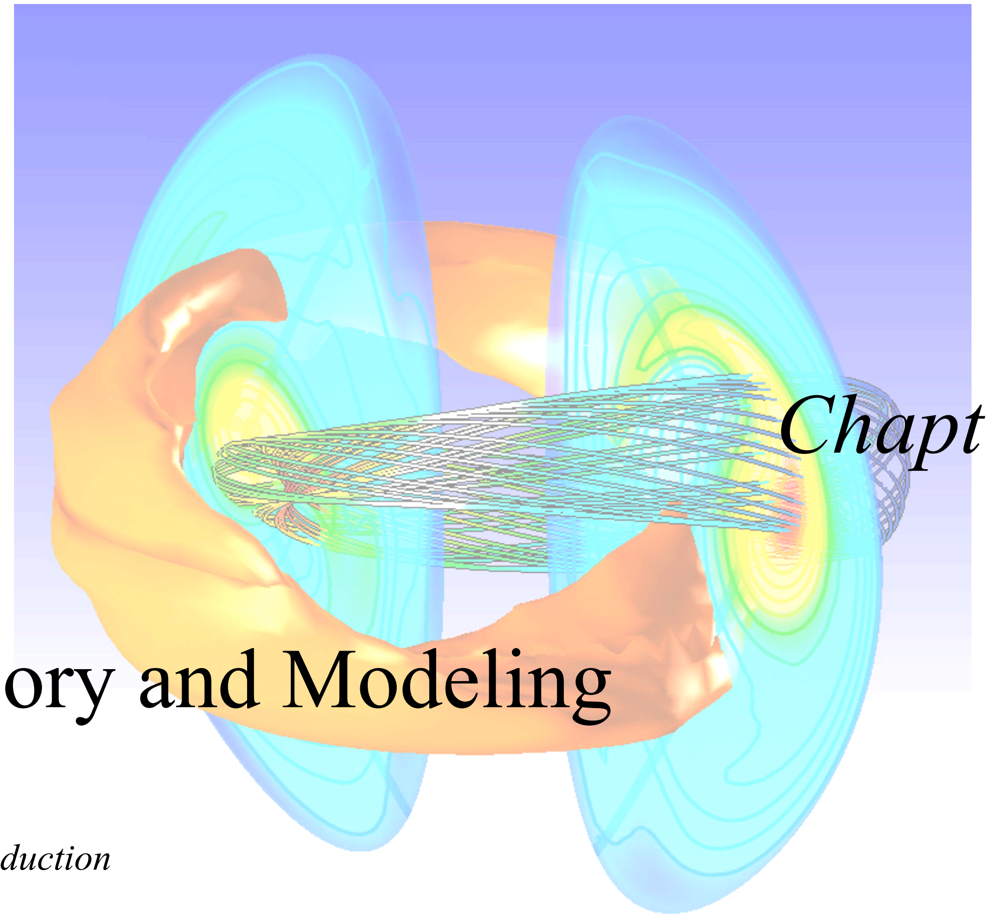

Chapter 5

Theory and Modeling

5.1 Introduction

The high beta, low aspect ratio, and low magnetic field of NSTX plasmas provide opportunities for extending the reach of theories and theory-based models that are used throughout the toroidal confinement research community. Detailed comparisons of experimental results to expectations from theories, which have been modified or developed to account for these extensions, will yield a strong physics basis for advancing the ST concept, and they will strengthen the basis for the predictive capability of other toroidal confinement devices. The potential power of making the most of the relationship between high beta ST operations and the plasma regimes associated with other devices has already been demonstrated, as highlighted by two examples. First, the predicted increased MHD stability margin of the ST is an outgrowth of MHD theory developed for moderate aspect ratio tokamaks and other toroidal confinement devices [1,2], and has been borne out by NSTX experiments. Second, high performance ST operation was preceded by considerable anticipation regarding the possible flow shear stabilization or intrinsic stability of long-wavelength microinstabilities [3,4]. This anticipation was grounded in turbulence theories developed for moderate aspect ratio, and has also been realized in NSTX experiments. In the future NSTX research will be in a position to contribute in a reciprocal manner to the development of theories applicable to all toroidal confinement concepts by demanding that theory account for the effects specific to low aspect ratio and high beta.

It has already been inferred from measurement that in high beta NSTX plasmas, local values of beta can approach unity as a result of improved stability. This has implications for the physics of MHD, transport and turbulence, and wave-particle interactions physics, and it indicates the importance of extending theories in these areas to account for these effects. An example regarding turbulence is the predicted emergence of electromagnetic effects at high beta, a feature that may have important and testable implications for electron thermal transport. Community-wide, an understanding of the turbulence that drives electron thermal transport remains elusive, and NSTX's controllable and wide range of beta provides a unique opportunity for testing appropriately complete theory with respect to this topic. Fast ions from the injection of neutral beams have velocities which exceed the Alfvén velocity on NSTX, yielding a population whose physics is relevant to that of burning plasmas and which offers the potential of increasing our understanding of fast-ion-induced MHD. The observed unusually high values of the ratio of flow velocity to the sound speed and Alfvén velocity can affect predicted stability properties, including the

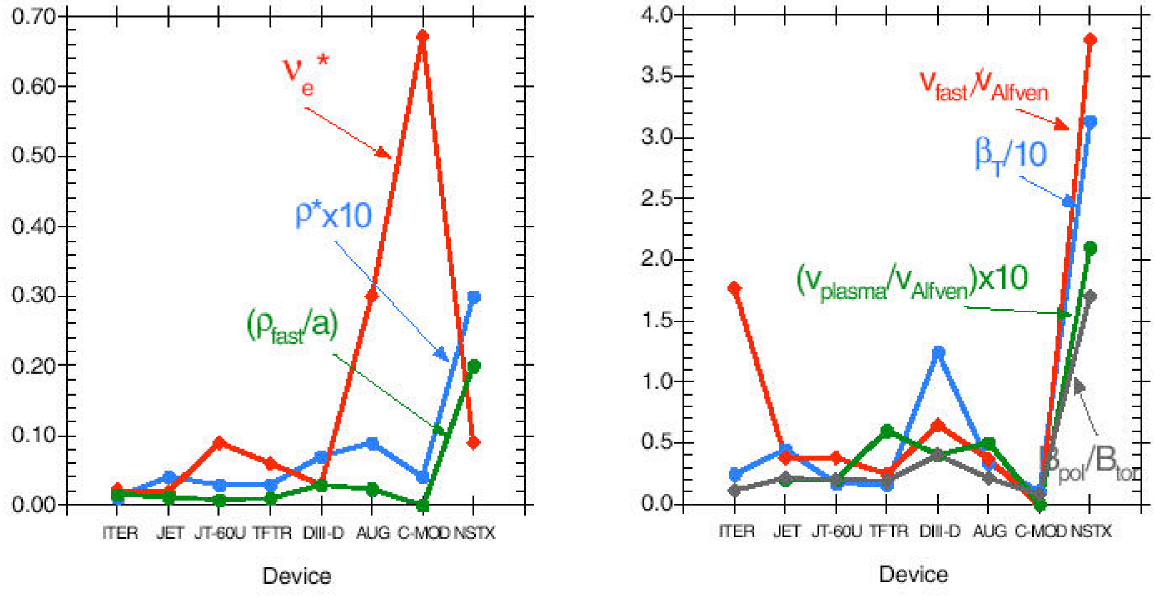

Figure 1. A comparison of some key plasma parameters which are used to describe plasma behavior in a variety of conventional aspect-ratio devices with NSTX. These include: the collisionality, thermal and fast particle Larmor radii, β, B_{pol} and plasma and energetic particle velocities in relation to the Alfven speed.

effectiveness of wall mode stabilization, as well as the stability of internal modes. In addition, features as fundamental as the plasma equilibrium are predicted to be and have been modified by rotation in significant and measurable ways, enabling tests of equilibrium and MHD theory. Many theories have been developed assuming that the ratio of ion Larmor radius to plasma minor cross section, $\square^* = \square_i/a$, is small. This includes frameworks as fundamental as neoclassical theory where NSTX allows accurate direct study of terms which may presently be sub-dominant in other configurations. Another fundamental study involves full wave codes that are used to describe RF wave propagation and damping. Low aspect ratio implies that larger gradients in **B** are present, affecting the shear in plasma flows that can modify micro- and macrostability. Also, the relatively high fraction of trapped particles, which approaches unity at low aspect ratio, has implications for theories of trapped particle instability drive. Finally, the low aspect ratio geometry yields relatively strong toroidal effects due to the reduced aspect ratio, and STs offer the prospects of operations at increased elongation and triangularity as compared to moderate aspect-ratio, all of which have an impact on theory. Examples of some theoretically important parameters are highlighted in Figure 5.1, which illustrates the quantitative differences in their values in low and moderate aspect ratio devices. A more elaborate discussion may be found in Section 3.2. In short, the study of high beta and low aspect ratio plasmas on NSTX offers opportunities to extend theoretical models into new regimes, and to experimentally test such models to the benefit of the ST and other magnetic confinement concepts alike.

In these early stages of NSTX research, the theory and modeling effort in the NSTX program is responding to many of these different opportunities. In what follows, examples of several levels of activity will be presented in each topical area. Generally, the first response, in each area, is to examine models and codes developed for conventional tokamaks, and to establish the extent of their validity in the ST context. This requires testing them for ST parameters and benchmarking against experimental data as well as analytic models, where available. The next level may require extensive modification of existing codes to make the model relevant to the ST limit. For topical areas where no code exists, new ones have to be developed. In addition to the code development and on a parallel track, analytic theory and models have to be re-examined to address the needs of modeling in extremes of parameter space.

There is a class of modeling tools that deserve special recognition. These are control, modeling and interpretive codes, which are an integral part of the experimental program. Examples of these include EFIT [C9] (for determining the plasma equilibrium based on magnetics and internal measurements), TRANSP [C42] (for interpretive transport analysis and predictive modeling), and DCON [C7], GATO [C18] and PEST [C37] (for MHD stability analysis). The development of these codes highlights the multi-institutional character of NSTX team research. For example, EFIT (originally developed within the DIII-D program) was extensively modified by NSTX team members (Columbia University [C10]). In addition, the DCON code (Los Alamos National Laboratory) has been integrated with EFIT so that between-shot stability analysis is available. Other examples of this class of codes are TRANSP and PEST, both codes are supported by the Computational Plasma Physics Group at PPPL. These codes continue to evolve as more physics is incorporated into them.

These examples also highlight the makeup of the NSTX theory and modeling group. NSTX is constituted as a national project and the theory group reflects this in its composition. Some of the members are on-site and others are off-site and visit for varying periods. A theory coordinator, based at PPPL, helps the NSTX team to coordinate their activities and to identify and develop needed resources. It is equally important to recognize that a significant fraction of the effort is not funded directly by the NSTX project. Those contributions are supported indirectly by other OFES projects. A notable example is the support from the Scientific Discovery through Advanced Computing initiative, SCIDAC, for modeling and theory advances in the area of RF modeling. Finally it should be noted that the NSTX project has greatly benefited from the work of scientists across the magnetic confinement program. This synergism is reciprocated by the inter-machine modeling comparisons, which are part of the NSTX research activity.

The theory and modeling plan for NSTX is driven by the following needs: meeting the near-term research goals of the NSTX program, advancing the understanding of the physics of spherical torii; and addressing the longer term IPPA goal to determine the attractiveness of an ST as a power plant. This includes assessment of confinement, heating, and stability at high beta as well as current drive and heat flux related issues. The science goal is to advance the fundamental understanding of plasma behavior in the ST and to exploit the unique NSTX parameter space to benchmark state-of-the-art theory and computational models to improve predictive capability for magnetic confinement systems, in all topical areas.

In the following sections, we introduce the goals specific to each topical area, highlight recent experimental and theoretical results, and identify the physics issues that have an impact the on modeling. This is followed by a description of the status and research plan for the topical area, which is identified.

All codes are shown in uppercase and are referenced to a distinct code reference section that follows the physics references, where the codes are listed in alphabetical order. Approximate dates for each task are appended in parenthesis wherever it is possible. These dates refer to the time frame for code preparation or application.

5.2 Macroscopic Stability

NSTX offers unique opportunities to advance MHD science, while addressing ST specific issues, such as high plasma flow velocity, strong toroidal effects and energetic super-Alfvenic particles. By developing comprehensive theoretical tools, which are valid in the ST regimes, the NSTX MHD theory program has an opportunity to take a leading role in advancing MHD science.

There are several characteristics of NSTX, that distinguish it from a conventional tokamak, some of which have already demonstrated significant consequences. Theoretical predictions of improved stability due to toroidal effects, [1,2] have been validated by experiments on NSTX, which has operated at a toroidial □ of 35% without the benefit of active feedback. Stabilization of the resistive wall mode by plasma rotation has been reported in discharges with sustained operation above the no-wall □-limit (Fig. 3.10 of Section 3.1), which is in qualitative agreement with theory [5]. Fast ion driven MHD is another area where theoretical modeling has been validated by experiment [6], and an area in which the theory development will be directly applicable to ITER since $v_{fast}/v_{Alfven}>1$ in both NSTX and ITER. These examples highlight the fact that NSTX has proven to be an excellent test-bed for MHD theory. Another area where NSTX has the opportunity to advance plasma science is to test the predictions of stabilization of ballooning modes by kinetic effects [7] and by sheared flow [8].

Establishing an extrapolatable physics basis for the spherical torus is a guiding principle of the theory program. This can be achieved through a national and international effort to develop or extend MHD codes for application in ST relevant regimes. Nonlinear MHD physics understanding is a critical element in such efforts. The effects mentioned above, as well as the high toroidal rotation velocity (v_{plasma}/v_{Alfven}~0.3) and flow shear rates (□ 1 MHz), are areas that require special attention. In addition, nonlinear MHD physics issues include: influence of error fields, mode locking, plasma rotation damping, reconnection physics associated with coaxial helicity injection, and cascading and damping of Alfvén modes driven either by microturbulence or by beam ions. Interest in some aspects of MHD science extends beyond the ST program into space and astrophysics. For example, fast ion interactions with MHD may play a role in ion heating in the solar corona, and advances in reconnection physics would have significant impacts in many physics areas. An important related topic where reconnection physics plays a role is coaxial helicity injection, and is discussed in a later section, 5.5. This section outlines the research issues and strategies for addressing these and other fundamental points that are important for building a physics basis for the ST.

5.2.1 Proposed research activities in MHD

Theory and modeling tools for assessing equilibrium and stability of NSTX are built upon the vast library assembled for conventional tokamaks. We start with a discussion of EFIT, a code used for control as well as interpretation of the experimental equilibrium. This code is the lynchpin of the modeling effort. It provides equilibrium information for a variety of applications extending beyond MHD. For example the interpretive/predictive transport simulation code, TRANSP, uses the plasma boundary and, sometimes, the internal equilibrium from EFIT. The computed equilibria have also been used as input to the stability code DCON, to provide between-shot stability analyses at multiple time points in the evolution of the discharge. EFIT continues to evolve to meet the needs of the project, for example, by introducing plasma flow in the model. A real time version, rtEFIT, which can provide approximations of the boundary shape and plasma profiles during the discharge, has been developed and is being tested as a basis for the real-time plasma control system. This will evolve to improve the quality of the equilibrium as new diagnostics, such as MSE, become available.

Equilibrium with Plasma Rotation*:* An important characteristic of NSTX discharges is the strong plasma rotation driven by NBI and the interaction with MHD. This is particularly significant for two reasons, the first being the effect of rotation on equilibrium properties and the second its effect on stability. Figure 15 of section 3.1 shows the measured rotation profile for an NBI-heated discharge, as well as the electron density and temperature profiles. The high rotation velocity leads to a separation of the temperature and density surfaces, and the mass density is no longer a flux function as the density profile develops poloidal asymmetry, the pressure anisotropy has similar consequences. The challenge of the large sheared flow velocities is in determining the equilibrium configuration and its stability. The conventional single-fluid Grad-Shafranov equation is not adequate to describe mass flows and pressure anisotropy. A Bernoulli equation for mass flow is added and special attention is required to handle hyperbolic regions when poloidal flow is considered. Equilibrium modeling will be done using several codes. At the interpretive level it will be introduced in EFIT. For a more comprehensive approach, which includes sheared toroidal and poloidal flow, as well as anisotropic pressure, the code FLOW [C15], will be used starting in FY03. Examples of modeling high flow velocity using FLOW, including supersonic flow, are shown in Fig. 5.2.1. The comprehensive non-linear resistive MHD codes, M3D [C29] and NIMROD [C33] will be used to benchmark the equilibrium code (FY03-04).

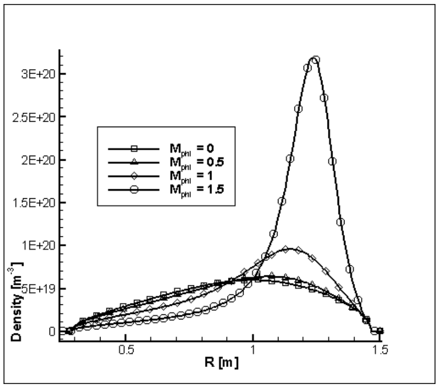

Figure 5.2.1 . Equilibrium density profiles from FLOW as the plasma velocity increases from zero to $M=V_{flow}f/V_{sound}=1.5$. Values of M~0.5 have been observed in NSTX .

Stability with Plasma Rotation: Analysis of stability becomes more difficult due to the additional energy from flow, which could serve as a new source for instabilities. On the other hand, if the flow is non-uniform, high flow shear can be stabilizing [9] and may also play a role in neutralizing the strong poloidal mode coupling.

In discharges with low q*, which are associated with high β_N, an m/n=1/1 mode is observed to play a critical role in the β-saturation or collapse. The M3D code has been applied to show that sheared toroidal flow can reduce the linear growth-rate and lead to non-linear saturation of the internal m/n=1/1 instability at a modest amplitude (Fig. 5.2.2). Proposed studies with M3D include the following: an assessment of rotation on linear stability of internal modes, which includes sawteeth as well as high-β internal mode stability (FY03-04), understanding the dissipative mechanism that governs the interaction of MHD modes with flow (FY03-08) and developing an understanding of Reconnection Events (FY03-08). The NIMROD code will be used to corroborate the M3D results, starting with internal kink stabilization with rotation (FY03-04). Codes such as M3D and NIMROD, which are computationally demanding, are best used to study fundamental physics issues, and to address non-linear physics associated with dissipation

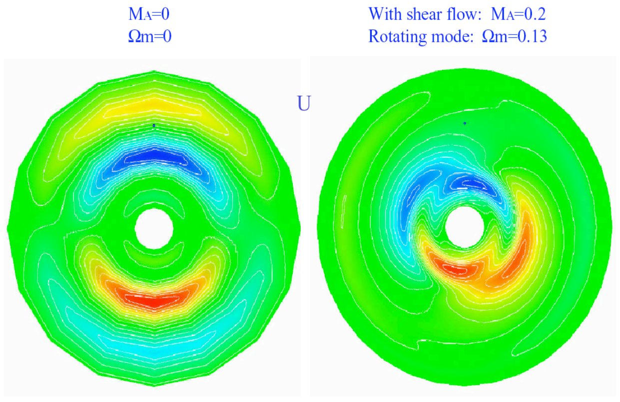

Figure 5.2.2. Internal kink mode saturates with a smaller amplitude as a result of sheared flow.

and rotation damping. Parameter studies and detailed comparison with experiment, however, requires a faster method for determining the linear stability. To accomplish this, we plan to develop a new code, NOVA-F, based on the NOVA[C34] series of codes. These are non-variational, eigenvalue stability codes, which can include kinetic effects and resistive wall models. It will use the output from FLOW and will be benchmarked against M3D and NIMROD (FY04-06).

Resistive wall modes: The role of rotation in the stability of the resistive wall mode (RWM) is well recognized [5], and an extensive campaign on this topic is ongoing on the DIII-D device. On NSTX we have the opportunity to extend the physics understanding from moderate to lower aspect-ratio and establish an extrapolatable physics base. To assess stability, several codes will be used. An extension of the VACUUM[C45] code which, in conjunction with DCON or PEST, will study at the effect of resistive walls in the absence of flow (FY 04). MARS [C30], a linear stability code, has already been tested on DIII-D and will be used for NSTX after issues of numerical convergence and speed at low aspect ratio have been resolved. These issues stem from the observation that at very high □, the Shafranov shift is relatively large as is the safety-factor at the plasma edge, and a large number of poloidal harmonics are required in the modeling. Specifically, MARS will be used to determine critical rotation frequency required for stabilization (starting in FY03). In addition, the MARS code is being coupled to the VACUUM code to predict mode structure, growth-rate and frequency for comparison with experiment (FY04-05). This approach to RWM analysis relies on rotating wall models and does not include the additional centrifugal flow energy. In order to account for this, the M3D code, which has a free boundary model with a resistive wall, will be applied to study the RWM (starting in FY03). In addition to a more self-consistent picture of stability with flow, the M3D code extends our analysis capability to the crucial non-linear regime. When the resistive wall model is implemented in NIMROD, it will be used for RWM studies. Implementation of the resistive wall model in NOVA-F will provide a code for parameter surveys of linear stability (FY05).

Feedback stabilization: In the context of feedback design studies, the major tool is VALEN [C46] code, which includes details of the external electro-magnetic structure with a fixed plasma model. It is the main tool for designing a feedback system for NSTX. Details are presented in Sec. 3.1.3 . This code will be upgraded to include multiple plasma modes (FY04-05). The VACUUM [C45] code, in conjunction with MARS, offers another tool to assess feedback stabilization when the experimental capability is in place and exercised. In contrast with the VALEN code, while this will have a simpler representation of the shell, it can include more physics, e.g. dissipation, in the plasma.

Rotation damping and error fields*:* When discussing MHD issues that relate to limiting the performance of the discharge, a critical issue is the physics of rotation damping. There are two related mechanisms that need consideration, nonlinear interactions of external helical error fields and the viscous damping due to self-generated islands (e. g., NTMs). The deleterious role of error fields was highlighted by the jump in achievable β in NSTX when the vacuum error field due to a shifted coil was largely eliminated. Modeling this result will help the understanding of the role of the error field in setting the β limit. Quasi-analytic and empirical models of error fields, rotating plasmas and anomalous braking [10,11] will be tested (FY04-05). The PIES [C39] code will be used to assess the impact of a variable resonant error field on high-β equilibria (FY04-05) through analysis of three-dimensional equilibrium models of the axisymmetric system with an imposed external helical field. This will also provide a valuable opportunity to interact with the stellarator community.

NTMs: As NSTX extends its pulse length, it will be important to assess the impact of NTMs and understand the underlying physics [12]. One requirement for modeling NTMs is the computation of Δ' at high-β, allowing for multi-mode coupling. This will be done with PEST-III [C38]. We can then assess the role of rotation as it affects the polarization term in the modified Rutherford equation (FY03-04). The ultimate goal is to estimate, in detail. the local heating and current drive requirements, including spatial resolution for external feedback stabilization. The main tool for this is EBW and the experiments are proposed for FY07-08.

Nonlinear and kinetic MHD*:* In addition to the specific topics listed above, there will be a continuing need to explore the underlying physics of various non-linear MHD phenomena. The main codes for this topic are M3D and NIMROD with their various extensions. As these codes improve their physics models and are benchmarked, they will be used for studying other non-linear and dissipative phenomenon, such as, IREs, mode locking, current diffusion and reconnection physics. (FY'04-08)).

ELMs: The ELITE [C13] code, which determines stability of moderate-*n,* (10~20), instabilities localized near the plasma edge, has been applied to DIII-D. With the assistance of the GA group, we propose to use it for NTSX (FY04-06). The recent inclusion of rotation in the code makes its application even more compelling. Comprehensive analysis requires detailed information on the profiles near the edge, in particular, j_{edge} and local shear.

5.2.2 Energetic particle physics

In STs the low field and high density imply that the Alfven speed is low, and fast particles due to NBI are generally super-Alfvenic with velocities of 2 to 4 times the Alfven speed. This allows for resonance between fast ions and the various Alfven eigenmodes, while the pressure gradient in real and velocity space provides a source for driving various Alfvenic waves, including toroidal Alfven eigenmodes, TAEs, energetic particle modes (EPMs) and fishbones, as well as compressional Alfven eigenmodes (CAEs). NSTX is unique in that the ordering of velocities of particles and waves is the same as that of a burning plasma experiment, such as ITER, with $v_{fast}/v_{Alfven}>1$. This offers the opportunity of studying ITER relevant fast ion confinement in NSTX. Experiments on NSTX show that in most cases fast ion modes are generally not implicated in significant fast ion loss. However, in some discharges, bursts of TAE modes and bounce frequency fishbones have been correlated with fast ion expulsion and drops in the neutron rate of up to 10%. There are three categories in the area of energetic particle physics: single particle confinement, low frequency modes and high frequency modes. Of these, the first two are of equal and higher priority than the third category.

The sub-cyclotron frequency modes observed in NSTX and identified as CAEs have a broad spectrum roughly equally spaced over a wide frequency range, $0.2< \square_{ci} < 1$ (see Fig. 17 of Section 3.1). The multi-mode excitation, symptomatic of mode resonances with fast ions as well as with the background ions, opens the possibility of particle diffusion in real and velocity space. In order to assess this, linear and nonlinear numerical modeling of “Alfven mode turbulence” needs to be performed. Some of the additional issues that need to addressed are as follows: the need to model compressional modes with □/□$_c$ corrections in both MHD and kinetic codes, finite Larmor radius effects, high-*q* and strong poloidal mode coupling, the requirement of full geometry representation due to the inadequacy of ballooning approximations, and strong anisotropy of plasma pressure and anisotropy of beam ion distribution function in velocity space. As indicated earlier, the ultimate challenge is to have the capability to model the non-linear consequence of these interactions self-consistently.

In addition to the influence of collective effects, the confinement of fast beam ions is influenced by their large Larmor radius and large drift orbit radial width. These features make new effects possible, such as non-conservation of the adiabatic invariant □, can have jumps in magnitude when the ion passes the equatorial plane on the low-field side of the plasma. If enhanced by the bounce resonances, this effect can result in stochastic fast ion diffusion that depends on both the ratio of the Larmor radius to the magnetic field scale length and the collisional scattering frequency [13]. The large Larmor radius in NSTX makes it necessary to use numerical tools for adequate modeling of prompt ion losses. In addition, strong electric fields due to co-injection of beams needs to be properly included to interpret the measurements of particle losses at the edge.

Low frequency (□ 200 kHz): The main developments needed are, to go beyond the present models, which use perturbative, □F type approaches and to move toward self-consistent multi-mode simulations with more kinetic physics. The NOVA-K [C35] code has been a workhorse of the community and will continue to be applied (started in FY02). The new activities are: a) develop and apply NOVA2 for assessment of non-perturbative Alfven mode excitation (FY03-04), b) develop and apply HINST with full kinetic and non-perturbative treatment for analysis of KBM and RTAE (FY04-05), c) extend applications of HYM [C28,20] a hybrid two-fluid plasma and gyro-kinetic fast ion □F code, to non-linear regimes (FY03-08), d) develop and apply a nonlinear M3D treatment as a two-fluid □F code (FY03-05), and e) develop and apply the Monte-Carlo ORBIT [C36] code with several fishbone dispersion relations to study bounce frequency fishbones (FY03-04).

High frequency (> 200 kHz): In order to correctly treat the high-frequency interactiona, the NOVA code will be modified to include ω/ω_c corrections to MHD theory (FY05-08). The HYM code will be upgraded to have the capability of treating arbitrary beam-ion distributions (FY04-05). It also needs to be modified so as to treat fast particle resonances non-perturbatively (FY05-08). With these modifications in place it will be possible to self-consistently model CAEs and GAEs in the non-linear regime. (FY06-08).

Particle confinement codes: The main issue here is to gain a better understanding of non-conservation of the magnetic moment, μ. This is a critical issue in the context of modeling particle motion, and it will allow for development of a theoretical model for the scattering frequency, which could be used in other codes that describe particle transport (FY04-05). Another task is to modify EIGOL [C11] to model local fast ion losses into the loss ion detector (FY03-04).

5.3 Transport and turbulence theory

Research on NSTX provides a challenge to theory to explain the experimentally observed confinement and transport properties, as well as gives an opportunity to further develop theoretical frameworks that address ST-specific physics issues and parameter ranges. The key parameters that differentiate the ST from conventional aspect ratio tokamaks include high-β ($<\beta_t> > 35\%$, with $\beta_{t,core} > 75\%$), the relative scale size of the thermal and fast ion gyroradii relative to machine size ($\rho_i/L \sim 0.2$ near the edge, $\rho_{fast}/a \sim 1/5-1/3$), large trapped particle fraction (~1) and high rotational shear (0.1 to 1.0 MHz). The high-β_t, larger relative gyroscale sizes and high flow shear can be attributed to the low toroidal field in NSTX, which is about an order of magnitude less than that in conventional aspect ratio devices. Most of the present theory frameworks have been developed for the higher-B_T devices at conventional aspect ratio, where perturbative ordering of these parameters could be assumed. In addition, the high rotation affects the plasma equilibrium on which microinstability calculations are based, and rotational shear influences the stabilization of the microturbulence.

There are a variety of experimental NSTX transport results that highlight differences with conventional aspect ratio tokamaks and indicate directions for theory/modeling research. Global and thermal confinement times are seen to be enhanced relative to conventional aspect ratio scalings, and there is an association between a steadily rising confinement time and a steady increase in plasma rotation velocity. Interpretive transport analysis indicates that the electrons are the primary loss channel, with ion heat and particle fluxes at or below the levels given by standard neoclassical theory. There are instances of regions of negative ion conduction flux, indicating the possible importance of stochastic heating mechanisms or heat and particle pinches, and instances of strongly resilient electron temperature profiles. On the other hand, electron Internal Transport Barriers (ITBs) are seen to develop in low-density neutral beam or HHFW heated plasmas.

An understanding of the transport physics in NSTX will evolve through detailed comparisons between the experimental results and expectations from neoclassical and microturbulence driven transport theory, as well as through further development of these theories. Preliminary comparisons have already been undertaken; linear calculations using the GS2 [C22] gyrokinetic code indicate that ITG modes are effectively stabilized by the high toroidal flow shear while the ETG modes remain unstable [14,15]. While non-linear calculations are needed in order to assess the expected levels of transport from these modes, the linear result is consistent with the experimental result that the ion heat flux is at or below the neoclassical level, and that electron transport loss dominates. These results point to theory development opportunities in both neoclassical and electron transport.

Most standard neoclassical theory is developed under the assumption that $\rho/L \sim 0$. While banana orbits are an integral part of neoclassical theory [16-18], none of these have considered the FLR effects that can be important in STs. Some work has been done to this end, in the context of ITBs in conventional aspect ratio discharges, to account for finite ρ/L within the barrier due to the presence of steep density gradients associated with the ITB [C24]. The results of this work, which was done in the high R/a, circular geometry limit, indicates a reduction of the neoclassical fluxes by an order of magnitude when considering finite ρ/L in a region of steep density gradient. This work is presently being extended to the low R/a, shaped plasma limit.

Also neglected up to now in the development of neoclassical theory is the effect of beam-thermal ion friction terms, which can result in particle and heat pinches. The direction of these pinches depends on beam aiming angle; co-injection results in inward pinches, while counter-injection results in outward pinches, an effect directly testable experimentally. These terms can be important in plasmas with very high ratios of beam to thermal velocities, which is typical of NSTX, but not of present conventional aspect ratio devices. While the theory for including these terms has been developed, the actual computation of the flux surface averaged friction terms requires upgrades to the Monte-Carlo beam code in TRANSP, and these upgrades are presently underway.

The upgrades to neoclassical theory may also help us to develop an understanding of the relation between $\square_{\square}$ and $\square_i$ in regimes where the long wavelength turbulence has been suppressed (see Chapter 3.2).

Because of the larger spatial scale lengths in NSTX than those at conventional aspect ratio, the shorter wavelength turbulence that is believed to be responsible for electron transport (i.e., ETG modes) can be more readily measured. This can be done with conventional microwave scattering in the mm wavelength range. NSTX, therefore, will find itself with a unique opportunity to benchmark theoretical predictions of ETG turbulence and associated transport with actual experimental results. Of considerable importance in this study is to develop an understanding of why electron confinement improves in certain situations with the development of an ITB.

Gyrokinetic modeling is a major tool for advancing our understanding of turbulent transport . There are, however, certain features of NSTX that challenge the present approaches to gyrokinetic theory. In particular the high value of $\square_t$ implies that electron dynamics must be taken into account explicitly in the gyrokinetic calculations and a full electromagnetic treatment of turbulence is necessary. FLR effects also have to be assessed in the context of long wavelength regimes (i.e., ITG/TEM). The strong toroidicity leads to large trapped particle fractions, which also needs to be considered. Because of the high elongation and very low aspect-ratio, the value of cylindrical approximations used to evaluate zonal flows, comes into question. Finally, since high rotational shears can have a profound effect on the microinstability thresholds and turbulence characteristics of both the ions and electrons, the experimentally observed shear rates need to be incorporated properly into both the linear and non-linear gyrokinetic calculations. The benefit of advances made in the ST context will extend to other devices, such as tokamaks and RFPs. For example correct treatment of trapped particles is relevant to tokamaks, and inclusion of electromagnetic effects in studying electron transport will extend application to the RFP regime [19].

5.3.1 Proposed research activities in transport theory

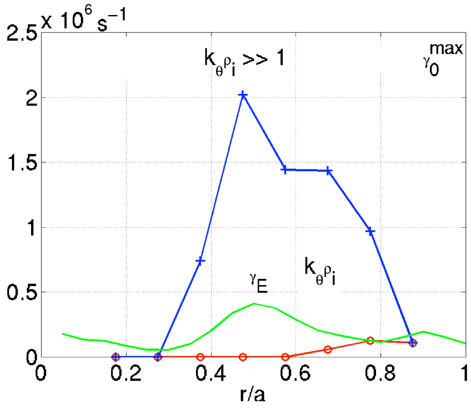

Figure 5.3.1. Growth-rates computed by GS2 show that short wavelength modes may dominate transport as their growth-rate exceeds the ExB shearing rate, while long wavelength modes are stabilized.

Microstability and turbulence simulations: The primary tools used to study the turbulence driven ion and electron transport are the FULL, GS2, GTC and GYRO codes. Each of these codes has different capabilities and strengths and complements each other in many ways. By using all of these codes, the NSTX project seeks to exploit their individual strengths and advance the science of transport and turbulence in STs. These codes represent the state of the art for tokamaks, but additional developments may be needed to meet the unique demands of NSTX, emanating from strong toroidicity, high- and high rotation speeds. A brief description of the capabilities, applications and future developments needed follows. The FULL[C17] and GS2 codes are local flux tube codes, which examine the stability in the limit of *=0. They are both well-established production codes, well coupled to equilibrium information from many sources, for example TRANSP, EFIT, and JSOLVER, and are well suited for systematic parameter studies. FULL is an eigenvalue code, which has the unique capability to distinguish all the possible modes. Thus, unlike other codes, which follow the growth of only the fastest growing mode, FULL can be used to look at sub-dominant modes, as well as the most unstable mode. FULL has been used extensively to benchmark the initial value codes, and will continue to serve in this support role. GS2 is an initial value code, which can be run in the linear and non-linear regimes, and follows the development of the most unstable mode in the frequency range of interest. By virtue of its formulation as an initial value code, GS2 offers a powerful capability to rapidly assess microstability properties, and has been applied extensively to NSTX as a linear code [14]. It has already been used to study the linear growth rates of drift wave instabilities in the ITG and ETG range of frequencies. The results in the ITG range are consistent with the observed improvement of ion confinement, in that the ExB shearing rate is greater than the predicted growth-rates and would stabilize the mode, Fig. 5.3.1. An interesting result in these studies was the observation of tearing parity eigenfunctions in some parameter regimes, Fig. 5.3.2. This observation contrasts with the results of simulating tokamaks, where the most unstable mode usually has even parity. Preliminary analysis indicates that the plasma conditions in this discharge, suppress the usual ITG modes and allow the normally sub-dominant tearing mode to be detected as the fastest growing mode, albeit with a relatively small growth-rate. Clearly much more work is required to include more physics and to understand and quantify these results.

In the ETG range of frequencies, the linear instability growth-rate is determined to be significantly larger than the shearing rate, consistent with the observation of lower electron confinement. Future work will involve non-linear calculations and an emphasis on high-k ETG physics. Specific plans include: identifying regions of k-space most likely to be affected by flow shear, and studying the dependence on T_e/T_i, n_e and n_i in turbulence driven and collisionally dominated plasmas. Particular attention will be paid to identifying parametric trends that can be tested experimentally (FY03-05). Gyrokinetic simulations using GS2 will focus on linear frequency, growth rate, wavelength and mode structure for ITG/TEM and ETG modes over a wide range of collisionality (FY04-06). The simulations will be extended to nonlinear regimes to complement linear analysis of short and long wavelength modes (FY04-07).

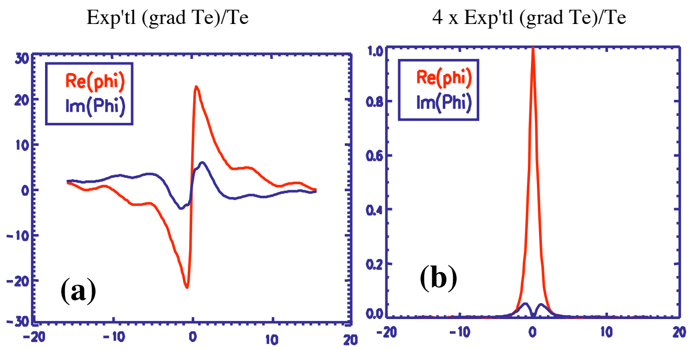

Figure 5.3.2 Eigenfunctions of the most unstable mode using (a) the experimental temperature gradient, note the tearing parity, and (b) with an artificial increase by a factor of four, the most unstable mode is the more commonly observed ITG-TEM mode.

As indicated earlier, GS2 and FULL are flux tube codes, to complement them we will use the global gyrokinetic codes, GTC[C23] and GYRO[C25]. While they incorporate similar physics, they use different approaches, GYRO is a Vlasov code, while GTC is a PIC, particle-in-cell code. These global codes simulate segments of the radial cross-section, up to the minor radius, and simulate the ExB flow in contrast with FULL and GS2, which treat the flow as an external constraint. The finite radius global geometry implies that zonal flows, an important characteristic of turbulence in plasmas, can be studied with these codes. At the present time GYRO can treat the effects of finite but small $\square^*$, finite $\square$, passing and trapped electrons, parallel electromagnetic perturbations, $\square B_{||}$ and real geometry from Miller local equilibrium. It has been used extensively to simulate conventional aspect-ratio tokamaks and applications to STs will start in FY03. Important model issues that might need to be considered are the effects of the larger $\square^*$ characteristic of NSTX, role of $\square B_{\square,}$ the validity of the Miller local equilibrium at low aspect-ratio, and other equilibrium effects associated with the strong plasma flow observed in NSTX.

The GTC code, with its PIC formulation, will complement GYRO in addressing $\square^*$ effects. It is being modified to be relevant to the ST parameter regime, in particular to use numerical MHD equilibria that model the experiment at high-$\square_t$. Simulations of plasma turbulence are computationally intensive, and computational techniques, which scale linearly in the number of particles and grid-points, are critical for their usefulness. A new multi-grid scheme has been formulated and will be implemented in the global codes. This will enable resolution of both small-scale turbulent modes and large-scale modes, zonal flows, in an efficient manner (FY03–04). It will also model full electrodynamics (FY04-05).

Following these initial tasks, non-linear calculations of ETG turbulence and predictions of density fluctuation amplitudes and (k, $\square$) spectra for comparison to experiment will be performed. As part of this, the in-out asymmetry of turbulence and associated transport, which is expected to be more pronounced on NSTX than in conventional aspect ratio tokamaks, will be simulated, and visualization techniques that will facilitate a comparison between results from gyrokinetic codes and experimental observations will be developed (FY05–06).

Neoclassical transport: In assessing the confinement properties of STs, it is important to accurately calculate the neoclassical dynamics. Typical ST features, which challenge the basic assumptions in theories, include low aspect-ratio, large orbit size, near unity trapped particle fraction, toroidal rotation and shear. Including these accurately with a self-consistent calculation of the electric field will help us to assess the model ion thermal transport and the bootstrap current. This is being done in GTC-NEO [C24] and NCLASS [C32] GTC-NEO is a variant of GTC that includes generalized geometry, finite $\square^*$, orbit effects, self-consistent electric fields, rotation and multiple species. It will be applied to NSTX plasmas to examine radial electric fields, heat fluxes, poloidal rotation and angular momentum transport, bootstrap current and possible particle and heat pinches (FY04-05). Eventually, this code will be integrated with GTC to provide a comprehensive code having both turbulence and neoclassical capabilities in generalized geometry, (FY06-07). The NCLASS neoclassical model calculates the bootstrap current, electrical resistivity and particle and heat pinches for shaped plasma at arbitrary aspect ratio and collisionality. It is a multi-species fluid model that correctly treats particle orbits near the magnetic axis (e.g., potato orbits and orbit squeezing effects due to radial electric fields), and will soon be upgraded to compute the beam-thermal ion friction terms. (FY03–04). Future work will involve incorporating finite □/L effects, especially in the outer region of the plasma. (FY05–06).

Experimental modeling. TRANSP is the standard code for performing interpretive transport analysis with state-of-the-art beam and RF modeling, neoclassical transport, multiple ion species and data handling modules. TRANSP can also be run in a predictive mode based on assumptions of neoclassical and turbulence-driven transport, the latter using the GLF23 [C20] and Multi-mode transport models.

Predictive TRANSP analysis, initially using semi-empirical models for the thermal diffusivities, and then using diffusivities taken directly from non-linear gyrokinetic calculations will be performed (FY03- 04). Gyrokinetic predictions of transport coefficients will be integrated into predictive simulations in a seamless fashion (FY05-06). After this, we will continue to develop fully predictive transport simulation capabilities by combining transport simulations with MHD stability to form a full, integrated scenario development package (FY07-08).

5.4 Radio-frequency-wave heating and current drive

RF wave heating and current drive are critical elements of the NSTX goal to “assess the attractiveness of the ST concept for pulse lengths which are long compared to the current diffusion time”. The theory and modeling of RF wave heating and current drive in a spherical torus is more challenging than in a conventional aspect ratio tokamak, because of the relative size of the Larmor radius and the high trapped particle fraction. In addition, the presence of fast particles, due to NBI, challenges models that assume that the ion velocity distribution is Maxwellian. Most computational models were developed for conventional tokamaks, where a finite Larmor radius expansion is often valid. In an ST, the fact that the ion Larmor radius, the ion banana width, the perpendicular wavelength, and the spatial separation of the ion cyclotron harmonic layers can be comparable, particularly for high-energy particles, poses significant challenges to those models, as many of the approximations used with conventional tokamaks may be inappropriate for RF wave dynamics in an ST plasma.

The unique features of an ST plasma affect all aspects of RF wave dynamics, i.e., wave propagation, absorption, heating and current-drive. In the context of wave propagation, in an ST plasma, the poloidal magnetic field is much larger, relative to the toroidal magnetic field, than in a conventional aspect ratio tokamak. The correspondingly larger tilt of the total magnetic field lines in the edge regions can modify the spectrum of waves that can be excited in the plasma by the launcher. In the core of the plasma, the larger shear in the magnetic field can modify the evolution of the local parallel wave number, thereby affecting wave penetration and absorption characteristics. In the highest beta ST discharges, when an internal magnetic well is formed, the presence of a reversed magnetic field gradient at the outer edges of the plasma may affect wave accessibility and absorption profiles. Finally, because of the inherently high beta and high dielectric constant in these devices, direct electron absorption of the waves via transit time magnetic pumping can be comparable to or greater than direct ion absorption via cyclotron damping.

As in other topical areas, there a large number of codes, which address the modeling needs of RF heating and current drive. The codes have different levels of sophistication in their physics assumptions, which is often reflected in their speed. The speed of the code is of particular importance when attempting time-dependent transport simulations including RF modeling. Thus the need arises for both full physics standalone codes, and reduced model codes, which can be used in transport simulations. The former can be used for benchmarking and to establish the regime of validity of the reduced model codes in parameter space.

An example of this, is that both ray tracing and full wave codes are used for modeling heating and current drive scenarios that utilize fast magnetosonic waves at high harmonics (HHFW) of the fundamental ion cyclotron frequency. Though the wavelengths in this regime are sufficiently small relative to the equilibrium gradient scale lengths to justify a WKB assumption, ray-tracing models can miss important 2-D wave coherence effects and are not able to treat mode conversion phenomena, which may be significant at lower cyclotron harmonics. Two-dimensional full wave codes exist that keep terms to all orders in a Finite Larmor Radius (FLR) approximation. However, these codes are sufficiently computationally intensive that they are impractical to use for the analysis of a large number of NSTX discharges. Other 2-D full wave models exist, which use simplifying assumptions to reduce the computation time required. The accuracy of these simplified models is currently being evaluated.

Another example arises from the fact that the HHFW systems are often used in conjunction with neutral beam injection. Experimental observations indicate that the fast ions can interact strongly with HHFW, leading to significant modifications of the fast ion velocity distributions as well as the partitioning of the wave power among the various plasma species. Initial modeling results, obtained with a 1-D full wave all-orders code, also indicate that significant modifications of the power partitioning and absorption profiles may be caused by inclusion of anisotropic velocity space characteristics. Hence, to insure accurate simulation capabilities, the 2D wave codes should be generalized to include effects of non-Maxwellian populations on wave propagation and absorption. Non-linear effects on the wave absorption that may arise due to overlap of the cyclotron layers for high-energy particles need to be assessed. Self-consistent Fokker-Planck models need to be developed that include quasilinear diffusion at high cyclotron harmonics in an ST equilibrium. These Fokker-Planck models are needed to assess HHFW non-inductive current drive efficiencies, including effects of particle trapping, in the ST geometry.

5.4.1 Proposed research activities in RF heating and current drive

The development of theory and modeling of RF physics in the ST is a greater challenge in comparison with efforts in other topical areas, as nearly all models have to be revised and many codes have to be modified. This effort relies heavily on contributions from a large number of institutions and also benefits greatly from the SciDAC effort led by ORNL. The goal is to develop ST relevant theory for HHFW and EBW heating and current drive. The approach is to develop comprehensive codes, which include all the relevant physics of wave plasma interaction, as well as codes based on approximations, which are less demanding in computational resources and hence are more suitable for extensive parameter studies. Both of these classes are important: the comprehensive physics codes serve to expand the fundamental understanding and are also available as benchmarks for the more approximate codes, which are used for routine modeling. A detailed description of the proposed activities follows.

Wave propagation: There are two approaches to modeling wave propagation in an ST: ray tracing codes, which utilize a WKB approximation, and full wave codes, which either retain all orders in a finite Larmor radius expansion of the dielectric tensor elements or else truncate the expansion at first order in $k_{\square}^{2}\square_{i}^{2}$. CURRAY [C6] and HPRT [C27] are ray tracing codes, which utilize a hot electron/cold ion approximation for computing the ray paths, but the full hot plasma dielectric tensor for calculating the power absorption profiles. TORIC [C41] is a full wave code that solves for the high harmonic fast wave fields using a novel reduced order approximation that retains effects of high cyclotron harmonics in the context of an FLR treatment for the wave polarizations. The 2-D full wave code, AORSA [C1], uses an algorithm to compute the wave fields and power absorption profiles that is valid to all orders of an FLR expansion. Comparison of these codes with each other and with experimental observations provides an opportunity to determine their individual domains of validity.

Initial results from both the ray tracing and the full wave codes indicate that the wave dynamics in NSTX plasmas with moderate densities and temperatures are dominated by fast wave physics with electron absorption dominant in this parameter regime, as expected from theory. Mode conversion to short wavelength ion Bernstein waves, which in principle can occur near the various cyclotron harmonics, does not appear to be significant in these plasmas. Similar results have been obtained from the 1-D all orders code, METS [C31]. The importance of mode conversion at higher toroidal fields and potentially at lower cyclotron harmonics, relevant to the next step ST device, will be evaluated (FY04-05).

Self-consistent particle velocity space distributions: The ray codes and the 2-D full wave codes discussed above currently assume that all the plasma species can be represented by Maxwellian distribution functions. However, wave propagation and absorption in a plasma with a sizeable fast ion population may be significantly different than in a plasma with only thermal components. Furthermore, the interaction of the waves with a resonant plasma species can drive the velocity distribution function of that species to be non-Maxwellian. As a first response to this challenge, we will assess the impact of non-Maxwellian distributions, using the faster 1-D all-orders code, METS (FY03). Preliminary results [21] indicate that absorption of the waves by a fast ion population can differ by up to a factor of two, if anisotropic velocity space effects are included. Further studies with this 1-D model need to be completed to better understand the extent to which non-Maxwellian ions or electrons modify the wave propagation and absorption. If significant modifications of the wave propagation and absorption cannot be represented well by equivalent Maxwellians, then the dielectric tensor operators in the 2-D full wave codes will be generalized to include non-Maxwellian species (FY04-05). This development work will be completed as part of the SciDAC project, “Numerical Computation of Wave-Plasma Interactions in Multi-dimensional Systems.”

To self-consistently account for the evolution of the distribution function in phase space, a Fokker-Planck treatment of the ion and electron distribution functions in ST geometry is needed that includes effects of quasilinear diffusion at high cyclotron harmonics, collisions, trapped particle effects, and particle losses. The main focus of this development is the GENRAY/CQL3D package. The CQL3D code will be modified in stages. Loss cones will be introduced in FY03, as will resonance overlaps. In FY04, finite orbit effects will be introduced. Coupling of the code to TRANSP will also commence in FY04. This will enable time dependent simulations and account for profile evolution. As modeling progresses, if full wave effects are determined to be important, the CQL3D code will be integrated with the full wave codes.

Current drive: A theoretical issue of importance in the simulation of current drive experiments concerns the accuracy of current drive modules based on the adjoint method or the Ehst-Karney parameterization of the adjoint solution generated for a conventional tokamak. CURRAY and TORIC each utilize either the Ehst-Karney parameterization [22] of current drive efficiency or a full adjoint solution to the Fokker-Planck equation [23] to estimate the driven current profile. Both codes have been used to model the inferred HHFW current drive in initial experiments without NBI. The results from the two codes are similar and consistent with the HHFW driven current, as inferred from loop voltage measurements. The codes are also in agreement when modeling the current drive efficiency at low plasma betas, up to about 15%. However, recent studies of current drive efficiencies in the lower hybrid range of frequencies have indicated that important 2-D velocity space effects on rf-driven currents are not included in the adjoint solutions [24]. Consequently, the current drive efficiencies estimated on the basis of the adjoint method tend to be too pessimistic in some parameter regimes. The CQL3D code, described previously, will be modified to compute the HHFW current drive efficiencies for NSTX experiments. Development work is underway to couple TORIC with the CQL3D Fokker-Planck package (FY04-05). At the same time the effects of the DC electric field arising from the ohmic current drive system, particle trapping, and electron transport will be incorporated into the full Fokker-Planck models. These theoretical and experimental studies, when combined with the generalized wave codes discussed above, will serve to elucidate the importance of various effects on HHFW heating and current drive in NSTX plasmas.

Time dependent transport modeling: The primary tool for the time-dependent analysis of NSTX experiments is the TRANSP simulation package. TRANSP is constructed to utilize auxiliary heating and current drive profiles, which are generated either offline by stand-alone wave modeling codes or from modules that have been integrated into the TRANSP package. Recently, the HPRT code has been used to generate power deposition profiles for use in TRANSP analysis of HHFW heating experiments in NSTX. Modules based on both the CURRAY and the TORIC codes are in the process of being incorporated in TRANSP. Time dependent transport analysis of RF heated plasmas in NSTX will commence in FY04.

EBW modeling and theory: In this topical area, the needs are for antenna design and modeling of heating and current drive. The primary tools for this are the ray tracing code, GENRAY [C19] and the bounce-averaged Fokker-Planck code, CQL3D [C5]. At the present time the limitations in GENRAY are that it requires that the rays be launched as EBW waves in the plasma, and it does not account for the effects of mode conversion while following the ray. It will be upgraded to include a realistic antenna pattern and refraction at the mode conversion layer. Options for mode conversion being considered are either a cold plasma model or the GLOSI [C21] code. The plan is to study antenna design using appropriate target equilibria and kinetic profiles starting in FY03 with GLOSI or RANT3D [C40]. Preliminary studies of the current drive indicate that the current can be localized, provided that the $n_{||}$ spectrum retains a narrow shape. This suggests that EBW could also play a role in NTM stabilization. The modeling of the CD required for NTM suppression will help assess the potential for feedback stabilization in NSTX in FY04. Integrated scenario development of a fully non-inductive, $\beta \sim 40\%$ NSTX plasma requires about 100 kA of off-axis current drive between r/a = 0.4 and 0.8. EBWCD can potentially provide this off-axis current drive if approximately three MW of EBW power is delivered to the plasma. During FY03, work will continue in a scoping study to explore the sensitivity of the EBW current drive efficiency to RF launch parameters (e.g., poloidal launch angle, $n_{//}$ and frequency), with the GENRAY and CQL3D codes. Part of this study will focus upon understanding and optimizing Okhawa current drive and its potential role in NSTX high β plasmas. This scoping study will also include developing scenarios for EBW-assisted non-inductive plasma startup. In order to facilitate these studies, both codes are being optimized for parallel processing. Modeling which includes the effects of transport and bootstrap current, in FY04-05, will improve the predictive capability. Assessment of driven parametric instabilities at high RF power near the mode conversion layer located near the edge of the plasma will also be investigated theoretically in FY03-04, and a theoretical analysis including relativistic effects, in collaboration with MIT, will determine whether relativistic effects should be included in the propagation and damping of the EBWs.

5.5 Non-inductive plasma-startup research

The success of the ST concept requires the ability to generate and sustain toroidal current non-inductively. This is because the inherently slim center stack limits the inductive flux. The NSTX program is addressing this need in several ways. The primary approach to generating non-inductive current is the method of co-axial helicity injection (CHI). Other startup methods being investigated are to use the outer poloidal field coils without energizing the ohmic solenoid and to use RF heating and current drive based on the ECH/EBW system. In this section we only discuss the modeling needs in relation to CHI, noting that the poloidal field startup will be modeled using the well established code TSC[C43], and the ECH/EBW current drive modeling is discussed in Sec. 5.4.

In CHI, current is driven poloidally between a pair of electrodes. The CHI method drives current initially on open field lines creating a current density profile that is hollow. In a continuously driven system (i.e., steady state CHI), Taylor relaxation [25] predicts a flattening of this current profile through a process of magnetic reconnection leading to current being driven throughout the volume, including closed field lines. The current penetration to the interior is needed for usefully coupling CHI to other current drive methods and to provide CHI produced sustained current during the long pulse non-inductive phase. Therefore, flux closure is one of the key issues on CHI research. Smaller machines have observed a non-axisymmetric n=1 toroidal mode which is deemed necessary to provide flux closure [26-29]. Assessment of flux closure in driven systems needs both experimental and theoretical tools. Theoretical tools include equilibrium reconstruction and discharge simulation codes to understand experimental data and MHD codes to understand the physics of closed flux generation. To date, good progress has been made in using the ESC code [C14] with capability for inclusion of current on open field lines and in the private flux region to reconstruct experimental NSTX CHI data. These features have also been included in the EFIT code. To understand CHI reconnection physics, a 3-D MHD code, CHIP [C4] is being used. The code has been used to model CHI processes in a simple geometry, Fig. 5.5.1. Implementation of the actual NSTX geometry will allow for a closer comparison of the simulation results with the experimental results, and help guide and understand the experiments.

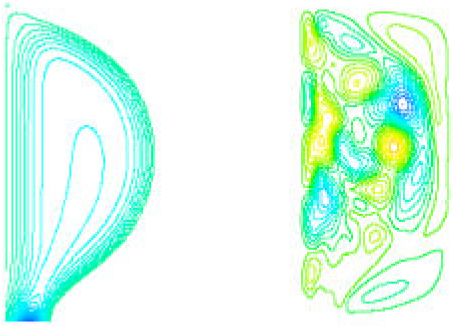

Figure 5.5.1 Simulations results from CHIP. The axisymmetric steady state solution on the left and on the right, the edge current driven n=1 kink instability.

Recently, a new method (known as transient CHI startup) was successfully used on the HIT-II experiment to demonstrate plasma startup using CHI. Because of this, the plasma startup and sustainment objectives on NSTX are being decoupled. Next step plasma startup experiments on NSTX will use the transient CHI method that does not rely on non-axisymmetric modes for closed flux generation. Closed flux generation can be unambiguously demonstrated by the persistence of toroidal current after the CHI injector current has been reduced to zero. This new work considerably narrows the scope of the TSC code, which will now be used specifically to develop transient startup scenarios for NSTX. Understanding steady-state CHI discharges, as described in the previous paragraph, is needed to establish the role of CHI for providing some edge current drive during full non-inductive operation and because it may have the potential for much higher initial plasma startup currents.

5.5.1 Proposed research activities in CHI.

The three primary research topics in this area are: modeling the experiment to assess flux closure, developing discharge startup scenarios, and advancing the understanding of the non-linear processes relating to reconnection. Assessing the flux closure through modeling requires equilibrium codes that can reconstruct the time averaged 2-D flux in the device. The codes need the capability of correctly treating current on open field lines correctly, as well as matching the measured currents in the coils and nearby conducting structures. This capability has been introduced in EFIT and ESC, and applications to NSTX started in FY03. In addition to these two codes, the TSC code is also available for such modeling. The TSC codes also provides a predictive capability, in the sense that it can be used to optimize the coil currents to optimize the shape and driven current density, and is therefore the most appropriate tool for developing scenarios. This modeling activity has started in FY03 and is expected to continue in parallel with experiments. Exploring the physics of reconnection and flux closure requires a 3-D code, as finite-n instabilities are known to play a role, and the 3-D MHD code, CHIP is being used for this purpose. As the physics of reconnection is of interest in many areas, including astrophysics, we hope to exploit progress made by other researchers as well, for example building on the work with M3D and NIMROD (FY04-08).

5.6 Boundary physics

Present boundary physics models, developed for conventional aspect ratio, are particularly challenged by the unique magnetic topology of NSTX and the associated high trapped particle fraction, large mirror ratio and the finite Larmor radius effects. In addition, observations of large-scale convective cells seen to propagate radially and poloidally, as measured by high-speed edge diagnostics near the plasma edge (Fig. 3.5.6), indicate that edge transport is primarily convective and not diffusive. Also seen on Alcator C-Mod, this latter observation offers a new opportunity for the development of convection-dominated edge transport models.

The most important role of theory and modeling is a well-defined one, namely to establish a physics basis for extrapolation to reactor regime plasmas, including NSST, CTF and ITER. These extrapolations need to be done in the key areas of Boundary Physics, which are particle control and fueling, power handling, H-mode physics and edge transport. NSTX provides a direct connection to ITER by accessing regions of parameter space not easily accessible to tokamaks, thereby providing an excellent test bed for theory. One example of this is to determine whether the H-mode pedestal width is related to the fast or thermal ion gyroradius. The large gyro-scale lengths in NSTX allow for this identification and differentiation. Another example of this is the high heat flux in NSTX (10 MW/m^2, Fig. 3.5.3), which is similar to that expected in ITER. Thus, it is necessary to develop and validate models in the high heat flux regimes in order to establish, with confidence, a basis for extrapolation to future, high heat flux devices.

The models developed for the conventional aspect ratio regime need to be examined for applicability in the spherical tokamak regime where several additional complicated factors arise. The ST mirror ratio in the scrape-off layer (SOL) can approach 4 in high triangularity discharges, and this leads to a high trapped particle fraction (~ 90%) and a change in the velocity-space loss cone. Trapped ions can experience an effective connection length much longer than the rather short physical connection length, allowing those ions more time to lose energy before striking and heating the target plate. Another challenge is the interpretation and extrapolation of edge measurements to determine accurately the location of the plasma separatrix. This is important since its radial location, coupled with the edge transport properties, help determine the power flux into the SOL. As in the MHD area, high flow speeds can influence the plasma equilibrium, but at present, rotation is not included routinely. The issue of separatrix location is complicated by the relatively large ion poloidal gyro-radius 2 to 3 cm in many NSTX H-mode discharges, which could lead to an ambiguous distinction between the closed and open field lines. The plasma and neutral transport at the edge is being modeled using fluid codes (e.g., UEDGE [C44], DEGAS 2 [C8] or EIRENE [C12]), and the large number of adjustable parameters in these codes almost assures a reasonable match between data and model. The challenge here is to independently use kinetic models of the SOL to estimate the magnitude of kinetic effects, and then devise diagnostic techniques to measure those effects. If these effects are confirmed to be important, then kinetic theory “patches” may be applied to the fluid models, for example with the use of free-streaming limit multipliers on parallel transport.

Plasma boundary interactions unique to the ST may play a critical role also in H-mode transitions. H-mode power threshold theories generally do not include trapped-particle effects properly. Typically the equations are linearized and expanded in inverse aspect ratio, epsilon, which runs counter to the assumptions that are valid in the ST regime. Work to generalize those models will be needed. Understanding the observed difference between the inboard and outboard density pedestal heights, and examining the possible role of local B-fields, will require a model including compression and rotation effects.

5.6.1 Proposed research activities in Plasma-Boundary Physics

Particle control: Measured ionization profiles and edge temperatures and densities will be used as a basis for determining the neutral density profile and plasma profiles in the SOL. The codes used here will include the edge plasma transport code UEDGE and the neutral transport code DEGAS 2 (FY03-04). DEGAS 2 analysis of particle control issues will assist in optimization of cryopump designs (FY04-06). Future plans for lithium-based particle control techniques in NSTX motivate the addition to DEGAS 2 of the infrastructure and data needed to treat lithium surfaces (FY05-06).

Power handling: The edge plasma and neutral transport modeling, along with an accurate reconstruction of the divertor flux geometry, are crucial to being able to estimate power fluxes to the PFCs and, consequently, to develop the means to ameliorate these fluxes. Both UEDGE and DEGAS2 will be important tools here also (FY03-04). Another topic important to heat flux studies is the role of fast events, such as ELMS, and reconnection events. Giant ELMS associated with energy drops of up to 25% have been observed in NSTX. Modeling these depends on detailed diagnostics and MHD codes like M3D and NIMROD (FY05), which will be used to assess the power deposition in a manner similar to that done for disruptions. Another outstanding issue is the need to integrate kinetic effects into the modeling tools in order to account for non-Maxwellian effects in the heat flux calculations, and to better model detached plasma operation. Development work is underway to extend a 1-D code, FPI [30] to 2-D and include appropriate physics (FY04-05).

H-mode physics. Because L-H transitions are often associated with suppression of local turbulence, possibly through ExB shear, modeling of this bifurcation will require transport calculations that are valid in the outer regions. The GYRO codes is suitable for assessing which modes are suppressed going from the L- to the H-mode, and why (FY04-05). L-H transitions have also recently been associated with fast ion driven MHD bursts and neutron drops, suggesting the possibility that non-ambipolar losses can set up radial electric fields that aid the transition. The fast ion loss in response to the MHD modes, and the generation of the radial electric field will be modeled with the M3D-K, NOVA and ORBIT codes (FY03-04). Knowledge of the scaling of the pedestal height with core parameters will help connect boundary plasma limits to the density and temperature at the magnetic axis, and is essential for assessing the viability of future ST devices. GYRO will be used to study modes in the pedestal region in the FY04-05 time frame, in conjunction with new diagnostic data. The ELITE code will be used to examine the role of intermediate peeling/ballooning modes in modeling ELMS when measurements of the current density at the plasma edge are available (FY05-06).

Edge physics: Gas puff turbulence imaging experiments suggest that cross-field transport near the edge may be convection dominated. The instabilities driving these convective cells have been and will continue to be modeled with boundary turbulence codes such as BAL [C2] and BOUT [C3], and the edge transport process will be modeled using a convective treatment of the edge transport in the UEDGE code (FY03-04). The simulations will attempt to explain qualitatively the differences between the emission patterns observed in H-mode and L-mode, provide a connection between observations and turbulence models and model the effect of convective cells on plasma transport and profiles (FY03-04).

Finally, kinetic effects on scrape-off layer transport will be explored. The large mirror ratio, up to a factor of 4, and short connection length at low aspect-ratio suggest important effects on electron heat transport, which may lead to different parallel and perpendicular temperatures. The UEDGE code will be modified to include this physics and simulations will be compared with the data as they become available (FY04-05).

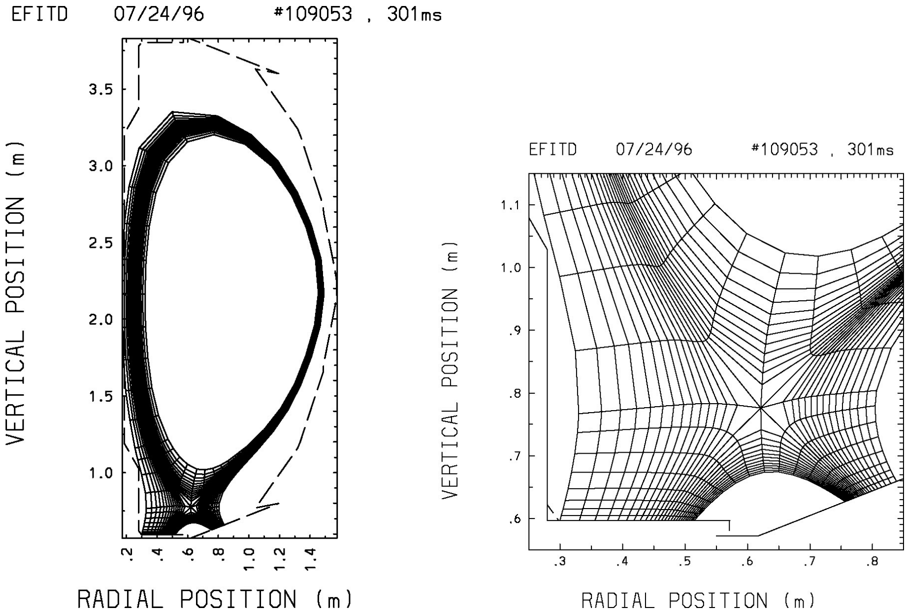

Figure 5.6.1 UEDGE computational mesh constructed from an EFIT equilibrium file. Note the significant relative variation in major radius along the scrape-off layer, indicative of a corresponding variation in the toroidal field that gives rise to mirror trapping.

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