DEUTERIUM NEUTRAL BEAM ORBITS IN NSTX-U NONAXISYMMETRIC VACUUM MAGNETIC FIELDS

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Abstract

Axisymmetry of the tokamak magnetic field provides good fast ion radial confinement. Perturbations from this symmetry could induce fast ion radial diffusion and loss. A nonaxisymmetric perturbation was chosen to model the effect of this symmetry loss on NSTX-U deuterium neutral beam ions. Passing and banana orbits in the perturbed field were simulated by integrating the Lorentz force over a duration shorter than the collision time of ions. Upon comparison with analogous orbits in the unperturbed field, the perturbation is shown to have a dispersive effect on the magnetic moment of particle orbit guiding centers. In particular, banana orbits acquire oscillating magnetic moments when subject to the nonaxisymmetric field. The behavior is modeled as a diffusion coefficient which varies with the magnetic moment and canonical angular momentum of the orbit.

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NSTX-U

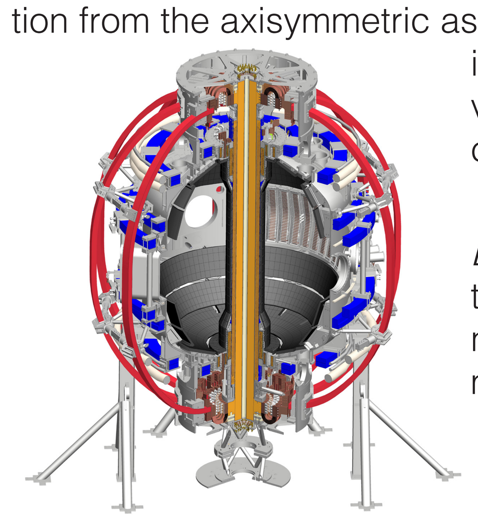
PPPL

Problem

Motivation

The magnetic field in NSTX-U is generally assumed to be axisymmetric. However, discreteness of the 12 toroidal coils surrounding NSTX-U breaks this symmetry from SO(2) to C(12). A perturbation of this type can induce fast ion radial diffusion and loss.

This project explains, characterizes, and evaluates the extent of loss caused by such a perturbation. To study the extent and nature of this loss, the perturbation from the axisymmetric assumption is modeled by integrating the Biot-Savart law over the twelve coils.



Left: Coils in red are toroidal. Their discreteness breaks SO(2) symmetry.

Approach

If ϕ is set to zero in the plane of one of the twelve coils, then the toroidal angle dependence is

$$\widetilde{\boldsymbol{B}}(r,\phi,z) = \widetilde{B_r}(r,z)\sin(12\phi)\hat{\mathbf{r}} + \widetilde{B_\phi}(r,z)\cos(12\phi)\hat{\boldsymbol{\phi}} + \widetilde{B_z}(r,z)\sin(12\phi)\hat{\mathbf{z}}$$

Where $B_\phi(r,z)$ is defined to assure divergenceless of the perturbation. The total magnetic field in NSTX-U is then the equilibrium magnetic field as calculated from the "G-eqdsk-file" of EFIT code added to a scaling factor multiplied by the perturbation.

$$\boldsymbol{B}_{eq}(r,z) = \nabla\Psi \times \nabla\phi + g(\Psi)\nabla\phi$$

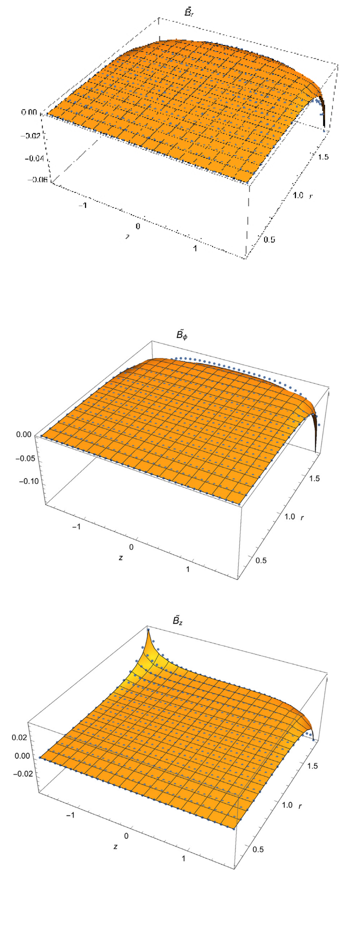
The scaling factor is calculated to best fit the experimental data. Note that divergenceless of the equilibrium magnetic field is assured by construction.

$$\mathbf{B}(r,\phi,z) = \boldsymbol{B}_{eq}(r,z) + \epsilon\widetilde{\boldsymbol{B}}(r,\phi,z)$$

Fitted functions are granted continuous first and second derivatives in all cases. Fitting and all data analysis is done on Mathematica to machine precision.

Perturbation

The magnetic ripple is fit using B-Splines on the domain .3<r<1.8 and -1.7<z<1.7.



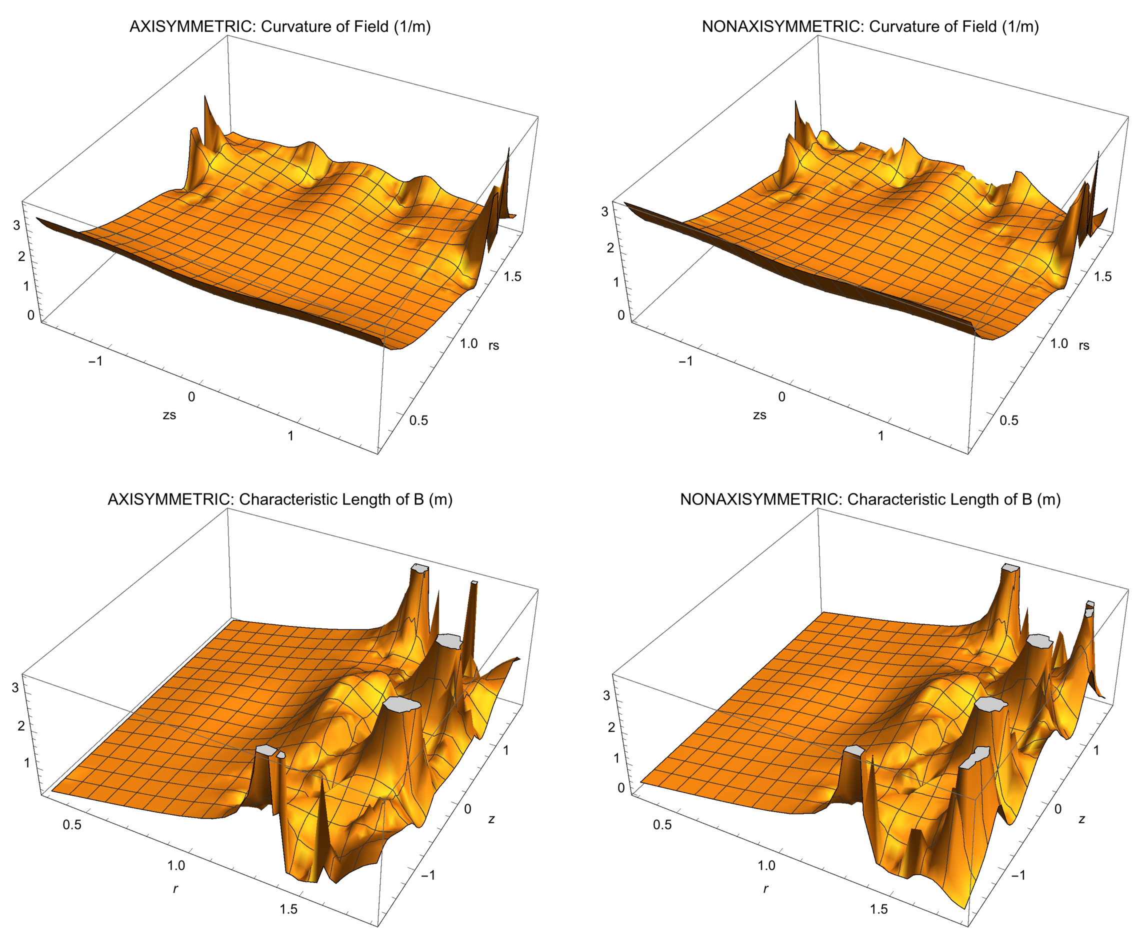
Left: Fitted perturbation functions. Order is .01 Teslas.

Right: Scale lengths of the perturbed and unperturbed fields

Relevant Parameters
- 90 keV
- B~0.5 T
- 2 m_p
- +1e
- t_f = 90 μs

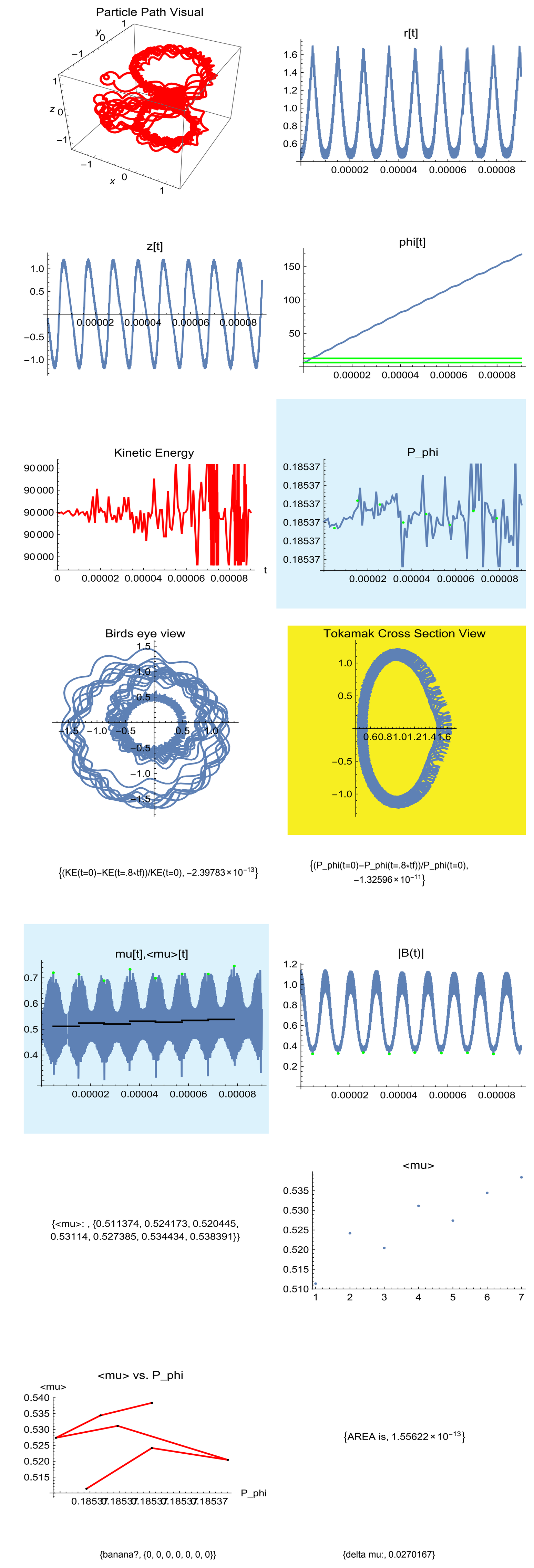
Quantities assumed to be small in the adiabatic approximation are the curvature κ and characteristic length L.

$$\kappa = \frac{|\gamma' \times \gamma''|}{|\gamma'|^3} \qquad L = \frac{B}{|\nabla B|}$$

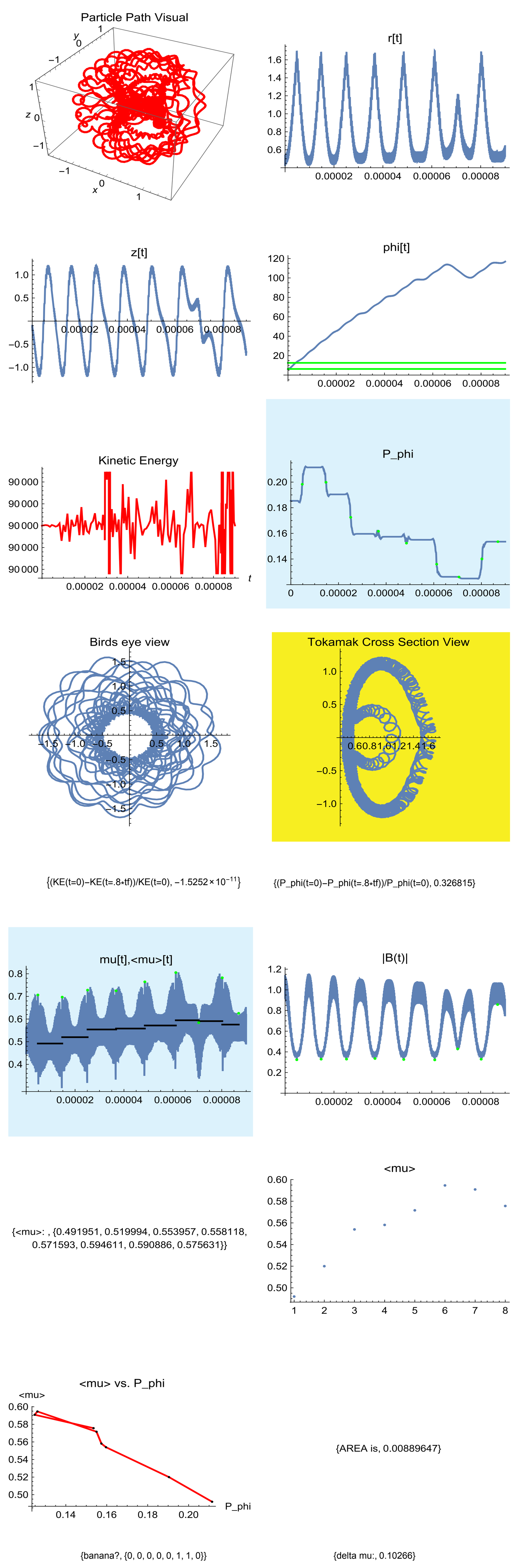


Results

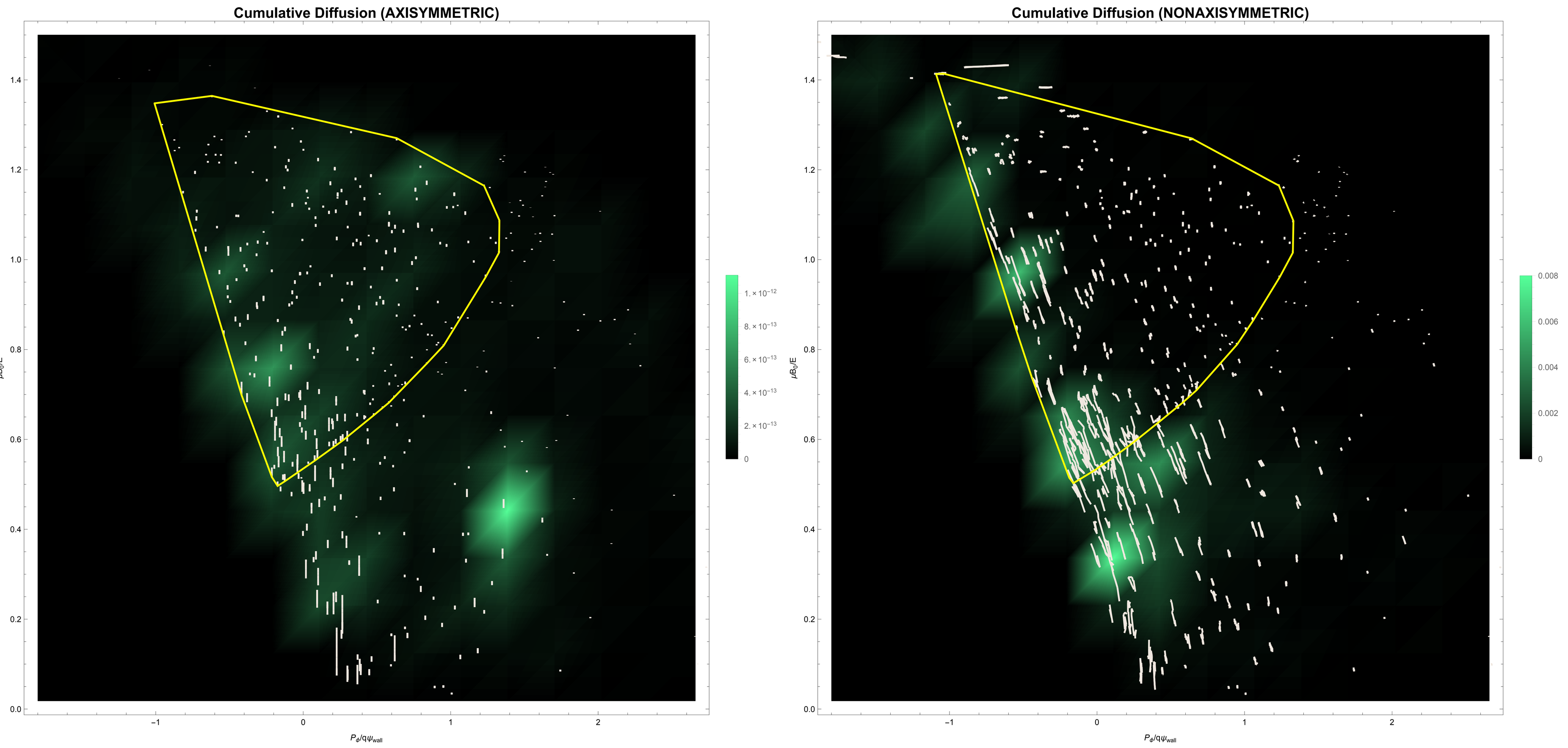
Axisymmetric

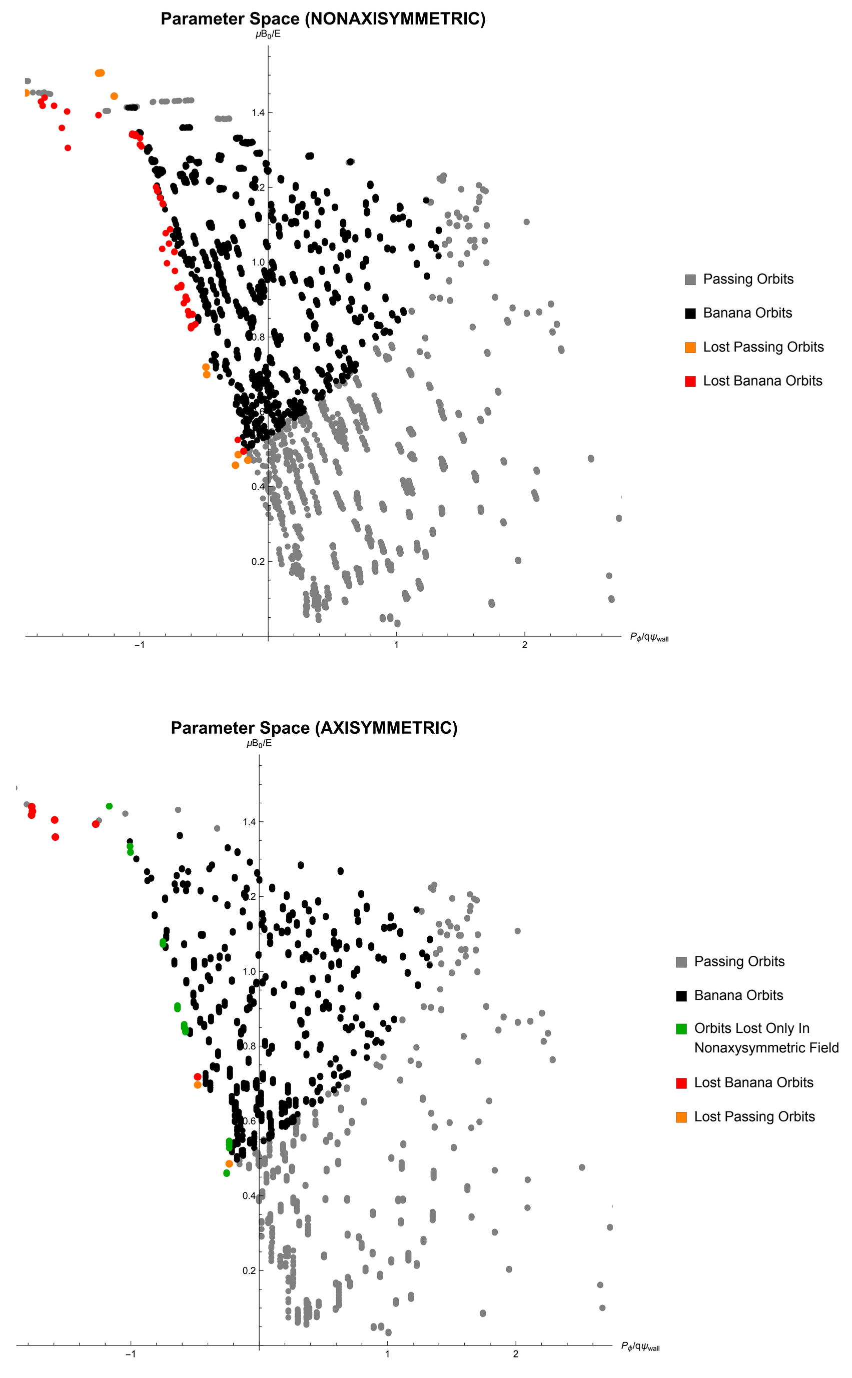


Nonaxisymmetric



Conclusions





Left: A scatterplot of initial conditions in paramater space. 14 orbits (11 banana, 3 passing) which are stable in the symetric field, are lost in the nonaxisymmetric field.

Above: The product range(mu)*range(P_phi) is calculated for all orbits and interpolated. The perturbation increases transport across the passing/banana boundary as well as the loss boundary.

Analysis

A variety of quantities were tracked for 471 orbits. In particular the first adiabatic invariant and canonical angular momentum were averaged over bounce motion.

$$\mu = \frac{mv_\perp^2}{2B} \qquad P_\phi = mr^2\dot{\phi} + q\psi$$

The class of orbit is determined purely by these two quantities. Orbits within the yellow boundary are banana orbits, orbits elsewhere are passing orbits. Orbits in the axisymmetric field exactly conserve angular momentum while orbits in the nonaxisymmetric field shift at regions of low |B|.

The data supports the theory that variation in the magnetic field over toroidal angle will cause fast ion loss in NSTX-U. More orbits will have to be tabulated to confirm this result before the findings of this project are published.

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