

Power Balance in Neutral Beam Heated Discharges on the National Spherical Torus Experiment (NSTX)

Thesis Proposal
Patrick Ross
Princeton University
Program in Plasma Physics

Advisors:
David Gates
Roscoe White

1 Introduction

The understanding of power balance is an important aspect of magnetic confinement. It is particularly important to understand loss mechanisms and transport. The inherently low toroidal field of low aspect ratio machines means that much of the analysis of standard aspect ratio devices must be modified. Typically, analyses of confinement and transport in large aspect ratio devices use the approximation that the gyroradius is very small compared to the system size. In a low aspect ratio machine, this is frequently violated because the low magnetic field significantly increases the gyroradius. For example, the minimum possible transport in a conventional aspect ratio tokamak is closely approximated by neoclassical estimates. However, in a low aspect ratio machine, such as NSTX, the gyroradius can approach or exceed the banana width, thus invalidating the approximation that the gyroradius is

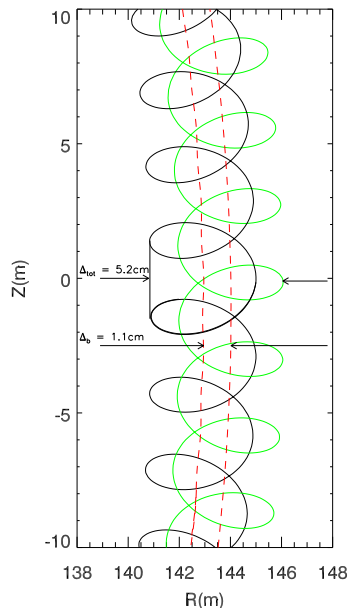


Figure 1: For high energy particles in NSTX the gyrorbit can exceed the banana width. The modification of neoclassical diffusion due the large gyrorbit effects has been termed “omniclassical.” (reproduced from Reference [1])

small, and leading to a new approximation for the minimum possible transport, termed “omniclassical.” [1] For beam ions and fusion products, the gyroradius can be a large fraction of the minor radius.

While much theory has been done in support of the experimental results on NSTX, there remain some unexplained results. In particular, during some neutral beam heated discharges a peculiarity has been observed in the ion temperature (T_i). [2] For some discharges, the ion temperature exceeds the electron temperature even when standard calculations are not clear why this should be the case. This cannot be explained by omniclassical calculations, because the omniclassical analysis can only increase the diffusion coefficient. Instead, calculations show that for some radii, the temperature of the ions is larger than it would be even if the diffusion term was zero. This leads to two possible conclusions. Either the analysis is incorrect, or there is some unexplained piece of physics that we have yet to understand.

In order for power balance to be fully understood, all significant power

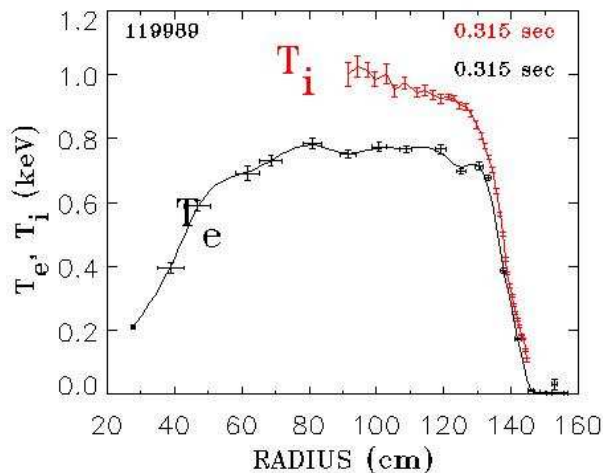


Figure 2: Diagnostic measurements of ion temperature and electron temperature for shot number 119989 at $t=0.315s$. Note that the ion temperature is 25% larger than the electron temperature. This is true even though most of the energy from the neutral beams is believed to be deposited on the electrons.

loss channels must be analyzed. To obtain the power balance equation, we take the second moment of the Boltzmann equation. Following Rose and Clark, [3] we obtain:

$$\frac{\partial}{\partial t} \left(\frac{nm\overline{v^2}}{2} \right) + \nabla_r \cdot \left(\frac{n}{2} m \overline{v v^2} \right) = \mathbf{j} \cdot \mathbf{E} + \int dv \frac{mv^2}{2} \left(\frac{\partial f}{\partial t} \right)_{coll} \quad (1)$$

where the first term is the rate of change of energy density with time, the second term is the leakage of energy from a closed surface bounding the element of interest, the first term on the right hand side is the work done on particles by the electric field and the second term on the right hand side is the energy per unit time added to the volume element due to collisions. Assuming the plasma is in equilibrium, we can extract the ion terms to get an ion power balance equation:

$$P_{in} = Q_{ie} + n\chi\nabla T + P_{loss} + P_{rot} \quad (2)$$

where P_{in} is the input power to ions in a volume element of plasma, Q_{ie} is the power transferred to the electrons due to collisions from the ions, $n\chi\nabla T$ is the

diffusion term from collisions with electrons, P_{rot} is the effect of rotation on power balance through drag and rotational stored energy, and P_{loss} represents all other ion loss terms such as wave-particle coupling or direct loss channels. For a more complete analysis of the effects of rotation on power balance, see reference [5].

I intend to explore several aspects of power balance. In particular, I will focus on both experimental and computational aspects of fast particle ion loss. Section II will focus on simulations of fast particle magnetic ripple loss in NSTX. Section III will focus on the development and implementation of a diagnostic to measure the edge neutral density profile in NSTX and using that measurement to evaluate the accuracy of present analyses. Section IV will describe future efforts to estimate the effect of the plasma rotation on the plasma density profile, and analyze the effects. The scope and timeline of this thesis project are given in Section V.

2 Magnetic Ripple and Full Gyroorbit Effects

One potential loss mechanism for any toroidal device is magnetic ripple. Magnetic ripple has been extensively studied for large aspect ratio tokamaks. [6, 7, 8, 9] Standard tokamak power balance theory assumes that the device and its magnetic field are axisymmetric. However, any physical machine requires a finite number of toroidal field coils. As a result, the magnetic field felt by the plasma varies as a function of toroidal angle. This principle is illustrated in the example of a solenoid field. Figure 3a shows the field created by a solenoid assuming an infinite number of windings. Figure 3b shows the field created if there is a finite number of windings. The field between the windings is weaker and is no longer strictly in the axial direction. The result is the same in a torus with a finite number of toroidal field coils. The field has perturbations in all three spatial directions that are functions of R , z , and ϕ . However, in the guiding center approximation, only the total magnitude of the \mathbf{B} field is used in calculating the particle motion. The total field becomes stronger near the coils and becomes weaker in between the coils. These perturbations can have a significant effect on particle motion. Magnetic ripple effects will alter the location of the bounce point of a particle's banana orbit (see Figure 4). As the particle precesses toroidally, the bounce

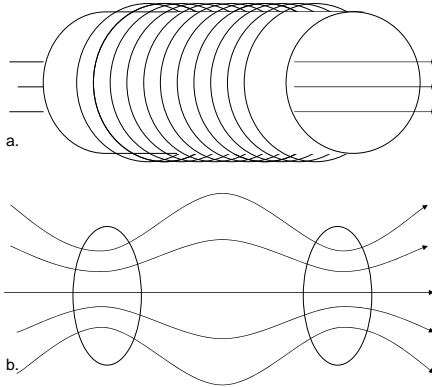


Figure 3: Magnetic field due to various windings. a) Magnetic field due to an infinite number of windings. b) The magnetic field has variations if there is a finite number of windings.

point occurs in areas where the ripple increases or decreases the total field. If the bounce point for a particular orbit occurs where the field is increased by the ripple, guiding center calculations predict that the particle's bounce will occur earlier in its orbit because of the increased B field magnitude. Since the particle has been drifting from its nominal flux surface, unless the particle bounces at the correct location, it will be a new nominal flux surface. If the particle bounces early, it moves to an outer flux surface. The opposite effect happens when the particle bounces in a region where the field is decreased by the ripple effect. The particle bounces at its banana tip later, and as a result moves to an inner nominal flux surface. As a particle precesses toroidally due to an electric field, the particle steps inward and outward radially. The inward and outward motion is periodic, with the center of the motion determined by resonances between the toroidal precession of the particle and the ripple field. However, if the ripple field is large enough, the resonances in some areas of phase space can overlap each other. As a result of the overlap, particles can undergo chaotic radial motion, allowing the particle to leave the machine. Hence any particle with banana tips in the ripple loss domain will eventually be lost, even disregarding collisions. However, if the collision coefficient is sufficiently large, ripple loss could be dominated by collisional loss. This is because without collisions, any particle with bounce points in the ripple loss domain will eventually be lost. Collisions can only serve to

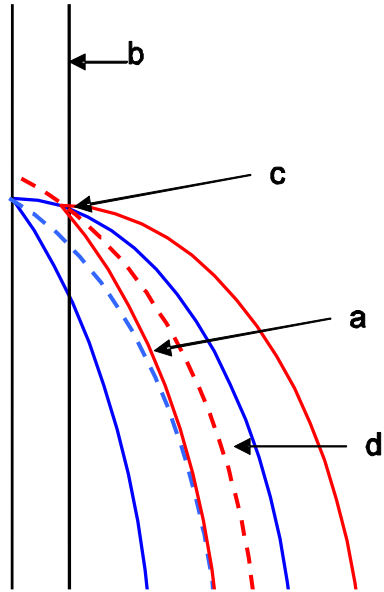


Figure 4: Particles can undergo random walk steps in flux surface from ripple field. A trapped particle initially has a given nominal flux surface (a) defined by the turning points. The guiding center of the particle follows the banana orbit shown as the solid blue line. If the particle experiences increased field due to ripple (b), it may bounce early (c), since the bounce location is determined by the magnitude of B . This has created a new nominal flux surface (d), and new banana orbit shown as the solid red line

detrap particles. [4] Therefore, it is important to study ripple in conjunction with collisional transport.

While magnetic ripple effects can be significant in a standard tokamak, the NSTX design minimizes this by placing the magnetic coils farther from the plasma. The result is that the magnetic ripple at the plasma edge is $\sim 1\%$ or less. This means that losses due to ripple effects should be dominated by collisional transport in most regimes. However, all of these calculations assume the guiding center approximation. As stated above, this approximation is clearly violated for high energy particles in NSTX. (See figure 1) While the collisional transport effects of large aspect ratio, low field machines has been evaluated [1], no similar evaluation has been performed for the full gyroorbit effects of ripple loss. It is unclear whether the full orbit will serve to mitigate or exacerbate the effects of magnetic field ripple. For this section of my thesis, I propose to study this problem.

In order to evaluate the effect of the full gyroorbit effects, I will use two simulations: ORBIT is a guiding center code and GYROXY is a full Lorenz code. These two codes accept NSTX Efit equilibria of the magnetic field. Both codes have the ability to include collisional effects. In addition both will be modified to include ripple effects. ORBIT includes a ripple modification, where the total field is altered by the four parameter fit

$$ripple = d_0 e^{\frac{\sqrt{(x-x_0)^2 + bz^2}}{w}} \quad (3)$$

The various parameters are determined by randomly generating the parameters, and comparing the result with a calculated 2-D field, based on engineering specifications of the field coils. This fit creates a ripple that is within ten percent of the Biot-Savart calculated ripple.

The full Lorenz code requires a 3-D ripple field that preserves the divergence free property of magnetic fields. In order to preserve this property for the ripple, a 2-D ripple field is calculated based on the engineering specifications. This field is calculated for the X and Z directions. The toroidal field ripple is then calculated using the equation:

$$\delta \mathbf{B} = (\delta B_R \hat{R} + \delta B_Z \hat{Z}) \sin N\phi + \delta B_\phi \hat{\phi} \cos N\phi \quad (4)$$

This ensures that the codes will preserve energy and magnetic moment in the particle motion, and is important in ensuring the accuracy of the result. This ripple is calculated for every point and is added to the equilibrium field.

The results of these two codes will be compared with and without collisions. It is expected that the full Lorentz calculations will not significantly affect ripple loss calculations due to the relative strength of the ripple field. However, this calculation is also important for the International Thermonuclear Experimental Reactor (ITER), which is expected to produce high energy alpha particles, which will have gyrorbits that are comparable in size to the expected banana width, violating the assumption of small gyroradius.

3 Edge Neutral Density Profile Measurements

Several diagnostics on NSTX make measurements of quantities related to power balance, particularly of fast particles. Of particular note are the Neutral Particle Analyzer (NPA) [10, 11] and the Scintillator Fast Loss Ion Probe (SFLIP). [12] The NPA measures plasma particles that underwent a charge exchange with neutral particles. Because of the high temperature and density of the plasma, the majority of neutral particles are near the edge, since any neutral particles entering the plasma quickly become ionized. In order to fully understand these charge exchange processes, It is important to understand the absolute neutral particle density of the plasma, particularly near the edge.

The SFLIP probe seeks to extract energy and pitch angle information from ions. The probe uses an aperture and a slit to allow various pitch angles to enter and strike the scintillator. The scintillator is angled to measure the gyroradius and thus the energy of the particles. Many of these ions come from the neutral beam particles that undergo charge exchange. However, in order to fully understand neutral beam deposition from these measurements, it is important to understand how these fast ions can be lost. Since they are beam particles, they have gyroradii that are a large fraction of the minor radius. Even ions from the neutral beam have orbits that extend into the scrape off layer where the majority of neutral particles are.

Both of these diagnostics rely on the density profile of edge neutral particles. In order to accurately measure the neutral density profile, a linear CCD camera will be placed on the outer midplane of NSTX during the 2006 run year. The camera will use a filter with peak transmission of 456 nm. This wavelength corresponds to the H_β line emission of the Balmer series. This emission line was chosen over the H_α line for two reasons. First, The H_α line falls near the CII carbon emission line. The H_α line has a wavelength

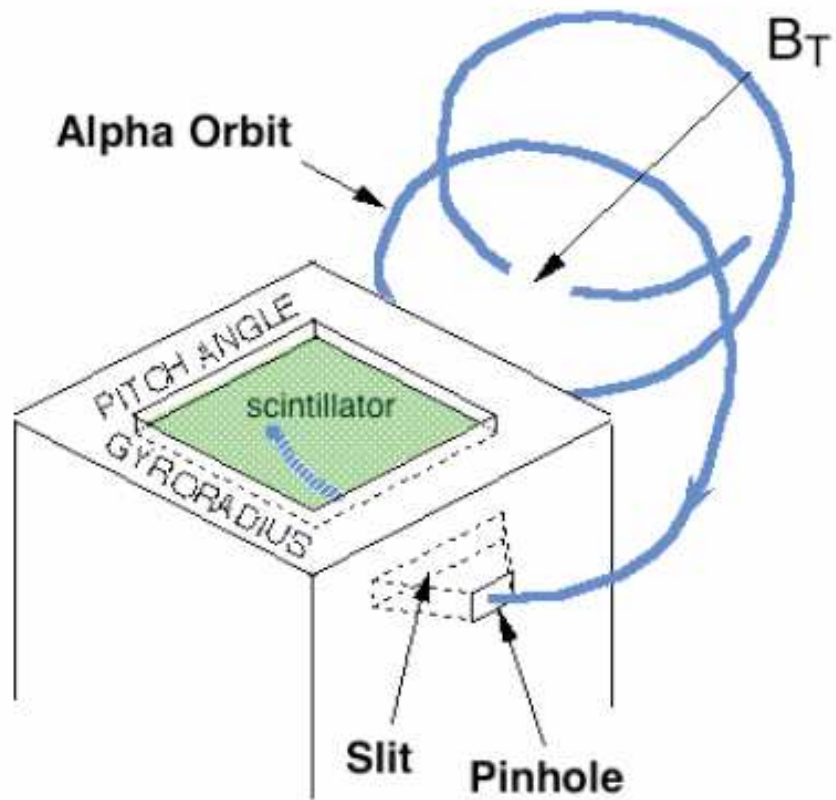


Figure 5: Ions following the magnetic field enter the probe through the aperture and strike the scintillator. The strike location indicates the energy and pitch angle of the particles. (Reproduced from [12])

of 656 nm, while the CII line has a wavelength of 657 nm. The filter has a transmission FWHM of 1.5 nm, and would therefore transmit this unwanted emission line, and give a false intensity reading. The H_β line does not fall near any emission lines of significant intensity in the plasma. Second, the magnitude of the H_α line could be large enough to saturate the camera. It is unclear if the camera can be set fast enough to avoid this problem.

In order to accurately obtain the absolute neutral hydrogen density, the camera must be both spatially and photometrically calibrated. The spatial calibration will occur in-vessel, and therefore will not be complete until the end of the 2006 run year. A calibrated Labsphere source will be used to determine the absolute photometric sensitivity of the camera.

Once the image is obtained, an Abel inversion algorithm will be used to unfold the spatial profile of the image. This will provide a radial profile of the absolute emission intensity. Using this information, along with electron temperature and density information from the Thomson Scattering experiment, I will then construct a model for the neutral particle density based on a collisional-radiative model.

This diagnostic has two other potential uses. First, it will be useful for further analysis of H-modes. We do not yet have a complete understanding of these phenomena, and this diagnostic provides an opportunity to observe another aspect of the high confinement plasmas. Second, this diagnostic provides an important tool for evaluating the effect of lithium on the plasma. It is assumed that the majority of neutral particles in the edge of the plasma are recycled hydrogen atoms, released as the plasma impacts the wall. It is also assumed that the lithium coating, which has a high affinity for hydrogen, will greatly reduce the amount of recycling occurring at the plasma edge. This was already demonstrated on the CDX-U experiment for a lithium tray. [14, 15] It is expected that this diagnostic will show a similar reduction in edge neutral particles for NSTX.

4 Density Perturbations

Plasma rotation has been shown to have a significant effect on stability properties of the plasma. [13] As the rotation of the plasma is increased, some MHD modes are stabilized. It is generally considered desirable to have significant rotation to try to mitigate these instabilities. However, plasma rotation can also cause perturbations in the equilibrium. Centrifugal forces

cause the plasma to shift outward. The assumption used in most analyses is that plasma density and temperature are functions of flux surface. However, it has been shown that plasma rotation can cause a density shift, such that density is no longer a function of flux surface. [16, 17] The constant density surface shifts toward a larger major radius. [18] Any analyses that rely on the flux surface assumption should be modified. Two areas of study are particularly important for NSTX. First, it will be important to study what effect this modification has on beam power deposition, which represents a significant fraction of the input energy of the plasma. Second, it will be important to estimate the effect of the plasma density perturbation on neoclassical diffusion. This perturbation could account for much of the discrepancy seen in the neoclassical diffusion calculations described in the introduction. The analysis from these calculations will be entered into the TRANSP code, which reconstructs and analyzes much of the physics from plasma discharges.

5 Scope and Timeline

I have been working on my thesis since August 2005. The edge neutral density diagnostics design was completed during the machine maintenance period from September 2005 to February 2006, and installation on NSTX was begun. However, the camera was found to be faulty and has to be repaired. The installation of the camera was expected to be completed by the end of the first maintenance week on NSTX. The in-vessel spatial calibration will be completed during the machine maintenance period following the run. The photometric calibration will also take place during maintenance period. This will involve removing the camera from the Test Cell and using a calibrated Labsphere light source. The diagnostic will operate during the run year 2007.

Concurrent with the development of the Edge Neutral Density diagnostic in 2006 will be calculation of full gyroorbit effects on magnetic ripple loss. This is expected to be completed by September 2006. Calculations and analysis of density perturbations will begin September 2006. This analysis is expected to take until the commencement of the 2007 run year. Any necessary upgrades or modifications to the diagnostic will occur during this maintenance period. During the 2007 run year, the diagnostic operation and analysis is expected to continue. Final analysis will occur at the conclusion of NSTX operation in late 2007. I will write my thesis from late 2007 until

early 2008. It is expected that my final public oral examination will occur in spring 2008.

References

- [1] D.A. Gates, H.E. Mynick, R.B.White, Phys. Plasmas, **11**, L45 (2004).
- [2] D.A. Gates, Phys. Plasmas **10** 1659 (2003).
- [3] D.J. Rose, M.Clark, *Plasmas and Controlled Fusion*, John Wiley & Sons, Inc., New York, (1961).
- [4] R.B. White, *Theory of Tokamak Plasmas*, North-Holland Press, Amsterdam, (1989).
- [5] R.J. Goldston, Basic Physical Processes of Toroidal Fusion Plasmas, Proc. Course and Workshop at Varenna, 165 (1985).
- [6] R.J. Goldston, J.J. Towner, Princeton Plasma Physics Laboratory Report No. PPPL-1637, (1980), (unpublished).
- [7] A.H. Boozer, Phys. Fluids, **23**, 2283 (1980).
- [8] R.J. Goldston, R.B. White, A.H. Boozer, Phys. Rev. Lett. **47** 647 (1981).
- [9] R.B. White, et al., Phys. Plasmas **3**, 3043 (1996).
- [10] S.S. Medley, A.L. Roquemore, Rev. Sci. Instrum., **69**, (7), 2651, (1998).
- [11] S.S. Medley, A.L. Roquemore, Rev. Sci. Instrum., **75**, (10), 3625, (2004).
- [12] D. Darrow, Pitch Angle Resolved Measurements of Neutral Beam Ion Loss from NSTX Plasmas, Division of Plasma Physics Conference, (2004).
- [13] J.E. Menard, et al., Nucl. Fusion, **45**, 539, (2005).
- [14] R.Majeski, et al., J. Nucl. Mater. **313-316**, 625 (2003).
- [15] R.Majeski, et al., Fusion Eng. Des. **72**, 121 (2004).
- [16] W.M. Stacey, Phys. Fluids B, (4), (10), 3302 (1992).

- [17] W.M. Stacey, Phys. Plasmas, **9**, (9), 3874 (2002).
- [18] F.L. Hinton, S.K. Wong, Phys. Fluids, **28**, 3083 (1985).