Workshop on Turbulence Diagnostics
For the National Spherical Torus Experiment Research Program

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Meeting participants

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F. Levinton, Nova Photonics
E. Mazzucato, PPPL
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I. Introduction and Charge of Workshop

The National Spherical Torus Experiment (NSTX) is one of a class of Proof-of-Principle (PoP) experiments in the Department Of Energy's science-based fusion research program. Successful completion of the PoP mission requires establishing a physics database that will enable extrapolation of measured performance characteristics to a larger class device (Performance Extension). The community's need to perform such an extrapolation based on a knowledge of local physics understanding is underscored in several documents produced with community-wide input, including the Integrated Program Planning Activity (IPPA) Report (November 2000). Indeed, Goal 1 of the IPPA Report speaks strongly to the value of a programmatic investment in turbulence diagnostics and analysis capability on NSTX that will complement turbulence research activity on other devices. The Turbulence and Transport Objective in the IPPA Report reads,

> **5-year Objective**: Advance the fundamental understanding of turbulent transport forming the basis for a reliable predictive capability in externally controlled systems.
> Progress will be measured by the evolving level of agreement between theory, simulation and experimental measurements of transport phenomena.

The report continues,

> "...The progress fusion scientists have made in this area is profoundly important. But the design and operation of future devices will increasingly depend upon the ability to predict transport with quantitative accuracy, and this ability will require *deeper understanding of turbulent mechanisms and effects*. Key issues include more complete understanding of the underlying processes responsible for transport barrier formation and evolution seen in experiments, and the need to understand electron transport more deeply."

Through a judicious choice of turbulence measurement techniques, the NSTX program can be in an excellent position to contribute to and expand the toroidal physics database of both long wavelength (dominating ion heat transport) and short wavelength (possibly dominating electron heat transport) turbulence dynamics. Indeed, transport and confinement are key issues that will determine the viability of the ST concept. Developing a physics basis for successful execution of the NSTX program in the area of transport requires a knowledge of the details of turbulence and turbulence dynamics in both the core and the edge.

The national program has an opportunity to development a confinement research strategy nationwide that uses the existing toroidal confinement device differences as leverage to reveal the physics differences revealed between low and high beta, low and high aspect ratio, and weak and strong magnetic field. To this end, a comprehensive strategy for turbulence research on NSTX can be made to complement the research program on other devices by examining the changes in turbulence properties brought about by these differences, and the implications of them. Such a strategy has the prospect of contributing to the basic physics of turbulence dynamics in plasmas and fluids in general. It will also contribute to the more practical goal of forming the physics basis required for making a scientifically sound decision on the direction of

the step beyond the PoP stage of development. At the Turbulence Diagnostic Workshop, possible elements of such a strategy were discussed and identified.

II. Summary and Recommendations

Preferred research strategies, including diagnostics options, follow. Considered in developing these strategies were the high beta, low aspect ratio physics accessible to each proposed measurement technique, and infrastructure requirements for supporting the development of each option on NSTX.

II A. Core turbulence diagnostics

Whatever the details of the strategy chosen, a compelling scientific need is the ability to study both low and high wavenumber fluctuations. Interest in both low and high k is reinforced by recent theoretical analysis of NSTX data that suggests that long wavelength modes may be suppressed at high beta under some circumstances, while transport induced by short wavelength modes may be robust.

Summary recommendation - A two-element research strategy is recommended for the core of NSTX. The diagnostics of this strategy are

1. A microwave scattering system for survey capability of low and high k modes. A system with radial launch offers some advantage regarding port space, since both it and item (2) can utilize a single large port.
2. A microwave imaging reflectometry diagnostic advanced diagnosis of the local character of long wavelength (low k) modes.

The single port strategy outlined above, utilizing both scattering and imaging, offers the promises of obtaining a required k survey capability and of significantly advancing diagnostic techniques for localization and visualization of turbulent phenomena. Both will qualitatively advance our plasma science program and address the IPPA goals. In particular, detailed local measurements now demanded by the need to compare with massively parallel computer simulations would likely be obtained.

This particular recommendation, in our view, provides one opportunity for developing survey and local measurement capability over a wide range of k that makes good utilization of limited diagnostic access. In addition to the physics that is potentially accessible with this pairing, a radial launch scattering system/imaging system pair offers the facility the advantage of utilizing a single, large viewing port on the NSTX device midplane.

It should be noted that a tangential launch microwave scattering system may be a viable option for sampling high k fluctuations with good spatial resolution and radial k resolution. Port access requirements are increased with such a system as compared to the single port approach outlined above. Between a radial and tangential launch scattering system, the tradeoffs regarding k

resolution, spatial resolution, range of k sampled, component of k sampled, and requirements for port size and number of ports have to be weighed carefully.

Peer review will be required to assess the technical viability of any suggested approach. Regarding (1), issues include the viability of successfully reflecting the launched signal off of a flattened tile on the NSTX center stack. Regarding (2), a feasibility study is underway at the TEXTOR device, with funding from DOE.

More specifically, this strategy fills the following physics needs that were identified at the Workshop:

1. *Physics need: Survey capability* – Microwave collective scattering was identified as the leading candidate for providing a survey capability of space and of wavenumber. Collective scattering offers a method of both surveying/monitoring the low wavenumber fluctuation content of the plasma while providing localized information at higher wavenumbers. For both low and high k, the region across the plasma midplane will be accessible, allowing for identification of in-out asymmetries that are expected to be exaggerated in high beta regimes.

   As the ST is uncharted territory with considerable theory-driven anticipation of turbulence characteristics in high beta plasmas, the program needs a core turbulence diagnostic capable of surveying a wide range of spatial locations and wavenumbers (reciprocal wavelengths, or k values).

   Importantly, a conclusion of the Workshop was that the ST field line geometry will enable spatial localization, under some conditions, beyond that seen at conventional aspect ratio. Thus, NSTX provides a unique opportunity to extend the range of applicability of collective scattering measurements.

2. *Physics need: Spatial resolution of the poloidal wavenumber of long wavelength modes* – Resolution of the poloidal wavelength of modes provides a measurement of distinguishing characteristics of turbulence that can serve to clarify turbulence dynamics physics. Microwave Imaging Reflectometry (MIR) provides the only known means of providing this information in the plasma core. Feasibility should be known in the very near term from measurements being funded by DOE on the TEXTOR device. Implementation of simultaneous launch of different frequencies will allow radial resolution of modes to be obtained as well. Successful implementation of this diagnostic technique would represent a qualitative advance in measurement capability.

3. *Physics need: Measurements of short wavelength turbulence* – High beta NSTX plasmas provide a unique opportunity to study the universally important physics issue of electron thermal question. Short wavelength turbulence, such as ETG modes, may be a significant contributor to anomalously high electron thermal transport rates that is found to persist in tokamaks even when ion transport is reduced. Recent microstability analysis using NSTX profile data suggests that such modes may be the dominant contributor to thermal transport in some high beta NSTX discharges. The comparatively large electron gyroradii at the lower NSTX fields make detection of these modes readily more accessible in a scattering system than they are in higher field devices. Thus, NSTX may be a favorable setting for studying this ubiquitous problem.

Collective microwave scattering would provide a means of acquiring spatially localized information on short wavelength modes. The radial launch microwave scattering system (Peebles, UCLA) and the tangentially launched microwave system proposal (Mazzucato) both potentially provide sufficient k resolution to resolve ETG modes.

The FIReTIP interferometry system would provide the basis of a system that, if scattering optics are implemented, would provide a useful survey of the activity of these short wavelength modes. A concern is that the port access currently planned for this diagnostic may not accommodate desired scattering geometries.

II B. Edge turbulence diagnostics

Several opportunities to enhance edge diagnostic measurement capability were discussed. In general, it was recognized that the ST geometry and relatively high beta edge conditions may yield turbuence characteristics that, when compared to those seen atstandard aspect ratio, allow important tests of different theories. Such issues include the nature of turbulence and transport in both the closed and open field line edge regions, L-H transition theory, the role of poloidal damping, physics of pedestal width determination in H mode plasmas, and more.

Three major thrusts were identified, and important and emerging analysis issues that underscore some of these experimental choices were noted.

i. Physics need: Capabiliity to measure the physics elements of turbulence-generated flows – Developing understanding of zonal flow physics has been recognized as being key to establishing predictive capability. Measurements of magnetic and electrostatic turbulence properties related to Maxwell and Reynolds stresses, and the generation of turbulence-generated flows, are therefore key. NSTX plasmas may change the relation between these flow generation mechanisms, and if so these differences should be observable in the plasma edge.

Hardware requirement: Modification of the soon-to-be-implemented probe head (H. Ji, PPPL) in collaboration with UCSD (Boedo), to access the relevant stress tensors would provide access to these physics elements.

ii. Physics need: Capability to measure edge turbulence properties at more than one poloidal location – Measurements of turbulence properties near the X-point of the plasma as well as in the scrapeoff region nearer the midplane were identified as providing qualitatively new information on edge turbulence dynamics. Such a capability might provide an additional test of edge turbulence simulations such as BOUT. Such a diagnostic is clearly also desired for the divertor studies as well and has been ranked with other divertor diagnostics in other proceedings.

Hardware requirement: Deployment of an additional edge probe that can gain access to the plasma's X-point region is required.

iii. Physics need: Capability to image edge turbulence - Turbulence imaging diagnostics results will likely suggest new ways of conceptualizing plasma transport in the edge region as well as the core. Such diagnostics are particularly suited to search for large-scale coherent or organized structures which may have convective-like (as opposed to turbulent diffusive) behaviors that are difficult or impossible to see using the statistical approach which currently dominates the field.

Hardware implications: Recent results from a fast camera imaging system of edge turbulence structures (Maqueda, LANL; Zweben, PPPL) demonstrate the feasibility of this technique. A second fast camera is desired that would enable images separated by 10's of microseconds to be obtained, generating information on plasma flows and evolution of turbulent structures.

Results from the development of a laser-induced fluorescence system (Levinton, Nova Scientific) were presented as well. Such a system would provide localized information on primarily density fluctuation activity.

Prioritization of these two imaging diagnostic activities was not discussed.

Other new probe diagnostics of interest included magnetic fluctuation diagnostics to search for possible E.M. effects at high beta (signature: increased magnetic fluctuation amplitudes) and, eventually, magnetic fluctuation induced heat transport, helicity transport, and current transport at high beta. A properly designed version of such a diagnostic might also be capable of looking at the scattering of HHFW RF by edge turbulence. Turbulence diagnostic priorities were discussed but no agreement was reached.

II C. Other diagnostic proposals

Beam Emission Spectroscopy - G. McKee (U. Wisconsin) developed an assessment of the viability of BES on NSTX. D. Johnson (PPPL) presented the results, in conjunction with his own analysis of sightline geometry requirements.

Conclusions: BES is technically viable, and the option should be included for future consideration. However, because of the large field pitch and radial variation of field pitch, special reentrant viewing optics are required and satisfactory spatial resolution will likely come over a somewhat limited spatial range. Also, in-out fluctuation asymmetry assessment will not be possible. It is noted that recent results on DIII-D demonstrate the capability of imaging of density fluctuations at the plasma edge. Based on an initial assessment of optical throughput available in a feasible reentrant system and comparisons with the DIII-D system, it appears that the NSTX pulse length is sufficiently long to allow fluctuation characteristics near the edge to be extracted by building up signal statistics over the length of the plasma current flattop.

D. Stutman presented information on a proposal to build an ultra-soft x-ray telescope for local impurity fluctuation measurements.

Conclusions - the same limitations above regarding pitch angle and spatial resolution apply here. The primary justification for this diagnostic should not reside in fluctuation measurements alone, but rather in the broader implications of making such spectroscopic measurements of local transport and impurity fluxes and diagnostic development of these high throughput, high time resolution systems.

Heavy Ion Beam Probe - P. Schoch (RPI) presented results of HIBP experiments obtained on the TEXT tokamak.

Conclusions: The HIPB technique has considerable potenntial for measurement of transport- and fluctuation-relevant parameters including fluctuating density, potential, and fluctuation-induced particle fluxes. It is reasonable to expect that measurements will be sensitive to fluctuations with wavenumbers up to 3 cm-1, based on experience from TEXT-Upgrade. The details of the wavenumber range sampled and the sample volume will depend on future analysis specific to NSTX. Resolution of the k spectrum is not provided by this technique. Rather, information on the average k value at a given frequency is provided in a manner similar to what is provided with a two-tipped probe. However, the interface expense and complexity for an HIPB system is significantly greater than for the other diagnostics discussed in this report. The proposed HIBP would not provide in-out access to assess fluctuation asymmetries that might be exaggerated in the ST geometry, although a higher energy HIPB could possibly do this.

III. Appendix

Fluctuation Diagnostics Meeting Agenda **Thursday, January 18** **B-318**

Speaker	Topic	Talk Time	Discussion Time
E. Synakowski	Meeting Charge	9 - 9:10 AM	
T.S. Hahm	Overview of ST Issues and Analysis Tools	9:10 - 9:35	9:35 - 9:45
D. Johnson	Practical Considerations for NSTX Turbulence Diagnostics	9:45 - 10:10	10:10 - 10:20
E. Mazzucato	Detection of turbulence fluctuations with microwaves	10:20 - 10:40	10:40 - 10:50
-- coffee break --		10:50 - 11:05	
H. Park	Detection of ETG modes using FIR Tangential Interferometer/Polarimeter on NSTX	11:05 - 11:25	11:25 - 11:35
P. Schoch	HIBP Measurements on NSTX	11:35 - 11:55	11:55 - 12:05
T. Peebles	Core and Edge Turbulence Measurements on NSTX	12:05 - 12:25	12:25 - 12:35
--- Lunch---		12:35 - 1:30	
J. Boedo	Edge Turbulence Diagnostic and Analysis Needs	1:30 - 1:50	1:50 - 2:00
R. Moyer	Coupling Between Turbulence and Low Frequency Fluctuations on NSTX	2:00 - 2:20	2:20 - 2:30
H. Ji	Measuring the Physics of Turbulent Flows	2:30 - 2:45	2:45 - 2:55
S. Zweben	Gas Puff Imaging of Turbulence on NSTX	2:55 - 3:15	3:15 - 3:25
--- break ---		3:25 - 3:45	
F. Levinton	Visualization of Edge Turbulence with LIF	3:45 - 4:05	4:05 - 4:15
G. Tynan	Possible UCSD Edge Turbulence Studies	4:15 - 4:35	4:35 - 4:45
G. Antar	Convective Turbulence in the SOL	4:45 - 5:05	5:05 - 5:15
Beginning of Open Discussion		Until 6 PM	

Friday Morning **Director's Conf. Room**

Discussion of Strategy Elements		8:30 - 12 noon	
Adjourn		12 noon	

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