Numerical Investigations of Instability-Induced Current Redistribution in a Spherical-Torus Plasma

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Abstract

Recent experimental observations suggest that interchange-type instabilities may play an important role in redistribution of the neutral beam injected current in the National Spherical Torus Experiment (NSTX). In our present work, the guiding center orbits of various test particles are integrated in the presence of a prescribed magnetic perturbation using a modified version of the ORBIT code. The perturbation modes are derived from NSTX diagnostic data during periods where instability-induced redistribution is observed experimentally. These results show the possibility of enhanced transport for certain regions of phase space. Simulations are also presented which show the time evolution of the neutral beam injected ion distribution, where the initial profile is obtained using a newly developed component for NUBEAM, part of the TRANSP software package. Ultimately, we hope to develop a self-consistent model for instability-induced current redistribution, including possible self-regulation between the fast-ion current and the core MHD instabilities.

Current Drive in ST Plasmas

- The spherical-torus (ST) configuration, and tokamaks in general, rely on a combination of non-inductive current drive mechanisms
  - Self-generated "bootstrap" effect
  - neutral beam injection current drive (NBICD)
  - electron cyclotron wave current drive

- Even when the majority of the current is driven by the bootstrap effect, additional current drive mechanisms and/or the action of benign MHD instabilities may be necessary to maintain an elevated central safety factor and avoid disruptive instabilities

- Recent experimental observations with NSTX identified saturated core-localized interchange-type (SCI) modes as a potential means of redistributing injected energetic particle current to produce an elevated saftey factor[1]

[1] *Menard et al., PRL **97**, 095002 (2006)*

Modeling SCI / NBICD Interaction

- The goal of this research is to develop a self-consistent model for the interaction of MHD SCI modes with the neutral beam injected current.

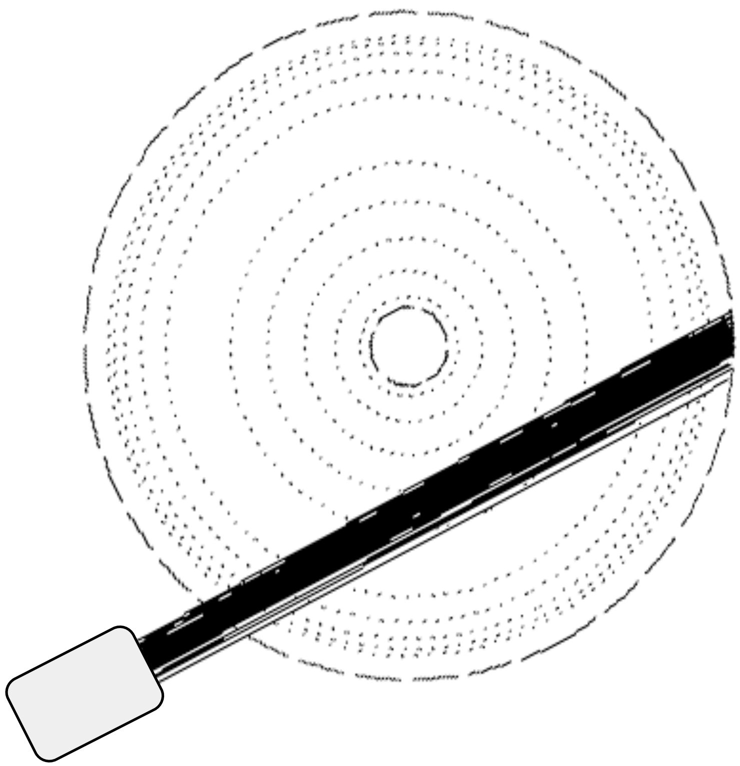
- Our initial efforts focus on just the influence of the MHD mode on neutral beam injected ions, without collisions or self-coupling between fast ion current and MHD activity.

- Modeling approach:
  - Obtain a realistic NBI deposition profile
  - Reconstruct appropriate MHD modes from experimental data
  - Numerically integrate the ion trajectories using the NSTX equilibirum with a superimposed MHD perturbation
  - Compute the fast-ion density and current distribution

NBI Deposition

- NUBEAM[2] is a component of the TRANSP software suite that computes neutral beam deposition profiles using a combination of experimental data and physics models
  - A set of neutral tracks through the plasma are generated based on models for the ion source (aperture size, beam diffraction, etc.)
  - The deposition distribution along each track is calculated using experimental data and atomic physics

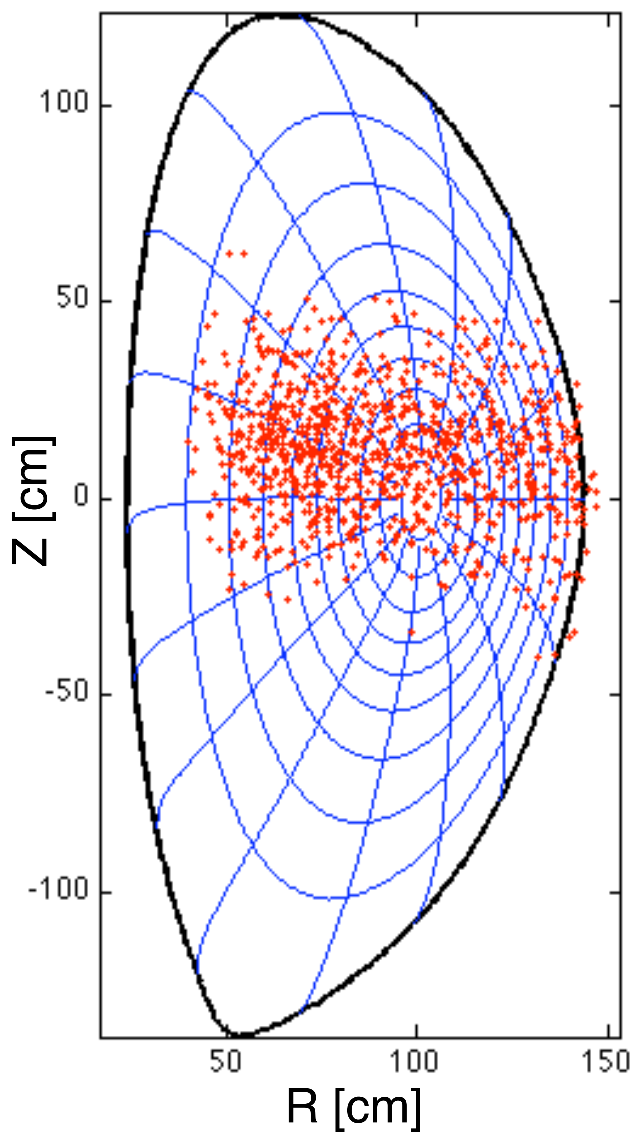
- For this work, a new output was written to sample guiding center location, pitch, and energy at the instant of ionization, thus providing appropriate initial conditions



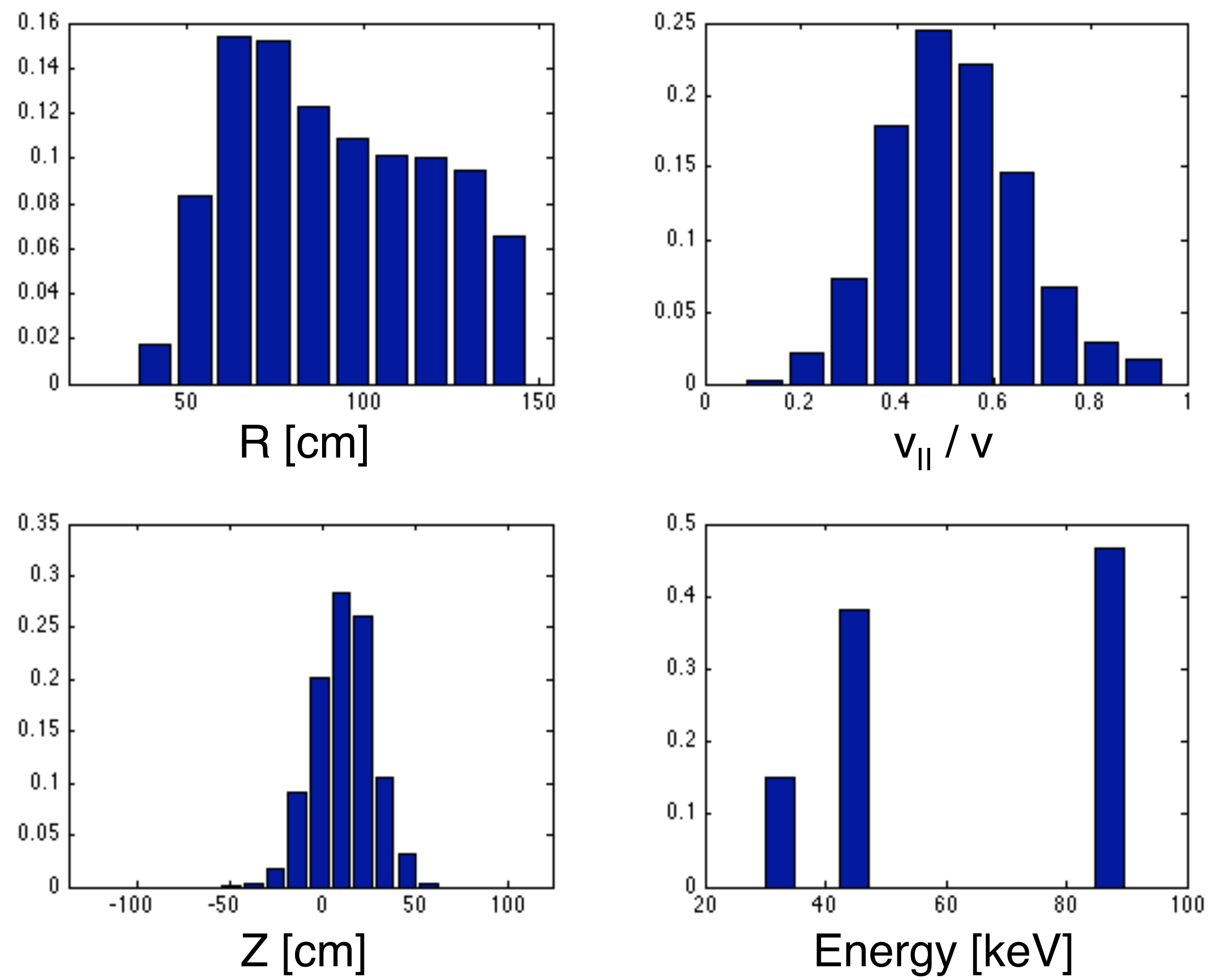
[2] *Pankin, McCune, Andre, Bateman, and Kritz, Computer Phys. Comm.* ***159*** *(2004) 157-184*

Nubeam Calculated Distribution

NSTX 116313



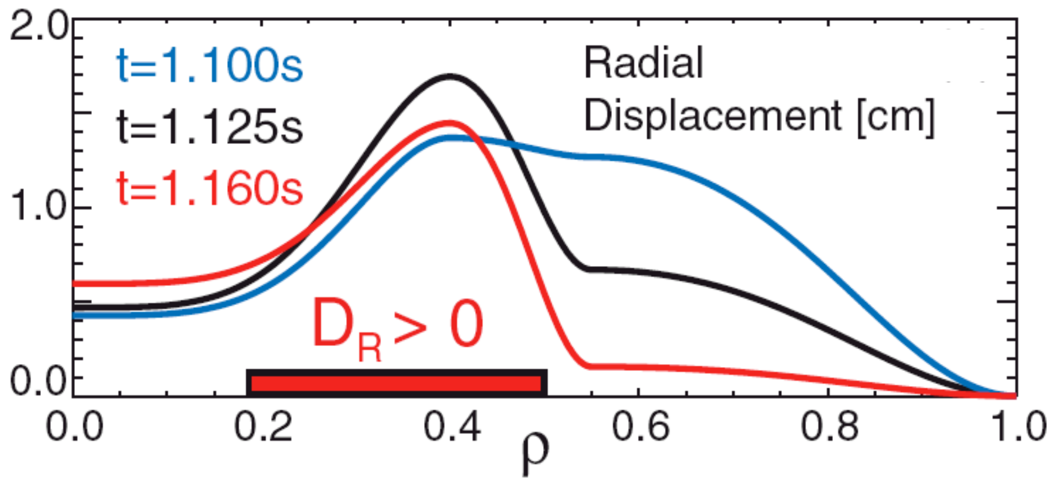
NBI Fast Ion Distribution [%] at t = 1100 ms



MHD Eigenmodes

- For the NSTX shot under consideration (116313), t = 1.05s marks the onset of the SCI mode, which persists for the rest of the discharge[1]

- The structure of the mode is obtained by inverting ultrasoft x-ray data
  - n = 1, m = 1, with the radial displacement shown below
  - Initially quite broad, the displacement beyond $\rho = 0.5$ drops to near zero by t = 1.14 s, after which the eigenfunction remains essentially constant
  - β and q profiles consistent with a resistive or quasi-interchange mode



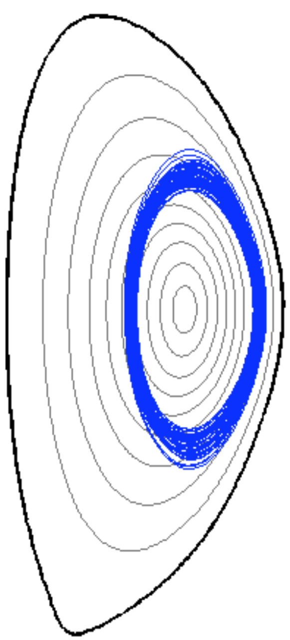
Reconstructed radial displacement amplitude during mode saturation

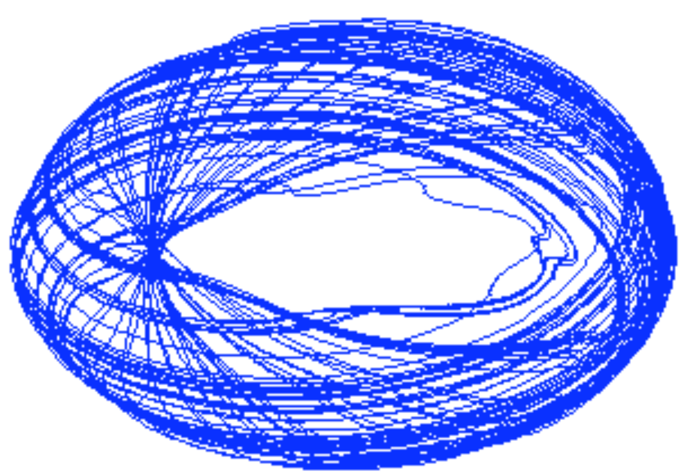
[1] *Menard et al., PRL **97**, 095002 (2006)*

Guiding Center Integration

- Our present work integrates the guiding center trajectories using a version of the Orbit code[3] that has been modified to read our MHD displacement profiles.

- Once the NSTX equilibrium and selected MHD eigenmode are loaded, the initial particle states are either artificially generated or else read in from an external file (which we sample from the nubeam statistics)





[3] *R.B. White and M.S. Chance, Phys. Fluids, Vol. 27, No. 10 (1984*

Poincare Analysis

- To better understand the orbits of the NBI deposited ions, Poincare plots are generated by running the Orbit code for 1000 on-axis toroidal transits (2.2 ms), with and without the MHD perturbation mode.

- D^+ ions are placed at Z = 0, R = [50:10:140]

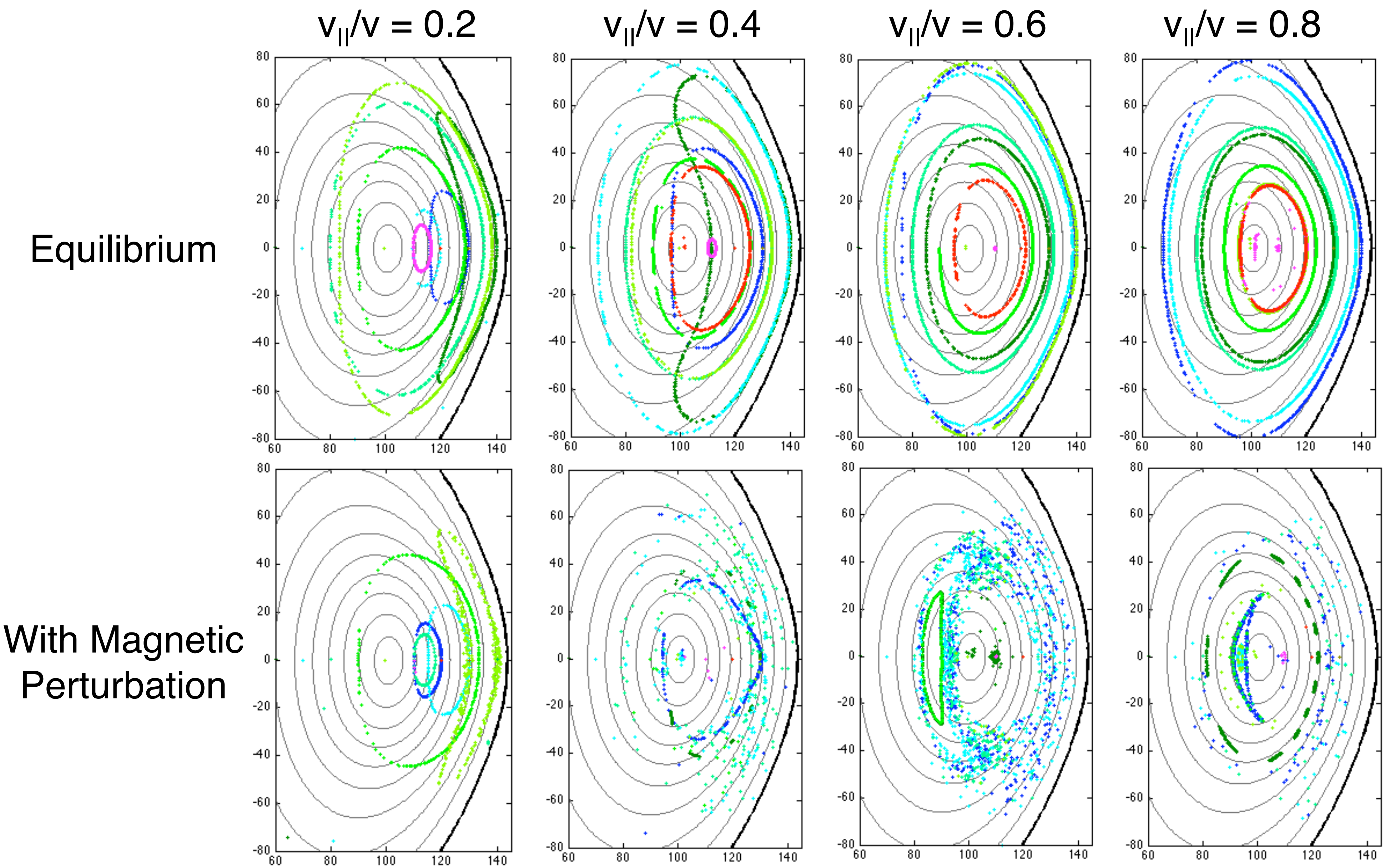
  E = {90, 45, 30} $v_{||}/v$ = {0.2, 0.4, 0.6, 0.8}

  Poincare plot colors denote initial particle locations:

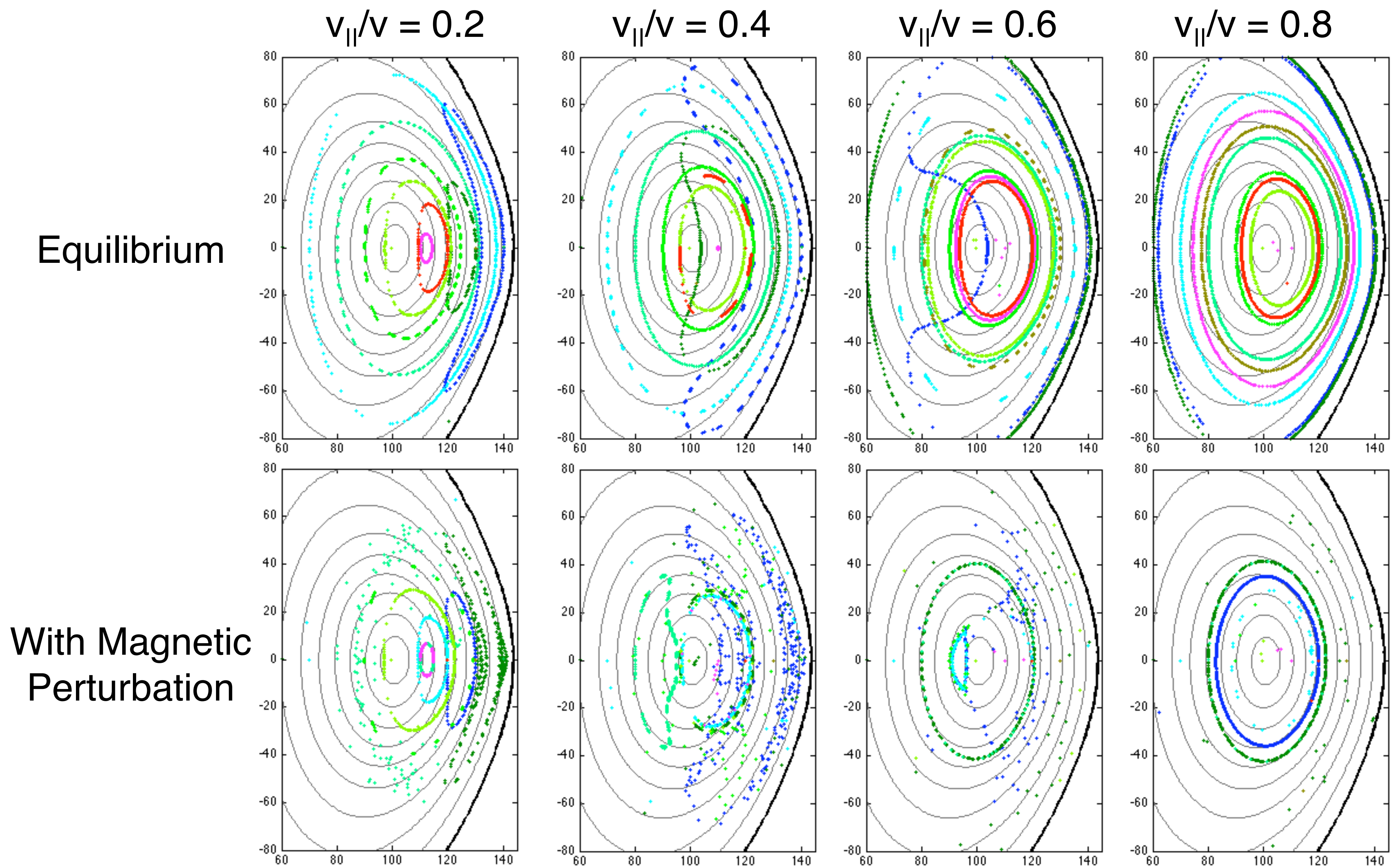
  - R = 50
  - R = 60
  - R = 70
  - R = 80
  - R = 90
  - R = 100
  - R = 110
  - R = 120
  - R = 130
  - R = 140

- Observational results indicate that with the magnetic perturbation:
  - many orbits become stochastic, particularly for $v_{||}/v$ = [0.4 : 0.6]
  - more particles are lost to wall, 25-50% within 100 on-axis toroidal transits compared to 20% for the equilibrium
  - some ions that would be on exterior flux surfaces for the equilibrium collapse to smaller radius surfaces

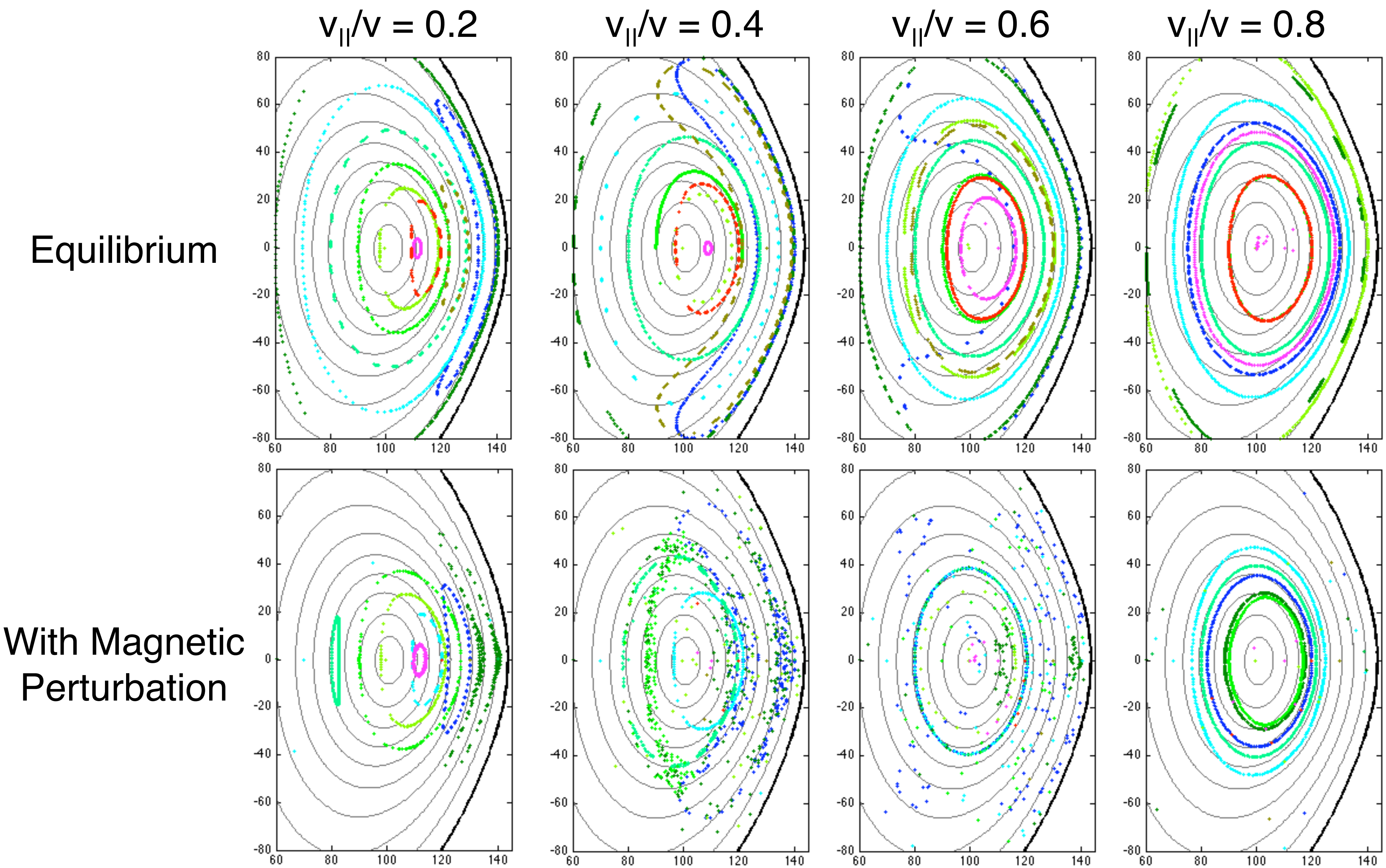
Poincare Plots: 90 keV D^+



Poincare Plots: 45 keV D^+

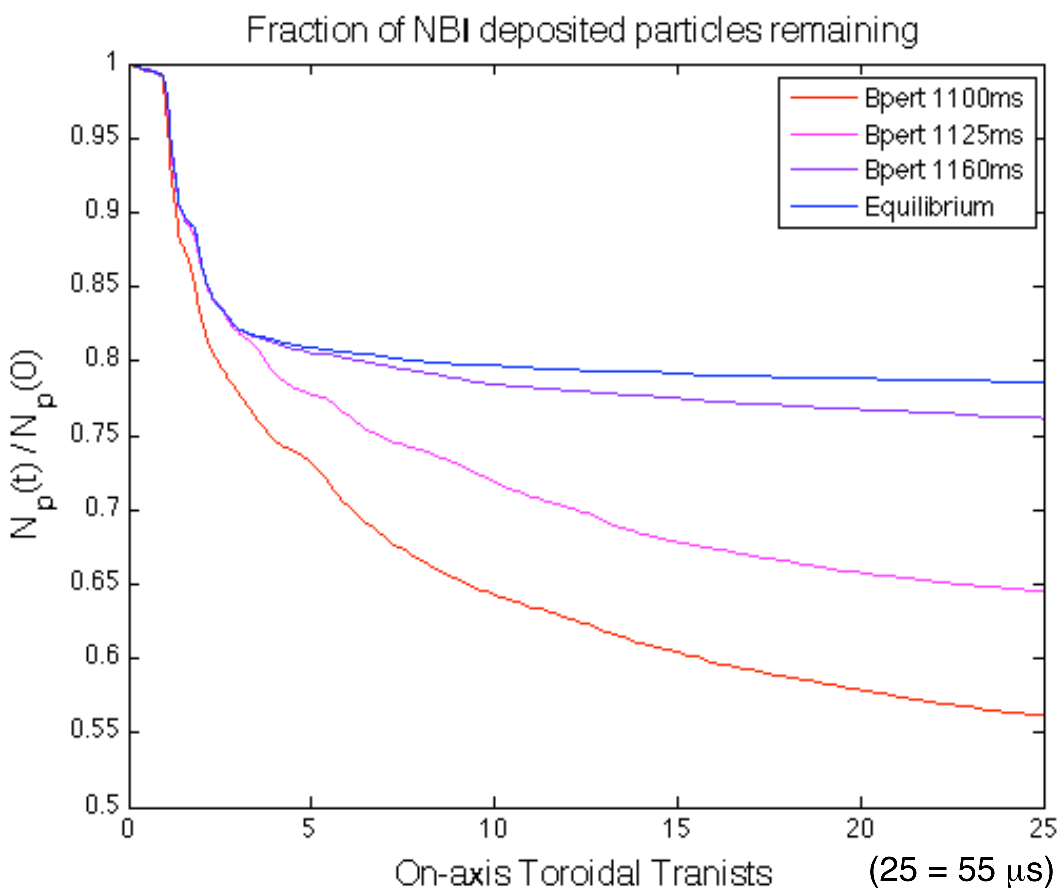


Poincare Plots: 30 keV D^+

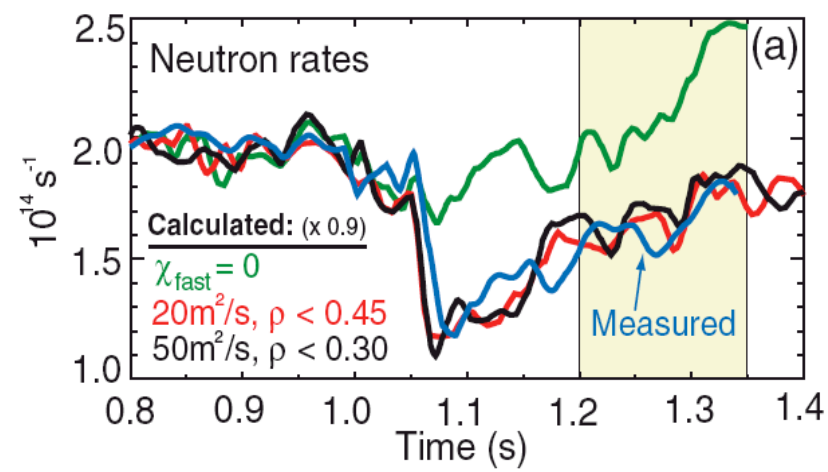


Particle Loss Rate

- Although all simulations indicate ~20% prompt loss, the presense of the magnetic mode results in further losses due to orbit stochastization
  - The loss rate is greatest for the boader 1100ms eigenmode
  - By 1160ms the loss rate has returned to near-equilibirum value



NSTX data indicates an initially large prompt decrease in neutral rate during this time, followed by a partial recovery[1]



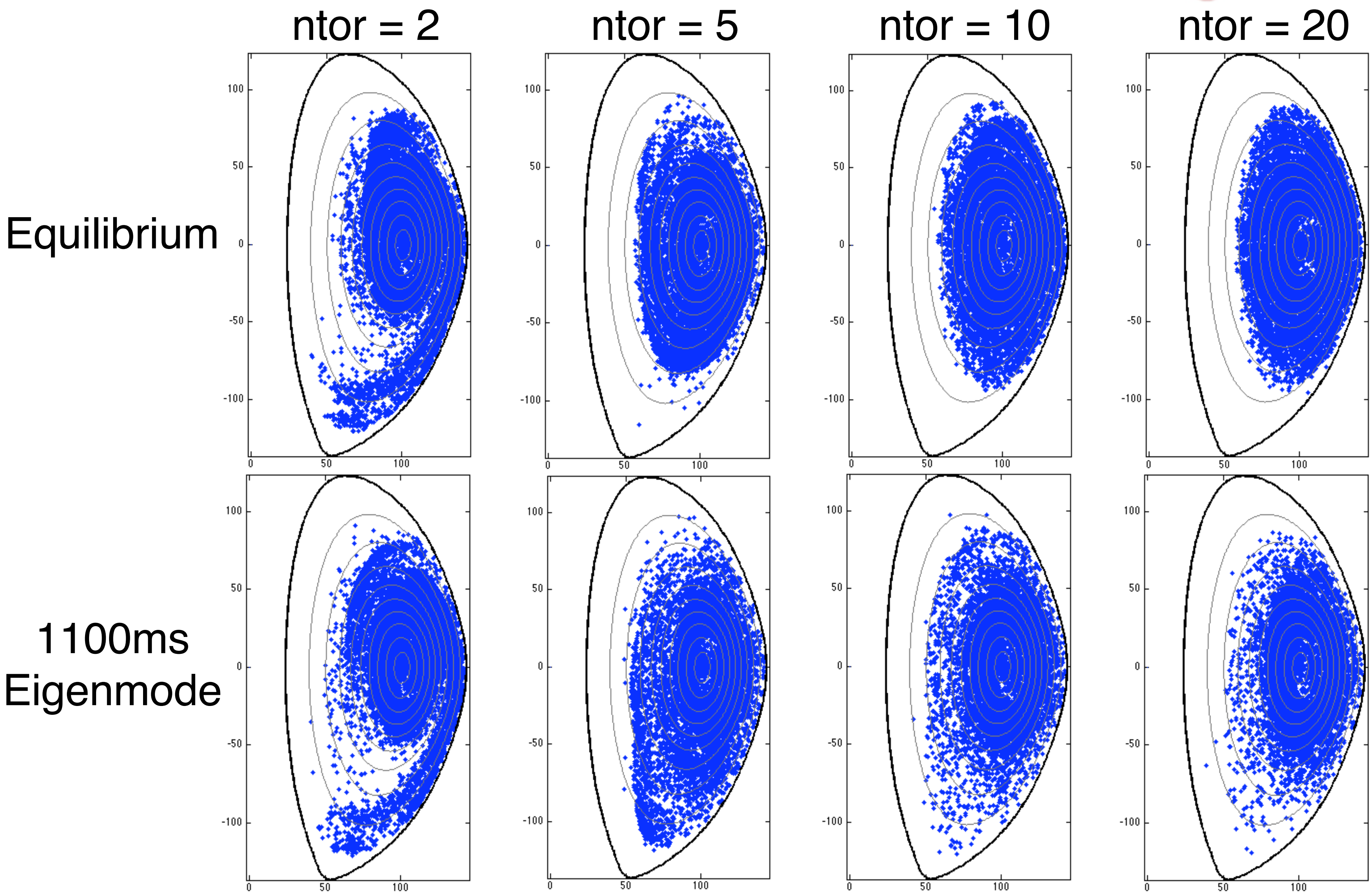
Time Evolution of the NBI Ion Profile

- To calculate the affect of the mode on the full NBI deposition distribution, large sample sets are loaded into orbit and integrated, both with and without the presense of the SCI mode

- The time scale of profile evolution is small compared to the mode oscillation period (5-8 kHz) and the ion collisional slowing down time
  - present work done without collisions or time-varying perturbation

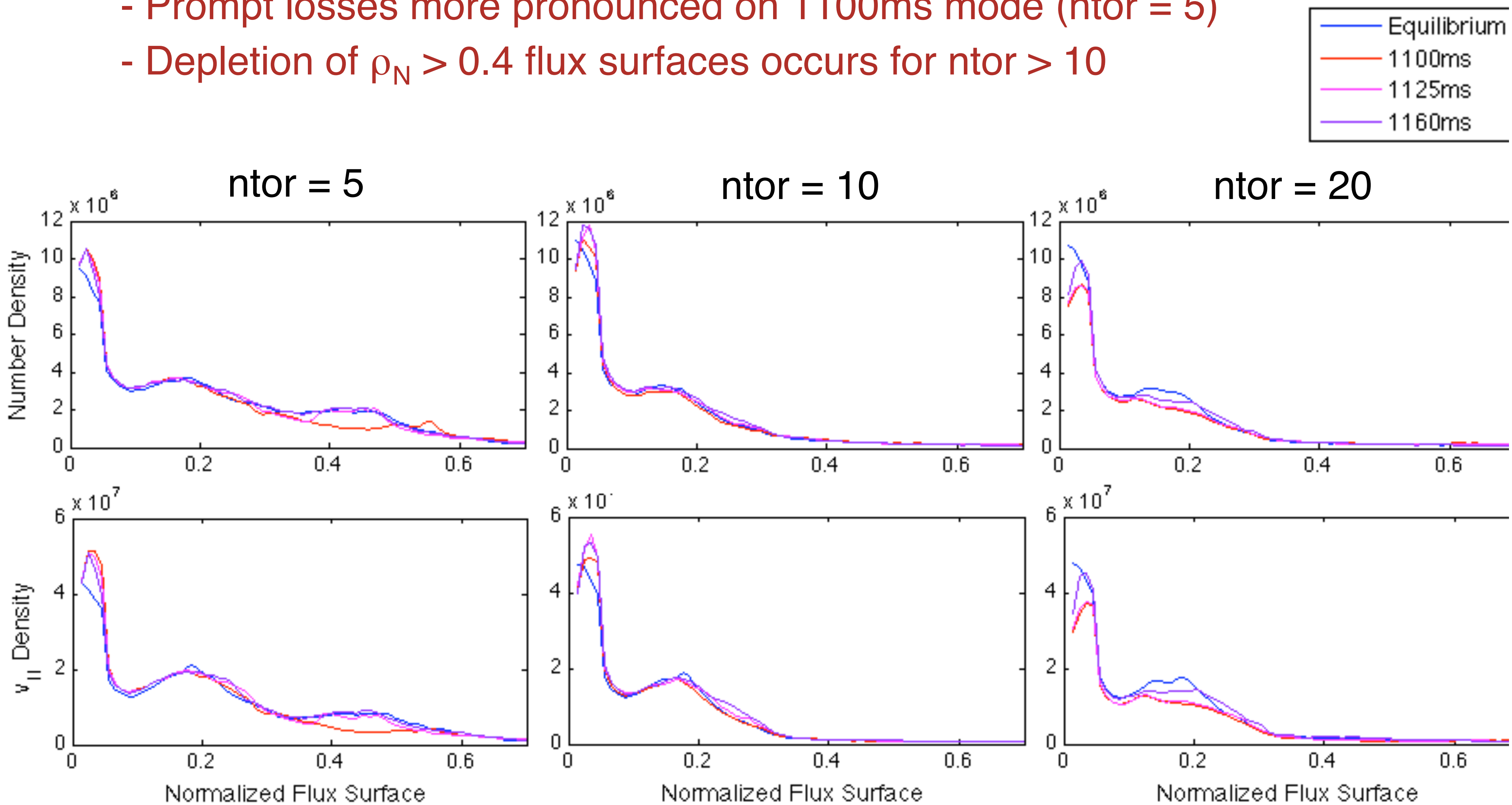
- Observational results indicate that with the magnetic perturbation:
  - significant ion loss occurs of ions on exterior flux surfaces

Guiding Center Location Scatter Plots



Flux Surface Averaged Quantities

- Averaged over θ, ζ and the preceeding 200 time steps (1 transit)
  - Prompt losses more pronounced on 1100ms mode (ntor = 5)
  - Depletion of $\rho_N > 0.4$ flux surfaces occurs for ntor > 10



Results Summary

- We have begun numerical investigations of the role of saturated core-localized interchange-type (SCI) modes in redistribution of NBI fast-ions

- The necessary tools for guiding center analysis (without collisions or coupling to the mode) have been developed
  - NBI deposition profiles obtained from TRANSP + NUBEAM
  - SCI eigenmodes reconstructed from ultrasoft x-ray data
  - Necessary modifications of the ORBIT guiding center code

- Initial results indicate enhanced transport due to the mode, as indicated by the loss rate, as well as NBI profile modification that includes depletion at exterior flux surfaces

References

(1) J.E. Menard et al., *Observation of instability-induced current redistribution in a spherical torus plasma*. PRL **97** 095002 (2006)

(2) A. Pankin et al., *The tokamak Monte Carlo fast ion module NUBEAM in the National Transport Code Collaboration library*. Computer Phys. Comm 159 (2004) 157-184

(3) R.B. White and M.S. Chance, *Hamiltonian guiding center drift orbit calculation for plasmas of arbitrary cross section*. Phys. Fluids **27** (1984)

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