BEAM PROFILE MEASUREMENTS IN THE RHIC ELECTRON LENS USING A PINHOLE DETECTOR AND YAG SCREEN*

T. Miller†, M. Costanzo, W. Fischer, B. Frak, D. M. Gassner, X. Gu, A. Pikin,
C-AD, BNL, Upton, NY, 11973, U.S.A.

Abstract

The electron lenses installed in RHIC are equipped with two independent transverse beam-profiling systems, namely the Pinhole Detector and YAG screen. A small Faraday cup, with a 0.2mm pinhole mask, intercepts the electron beam while a pre-programmed routine automatically raster scans the beam across the detector face. The collected charge is integrated, digitized and stored in an image type data file that represents the electron beam density. This plungeable detector shares space in the vacuum chamber with a plunging YAG:Ce crystal coated with aluminium. A view port at the downstream extremity of the collector allows a GigE camera, fitted with a zoom lens, to image the crystal and digitize the profile of a beam pulse. Custom beam profiling software has been written to import both beam image files (pinhole and YAG) and fully characterize the transverse beam profile. The results of these profile measurements are presented here along with a description of the system and operational features.

INTRODUCTION

In order monitor the quality of the electron beam in the electron lens used to compensate for the effects of head-on Beam-Beam interactions in the collider [1], two parallel methods of beam profile measurement were developed and tested on a test bench [2] toward the end of 2011. Final designs were made and these systems were installed during the shutdown beginning in the summer of 2012 on the electron lens prepared for the RHIC blue beam [3]. Installation of both the electron lenses, one for blue and one for yellow RHIC beams, continued throughout the rest of 2012. The two beam profile measurement instrumentation systems were tested, along with applications for single-bunch beam-beam compensation, during the 2013 polarized-proton run in RHIC [4].

Table 1: Beam Parameters During Measurement

Parameter	YAG	PinHole
Beam Energy	6 keV	6 keV
Beam Current	70 mA	210 mA
Pulse Width	1 µs	12.5 µs
Rep Rate	1 Hz	10 Hz
Resolution	~40 pixels/mm	~8.5pts/mm

In this paper we present the final design and function of the YAG and pinhole scan system and the results of the profiles measured using the two methods. Table 1 summarizes the electron beam parameters, reduced from normal operation during the two profile measurements.

YAG SCREEN IMAGING

A mono-crystalline Cerium doped YAG crystal is used as the scintillating screen. Measuring 30mm diameter and 0.1mm thick, it is coated with a 100µm layer of evaporated aluminium to drain accumulated charge. The mechanical arrangement used on the test bench, presented earlier [5], was repeated in the installation in RHIC. The Gigabit Ethernet camera was upgraded from a Manta G201B to a G145B. The 21% larger sensor has 1.4 megapixels (MP) instead of 2 MP and thus provides increased sensitivity due to the larger pixel size on its SonyICX285 2/3 image sensor. The camera is used in its external trigger mode and is synchronized to the pulsed electron beam by the timing system.

Although two lenses were compared during tests on the test bench [5], the Sigma 70-200mm f/4-5.6 APO DG Macro lens with C-mount adapter was chosen. Its large aperture mates well with the high sensitivity of the camera. The drawback of this commercially available low cost lens is its fragile plastic body and lack of locking mechanism. The focus adjustment was very sensitive as the depth of field was very shallow with the aperture wide open. Sitting 86cm downstream of the YAG crystal, the zoom lens was adjusted to fill the camera's view with the 20mm useable area of the YAG screen. At this zoom, the focus adjustment was at its limit, suggesting an imperfect but sufficient setup of the optical system. The resulting resolution of the 20mm screen projected onto the camera's sensor was measured to be 39.4 pixels/mm. Fig. 1 shows the result of the high-resolution image of the

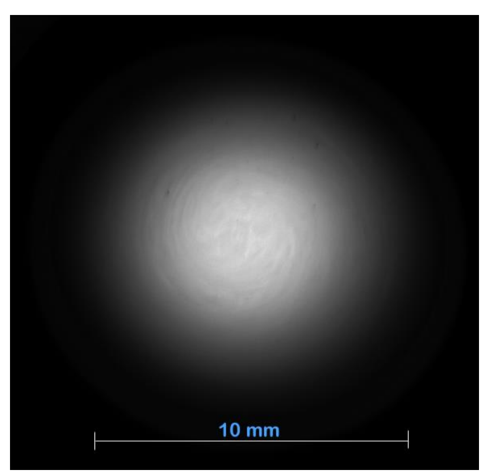

Figure 1: YAG screen profile of the electron beam.

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†tmiller@bnl.gov

electron beam. Notice the structure seen in the image that is likely indicative of variations in quantum efficiency of the thermionic cathode's surface coating.

Some diagnostics were included to check the health of the YAG crystal since damages from over-exposure to beam occurred several times in the past. A 450nm high-brightness, focused LED was used to flood the YAG crystal with a wavelength of light at which it fluoresces most efficiently. Figure 2a shows a uniform fluorescence of the YAG crystal during a 500ms exposure with a camera gain of 20dB, under 80mA of LED current. The motive is to look for cracks or reduced fluorescence due to over heating, as was found during the YAG crystal damage discussed previously [5]. The bright spot in the image is believed to be an unwanted reflection that appeared with a long exposure time.

A 405nm, 4mW laser was also injected through the lens onto the crystal. Figure 2b shows the structure in the inexpensive laser beam as it appears on the YAG crystal. This structure was used as a focusing aid during set up.

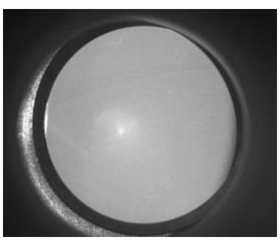
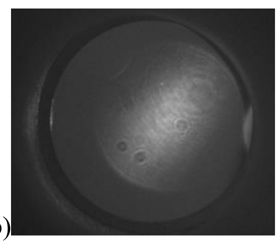
a)  b) 

Figure 2: YAG crystal illuminated with a) uniform 450nm LED light and b) 405nm expanded laser beam.

PINHOLE SCAN IMAGING

An image of the electron beam is created by taking current measurements throughout a matrix of positions over the cross-section of the electron beam. The pinhole scanning system is comprised of a faraday cup plunged into the beam via a pneumatic actuator and with a 0.2mm diameter pinhole mask. As this electrode sits at a fixed position at the center of the beam pipe, the electron beam is raster scanned over it and the beam current is recorded at each position in the matrix.

The pinhole faraday cup electrode sits in an instrument cluster mounted to the opening of the beam dump. Thus, the instrument cluster is biased at the potential of the beam dump (up to +/-10kV). Consequently, the pinhole motion control and signal integrating electronics must also sit in a chassis biased above ground potential. The current signal from the masked faraday cup is carried to the integrator electronics through nearly 80m of Belden 9311 coaxial cable, in a high voltage sleeve inside steel conduit.

Control System

An array of positions is created from parameters defining the minimum & maximum steering currents for the horizontal and vertical coils and the number of points along each axis. The timing system coordinates power supply settings and data acquisition hardware. There are four major BNL standard custom hardware components as described below and shown in the block diagram of Fig. 3.

- Waveform Generators – pair of modules comprised of a controller with waveform table, coupled via fiber to a remote power supply controller module having an analog output as well as 4 analog input channels for power supply readbacks. The generator pair generates the scanning waveforms and supports external timing signals to synchronize stepping through the waveform table.
- Data Acquisition Module – Module having 4 Analog input channels and is isolated from its controller by a bidirectional fiber optic link. The controller contains a readback buffer for the data as well as external timing inputs to synchronize data acquisition times.
- Trigger Generator – Multi-channel module that utilizes a widely-distributed master clock and event link to generate output pulses with programmable delays and widths that have deterministic timing.
- Front End Computer – VME-based controller running the VxWorks Operating system, used to control the other three components above and to bridge their parameters and data with the rest of the controls system infrastructure over an Ethernet network.

Scan parameters are entered into the application GUI, including (but not limited to) the number of points to be scanned, the horizontal and vertical current limits of the scan, and the frequency at which the system advances through measurement points. The application software begins executing steps to execute the scan. Waveform tables are generated with the appropriate steering magnet currents in sequence to generate a raster-scan pattern. These tables are loaded into the horizontal and vertical waveform generator internal memories. The trigger generator channels are configured to generate a trigger sequence to advance the waveform generator points, allow the steering coil currents to settle, generate an electron beam pulse, initiate one or more data acquisition pulses including control of the integrator (reset and gate), and finally transfer data back to the application software to be buffered. The pinhole scan is then initiated by enabling an appropriate event on the trigger generator event link. At this point events begin occurring at the predetermined rate on the link and the trigger generator channels respond to each event in turn advancing the steering magnets, firing the electron beam, gating the integrator equivalently to the length of the beam pulse and triggering the data acquisition. When the appropriate number of points has been scanned through, the events cease and the data is stored in a linear array.

The speed of the scan is limited by the settling time of the current in the steering coils after each step change. The settling time is directly affected by the step size. In

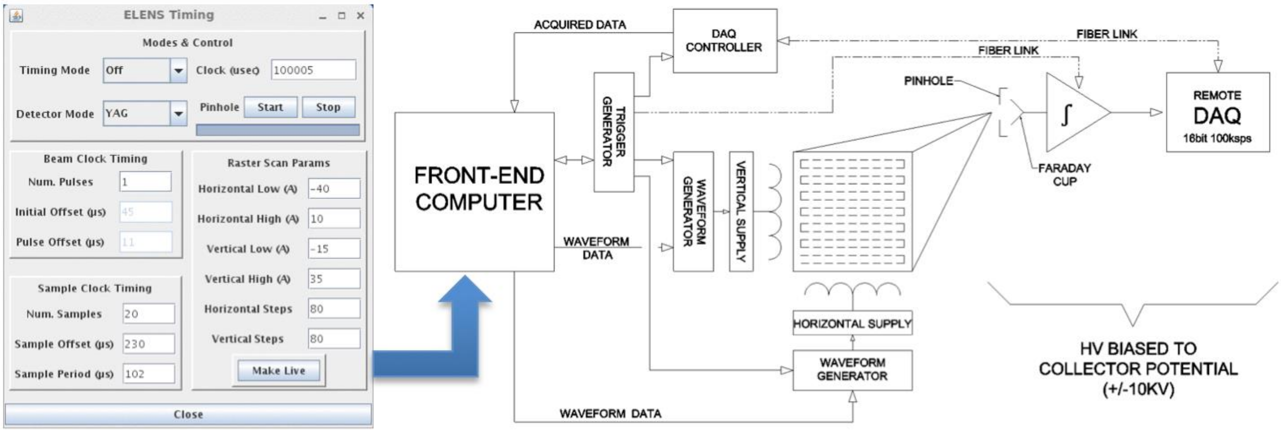


Figure 3: Block diagram of Pinhole scan hardware and software control GUI.

order to minimize the step size in the horizontal scan sequence, the horizontal scan lines alternate in direction.
Note the serpentine dashed lines depicting this in Fig.3. The steering coils, embedded in water-cooled solenoid magnets, have power supplies capable of up to 400A. The steering coils have a steering effect of ~0.2mm/A. Thus, beam can be scanned over more than the full aperture of the beam pipe. A 100x100 scan running at 10Hz requires just under 17 minutes to complete; however, tests have shown that scan rates of up to 100Hz with steps under 13A are possible.

As each scan line alternates in direction, the linear array is picked apart and reassembled into an 2D-array with the original number of horizontal and vertical points. Although this tightly packed array of intensity data point does represent an image of the beam, it must be scaled in each direction as a function of the strength of the steering coils in order to represent the actual beam size. To accomplish this, a calibration procedure using the YAG crystal and camera is used to define deflection coefficients for each axis (in A/pixel) and then to measure the number of pixels per mm in order to calculate A/mm.

Calibration Using YAG Imaging

The size calibration of pixels/mm is found by drawing a reference circle on an image of the YAG crystal, illuminated to see the crystal support frame, as shown in Fig. 4. Controls are provided to position the circle and adjust its radius to match the known 20mm diameter of the frame's bezel. Once defined within the image, the scaling coefficient can be calculated. It is shown in Fig. 6 in the calibration interface as 39.4 pixels/mm.

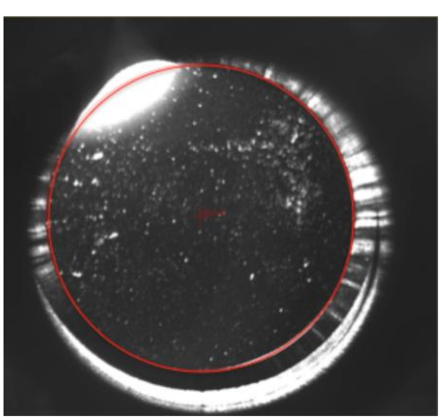
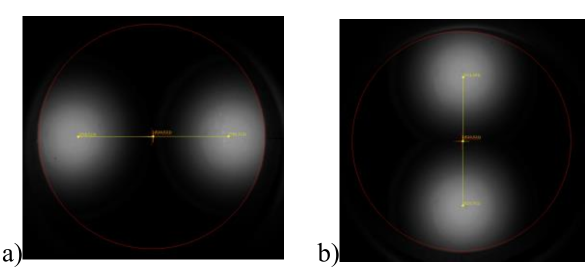


Fig. 4: Calibration circle defined along the 20mm inside diameter of the mounting fixture bezel.

Deflection coefficients for both the horizontal and vertical axes are found by a procedure of steering the beam to the maximum and minimum scan limits for the pinhole scan and taking the four corresponding images of the beam with the YAG profiling system. Software developed to control all parameters of the pinhole scan first finds the center of gravity of the beam profiles. It then overlays the two images taken for each of the two horizontal and vertical axes, generating two new images. A line is drawn between the centers of gravity of the two deflected beam spots. The distance is measured in pixels and then translated to millimetres from the pixels/mm factor found using the reference circle. Figure 5 shows the resulting two images. Offset coefficients are also generated for the horizontal and vertical axes.



a) b)

Figure 5: Composite images for calculation of deflection coefficients, skew angles, and offsets for the a) horizontal and b) vertical axes.

Moreover, a skew angle is measured from the horizontal or vertical for each image. These skew angles are used to correct the image data for coupling between the horizontal and vertical steering coils. These calibration coefficients are shown in the screen shot of the calibration interface in Fig. 6.

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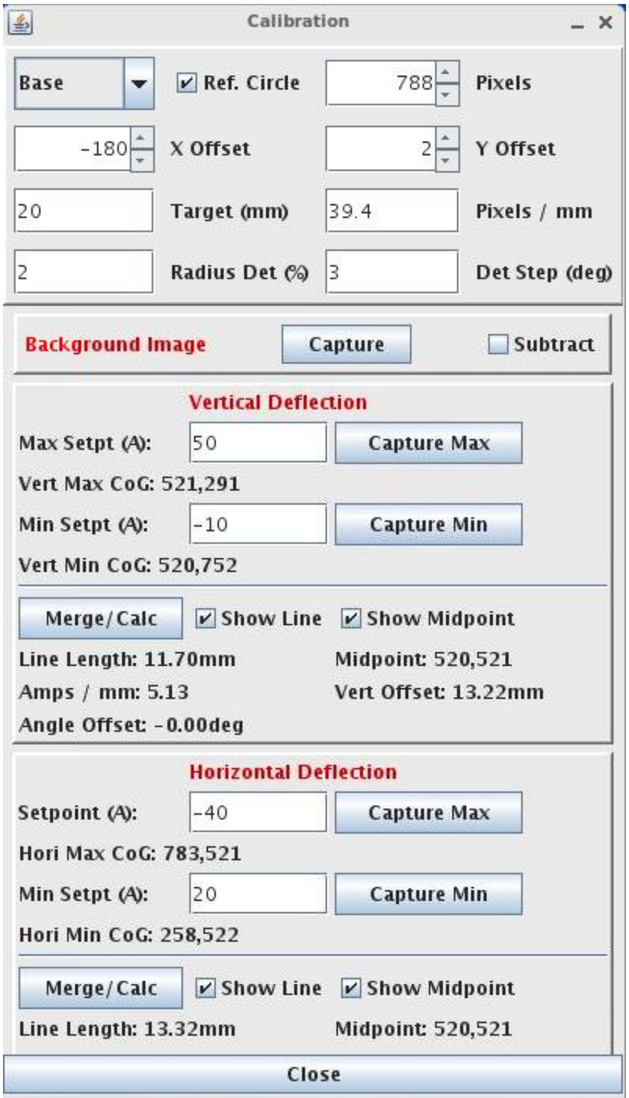

Figure 6: Calibration procedure software interface screen.

Example Scan

With the parameters shown in the GUI in Fig.3, the span of the steering magnets in the horizontal and vertical directions was 60A while the array size was 100 x 100.

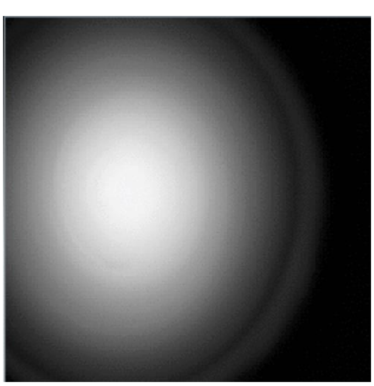

Figure 7: 100x100 point pinhole scan rendered to an image.

Thus an array of 10,000 points with a step size of 600mA was created. Once the image is generated from the data array, it is scaled by the deflection coefficient constants using standard java image library functions. This accounts for in-equivalent gains of the two steering coils. Also, the horizontal and vertical axes of the image are skewed by the negative of the skew angles to compensate for coupling between axes. Finally, a smoothing algorithm is applied and the final image is rendered in the same format as the image taken from the YAG screen camera so that the profiles of the two images can be measured using the same set of tools. Figure 7 shows the rendered image resulting from the scan.

IMAGE ANALYSIS

The images of the beam profile, whether taken by the YAG screen camera or rendered from a pinhole scan, can be sliced along the X, Y or user defined arbitrary axes. The software developed for this application determines the center of gravity of the locus of points and then allows the user to define an arbitrary axis about that center. The axes are then divided into segments over which the intensity is averaged.

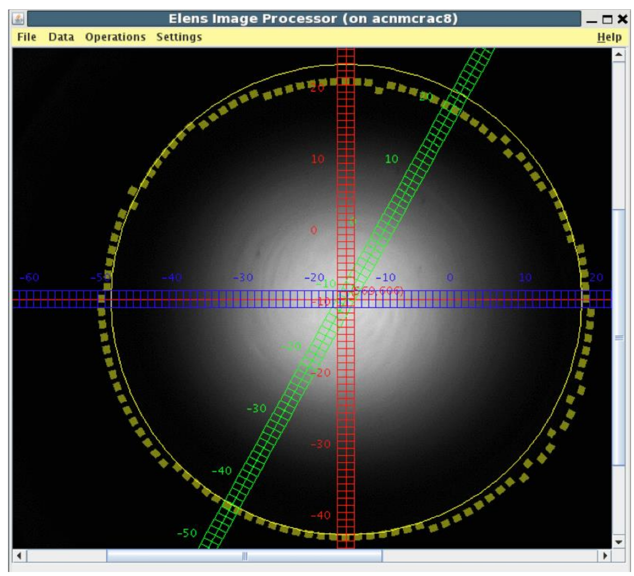

Figure 8: YAG beam profile, magnified, with analysis axes and beam radius boundary shown.

Figure 8 shows the beam profile taken from the YAG screen camera with the axes added and the averaging segments shown as blocks along the axes. Also, the beam radius boundary is automatically defined by a fitted circle through points that lie at 2.5% of the intensity.

A 2D plot is then made of the average intensity versus distance. The distance calibration came from the reference circle definition and the image scale factors from the deflection coefficients. Figure 9 shows the profile along the arbitrary axis of the rendered pinhole scan. The program overlays a fitted Gaussian curve and displays statistical data about the curve, such as its formula, radius, sima, and X^2 parameters.

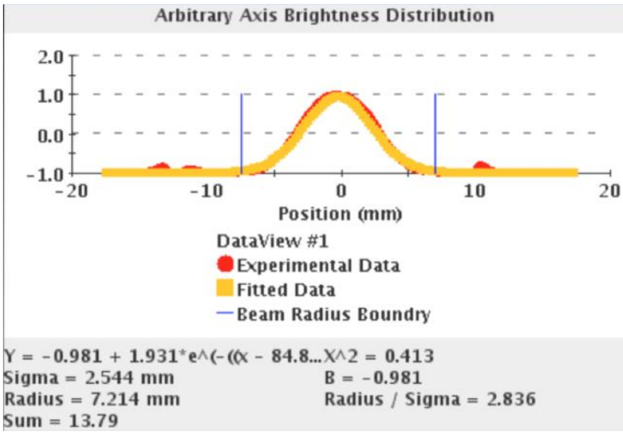

Figure 9: Profile of the electron beam taken through the arbitrary axis, here defined at 60° from Fig 8.

Comparison of Methods

Two profiles were measured and compared, one taken with the YAG screen camera and the other rendered from a pinhole scan, each with the parameters shown in Table 1. Excellent agreement can be seen in the comparison of the profiles from the two methods. Although the two measurements were taken at different beam currents, previous tests on the eLens test bench showed the YAG screen profile to scale linearly with beam current, thus retaining its Gaussian shape. A comparison of the two is shown in Fig. 10.

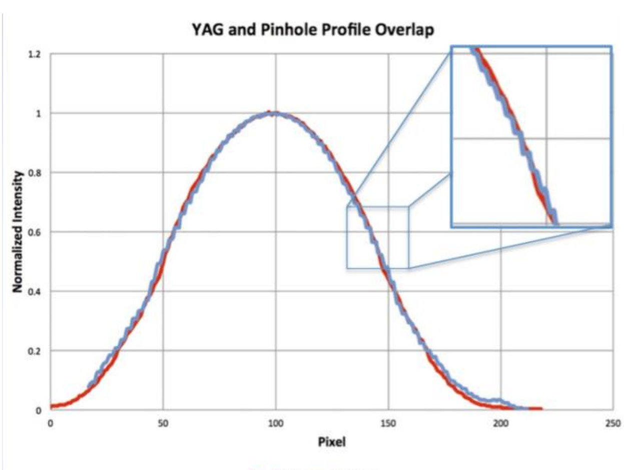

Figure 10: Comparison of the YAG vs PinHole generated profiles.

Note the coarser resolution of the pinhole data (~8.5 pts/mm) compared to that of the YAG screen data (~40 pixels/mm) as shown in the magnified window in Fig. 10.

CONCLUSION

Two successful methods of measuring the electron beam profile are now operational on two electron lenses installed in RHIC. Since results from the two methods concur, the YAG screen method will be the instrument of choice as provides is a faster measurement. However, due to the fragile nature of the YAG crystals, the pinhole scan system will remain as a back-up system of measurement. Plans are underway to upgrade the YAG crystal holder to a multi-crystal system that will allow a choice of several redundant crystals to be selected and provide for testing of alternate scintillating media.

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