3.2 Transport and Turbulence

3.2.1 Transport Goals and Relation to IPPA Milestones

The development of the ST concept into proof-of-principle experimental devices such as NSTX and MAST has opened up new vistas in the exploration of the turbulence and transport physics 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. Among the key transport goals are:

- To establish the key scalings of both the global and local transport properties of ST plasmas with emphasis on delineating the role of electron vs ion transport and their dependences on ρ^*, β and rotational and magnetic shear,
- To measure and relate low and high-k turbulence to anomalous transport properties and possible stochastic heating of the plasma components,
- To assess fast-ion confinement in an ST geometry, as well as the influence of the fast ions on neoclassical transport and turbulent heating and transport,
- To determine the influence of the radial electric field and resulting large rotational shear on turbulence dynamics and transition into high energy state (H-mode) plasmas,
- To establish the theoretical basis for heating and transport in ST plasmas through theory development and extensive experiment/theory benchmarking, and, ultimately,
- To use the knowledge gained to control plasma (in particular, electron) transport as a means of producing plasma kinetic and current profiles that are optimal for high-confinement, high-β_T and non-inductive current generation.
- To use well diagnosed NSTX plasmas as a laboratory for studies relevant to questions surrounding the physics of high-beta electromagnetic turbulence in certain astrophysical plasmas.

These goals will be addressed through experimental research with advanced diagnostics, and by using theoretical and numerical tools that will allow detailed comparisons between experiment and theory.

The achievement of the overall transport goals, as outlined above, in a timely manner is essential for achieving the overarching FESAC IPPA objectives for assessing the ST as an attractive fusion concept. The two FESAC goals that are most connected to the transport goals are the five-year goal (IPPA 3.1.1, end of FY2005);

- Advance the scientific understanding of turbulent transport, forming the basis for a reliable predictive capability in externally controlled systems,

and the ten year goal (FY2009)

- Develop fully integrated capability for predicting the performance of externally controlled systems including turbulent transport, macroscopic stability, wave- particle physics and multi-phase interfaces.

The achievement of the NSTX transport goals are clearly essential for being able to produce the high-performance, quasi-steady discharges required to address the nearer-term IPPA goal, and the development of a predictive capability and experimental control techniques will allow for extrapolation to a Component Test Facility and a power plant scenario.

3.2.2 Unique Opportunities of NSTX

The low toroidal field of NSTX, approximately a factor of ten 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 benchmark theory and to make new diagnostic measurements. The Figure 3.2.1 images show a set of key plasma physics parameters for various devices at conventional aspect ratio, including ITER, and for NSTX. While the collisionality of NSTX is comparable to that of larger, conventional aspect ratio devices with higher auxiliary heating power, the fast ion and thermal gyroradii normalized to the plasma minor radius (ρ_{fast}/a and $\rho^*=\rho_i$/a respectively) are up to an order of magnitude greater for NSTX than for these other devices due to the low toroidal field in NSTX. This result indicates the importance of including FLR effects correctly in the treatment of neoclassical and turbulent transport physics. In particular, the thermal ion gyroradius can be between one and three cm near the outboard edge of the plasma, which implies ρ_i/L~0.2 to 0.3 at that location, where L is a characteristic scale length (density, temperature, pressure). This brings into question the validity

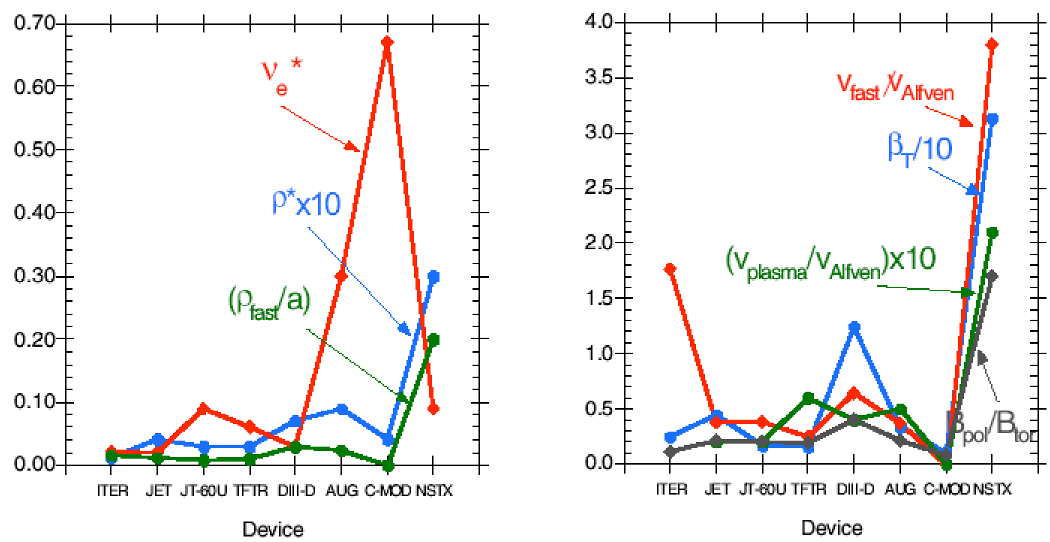


Fig. 3.2.1 Comparison of key volume-averaged physics parameters among various conventional aspect ratio tokamaks and NSTX. The higher values for NSTX are generally the result of lower toroidal field. The lines connecting the points are to guide the eye.

of the spatial scale length ordering, as applicable to NSTX, in the various transport theories. Furthermore, because of the large trapped particle fraction, which approaches one at this low aspect ratio, electrons can no longer be treated validly as a fluid. Low toroidal field also leads to high-β_T operation, with volume-averaged values up to 35% (right panel) and local core values near 1. Consequently, electromagnetic turbulence and magnetic stochasticity may play an important role in plasma transport. The high β_T, large gyroradius and large trapped particle fraction all indicate the necessity for further development of the gyrokinetic treatment of low aspect ratio plasmas in the neoclassical and turbulent regimes.

To date, FLR corrections to neoclassical theory have been made only for high aspect ratio and circular geometry [1]. In this limit, finite orbit effects lead to ion thermal transport fluxes that are reduced by almost an order of magnitude from standard neoclassical levels [2] in regions of steep density gradient. This has direct application not only to ST plasmas where ρ_i/L is relatively large due to the large gyroradius, but also to the physics of transport barriers (i.e., small L_T, L_n) at conventional aspect ratio.

The plasma Alfvénic Mach number (right panel of Fig. 3.2.1) is of order 0.2, with a velocity that is a significant fraction of the sound speed, indicating potentially high flow shearing rates. High ExB flows, with flow shear rates of order 10^5 to 10^6 sec^{-1}, have been observed. These flow shear rates are up to one order of magnitude greater than those at conventional aspect ratio [3,4], and they can have a profound effect on ST transport by suppressing, most notably, long-wavelength microturbulence. This, along with the high-β_T nature of NSTX, indicates that NSTX has a unique opportunity to study electron transport dominated plasmas with its present set of profile diagnostics and future fluctuation diagnostics. This study extends beyond STs and tokamaks, as electron transport in electromagnetic regimes is important in RFPs as well [5].

The ratio of fast ion velocity to Alfven velocity is three to four, owing to the low toroidal field and high beam energy (80 to 100 keV), allowing for destabilization of fast ion driven instabilities. These Compressional and Global Alfven Eigenmodes (CAE/GAEs) may in turn serve to heat thermal ions [6]. These studies have direct relevance to ITER, where $v_{fast/}v_{alfven} > 1$ also. In addition, the high ratio of B_{pol} to B_{tor} on the outboard midplane, similar to what is found in spheromaks, is large enough to cause the major portion of the field line length to be in the good curvature region, thus reducing the microinstability drive [7].

Finally, the prospect of studying turbulence with good wavenumber and spatial resolution from electron to ion gyroradius scales in plasmas with local beta values approaching unity on NSTX opens the door to making important contributions to to both fusion-relaetd transport and astrophysical studies as well. Turbulence studies in fusion plasmas initially focussed on electrostatic fluctuations which dominate at low beta. But in recent years gyrokinetic codes have been extended to include fully electromagnetic fluctuations that are particularly important in high beta plasmas in NSTX and astrophysics. While there isn't an exact correspondence between NSTX and specific astrophysical plasma systems, and the driving instabilities at long wavelengths are probably different (i.e., magnetorotational instabilities in astrophysical accretion disks vs. drift waves in NSTX), as turbulence cascades to smaller scales it often develops more universal characteristics. Also, testing gyrokinetic codes in NSTX gives experience and confidence in them that is useful when extrapolating these codes to astrophysical systems. In the astrophysical context, gyrokinetic codes are presently being used to explore important problems, including MHD turbulence cascading to ion scales and the subsequent wave damping of turbulence, a process potentially relevant to determining the temperature of the solar wind and the luminosity of the accretion disks of black holes [8]. As an example of such a problem, recent observations from the Chandra X-ray telescope suggest that the accretion disk surrounding the black hole at the center of our own galaxy is a factor of 100,000 times dimmer than expected, unless the turbulence is primarily damping on ions instead of electrons or the accretion rate is much lower than initial estimates indicated (for example, see reference [9] and references therein). In plasmas with beta of order unity, important dynamic processes in the MHD turbulence cascade should begin to emerge that are relevant to the turbulence believed to be present in such exotic systems. Thorough diagnosis of NSTX plasmas in these high-beta regimes, and detailed comparisons to gyrokinetic theory, is thus relevant to this and other important extraterrestrial plasma physics dilemmas. Regarding STs and NSTX in particular, the possibility exists that turbulence generated by electron temperature gradients damps on the plasma ions, potentially heating the ion species. This possibility can be explored with gyrokinetic theory codes that have been tested by comparisons with core turbulence diagnostics that NSTX is planning to deploy.

3.2.3 Experimental Studies

Core Transport — Global confinement

Results

Global confinement studies in NSTX to date have been based on confinement time values determined by magnetic reconstructions of quasi-steady discharges using the EFIT code. These confinement times include the fast ion component. These global confinement times, for both H-mode and L-mode edge plasmas, are plotted against the ITER97L L-mode global scaling [10] in Fig. 3.2.2. Both the H-mode and L-mode edge points show large enhancements relative to this scaling, with maximum enhancement factors between 2 and 3. A sufficient range of operating

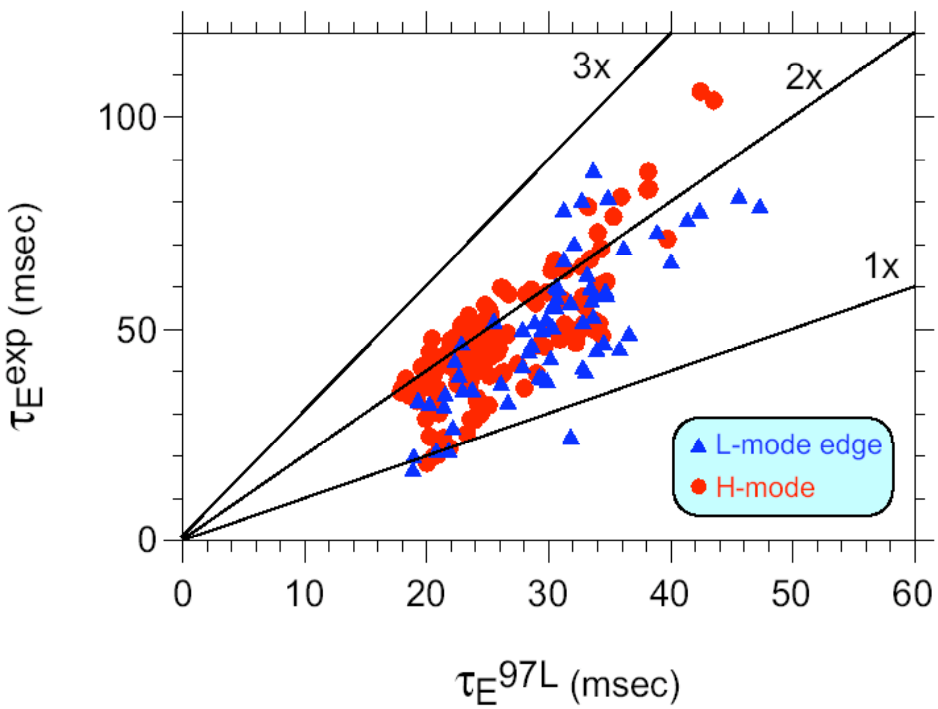


Fig. 3.2.2. L- and H-mode confinement times normalized to the ITER97L parametric scaling.

space was accessed during L-mode studies to enable the development of a preliminary parametric scaling of confinement for these data. These L-mode data indicate parametric scalings similar to those at conventional aspect ratio, but with a slightly stronger power degradation, with $\tau_E \sim I_p^{0.76} B_T^{0.27} P_{heat}^{-0.76}$, and with no significant dependence on plasma density. We have already started to calculate the fast ion stored energy and beam losses, which can be significant and which depend strongly on plasma current, in order to extract the thermal energy confinement time and to study the scaling of this parameter in relation to that from conventional R/a devices. The H-mode thermal confinement times calculated so far are enhanced by a factor of 1.1 to 1.5 over the values given by the ITER98pby,2 thermal scaling [11], indicating the need to reassess the aspect ratio scaling. Since these parametric dependencies are similar to those at conventional aspect ratio, it is necessary to reassess the aspect ratio dependence of the confinement scalings with the NSTX data included in the analysis. These new fits, along with their residuals, will help determine the degree of confinement enhancement over that from conventional aspect ratio devices. The global assessment will be done keeping in mind possible differences in the dominant transport channel (i.e., electrons vs ions) between conventional aspect ratio and ST devices. In addition, the high-β_t operation in NSTX presents an opportunity to study the degradation of confinement on β_t over a large range in this parameter.

The unique operating regime of NSTX (high-β_t, high rotation, low B_T) will challenge the conventional aspect ratio scalings and will help in identifying the underlying confinement physics.

Global Confinement Plans (years refer to fiscal years)

<u>2003:</u>

Global confinement scaling analysis will be pursued to determine whether the power degradation in both L- and H-modes is due to MHD activity or transport. Larger amounts of data will be analyzed in this fashion and will be submitted to the ITER confinement database for this purpose.

<u>2004:</u>

Dedicated scans of H-mode plasmas will be performed to determine the full range of parametric dependencies. The aspect ratio dependence will be determined in neutral beam heated plasma both within NSTX and by performing similarity experiments across platforms such as NSTX and DIII-D. Experiments to determine how confinement scales with the dimensionless parameters ν^* and β_T will start. The role of rotation in confinement dynamics will be studied making use of error field correction coils to control rotation. Confinement trends will be studies in relation to variations in the q-profile, as measured by the CIF MSE system.

<u>2005:</u>

Rotation dynamics studies and its effect on confinement will be extended with the implementation of the poloidal CHERS system.

2006:

Studies of the dependence of global confinement on q-profile and E_r will be extended with the maturation of the LIF MSE diagnostic.

2007-2008:

Profile control techniques will be employed to optimize confinement as part of the effort to produce non-inductive discharges at high-β.

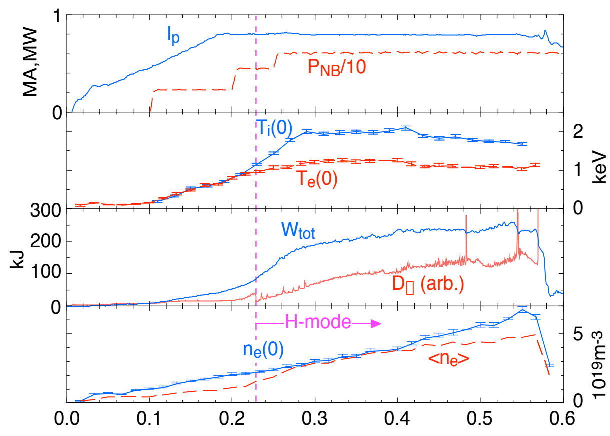


Fig. 3.2.3a Time evolution of a NB heated L-mode discharge.

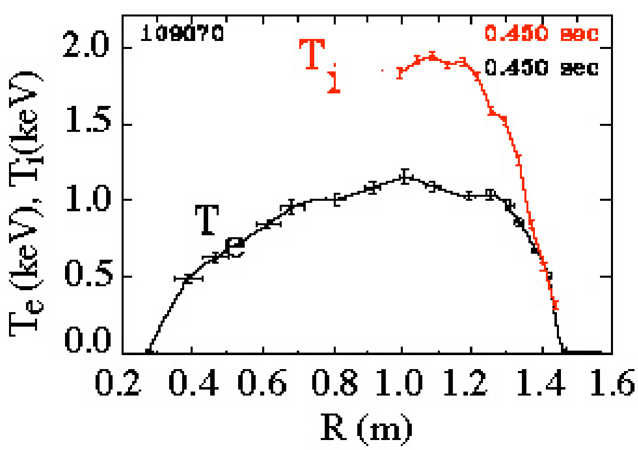


Fig.3.2.3b Electron and ion temperatures at t=0.45 sec

Ion Energy Transport — Results

One of the device physics design predictions for NSTX was the possibility of suppressing ITG modes due to both geometric considerations and ExB flow shear [7, 12]. Results of NB heating experiments have indeed shown that ion transport is relatively low, inferred to be at or below neoclassical levels. An example of a neutral beam heated discharge evolution is shown in Fig. 3.2.3a, where it is seen that $T_i(0)>T_e(0)$ throughout the NBI heating phase. A snapshot of the ion and electron temperature profiles at t=0.45 sec is shown in Fig. 3.2.3b. Because the beam ion energy (80 to 100 keV) is high compared to the electron temperature (~1 keV), classical collision theory predicts that only about 1/3 of the beam heating power is deposited into the ions; this, along with the fact that T_i remains higher than T_e over most of the profile, in itself suggests good ion confinement.

Ion thermal diffusivities can be determined from power balance calculations and the measured profiles using the TRANSP transport analysis code in interpretive mode. The results shown in Fig. 3.2.4 indicate that the thermal diffusivities are seen to decrease from core to edge, a trend opposite to what is observed at conventional aspect ratio. In addition, χ_i<χ_e, and χ_i is comparable to the value given by the NCLASS neoclassical theory [13]. In the cases studied so far, the ion thermal diffusivity is at, or more generally, below the neoclassical value as given by NCLASS. This in itself indicates the need to revisit the neoclassical framework in light of the unique characteristics of ST plasmas. As discussed earlier, relatively large values of ρ_i/L can lead to up to an order of magnitude reduction in the calculated neoclassical heat flux.

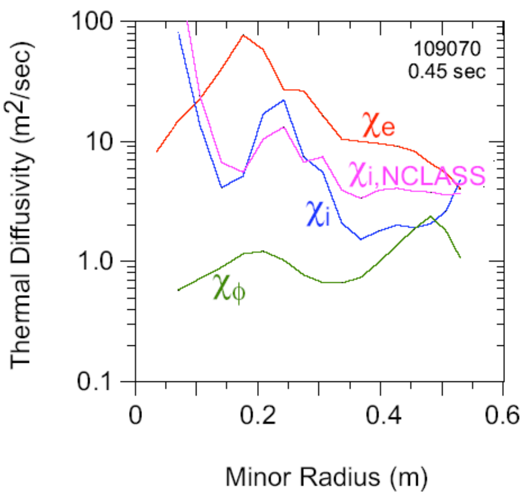


Fig. 3.2.4 Thermal and momentum diffusivities calculated from TRANSP power balance calculations. Shown for comparison is the neoclassical thermal diffusivity from the NCLASS neoclassical model

In some cases, we find the calculated ion thermal diffusivity to be negative in the outer portion of the plasma due to the large ion to electron coupling there. Over the course of several data recalibrations, the region of negative χ_i has shrunk to the point where, if present, it encompasses only one or two spatial locations of the T_i measurement. Work will continue on assessing these regions of negative χ_i through further data calibration and by further developing and applying theories of stochastic heating and heat and particle pinches.

Preliminary gyrokinetic calculations of the linear growth rate of ITG modes in NB L-mode heated NSTX discharges indicate that the ExB flow shear is large enough to suppress the residual low-k turbulence usually attributed to ITG modes [14]. The expected low thermal ion transport is consistent with the results of the power balance calculations.

Ion Energy Transport — Plans

<u>2003:</u>

Studies of ion transport will focus on establishing the baseline for the ion thermal diffusivity through detailed comparison between experiment and theoretical expectations of neoclassical and turbulent transport. Preliminary comparisons between deduced ion transport and expectations from comprehensive gyrokinetic codes will be made.

Neoclassical theory and its calculated energy and particle fluxes will be developed further. Present neoclassical calculations (i.e., NCLASS) do not consider the large ion banana orbits near the magnetic axis (large $\square_b/a$), nor is it valid where □/L is finite, a situation that can exist in the outer regions of the NSTX plasma. Of importance may be the inclusion of beam-thermal ion friction terms, which have been neglected in previous treatments but which can be important in NSTX due to the large value of $v_{beam}/v_{th,i}$. These terms can provide heat and particle pinches.

<u>2004:</u>

The effect of ITG modes on plasma transport will be assessed by varying parameters known to affect ITG growth and damping. The ratio T_i/T_e can be varied by using RF in conjunction with NBI and/or by changing target densities, and the ExB flow shear can be modified by using RF heating instead of NBI, and by error field correction coils. It has been suggested that stochastic heating of thermal ions could result from CAEs driven unstable by fast ion velocity space anisotropies [6]. Calibrated reflectometry will be used to measure these mode amplitudes at the relevant radial locations (1.35 to 1.45 m) to assess their potential for anomalous heating. Similarly, ETG modes that have cascaded to lower k_{radial} (i.e., streamers) may also heat the thermal ions [15].Detailed comparisons between experimental transport results and results from gyrokinetic codes will continue.

2005:

Co- versus counter-NB injection discharges will be used, in conjunction with the poloidal CHERS diagnostic to study the effect of flow shear on ion transport. In addition, the effect of beam-thermal ion friction terms in the modified neoclassical treatment (see FY03 plans) will be tested directly with co- and counter-injection. The parallel force from this friction term can lead to an inward particle and heat pinch when the NB injection is in the co-direction, and an outward pinch for counter-NB injection.

Density gradients and [illegible]' will be modified using pellet injection with the implementation of a deuterium pellet injector, and will serve as a basis for perturbative studies of ITG turbulence induced transport. Initial studies relating ion transport to measured low-k fluctuations will be carried out.

2006:

Details of the relation between ion transport and turbulent fluctuations will be studied. With the maturation of the LIF MSE diagnostic it will be possible to relate the variations in q and E_r profiles to changes in ion transport.

2007-2008:

Studies of ion transport and the full k-spectrum of fluctuations will continue. Detailed comparisons between observed transport and fluctuation characteristics and predictions of both from comprehensive gyrokinetic calculations will be made in order to develop a high-confidence predictive capability.

Electron Transport — Results

As ion transport appears to be relatively low on NSTX, the electrons are, therefore, the dominant loss channel, with χ_e values generally in excess of 10 m^2/sec across a significant portion of the plasma profile. Not only do we need to improve our understanding of electron transport, we need to develop the means to improve the transport itself.

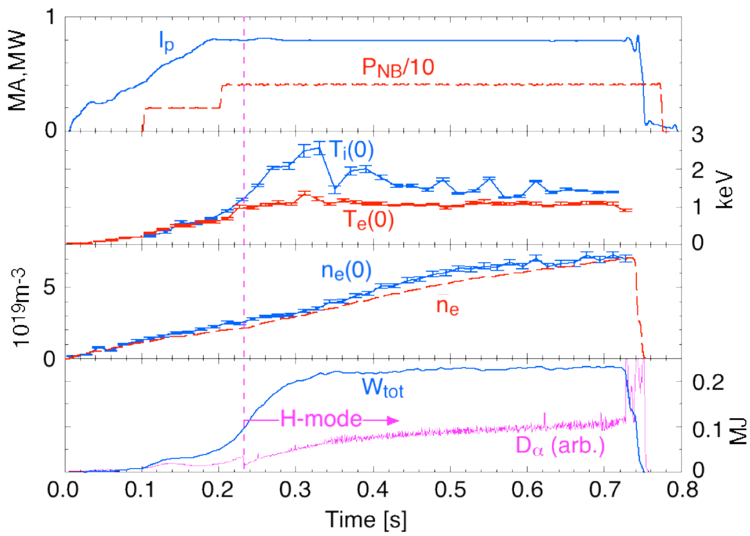


Fig. 3.2.5 Time history of H-mode discharge showing constant $T_e(0)$ despite density increase and transport events as seen in $T_i(0)$.

In some neutral beam heated scenarios, the electrons appear to be impervious to transport/MHD events that affect the ions, as shown in the time trace in Fig. 3.2.5, where the $T_e(0)$ remains constant in time even as the $T_i(0)$ is seen to decrease at certain times. The electron temperature profiles exhibit remarkable resilience over a significant period of time (Fig. 3.2.6), suggesting the possibility that the electron heat flux is a highly nonlinear function of the electron temperature gradient and increases rapidly when the inverse scale length exceeds a critical value.

The critical temperature gradient paradigm that appears to limit the electron confinement can, however, be broken in one of two ways, both resulting in the development of electron Internal

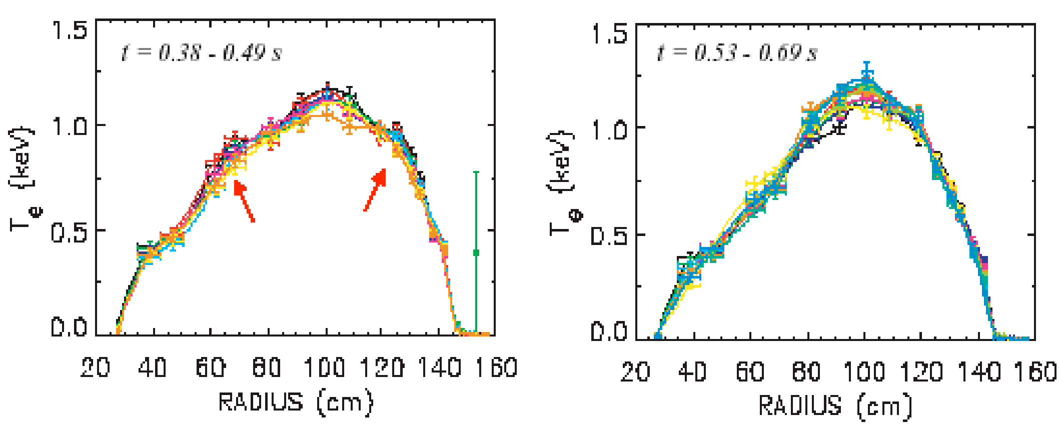


Fig. 3.2.6. Electron temperature profiles during two lengthy discharge durations exhibiting profile "stiffness."

Transport Barriers (ITBs) and an associated reduction in electron transport. The first method is to operate at low density in neutral beam heated discharges, during which reversed magnetic shear is believed to develop. This reversed shear can lead to a reduction in ETG growth rates, as indicated by gyrokinetic calculations, and, in fact, electron ITBs are observed experimentally in low density operation. The second method is to apply HHFW heating, an example of which is shown in Fig. 3.2.7a, where the core T_e is seen to rise continuously during the HHFW heating phase. Associated with this increase is a continuous reduction in the electron thermal diffusivity, decreasing a factor of two to three at mid-radius (r/a~0.5) with an order of magnitude decrease in the plasma core, as shown in Fig. 3.2.7b. Preliminary calculations of linear growth rates using GS2 indicate growth that, unlike the ITG and TEM/CTEM modes, ETG modes cannot be suppressed by velocity shear alone [14]; however, the growth rates can be reduced in a bootstrapping fashion as T_e/T_i increases [16].

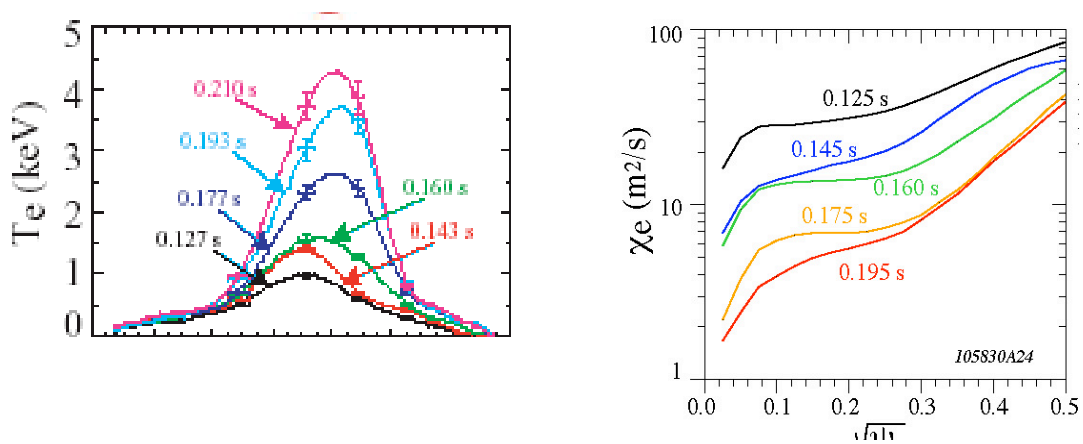


Fig. 3.2.7. (a) Electron temperature profile evolution, and (b) associated change in electron thermal diffusivity.

The larger gyro-scales and higher-β_t associated with the low toroidal field provides NSTX with the unique opportunity to address one of the outstanding issues that has broad applicability across other tokamaks and confinement devices, namely, electromagnetic turbulence and electron transport. The NSTX program features the components necessary for a successful study of this kind: profile diagnostics, means to modify the electron transport, a special parameter regime that allows for possible measurement of ETG turbulence and ion and electron transport that are decoupled. Supporting such a study will be the availability of comprehensive gyrokinetic codes with full electron dynamics.

Electron Transport — Plans

<u>2003:</u>

Studies of electron transport in FY03 will focus on establishing the baseline for the electron thermal diffusivity through detailed comparison between experiment and theoretical expectations of turbulent transport. Preliminary comparisons between deduced electron profile stiffness/transport and results from comprehensive gyrokinetic codes will be made.

<u>2004:</u>

Detailed studies to produce electron ITBs will commence. These will involve neutral beam injection into low density discharges and HHFW heating, two methods already seen to be successful in producing these ITBs. These techniques will be used to vary the magnetic and rotational shear, □', n_e, and T_e/T_i, parameters that are expected to affect ETG mode growth. Modulated HHFW heating pulses will be used to probe local electron critical gradient physics, with the response to these pulses measured by both the USXR or mode-converted EBW emission. These studies will be aided with actual q-measurements from CIF MSE. Detailed benchmarking between electron transport results and expectations from gyrokinetic codes will continue.

<u>2005:</u>

Deuterium pellet injection will be used to study the effect of varying □' and $□_e$ in order to modify the electron transport and ETG mode growth. A diagnostic will be introduced which will allow for the first time the measurement of fluctuations in the ETG wavelength regime, which is of the order of several mm for NSTX. This will allow a measurement of the microturbulence that is believed to influence the electron transport. Studies of the effect of poloidal flow shear on electron transport and ETG turbulence will be initiated, aided by measurements from the poloidal CHERS diagnostic.

2006:

The first tests of electron transport and turbulence modification using the local deposition of Electron Bernstein Waves will be carried out at the 1 MW level. Studies will include the application of EBW early in the discharge to modify the q profile evolution and possibly to induce transport barrier formation, as has been demonstrated on the DIII-D and ASDEX-U tokamaks. Details of the relation between electron transport and turbulent fluctuations will be studied. These studies will include the use of EBW waves to probe the turbulent k spectra response as the local temperature gradient is pushed past its marginally stable value. With the maturation of the LIF MSE diagnostic it will be possible to relate the variations in q and E_r profiles to changes in electron transport. Detailed experiments whose goal is to reduce electron transport through changes in magnetic shear and other effects will be performed.

2007-2008:

Studies of electron transport and the full k-spectrum of fluctuations will continue. In FY08, these will take advantage of 3 MW of EBW heating. Detailed comparisons between observed transport and fluctuation characteristics and predictions from comprehensive gyrokinetic calculations will be made in order to develop a high-confidence predictive capability. Electron transport control and reduction techniques will be established and implemented.

Momentum Confinement — Results

NSTX operates in a unique regime in which M_A~M~0.3 for the main plasma species, and for which the impurity ions are supersonic. The critical role that ExB shear has on turbulence suppression underlies the importance of momentum transport studies to understand and ultimately control the turbulence. As the ion transport is low in the NBI plasmas, so too is momentum transport, with $\chi_\phi < \chi_i \approx \chi_{i,neo}$ by an order of magnitude.

It has been discussed previously [17] that, in the limit where electrostatic ITG turbulence is believed to be the primary cause of transport, $\chi_\phi \sim \chi_i > \chi_{i,neo}$. The very different ordering of these diffusivities in NSTX may reflect the results the long-wavelength ITG modes are indeed suppressed, and thus the study of momentum transport will allow us to assess this cleanly, without impact by neoclassical transport. Key to determining this is a comparison between the experimental χ_ϕ's and those expected from both neoclassical and turbulence-dominated transport theories.

Momentum Confinement — Plans

<u>2003:</u>

Comparisons of deduced momentum diffusivities and rotation velocities to neoclassical expectations by gyrokinetic calculations will be made. Detailed comparisons between χ_ϕ and χ_i will be made.

<u>2004:</u>

An experimental study of momentum transport will be started and will involve comparisons between NBI, which provides torque through collisional processes, and HHFW, which does not. The experiments will include scaling with HHFW and T_e/T_i. Rotation studies will make use of the error field correction coil, which will be used to vary the static island size and, thus, plasma rotation.

<u>2005:</u>

Co- versus counter-NBI injection comparisons will be done. These will enable assessment of the importance of non-ambipolar losses and direct torques on flow generation. The implementation of the poloidal CHERS diagnostic will be essential for this study.

<u>2006-2008:</u>

E_r will be measured directly by LIF MSE, and it will be studied in relation to the flows as measured by the CHERS systems. The relationship among flow shear generation, rational q-surfaces and ITB formation will be studied making use of these diagnostics as well. Studies to identify zonal flows and establish the causal relation between rotation and confinement dynamics will start with the implementation of a high time resolution (□1 msec) edge spectroscopy.

Particle/Impurity Transport — Results

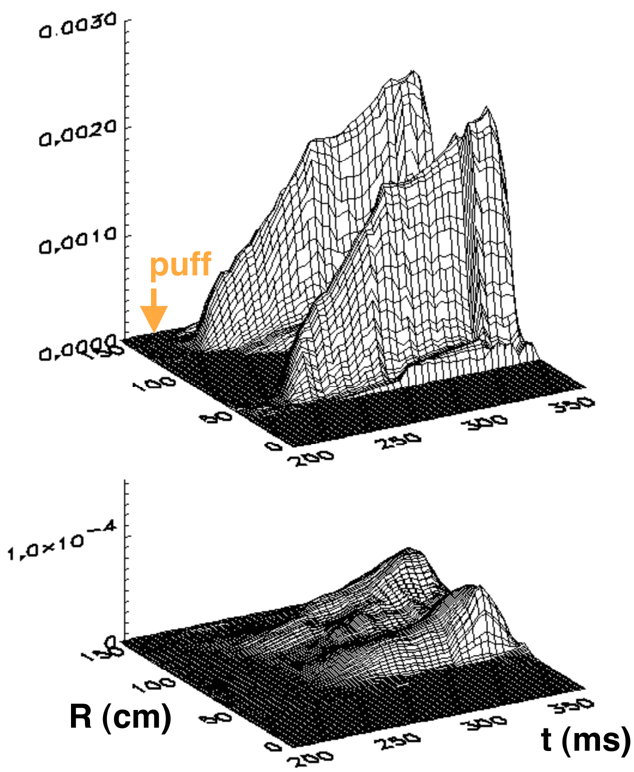


Fig. 3.2.8. Neon emissivity measured after neon puff. The top panel is the emissivity of the Helium-like neon (>0.4 keV), while the bottom panel shows the emissivity of the fully stripped neon (>1.4 keV)

Studying impurity transport provides another means from which to infer the transport properties of NSTX and scaling with $\square^*$ and $\square_T$. Initial neon puffing experiments on NSTX have indicated that impurity ion transport from the edge to the core is low. These experiments were carried out so far only in L-mode plasmas at low-$\square_T$, and the results are shown in Fig. 3.2.8. Both the He-like and fully stripped neon emission show sustained hollow profiles after the neon puff, indicating the low particle transport. Analysis indicates that the particle diffusivity is at the neoclassical level in the core region. At higher $\square_T$, the impurity transport experiments will help discriminate between electrostatic and electromagnetic transport, and the parameter regimes in which each dominate.

Particle/Impurity Transport — Plans

2003:

Analysis of impurity transport results will continue.

2004:

Perturbative particle and impurity transport experiments will be carried out using standard impurity and supersonic gas injection, where the latter will produce a highly collimated beam and thus better control and localization of the impurity injection, as well as with the Li/B pellet injector. New and upgraded diagnostics will aid in these experiments. The USXR and transmission grating spectrometer will provide 1-D (radial) diagnosis of the transport, and the GEM detector will employ a scheme to follow both the radial and poloidal heat flux propagation.

2005:

Deuterium pellet injection will be used as a basis to study particle transport perturbatively.

2006-2008:

The relation between electron thermal and particle transport, supported by some recent observations from the Alcator C-Mod [18] and ASDEX-U [19] tokamaks, will be probed using local Electron Bernstein Wave heating and measuring the response in the dynamics of the electron density profile.

Fast Ion Confinement — Results

The low magnetic field of NSTX means that energetic ions (neutral beam ions in NSTX and charged fusion products in a reactor-scale ST) have gyroradii, which are a significant fraction of the minor radius. This can cause more rapid loss of fast ions due to orbit effects, including prompt orbit loss, MHD-induced radial transport, and diffusive transport. Losses of fast ions may, in turn, generate radial electric fields that affect bulk plasma confinement, rotation, and flow shear. A fundamental question, which must be addressed if STs are to be run in D-T or considered as reactor prototypes, is whether an ST plasma can maintain good confinement of energetic ions (especially alpha particles) with a significant fast ion beta.

In the area of single particle orbit effects, initial measurements from the NPA and the decay time of the neutron signal after the beams turn off indicate classical slowing down of beam ions in the plasma. Initial loss rate measurements from fast ion probes are not, at present, in good agreement with modeling. The discrepancy between the modeling and experimental results is both in the magnitude of the loss current (measured loss is smaller) and the trend with plasma current (measured variation is less rapid than that from the model). The development of a more detailed and more diagnostically local model is underway.

Since the parameter operating regime for both NSTX and ITER is one in which $v_{fast}/v_{Alfvén}>1$, and because of the complement of diagnostics presently on or planned, NSTX is well positioned to undertake ITER-relevant studies of the effect of fast ion-driven collective modes on the fast ion confinement itself.

Fast Ion Confinement — Plans

2004:

Studies to understand overall fast ion confinement effects will be initiated with detailed comparisons between measured distributions of confined and lost NB ions and theoretically predicted distributions over a wide range of plasma parameters and in L- vs H-modes. Attempts will be made to control the beam loss fraction by varying the gap between the plasma and the outboard midplane wall. A pitch angle and energy resolving fast ion loss detector will be commissioned, allowing a more detailed study of fast ion loss mechanisms that are active in NSTX.

2005:

A comparison between co-injection and counter-injection will be used as a basis for studying the effect of non-ambipolar losses, since the loss fraction during counter-injection is expected to be much higher (40% vs 5% for 1 MA discharges with 15 cm outer gaps). Neutron collimation will provide a measurement of the beam ion deposition profile, which will be compared to the predictions from both guiding center and full orbit codes.

<u>2006-2008:</u>

These studies will be continued and extended with solid-state neutral particle detectors being implemented in FY07.

Edge Transport and Fluctuations — Results

Understanding and controlling L to H-mode transitions are key to the ultimate success of NSTX in that H-mode operation allows for the broader pressure profiles that enable steady-state operation at high-β_T and high bootstrap fraction. It was found that entry into the H-regime required at least twice the power given by recent ITER scalings [19]. The powers required to get into the H-mode (0.5 to 1.5 MW) are not restrictive, however, and high performance H-mode operation has become fairly routine.

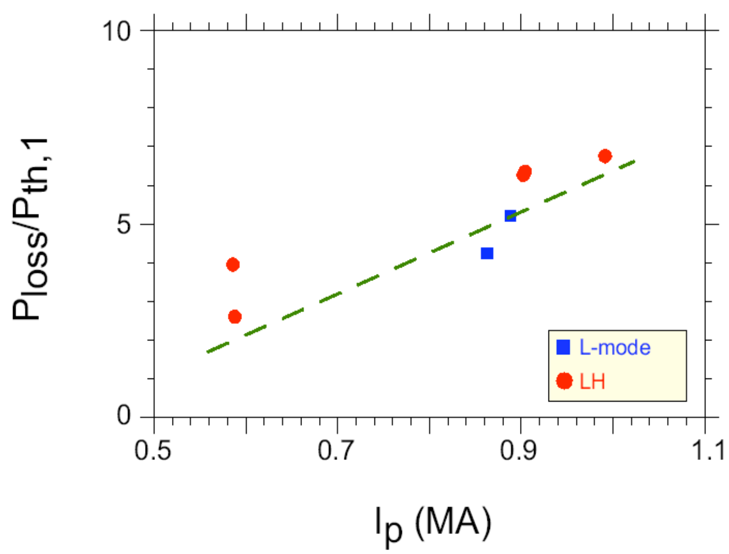


Fig.3.2.9 Power through separatrix at the L-H transition normalized to an L-H threshold scaling versus plasma current.

When the “expected” density, toroidal field and size scalings are accounted for, the threshold power exhibits a residual dependence on plasma current, as is seen in Fig. 3.2.9. A source of this current scaling may be the radial electric field resulting from fast ion loss, which is relatively much greater at low current (40% at 600 kA) than at higher current (5% at 1 MA). Supporting the contention of the importance of fast ion loss are recent observations of L-H transitions associated with bounce-precession fishbones and associated fast ion loss.

Edge turbulence diagnostics have provided an initial glimpse into the fluctuations that may be causing plasma transport in the outer region, including the scrape-off layer. Density fluctuation amplitudes generally decrease going from L-mode to H-mode. Of particular importance for both confinement states is the presence of large-scale (several cm) convective cells measured by both gas puff imaging (GPI) and fast reciprocating probe diagnostics. Similar observations have been made on Alcator C-Mod [20]. These cells break off from the main plasma near the separatrix and propagate primarily radially and poloidally. The existence and ubiquity of these cells bring into question the validity of the diffusive energy transport paradigm in this region of the plasma.

Edge Transport and Fluctuations — Plans

<u>2003:</u>

Discharge data near the L-H transition will be submitted to the ITER Threshold database in order to develop an understanding of how the L-H threshold power depends on aspect ratio.

<u>2004:</u>

The role of E_r on L-H transitions will be studied experimentally using plasma current variations and RF heating. Studies to determine which dimensionless parameters, other than aspect ratio, determine the L-H transition through complementary experiments in other devices and through comparisons with ST relevant theory will be initiated in FY04. Edge pedestal characterization, making use of the fast reciprocating probe, will begin. Edge fluctuations and convective cell transport will continue to be assessed in using GPI, reflectometry and the fast reciprocating probe. Radial correlation lengths, as determined from reflectometry, will be studied in conjunction with global confinement and local transport results. Calibrated density fluctuation amplitudes will be made with reflectometers in the edge region of the plasma. It will be important to compare fluctuation levels and structures to theory and understand how kinetic effects influence the turbulence levels. Far-infrared interferometers will be used to study low-k fluctuations in L-mode plasmas starting this year.

2005:

The role of E_r on transitions will be studied with co- vs counter-NBI injection comparisons. Studies of both low- and high-k turbulence will extend into this year as the advanced fluctuation diagnostics are implemented. Detailed comparisons between measured mode characteristics and non-linear results of comprehensive gyrokinetic codes will be made.

2006-2008:

Pedestal characterization will be extended with the He beam spectroscopy diagnostic to measure n_e and T_e. The fast CHERS system will be used to characterize the edge and pedestal regions. The CT injector would be used in attempts to produce edge transport barriers. Studies of the role of E_r on transitions will be extended with actual measurements of E_r made by the LIF MSE diagnostic. Diagnosis of the full spectrum of fluctuations will continue.

Theory and Modeling — Tools

For completeness, an outline of the theory and modeling tools for transport research studies is given here. A more detailed exposition regarding available resources and programmatic needs and plans is given in the Theory and Modeling section of this chapter.

One of the mainstays of present theoretical analysis of toroidal plasma transport is the use of gyrokinetic codes which approach this problem from first principle equations incorporating as much physics as is viable computationally. Various codes using this approach are available and will be used to analyze NSTX plasmas. GS2 is an electromagnetic code that can provide both linear and non-linear simulations of ETG and ITG turbulence, and it has already been used in initial studies [12, 14]. Further advances in GS2 will focus on high-k ETG physics. The GTC code is a global gyrokinetic code that is presently valid for ITG modes, zonal flow and neoclassical calculations. Further development will involve incorporation of electrostatic and trapped electrons, finite-β_T effects, and 3-D numerical equilibrium solutions. The neoclassical treatment in GTC will be reassessed for the large ρ/L_n and B_{pol}/B_{tor} in NSTX. The GYRO code is fully operational and can simulate the turbulent transport of energy, particles and momentum. It can handle finite ρ^*, finite β and electromagnetic effects, collisions, non-adiabatic electrons and generalized geometry. The BOUT, BAL and UEDGE codes will be used to study plasma transport in the edge and scrape-off layer.

The workhorse for performing interpretive transport analysis is the international standard TRANSP code, which incorporates state-of-the-art beam modeling, neoclassical (NCLASS), plasma species coupling, RF wave deposition packages and data handling modules in order to infer particle, energy and momentum transport coefficients. Up-to-date turbulent transport models (GLF23 and Multi-mode) have also been incorporated for theory/experiment comparisons when TRANSP is run in a mode that predicts temperature profiles based on these models or assumptions of ion neoclassical transport. Predictive comparisons between experiment and theory overcome many of the problems in inferring transport coefficients using kinetic profiles that are not well resolved spatially. In addition, χ_i and χ_e are not good parameters for comparison if the transport is very stiff.

Theory and Modeling — Plans

<u>2003:</u>

Transport coefficients from the critical gradient formalisms will be used as input to predictive TRANSP analyses, and the calculated temperature profiles will be compared to measured values to identify the theories that best reproduce the experimental results and to clarify the need for considering anomalous heating/transport processes and further theory development. This work will be starting in FY03 using analytic approximations to the diffusivities. A particular challenge for edge transport will be to assess the role of convective cells; this modeling will be done with the BAL, BOUT and UEDGE codes assuming non-diffusive transport.

A major challenge to theory in the analysis of NSTX transport results is to first ensure the validity of the various models in the low toroidal field, low aspect ratio regime. Starting in FY03, neoclassical theory will be updated to take into account the relatively large ρ/L, and beam-thermal ion friction terms, which can lead to inward or outward pinches, will be included. These updates will affect both transport fluxes as well as estimates of the bootstrap current.

Benchmarking the various gyrokinetic codes to identify the key differences among them will start in FY03 using similar treatments among codes.

Since the fast ion gyroradius can be comparable to the magnetic field gradient scale length, guiding center orbit theory begins to fail and the magnetic moment of the fast ions is not invariant. Improvements to the theoretical and computational ability to calculate how the fast ion population will redistribute and possibly be lost due to this non-conservation will begin.

<u>2004:</u>

Predictive TRANSP analyses will continue in FY04 and beyond with thermal diffusivities taken directly from the gyrokinetic codes. Incorporation of large ρ^*, large trapped particle fraction, high-β_T and extreme plasma shaping effects begin. Non-linear, self-consistent calculations to determine saturated amplitudes of ITG, ETG, and CAE modes will allow a comparison between experiment and theory to assess the role of turbulence at different wavenumber and the potential for anomalous heating. These comparisons can be made once the advanced fluctuation diagnostics are implemented.

<u>2005:</u>

Inclusion of strong ExB shear and the possibility of large non-local effects due to large spatial scale lengths into the gyrokinetic calculations will start. Anomalous heating models beyond the ad hoc stage will be developed based on results of the non-linear calculations and comparisons with turbulence measurements. Two possibilities for anomalous heating are ETG/streamers and CAEs.

2006:

Once the important physics effects are identified and incorporated into the gyrokinetic codes, these tools can be used as part of the basis for developing a high-confidence predictive transport capability.

2007-2008:

Fully predictive transport simulation capabilities will continue to be developed. The transport simulations will be combined with those of MHD stability to form a fully integrated scenario development package. The results will be used as a basis for developing actual experimental scenarios to making use of pressure and current profile control techniques to achieve high-confinement, high-β_T, high-non inductive current fraction discharges.

Facility and Diagnostic Upgrades

2004:

A supersonic gas injector will be used to provide a particle source for perturbative impurity transport studies. The study of core and edge transport processes involves a suite of both profile and turbulence diagnostics. A new 51-channel, 10 msec time resolution CHERS (T_i, v_ϕ) system has been implemented, as has a dedicated diagnostic to measure v_ϕ and v_θ at the edge by spectroscopic means. The latter diagnostic will aid in assessing the role of flow shear and momentum. The CIF MSE diagnostic will provide initial measurements of the q-profile. Multi-sightline NPA will provide indirect measurements of beam deposition profiles through fast ion charge-exchange neutrals. A diagnostic has been developed that will resolve the pitch angle and energy of fast ions lost to the vessel wall.

Perturbative heat transport studies can be attempted using localized electron heating from HHFW and a high-power EBW system. A higher time resolution (90 Hz) and spatial resolution (30 channels) Thomson scattering diagnostic is planned.

Perturbative impurity transport studies will be carried out using the Li/B pellet injector.

Density fluctuation measurements will be used to assess turbulence levels and the related transport, as well as the potential for anomalous heating. Long-wavelength turbulence is associated with ITG modes and can be detected using the technique of microwave imaging reflectometry. The diagnostic will provide a time resolved mapping of k_r and k_θ, extending the range of fluctuations that can be measured by conventional reflectometry techniques.

Diagnosis of ETG modes has been an almost insurmountable challenge in conventional aspect ratio tokamaks because of the large wavenumbers and small fluctuation levels. At low field and low aspect ratio, the expected ETG wavelengths are higher (several mm), making these modes accessible diagnostically, giving NSTX the unique opportunity to study these modes and their effect on electron transport. Microwave scattering can be used for this purpose. These advanced fluctuation diagnostics for both low- and high-k fluctuations will be implemented in the FY04 or 05 time frame.

These developing diagnostics will be augmented by reflectometry already implemented, which can provide a temporal overview of density fluctuations along with the determination of radial correlation lengths. Calibrated reflectometers will provide information on CAE/GAE mode amplitudes in the outer region of the plasma.

<u>2005:</u>

Deuterium pellet injection will provide localized fueling that can change the density gradient dramatically and thus is key to being able to assess the role of η_e and η_i in ITG and ETG modes. Fuelling from the pellet injection will be used to study particle transport, while cold pulse propagation will be used to study heat transport. A poloidal CHERS system for v_θ measurements will be implemented. The LIF Motional Stark Effect will provide the ability to measure the q-profile as well as E_{radial} directly to aid in the flow shear study. Neutron collimators will provide an almost direct measurement of the beam deposition profile and comparisons to the expected neutron rates as determined by classical collisional theory. A lithium coating will be used for particle control.

FY06-08

The fast spectroscopic diagnostic will provide $\leq$1 msec time resolved T_i and v_ϕ profiles. An array of solid state (diamond and silicon) detectors will be added to measure simultaneously the energetic neutral flux along multiple sightlines. A He beam spectroscopy diagnostic will be used to measure edge T_e and n_e. Liquid lithium modules and a divertor cryopump will be installed for density control. A CT injector, if installed, will be used for fueling. These latter control techniques will be critical for profile optimization.

Summary of Research Plan Elements

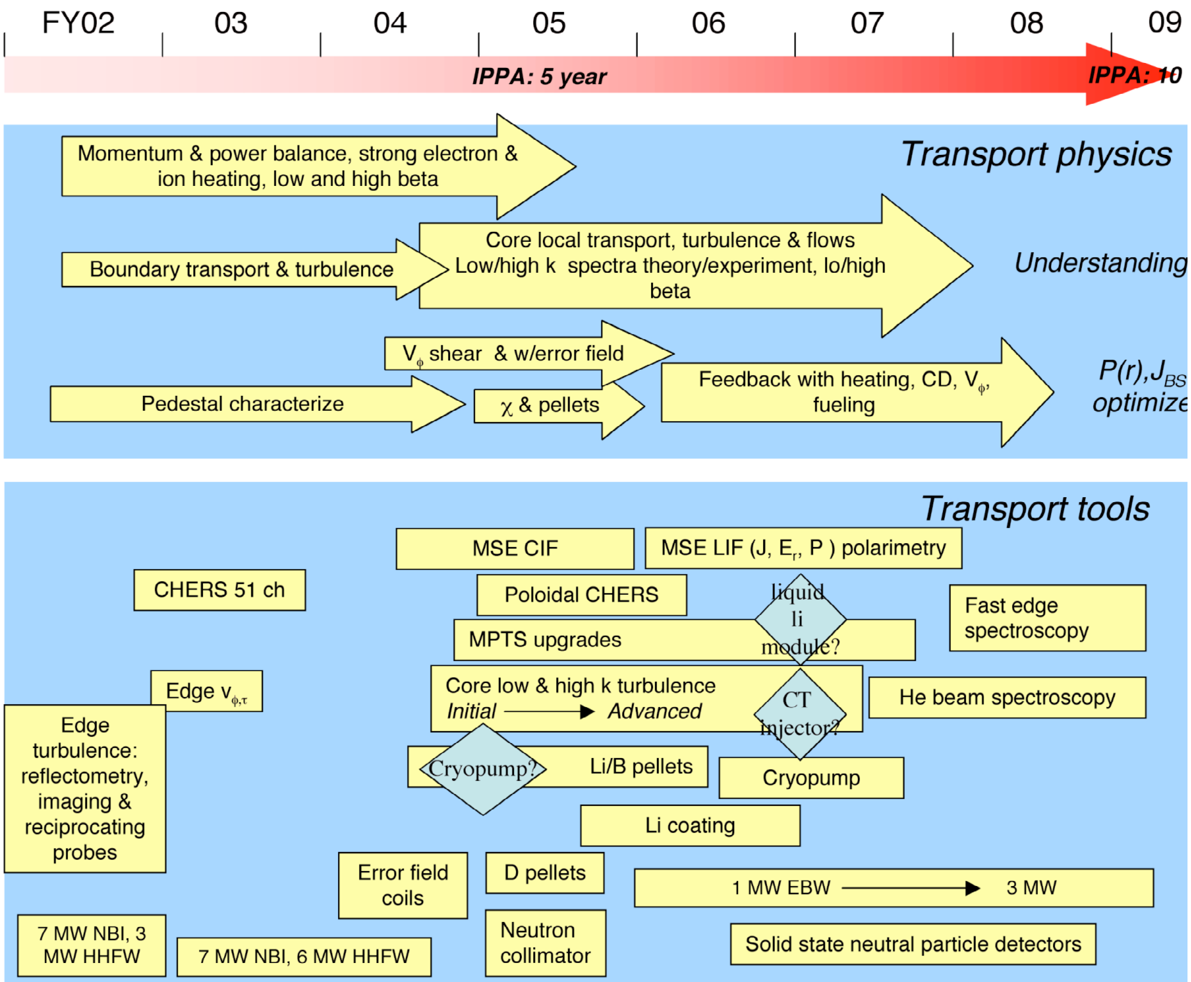
To summarize, the main topical elements of transport research over the next five years are:

- Global confinement – Establish general parametric scalings on engineering and dimensionless parameters, with emphasis on the dependence on aspect ratio and β_T for both L- and H-mode.
- Ion transport – Establish the basis for ion transport at high-β_T with respect to neoclassical and ITG turbulent transport, considering the effects of flow shear. Relate energy transport to particle transport. Clarify need for stochastic ion heating to explain the ion power balance.
- Electron transport – Establish the basis for electron transport with respect to ETG modes at high-β_T, considering the effect of flow shear. Study dynamics of ITBs. Improve electron confinement.
- Momentum transport – Assess role of rotational shear, zonal flows and relate momentum transport to energy and particle transport within both the turbulent and neoclassical frameworks.
- Fast ion transport – Assess fast ion confinement over a range of conditions, as well as the effect non-ambipolar losses have on the generation of E_{radial} and resulting ExB flow shear.

- Turbulence (core and edge) – Measure ITG/ETG turbulence and relate to ion/electron transport. Establish importance of electromagnetic transport at high-β_T. Assess role of edge convective cells relative to diffusive transport paradigm. Determine potential for stochastic heating from ETG, CAE turbulence.
- Theory – Enhance validity of neoclassical and gyrokinetic theory at low R/a, large ρ^*, high-β_T, large trapped particle fraction. Develop physics-based anomalous heating models. Develop predictive transport capability.
- Combine experimental and theoretical understanding to optimize the pressure profile through transport and current profile control.

The overall five-year plan is shown at the end of this section. The plan incorporates elements from experimental research, theory and code development, diagnostic development and facility improvements to form a logical progression of research activities in pursuit of the main transport goals.

As can be seen in the plan, the emphasis over the first year or two will be on establishing global scalings, establishing reliable methods for high-performance H-mode operation and laying the groundwork for understanding the local transport properties at low aspect ratio and high-β_T. The experimental results will be compared to linear calculations of turbulence growth rates. As profile diagnostics and theory mature, subtle effects such as the role of toroidal and poloidal rotation shear and zonal flows will be studied with detailed comparisons between theory and experiment. For instance, tests of critical gradient models will be studied using perturbative techniques. During this time, both neoclassical and turbulent transport theories will be upgraded to take into account the unique NSTX physics regime parameters. The implementation of low and high-k turbulence diagnostics will allow for direct measurement of both ITG and ETG mode amplitudes and spectra, which will then be compared with expectations from non-linear calculations. The theory and measurements will be used to determine quantitatively the role of anomalous ion heating. Studies of high beta, electromagnetic turbulence over a wide range of wavenumber and comparisons to predictions from gyrokinetic codes will also enable the NSTX program to



contribute to the dialogue surrounding certain astrophysical mysteries involving turbulence and turbulence damping.

These elements are steps toward the ultimate goal of understanding the turbulence and transport properties of NSTX plasmas well enough to, on one hand, develop a theoretical/numerical predictive capability, and, on the other, to be able to control both the kinetic profiles and current profile to understand and optimize performance in a self-consistent manner.

References

[1] Wang, W.X., Hinton, F. L. and Wong, S. K., Phys. Rev. Lett. **87** (2001) 055002-1.

[2] Chang, C.S. and Hinton, F. L., Phys. Fluids **25** (1982) 1493.

[3] Ernst, D.R., *et al*., Phys. Plasmas **5** (1998) 665.

[4] Kinsey, J., *et al*., Phys. Rev. Lett. **86** (2001) 814.

[5] Tuszewski, M., Nuc. Fusion **28** (1988) 2033.

[6] Gates, D., Gorelenkov, N. and White, R., Phys. Rev. Lett. **87** (2001) 205003-1.

[7] Rewoldt, G., *et al*., Phys. Plasmas **3** (1996) 1667.

[8] Quataert, E., E. and Gruzinov, A., Astrophysical J. **520** (1999) 248.

[9] Quataert, E. and Gruzinov, A. Astrophysical J. **545** (2000) 842

[10] Kaye, S.M., *et al*., Nuc. Fusion **37** (1997) 1303.

[11] ITER Physics Team, Nuc. Fusion **39** (1999) 2145.

[12] Kaye, S.M., *et al*., Fusion Technology **36** (1999) 16.

[13] Houlberg, W., *et al*., Phys. Plasmas **4** (1997) 3230.

[14] Redi, M., *et al*., presented at the Sherwood Theory Conference, Corpus Christi, TX, (2003).

[15] Menard, J., private communication (2002).

[16] Bourdelle, C., *et al*., accepted for publication in Phys. Plasmas (2003).

[17] Scott, S.D., *et al*., Phys. Rev. Lett. **64** (1990) 531.

[18] Stober J., *et al Nucl. Fusion* **41** (2001) 1535.

[19] Snipes, J., *et al*., presented at 19th IAEA Fusion Energy Conference, Lyon, France (2002).

[20] Terry, J., *et al*., Phys. Plasmas **10** (2003) 1739.