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IONIZATION PROFILE MONITOR DESIGN AND EXPERIMENTS IN HIRFL-CSR*

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Abstract

To meet the needs of real-time profile monitoring, injection match optimization, transverse cooling mechanism research in Cooling Storage Ring of Heavy Ion Research Facility of Lanzhou (HIRFL-CSR), and the profile measurement of future intense facilities like High Intensity Heavy-ion Accelerator Facility (HIAF) and China Initiative Accelerator Driven System (CiADS) in Huizhou China, some IPM research and experiments has been proceed since 2013. In 2016, the first IPM was developed with MCPs, phosphor screen and camera acquisition system for vertical profile diagnostics in HIRFL-CSRm. Then another horizontal IPM with new framework and less field distortion was also deployed in CSRm at 2018 summer. Besides, two more IPMs will be installed in HIRFL-CSRe during next summer maintenance. This paper mainly presents the horizontal IPM design concerns, HV settings influence, some experiment anomalies, as well as experiments for transverse electron cooling at HIRFL-CSR in December 2018.

INTRODUCTION

Heavy Ion Research Facility in Lanzhou (HIRFL) [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. The layout of this accelerator complex is shown in Fig. 1, where two Ionization Profile Monitors (IPMs) and electron cooler are displayed with coloured marks.

As one of the most valuable non-invasive profile instruments in proton and heavy ion accelerator [2–4], IPM measures the distribution of ions or electrons originating from the residual gas ionization during beam passage. Presently many IPMs [5, 6] in the world are designed by electron collecting mode, tandem resistors for bias voltage and anode-electronics acquisition system for the advantage of fast time response, while major drawback is the relative poor spatial resolution due to anode size limitation. Considering the small beam size in HIRFL-CSRm with electron cooling on, the IPM with ion collection mode and optics acquiring system turns out to be our practical choice.

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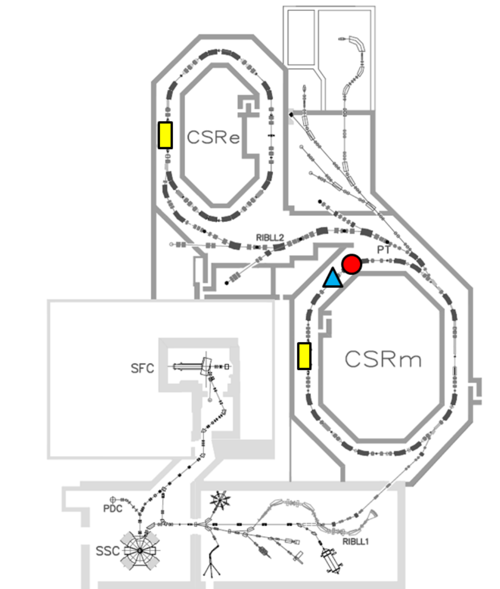

Figure 1: The Layout of HIRFL, the red circle, blue triangle and yellow rectangles representing vertical IPM, new horizontal IPM and electron coolers respectively.

NEW IPM FEATURE AND UPGRADE

Mechanism Design and Data Process

IPM mainly collects ions or electrons resulting from the residual gas ionization during the beam passage. Fig. 2 left is the vertical IPM tested in SSC Linac, which utilizing tandem resistors for bias voltage like most IPMs now. Right is the horizontal IPM with new compact framework design and less electrostatic field distortion. In case of the units degradation under harsh thermal baking and beam loss irradiation, new IPM is determined to use separate electrodes for HV supply instead of tandem resistors. This surely causes voltage supply expenses, while it allows to supply HV on each electrode precisely and controllably for operation or experiments.

Due to small transverse emittance, new IPM is constructed as ion collection mode with dual MCPs, P46 and optics acquisition. The spatial uncertainty from dual MCPs is generally considered to be 2.5–3 times the core diameter of 12 µm, thus the optics system spatial resolution calibrated about 63 µm seems convincing. The 4.2 Megapixels SCMOS chip using double Camera Link for data transmission achieves 100 fps. Data processing was upgraded by EPICS ioc to realize multiple functions such as ROI selection, data fitting and historical profile display. It also can exploit the

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DCCT value as trigger for simultaneously data storing. The whole system reaches about 300 ms with full pixel resolution, which is much less than the camera response of 10 ms. This mainly results from massive data processing via upper level EPICS PVs rather than by FPGA.

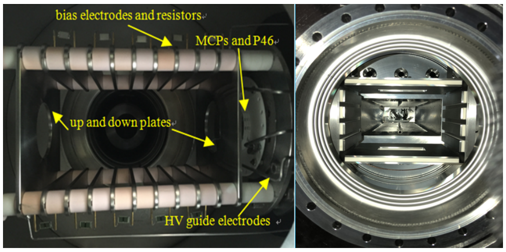

Figure 2: Left picture is the vertical IPM with 170 mm clearance and resistors for field shaping, the right new IPM has 120 mm clearance, 9 HV supplies and less field distortion.

Space Charge Effect Analysis

Theoretically three factors can badly influence the IPM measurement accuracy, namely the initial velocity of signal particles, the space charge field and the electrostatic field non-uniformity. Usually the initial velocity is negligible when IPM works with ion collecting mode. For a realistic beam with non-uniform distribution, the electromagnetic force of beam particles can be approximatively calculated with Eq. (1) [7]:

$$|F_{\text{em}}| = e(|\overrightarrow{E_r}| + |\overrightarrow{v} \times \overrightarrow{B}|) = \frac{I}{2\pi\varepsilon_0\beta c\gamma^2} \cdot \frac{1}{r}\left(1 - e^{-r^2/2\sigma^2}\right), \qquad (1)$$

where I is the beam current, ε_0 is the vacuum permittivity, βc is the beam velocity, γ equals $1/\sqrt{1-\beta^2}$, v is the charge velocity, B is the magnetic field of beam particles, σ is the standard deviation of a gaussian distribution beam, and r represents the distance from beam centre.

Considering a cooled beam with $\sigma = 1$ mm, and substituting the beam parameters of Kr^{30+} with 422 MeV/u energy, 1.4 mA current and $r = 2\sigma$, F_{em} is calculated about 3.8×10^{-18} N. The guide electrostatic force of 6 kV voltage between 120 mm clearance turns out to be about 8×10^{-15} N, roughly two thousand times of F_{em}. Therefor, the space charge effect is also negligible and the guide field non-uniformity becomes the major concern in HIRFL-CSRm.

SIMULATIONS AND BEAM EXPERIMENTS

HV Settings VS Field Distribution

Due to the existence of gaps and holes in the IPM framework, the real field distribution may varies with different HV settings. IPM mainly works with two kinds of HVs on the upper and lower plane electrodes, namely the symmetric voltages like +5 kV to −5 kV or the 10 kV to 0 kV type. To explore this issue, commercial code simulation and beam experiments are both done with three different HV settings shown in Table 1.

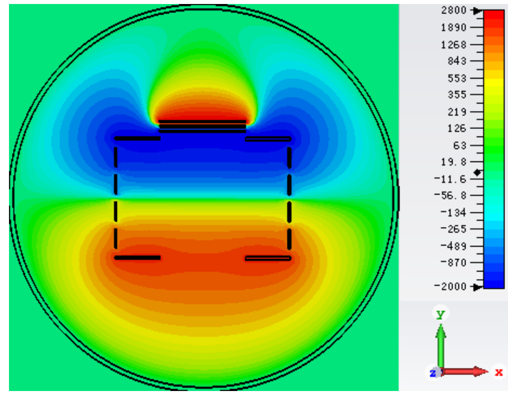

Figure 3: Electrostatic field simulation of item A.

The field simulation in Fig. 3 clearly shows that item A has uniform and flat equipotential lines inside detection region. Particle tracking simulation in Fig. 4 also confirms that item A has only slightly broadening effect with the least relative error of +1.5%, while item B and C indicate a focusing effect with error of −7.5% and −15.6% respectively. In addition, simulation results of three items all show good consistency in the longitudinal and vertical directions.

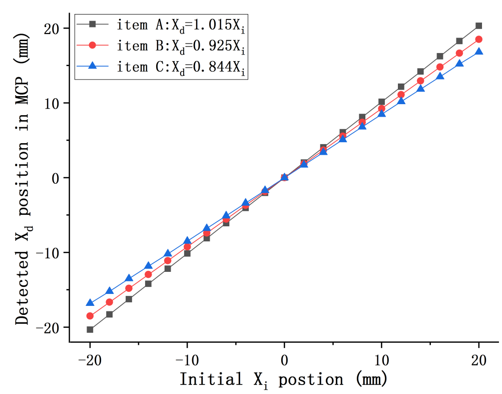

Figure 4: Particle tracking simulation starts from the initial coordinate of $(x, 0, 0)$ and by interval distance of $x = 2$ mm.

Fig. 5 reveals the IPM measurement results of a relative error about 16.8% between item A and C by double gaussian fitting, which agrees well with the simulation result of 17.1%. Moreover, the beam position of item C moves sightly toward the MCP centre. This can be easily explained than item C has a stronger focusing force than A. In a word, beam experiments present similar results with simulations. The HV setting indeed affects the field distribution and the symmetric HV option seems to cause less field distortion.

Beam Experiment Anomalies

Some unexpected phenomena during experiments need to be paid attentions to. Firstly, an induced potential usually occurs when the two high resistance MCPs are supplied

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Table 1: Three HV Settings in IPM Experiments

item	upper plate	lower plate	upper MCP	lower MCP	P46
A	2 kV	-2 kV	-1.8 kV	0 kV	2.8 kV
B	6 kV	0 kV	0 kV	1.8 kV	4.6 kV
C	6 kV	0 kV	-1.8 kV	0 kV	2.8 kV

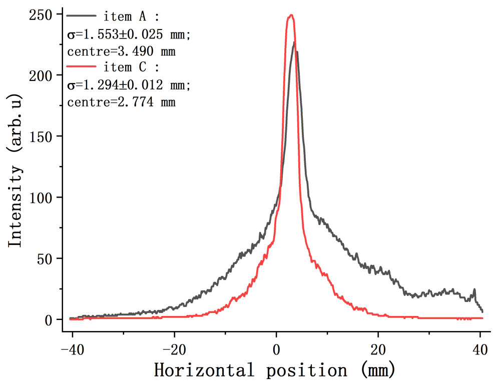

Figure 5: IPM measurements of item A and C with beam parameters of Kr^{28+}, 4.98 MeV/u, 450 µA and 8×10^{-12} mbar.

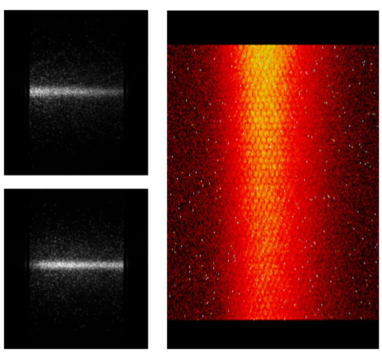

Figure 6: Left upper and lower figures are achieved by new IPM with HV setting of item B and C respectively. Right picture recited from Jülich IPM shows same longitudinal asymmetry.

by two HV channels with the same polarity, which always makes the lower HV MCP improper. Fortunately this can be corrected by using opposite polarity HV channels for two MCPs.

Additionally as shown in Fig. 6, IPM obtains an asymmetric profile distribution in longitudinal direction, while simulations show no evidence to explain it. A similar situation also happened in Jülich IPM [8, 9], which was deduced to be phosphor screen defect. Under such a short longitudinal distance and multi-turn average measurement, the reason is unlikely to be the influence of transverse emittance or bunch variation. During our experiments, this anomaly even disappears and can be repeated again along with the HV setting changes. Thus, it probably results from the Zero potential on the upper MCP, which makes MCP vulnerable for secondaries impact or field distortion.

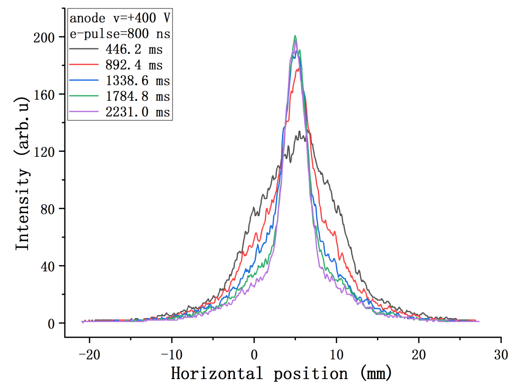

Figure 7: Transverse profile variation during electron cooling in HIRFL-CSRm.

TRANSVERSE ELECTRON COOLING STUDY

On each ring of HIRFL, an electron cooler is deployed to provide high-quality beams for all sorts of experimental applications. Some parameters need to be studied for best transverse cooling effect. For instance anode voltage actually relates to the peak current of electron gun and will certainly influence the cooling strength, as well as the electron profile, electron frequency and electron pulse length et al. More details about electron cooling in HIRFL-CSR and transverse cooling study can be seen in references [10–12].

Figure 7 depicts an obvious profile shrinking trend under the settings of synchronous electron frequency, + 400 V anode voltage and 800 ns *e*-pulse length. Moreover, experiments reveal a positive correlation between anode voltage and cooling power in a certain range. Due to the limitation of ion drift time, image transmission and data processing delay, more delicate work has to be done by another IPM with electron collection mode and multiple-channel electronics acquisition fast up to tens MHz.

SUMMARY

In 2018 summer, a new horizontal IPM was deployed in HIRFL-CSRm with compact mechanical design and upgraded data processing. Simulations and beam experiments were carried out to verify the impact of HV settings on electrostatic field distribution. Meanwhile, some unusual phenomena were found and studied, especially the longitudinal profile asymmetry which is probably because of the ground potential on upper MCP. In the end, with the help of IPM the transverse electron cooling research had also been done in HIRFL-CSR, which strongly validates the great value of this non-invasive instrumentation for profile monitoring in proton and heavy ion accelerators.

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