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Physical Mechanisms of Fast-Ion Loss[1] E.M. CAROLIPIO, W.W. HEIDBRINK, University of California, Irvine, R. WHITE, Princeton University — Theoretical analysis and simulations with a Hamiltonian guiding center code are used to understand fast-ion transport in several experiments. In one study, the stationary magnetic islands produced by large tearing modes reduce the neutral beam current drive efficiency and 2.5 MeV neutron emission by as much as 65%.[2] The losses are caused by intrinsic orbit stochasticity. In another study, the confinement of 1 MeV tritons is usually unaffected by externally-imposed helical fields, apparently because the rotating plasma reduces the amplitude of the perturbed field. In a third study, the measured magnetic fluctuations are too small to explain beam-ion losses during TAE activity; we speculate that parallel electric fields play a role in the observed transport.

[1]Supported by U.S. DOE Contracts DE-AC02-76CH03073 and DE-AC03-99ER54463.
[2]C.B. Forest *et al.*, Phys. Rev. Lett. **79** (1997) 427.

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Special instructions: DIII-D Poster Session 2, immediately following S Bernabei

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This poster contains three separate studies of the effect of helical fields on energetic-ion confinement in the DIII-D tokamak:

1. Simulations of Beam Ion Transport during Tearing Modes

by E.M. Carolipio, W.W. Heidbrink, C.B. Forest, R.B. White

2. The Weak Effect of Static, Externally Imposed, Helical Fields on Fusion Product Confinement

by W.W. Heidbrink, E.M. Carolipio, R.J. La Haye, J.T. Scoville

3. The TAE Mode Structure in DIII-D: Implications of Soft X-ray and Beam-Ion Loss Data

by E.M. Carolipio, W.W. Heidbrink, C.Z. Cheng, M.S. Chu, G.Y. Fu, A. Jaun, D.A. Spong, R.B. White

The studies were performed by E.M. Carolipio for his Ph.D. thesis. Each paper is being submitted for publication as a separate journal article.

Effect of Large Tearing Modes on Beam Ions

- In low density, high β_p plasmas (Fig. 1), large tearing modes are measured (Fig. 2).

- Reductions in the neutron rate (Fig. 1) and driven current (Fig. 3) indicate degraded beam-ion confinement.

- Mynick's analytic theory:
Resonances between n=0 orbit shifts (grad B and curvature drifts) and helical orbit perturbations cause islands in the particle's phase space. Intrinsic orbit stochasticity occurs when the drift islands overlap.

- Stochasticity is predicted in this discharge for circulating beam ions.

- Numerical studies are performed with White's ORBIT code (Fig. 4).

- The perturbation reduces the neutron rate and current drive (Fig. 5). The calculated losses agree with experiment (Fig. 6).

- The calculated losses are of high energy, circulating beam ions (Fig. 7) and scale as $(\delta B)^2$, as expected for intrinsic orbit stochasticity.

Mynick, Phys. Fluids B 5 (1993) 1471.

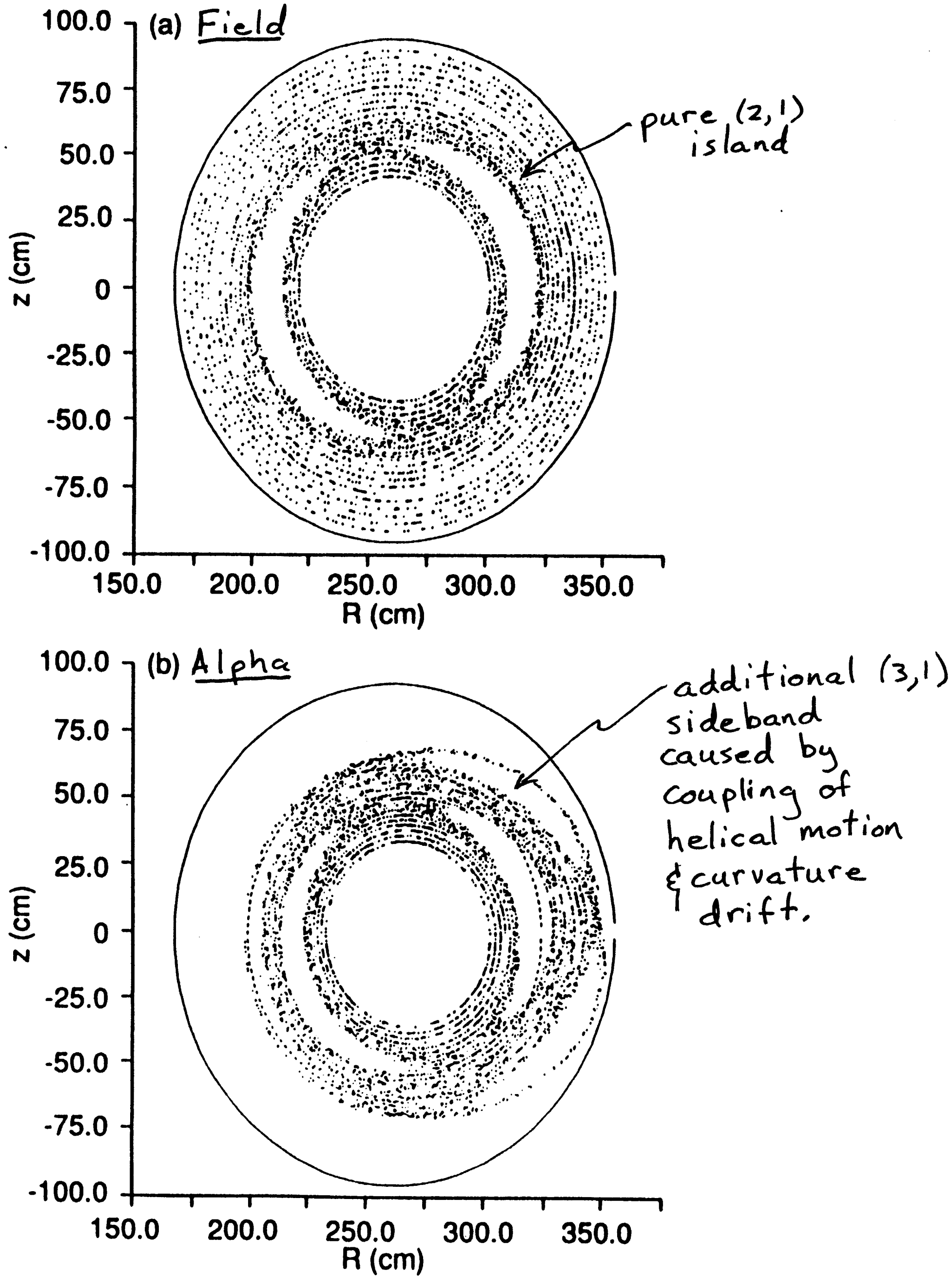

FIG. 4. Poincaré maps for (a) the magnetic field and (b) alphas with energy $E=1.75$ MeV, and $\lambda=1$, for a (2,1) mode with $\alpha_{mx}=10^{-4}$.

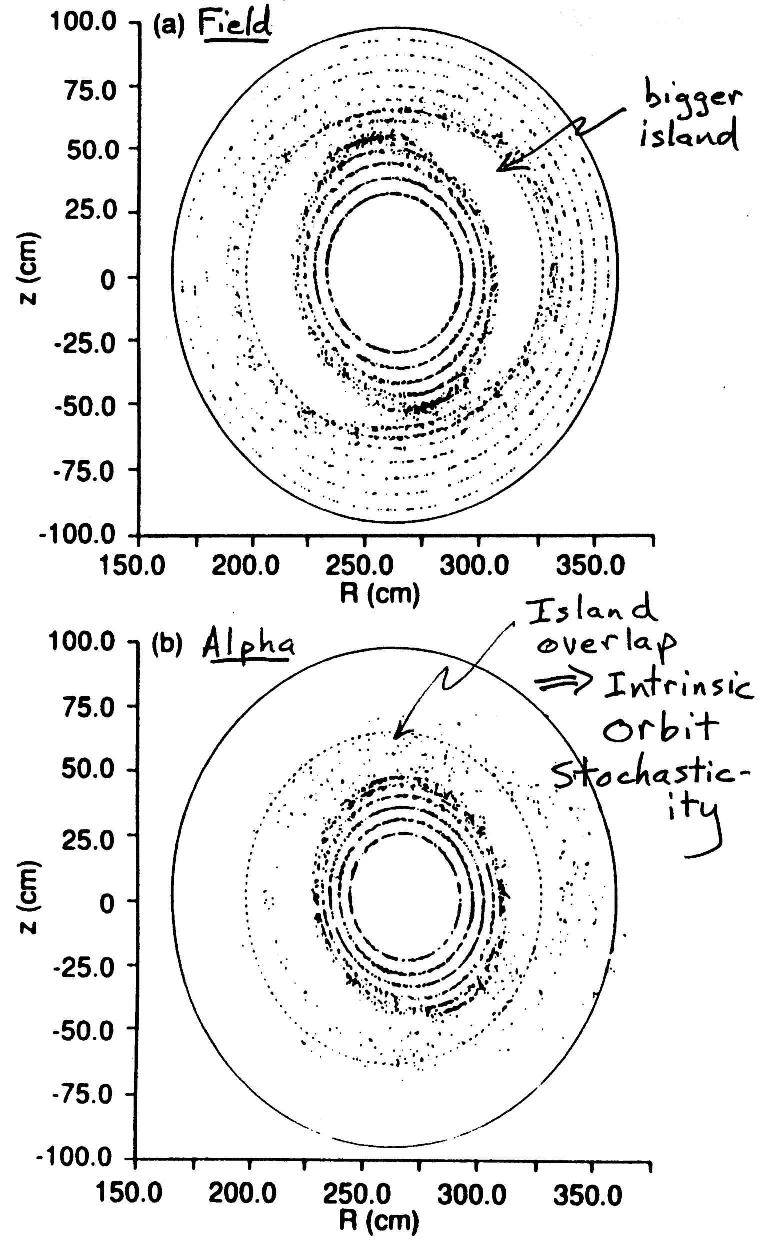

FIG. 5. Same plots as for Fig. 4, but with $\alpha_{mx}=3\times 10^{-4}$.

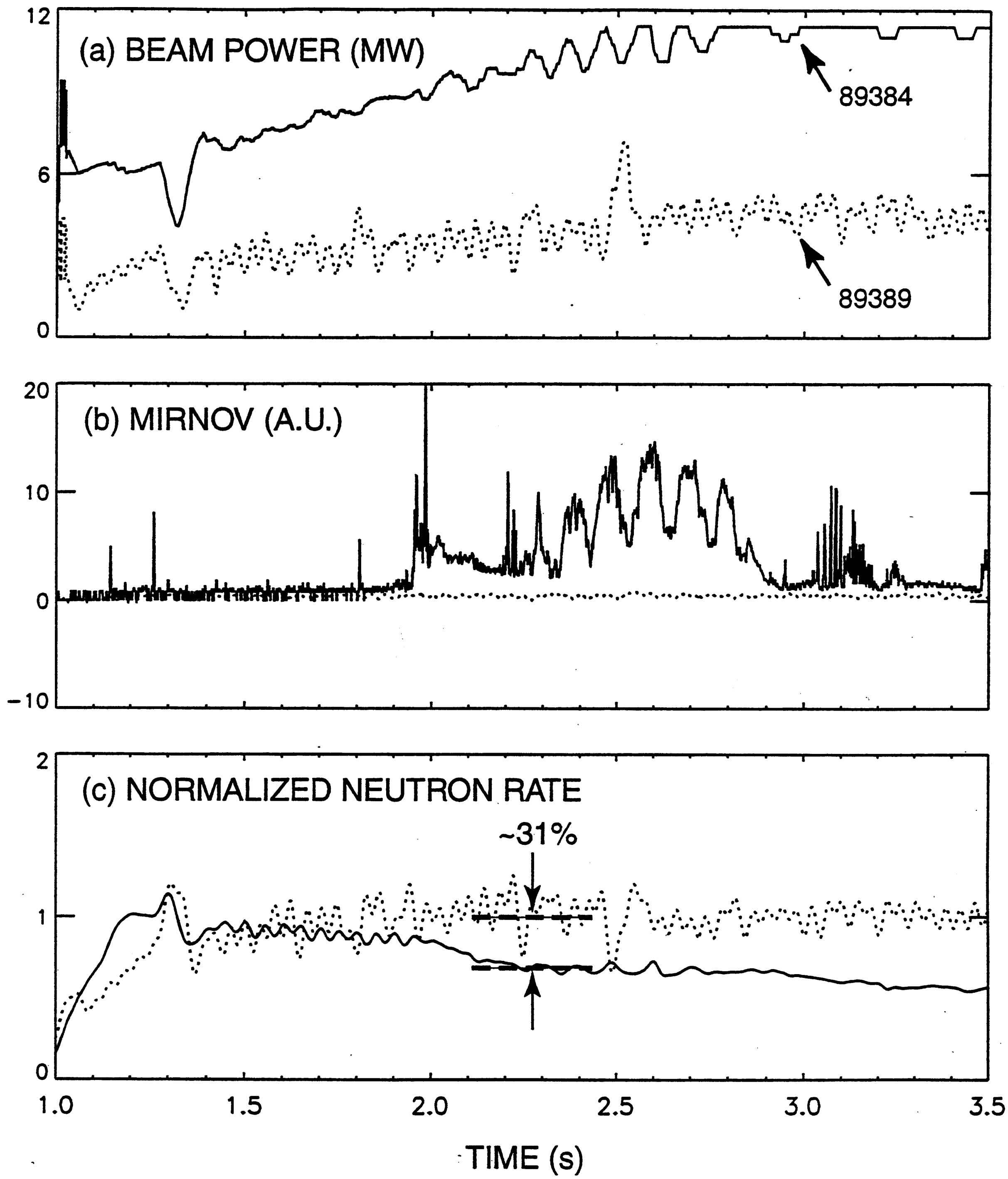

Figure 1. Comparison of two discharges: one with a large tearing mode and one without. The neutron rate is lower than classically predicted in the discharge with a large $m/n = 2/1$ tearing mode.

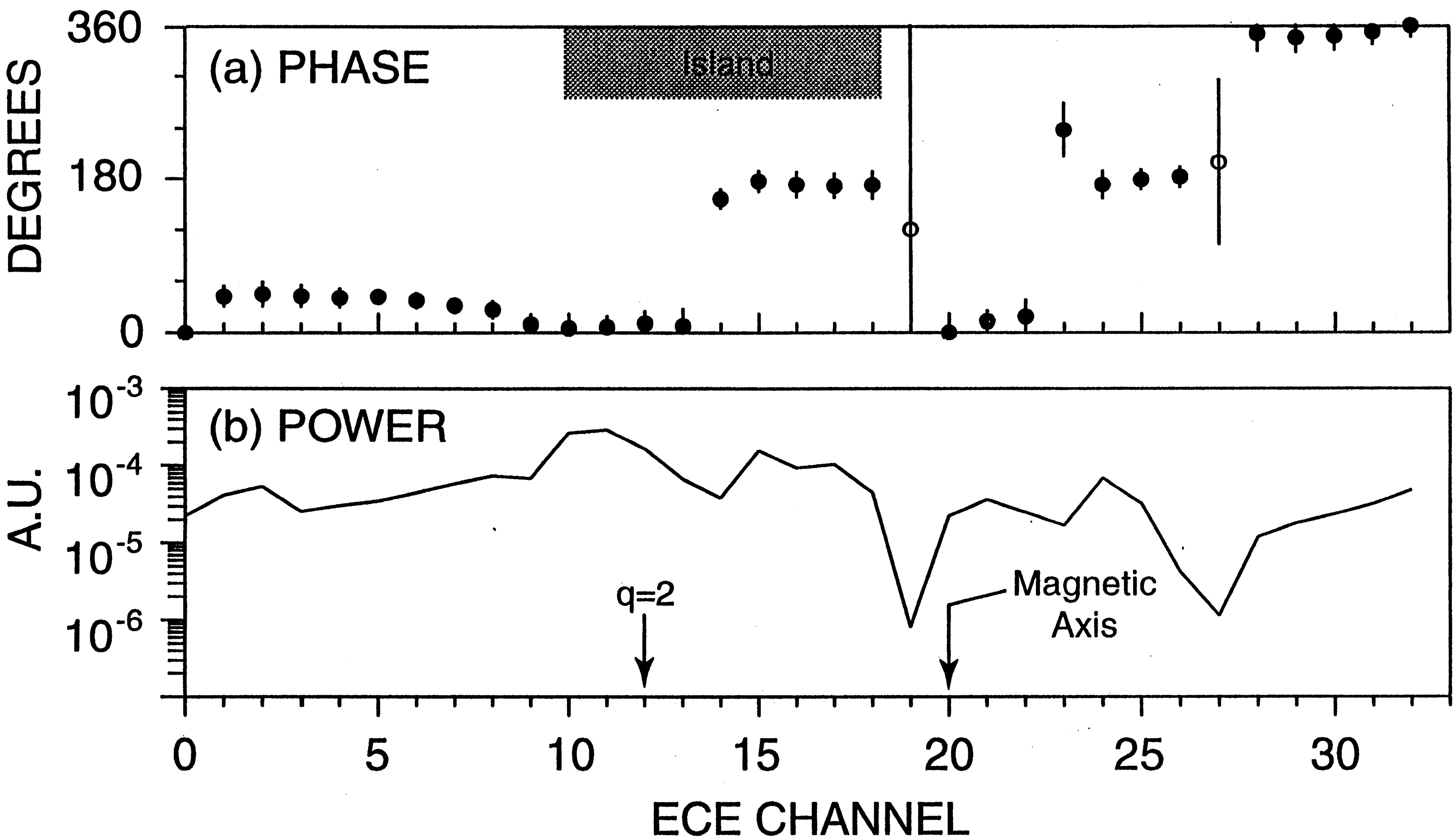

Figure 2. ECE data showing a large tearing mode near the $q = 2$ surface.

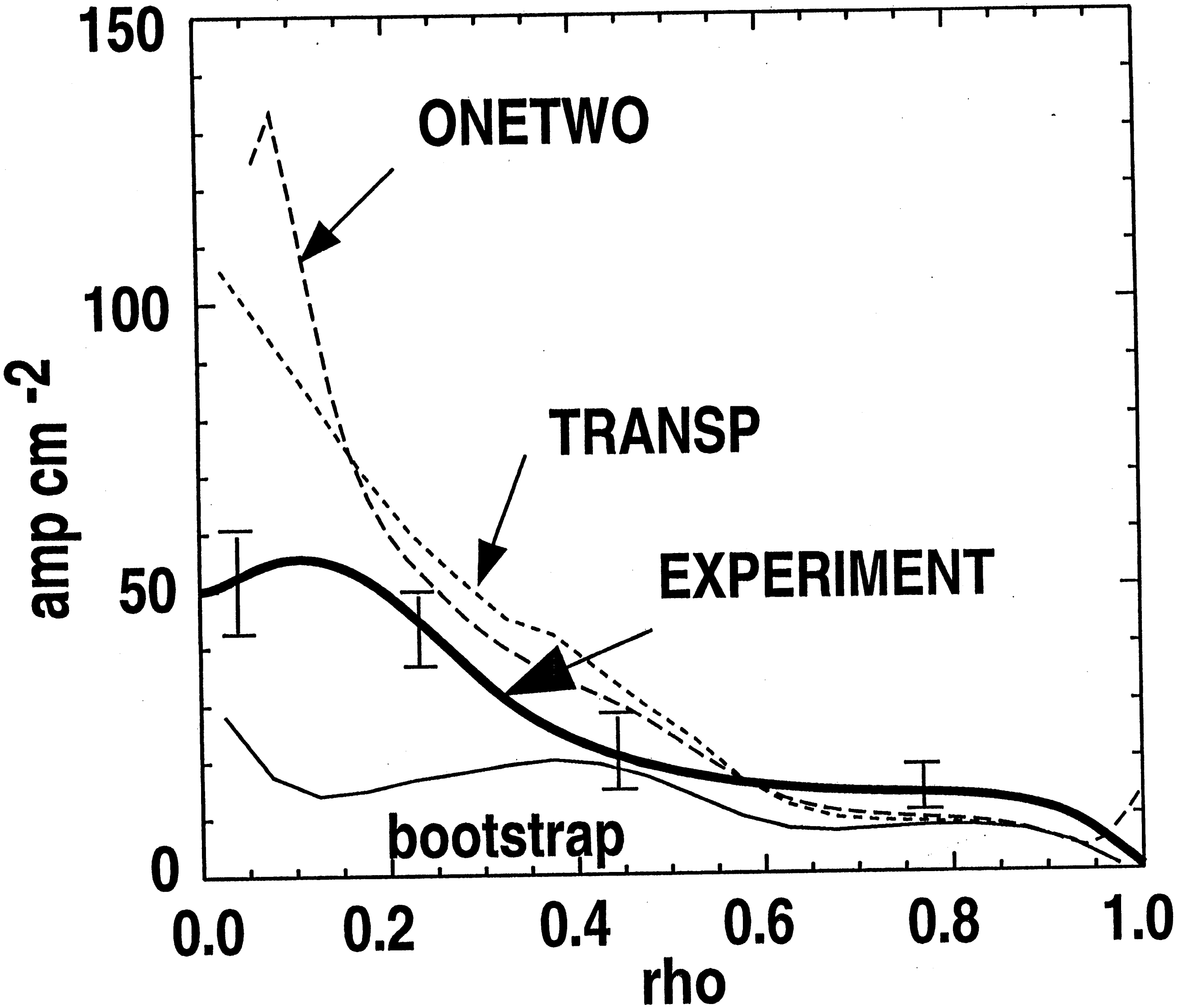

Figure 3. In the center of the plasma, the neutral beams drive much less current than classically expected in the discharge with a large tearing mode.

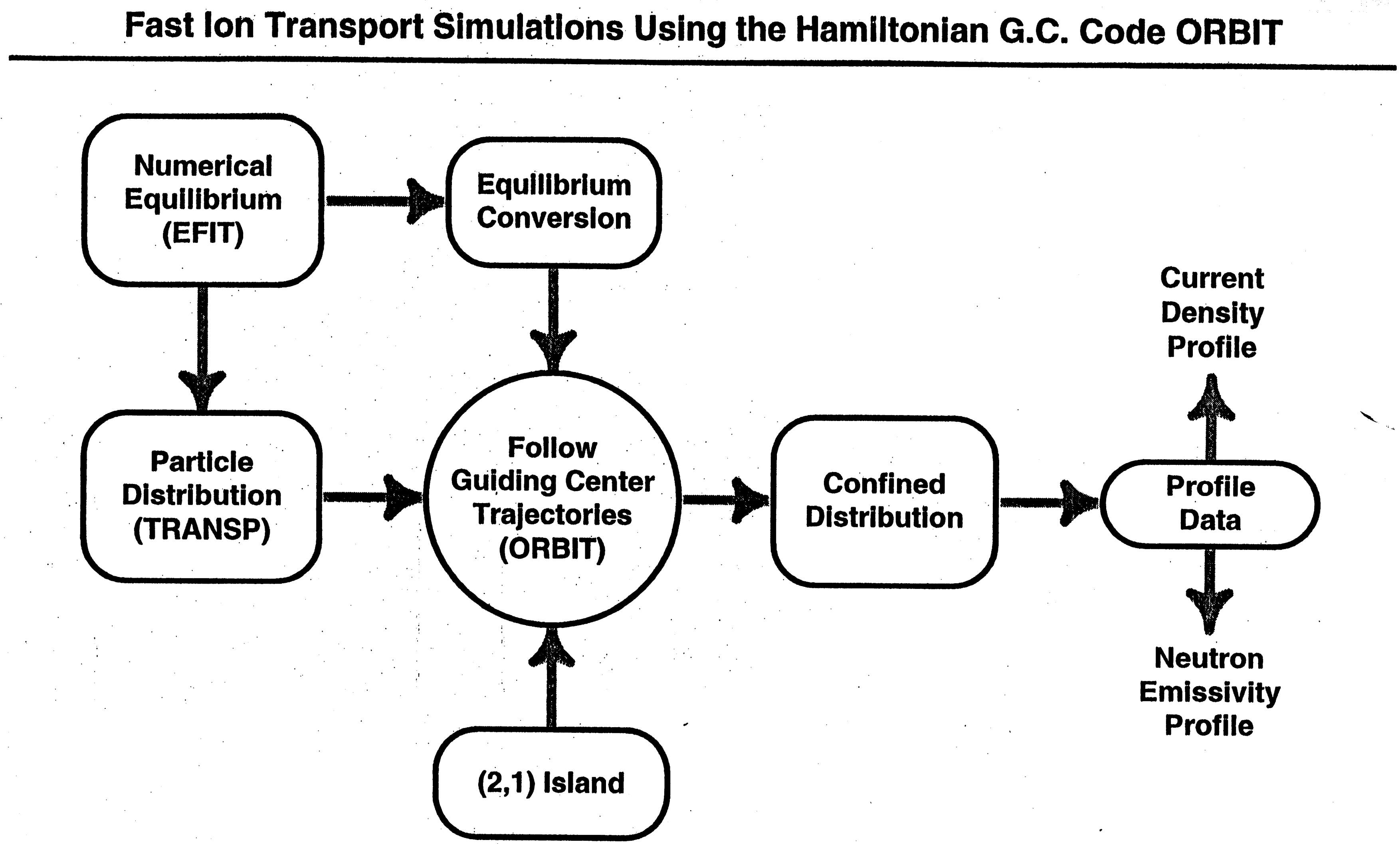

Figure 4. Flow diagram for Monte Carlo simulations with the ORBIT code.

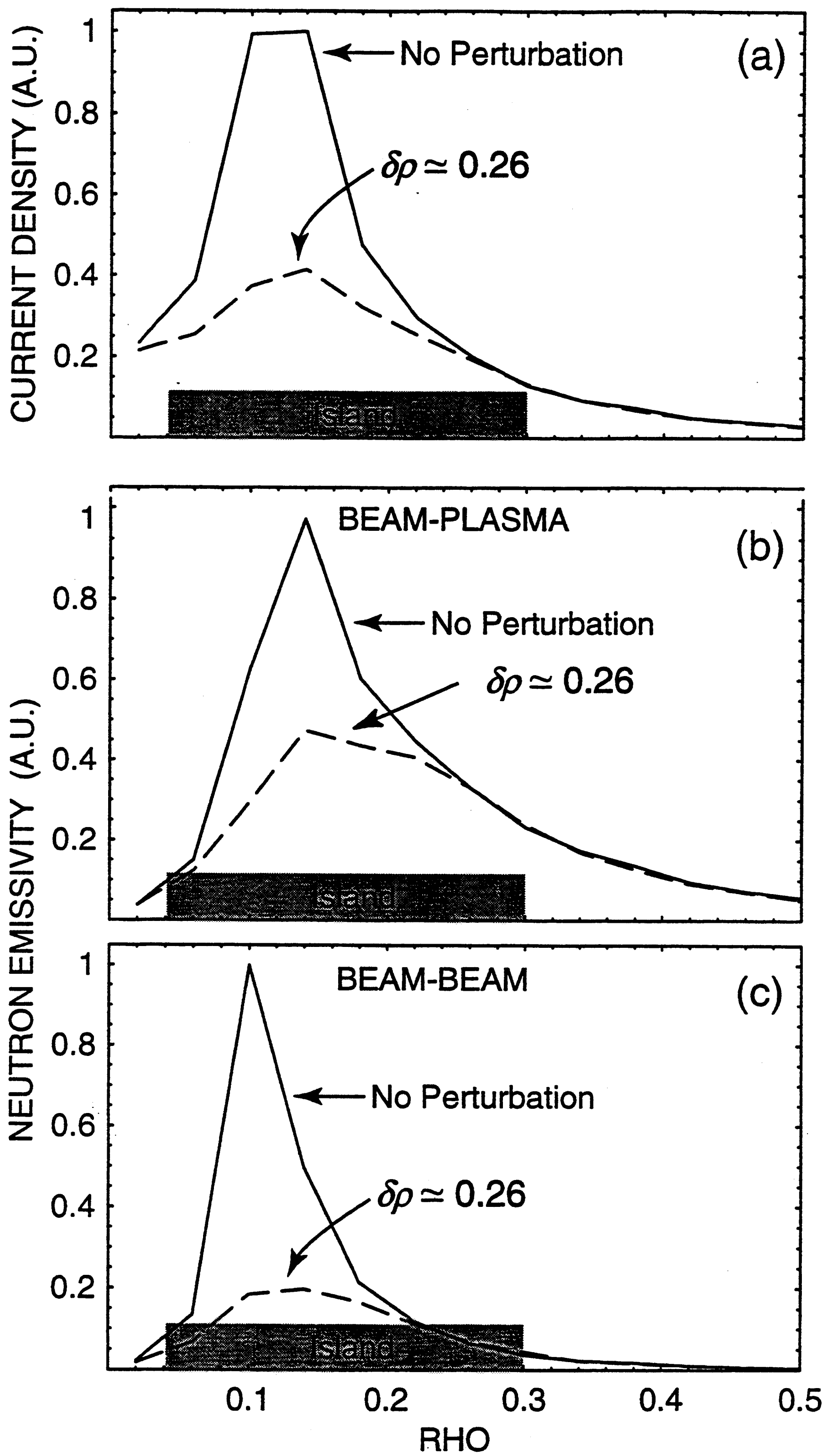

Figure 5. Inclusion of a large $m/n = 2/1$ island in the simulations reduces the predicted neutral beam current drive and neutron rate.

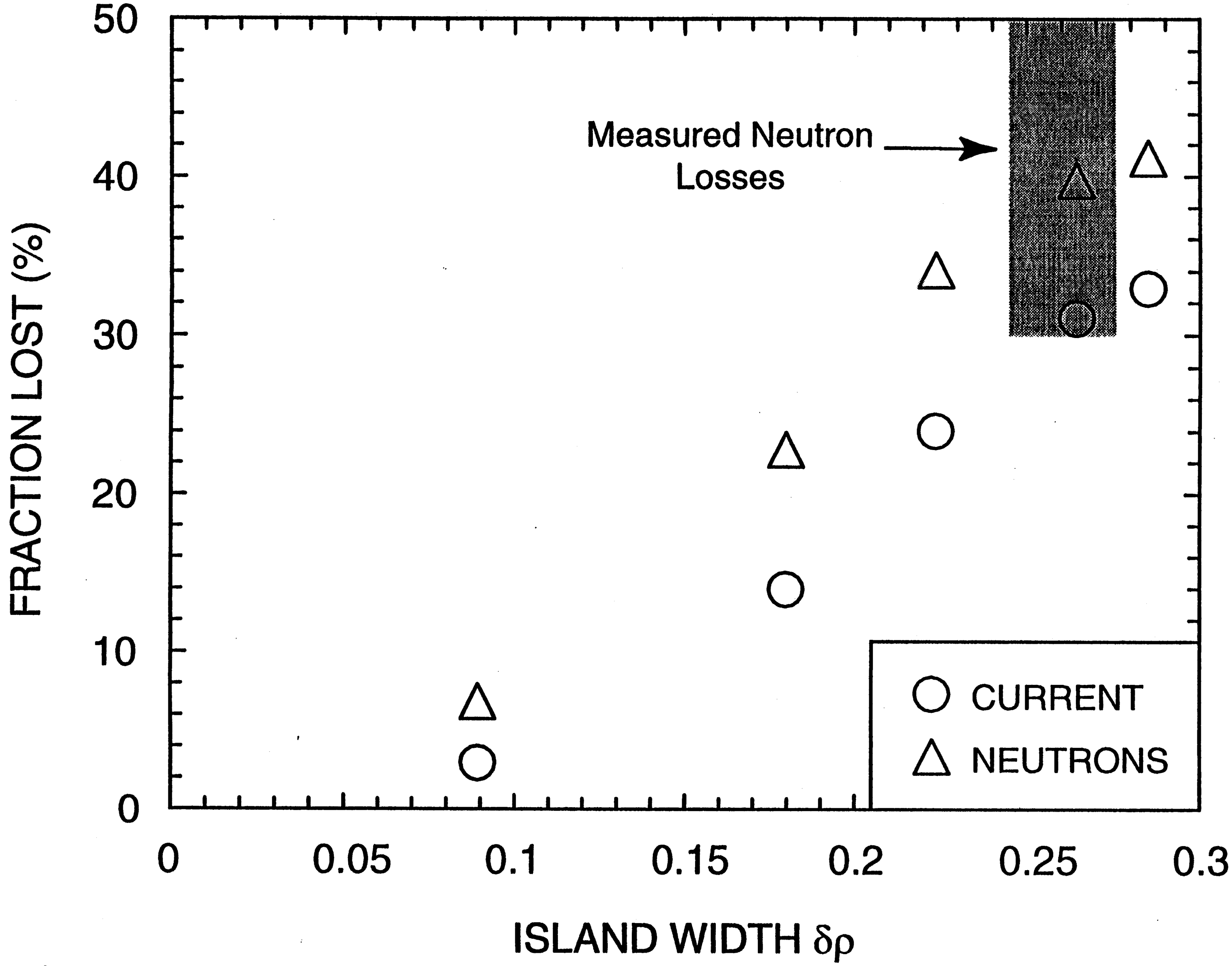

Figure 6. When the simulated island equals the measured island width, the predicted reductions in central current drive and neutron rate agree with the measured reductions.

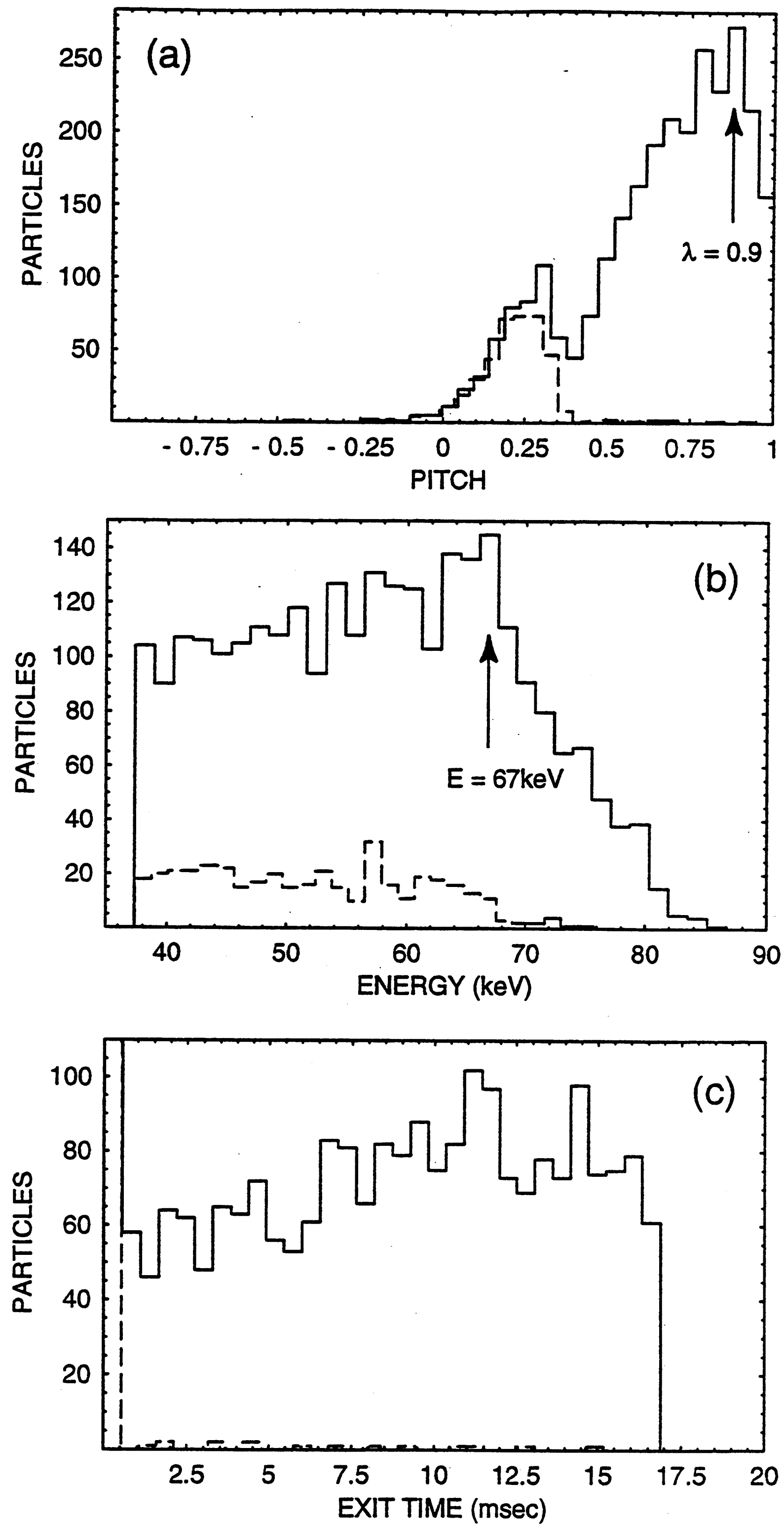

Figure 7. The calculated losses are of (a) strongly circulating, (b) high energy beam ions. The losses accumulate steadily (c). Intrinsic orbit stochasticity theory is qualitatively consistent with these numerical results.

The Effect of External Helical Fields on Fusion Products

- Use the burnup of 1 MeV tritons to monitor fusion product confinement. Use external coils to produce helical fields (Fig. 1).

- The vacuum perturbations are ~ 10 G. Helicities that resonate with a rational q surface and non-resonant helicities are both tried (Fig. 2).

- The burnup in discharges with a helical field is compared to discharges with no field (Fig. 3). To within 15% uncertainty, no effect on the triton burnup is observed (Fig. 4).

- Tearing modes have a larger impact on the triton burnup (Fig. 5).

- Larger helical fields cause disruptions ==> stationary helical fields cannot be used to control alpha ash.

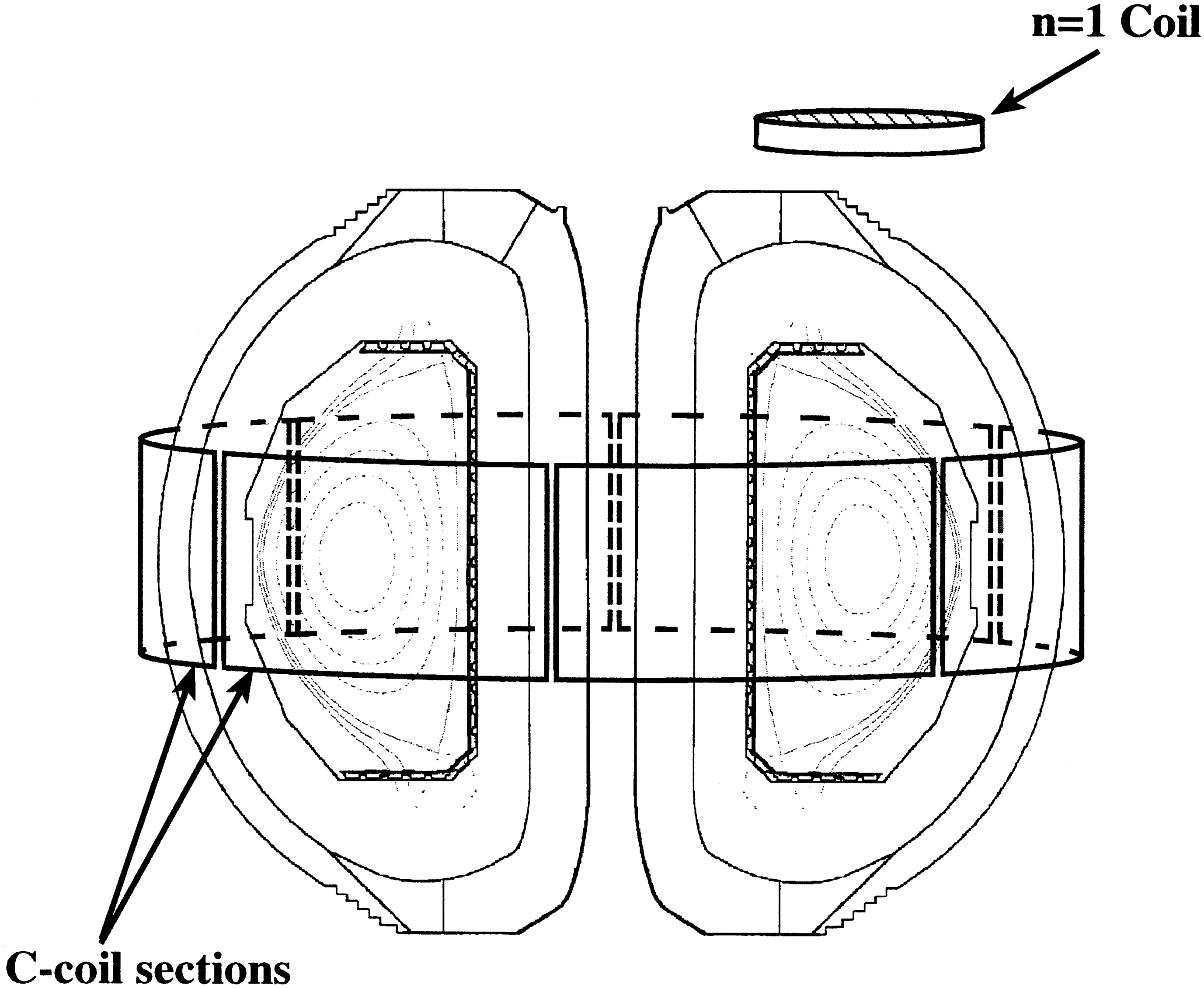

Figure 1. Illustration of the coil sets used to produce $n = 1$ and $n = 3$ helical perturbations.

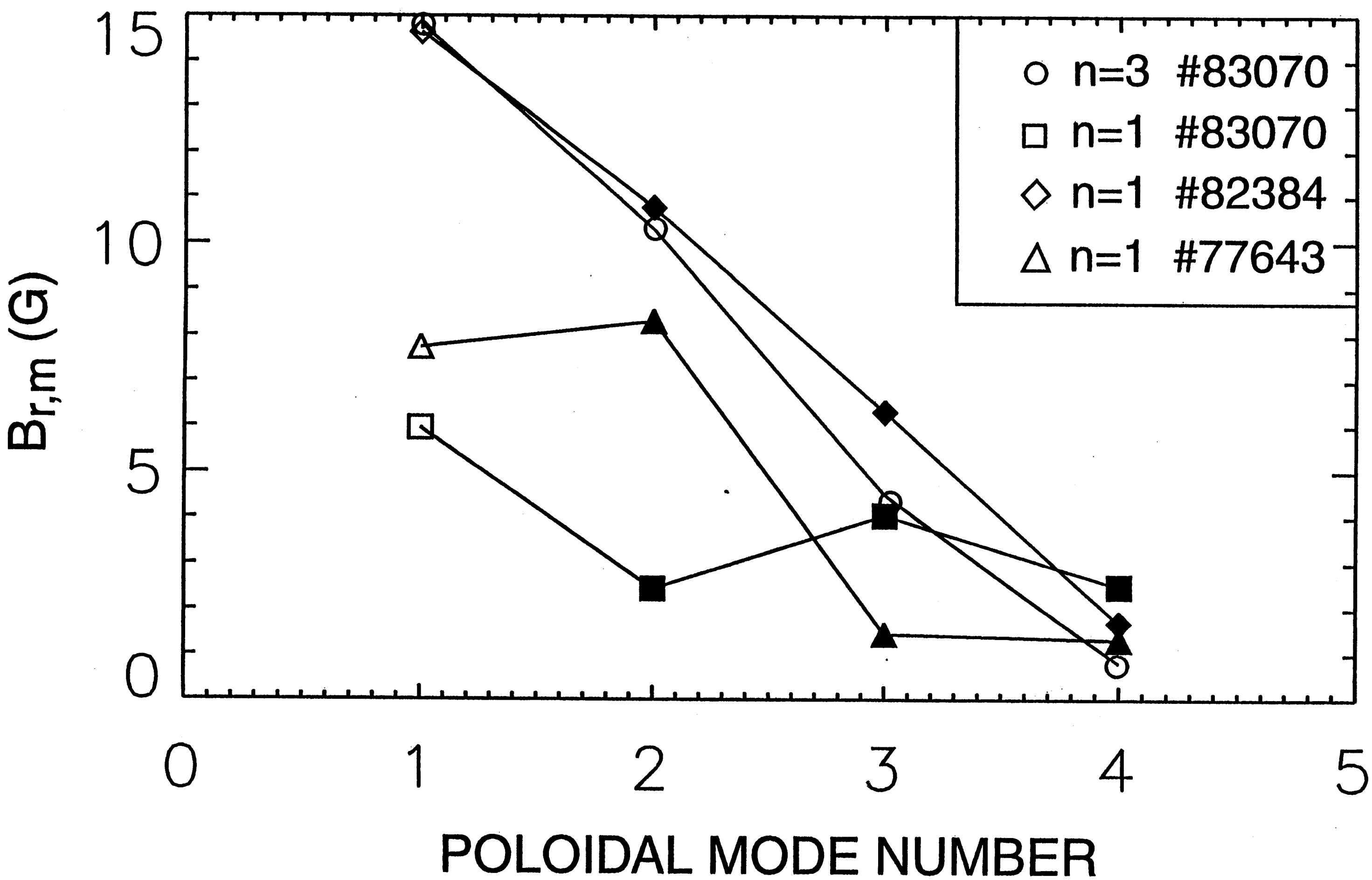

Figure 2. Examples of the field perturbations produced by the coils. The solid symbols represent helicities that resonate with a rational q surface in the plasma.

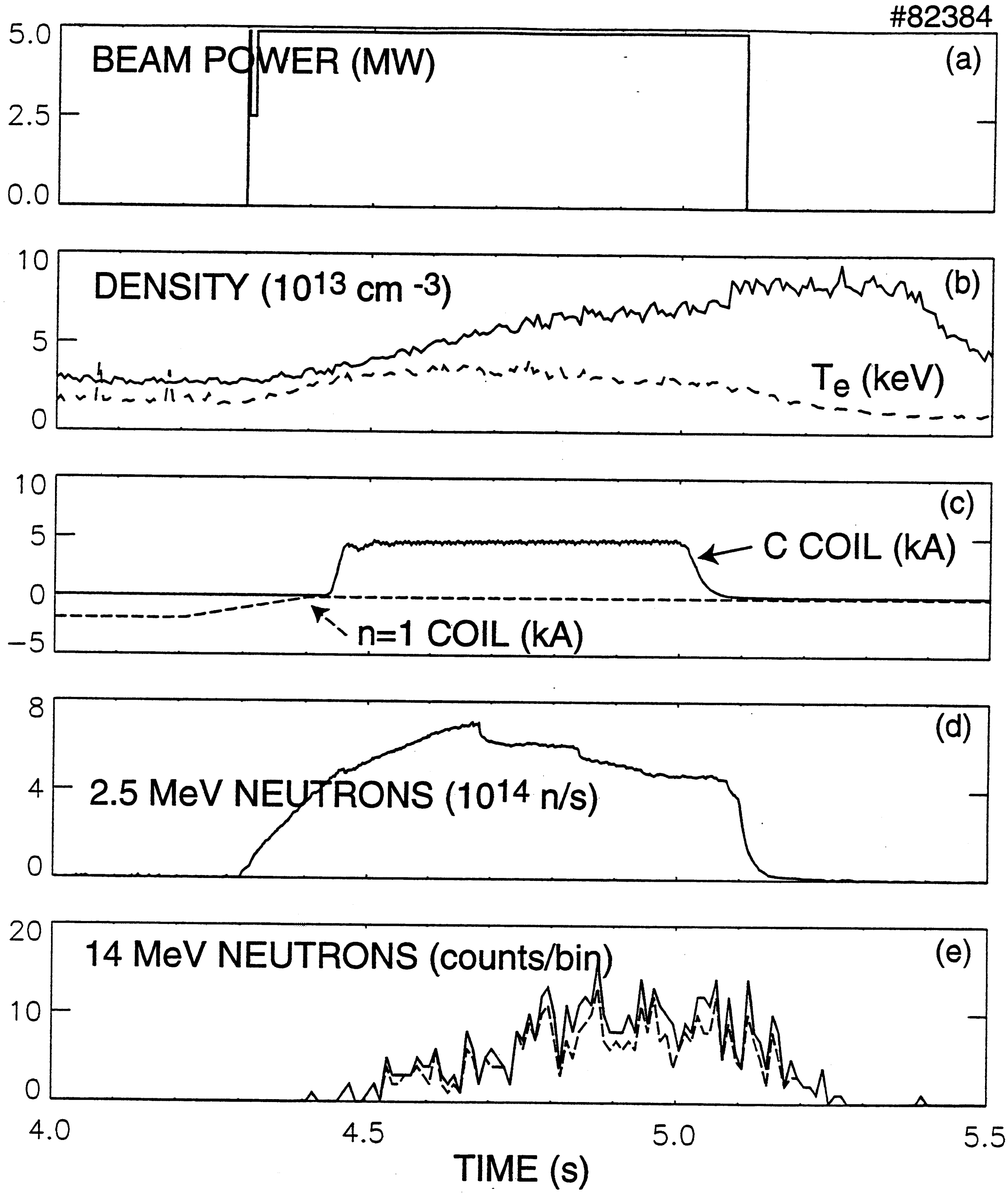

Figure 3. Typical data. In this case, the C-coil produces the helical perturbation. The ratio of the 14-MeV neutron fluence to the 2.5-MeV neutron fluence monitors the confinement of the triton fusion product. As expected classically, the tritons take ~ 0.2 s to reach the peak of the d(t,n) cross section.

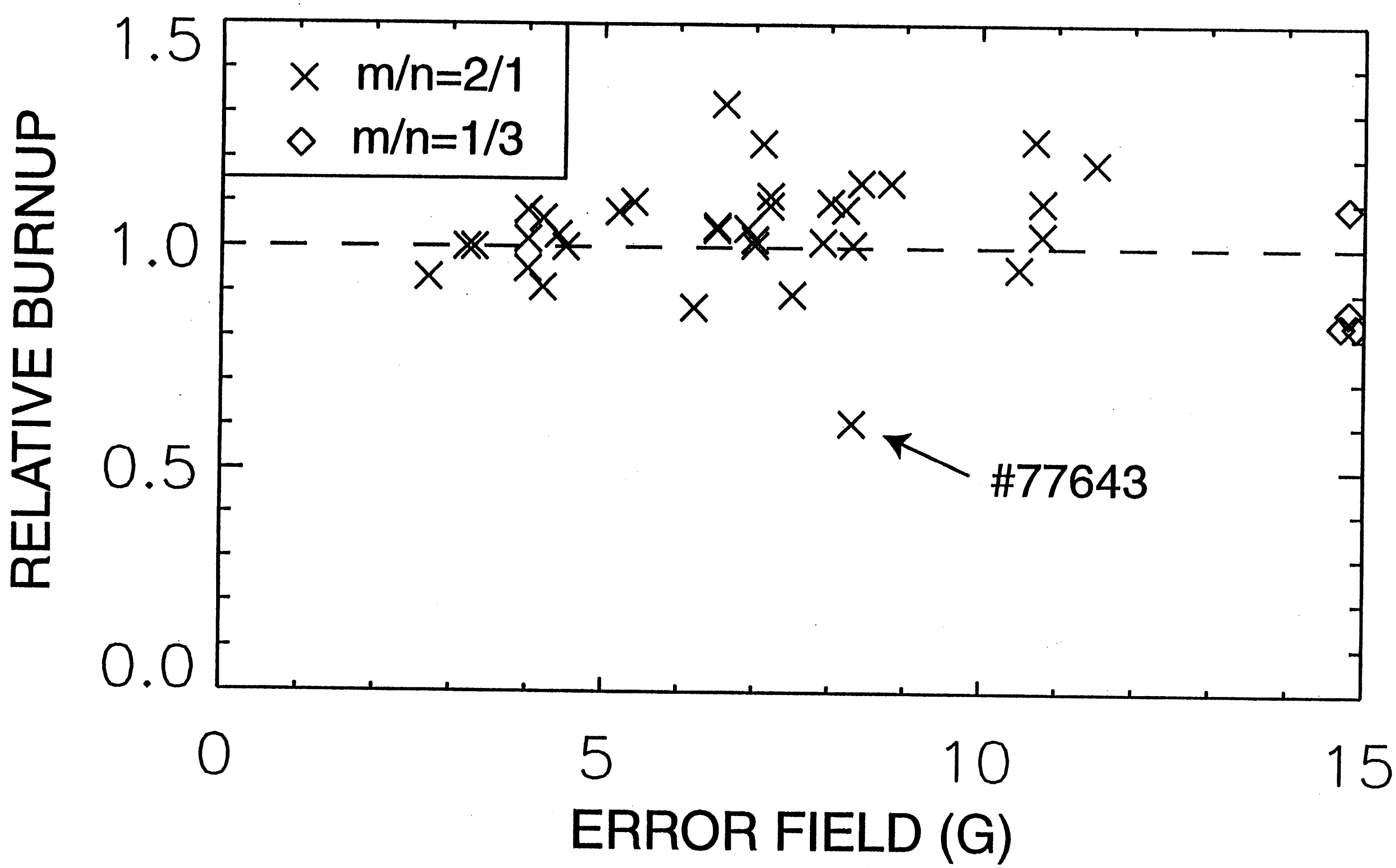

Figure 4. On average, the external helical fields have no impact on the triton confinement.

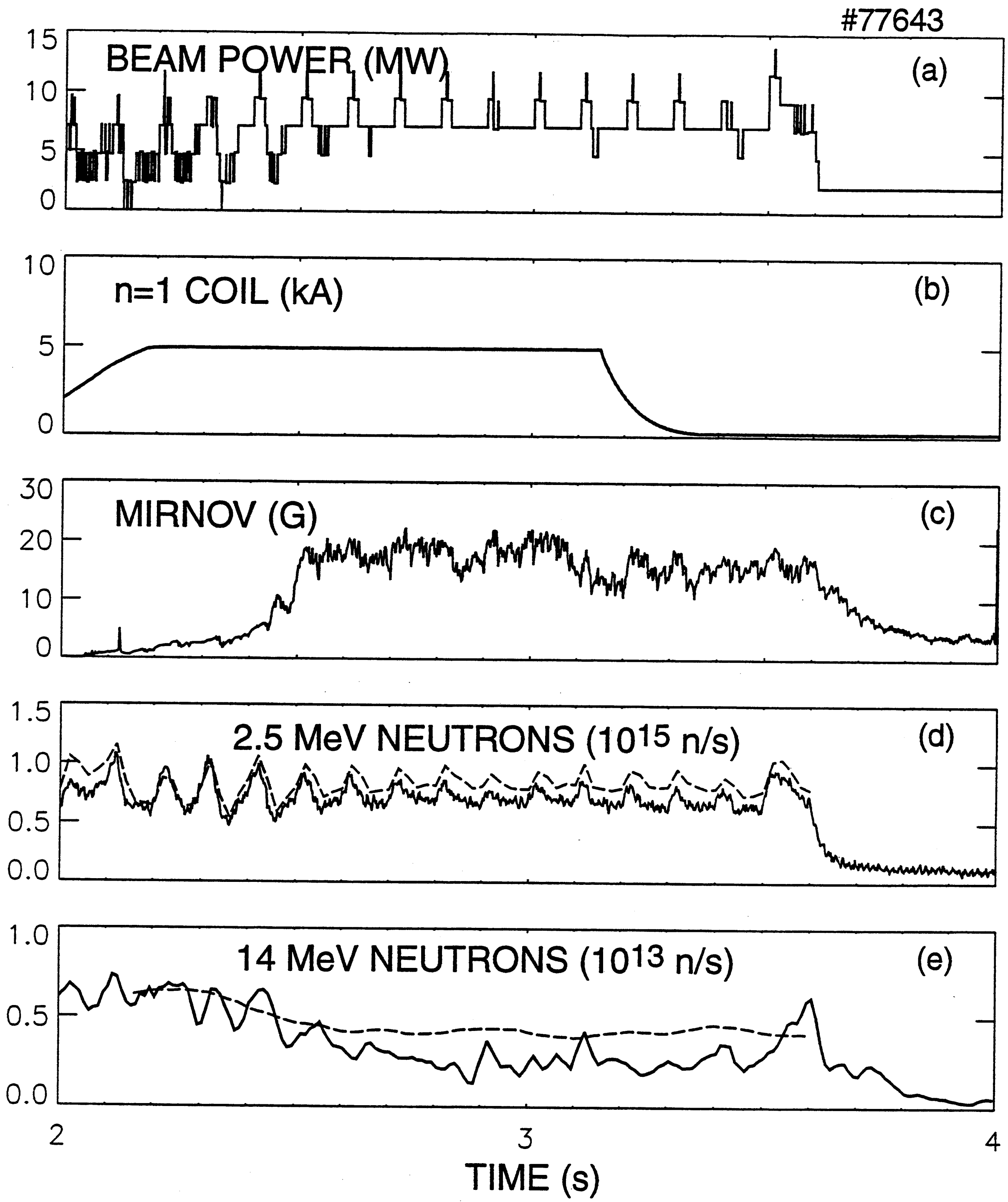

Figure 5. A discharge with anomalous triton burnup. The $n = 1$ coil produces the external helical field in this case. The onset of a large, rotating $m/n = 2/1$ tearing mode has a much larger effect on the triton burnup.

TAE Mode Structure

- Use three codes to calculate the TAE eigenfunction (Fig. 1).

- The ideal MHD eigenfunction disagrees with the soft x-ray data (Fig. 2); the gyro-kinetic eigenfunction is better (Fig. 3).

- Measurements indicate ~7% of the beam ions are lost at each TAE burst (Fig. 4).

- Use White's ORBIT code to see if the theoretical eigenfunctions can explain the measured losses. The ideal MHD eigen-function is inconsistent with the data (Fig. 5).

- Finite $E_{||}$ may be necessary to explain the observations.

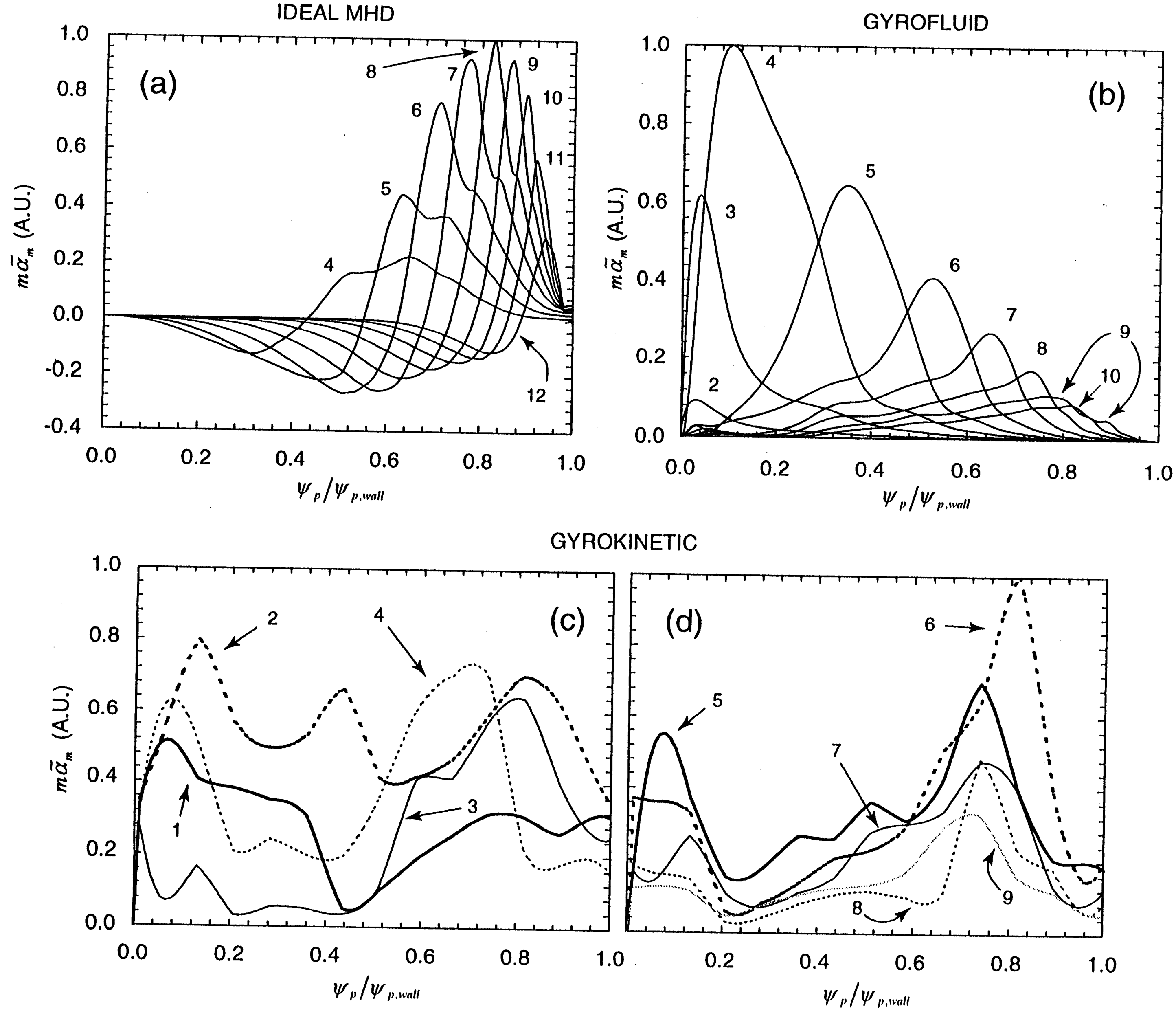

Figure 1. TAE eigenfunctions calculated by three different codes for the same discharge. (a) Ideal MHD code NOVA-K. (b) Oak Ridge gyrofluid code. (c,d) PENN gyrokinetic code.

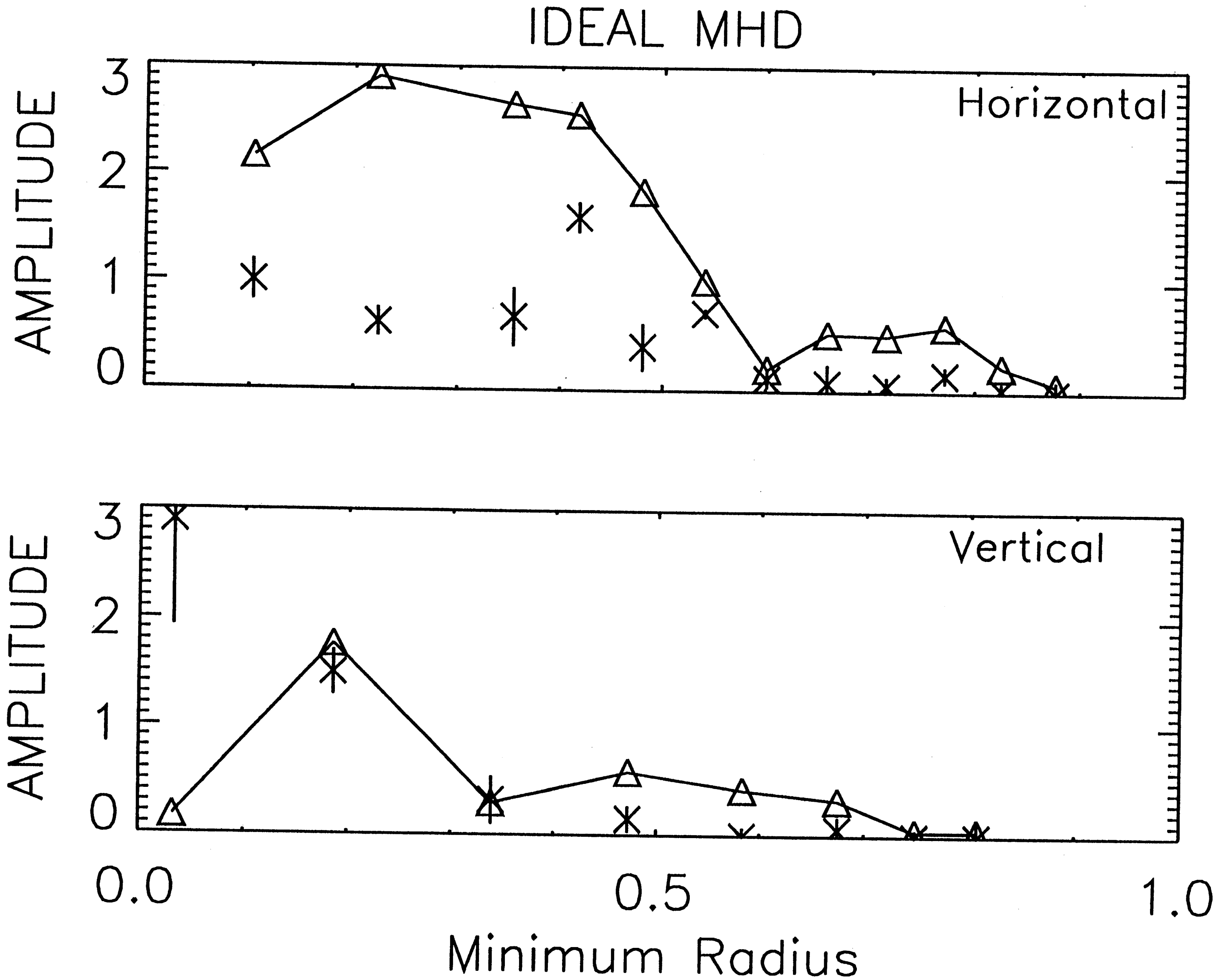

Figure 2. Comparison of the measured soft x-ray fluctuations (×) with the fluctuations calculated from the NOVA-K eigenfunction (△).

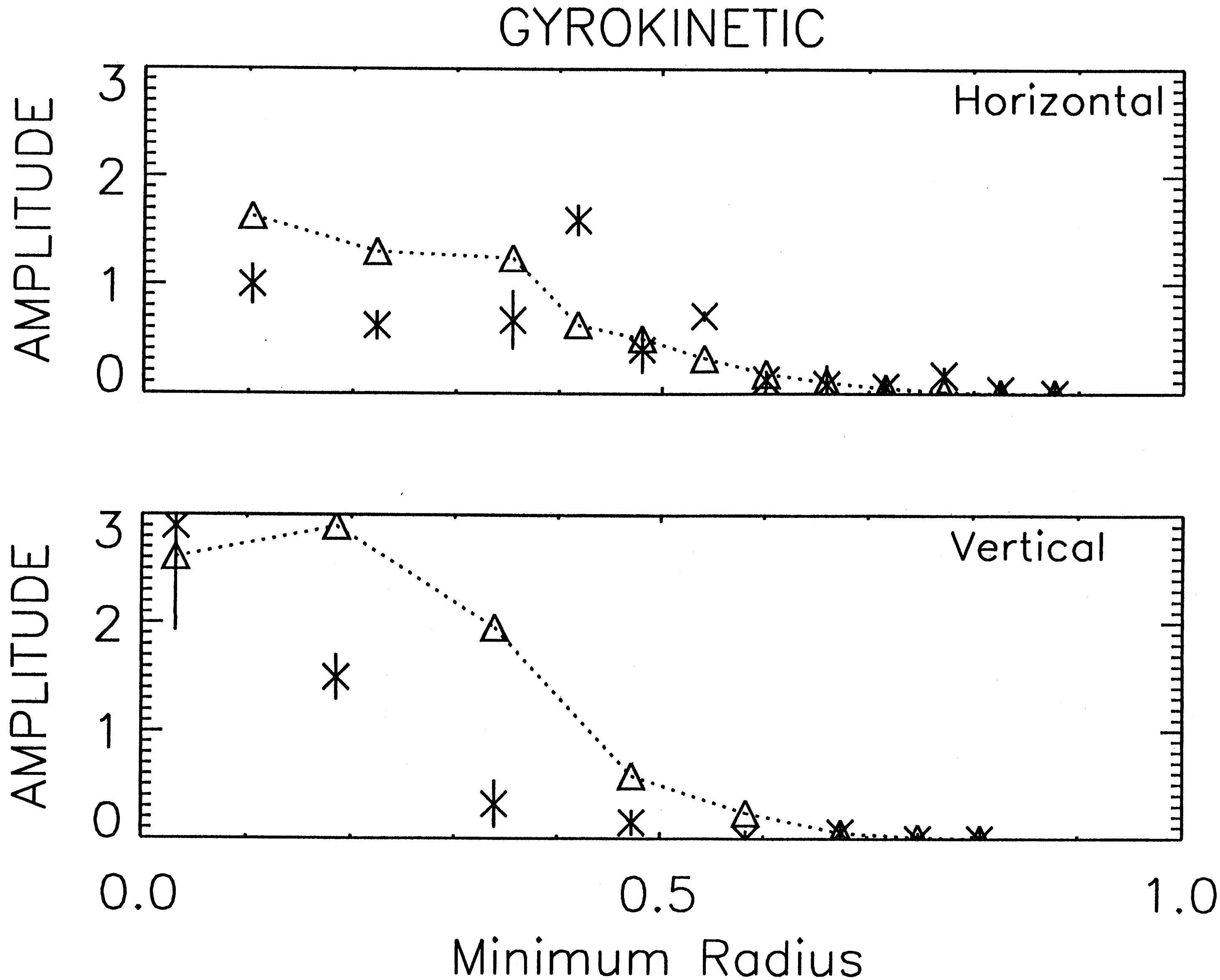

Figure 3. Comparison of the measured soft x-ray fluctuations (×) with the fluctuations calculated from the PENN eigenfunction (△).

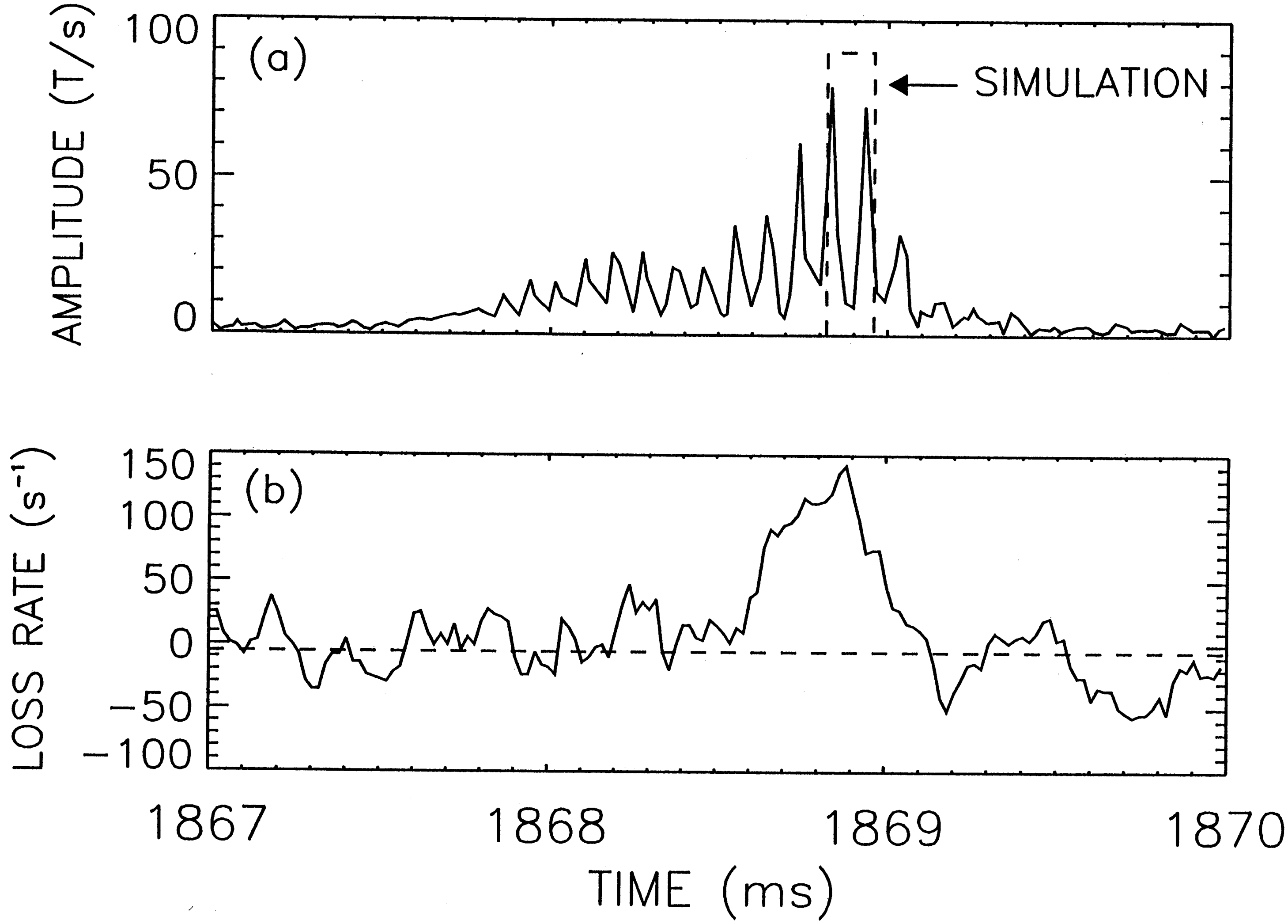

Figure 4. Data from a TAE burst. (a) Filtered Mirnov coil signal. (b) Beam-ion loss rate inferred from the neutron rate.

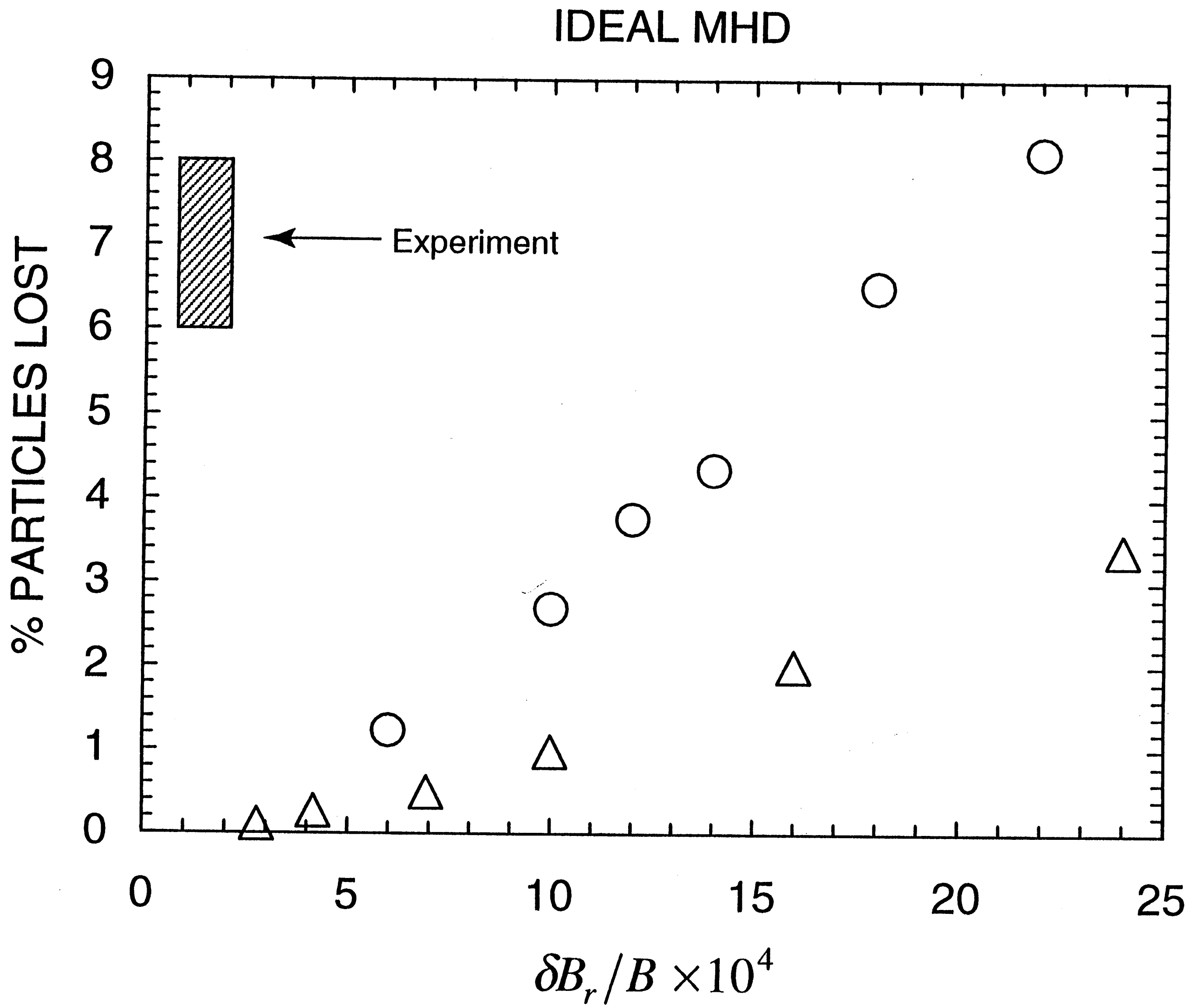

Figure 5. Results of ORBIT simulations using the NOVA-K eigenfunction. The simulated losses are much smaller than the measured losses at the experimental amplitude.

Conclusions

- Intrinsic orbit stochasticity is responsible for the observed beam-ion transport. Both analytic theory and numerical simulations agree quantitatively with experiment.

- Stationary helical perturbations with $\delta B/B \sim 10^{-3}$ cause no degradation in fusion product confinement. Rotating helical fields must be used for alpha ash control.

- The radial eigenfunction of TAEs predicted by ideal MHD theory is inconsistent with the data. Kinetic modifications to the eigenfunction are important.