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A Residual Gas Ionization Profile Monitor Developed for HIRFL-CSR

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Abstract: A new non-intercepting beam profile monitor, residual gas Ionization Profile Monitor (IPM), has been developed and tested at the main Cooling Storage Ring of Heavy Ion Research Facility in Lanzhou (HIRFL-CSRm). It has been successfully used for studies of electron cooling mechanisms, as well as profile monitoring under normal-mode operation in HIRFL-CSRm. The IPM measures the distribution of ions resulting from the residual gas ionization during the beam passage. The gas ions are collected and multiplied by tandem-type MCPs and a phosphor screen, and eventually captured by a commercial CCD camera outside the vacuum chamber. Before formally applied in HIRFL-CSRm, the IPM was tested and compared with a conventional wire scanner profile monitor at Sector Separated Cyclotron Linac (SSC Linac). Both results show good agreement. Besides, the IPM has higher signal to noise ratio than the wire scanner. It also has a very high spatial resolution of around 60 μm. This monitor can be used for low vacuum like Linac with resistance for bias voltage, or for ultra-high vacuum with discrete electrodes for bias voltage where the bake-out process is essential. Furthermore, a novel and compact design of one IPM with capability of detecting both horizontal and vertical profile is proposed. This compact IPM is quite suitable for non-invasive profile diagnostics at space shortage and high-current Linac.

Key words: SSC Linac; IPM; RGM; HIRFL-CSRm; profile monitor

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1 Introduction

The Cooling Storage Ring of Heavy Ion Research Facility in Lanzhou (HIRFL-CSR)[1] is a multi-functional cooling storage ring system which consists of a main ring (CSRm), an experimental ring (CSRe), and a radioactive beam line (RIBLL2) to connect the two rings. On each ring, an electron cooler is installed to provide high-quality beams for all sorts of experimental applications. The layout of the whole facility is shown in Fig. 1 and the Ionization Profile Monitor (IPM) is marked with a red circle.

Presently most of IPMs in the world[2–7] are using the electron collecting mode with anode-electronics acquiring system by the advantage of fast time response, while these IPMs usually have a relatively poor spatial resolution of larger than 1 mm due to the anode size limitation. Considering the electron-cooled beams in CSRm with small emittance, an IPM with the ion collecting mode and optics acquiring system is developed.

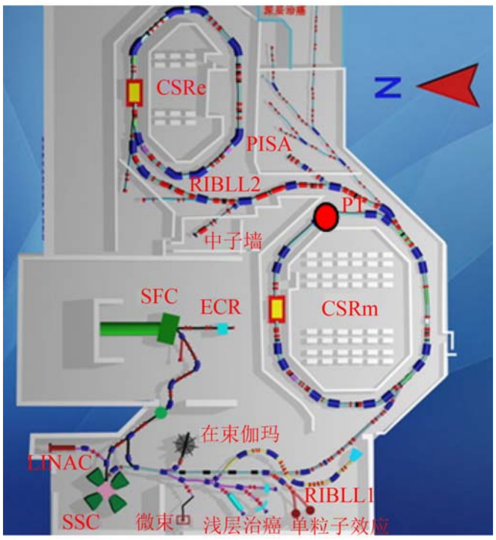

Fig. 1 (color online) The Layout of HIRFL, the red circle and yellow rectangle representing IPM and electron cooling respectively.

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Although IPM has been studied and used at foreign laboratories with the advantage of non-destructive device, it is still not utilized as a regular profile detector in domestic accelerator facilities. Therefore, the development of an IPM with the high spatial resolution for HIRFL-CSRm becomes necessary and urgent. It can help to study the cooling mechanisms during the cooling process, and beam dynamics under routine operation as well.

2 Beam experiments of IPM at SSC Linac

2.1 The wire scanner measurement result in SSC Linac

As shown in Fig. 1, the Sector Separated Cyclotron Linac (SSC Linac)[8] is a new alternative linac injector for SSC, aiming to improve the injection efficiency of HIRFL. The IPM was first installed and tested on the beam diagnostics platform of SSC Linac, which is shown in Fig. 2. After a 2.5 m long drift without any focusing units, the beam size is large. Therefore an upstream slit was used to make the beam arrive at IPM with an acceptable size. A wire scanner in front of IPM was also applied to cross check the measured profile results.

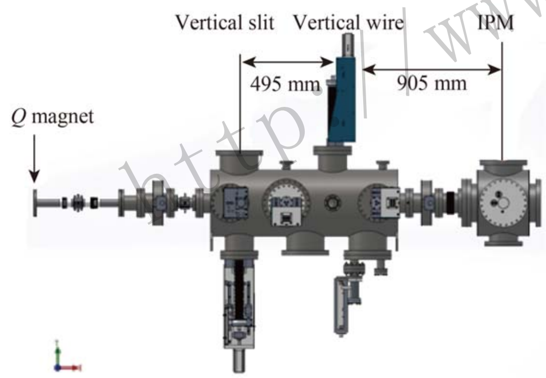

Fig. 2 (color online) The sketch of beam diagnostics platform.

Theoretically, the beam size at IPM site can be deduced by linear extrapolation due to lack of quadrupole magnet. As for beam energy of 293 keV/u and low current about 1 μA, the space charge effect can be neglected. Therefore, after the slit the particles almost travel linearly with intrinsic transverse emittance. The approximation of space charge field for a nonuniform distribution beam is presented in Eq. (1)[9]:

$$E_r = \frac{I}{2\pi\varepsilon_0\beta c}\cdot\frac{1}{r}\left(1-\mathrm{e}^{-r^2/2\sigma^2}\right), \qquad (1)$$

where I is the beam current, ε_0 is the vacuum permittivity, βc is the beam velocity, r represents the distance from beam centre.

The slit width is 0.2 mm, which can be regarded as a single point when comparing the 1.4 m drift from slit to IPM. Fig. 3 is the measured result with the wire scanner where the rms value is calculated to be 0.68 mm. By linear extrapolation, the theoretical profile rms value at the IPM should be

$$\sigma_{\text{theory}} = 0.68\times\frac{(905+495)}{495} = 1.92\ (\text{mm}). \qquad (2)$$

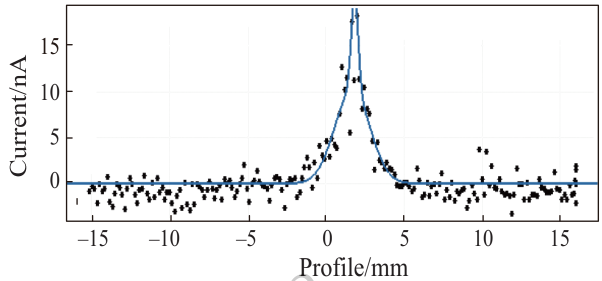

Fig. 3 (color online) The wire scanner data in SSC Linac with its double Gaussian fitting result of σ_{wire}=0.68 mm.

As presented in Fig. 3, the profile data have a small slope at the rising edge, which is caused by the particles with different energy. Because the buncher was not installed between Drift Tube Linac (DTL) and Radio Frequency Quadrupole (RFQ). Inside DTL the beam spread was too large and some particles out of the accelerating acceptance was decelerated instead. This was also confirmed by the energy dispersion measurement.

2.2 The IPM measurement result in SSC Linac

The experiment setup on SSC Linac is shown in Fig. 4. Inside the vacuum a set of biased electrodes with plastic resistances produces an electric field to accelerate the gas ions to MCP assembly. One of the profile measurement results by IPM is shown in Fig. 5.

In order to perform a spatial calibration, two tungsten wires with a spacing of 17 mm are mounted in parallel just behind the P46 screen, which can be clearly observed as two vertical black lines in Fig. 5. The pixel difference is measured to be 283 between two wires in the image. Then the spatial resolution of whole IPM optics system turns out to be 60.07 μm per pixel.

From the raw data of the profile distribution in Fig. 5, there is an apparent slope in its rising edge. It shows the same result as the wire scanner in Fig. 3. By double Gaussian fitting, the rms value of IPM measurement is 1.75 mm, which has a good agreement with the derived theoretical value of 1.92 mm by the wire scanner.

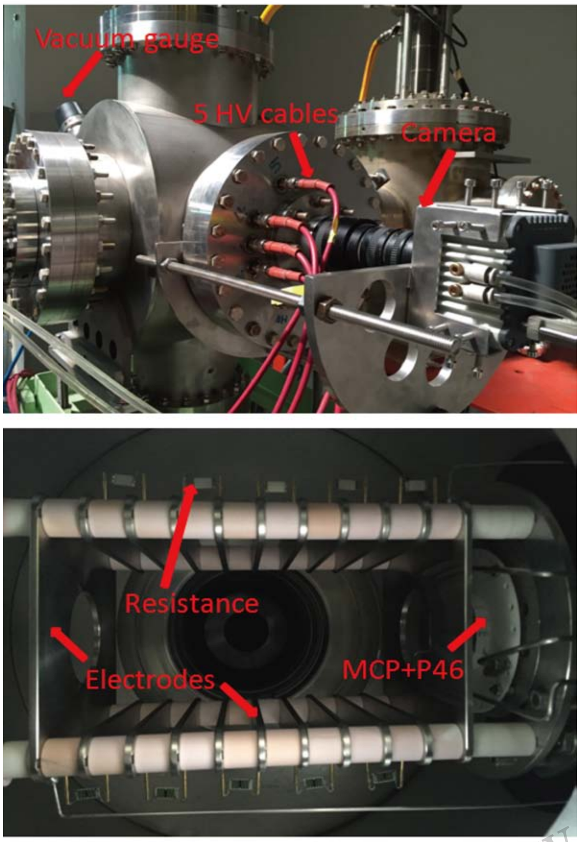

Fig. 4 (color online) IPM components in SSC Linac (upper) and electrostatic framework inside target chamber (lower).

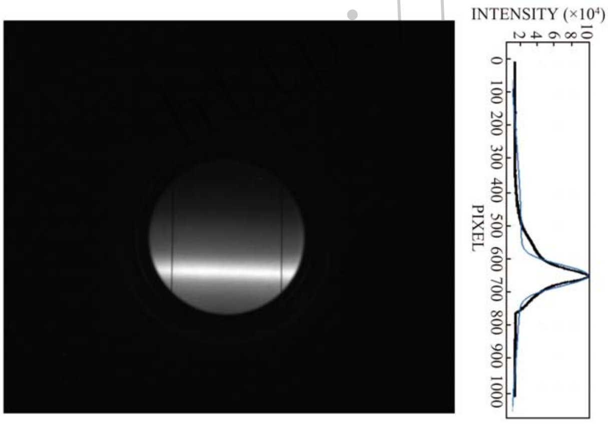

Fig. 5 (color online) The original image acquired by IPM, with a CW beam of O^{5+} ion at kinetic energy of 293 keV/u and beam current of 1 μ*A*. Right side are the raw data (black) and single Gaussian fit (blue).

3 Beam experiments of IPM on HIRFL-CSRm

After the successful beam tests in SSC Linac, we decided to move this IPM to HIRFL-CSRm. However, HIRFL-CSRm runs under ultra-high vacuum condition of 1×10^{-9} Pa, which requires bake-out process along all beam pipes with a temperature up to 300 ℃. The soldered resistors for bias voltage in SSC Linac setup, which is commonly used in J-Parc, DESY[10, 11] and so on, can not work out anymore. Therefore, as shown in Fig. 6, the IPM was modified with separate enameled wires for the voltage supply of bias electrodes.

Fig. 6 (color online) Enameled wires for each bias electrode (left) and 18 bias electrodes connected to 9 feedthroughs (right).

The IPM measurement results in CSRm during electron cooling are shown in Fig. 7. Without electron cooling, parts of beam are out of MCP range and the background noises play an important role, while after electron cooling the vertical profile projection can be observed clearly by IPM.

By double Gaussian fit with MATLAB code, the profile rms value of IPM is 0.96 mm. The theoretical vertical profile size can be deduced to be 0.93 mm by Eq. (3), since the beam transverse size is determined by tune shift during electron cooling procedure[12]. Two profile results show a nice agreement. Furthermore, the improvement with discrete electrodes for bias voltage turns out to be practical and successful.

$$\varepsilon=\frac{\sigma_{\perp}^{2}}{\beta_{\perp}}=\frac{NRr_{\mathrm{i}}}{\pi l_{\mathrm{b}}\beta^{2}\gamma^{3}dv},\qquad(3)$$

where $\gamma=1+(E/938)$ and $\beta=\sqrt{1-(1/\gamma^{2})}$, $N=5.57\times10^{7}$, $l_{\mathrm{b}}=161/(2\sqrt{\pi})$, $r_{\mathrm{i}}=(Ze)^{2}/AM$ is the classical ion radius of Ar^{15+} , $\beta_{\perp}$ is the beta function of IPM site, $R=164/(2\pi)$ is the radius of the storage ring, with $dv=0.1$ and $\beta_{\perp}=15$ mm in the case, which eventually gives a theoretical $\sigma_{\perp}$ of 0.93 mm.

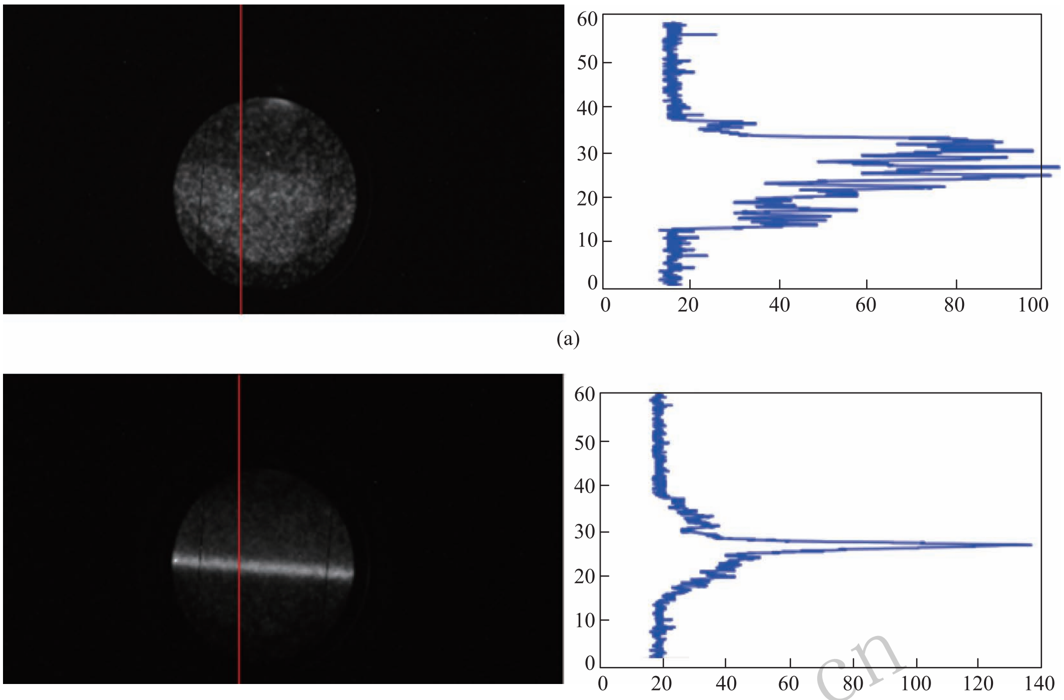

Fig. 7 IPM signals at HIRFL-CSRm with an Ar^{15+} beam of 6.89 MeV/u and 30 μA. (a) is the acquired image before electron cooling with bad SNR. (b) is an image with clear profile projection after electron cooling.

4 Novel design with one IPM measuring both transverse profiles

Saving space is always a critical issue for beam diagnostics in accelerator, especially for Linac. A new compact design with one IPM detecting both horizontal and vertical profiles is under design. The key component of this compact IPM is shown in Fig. 8. The E-field structure consists of four 180 mm×180 mm plane plates, two sets of MCP and phosphor screen with a size of 20 mm×55 mm, and 16 bias electrodes set to be 25 mm×180 mm.

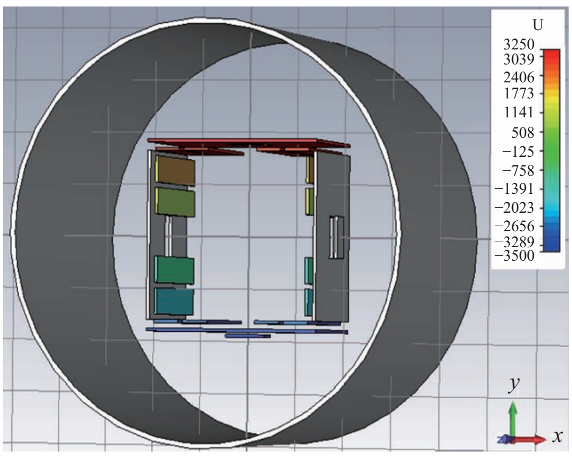

Fig. 8 (color online) The electrostatic field structure design.

4.1 Analysis of horizontal profile measurement

Assuming a vertical profile size of 5 mm, then the initial position of signal ion can be set at (x, y, z)=(2.5, 0, 0). In addition, the gap between the lower plane plate and MCP is set to be 2 mm. As shown in Fig. 9, the electrostatic field distribution shows a pretty flat equipotential line. Fig. 10 shows the trajectory simulation result with a deviation of about 0.03 mm in the horizontal direction, which represents only a small field nonuniformity ratio of $E_x/E_y = 0.03\%$. The simulation results prove a high accuracy in horizontal profile measurement.

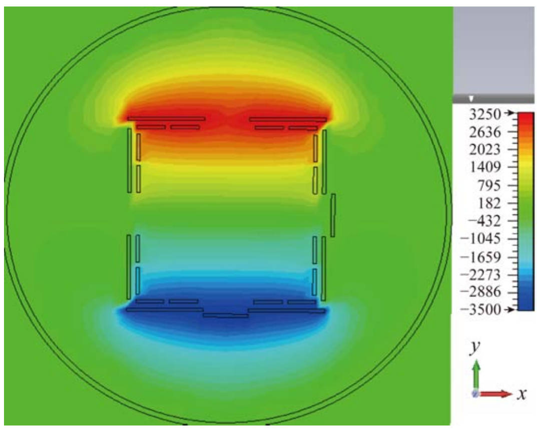

Fig. 9 (color online) The electrostatic field distribution for horizontal profile measurement.

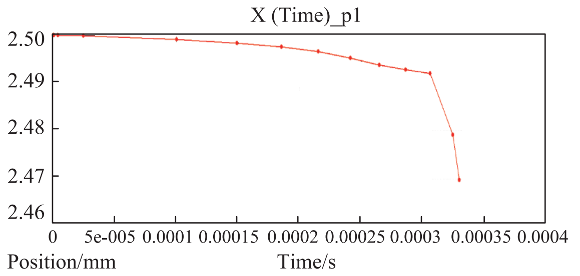

Fig. 10 (color online) The trajectory simulation result for horizontal profile measurement.

4.2 Analysis of vertical profile measurement

The initial coordinate of ion is set to be (x, y, z)=(0, 2.5, 0), while the distance between the right plane plate and MCP is now 5 mm. As shown in Fig. 11, the electrostatic field also shows a homogeneous distribution. The E_y/E_x can be calculated to be about 0.11% from Fig. 12, which is a little worse than horizontal profile simulation due to a larger distance between plane plate and MCP. Generally, the simulation results are also good enough to measure the vertical profile precisely.

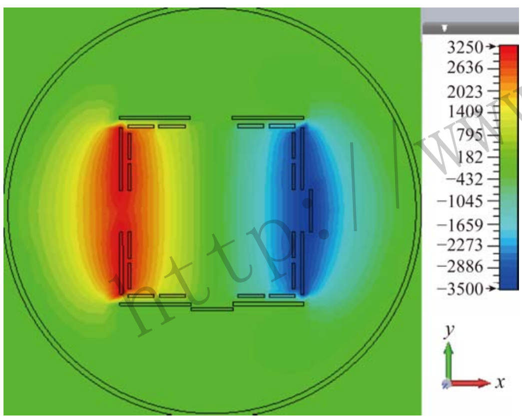

Fig. 11 (color online) The electrostatic field distribution for vertical profile measurement.

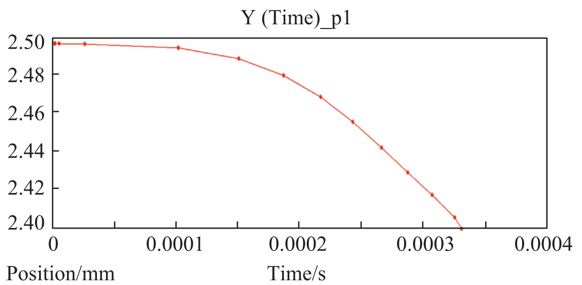

Fig. 12 (color online) The trajectory simulation result for vertical profile measurement.

Having the advantage of space saving and high spatial resolution, this compact IPM surely will be of great value for profile diagnostics in space shortage and high intensity Linac[?]. Recently, the purchased MCPs have already arrived and the electrodes are under manufacture. The accomplishment and performance of this compact IPM are highly expected in future beam tests.

5 Conclusions

By two beam experiments, the IPM shows pretty good sensitivity, accuracy and reliability. The upgrade with discrete electrodes for bias voltage in CSRm also turns out to be a successful creativity. Besides the advantages of high sensitivity under the ultra-high vacuum of 1×10^{-9} Pa and high spatial resolution of 60 μm for small beam size in CSRm, this monitor is also very suitable for the high-current Linac without the risk of material melting by the large beam power deposition.

In general, IPM is a practical and reliable instrument for transverse profile measurement. We plan to install further three sets of IPM on HIRFL-CSR, one for horizontal profile measurement on CSRm, and two for horizontal and vertical profile measurement on CSRe respectively. Additionally, a compact design of one IPM measuring two transverse beam profiles is also ongoing, of which the performance is highly expected in future beam experiments.

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一种应用于 HIRFL-CSR 上的非拦截式剩余气体电离束流剖面探测器

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摘要： 兰州重离子加速器冷却储存环主环 (CSRm) 上成功应用了一种剩余气体电离剖面探测器 (IPM)，这种新型非拦截式剖面探测器的应用服役对 CSRm 的束流冷却研究及常规调束的实时剖面监测具有重要意义。IPM 探测器通过收集束流与剩余气体之间的电离产物 (气体离子或电子)，利用偏转静电场将电离产物加速至多重微通道板 (MCP)，并在其上进行电子放大，放大的信号电子随后在荧光屏 (P46 等) 上进行电子-光子转换，最终含有束流剖面信息的投影光子被真空靶室外的 CCD 相机获取。在正式应用于 CSRm 之前，IPM 探测器还在分离扇回旋加速器直线 (SSC Linac) 上进行了束流实验，并与传统单丝扫描剖面探测器进行了对比。IPM 探测器与单丝刮束器的剖面测量结果相近，并且具有较好的信噪比和约 60 μm 的较高空间分辨率。这种 IPM 探测器可以利用电阻串联进行均匀分压，较便捷地应用于真空度较低的直线加速器，还可以改造为分离电极单独供压的结构，应用在超高真空需要烘烤的环形加速器。最后还介绍了一种全新紧凑型结构的 IPM 探测器设计，该设计利用一套 IPM 探测器实现束流横向水平与垂直两个方向的剖面测量功能，这种紧凑型 IPM 结构尤其在空间紧缺型的强流直线加速器上具有重大的应用价值。

关键词： 分离扇回旋加速器直线；电离型剖面探测器；剩余气体电离；兰州重离子加速器冷却储存环；剖面探测器

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