Chapter 3 - Transport and Turbulence

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3 Transport and Turbulence

3.1 Understanding and Optimizing Transport & Turbulence in the Spherical Torus

The low toroidal field of NSTX, approximately a factor of five lower than that in conventional aspect ratio devices, leads to plasma operations in parameter regimes that are different than those at higher aspect ratio, which in turn lead to new opportunities to extend and benchmark theory and to make new diagnostic measurements. The enhanced toroidicity and natural shaping at low aspect ratio is predicted to lead to reduced microturbulence levels, and thus reduced transport associated with the microturbulence. Enhanced toroidicity also results in higher trapped particle fractions, which can influence Trapped Electron Mode (TEM) turbulence and zonal flow damping. Furthermore, the low toroidal field and near Mach flow yields large values of the ExB shearing rates, believed to be important for the suppression of long wavelength microturbulence and its associated transport. NSTX operates in regimes whose plasma collisionality is similar to that at conventional aspect ratio (and to that of ITER), but in which both the plasma beta, β_{th}, and the electron and ion gyroradii, ρ_e, ρ_i respectively, can be up to a factor of 10 greater than those at higher toroidal field and aspect ratio. The high β (up to 40%) enables NSTX to explore electromagnetic and stochastic magnetic effects that may influence transport, and the large electron gyroradius (0.1 mm) allows for a direct measurement of spatially-resolved electron-scale turbulence.

Because of the expanded parameter regime in which NSTX operates, the results will naturally extend and challenge theory. The robustness of theories being used for extrapolation to future devices at higher aspect ratio will be tested by extending them into a wider operating regime at low aspect ratio. Thus, the validity of these theories will be assessed, and this will aid in identifying modifications and additions to improve their physics basis and make them more relevant to operational scenarios at all aspect ratio. Answers to these questions will necessarily deepen our understanding of basic toroidal confinement physics, which will naturally lead to more confidence when extrapolating this physics to future devices.

Not only will the physics theories themselves be tested, but complex numerical calculations that will push the limits of present computational resources will be necessary to gain this understanding. For instance, the non-linear simulation of short-wavelength, electron-scale instabilities will require use of state-of-the-art computational tools, especially under circumstances where scale separation between electrons and ions (i.e, high and low-k) modes, is not possible. NSTX operation does offer some regimes where such scale separation may be possible, regimes in which anomalous ion transport is low and thus the ions can be treated adiabatically, but the difficult issue of turbulence spreading may require fully kinetic treatment of the ions.

These requirements, and the validity of the results of the calculations, will be determined through extensive benchmarking. This benchmarking procedure, which has been ongoing through the life of the NSTX project, and has recently been called out as Verification and Validation by the wider fusion community, will be a true test of the validity of the codes (Verification) and transport physics models (Validation). As the codes for simulating the plasma transport become more sophisticated, so too will the diagnostics for measuring this turbulence and its associated transport. This will offer the opportunity to test theory at all levels, from the specific fluctuating quantities to an overall level of transport. Agreement between actual measurements and those from synthetic diagnostics built into the codes at all these levels will give enhanced confidence in our understanding of the processes controlling the plasma transport.

The goal of this research is to develop a comprehensive picture of transport and turbulence in NSTX by combining and benchmarking results from measurement, analysis and theory, with an ultimate target of developing a fully predictive tool for energy, particle and momentum transport that can be used with confidence for predicting performance of future devices, both ST and non-

ST. NSTX research is critical to justifying, and perhaps modifying, key assumptions for achieving the performance objectives of future devices. In particular, for an ST-based Component Test Facility, crucial assumptions include those of achievable confinement enhancement factors and operation in the Hot-Ion H-mode regime. Global confinement and ion transport and turbulence research at high P_{heat}/P_{LH}, including understanding the role of ExB flow shear in suppressing ion-scale microturbulence, addresses these assumptions. Of overriding importance for both future ST and non-ST burning plasma devices is the optimization of neutron production and/or fusion gain, both of which are tied directly to understanding and optimizing electron transport, a task for which NSTX is ideally suited.

Laying the foundation for this comprehensive understanding and predictive capability will necessarily involve coordinated research with other major devices both in the U.S. and internationally, and will allow for discharge scenario development in NSTX and in future devices such as a possible NSTX follow-on (NHTX), an ST-based Component Test Facility, and longer-range targets such as an ARIES-ST prototype reactor. Such an understanding will allow for

a) confident extrapolations of transport and turbulence properties to ensure that confinement requirements can be satisfied at high input powers (greater than the L-H threshold power) and high power density divertors (e.g., P/R),
b) understanding and extrapolating momentum transport to assure adequate rotation and ExB shear for the suppression of microturbulence and MHD modes,
c) determining regimes in which plasma profiles for current drive and fusion production are optimized.

Further, the detailed physics understanding gained from this coordinated effort will aid in the prediction of performance of confidence for success of future devices at conventional aspect ratio, such as ITER.

3.2 Overview of Research Plans for FY2009-2013

The unique operating regime of NSTX will allow exploration of the transport and turbulence properties that govern toroidal confinement. Both as a complement to conventional aspect ratio tokamaks and as a confinement concept in its own right, NSTX will move in a direction to identify and control the fundamental physics mechanisms that are most important in determining energy, particle and momentum transport. The key transport goals for the period from 2009 to 2013 are:

- To verify global scaling trends in an expanded parameter space and to establish the dependence of confinement on aspect ratio,
- To establish conditions for neoclassical ion transport through coupling low-k turbulence measurements to results of non-linear gyrokinetic simulations addressing both neoclassical and turbulence physics,
- To determine the role of both low-k and high-k turbulence, through measurement and non-linear theory, in setting the level of anomalous electron transport,
- To understand momentum transport and to determine the source of the plasma rotation/radial electric field and its influence on both low- and high-k turbulence,
- To understand the relation of particle and impurity transport throughout the plasma to measurements and simulations of microturbulence, ultimately to
- To participate in national and international efforts to develop a validated, fully-predictive tool for developing confinement-optimized discharge scenarios for both NSTX and future ST and non-ST devices.

A summary of the key physics results and issues, what is needed in order to gain a better understanding of them, and how NSTX upgrades will allow this is as follows. In present spherical torus experiments, the energy confinement time in neutral-beam heated H-modes has different parametric dependences than it does at higher aspect ratio, scaling almost linearly with

B_T ($B_T^{0.9}$), but more weakly with plasma current ($I_p^{0.4}$). The ion transport is typically inferred to be near neoclassical levels, and the ion turbulence is apparently suppressed by large shear in the plasma flow. In contrast, electron energy transport is observed to be anomalous, and it dominates the overall energy loss.

At least four micro-instabilities could play a role in anomalous electron transport in tokamaks and STs: micro-tearing modes (electromagnetic), collisionless trapped electron modes – CTEM (electrostatic), electron temperature gradient modes – ETG (electrostatic), and Global Alfven Eigenmodes – GAE (Alfvenic). Micro-tearing, ETG, and GAE modes have been correlated in a preliminary way with anomalous electron transport under different discharge conditions. Multiple instabilities may be present simultaneously, and isolating the effects of individual instabilities is difficult. The baseline approach for developing an understanding of the source of anomalous electron transport in the ST is to increase the operating toroidal field and plasma current, and, along with Lithium conditioning, reduce the collisionality by up to an order of magnitude. The lower collisionality can result in suppression of micro-tearing modes. Higher magnetic field would provide access to reduced fast-ion instability drive and enable the reduction (possibly suppression) of GAE modes. Thus, access to higher magnetic field would provide control of the onset of electromagnetic and Alfvenic modes, and separate the impact of these modes from electrostatic modes.

Higher field and current will also reduce neoclassical ion transport by up to an order of magnitude (due to smaller orbit sizes and reduced collisionality) thereby enhancing the relative importance of anomalous ion transport in the overall ion transport. This capability would also provide new insight into the underlying causes of anomalous momentum transport (most likely ITG and/or CTEM) and the flow-shear suppression of ion turbulence in the ST. Reduced/suppressed ion turbulence is especially important for achieving a “hot-ion” H-mode regime for high fusion gain in next-step ST-based CTF devices.

Overall, the planned major upgrades of NSTX, which include replacing the center stacks in both experiments and the installation of a Liquid Lithium Divertor, would greatly enhance the ability to isolate the roles of different micro-instabilities in anomalous electron and ion transport by doubling the achievable toroidal magnetic field and thereby increasing the accessible range of magnetic field variation to over a factor of three and expanding the range of collisionality by up to an order of magnitude. Importantly, the minimum collisionality made accessible by the major upgrades would approach (to within a factor of two) the collisionality values expected of next-step STs assuming comparable Greenwald density fractions. Existing high-k diagnostics and planned low-k diagnostics (BES) will provide the ability to distinguish between the electrostatic CTEM and ETG modes, and BES and high-k may also be capable of measuring GAE fluctuations. In parallel, and coupled to the fluctuation and transport measurements, theory model validation will permit extrapolation to future devices.

Detailed results and plans follow.

3.3 Transport and Turbulence Results and Plans by Topical Area

3.3.1 Energy Transport

Understanding and ultimately being able to control the sources of ion and electron transport is critical to the success of creating high performance plasmas in present day experiments. Furthermore, it is equally critical for being able to extrapolate to future device operation through high-confidence predictions. One of the goals of NSTX is to develop a comprehensive picture of energy transport for both electrons and ions. This can be done using a multi-faceted approach whose elements include:

- Detailed profile measurements
- Transport analysis resulting in energy, momentum and particle fluxes and transport coeffiecients
- Measurements of turbulence spectra
- Turbulence code predictions of fluxes and turbulence spectra from synthetic diagnostics, using the measured profiles as input.

Of particular importance in this area of research is the study of electron transport, which, in NSTX, is anomalous and dominant in all operational regimes. NSTX is particularly suited to study the electron turbulence and transport physics, since in many regimes the ion transport is at or near neoclassical levels, leading to an electron-transport dominated operating regime. Because of the high neutral beam injection energy relative to the electron temperature in NSTX, the electrons are preferentially heated, by a 2:1 ratio, emulating the dominant electron heating in ITER as well as in possible future ST devices. Furthermore, the low toroidal field in NSTX leads to electron gyroradius scale-lengths that are approximately 0.1 mm, meaning that microturbulence on these scales is readily measurable with high spatial resolution using microwave scattering technology. These attributes, coupled with state-of-the-art computational tools, make NSTX an excellent laboratory in which to study electron transport.

A major part of the transport research will be the use of both linear and non-linear gyrokinetic calculations. These calculations will cover the range of neoclassical transport of ions, impurities and momentum using a kinetic (i.e., finite banana width and ultimately multiple species and full Larmor radius effects) approach, to a determination of the unstable microinstabilities and their characteristics. An important part of these calculations will be detailed benchmarking of codes and physics models with respect to one another and with respect to measured quantities. This Verification and Validation has been ongoing, but more sophisticated approaches will allow for more detailed benchmarking on a variety of levels. For instance, synthetic diagnostics will be built into the various simulation codes, and these will allow us to make direct comparisons with equivalent measured data such as the plasma density fluctuations. Comparisons will be made between the measured and simulated primary characteristics of the fluctuation spectra, such as δn and cross-phase, as well as secondary characteristics, including Zonal Flows, and wavenumber and frequency spectra. At a higher level, local heat fluxes or thermal diffusivities calculated by the codes will be compared to those inferred from experiment. Ultimately, a physically valid and relevant model will yield agreement with measurements at those levels and at the highest level, which is a predication of global trends (i.e., the parametric dependence of confinement scaling). A successful Verification & Validation procedure will lead to a high confidence predictive tool for extrapolation to future devices.

Since transport and turbulence are inexorably related, they will be integrated into a single, coherent plan.

3.3.1.1 Global Confinement

Results

Dedicated global confinement studies that have been carried out over the last several years have focused on several issues: to establish the basic parametric dependences of the L-H threshold power and energy confinement at high heating power, and to address global confinement issues of particular importance to ITER and for which NSTX is particularly suited.

Early studies of the L-H threshold in NSTX have indicated an apparent dependence of the threshold power on I_p (Fig. 1), unlike at higher aspect ratio, and that the L-H transition occurred at lower powers with high-field-side gas fueling. It was also found that plasma shape affected the threshold power, most notably triangularity, X-point height and configuration.

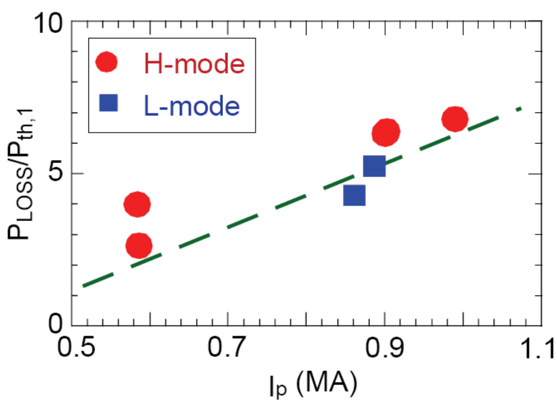


Fig. 1 L-H power threshold normalized to the ITER-scaling value [1] as a function of plasma current. There is a clear plasma current dependence in the threshold power that is not reflected in the scaling.

Dedicated confinement scans to elucidate the basic parametric dependences, such as the I_p and B_T scaling, were carried out in H-mode plasmas with elongation κ of 2.1 and triangularity δ of 0.6 at fixed beam power (P_{input}=4 MW) and at similar densities. These dedicated studies have revealed confinement trends that differ from those at conventional

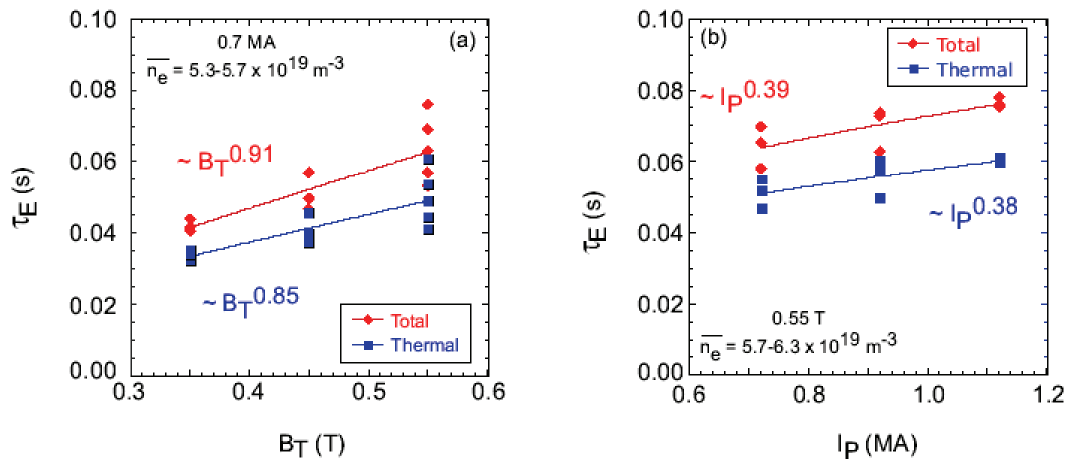


Fig. 2 Thermal and global confinement time scalings as a function of (a) B_T and (b) I_p from dedicated scans at constant injected beam power, 4 MW, and density.

aspect ratio, as is illustrated in Fig. 2, where the results of the B_T and I_p scans at constant I_p and B_T respectively are shown. Unlike at conventional aspect ratio, where the dependence of τ_E on B_T is weak ($\tau_E \sim B_T^{0.15}$ in the ITER98(y,2) scaling [2]), the dependence on B_T in NSTX is stronger, with $\tau_E \sim B_T^{0.9}$ for both thermal and global confinement time. Alternatively, the dependence on plasma current is much weaker than what is observed at conventional aspect ratio, with $\tau_E \sim I_p^{0.4}$ as compared to $I_p^{0.9}$ for ITER98(y,2). The results of these dedicated scans [3, 4] verify trends that were extracted from earlier data by statistical means [5].

The results of the dedicated scaling experiments also showed a very strong dependence of confinement on collisionality, as is seen in Fig. 3. The scan was conducted at constant ρ_e, β and q, with the variation in ν_e^* being associated with the variation in I_p and B_T at constant I_p/B_T. The normalized confinement is seen to scale essentially inversely with ν_e^*. The thermal transport in both the electron and ion improves as collisionality is reduced. If this scaling holds at even lower collisionality values, large increases in the global confinement could be realized.

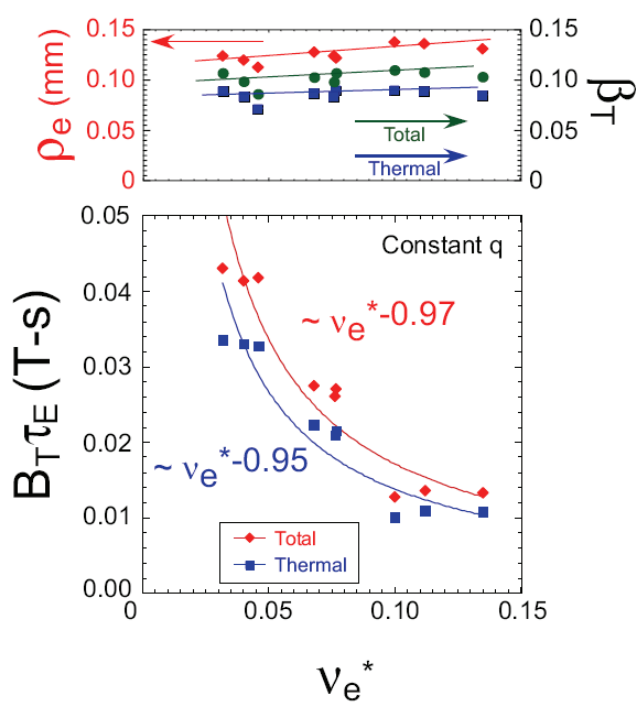


Fig. 3 Results of collisionality scan at fixed ρ_e, β and q (I_p/B_T).

The confinement experiments have focused also on studying the dependence of confinement on plasma β, an issue that is critical to assessing the potential for success of the ITER Advanced Tokamak scenario, which will operate at higher β than the standard target. Key to this is whether there is the degree of degradation (if any) of confinement with plasma beta. The results from standard aspect ratio

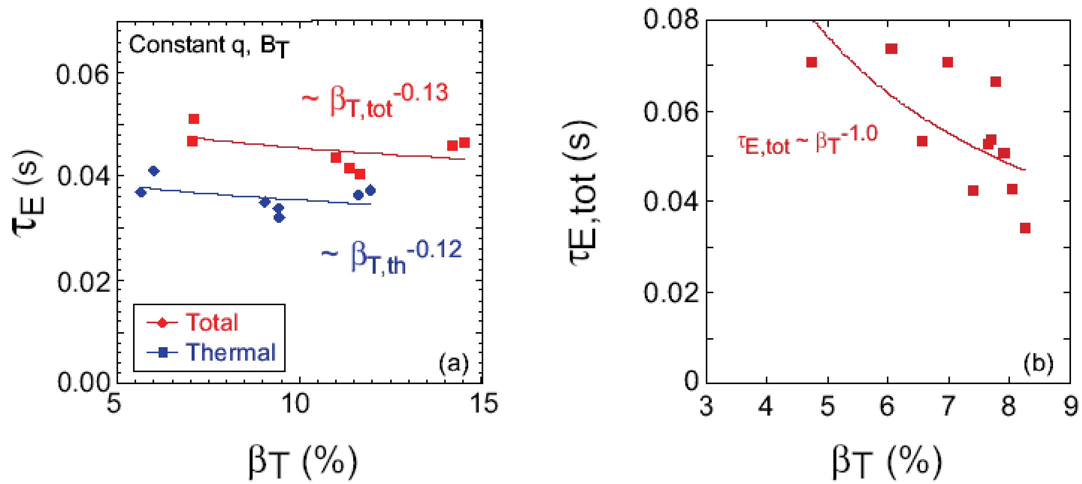


Fig. 4 Scaling of H-mode confinement with β at fixed B_T, I_p for a plasma with (a) κ=2.1, δ=0.6 and (b) κ=1.85, δ=0.4

tokamaks are mixed; while JET and DIII-D experiments [6,7] have shown no degradation of τ_E on β, experiments run by JT-60U and ASDEX-U [8,9] have shown degradation that is similar to what is predicted by the ITER98(y,2) scaling, where $B\tau_E \sim \beta^{-0.9}$. One difference between the two sets of scans is that the results showing the strong degradation were from discharges that had lower κ and δ. NSTX is particularly well-suited to address this problem, in that not only can a large range of β be covered in a scan, but shape comparisons can be performed within the NSTX device itself. The results of the scans are shown in Fig. 4, where the β scan was performed by varying power at fixed I_p and B_T. Across this range of power and beta, other dimensionless variables such as ν^* and ρ^* were held constant to within 20%. In the case with strong shaping, κ =2.1 and δ=0.6, the confinement time showed no degradation with β, while in the more weakly shaped plasmas, with κ=1.8-1.9 and δ =0.4, the confinement time was seen to degrade with β rather strongly, with $\tau_E \sim \beta^{-1.0}$.

One of the key results of the scan showing the degradation is the variability of the edge stability, as reflected by the variability of the ELM severity. In the high elongation/triangularity discharges, only small, Type V ELMs were observed for all powers, while in the lower κ/δ scans, the ELM type varied from Type III at low power to Type I at high power. In order to assess better the dependence of confinement on β, it is necessary to compare plasmas which similar ELM characteristics. Lithium evaporation and LLD provide a means to do this.

Significant increases in plasma confinement were seen with Lithium evaporation. An example of this is shown in Fig. 5, which compares a 4 MW discharge with no Lithium to 2 and 3 MW discharges with Lithium evaporation. The stored energies in the 2 MW Lithium and 4 MW no Lithium cases were essentially the same, indicating a near doubling of the energy confinement

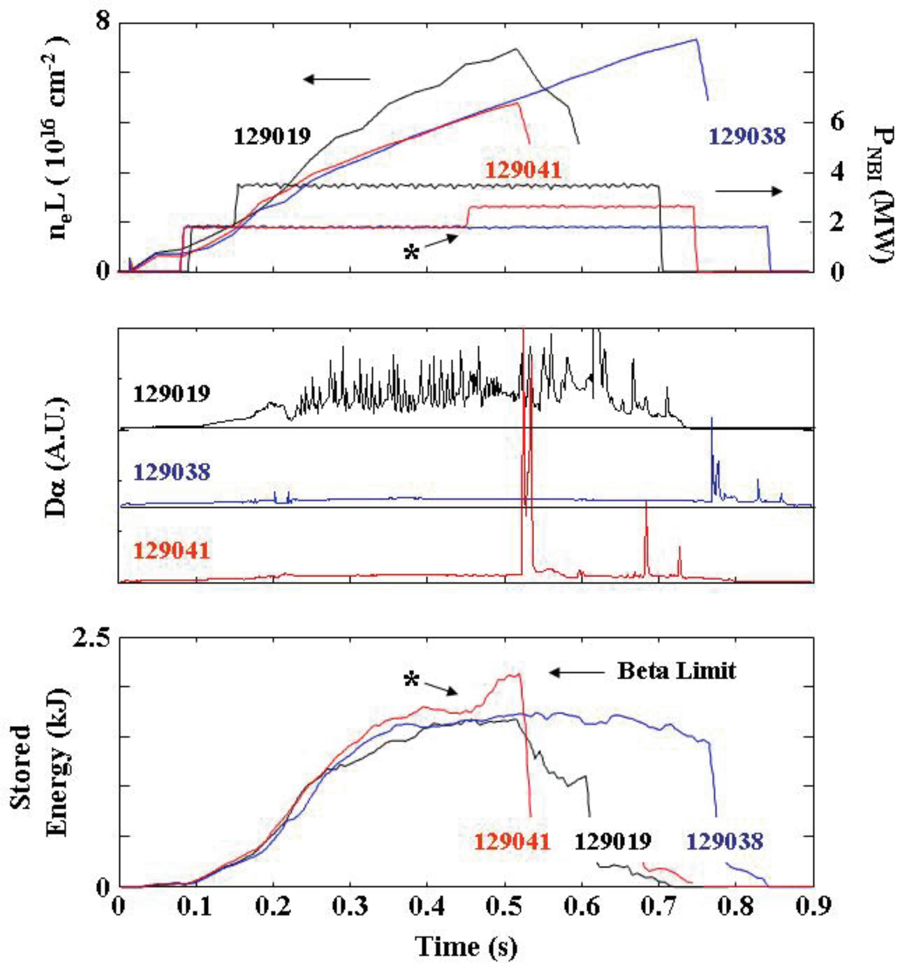


Fig. 5 Comparison of 4 MW no Lithium discharge to 2 and 3 MW discharges with Lithium evaporation.

time. This confinement improvement is reflected by an increase in the $H_{98y,2}$ enhancement factor from 0.85 in the no Lithium discharge to 1.30 in the Lithium discharge. The 3 MW Lithium discharge is β-limited at this relatively low power. Lithium evaporation also was seen to suppress ELMs during the H-mode phase. The Lithium evaporation and Liquid Lithium Divertor provide a set of tools for studying the L-H threshold and the ramifications of ELM stability. In particular, these tools will allow for an assessment of the β-dependence of confinement (as described above) in lower κ/δ discharges that are ELM-free due to the Li conditioning.

Plans

A key question that needs to be answered is whether the B_T and I_p scalings observed in NSTX, which differ from those at higher aspect ratio, are due to the relatively low B_T and I_p in the present operating space, or does confinement at low aspect ratio continue to scale in the present manner at higher B_T and I_p? Are there other dependences, such as with β and ν^*, that affect the confinement scalings? ν^* will be reduced by up to an order of magnitude with the new centerstack and LLD, bringing the operating space in this parameter closer to that of NHTX and ST-CTF. L-H studies are important for NHTX and ST-CTF, which need to operate well above the L-H threshold to allow large radiated power. NSTX needs to determine how the L-H threshold power continues to scale with B_T, I_p and configuration.

<u>2009-2011:</u>

Studies will be carried out which will determine the quantitative dependence of the L-H threshold power on I_p, B_T and plasma shape. In addition, the effect of rotation on the L-H threshold will be studied using n=3 magnetic braking and HHFW. Experiments will be carried out to determine the dependence of confinement on aspect ratio, both within NSTX and in conjunction with conventional aspect ratio devices (e.g., an NSTX/DIII-D similarity experiment) in order to optimize NHTX and ST-CTF designs. The effect of lower collisionality and recycling in the presence of Lithium PFCs on the L-H threshold and confinement will be established through global and local studies. Finally, the source of the variation of β degradation of confinement will be explored in both strongly and weakly shaped plasmas while using Lithium evaporation and the LLD to suppress ELMs, to understand whether it is plasma shape or edge stability that results in the varied scaling results with this parameter.

2012-2013:

The new centerstack will be installed and operational during this time period, giving a factor of two increase in the achievable range and magnitude of both B_T and I_p. Operation at higher B_T and I_p will allow for determining whether the difference in the B_T and I_p dependences between NSTX and conventional aspect ratio tokamaks is due to differences in B_T, β_T, ν^* or whether it is due to differences in aspect ratio. The higher T_e expected at higher B_T, coupled with operation with Lithium PFCs, will allow exploration of confinement trends at collisionalities reduced by up to an order of magnitude to a regime that is closer to that expected for NHTX and ST-CTF. This will allow an assessment of the confinement scaling with collisionality in this regime. Also during this period, L-H threshold studies will be carried out to determine whether the threshold power continues to scale with I_p in this expanded parameter range. additional divertor diagnostics will enable evaluation of the role of the X-point position in determining the L-H power threshold. Experiments with the 2nd NBI (incremental budget) will be carried out to study trends at higher power and with different heating deposition profiles.

3.3.1.2 Ion Turbulence and Transport

Results

Ion transport in NSTX H-mode plasmas has been determined to be at or near neoclassical levels in the gradient region (e.g., r/a=0.3-0.7) of well-controlled and relatively MHD-queiscent H-mode plasmas. It was found further, that while the ion transport did not exhibit much variation with B_T, it was this channel, and, in fact, the variation of the neoclassical transport that was predominantly responsible for the scaling of global confinement with plasma current [3]. The variation of the ion thermal diffusivity profiles with I_p and B_T from these dedicated scans are

shown in Fig. 6. As can be seen, while the ion thermal diffusivity outside of r/a=0.5 did not vary much at different values of B_T for fixed I_p, there was a much stronger variation in the I_p scan, with χ_i decreasing with increasing plasma current. Also shown in the figure is the range of neoclassical transport, given by the cross-hatched rectangular region for the B_T scan, and by the solid, color-coded rectangles for the I_p scan. For this latter scan, the rectangles indicate the neoclassical levels in the region from r/a=0.4 to 0.7. For both scans, the neoclassical levels were determined by the GTC-NEO code [10], which performs a gyrokinetic calculation based on measured plasma and impurity profiles, and which includes non-local effects, such as those due to the finite banana-width, to determine neoclassical levels.

A picture in which the ion transport is near the neoclassical level during the H-phase of the NSTX discharges, dropping from an anomalous level during the L-phase, is supported by both linear and non-linear gyrokinetic calculations. Shown in Fig. 7 are results from linear GS2 flux-

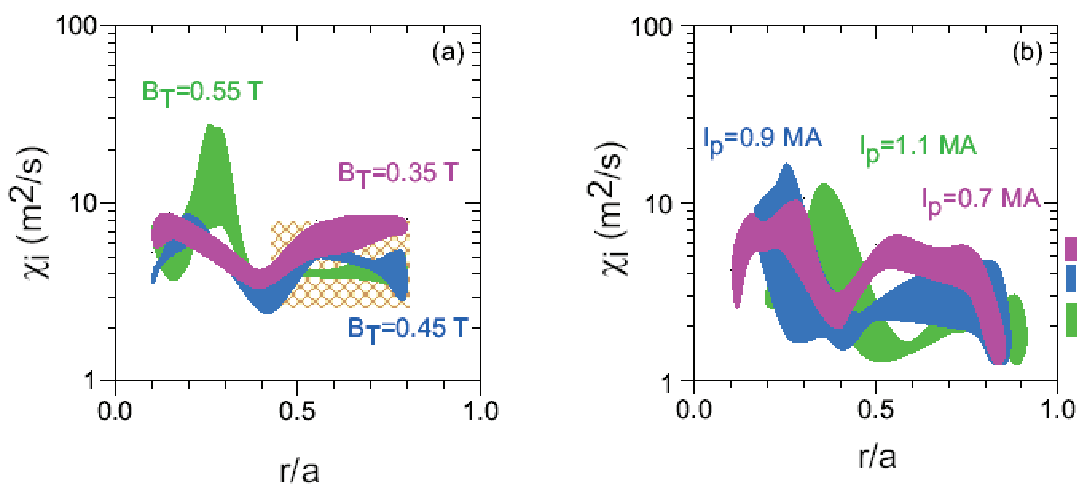


Fig. 6 Ion thermal diffusivity at fixed heating power and density as a function of (a) B_T at fixed I_p (b) I_p at fixed B_T. The cross hatched box in (a) and the color coded rectangular boxes in (b) indicate levels of neoclassical transport as determined by GTC-NEO.

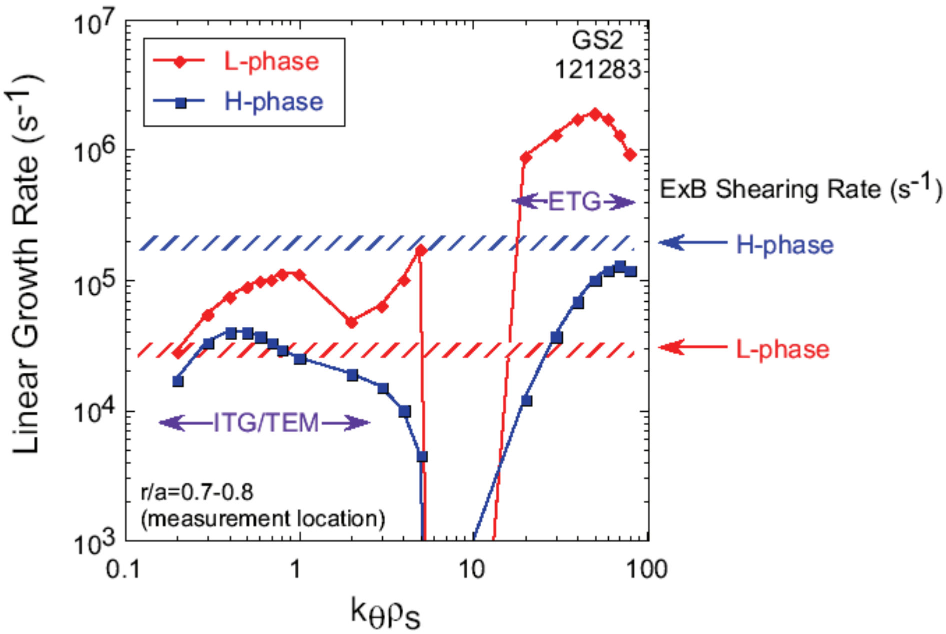


Fig. 7 Linear growth rates as a function of $k_\theta\rho_s$ for an L-mode phase and a subsequent H-mode phase. Also shown are the ExB shearing rates for both phases.

tube calculations, showing much larger growth rates for low-k modes during the L-phase than during the H-phase of a selected discharge. Non-linear, global GTS calculations indeed show that the neoclassical ion heat flux is greater than the turbulence-driven flux during the H-phase of these discharges. Also adding to the suppression of these low-k modes during the H-phase is an increased level of ExB shearing rate, reaching values of up to five times the linear growth rate during the H-phase (see Fig. 6). Furthermore, the magnetic shear is seen to have a profound effect on the ion transport as well in L-mode plasmas, with the transport being anomalous in low magnetic shear or monotonically increasing q plasmas, while the transport drops to near the neoclassical level in reversed magnetic shear plasmas, giving rise to ion Internal Transport Barriers in RS plasmas [4, 11-12].

Ion transport barrier physics has been studied further in the Enhanced Pedestal H-mode plasmas, plasmas exhibiting much higher pedestal ion and electron temperatures than in standard H-modes, where very strong T_i gradients are observed in regions of zero toroidal and zero poloidal

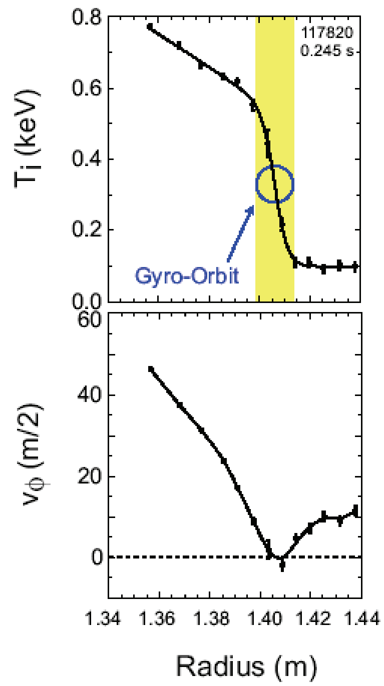


Fig. 8 Ion temperature gradient and toroidal velocity near plasma edge during an Enhanced Pedestal H-mode plasma

velocity (Fig. 8). The gradients are so strong that their scale lengths are of order the ion gyroradius (~1 cm). Standard neoclassical theory would suggest gradients to be limited to scales of order the banana width, and thus the smaller gradient scale lengths seen in NSTX may be indicative of neoclassical banana orbit squeezing [13]. Analysis to test this theory is underway, as is determining the effect that these strong gradients would have on destabilization of low-k microturbulence (e.g., ITG modes).

Plans

An important goal of ion transport research on NSTX is to determine whether a future ST such as NHTX or an ST-CTF will operate in the ion neoclassical regime. Operation at higher B_T, I_p and lower ν^* will be in a regime in which $\chi_{i,neo}$ is predicted to be reduced by up to an order of magnitude from the range in present operating regimes. Further, ITG and this could make neoclassical transport sub-dominant to turbulent transport. Operation with the new center-stack readily allow a test of this possible transition between the neoclassical- and turbulence-dominated regimes.

<u>2009-2011:</u>

The study of ion energy transport will continue to determine the conditions under which ions are governed by neoclassical transport vs either electrostatic or electromagnetic turbulent transport. This will be done experimentally by actively changing the T_i/T_e driving/damping terms for ITG/TEM turbulence in L- and H-mode using RF injection into NBI discharges. The ExB shear damping term of ITG turbulence will be controlled through n=3 magnetic braking using the Non-

Resonant Magnetic Perturbations (NRMP) in fine steps to slow the plasma down, and determine the ExB level at which the ITG is sustained and ion transport becomes anomalous. Low-k turbulence measurements will be made using a Beam Emission Spectroscopy diagnostic, implemented in 2009, and the turbulence will be compared to ion transport and predictions of microturbulence levels and transport from non-linear gyrokinetic codes, for both neoclassical and turbulent driven transport. BES and Doppler reflectometry will be used to assess the role of Zonal Flows in the plasma core and at the edge. All these results will be coupled to results from non-linear gyrokinetic calculations, an input to which will be the full radial electric field determined from v_ϕ, v_θ and ∇p measurements. This will allow a preliminary validation of neoclassical and low-k turbulent transport theories. Ion Internal Transport Barrier studies will continue, focusing both on the potential for improved core fusion performance, and on regimes of strong T_i gradients and their relation to zonal flows, current profile and low-order rational q-values. The strong T_i gradient regions and possible orbit squeezing effects will allow validation of neoclassical theory at low aspect ratio.

2012-2013:

The higher B_T and I_p, and the lower collisionality operation with the new centerstack will allow for an extension of the study of χ_i to determine whether neoclassical transport still dominates over turbulence-induced transport in the H-mode in this extended parameter regime. In particular, will $\chi_{i,neo}$ be low enough at the lower ν^* for turbulent transport to become dominant? Will the reduction in ion-scale turbulence by ExB shear still be expected at the higher B_T and I_p and lower collisionality? This is coupled to the important area of momentum transport, which will be discussed in a later section, and the determination of whether the source of ion transport changes as the parameter regime is extended will be addressed also by direct measurement of the ion-scale turbulence by BES. The relation of inferred ion diffusivity to low-k fluctuations will be assessed in more detail using the low-k BES diagnostic, and this, coupled with results from non-linear gyrokinetic calculations, will allow for a very high-level test of neoclassical and ITG theory in the NSTX plasmas. Zonal flow measurements by BES will be made both near the core and edge, which will enable a test of the possible q dependence. Studies of ion transport barrier physics will continue, with new information over a range of B_T and I_p measured by BES. Neoclassical theory that takes into account multiple species and full Larmor radius effects will be developed during this period. Internal control coils will be used for finer control of magnetic braking to determine the role of ExB for suppressing low-k modes and affecting ion transport (incremental budget). These comparisons will allow us to draw definitive conclusions regarding the source of ion transport under various operating conditions, and they will also allow for an assessment of the non-local nature of turbulence due to the large ρ^*. These more comprehensive studies will help establish a predictive understanding of the transition between neoclassical and turbulent ion transport, and how to predict ion transport in future devices with higher confidence.

3.3.1.3 Electron Turbulence and Transport

Results

NSTX operates in an electron-transport loss dominated regime in both L- and H-modes. It was

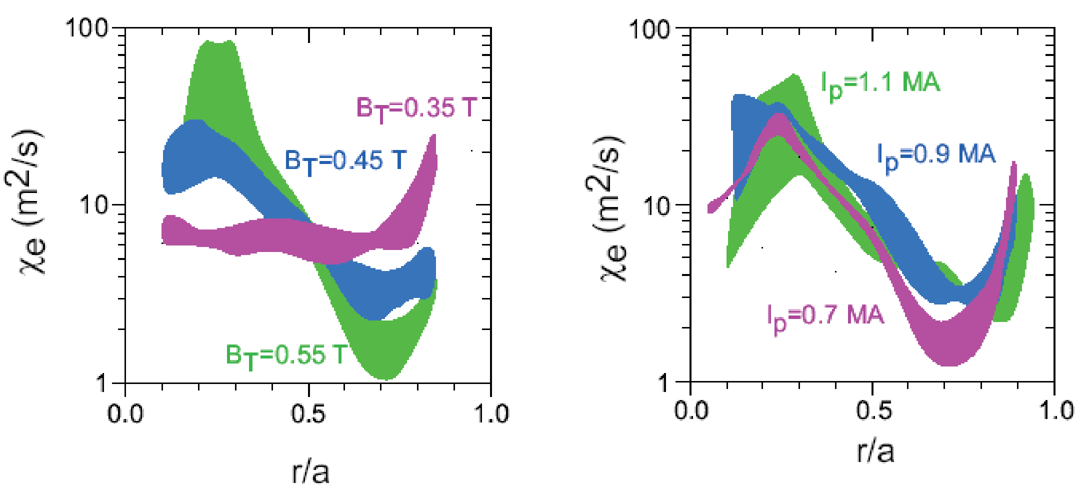


Fig. 9 Electron thermal diffusivity at fixed heating power and density as a function of (a) B_T at fixed I_p (0.7 MA) (b) I_p at fixed B_T (0.55 T).

the variation of electron transport that was found to govern the B_T scaling in the H-mode, as can be seen in Fig. 9. Seen in this figure is a strong decrease in χ_e outside of r/a=0.5 with increasing

B_T that led to a broadening of the electron temperature profiles. Inside of this radius, the χ_e increases with increasing B_T, although the temperatures in this region are comparable for all values of the toroidal field. Thus, the increase in χ_e within r/a=0.5, where the total plasma volume is relatively small, does not significantly impact the overall improvement of electron and global confinement with increasing toroidal field. The change in electron thermal diffusivity in these two regions of the plasma is qualitatively consistent with the change in the measured high-k fluctuation levels with toroidal field at these two locations, as is seen in Fig. 10. Shown in this figure are results from the microwave scattering diagnostic, which reveals a higher fluctuation level at higher B_T in the core of the plasma (r/a~0.25), while the fluctuation levels are lower at the higher field at r/a~0.75. Furthermore, linear and non-linear theory simulations indicate that ETG modes with the development of radial streamers are unstable in the outer part of the plasma (r/a>0.5) for the lowest toroidal field (Fig. 11), but not for higher toroidal fields. For both the low and high-field cases, the measured electron temperature gradients are within 15% of the calculated critical gradients for ETG modes. Non-linear saturated heat fluxes calculated from ETG/radial streamer theory

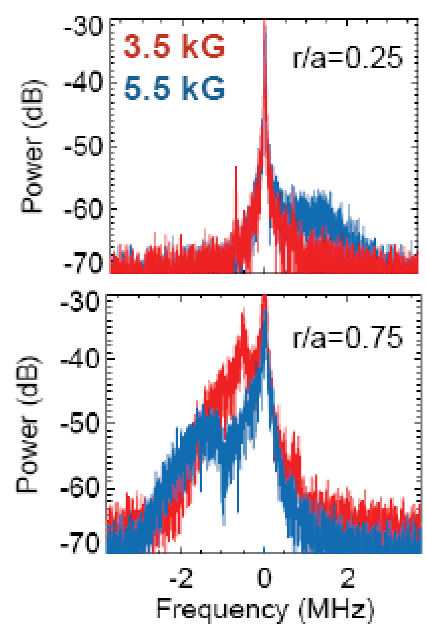


Fig. 10 High k-fluctuation ($k_\theta\rho_e$~0.18) spectra for 0.35 T (red) and 0.55 T (blue) for the core, r/a=0.25 (top panel), and farther out, r/a=0.75 (bottom panel).

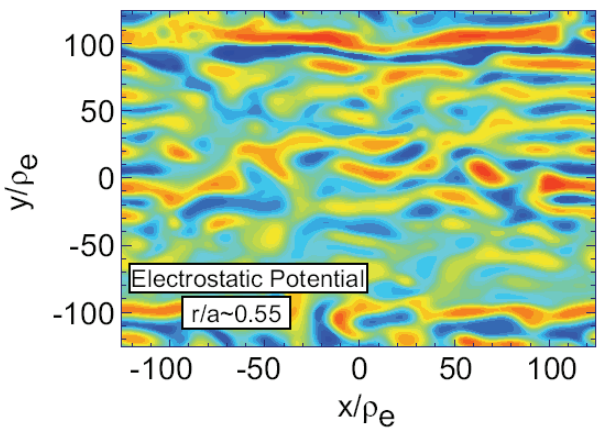


Fig. 11 Results of non-linear calculation showing the formation of radial streamers from ETG modes at B_T=0.35 T

[14] are comparable to those inferred from the TRANSP transport analysis. Just as the ion transport in L-mode plasmas improves with reversed magnetic shear, so to does electron transport, leading to electron Internal Transport Barriers (Fig. 12). While ETG modes are expected to be unstable outside the reversed shear region, and non-linear GYRO calculations predict electron heat fluxes that are consistent with those inferred from TRANSP analysis (Fig. 13), the reduction in electron transport in the reversed-shear core region may be in fact due to a suppression of the high-k ETG and low-k microtearing modes. Microtearing modes, which are calculated to be important in NSTX [15] are low- k, electromagnetic modes extended along field lines that are important in the collisionality range within which NSTX operates. The instability of these modes is also dependent on magnetic shear profiles, and it is found that accompanying the reduction in transport with reversed magnetic shear is a narrowing of the wavenumber range over which microtearing modes are unstable.

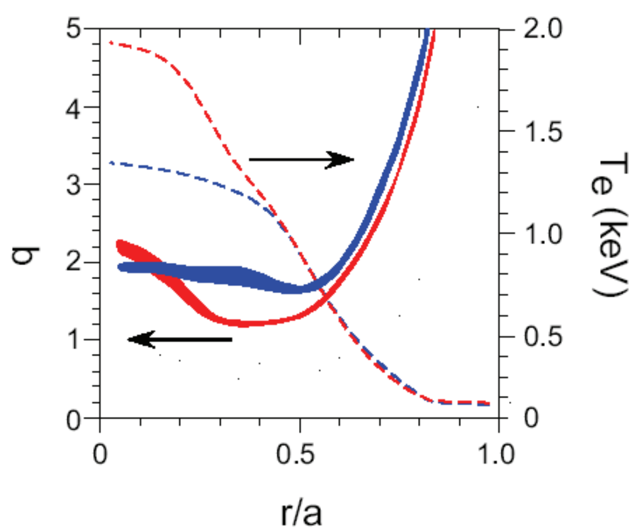


Fig. 12 Electron temperature and q-profiles showing the development of an electron Internal Transport Barrier with reversed magnetic shear.

Calculations of the electron thermal diffusivity predicted by the magnetic stochastization due to microtearing modes in the core region of

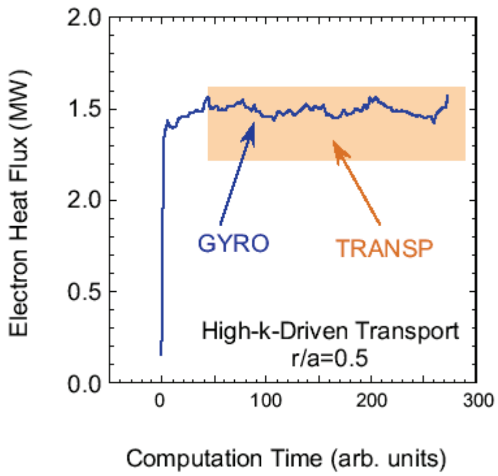


Fig. 13 Electron heat flux outside the region of reversed magnetic shear calculated by non-linear GYRO simulations and inferred from TRANSP

"hybrid" NSTX plasmas show agreement to within a factor of two to that inferred from transport analysis (Fig. 14). It is clear from these and the ETG results that there may be multiple instabilities across a range of wavenumbers that control electron transport. Experiments to determine the critical electron temperature of the transport-inducing modes have just begun. These experiments make use of High Harmonic Fast Wave heating to change the electron temperature gradient, and the change in high-k fluctuations accompanying the change in the mode driving term is measured by the microwave scattering diagnostic. An example of this is shown in Fig. 15. Seen in the figure is a strong peaking of the T_e profile as the RF heating is applied (Fig. 15a). The high-k fluctuations grow and are the strongest when the experimental R/L_{Te} exceeds the critical value for ETG growth, as estimated by an empirical formula [16]. Linear gyrokinetic calculations confirm that ETG modes in the wavenumber range covered by the high-k scattering diagnostic are expected to be unstable for these R/L_{Te}.

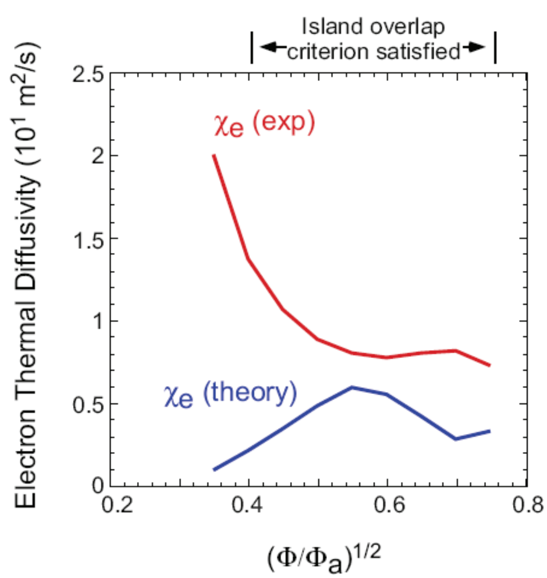


Fig. 14 Experimental χ_e inferred from TRANSP (red) compared to χ_e predicted by microtearing theory (blue)

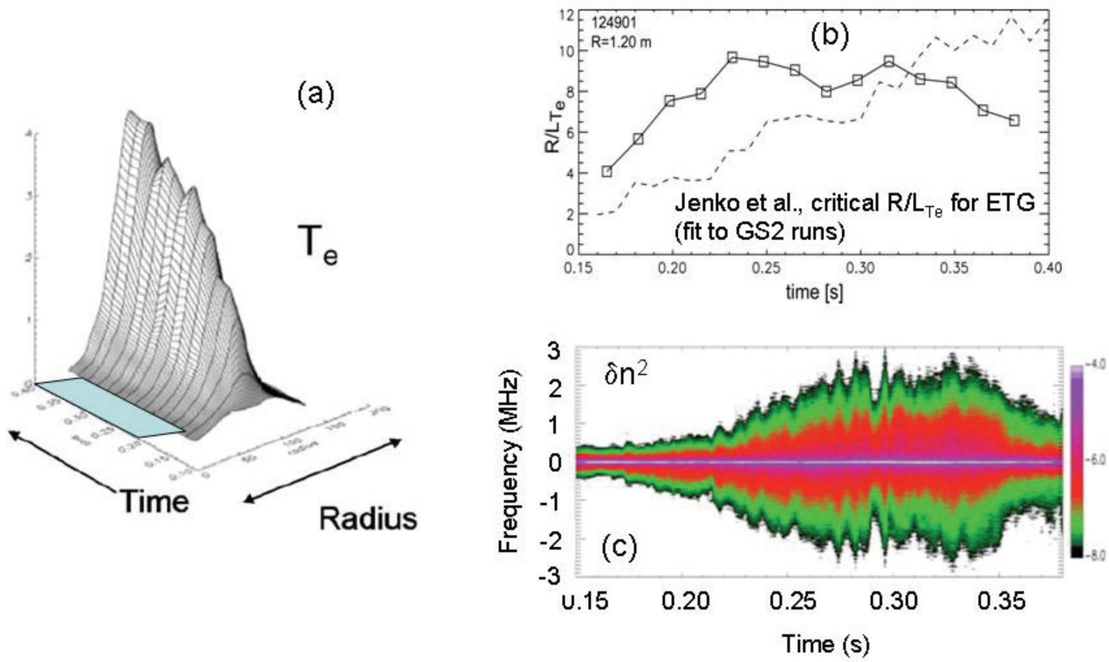


Fig. 15 (a) T_e profile as a function of time and radius with HHFW injection (b) Measured R/L_{Te} (solid line) and R/L_{Te} from a fit to GS2 runs (dashed line) as a function of time (c) high-k scattering signal at 14 cm^{-1} as a function of time

One of the outstanding questions in electron transport for all aspect ratio devices is what drives transport in flat temperature regimes, where the microinstability drive is absent since $\nabla T_e \sim 0$? Recent observations on NSTX have shown a relation between the strength of core, fast ion-driven Global Alfvén Eigenmode activity in both L- and H-modes, and electron transport. Fig. 16 shows a series of L-mode discharges with increasing GAE activity associated with increasing neutral beam power. Associated with the higher level of GAE activity are flatter electron temperature profiles and higher inferred values of χ_e in the core, where the GAE mode is predicted to exist. Preliminary theoretical estimates show that the measured GAE fluctuation levels can lead to core χ_e values comparable to those inferred from transport analysis.

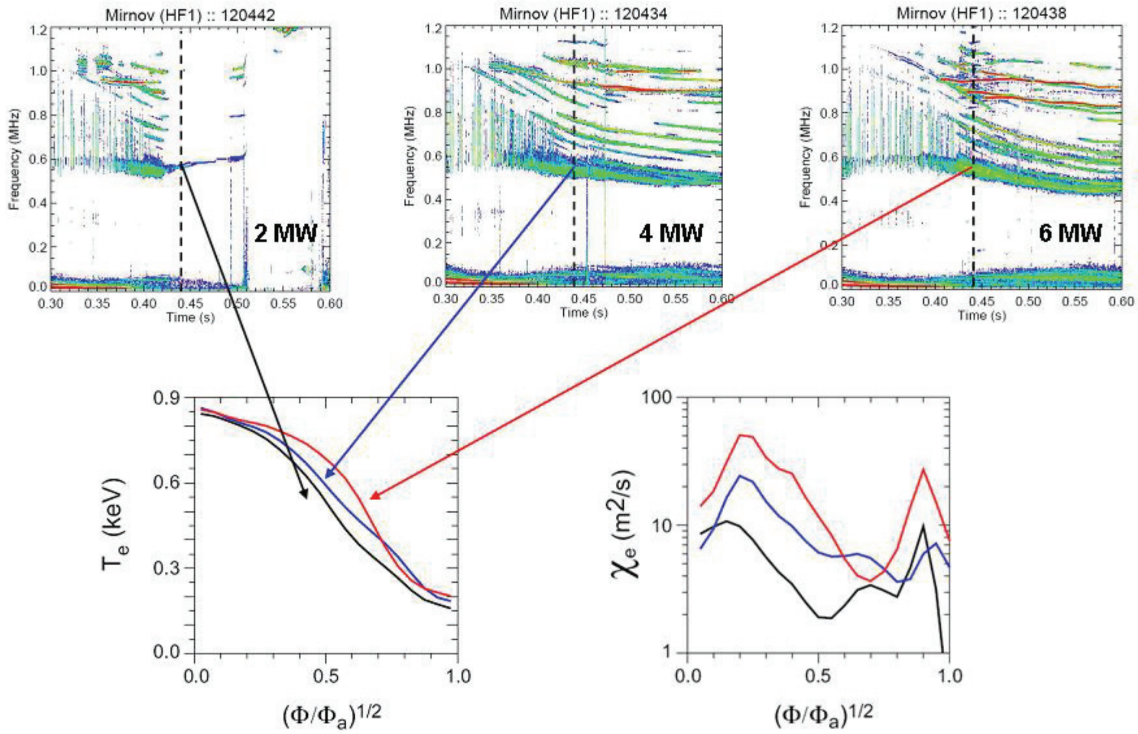


Fig. 16 Series of discharges showing increasing GAE activity with increasing beam power. The temperature profiles in the core are flatter and the central electron thermal diffusivities are higher with higher levels of GAE activity.

Plans

NSTX is in an excellent position to study and understand the key areas of electron turbulence and critical gradient physics. This is the top priority in the Transport and Turbulence Five Year Plan. Because of the relatively large ρ_e at the low fields at which NSTX operates, electron scale length turbulence can be measured. The microwave scattering diagnostic on NSTX, which is radially scannable and which provides a highly localized (±2.5 cm) k_r measurement, is unique and particularly well-suited for measuring ETG and short wavelength TEM modes. Additionally, SXR arrays can be used to monitor fast changes in the electron temperature profiles due to turbulence. Since the turbulent-driven ion transport is subdominant to ion neoclassical transport in H-modes, non-linear gyrokinetic ETG simulations with adiabatic ions and scale separation are possible. The ultimate goal is to develop a comprehensive picture of electron transport for developing a predictive capability for future STs.

2009-2011:

During this period, continued identification of TEM and ETG modes will be made using the present high-k scattering system. Collisionality scans, using HHFW and the LLD, will be made to differentiate modes. The critical gradient necessary for destabilizing high-k turbulence will be assessed experimentally using HHFW to change the R/L_{Te} in fine steps and at various collisionalities using the LLD. Once established experimentally, the critical gradient will be benchmarked against that predicted by gyrokinetic simulations to identify the responsible mode. Experimental studies of the roles of reversed magnetic shear and low order rational q surfaces in the development of electron Internal Transport Barriers will be carried out by varying key parameters that affect mode stability, such as the magnetic shear, density gradient, ∇n_e, β, T_e/T_i, etc. Furthermore, the issue of whether the ST geometry, such as that which gives rise to precession reversal, reduces the TEM mode severity will be studied. The effect of ExB shear on the suppression of ETG modes will be explored. Microtearing modes will also be studied experimentally in order to determine their importance in driving electron transport by changing the driving terms such as β and collisionality, and by making initial measurements of internal B-field fluctuations possibly using MSE and polarimetry. It is expected that the sensitivity of these two diagnostics will be 5 to 10 G up to 100 kHZ, the maximum frequency expected for microtearing. The first measurements will attempt to determine whether this sensitivity is low enough for measuring microtearing fluctuations.

Key to all these studies will be the direct connection and benchmarking against results from a suite of gyrokinetic simulations from different research groups at all levels. Synthetic diagnostics such as the high-k scattering and SXR and magnetic fluctuations will be built into the gyrokinetic codes for comparison with experiment. This could also help establish the importance of the high-k modes relative to the lower-k microtearing. Of importance is to determine the source of electron transport in the core of plasmas where both the density and temperature profiles are too flat to destabilize the electrostatic instabilities such as ITG and ETG, as well as microtearing. The presence of high frequency magnetic fluctuations, such as those associated with the core-localized Global Alfven Eigenmodes, as seen to be associated with high inferred levels of electron transport in flat T_e and n_e regions, and the causal relation between the two will be explored. The GAE mode structure may be measured with BES. Perturbed electron transport studies will investigate the cold pulse propagation from ELMs and pellets using high resolution measurements near the boundary with a multi-color soft X-ray array for fast T_e, n_e and n_{imp} profile measurements. Finally, BES and Doppler reflectometry can be used to study the existence of Zonal Flows in the core and at the edge of the plasma in H-modes, and throughout the plasma in L-modes, and their effect on modes that are believed to drive electron transport.

<u>2012-2013:</u>

The higher B_T, I_p and lower collisionality will allow for a critical examination of which modes are responsible for electron transport and under what conditions. In particular, the higher field and lower collisionality can lead to a suppression of the GAE and microtearing modes respectively. The reduction of n^* at higher field and with LLD operation is expected to be up to an order of magnitude, which is sufficient to stabilize the microtearing modes for electron temperature gradients typical of present operaton. Further, the high-frequency GAE activity is expected to be reduced with lower $v_{fast}/v_{Alfvén}$ at the higher field. Thes would leave the TEM and ETG as the only candidates for causing turbulent-driven electron transport. The new centerstack and the LLD will provide this capability. Whether the electron transport continues to dominate the plasma energy loss at higher B_T and I_p will be studied during this operation period. Experimental identification of microtearing modes will also be pursued experimentally by assessing the extent of these modes along the field line using the low-k diagnostic and from the internal B-field fluctuation measurements that may be obtained by MSE or polarimetry. Modification of the high-k scattering system would enable measurements of the full range of medium-to-high k_r and k_θ turbulence. This diagnostic will yield information on mode structure, full frequency spectra and dispersion characteristics. Coupled with the BES measurements, the studies of microturbulence using the more detailed k_r and k_θ information will allow for much more comprehensive validation of the gyrokinetic simulations across the full k-range. Included in this exercise will be the results of probing the structure of the higher-k fluctuations. For instance, both TEM and ETG are strongly ballooning to the outside, and radial streamers may be expected from ETG. The existence or not of the radial streamers can be assessed with simultaneous measurements of k_r and k_θ from the microwave scattering.

Electron transport and turbulence modification will be tested using local heating via local deposition of EBW at the multi-hundred kW level (incremental budget). This will include early application of EBW to modify the q-profile and possibly induce ITB formation. Turbulent spreading into the linearly stable region will be examined using the scannable high-k diagnostic, and this spreading will be related to the ExB shear layer and variation in magnetic shear. Modulated EBW will be used to probe the local critical gradient physics and regions of good and bad transport along with the formation of Internal Transport Barriers, using a tangential optical soft X-ray system (TOSXR) with good signal-to-noise characteristics, and an upgraded MPTS. In order to use the MPTS for this, it will be necessary to combine several shots with different timing to get a complete evolution. The multi-hundreds of kW EBW system will be used for localized deposition and heating to probe critical gradient physics and turbulence spreading. These measurements, in turn, will be compared to output of similar synthetic diagnostics from gyrokinetic codes for a detailed assessment of the microturbulent sources of electron transport.

3.3.2 Momentum Transport

The rotation in NSTX has been observed to be quite high, with toroidal velocities up to 300 km/s in the core, and this leads to strong ExB shearing rates that can be up to five times greater than the linear growth rates of low-k instabilities (Fig. 7). Thus, it is expected that the high rotation can effectively suppress these low-k instabilities, and indeed non-linear gyrokinetic calculations suggest that this is so. The rotation is important not only for suppressing the microturbulence, but also for suppression of both internal and external MHD modes and leading to achieving high performance goals both in NSTX and potentially in future devices. Consequently, it is important to understand the source of this rotation, how momentum diffusivity relates to electron and ion thermal and particle diffusivities, the effect of rotation and ExB shear on energy and particle confinement, and the source of intrinsic rotation on NSTX. In particular, will the ExB shear be high enough in future devices to suppress the low-k turbulence and maintain the ion energy transport at neoclassical levels?

Results

In H-mode discharges, the momentum diffusivity was found to be highly anomalous relative to GTC-NEO neoclassical predictions, despite the fact that the ion thermal transport was close to neoclassical in these discharges. The momentum transport varied most strongly with B_T, showing very weak or no effect with I_p, which is more consistent with the observations of the electron thermal transport reported in [4]. However, over a wide database of plasma conditions, this correlation is not robust, with only a weak dependence on χ_ϕ on χ_e emerging.

The lack of scaling of χ_ϕ with χ_i seen in the dedicated scaling experiments is also clear statistically in the inner half of the plasma ($\rho \leq 0.4$), where ρ is the square root of the normalized toroidal flux. In this region, χ_i can be up to a factor of 30 greater than χ_ϕ. Farther out, at $\rho \geq 0.65$, χ_ϕ is broadly seen to scale with χ_i, more consistent with results from conventional aspect ratio tokamaks [17,18], although χ_i still tends to be a factor of about 10 greater than χ_ϕ. The scaling, however, is not particular tight, with approximately an order of magnitude scatter in the data.

Dedicated momentum confinement scaling experiments have been carried out in NSTX, making use of Non-Resonant Magnetic Perturbation (i.e., application of n=3 error fields) to slow the plasma. The NRMP were applied for 50 ms, and a momentum confinement analysis was performed at the time when the NRMP was turned off, when NBI was the only known source of torque. This perturbative technique allowed for determination of τ_ϕ, χ_ϕ and v_{pinch} through the plasma. Fig. 17 shows the results of this analysis for χ_ϕ and v_{pinch}. Consistent with the results from Fig. 17, both the global momentum balance and perturbative fit determination of the momentum confinement time indicates values in excess of 150 ms, and these values exceed the energy confinement time by a factor of approximately four to five. Additionally, the analysis indicates a significant inward pinch velocity, with values reaching 40 m/s, and momentum diffusvities of order several m^2/s, which are closer to the values of χ_i than are the χ_ϕ's deduced from the global momentum balance. Furthermore, the inward pinch velocity is consistent with values predicted by the theories of Peeters et al. [19] and Hahm et al., [20], both theories predicated on low-k turbulence induced momentum transport (Fig. 18). Previous work [21] has shown the change in angular momentum due to NRMP application is consistent with Neoclassical Toroidal Viscosity theory [22], and this will be used in the future as a basis for momentum confinement and transport studies during the NRMP application. Because of near-zero value of neoclassical momentum transport, the

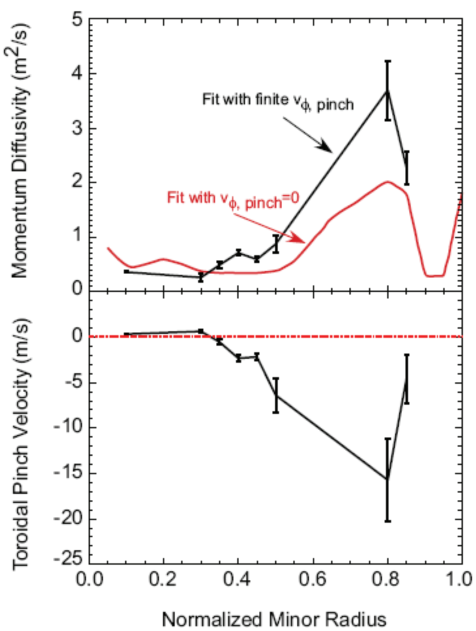


Fig. 17 Results of perturbative analysis to determine the momentum diffusivity and inward pinch velocity.

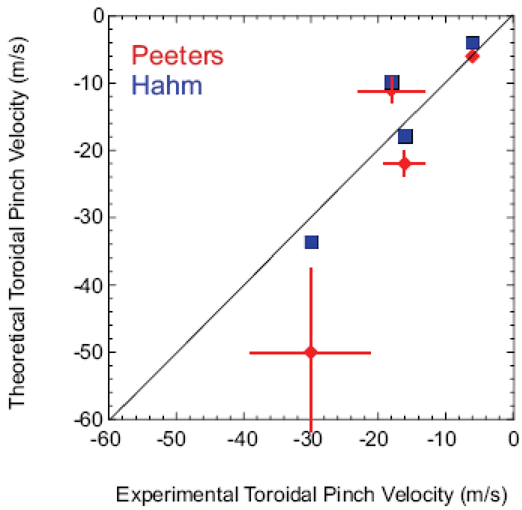


Fig. 18 Comparison of experimental and theoretical toroidal momentum pinch velocities.

observed momentum transport in NSTX will be a better probe of the effects of low-k turbulence than ion energy transport would be.

Plans

The essential questions to be addressed over the course of the Five Year Research Plan are "what is the source of momentum transport, and how does momentum transport couple to energy transport, and will the ExB shear be sufficient to suppress both low- and high-k turbulence?"

<u>2009-2011:</u>

Poloidal CHERS will be used to measure v_θ under a variety of discharge conditions, and these measurements will be used to test the validity of neoclassical theory. Non-Resonant Magnetic Perturbation studies will continue in order to infer τ_ϕ, χ_ϕ and v_{pinch} at NRMP turn-off under a variety of discharge conditions. Beam blips will be used to assess τ_ϕ, χ_ϕ and v_{pinch} close to the plasma center. The inferred pinch velocities at different L_n will be used to differentiate between momentum pinch theories [19,20]. NTV theory will be used to estimate the torque due to the error field and thus the momentum transport properties during application of NRMP. These values will be compared to the post-NRMP values to check consistency and determine whether NTV theory provides a consistent picture that can be used for extrapolation to future devices and scenario development. The momentum transport will be compared in L- vs H- plasmas, with a focus on the relation between χ_ϕ and χ_i, χ_e. Comparisons between momentum transport metrics and low-k measurements will be made.

2012-2013:

Higher B_T, I_p and lower ν^* provided by the new centerstack and LLD are the tools necessary not only to develop a further understanding momentum transport in this expanded parameter regime, but also to determine whether the ExB shear will be able to suppress low- and high-k microinstabilities in regimes close to those of future ST and non-ST devices. Rotation modulation studies will continue using NRMP. The low-k diagnostic will allow for a determination of the relation of low-k fluctuations to variations in momentum transport in both L- and H-modes. In particular, the v_θ measurements will allow an assessment of the importance of neoclassical effects in this extended parameter regime, which will allow a closer coupling to the operational space expected for NHTX and an ST-CTF. This low-k diagnostic will also allow for Zonal Flow/GAM studies, and these will entail coupling of these large-scale flows to other microinstabilities at all k, bicoherence analysis to determine the most robust coupling of these flows and modes, and the effect of these large-scale flows on transport. Application of NRMP from off-axis internal coils will permit finer control of the magnetic braking for momentum diffusivity and pinch velocity determinations (incremental budget).

3.3.3 Particle Transport

Particle transport, which is not well understood at present either at low or conventional aspect ratio, is a fertile area for study. Understanding particle transport is yet another level of validation of physics models describing microturbulent vs neoclassical transport, and it is complementary to energy transport studies. Another issue of importance is impurity transport in ion neoclassical plasmas and plasmas with Lithium. Helium transport studies in NSTX relate to the Helium ash issue in ST-CTF and ITER. Much of the necessary data for analysis already exists, and thus analysis can proceed immediately. Diagnostic and facility enhancments will, however, aid these studies. In addition, some of the unique features of NSTX add another dimension to the particle transport studies; these include the high mirror ratio in the Scrape-Off Layer (SOL) and thus a high trapped particle fraction, and the ability to extend the ranges in collisionality, q and β for these studies.

Results

To date, the particle transport studies in NSTX have focused on studies of impurity transport in beam-heated H-mode plasmas. These studies were carried out primarily using Neon injection into MHD quiescent plasmas. For these studies, the tangential array of Soft X-ray detectors with multi-foil capability for energy and thus radial discrimination was used to track the transport of the impurity. A synthetic SXR diagnostic with the multi-foil capability was built into the MIST code for comparison between simulated and measured impurity profile evolution. Fig. 19 shows this comparison, with very good agreement at this level of comparison between the measured

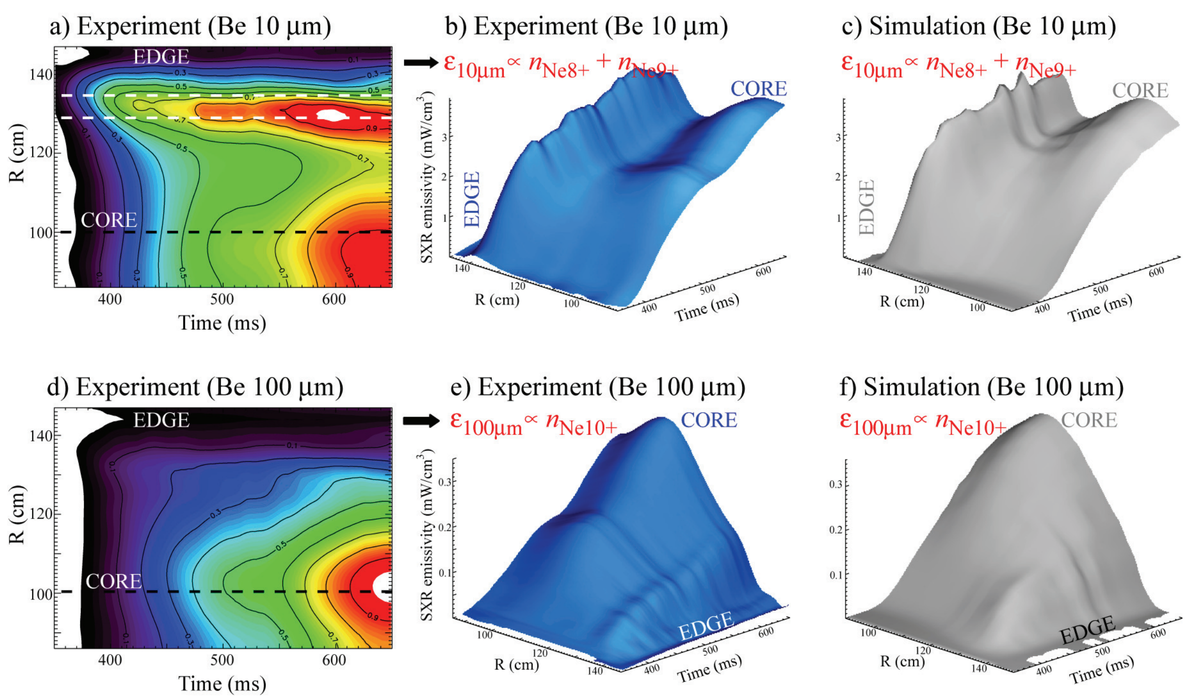


Fig. 19 Comparison of measured soft X-ray profile evolution for two different filters (left) with those from MIST simulations assuming neoclassical diffusivity for Neon. A small inward pinch is also required for agreement.

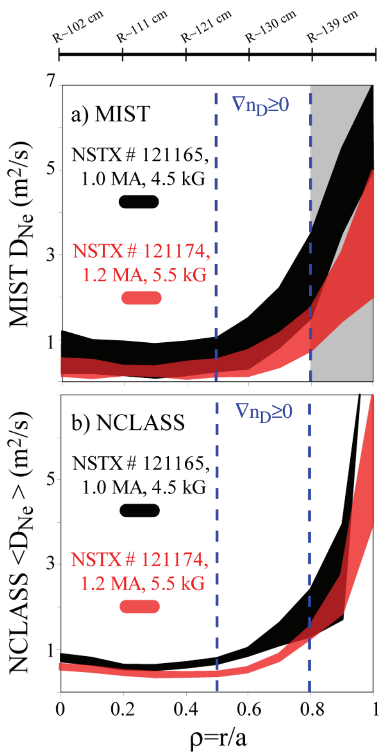


Fig. 20 Particle diffusivity values assumed in MIST for the Neon transport (upper panel) compared to the neoclassical values (lower panel).

and simulated profile evolution. In order to achieve this, a low core impurity particle diffusivity of D~1 m^2/s was required. This value of D is at the neoclassical transport level for the Neon impurity, as is shown in Fig. 20. This result complements those of the ion energy transport, which as described in a previous section, also suggests neoclassical levels of transport in these plasmas.

Plans

What are the properties of particle and impurity transport, and how do they relate to energy transport and low-k turbulence measurements? Does collisionality control the transport properties?

<u>2009-2011:</u>

The effect of low collisionality and recycling with Lithium evaporation and the Liquid Lithium Divertor on the particle and impurity transport will be established. Particle and impurity transport levels in the core, within the dominant NBI-fueling regime (r/a<0.55) will be studied using the TRANSP code. The fueling from NBI is dominant in this regime, and the particle source can be determined straightforwardly through the TRANSP beam Monte-Carlo calculation. The aim would be to understand the systematic variation of particle diffusivity with power, current, toroidal field, etc. from the pre-existing database. The relation of the particle to thermal diffusivities will be assessed to determine whether they have the same parametric dependences and what the differences are between L- and H-mode; are the particles driven by turbulent transport in high density L-modes as the thermal ion heat flux seems to be?

Density peaking studies and the effect of particle pinches, in conjunction with ITPA, will be carried out in order to determine the regimes in which fusion power production can be maximized for devices such as ITER and ST-CTF. There is a clear trade-off between maximizing core reactivity (i.e., peaked profiles) and plasma stability.

Impurity transport will be assessed using high-Z impurity injection and TESPEL (Tracer Encapsulated Solid PELlet) injection at the edge in Lithium and no-Lithium plasmas. Tracking the impurities can be done with either the high-resolution edge/pedestal soft X-ray array or the CHERS diagnostic. The simultaneous inclusion of the multi-energy SXR array and the bolometer data, along with the time-dependent MIST modeling, puts a strong constraint in the determination of both D and v_{pinch} for r/a<0.8. The possible relation between the particle pinch and the momentum pinch will be investigated.

2012-2013:

The higher B_T, I_p and operation with LLD will provide information on particle transport in lower collisionality plasmas. The effect of the LLD and Lithium wall conditioning on particle, impurity and Helium transport will be assessed; i.e., how do D and v_{pinch} change with changes in collisionality and recycling? The role of low-k turbulence in controlling core particle transport will be assessed with the low-k turbulence diagnostic in order to test particle transport models. The variation in density fluctuations will be studied as a function of D/D_{neo} in a variety of plasmas: L vs H over the full range of I_p and B_T, high vs low density (collisionality) and reversed magnetic shear vs low central shear (q-profile). Modulated core fueling studies with beam blips will be carried out, taking advantage of the upgraded MPTS diagnostic as well as higher beam power (incremental budget). The evolution of the density profile will have to be built up from numerous discharges in order to use amplitude and phase analysis to determine τ_p^*. The modulated studies will also allow a separation of D and v_{pinch}, to be compared both to the steady-state particle balance value of D (i.e., from TRANSP) and to theory.

Edge particle transport studies will be performed with modulated fueling from the supersonic gas injector (SGI) and pellet fueling with a D pellet injector, again taking advantage of the upgraded MPTS. Outside of r/a=0.55, the fueling is dominated by wall fueling and recycling, and estimating the source rate of the will be done using DEGAS2 and UEDGE. These neutral source profiles can be input to TRANSP for a determination of the particle diffusivities across the full plasma radius.

The understanding of Helium transport is needed for assessing the likelihood of success for integrated scenarios in future devices. Helium transport studies in NSTX can be carried out with either He puffing into deuterium discharges, or with Helium discharges themselves.

3.4 Theoretical Tools and Modeling

The coupling of Theory and Modeling to experimental results is critical for developing a fundamental understanding of key physics issues and for helping develop a tool that will allow performance predictions with high confidence.

Present Tools

The international standard code, TRANSP, is and will continue to be used for steady-state energy, particle and momentum transport studies. A predictive tool under development that is based on codes from a number of research institutions, pTRANSP, is being used for predictive transport analysis and discharge scenario development. Low aspect ratio data will provide key tests of theory-based transport models; for instance, studies to validate the TGLF model [23] are underway.

Linear and non-linear gyrokinetic analysis is being done by a variety of codes. GTC-NEO takes into account finite banana width and thus non-local effects for determination of neoclassical transport. The GS2 flux tube code contains kinetic electron and ion, finite beta and generalized geometry descriptions, and it can be run in both linear and non-linear modes. However, for NSTX, global codes such as GTS, GYRO and GEM are required due to the large gyroradii of both electrons and ions. Verification of these codes using low aspect ratio data is underway.

Plans

All available tools will be used, with a focus on Verification and Validation of codes and physics models developed by a number of research groups..

2009-2011:

A 2D/3D state-of-the-art neutrals package will be implemented in TRANSP to aid in particle transport studies. pTRANSP will be used to validate predictive models such as those given by TGLF [23]. GTC-NEO will be upgraded with multiple species and will be utilized to test neoclassical theory with v_θ measurements. Non-linear GYRO simulations with synthetic diagnostics over the full range of k will be carried out. Non-linear GTS simulations with kinetic electrons and synthetic diagnostics for high-k will begin. A multiple ion species capability will be implemented in GTS. Non-linear GEM simulations for low-k microtearing modes will be carried out. A version of GEM with kinetic electron physics implemented will be developed and used. Results from GTC-NEO calculations and results from non-linear calculations (GYRO, GTS) will be used to evaluate the neoclassical and the non-diffusive turbulent flux (pinch and ∇p-driven residual stress) for toroidal angular momentum transport. Comparisons between low-k fluctuation measurements and results from synthetic diagnostics in non-linear gyrokinetic simulations will be made.

2012 - 2013:

More detailed and comprehensive comparisons between low-k fluctuation measurements and results from synthetic diagnostics in non-linear gyrokinetic simulations will be made. The role of Zonal Flows and their relation and coupling to low-k turbulence will be assessed. pTRANSP simulations will become more sophisticated as the plasma transport properties become more fully understood and the models become more physics-based. Tests of turbulence spreading using results from local EBW deposition experiments (incremental budget) will begin with comparisons to code predictions.

Predictions of ion and electron heat, particle and momentum transport profiles with respect to dimensionless variables will be made using gyrokinetic analysis with full features (i.e., collisions, turbulence spreading, etc). Transport codes such as TGLF will be used to predict full plasma profiles, and these will be compared to measured profiles as part of the Verification and Validation procedure.

Fully predictive transport simulation capabilities will be developed. These will be combined with other simulations (e.g., MHD) to form a fully integrated scenario package. This package will be used as a basis for developing actual experimental discharge scenarios in NSTX and in future devices.

3.5 Facility and Diagnostic Upgrades

The facility upgrades, such as the new centerstack and LLD are crucial for testing the critical physics issues affecting the prediction of performance of future devices, both ST and non-ST.

2009 - 2011:

A Liquid Lithium Divertor will be installed, allowing operation at lower collisionality than presently.

Additional MPTS channels will provide a more complete electron temperature and density profiles. The full complement of poloidal CHERS channels will be available for measuring the poloidal velocity. The full complement of FIDA channels and neutron collimators will be available for measuring beam deposition profiles necessary for higher confidence power balance calculations. A low-k fluctuation diagnostic (BES) will be implemented. The ability to use MSE and/or polarimetry to measure internal B-field fluctuations will be assessed. A modification of the high-k scattering system will provide k_θ in addition to k_r information. A high resolution, tangentially-viewing soft X-ray array for diagnosing the plasma edge/pedestal region will be implemented to support edge impurity and electron thermal transport studies.

Additional filters for CCD cameras will aid in Helium transport and recycling studies. Extra channels will become available for the Edge Rotation Diagnostic for measuring the edge toroidal and poloidal rotation.

2012 - 2013:

An upgraded centerstack, allowing for operation with I_p up to 2 MA and B_T up to 1 T. which will allow operation at even lower collisionality, will be installed and operational. Internal off-axis control coils and up to 700 MW of EBW are in the incremental budget.

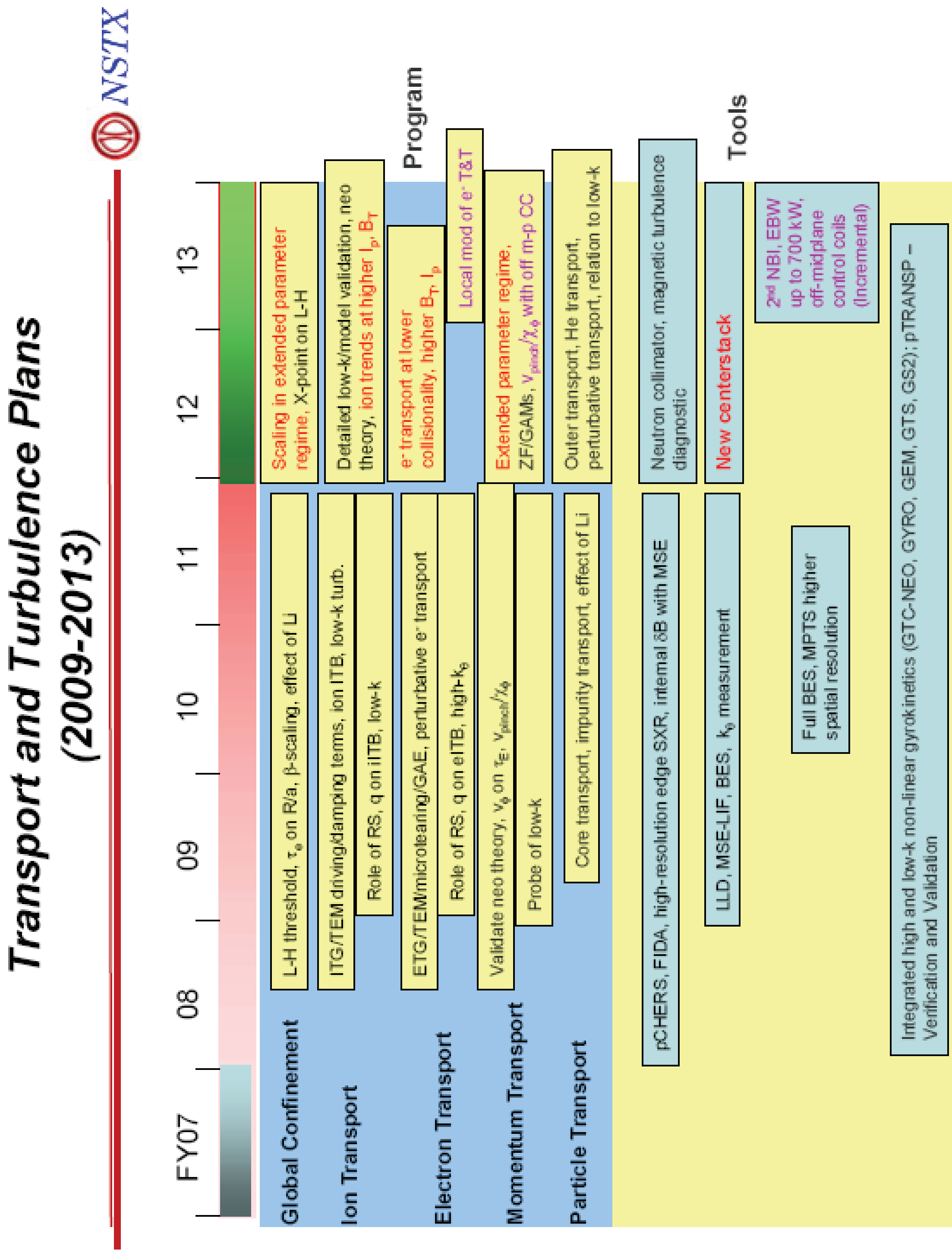
MPTS will be upgraded to 45 channels and 100 Hz. The microwave scattering diagnostic will be modified to include k_θ measurement. The core multi-color soft X-ray array, upgraded for high signal-to-noise, will provide better discrimination and faster profile measurements of small localized heat pulses for probing internal transport and barrier formation. A divertor Thomson Scattering system is in the incremental budget.

3.6 Summary of Research Goals for FY2009-2013

The major NSTX Transport and Turbulence research goals by topical area from section 3.2.3-4 are re-stated below to summarize the proposed research plan for the upcoming five-year period. The proposed research program time line is shown following these goals.

- To verify global scaling trends over an extended B_T and I_p range, and to establish the dependence of confinement on aspect ratio,
- To establish conditions for neoclassical ion transport through coupling low-k turbulence measurements to results of non-linear gyrokinetic simulations,
- To determine the role of both low-k and high-k turbulence through measurement and non-linear theory in setting the level of anomalous electron transport,
- To understand momentum transport and to determine the source of the plasma rotation/radial electric field and its influence on both low- and high-k turbulence,
- To understand the relation of particle and impurity transport throughout the plasma to measurements and simulations of microturbulence, ultimately to
- To participate in national and international efforts to develop a validated, fully-predictive tool for developing confinement-optimized discharge scenarios for both NSTX and future ST and non-ST devices.

The timeline for the research and tool development is shown on the next page.


Transport and Turbulence Plans
(2009-2013)
NSTX
FY07
08
09
10
11
12
13
Program
Global Confinement
Ion Transport
Electron Transport
Momentum Transport
Particle Transport
L-H threshold, τe on R/a, β-scaling, effect of Li
Scaling in extended parameter regime, X-point on L-H
ITG/TEM driving/damping terms, ion ITB, low-k turb.
Role of RS, q on iITB, low-k
Detailed low-k/model validation, neo theory, ion trends at higher Ip, BT
ETG/TEM/microtearing/GAE, perturbative e- transport
Role of RS, q on eITB, high-kθ
e- transport at lower collisionality, higher BT, Ip
Local mod of e- T&T
Validate neo theory, vφ on τE, vpinch/χφ
Probe of low-k
Extended parameter regime, ZF/GAMs, vpinch/χφ with off m-p CC
Core transport, impurity transport, effect of Li
Outer transport, He transport, perturbative transport, relation to low-k
Tools
pCHERS, FIDA, high-resolution edge SXR, internal δB with MSE
Neutron collimator, magnetic turbulence diagnostic
LLD, MSE-LIF, BES, kθ measurement
New centerstack
Full BES, MPTS higher spatial resolution
2nd NBI, EBW up to 700 kW, off-midplane control coils (Incremental)
Integrated high and low-k non-linear gyrokinetics (GTC-NEO, GYRO, GEM, GTS, GS2); pTRANSP – Verification and Validation

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