rates, and a significant RF-induced enhancement was found, consistent with the enhanced tail.

## EXPERIMENTAL STUDIES

For all shots analyzed, the neutral beam injected deuterium into the plasma at  $E_{beam} \approx 80 \text{ keV}$ ,  $P_{beam} \approx 1.6 \text{ MW}$ . Without RF, the energy spectrum observed by the NPA dropped out above  $\sim 80 \text{ keV}$ . With RF, the energy spectrum extended to  $\sim 130 \text{ keV}$ . Furthermore, after RF turnoff with NBI remaining active, the tail decayed to the no-RF spectrum on a time scale comparable to that for decay of a beam-only distribution, as seen in Figure 1. The ZnS and fission neutron detectors also saw a significant signal enhancement with RF. This signal began dropping immediately upon RF turnoff as well. As shown in Figure 2a, for similar shots with and without RF, within 25 ms of RF turnoff the enhanced neutron rate decays to the no RF value.

To further examine the fast ion absorption dependence on various parameters, scans in  $B_0$  and  $k_{\parallel}$  were performed. These shots all had similar electron temperature and density profiles, so the scan in  $B_0$  effectively became a  $\beta_t$  scan. As demonstrated in Figure 3, the neutron rate was found to decrease with decreasing toroidal field, and the fast ion tail on the NPA dropped to nearly a no-RF spectrum. In Ref. [2], total

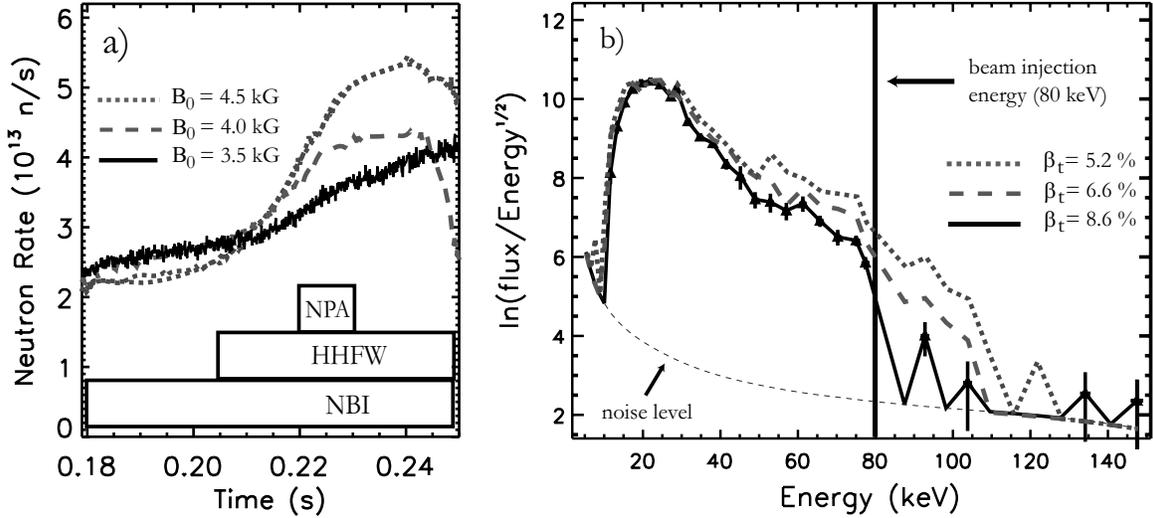


**FIGURE 2.** a) Neutron rates for NSTX shots 105906 (no RF) and 105908 (RF). b) Neutron rate for no RF vs. TRANSP prediction. After RF turns off, rate decays close to measured and predicted no RF value. c) Measured neutron rate for RF shot significantly exceeds TRANSP prediction without RF input.

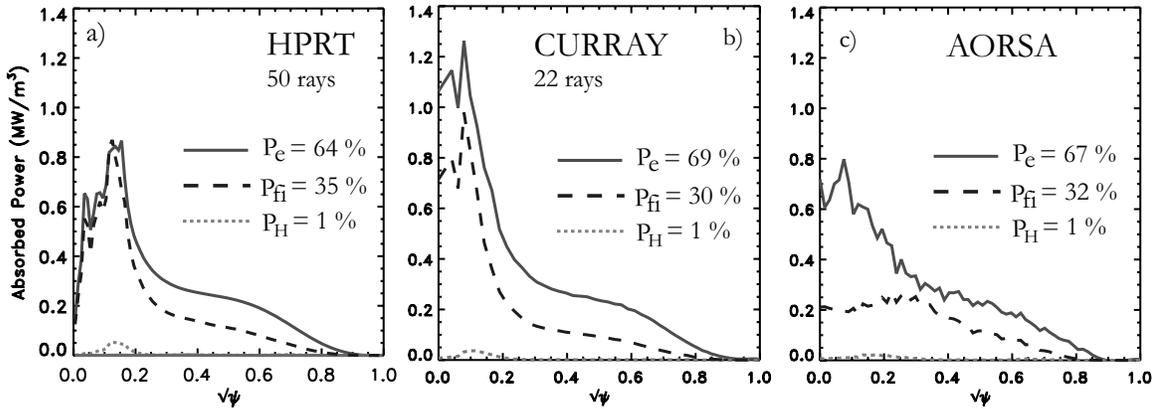
absorption is predicted to increase with  $\beta$ , and because the fast ion population is quite centralized, these experimental results are consistent with theory as less power from an antenna on the outboard side of the plasma would be available to core fast ions in a high  $\beta$  shot. Though greater ion absorption is predicted with lower  $k_{\parallel}$  [3,4], surprisingly little variation in the tail was observed, along with a small neutron rate enhancement with higher  $k_{\parallel}$ . This discrepancy may be due to different edge coupling conditions at different antenna phasings. The antenna performance and reliability have recently been significantly improved, so this will be reinvestigated in the next NSTX campaign.

## THEORETICAL STUDIES

For analysis, the TRANSP [5] transport analysis code was used to calculate fast ion energy and particle density profiles, and this information was used to estimate an effective Maxwellian temperature for the fast ion population. These profiles, along with EFIT and Thomson data, were fed into HPRT, a 2-D ray-tracing code which uses the full hot plasma dielectric with complex  $k$  to compute power deposition profiles along the hot electron/cold ion ray path [3]. As shown in Figs. 4a and 5a, fast ion absorption was calculated to be competitive with electron absorption in sustained neutral beam shots, often taking  $\sim 35\%$  of the total RF power. Figures 4a-c show that these results and profiles matched those of CURRAY [6], an independently developed ray-tracing code, and AORSA [7], an all orders full wave code, reasonably well for RF+NBI equilibria. CQL3D [8], a quasi-linear code which currently uses a model of the fast ion distribution function rather than an effective Maxwellian, has also calculated 35% ion absorption for this shot, and finds a similar ion deposition profile. A comparison of typical ray paths in HPRT vs. wave front propagation calculated by AORSA is shown in Figure 6. Both codes launch waves from identical antenna geometry on the outboard side of the plasma. The flow of these paths are remarkably similar considering the quite different methods of calculation. It also helps demonstrate the importance of including



**FIGURE 3.** a) Neutron rates for otherwise similar NSTX shots at  $B_0 = 3.5, 4.0,$  and  $4.5$  kG, which correspond to  $\beta_t = 5.2, 6.6,$  and  $8.6\%$ , respectively. b) NPA signals at  $R_{\text{tan}} = 70$  cm for  $B_0$  scan, averaged over time window displayed in a). The larger  $\beta$  profile at lower  $B_0$  may promote greater off-axis electron absorption, reducing the fraction of power available to the centralized fast ion population.



**FIGURE 4.** Power deposition profiles for NSTX shot 108251,  $t = 235$  ms,  $n_\phi = 24$  from a) HPRT, 50 rays, b) CURRAY, 22 rays, and c) AORSA. Good agreement is found in fractional absorption and profiles between codes for RF+NBI shots.

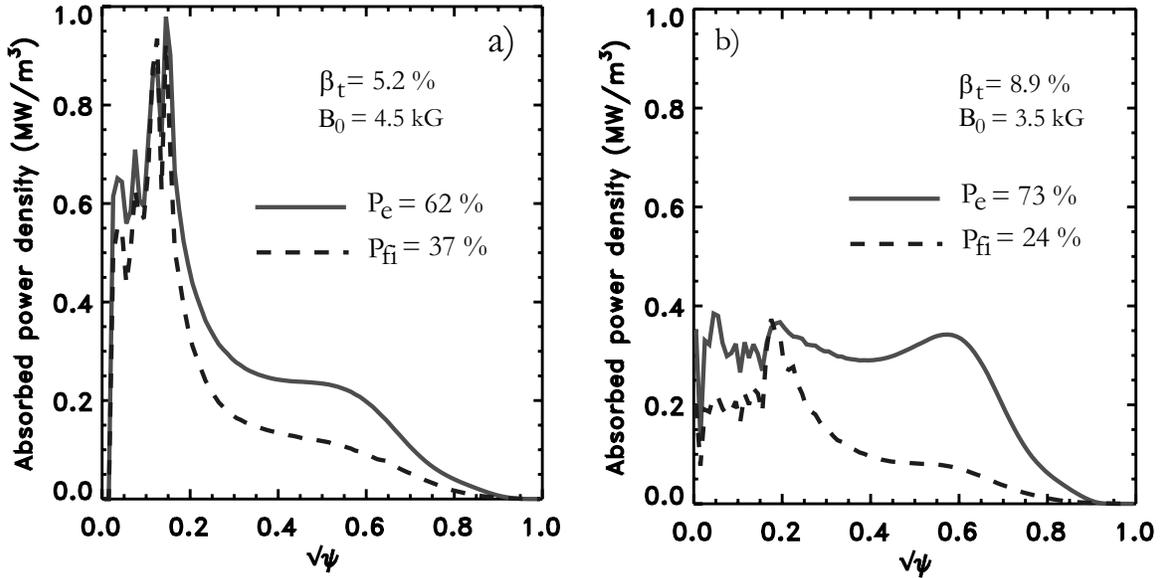


FIGURE 5. a) HPRT power deposition profiles for NSTX shot 108250,  $t = 230$  ms,  $B_0 = 4.5$  kG,  $\beta_t = 5.2\%$ . b) Shot 108252,  $t = 230$  ms,  $B_0 = 3.5$  kG,  $\beta_t = 8.9\%$ . Lower on-axis absorption is calculated for lower  $B$ , higher  $\beta$ , in agreement with neutron rate and NPA signals.

2D effects in absorption calculations for ST equilibria. Figure 5 shows HPRT calculated deposition profiles for the experimental magnetic field scan. Lower on-axis absorption is calculated for lower  $B$ , or higher  $\beta$ , in agreement with the neutron rate and NPA signals in Figure 3, as the greater off-axis electron absorption in higher  $\beta$  shots would prevent as much RF power from reaching the bulk of the fast ion population near the magnetic axis. An increased fast ion loss fraction at lower  $B$  may also contribute to suppression of the observed tail, so loss codes EIGOL [9], which follows the full fast ion orbit, and CONBEAM [10], which follows the guiding center of the orbits and accounts for finite larmor radius effects, were used to determine the significance of this factor. For 120 keV ions, EIGOL calculates a loss fraction of 17% for a  $B_0 = 4.5$  kG equilibrium - NSTX shot 108250,  $t = 235$  ms, and 23% for  $B_0 = 3.5$  kG - shot 108252,  $t = 235$  ms. CONBEAM calculates a loss fraction of 21% for  $B_0 = 4.5$  kG, and 25% for  $B_0 = 3.5$  kG. According to the NPA data, the tail is suppressed by at least a factor of 8 between high and low field, so the tail reduction is more likely due to an RF effect.

Without providing RF input in either case, TRANSP was also used to calculate the neutron rates for similar RF and no-RF shots. As shown in Figure 2, the measured rate matched the prediction well in the no-RF case, and for the RF shot grew to nearly double the predicted rate. It then decayed to approximately the computed rate after RF turnoff. Figure 7a demonstrates that a single effective Maxwellian, matching fast ion particle and energy density exactly, fits the TRANSP  $f(E)$  remarkably well, however it exceeds the neutron rate calculated from the TRANSP distribution function by  $\sim 20\%$ . Figure 7b shows that the single Maxwellian has too large of a contribution to  $\int_0^E dE f(E) \sigma v$ , which is proportional to the neutron rate, above the beam injection energy, 80 keV. To model this neutron rate enhancement, multiple Maxwellians may

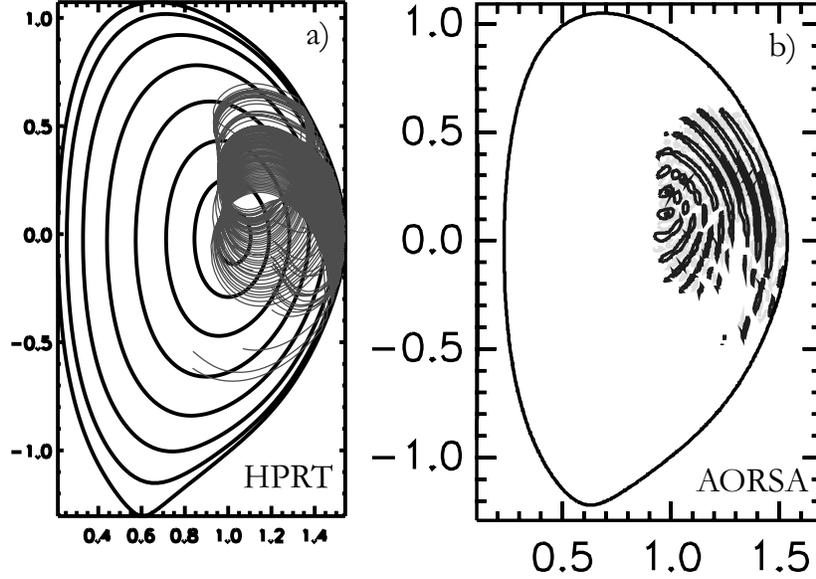


FIGURE 6. a) 50 HPRT ray paths, with initial positions distributed evenly over poloidal range of antenna, for NSTX shot 108251,  $t = 235$  ms,  $\beta = 5.2\%$ ,  $n_\phi = 24$ . Each ray stops when 99% of its power is absorbed. b) AORSA wave fronts for same shot.

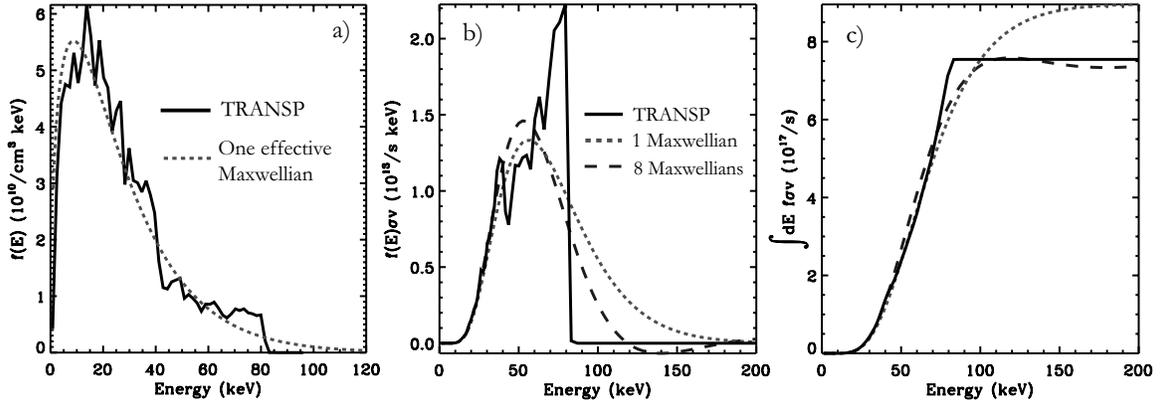


FIGURE 7. a) TRANSP  $f(E)$  for NSTX shot 108251,  $t = 235$  ms,  $r/a = 3\%$  vs. an effective Maxwellian matching its total energy and particle density exactly. The neutron rate from this Maxwellian exceeds TRANSP's by  $\sim 20\%$ . b) TRANSP  $f(E)\sigma v$  vs. one effective Maxwellian, as well as an 8 Maxwellian  $f(E)$ . c) TRANSP  $\int_0^E dE f(E)\sigma v \propto$  neutron rate vs. other two functions. Although  $f(E)\sigma v$  cannot be fit well with isotropic, unshifted Maxwellians used in most wave power absorption codes, total neutron rate can, and  $\sim 80\%$  of neutrons created below energy range of largest discrepancy, so using this  $f(E)$  to estimate neutron rate may have some validity.

provide a more accurate estimate. Although  $f(E) \sigma v$  cannot be fit well with isotropic, unshifted Maxwellians used in most wave power absorption codes, total neutron rate can. As shown in Figure 7c,  $\sim 80\%$  of neutrons are created below the energy range of largest discrepancy in  $f(E)\sigma v$ , so using this  $f(E)$  to estimate neutron rate may have some validity. The next steps in calculating a rough neutron rate enhancement are to compute the fast ion power deposition profiles and confinement times for each Maxwellian, perturb the temperature of each accordingly, and recalculate the neutron rate with the perturbed distribution function. CQL3D may also be used to calculate this enhancement, and will soon be able to read in the TRANSP distribution function to provide more quantitative agreement between experiment and theory.

For equilibria without fast ions, low  $n_\phi \approx 6$ , and high thermal  $T_i(0) \approx 2$  keV, less agreement between wave absorption codes has been found, often differing in bulk deuterium absorption by a factor of  $\sim 2$ , with HPRT consistently calculating less than CURRAY or AORSA. This is surprising considering the level of agreement for the fast ion shots which actually had  $T_i(0) \approx 1.5$  keV. CURRAY and HPRT have been found to agree in ray path and deposition profile quite well for RF+NBI and equilibria dominated by electron absorption. A possible explanation is that HPRT is using the complex  $k$  in its dielectric tensor, whereas CURRAY does not, and the impact only arises in this particular parameter regime. As outlined in [11], HPRT's equation for absorbed power density

$$\frac{\partial W_{ps}}{\partial t} = \mathbf{E}_1^* \cdot \mathbf{j}_s - \nabla \cdot \mathbf{T}_s \quad (1)$$

thus includes the latter kinetic flux term:

$$\nabla \cdot \mathbf{T}_s = \frac{\omega}{8\pi} \mathbf{E}_1^* \cdot \left( \mathbf{k}_i \cdot \frac{\partial}{\partial \mathbf{k}} \bar{\bar{\epsilon}}_{\text{Hs}} \cdot \mathbf{E}_1 \right) e^{2\phi_i}. \quad (2)$$

while CURRAY, because it keeps  $k$  real in the evaluation of its dielectric tensor, sets  $\partial W_{ps}/\partial t = \mathbf{E}_1^* \cdot \mathbf{j}_s$ . It should be noted that a rigorous derivation from the energy moment of the Vlasov equation to this form of the kinetic flux term with complex  $k$  has yet to be performed. Noting that there is currently discrepancy between theory and experiment in the  $k_{\parallel}$  scan (there has yet to be any experimental evidence of significant bulk ion absorption at all in NSTX), and there is a discrepancy between ray-tracing codes at lower  $k_{\parallel}$ , a breakdown of the theory at lower  $k_{\parallel}$  should not be ruled out.

## CONCLUSIONS

Analysis of recent NSTX shots has revealed that under some conditions when neutral beam and RF power are injected into the plasma simultaneously, a fast ion population with energy above the beam injection energy is sustained by the wave. In agreement with modeling, these experiments find the RF-induced fast ion tail strength and neutron rate at lower B-fields to be less enhanced, likely due to a larger  $\beta$  profile, which promotes greater off-axis absorption where the fast ion population is small. Ion

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