A PROTOTYPE OF RESIDUAL GAS IONIZATION PROFILE MONITOR FOR J-PARC RCS

K. Satou*, N. Hayashi, JAEA, Tokai, Ibaraki, Japan
S. Lee, T. Toyama, KEK, Tsukuba, Ibaraki, Japan

Abstract

A prototype of residual gas ionization profile monitor (IPM) with wiggler type 3-poles magnet for J-PARC 3 GeV Rapid Cycling Synchrotron (RCS) has been developed. The monitor was installed in the main ring of the proton synchrotron at KEK. The ion collection mode and the electron collection mode of the IPM were tested for actual synchrotron beam. The dependences of observed profiles for electric and magnetic guiding fields were confirmed with Monte-Carlo simulations to estimate the required fields for the J-PARC RCS. Both experimental and calculation results suggest that the profile measurements collecting electrons with the magnetic guiding field is an effective method in the J-PARC RCS.

INTRODUCTION

The Japan Proton Accelerator Research Complex (J-PARC) [1] has been constructed as a joint project between Japan Atomic Energy Agency (JAEA) and High Energy Accelerator Research Organization (KEK). The accelerators consist of 181/400 MeV Linac, 3 GeV Rapid Cycling Synchrotron (RCS) with 25 Hz repetition, and 50 GeV Main Ring Synchrotron. The expected beam intensity is 8.3×10^{13} ppp for the RCS, corresponding to the beam power of 1 MW. The beam emittance will be 216 π mm mrad at injection. It is indispensable to develop non-destructive beam diagnostic system to avoid vital damages to the devices by the beam losses. We have been developing the residual gas ionization profile monitors (IPMs) for the J-PARC RCS [2]. The IPM is expected as a main diagnostic tool for beam tuning in the commissioning phase, and also used to measure beam halos in high intensity operations.

A prototype of the IPM has been developed to check the performances. It was installed in the main ring of the proton synchrotron at KEK (KEK-PS) and has been examined for the proton beam. In this study, feasibilities of the IPM for an intense proton beam was investigated, and operational parameters for precise profile measurement in the J-PARC RCS were estimated.

PRINCIPLE OF THE IPM

Composite of the Prototype

The proton beams passing through a vaccum chamber ionize the residual gas, and consequently electrons-ion pairs are produced. The IPM detects these charged particles not to perturb the circulating beam. It has two operation modes that is ion collection mode and electron collection mode.

Fig. 1 shows the apparatus of the prototype. It consists of electrodes producing electric field to collect the charged particles, a Micro Channel Plate detector (MCP) with 32ch multi anode strips as a signal read-out device where the effective area is 81mm×31mm and the width of the each anode strip is 2.5 mm, an electron generator (EGA [3]) to confirm the gain balance of the MCP channels, and a wiggler type 3-poles magnet producing guiding field (B_g) for collecting electrons. The magnet was designed to cancel the total BL product by itself.

The applied high voltage (HV) on the electrodes was divided equally by the 100 MΩ resisters to generate the homogeneous external field (E_{ext}). The collected particles were injected into the MCP. The each anode signal was transported by the coaxial cable of about 150 m long and directly inputted into 8 bit 100 MS/s digitizers with input impedance of 1 MΩ.

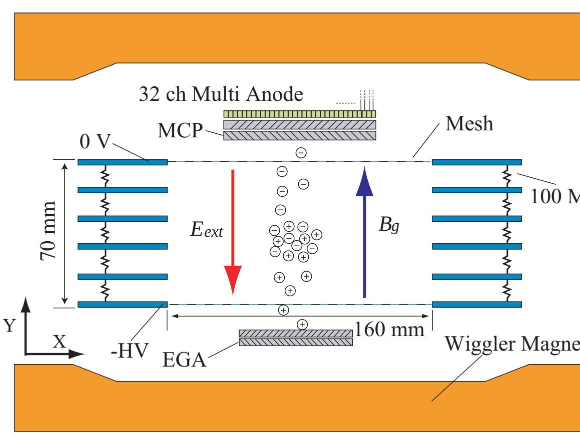

Figure 1: Cross section view of the prototype.

The Space Charge Effect

The charged particles will be kicked horizontally by the space charge electric field during the collection period from an ionization point to the MCP surface. The position shift $\triangle x$ can be expressed as,

$$v_{\perp}(t) = \sqrt{\left|\frac{2q}{m}\int_0^t \frac{\partial \phi(x,y)}{\partial x}\frac{dx(t')}{dt'}\,|_s\,dt' + v_{\perp 0}^2\right|} \quad (1)$$

* kenichirou.satou@j-parc.jp

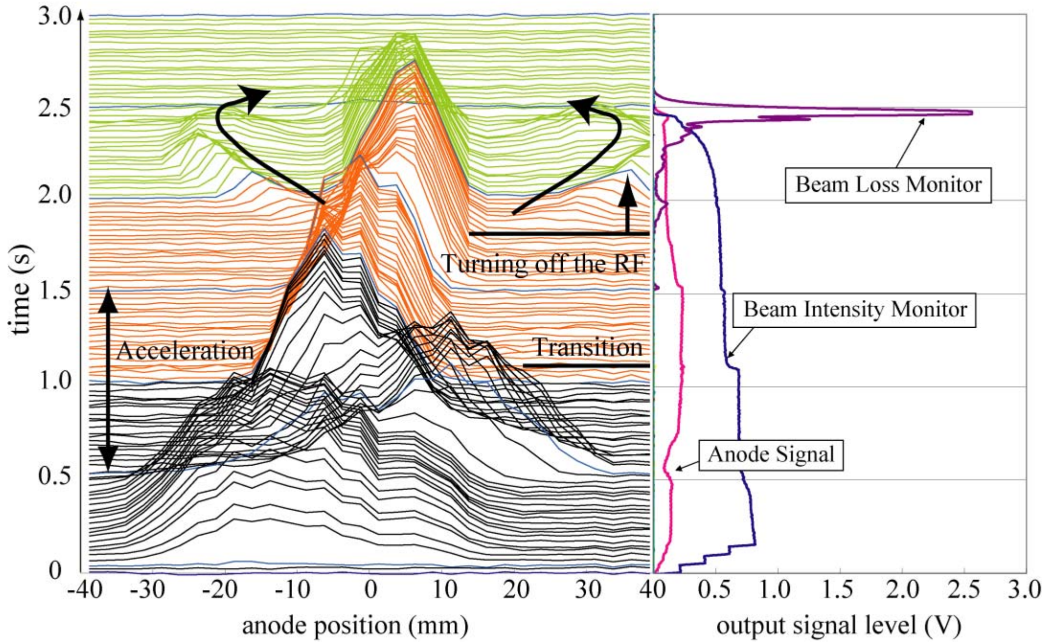

Figure 2: Mountain view of the obtained profiles for the ion collection mode (left). Raw signals from the MCP central anode (-1.25 mm from the center), a beam intensity monitor, and a beam loss monitor are also shown (right).

$$\phi(x,y) = \phi_{ext}(y) + \phi_{sc}(x,y) \quad (2)$$

$$\triangle x = x_f - x_i = \int_0^{\tau} v_{\perp}(t)dt - x_i \quad (3)$$

where $\phi(x,y)$ the potential produced by the HV ($\phi_{ext}(y)$, where $\frac{d\phi_{ext}(y)}{dy} = E_{ext}$) and space charge of the beam ($\phi_{sc}(x,y)$), m the mass of the charged particle, q the charge state, $v_{\perp 0}$ the x component of the initial velocity, x_i the ionized point, x_f the arrival position on the MCP surface, and τ the transition time to the MCP. The factor $\frac{dx(t')}{dt'} |_s$ in eq. (1) means differential coefficient along the moving pass. This space charge effect will cause a large position shift $\triangle x$ in case of high intensity beam profile measurements.

For the ion collection mode, to compensate the profile broadening due to this effect, a high external field considerably larger than the space charge electric field should be applied: the maximum space charge electric field for the KEK-PS was about 20 kV/m, while it will be 60 kV/m for the J-PARC RCS. On the other hand, for electrons, this effect becomes more serious for its small rest mass. The method using the guiding field has been established and adopted at various accelerators [4].

Guiding Filed for Electron Collection

The guiding field is applied parallel to the external field. The equations of motion of an electron in the external and the guiding field are written as follows,

$$m\ddot{y} = -e(E_{ext} + \frac{\partial \phi_{sc}(x,y)}{\partial y}) \quad (4)$$

$$\dot{s} = \frac{\partial \phi_{sc}(x,y)}{\partial x} \times B_g / B_g^2 \quad (5)$$

$$m\dot{v}_{\perp} = -ev_{\perp}B_g \quad (6)$$

where first equation represents the vertical motion with the external and the space charge electric field, second one the so called $\vec{E} \times \vec{B}$ drift along the beam axis, and the last one the Larmor rotation along B_g where $v_{\perp}$ is an electron velocity perpendicular to B_g. The external field should exceed the space charge electric field, that is $| E_{ext} | \geq | \frac{\partial \phi_{sc}(x,y)}{\partial y} |$. These equations suggest that the Larmor rotation with the radius of $r_L = mv_0/eB_g$ provides the horizontal position shift, where v_0 the initial electron velocity perpendicular to B_g. Therefore the position resolution is no longer affected by the space charge effect. The initial velocities of dissociated electrons and the intensity of the guiding field are the essential parameters to evaluate the operational ability of the IPM.

EXPERIMENTAL RESULTS AND DISCUSSIONS

The beam test was performed on 4 bunched beams of 7.5×10^{11} ppb. The measured profiles for the ion collection mode are shown in Fig. 2 with raw signals from the MCP channel positioned at central, a beam intensity monitor, and a loss monitor. The obtained results show the position shift during acceleration, and also show the beam blow up and large beam loss after the turning off the RF.

Typical profiles measured for the two operation modes are shown in Fig. 3. In this case, the profile measurement for the electron collection mode was performed on the guiding field of 460 Gauss and the HV of 6 kV corresponding to the external field of 86 kV/m. While for the ion collection mode, the measurement was performed on the maximum HV of 10 kV. As shown in the Fig. 3-(a), the background component due to the beam induced secondary electrons was probably superimposed on the actual beam profile. The obtained profiles were assumed as a Gaussian shape beam profile including a flat noise level. The full width of half maximum value (σ_{FWHM}) was extracted.

The Fig. 4 shows the dependences of measured beam sizes collecting electrons on the intensity of the guiding field (a) and that collecting ions on the applied HV (b). The obtained tendencies were confirmed with Monte-Carlo simulations.

For the electron collection mode, we performed the calculations taking into account the position shift due to the Larmor rotation. Initial velocities of dissociated electrons were calculated using the equations of ref. [5], here the gas components in the air were assumed. Note that the velocities strongly depend on ionization energies of residual gas components. Unfortunately, the real beam size required for this estimate was unknown, it was assumed so that the calculations agree with the data around 460 Gauss.

The calculated results are well agreed with the data above 150 Gauss. The calculations suggest that the measured beam size at 460 Gauss is about 1 percent larger than the expected beam size. These results suggest that the guiding field stronger than 500 Gauss should be prepared for precise measurement in the J-PARC RCS.

To estimate the space charge effect for the ion collection mode, two dimensional calculations for the x and y coordinates were performed. The space charge electric field of the bunched beam with the Gaussian shape profile was taking into account. The beam size was assumed so that the calculations reproduce the data at HV = 10 kV.

The calculated result well agree with the data, and indicates that the obtained beam size at HV = 10 kV is about 8 % larger than the expected beam size. This survey possibly explains the broadening of a measured profile. The maximum external field of the IPM designed for the J-PARC/RCS is 150 kV/m (45 kV/300 mm). The profile broadening can be estimated to be 50 % for the J-PARC RCS beam conditions, σ_{FWHM} = 30mm and bunch length of 250 ns.

The present experimental and calculation results show an advantage of the electron collection mode method for a precise profile measurement in a high intensity proton machine, and also suggest the requirement of secondary electron suppression in future investigations.

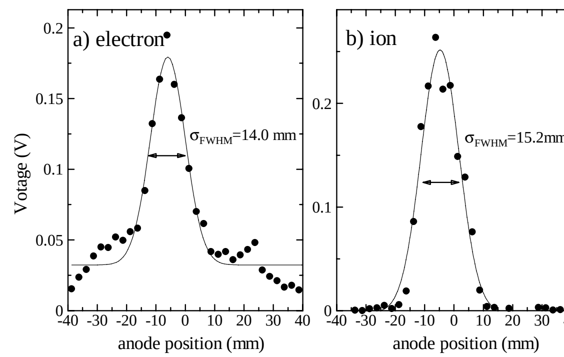

Figure 3: Typical beam profiles obtained at just before the transition energy, 1 s after the injection, for electron collection mode a) and for ion collection mode b). The solid lines are the fitted results.

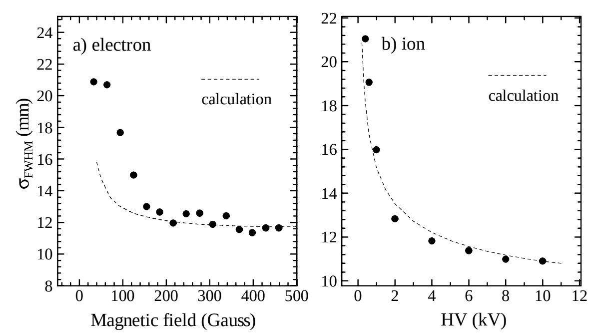

Figure 4: The dependences of measured beam sizes on the guiding field for the electron collection mode a) and on the applied HV for the ion collection mode b). The dashed lines are the calculated results.

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