Development of magnetic field mapping via heavy ion beam spectral imaging

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Mapping magnetic fields via heavy ion beam spectral imaging relies upon establishing a high quality ion beam, identifying beam emission at wavelengths favorable for imaging, and designing an appropriate imaging configuration. Identifying emission lines suitable for imaging is difficult due to intense, broadband radiation of the target reversed field pinch plasma. To compensate, we have worked to raise the beam emission intensity. Simulations of the beam optics and characteristics have led to a technique that achieves a narrower beam and increased ion current at the plasma. Additionally, we are developing computer vision tools to reconstruct beam trajectories based on various camera and system configurations. We simulate charge coupled device images of the vessel interior and beam trajectories, and reconstruct three dimensional trajectories from image pairs. Analysis of the simulated images will guide the system specifications. We present results of the beam optics and camera simulations, surveys of radiation, and status of the diagnostic. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1789595]

I. INTRODUCTION

Spectral emission along the trajectory of a heavy ion beam may be used to infer the magnetic field in a plasma.[1] Traditional heavy ion beam probe (HIBP) measurements use only a small fraction of the injected ions that have undergone electron impact ionization.[2] We propose a new measurement that uses the bulk of the injected singly charged ions that are available to undergo electron impact excitation.

A heavy ion beam is deflected by the poloidal and toroidal magnetic fields of the Madison Symmetric Torus (MST) reversed field pinch plasma being used to develop this technique. We plan to image beam emission with two charge coupled device (CCD) cameras and reconstruct a three dimensional (3D) trajectory. We will use the trajectory to determine the direction of the ion velocity vector as a function of position and time. Force balance, $m(d\mathrm{v}/dt)=q(\mathbf{E}+\mathrm{v}'\times\mathbf{B})$, can then be used to compute the magnitude and direction of the magnetic field **B**. The mass of the ion m and the initial beam velocity v are well known. In many cases the force due to the electric field **E** is small compared to the vwin$\times$**B** term, the magnitude of the velocity can be approximated as constant, and the calculation of **B** along the trajectory is straightforward. In other cases **E**, measured using conventional HIBP methods, can be included in the computation.

We discuss the foundations of a new, viable imaging diagnostic, preliminary experimental results, and directions identified as future work.

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II. FOUNDATIONS OF IMAGING

We require: (1) a high quality ion beam, (2) computer vision and image processing techniques for isolating and reconstructing the beam, and (3) wavelengths suitable for imaging. Advances realized in each of these areas are described below.

A. Ion beam characteristics

The emissivity of an ion beam in a plasma can be estimated as $r=n_e n_i\langle\sigma\nu\rangle$, the rate of photons produced per unit volume. The thermal speed of the plasma electrons ν and the density of the plasma electrons n_e are determined by the target plasma, while the cross section for electron impact excitation of the beam ions σ and the density of the beam ions n_i are beam parameters. We have sought to increase n_i in an effort to maximize the beam emission intensity.

Optimization of beam focus and current will maximize the beam current density and the emission. Well-localized intensity will increase the signal to noise ratio, and the minimized emission area will improve the resolution of the acquired images. Improved beam characteristics will also contribute to the success of the spectral survey discussed below.

The physical structure of the HIBP accelerator and the methods by which it is operated determine both the beam characteristics and the ion optics of the system. Since the optics and ion trajectories are not visually available, we have modeled the system with the commercially available software SIMION.[3] These simulations result in efficient methods of operation.

In the simulation, the geometry of the gun, including the Pierce, extractor, and focus electrodes, and the accelerator column consisting of 19 electrodes, are defined on a grid

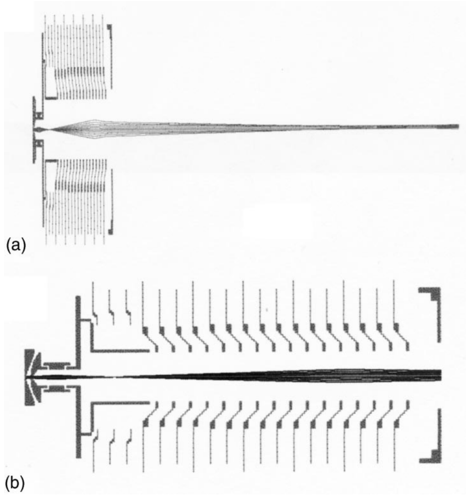

FIG. 1. (Color online) (a) Simulation of HIBP accelerator and ion beam (not to scale) that is well focused near the plasma. (b) Closeup of accelerator and beam. Beam is being focused by five rightmost column electrodes.

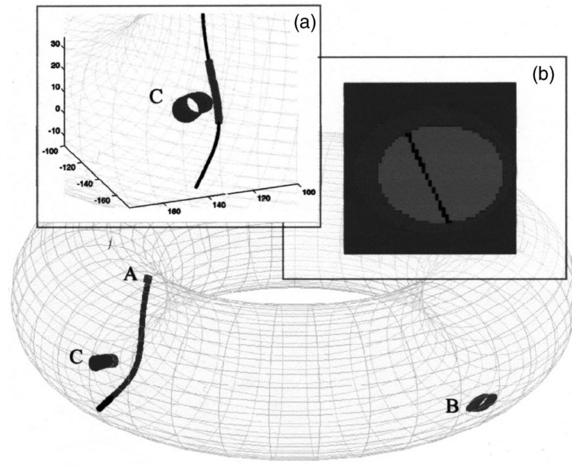

FIG. 2. (Color online) PerSpect simulation. (a) Enhanced segment of the trajectory is portion visible from end of wedge shaped chamber at port C. (b) The corresponding, simulated, CCD camera low-resolution image.

with a resolution of 1/32 in. The characteristics of the ion source, including the dimensions, mass, and ionization state, are prescribed. In the simulations we fix the voltage of the Pierce electrode and manually adjust the voltages of all other electrodes; conventional operation applies a nearly uniform gradient across the 19 column electrodes. We require that the beam is well focused at the surface of the plasma and that it does not intersect any physical structures within the accelerator or the beamline that contains electrostatic beam steering plates, and extends approximately 2.5 m from the end of the accelerator column to MST.[4]

Figure 1(a) illustrates a simulation of a 60 keV beam (figure not to scale). It is achieved with bias voltages of 60, 50, and 57.8 kV at the Pierce, extractor, and focus elements, respectively. The first 14 elements of the accelerator column are biased at 50 kV. A linear gradient across the last five electrodes (terminating at 0 V) provides the majority of the acceleration and serves as a second focusing element. Figure 1(b) is a closeup of the accelerator region from the same simulation; beam repulsion is not included.

Experiments in which we have applied the simulated parameters to actual hardware have confirmed significant improvements in beam current and focus. The beam current is now reliably on the order of 100 μA and the diameter of the beam near the plasma is approximately 1 cm full width at half maximum.

B. Imaging configuration

Accurately determining the magnetic field from spectroscopic images depends on a suitable camera configuration and appropriate computer vision techniques. We have developed a MATLAB tool called PerSpect (perspective view of spectral images) to address both issues. A goal of the simulation is to provide an accurate rendering of an image acquired by a camera in a particular position on MST. The code is currently able to simulate 2D CCD images of the vessel interior and beam trajectories from cameras with arbitrary positions, orientations, resolutions, and fields-of-view. Pairs of simulated beam images from appropriately placed cameras can be used to reconstruct partial 3D trajectories which will be used to infer the local magnetic field and to test the accuracy of the method. This analysis will help determine the specifications of the imaging hardware to be installed, such as minimum camera resolution and sensitivity, acceptable camera positions, viewing angles, and fields-of-view.

A rendering of the simulated environment generated by PerSpect is shown in Fig. 2. The primary ion beam, the bold-curved line within the torus, is injected into the plasma through port A. Two 4 1/2 in. ports, initially selected as viable camera locations, are also shown in the image and are labeled B and C. Port B has been used during the spectral survey described below, but is commonly occupied by other plasma diagnostics and thus we are investigating the viability of additional port pairs. PerSpect has already guided the installation angle of a wedge shaped transition chamber recently installed on Port C. The angle was chosen to maximize the fraction of the beam trajectory visible from the end of the chamber; the portion visible is illustrated with a thicker cross section in inset (a). Inset (b) shows the corresponding, simulated CCD camera low-resolution image.

C. Spectral characteristics

Identifying the wavelengths suitable for imaging requires knowledge of both the wavelengths and intensities of beam ion and plasma emission. The wavelengths at which emission may be produced by beam ions within a plasma are identified using tabulated data within the NIST atomic spectra database.[5] We normalize the data by computing an intensity percentage using emission intensity as a function of wavelength divided by the sum of all intensities of interest. Examples of intensity percentages versus wavelength of Na^+ and K^+ are shown in Fig. 3. The emission we are examining is largely ultraviolet and visible. It is fortuitous that there are some narrow wavelength bands that exhibit multiple transitions. During the CCD imaging phase, we hope to use bandpass filters to take advantage of the additive effect of emission from multiple transitions.

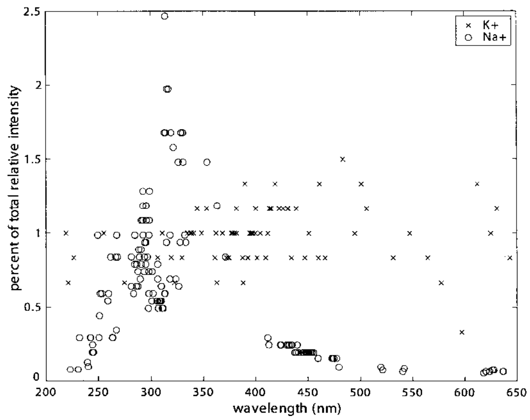

FIG. 3. Normalized Na^+ and K^+ emission intensities.

The target plasma does not exhibit strong emission from singly ionized Na, K, Rb, Cs, or Tl (traditional HIBP probing ions), but the background radiation is intense and broadband. It is dominated by H, He, B, C, N, O, and Al line emission as well as continuous molecular deuterium emission. We are comparing wavelengths of strong plasma emission, with those of HIBP ions in an effort to choose regions where background is relatively weak and beam emission is strong.

III. EXPERIMENTAL RESULTS

A preliminary spectral survey has been conducted with an Acton Research SpectraPro 500i spectrometer, equipped with a Princeton Instruments liquid nitrogen cooled CCD. The system operates with a single exposure, the duration of which is limited by the shutter speed on the CCD camera. The exposure is comprised of an adjustable dwell duration, bracketed by 10 ms opening and 27 ms closing phases. A grating of 1800 grooves/mm is used to acquire spectral measurements covering approximately 11 nm at one time. The sensitivity and wavelength coverage should allow us to resolve the beam emission from the background. The viewing lens and fiber are positioned at Port B in Fig. 2, a 94° toroidal displacement from the injection port of the ion beam.

The duration of the plasma discharge is 60–70 ms and the discharge is punctuated by sawteeth. Emission from the plasma is strongest during plasma startup, sawteeth, and rampdown. The background emission is generally consistent from shot to shot. We have adjusted the CCD exposure to avoid the startup and rampdown light of the discharge, but are unable to avoid the light due to sawteeth since they occur on a 6–10 ms cycle and the exposure time is currently limited by the shutter speed.

The spectra obtained from a multiple-plasma-discharge average, at wavelengths where the background radiation levels are relatively low are shown in Fig. 4. The wavelengths at which we may expect to see emission from K^+, when the beam is injected into the plasma, are shown as vertical dashed lines. During this survey of background emission, preliminary efforts were made to detect beam emission. Due to the long exposure time and the inclusion of light from sawteeth, emission from the beam was not seen.

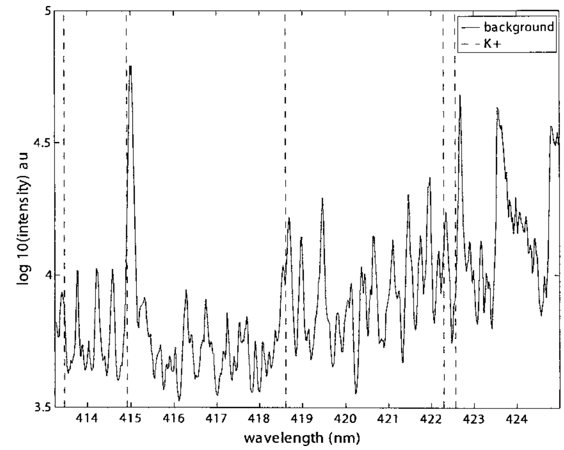

FIG. 4. Discharge averaged background plasma emission. The wavelengths at which we may expect to see emission from K^+, when the beam is injected into the plasma, are shown as vertical dashed lines.

IV. FUTURE WORK

Features of the spectral survey suggest that the integrated background radiation must be reduced to identify the wavelengths at which the beam emission is strongest. A variety of methods, implemented in parallel, will increase the likelihood of successful reduction. A fast, programmable shutter that will allow us to select the exposure time and duration will be added to the system; the plasma startup, rampdown, and sawteeth will be omitted from the integration time. The absolute background radiation levels will also be minimized through a reduction of impurities and plasma–wall interactions; boronization will be used to decrease impurities and enhanced confinement discharges will be used to decrease wall interaction. Data acquired during multiple time windows during many shots will be averaged to decrease statistical noise. Finally, the path length for background light will be reduced by viewing the plasma in the poloidal plane of the ion beam from port C in Fig. 2.

PerSpect is being used to determine the positions and orientations of a camera pair installed on MST that will maximize the portion of trajectory that can be reconstructed in three dimensions. Simulated images will be iteratively produced with various hardware configurations and the corresponding, reconstructed 3D trajectories used to compute the magnetic field and to assess the accuracy of the technique. The simulation results will determine the minimum requirements of the measurement hardware.

ACKNOWLEDGEMENT

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