

Working Group 4 Report
Turbulence and Transport

NSTX Research Forum
December 3-5, 1997

E.J. Synakowski	PPPL, Leader
D. Newman	ORNL, Assistant Leader
M. Beer	PPPL
W. Dorland	UT-Austin
P.C. Efthimion	PPPL
R.J. Fonck	U. Wisc.
C. Greenfield	GA
K. Hill	PPPL
E. Mazzucato	PPPL
S. Paul	PPPL
A. Peebles	UCLA
G. Rewoldt	PPPL
G. Schmidt	PPPL
S. Zweben	PPPL

I. Introduction

The NSTX Research Forum of December 3-5, 1997, presented an opportunity for physicists to reexamine the goals accompanying needs of the NSTX program, both from the point of view of research planning and diagnostic development. In the Transport and Turbulence Working Group (Working Group IV), this process took the form of studying the conclusions and recommendations of last year's Working Group IV report, reexamining the research priorities, and assessing the progress of diagnostic development efforts that are required to meet the unique needs of NSTX.

In discussions, attention was paid to the Department of Energy's charge to reshape the fusion effort and to emphasize using a more fundamental plasma science understanding as a basis for the development of a viable fusion reactor concept. This group is asked to recommend a path that meets these scientific needs as they pertain to transport and turbulence studies on NSTX. As the Working Group members discussed the progress and goals of NSTX's program, an eye was kept on recommending a program that would be best suited to unravel the complicated physics underlying the fundamental transport mechanisms, and would address obtaining the physics understanding necessary for scaling to a reactor-scale ST. The group takes the recent program redirection as a mandate to recommend a plan that is aggressive and appropriately targeted.

Below, a recommended research program is outlined for this first two-year period. This is followed by a discussion of diagnostic needs that must be met to carry out this program. Emphasis is placed on items that are not presently included in the baseline diagnostic set.

II. Research and Diagnostic Priorities

As the ST concept represents such a radical departure from moderate aspect-ratio tokamaks, it is essential that certain basic elements that will underpin subsequent research be verified. The history of the moderate aspect ratio research program provides some guidance - core pieces of physics understanding and characterization obtained early in the tokamak's history continue to serve as the foundations of much of the present day program. ST research will deserve attention in these areas as well.

In addition, priorities also emerge as a result of the US program's strength in local transport studies. This particular emphasis has served the US program well in solidifying a niche in the international dialogue. With other ST's operating or coming on-line soon, the US should be aggressive in continuing to distinguish itself through its characterization of local transport physics.

With these items as motivation, priorities were outlined for the first and second year research program as follows:

1. *Contribute to the global scaling databases (Begin in first year)*

This issue will likely be performed in the early days of operation of NSTX, when diagnostics are just coming on-line. Global confinement scaling with average electron density $\langle n_e \rangle$, plasma current, RF heating power, and aspect ratio would be explored. Basic empirical trends that are observed to be robust in tokamaks but represent uncharted territory in ST's should be pursued initially, such as confinement time saturation with electron density in Ohmic regimes

Implications for diagnostic and development needs: As stressed in last year's report, consideration of these early studies highlights the importance of early diagnostic coverage. Sensible contributions to even the global database require knowledge of the confinement regime that has been accessed. This points to the need for edge diagnostics to look for signatures of an H mode transition and to obtain pedestal characterization, such as

1. H_α detectors
2. Edge n_e and T_e . This should be possible with the Thomson scattering diagnostic, but edge probe measurements will be of great value in this regard as well
3. Edge fluctuations: Edge Langmuir probes provide a wealth of information for little cost. It was pointed out at this forum that much of the hardware for a reciprocating probe system resides on PBX-M.

2. *Verify understanding of parallel transport and resistivity (begin early in first year)*

Experiments in moderate aspect-ratio tokamak experiments have provided verification of the validity of our understanding of parallel transport and resistivity. NSTX should benchmark its measured resistivity against calculations to ensure that the same level of understanding accompanies parallel transport in ST's.

Implications for diagnostic and development needs: The necessity of this effort reinforces the early need for diagnostics central to assessing the resistivity, i.e. spatially resolved measurements of the electron temperature, impurity concentration obtained through density and visible bremsstrahlung measurements, and current density profile estimates.

Proper assessment of our understanding of plasma resistivity in a ST is intimately linked to the problem of current diffusion in an ST, and therefore requires knowledge of the current profile. The need for current density profile measurements prior to the implementation of neutral beam heating is partly driven by the fact that plasma current relaxation times may rival the available Ohmic flattop times as the higher currents are approached. Also, there will be periods of operation before neutral beam operation which will have significant levels of RF heating.

Making connection between theory and experimentally inferred heat and particle fluxes will require knowledge of the current profile in these cases as well.

3. Assess understanding of local heating sources

Confirming understanding of local heating source profiles is central to unraveling local transport physics.

a. Study fast ion transport (year one, with RF generation of tails; year two, with advent of NBI)

There is a need to validate our understanding of fast ion transport early. [Mikkelsen, 1997] has shown that expected ion orbit physics in a ST is a complex issue. Grounding our modeling experience in experiment is essential for reasons that reach beyond issues pertaining to transport. From the narrower perspective of transport studies, assessing the beam ion orbit physics is critical so that power balance analysis of local transport characteristics can proceed on solid footing. In present tokamaks, this grounding is based in part on having global neutron measurements.

b. Measure perturbed heating sources from RF

RF wave physics (propagation and deposition) represents a challenge for NSTX. The moderate A tokamak program benefits from perturbative measurements of RF energy deposition, through changes in the local temperature profiles. However, Thomson Scattering will likely not have the temporal resolution to perform such studies.

Implications for diagnostic and development needs: Ensure that development of a global neutron detection system take place, to be ready at the latest by the early stages of neutral beam injection.

Neutral particle charge exchange analysis should be implemented early in the NSTX program. Analysis of the spectrum of lost neutrals has served as a powerful tool for examining fast ion dynamics in the past.

The Working Group again recommends that resources be allocated to pursue the development of a fast electron temperature diagnostic, such as one based on the detection of the Electron Bernstein Wave (EBW).

4. Particle and power balance analysis in different regimes (begin in first year)

Distinction between ion and electron energy flows is central to the dialogue pertaining to transport physics in toroidal devices. Being able to separate these flows early in the NSTX program is critical for investigating basic local transport studies. While fundamental physics questions examined on existing tokamaks center around the issue of power flows in the ion and electron channels, and understanding the physical basis for differences observed, this landscape is almost completely unknown in an ST. Early results from START suggest that ion channel

thermal transport may be neoclassical, while electron channel thermal transport is anomalously high. NSTX must be poised to enter this debate early. The topic of ion vs. electron thermal flows is especially relevant for ST's in general: much of the promise of the ST as a reactor concept may hinge on the ability to understand and control transport in these different channels.

Implications for diagnostic and development needs: Early participation in this research topic will require the density and temperature information contained in the Thomson scattering system. It also argues strongly for an ion temperature measurement that will precede neutral beam injection. X-ray crystal measurements are a possibility; the viability of visible spectroscopy determination of T_i from naturally occurring light impurity emission should also be explored.

Continued development of the charge exchange recombination spectroscopy-based ion temperature and rotation velocity measurements for implementation in the first days of neutral beam operation is also urged.

5. *Assessment of core fluctuation characteristics (year 1)*

A strong group recommendation emerged that the NSTX program should pursue the early implementation of a survey of core fluctuations. The physics and development time considerations leading to this recommendation are based on the strong possibility that characterizing and controlling fluctuations may be central to assessing the viability of the ST as a viable reactor concept.

Much of the scientific motivation for aggressive diagnosis of NSTX originates from provocative theory work suggesting that the ST may have striking stability properties against microturbulence. The nature of such predictions, e.g. possibly intrinsically low instability growth rates [Rewoldt, 1995] and potentially enormous $E \times B$ shearing rates [Stambaugh, 1995], elevates the importance of early fluctuation studies on NSTX. In addition, [Kotschenreuther] argued at this Forum that the viability of the ST as a volume neutron source might hinge in part on the ability of $E \times B$ shear to suppress the local microinstabilities if the plasma profiles assumed by [Rewoldt] are not realized.

The evolution of plasma diagnostic techniques and theoretical analyses in the past several years and the experimental successes in reducing microturbulence in many toroidal devices suggest that our usual assumptions regarding the timing of the implementation of core fluctuation diagnostics be revisited.

Implications for diagnostic and development needs: Developing a new measurement for local fluctuation in the core requires significant lead-time, and can strongly benefit from a survey instrument. The time required for this assessment and development of this local measurement is what drives the need for a survey instrument early on. Ultimately, the program must strive for

obtaining local measurements of core fluctuations. However, the development path for local fluctuation measurements represents a research challenge in itself. Characterization of the fluctuation landscape with a survey instrument, such as FIR scattering, will be invaluable in guiding this development, as well as giving early feedback to theory.

The Working Group repeats its call to assemble a group of experts to recommend a path for core fluctuation measurements. Such a path might begin with a survey instrument to broadly characterize the fluctuations and serve as initial input to theory. This would be followed by the development of a local measurement based on information obtained in the early days of operating NSTX.

6. *Perturbation studies*

The value of perturbation studies in revealing transport trends in existing devices is high. At present, the only diagnostic that is currently in the research plan that has relatively high assurance of providing the time response required for useful perturbation studies is charge exchange recombination spectroscopy. This will allow for perturbation studies of impurities, momentum, and perhaps ion temperature.

An important class of physics is revealed through the study of the perturbation of bulk quantities such as the electron particle flux and thermal electron and ion heat fluxes. Most of these studies will not be possible unless a fast time-resolved electron density and temperature diagnostic set is implemented on NSTX. The path forward for a time- and space-resolved measurement of either of these quantities is not identified as of yet.

Implications for diagnostic and development needs: Recommendations include the investigation of the viability of the EBW electron temperature diagnostic. Mid-plane interferometry for electron density diagnostics requires design study for implementation.

III. Diagnostics and other tools required to address needs of the broader program

Several diagnostic needs that are not particular to any one research topic highlighted above are central to the NSTX program and must be met. Below are listed diagnostic needs that were highlighted in last year's report. Progress in their development and update of the recommendations are given below. Highlighted following this list are other items that may have potential near-term value for transport studies.

1. Diagnostic issues

A. *Electron temperature measurements.* The Working Group recognizes that significant resources have been directed towards fulfilling the call of last year's forum to implement a time- and space-resolved Thomson scattering as a Day 1 diagnostic.

The loss of ECE-based electron temperature measurements is significant for NSTX, and the need to pursue an Electron Bernstein Wave-based system is still present.

B. *Ion temperature and ion rotation measurements.* Still high priority for NSTX, this year's Working Group strengthened the call for a pre-neutral beam measurement (see above).

The Working Group recognizes that some detailed studies regarding access for viewing sight-lines for a CHERS (CHarge EXchange Recombination Spectroscopy) system has recently begun. This includes identification of the best available lockdown views for a V_θ measurement.

C. *Electron density measurements.* While a multiple time-point Thomson scattering system might be used, interferometry must seriously be considered for this needed measurement due to its superior time response. However, it was learned this year that the access required for the existing TFTR MIRI system would not be available on NSTX.

Last year the Working Group pointed out that the assumption of toroidal symmetry is particularly useful for interferometric systems applied on the mid-plane. This approach would also permit the determination of the toroidal magnetic field profile through a simultaneous Faraday rotation measurement. The roles of paramagnetic and diamagnetic effects in a high beta device like NSTX are exaggerated compared to higher aspect ratio tokamaks, and measurement of B_T may supplement or surpass the finite beta corrections made possible by kinetic profile measurements. Is this possibility being pursued?

Development of the Imaging Second Harmonic Interferometer (ISHI) system on Alcator C-Mod was suggested and received with great enthusiasm last year. However, it looks as if little progress has been made in this area. This year's Working Group reasserts the potential for spatial resolution of ~ 2 mm at the edge is attractive, as is the system's inherent immunity to vibration.

D. *Poloidal magnetic field measurements.* Owing to the low toroidal field on NSTX, the applicability of standard techniques for measuring B_θ and the q profile is highly questionable. Last year's forum resulted in the assembling of an expert group to recommend a diagnostic path forward in this regard. In fact, NSTX may be a device for which a combination of core B_θ profile measurement techniques and magnetics must be used in order to constrain the plasma equilibrium.

The Motional Stark Effect technique has the broadest support as a possible measurement technique for the beam-based phase of operation on NSTX. Low field operation changes the fundamental character of the measurement, however. Improvements in signal-to-noise may be improved by the use of laser-induced fluorescence with the MSE diagnostic. Importantly, if ST plasmas are characterized by strong radial electric fields, it is of considerable concern as to whether the plasma's own electric field will dominate in at least some portions of the plasma over the electric field experienced by beam neutrals as they traverse the plasma's magnetic field.

Recommendations follow. Some were made last year but still should be pursued:

1. Continue examination of signal-to-noise of pitch angle measurements. Under the best of conditions, what is the obtainable accuracy and what are the resultant uncertainties in q ?
2. Examine the value of a direct B_T measurement through interferometry, discussed above. It may be a valuable component in obtaining the q profile, in conjunction with the pitch angle measurement.
3. Consider the application of a heavy ion beam probe for the measurement of poloidal magnetic field.
4. Continue to pursue X-ray pinhole camera-based flux surface reconstruction. Inversion of the emission might be aided by the development of a detector array that images individual horizontal slices with a minimal vertical component to the sightlines.

E. *Core fluctuations.* The importance of this issue was stated above in Section II. Diagnostic-related concerns highlighted in last year's report include the following.

In the expected parameter range in NSTX electron cyclotron emission-based scattering techniques will not be possible. O-Mode reflectometry in the 20 - 60 GHz range may provide a means of making core measurements, as it is well suited to the small poloidal wavenumbers expected. This technique's utility is limited to density profiles with some degree of peaking. Also, launch issues pertaining to the pitch angle of the magnetic field need to be assessed. In the event that flat density profiles are dominant on NSTX, collective FIR scattering can be performed, but little spatial and k resolution will be possible.

A potential difficulty of fluctuation measurements by Beam Emission Spectroscopy (BES) was identified in this workshop, namely, the presence of large poloidal pitch angles, especially near the plasma edge. On TFTR and DIII-D, advantage is taken of the fact that midplane sightlines view along a field line within the neutral beam volume, thus providing poloidal spatial resolution. On NSTX, such a midplane view would result in poor resolution, since the pitch angle of the field lines will be many tens of degrees. Core measurements with BES appear to be more tractable using mid-plane views.

Note that, although long wavelength modes are expected, the program should be prepared to examine the shorter wavelength regions as well. This issue may be of particular importance to the understanding of the anomalously high electron transport observed on larger aspect ratio devices even when the ion channel is suppressed.

Recommendations for near term are also stated in Section II, and include the formation of an expert group to recommend a diagnostic development path.

F. *Radial electric field measurements.* Research in the last year continues to reinforce the importance of electric fields in understanding the dynamics of magnetized plasmas. Direct E_r measurements will be of high value to the NSTX program. Supplementing the determination of E_r through solution of the impurity force balance equation may be more than a luxury, since the potential accuracy of needed B_θ measurements is not known. Also, the accuracy of V_θ by CHERS may hinge on up-down symmetry of impurity emission that may well be violated at low aspect ratio. The viability of using the D_α emission from different energy components of the neutral beam should be assessed.

Work assessing the expected uncertainties in an E_r measurement based on the Stark effect are ongoing. The implementation of a heavy ion beam probe should also be considered for this application.

G. *Edge transport diagnostics.* The topic of fluctuations and transport is of utmost importance at the plasma edge as well. As Langmuir probes are relatively inexpensive, and the edge of ST devices is unexplored territory, they should be implemented in such a way to permit poloidal coverage as well as mid-plane coverage. Reciprocating probes should also be considered. As mentioned above, existing hardware on the PBX-M tokamak might be used in this regard. Edge reflectometry techniques should also be considered for edge electron density measurements. They also can provide poloidal coverage.

Multilayer mirror spectroscopy is also suggested as a possible means for obtaining edge temperatures and impurity information, and its potential for characterizing edge MHD activity has been demonstrated.

2. Different fueling schemes; preliminary E_r control

Pellet injection on tokamaks provided some of the first observations of the possibilities of improved core confinement. Enhanced core confinement with pellet injection has frequently been observed during ohmic operation on many tokamaks, including Alcator C, TEXT, and ASDEX.

Part of the attractiveness of pellet injection comes from the fact that rapid densification of the plasma will be adiabatic, keeping the pressure constant, while changing the relative roles of

the density gradient and the temperature gradient in determining poloidal flows. As such, it offers the possibility of being used as a control tool for transport barriers.

Compact toroid injection was suggested at this year's forum as well. This suggestion accompanies the recent observation from TdeV that their first observed H modes occurred following CT injection. If the funding can be found to pursue such a program, CT injection would yield intriguing possibilities regarding fueling and profile modification.

IV. Computational needs/theory-experiment comparisons

Examination of a number of theory-related issues should be pursued in the near term. Many of these needs were highlighted in last year's report, and are reasserted here. Resources from the NSTX program should be allocated to permit these studies to take place within the context of the existing program.

A. Work to be performed or begun before the start of NSTX operations

These represent work that theorists should perform to examine a broad class of ST-related issues. To make for a set of self-consistent exercises, they can be performed using a set of standardized NSTX density, temperature, and rotation profiles that is recommended by this Working Group (See Section V). As such, the work can and should begin before the start of NSTX.

1. *Kelvin-Helmholtz instabilities.* Due to the presently envisioned unbalanced beam injection, attention should be paid to the possible onset of Kelvin-Helmholtz instabilities for NSTX-like plasmas in gyrokinetic simulations. This can be examined as a matter of course in gyrokinetic studies of microinstabilities in general, but only if rotation is explicitly included in the assumed profiles. This again points to the need for a self-consistent estimate of a range of obtainable toroidal rotation velocities. The issue is potentially of concern for NSTX, owing to the stronger toroidicity of small aspect ratio plasmas.

2. *Neoclassical performance of NSTX plasmas.* A related issue was pointed out above, but the importance of understanding the implications of neoclassical transport for NSTX is emphasized here by pointing out that there may be issues for MHD stability if somehow neoclassical transport is realized. Is neoclassical transport, and the accompanying pressure gradients, consistent with the stability requirements of NSTX? What is the beta limit with the available power if neoclassical theory dominates?

Related to this issue is an assessment of the applicability of neoclassical theory to ST's in general. Does neoclassical theory exist in sufficient sophistication to cope with the large orbit

sizes that will occur in ST's, especially in light of the possibly steep pressure and electric field gradients? Will the neoclassical transport really be small, given the large orbits

3. *Nonlinear neoclassical viscosity regimes.* Strong damping of poloidal flows is expected in NSTX, due to the large gradient in the toroidal magnetic field. However, due to large orbit and drift orbit widths and the expected high beta limit, significant orbit squeezing is expected. Do these effects lead to the possibility of approaching a nonlinear neoclassical viscosity regime in which the damping is overcome?

4. *Microinstability and nonlinear analysis of standardized profiles.* The standardized profiles discussed above should be checked with microinstability calculations and nonlinear simulations to determine whether they are reasonably self-consistent. Preliminary work in this area has begun [Rewoldt], but the profiles should be varied in a way consistent with the expected input power.

B. Experiment/theory comparisons of local transport trends to begin in the first year of NSTX operation

These recommendations are motivated by successful interactions between experiment and theory that have been performed by the tokamak community over the last 5 - 7 years. The power of these comparisons in the past, and the emphasis for work on NSTX, is comparing experimental confinement trends and comparing them to predictions from evolving theoretical models.

These exercises generally require sufficient profile diagnosis for power balance analysis and some estimate of $q(r)$:

1. *Comparisons of measurements of ratios of local particle and energy fluxes to gyrokinetic simulations*

Emphasis to be on different confinement regimes, plasmas with different scale lengths, q profiles

2. *Comparisons of trends observed in measured and modeled temperature profiles, using measured boundary conditions*

Examples of this work include present day comparisons with a multi-mode model, or the IFS-PPPL model

3. *Comparison of measured temperature dependence of particle and energy fluxes to predictions from gyrokinetic and gyrofluid modeling*

Following the work performed on TFTR, this would be performed as an RF or NBI power scan at constant density. Few ms response of $n_e(r,t)$ or $n_z(r,t)$ is desirable, but power and particle balance analysis will yield useful results

4. *Comparison of measured density dependence of particle and energy fluxes to predictions from gyrokinetic modeling*

A similar approach would be used as in (3), with emphasis on maintaining a constant temperature profile while varying the density

5. *Comparison of observed edge and core transport barrier dynamics to those predicted by a dynamic model*

This would clarify the trends of threshold power with variations in toroidal field, q , and density; barrier propagation speeds; and fluctuation behavior.

6. *In the advent of a core barrier, comparison of measured transport coefficients to neoclassical predictions*

Requires power and particle balance analysis, profile measurements including q . Will challenge theory to account for different ordering that usually assumed in neoclassical theory, but possibly present in an ST.

V. Need for a standardized set of NSTX profiles

Discussion of diagnostic and other programmatic issues would be greatly facilitated by the widespread use of standardized profiles.

Forward modeling with a self-consistent equilibrium, under some agreed-upon set of assumptions, should be performed to generate standardized profiles of electron density, electron and ion temperature, impurity concentration, q profile, and toroidal rotation profile. Three sets of conditions were identified as being potentially useful:

1. L mode
2. H mode
3. High performance (neoclassical ions)

Availability of profiles under these classes would serve to give the community a broad sense of the possible ranges of plasma operation on NSTX, and at least as importantly would give physicists a standardized set of profiles with which diagnostic system development can be guided. Profiles generated with reasonable assumption regarding momentum transport (e.g. $\chi_\phi =$

χ_i , as is often observed on TFTR, or $\chi_\phi = \chi_e$, as is often seen on DIII-D) would also be of practical value to those considering fluctuation diagnostics, for example, as it might help the user decide for which frequencies a fluctuation diagnostic should be optimized.

While some profiles do exist that have been optimized with respect to the beta limits and the plasma pressure, they are not widely available in general. Also, since the future performance of NSTX is such an unknown, the availability of standardized profiles over a wide range of confinement possibilities is highly desirable.

VI. The planning process and moving towards realization of the Forum's goals

The standards for participating in a meaningful way in a dialogue about transport and turbulence in the US and the international community are high. In an effort to promote a vital plasma science program on NSTX, a significant investment in diagnostic development time must be made. However, a pervasive concern of the Working Group was made manifest upon examination and discussion of the last year's Working Group report, discussion of the goals presented, and the degree of follow-up that has taken place.

Last year's report identified many areas of diagnostic development that should take place of a well-balanced research program is to be realized reasonably quickly. A successful outcome from last year's forum was a result of strong recommendations that time- and space-resolved Thomson scattering be considered a Day One diagnostic. The Working Group recognizes the resultant commitment that has been made, and that this will make a considerable contribution to the initial physics studies on NSTX.

However, this is something of an exception, and there are many diagnostic and development-related suggestions made that have had little or no follow through. The process at present does not provide any means for development activities to be fostered after strong group suggestions are made. Examples of some (but not nearly all) recommendations from last year that have not been pursued to a significant degree include:

- 1) the examination of the viability of a two color interferometry system for line-averaged density measurements;
- 2) the formation of an expert working group to make recommendations for a course of action on core fluctuation diagnostic development;
- 3) the development of an Electron Bernstein Wave (EBW) based electron temperature diagnostic; and
- 4) the examination of the viability of the installation of a Heavy Ion Beam Probe for plasma potential and density fluctuations, as well as pitch angle measurements.

While the Working Group in general recognizes that this situation is in part a consequence of constrained budgets, etc., it must be recognized at all levels that further delaying these

development efforts runs considerable risk of having a significant adverse impact on the NSTX Research Program.