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Heavy Ion Beam Probe Measurements in the Interior of Improved Confinement MST Reversed Field Pinch Plasmas

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The Madison Symmetric Torus (MST) is a Reversed Field Pinch (RFP), a toroidal magnetic fusion device in which the toroidal magnetic field is comparable to the poloidal magnetic field. The magnetic field in a RFP is primarily generated by current in the plasma. The low toroidal field at the edge allows for high beta, in addition, a high magnetic shear aids in MHD stability [1].

In standard RFP operation, significant magnetic fluctuations cause large transport [2]. However, magnetic-fluctuation-induced transport can be dramatically reduced by inductive current profile control. Recent developments in improved confinement discharges [3-5] have increased the global energy confinement time to 12 ms, a large improvement over the 1 ms standard discharge confinement time. At high plasma current (500 kA in MST) the electron temperature is increased to 2 keV, and the ion temperature is increased to over 1 keV, which is sustained throughout the improved confinement period. The effective global average diffusivity is decreased to 5 m^2/s, with electron thermal diffusivity as low as 1-2 m^2/s where the pressure gradient is steepest. This results in a peaked temperature profile and electron heat diffusivity of the same order as similarly sized tokamaks [6].

As RFP plasmas approach these regimes, and the magnitude of magnetic fluctuations decreases, electrostatic-fluctuation-induced transport may become a significant factor. Fokker-Planck modeling of hard x-ray flux measurements taken during improved confinement discharges indicates that the energetic electron diffusivity does not match the expected value for stochastic magnetic transport. Instead, the diffusivity is independent of parallel electron velocity, which suggests that electrostatic turbulence may be dominant in these plasmas [7]. This motivates the desire for a measurement of electrostatic fluctuations in the core of the plasma. The use of a Heavy Ion Beam Probe diagnostic is one method of quantifying these fluctuations.

The Heavy Ion Beam Probe, described in references [8-10], is capable of measuring spatially resolved density and potential fluctuations in the interior of the plasma. From these measurements, inferences of particle flux can be made. The HIBP is currently the only method for simultaneously determining these quantities in the interior region of high-temperature plasmas.

There are several challenges associated with operation of an HIBP on RFPs [11]. The most general challenge is the uncertainty in the plasma-generated magnetic field; the poloidal current induced during improved confinement plasmas causes the magnetic equilibrium to evolve rapidly. This can lead to alteration of the primary and secondary ion beam trajectories both as a function of time during individual discharges and from shot-to-shot. These variations, as well as those caused by magnetic fluctuations can lead to motion of the sample volume and motion of the secondary ion beam at the detector. These factors are motivating the development of a new beam trajectory simulation, which includes a more comprehensive electromagnetic model than used in the past. This model, which aims to better approximate the fields encountered by the beam, includes a finite-element simulation of the beam-steering electric fields, analytic models of the HIBP magnetic plasma suppression structures [12] and magnetic field distortions due to the MST ports, and measurement-normalized simulations of the MST equilibrium field [13] and the magnetic fluctuations. Its use and refinement will improve trajectory simulation, beam injection initialization, and sample volume localization.

The new simulation allows us to investigate the effect of each modeled electromagnetic field component on the primary and secondary beam trajectories and the sample volume. It includes user specification of ion beam injection parameters (such as energy, ion species, beam diameter, and source location) and primary and secondary electrostatic sweep plate voltages (which determine injection and detection angles). Ongoing simulation development will incorporate finite-sized beam modeling that will enable us to examine the effects of beam scrape-off (which is the loss of signal due to interaction with physical structures such as sweep plates within HIBP beamlines and the MST ports).

Simulations of beam trajectories using magnetic equilibria of 380 kA improved confinement plasmas during which HIBP data have been acquired are being studied. Each modeled electromagnetic element encountered by the beam can be turned on or off in the simulation to determine its effect on the deflection of the primary and secondary ion beams. Though the studies are ongoing, preliminary results suggest an ordering of effects; the most important is the accuracy of the magnetic equilibrium reconstructed for the plasma. A 1% change in equilibrium is similar to a 10-25% change in the primary beam injection angles (which are the next most important quantities). The field error introduced by the MST ports, the magnetic fluctuations, and the radial electric field present in MST have smaller, though important, effects on the beam trajectory. These results are illustrated in figure 1, which shows the motion of the sample volume within the plasma and at the detector aperture of the analyzer. In figure 1, the R, X, Y, and Z axes in the upper plots correspond to the MST coordinate system, with $R = \sqrt{(X^2 + Y^2)}$. The x, and y axes correspond to positions along the detection plane of the HIBP, centered at the secondary beamline axis.

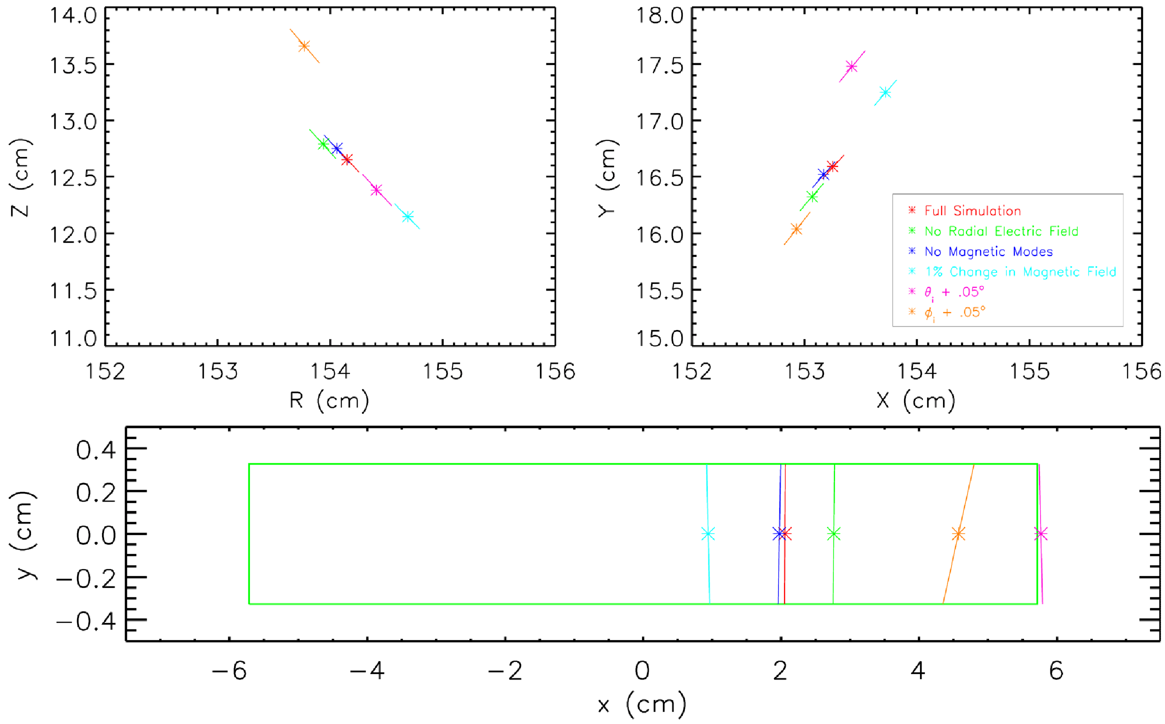

Figure 1. Changes in detection location by varying the electromagnetic elements and injection parameters. The stars correspond to the path that lands along the center-line of the detector set, and the lines correspond to the analyzer entrance aperture width.

Recent measurements during improved confinement plasmas using beam operational and focusing upgrades [14] are achieving signals in excess of 200 nA on each detector set, a large increase in acquired signal from previous measurements. Measurements made at r/a of 0.5 in rotating 380 kA improved confinement plasmas at an electron density of 0.6×10^{13} cm^{-3} indicate a positive plasma potential with a magnitude on the order of 1 kV. The HIBP signals [15] are digitized at 1 MHz, allowing resolution of spectra of potential and density fluctuations to a maximum frequency of 500 kHz. Most of the fluctuation power is concentrated below 100 kHz, with peaks at the core and edge mode-resonant plasma frequencies. The interpretation of these fluctuations is highly dependant on accurate sample volume localization, underlining the need for an improved trajectory simulation.

In summary, measurements during improved confinement operation of MST may reveal if electrostatic-fluctuation-induced transport is significant in this regime. The Heavy Ion Beam Probe installed on MST is making measurements to determine the magnitude of these fluctuations and infer electrostatic particle flux. A simulation for which allows for in-depth studies of the effects of the various electromagnetic elements on HIBP trajectories, sample volumes, and beam scrape-off is under development. Preliminary results indicate an ordering of the magnetic effects' influence on beam trajectory with the reconstructed magnetic equilibrium being paramount, followed by the beam injection parameters, and then the lower order electromagnetic field effects (i.e. port field errors, MST electric field, magnetic modes). Trajectory simulations, sample volume calculations, and measurements with improved beam operation and focusing of the HIBP during improved confinement are ongoing.

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