The Confinement of Dilute Populations of Beam Ions in the National Spherical Torus Experiment

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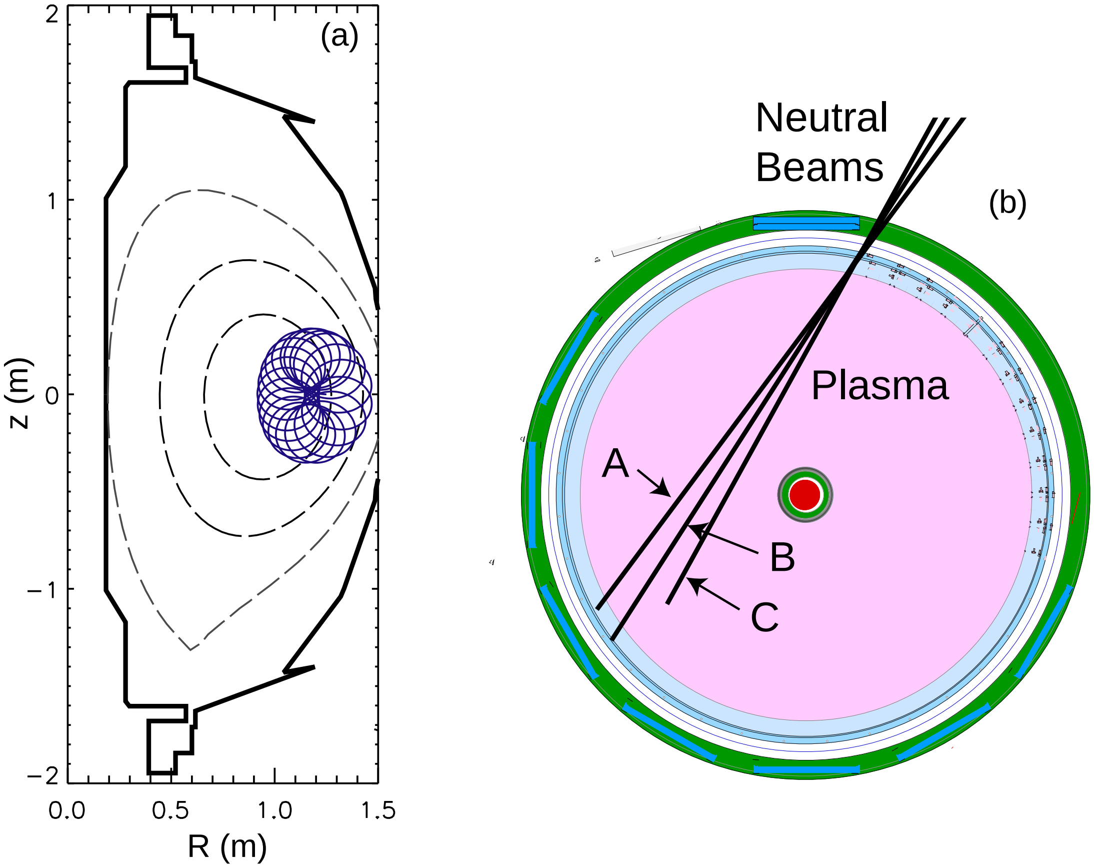
Short ∼ 3 ms pulses of 80 keV deuterium neutrals are injected at three different tangency radii into the National Spherical Torus Experiment (NSTX). The confinement is studied as a function of tangency radius, plasma current (between 0.4-1.0 MA), and toroidal field (between 2.5-5.0 kG). The jump in neutron emission during the pulse is used to infer prompt losses of beam ions. In the absence of MHD, the neutron data show the expected dependencies on beam angle and plasma current; the average jump in the neutron signal is $60 \pm 23\%$ of the expected jump. The decay of the neutron and neutral particle signals following the blip are compared to the expected classical deceleration to detect losses on a 10 ms timescale. The temporal evolution of these signals are consistent with Coulomb scattering rates, implying an effective beam-ion confinement time $\gtrsim$100 ms. The confinement is insensitive to the toroidal field despite large values of $\rho\nabla B/B$ ($\lesssim$0.25), so any effects of non-conservation of the adiabatic invariant μ are smaller than the experimental error.

Motivation

- The beams are a major heating system on NSTX–need to confirm their performance.
- Beam ions in NSTX are like alphas in a ST reactor.
- In a ST, conventional tokamak drift-orbit theory may break down for energetic ions because μ is not conserved.

Neutral Beams Inject at 3 Angles; Produce Beam Ions with Large Orbits



Experimental Technique

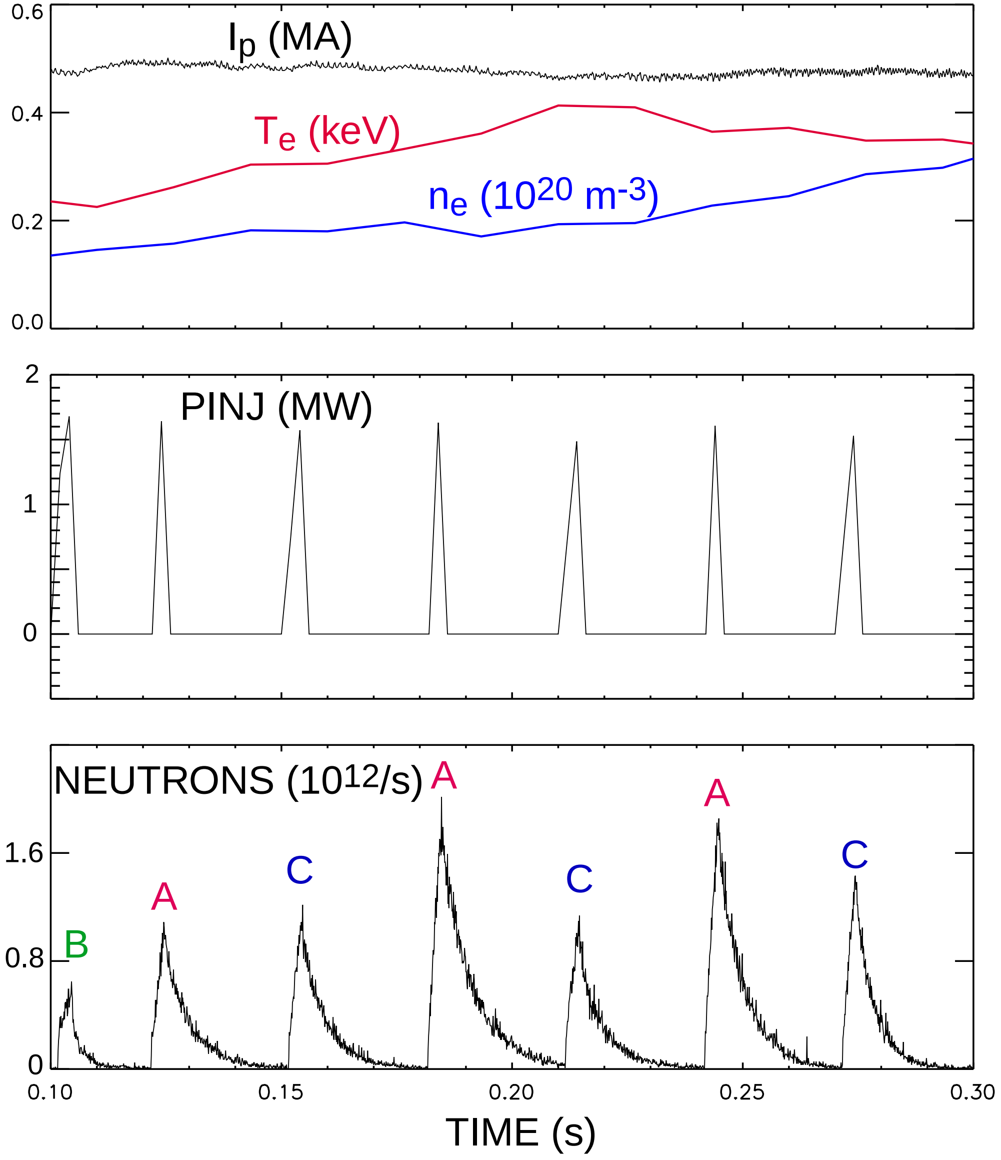
- Short beam pulses ("beam blips") produce a convenient population of approximately monoenergetic beam ions ⟶ deconvolves beam-ion thermalization and confinement.
- Thomson scattering measures the T_e and n_e profiles. These data are used to calculate classical deceleration.
- Magnetics monitor MHD activity.
- A database is formed of beam blips that satisfy two conditions: 1) similar Thomson profiles before and after the blip and 2) no major MHD activity.
- The neutron signals are fit by the equation $\dot{I}_n = c - I_n/\tau_n$ during the beam blip. The constant c reflects the prompt confinement of the injected beam ions and should equal

$$\dot{c} \simeq \dot{N}_b n_d \langle \sigma v \rangle, \qquad (1)$$

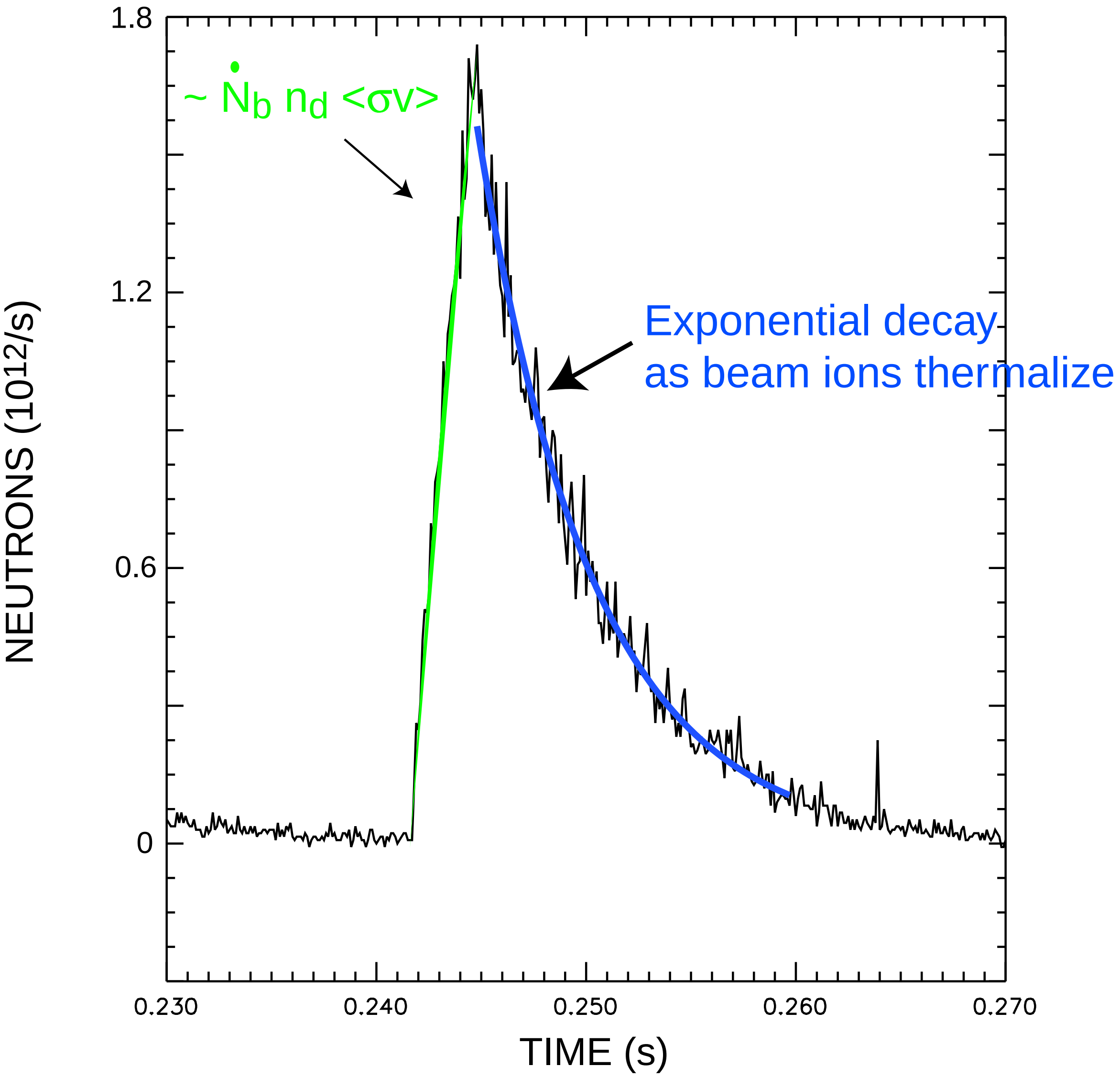
if all of the injected beam ions are confined in the plasma center. Here $\dot{N}_b$ is the rate at which full-energy beam ions are injected into the device, n_d is the central deuterium density, and $\langle \sigma v \rangle$ is the d-d reactivity.

- After the pulse, the neutron signal is fit by $\dot{I}_n = -I_n/\tau_n$. If the decleration is classical, $\tau_n = (2.63\nu_E)^{-1}$, where ν_E is the classical deceleration rate of 80-keV deuterons.
- Beam ions in NSTX often destabilize modes with frequencies between 50 kHz and several MHz. In these experiments, the beam population is intentionally kept small in order to study classical confinement. No evidence of any TAE or CAE activity is observed for any of the discharges.

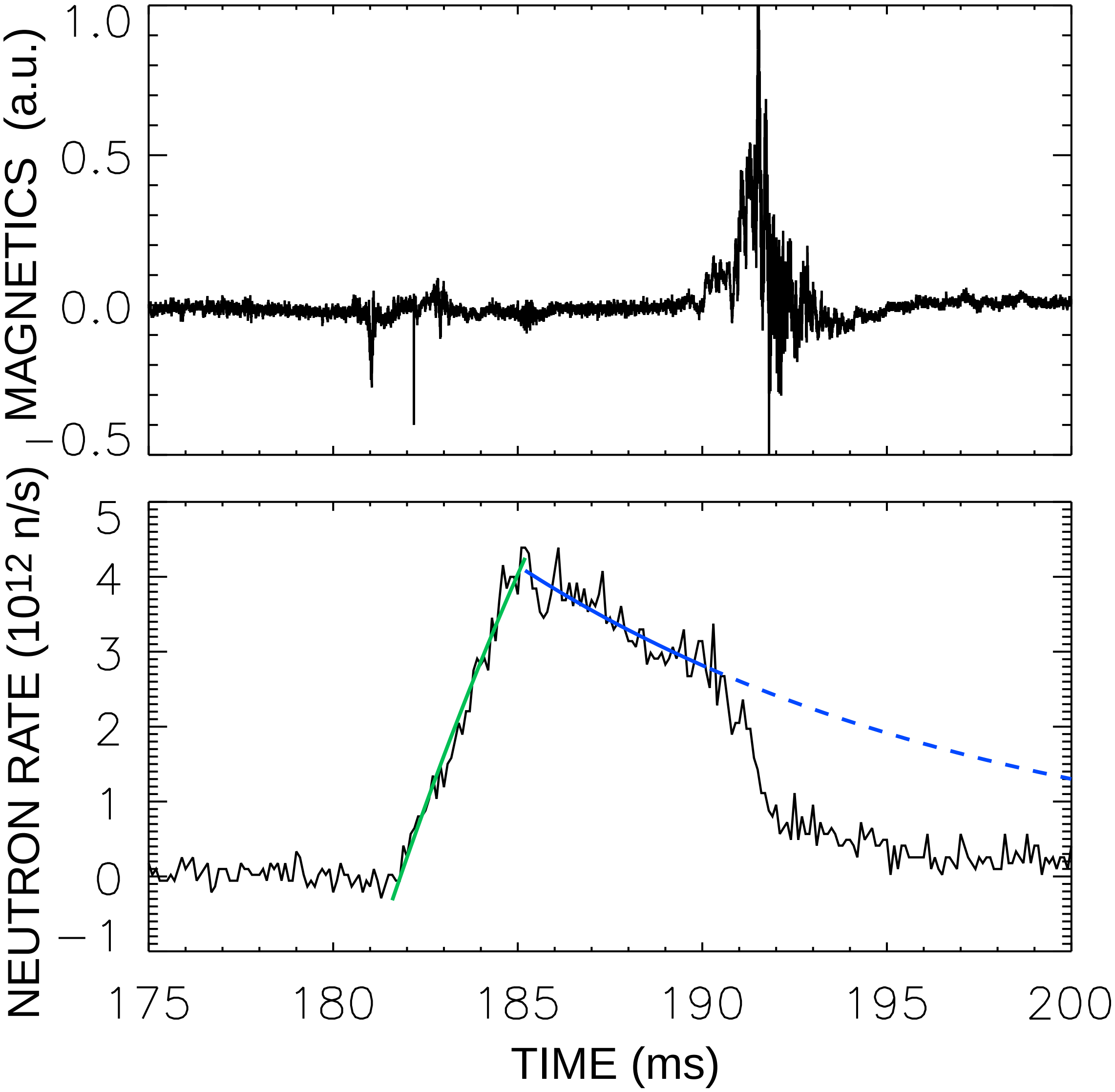
$\sim$ 3 ms Beam Blips Injected into Ohmic Plasma to study Beam-Ion Confinement



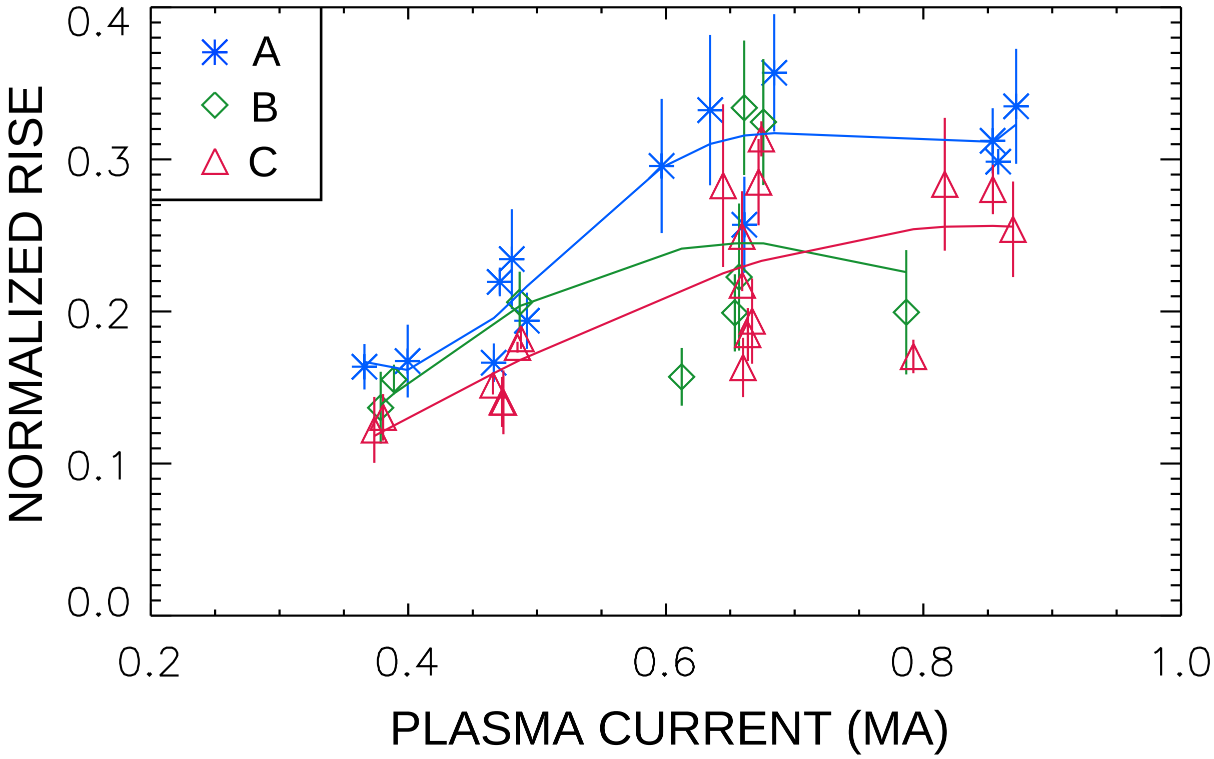
Prompt Confinement from Initial Rise; Delayed Losses from Subsequent Decay



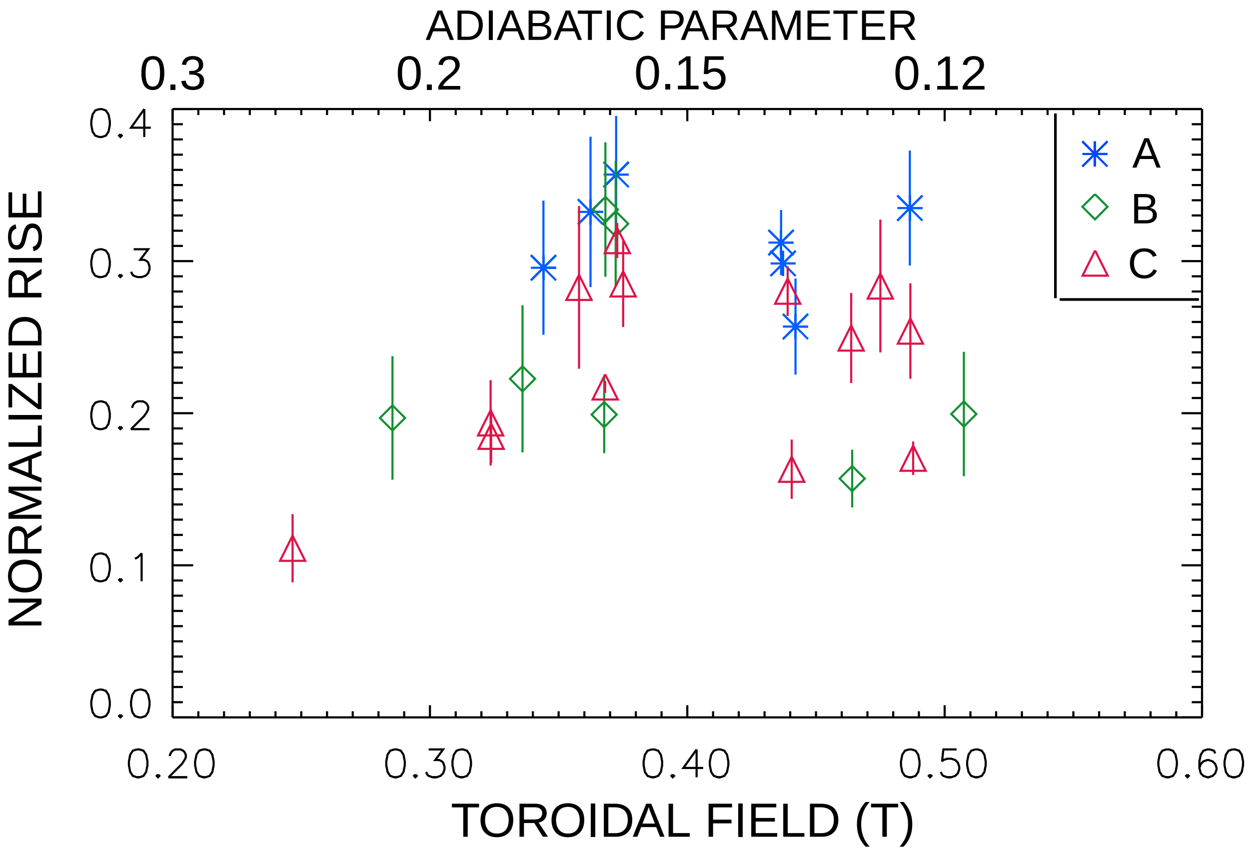
A Minor Disruption “Clobbers” the Beam Ions



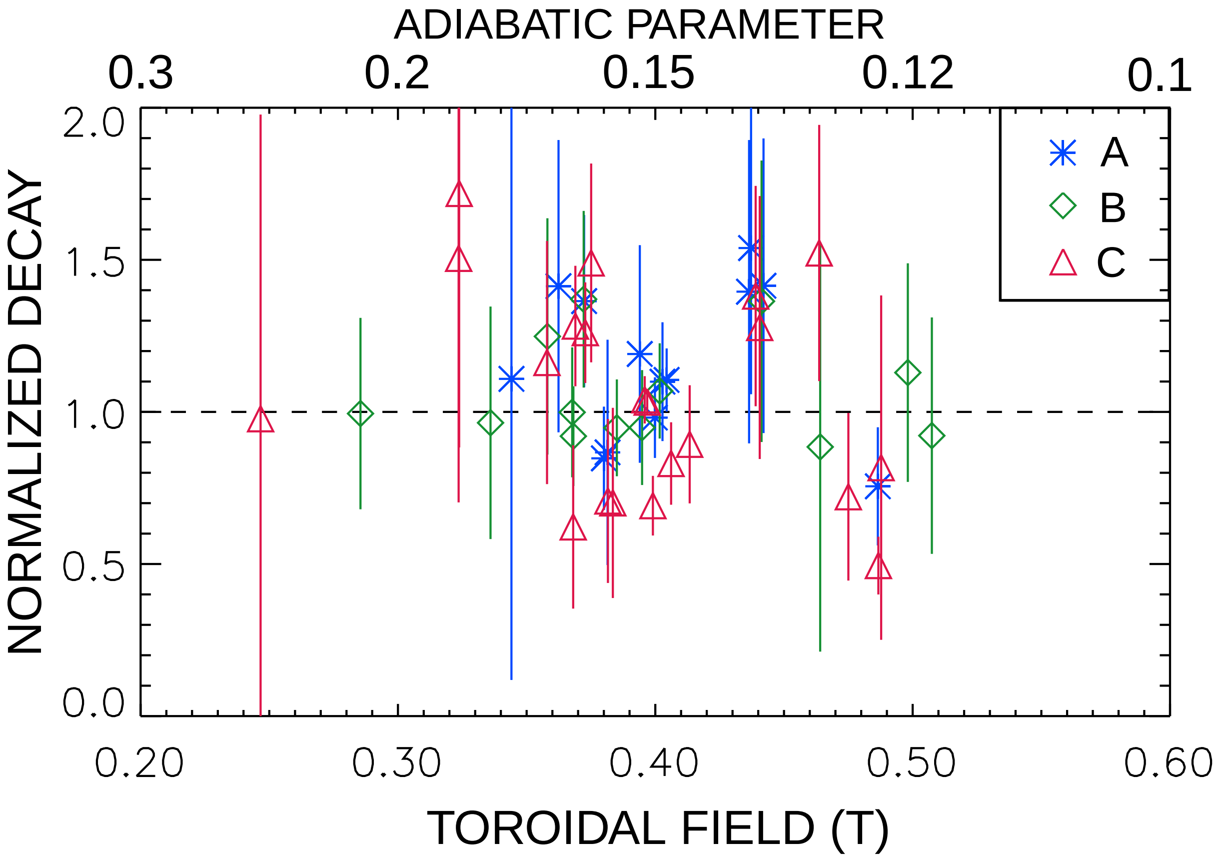
More Prompt Losses at Low Current; Expected Drift Orbit Effect



Weak Dependence of Prompt Confinement on Toroidal Field



Little Evidence of Delayed Losses



Empirical Results

- For all three injection angles, confinement is degraded for currents below 0.5 MA, as expected.
- The effect is strongest for the most perpendicular injection angle, as expected.
- The dependence of the prompt losses on toroidal field is generally weak, as in conventional tokamaks.
- No evidence of a significant effect due to breaking of μ invariance.
- Decay time consistent with classical theory for all parameters $\longrightarrow$ delayed losses relatively unimportant (as expected for classical scattering).
- No difference in decay time for different sources. This is expected, since pitch-angle scattering is too slow to scatter ions across loss boundaries in this regime.

- Strong MHD activity degrades the confinement.

Why is the Scatter So Large?

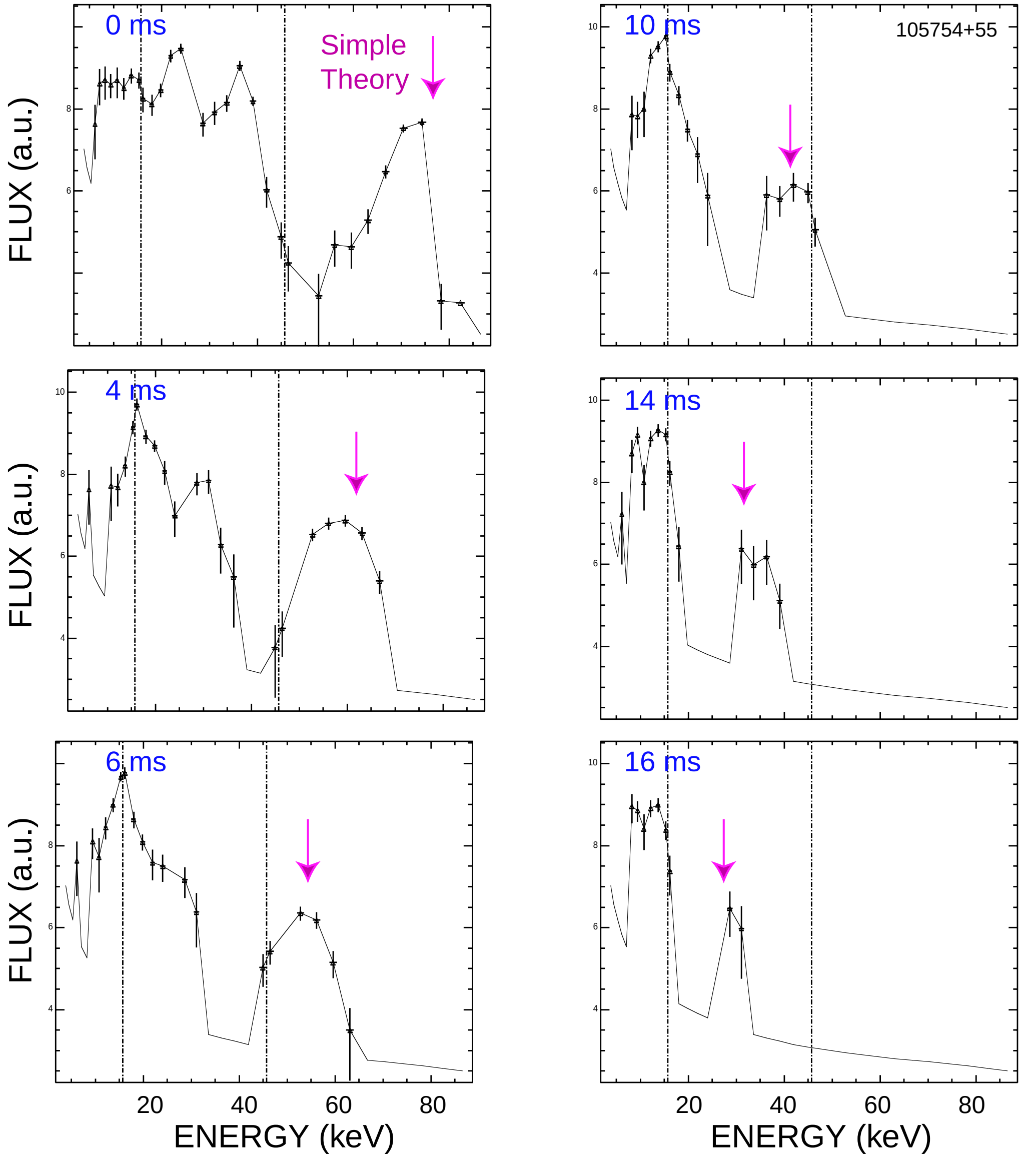
- Uncertainties associated with fitting the neutron data to the model rise and decay equations are only $\sim 10\%$.

- The rise depends upon the deuterium density n_d, which itself depends upon both the electron density n_e and Z_{eff}. The random error in the Thomson scattering measurements of electron density is typically 5%. In addition, measurements are only acquired every 17 ms. In the analysis, the average of the density measurements before and after the blip is employed but rapid changes in density introduce additional errors.

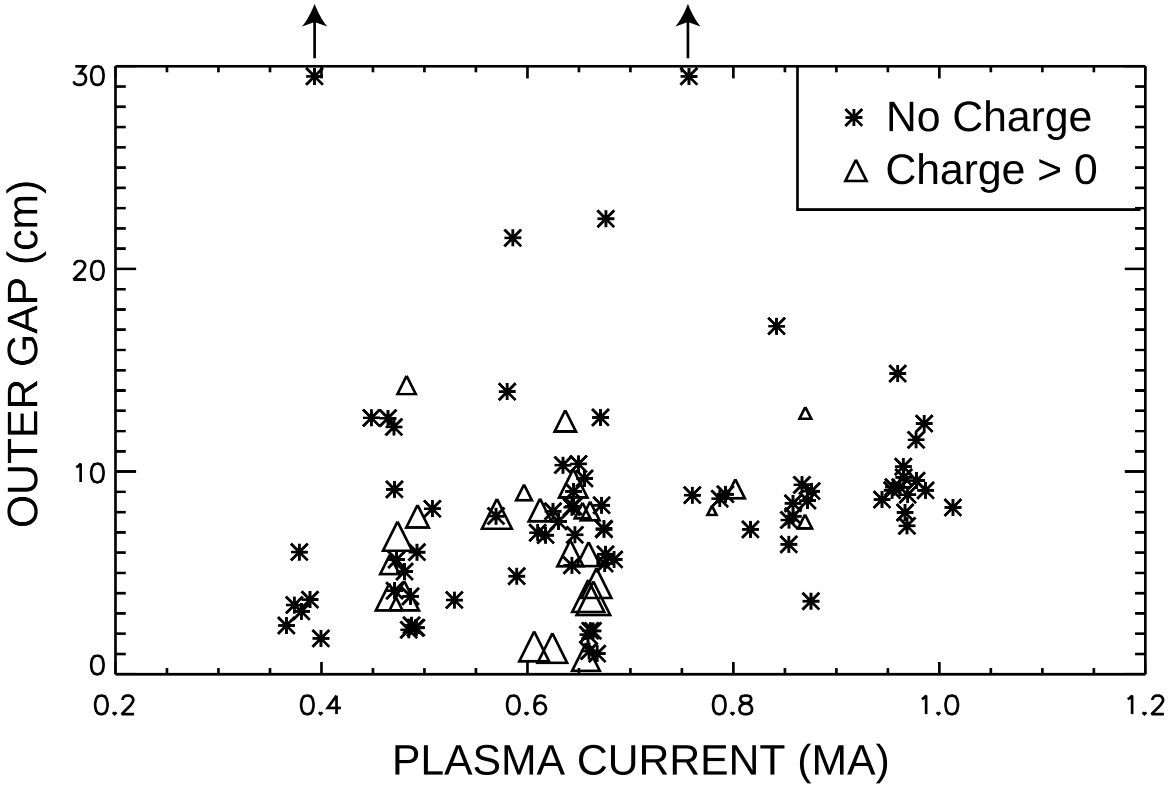
- The Z_{eff} measurement is an average value. The uncertainty is difficult to quantify but could be substantial. It is also assumed that carbon is the dominant impurity so $n_d/n_e = (Z_{eff} - 1)/(6 - 1)$ but this may not always be the case.

- The neutral beams were not instrumented to measure the time evolution of the beam power throughout the beam blip at the time of this experiment. Generally, the beam voltage and power are only available for a single time point during the blip. Any power fluctuations or error in this single measurement contributes to the overall error.
- The relative error in the neutron measurement is small and is included in the fitting uncertainties given above. On the other hand, the absolute error is estimated as 25%.
- MHD is probably *not* responsible. The level of MHD activity in the analyzed data is at a much lower level than degrades beam-ion confinement in a conventional tokamak. Moreover, inclusion of beam blips taken during stronger (but still low) MHD activity does not significantly alter the results.
- If these don't account for the large scatter, what does?

Neutral Particle Measurements Agree with Classical Deceleration



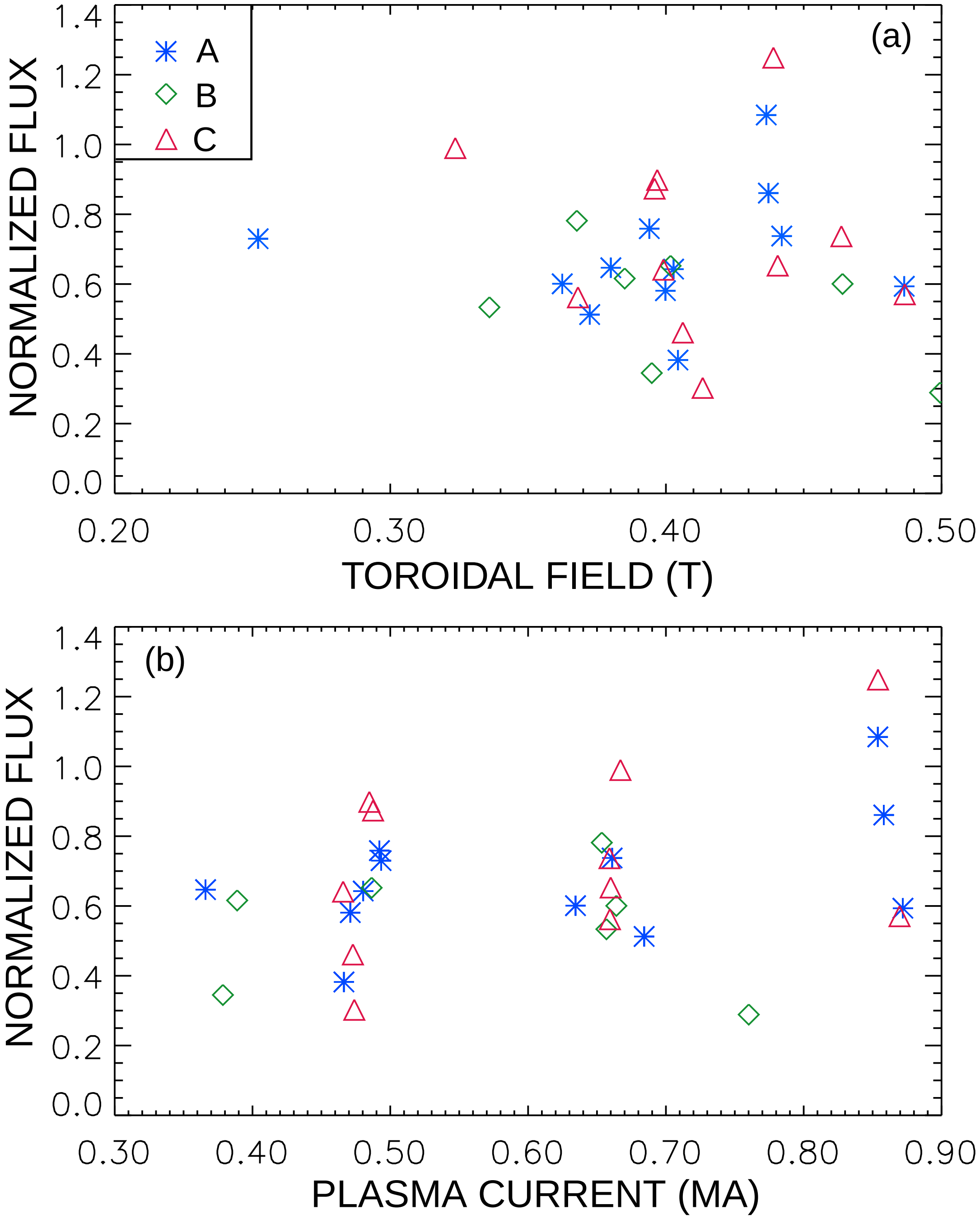
Beam Ion Losses Measured at Wall Correlate Weakly with Other Parameters



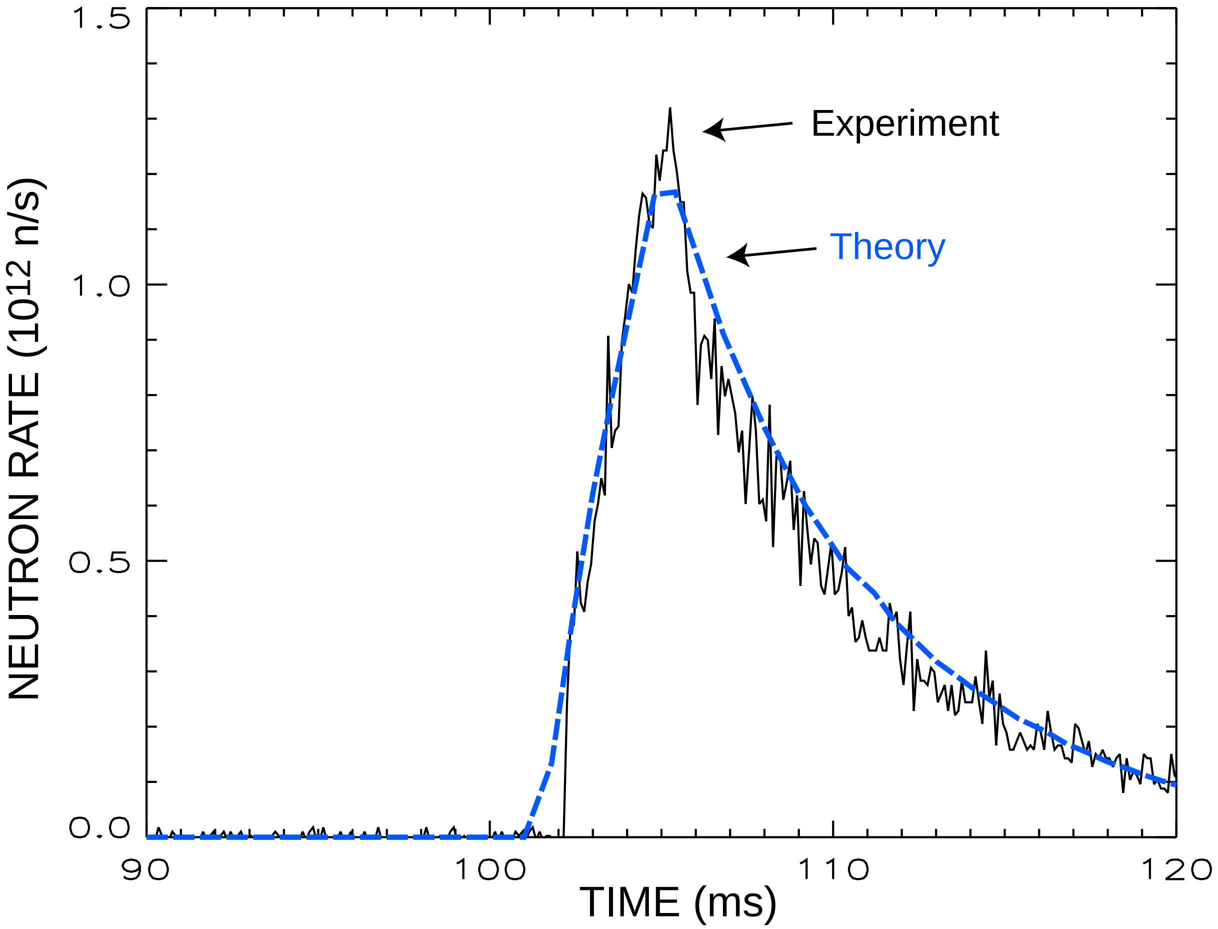
Comparison with TRANSP Predictions

- TRANSP includes beam deposition, averaging of Coulomb drag over beam-ion orbits, and charge-exchange losses. It assumes μ is conserved.
- The ratio of measured neutron signal to predicted signal is independent of plasma current, toroidal field, and injection energy, indicating TRANSP correctly models the dependencies on these parameters.
- Although the agreement is excellent in a few cases, the average ratio is only $60 \pm 23\%$.
- Decay time is in excellent agreement with TRANSP predictions. The effective confinement time for initially confined beam ions exceeds 100 ms.

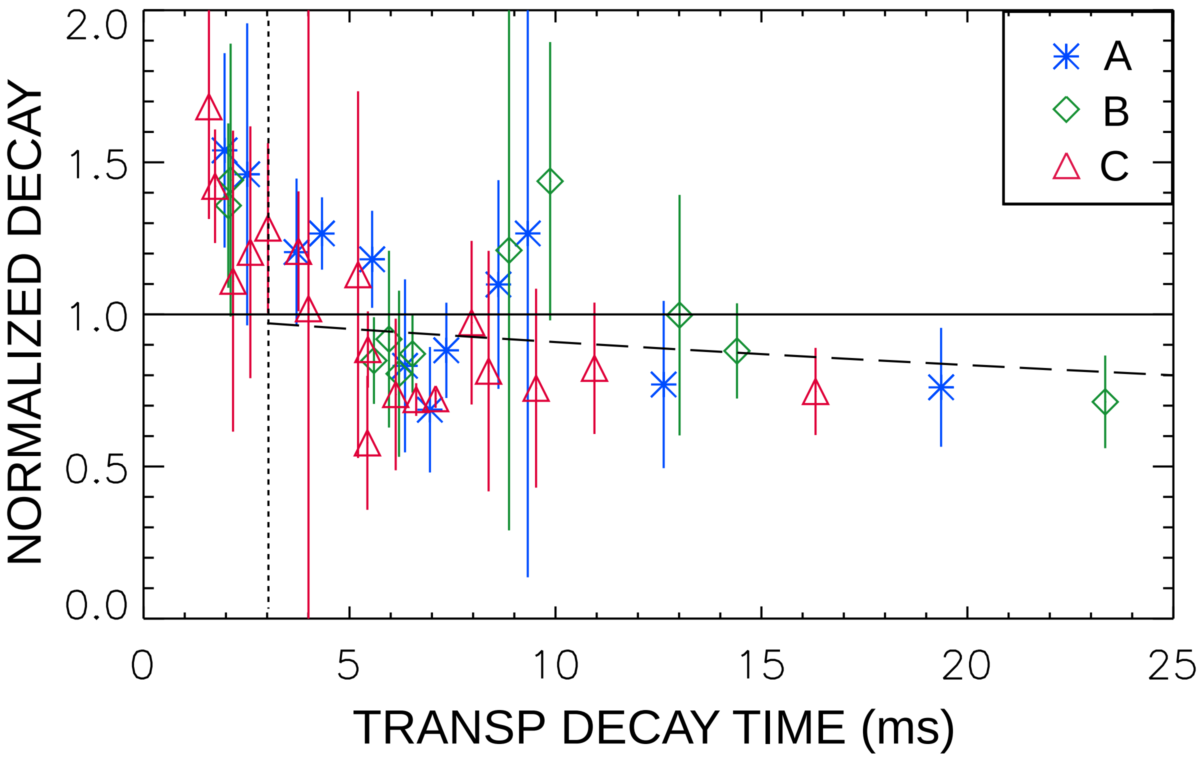
Comparison of Initial Rise with TRANSP



An Example of a Blip with Excellent Agreement



Comparison of the Decay with TRANSP



Conclusions

- Standard tokamak drift orbit and Coulomb scattering theory describe the basic trends.
- The absolute magnitude of the signal is smaller than expected. The pervasive nature of this discrepancy suggests a diagnostic error in the neutron calibration, in the beam parameters, or in Z_{eff}. Alternatively, large unexpected prompt losses on a timescale much shorter than 1 ms may be occurring.
- Many NSTX plasmas have unusually high values of ion temperature. The good agreement between the measured decay rates and classical Coulomb scattering theory suggests that the confined beam ions are transferring their energy to electrons, as expected.
- Statistically significant variations in either prompt or delayed confinement with $\rho \nabla B / B$ are absent in these data. Recent theoretical

studies[1] predict reductions that are smaller than the experimental uncertainty so, although this result is consistent with theory, it does not constitute a rigorous test of the predictions.

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[1] Akers *et al.*, Nucl. Fusion **42** (2002) 122; Carlsson, Phys. Plasmas **8** (2001) 4725; Kolesnichenko *et al.*, Phys. Plasmas **9** (2002) 2639; Yakovenko *et al.*, PPPL-3712.

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