6th North American Particle Accel. Conf. (NAPAC2025), Sacramento, CA, USA JACoW Publishing
ISBN: 978-3-95450-261-5 ISSN: 2673-7000 doi: 10.18429/JACoW-NAPAC2025-MOP053

INVESTIGATION OF IPM PROFILE CHANGES WITH VARIATIONS IN THE APPLIED ELECTRIC FIELD*

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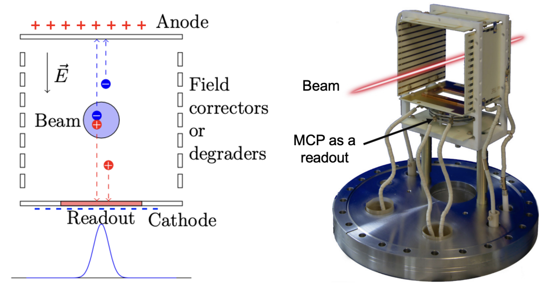
Abstract

Variations in the applied electric field in the Ionization Profile Monitor (IPM) affects the time of flight for the ionized particles (primarily electrons) which could affect the measured transverse beam profile. In addition, the applied electric field may affect the space charge of the ionized electrons inside the IPM. In this paper, we present an experimental beam study of RHIC IPM profiles, examining the effect of varying applied electric fields. Such a beam study will be helpful to enhance the design of the future IPMs for the Electron-Ion Collider. We analyzed horizontal and vertical profiles of gold and proton beams, comparing measured data with simulations along with the procedure we used for measurement. Potential causes for discrepancies between measured and simulated results are also discussed.



(a) Working principle (b) IPM internal view

Figure 1: Schematic of the IPM working principle (left) and a photograph of its internal components (right), reproduced from Ref. [1].

INTRODUCTION

The Ionization Profile Monitor (IPM) is a non-invasive diagnostic tool commonly used to measure the transverse profile of high-intensity hadron or heavy-ion beams. Unlike wire scanners, which are suitable for low-intensity beams, IPMs are essential for high-intensity operations where the destructive nature of the beam can damage invasive diagnostics. As each IPM provides profile information in a single transverse plane, two orthogonally oriented IPMs are typically employed to obtain both horizontal and vertical beam profiles.

The IPM reconstructs the transverse beam profile by detecting particles generated through beam-induced ionization of residual gas molecules in the vacuum chamber. As the beam traverses the chamber, it ionizes a small fraction of these gas molecules, producing electrons and ions. An external electric field, applied via high-voltage electrodes, extracts the ionized particles toward opposing directions due to their opposite charges. A sufficiently strong electric field is required to efficiently collect the ionized particles without significantly distorting the spatial distribution, thereby enabling accurate profile reconstruction. A schematic representation of this principle is shown in Fig. 1(a), where the electrons and ions are observed drifting toward opposite electrodes under the influence of the applied field.

The accuracy of the transverse beam profile measured by an IPM is influenced by several factors, including beam velocity (which relates to space charge), bunch intensity, and the uniformity of the applied electromagnetic fields. To preserve the spatial distribution of the extracted electrons as they drift toward the micro-channel plate (MCP) or readout plate, it is critical to maintain a highly uniform extraction electric field. This is achieved through the use of field correctors, as illustrated in Fig. 1(a), which minimize field distortions near the beam path. Furthermore, a transverse magnetic field is often superimposed to constrain the electron trajectories along the drift direction, thereby suppressing electron divergence due to beam-induced space-charge forces [2, 3].

Historically, both ion-collecting and electron-collecting IPMs have been used. However, recent studies show that ion-collecting IPMs are highly sensitive to space-charge effects from the circulating beam, causing significant variations in the measured beam profile [4]. In contrast, electron-collecting IPMs are less affected by space-charge effects and therefore provide more reliable measurements. Another investigation on the effect of space charge on IPM profiles can be found in Ref. [5].

The number of ionized particles generated by a heavy ion beam is smaller as we maintain an ultra-high vacuum inside the beam pipe. To amplify the number density of the electrons, we use a MCP. When a particle hits the MCP hole entrance, secondary electrons are emitted. Due to the potential difference, these electrons are accelerated toward the channel output, striking the hole walls and generating additional secondary electrons in a cascading effect [1].

A position-sensitive detector, typically composed of conductive strips (or a phosphor screen, which converts electrons into visible photons), is placed on the detection plane to detect the electrons flowing via each strips. The ionization current flowing through these strips is recorded to determine the spatial distribution and reconstruct the transverse beam profile. One of the pioneering papers on beam detection using residual gas ionization can be found in Ref. [6].

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 with the U.S. Department of Energy.
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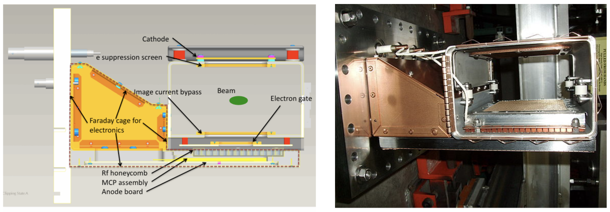

Figure 2: Simplified sketch for a RHIC IPM (left), and its real image showing the internal components (right).

RHIC IPMS

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) accelerates and collides beams of different ion species ranging from protons to uranium nuclei. To accelerate counter-rotating beams, RHIC consists of two superconducting rings which are named as 'yellow' and 'blue' rings. Each ring is equipped with two IPMs to independently measure the horizontal and vertical beam profiles [7]. A simplified sketch for the RHIC IPM, along with a photograph depicting its internal structure, is shown in Fig. 2.

In the RHIC IPM system, ionized electrons are transversely extracted toward a position-sensitive wire array (collector or detector) using an electric field of 60 kV/m (corresponding to a sweep voltage of 6 kV across a 10 cm gap). To mitigate the natural divergence of the electrons due to their initial momentum and space-charge effects, a parallel magnetic field is applied along the drift direction. Additional details regarding the RHIC IPM design and performance can be found in Refs. [7, 8].

BEAM PROFILE INVESTIGATION

We conducted a combined experimental and simulation study to investigate the dependence of RHIC IPM profiles with the applied extraction electric field. The primary objective of this work is to improve the understanding of the operational characteristics of the existing RHIC IPMs and to evaluate their feasibility for potential implementation in the Electron-Ion Collider (EIC) Hadron Storage Ring (HSR).

Simulation of Beam Profiles

We used Virtual IPM [9] code to simulate the transverse beam profiles of RHIC gold and proton beams, having the beam parameters listed in Table 1, with nominal IPM dimension and magnetic field. Simulations with the gold beam showed no variations in the transverse beam profile when reducing the guiding electric field from 60 kV/m to 30 kV/m as shown in Fig. 3.

To cross-check the simulated results, we conducted a beam study by varying the applied electric field, which we discuss in the following section.

Measurement of RHIC IPM Profiles

We conducted two beam studies during the RHIC 2023 and 2024 runs using both gold and proton beams, with the same beam parameters listed in Table 1. Our initial experiment was performed with a stored-energy gold beam in the yellow ring to record IPM profiles under nominal operating conditions to establish a baseline. Subsequently, the guiding electric field was systematically varied from 6 kV to 4 kV in 0.5 kV increments. To ensure consistency and eliminate the effect of automatic bias voltage adjustments, the bias increment was fixed at zero volts throughout the scan. We measured both horizontal and vertical IPMs profiles to capture the full transverse beam distribution.

Table 1: Updated RHIC Beam Parameters for Simulations

Parameters	Beam Species	
	Gold	Proton
Number of particles	1.09×10^9	2.23×10^{11}
Bunch charge (nC)	13.4	35.72
Beam Energy (GeV/n)	100	23.80
Number of bunches	56	56
Bunch spacing (ns)	210	210
Bunch length σ (ns)	5.0	7.0
H-beam size σ_x (mm)	1.978	2.56
V-beam size σ_y (mm)	1.868	2.25
Magnetic Field (T)	0.10	0.10

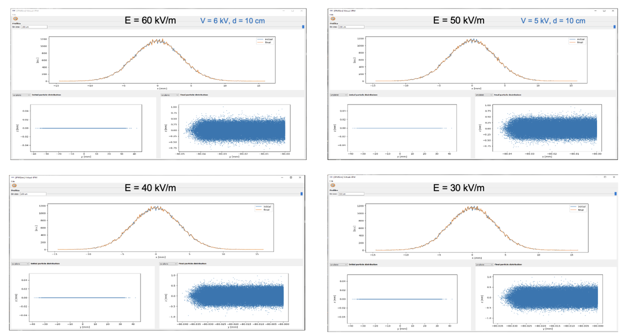

Figure 3: Simulated transverse beam profiles of the RHIC gold beam with various electric field using Virtual IPM.

Figure 4 shows the measured transverse beam profiles: horizontal (left) and vertical (right), with applied (or sweep) voltages of 6.0 kV, 5.5 kV, 5.0 kV, 4.5 kV, and 4.0 kV. The results clearly demonstrate a dependence of the measured beam profile on the applied electric field strength, in contrast to the simulation predictions.

We repeated the measurement with a different beam species and RHIC ring during the FY24 RHIC run as the measured and simulated IPM profiles exhibited differing behaviors in FY23 run. Despite changing beam species, energy, and using the blue ring instead of the yellow, we observed similar beam profile trends with applied electric field.

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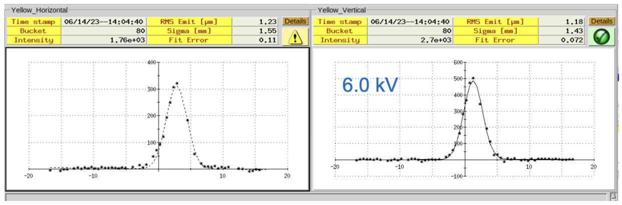
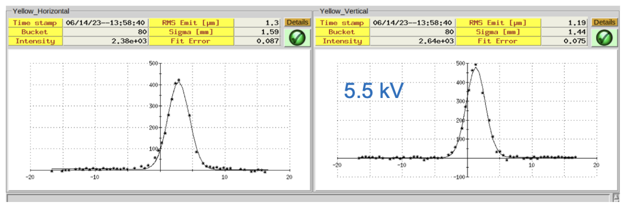
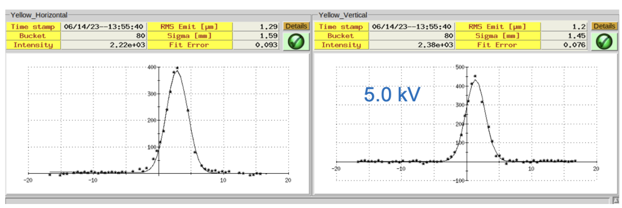


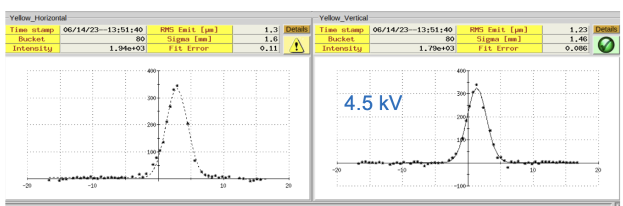
(a) 6.0 kV



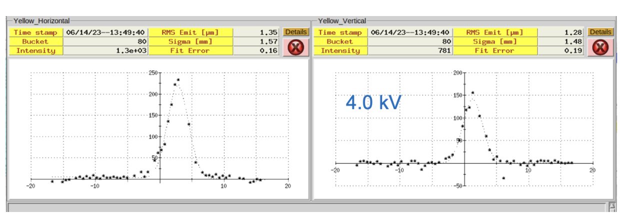
(b) 5.5 kV



(c) 5.0 kV



(d) 4.5 kV



(e) 4.0 kV

Figure 4: Yellow horizontal and vertical IPM profiles for gold beam with various sweep voltages.

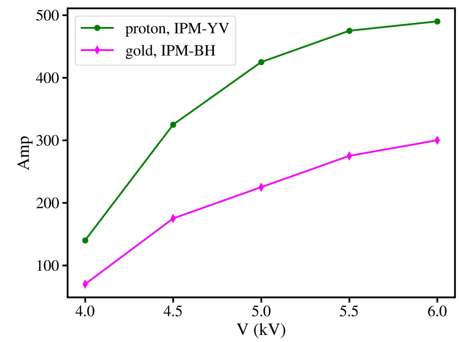


Figure 5: Amplitude of the measured IPM profile variation with sweep voltage for the proton and gold beam.

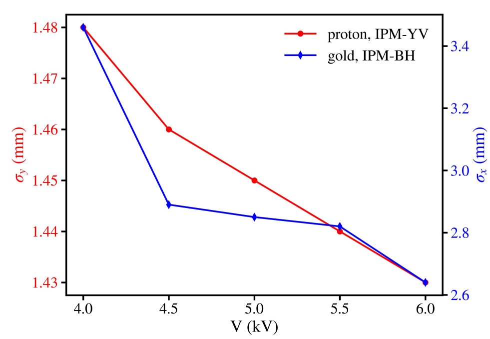


Figure 6: RMS beam size variation with sweep voltage for the proton and gold beam.

DISCREPANCY BETWEEN MEASUREMENTS AND SIMULATIONS

Several factors may contribute to the discrepancy between simulation and measurement, one of which is the gain variation across the MCP due to aging—an effect not included in the simulation. A typical IPM profile is of Gaussian type, where the MCP detector receives most ionized electrons in the central region. Over time, the MCP gain depletes more in this central region due to more exposure in comparison to outer region. Ideally, the MCP gain should remain uniform throughout the entire area. Although we attempt to compensate for this gain variation during setup, achieving perfectly uniform gain is challenging. In contrast, the simulation assumes an ideal, uniform MCP gain.

In addition, we found that the amplitude of the measured IPM profile decreases with the decrease in electric field, as shown in Fig. 5, for both proton (green curve) and gold (magenta curve) beams. The MCP gain decreases with decreasing electron beam energy, a result of the reduced applied electrical voltage. Consequently, the amplitude of the IPM profile decreases with the decreased field. This gain depletion is not accounted in the simulation.

Finally, we also observed that the rms beam size decreases with increase in sweep voltages, as shown in Fig. 6, for both beams. A possible explanation for this is related to MCP gain depletion and the lower e-beam energy.

SUMMARY

This paper presents an experimental study of RHIC IPM beam profiles under varying electric fields. Measured horizontal and vertical profiles for gold and proton beams showed clear changes with sweep voltage, unlike Virtual IPM simulations, which assumed uniform gain. The discrepancy likely stems from unmodeled gain variations in the micro-channel plate. Future work will assess RHIC IPM's suitability for the EIC Hadron Storage Ring.

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