Gated Beam Imager for Heavy Ion Beams

Larry Ahle and Harvey S. Hopkins

Lawrence Livermore National Laboratory
P.O. Box 808, Livermore, CA 94551

Abstract. As part of the work building a small heavy-ion induction accelerator ring, or recirculator, at Lawrence Livermore National Laboratory, a diagnostic device measuring the four-dimensional transverse phase space of the beam in just a single pulse has been developed. This device, the Gated Beam Imager (GBI), consists of a thin plate filled with an array of 100-micron diameter holes and uses a Micro Channel Plate (MCP), a phosphor screen, and a CCD camera to image the beam particles that pass through the holes after they have drifted for a short distance. By time gating the MCP, the time evolution of the beam can also be measured, with each time step requiring a new pulse.

INTRODUCTION

Lawrence Livermore National Laboratory has, for the past few years, been developing the world's first circular ion induction accelerator, or recirculator, as part of its heavy-ion fusion research program. A critical task of this development is measuring and understanding any change in beam quality as a pulse travels around the accelerator. Of specific interest is the measurement of the first and second moments and the emittance growth. The standard tool used to measure the emittance of heavy ion beams is the slit scanner. This device uses two parallel slits, one downstream of the other, to measure the two-dimensional, either x-x', in plane, or y-y', out of plane, phase space. Not only is this device not able to measure both simultaneously, it also requires many beam pulses for one emittance measurement, i.e. one beam pulse each time one of the slits is moved.

In an effort to improve on this measurement device, the Gated Beam Imager (GBI) was developed at LLNL. This device uses small holes instead of slits, a micro-channel plate (MCP) to convert ions to electrons, and a phosphor screen to produce images on a CCD camera. The result is a device which measures both x and y emittance for a given time interval with a single beam pulse. Changing the timing gate of the MCP allows one to measure the time evolution of the beam pulse. Thus, the Gated Beam Imager obtains the same information as the slit scanner with a factor of 20 reduction in the number of beam pulses required.

THE DEVICE

The Gated Beam Imager is based on the pepperpot beam diagnostic method which has previously been used to diagnose electron beams (1). In the pepperpot method where a mask, or hole plate, with small holes (the pepperpot) is introduced into the beam, the beam ions are stopped by the hole plate except where they pass through the holes forming small beamlets. These beamlets pass through a drift region where they freely expand from space-charge and emittance forces. Making the holes small enough limits the space charge-induced expansion of the beamlets to a small percentage of the expansion due to emittance, the quantity of interest. The beamlets are intercepted by a detector which is excited and the spots are observed with a CCD camera, and digitized for analysis. Figure 1 shows a schematic of the GBI with several key dimensions listed.

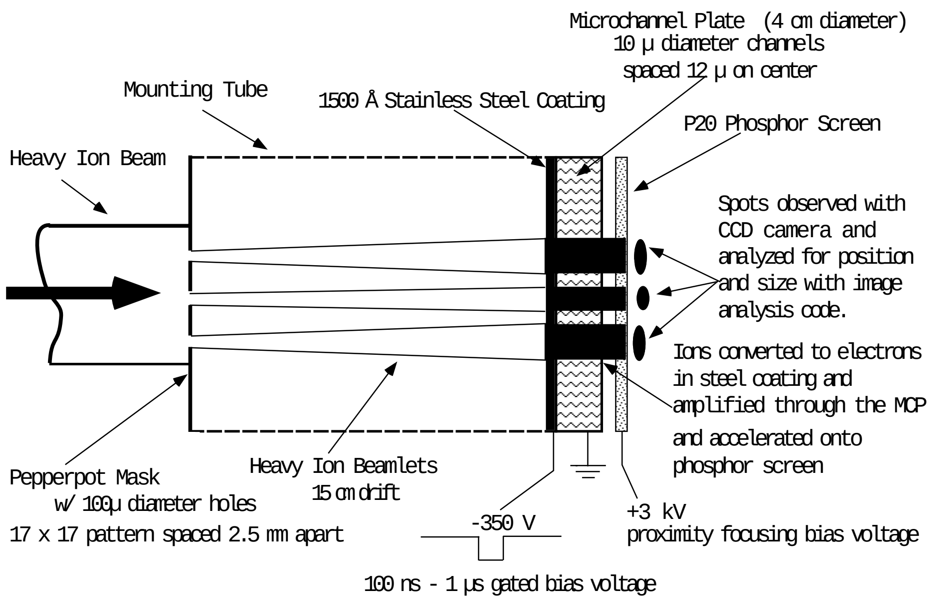

FIGURE 1. Schematic view of GBI.

Several dimensions of the GBI such as pepperpot hole size, hole spacing, and beamlet drift length must be sized to achieve the goal of maximizing the beamlet's growth due to emittance while minimizing the growth from remaining space-charge forces. Additionally, adequate signal strength must be present at the CCD camera and the beamlet image spot size must be much greater than the camera system resolution so that statistical averages of the CCD pixels are valid. These requirements place constraints on the pepperpot hole size, hole spacing, and beamlet drift length.

The application of a micro channel plate as the GBI detector allows consistent and repeatable signal output with increasing cumulative exposure to damaging heavy ions. The 1500-angstrom stainless steel coating on the input side of the MCP stops the heavy ions, resulting in a secondary electron signal proportional to the input heavy-ion signal (2). These electrons are then amplified through the MCP and proximity focused onto an output phosphor screen and viewed by a CCD camera through an optical lens. The optical focus allows the small CCD chip to see the entire phosphor screen at the cost of a large image pixel size. The proportional conversion of ions to electrons while maintaining the spatial relationship sidesteps the signal reduction with increasing dose observed when the phosphor output is directly exposed to heavy ions (3). The microchannel plate detector also allows amplifying weak signals making it possible to gate the beamlets rapidly and still have enough output signal at the phosphor screen.

THE ANALYSIS

After taking an image with the GBI, two corrections to the image must be made before it can analyzed to the find the emittance. First the dark charge contribution must be subtracted away. When the CCD chip has its bias voltages applied, a small amount of charge will build up in each pixel due to the thermal creation of electron-hole pairs. The longer the exposure, the more dark charge is built up. Since, the CCD chip reads out one pixel at a time, the amount of dark charge will be different for each pixel, less for the first pixel read out, more for the last. This effect is corrected for by taking an image with no incident light on the chip and subtracting that image from the real data image. Beyond this dark charge correction, the image must be corrected for any nonuniform response of the detector, or flat fielded. A uniform x-ray source is used as the baseline and an image of this source is taken. This image is used to calculate a correction factor for each pixel.

Once both of these corrections have been made to the data image, it can then be analyzed to determine the emittance. The first step is to search for beamlets on the CCD image. Contiguous groups of pixels above an intensity threshold are found. The exact value of the threshold is a little bit trial and error, but should be large enough so that pixels with only background do not contribute to these groups. If a single group consists of enough pixels, the group is said to be a beamlet. This cut on the number of pixels is to insure that holes in the hole plate which only have a fraction of its area overlapping with the cross section of the beam do not contribute to the emittance calculation. After finding all beamlets on the image, each one must be associated with the appropriate mask hole. This is facilitated by four extra holes around the center hole of the hole plate. This uniquely determines the center hole beamlet on the CCD image and the other beamlets are matched with holes relative to the center hole.

After this beamlet image to hole association, the moments are then calculated. Only a single row(column) of pixels for each beamlet is used in the $x(y)$ emittance calculation. This is done to more closely emulate a slit scanner analysis for comparison and to eliminate any correlations in the x and y moments which arise from the circular hole shape. The row and column used is determined by the pixel of peak intensity for each beamlet. The extent of pixels used in each row and column is determined by the first pixel on each side of the peak pixel, that has an intensity below 10% of the peak intensity. This cut is an exclusive one.

For each pixel that has passed this cut, there is an intensity, I_m, and position of the center of the pixel, x_m. Let x_h equal the center position of the hole, then

$$x'_m = \frac{x_m - x_h}{L} \qquad (1)$$

where L is the drift length. Also, let

$$I_{tot} = \sum_m I_m \qquad (2)$$

where this sum and all sum subsequent are over all pixels used for all beamlets. Given these equations, one uses Equations 3 through 7 below to calculate the moments.

$$\langle x \rangle = \frac{1}{I_{tot}} \sum_m x_m I_m \tag{3}$$

$$\langle x' \rangle = \frac{1}{I_{tot}} \sum_m x'_m I_m \tag{4}$$

$$\langle x^2 \rangle = \frac{1}{I_{tot}} \sum_m \left(x_m - \langle x \rangle \right)^2 I_m \tag{5}$$

$$\langle x'^2 \rangle = \frac{1}{I_{tot}} \sum_m \left(x'_m - \langle x' \rangle \right)^2 I_m \tag{6}$$

$$\langle xx' \rangle = \frac{1}{I_{tot}} \sum_m \left(x_m - \langle x \rangle \right)\left(x'_m - \langle x' \rangle \right) I_m \tag{7}$$

The definition of emittance used for this experiment is the rms emittance, defined below as,

$$\varepsilon_{rms}^2 = \langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2 \tag{8}$$

with the definition of normalized emittance as,

$$\varepsilon_{norm} = 4\gamma\beta\varepsilon_{rms} \tag{9}$$

where β and γ have the usual definitions of special relativity and whose product equals 0.00209 for this experiment.

VERIFICATION

The Gated Beam Imager was designed as an improvement to existing diagnostic devices, so it should give similar results. To verify this, measurements were taken on the Recirculator at similar positions for the GBI and the slit scanner. The configuration of the Recirculator was a 80 keV, 1.8mA, 4 μs long, K+ beam pulse. The measurement was done after the beam had traveled through a 90 degree bend without any acceleration. The slit scanner used had two 50 μm-wide slits with one 7.4 cm downstream from the other. The downstream slit had a Faraday cup attached behind it to measure the current of the beam that made it through both slits. Figures 2 and 3 show the results.

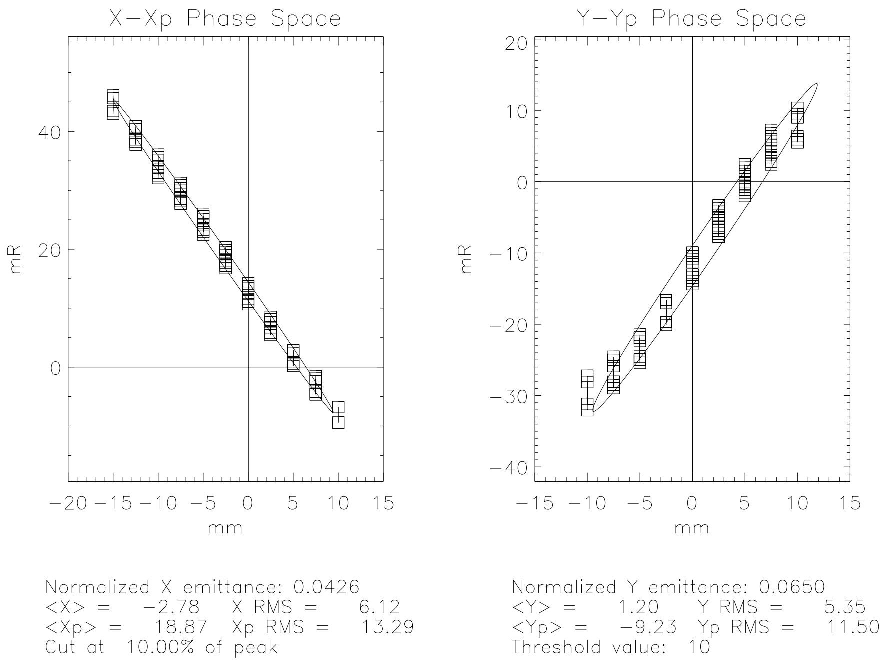

FIGURE 2. Gate Beam Imager data.

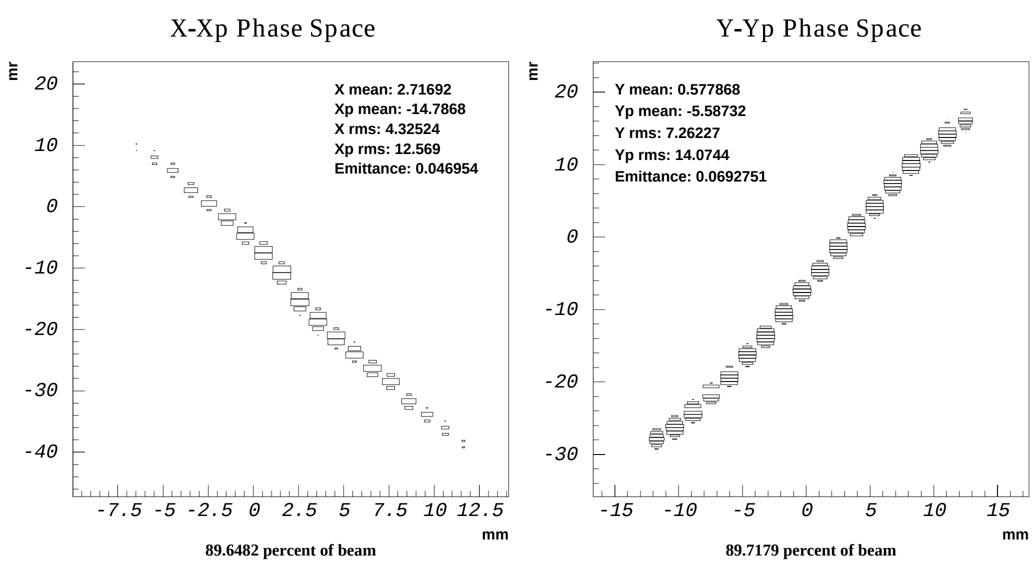

FIGURE 3. Slit Scanner results.

When comparing data from the two devices one should ignore the differences in the first moments, since this is a function of the inability to precisely align the beamline with the vacuum tank that housed both detectors. While the GBI is in this vacuum tank, slit scans cannot be done. The whole tank had to be rotated to do the slit scan in both directions. In addition, the second moments are also slightly different because the beamline position of the two devices differed by 18 cm. The Recirculator has a standard FODO design and so the beam has just exited a quadrupole before it is incident on the diagnostic devices. Thus, the downstream device, the slit scanner, will have a smaller *x* rms and a larger *y* rms than the upstream device, the GBI. This is verified by the data.

A real direct comparison can be made by looking at the normalized emittance values. The GBI values are 0.043 for the *x* emittance and 0.065 for the *y* emittance. This compares to 0.047 and 0.069 from the slit scanner. Given the systematic errors of the two devices and the different thresholding techniques used to ignore background, this is excellent agreement. Also, notice the qualitative agreement in the plots of the phase space measured by the two devices. It should be kept in mind that the GBI data was obtained from just one beam pulse, while the slit scanner required 800 pulses.

THE FUTURE

One drawback of the current GBI design is the fact the CCD camera is disjoint from the rest of the device. Thus, every time the GBI is inserted in the beamline, the camera has to be refocussed and the image pixel size must be determined. This not only costs time, but hinders flat fielding of the device, since the flat field image will have a different pixel size than the data image. To get around this, an improved model is currently being designed where the CCD chip sit in the vacuum and is directly coupled to the back of the phosphor screen, which implies the CCD chip will have to be as large as the phosphor screen. This will mean that the image pixel size will be the same as the physical pixel size of the chip for all images, including the flat field image. This design will also allow the device to be positioned at many different locations along the beam line, instead of just at the end of the machine.

Another improvement currently being planned is the use of a hole plate with square holes. It is currently possible to make 100-micron square holes where the corners have a radius of curvature of 12 microns. The use of this plate will allow a large increase in the number of pixels used without having to deconvolute the effect of the hole shape on the *x* and *y* moments.

CONCLUSION

The HIF group at LLNL has developed a new device, the Gated Beam Imager, to measure the first and second moments of an ion beam and its emittance. The device is an adaptation of the pepperpot design used for characterizing electron beams. It measures both the in-bend plane and out-of-bend plane transverse emittance simultaneously which the slit scanner cannot do. It also reduces the required beam pulse by a factor of 20 to fully map the transverse moments as a function of time. The emittance measurements from the GBI agree quite well with measurements from the slit scanner. Further improvement of the GBI are planned and the full usefulness of this device is just beginning to be exploited.

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