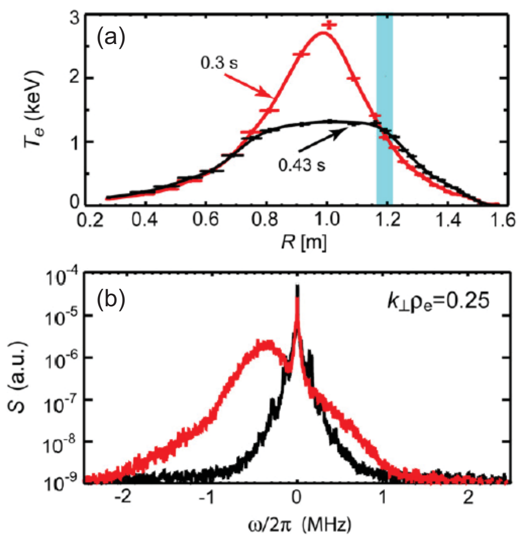
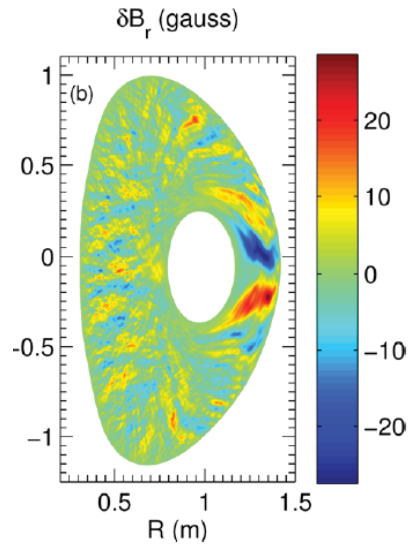
Table of Contents for Chapter 3

Chapter 3





Research Goals and Plans for Transport and Turbulence

3.1 Introduction

The long-term goal of NSTX and NSTX-U transport and turbulence research is to achieve the capability of predicting and optimizing the confinement performance of future fusion devices, e.g. ST-FNSF [1] and ITER. Considerable achievements have been made toward this goal during the operation of NSTX. Built on the success of NSTX, NSTX-U will have much improved capabilities and aims to deliver substantial advances toward the goal. In order to guide the detailed planning of NSTX-U Transport and Turbulence research, three research thrusts are proposed: 1. characterize H-mode global energy confinement scaling in the lower collisionality regime of NSTX-U; 2. identify regime of validity for instabilities responsible for anomalous electron thermal, momentum, and particle/impurity transport in NSTX-U; 3. establish and validate reduced transport models (0D and 1D). The research thrusts and associated research plans will support all of the 5 high-level 5 year plan research goals presented in Chapter 1.

NSTX has distinguished itself as a unique experimental platform for studying transport and turbulence in toroidal confinement devices. The observed neoclassical-level ion thermal transport observed in most NSTX H-mode plasmas is consistent with the suppression of low-k (ion-scale) turbulence resulting from the high beta, low aspect ratio ($\gtrsim$1.3), naturally shaped equilibria of NSTX, and also from the large E×B shear driven by neutral beam injection (NBI), as supported by experiments and modeling [2,3]. On the other hand, the anomalous electron thermal transport determines the confinement properties of NSTX. The NSTX H-mode energy confinement has been shown to have strong inverse dependence on collisionality ($B\tau_E \sim 1/\nu^*_e$) with and without lithium wall coating [4,5], a trend consistent with that on MAST [6]. This strong collisionality dependence is dramatically different from the ITER98y,2 scaling ($B\tau_E \sim$ independent of ν^*_e) [7] and is favorable for next generation STs operating in low collisionality regime. The change in anomalous electron thermal transport is found to be responsible for this.

Several mechanisms have been identified as potential candidates for anomalous electron thermal transport in different operational scenarios at different spatial regions, which are listed in Table 3.1.1. These include ion scale (low k_θ) drift wave instabilities such as ion temperature gradient (ITG) [8], trapped electron mode (TEM) [9], kinetic ballooning mode (KBM) [10], and microtearing (MT) [11]; electron scale (high k_θ) electron temperature gradient (ETG) drift waves [12]; and energetic-particle-driven global and compressional Alfven eigenmodes (GAE and CAE) [13].

Transport Mechanism		**Transport channel affected**			
		ion energy	electron energy	particle/ impurity	momentum
Drift waves	ITG (low k_θ)	×	×	×	×
	TEM (low k_θ)	×	×	×	×
	KBM (low k_θ)	×	×	×	×
	MT (low k_θ)		×		
	ETG (high k_θ)		×		
Neoclassical		×		×	
Energetic particle (GAE/CAE)			×		

Table 3.1.1: Transport mechanisms expected to be important in NSTX and NSTX-U plasmas and the corresponding transport channels affected. The drift wave instabilities include ion temperature gradient (ITG), trapped electron mode (TEM), kinetic ballooning mode (KBM), microtearing (MT), and electron temperature gradient (ETG). The energetic particle instabilities include global Alfven eigenmodes (GAE) and compressional Alfven eigenmodes (CAE).

It can be seen in Table 3.1.1 that in addition to thermal transport, low-k turbulence can influence other transport channels. While neoclassical physics has been shown to capture the gross features of NSTX impurity profiles in many H-mode plasmas, there is evidence of anomalous convective contributions in some discharges [14,15]. Momentum transport is also usually anomalous despite ion thermal transport in H-mode plasmas being very close to neoclassical levels [2]. These instances of anomalous impurity and momentum transport suggest that some residual level of low-k turbulence may be important even in the presence of relatively large E×B shear.

These theoretical mechanisms often depend distinctly on various plasma parameters which determine when they will be important. One such parameter which NSTX uniquely has the ability to vary over a significant range is the plasma β. For example, as will be discussed later, ETG modes are found to be important in the internal transport barrier (ITB) in low β reversed shear plasmas [16,17], ETG and ITG modes in low β NBI-heated L-mode [3] and H-mode [18] plasmas. On the other hand, microtearing and KBM are important in high β H-mode plasmas [19-21], while GAE/CAE instabilities occur near the magnetic axis of high power NBI H-mode plasmas that exhibit large fast ion beta [13].

In addition to plasma β the various modes also respond differently to changes in collision frequency. All of the ion scale ballooning modes (ITG, TEM, KBM) tend to be stabilized by increasing collisionality, while ETG is insensitive to collisionality and microtearing is often more unstable at higher collisionality. Using these unique parametric dependencies should help clarify the regimes of validity for the different mechanisms responsible for electron thermal transport. This is one of most important transport issues for NSTX and NSTX-U in order to achieve the predictive capability for electron temperature for future ST-FNSF and ITER.

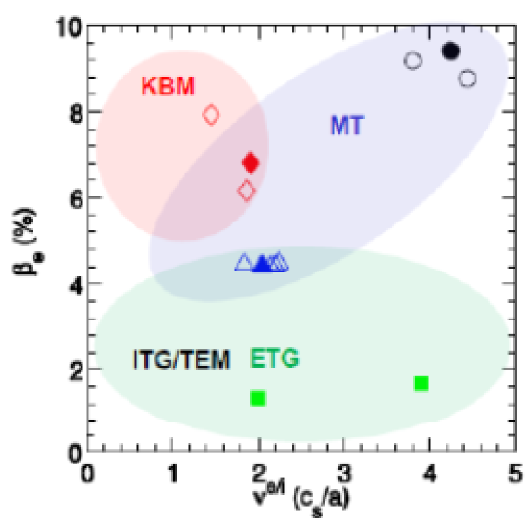


Fig. 3.1.1 Local values of β_e and $\nu^{e/i}$ (r/a=0.6-0.7) for various NSTX H-mode discharges. The colored regions illustrate where various microinstabilities are generally predicted to occur. $\nu^{e/i}$ is the electron-ion collision frequency.

The diversity of drift wave mechanisms and in what instances they are predicted to be unstable is illustrated in Fig. 3.1.1. The symbols indicate values of electron β and collisionality evaluated at r/a=0.6-0.7 for a number of NSTX discharges while the color shaded regions indicate the dominant unstable mode predicted (using gyrokinetic simulations as will be discussed later in the chapter). Having the ability to access such a broad range of β will allow NSTX-U to study the importance of finite beta electromagnetic effects on transport and confinement which is important for future devices including ITER.

NSTX-U [22] compared to NSTX will have enhanced capabilities that will make it possible to address the above transport issues in parameter regimes more relevant to future devices. The increase in plasma current, toroidal field and heating power is expected to improve confinement, naturally leading to higher temperatures and reduced collisionality. However, the influence of the different mechanisms will themselves vary as discussed above, leading to the inherent limit in confinement improvement and collisionality reduction. The installation of the cryopump during the five year period will provide additional operational flexibility to manipulate collisionality through density control to better isolate its effects on energy confinement and the various transport mechanisms.

In addition to the expanded achievable variation in collisionality, the NCC coils (see Sec. 2.2.2.2.5) will also allow for a broader manipulation of toroidal flow profiles and corresponding E×B shear flow to study its impact on the various transport mechanisms. Although a complex function of collisionality and toroidal flow, the NTV torque applied from the NCC coils is predicted to be nearly as large as that injected from the neutral beams. Furthermore, the radial profile of NTV torque density can be varied with the flexibility of the NCC coils (see Fig. 2.2.2.2.5-2). In addition, the additional neutral beams will inject energy and torque at different tangency radii (Fig. 9.12). Altogether, the flexibility to inject torque and apply flow damping at different locations with different strengths will provide greatly expanded ability to vary flow profile and to test the influence of flow shear suppression on turbulent transport.

Building on the knowledge gained from NSTX, the NSTX-U transport and turbulence research will focus on characterizing/validating H-mode global energy confinement scaling in the lower collisionality regime, identifying the regime of validity of instabilities responsible for anomalous electron thermal, momentum and particle/impurity transport, and also on establishing and validating 0D/1D reduced transport models which are essential to the goal of projecting and optimizing the performance of future devices. In particular, being able to achieve a factor 3-6 decrease in collisionality while at high beta is one of the most important enhancements of NSTX-U compared to NSTX, allowing the access to the upper limit of collisionality of future ST-FNSF. This reduction in collisionality not only provides a unique opportunity to assess the validity of the observed ST confinement scaling on collisionality and to possibly establish a new 0D confinement scaling, but it also provides opportunities to test and improve existing 1D reduced models and to formulate new reduced models in this new regime of NSTX-U and to extrapolate to future devices. The improvement in accessible parameter regimes also makes it possible to obtain new turbulence measurements and to isolate/determine the regime of validity of the candidate instabilities in driving anomalous transport. The planned enhanced beam emission spectroscopy (BES) diagnostic ([23] and see Sec. 10.6.2.2 and Sec. 11.2.26), a new FIR high-k_θ scattering system ([24] and see Sec. 10.6.2.1 and Sec. 11.2.19), improved reflectometry (see Sec. 10.6.5.2) and polarimetry ([25] and see Sec. 10.6.2.3 and Sec. 11.2.21) diagnostics, coupled with facility enhancements of NSTX-U, will allow new turbulence and steady-state/perturbative transport measurements in a wide range of plasma conditions.

The new experimental opportunities on NSTX-U will couple to turbulence theories and reduced and first principle models in order to identify observed turbulence, to assess its parametric dependence and to identify its operational regime. The new transport and turbulence measurements in the extended parameter region of NSTX-U will naturally challenge existing theories and models and will help extending them to the new regimes and to incorporate new physics, e.g. all aspect ratio, large ExB flow shear, large magnetic shear, fully electromagnetic effects at high beta and multi-scale and global capabilities. For example, comparisons with polarimetry measurements, measured turbulence spreading, e.g. from BES, and coexistence of low-k and high-k turbulence (e.g. from BES and the FIR high-k_θ scattering system) will require electromagnetic effects, global and/or multi-scale capabilities in existing or new numerical codes. This will present a great challenge to computational resources but, on the other hand, will offer new opportunities for validating codes and improving numerical algorithms. Furthermore, as turbulence measurements become more sophisticated in NSTX-U, comparisons with numerical calculations will not be limited to transport levels but will extend to quantitative local/line-integrated multi-field fluctuation levels and fluctuation wavenumber/frequency spectra by utilizing dedicated synthetic diagnostics.

In summary, with the enhanced capabilities of NSTX-U, the planned transport and turbulence research on NSTX-U will be able to address the following important transport questions:

1. Is the ST H-mode global energy confinement scaling still valid in the low collisionality regime achievable by NSTX-U? If not, what is the new scaling in this regime and how does it compare to ITER ELMy H-mode scaling?
2. What is the regime of validity of the instabilities found to be correlated with anomalous electron thermal transport on NSTX? Do predictions from existing first principles simulations and reduced models compare well with experiments with respect to transport levels, multi-field fluctuation level and spectra?
3. Is ion thermal transport still at neoclassical level in NSTX-U H-mode plasmas in the reduced collisionality regime? What are the individual roles of E×B shear and natural shaping of ST in reducing turbulence ion thermal transport?

4. What instabilities are responsible for observed anomalous momentum transport and intrinsic torque/rotation? What is the regime of validity of these instabilities?
5. What are the roles of neoclassical physics and turbulence in driving particle/impurity transport, especially in the reduced collisionality region?

By addressing these questions, NSTX-U will further clarify the validity of the observed H-mode global energy confinement scaling in the lower collisionality regime of NSTX-U, the roles of turbulence in driving anomalous transport, coupled with which development and validation of 0D and 1D reduced models can be carried out. In this five year plan, NSTX-U transport and turbulence research aims to provide predictive capability for core ion and electron temperature profile. Building on the success of this effort, the long-term goal is to deliver a set of tools to predict temperature, plasma flow, particle/impurity profiles with given boundary conditions, e.g. from a plasma edge model of H-mode, and sources and sinks will be delivered for optimizing MHD stability (e.g. pressure and current profile) and fusion gain in order to provide a reliable projection and optimization of confinement performance of future ST-FNSF and ITER.

3.2 Overview of NSTX-U transport and turbulence research plans

Here most relevant operation scenarios and transport issues to future devices are identified and prioritized for the planning of NSTX-U transport and turbulence research, based on which we propose the three research thrusts to guide the detailed planning as presented in subsequent sections. In Sec. 3.2.3, we will briefly summarize the turbulence diagnostic capabilities of NSTX-U to support the validation effort emphasized in Thrusts TT-2 and TT-3.

3.2.1 Most relevant operation scenarios and transport issues

In NSTX-U, we will focus on the transport issues in the most relevant operational scenarios to future devices. Transport and turbulence studies in H-mode, the baseline operational scenario for both ST-FNSF and ITER, will have the priority. In particular, characterization and validation of the ST H-mode global energy confinement scaling in the low collisionality regime will be one of the most important transport studies in the first two years of NSTX-U operation, in particular to assess if the confinement scaling dependence on collisionality remains favorable and will still unify the different engineering scalings found with different wall conditioning, i.e. boronized vs lithiated PFCs. Furthermore, new transport and turbulence measurements, enabled by diagnostics and facility enhancement, and development and validation of reduced/first principle models in H-mode plasmas will also be given priority in NSTX-U. The plan is to measure thoroughly and document transport and turbulence characteristics of H-mode plasmas of NSTX-U, guided by nonlinear gyrokinetic simulations. These measurements will allow the identification of operational regimes of instabilities underlying anomalous transport and the compilation of a profile database for validation and development of reduced/first principle models. In particular, we would like to emphasize the study of electron anomalous transport and mapping out the regime of applicability of neoclassical ion thermal transport. Both are important for the determination of heating requirement for future devices. For example, understanding the ion thermal transport is important for achieving the hot-ion regime envisioned for FNSF. The dependence of ion thermal transport on plasma shaping, E×B shear and ν^* has to be determined in order to predict the required plasma shaping and flow profile for minimizing ion thermal transport in future devices.

In addition, transport and turbulence measurements in fully non-inductive and partially inductive long pulse plasmas will also be of particular importance due to their relevance to the requirement of long pulse and steady-state operation for ST-FNSF and ITER. These plasmas will have plasma current driven largely by NBI and/or RF and bootstrap current, and it is unclear how global energy confinement scaling would change in fully-relaxed plasmas and plasmas with large non-inductive current fraction, let alone the local transport and plasma turbulence. For example, the reduction or even removal of inductive electric field will significantly reduce/remove the Ware pinch effect, which will certainly enhance the role of turbulence in particle transport and thus affect the evolution of density profile and the bootstrap current. The transport and turbulence research in these scenarios will be coordinated with the scenario development as discussed in Chapter 9. Transport and turbulence research will also be emphasized in other advanced tokamak scenarios, e.g. plasmas with internal transport barrier [26] and enhanced pedestal H-mode identified on NSTX [27]. These advanced scenarios have better performance than normal H-mode plasmas and are candidate operational scenarios for future devices. Understanding their transport properties and underlying turbulence can help the achievement of these scenarios in NSTX-U and extrapolation to future devices.

While transport and turbulence studies on NSTX-U will focus on the above operation scenarios, other scenarios, e.g. RF-heated/NBI-heated L-mode and Ohmic-heated plasmas, will provide additional parameter regimes where operational turbulence could be different from that in H-mode, and thus they provide additional opportunities for testing and validating theories and models against transport and turbulence measurements and facilitate the improvement of existing models and development of new models. In particular, recent studies of NSTX NBI-heated L-mode plasmas [3] show that NSTX-U will be well positioned to address the L-mode transport shortfall found in conventional tokamaks [28].

3.2.2 Research thrusts for NSTX-U transport and turbulence research

As we have shown in previous sections, for NSTX-U, a broad range of transport issues are important in a variety of relevant operation scenarios to future devices. The plans to address these transport issues can be further organized into three overarching research thrusts that will guide our detailed planning in Sec. 3.3.

Thrust TT-1: Characterize H-mode global energy confinement scaling in the lower collisionality regime of NSTX-U

As discussed in Sec. 3.1., the ST H-mode global energy confinement scaling [5] extrapolates to much better confinement performance for future STs, e.g. ST-FNSF, than that from ITER98y,2 scaling [7]. Thus it is of great importance to investigate whether the observed H-mode global energy confinement scaling ($B\tau_E \backsim 1/\nu_e^*$) is valid in the lower collisionality regime of NSTX-U with a factor of 3-6 reduction in ν_e^*, and we particularly propose the first research thrust to addresses this important issue. The plan for this research thrust will closely follow the planned progress in NSTX-U engineering capabilities, e.g. B_T and I_p. By using regression analysis, global energy confinement scaling will be obtained from a large set of NSTX-U H-mode discharges with collisionality varied from the NSTX regime to the lower collisionality regime of NSTX-U and be compared with the existing ST energy confinement scaling. Previous studies in NSTX have shown that the reduction in electron collisionality is mainly induced by the broadening in electron temperature profile which is found to be induced by the increase in toroidal field without lithium wall coating and by the increase of the amount of lithium deposition with lithium wall coating. Studies have also shown that the global energy confinement dependence on collisionality is independent of how collisionality is varied [5], and this conclusion will be further verified by employing both techniques to vary collisionality in NSTX-U. The resulting validated global energy confinement scaling will be used to project the confinement performance of ST-FNSF.

Thrust TT-2: Identify regime of validity for instabilities responsible for anomalous electron thermal, momentum, and particle/impurity transport in NSTX-U

As we have briefly reviewed in Sec. 3.1., NSTX has made considerable progress in identifying possible mechanisms responsible for the anomalous transport observed in NSTX. In particular, multiple instabilities have been identified as potential candidates responsible for anomalous electron thermal transport, which may ultimately limit the confinement performance of future devices and thus is of critical importance. Furthermore, experiment and modeling show that low-k turbulence is likely responsible for observed anomalous momentum and impurity transport whose understanding is important for calculating flow, bootstrap current and density profile in future devices and thus is crucial for predicting and optimizing plasma stability, fusion gain, and for achieving scenario sustainment. For example, to achieve the hot-ion scenario, low-k instabilities have to be controlled by E×B shear with optimized flow profile.

Having identified many candidates, the second research thrust of NSTX-U transport and turbulence research is to identify the regime of validity for these instabilities. This involves theoretically identifying isolated regimes for the instabilities, experimental measuring turbulence and transport in these regimes, and then comparing the measured transport levels and turbulence characteristics with first principles simulations or other theoretical model predictions. Experimental parametric dependences can be used for further distinguishing different instabilities. For example, in addition to the beta and collisionality dependences discussed above, the dependence of microtearing and ETG modes on s/q and Z_{eff} are opposite to each other [29]. The enhanced capabilities of NSTX-U, i.e. increased range of collisionality (with doubled toroidal field and plasma current), doubled heating power from the 2nd NBI and active flow and current profile modification using the 2nd NBI and external and NCC coils, provides a versatile set of experimental knobs for modifying transport and turbulence which will valuable for achieving the goal of the thrust 2. In the process of achieving the thrust 2, the dependence of transport produced by the above instabilities on collisionality, plasma β and the toroidal angular velocity will be emphasized since these dependences are most relevant for the projection to future ST-FNSF. We also note that the validation of first-principles simulations and turbulence theory against experiments is essential to the achievement of the goal of Thrust 3.

Thrust TT-3: Establish and validate reduced transport models (0D and 1D)

It is important to develop reduced transport modeling capability to predict plasma profiles, which determine confinement scaling, MHD stability, and current profiles (from bootstrap and NBI/RF driven current). The validated transport models can be used in self-consistent integrated modeling scenarios to study and develop advanced operating regimes, such as steady-state fully non-inductive scenarios. Even without fully validated 1D profile predictive capability, it is useful to have 0D confinement predictions validated with observed global (0D) energy confinement scaling trends that can be used to compare with empirical scaling observations when extrapolating to future devices (e.g. ST-FNSF or Pilot).

Thrust 3 will focus on advancing the physics basis of the various instability mechanisms (as elucidated in Thrust 2) and the resulting transport they cause, which will be used to develop and improve predictive transport capability. The bulk of the research will focus on developing reduced transport models that are guided by first principles simulations for the various relevant transport mechanisms (neoclassical, drift wave, energetic particle Alfven eigenmodes). (Note, a summary of the various codes used and their unique capabilities is given in Sec. 3.4.) The highest priority focus is on electron temperature profile as so many mechanisms can potentially influence it. However, it is also important to predict density and toroidal flow profiles consistently, as they both interact with the underlying transport mechanisms. For validating turbulence theories with experimental core measurements, boundary conditions can be taken directly from measured profiles, such as near the pedestal top in H-modes. However, a truly predictive capability for projecting both 0D and 1D performance will require a predicted pedestal height and location of each plasma species (and flow for flow profiles), which will be coupled with research described in the following chapter on Boundary Physics.

3.2.3 Turbulence Diagnostic Capabilities of NSTX-U

Diagnostics	Measuring quantity	Radial coverage	Radial resolution	k coverage	k resolution
BES	$\tilde{n}_e$, density fluctuation	$r/a \gtrsim 0.1$	2-3 cm (channel spot size)	$k_\theta \lesssim 1.5\ cm^{-1}$	$\gtrsim 0.25\ cm^{-1}$
16-channel reflectometer	$\tilde{n}_e$	*Cutoff density $\lesssim 6.9 \times 10^{13}\ cm^{-3}$	*$\gtrsim 0.5\ cm$ (channel spacing)	*$k_r \lesssim 6\ cm^{-1}$	*$\lesssim 0.8\ cm^{-1}$
Polarimeter	$\tilde{B}_r$, radial magnetic field fluctuation	Line-integrated over major radius at midplane	Line-integrated	Line-integrated	Line-integrated
FIR high-k_θ scattering system	$\tilde{n}_e$	$r/a \gtrsim 0.1$	1-5 cm$^+$	$k_\theta \sim 10 - 50\ cm^{-1}$	$\sim 1\ cm^{-1}$

*Table 3.2.1: List of turbulence diagnostics planned for NSTX-U and their measurement capabilities. *Density profile dependent. + Determined by scattering volume and wavenumber.*

In Thrusts TT-2 and TT-3, we emphasized the validation of reduced/first-principle models and turbulence theories against experiments, and this requires simultaneous measurements of multi-scale, i.e. low-k and high-k, and multi-field, e.g. density and magnetic field, fluctuations. Thus multiple diagnostics need to operate simultaneously in operational scenarios of NSTX-U featuring a wide range of plasma parameters. To demonstrate that NSTX-U is well prepared in this regard, the capabilities of turbulence diagnostics planned for NSTX-U are summarized in Table 3.2.1 (more detailed description of these diagnostics can be found in Chapter 10).

As seen in Table 3.2.1, we would like to point out that the radial and wavenumber coverage and resolution of the 16-channel reflectometer will be affected by plasma density profile, e.g.

reduced radial coverage but increased radial wavenumber (k_r) coverage in high performance NSTX-U NBI-heated H-mode plasmas where density is high. The other diagnostics, namely BES [23], polarimeter [25] and the FIR high-k_θ scattering system [24], are less affected by density profile and thus can provide more radial coverage and simultaneous measurements of both low-k and high-k turbulence in high density plasmas. On the other hand, BES requires NBI and thus in RF-heated and Ohmic plasmas, we will rely on the reflectometer, polarimeter and the high-k_θ scattering system to provide multi-scale and multi-field measurements. This is possible since density is usually lower in these scenarios and the reflectometer should be able to provide good radial coverage (but with reduced k_r coverage). Overall, with the combination of planned turbulence diagnostics multi-scale and multi-field turbulence measurements will be possible for NSTX-U operational scenarios. Furthermore, with incremental funding, the implementation of Phase Contrast Imaging (PCI) and Doppler back-scattering diagnostics can be started in FY18. These diagnostics can provide the coverage of the wavenumber gap between BES ($k_\theta \lesssim 1.5\ cm^{-1}$) and the FIR high-$k_\theta$ scattering system ($k_\theta \gtrsim 10\ cm^{-1}$).

3.3 Research plans

Since NSTX-U presently is scheduled to start operation in FY 15, plans for FY 14 will be presented first. In FY 14, data analysis, modeling/simulations, diagnostic preparation and collaboration activities will be the focus, and these activities will provide solid ground for NSTX-U operation in FY15 and beyond. Then the detailed plans for each research thrust are presented: progress will be reviewed, issues will be identified and detailed plans for Year 1, 2 and long term (Year 3-4) of NSTX-U operation. As presently planned, Years 1-4 of operation correspond to FY 15-18.

3.3.1 NSTX-U transport and turbulence research plans for FY14

In FY14, transport and turbulence research activities will focus on the preparation for the initial operation of NSTX-U. One aspect of the preparation is to continue analyzing the existing database of NSTX turbulence and transport data from the BES, a k_r backscattering system [30], a high-k_r microwave scattering system [31], reflectometry and a multi-energy soft x-ray (ME-SXR) diagnostic ([32] and see Sec. 10.6.1.3 and Sec. 11.2.6). The analysis of data and comparisons with gyrokinetic simulations will improve understanding of the relation between turbulence and transport and will also be help us identify possible experiments on NSTX-U. In addition, the data analysis will also help us prepare data analysis tools for NSTX-U, e.g. BES synthetic diagnostics, high-k_μ scattering system scattering volume calculation and a neural network for fast T_e profile analysis using ME-SXR data.

Another important task in FY14 is to prepare turbulence and transport diagnostics for NSTX-U. Integrated bench testing of the FIR high-k_θ scattering system with FIR laser and detectors will be carried out. Sixteen more detecting channels for the BES diagnostic will be installed and calibrated to increase the total number of channels to 48 for use on NSTX-U for the coming run campaigns. A one-channel microwave polarimetry system will be moved from DIII-D (originally from NSTX) to be installed on NSTX-U. Further optimization of the ME-SXR diagnostic design for NSTX-U will also be carried out with the help of an ongoing collaboration with EAST tokamak. Collaboration with FTU tokamak on high-Z impurity transport using an upgraded Transmission Grating Imaging Spectrometer will also occur.

In FY 14, further simulations and modelings for NSTX and NSTX-U will be carried out, e.g. to predict T_e and T_i profiles in a variety of NSTX scenarios with the transport code (P)TRANSP [33] and the transport solver TGYRO [34] and to predict the turbulent transport in NSTX-U (e.g. using the GTS code [35] with kinetic electrons). More details of the planned simulation and modeling activities can be found in the 2014 plans for Thrust TT-3 in Sec. 3.3.4.2.

3.3.2 Thrust TT-1: Characterize H-mode global energy confinement scaling in the lower collisionality regime of NSTX-U

A global energy confinement scaling with strong inverse dependence on collisionality has been established for STs [2,4,6]: $B\tau_E \backsim 1/\nu_e^*$ (see Fig. 3.3.1), while the ITER scaling on collisionality is much weaker: $B\tau_E \backsim \nu_e^{*-0.01}$[7]. The ST confinement scaling leads to an order magnitude of

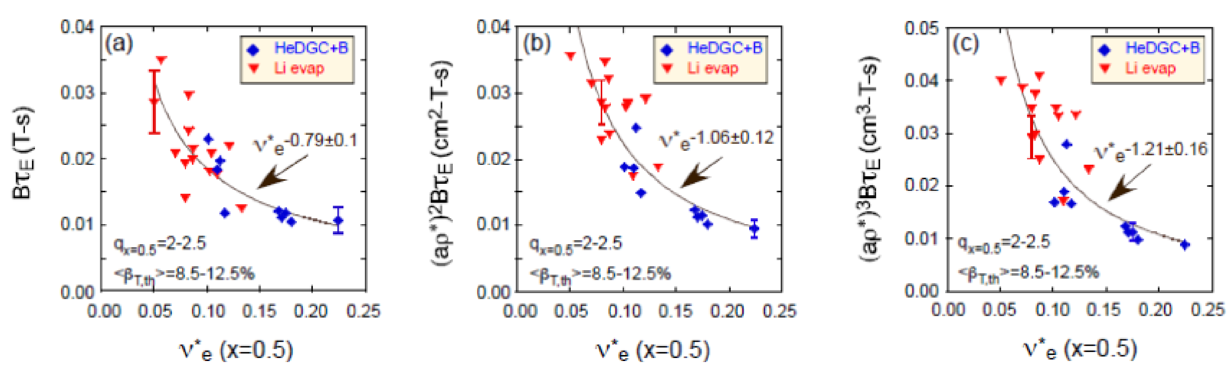


Fig. 3.3.1. Normalized confinement time as a function of collisionality at ρ=0.5 for the ν_e^* scan for assuming (a) $B\tau_E \sim \rho_*^0$, (b) Bohm scaling, $B\tau_E \sim \rho_*^{-2}$ and (3) gyroBohm scaling, $B\tau_E \sim \rho_*^{-3}$. Blue points are from discharges that used HeGDC+B wall conditioning, while red points are from discharges that used Li evap. Discharges from the above scans were constrained to have minimal variation in $q_{r/a=0.5}$ (2-2.5) and $\langle\beta_T\rangle$ (8.5-12.5%). Note that to account for the variation in ρ_*, scalings were also determined assuming either a Bohm ($B\tau_E \sim \rho_*^{-3}$) or gyroBohm ($B\tau_E \sim \rho_*^{-3}$) dependence. Stronger dependence with collisionality, $B\tau_E \sim \nu_e^{*-1.06}$ and $B\tau_E \sim \nu_e^{*-1.21}$, is found for Bohm and gyroBohm scaling assumptions.

improvement in projected performance of ST-FNSF in contrast to that from the ITER scaling as seen in Fig. 1.1.4. Furthermore, as seen in Fig. 3.3.1, this ST global energy confinement scaling is seen to be independent of wall conditioning, either using Helium Glow Discharge Cleaning plus occasional boronization for wall conditioning (HeGDC+B) or between-shot lithium conditioning of the vessel walls through evaporation from two LITERs (LIThium EvapoRators) mounted at the top of the NSTX vessel [5]. This collisionality dependence also unifies the different engineering scaling observed with different wall condition: $\tau_{E,th} \sim Ip^{0.37}B_T^{1.01}$ for HeGDC+B wall conditioning and $\tau_{E,th} \sim Ip^{0.79}B_T^{-0.15}$ for lithium wall conditioning [5] with the latter scaling similar to those in conventional aspect ratio tokamaks, as embodied in the ITER98y,$_2$ scaling [7] with a strong I_p dependence and a weak B_T dependence. This unification implies that collisionality is more fundamental in determining energy confinement and the difference in engineering scalings comes from what engineering parameter collisionality is correlated with. Indeed, it is found that with HeGDC+B wall conditioning, reduction in collisionality is mostly correlated with the increase in B_T and on the other hand, when lithium is used for wall conditioning, reduction in collisionality is correlated well with increase in amount of lithium deposition.

In the research plan for the Thrust TT-1, we are planning to carry out extensive studies of the ST H-mode global energy confinement scaling in the first two years of NSTX-U operations utilizing the full capabilities of NSTX-U to achieve lower collisionality with the different wall conditioning technique, and the emphasis will shift to H-mode confinement scaling in long-pulse and fully non-inductive scenarios in the rest 3 years.

3.3.2.1 Research plans by year for Thrust TT-1

Year 1

The baseline global energy confinement scaling for NSTX-U will be re-established in the first year of operation for comparison with previously observed NSTX scaling (B_T/I_p<0.55 T/1.2 MA). Confinement time scaling will then be extended to higher field strength and plasma current (with operational goals of $B_T/I_P \leq 0.8$ T/1.6 MA) for modest duration discharges (~1-3 seconds) as these engineering improvements become available. This extension in I_p, B_T (and increased NBI power from day one) will allow us to attain lower ν_e^* to assess the validity the favorable confinement ($B\tau_E \backsim 1/\nu_e^*$) scaling in the lower collisionality regime. Of particular interest will be determining the I_p and B_T scaling and how they compare to the different scalings found on NSTX depending on wall conditioning technique (HeGDC+B vs. lithiated) as discussed above.

Year 2

In the second year of NSTX-U, the confinement time scaling will be extended to the full field strength and plasma current (with operational 1.0 T/2 MA) which, together with increased NBI, will allow us to attain the lowest ν_e^* values to verify the range over which favorable confinement ($B\tau_E \backsim 1/\nu_e^*$) scaling occurs and whether a roll-over at lowest ν_e^* is found. The expanded empirical confinement scaling will be used to begin projecting 0D performance for relevant next generation STs, e.g. FNSF, Pilot. Select discharges from the expanded confinement database, especially those that have the most complete profile and turbulence diagnostic coverage used for validation studies in Thrust TT-2, will provide the basis for a 1D profile database for testing the development of reduced transport models (Thrust TT-3).

The confinement scaling trends will be separated into both core (W_{core}) and pedestal (W_{ped}) contributions to better understand the relative importance of each in setting the overall I_p, B_T, and ν_* scalings. W_{ped} will be determined from Thomson scattering system with improved edge resolution [36] and CHERS system [37].

Years 3-4

In later years the confinement scaling will be characterized (i) for longer duration discharges that approach the engineering limit (~5 s), (ii) for advanced scenarios, e.g. fully non-inductive discharges, as they are developed (outlined in Sec. 9.2.1), and (iii) for varying PFC wall boundary conditions (sec. 5.3). It will be important to re-confirm the empirical scaling in long-pulse and fully non-inductive advanced scenarios, or if necessary, develop empirical scaling appropriate for refining 0D performance predictions to FNSF or Pilot that are based on the most relevant NSTX-U discharge scenarios.

As steady-state density control using cryopump is implemented in NSTX-U in this time period, we are planning to investigate ρ_* scaling of confinement and transport, which for constant q, β and ν_e^* requires that density vary like $n \sim \rho^{*-2}$. Therefore, to achieve a variation in ρ^* of 1.7 (similar to DIII-D experiments [38]), density will need to be varied by a factor of 3. These ρ^* experiments will help to clarify whether ST confinement scaling follows Bohm or gyroBohm expectations, which influences the inferred strength of the ν_e^* scaling discussed above. It will also test whether turbulence correlation lengths and times follow gyroBohm scaling expected from local drift wave theories. These experiments, coupled with simulations, will provide a more direct measure of the relative importance of non-local effects in STs that should become weaker at smaller ρ^*. If such non-local effects are shown to be important, they will have to be accounted for in associated predictive transport modeling (see Thrust TT-3).

3.3.3 Thrust TT-2: Identify regime of validity for instabilities responsible for anomalous electron thermal, momentum, and particle/impurity transport in NSTX-U

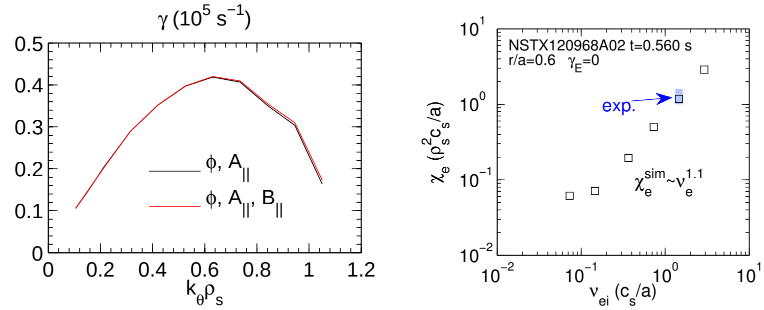


Fig. 3.3.2 (a) Converged linear microtearing growth rate spectra with and without compressional magnetic perturbations ($B_{||}$); (b) Normalized electron thermal diffusivity vs. normalized electron collision frequency (log-log scale). The shaded region shows the experimental values with uncertainties. All calculations are based on an NSTX H-mode plasma using GYRO code (see Sec. 3.4.1.1. for more information about GYRO).

3.3.3.1 Electron Thermal Transport

Electron thermal transport will likely pose the ultimate limit to the confinement performance of future devices. For example, electron heating will be dominant in ITER discharges, and efficient heating of fuel ions by electrons requires good electron thermal confinement. It is well established in NSTX that although ion thermal transport could be reduced to neoclassical level in a variety of operation scenarios [4], electron thermal transport is consistently anomalous. Up to now, a universal mechanism for explaining anomalous electron thermal transport is out of reach, and there is good indication that perhaps there is no unique one. It is likely that anomalous electron thermal transport is driven by different instabilities in different parameter regimes, i.e. in different operation scenarios and radial regions.

A recent breakthrough in understanding anomalous electron thermal transport is the identification of the importance of electromagnetic effects in driving electron thermal transport in outer half of a set of NSTX high beta H-mode plasmas through state-of-art nonlinear gyrokinetic simulations [19,20]. Microtearing modes are shown to be linearly unstable [Fig. 3.3.2(a)] and predicted transport varies with collisionality in a manner consistent with that observed in experiments [Fig. 3.3.2(b)]. It is also shown that experimentally relevant electron thermal transport is driven almost exclusively through the stochastic magnetic field.

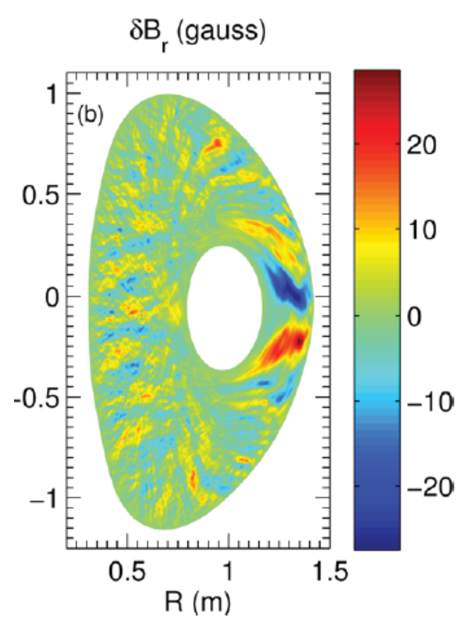


Fig. 3.3.3. δB_r (in Gauss) in a (R,Z) toroidal plane from a nonlinear microtearing simulation of a NSTX H-mode plasma using GYRO code.

Further parametric scans demonstrate that the s/q, Z_{eff}, β and collisionality dependences of microtearing modes are different to those of ETG modes [29], which provides a potential way for distinguishing between them experimentally. Given the strong collisionality dependence of microtearing modes, their importance in the low collisionality regime of NSTX-U and future devices is unclear. Fortunately, the large scale (n~10) magnetic fluctuations associated with microtearing modes (Fig. 3.3.3) make it possible to measure magnetic fluctuations directly through Faraday rotation effects. A polarimetry diagnostic will be installed on NSTX-U at beginning of its first run campaign (see Table 3.2.1 and more details in Chapter 10) and is shown to be sensitive enough to measure magnetic fluctuations from microtearing modes through a synthetic diagnostic [25,39].

In addition to microtearing modes, other ion scale ballooning instabilities could also play important roles in determining electron thermal transport in high beta H-mode plasmas. It is found that in NSTX low collisionality H-mode plasmas, a microtearing instability is usually subdominant to a ballooning instability [see Fig. 3.3.4 (top)]. The ballooning instability exhibits characteristics very similar to a TEM: driven unstable by electron density and temperature gradients (a/L_n, a/L_{Te}), weakly dependent on ion temperature gradient (a/L_{Ti}), and strongly stabilized by increasing collisionality (ν_{ei}) [see Fig. 3.3.4 (middle)]. However, unlike a traditional electrostatic TEM instability, this mode is extremely sensitive to β_e with the appearance of an effective threshold ($\beta_{e,crit}$~0.8%) similar to that expected for a KBM instability. The fact that the scaling of the growth rates are unified by the MHD alpha parameter [see Fig. 3.3.4 (bottom)], $\alpha_{MHD}=-q^2R\nabla\beta$ [where $\beta=\Sigma(n_sT_s)\cdot 2\mu_0/B^2$], highlights the KBM nature of the instability, so we refer to it as a “hybrid” TEM/KBM [21]. Similar KBM behavior has been

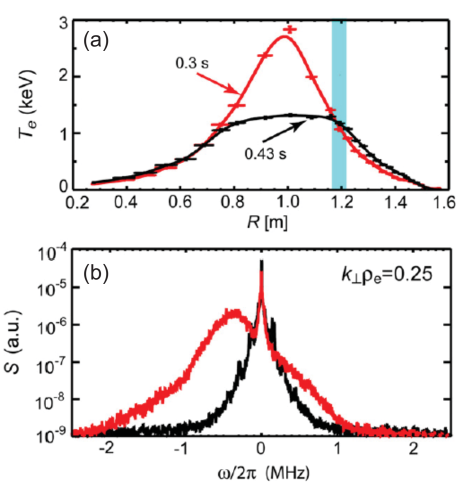


Fig. 3.3.5. Temperature profiles (a) and spectral density of fluctuations (b) at 0.3 (red) and 0.43 s (black). The blue stripe indicates the location of measurement where L_{Te} is 15 cm and 50 cm, respectively. Negative frequencies (b) correspond to wave propagation in the electron diamagnetic direction.

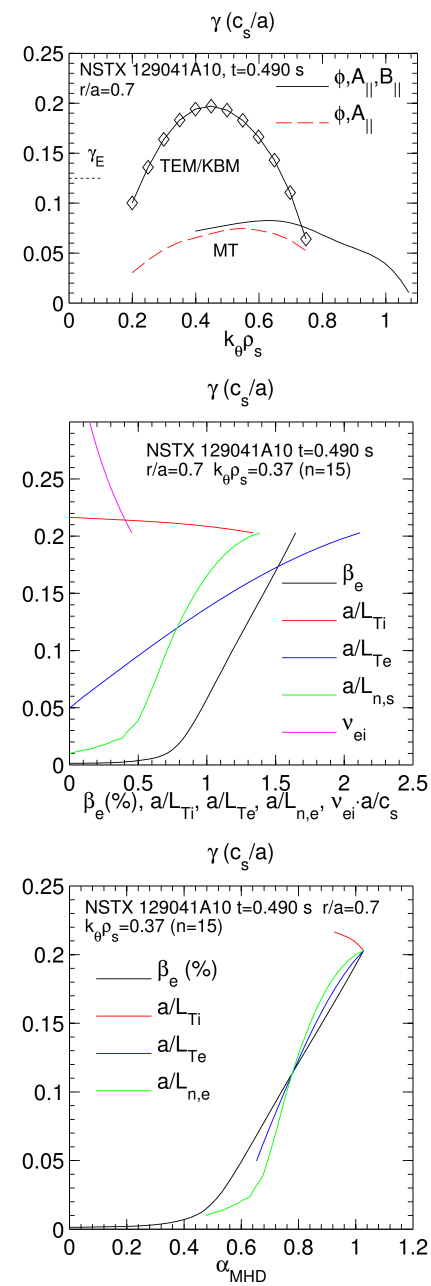


Fig. 3.3.4. (top) Linear spectra of overlapping MT and KBM/TEM instabilities. (middle) Scaling of ballooning mode growth rate with β_e, a/L_{Ti}, a/L_{Te}, a/L_n, ν_{ei}. (Bottom) Ballooning growth rates vs. α_{MHD}.

predicted in GS2 simulations near the top and inside of the pedestal region [40]. Parametric studies in NSTX-U low collisonality H-mode plasmas coupled with gyrokinetic simulations and the BES/polarimetry diagnostics will further clarify the role of these TEM/KBM instabilties in driving electron thermal transport.

Electron-scale turbulence has long been considered as a potential candidate in driving electron thermal transport, i.e. ETG turbulence [41], and its correlation with electron thermal transport has been observed in NSTX. Electron-scale turbulence has been identified in NSTX by using a high-k_r microwave scattering system [31] to measure changes in electron-scale turbulence when the local electron temperature gradient was varied by RF heating in NSTX L-mode plasmas [42]. Figure 3.3.5(a) shows large T_e gradient at the measurement region of high-k scattering system with RF heating (red) and much smaller T_e gradient after RF is turned off (black). In Fig. 3.3.5(b) the appearance of the scattered signal (denoted by the off-center spectral peak shown in red) is correlated with the large T_e gradient. In particular, the appearance of electron-scale turbulence is found to be correlated with the electron temperature gradient exceeding the critical gradient predicted for ETG modes.

Studies of parametric dependences of observed electron-scale turbulence show gross agreement with those of ETG modes. It is observed that ExB shear could stabilize electron scale turbulence when ETG modes are marginally unstable and ExB shearing rate is comparable to ETG growth rate [43]. Suppression of electron-scale turbulence is found in NSTX reserved-shear plasmas with electron internal transport barrier (eITB) and is correlated with large reversed magnetic shear and the formation of eITB [16]. Numerical simulations have shown that the large T_e gradient observed in eITB is shown to be consistent with the reversed-shear-induced nonlinear up-shift of critical T_e gradient for ETG-driven electron thermal transport [17]. Electron-scale turbulence is also found to be stabilized by density gradient, which consistent with increased linear threshold of ETG modes by density gradient, and the observed reduction in electron turbulence is correlated with decrease in electron thermal transport [44] (see Fig. 3.3.6). Nonlinear gyrokinetic ETG simulations reproduce consistent density gradient

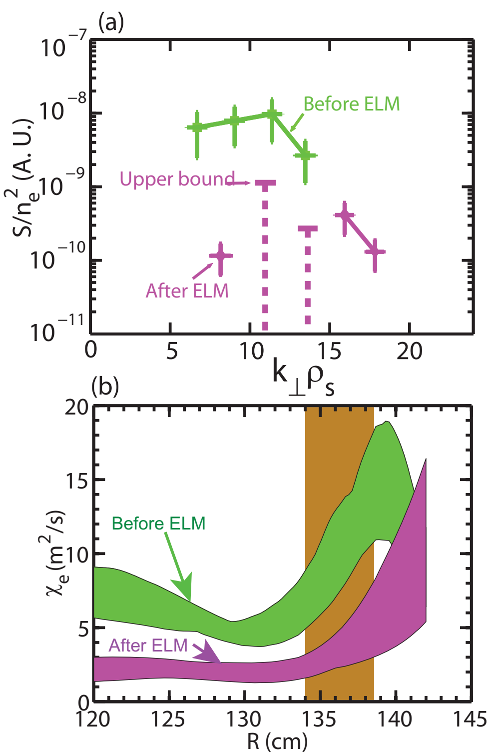


Fig. 3.3.6. An ELM event leads large density gradient in the high-k measurement region [vertical bar shown in (b)] after ELM. (a) The normalized scattered power $k_\perp$ spectra in arbitrary unit before and after ELM; (b) $\hat{A}_e$ radial profiles before and after ELM. $\hat{A}_e$ in the high-k measurement region is reduced after ELM.

dependence on both turbulence and transport [18]. On the other hand, an experimental collisionality scan shows that electron thermal transport and measurement electron-scale turbulence spectral power seem to be anti-correlated, and nonlinear gyrokinetic simulations only show consistent electron heat flux at one location but not across wider radius [18]. Linear stability analysis and nonlinear simulations have shown that ETG mode growth rates and saturation level are sensitive to small profile variations, particularly q and density gradient [18]. It is important to point out that the high-k scattering system used in these experiments could not capture the predicted spectral peak of predicted ETG turbulence, let alone determining the existence of ETG streamers which are predicted to be important for driving electron thermal transport. The new high-k_θ FIR scattering system has been designed to do both [24] (see Table 3.2.1 and Chapter 10 for details).

Alfven eigenmodes (GAE/CAE) are found to be potentially important for electron thermal transport in the core (r/a<0.4) of NSTX high-power NBI H-mode plasmas. This electron thermal transport mechanism is potentially important for ITER since fusion α particles in ITER may drive AE activities and thus could lead to degraded electron thermal confinement. The Alfven eigenmodes are excited by fast particles from NBI due to their super-Alfvenic velocity. In a set of H-mode plasmas, flattening of central electron temperature profile is observed as NBI power is increased from 2 MW to 6 MW with increased AE activity indicated by Mirnov coil measurements [13]. Power balance analysis using TRANSP clearly shows about a factor of 10 increase in electron thermal diffusivity with increased AE activities. A reduced model based on electron drift orbit stochasticity in the presence of multiple core localized AE produces a steep dependence of electron thermal transport on AE amplitude ($\propto \alpha^6$, where α represents the mode amplitude), and experimentally relevant electron thermal transport is predicted by using measured mode amplitude and assumed mode structure using ORBIT code [45] (see section

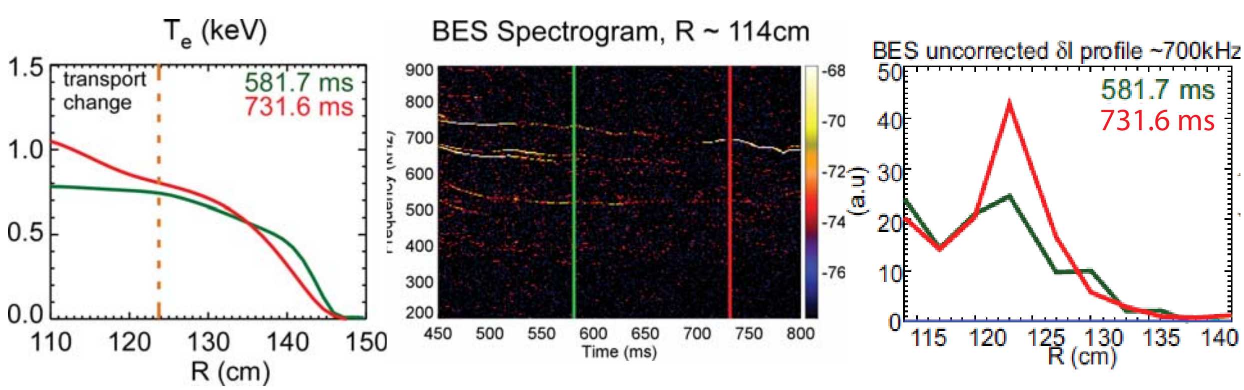


Fig. 3.3.7. (Left) T_e profiles at two time points of interest with different central peaking; (Middle) BES spectrogram at R~114 cm with times of interest denoted by lines with same color codeing in the left panel; (Right) Radial structure of dominant AE frequency at about 700 kHz. Note that the existence of a single dominant mode at t=732 ms (red) shown [see the middle and right panels] corresponds to a peaked T_e profile and a flat central T_e profile corresponds to the existence of multiple modes at t=582 ms (green) shown in the middle panel but with smaller amplitude (see the right panel), which is consistent with ORBIT simulations that multiple AEs are required to generate stochastic electron thermal transport.

3.3.4 for more discussions on reduced model validation and development). Recent measurements from BES diagnostic support that multiple AEs are needed for producing anomalous electron thermal transport (see Fig. 3.3.7). Since a first principle model is not available, experimental investigation of the mode structure and amplitude and their dependence on toroidal field, plasma current and fast particle energy/population has to been carried out to assess the characteristics of these modes in future devices. In parallel, the measured calibrated BES mode structures will be used in future ORBIT simulations to compare predicted electron thermal transport with that from experiments. These experimental studies will also facilitate the development of first-principles and reduced transport models.

In general, NSTX L-mode plasmas (NBI/RF-heated) provide additional parameter regimes where mechanisms for electron thermal transport are different from those in H-mode plasmas and thus provides opportunities for validating theories and models in extended parameter regimes. NSTX L-mode plasmas have suggested additional mechanisms for anomalous electron thermal transport. Experimental observations in a set of NSTX NBI-heated and center-stack-limited L-mode plasmas indicates that ITG modes can drive both electron and ion thermal transport [3]. The increase of the ratio between the ExB shearing rate and the maximum linear growth rate for ITG modes, $\omega_{E\times B}/\gamma_{max}$, is found to be correlated with the reduction in thermal transport in both electron and ion channels, consistent with ExB shear stabilization of ITG turbulence [46,47] (see Fig. 3.3.8, where both the Hahm-Burrell ($\omega_{\mathrm{E\times B,HB}}$) [48] and Waltz-Miller ($\omega_{\mathrm{E\times B,WM}}$) [49] E×B shearing rates are shown). In particular, ion thermal transport is found to be reduced to 2-3 times of neoclassical level when ExB shear stabilization is large enough. Further nonlinear gyrokinetic studies of NSTX NBI-heated L-mode plasma show that future studies of L-mode plasmas in NSTX-U can contribute to the L-mode transport shortfall found in conventional tokamaks [28].

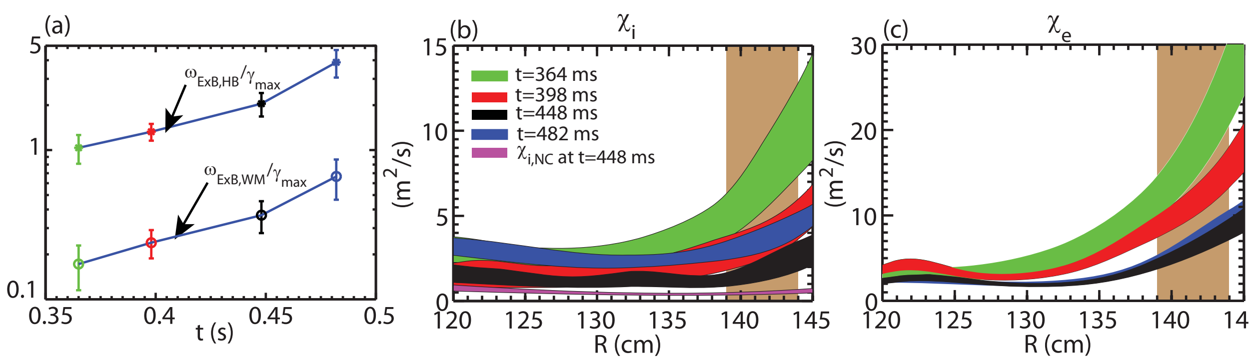


Fig. 3.3.8. (a) The ratio between the ExB shearing rate and the maximum linear growth rate for ITG modes; (b) Radial profiles of ion thermal diffusivity, χ_i, at at the same time points as in (a) and radial profile of neoclassical ion thermal diffusivity at t=448 ms (magenta); (c) Radial profiles of electron thermal diffusivity, χ_e. Note that the width of the colored regions denotes the experimental uncertainty. The width of rectangular shaded region denotes the high-k measurement region. Both χ_i and χ_e in the high-k measurement region continuously decrease from t=364ms to 448 ms as $\boldsymbol{\omega_{E\times B,WM}}$ increases from about 0.2 to 0.4, and the increase of χ_i (and invariance in χ_e) from t=448 ms to 482 ms is correspondent with increased MHD activities.

The above NSTX research on electron thermal transports signifies the importance of identifying the regime of validity of each potential instability, which is required for validating/developing existing/new reduced models.

3.3.3.1.1 Research plans by year for Thrust TT-2: Electron thermal transport

Year 1

The first year of electron thermal transport research is planned according to the timeline for diagnostic and facility upgrades (see the last section of this chapter). Low-k diagnostics (BES, reflectometry and polarimetry) will be installed and will be fully functioning at the beginning of the first NSTX-U run campaign, and the study of electron thermal transport will focus on measurements of low-k turbulence with these diagnostics in H-mode plasmas in the first year of NSTX-U operation. One key physics question is to identify dominant modes in the lower collisionality high beta H-mode plasmas of NSTX-U. Turbulence measurements will be carried out in the experiments addressing Thrust TT-1. Variation in low-k turbulence will be documented as ν_e^* is varied and will be correlated with energy confinement scaling trends. In particular, an assessment will be made on whether density (from BES) or magnetic fluctuations (from polarimetry) correlate better with electron thermal transport. Furthermore, the BES diagnostic is also able to provide zonal flow measurements, which provides an opportunity to study the parametric dependence of zonal flow and its interplay with low-k turbulence. In addition, the unification of engineering scalings with different wall conditions (without and with lithium) by ν_e^* global confinement scaling will be assessed with low-k turbulence measurements. Linear/nonlinear gyrokinetic simulations will be used to identify responsible modes and compare global confinement trend with experiments, and turbulence characteristics will be compared with low-k turbulence measurements (via synthetic diagnostics). Low-k turbulence measurements will also be carried out in microtearing-dominant regimes, e.g. in high β and collisionality H-mode plasmas, with the guidance from gyrokinetic simulations, and change in low-k turbulence will be documented as plasma parameters are varied into and out of the isolated regime, e.g. by lowering collisionality and active q (magnetic shear, $\hat{s}$) and flow profile (E×B shear and parallel velocity shear) variations using the 2nd NBI and existing external 3D coils.

AE (CAE/GAE) mode structures will be measured using calibrated BES/reflectometry with a range of B_T, I_p, collisionality and NBI power in NSTX-U H-mode plasmas, and the measured mode structure and amplitude will be used in ORBIT simulations to assess predicted electron thermal transport in comparison with measured electron thermal transport trends with B_T, I_p, collisionality and NBI power. Polarimetry measurements of line-integrated CAE/GAE magnetic fluctuations will provide a strong constraint on the magnetic fluctuation amplitude inferred from BES/reflectometry density fluctuation measurements.

Year 2

In the second year of NSTX-U, the confinement time scaling will be extended to the full field strength and plasma current attaining even lower ν_e^* values. Similar to the plan of year 1, low-k turbulence changes will be documented as NSTX-U achieves lower ν_e^* (compared to year 1) and will be compared with linear/nonlinear gyrokinetic simulations. The new FIR high-k_θ scattering system will be installed in the first year of NSTX-U operation, and the commissioning the complete system will be carried out in the second year. Preliminary high-k measurements together with low-k turbulence measurements in ETG-dominant regime, e.g. low β and low Z_{eff} H-mode plasmas and L-mode plasmas with eITB, guided by gyrokinetic simulations will be made, and correlation with electron thermal transport will be assessed. In particular the 2nd NBI and external coils will be used to study the dependences of ITBs (both electron and ion ITBs) formation on q, $\hat{s}$ and ExB shear.

A laser-blow off system will become available in FY16 and preliminary experiments of cold pulses propagation from non-recycling impurity injection, coupled with fast T_e measurements from a multi-energy SXR system, will be conducted in both H and L-mode plasmas to study profile stiffness and corresponding change in measured turbulence will be documented. Measurements will be carried out in isolated regimes for low-k modes, e.g. ITG/TEM dominant discharges (in NBI and RF-heated L mode plasmas) with the guidance from gyrokinetic simulations. Active q and flow profile variations using the 2nd NBI and external coils will be used to identify parametric dependence of transport and turbulence. Nonlinear gyrokinetic simulations of these L-mode plasmas will help clarify the L-mode transport shortfall problem in conventional tokamaks [28]. Studies of AE (CAE/GAE) mode will continue with the improved capabilities of NSTX-U. Furthermore, a row of high-Z divertor title will be available in this year, and its effects on electron thermal transport will be investigated.

Years 3-4

The plan for the year 3-4 of electron thermal transport research is made to fully utilize the improved diagnostics and facility upgrades, in particular the high-k scattering system, the laser blow-off system, cryopump for density control and improved reduced/first-principle models and developed synthetic diagnostics, e.g. for the high-k scattering system. The emphasis in years 3-4 is to identify operational regimes of ETG, microtearing and AE (CAE/GAE) modes using the high-k_θ scattering system, the BES, reflectometry and polarimetry measurements with full range of NSTX-U parameters, improved capabilities of varying plasma parameters/profiles [using the 2nd NBI, external coils (and NCC when available) and cryopump] and PFC/divertor condition (different PFC/divertor materials and reduced recycling regime with litihum deposition). Transport and turbulence characteristics dependence on collisionality, plasma β and flow profile will be particularly emphasized. Both steady-state/perturbative transport measurements will be conducted. In particular, cold pulse propagation experiments together with active profile variation from 2nd NBI and external/NCC coils will allow us to address: 1) the dependences of stiffness of electron thermal transport on q, $\hat{s}$ and ExB shear, 2) the identification of responsible turbulence. The turbulence and transport measurements will be compared with interpretative and predictive gyrokinetic simulations/reduced models and synthetic diagnostics in order to identify the operational turbulence and assess its regime of validity. Identifying responsible turbulence for electron thermal transport in long-pulse and fully non-inductive scenarios will be particularly emphasized in the years 3-4.

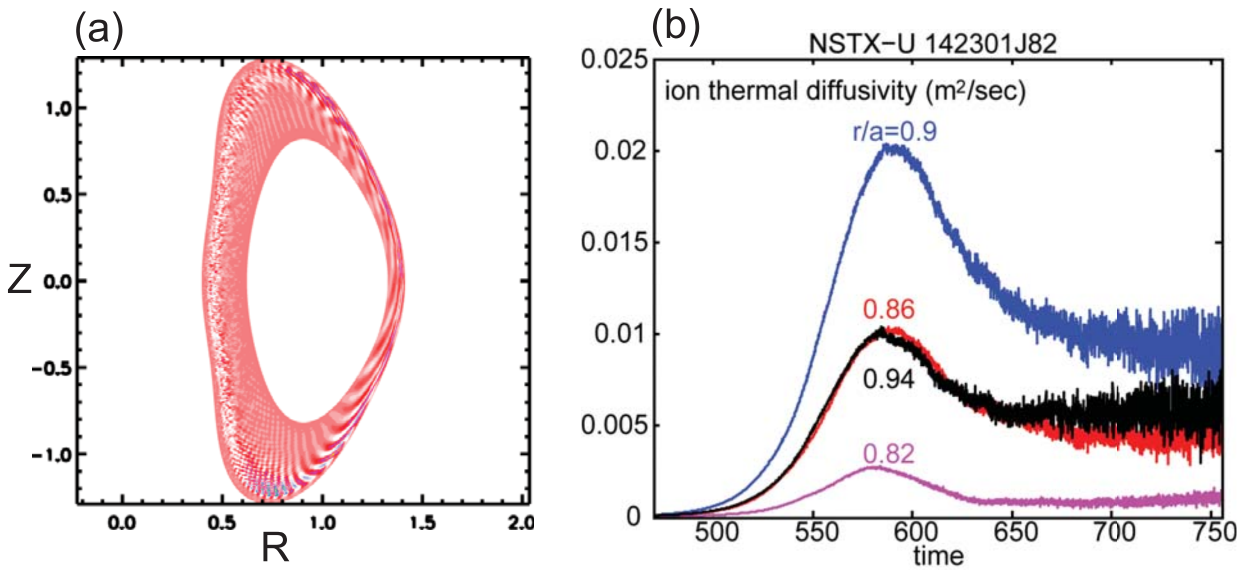


Fig. 3.3.9. Nonlinear gyrokinetic ITG simulation for predicted NSTX-U H-mode plasmas using GTS code. (a) Density fluctuation in (R,Z) plane; (b)Ion thermal diffusivity time evolution at four ITG unstable locations.

3.3.3.2 Ion Thermal Transport

The near-neoclassical level of ion thermal transport in NSTX H-mode plasmas is one of the most important observations made on NSTX [4]. This is consistent with theoretically predicted E×B shear and plasma shaping stabilization of low-k turbulence and has been used to predict ion temperature profiles in NSTX-U scenario development (see Chapter 9 and Ref. [50]). Since neoclassical ion thermal transport will be greatly reduced in NSTX-U and future devices, it is important to determine experimentally in what regime ion thermal transport remains predominantly neoclassical, and its dependence on plasma shaping and E×B shear. This is important since identifying the needed E×B shear and shaping to minimize ion thermal transport in future devices is essential for achieving the envisioned hot-ion regime for ST-FNSF. A numerical prediction of ion thermal transport using GTS gyrokinetic code [35] and predicted NSTX-U H-mode profiles shows negligible turbulent ion thermal transport driven by ITG modes more than 100 times smaller than neoclassical diffusivity ($\chi_{i,neo}$≈1.6 m^2/s at r/a=0.9) (see Fig. 3.3.9), where flow shear was found to play a small role. However, adiabatic electrons were used in the simulation, and it is possible that trapped electrons may enhance ITG/TEM/KBM modes to drive more ion thermal transport.

Indeed, collisionality scans in NSTX H-mode plasmas shows an increase in ion thermal diffusivity relative to neoclassical values as collisionality is reduced (see Fig. 3.3.10 and Ref. [5]). As shown in Fig. 3.3.8, ITG modes can play an important role in determining ion thermal transport in NSTX L-mode plasmas, and thus L-mode plasmas provides additional opportunities for turbulence and transport measurements and for validating reduced/first-principle models for ion thermal transport.

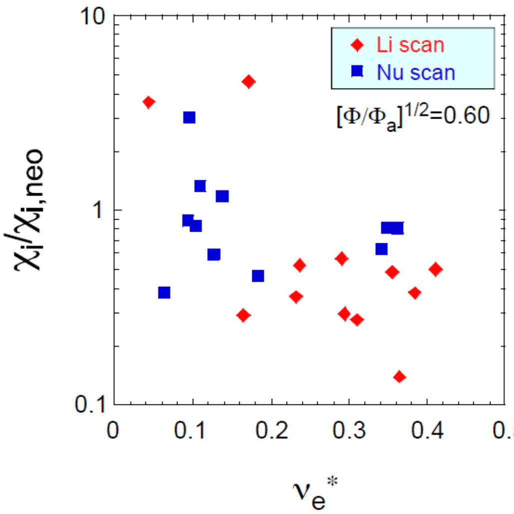


Fig. 3.3.10. Ion thermal diffusivity, χ_i, normalized to the neoclassical ion thermal diffusivity as determined by NCLASS as a function of electron collisionality at ρ=0.6.

3.3.3.2.1 Research plans by year for Thrust TT-2: Ion thermal transport

Year 1

In the first year of NSTX-U operation, χ_i will be determined through power balance analysis in the experiments addressing Thrust TT-1 where lower collisionality H-mode plasmas will be achieved with the extended range of B_T and I_p, and observations will be compared with neoclassical calculations, e.g. using NCLASS[51]/GTC-NEO[52]/NEO[53]. The $\chi_i/\chi_{i,neo}$ as a function of ν_e^* will be evaluated to determine if the trend observed in Fig. 3.3.10 is still valid in the lower ν_e^* H-mode regime of NSTX-U. In addition, to further assess how ion thermal transport is related to low-k turbulence, the 2nd NBI and external coils are to be used to vary q (magnetic shear, $\hat{s}$) and flow profiles (E×B shear and parallel velocity shear) particularly in low collisionality H-mode plasmas where ion thermal transport was found to be more anomalous, and we will determine if observed change in ion thermal diffusivity is correlated with low-k turbulence measurements from BES, reflectometry and polarimetry. Comparison with nonlinear gyrokinetic simulations on both determined transport trend and measured turbulence through synthetic diagnostics will be carried out.

Year 2

The study of $\chi_i/\chi_{i,neo}$ as a function of ν_e^* will continue in the second year of NSTX-U operation as NSTX-U operation is extended to the full field strength and plasma current attaining the lowest ν_e^* values. Combinations of applying the 2nd NBI and external coils will be explored to reduce ion thermal transport to neoclassical level in the lowest ν_e^* regime. Furthermore, ion thermal transport and low-k turbulence will be measured in isolated regimes for ITG/TEM modes, e.g. in NBI and RF-heated L mode plasmas, with the guidance from gyrokinetic simulations, and modification of q and flow profiles ($\hat{s}$, E×B shear) by the 2nd NBI and external coils will be used to vary the strength of anomalous ion thermal transport and low-k turbulence. In particular, L-mode plasmas with ion ITB will be be used to study the dependences of ion ITB formation on q, $\hat{s}$ and ExB shear. These experimental measurements will be used to validate gyrokinetic codes, and in particular, the L-mode transport shortfall problem [28] will be addressed.

Year 3-4:
In the years 3-4 of NSTX-U operation, we will continue the investigation of the parametric dependence of $\chi_i/\chi_{i,neo,}$ e.g. on β, ρ^*, T_i/T_e and $Z_{eff,}$ expanded beyond B_T, I_p, collisionality, $\hat{s}$ and E×B shear dependences studied in previous years. In particular, the dependence on plasma β will be emphasized. Coordinated with experiments planned to address confinement scaling in fully relaxed and fully non-inductive scenarios, these parametric dependences will also be investigated in these advanced scenarios to form an extensive database. Such a database will allow us to identify relevant low-k turbulence (ITG/TEM/KBM) to ion thermal transport and their operational regime and also provides validations to gyrokinetic codes and reduced models. Again, combinations of applying the 2nd NBI and external 3D coils/NCC will be investigated to reduce ion thermal transport to neoclassical level.

3.3.3.3 Momentum Transport

To project confinement performance of future devices, predicting flow profile is of great importance since E×B shear is known to play an important role in stabilizing low-k turbulence and thus affects both electron and ion thermal transport, e.g. see Fig. 3.3.8. Flow profile projection requires the knowledge of momentum source and transport, e.g. intrinsic torque, diffusivity and pinch. While NBI-heated plasmas have dominant external momentum injection from NBI that can be calculated with reasonable accuracy, the intrinsic torque driven by plasma turbulence is not well understood and its prediction is of particular importance to ITER, which will have small external torque input. In addition to knowing the sources, predictions of momentum diffusivity and pinch are required, and this is particularly important for ST-FNSF where externally input torque by NBI will be the dominant momentum source.

Momentum transport has been studied in both NSTX NBI-heated L and H-mode plasmas and was found to be anomalous in both scenarios (see Fig. 3.3.11 and note that the neoclassical mechanism essentially provides no momentum transport), in contrast to the fact that ion thermal transport is close to neoclassical level in NBI-heated H-mode plasma and is anomalous in NBI-heated L-mode plasmas [2]. The anomalous momentum transport and neoclassical ion thermal transport in NBI-heated H-mode plasmas indicate that some residual low-k turbulence is

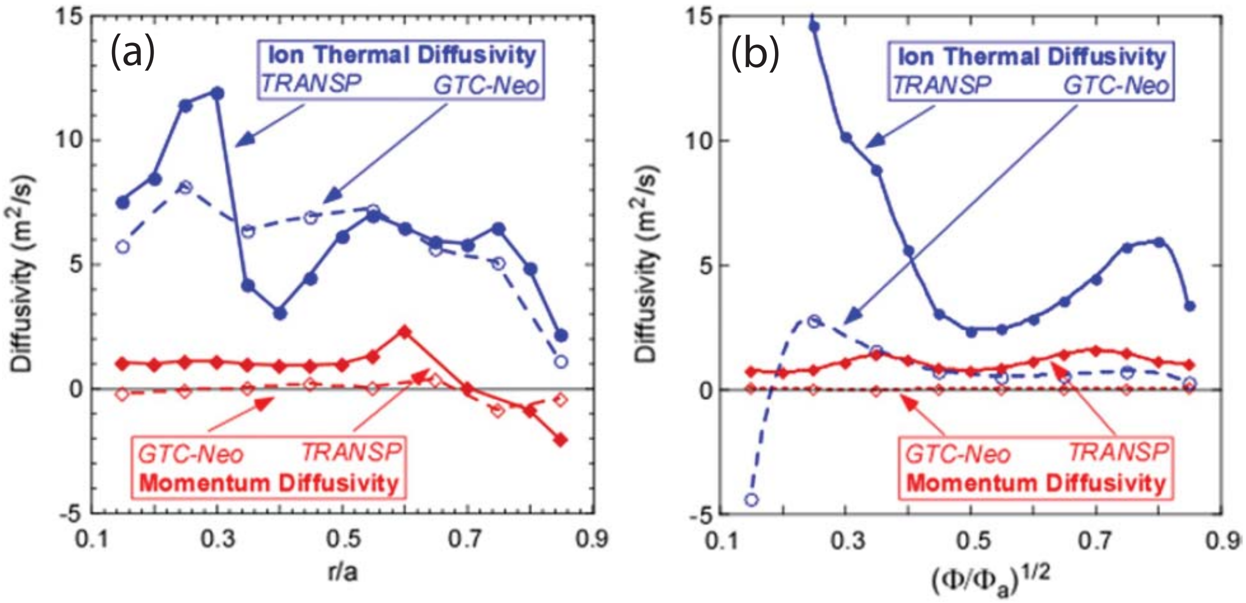


Fig. 3.3.11. Experimentally inferred values of χ_i and χ_ϕ compared with the neoclassical values computed by GTC-NEO for an H-mode (a) and an L-mode (b) plasma.

responsible for observed anomalous momentum transport but produces much smaller anomalous ion thermal transport compared to the neoclassical value. Indeed, perturbative momentum transport experiments using magnetic braking show that the inferred momentum pinch in the outer region of NSTX H-mode plasmas is consistent with that predicted by theoretical models involving low-k ITG turbulence (see Fig. 3.3.12 and Refs. [54], [55]).

Linear analysis has been pursued to calculate quasi-linear Prandtl and momentum pinch numbers (RV_φ/χ_φ) for the peturbative momentum transport experiments reported in Ref. [2]. In many of these discharges microtearing modes dominant the unstable spectra, although there are sub-dominant ballooning modes, at least some of which behave like the hybrid KBM mode. The theoretically calculated Prandtl numbers for the hybrid KBM modes range between Pr<0.2-0.6 over the measurement region (Fig. 3.3.13). However, it may not be meaningful to use the Prandtl number as a figure of merit as the ion thermal transport is near neoclassical levels ($\chi_i \approx \chi_{i,neo}$). The pinch parameters are always rather small or even predict an outward convection of momentum (RV_φ/χ_φ=0-2) which is in contradiction to the experimental analysis (Fig. 3.3.12). While the KBM mode provides a mechanism for momentum transport, there is clearly a lack of understanding

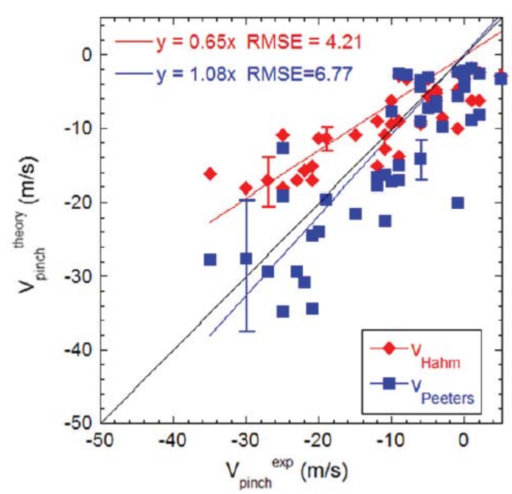


Fig. 3.3.12. V_{pinch} as computed by the Hahm (red) and Peeters (blue) theories versus experimentally inferred values for the outer region of the plasma.

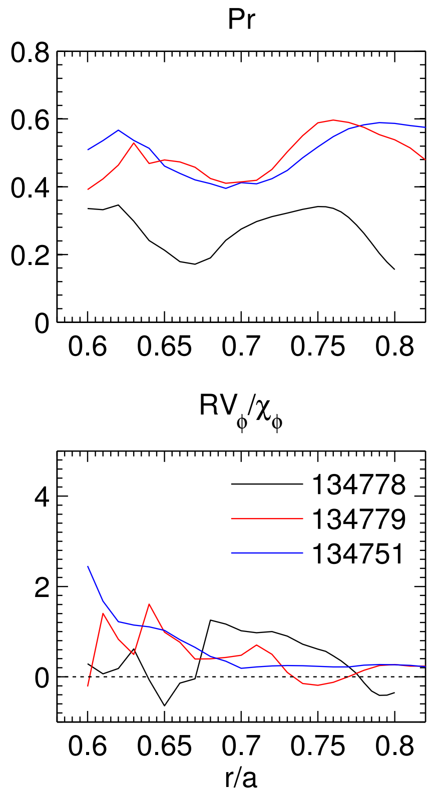


Fig. 3.3.13. Quasilinear Prandtl and pinch parameter (RV_φ/χ_φ) from hybrid ITG/KBM modes determined from linear GYRO simulations (for three discharges in Fig. 3.3.12).

relating the theoretical predictions with experimental measurements. Nonlinear gyrokinetic simulations are required to assess the Prandtl and Pinch numbers in the nonlinear state.

Intrinsic rotation generation was studied through the L-H transition in NSTX Ohmic plasmas, taking advantage of the zero momentum input and the long momentum transport time scale (~100 ms) compared to L-H transition time (~ 10 ms) [56]. The inferred intrinsic torque was found to correlate best with ion temperature gradient [see Fig. 3.3.14(a)], consistent with a theoretical prediction of residual stress driven by low-k turbulence [57]. Intrinsic torque is also measured in NSTX NBI-heated H-mode plasmas by using NBI torque steps and is found to have some correlations with pedestal pressure gradient [see Fig. 3.3.14(b)]. This result is qualitatively similar to the dependence on pedestal pressure gradient in DIII-D. We note that obtaining long-pulse steady-state plasma would be very beneficial for such a perturbative technique to measure intrinsic torque, and NSTX-U long-pulse scenarios would be ideal. To project intrinsic torque to future devices, the low-k turbulence generating intrinsic torque has to be identified. The research on intrinsic torque will be emphasized on NSTX-U.

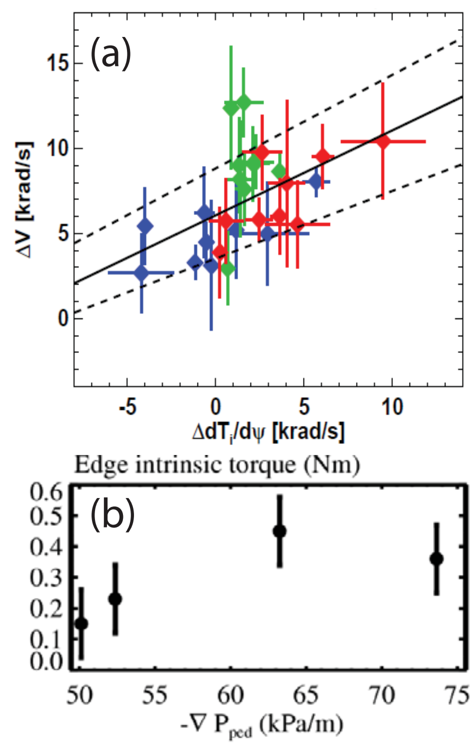


Fig. 3.3.14. (a) Change in intrinsic rotation (proportional to intrinsic torque) as a function of change in ion temperature gradient measured through Ohmic L-H transition (The blue colors for $0.64 < \rho < 0.72$, the green colors for $0.72 < \rho < 0.80$, the red colors for $\rho > 0.80$); (b) Edge intrinsic torque as a function of pedestal pressure gradient in NSTX H-mode plasmas.

The plan on momentum transport is to measure the responsible turbulence for transport and intrinsic torque and identify its regime of validity taking advantage of increased parameter regime of NSTX-U and its diagnostic and facility upgrades.

3.3.3.3.1 Research plans by year for Thrust TT-2: Momentum transport

Year 1

The plan of the first year of NSTX-U operation on momentum transport research will take advantage of the set of low-k turbulence diagnostics, BES, reflectometry and polarimetry, which will be ready at the beginning of first NSTX-U run campaign. Effective χ_φ will be determined through TRANSP analysis together with ion thermal transport in H-mode plasmas achieving lower collisionality with the extended range of B_T and I_p (the experiments addressing Thrust TT-1). Trends in both χ_ϕ and $\chi_i/\chi_{i,neo}$ vs B_T, I_p and collisionality will be studied to identify correlations. Linear gyrokinetic simulations will be used to identify relevant linear instabilities, and inferred momentum transport and low-k turbulence measurements will be compared with nonlinear gyrokinetic simulations. The 2nd NBI and external coils will be used to vary q and flow profiles (E×B shear and parallel velocity shear) to modify underlying turbulence in order to explore the correlation between low-k turbulence and momentum and ion thermal transport. Furthermore, momentum diffusivity, pinch and intrinsic torque will be measured in perturbative momentum transport experiments using NBI and external coil pulses in H-mode plasmas, particularly in microtearing-dominant and ETG-dominant regimes. These studies will be guided by gyrokinetic simulations, and their predicted parametric dependence on q, $\hat{s}$ and flow profiles (E×B shear).

Year 2

The study of effective χ_φ dependence on B_T, I_p and collisionality will be continued in the second year of NSTX-U operation as NSTX-U operation is attaining even lower ν_e^* values with full field strength and plasma current. Perturbative momentum transport experiments will also be carried out in selected H-mode plasmas to determine momentum diffusivity, pinch and intrinsic torque, with a goal of studying their parametric dependence in the expanded parameter range of B_T, I_p and collisionality. Additional perturbative momentum transport experiments will be carried out in isolated regimes for ITG/TEM modes, e.g. in NBI-heated L mode plasmas, guided by gyrokinetic simulations. Validation of gyrokinetic codes against the above experiments will be performed.

Studies of intrinsic rotation will be carried out with passive CHERS in scenarios with negligible external momentum input (e.g. RF-heated and Ohmic plasmas) coupled with low-k turbulence measurements, i.e. reflectometry and polarimetry, and its parametric dependence on B_T, I_p and collisionality will be investigated.

Year 3-4

The long-term goal for momentum transport research is to identify low-k turbulence responsible for anomalous momentum transport and intrinsic torque and its operational regimes coupled with gyrokinetic simulations. This long term goal will be carried out through investigation of the further parametric dependence of momentum diffusivity, pinch and intrinsic torque, e.g. on β, ν^*, T_i/T_e and Z_{eff}, coupled with low-k turbulence measurements, and it will be facilitated by density control capability from the planned implantation of a cryopump, which will help decouple ρ^* and ν_e^* dependence. Perturbative momentum transport measurements with NBI and external 3D coil/NCC pulses will be the main experimental method to measure momentum diffusivity, pinch and intrinsic torque. Furthermore, the effect of 3D effects (from external 3D coil and NCC) on intrinsic torque will be addressed with the combination of experiments and modeling with global gyrokinetic codes, e.g. GTS and XGC1 [58]. The engineering capabilities of NSTX-U will be exploited to expand achievable plasma parameters. In particular, momentum transport studies in long-pulse and fully non-inductive scenarios will be emphasized in this period. Studies of intrinsic rotation will continue with expansion in parametric dependences and coupling with gyrokinetic simulations.

3.3.3.4 Particle/impurity Transport

Understanding particle/impurity transport is also of great importance to the performance of future devices. Predicting density profile is required to predict bootstrap current which is essential to develop non-inductive long pulse scenarios required for operating all future devices. Understanding the mechanisms underlying impurity transport is important for controlling impurity accumulation in the core of plasma which dilute fuel ions (low-Z impurity) and increase radiation loss (high-Z impurity).

In NSTX, particle transport has been studied by using particle balance analysis. One example is shown in Fig. 3.3.15, where the range of inferred particle fluxes and predicted levels for neoclassical particle transport for the thermal deuterium ions is plotted as function of square root of normalized toroidal flux for an NSTX NBI-heated L-mode plasma. This comparison indicates that the particle flux ranges are comparable to what would be expected from neoclassical transport within r/a~0.6. A greater difference between the two is seen for larger radii, but the experimental determination of particle transport is very uncertain at larger radius due to not knowing the precise source of neutrals from gas puffing. Particle transport of the main plasma species appears to be somewhat decoupled from the energy transport (see Fig. 3.3.8) in that the

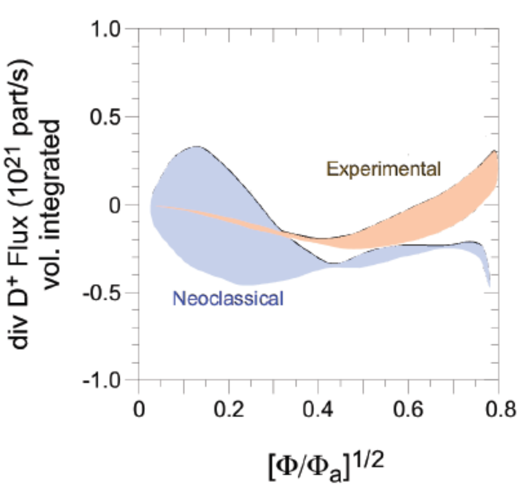


Fig. 3.3.15. Inferred and neoclassical deuterium particle fluxes for L-mode scan

particle transport appears to be consistent with neoclassical estimates in the core (r/a<0.5) of the plasma, while the ion thermal transport for these plasmas is anomalous. Future steady-state particle transport analysis will require better modeling and measurement of edge neutral source (from gas puff and recycling) and neutral penetration into plasma.

In order to understand impurity transport and thus to control impurity content, impurity transport has been emphasized, particularly in ELMy (with boronized PFCs) and ELM-free (with lithiated PFCs) NSTX H-mode plasmas. Carbon is the main impurity in NSTX and CHERS diagnostic provides measurement of its density profile. Carbon transport in NSTX H-mode plasmas is studied with predictive modelings using MIST (an impurity transport code) [59] coupled with NCLASS (a local neoclassical code) [51], where fully predictive MIST runs with time-dependent neoclassical values for both D and v determined from NCLASS are used to derive the full neoclassical prediction of the impurity charges states. In Fig. 3.3.16 the experimental carbon density (n_c) and the n_c evolution as predicted by MIST, assuming neoclassical transport coefficients, are plotted versus radius and time for a discharge with boronized PFCs (ELMy) and a discharge with lithium coatings (ELM-free). The neoclassical prediction for the discharge with boronized PFCs is in reasonable agreement with the experimental profiles. Edge peaking

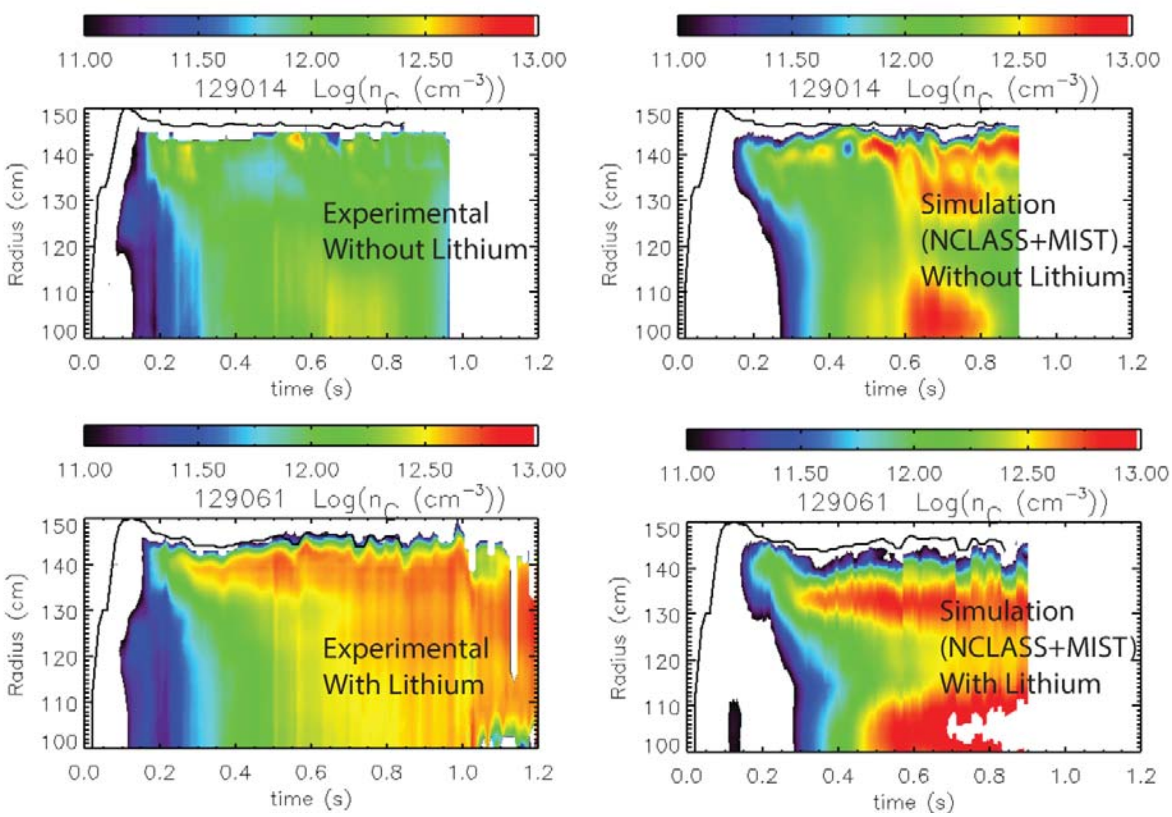


Fig. 3.3.16.. Evolution of the carbon density profile vs time and radius for the experimental measurements in a NSTX H-mode plasma (left panel; boronized discharge- TOP - lithiated discharge - BOTTOM), predictive MIST calculation (right panel; boronized discharge- TOP - lithiated discharge - BOTTOM).

stronger than that observed experimentally can be associated to the impurity flushing effect of ELMs. The neoclassical prediction for the discharge with lithium coatings again shows agreement in the early evolution of the discharge while for later times, when the fuel dilution becomes more important, only qualitative agreement is found. Further analysis shows that an anomalous outward convective component in discharges with lithium conditioning is needed to explain the experimental profiles.

Perturbative trace impurity transport has also been measured with a multi-energy SXR diagnostic in NSTX H-mode plasmas coupled with the STRAHL 1D impurity ion radial transport code [60]. The impurity transport profiles calculated by STRAHL for an I_p = 0.8 MA, B_T = 0.40 T

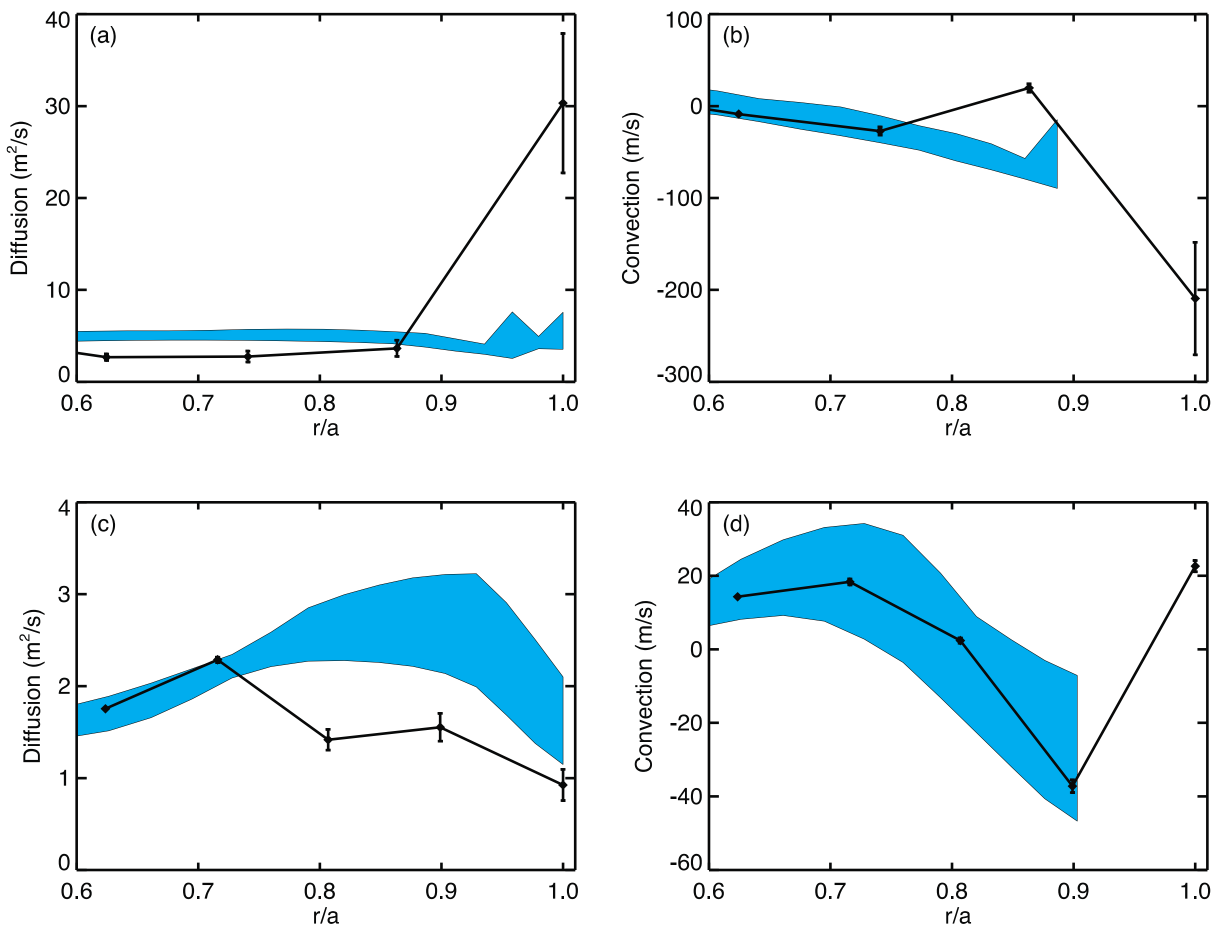


Fig. 3.3.17. The resulting diffusion profile and (b) convection profile from the I_p = 0.8 MA, B_T = 0.40 T discharge. The shaded region represents the results from NCLASS neoclassical transport calculations, covering the variation in the calculations during the time frame of the measurement.. (c) Diffusion profile and (c) convection profile for the I_p = 1.1 MA, B_T = 0.55 T case. The radial knots are defined for fixed values of ρ_{pol} and thus shift radially between the two cases with different q profiles.

discharge and an I_p = 1.1 MA and B_T = 0.55 T discharge together with neoclassical transport calculations (shaded regions) are shown in Fig. 3.3.17. The error bars represent the uncertainty in the transport profiles due to uncertainty in the ME-SXR and Thomson measurements and in the neoclassical values used to constrain core transport.

The results from the measurements roughly match neoclassical calculations, in agreement with previous results from the core [14,61]. The diffusion coefficients obtained from measurements are within a factor of 2 of neoclassical transport across most of the plasma radius. Deviations from neoclassical diffusion in the edge region, particularly in the far edge of the low-field discharge, are likely due to edge turbulence. The convection profiles also roughly agree with neoclassical values, though NCLASS does not provide reliable convective velocities outside of r/a ~ 0.9. For the two cases shown, the neoclassical convective velocity remains outward far into the core, which is consistent with the hollow neon profile found in the STRAHL simulations at later times. Previous results from core measurements have shown that neon convection near mid-radius can be either inward or outward, depending on the ion temperature and density profiles, and that neon profiles can thus be either peaked or hollow [14, 61]. The conclusion is that inside the pedestal region and under the conditions of these quiescent discharges, plasma turbulence is not sufficient to alter transport from neoclassical levels, consistent with the steady-state impurity transport analysis shown in Fig. 3.3.16.

The above particle and impurity transport results in NSTX H-mode plasmas signify the importance of neoclassical transport in determining both density and impurity profile and also indicates that turbulence-driven anomalous transport can play a role. As we have pointed out, NSTX-U plasmas will have a factor of 3-6 reduction in collisionality and this will significantly reduce neoclassical transport. Thus it is important to determine how important neoclassical mechanism is to particle and impurity transport in the low collisionality regime of NSTX-U and what turbulence and its operational regime in driving anomalous particle and impurity transport. Furthermore, the installation of a laser blow-off system and metal PFC in year 2 (and more metal PFC in subsequent years) will allow us to study high-Z impurity transport in NSTX-U and compare it with neoclassical transport. Results will be compared with those from large aspect ratio tokamaks, e.g. DIII-D. Understanding high-Z impurity transport is important since both ST-FNSF and ITER will have all metal PFC. NSTX-U will have the unique capability to address high-Z impurity transport in low collisionality and high β regime which is relevant to ST-FNSF and ITER.

3.3.3.4.1 Research plans by year for Thrust TT-2: particle/impurity transport

Year 1

In the first year of NSTX-U operation, impurity and particle transport will be studied in H-mode plasmas achieving lower collisionality (and lower neoclassical transport) with the initial extended range of B_T and I_p (similar to experiments addressing Thrust TT-1) in both ELMy (with boronized PFCs) and ELM-free (with lithiated PFCs) regimes. Impurity diffusivity and pinch will be determined using perturbative methods (trace-impurity with the Multi-energy SXR diagnostics [32]), and carbon and lithium transport will be studied using CHERS measurements coupled with interpretive and predictive modeling using impurity transport codes, e.g. MIST [59] and/or STRAHL [60], and neoclassical codes, e.g. NCLASS [51], GTC-NEO [52] and NEO [53]. Particle transport studies will be carried out through steady-state analysis by TRANSP, coupled with modeling and measurement of edge neutral source (with calibrated D_α measurements from MSE and/or BES diagnostics as a constraint) and neutral penetration into plasma using neutral transport code DEGAS 2 [62]. It is important to determine the trend of impurity and particle transport with respect to neoclassical transport as a function of collisionality and the correlation with low-k turbulence, particularly in lower collisionality H-mode plasmas of NSTX-U that are most relevant to the operation scenario to future machines. Particle and impurity measurements will also be carried out in microtearing-dominant and ETG-dominant H-mode plasmas (guided by gyrokinetic simulations), taking advantage of improved NSTX-U plasma and engineering parameters and the set of low turbulence diagnostics. Impurity transport will be correlated with low-k turbulence measurements with BES, reflectometry and polarimetry coupled with neoclassical calculations and gyrokinetic simulations using synthetic diagnostics. Profile variation capabilities for q and flow profiles using 2nd NBI and external coil will be used to alter neoclassical transport and low-k turbulence, helping to separate neoclassical and turbulent drives underlying impurity transport.

Year 2

In the second year of NSTX-U operation, we will continue impurity and particle transport studies in NSTX-U H-mode plasmas toward even lower ν_e^* values (compared to year 1) with full field strength and plasma current. In particular, a laser blow-off system will be available in this year and will allow us to conduct non-recycling (high-Z) impurity injection, and the installation of metal PFC will also allow the study of high-Z impurity transport with steady-state analysis coupled with impurity transport codes. Impurity and particle transport against neoclassical transport will be assessed in even lower ν_e^* H-mode plasmas achieved in this period, and a combination of applying 2nd NBI and external 3D coils will be utilized to reduce anomalous impurity transport and to modify neoclassical transport in order to control impurity transport. Furthermore, the effect of RF-heating with High Harmonic Fast Wave (HHFW) on high-Z impurity transport will be assessed. Measurements will also be carried out in ITG/TEM-dominant regime, e.g. NBI and RF-heated L-mode plasmas. Particle and impurity transport is expected to be anomalous in such plasmas due to small ExB shear leading to strong low-k turbulence. Again, profile variation capabilities for q and flow profiles using 2nd NBI and external 3D coils will be used to separate neoclassical and turbulent drives underlying particle and impurity transport. Measured particle and impurity transport in above experiments will be correlated with low-k turbulence measurements with BES, reflectometry and polarimetry coupled with neoclassical calculations and gyrokinetic simulations via synthetic diagnostics to determine the underlying turbulence. Furthermore, as a more robust validation of gyrokinetic codes, simultaneous comparison of thermal, momentum and particle/impurity transport and low-k turbulence measurements with nonlinear gyrokinetic simulations will also be carried out.

Years 3-4

In long term, low-k turbulence responsible for anomalous particle/impurity transport and its operational regime will be identified with low-k turbulence measurements, steady-state/perturbative impurity transport measurements, particularly using the laser blow-off system for non-recycling (high-Z) impurity injection, and measurements will be coupled with neoclassical calculations and gyrokinetic simulations through synthetic diagnostics developed in previous years. The identification will take advantage of the full range of plasma parameters of NSTX-U with parametric dependences expanded to β, ρ^*, T_i/T_e and Z_{eff} etc., which facilitates distinguishing individual instabilities. In particular, particle and impurity transport properties and underlying mechanisms in long-pulse and fully non-inductive scenarios will be emphasized due its relevance to the long pulse and steady-state operation of future devices. It is worth pointing out that in this period of NSTX-U operation, more high-Z (Mo/W) PFCs will be installed and impurity transport studies of Mo/W will receive increased emphasis. In addition, 1 MW ECH/EBW heating will be available in this period and its effect in controlling high-Z impurity accumulation will also be assessed.

3.3.4 Thrust TT-3: Establish and validate reduced transport models (0D and 1D)

During the next five year period substantial emphasis will be placed on using the transport code (P)TRANSP [33] and the transport solver TGYRO [34] incorporating various transport models to predict core plasma profiles in NSTX-U plasmas. As discussed in Section 3.3.3 (Thrust TT-2), there are multiple core transport mechanisms to consider including (i) neoclassical, (ii) drift wave microinstabilities, and (iii) energetic particle instabilities. Neoclassical theory is largely well established for tokamaks, with various models available based on analytic theories [63,64], moment-method approach (NCLASS) and kinetic calculations (GTC-neo; NEO; XGC-0 [65]).

The drift wave microinstabilities (ITG, TEM, ETG, MTM, KBM) are driven by gradients in thermal plasma parameters, which can generally contribute transport in all channels (heat, particle, momentum). Reduced transport models for drift waves are less developed (not as broadly successful at predictions compared to neoclassical theory), although significant advances in theory-based models have been made such as TGLF [66] and the Multi-Mode Model [67]. One goal of this thrust will be to validate the available reduced models with first principles gyrokinetic simulations for parameters relevant for NSTX-U. Semi-empirical or analytic models based on simulation results will also be considered depending on the success of the available reduced transport models.

The energetic particle driven GAE and CAE modes are driven by phase space gradients in the fast ion distribution function. An important consequence of these modes is that they redistribute fast ions (Chapter 6), although for the purposes of this chapter we are interested predominantly in their effect on electron thermal transport. There have been recent advances for modeling the electron thermal transport due to stochastic particle orbits in the presence of energetic particle driven modes like GAEs and CAEs, assuming a knowledge of the mode spectrum and amplitude (e.g., from measurement). Simulations are required to develop theory based description of mode onset and nonlinear spectra that would provide foundation for a purely theory-based transport model.

The following section will discuss recent results relevant for developing predictive capability for these various mechanisms. Following this are the research plans for the five year period.

3.3.4.1 Recent results

As shown in Sec. 3.3.3.1 ion thermal transport in NSTX H-modes is often well described by neoclassical theory (Figs. 3.3.10, 3.3.11). A validation of the predictive capability of neoclassical theory has been demonstrated for ion thermal transport by using only the Chang-

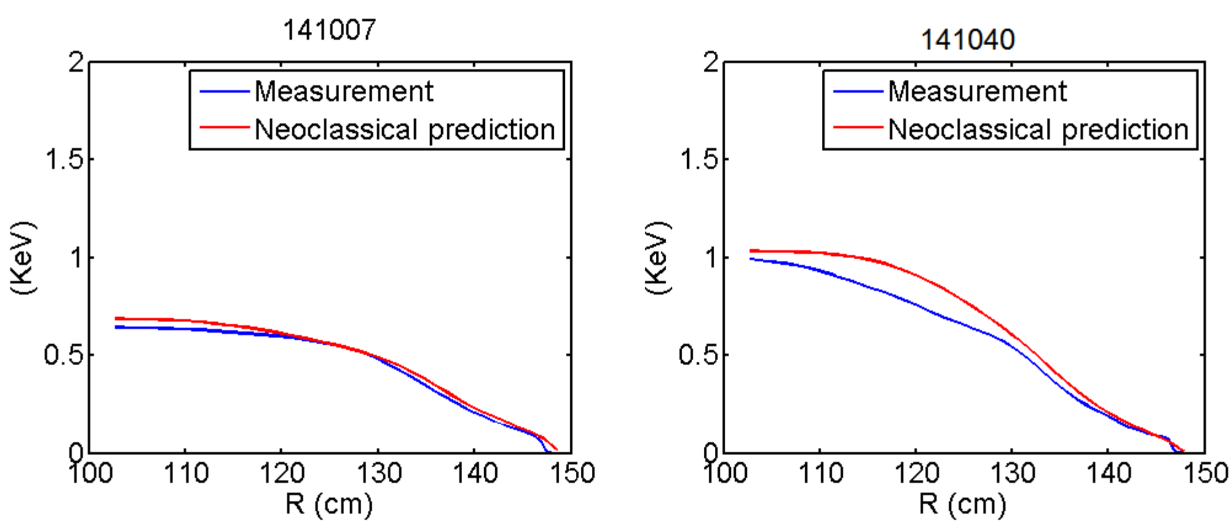


Figure 3.3.18. Prediction of T_i using TRANSP with the Chang-Hinton neoclassical transport model in NSTX H-modes.

Hinton model to predict T_i profiles. This is accomplished in TRANSP using the experimentally inferred heat flux and keeping density and electron temperature fixed to the experimental profiles. Fig. 3.3.18 shows the neoclassical predictions agree well with the measured T_i profile in two H-mode discharges that are part of a recent ν_* scaling experiment [18]. Similar agreement has been found in other H-mode predictions providing a level of confidence in using neoclassical ion predictions in the NSTX-U scenario studies [22,50]. However, as seen in Fig. 3.3.18, the neoclassical prediction for the lower collisionality NSTX discharge (141040) is already becoming larger than experiment in the inner core suggesting a non-negligible anomalous contribution.

We also note that particle and impurity transport predictions using only neoclassical theory are able to predict carbon profiles shapes in some cases as shown in Sec. 3.3.3.3. One exception occurs at low collisionality with lithium wall conditioning (Fig. 3.3.16). Whether this is due to inadequacy of local neoclassical theory (which can be tested with global codes like GTC-neo) or an unaccounted for anomalous contribution is presently under investigation. Understanding and improving these ion temperature and density profile predictions at low collisionality are of high priority for NSTX-U.

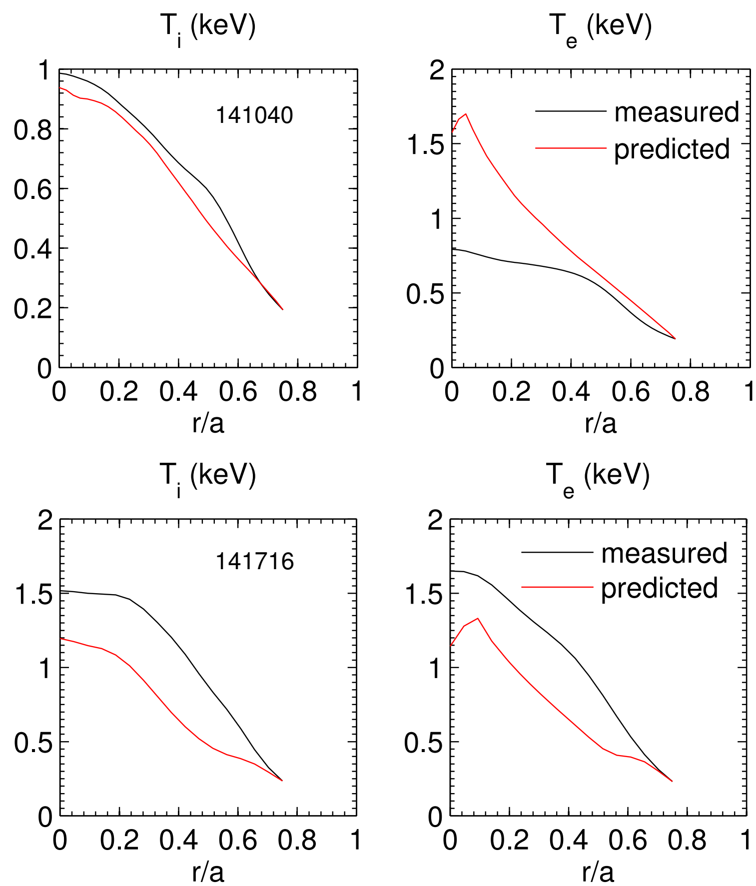


Fig. 3.3.19. Predicted (left) T_i and (right) T_e profiles using TGYRO+TGLF+NEO for (top) low beta NBI H-mode (141040), and (bottom) NBI L-mode.

Predictions of both ion and electron temperature profiles have also begun using the TGYRO transport solver including both neoclassical (NEO) and anomalous drift wave contributions as predicted by TGLF. For a discharge linearly unstable to ETG modes (Fig. 3.3.19, top), there is reasonable agreement in the T_e profile in a narrow region of r/a=0.5-0.7, but the discrepancy becomes quite large inside r/a<0.5. This is likely a result of either a missing transport contribution from energetic particle modes (GAE, CAE), inaccuracy of TGLF for these particular NSTX parameters, or non-local turbulence spreading which is not captured in the local TGLF model. The T_i prediction remains close to experiment, although in this case is completely fortuitous as the model predicts the ion heat flux is dominated by turbulent modes inconsistent with experimental analysis. For an L-mode dominated by ITG instability (Fig. 3.3.19, bottom), both T_e and T_i are severely underpredicted. These NSTX transport predictions illustrate a number of issues that must be resolved including (i) developing and integrating a model for energetic particle induced electron thermal transport, (ii) improving quantitative accuracy of drift wave models for ST parameters, and (iii) incorporating non-local effects in the models (possibly important for relatively large $\rho^*=\rho/a$ values in NSTX).

As shown in Sec. 3.3.3.1 previous work has uncovered a strong correlation between Global Alfven eigenmode (GAE) activity and core electron transport in the core of high power NBI-heated NSTX H-mode plasmas [13]. Simulations using the ORBIT guiding center code showed that GAE activity can enhance electron transport when a large numbers of modes (> ~15) have sufficient amplitude to overlap and induce stochastic particle orbits [45]. The simulations demonstrate an extremely strong scaling of transport with amplitude (~ a^{3-6}) and showed that the amplitudes measured in the experiment could induce thermal transport that roughly agreed with the experimentally measured values from TRANSP [68].

Further analysis comparing mode frequencies to dispersion equations indicate that the observed modes with frequencies ~400-1000 kHz can actually be a mixture of both GAEs and Compressional Alfven Eigenmodes (CAEs) [69]. Additional simulations using the ORBIT code, modified to include compressional magnetic field perturbations [70], demonstrate transport from CAEs scale similar to GAEs, as illustrated in Fig. 3.3.20. First, a Gaussian radial structure for the CAE modes is chosen to match the experimentally measured mode peak location and width. Frequencies and toroidal and poloidal mode numbers are determined using measurements and theoretical dispersion equations. From these, ORBIT simulations predict a strong scaling of transport with mode amplitude (~ a^{3-4}). The predictions illustrate that CAE & GAE modes

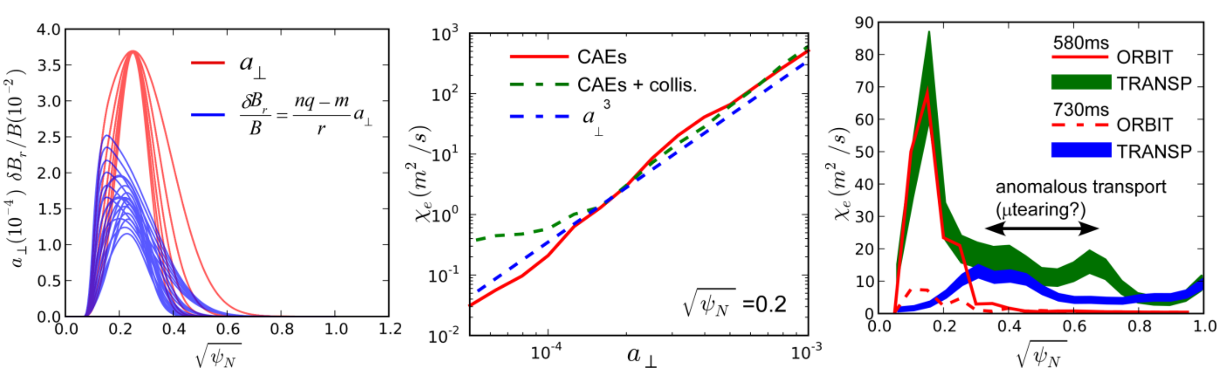


Fig. 3.3.20. (left) CAE model used for ORBIT simulations. (middle) Scaling of simulated CAE-induced electron transport with mode amplitude. (right) Comparison between ORBIT simulated electron transport and TRANSP experimental values.

combined can produce high levels of electron transport (~70 m^2/s) for r/a < 0.2 earlier in this particular discharge. Later in time the number of CAE modes appears to decrease and the corresponding predicted transport is smaller following the experimental trend.

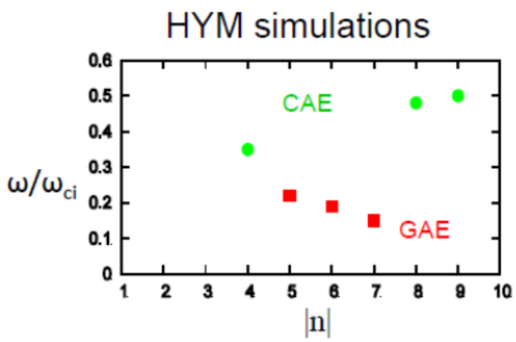


Fig. 3.3.21. Frequency vs. toroidal mode number for most unstable GAE (red) and CAE (green) modes, from HYM simulations for NSTX shot 141398. Frequency is normalized to ion cyclotron frequency at the axis (f_{ci}=2.5MHz).

The consistency between the ORBIT simulations and the TRANSP values for the core electron transport indicates that CAE/GAE modes are a good candidate to explain the high levels of core electron transport and flat electron temperature profiles in high power, NBI-heated, H-mode plasmas on NSTX. However, the predictions rely on measured mode structures and frequencies. Improved predictive capability will require first principles predictions of the unstable mode spectra, structure and nonlinear amplitude. For instance, recent simulations using the Hybrid MHD code (HYM) found that CAEs could in fact be destabilized simultaneously with GAEs (Fig. 3.3.21) in the core plasma region which matches the BES and reflectometer measurements of the radial mode structure. Future work will focus on additional linear and nonlinear simulations of GAE and CAE stability and saturation, and developing and implementing a model for electron thermal transport due to GAE/CAE mode that can be incorporated into transport solvers.

Improving the accuracy of reduced drift wave models requires validating them against first principles gyrokinetic simulations. This is complicated in NSTX plasmas as the high values of beta lead to many microinstability mechanisms (Table 3.1.1, Fig. 3.1.1), each of which exhibit their own unique thresholds and scalings. For accurate predictive capability it will be important to demonstrate that reduced transport models can recover the various microinstabilities and their thresholds and scalings. Such work has recently begun comparing the linear model within TGLF with gyrokinetic simulations. For an L-mode case, TGLF does in fact predict a dominant ITG mode (Fig. 3.3.22, left) with reasonable agreement in real frequencies, but with much larger growth rates. This is likely one reason why the predicted temperatures in Fig. 3.3.19 (bottom) were lower than experiment. For the low beta H-mode, TGLF also predicts ETG modes to be unstable with reasonable agreement in both real frequencies and growth rates (Fig. 3.3.22, right). For a higher beta H-mode, TGLF is also able to predict tearing parity modes over a range of k_θ with a destabilizing dependence on beta, similar to the microtearing modes predicted by GYRO. However, it does not reproduce the correct collisionality scaling. While TGLF can predict some of the appropriate behavior expected from first principles gyrokinetic simulations much more comprehensive validation must be pursued to demonstrate quantitative accuracy over the broad range of parameters accessible by NSTX-U. Similar comparisons will need to be done for other reduced models such as the Multi-Mode Model.

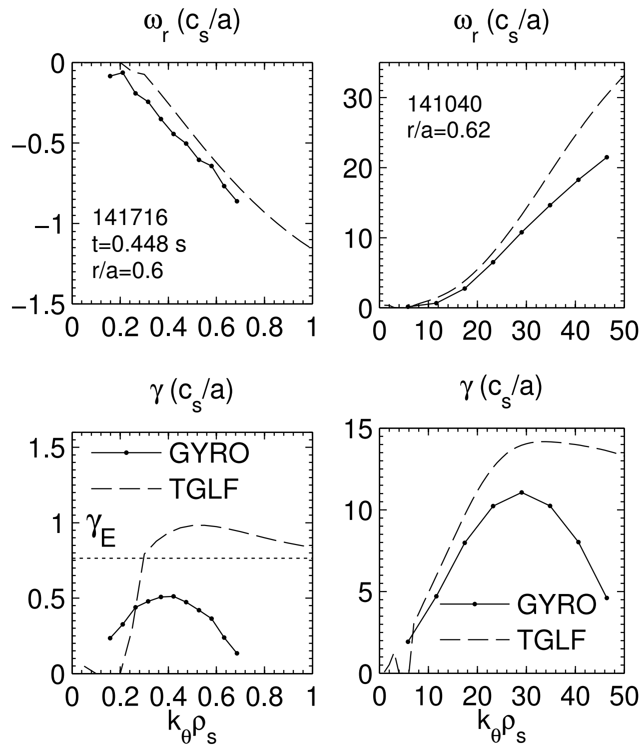


Fig. 3.3.22. (left) Real frequency and growth rates for ITG instability at r/a=0.6 in an NSTX L-mode from both linear gyrokinetics (GYRO, solid) and model (TGLF, dashed). (right) The same for ETG in a low beta NSTX H-mode.

Along with predicting the correct instability mechanisms, reduced transport models ultimately need to predict the correct magnitude of transport and parametric scalings, which can be validated with non-linear gyrokinetic simulations. Recent progress has been made simulating the nonlinear turbulence of each of the above microinstabilities, based directly on NSTX experimental equilibrium and measured profiles. Many of these were discussed already in Thrust TT-2. For example, the predicted microtearing transport (normalized to gyroBohm, $\chi_{GB}=\rho_s^2 c_s/a$) scales almost linearly with increasing electron collisionality, $\chi_{e,sim}/\chi_{GB}\sim(\nu_{ei}\cdot a/c_s)^{1.1}$, roughly consistent with the observed energy confinement time scaling in dedicated dimensionless experimental scans, $\Omega\tau_E\sim\nu^*_e{}^{-0.95}$ [4,5].

The predictions are also sensitive to increases in electron temperature gradient and beta, with transport increasing rapidly above the linear threshold in both β_e and a/L_{Te}. It is also found that experimental levels of E×B shear can significantly suppress the transport. It's important to note that microtearing transport models [71] based on Rechester-Rosenbluth stochastic transport estimates do not capture these predicted scaling trends. Using a quasi-linear estimate of saturated amplitudes ($\delta B/B \approx \rho_e/L_{Te}$ [72]) the gyroBohm normalized model diffusivity can be written as [71]:

$$\frac{\chi_e^{RR}}{\rho_s^2 c_s / a} = \min\left[1, \frac{1}{\varepsilon^{3/2}\nu_{*e}}\right]\frac{1}{\mu}\frac{qR}{a}\left(\frac{a}{L_{Te}}\right)^2$$

where $\mu=(m_i/m_e)^{1/2}$, $\varepsilon=a/R$, $\nu^*_e= \nu_{ei}\cdot qR/\varepsilon^{3/2}v_{Te}$, and $\min[1,1/\varepsilon^{3/2}\nu^*_e]$ represents the collisionless ($L_c=qR$ for $\lambda_{MFP}>qR$) and collisional ($L_c=\lambda_{MFP}$ for $\lambda_{MFP}<qR$) limits. From this expression we see the model does predict a nonlinear dependence of transport with a/L_{Te} (similar to a stiff dependence). However it does not reproduce the threshold behavior in a/L_{Te} and β_e and if anything predicts a ν_* scaling opposite to that found from the non-linear simulations, illustrating the importance of pursuing the non-linear simulations for developing an accurate predictive transport model.

Recent simulation results have also been obtained for the hybrid TEM/KBM turbulence discussed in Thrust TT-2 (Fig. 3.3.4) [21]. In addition to electron heat flux, these simulations predict significant ion heat, particle, and momentum fluxes with significant contribution from the $B_{\|}$ perturbations (rms $\delta B_{\|}/B$~0.08%). This TEM/KBM, or overlapping TEM/KBM+MTM turbulence, provides one possible mechanism that could account for both anomalous electron and momentum transport in NSTX [2], and such simulations can eventually be used to validate impurity and momentum transport models for NSTX-U.

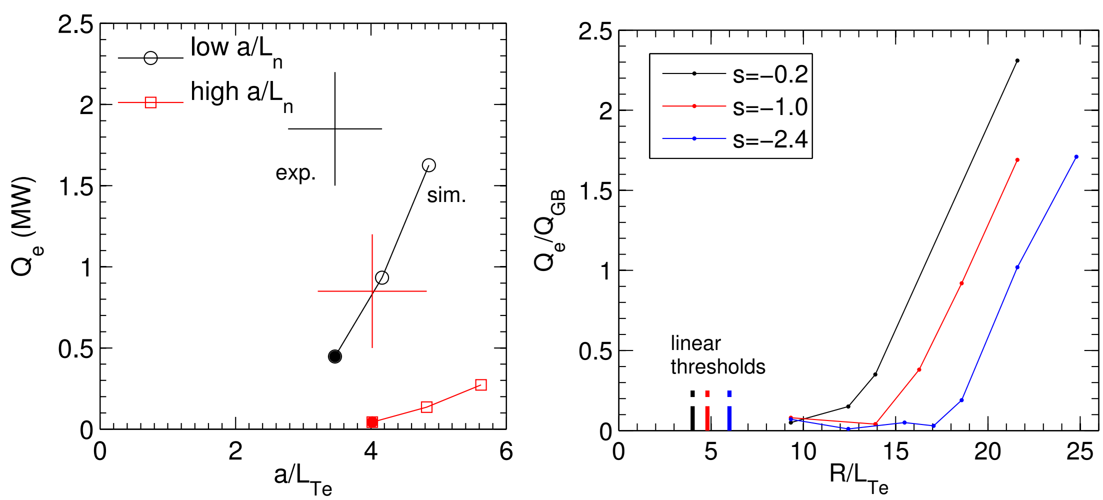


Fig. 3.3.23. (left) Predicted ETG heat fluxes vs. normalized temperature gradient for two different scenarios with significantly different density gradient. (right) Local nonlinear ETG transport vs. R/L_{Te} for varying magnetic shear illustrating the nonlinear upshift in effective threshold gradient.

The nonlinear trends discussed above generally follow linear predictions at least qualitatively, and it is hoped that reduced transport models like TGLF and MMM that are based on quasi-linear transport estimates will be able to capture such features. However, there are often specific non-linear effects that are not so easily captured. For example, nonlinear ETG simulations using dramatically different density gradient (Thrust TT-2, Fig. 3.3.6) show the predicted "stiffness" of ETG transport (i.e. the incremental increase of heat flux for incremental increase in driving gradient) is much smaller with larger density gradient (Fig. 3.3.23, left) [18]. On the other hand, for ETG simulations with strong reverse shear (Sec. 3.3.3.1), the transport stiffness is effectively the same regardless of variation in magnetic shear (Fig. 3.3.23, right) but the nonlinear threshold is varied considerably [17]. Successful transport models must also account for these effects that arise non-linearly.

3.3.4.2 Research plans by year for Thrust TT-3

The highest priority goal of this thrust is to significantly improve predictive capability for both ion and electron temperature profiles, especially the electron temperature as the T_e profile strongly influences confinement scaling, MHD equilibrium (through both resistivity and bootstrap current profiles), and MHD stability through pressure peaking. Towards the end of the five year period we hope to move towards a more integrated predictive capability including particle/impurity and momentum transport, although it is recognized these are often considerably more complex than the thermal channels to accurately model. To accomplish these goals, throughout the five year period we will continuously make and refine predictions with NSTX and NSTX-U data, employing (P)TRANSP and TGYRO, coupled with various transport modules for neoclassical transport, drift wave transport, and energetic particle driven electron thermal transport. As discussed above, we will also emphasize validating the reduced models with first principles simulations.

2014

In the year prior to NSTX-U operations additional effort will be applied to test predictive models for existing NSTX data over a wide range of scenarios, including NBI H-modes, RF discharges and L-modes. This will included more predictive tests of T_e and T_i profiles as discussed above using neoclassical and drift wave transport models. During this year we also intend to perform more validation studies of local neoclassical theory with global codes such as GTC-neo and XGC0.

Although a model for GAE/CAE electron thermal transport will not be available for predictive transport simulations (predicting profiles), modeling development based on ORBIT simulations for predicting electron thermal transport in the presence of GAE/CAE modes will continue. For this period models will predominantly be based on measured or assumed mode structures and amplitudes to better characterize the sensitivity of predicted χ_e to these parameters. Linear HYM (see Sec. 3.4.1.3 for more about HYM code) simulations of the GAE/CAE stability properties will also continue throughout this year to better understand the threshold scalings of these modes with relevant parameters such as fast ion beta and phase space structures. A first attempt is planned to couple the ORBIT particle following code with HYM CAE/GAE mode calculations to predict core electron thermal transport due to these high-frequency fast ion-driven modes.

In addition, the available drift wave transport models (TGLF, MMM) will also be compared with linear and nonlinear gyrokinetics based directly on NSTX parameters to begin validating the accuracy of these reduced models. For comparison, linear gyrokinetic stability calculations will be pursued not only in the core, but also into the top of the pedestal and down into the sharp-gradient pedestal region, which has already begun [40,73]. This will be investigated using local and global codes to better characterize the influence of profile variations at the larger values of ρ/L in this region. This work will be tightly coupled with the boundary group (Chapter 4, Sec. 4.2.1).

Nonlinear simulations will also be used to calculate the magnitude and parametric scaling of the various turbulence mechanisms. Significant effort will be focused on understanding and demonstrating numerical convergence for the high beta, electromagnetic scenarios (from high performance discharges) as these are challenging computationally but critical to the successful validation of reduced models. In scenarios with multiple unstable modes (such as microtearing plus any of ITG,TEM, or KBM), parameter scans will used to elucidate how mode dominance varies in the nonlinear saturated turbulence, and how dynamics from fundamentally different modes interact and establish not just the magnitude of transport, but also the partition in different transport channels (thermal, particle, momentum). In addition, predictions of the turbulent transport in NSTX-U will be carried out using nonlinear gyrokinetic simulations, e.g. using the GTS code with kinetic electrons.

Year 1-2 of operation

One of the primary goals will be to verify the range over which neoclassical theory successfully predicts ion thermal transport. Predictions of T_i using only neoclassical theory will be performed for various H-mode scenarios to determine if and when discrepancies arise. In the first two years the focus will be on shorter duration discharges that span the full range of I_p, B_T, and P_{NBI}. It may be expected that if ion ballooning mode turbulence becomes more important at lower collisionality, neoclassical predictions will overpredict T_i as suggested by existing NSTX simulations. Throughout the analysis, and especially in regions where discrepancies do arise, the PPPL Theory codes GTC-neo (global) and XGC-0 (global, full-F) will also be used to validate the accuracy of the local neoclassical transport models.

In this period, impurity transport predictions will also be pursued in the same fashion as ion thermal transport for the extended range of NSTX-U operations. As there are uncertainties in the magnitude of the edge sources, only the profile shape will be predicted. The predictions will continue to use impurity transport codes such as MIST and STRAHL coupled with neoclassical models. NEO will be used to investigate the importance of centrifugal effects on the impurity transport as it is unknown how toroidal flow profiles will change for the extended NSTX-U operational space. In scenarios where both T_i and impurity profiles are well described by neoclassical theory, it should be straightforward to simultaneously predict T_i and impurity profiles self-consistently (while holding n_e and T_e fixed) as a first step towards multi-channel transport predictions.

Integrated transport modeling that includes both neoclassical and drift wave turbulent transport contributions (TGLF, MMM, …) will commence for predicting both T_e and T_i profiles based on NSTX-U discharges using boundary conditions chosen from measured profiles near the H-mode pedestal top (or near the edge in L-mode plasmas). The focus in the first two year period will be to identify if and when the predictions work well, particularly in the outer two thirds of the minor radius where drift waves are expected to be most important. Without a model for electron transport from energetic particle modes in the core, T_e predictions are likely to be inadequate. We will characterize when this discrepancy arises in operational space (I_p, B_T, n, P_{NBI}) as well as in radius ($0<r/a<0.5$), and investigate possible correlations with measured energetic particle mode activities (GAE, CAE) to better understand their possible contribution in modifying the core T_e profile. Although predicted core profiles may not be accurate near the magnetic axis, the discrepancy in stored energy should be relatively small due to the small plasma volume in that region ($V\sim r^2$). Therefore it should be reasonable to compare overall energy confinement times with those derived from scaling studies (Sec. 3.3.2.1) to assess whether the physical understanding encapsulated in the neoclassical and drift wave transport models is capable of recovering the favorable ν^*_e confinement scaling observed in NSTX plasmas.

Linear and nonlinear gyrokinetic simulations will be used to continue investigating parametric dependencies of each instability mechanism, each of which is critical for validating reduced transport models. These will be based on discharges in different experimental regimes of interest, including NBI H-modes and L-modes, and RF heated discharges, which will be tightly coupled with the validation work proposed in Thrust TT-2. However the emphasis for this thrust will be on better determining the most important parametric dependencies and quantitative thresholds of each instability mechanism (e.g. β_e and a/L_{Te} for microtearing, a/L_{Te} for ETG, α_{MHD} for the hybrid KBM modes), which can subsequently be used to validate reduced transport models.

Model linear stability predictions from TGLF and MMM will be validated with local linear gyrokinetic simulations, for a wide range of NSTX scenarios, comparing against the scaling and thresholds of the various instabilities. As TGLF is an eigenvalue solver for gyrofluid equations that fundamentally can represent each mode of interest, it can be also be validated in regimes of overlapping unstable modes such as the TEM/KBM+microtearing discussed above. The quasi-linear fluxes for each transport channel and from each field contribution (φ, $A_{||}$, $B_{||}$) will also be validated with the gyrokinetics as this forms the basis for the TGLF transport model.

The nonlinear gyrokinetic simulations will be used to validate model transport. The initial focus in the first two years will be on thermal transport, especially χ_e, as an overall high priority goal is developing predictive capability for T_e and T_i profiles in NSTX-U over the full range of I_p, B_T, and P_{NBI}. In this period we will also explore developing alternative reduced models specifically for electron thermal transport. This could be as simple as prescribing analytic expressions to capture the most important χ_e dependencies predicted in the nonlinear simulations such as those discussed above for microtearing and ETG. These various contributions could be summed in the spirit of a "multi-mode model" and used in initial integrated transport predictions specifically for the electron temperature profile.

Global nonlinear simulations will be initiated in L-mode plasmas where predominantly electrostatic ITG,TEM instabilities are dominant. These low beta global simulations will allow us to most easily investigate the influence of non-local effects (turbulence spreading, diamagnetic shear, etc…) at the relatively large ρ^* values in NSTX and NSTX-U. If non-local effects are indeed found important, the possible incorporation of heuristic turbulence spreading models [74] will be investigated.

ORBIT simulations will continue using measured GAE/CAE mode structures to predict electron thermal transport, performed for numerous discharge conditions, especially high beta H-modes with different GAE/CAE characteristics (spectra and amplitude). Throughout this two year period it is should be possible to develop a stronger relation between assumed spectrum and amplitude of modes and the resulting stochastic electron thermal transport, and validate with experimental analysis (coupled with Thrust TT-2). In addition, predictions of GAE/CAE stability and mode properties will be continued using the HYM code across a range of operational space (P_{NBI}, n, I_p, B_T) to investigate the sensitivity and scaling of linear spectra with fast ion distribution function. Limited nonlinear HYM simulations will also continue to calculate saturated mode amplitudes which can be eventually be used directly in the ORBIT modeling simulations.

Years 3-4 of operation

In later years of the five year period the focus will shift towards modeling more advanced scenarios that should become achievable in NSTX-U operations. This will included long pulse, non-inductive scenarios (Sec. 9.2) which requires accurate bootstrap current calculations (sensitive to plasma profiles) for predictive capability. New machine wall/boundary conditions such as different plasma facing components (Sec. 5.3) or installation of a cyropump (Sec. 4.2.3) will both likely influence particle sources and resulting density profiles. These scenarios should offer the best access to a wide range of collisionality and presumably be those best suited for basing extrapolations to next generation designs such as ST-FNSF and are therefore of great interest for validating predictive capability.

To accomplish this will require continued improvements and testing of the various transport modules, including an appropriate χ_e model for GAE/CAE driven transport. Throughout this period it is expected that results from additional linear and nonlinear HYM simulations will better clarify the most important criteria for characterizing GAE/CAE stability and mode structure. This information, coupled with ORBIT simulations, should allow for the development of a theory-based χ_e transport model for GAE/CAE modes. When available such a model will be integrated into the transport solvers and validated with NSTX-U data. The successful development and implementation of an energetic particle model for electron thermal transport is essential to achieve the high priority goal of T_e and T_i profile predictions. As the development of such a model is limited by available NSTX and PPPL Theory personnel, it could possibly be accelerated with incremental funding.

It is likely that the available drift wave models will also require improvements. For example, at present the Muti-Mode Model does not include a prediction of transport from microtearing modes. There are also known areas in the TGLF model that, if modified, will likely improve the agreement for low aspect ratio, high beta ST parameters, including separating curvature and grad-B drift effects (which is important at large equilibrium pressure gradient, and also related to $B_{||}$ dynamics critical to the TEM/KBM modes) and treating the different spatial scales of the eigenfunctions for microtearing modes (extended potential, narrow $A_{||}$). Both of these enhancements are being pursued by General Atomics with whom we will be working and providing feedback throughout this five year period on NSTX-U validation efforts in an attempt to improve the overall accuracy of TGLF for high beta plasmas.

Depending on the success of with T_e and T_i profile predictions, integrated transport simulations can be pursued, simultaneously evolving MHD equilibria with temperature profiles to study long discharge evolution to fully relaxed current profile (validating neoclassical resistivity) as well as ramp-up and ramp-down phases. Boundary conditions will likely be taken from measured edge profiles near the pedestal top. For a truly predictive capability of the entire H-mode profile, either empirical or theory based predictions of the H-mode pedestal parameters will be required, including pedestal temperature height and width for each plasma species. With a lack of predictive pedestal capability we will also test the sensitivity of the core profile predictions to uncertainties in the pedestal parameters.

Beyond establishing accuracy in temperature predictions, additional effort will be given to investigate and better predict particle, impurity and toroidal rotation. All of these profiles are important in determining a self-consistent understanding of the core confinement (e.g. density through instability drive, and q profile via bootstrap current; toroidal flow through stabilization of turbulent transport and macroinstabilities). It is difficult to assess the difficulties that may arise regarding this prediction as momentum transport is one of the least understood. However, we will continue to pursue integrated simulations in an attempt to best clarify strengths and weaknesses in the transport models; e.g., addressing scenarios that are theoretically only unstable to microtearing and/or ETG should lead to virtually no anomalous contribution to momentum or impurity transport. If these scenarios are not explained by neoclassical theory (or possibly energetic particle modes), there is quite likely a deficiency in our understanding of the predicted transport mechanisms. Integrated transport simulations will be used to test the ability of drift wave models and neoclassical theory to predict density (all species) and toroidal flow profiles. Initial simulations could test individual transport channels, for example fixing temperature and flow profiles to predict density. In cases where temperature profiles are successfully predicted, it should be viable to predict densities and temperatures self-consistently.

Transport models will also be validated for particle, impurity and momentum fluxes using available simulations. Both linear and nonlinear simulations can also be used to calculate the predicted scaling of Prandtl (χ_φ/χ_i) and momentum pinch (RV_φ/χ_φ) numbers, although it will likely be necessary to reconsider the relevance of the Prandtl number in scenarios where ion thermal transport is neoclassical ($\chi_i \approx \chi_{i,NC}$). Similar analysis for particle and impurity transport can be pursued analogous to the momentum transport to calculate the relative size of impurity diffusivity and convective fluxes (e.g., V_Z/D_Z). Nonlinear simulations will also be used to address the issue of residual stresses and intrinsic rotation. Such efforts will help elucidate the relative importance of the various mechanisms that may contribute to residual stresses in NSTX-U, e.g. up-down asymmetry [75] or finite ρ^* effects [76] and the ability of transport models to accurately predict these effects.

As PPPL Theory global gyrokinetic codes (GTS, XGC-1) progress to include complete electromagnetic response, global simulations will be pursued to investigate non-local effects in high beta H-modes where different unstable modes can co-exist at similar wavenumbers and the dominant unstable mode can vary depending on minor radius. In particular, XGC-1 fully global simulations that include the H-mode pedestal will allow for investigation of the turbulence interaction between pedestal, top of pedestal, and confinement regions in the larger ρ^* plasmas in STs (in conjunction with the Boundary group, Sec. 4.2.1), and if successful should provide a first principles profile prediction without the need for a reduced transport model.

3.4 Summary timeline for tool development to achieve research goals

3.4.1 Theory and simulation capabilities

3.4.1.1 Gyrokinetic codes

GS2

GS2 [77] is a local "flux-tube" Eulerian gyrokinetic code based on the delta-f formulation, capable of including comprehensive physics: arbitrary numerical MHD equilibria, multiple gyrokinetic species, sophisticated collision operator, fully electromagnetic perturbations (shear and compressional), toroidal flow and flow shear. It is run for rapid linear stability calculations as well as nonlinear simulations. There are many users and good documentation with support available from code developers (Maryland, MIT, Culham).

GYRO

GYRO [78] is similar to GS2 except also has capability for including profile variations (often referred to as global) for studying non-local, finite ρ_* effects which is important for the relatively large $\rho_*=\rho_s/a$ values in NSTX and NSTX-U. It has excellent documentation with prompt support from code developers (General Atomics).

GENE

GENE [79] is similar to GS2 and GYRO. It has recently expanded to perform radially global simulations, as well as poloidally global to address 3D geometry effects e.g. from external coil perturbations. It also has unique numerical algorithms that have been developed to improve performance for the extreme parameters that occur in the pedestal region. It has excellent documentation with support available from code developers (IPP-Garching).

GKW

GKW [80] is similar to GS2, GENE and GYRO. It is presently the only gyrokinetic code to have implemented centrifugal effects for large toroidal flow, allowing for investigation of poloidal asymmetry on particle and impurity transport, as well as influence of poloidally varying density gradient on mode thresholds (such as KBM). There is a growing number of users with much documentation available and available support from code developers (Bayreuth).

GTS

The Gyrokinetic Tokamak Simulation (GTS) [35] code is a full geometry, massively parallel, global delta-f particle-in-cell code developed at PPPL. It can use globally consistent numerical

MHD equilibria reconstructed by MHD codes and employs general magnetic coordinates and a field-line-following mesh. Fully-kinetic electron physics is included in GTS. The real space, global Poisson solver, in principle, retains all toroidal modes from (m/n = 0/0) all the way up to a limit which is set by grid resolution, and therefore retains full-channel nonlinear energy couplings.

Ongoing code development which extends GTS physics capability focuses on:

- Implementation of a new split-weight scheme to achieve a robust, global EM capability critical for high-β, strongly shaped plasmas (e.g., NSTX-U). The new scheme uses fully-kinetic treatment of non-adiabatic electrons with the adiabatic part defined with respect to the total magnetic field $B_0+\delta B$ (including the magnetic perturbation). This unique, physics-based approach is mostly suitable for studying global Alfvenic turbulence and microtearing modes in high-beta fusion plasmas and magnetic reconnections.
- Upgrade of GTS to use equal-arc-length coordinates combined with field-line aligned mesh for improved resolution, efficiency and robustness which are critical for NSTX/U simulations.
- GTS will be extended to treat 3D MHD equilibria, including perturbed tokamak equilibria with islands, so as to simulate 3D effects in burning plasmas, including the NTM dynamics, MHD-turbulence interaction, and particle and heat transport across magnetic island and stochastic magnetic fields.
- The current treatment of energetic particles at GTS will be extended to inclusion of fully nonlinear dynamics.

XGC-1

(See Chapter 4, Sec. 4.3) XGC-1 [58] is a full-F, global PIC code developed at PPPL capable of uniformly treating closed flux surfaces all the way to the magnetic axis, separatrix, and scrape off layer.

3.4.1.2 Neoclassical codes

NCLASS

NCLASS [51] is a well-established, validated, comprehensive neoclassical model which calculates local neoclassical transport properties of a multi-species axisymmetric plasma of arbitrary aspect ratio, geometry and collisionality. NCLASS uses the Hirshmann and Sigmar formulation of neoclassical theory for a multi-species plasma, based on a fluid-moment approximation for the parallel and radial force balance equations to calculate resistivity, bootstrap current, particle and heat transport, rotation and radial electric field. NCLASS can be run as a standalone or as module integrated into TRANSP.

NEO

NEO [53] is a delta-f Eulerian code which provides first-principles based numerical calculations of the neoclassical transport (particle flux, energy flux, bootstrap current, poloidal flows, etc.). NEO solves a hierarchy of equations derived by expanding the drift-kinetic equation in powers of ρ^*, the ratio of the ion gyroradius to the system size. NEO includes the self-consistent coupling of electrons and multiple ion species via complete cross-species collisional coupling, the calculation of the first-order electrostatic potential via coupling with the Poisson equation, general geometry effects, and rapid toroidal rotation effects (including centrifugal effects). NEO has recently been upgraded to include the full linearized Fokker-Planck collision operator. Various reduced collision models are also implemented (Hirshman-Sigmar, zeroth-order Hirshman-Sigmar, and the Connor model) for comparison with analytic theory and testing. NEO has been extensively benchmarked and compared with analytic neoclassical theory.

GTC-NEO

GTC-Neo [52] is a full geometry, delta-f PIC code developed at PPPL to calculate nonlocal neoclassical transport and a self-consistent radial electric field due to the effects of finite orbit size and large plasma profile gradients. Without using any small parameter expansion, GTC-NEO directly solves the drift kinetic equations globally as an initial value problem, from the magnetic axis to the separatrix with appropriate boundary conditions, and with full particle drift orbit dynamics. Moreover, the large scale ambipolar electric field is also consistently calculated by solving the Poisson equation. GTC-NEO will be extended to treat 3D MHD equilibria, including perturbed tokamak equilibria with islands, so as to simulate 3D effects on neoclassical transport, including particle and heat transport across stochastic magnetic fields. The 3D capability of GTC-NEO will be coupled with linear MHD stability calculations, providing an effective approach for including comprehensive, global kinetic effects in MHD stability analyses.

XGC-0

(See Chapter 4, Sec. 4.3) Axisymmetric version of XGC-1, developed at PPPL which ignores turbulence field. It is unique for neoclassical calculation as it allows validation of local codes since it is not restrained by low ρ/L ordering assumption. It also includes neutral particles self-consistently.

3.4.1.3 Energetic particle codes

ORBIT

(see Chapter 6, Sec. 6.4.1) ORBIT [45] is a particle following code used to integrate particle trajectories for estimating stochastic orbit transport from GAEs and CAEs.

HYM

(see Chapter 6, Sec. 6.4.5) HYM [81] is a hybrid-MHD 3D global stability code that can be used to study the excitation of GAE and CAE modes.

3.4.1.4 Transport codes

TRANSP/PTRANSP

TRANSP [33] is a time-dependent, 1 ½-D tool for both interpretive and predictive analysis of tokamak, ST and RFP plasmas. The TRANSP code, first developed at PPPL, has been a centerpiece for transport analysis of the experimental fusion program in the U.S. since the 1970s. All the U.S tokamaks and many outside the U.S. (including JET, MAST, AUG, EAST and KSTAR) are able to analyze the rich set of diagnostic data they obtain by running TRANSP. The synthetic diagnostic capability of TRANSP has allowed it to be used effectively for diagnostic validation. Both the use and development of the TRANSP code is a world-wide effort. Physicists and software engineers from PPPL, Princeton Univ., Lehigh Univ., MIT, ORNL, General Atomics, JET and EAST have been or presently are directly involved in code development, ensuring a validated wide range of code capabilities hat can address a similar wide range of experimental scenarios.

In its interpretive mode, TRANSP converts measurements of temperatures, densities, magnetic fields and flow velocities into inferred energy/particle/momentum transport coefficients which are then suitable for understanding transport trends, comparison to saturated transport levels computed in non-linear gyrokinetic simulations, and other related analyses. This is only possible because so much effort has gone into developing and validating the routines that calculate the detailed heating, momentum, and particle sources from neutral beams, fusion products, RF,

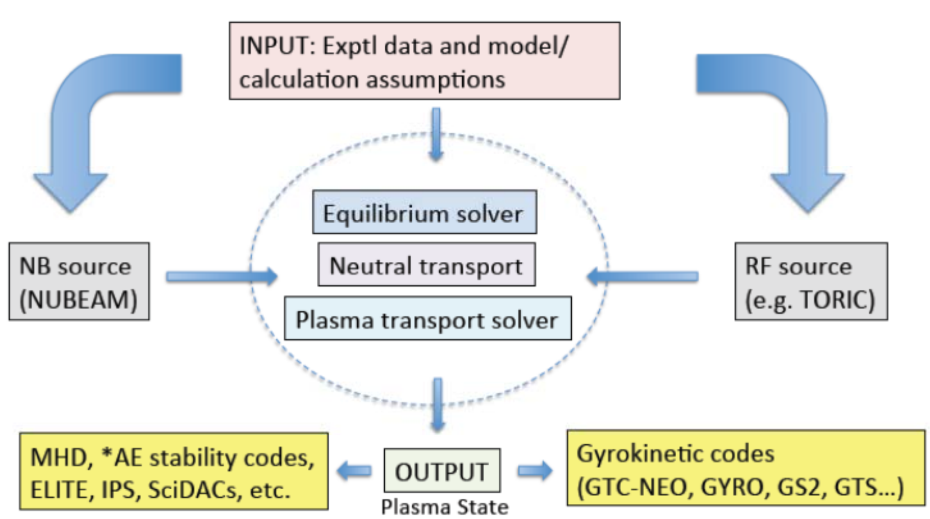


Fig. 3.4.1: Data and calculation flow for TRANSP

Ohmic, and compression. A chart of the data and calculation "flow" of TRANSP is shown in Fig. 3.4.1. Experimental data as well as model/calculation assumptions are fed into both the source modes (e.g., RF and NBI) and the kernel of the transport calculation, which consists of an equilibrium solver, neutral transport model and plasma transport solver.

The use of 0-, 1- and 2-D experimental data is integral to TRANSP. As examples, 0-D data and information include device geometry and NB/RF source configurations, 1-D data include I_p, B_T, diamagnetic flux, V_{loop}, D_a, neutrons, recycling coefficient, outer boundary, etc. as functions of time, and 2-D data include n_e, $T_{e,i}$, n_{imp} or Z_{eff}, P_{heat}, P_{rad}, $v_{f,q}$, B_q/B_T, neutrons, the full equilibrium, etc. as functions of time and space. TRANSP has the flexibility to calculate its own equilibrium internally by solving the poloidal field diffusion and Grad-Shafranov equations, or use a pre-calculated equilibrium from magnetic reconstruction codes such as EFIT. The plasma transport coefficients are then computed using this input and advancing the neutral particle transport equations coupled to the plasma particle, energy and momentum transport equations as functions of time and space. The inferred transport coefficients and fluxes can then be compared to those as calculated from models (simple or sophisticated) to attempt to determine whether the plasma is behaving neoclassically or is governed by turbulent processes, and if the latter to identify the modes driving the transport.

The NB and RF source models in TRANSP are state-of-the-art. NUBEAM [82] uses a 2/3-D Monte-Carlo approach with FLR effects to determine the neutral beam heating and current drive profiles, as well as the fast ion population. Both ad-hoc and, eventually, physics-based 2-D anomalous fast-ion diffusion can be included in this determination. NUBEAM is the most accurate and precise treatment of neutral beam deposition that is integrated into transport codes, and it is used world-wide. TORIC [83] is a full-wave code that addresses deposition of both ICRF and LH waves.

A notable development during this same time period has been the introduction of the Plasma State (PS) software and it subsequent use internal to TRANSP and in other projects. The PS is a netCDF-based file that contains all the physical quantities required to completely define the state of a tokamak plasma at a given time. This includes all variables related to the magnetic equilibrium, heating and current drive sources, and even the fast particle distribution. This well-documented standard interface for exchanging information between plasma physics codes was adopted by the both the SWIM and FACETS projects and It has become the de-facto standard in the U.S. plasma physics community. For example, self-consistent TRANSP output in the form of Plasma State files can easily be input to micro- and macro-stability codes for more fundamental, first-principles, analysis.

While TRANSP could always be run in a predictive mode, over the last several years the TRANSP developers have greatly expanded these predictive capabilities while simultaneously modernizing the code, increasing its modularity, and expanding and standardizing its ability to interface with other codes. It is now possible to develop discharge scenarios in present and future devices by using the predictive capabilities to predict the time evolution of the temperature profiles in a time-evolving, free-boundary magnetic configuration. The predictive code is called "PTRANSP", although it is really the same TRANSP code with certain input variables changed to indicate prediction rather than interpretation. In this mode of operation, the user specifies the thermal conductivity model to use as well as the boundary conditions on the magnetic equilibrium. All the heating, momentum, and particle source routines are identical for the PTRANSP and TRANSP modes of operation.

Developments to enable the full-predictive use of TRANSP over the last few years include (1) the development of a free-boundary equilibrium evolution capability with the correct flux and entropy constraints, and (2) the development of a parallel Newton-based temperature evolution capability that can accurately converge on solutions using modern thermal-conductivity models, among them GLF23, TGLF, and MMM. The free-boundary equilibrium solver, ISOLVER, allows for a self-consistent equilibrium solution that includes realistic constraints on currents in the actual set of poloidal field coils. This free-boundary evolution capability will be extended to incorporate poloidal field circuit equations in a form that can be used to develop algorithms for shape and profile control that can form the basis for actuator control. This capability can be used on present day tokamaks as well as on ITER. The newly implement transport solver, "PT_SOLVER", allows for a multi-zone treatment of the plasma transport, where different models can be used in zones representing the core, the gradient region and the edge. The solver is particularly suited to handle the stiff transport models as reflected in TGLF, GLF23, etc. A large collection of state-or-the-art, as well as older, transport models can be used for the predictive analysis.

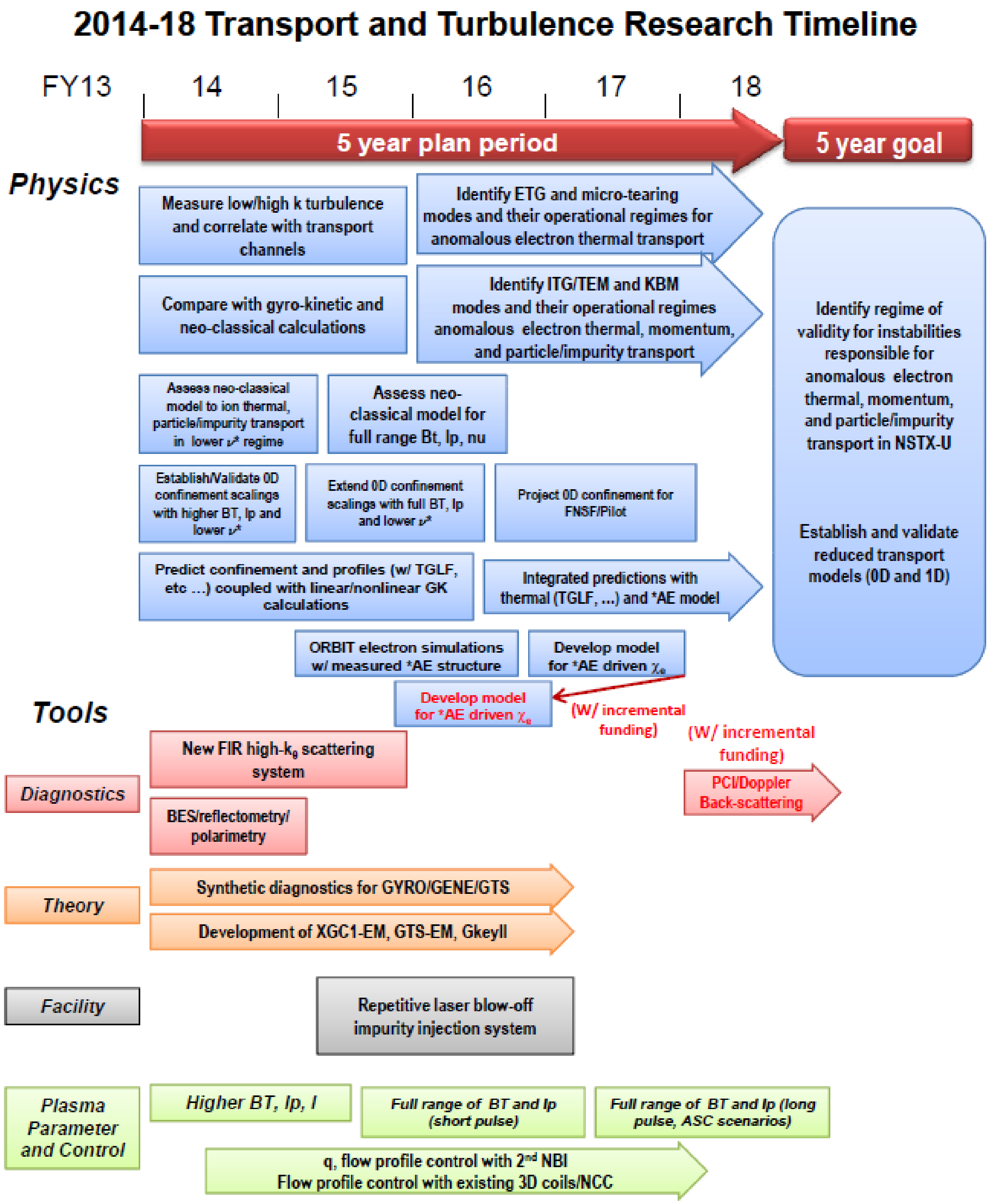
Other developments leading to an enhanced fully-predictive capability include: (3) having the NUBEAM package for calculating neutral beam and fusion product heating now running in a parallel processing mode, and (4) the full coupling to the parallel processing version of TORIC for RF heating calculations. These four capabilities, taken together, have combined to make PTRANSP a unique tool for predictive modeling of present and future tokamaks, including ITER. The code's parallel structure and algorithms are well suited to make effective use of modern parallel computing clusters and supercomputers such as exist at PPPL, NERSC and ORNL.

TGYRO

TGYRO [34] is a parallel transport manager with the ability to call multiple instances of GYRO and NEO in order to obtain steady-state temperature and density profiles. It has the capability to include turbulent fluxes from GYRO, TGLF or the simple IFS-PPPL model and neoclassical fluxes from NEO, NCLASS or simpler Hinton-Hazeltine and Chang-Hinton theories.

DEGAS 2

DEGAS 2 [62] is a Monte Carlo code for studying neutral transport in plasmas, with emphasis on fusion applications. DEGAS 2 simulates the transport and behavior of neutral species generated by plasma wall interaction (as well as neutrals sourced externally or by volumetric electron-ion recombination).


2014-18 Transport and Turbulence Research Timeline
FY13
14
15
16
17
18
5 year plan period
5 year goal
Physics
Measure low/high k turbulence and correlate with transport channels
Identify ETG and micro-tearing modes and their operational regimes for anomalous electron thermal transport
Compare with gyro-kinetic and neo-classical calculations
Identify ITG/TEM and KBM modes and their operational regimes anomalous electron thermal, momentum, and particle/impurity transport
Assess neo-classical model to ion thermal, particle/impurity transport in lower ν* regime
Assess neo-classical model for full range Bt, Ip, nu
Establish/Validate 0D confinement scalings with higher BT, Ip and lower ν*
Extend 0D confinement scalings with full BT, Ip and lower ν*
Project 0D confinement for FNSF/Pilot
Predict confinement and profiles (w/ TGLF, etc ...) coupled with linear/nonlinear GK calculations
Integrated predictions with thermal (TGLF, ...) and *AE model
ORBIT electron simulations w/ measured *AE structure
Develop model for *AE driven χe
Develop model for *AE driven χe
(W/ incremental funding)
Identify regime of validity for instabilities responsible for anomalous electron thermal, momentum, and particle/impurity transport in NSTX-U
Establish and validate reduced transport models (0D and 1D)
Tools
Diagnostics
New FIR high-kθ scattering system
BES/reflectometry/ polarimetry
(W/ incremental funding)
PCI/Doppler Back-scattering
Theory
Synthetic diagnostics for GYRO/GENE/GTS
Development of XGC1-EM, GTS-EM, Gkeyll
Facility
Repetitive laser blow-off impurity injection system
Plasma Parameter and Control
Higher BT, Ip, I
Full range of BT and Ip (short pulse)
Full range of BT and Ip (long pulse, ASC scenarios)
q, flow profile control with 2nd NBI
Flow profile control with existing 3D coils/NCC

References

[1] J. E. Menard et al., Nuclear Fusion **51** (2011) 103014.
[2] S.M. Kaye et al., Nucl. Fusion **49** (2009) 045010.
[3] Y. Ren et al., Proc. 24th Int'l. Atomic Energy Agency Fusion Energy Conference, San Diego, USA, 8-13 October 2012, CD-ROM file EX/P7-02 (IAEA, San Diego, 2012).
[4] S. M. Kaye et al., Nucl. Fusion **47** (2007) 499.
[5] S. M. Kaye et al., Proc. 24th Int'l. Atomic Energy Agency Fusion Energy Conference, San Diego, USA, 8-13 October 2012, CD-ROM file EX/7-1 (IAEA, San Diego, 2012).
[6] M. Valovič et al., Nucl. Fusion **51** (2011) 073045.
[7] ITER Physics Basis, Nucl. Fusion **39** (1999) 2178.
[8] B. Coppi and F. Pegoraro, Nuclear Fusion **17** (1977) 969.
[9] B. Kadomtsev and O. Pogutse, Nuclear Fusion **11** (1971) 67.
[10] C. Bourdelle et al., Phys. Plasmas **10** (2003) 2881.
[11] R. D. Hazeltine and H. R. Strauss, Phys. Rev. Lett. **37** (1976) 102.
[12] Y. C. Lee et al., Physics of Fluids **30** (1987) 1331.
[13] D. Stutman et al., Phys. Rev. Lett. **102** (2009) 115002.
[14] L. Delgado-Aparicio, Nucl. Fusion **47** (2009) 085028.
[15] F. Scotti et al., Proc. 24th Int'l. Atomic Energy Agency Fusion Energy Conference, San Diego, USA, 8-13 October 2012, CD-ROM file EX/P3-34 (IAEA, San Diego, 2012).
[16] H. Y. Yuh et al., Phys. Rev. Lett. **106** (2011) 055003.
[17] J. L. Peterson et al., Phys. Plasmas **19** (2012) 056120.
[18] Y. Ren et al., Phys. Plasmas **19** (2012) 056125.
[19] W. Guttenfelder et al., Phys. Rev. Lett. **106** (2011) 155004.
[20] W. Guttenfelder et al., Phys. Plasmas **19** (2012) 056119.
[21] W. Guttenfelder et al., Proc. 24th Int'l. Atomic Energy Agency Fusion Energy Conference, San Diego, USA, 8-13 October 2012, CD-ROM file TH/6-1 (IAEA, San Diego, 2012).
[22] J.E. Menard et al., Nucl. Fusion **52** (2012) 083015.
[23] D. R. Smith et al., Rev. Sci. Instrum. **83** (2012) 10D502.
[24] R. Barchfeld et al., http://meetings.aps.org/link/BAPS.2012.DPP.PP8.38
[25] J. Zhang et al., Rev. Sci. Instrum. **83** (2012) 10E321.
[26] H. Y. Yuh et al., Phys. Plasmas **16** (2009) 056120.
[27] R. Maingi et al., J. Nucl. Mater. **390-91** (2009) 440-443.
[28] C. Holland et al., Phys. Plasmas **16**, 052301 (2009).
[29] W. Guttenfelder et al., Phys. Plasmas **19** (2012) 022506.
[30] S. Kubota et al., Rev. Sci. Instrum. **77** (2006) 10E926.
[31] D. R. Smith et al., Rev. Sci. Instrum. **79** (2008) 123501.
[32] K. Tritz et al., Rev. Sci. Instrum. **83** (2012) 10E109.
[33] R.J. Hawryluk, "An empirical approach to tokamak transport", in Physics of Plasmas Close to Thermonuclear Conditions: Proceedings Course (Varenna 1979) **vol. 1**, page 19, CEC, Brussels (1980).
[34] J. Candy et al., Phys. Plasmas **16** (2009) 060704.
[35] W.X. Wang et al., Phys. Plasmas **13** (2006) 092505.
[36] B. P. LeBlanc et al., Rev. Sci. Instrum. **83** (2012) 10D527.

[37] R. E. Bell, Rev. Sci. Instrum. **77** (2006) 10E902.
[38] G.R. McKee, Nucl. Fusion **41** (2001) 1235.
[39] J. Zhang, et al., Plasma Phys. Control. Fusion **55** (2013) 045011.
[40] J. Canik et al., Proc. 24th Int'l. Atomic Energy Agency Fusion Energy Conference, San Diego, USA, 8-13 October 2012, CD-ROM file EX/P7-16 (IAEA, San Diego, 2012).
[41] W. Dorland et al., Phys. Rev. Lett. **85** (2000) 5579.
[42] E. Mazzucato et al., Phys. Rev. Lett. **101** (2008) 075001.
[43] D. R. Smith et al., Phys. Rev. Lett. **102**, (2009) 225005.
[44] Y. Ren et al., Phys. Rev. Lett. **106** (2011) 165005.
[45] N.M. Gorelenkov et al., Nucl. Fusion **50** (2010) 084012.
[46] K. H. Burrell, Physics of Plasmas **4** (1997) 1499.
[47] J. E. Kinsey et al., Physics of Plasmas **14** (2007) 102306.
[48] T. S. Hahm and K. H. Burrell, Phys. Plasmas **2** (1995) 1648.
[49] R. E. Waltz and R. L. Miller, Physics of Plasmas **6** (1999) 4265.
[50] S.P. Gerhardt et al., Nucl. Fusion **52** (2012) 083020.
[51] W.A. Houlberg et al., Phys. Plasmas **4** (1997) 9.
[52] W.X. Wang, et al., Computer Phys. Commun. **164** (2004) 178.
[53] E. Belli and J. Candy, Plasma Phys. Control. Fusion **50** (2008) 095010.
[54] A. G. Peeters and C. Angioni, Phys. Plasmas **12** (2005) 0725157.
[55] T. S. Hahm et al., Phys. Plasmas **14** (2007) 072302.
[56] J. K. Park et al., Nuc. Fusion (2013) *in press.*
[57] Y. Kosuga et al., Phys. Plasmas **17** (2010) 102313.
[58] S. Ku, C.S. Chang, and P.H. Diamond, Nuclear Fusion **49** (2009) 115021.
[59] R. Hulse, Nucl. Technol. Fusion **3** (1983) 259.
[60] K. Behringer, Description of impurity code 'STRAHL', Technical Report JET-IR(87)08, JET Joint Undertaking, Oxfordshire: Abingdon (1987).
[61] L. Delgado-Aparicio, et al., Nucl. Fusion **51** (2011) 083047.
[62] D. P. Stotler and C. F. F. Karney, Contrib. Plasma Phys. **34** (1994) 392.
[63] F.L. Hinton and R.D. Hazeltine. Rev. Mod. Phys. **48** (1976) 239.
[64] C.S. Chang and F.L. Hinton. Phys. Fluids **25** (1982) 1493.
[65] G.Y. Park, C.S. Chang, et al, Physics of Plasmas **17** (2010) 102503.
[66] G.M. Staebler, J.E. Kinsey, and R.E. Waltz, Phys. Plasmas **12** (2005) 102508.
[67] T. Rafiq et al., http://meetings.aps.org/link/BAPS.2010.DPP.NP9.2
[68] K. Tritz, et al., "Effects of Global Alfven Eigenmodes on Electron Thermal Transport in NSTX," Invited talk: 52st APS Division of Plasma Physics Meeting, November 8-12, 2010, Chicago, IL
[69] N. A. Crocker et al., Plasma Phys. Control. Fusion **53** (2011) 105001
[70] K. Tritz, et al., http://meetings.aps.org/link/BAPS.2012.DPP.GO6.4
[71] K.L. Wong et al., Phys. Rev. Lett. **99** (2007) 135003.
[72] J.F. Drake et al., Phys. Rev. Lett. **44** (1980) 994.
[73] A. Diallo et al., Proc. 24th Int'l. Atomic Energy Agency Fusion Energy Conference, San Diego, USA, 8-13 October 2012, CD-ROM file EX/P4-04 (IAEA, San Diego, 2012).
[74] R. E. Waltz and J. Candy, Phys. Plasmas **12** (2005) 072303
[75] Y. Camenen et al., Plasma Phys. Control. Fusion **52** (2010) 124037.
[76] A.G. Peeters et al., Nucl. Fusion **51** (2011) 094027.

[77] M. Kotschenreuther et al., Comp. Phys. Comm. **88** (1995) 128.
[78] J. Candy and R. E. Waltz, Phys. Rev. Lett. **91** (2003) 045001.
[79] F. Jenko et al., Phys. Plasmas **7** (2000) 1904.
[80] A.G. Peeters et al., Computer Phys. Commun.**180** (2009) 2650.
[81] E. V. Belova et al., Phys. Plasmas **7** (2000) 4996.
[82] A. Pankin et al., Computer Physics Communications **159** (2004) 157.
[83] M. Brambilla and T. Krücken, Nuclear Fusion **28** (1988) 1813.