Sweep system design for a heavy ion beam probe on Madison Symmetric Torus

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The sweep system for the heavy ion beam probe on the Madison Symmetric Torus (MST) is described. The two components of the system are the primary sweep optics and secondary collimation plates. Key issues in the sweep system design are the small entrance and exit ports available on MST, the significant toroidal beam motion induced by the strong poloidal magnetic field, and the excessive current loading due to plasma and ultraviolet (UV). The design accommodates these issues using a crossover sweep plate design in two dimensions for the primary beam as well as two dimensional sweeping on the secondary beam. The primary beam sweep design results in a sweep range of ±20° in one direction and ±5° in the perpendicular direction. The secondary beam sweep design results in entrance angles to the energy analyzer of <3° in radial and ~0° in toroidal directions. The procedure for calculating sweep performance including fringe fields, a system for active trajectory control, and initial experiments on plasma and UV loading are also discussed. © *1999 American Institute of Physics.* [S0034-6748(99)67001-0]

I. INTRODUCTION

A heavy ion beam probe measures a variety of plasma parameters in magnetically confined plasmas, including the electrostatic potential profile, potential and density fluctuations, and the magnetic field.[1] These parameters are important for reversed field pinch (RFP) research in anomalous transport, magnetic equilibrium, current profile modifications, and instability studies.[2]

In a heavy ion beam probe (HIBP) experiment, a singly charged ion beam (the primary beam) is injected into the plasma. As the beam passes through the plasma, doubly charge ions (the secondary beam) are created. Only those secondaries created in a relatively small sample volume determined by a detector aperture are measured. Information about the electron density, electric potential, and magnetic field is contained in the secondary beam intensity, energy, and toroidal deflection, respectively.

The sample volume position is controlled by changing the entrance angle of the beam to the plasma using electrostatic sweep plates. The design of the HIBP on the Texas Experimental Tokamak (TEXT) was briefly reviewed in Ref. 1.

The Madison Symmetric Torus (MST) HIBP requires novel design features in order to reach the desired sample volumes and these are the subject of this article. The principle reason for the complication is the small ports available on MST. The MST vacuum vessel also acts essentially as a coil system carrying large currents. Large ports would perturb the vacuum chamber currents and are therefore not allowed. Hence the HIBP experiment will use a 5-cm-diam entrance port and a 11.4-cm-diam exit port. These are substantially smaller than ports on previous experiments.

In an idealized case, the HIBP is modeled as having all trajectories originate from a sweep point. With small ports, this sweep point is forced to be much closer to the port than normal. This in turn, results in a large required sweep angle range and increased exposure of the sweep plates to UV radiation and plasma streaming out of the port. Similar constraints will also affect the National Spherical Torus Experiment (NSTX)-HIBP design.[3]

A large angular range is present on both the primary and secondary beam lines. The secondary beam angular range is larger than can be accommodated by the energy analyzer used to determine beam energy. Therefore, a secondary sweep system will also be required. Secondary sweep plates have been used on T10-HIBP[4] and HIBP on the compact helical system (CHS),[5,6] but have never been used on Rensselaer HIBPs.

Finally, the sweep system design is complicated due to the fact that the poloidal and toroidal magnetic fields have comparable strengths. This results in a fully three-dimensional trajectory and sweep systems with significant requirements in two dimensions. The design model and the results of the primary and secondary sweep system designs are described in Sec. II. Control of those trajectories to reach core or edge regions is discussed in Sec. III. Initial plasma/ultraviolet (UV) loading tests have been done on MST and are discussed in Sec. IV. Conclusions and future work are discussed in Sec. V.

II. DESIGN OF THE SWEEP SYSTEMS

A. Design model

With one pair of sweep plates, the ion beam velocity and position are both changed. This makes it difficult to get a large range of angles through a small port. Figure 1 shows a schematic of a one-dimensional crossover sweep system that can be used to get a large angular range through a small port. This is the approach used in this design.

The various elements of the sweep system can be modeled as combinations of the elements shown in Figs. 2(a) and

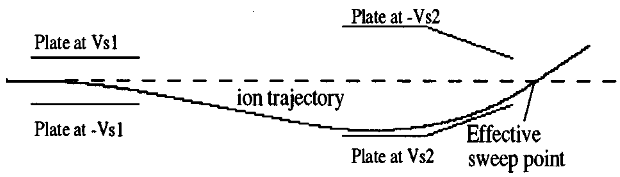

FIG. 1. Illustration of 1D crossover sweep.

2(b). The simplest model assumes that the electric field is uniform in the straight plates region and zero outside, while the electric field in the flared region can be modeled using the average vertical component of the field at a given position and neglecting other field components.[7] Mathematically, this can be analyzed using the ion optics transfer matrices below for the straight and flared regions, respectively:

$$\begin{bmatrix} x \\ \frac{dx}{dz} \end{bmatrix} = \begin{bmatrix} 1 & z \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_0 \\ \left.\frac{dx}{dz}\right|_0 \end{bmatrix} - f\,\frac{z}{a} \begin{bmatrix} z/2 \\ 1 \end{bmatrix}, \tag{1}$$

$$\begin{bmatrix} x \\ \frac{dx}{dz} \end{bmatrix} = \begin{bmatrix} 1 & z \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_0 \\ \left.\frac{dx}{dz}\right|_0 \end{bmatrix} - \frac{f}{k} \ln\left(1 + \frac{kz}{a}\right) \begin{bmatrix} \frac{a}{k} + z \\ 1 \end{bmatrix} + \frac{fz}{k} \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \tag{2}$$

where x_0 and $dx/dz|_0$ are position and slope at the entrance to a region, z is horizontal length of a region, $f = qV_s/W_b$ represents deflecting strength of the plates, q is ion charge in unit of e, W_b is ion beam energy in unit of eV, V_s is the sweep plate voltage in unit of V, and $k = 2\tan(\beta_{sw})$, is the slope of the plates. For a drift region, set $f = 0$ in Eq. (1).

The fringe field is neglected in the model above, and $W_b = m_i v^2/2 = \text{const.}$ is assumed. In previous experiments, this model has had errors of roughly 10%–20%.[1] Although the analytical solution of the electric field including fringe fields can be found, a transfer matrix describing the ion trajectory has not been found. Instead, a simple modified model is used to take fringing effects into account. As shown in Figs. 2(c) and 2(d), the modified model assumes that the electric field in the plate region has the same form as before, but linearly drops to zero outside the plates over a distance given by $c_1 \times a_1$ or $c_2 \times a_2$. c_1 and c_2 are dimensionless coefficients, and their values have been set by examining two-dimensional (2D) numerical solutions to Laplace equation. Typical values are 1 for large b/a (e.g. >1.5), and smaller (e.g. 0.8) for $b/a \simeq 1$.

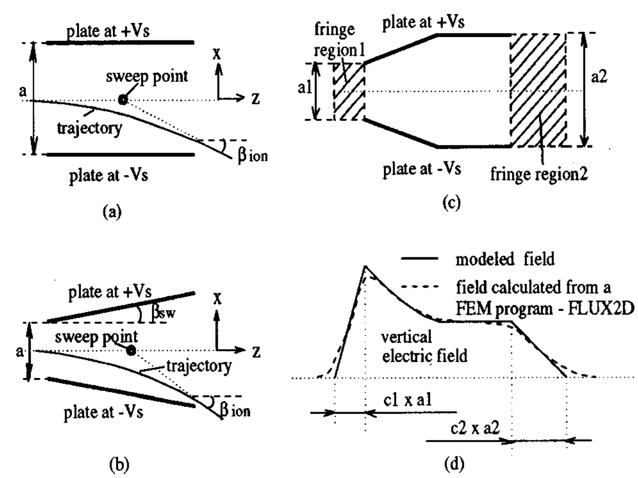

FIG. 2. Illustration of sweep plates: parameters and geometry (a) straight plates; (b) flared plates; (c) a combined plates and an illustration of fringe fields model; (d) illustration of field distribution of case (c).

The ion trajectory in the front and back fringe regions are decided by the following equations, respectively:

$$\begin{bmatrix} x \\ \frac{dx}{dz} \end{bmatrix} = \begin{bmatrix} 1 & z \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_0 \\ \left.\frac{dx}{dz}\right|_0 \end{bmatrix} - f\,\frac{z^2}{2a_1^2} \begin{bmatrix} z/3 \\ 1 \end{bmatrix}, \tag{3}$$

$$\begin{bmatrix} x \\ \frac{dx}{dz} \end{bmatrix} = \begin{bmatrix} 1 & z \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_0 \\ \left.\frac{dx}{dz}\right|_0 \end{bmatrix} - \frac{fz}{a_2} \begin{bmatrix} z/2 \\ 1 \end{bmatrix} + \frac{fz^2}{2a_2^2} \begin{bmatrix} z/3 \\ 1 \end{bmatrix}, \tag{4}$$

where parameters have the same meanings as before. We have compared the trajectories from the modified model with those from solving Laplace field using a finite element method (FEM) program-FLUX2D, and the calculation error with the modified model is reduced to below 5%. Equations (1)–(4) are used to determine the system design and the required sweep voltages.

B. Primary sweep system

Primary sweep plates are used to control the angle at which the primary beam enters the plasmas magnetic field. According to our MST-HIBP trajectory calculations, the required sweep angle ranges are $\sim\pm 20°$ radially and $\sim\pm 5°$ toroidally. This is several times larger than on previous systems. Crossover sweep is needed because of the small port. Figure 3(a) is a schematic view of the primary sweep system that has been designed using the transfer matrix technique. Note that all directions in the figure have the same scale. Not shown are guard rings at the sides of some sweep plates to compensate for fringe field effects there. Two pairs of sweep plates are used in each direction in order to obtain a 2D crossover sweep. This moves the effective sweep point beyond the ends of plates. The design is able to steer a 200 keV ion beam over the required angular ranges. 200 kV is the maximum accelerator voltage available although most experiments will operate at lower voltages. Existing 20, 10, and 4 kV power supplies with fast slew rates will be used to power the sweep plates. The system is designed to be as compact as possible and has a total length of $\sim$110 cm. The distance between the plasma and the front plates is 10 cm. The 5-cm-thick vacuum chamber and hardware to reduce plasma loading will be in this 10 cm region. The mechanical support structure for the plates is under design now. To increase flexibility, the system will be rotatable around the beamline to get the best combined radial/toroidal angles for a given experiment and it will also be movable along the beamline to reduce the plasma/UV loading effect.

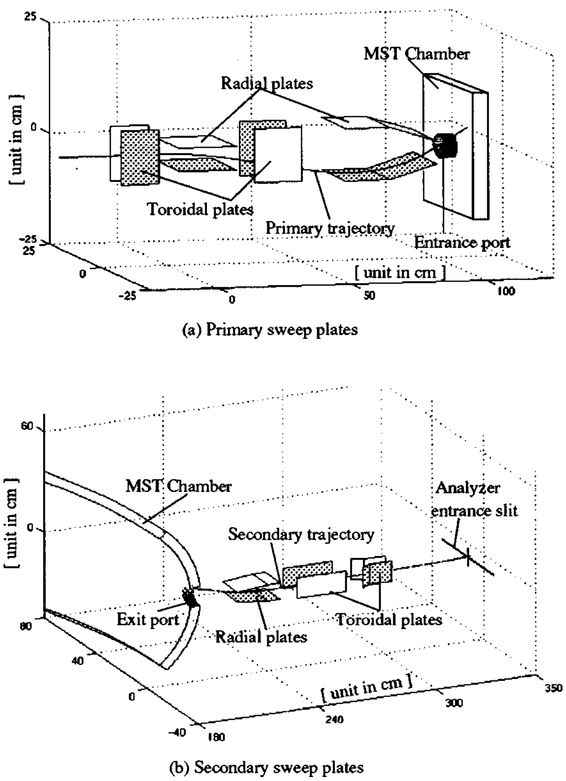

FIG. 3. Schematic view of the sweep system designed.

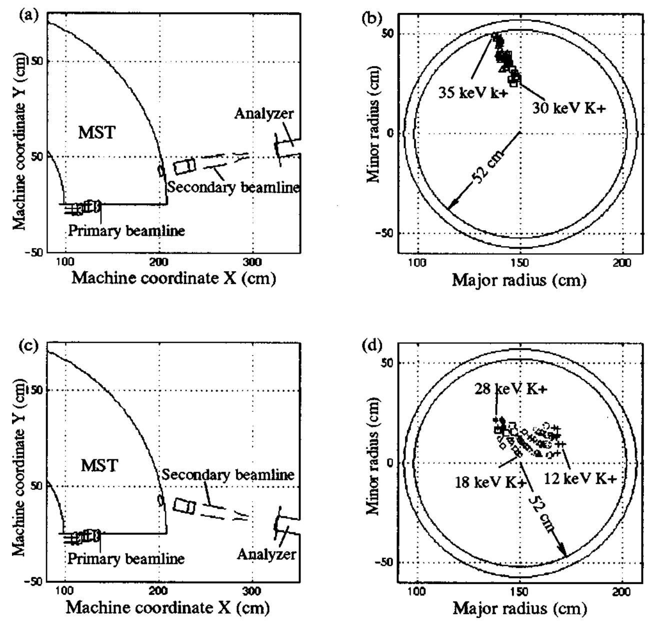

FIG. 4. Top view of the beamline arrangements and their observation points: (a) and (b) for edge diagnostics; (c) and (d) for core diagnostics.

C. Secondary sweep system

In past Rensselaer Polytechnic Institute (RPI) beam probes, the energy analyzer was located at the detection point decided by a trajectory program. Although the analyzer is designed so that it is insensitive to the beam entrance angle in the vertical (i.e., radial or poloidal) direction, it is desirable to limit the entrance angle variation to less than $\pm 5°$. Furthermore, it is critical to keep the horizontal entrance angle less than 1°. The angular range at the detection point in the calculations is much larger than those of past HIBPs because of the small ports. In addition, the MST magnetic field which has comparable B_t and B_p results in large toroidal (horizontal) entrance angles. Simply moving the analyzer away from the plasma would reduce the entrance angle range, but this would result in an unacceptably small number of sample volume locations. A secondary sweep system has been designed that reduces the beam entrance angle and positions to acceptable values. It has the further advantage of placing the analyzer further from the plasma which will reduce its UV loading.

Figure 3(b) shows the secondary sweep system. As with the primary sweep system, the design can steer a beam over the full desired angle range for a 200 keV ion beam and utilizes existing power supplies. Total length of the sweep system is ~80 cm resulting in an analyzer location that is 140 cm away from the exit port. The first set of plates, powered by 10 kV supplies, steers the beam in the radial (vertical) direction and changes the incident angle range from $\pm 17°$ to $\pm 3°$ at the analyzer entrance slit. The 2nd and 3rd sets of plates use 4 kV power supplies and a crossover type design to steer the beam so that it enters the analyzer on the horizontal (toroidal) midplane with 0 toroidal angle. The incident angle range without sweep plates is $\pm 5°$. The mechanical support system for the plates is being designed and will also be rotatable and translatable to increase flexibility.

Despite the wide angle range handled by this design, it still cannot look at all possible sample volume positions with a single analyzer position. Therefore, the secondary beamline is being designed with the possibility of changing analyzer locations by pivoting the beam line. Two beamline orientations that are optimized for edge ($r/a > 0.5$) and core ($r/a < 0.5$) are shown in Fig. 4.

III. ACTIVE TRAJECTORY CONTROL

In order to look at multiple sample volumes within a single shot, it will be necessary to control the sweep voltages on all sweep plates simultaneously. The various sweep voltages are set by four independent parameters. On CHS, such an active trajectory control system was implemented using results from trajectory calculations.[5] In that case, the fields in the helical plasma were well known and only slightly changed due to the presence of the plasma. However, in MST, the plasma generated magnetic fields dominate and are only partially known. Hence, we expect that our initial operation will involve running multiple trajectories for a few plasma conditions until a database is built up with sample volume locations and sweep voltages. Accuracy will be improved by iterating experimental results and trajectory simulations. Ultimately, active trajectory control like that achieved on CHS is the goal.

IV. PLASMA/UV LOADING EFFECTS AND MITIGATION TECHNIQUES

The sweep plates design assumes there is no charge between the plates. This is basically true for previous experiments because the sweep plates were located far away from the ports. It will be more difficult to achieve this on MST. The primary sweep plates will be as close as 5 cm away from the 5 cm entrance port, and the secondary sweep plates will be ~20 cm away from the 11.4 cm exit port. There are two sources of electric charges in the sweep region. The first is plasma diffusion through the vacuum chamber port. A rough estimate suggests that n_e can be as high as $10^{11}-10^{12}$ cm^{-3} just outside the port. The second source of charge is photoelectrons generated when UV photons strike the sweep plates. These electrons can create a plasma between the plates that leads to voltage breakdown and an electrical short if the power supply current limits are exceeded. A series of loading tests have been conducted on MST to identify possible problems. Results show that loading is plasma dominated. A magnetic field (~0.15 T) applied normal to the beamline at a position between the test plates and the port reduced plasma loading substantially as would be expected if the loading was due to plasma. Since the effective sweep points are located between the plates and the ports, the range of beam positions is limited in this region and it is not difficult to place permanent magnets close enough to each other to reduce the plasma loading while simultaneously not obstructing the diagnostic beam. This magnet structure is currently being designed. In another test, a mesh screen was placed between the plates and the port. The grid was fairly coarse with a spacing much greater than the Debye length ($\lambda_D \sim 0.1$ mm). Nevertheless, it also showed a noticeable reduction in loading. A mesh as part of the final HIBP design will require high transparency (>90%) which will conflict with the ability to effectively screen out the plasma. We plan to initially use permanent magnets, but will keep a mesh screen as an option.

V. CONCLUSIONS AND FUTURE WORK

Primary and secondary sweep systems for the MST HIBP have been designed using a transfer matrix method. A simple model has been introduced to deal with fringe field of the sweep plates. Crossover design of the sweep plates moves the effective sweep points to the positions between the plates and the ports, which is necessary with the small MST ports. The primary sweep system designed provides ±20° radial and ±5° toroidal sweep ranges, which enable the ion beam to cover a large area of the plasma. The secondary beam sweep system has been designed to handle the large emittance from the exit port, and reduce the angular range and beam location at the analyzer to acceptable values. The analyzer location is also moved away from the exit port.

Experiments have shown that plasma loading is the dominant loading effect on the sweep plates, and that magnetic fields can suppress this effect. Other mitigation techniques are also being considered.

Two elements of the system design that still must be completed are the sweep plate support structure and the arrangement of permanent magnets to reduce plasma loading on the plates. In addition, further tests of mitigating structures are planned in the near term.

Once the system is operational, we eventually would like to use active trajectory control to scan the plasma. In order to do this, a combination of experimental data, sweep system calculations using Eqs. (1)–(4), and trajectory simulations in the plasma will be used to build a database of sweep voltages and sample volume positions. This will be repeated for several different plasma configurations.

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