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GAS SHEET IONIZATION DIAGNOSTIC FOR HIGH INTENSITY ELECTRON BEAMS

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Abstract

We present the development of a minimally invasive, non-destructive gas sheet ionization diagnostic that will be capable of characterizing high intensity charged particle beams. For this diagnostic, we tailor a neutral gas into a curtain-like, thin sheet distribution at the interaction point with an electron beam. The electron beam ionizes the neutral gas, leaving a footprint of the beam transverse distribution. The ion cloud is subsequently transported and imaged on a detector plane with a series of electrostatic lenses. The detector image, in conjunction with a reconstruction algorithm, is used to inform the electron beam profile at the interaction point. In this paper, we present progress on the development of this diagnostic for the characterization of high charge, 10 GeV electron beams with small transverse distributions, with an emphasis on the ion microscope optimization and construction.

INTRODUCTION

The characterization of transverse profiles for very intense beams is necessary for next generation accelerator facilities. While there are many methods for profile monitoring, many rely on imaging the beam with a phosphor or scintillator, or the use of wire scanners to measure beam loss. Such intercepting methods are not feasible in facilities with very high power and high intensity, especially at the beam focal point where the diagnostic would not survive beyond a few shots [1].

In this paper we describe a prototype gas sheet ionization diagnostic to measure the transverse profile of high-intensity beams. The prototype is based on the principle of imaging the ionization products from an interaction between a neutral gas and a particle beam [2]. The gas is tailored into a sheet geometry, or "curtain", such that it forms a 45° angle with respect to the incoming beam. The ion cloud that is formed after interaction contains detailed information on the beam profile. The ion distribution is subsequently transported and magnified with an ion microscope, and imaged on a spatially resolved detector. In a minimally invasive manner, the beam profile in both dimensions is reconstructed from a single-shot, using the information from the ionized beam. The gas sheet ionization diagnostic is one of the only methods available to provide real time spot size information for intense beams at focal points where other techniques are impracticable.

GAS SHEET DIAGNOSTIC

The diagnostic is modeled in Fig. 1. The entire setup consists of nozzles and skimmers to shape the gas jet into a thin sheet at the interaction chamber. A circular nozzle (200 µm diameter) provides a means to collimate the molecular gas beam that is introduced with a rapid action valve. A rectangular skimmer (80 µm by 8 mm) shapes the gas jet into a sheet of approximately 100 µm thick, and oriented at 45° with respect to the incoming beam. The local gas density is directly controlled by the size, shape and relative locations of the nozzle and skimmer when the gas jet is in the supersonic regime.

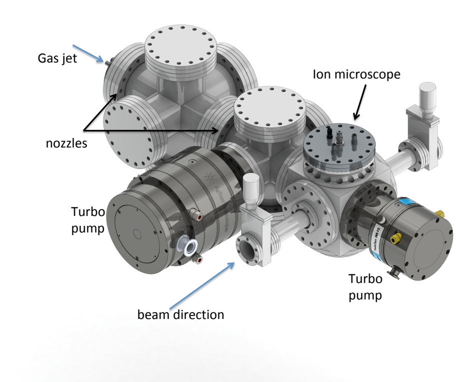

Figure 1: Model of gas sheet ionization monitor. The distance in the beam direction is <50 cm and the system incorporates a series of skimmers and pumps to deliver the gas sheet at the interaction point.

The molecular gas sheet terminates in a beam dump with another high volume turbomolecular pump. The differential pumping in the system allows for operation of vacuum levels in the 10^{-9} mbar range at the interaction chamber. The gas sheet is characterized, initially on the bench, with a cylindrical feed through attached to a vacuum gauge, that is translated across the localized region, providing a two-

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dimensional map of the gas density distribution at the interaction point.

ION MICROSCOPE

The ion microscope subsystem is responsible for transporting, magnifying, and imaging the ion beam that is generated at the gas sheet and electron beam interaction point. The ion microscope consists of an array of electrostatic lenses, or rings, held at constant voltage to provide the necessary electric field for transport of the ions to the detector. In certain arrangements, the lenses can provide magnification and aberration control [3]. The target design goal for the ion microscope was to magnify the ion distribution ten times on a microchannel plate (MCP) detector, so that at a beam size of $< 10\,\mu$m, the image could be resolved on standard diagnostics.

The optimization process started with idealized aperture lenses where the ion beam behavior is predictable with transport matrices [3]. The first step was optimized with three plates that had small apertures with constant electric field in between, as seen in Fig. 2. The ion beam originates between a repelling plate and the first lens plate. The two plates are maintained at equal magnitude but opposing sign to ensure zero potential at the electron beam/gas sheet interaction point. The three plate system was simulated in CST [4] and achieved a magnification of two. The test ion beam had stripped fiducials in the initial distribution to help determine when the imaging condition was satisfied. The test ion beam assumed a Gaussian distribution for the initial transverse momentum.

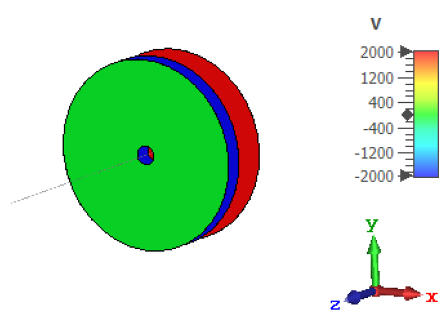

Figure 2: The idealized aperture lens system that was the building block for the larger electrostatic lens system. The ion beam is formed between the red repelling plate and the middle blue plate and travels in the positive z direction.

In the prototype diagnostic, ring electrodes will be used instead of plates. Once the solution using plates was ascertained, the plate dimensions were slowly walked to the dimensions of commercially available rings. It was necessary to modify the voltage on the last plate to a more positive potential in order to maintain the imaging condition with magnification equal to the idealized plate result.

Once a three ring system produced a twice magnified image, the array was repeated twice more. The start of the next lens set was placed at the image location from the previous three ring set. The current best electrostatic ring array is shown in Fig. 3 and has a magnification of ~8 times.

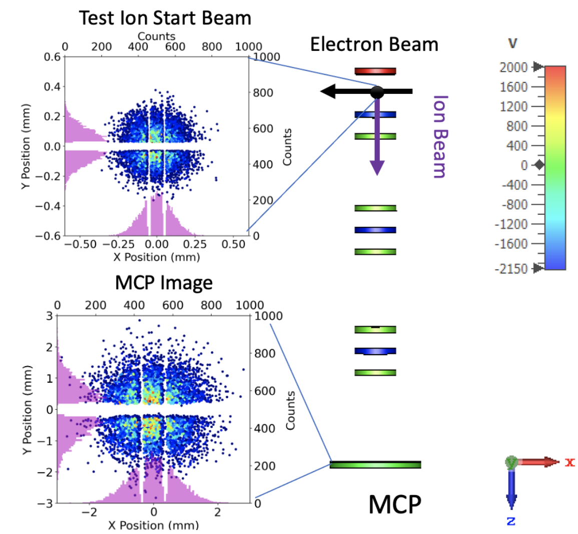

Figure 3: The current model for the electrostatic lens system. The upper left particle distribution is an artificially fiducialized test beam. The bottom left particle distribution shows the ion beam after it has traveled through the ion microscope. This system produces a magnification of -8 times.

The axial potential for the current configuration of electrostatic lenses is shown in Fig. 4. The potentials will be managed with high-voltage feedthroughs and ceramic standoffs between rings to reduce overlap and produce axially symmetric electric fields at the central axis of the ion beam. The fields modeled in CST include the effects of the (grounded) vacuum vessel and a voltage applied on the detector.

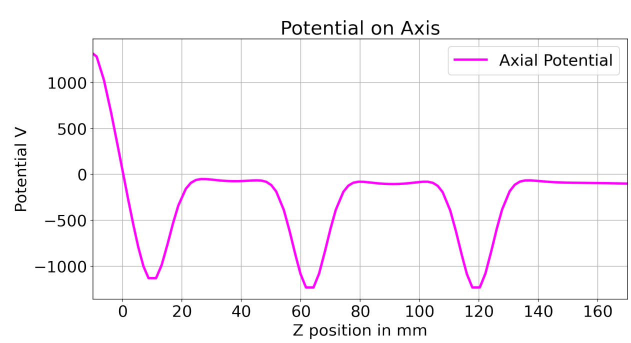

Figure 4: The potential on axis for our ion microscope system that achieves a magnification of -8 in CST

SLAC FACET TEST CASE

The detector used for the ion distribution is a microchannel plate (MCP), which, when biased, provides enough sensitivity for low charge detection, and, with appropriate magnification in the ion microscope, provides enough resolution in the beam image to reconstruct the electron beam parameters at interaction.

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We capture the ionization process for high intensity beams interacting with the gas sheet using the code WARP [5]. The gas sheet parameters are fixed at 100 μm thickness, and 10^{17} – $10^{21}\,\mathrm{m}^{-3}$ density for the initial studies. The thickness is estimated from gas dynamics simulations with the code MolFlow+ [6], using the installed nozzle and skimmer. The density is chosen such that differential pumping can be employed while still maintaining tolerable background levels for regular beam operation. In addition, lower density gases are less invasive to beam operations and downstream diagnostics. The beam parameters cover the multiple scenarios expected for a beam test at FACET-II at SLAC National Accelerator Lab. This included less intense beams expected at facility startup, and extreme intensity beams later in the experimental run. In our initial tests, we only considered tunnel ionization as the primary mechanism, as the beam density was sufficient for the radial electric field to drive the ionization. However, in some cases, impact ionization is the dominant mechanism and will be included in future models.

Simulations were carried out for specific cases of expected beam parameters at the FACET-II facility, which will host the first tests of the prototype. For a first scenario, we modeled a 10 GeV electron beam of charge 0.5 nC, σ_z=14 μm, σ_x=5 μm, σ_y =7.5 μm. The corresponding electric field for this bunch is 20 GV/m, placing the scenario well within the ADK regime [7]. The beam is sent through a N_2 gas curtain of 10^{19} m^{-3} density, and 100 μm thickness. The resultant ionization distributions are plotted in Figure 5. The tunnel ionization is evident in the annular structure of the ion cloud in the transverse plane at the interaction region. The total charge of the ion bunch in this case is only 0.2 fC.

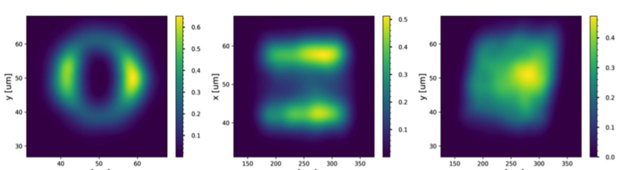

Figure 5: Ion beam distribution at the interaction point

CONCLUSION

The prototype gas sheet ionization diagnostic is still in the design phase but has shown promise for use as a single shot, non-invasive transverse profile monitor for high power particle beams. Bench tests are underway to test and characterize the gas sheet formation as well as document the system's differential pumping capability. The ion microscope design currently achieves adequate magnification through the transport and is being fine tuned to incorporate all practical engineering constraints. Once the design is cemented, both custom and off-the-shelf components will be used to construct the electrostatic column of the ion microscope.

Once the prototype is fully fabricated and bench tested, a flange to flange installation of the prototype will be installed at the FACET-II facility at SLAC National Accelerator Lab. Initially, the diagnostic will be tested at low beam powers to compare and benchmark against existing profile monitors. As FACET-II ramps up beam power capabilities, the testing of the gas sheet ionization diagnostic will also progress to higher beam powers that would prove damaging to existing profile monitoring technologies.

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