PREPARED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT DE-AC02-76CH03073

PPPL-3614
UC-70

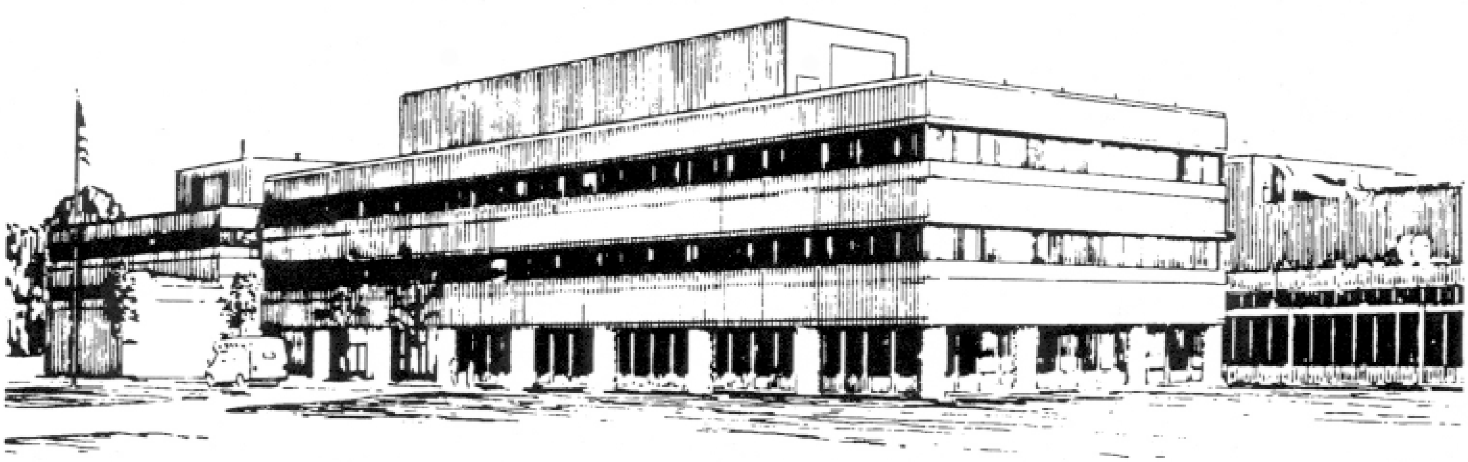
PPPL-3614

Diagnosis of ST Plasmas in NSTX: Challenges and Opportunities

by

D. Johnson, P. Efthimion, J. Foley, B. Jones, E. Mazzucato,
H. Park, G. Taylor, F. Levinton, and N. Luhmann

September 2001



PRINCETON PLASMA PHYSICS LABORATORY
PRINCETON UNIVERSITY, PRINCETON, NEW JERSEY

PPPL Reports Disclaimer

Availability

This report is posted on the U.S. Department of Energy's Princeton Plasma Physics Laboratory Publications and Reports web site in Calendar Year 2001. The home page for PPPL Reports and Publications is: http://www.pppl.gov/pub_report/

DOE and DOE Contractors can obtain copies of this report from:

U.S. Department of Energy
Office of Scientific and Technical Information
DOE Technical Information Services (DTIS)
P.O. Box 62
Oak Ridge, TN 37831

Telephone: (865) 576-8401

Fax: (865) 576-5728

Email: reports@adonis.osti.gov

This report is available to the general public from:

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Telephone: 1-800-553-6847 or
(703) 605-6000

Fax: (703) 321-8547

Internet: http://www.ntis.gov/ordering.htm

DIAGNOSIS OF ST PLASMAS IN NSTX

Challenges and Opportunities

D. Johnson, P. Efthimion, J. Foley, B. Jones, E. Mazzucato, H. Park, G. Taylor, F. Levinton, and N. Luhmann*

1. INTRODUCTION

During the past decade, considerable experimental and theoretical progress has been made in the development of the Spherical Torus (ST) configuration. A second generation of 'proof of principal' devices, including GLOBUS-M, MAST and NSTX, are now operating with plasma currents in the 1-2 MA range. The ST has already been the basis of a reactor study, and the concept has also been considered in the context of a volume neutron source.

As the aspect ratio of a conventional circular tokamak is reduced towards one, the cross-section naturally assumes a shape with high elongation and triangularity, with only modest requirements for shaping fields. This configuration can sustain high plasma current with high values of edge q, meaning that the toroidal field can be much lower than that in a conventional tokamak. Compared to a standard tokamak, the magnetic field pitch can be very large (pitch angles > 50° at outer midplane). High values of toroidal beta can reached, and the combination of high β, high κ, and high q(a) leads to the potential for a large bootstrap current sustainment.

The National Spherical Torus Experiment (NSTX) is a low-aspect-ratio torus ($R/a \leq 1.3$) designed to produce and study high β_T (25-40%) plasmas that are non-inductively sustained with high bootstrap fraction (≤70%). Heating and current drive is done with a 3-source neutral beam (5 MW) and a 12 strap, high-harmonic-fast-wave (HHFW) antenna (6 MW). In addition, coaxial-helicity-injection (CHI) is used for non-inductive plasma current initiation. Basic device capabilities are R=0.85 m, a=0.68 m, $I_P \leq 1.4$ MA, $B_T \leq 0.45$ T with elongation ≤ 2.0 and triangularity ≤ 0.5. Central plasma parameters in the range of $n_e = 4\text{-}5 \times 10^{19}$ m^{-3} and $T_e, T_i = 3\text{-}4$ keV are obtained for high power heating experiments, which began in late 2000.

* D. Johnson, P. Efthimion, J. Foley, B. Jones, E. Mazzucato, H. Park, G. Taylor, Princeton Plasma Physics Lab, P.O. Box 451, Princeton, NJ, 08540. F. Levinton, Nova Photonics, 1 Oak Place, Princeton, NJ, 08540. N. Luhmann, University of California, Davis, 228 Walker Hall, Davis, California 95616

This paper will highlight some of the challenges and opportunities present in the diagnosis of ST plasmas on NSTX, and discuss the corresponding diagnostic development that is currently underway. After a brief description of diagnostic systems currently installed, examples of ST-specific diagnostic challenges will be highlighted, as will another case, where the ST configuration offers opportunities for new measurements.

2. PRESENT DIAGNOSTICS

The evolving NSTX diagnostic set currently has a set of magnetic sensors adequate for plasma control and between-shot equilibrium reconstruction. Filtered, fast visible cameras provide valuable information on overall discharge evolution, with focussed views on edge turbulence and divertor region. IR cameras view areas such as the divertor region which have significant power efflux. Profile diagnostics include a multi-pulse Nd:YAG Thomson scattering system (T_e and n_e), edge reflectometry (n_e), charge exchange spectroscopy (T_I and v_ϕ), bolometer arrays (P_{rad}), and VB arrays (Z_{eff}), Impurities are monitored by visible and UV spectrometers, filtered fiberscopes, and soft x-ray detectors. A scanning neutral particle analyzer and fixed fast ion loss probe measure fast ion behavior. MHD activity is monitored by Mirnov arrays, soft x-ray arrays, and correlation reflectometry. Measurement developments in the next period will emphasize diagnostics for the divertor, for q(R), and for turbulence.

3. ELECTRON BERNSTEIN WAVE RADIOMETRY

At the low toroidal field and moderate densities on NSTX, $\Omega_{ce} << \omega_{pe}$, and electromagnetic radiation is not generated for the first several cyclotron harmonics, making it impossible to use standard electron cyclotron emission as a fast profile diagnostic for electron temperature. Although multipoint Thomson system provides periodic snapshots, these are generally not adequate for MHD studies and detailed studies of other fast transients in $T_e(R)$. A promising new development for diagnosing electron temperature is electron Bernstein wave (EBW) radiometry[1], which is currently being pursued at PPPL on NSTX as well as the smaller ST, CDX-U.

EBW's are electrostatic waves that can propagate in ST plasmas and exhibit high optical thickness at the electron cyclotron resonances. These waves can only exist within the upper hybrid resonance layer typically located near the outside edge of the plasma. If the density scale length L_n^{UHR} at this layer is short enough, these waves will mode convert and tunnel to fast X-mode electromagnetic waves, which can be easily detected and provide information on $T_e(R,t)$. Studies are underway at PPPL to measure the mode conversion efficiency and its strong dependence on L_n^{UHR}. On NSTX, there is a sudden increase in the measured core emission as the density scale length shortens at the onset of the H-mode transition, and the inferred $T_{rad}/T_e(0)$ increases from 3% to 13%, in agreement with model calculations on the scaling with L_n^{UHR}. On CDX-U, a local, radially-scannable limiter has been used to modify L_n^{UHR} in the vicinity of the receiving horn, and thereby maximize the conversion efficiency at near 100%.

4. MOTIONAL STARK EFFECT MEASUREMENTS OF q(R) AND E_r

Since non-inductive current initiation and sustainment are top level NSTX research goals, measurements of the current profile J(R) are essential to many planned experiments. On tokamaks with neutral beams, the standard technique for this task is motional-stark-effect polarimetry (MSE),[2] which recently has also been crucial in measurements of $E_r(R)$. The standard implementation of this technique would be impossible on NSTX, due to the difficulty of spectrally isolating the polarization components at the low magnetic field.

Several modifications are planned to adapt the MSE technique to lower field.[3] First, the Doppler broadening of the individual components will be minimized, by reducing the spread in angles between the beam and the viewing aperture. This will be done by narrowing the viewing aperture in the horizontal dimension, and to compensate, vertically elongating the aperture. Second, a narrower bandwidth birefringent filter is being developed, based on a Lyot design currently utilized in solar spectroscopy and dye laser tuning. The goal of this development is an effective passband width of 0.075 nm, compared to 0.7 nm width of standard interference filters. Figure 1 shows the transmission of a single stage of this multistage filter. To block all but the central peak, it will be used in series with two subsequent stages with spectral frequency 1/2 and 1/4 that shown, in addition to a standard interference filter. Modeling the performance of a system, with the new aperture shape and a 0.075 nm filter passband, one obtains polarization fractions of P_f = 0.2-0.4 for the central σ_0 component. Typical MSE systems operate with a $P_f \sim 0.8$. To compensate, the optical throughput on the NSTX system will be much larger than on previous systems. The optics is designed to image the beam onto 19 fiber optic bundles, providing spatial resolution of 2.5 cm at the edge and 3.0 cm in the core.

The emission used in MSE systems results from collisionally-induced-fluorescence (CIF) arising from collisions between injected D^0 atoms and the background plasma. Using a tunable laser to induce this emission can have significant advantages. On a somewhat delayed but parallel path to the MSE work described above, development is underway on laser-induced-fluorescence (LIF) MSE. The plan is to inject a hydrogen diagnostic neutral beam with a coaxial tunable dye laser resonant with the Doppler shifted H_α transition. The linear polarization of the laser is rotated, and the phase between the laser polarization and the induced fluorescence is used to determine the pitch angle. With a narrow spectral width, polarization fractions near unity are predicted even at the low fields of NSTX. In a lab test with no B field, initial LIF signals have been observed with a beam operating at 32 keV and 25 mA, with a 1.2 cm diameter. If the CIF and LIF MSE systems described above are successful on NSTX, determination of both q(R), and E_r will be possible.

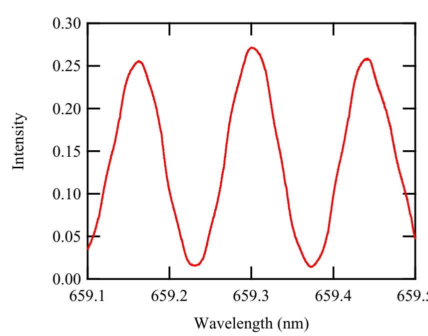


Figure 2 Transmission of a single stage birefringent filter in arbitrary units.

5. MICROWAVE SCATTERING STUDIES OF HIGH-k TURBULENCE

In recent years, experimental and theoretical studies of internal transport barriers in tokamaks have indicated that different turbulent mechanisms drive electron and ion transport. Numerical studies have shown that on NSTX, fluctuations with $k_\perp \rho_t < 1$ are absent or completely suppressed by **ExB** velocity shear, but also that Electron Temperature Gradient (ETG) modes with $k_\perp \rho_e \sim$ 0.1-0.3 ($k_\perp \sim$ 10-40 cm^{-1}) are unstable over most of the plasma cross-section.[4]

Mazzucato has proposed a microwave scattering diagnostic, which takes advantage of the large pitch angles on an ST, to provide spatially and spectrally resolved measurements of $k_\perp$ for this turbulence. The scattering geometry is shown in Figure 2.

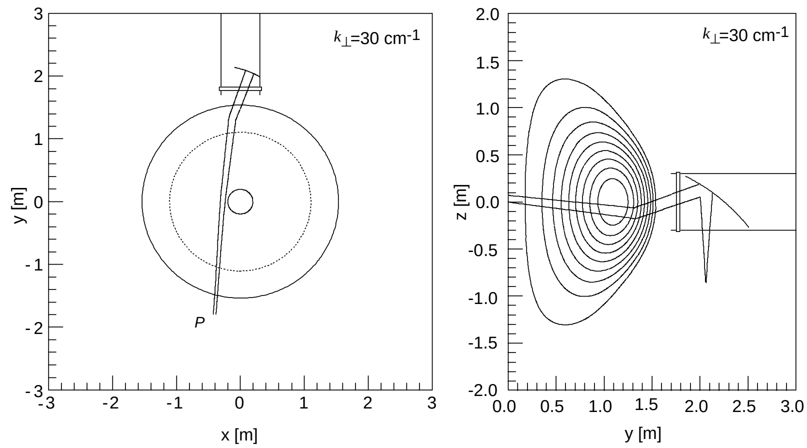


Figure 2. Equatorial and poloidal projections of scattering geometry to probe ETG turbulence.

A 290 GHz beam with a waist of 2 cm is launched through a window ~ 30 cm above the midplane and traverses the plasma near the center stack to a scattering region. The scattered light is imaged by a large mirror through a window to a detector plane, where light from different values of R and $k_\perp$ are dispersed in 2 dimensions. Radial resolution of 1-3cm for the outer 90% of the plasma, and spectral resolution of ~ 1 cm^{-1} for $k_\perp \sim$ 10-40 cm^{-1} appear feasible. Using available sources and detectors, such a system is predicted to easily have adequate sensitivity to detect the fluctuation amplitudes ($\delta n/n \sim 10^{-3}$) predicted from a mixing length criterion for NSTX parameters

6. REFERENCES

1. G.Taylor, P.C. Efthimion, B. Jones, *et al.*, "Electron Bernstein Wave Research on CDX-U and NSTX", Proceedings of 14th Topical RF Conf., (Oxnard, Calif., May 2001) To be published in proceedings by American Institute of Physics
2. F. M. Levinton, Rev. Sci. Instrum., **70**, 810 (1999)
3. F. M. Levinton, private communication.
4. C. Bourdelle, *et al*., Joint US-EU Transport Task Force Mtg. Fairbanks, Alaska, May 16, 2001

External Distribution

Plasma Research Laboratory, Australian National University, Australia
Professor I.R. Jones, Flinders University, Australia
Professor João Canalle, Instituto de Fisica DEQ/IF - UERJ, Brazil
Mr. Gerson O. Ludwig, Instituto Nacional de Pesquisas, Brazil
Dr. P.H. Sakanaka, Instituto Fisica, Brazil
The Librarian, Culham Laboratory, England
Library, R61, Rutherford Appleton Laboratory, England
Mrs. S.A. Hutchinson, JET Library, England
Professor M.N. Bussac, Ecole Polytechnique, France
Librarian, Max-Planck-Institut für Plasmaphysik, Germany
Jolan Moldvai, Reports Library, MTA KFKI-ATKI, Hungary
Dr. P. Kaw, Institute for Plasma Research, India
Ms. P.J. Pathak, Librarian, Insitute for Plasma Research, India
Ms. Clelia De Palo, Associazione EURATOM-ENEA, Italy
Dr. G. Grosso, Instituto di Fisica del Plasma, Italy
Librarian, Naka Fusion Research Establishment, JAERI, Japan
Library, Plasma Physics Laboratory, Kyoto University, Japan
Research Information Center, National Institute for Fusion Science, Japan
Dr. O. Mitarai, Kyushu Tokai University, Japan
Library, Academia Sinica, Institute of Plasma Physics, People's Republic of China
Shih-Tung Tsai, Institute of Physics, Chinese Academy of Sciences, People's Republic of China
Dr. S. Mirnov, TRINITI, Troitsk, Russian Federation, Russia
Dr. V.S. Strelkov, Kurchatov Institute, Russian Federation, Russia
Professor Peter Lukac, Katedra Fyziky Plazmy MFF UK, Mlynska dolina F-2, Komenskeho Univerzita, SK-842 15 Bratislava, Slovakia
Dr. G.S. Lee, Korea Basic Science Institute, South Korea
Mr. Dennis Bruggink, Fusion Library, University of Wisconsin, USA
Institute for Plasma Research, University of Maryland, USA
Librarian, Fusion Energy Division, Oak Ridge National Laboratory, USA
Librarian, Institute of Fusion Studies, University of Texas, USA
Librarian, Magnetic Fusion Program, Lawrence Livermore National Laboratory, USA
Library, General Atomics, USA
Plasma Physics Group, Fusion Energy Research Program, University of California at San Diego, USA
Plasma Physics Library, Columbia University, USA
Alkesh Punjabi, Center for Fusion Research and Training, Hampton University, USA
Dr. W.M. Stacey, Fusion Research Center, Georgia Institute of Technology, USA
Dr. John Willis, U.S. Department of Energy, Office of Fusion Energy Sciences, USA
Mr. Paul H. Wright, Indianapolis, Indiana, USA

03/26/01

The Princeton Plasma Physics Laboratory is operated
by Princeton University under contract
with the U.S. Department of Energy.

Information Services
Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, NJ 08543

Phone: 609-243-2750
Fax: 609-243-2751
e-mail: pppl_info@pppl.gov
Internet Address: http://www.pppl.gov