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TWO-DIMENSIONAL RECONSTRUCTION BY THE MULTI-STRIP IONIZATION CHAMBER AT PREF

Tong Liu*[1], Liping Yao[1], Hang Ren[1], Zhixue Li[2], Tian Wang[2],Kewei Gu[2], Junxia Wu[2], Yongliang Yang[2], Guangyu Zhu[2], Xiaoxuan Qiu[2], Jiajian Ding[1], Lili Li, Long Jing[2], Lingxiao Hou[2]
Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, China
[1]also at Huizhou Ion Science Research Center, Huizhou, China
[2]also at University of Chinese Academy of Sciences, Beijing, China
Ning Li, Advanced Energy Science and Technology Guangdong Laboratory

Abstract

The 60 MeV Proton Radiation Effects Facility (PREF) spent nearly 1 month at the commissioning phase, during which the multi-strip ionization chamber (MIC) at the experimental terminal offered the core parameters, beam spot, scanning area, scanning uniformity, beam flux. However, the projection distribution provided by the MIC loses some information, such as the flux and the uniformity in a selected area less than the scanning area. This paper used a method of two-dimensional reconstruction to provide a 2D (two dimensional) uniformity of selected area. Revealing the trace of the pencil beam at a sampling rate of 10 ksps.

INTRODUCTION

Aiming for displacement damage effect experiments, the 60 MeV Proton Radiation Effects Facility (PREF) [1] was completed the commissioning phase at September, 2023 after a 5-year construction. To improving the radiation hardness of various materials, each experimental terminal equipped a MIC with large sensitive area to monitor the beam position, intensity, radiation field and uniformity. In general, MICs [2–4] or PICs (Pixel Ionization Chambers) [4–6] are applied at the slow extraction radiation terminals.

The homemade electronics with 128 ultralow noise analog front-ends (AFEs) and 16 eight-channel simultaneous sampling analog-to-digital converters (ADCs) [7] were developed for the MIC. The typical parameters of the electronics are listed in Table 1. With the electronics, the MICs worked successfully during the commissioning phase and the last expert acceptance examination.

Table 1: Typical Parameters of the Electronics

Parameter	Value
Channels	128 × 2
Current	25 pA - 1.8 µA
Sampling Rate	10 kHz
Nonlinearity	<0.12 %
ENOB at a gain of 50 kΩ	12 bits

Providing the 1D (one dimensional) projection information, the MIC lost the values of the 2D uniformity and flux. Developing a 2D reconstruction method, a 2D Gaussian fitting based on a 10 ksps data is built. In this contribution, the examination setup and conception is described. We report the 2D reconstruction and the trace of the pencil beam.

EXPERIMENTAL SETUP AND CONCEPTION

The MIC collected the 1D projection information, the calculated uniformity lost the 2D information after 1 spill. In this way, we couldn't directly provide the 2D uniformity and the flux in a selected area when the area is less than the radiation field. The frequency of the scanning magnet is from dozens to 200 Hz. When the scanning frequency is 150 Hz with a 150 mm × 150 mm radiation field. Apparently, each direction of the spot moves as follows:

$$\Delta x = \frac{f \cdot D_x}{SR} = 2.25\,\text{mm}, \Delta y = \frac{f \cdot D_y}{SR} = 2.25\,\text{mm}\,, \quad (1)$$

here, Δx and Δy are the distance changing within 100 µs. D_x and D_y are horizontal and vertical scanning dimension respectively. SR is the sampling rate of the MIC. The sigma of the beam spot projection is around 6 mm. So the error of each direction is shown as:

$$\epsilon_x = \frac{\Delta x}{6 \cdot \sigma_x} = 6.25\,\%, \epsilon_y = \frac{\Delta y}{6 \cdot \sigma_y} = 6.25\,\%\,, \quad (2)$$

ϵ_x and ϵ_y are the horizontal error and vertical error respectively. The full width of the spot is $6 \cdot \sigma_y$. Thus, the error caused by the moving is derived as :

$$\epsilon = \sqrt{\epsilon_x^2 + \epsilon_y^2} = 8.84\,\%\,, \quad (3)$$

ϵ is the 2D error. Equation (1) tells that the error will be lower if the scan dimension is lower than 150 mm or the scanning frequency is less than 150 Hz.

In this way, a radiation field of 120 mm × 120 mm and a scanning frequency of 110 Hz, 115 Hz with respect to horizontal and vertical were set in an experiment. The beam parameters are listed in Table 2. With the 10 ksps raw data, a minimal 2D Gaussian fitting of 100 µs is built. The sum and part of the sum of the fittings shows the 2D information of the whole 1.5 - second spill.

* Corresponding author: liutong@impcas.ac.cn

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Table 2: Beam Parameters in the Experiment

Parameter	Value
Beam species	proton
Beam energy	60 MeV
Beam intensity	~1.4 × 10^9 pps
Spot size (sigma)	~5 mm (H, V)
Extraction mode	Slow extraction
Extraction period	1.5 s
Scanning frequency	110 Hz (H), 115 Hz (V)
Radiation field	120 mm × 120 mm

2D RECONSTRUCTION

2D Reconstruction of a Single Beam Spot

Figure 1 shows the projection distribution of the beam spot in 100 µs. The data is selected at the 1s after the start of RFKO (Radio Frequency Knockout) where the beam intensity is relatively high. Figure 1a and Fig. 1b are the horizontal and vertical projection distribution respectively. The sigma of the horizontal distribution is 6.16 mm and vertical is 5.60 mm. Δx is 1.32 mm and Δy is 1.38 mm deriving from Eq. (1). According to Eq. (2), ϵ_x and ϵ_y are 3.57 % and 4.11 %. Finally, substituting Eq. (2) into Eq. (3), ϵ equals 5.44 %.

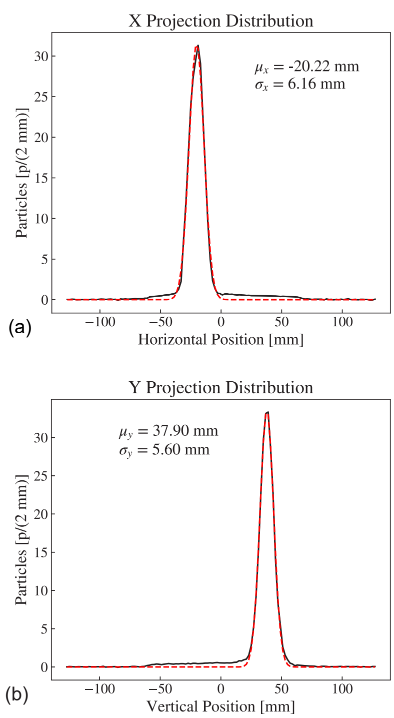

Figure 1: The projection distribution of the beam spot.

Figure 2 depicts the 2D Gaussian fitting from the projection data. Figure 2a and Fig. 2b are the 2D view and 3D view of the fitting respectively. It is intuitively shows the possibility of the 2D reconstruction of each single beam spot. The 2D reconstruction of one spill and the trace reconstruction of the beam painting are described as follows.

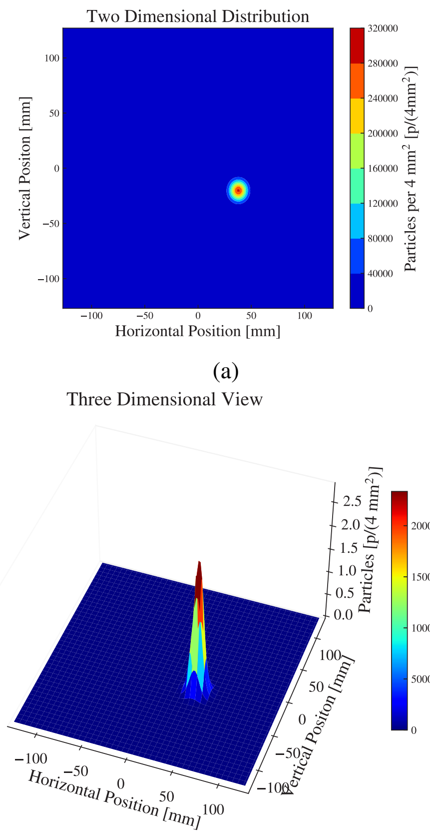

Figure 2: The 2D Guassian fitting of the beam spot.

2D Reconstruction of One Spill

The uniformity, flux of the selected area are the major parameters at the commissioning acceptance examination. These parameters provide by MIC are indirectly measured, which lose some 2D information. There are infinite kinds of 2D distribution correspond to the same projections. It is possible that 2D uniformity, flux can be reconstructed if the sampling rate is high enough to record the beam spot clearly as mentioned above.

Figure 3 illustrates the projection distributions of one spill. Figure 3a shows the horizontal projection distributions and Fig. 3a is for the vertical. The blue curve is cumulative profile from raw data. The orange one is the projection from 2D reconstructed cumulative data. The calculation of uniformity is based on the equation :

$$U = (1 - \frac{N_{\max} - N_{\min}}{N_{\max} + N_{\min}}) \times 100\,\% \,, \tag{4}$$

here, U is the uniformity. $N_{\max}$ and $N_{\max}$ are the maximal and minimal particles numbers of the selected data, respectively. The uniformity values with a selected area of 100 mm are listed in Table 3. The pitch of the detector is 2 mm in both direction.

Figure 4 demonstrates the 2D reconstruction of one spill. Figure 4a is the 2D view of reconstruction. Figure 4b is the 3D view of reconstruction. The green curve is the horizontal

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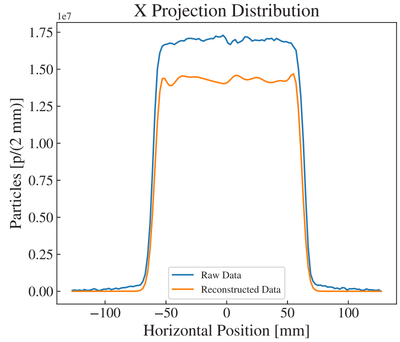
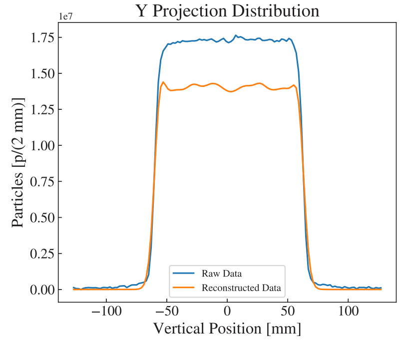


(a)



(b)

Figure 3: The projection distributions of one spill.

Table 3: Typical Parameters of the Electronics

Figure	Color	Symbol	Value
Fig. 3a	Blue	U_{rx}	98.16 %
Fig. 3b	Blue	U_{ry}	98.52 %
Fig. 3a	Orange	U_{2dx}	97.31 %
Fig. 3b	Orange	U_{2dy}	97.04 %

projection and the blue is for the vertical. As you can see, it's graphic that the 3D view sketches the flux distribution.

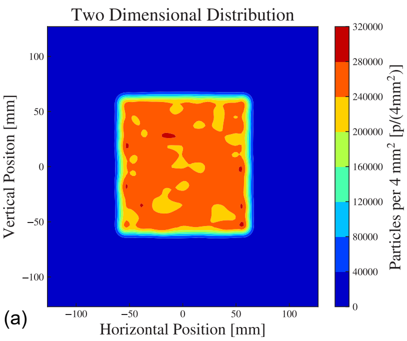
After setting a radiation field of 100 mm × 100 mm, the 2D uniformity is 86.69 %. The granularity of the uniformity is 2 mm × 2 mm. The projection uniformity values have similarly closed to 100 %. But the 2D uniformity is lower than 90 %. It revealed that values of the profile and the 2D uniformity might vary widely.

2D Reconstruction of a Trace

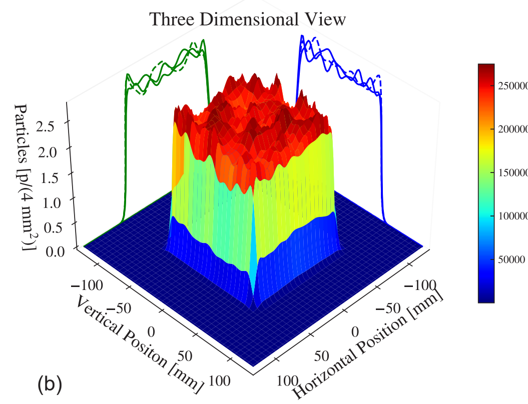
Now, the method of 2D reconstruction based on 100 µs is built. With the tool, we can explore how the pencil beam paints in the radiation field. A trace reconstruction within one cycle is studied as follows.

Since the scanning frequencies are 110 Hz (H) and 115 Hz (V), the numbers of the profiles travelling one cycle are 90.9 and 87.0. To avoid the overlapping, 70 consecutive profiles selected between 1.015 s and 1.022 s are analysed for the trace research.

Figure 5 displays the projection distribution of the trace. Figure 5a shows the horizontal projection distribution and Fig. 5b is the vertical. It is not clear enough through the two figures to get the trace information. The two directional uniformity values are 75.80 % and 58.43 %.

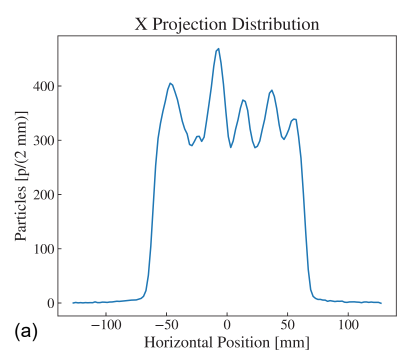


(a)

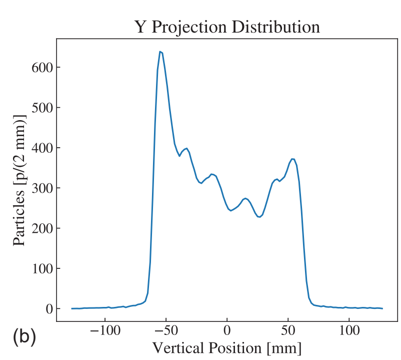


(b)

Figure 4: The 2D reconstruction of one spill.



(a)



(b)

Figure 5: The projection distribution of the trace.

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Figure 6 indicates the 2D reconstruction of the trace. An elliptical orbit is appeared in Fig. 6a, which shows the exactly trace of the beam painting. A more detailed in terms of flux distribution is reflected in Fig. 6b. Beyond those, the different flux reveals the fact that the fluctuating of the beam delivery. It shows the possibility of 3D reconstruction of the beam structure.

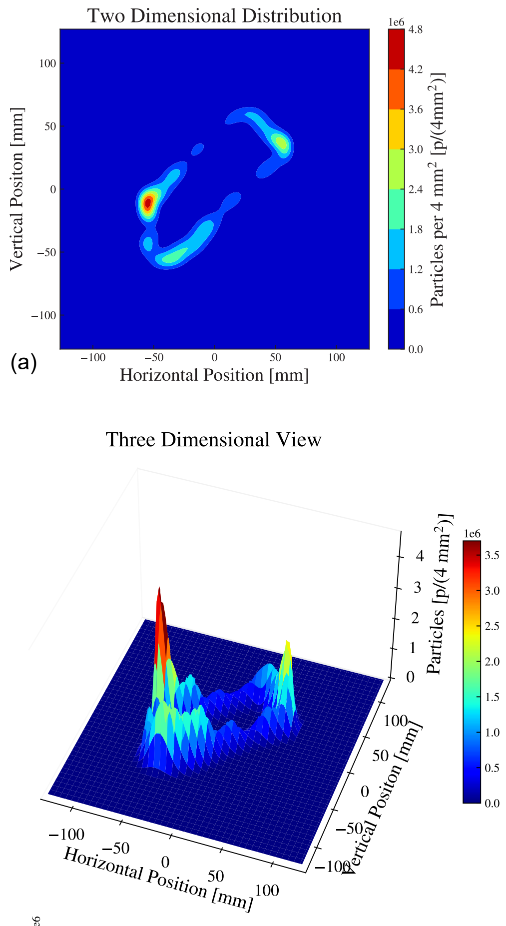

Figure 6: The 2D reconstruction of the trace.

CONCLUSIONS AND FURTHER IMPROVEMENTS

With a sampling rate of 10 ksps, the ability of single beam spot's 2D reconstruction is established by the 2D Gaussian fitting. The 2D reconstruction of the whole spill reveals the fact that 2D uniformity is not equal to the projection's ones. The work is imperative for the MICs when measures the 2D parameters. By the trace study, we find a way to know how the pencil beam painting and the perspective of the 3D construction.

Lacking the verification, the 2D flux distribution from the reconstruction requires the comparison to a standard 2D detection. A Gafchromic EBT (External Beam Therapy) film as a verified detector is prepared in the near future. A calibrated PIC is under development which will enhance the ability of quick check. The 2D reconstruction work is based on the raw data in 10 ksps, which is a offline analysis. It will be a significant milestone where the function in FPGA is realized in the online application.

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