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DEVELOPMENT OF A HIGH-GAIN RESIDUAL GAS IONIZATION PROFILE MONITOR (HGRGIPM) FOR THE SLOW EXTRACTION PROTON BEAMLINE AT THE J-PARC HADRON EXPERIMENTAL FACILITY*

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Abstract

We have developed a highly sensitive beam profile monitor, the High-Gain Residual Gas Ionization Profile Monitor (HGRGIPM). The HGRGIPM detects electrons ionized by the proton beam in residual gas, which are guided by electric fields to a phosphor screen. The fluorescence is collected by an optical system. RGIPMs have proven to be powerful diagnostic tools for high-intensity beams because they have non-destructive nature. They have been used as the main profile monitors in the primary beam line, A-line (30 GeV, 92 kW, 8.1x10^{13} protons/spill, 4.24 s cycle, vacuum ~0.3 Pa). However, the newly constructed B-line (30 GeV, 11 W, 1.0x10^{10} protons/spill, 4.24 s cycle) presents a significant challenge, as its beam intensity is four orders lower than that of the A-line. To overcome this issue, several improvements were made in the design of the HGRGIPM. These include the use of a thin phosphor screen to enhance the signal-to-noise ratio, optimizing electrode geometry for higher acceleration voltages and improved sensitivity, and incorporating a high-efficiency optical system. These innovations allow profile monitoring even in the low-intensity B line. In this paper, we report on the HGRGIPM's design and performance, beam response measurements, and future prospect.

INTRODUCTION

The A-line, the primary beam line of the J-PARC Hadron Experimental Facility, delivers a high-intensity proton beam (30 GeV, 92 kW, 8.1x10^{13} protons/spill, 4.24 s cycle) to a variety of particle and nuclear physics experiments [1, 2]. For safe and stable operation of such a high-intensity beam, continuous monitoring of the beam profile is essential. Moreover, the beam profile monitor must be non-invasive to avoid any beam loss. In this facility, the vacuum level inside the beam line is maintained at approximately 0.3 Pa, and a non-destructive beam profile monitor, the RGIPM (Residual Gas Ionization Profile Monitor) that collects electrons generated by ionization of residual gas in the beam duct was successfully developed [3] and is currently in use.

Meanwhile, a new branch beam line, the B-line, has recently been constructed off the A-line. The B-line operates at a lower beam power (30 GeV, 11 W, 1.0x10^{10} protons/spill, 4.24 s cycle) and is located in close proximity to the A-line, resulting in a high background environment and a low signal yield. To address these challenges, we have developed a high-sensitivity beam profile monitor, the HGRGIPM (High-Gain Residual-Gas Ionization Profile Monitor).

LAYOUT AND INSTALLATION

Figure 1 shows the layout of the HGRGIPM. Electrons ionized by the beam are collected upward by internal electrodes. A magnetic field (up to 400 Gauss), provided by Helmholtz coils, is applied parallel to the electric field in the measurement region. This magnetic field helps suppress the diffusion of electrons due to scattering with residual gas. Outside the internal electrodes, a thin phosphor screen (Gd_2O_2S, 20 μm thick) is installed and biased with a high voltage (up to 4 kV). By accelerating the ionized electrons with this electric field, the signal intensity is increased. The thin phosphor layer also helps reduce background light, primarily from upstream of the beam line. The scintillation light generated by the phosphor is transmitted through a fused silica optical window and detected by an optical system and a radiation-resistant CID camera (Thermo Fisher Scientific inc.) housed in a light-tight enclosure.

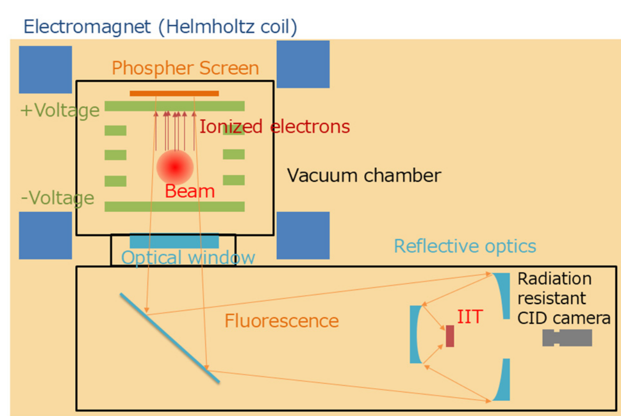

Figure 1: HGRGIPM layout.

Figure 2 shows the HGRGIPM installed in the B-line. The optical system is mounted below the beam line. The relay lens, made of BK7 glass and relatively vulnerable to radiation, is positioned approximately 1500 mm away from the beam line, reducing the frequency of replacement.

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Figure 3 shows the optical design of the HGRGIPM. The primary mirror is a 250 mm-diameter all-metal parabolic mirror, while the secondary mirror is a 130 mm-diameter spherical mirror based on Pyrex. The optical system is based on the Schwarzschild-Couder design and optimized to maximize the solid angle, focusing light onto an image intensifier tube (IIT). The light from the IIT is reflected by a diagonal mirror at 90 degrees and then focused onto a radiation-resistant CID camera using a 2x relay lens. The entire system achieves a spatial resolution of approximately 1 mm, with a magnification of about 1/5.6.

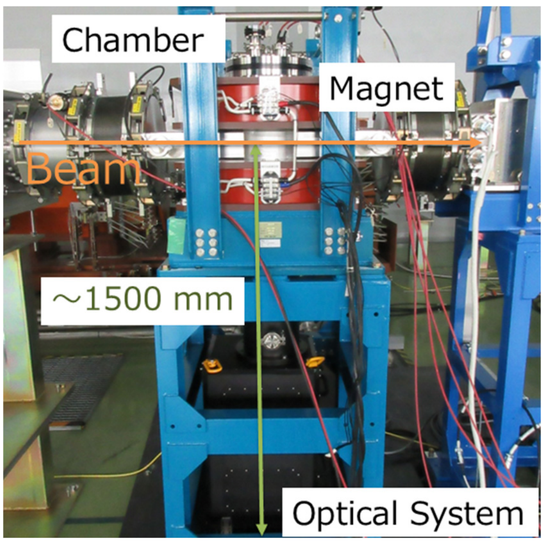

Figure 2: HGRGIPM installed in the B-line.

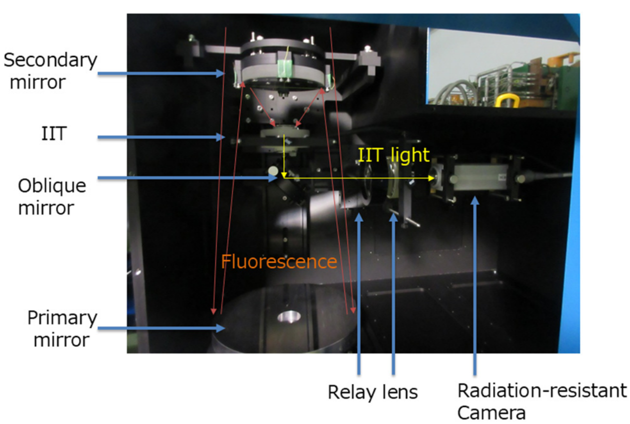

Figure 3: HGRGIPM optics.

CAPTURED IMAGES AND DATA ANALYSIS

Figure 4 shows a typical captured raw image. The beam profile can be observed during the 2 second slow extraction period. The frame rate is about 15 frames per second. The circular emission visible around the beam trace is due to background-induced scintillation across the entire phosphor screen.

Figure 5 shows a typical histogram obtained by projecting the background-subtracted and averaged image onto the X-axis. The beam profile is fitted using a Gaussian plus a first-order polynomial function to determine the width and position. The number of pixels on the horizontal axis is converted to physical length based on calibration target data.

The following data are based on the following conditions:

- Helmholtz coil current: 20 A.
- Vacuum pressure: 1 Pa.
- Acceleration voltage on the phosphor screen: 4 kV.

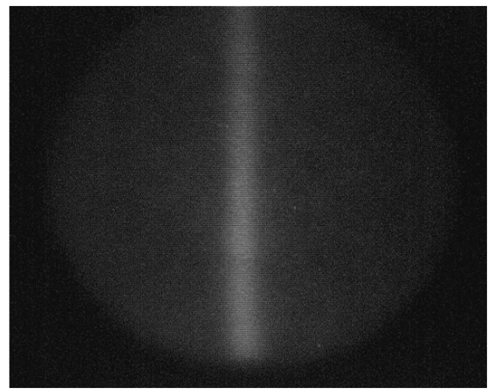

Figure 4: Typical raw data of a captured image. The horizontal axis corresponds to the transverse (X) direction, while the vertical axis represents the beam (Y) direction.

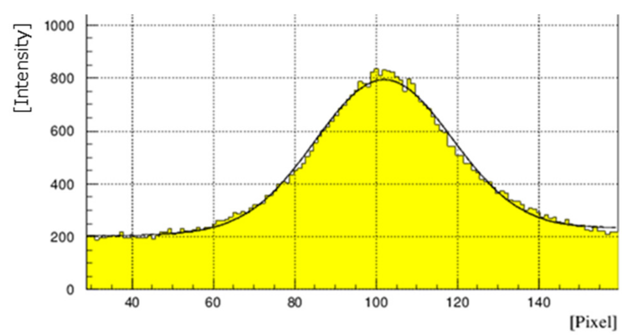

Figure 5: Typical data fitting of X projection of background-subtracted and averaged images.

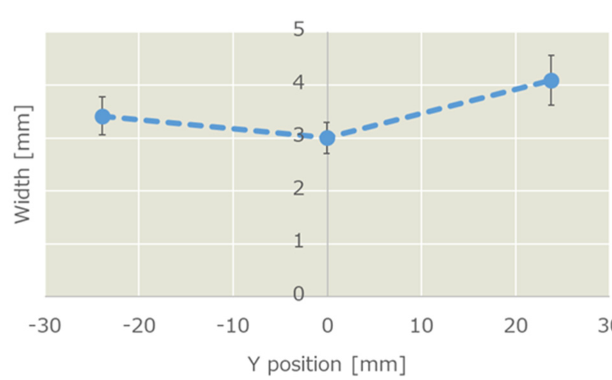

Figure 6: Y position dependence of measured beam width.

Figure 6 shows the dependence of the beam width on the Y position along the beam direction. The fact that the beam

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width remains consistent across different Y positions indicates sufficient uniformity in the electric and magnetic fields, as well as in the phosphor screen. Therefore, in the following analysis, data projected along the X-axis over the entire Y range are used.

Figure 7 presents the dependence of beam width on the magnetic field strength at different vacuum levels. At vacuum levels below 1 Pa, applying a magnet current of 10 A or more results in stable beam profile widths, indicating that the true beam width is successfully measured under these conditions.

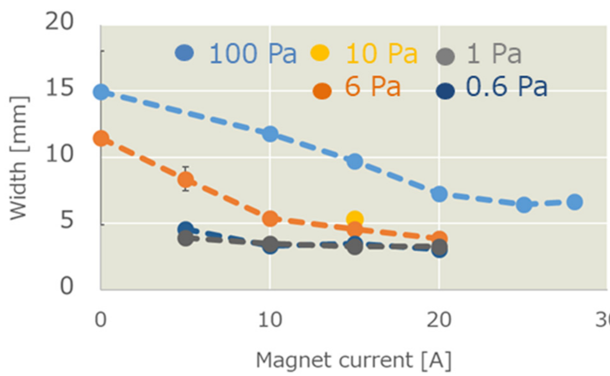

Figure 7: Magnet current dependence of measured beam width for each vacuum level.

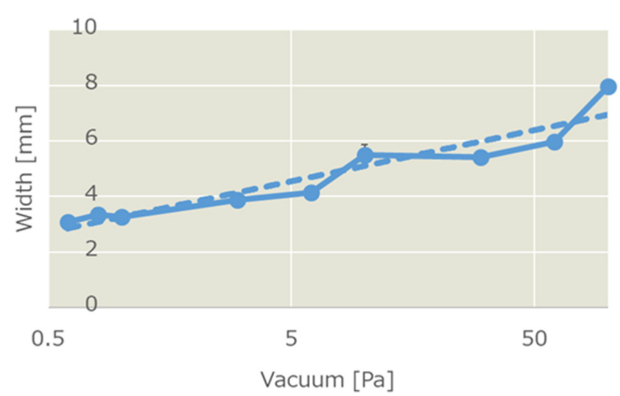

Figure 8: Vacuum level dependence of measured beam width.

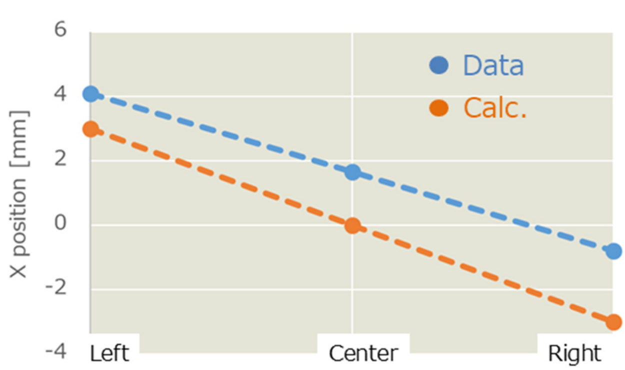

Figure 9: Measured beam position response when the beam is moved left and right.

Figure 8 shows the dependence of the beam width on vacuum pressure. The dashed line represents a fitting function proportional to the square root of the vacuum pressure, which agrees reasonably well with the measured data.

Figures 9 and 10 demonstrate the response of the HGRGIPM to changes in beam position and beam width. Although the absolute values do not match the calculated values due to calculation limitations, the trends are consistent, indicating that the monitor responds appropriately to changes in the beam.

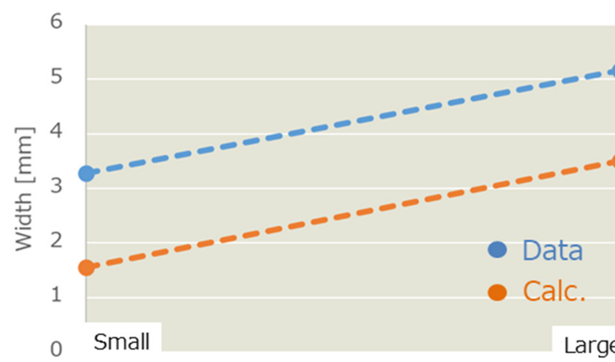

Figure 10: Measured beam width response when the beam size is changed.

CONCLUSION

In this study, we have developed a High-Gain Residual Gas Ionization Profile Monitor (HGRGIPM). It was installed in the B-line of the Hadron Experimental Facility, and various beam tests were conducted. From these results, the following conclusions were obtained:

- The detection sensitivity was confirmed to be sufficiently uniform, indicating no significant issues with the uniformity of the phosphor screen, electric/magnetic fields, and optical system.
- Under a magnetic field generated by a 20 A magnet current and vacuum pressure below 1 Pa, the true beam width can be accurately measured.
- The monitor successfully tracked changes in beam position and width.

For future work, we are investigating the potential application of this method to the upstream high-vacuum section of the A-line, where the vacuum level is below 10^{-6} Pa and the implementation of a fully non-invasive profile monitor is difficult.

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