Fast Ion Loss Diagnostic Plans for NSTX

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Abstract

The prompt loss of neutral beam ions from the National Spherical Torus Experiment (NSTX) is expected to be between 12% and 42% of the total 5 MW of beam power. There may, in addition, be losses of fast ions arising from high harmonic fast wave (HHFW) heating. Most of the lost ions will strike the HHFW antenna or the neutral beam dump. To measure these losses in the 2000 experimental campaign, thermocouples in the antenna, several infrared camera views, and a Faraday cup lost ion probe will be employed. The probe will measure loss of fast ions with E>1 keV at three radial locations, giving the scrape-off length of the fast ions.

Introduction

NSTX [1] is a spherical tokamak with typical parameters R=0.86 m, a=0.68 m, I_p=1 MA, B_T=0.3 T, and κ=2. The first plasma in NSTX was created in 1999. The principal goal of the

NSTX research program is to investigate plasma behavior in the high beta plasmas that should be easily obtainable at low aspect ratio. To attain high beta in the 2000 experimental campaign, there will be 5 MW of 30 MHz HHFW heating and current drive available. Starting in October 2000, there will also be 5 MW of 80 keV deuterium (D) co-going neutral beam (NB) injection to heat the plasma.

Numerical modeling of prompt orbit loss using NSTX equilibria predicts NB ion loss fractions between 12% and 42%, depending upon plasma conditions.[2,3] This loss will reduce the NB heating efficiency and will produce substantial (≤11 MW/m^2) heat loads on structures near the plasma. In addition, HHFW heating may produce energetic tail ions and accelerate NB ions that will also be subject to loss. It would be valuable to measure the fast ion loss, either directly or through the heating it produces in plasma facing components, in order to check the validity of these loss models and to look for loss arising from other mechanisms. Ultimately, models suitably benchmarked against experiment will be used to predict alpha particle loss fractions from a reactor-scale spherical tokamak.

Fast Ion Loss Detection from Temperature Measurements

Modeling of fast ion orbits in NSTX reveals that nearly all lost orbits strike either the HHFW antenna or the NB dump, and the loss is concentrated near the midplane. This occurs because the orbits have their largest radial excursion from the plasma center at the midplane. Therefore, the midplane is the location most suitable for making fast ion loss measurements. (At low plasma current, ~250 kA, some of the loss will strike the lower divertor plates, but study of this loss is less relevant to reactor-scale fast ion confinement). At the midplane, the antenna and NB dump project inward 10 cm farther than any other structures and hence receive the preponderance of the fast ion efflux.

One method of diagnosing fast ion loss is to measure the temperature of the antenna and NB dump. The side of the antenna will receive the highest power density from NB loss (~11 MW/m^2 for some equilibria). The side is comprised of several boron nitride (BN) plates, ~20 cm high x 8 cm wide x 1 cm thick. Each of these has recently been fitted with a thermocouple (***Type & Maker?***) that will be sampled every 0.2 s. The difference between the plate temperatures before and after each plasma will give a measure of the total energy deposited in each plate during the shot, and that deposition should be dominated by beam ion loss.

Infrared cameras (Indigo Systems Corp. “ALPHA” microbolometer cameras) will also measure the temperature over much of the antenna and beam dump surfaces. The fields of view of the different camera positions are shown in Fig. 1, and cover all of the NB dump and most of the antenna surfaces. With some modeling to account for diffusion of heat into the bulk material from each surface, the heat flux due to beam ion loss can be inferred from the temperature distributions. The IR camera data will be particularly useful as it will give the power deposition pattern as a function of position on these surfaces, and this information can then be compared directly with loss simulation results. The heat flux to the side of the antenna, in particular, should be dominated by beam ion loss and not thermal plasma loss. The antenna side is also of relatively simple construction, flat BN plates, so interpretation of the surface temperature distribution should be straightforward.

Fast Lost Ion Probe

In addition to the temperature instrumentation, fast ion losses will be measured with a Faraday cup probe, which has recently been installed. The probe is shown in Fig. 2, and is mounted on the vessel wall at the midplane, between Bays J & K, a location which is ~45° clockwise toroidally from the leading edge of the NB dump. The structure of the probe is depicted in Fig. 3. It consists of a stainless steel probe shaft into which several apertures have been drilled. Behind each aperture is a set of Faraday cups to collect the current of fast ions that pass. A tube surrounding the cups can be biased in order to suppress secondary electron emission when the fast ions strike the cup surface. The probe shaft is covered by a carbon fiber composite cap that protects it from thermal and beam ion heat fluxes. The shaft is welded to a flange that bolts to the vessel wall. Overall, the probe is 10.2 cm long and 7.6 cm in diameter. The tip of the probe is located at a major radius (R) of 158.3 cm, 0.1 cm farther out than the front of the HHFW antenna.

The probe has three apertures to accept co-going fast ions. Each aperture is 0.6 cm in diameter, and the apertures are centered at R=160.7 cm, 163.2 cm, & 166.1 cm. Modeling with a Lorentz orbit code [4] indicates that all three apertures are able to receive orbits that would be characteristic of 80 keV D beam ions, which are injected co-going only. There is one aperture oriented to receive counter-going fast ions, located at R=160.8 cm. Modeling indicates that 80 keV D orbits to this aperture would be scraped off by the vessel wall, so this aperture will only receive ions at a lower energy, perhaps if HHFW heating produces counter-going fast ion tail.

The aperture diameter, spacing between the apertures and Faraday cups (3.9 cm), and the cup size (2.3 cm square) define a minimum gyroradius that an ion must have to reach the cup. This is 2.5 cm, and for standard conditions in NSTX it corresponds to a minimum energy of 950 eV for D ions and 1900 eV for H ions. Orbit modeling indicates that these apertures can accept 80 keV D ions with pitch angles between 34° and 70° (where 0° means that the particle velocity is entirely along the magnetic field line).

The probe was designed with three apertures on the co-going side so that simultaneous measurements of the fast ion loss rate at different major radii could be made. With these measurements, it will be possible to infer the fast ion scrape-off length for each plasma condition. Loss modeling predicts a scrape-off length of 4.2 cm on the side of the antenna and it seems reasonable to expect the same at the probe location. The same calculations predict a peak loss on the side of the antenna of ~11 MW/m^2, which corresponds to ~13 mA/cm^2 of beam ion current. For the given aperture size, this would produce a signal of ~4 mA.

Behind the single counter-side aperture, the Faraday cup consists of a single piece of stainless steel sheet. However, for the two innermost apertures on the co-going side, there are four smaller Faraday cups in a quadrant arrangement, centered on the centerline of the aperture. By taking ratios of different pairs of currents, this quadrant arrangement then allows determination of the mean displacement up/down and left/right of the detected ions, relative to the aperture center. In this way, a mean pitch angle of the detected ions can be inferred.

Behind the co-side aperture at largest R is a multilayer thin foil Faraday cup similar to one used in JET for alpha particle loss detection.[5] This detector consists of two nickel foil layers, each 2.5 microns thick, with an intervening mica layer, also 2.5 microns thick. The first nickel layer is thick enough to stop all ions up to ~1 MeV. Because the fusion rate in NSTX is expected to be small (~10^{14} fusions/s), there should be only an undetectably small current of charged fusion products (CFPs) that can penetrate to the rear foil of this assembly. This arrangement is a prototype for a possible upgraded fast lost ion probe for a future NSTX campaign. Finally, there is a Faraday cup on the counter-going side of the probe which has no corresponding aperture. This cup will serve to measure the background electrical noise to which the probe and its electronics are subject.

From the modeled loss rates, it is estimated that the whole probe will absorb ~18 kJ of lost beam ion energy in one 0.5 s beam pulse. This will result in a transient temperature rise of ~200° C at the tip of the probe, relaxing to a steady-state temperature drop along the length of the probe of ~40° C in between shots (300 s minimum between plasmas). All the components of the probe are constructed of carbon fiber composite, stainless steel, Micamat, and Nextel woven ceramic insulation, with copper wiring. Some pieces of the probe are bound together with Fortafix Fiborclad adhesive. All of these materials should withstand at least 500° C without degradation, so this heat load should not interfere with probe operation.

For future experimental campaigns, we hope to design and construct a fast ion loss detector that would resolve the pitch angle and energy of lost fast ions, in order to learn more details about the processes causing loss. This detector might utilize a scintillator, as did the TFTR fast ion loss diagnostic [6,7], or might utilize multilayer thin foil Faraday cups configured to resolve the pitch angle of the loss.

Fusion Source Profile Measurement from CFP Loss

Even at the maximum plasma current of 1 MA, CFPs such as the 3 MeV proton and 1 MeV triton from DD fusion reactions are not confined more than approximately one Larmor gyration in NSTX. This lack of confinement of CFPs may be used to measure the fusion source profile, something which gives useful information about the radial transport of fast ions. This quantity can be measured by recording the flux of CFPs as a function of pitch angle at a point on the wall.

Figure 4 illustrates an example in which a detector mounted on a vessel port cover at 30 cm below the midplane is able to detect orbits that span the plasma from it center to its edge.

To determine the fusion source profile, the magnetic equilibrium of the discharge must be known. Model orbits from each pitch angle sensed by the detector can be followed through the plasma, tallying the length of the orbit spent in thin shells around each flux surface. From this breakdown of the orbit length vs. flux surface and the measured CFP loss vs. pitch angle, the fusion source profile may be computed by Abel inversion.

The advantage of this technique is that a small detector can measure the fusion source profile. On large, high-field tokamaks, this quantity can only be determined by detecting the neutrons along collimated lines of sight through the plasma. The collimation requires tons of shielding material, making it a large and expensive diagnostic to construct.

We hope to construct a compact fusion source profile diagnostic for a future campaign on NSTX using a natural diamond detector (NDD)[8] or silicon barrier diode detector. The detector would be constructed to have an linear array of front contacts which, combined with a single aperture, would resolve the pitch angle of incident CFPs into narrow bins. NDDs offer the advantage that the detection element can operate at elevated temperatures, up to ~200° C, while SBDs are functional only to ~50° C. During plasma operation, the NSTX vessel is intended to be at 50° C, meaning that an SBD detector would have to be actively cooled.

Acknowledgements

This work was supported by US Department of Energy contract number DE-AC02-76CH03073. Able technical assistance was provided by J. Gorman, L. Guitadora, and T. Holoman.

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Figures

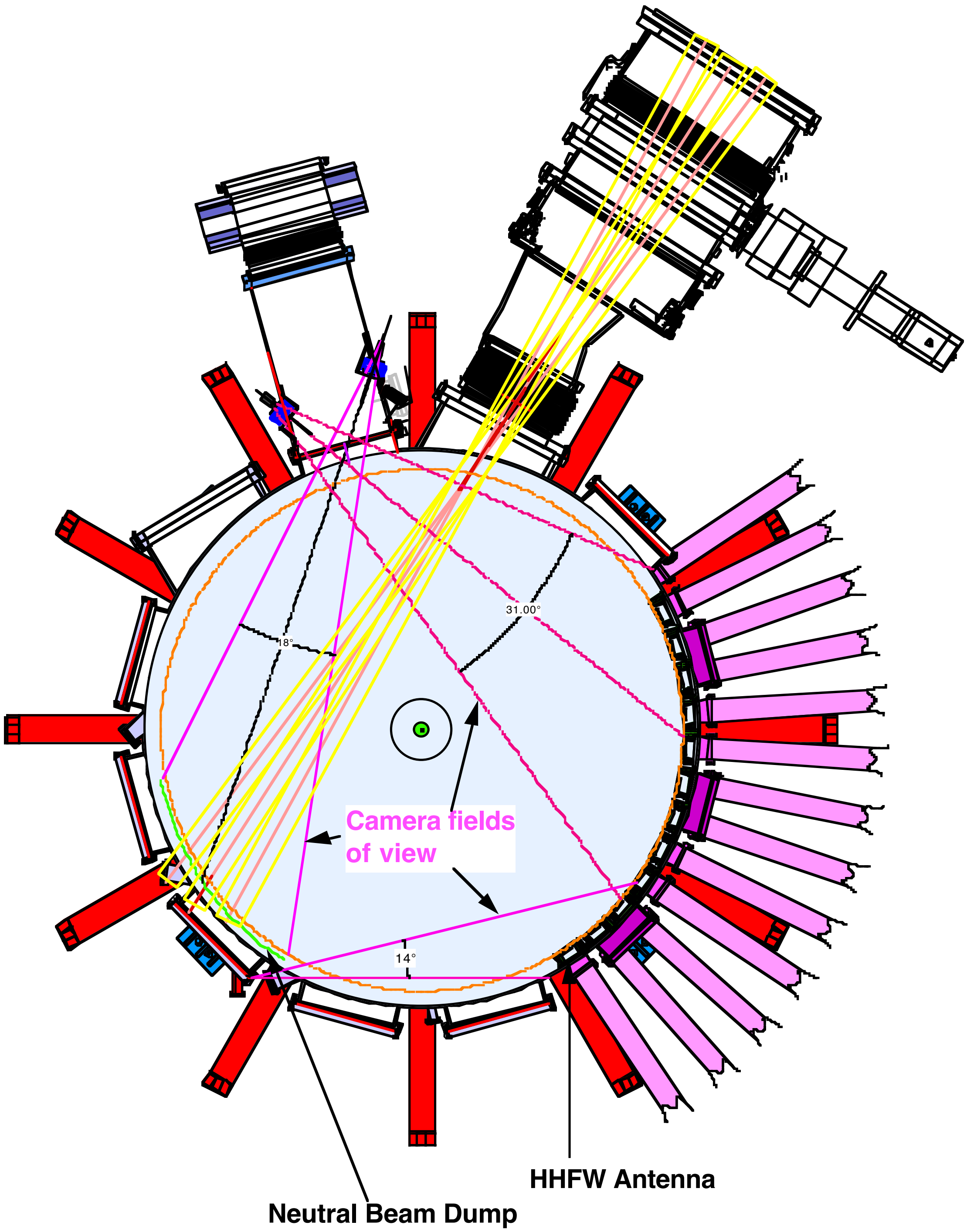

Figure 1: Midplane section of the NSTX vacuum vessel showing the centerlines of the neutral beams, the location of the HHFW antenna, the fields of view of the IR cameras, and the location of the Fast Lost Ion Probe.

Figure 2: Photograph of the Fast Lost Ion Probe on the NSTX vessel wall, at the midplane between Bays J & K.

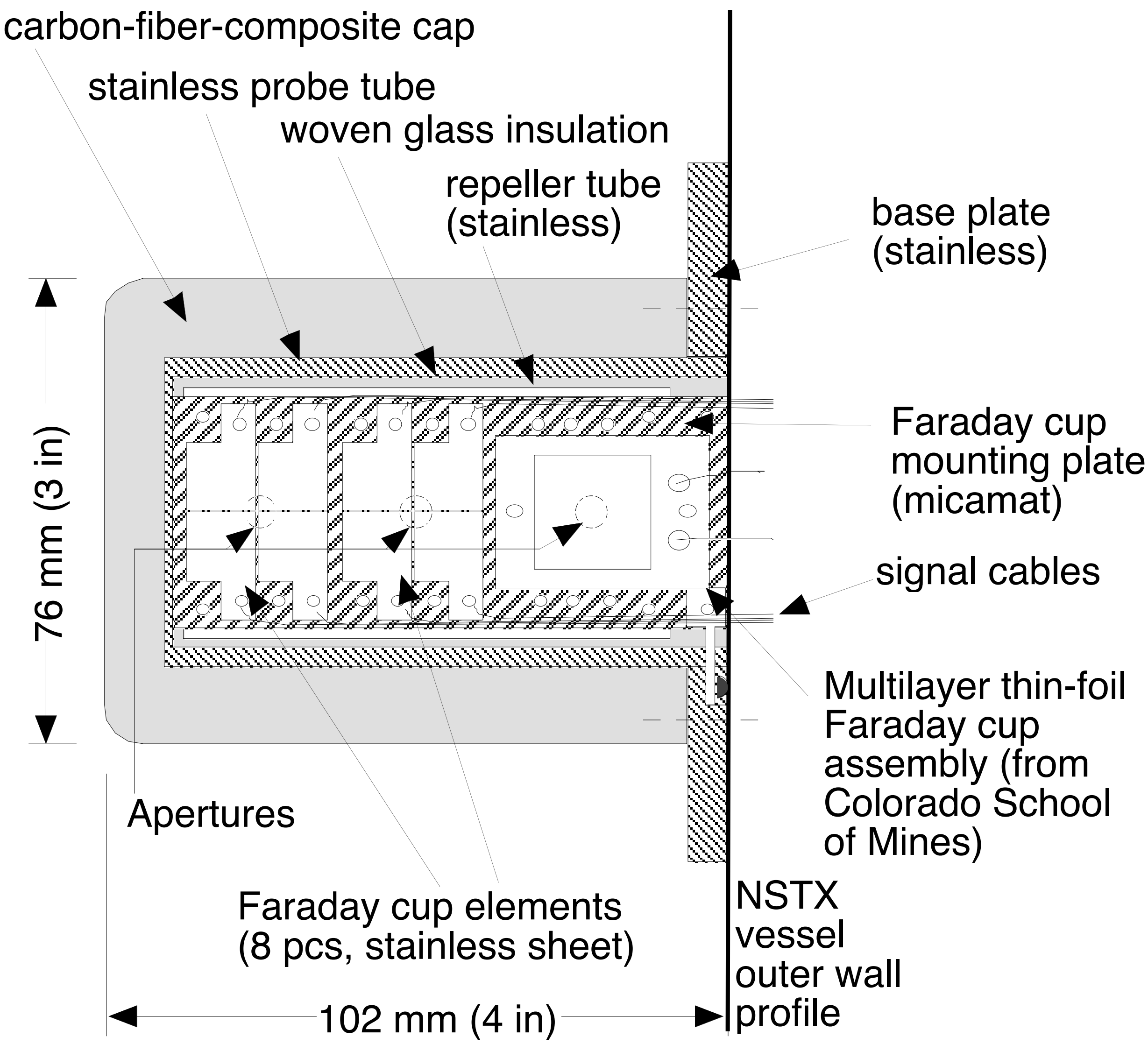

Figure 3: Diagram of the Fast Lost Ion Probe for NSTX. This diagram shows the arrangement of the Faraday cups inside the half of the probe which detects co-going fast ions.

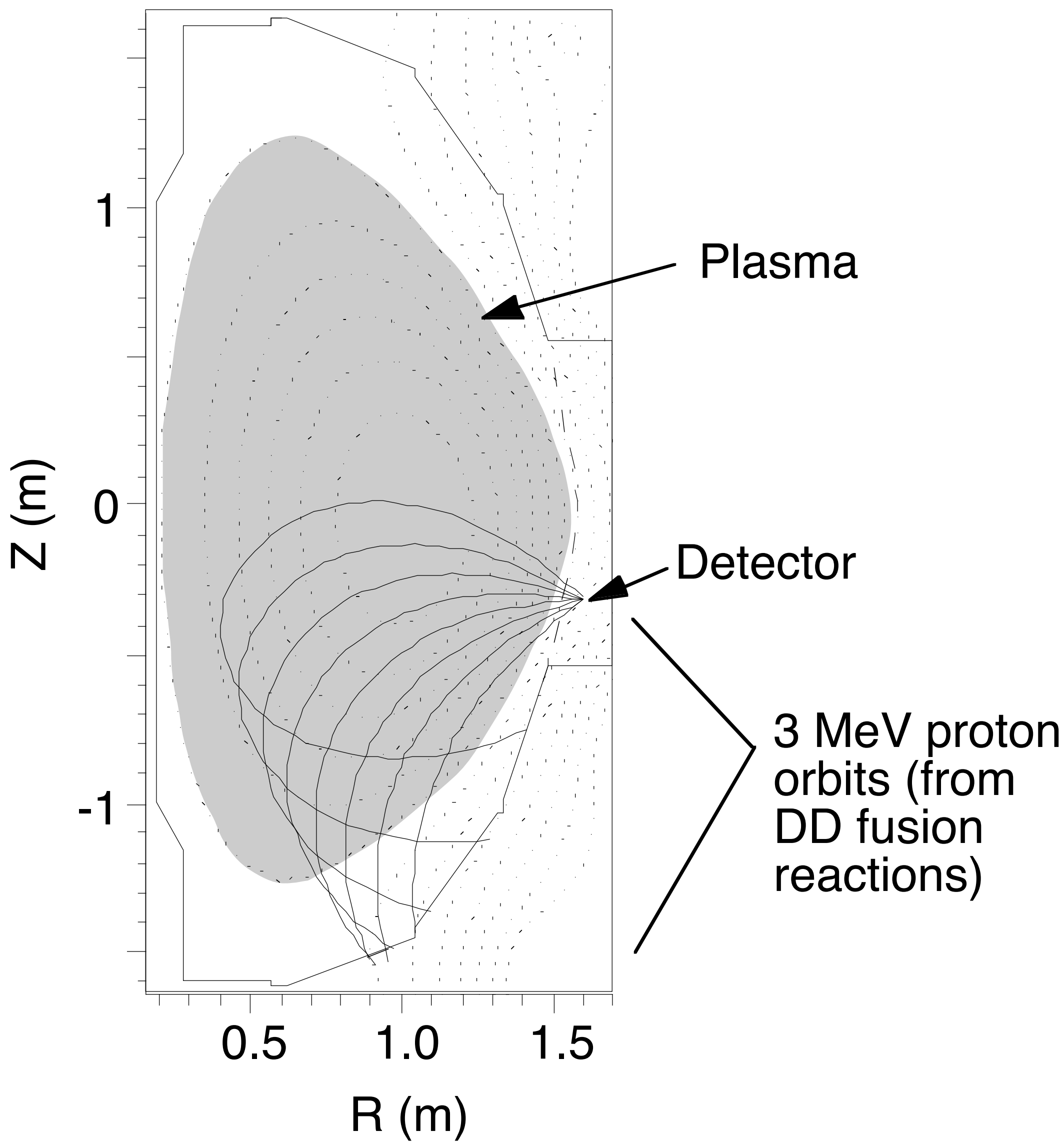

Figure 4: Principal of operation of a proposed fusion source profile diagnostic based upon charged fusion product loss. Shown are the computed orbits of 3 MeV DD fusion protons at eight different pitch angles coming to a loss detector on the wall. The orbits span the plasma from center to edge.