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Initial Diagnostics for the National Spherical Torus Experiment

R. Kaita, D. Johnson, H. Kugel, B. McCormack, A. L. Roquemore,
and the NSTX Team

*Princeton Plasma Physics Laboratory, Princeton University,
P. O. Box 451, Princeton, New Jersey 08543-0451 USA*

1. INTRODUCTION

The spherical torus (ST) approach[1] to magnetic confinement has many attractive features as both a fusion reactor concept and a volume neutron source. The National Spherical Torus Experiment (NSTX) is under construction at the Princeton Plasma Physics Laboratory (PPPL), and it is designed to achieve plasma parameters needed for a proof-of-principle test of the ST concept. Discharges with magnetic fields of 2.3 kG on axis and plasma currents of 1 MA will be heated with 6 MW of radio frequency (RF) power and 5 MW of neutral beams, and pulse lengths up to 5 seconds are planned. Central electron temperatures of about 4 keV are expected with RF heating, and theoretical studies show that high values of b and b_N can be achieved.[2]

2. INITIAL DIAGNOSTIC SET FOR NSTX

The initial diagnostic set was planned to provide the measurements required for a basic understanding of the first plasmas in NSTX. They are needed for machine operations and a characterization of fundamental discharge parameters, including shape, position, plasma current, impurity concentrations, core ion and electron temperatures, and MHD activity. Most of them rely on relatively straightforward techniques requiring little or no research and development, and whenever possible, their costs were minimized by making use of equipment from earlier magnetic confinement devices at PPPL Some diagnostics, however, were challenging to implement because of the ST geometry. In particular, the high temperatures and very limited space on the center stack placed severe constraints on any sensors in this region.

Based on these criteria, the following diagnostics were chosen for initial NSTX diagnostics. For plasma control and equilibrium determination, there are magnetic diagnostics and discharge imaging with visible cameras. An initial survey of confinement and transport will rely on electron and ion temperature, density, and impurity profile diagnostics. Magnetic and X-ray fluctuation diagnostics will be used to characterize MHD activity, and spectroscopic and bolometric systems, thermocouples, and edge Langmuir probes will provide data for scrapeoff layer and divertor physics studies. These are listed in Table I.

3. DIAGNOSTICS FOR FIRST PLASMA

The diagnostics essential for the initial achievement of NSTX discharges had highest priority. Large power densities were not expected for first plasma, and there was an aggressive schedule for achieving this milestone in February, 1999. For these reasons, the carbon tile plasma facing components (PFC's) were not installed, and the passive stabilizers were not mounted.

The diagnostic effort was first focused on magnetic sensors because of their importance for determining discharge position, shape, and current. Their locations can be described in terms of the regions around the NSTX vacuum vessel (Fig. 1). Seventeen equally-spaced flux loops were installed in Region 1, and on each of the nine poloidal field coils. In addition, four flux

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loops were placed behind where the passive plates would be (Regions 4 and 5), with two above and two below the horizontal midplane on the vacuum vessel wall.

Two Rogowski loops were placed around the vacuum vessel to provide redundant plasma current measurements. The Rogowski loops had to fit in the small space between the Ohmic heating solenoid and the thermal insulation between it and the vacuum vessel in the CS region (Region 1 in Fig. 1). The very limited room mean that the dimensions of the loop mandrel had to be limited to 1.1" x 0.048" with rounded edges, or a cross sectional area of 0.4255 cm^2. The Rogowski loops had about 31,000 turns to provide a signal of approximately a volt for a current ramp of 5 MA/s.

Table I. Baseline Diagnostics Summary

System	Function
Plasma current Rogowski coils	Total plasma current
Eddy current Rogowski coils	Halo current monitoring
Flux loops	Poloidal flux for plasma control
B_Z and "2D" (combined B_r and B_Z) coils	Plasma control/magnetic fluctuations
Mirnov coils	Magnetic fluctuations
Visible TV camera	External shape for plasma control
IR camera	Heat loads
"Slow" diamagnetic loop (using toroidal field coil)	Stored energy
Multichannel bolometer	Radiated power profile
Microwave interferometer	Line-integrated plasma density
Survey spectrometer (SPRED)	Plasma impurities
Soft X-ray imaging system	Plasma instabilities and fluctuations
H_a detectors	Edge recycling
Charge-exchange recombination spectroscopy (CHERS)	Ion temperature & toroidal rotation
Visible bremsstrahlung array	$Z_{eff}(r)$
X-ray pulse height analysis	Core electron temperature
Neutral particle analyzer	Core ion temperature and fast ions
Visible spectrometer	Edge/divertor spectroscopy
Ultra-soft X-ray array	Start-up and impurity studies
Langmuir probes/thermocouples	Divertor parameters

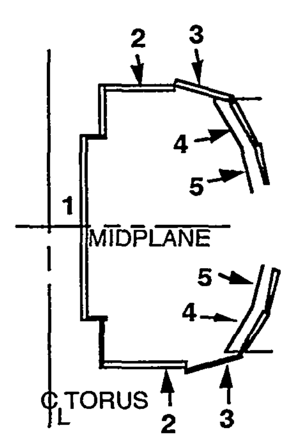

Fig. 1 - Major regions around the NSTX vacuum vessel.

A 170 GHz interferometer for line-averaged densities and fast and slow visible cameras for monitoring plasma position and shape completed the diagnostics for first plasma, which was obtained on February 12, 1999. Plasma currents of up 280 kA, after correction for vacuum vessel eddy currents, were measured with the Rogowski loops during the subsequent week of operations. Preliminary equilibrium reconstructions were also performed with the flux loop data.

4. DIAGNOSTICS FOR THE FIRST PHYSICS OPERATIONS PERIOD

The remaining diagnostics in the initial NSTX set will be added during the period of plasma operations that begins in August, 1999. They will include Langmuir probes, thermocouples, and magnetic pickup coils, which were not available for first plasma because they were designed to fit in the PFC's.

While designs for sensors in high temperature environments exist,[3] the situation on NSTX is complicated by very limited space, particularly in the CS region where the tiles are as thin as 1.3 cm. Maximum tile temperatures are expected to range from 375° C during bakeout to 600° C during plasma operations.

The magnetic coils must fit in a graphite tile that has a 1.4" diameter hole which is 0.125" deep. In the CS region, there will be a poloidal array of 20 B_Z coils at one toroidal location, and a set of B_Z coils in the horizontal midplane. The coils have three layers of 90 turns each, so that nA = 1.37 x 10^{-2} m^2 turns. The poloidal array continues around the vacuum vessel (Regions 2-5 in Fig. 1) with larger B_Z coils between the passive stabilizer plate sections, which are separated by 2" gaps. Because of the space, these coils have nA = 3.6 x 10^{-2} m^2 turns.

There are also be four Rogowski loops in Region 1, placed symmetrically above and below the midplane and encircling the CS, to measure halo currents. Rogowski loops are also placed on four supports 90 degrees apart for the lower primary passive plates and on the secondary passive plate supports at one toroidal location. These loops are used for determining any asymmetries in the eddy currents flowing from the passive plate segments through the vacuum vessel.

The passive stabilizer plates and outer divertors (Regions 3 in Fig. 1) have 22 flux loops, and there are also 14 voltage loops, equally spaced poloidally outside the vacuum vessel for eddy current measurements. This completes the initial set of magnetics for NSTX, and more details about their design are provided elsewhere.[4]

Among the diagnostics in preparation for the August 1999 operational period is X-ray pulse height analysis (PHA) for estimates of the core the core electron temperature. It uses a lithium-drifted silicon detector with a temporal resolution of about 50 ms over an energy range of 1 to 50 keV.[5] A multipulse/multipoint Thomson scattering system is also under construction for time-resolved electron temperature and density profiles.[6]

A mass-resolving charge-exchange neutral analyzers (CENA) originally developed for TFTR will be installed to measure the ion temperature and the distribution of energetic ions during auxiliary heating.[7] The CENA can cover an energy range from 0.5 keV to 600 keV with a time resolution of 10 ms, and it will be mounted on a movable cart.

Ion temperature profiles are to be provided by the charge-exchange recombination spectroscopy (CHERS) diagnostic. It is expected to have a spatial resolution of 5 cm and a temporal resolution of 30 ms. The TFTR heating beam which CHERS requires will not be available until 2000, but edge ion temperatures can still be measured without neutral beam doping.

The initial impurity diagnostics are a visible bremsstrahlung (VB) detector and a vacuum ultraviolet survey spectrometer (SPRED).[8] The VB sightline is located in the horizontal midplane of NSTX, and it will be used to prototype an array planned for radial measurements of Z_{eff}. The SPRED diagnostic has a 2Å spectral resolution over a range of 100Å to 1200Å, and a temporal resolution of 1 ms.

A soft X-ray diode array views a poloidal cross section of the plasma from a vertical port on top of the vacuum vessel, and will have a spatial resolution of 2-3 cm at a temporal resolution of 0.001 ms. It complements the ultra-soft X-ray arrays,[9] which will measure the temporal evolution of the plasma location and shape during startup. The flexibility of its design enables it to be a bolometer as well as an X-ray array, depending on the choice of detectors. There is also a separate multichannel bolometer array located in the NSTX horizontal midplane, and its signals can be inverted to provide a radiated power profile.[10]

5. SUMMARY

The diagnostics that were needed for initial achievement of NSTX plasmas included basic magnetics, interferometry for line-averaged densities, and TV cameras for monitoring plasma position and shape. The first physics operations period will focus on discharge startup with coaxial helicity injection and the characterization of Ohmically-driven plasmas. The resulting emphasis on measuring electron and impurity parameters puts a priority on diagnostics such as X-ray PHA and Thomson scattering for electron temperatures, SPRED and VB for impurities, and soft X-ray arrays for MHD. Edge diagnostics such as Langmuir probes, infrared cameras, a mutichannel bolometer array, H_a detectors, and a visible spectrometer will also be important. Neutral beam injection will not be available until next year, and full implementation of the CHERS system will not be possible before then. Preliminary radio frequency heating experiments are planned, however, and the CENA will be useful for ion temperatures and energetic ion distributions when they are performed.

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