RESIDUAL GAS IONIZATION PROFILE MONITORS IN J-PARC SLOW-EXTRACTION BEAM LINE

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Abstract

Residual gas ionization profile monitors (RGIPMs) for slowly extracted proton beams at Japan Proton Accelerator Facility Complex (J-PARC) have been developed to monitor transverse profiles of intense proton beams up to 50 GeV-15 μA. To minimize beam loss and residual dose on the beam line devices, the RGIPMs working around 1 Pa vacuum pressure have been developed. The present manuscript reports the working principles, fabrications, installations, and operations of the RGIPMs in detail.

INTRODUCTION

Hadron Experimental Facility at J-PARC is a multi-purpose facility for particle and nuclear physics, using intense secondary beams [1]. Primary proton beams accelerated up to 30 GeV in the Main Ring are continuously extracted for 2 seconds in every 6 seconds, and transported to Hadron Experimental Facility through the slow-extraction beam line. The maximum beam power is designated to be 50 GeV-15 μA (750 kW in total power). Since the beam loss on the transport beam line must be minimized to keep residual activation of beam line devices as low as possible, non-interceptive type of beam monitor is desirable.

Residual gas ionization profile monitors (RGIPMs) are widely used in many accelerator rings [2][3]. Electrons or ions produced by proton beams passing through residual gas, whose pressure is normally 10^{-6} Pa or less, are guided to a micro-channel plate (MCP) with electrostatic and /or magnetic fields applied between gap electrodes. The signals amplified in a MCP by typically a factor of 10^4 are observed as transverse profile distributions. The conventional RGIPM with MCPs is an acceptable choice, but they have some issues as follows;

1. More than ten monitors required in a transport beam line enhance purchasing cost due to MCPs.
2. MCPs do not have sufficient hardness against severe radiation around the production target.

The present RGIPMs have been developed to overcome above issues [4]. Since the vacuum pressure in the slow-extraction beam line is about 1 Pa, the signal is sufficiently large enough without MCP. The amount of charge measured by the RGIPM can be estimated as follows,

$$Q = N_p \frac{dE}{dx} \rho_{air} \frac{P_{air}}{P_{stp}} \frac{1.602\times10^{-19}}{N_I} L, \qquad (1)$$

where Q is measured charge in coulomb per unit length, dE/dx is an energy loss per unit length when 30 GeV protons are passing through air, N_p is a number of protons, ρ_{air} is density of residual gas, P_{air} is pressure of residual gas in a beam pipe, P_{stp} is a standard temperature pressure, N_I is mean energy to produce an electron-ion pair in normal air, L is length of electrode in beam direction. When N_p is 10^{13}, dE/dx is 2 MeV/(g/cm^2), ρ_{air} is 1.2×10^{-3} g/cm^3, P_{air} is 1 Pa, N_I is 38 eV/pair, and L is 8 cm, the equation (1) gives 8 nC, that is sufficient amount for charge integration circuits without amplification.

Operation of RGIPM in 1 Pa pressure arises a different issue. The mean free path of the electrons drifting in 1 Pa pressure (λ_e) is estimated to be about 30 mm, assuming that typical elastic cross section of electrons on nitrogen and oxygen molecules is 10^{-15} cm^2 [5]. Since typical gap length between electrodes in the present RGIPMs is 10 cm or more, observed profile distributions would become considerably broader than the actual size of beam when electrons are guided with a uniform electric field between the electrodes.

To reduce broadening due to diffusion, a uniform magnetic field can be applied parallel to the electric field in the present RGIPMs. Motion of the electrons drifting in a uniform magnetic field is limited in a Larmor radius (r_e). According to a standard transportation theory [6] under a magnetic field, the diffusion coefficient of drifting electrons with an electrostatic field (D) is given by,

$$D = \frac{\lambda_e^2}{2\tau}, \qquad (2)$$

where τ is mean collision time, dependent on mean velocity of electrons. When a magnetic field is applied parallel to the electric field, the diffusion coefficient of electrons across a magnetic field ($D_\perp$) is given by,

$$D_\perp = \frac{r_e^2}{2\tau}, \qquad (3)$$

When the applied magnetic field is set to be 420 gauss and the Larmor radius of electron is 0.25 mm, the diffusion coefficient given by the equation (3) is reduced by factor of $(\lambda_e/r_e)^2$= $(30/0.25)^2$=14400. A naive evaluation of broadning due to diffusion of electrons with a kinematic energy T_e is estimated as follows,

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ISBN 978-3-95450-119-9

$$\sigma_e = \sqrt{2D_\perp t},\ t = G\sqrt{\frac{m_e}{eV_g}}\ , \tag{4}$$

where σ_e denotes broadening width at the electrode, t is travelling time from the center to the electrode in the gap, G is width of the gap, m_e is electron mass, and V_g is voltage applied between the gap. When G is 10 cm and V_g is 100 V, initial kinetic energy of an electron is 10 eV, σ_e is 0.27 mm, which is sufficiently good spatial resolution for profile measurement.

FABRICATIONS AND INSTALLATION

Figure 1 and 2 are photos of the present RGIPM. The gap width of inside electrodes is 10 cm. The gap electrodes are made of ceramic or G10 boards plated with nickel-gold. The segmented pattern (typically 32 channels) is made on the surface plane, and the other area surrounding the patterned area is connected to signal ground. The signal cables are mounted on the backplane with through holes. By omitting MCP, the structure of electrodes is quite simplified and robust against radiation damage.

Two permanent magnets made from strontium-ferrite material for horizontal and vertical monitors are mounted outside the chamber. Field strength at the centre of the gap is 420 gauss in the case of 10 cm gap length. It is known that some type of permanent material, especially neodymium-iron-boron (NdFeB), shows significant demagnetization by radiation [7][8][9]. Since the present RGIPM is installed near the production target, the lifetime of monitor due to demagnetization of strontium-ferrite must be evaluated. A radiation damage test of permanent magnet materials of NdFeB, Sr-ferrite, Sm_1Co_5, and Sm_2Co_{17} was carried out up to irradiation of 10^{17} protons/cm^2 with 60 MeV proton beam at Tohoku University Radioisotope Center [10]. No demagnetization was observed in Sr-ferrite material chosen for the present RGIPM up to 110 MGy (10^{17} protons/cm^2). According to the MARS15 simulation code [11], the accumulated dose near the production target, on which beams of 30 GeV-10^{14} protons per second at maximum were irradiated for 2500 hours per year, it takes 7.4 year to reach 10^{17} hadrons/cm^2. Therefore, the present RGIPM is considered to have sufficient lifetime under severe radiation environment.

For the slow-extraction beam line at J-PARC, several types of RGIPMs with different gap width are fabricated, as shown in Table 1. In total 14 RGIPMs are installed in the beam line. Two RGIPMs installed near the beam dump, no magnetic field is applied in the monitor since the profile width near the beam dump is wide enough. Vacuum pressure in the beam duct is controlled by MKS 250E mass flow controller. Total amount of charge is adjustable in a desired dynamic range for charge integration circuit.

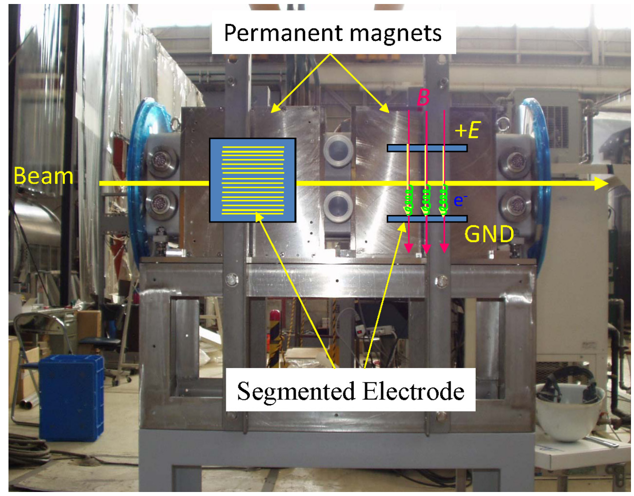

Figure 1: A side view of RGIPM.

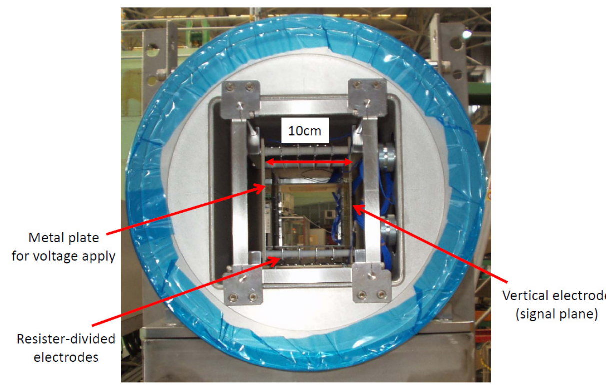

Figure 2: A front view of RGIPM.

Table 1: Specifications of RGIPMs installed in the slow-extraction beam line at J-PARC

Gap width (cm)	**Pitch** (mm)	**# of channels**	**Mag. field at center** (gauss)	Amount
10	1	64	420	1
10	2	32	420	1
10	3	32	420	6
30	6	32	220	4
40	10	32	0*	2

* Collecting positive ions

READOUT ELECTRONICS

The signals of RGIPMs are transferred to charge integration circuits outside shielding enclosure. The 32 channels of charge integration circuit with a dynamic range of 4nC/5V are fabricated on a standard VME board [12]. Output voltage signals are scanned by analog-to-digital converters with 12 bit resolution (ADVANET advme2607 [13]). Charge signals from the monitors are integrated twice in the acceleration and the extraction period. Subtracting the background distributions measured in the acceleration period (no beam in the beam line) from the distributions measured in the extraction period improves signal-to-noise ratio significantly. Gate timing for the integrators are precisely controlled via J-PARC timing distribution system [14]. Digitized data of the profile distribution of each monitor are processed by a VME on-board computer (VMIVME7807 [15]) and stored to EPICS [16] waveform records. Users can display and print out all the profile monitors with a GUI program based on WxPython [17]. When the amount of signals is increased as the beam intensity increases, a mountain plot of the profile distribution during extraction period would be possible by multiple trigger during a single extraction.

COMMISSIONING AND OPERATION

Figure 3 shows typical profile distributions measured by the present RGIPM near the production target. The horizontal and vertical widths of the profiles are 1.2 mm and 1.9 mm in RMS, which is consistent with the design values. Clear profile distributions are obtained by subtracting background profiles during beam-off period from those measured in beam-on period. Figure 4 show summed signals measured by the RGIPMs with 10 cm and 30 cm gap, changing applied voltage. Flat regions have been observed in the RGIPMs with both 10 cm and 30 cm gap. As applied voltage increases, amount of charge increases due to multiple-ionization process in residual gas. The operating voltage of the RGIPMs with the 10 cm and 30 cm gaps is set to be 100 V. The amount of charge measured with the RGIPM in the plateau region is consistent with the one evaluated by the equation (1). The main difference comes from ambiguity of measurement of vacuum pressure with Pirani gauges.

Currently, the maximum beam intensity extracted to the slow-extraction beam line is 1.7×10^{13} PPP (14 kW in power), and all the RGIPMs are working properly. No demagnetization due to radiation dose is observed.

Figure 5 shows a comparison of the vertical profile distributions measured by the RGIPM with a 10 cm gap and aluminium wire scatter installed close to the RGIPM. The aluminium wire with a 300 μm diameter was scanned in the vertical direction and the number of the scattered particles was counted by coincident signals of three photomultipliers. The observed profile distributions well agree in each other.

Figure 6 shows the measurements of the horizontal and vertical beam emittance with the parabola method. The RGIPM with a 30 cm gap was used to measure horizontal and vertical profile widths by changing the focusing power at the monitor position with a quadrupole magnet located upstream of the monitor. The measured horizontal and vertical beam emittances are 2.35 π and 5.60 π mm mrad, respectively, compared to the designed value of 4.4 π and 10.4 π mm mrad for the maximum beam intensity (30 GeV-9 μA). The difference of the measured emittances from the design values may be attributed to smallness of space-charge effect for the current beam intensity.

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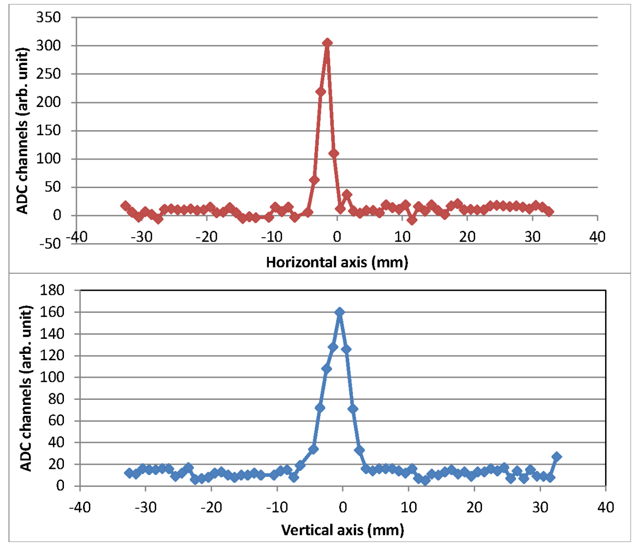

Figure 3: Typical horizontal and vertical distributions measured by the present RGIPM with 64 channel segmented electrodes of 1 mm pitch. The beam intensity is 30 GeV-7.1×10^{12} (6 kW) protons per pulse (PPP) and the vacuum pressure is 0.3 Pa.

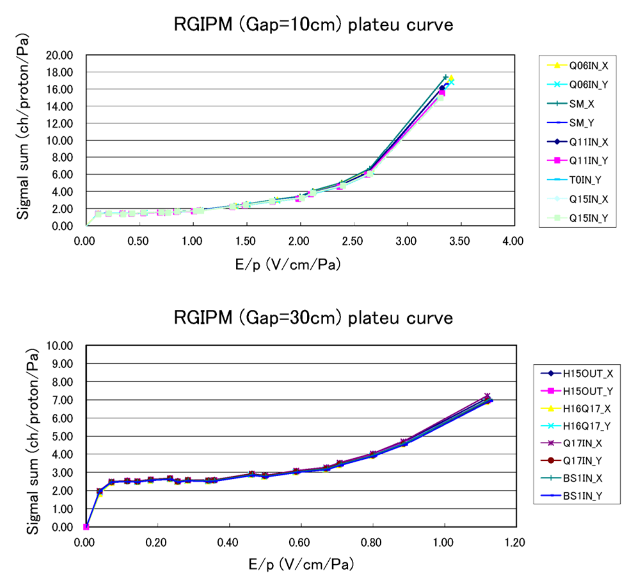

Figure 4: Plateau curve measurements with 10 cm and 30 cm gap RGIPMs.

ISBN 978-3-95450-119-9

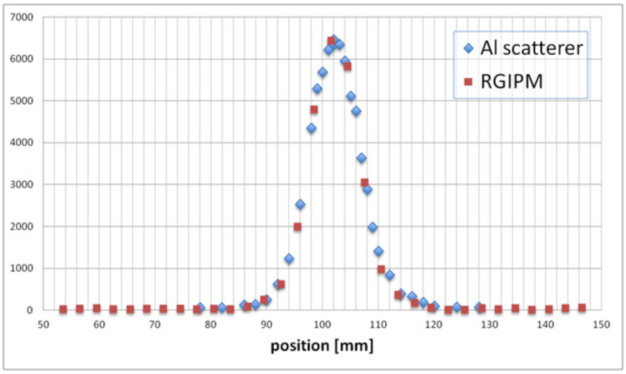

Figure 5: Comparison of vertical profile distributions measured by the RGIPM with a 10 cm gap and aluminium wire scatter. The horizontal axis is relative position of the scatter and the vertical axis is normalized counts.

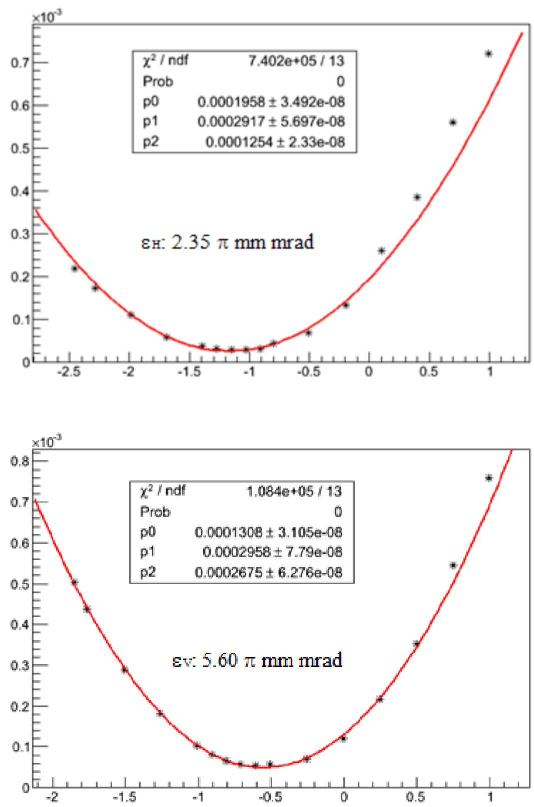

Figure 6: Horizontal and vertical emittance measurements by the parabola method. Measured horizontal and vertical emittances are 2.35 π and 5.60 π mm mrad, respectively.

SUMMARY

Residual gas ionization profile monitors working in 1 Pa pressure have been developed and installed in the slow-extraction beam line at J-PARC. Applying a magnetic field parallel to the electric field in the gap electrodes reduces diffusion of electrons, and the spatial resolution less than 1 mm is achieved. All the monitors are working properly up to 30 GeV-1.7×10^{13} proton beams. No significant demagnetization due to radiation has been observed. The present RGIPMs are indispensable devices for the beam commissioning of the slow-extraction beam line at J-PARC.

ACKNOWLEDGMENT

The present work was supported in part by Grants-in Aid for Scientific Research (A) No.17204019, (C) No.23450357, and for Encouragement of Young Scientists (B) No.17740715 of the Japan Ministry of Education, Culture, Sports, Science and Technology.

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ISBN 978-3-95450-119-9