Comparison of Full Lorentz Model and Guiding Center Model of Ripple Loss Simulations in NSTX

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Abstract

Simulations of energetic particle ripple loss in National Spherical Torus Experiment (NSTX) are presented. Numerical calculations of large gyroradius effects on magnetic ripple induce particle loss are presented. Of particular interest is the comparison between the full Lorentz code GYROXY and guiding center code ORBIT in accurately estimating ripple loss. Both codes use EFIT equilibrium reconstruction of NSTX discharges with a calculated magnetic ripple added. Comparison is made in the particle loss rates for the two cases and the validity of the guiding center approximation in NSTX is discussed. The relative magnitude of ripple loss to other loss mechanisms is also presented.

Power Balance

Boltzmann Equation:

$$\frac{\partial f_s}{\partial t} + \vec{v} \bullet \nabla f_s + \frac{q_s}{m_s}(\vec{E} + \frac{\vec{v} x \vec{B}}{c}) \bullet \nabla_v f_s = \frac{df_s}{dt}\Big|_{collisions}$$

0th Moment: Continuity

$$\frac{\partial \rho}{\partial t} + \nabla \bullet (\rho \vec{u}) = S$$

1st Moment: Momentum Balance

$$mn\frac{d\vec{u}}{dt} = nq(\vec{E} + \vec{u} x \vec{B}) - \nabla \bullet \vec{\vec{P}} - mS\vec{u}$$

2nd Moment: Power Balance

$$P_{in} = Q_{ie} + n\chi\nabla T + P_{loss}$$

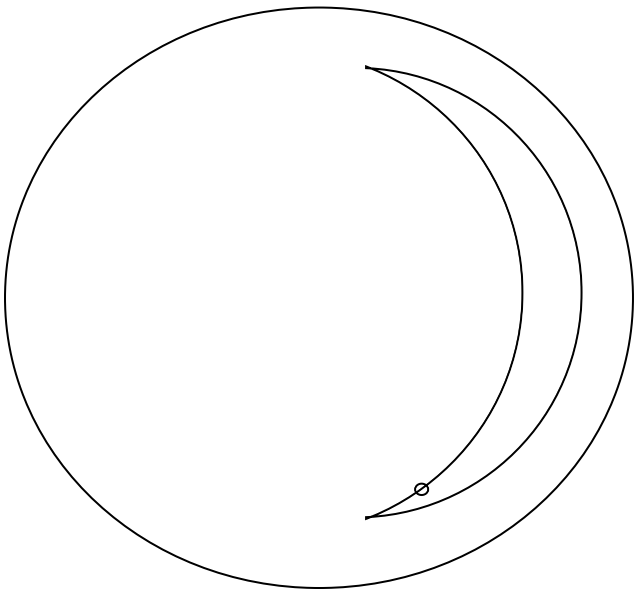
Heat lost to electrons

Diffusion

Any other loss mechanisms

Diffusion in NSTX

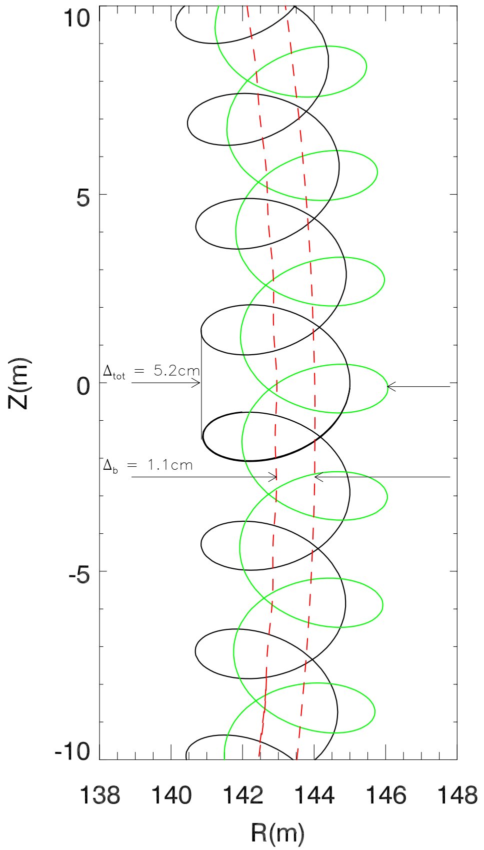
Neoclassical Diffusion
in a standard tokamak



$$\text{Step size} \approx \Lambda_i = \frac{\rho_i q}{\varepsilon^{\frac{1}{2}}} >> \rho_i$$

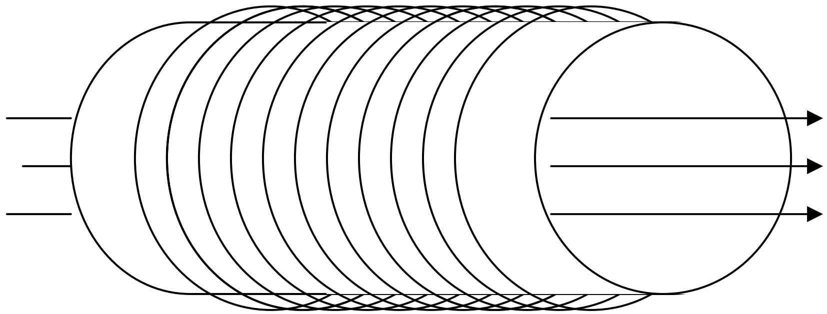
$$\text{Frequency} \approx \frac{\nu_{ie}}{\varepsilon}$$

Neoclassical Diffusion
in NSTX

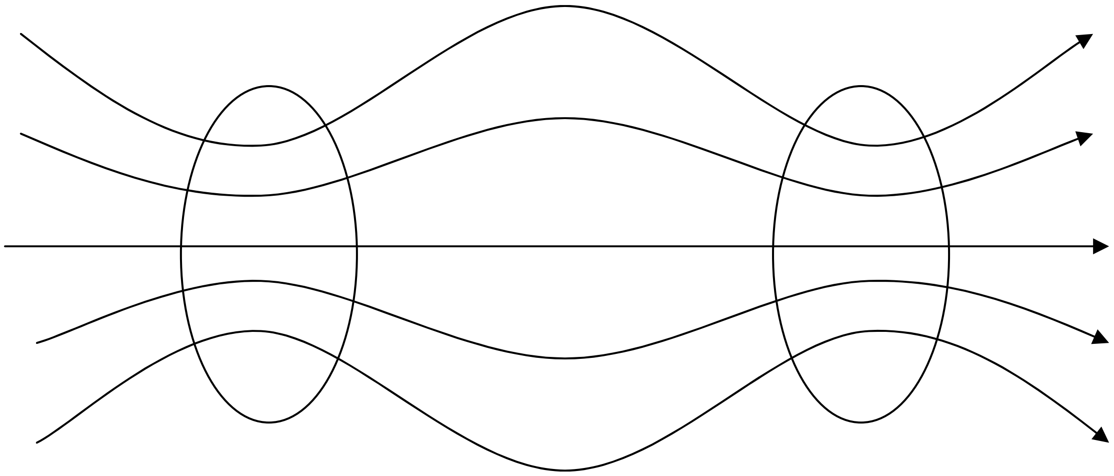


$$\text{Step size} = ?$$

How is Magnetic Ripple Created?

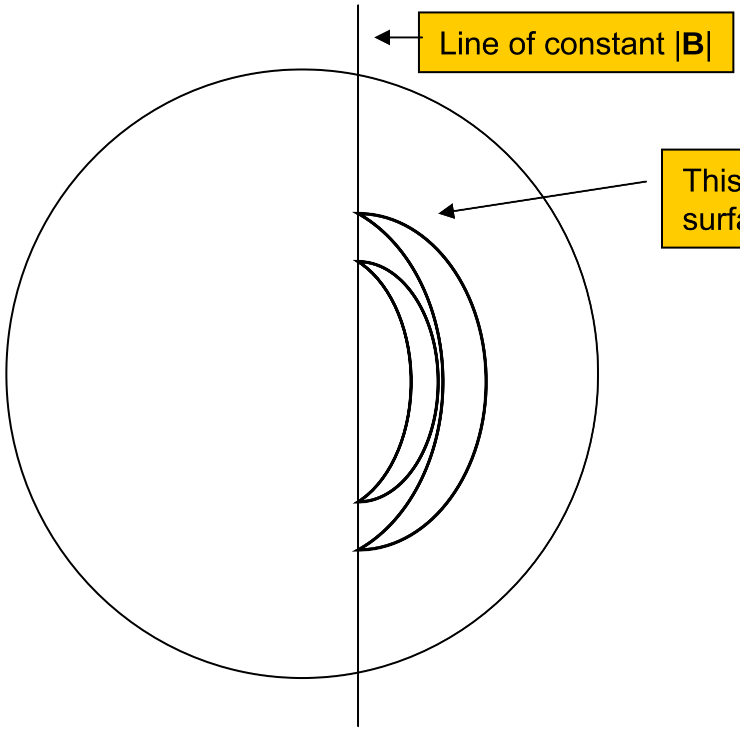


Solenoid field assumes infinite number of windings



Finite windings result in field variations

How can Ripple cause Particle Loss?



This orbit conserves E and μ. If the particle can move from the inner surface to outer surfaces, it can eventually leave the machine.

We are looking for a mechanism that can increase the flux surface of a particle faster than collisions.

$$E = \frac{1}{2} m v_{\|}^2 + \mu B$$

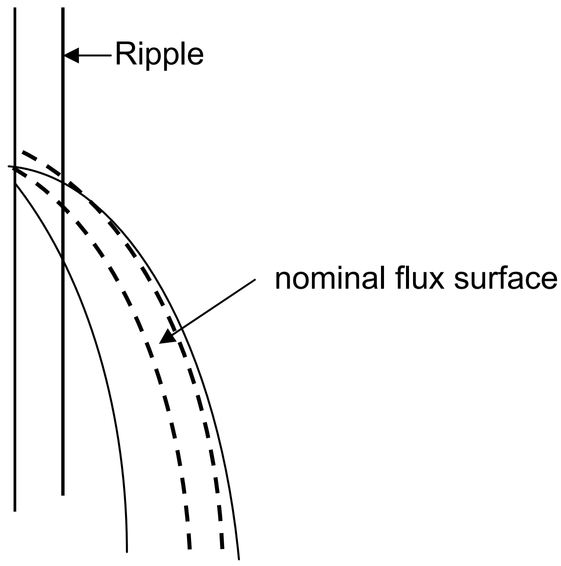
$V_{\|}$=0 at turning points, so

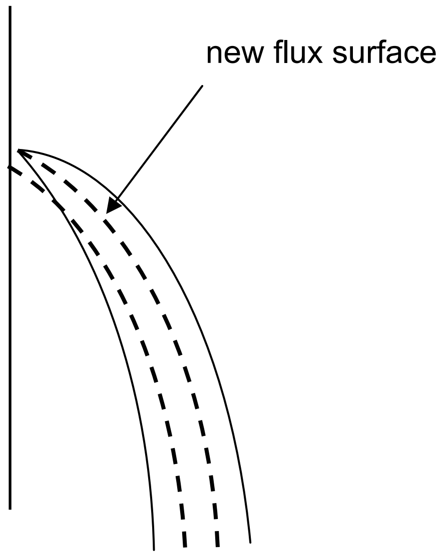
$$E = \mu B_{TP}$$

How do we get there without collisions?

How can a Particle Escape?

Nominal flux surface is defined by where a particle bounces



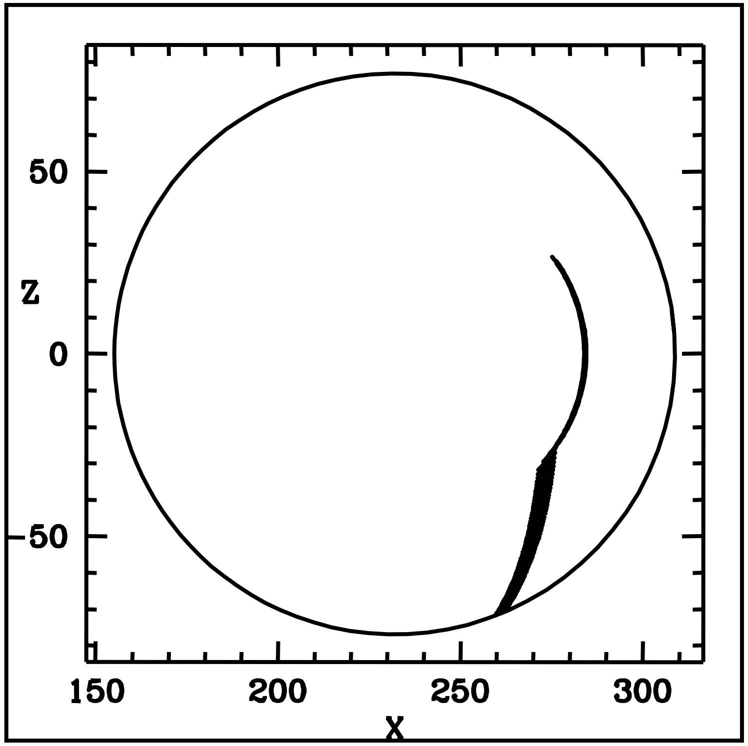


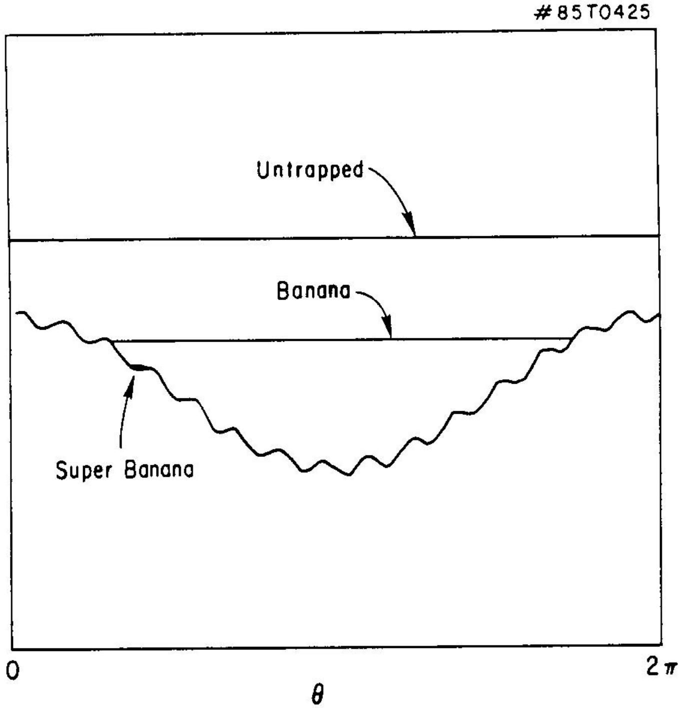
Magnetic Ripple causes the particle to bounce early and change nominal flux surface

If the particle experiences no ripple on the next bounce, it will be on a new flux surface

Magnetic Ripple in Tokamaks

Super Bananas- particles can be trapped in magnetic wells and be lost very rapidly

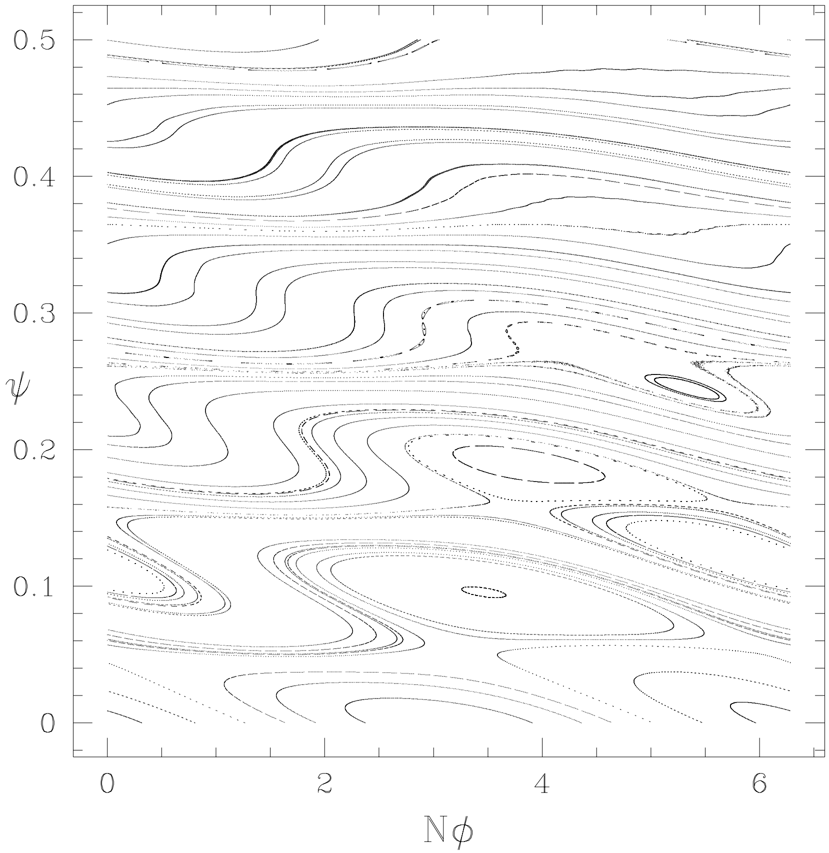


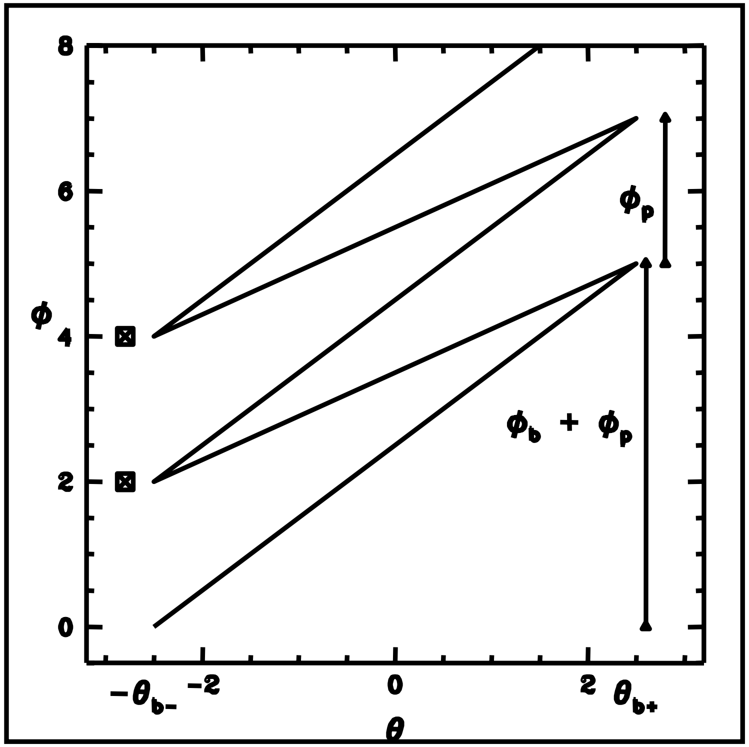


Magnetic Ripple in Tokamaks

Magnetic Ripple causes perturbations in phase space of the particles. If the perturbations become too large, particles can escape.

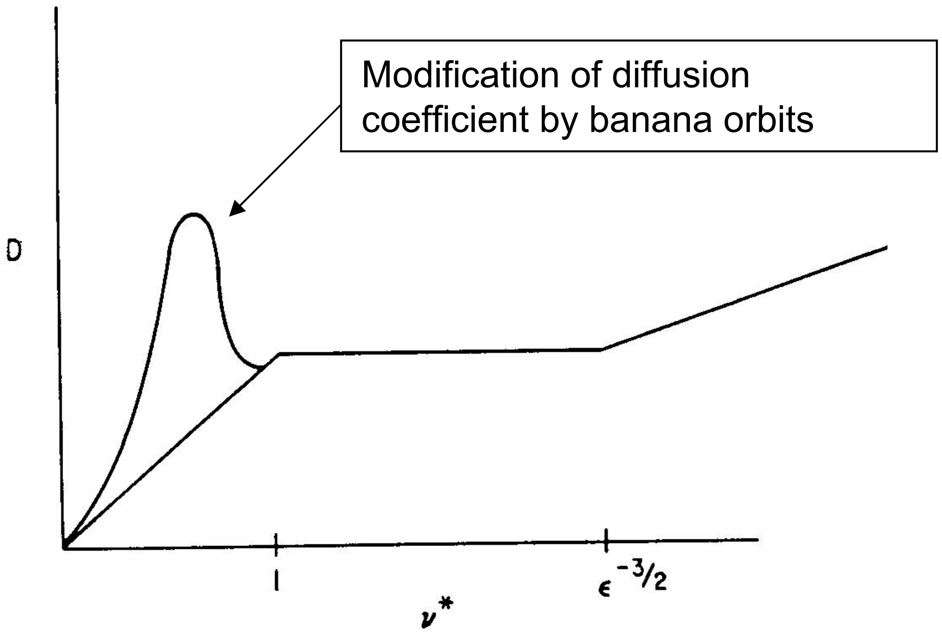
Stochastic processes cause the nominal flux surface to vary by a small amount. The result is a diffusion like effect.

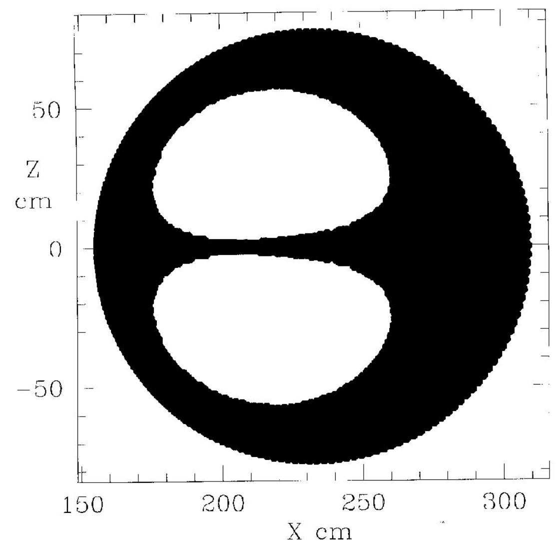




Magnetic Ripple in Tokamaks

Magnetic ripple is small (<3%), but still can lead to large loss





Any particles with turning points in ripple loss domain (shaded region) can become lost through stochastic diffusion of nominal flux surface

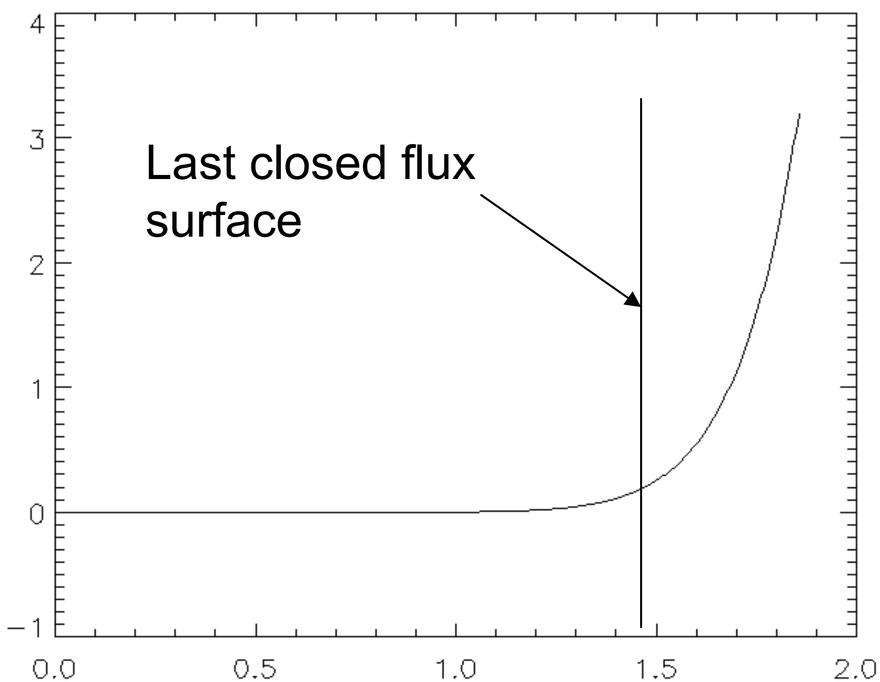
Ripple Loss in NSTX

- NSTX has low ripple loss because…
  - Large particle orbits might be able to sample enough field to cancel ripple effects
  - Low field causes other loss mechanisms to dominate (neoclassical diffusion, etc.)
  - Machine design places plasma far from coils
  - These factors dominate over factors that increase ripples such as:
    - a unique shape in ST's that increases ripple at the edge
    - Few coils (NSTX has 12 coils)

Magnetic Ripple in NSTX Plasmas is small

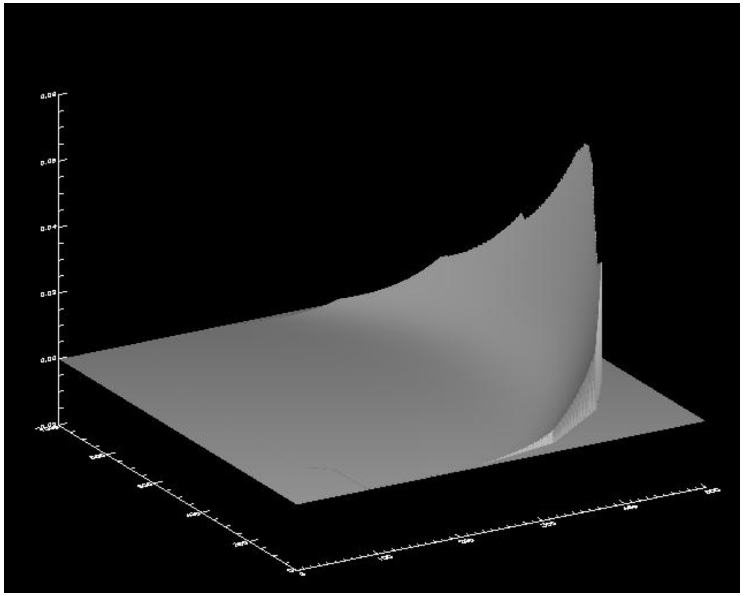
Ripple is calculated using a 4-parameter ellipse fit. This fit was used with previous tokamaks. It may not be good enough for NSTX, due to the coil design.

Ripple percent at midplane



Major Radius (cm)

Calculated |**B**| Ripple in NSTX



Ripple varies sinusoidally in the toroidal direction

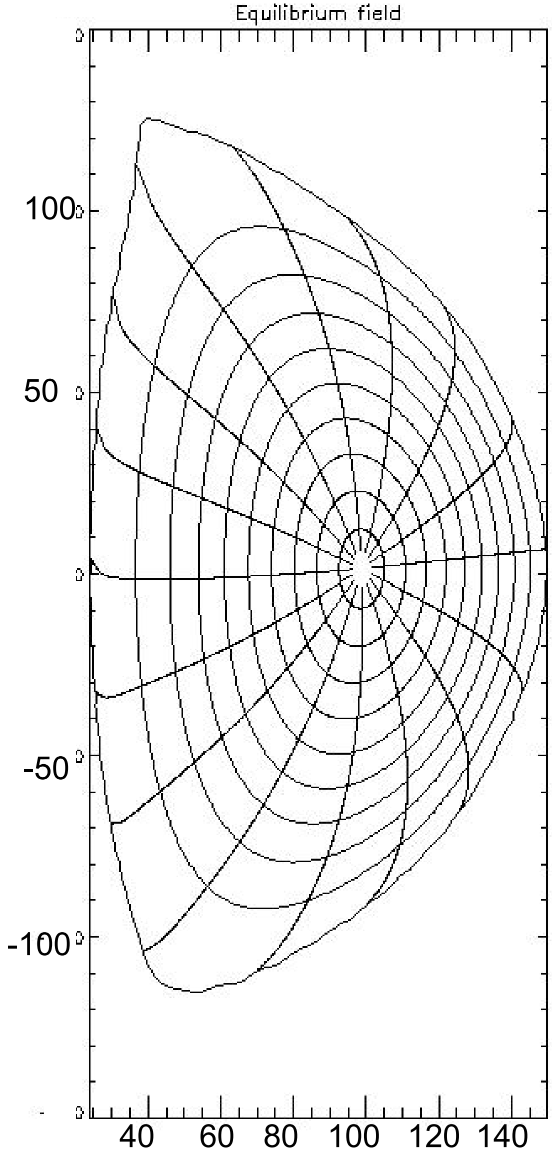
Comparing Guiding Center and Full Lorentz Codes

ORBIT	GYROXY
•Guiding Center code	•Full Lorentz code
•Underestimates neoclassical diffusion	•Accurately estimates diffusion in low field (NSTX)
•Only requires |**B**|	•Uses a 2-D **B** field fit and calculates 3rd dimension.
•Ripple is estimated by a best 4-parameter fit	•Toroidal variation is sinusoidal
•Toroidal variation is sinusoidal	•Much slower (estimate at least 10x as long)
•Already has structure for ripple (used previously for other tokamaks)	•Uses standard cylindrical coordinates
•Uses Efit equilibrium	•Uses Efit equilibrium

ORBIT Equilibrium

- Shot number 117701

  Time= 400 ms



•Equilibrium is read in from the EFIT equilibrium calculator
•ORBIT splines the EFIT data
•The ORBIT code does not handle highly shaped equilibriums well
  •Some equilibriums have significant oscillations at inboard edge

GYROXY Equilibrium

- Highly shaped NSTX equilibrium is particularly difficult to spline
  - Outer flux surface sometimes contains errors, which transfer inward
- GYROXY requires a full 3-D field. ORBIT requires only |**B**|.

Computational Problems

In GYROXY (full orbit code), a 3-D field is needed.
(only needed magnitude of B for guiding center code)
The magnetic field must be divergence-free and periodic, so let

$$\delta\vec{B} = \delta\vec{B}_1(x,z)\sin(N\phi) + \delta\vec{B}_2(x,z)\cos(N\phi)$$

Solving the divergence, we get

$$\text{(sin)} \quad \frac{1}{x}\delta B_{1x} + \frac{\partial \delta B_{1x}}{\partial x} - \frac{N}{x}\delta B_{2\phi} + \frac{\partial \delta B_{1z}}{\partial z} = 0$$

$$\text{(cos)} \quad \frac{1}{x}\delta B_{2x} + \frac{\partial \delta B_{2x}}{\partial x} + \frac{N}{x}\delta B_{1\phi} + \frac{\partial \delta B_{2z}}{\partial z} = 0$$

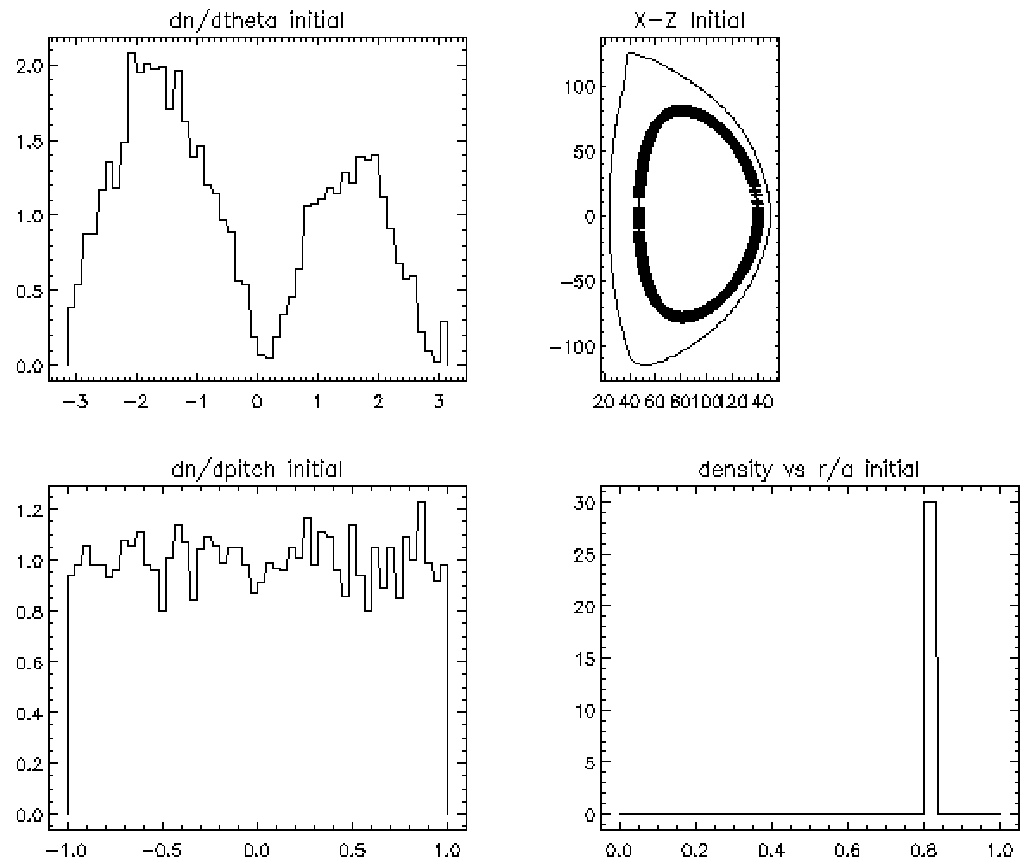
Based on the machine geometry, we eliminate the cos equation

$$\delta\vec{B} = \left[\delta B_x(x,z)\hat{x} + \delta B_z(x,z)\hat{z}\right]\sin(N\phi) + \delta B_\phi(x,z)\hat{\phi}\cos(N\phi)$$

We use a Biot-Savart integration code to obtain δB_x and δB_z and calculate δB_Φ.

ORBIT Initial Distribution

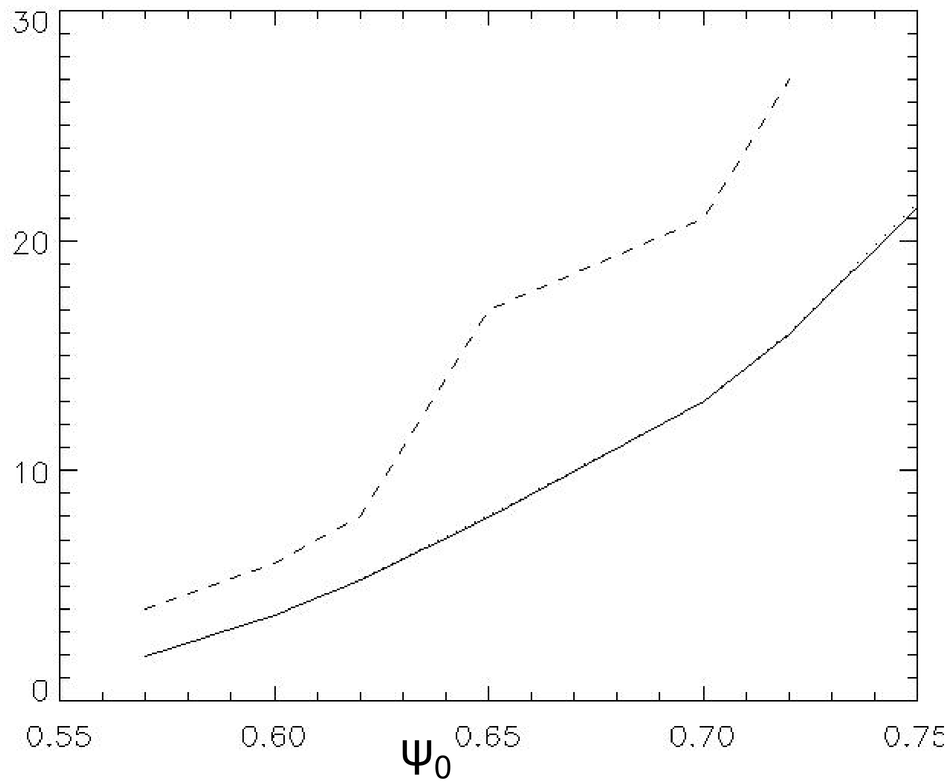
- All particles are placed on a single flux surface
- All particles have uniform energy
- Particles are distributed randomly in θ and Φ,
- Particles are distributed randomly in pitch
- Particles are distributed isotropically (not a beam distribution)



Preliminary Calculations

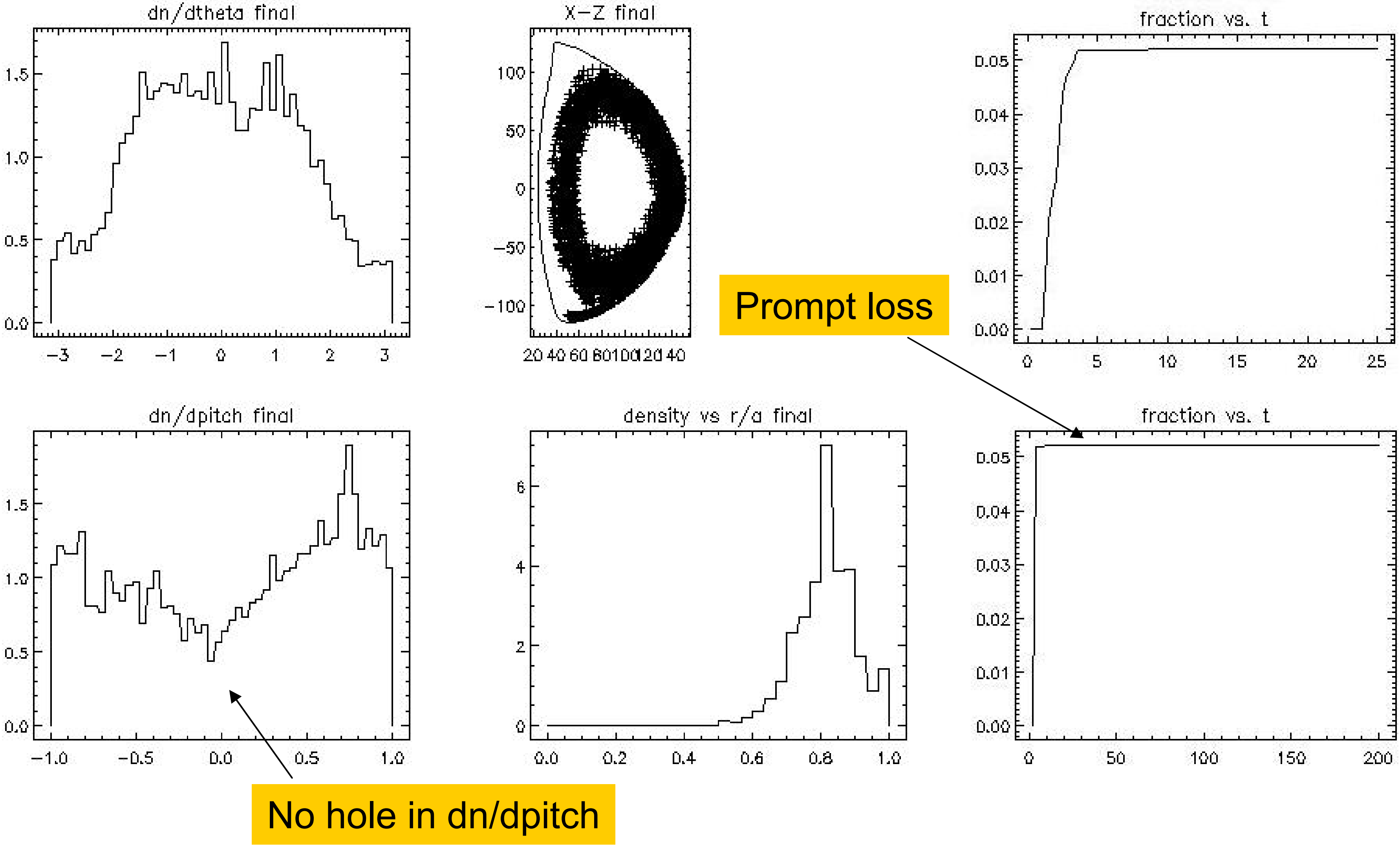
- ORBIT (Guiding Center) code appears to show small ripple loss (~2% of the particles at any given flux surface)
- Ripple loss is dominated by collisional effects
  - At ψ_0=0.75, ripple loss ~ 0.1%, while collisional diffusion resulted in ~60% particles lost
- Significantly increasing the ripple causes the loss to become stochastic

Percentage of 50 keV particles lost for cases at various flux surfaces.

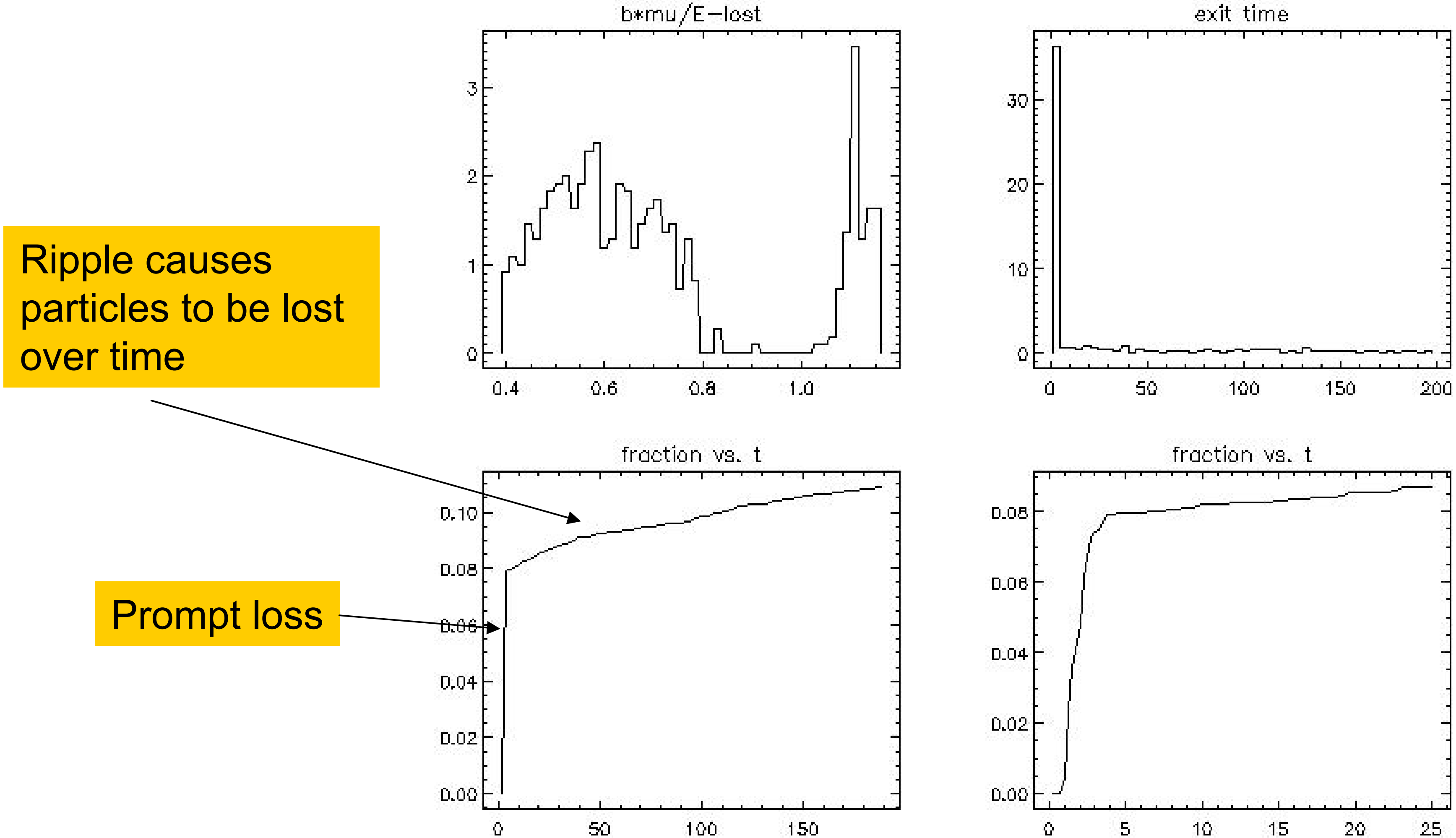


Solid line shows no-ripple cases.
Dotted line includes ripple effects with NSTX calculated ripple.
Dashed line shows with 10x ripple.

ORBIT Data Shows No Significant Particle Loss for Calculated Ripple



Increased Ripple leads to Stochastic Loss



Conclusion

- Study of power balance in NSTX is important to make quantitative predictions about the future of ST's
- Ripple loss presents a potential loss mechanism in ST's
  - Large gyro-orbits have an undocumented effect on the ripple loss rate
  - Preliminary calculations with ORBIT indicate it might not be a significant method of particle loss
- Multiple aspects (theory, computational, experimental) are needed to fully understand the power balance

Continuing Work

- Perform ORBIT runs for several different energies and flux surface values
- Determine stochasticity threshold and determine accuracy of calculated ripple
- Make calculations with GYROXY for cases similar to those by ORBIT
- Evaluate the accuracy of ORBIT code determine if it can be effectively used to study transport and loss in NSTX
- Collect statistics from most useful code
- Collect data using SFLIP probe to verify results
- Install and calibrate linear CCD camera on NSTX to measure neutral density profile
- Put the pieces together for a global picture of power balance