

MULTIFUNCTION INSTRUMENT DESIGNS WITH LOW IMPEDANCE STRUCTURES FOR PROFILE, ENERGY, AND EMITTANCE MEASUREMENTS FOR LEReC AT BNL*

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Abstract

The low energy RHIC electron cooling (LEReC) upgrade project [1], being installed over the next two years will require a low impedance beam line so that the soft 1.6MeV electron beam will not be perturbed by induced electromagnetic fields, especially in the instrumentation chambers. Novel designs of the Profile Monitors, Emittance Slit Scanners and BPMs are presented along with Particle Studio simulations of the electron beam wake-field induced electric potentials. The design of a new instrument incorporating a button beam position monitor (BPM) and YAG screen profile monitor in the same measuring plane is presented as part of a method of measuring beam energy with an accuracy of 10^{-3} .

INTRODUCTION

In support of the Beam Energy Scan Phase-II physics program, in search of the QCD critical point and verification of several QCD models [2], a bunched beam electron cooler based on a SRF LINAC is being developed with operation planned for 2018-19. Effective cooling of the low energy Au ion beams below 20 GeV can be accomplished by co-propagating low energy electron beams of 1.6 – 5.0 MeV [2]. With the portion of this new electron machine sharing vacuum space with RHIC, an aggressive design and installation schedule has been set forth to allow the installation of the cooling section components, as shown in Fig. 1, during this year’s 2015 shutdown. This has accelerated the design and fabrication of specialized beam instrumentation components for measurements such as profile, position, emittance, energy and energy spread. A key critical requirement of these components is that this instrumentation present minimal impedance to the electron beam; thereby minimizing the effects of longitudinal wake fields to preserve the strict requirements on intrabunch longitudinal beam energy spread. An impedance budget of 5.0 V/pC has been set for the entire beamline. As a result, all beam line elements will be evaluated for their impact on this budget.

This low impedance requirement has necessitated the specialized design of the vacuum chambers within which YAG crystals are held for profile measurements, emittance slit masks are scanned for slice emittance measurements, and capacitive pick-up electrodes are mounted for position monitoring. These three chamber

types, supporting instruments in the cooling section, were designed to minimize the rate of change of the beam transport aperture; thereby minimizing perturbations in the beam’s wake field that can set up oscillating electromagnetic fields and in turn impacting the quality of the beam. Modeling in Particle Studio [3] has led to a refining of the chamber design resulting in a balance of lowest possible induced electric potentials within the chamber against a minimum compromise of the beam aperture to support insertion components and viewing ports.

Finally, the optimized profile monitor design was combined with a newly designed BPM chamber to produce a new hybrid device capable of using optical beam measurement techniques to calibrate integrated BPM pick-ups for better than 50µm absolute position accuracy. This high level of absolute accuracy is provided by the use of BPMs upstream and downstream of and in conjunction with the 180° dipole magnet between cooling sections to make absolute beam energy measurements to an accuracy of 10^{-3} .

Beam Parameters

The electron beam has a nested pulse structure, as previously illustrated [1], so that 120 ps bunches at 705MHz are grouped in macro bunches and positioned to overlap with the RHIC ion beam. These macro bunches (and ion bunches) are spaced at 9.1 MHz and grouped into a train of macro bunches. The train length is one turn around RHIC with a gap between consecutive trains that aligns with the RHIC abort gap. Other key parameters of the electron beam are listed in Table 1.

Table 1: Electron Beam Parameters in the Cooling Section

Parameter	Value
Energy	1.6 – 5 MeV
Bunch Charge	100 – 300 pC
Macro bunch Charge ($\gamma_{ion} = 4.1-10.7$)	3 – 5.4 nC
Average beam current	30 – 50 mA
Bunch / Macro bunch Rep Rates	704 / 9.1 MHz
Bunch Length	37 mm
Max. Allowable Energy Spread ($\Delta p/p$)	5×10^{-4}
Beam trans. size	$\sigma = 3.84$ mm

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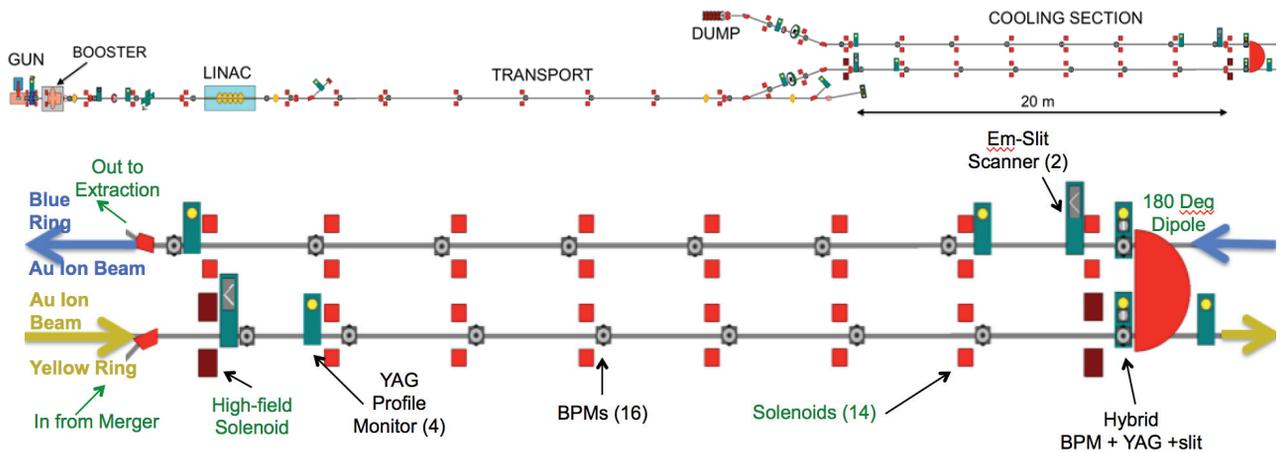


Figure 1: Overall layout of the LEReC machine (top) and the detail of the cooling section (bottom).

The macro bunch charge shown in Table 1 is not a constant. As the ion bunch length reduces when RHIC operation changes from $\gamma = 4.1$ to $\gamma = 10.7$, the number of bunches in the copropagating and overlapping macro bunch will be reduced from 30 to 18. In compensation, the charge per bunch will be increased from 100 pC to 300 pC. Note also that the beam transverse size in the cooling section has a full width of nearly 20 mm.

CHAMBER DEVELOPMENT

To meet the strict demand of low impedance to the electron beam, the typical use of a 6-way cube or cross as a vacuum chamber for instrumentation was abandoned. Starting from a cylindrical design, matching the 4.78" I.D. beam pipe, orthogonal ports were added to accommodate the insertion of detectors as well as viewports for imaging.

Profile Monitor

Requirements for profile measurements in the LEReC cooling section ask for a relaxed resolution of 10% of the beam size (23 mm at 3σ or 99% full width in the cooling section) on a screen measuring 45 mm in diameter in order to make profile measurements at the beginning and end of each of the two cooling sections. The design started with four typical YAG crystal based profile monitors with two-position actuators, placed at each end of each of the two cooling sections as shown in Fig. 1. These units are being designed and built in-house in order to meet an aggressive project schedule and to cope with the demand of presenting low impedance to the electron beam. Both the actuator and optics view ports were kept as small and short as possible to accommodate the YAG-mirror holder assembly and allow imaging & illumination through the optics port.

The YAG-mirror assembly holds a 0.1×50 mm YAG crystal with a 100 nm Al-coating and is optimized for an aperture of 45 mm. The YAG crystal is held normal to the beam and therefore is imaged through a polished copper mirror held at 45° just behind the crystal. Fig. 2 shows the assembly model.

The large aperture introduced by the actuator port was shown, by simulation of wake field induced electric potentials in its vacuum chamber and on the in-vacuum components using Particle Studio code, to have peak values that were higher than desired. Thus, a NiZn ferrite absorbing block, type CMD5005, was selected and designed to have a surface area of 23.42 in² and volume of 4.83 in³ and positioned in the actuator port.

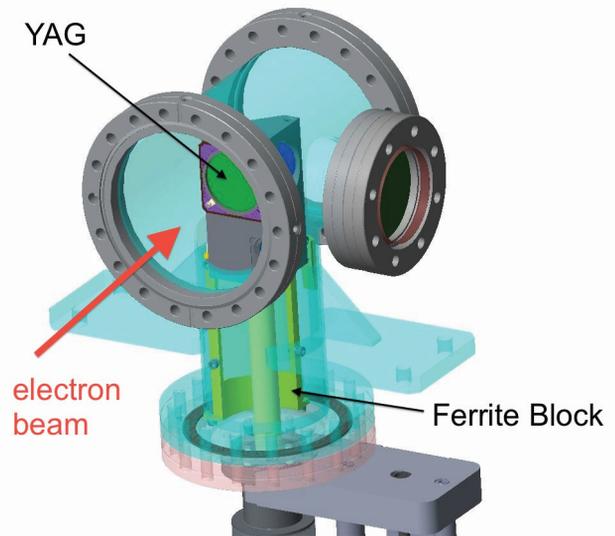


Figure 2: Model of the profile monitor with ferrite absorber, actuator not shown.

Emittance Slit Scanner

Requirements for emittance measurements in the LEReC cooling section demand a measurement with better than 10% error at the beginning of each of the two cooling sections. Although a 2mm thick Tungsten mask was chosen for its low penetration depth of the 1.6 – 5 MeV electrons and mechanical rigidity, the 150 μ m wide slits at this plate thickness will cause an aperture reduction of > 23 %/degree of misalignment error. Considering a thinner plate, compensation for the “detour factor,” [4] where electrons follow zigzag path through the material (exceeding the penetration depth), would

suggest a mask thickness of 1.0 mm in order to stop the electrons. However, simulations previously reported [5] made with beams energetic enough to penetrate a pepper pot mask showed negligible blurring of the resultant image because the degraded electrons that pass through the plate are so widely scattered over a large angular range that the background they generate is very small. Therefore, we are considering milling a ~5 mm wide area along the slits down to a thickness of 300 – 500 μm, thereby reducing the aperture reduction factor down to under 6 %/degree. Thus design calls for a 1° alignment error during installation and must be held to within a rotational tolerance of 5 mrad during operation to hold the effective slit width constant.

In order to provide both horizontal and vertical slice emittance measurements at each location, two dual slit stepper-motor-driven mask scanners were designed with similar constraints on their vacuum chambers. Although only an actuator port is necessary from which to insert the large tungsten plate-mask, the length of the plate required to support both horizontal and vertical slits on a single 45° scan axis exceeded the chamber diameter; thereby requiring an opposing port to receive the over-travel of the mask during a scan. Since only the thin mask need be inserted into the beam aperture, the chamber walls remain contiguous with the exception of two opposing narrow slits through which the mask travels. This relieved much of the effect of the aperture otherwise created by the 2.56” I.D. actuator and over-travel ports accommodating the 2” wide orthogonal-slit mask. Figure 3 shows the assembly model. Figure 4 shows the slit mask in four key positions through a scan over the horizontal and vertical slits with an overlay of the beam spot.

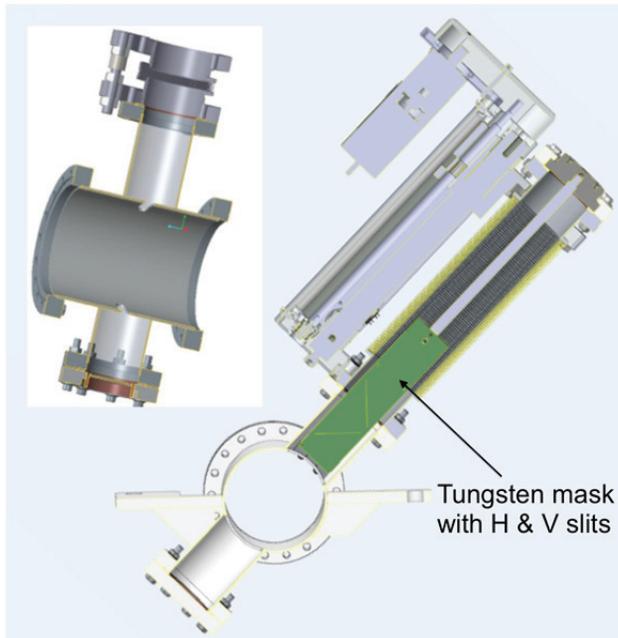


Figure 3: Cut-away model of the emittance slit scanner and cut-away view of the chamber.

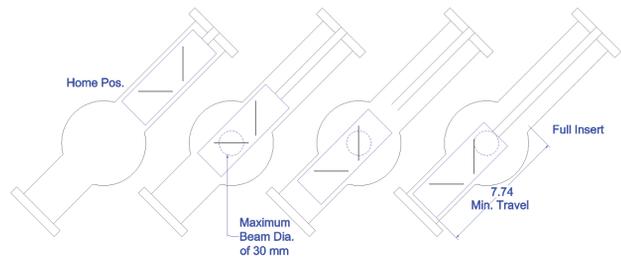


Figure 4: Detail of the emittance slit mask in its key positions along the scan with the beam spot shown.

MODEL SIMULAITON

Although the mechanical models of the profile monitors and emittance slit scanners were made with best efforts to reduce the impact on beam loading, an iterative refining process of numerical simulation of the wake-field induced electric potentials by a short bunched packet of charge followed by adjustments to the mechanical design in an effort to arrive at a final design with as low a wake potential as possible.

To do this, simplified 3-D models of the chambers were made to run in a Particle Studio simulation with a representative electron bunch passing through the chamber. The induced electric potentials were plotted to express the impedance vs. frequency as well as wake potential per beam charge as a function of distance behind the bunch.

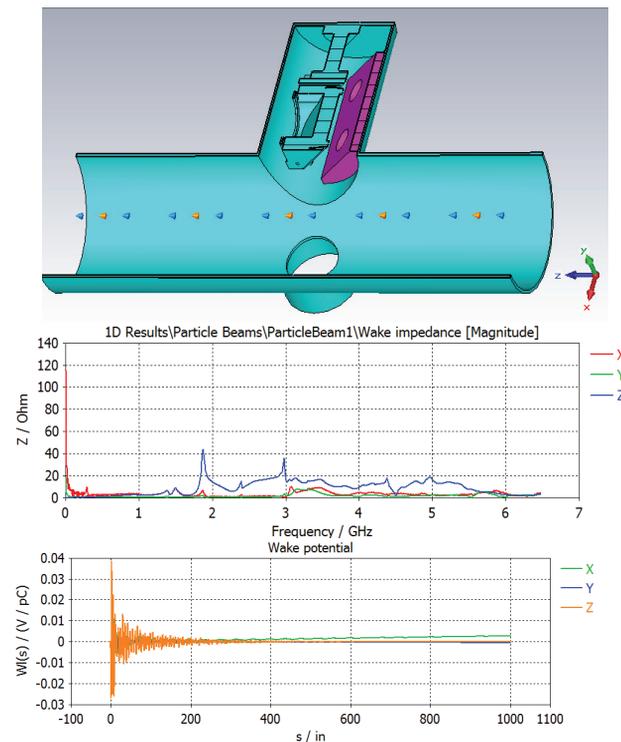


Figure 5: a) Simulation model for profile monitor with b) resulting impedance and c) wake potential plots.

The latter is used to confirm that the ringing electromagnetic fields in the chamber dampen before the next beam bunch arrives. Figure 5 shows the simplified version of the model used in the simulation for the profile monitor with the beam path indicated, along with the resulting impedance vs. frequency spectrum and the wake potential plot vs. trailing distance. As the preliminary design of the emittance slit scanner chamber contained a minimally intrusive opening for only the mask to protrude, no design modifications resulted from the simulations.

In order to determine how low the wake induced potential must be; all beam line devices are being analyzed and tabulated to ensure that the 5.0 V/pC budget is not compromised. Table 2 summarizes the potentials of various beamline components found from Particle Studio simulation ran with 300 pC bunches, 1.5 cm_{rms} long. Thus far, efforts have been concentrated on devices in the cooling section. Some of the devices remaining to be analyzed include the 180° dipole chamber, various Y-chambers, “Flying Wire” profile monitors, RF cavities, and transport section BPMs. Analysis of the Conflat® flanges where the copper gasket I.D. is larger than the beam pipe I.D. must be analyzed as well since the resulting tiny cavities can also “ring.”

Table 2: Device Wake Loss Factor

Device	(V/pC)
Cooling Section Profile Monitor	2.33×10^{-2}
Cooling Section Emittance Slit Scanner	1.68×10^{-2}
Cooling Section BPM	5.30×10^{-3}
Welded Bellows	9.07×10^{-2}
Formed Bellows	3.00×10^{-2}
40cm of 4.78” ID beam pipe	5.70×10^{-4}
Hybrid BPM+Profile Monitor+Slit	6.28×10^{-2}

Grounding

Another effect of wake-field induced potentials by the short bunched electron beam are those induced on the YAG crystal and its holder as well as on the large surface of the tungsten emittance slit mask. These voltages can set up large “ringing” “L-C” oscillations on these elements that can be significant enough to distort the electron beam; thereby corrupting the attempted measurement.

Models of the instruments were made for simulation with their in-vacuum elements in the retracted position to aid in the design of the cavity. Simulations were also made of the instruments with their in-vacuum elements in the inserted position. This provided insight into the magnitude of the induced voltages on the elements that interact directly with the beam. The determination was made that local grounding connections were necessary to

shunt the wake-filed current to mitigate these ringing electromagnetic fields.

Parallel design efforts continue for the inclusion of a sliding electrical contact within the actuator port of the vacuum chamber to electrically ground the in-vacuum element, as shown in Fig. 6. Simulations will be run with and without this ground connection to determine its effectiveness.

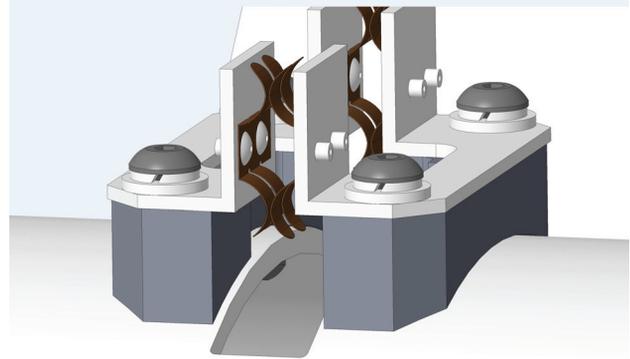


Figure 6: Sliding ground contact in emittance slit scanner mounted over entrant slot (mask removed).

POWER & EXPOSURE CALCULATIONS

Profile Monitor

Tests were made at the electron lens (eLens) test bench at BNL in 2012 [6] with YAG crystals used to image a 5keV, 5 mm (FWHM) Gaussian electron beam. Results showed a linear response of the crystal without saturation under beam pulses up to 40 μs long at up to 500 mA. Although this is under investigation in order to scale the results to fit the LEReC beam parameters, the tests were made with single shots and thus don't contain the steady state temperature effects needed for scaling. The approach will be to determine a maximum local temperature rise at the beam spot on the YAG crystal above which the response of the YAG begins to degrade, resulting in a flattening of the Gaussian profile. This ΔT limit will then be used to find an exposure limit to the LEReC beam at maximum charge and repetition rate. Saturation mechanisms other than those due to heating are being explored. If these other mechanisms can be neglected, then the resulting ΔT limit will then be applied to the profile monitor located in the merger section of the LEReC beam line where the beam size is the smallest with σ = 0.3 mm. A limit for the cooling section profile monitors, where the beam σ = 3.84 mm, will scale with σ², thus allowing many more macro bunches resulting in a longer exposure time in the cooling section.

With this approach of using the eLens test bench results, estimates will be conservative because the minimum beam spot considered is much smaller than that of the beam on the test bench, thus allowing heat conduction to play a more significant role, where the temperature gradients will be larger. These estimates may be made even more conservative by improving radiative

cooling of the crystal by applying a thin carbon coating on top of the aluminum coating on the YAG crystals.

Emittance Slit Scanner

The emittance slit mask and support assembly is intended to safely absorb 10 W of average power from the electron beam on the mask with a mask $\Delta T < 200$ °C without the need for water-cooling inside the vacuum chamber, based on a 1 minute exposure to 10 W of average beam power, allowing a 5 minute cool down period between exposures with a maximum of 5 exposures per hour.

The slit is scanned over the entire beam diameter in 0.5 mm steps. The measurement rate is limited by the 1-second image capture rate of the associated Profile Monitor. Thus to scan the largest beam diameter of 30 mm, in 0.5 mm steps, a scan time of 60 seconds is required. As this mask contains two slits for both horizontal and vertical scan data, the mask is planned to endure two consecutive 60-second scans.

Equation 1 gives the exposure time (T) corresponding to the 10 W limit, based on the beam energy and macro bunch charge & frequency

$$T = \frac{P \cdot t}{V} \cdot \frac{1}{Q_{MB} \cdot f} \quad (1)$$

where P = 10 W average power, V = 5 MeV max. beam energy, t = 1 s repetition rate, $Q_{MB} = 5.4$ nC max. charge per macro bunch (18×300 pC = 5.4 nC [2]) and f = 9.1 MHz macro bunch repetition rate. This results in a total charge of 2000 nC each second, distributed over 370 macro bunches, for an exposure time of 40 μ s per pulse train per second; thereby limiting the beam power to under 10 W.

HYBRID DESIGN

Absolute Energy Measurement

In order to support an absolute beam energy measurement with an accuracy of 10^{-3} , two BPMs will be used with the 180° dipole magnet in the cooling section as a spectrometer. The beam entry and exit points in the dipole are separated by 700 mm. Hence, an accuracy of position measurement to better than 700 μ m is required from the BPMs to guarantee the 10^{-3} energy measurement accuracy. In order to provide a real time calibration of these two BPMs, a YAG screen profile monitor is inserted into the BPM chamber in the same X-Y plane as the BPM buttons. To accommodate the actuator port for the YAG screen, one plane of buttons was eliminated, leaving only the horizontal sensing plane of the BPM. These BPMs shall only be used for horizontal position measurement in the spectrometer arrangement. Therefore, the optics viewport opposes the actuator, requiring a special design of the YAG and mirror holder, as shown in Fig. 7

A Particle Studio simulation was run on this model and found that a ferrite absorber was needed to reduce the wake-field induced oscillations in the extracted position. Moreover, a grounding contact was added to mitigate

large oscillations on the structure from the effects of the 704 MHz and 9 MHz beam structures. A ferrite ring was chosen to fit into the optics port due to limited space in the design.

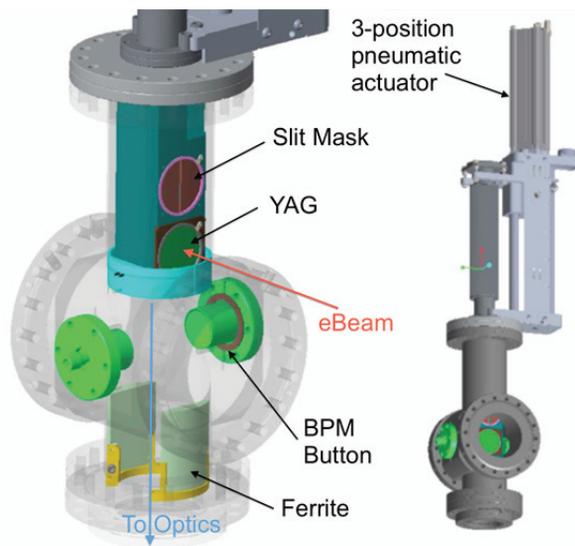


Figure 7: left: Hybrid BPM + Profile Monitor + Slit Mask, shown in the extracted position; right: transparent view of chamber only, full assembly view.

Energy Spread Measurement

An energy-spread measurement is required with a resolution of better than 10% of the maximum $\Delta p/p$ of 5×10^{-4} . To perform this measurement in the cooling section, the 180° dipole magnet is used in conjunction with the two new Hybrid monitors to measure the horizontal dispersion due to energy spread. The Hybrid monitors are equipped with a 3-position actuator such that a vertical slit can be inserted at the station upstream of the dipole (#1). There is a standard profile monitor downstream (or behind) the dipole (#2) that will image the beam through the slit with the dipole turned off, giving a measurement of initial condition. With the dipole turned on, the beam will propagate around the dipole bend radius to the downstream Hybrid monitor (#3) where its profile will be imaged by the YAG screen. The path length between monitors #'s 1 – 2 and 1 – 3 are equivalent.

The solenoid just upstream of the dipole is a high field solenoid that will be used to focus the beam to a minimum at the Hybrid monitor (#3). Simulations using Parmela, not accounting for the use of the slit, predicts an increase of the horizontal beam size from 0.71 –1.30 mm (rms). This difference of 590 μ m on the 45 mm YAG screen using a 2MP CCD camera will be resolved over 13 pixels, providing a 7.6% resolution measurement. This will require optics with better than 40 μ m resolution (limited only by pixel resolution).

BPM Calibration Procedure

Relying on mechanical survey data of fiducial points on the profile monitor, an accurate absolute position of the YAG crystal can be known. Four optical features on the YAG holder (whose positions are fixed to the survey data) can be imaged along with a beam profile, as shown in the simulated representation in Fig. 8. The center of gravity (CoG) calculation of the beam center is compared in position to the center of the reference circle drawn through the optical features. The two resulting X and Y offset values are then fed into the BPM data processing as offsets from actual center. The expected resolution of the profile monitors at this low energy is 50 – 100 μm . This should be sufficient to support the calibration of the BPM with the required accuracy of 700 μm .

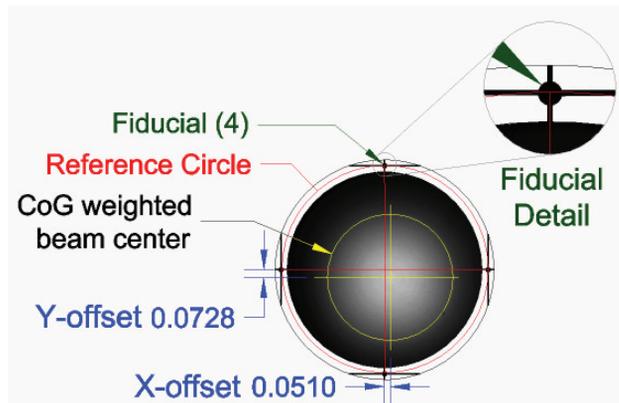


Figure 8: Hybrid BPM + Profile Monitor + Slit Mask simulated calibration procedure (4 fiducials, reference circle, example beam image with center, and X-Y offsets.)

STATUS AND CONCLUSION

The design of the Profile Monitors, Emittance Slit Scanner and Hybrid Unit were tailored to minimize the impedance of these three new instruments for LEReC in order to preserve the quality of its “soft” low energy electron beam. The large beam diameter in the cooling section has necessitated a large aperture YAG crystal and hence required large ports into the chamber, requiring damping with ferrite absorbers.

The tight requirement for absolute position measurement near the 180° dipole magnet for energy measurements has led to a novel hybrid design incorporating a combination of three typical instruments. Although the mechanical design has been relatively straight forward, the challenge to design suitable optics in order to achieve the required optical resolution is a challenge that awaits completion.

The chamber and in-vacuum elements of the profile monitors and emittance slit scanners were designed in-house and are being fabricated on site; while the actuators were outsourced with custom specifications. The design of the hybrid BPM+PM was made in-house and the in-vacuum elements will be fabricated on site; while the fabrication of the vacuum chamber and actuator will be

outsourced. The goal is to install the total of eight devices before the RHIC start-up in January 2016.

Ongoing work includes continued beam component modeling to completely account for wake field potential factors throughout the entire beam line and ensure the budget of 5.0 V/pC is not exceeded. Other work includes the design of the profile monitor optics as well as the fabrication, testing and installation of the component vacuum chambers and in-vacuum components by the end of the year.

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