ISBN: 978-3-95450-203-5 doi:10.18429/JACoW-HIAT2018-MOPB15

DEVELOPMENT OF A PEPPER POT PROBE TO MEASURE THE FOUR-DIMENSIONAL EMITTANCE OF LOW ENERGY BEAM OF ELECTRON CYCLOTRON RESONANCE ION SOURCE AT IMP

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Abstract

The ion beams extracted from an Electron Cyclotron Resonance (ECR) ion source always exist strong transverse coupling effect that is caused by the field of the axis mirror magnets and the extraction solenoid. A Pepper Pot probe was developed and used to obtain the full four-dimensional (4D) phase space distribution of the low energy beam extracted from the ECR ion source at IMP. This paper describes the design of the Pepper Pot, the setup configuration, the detailed image processing procedure, especially the analysis results verification compared to another type emittance meter. The first 4D emittance is also determined through the Pepper Pot probe. The transverse phase space distribution measurement data of oxygen beams from the LECR4 experimental platform are presented and discussed.

INTRODUCTION

Electron cyclotron resonance (ECR) ion sources [1] were widely used in the particle accelerator because of their high performance on producing highly charged ions. During the last few years it became the evident that the ion beam extracted from the ECR ion sources excited complicated structure of phase space distributions [2]. The ion beam in the horizontal and vertical planes are strongly coupled due to the strength field of solenoid include extraction coil of the axial mirror magnets and the extraction solenoid [3]. In order to obtain the transverse distribution, some type of emittance device were previously used, like Slit to wire meter [4], Allison type meter [5], but these devices cannot provide full phase space distribution. Pepper Pot probe is another type emittance meter that can acquire 4D emittance. Another significant advantage of the Pepper Pot probe is the very short time of measurement progress. Pepper Pot probe were widely used to measure both electron [6] and heavy ion [7] emittance of the low energy beam transport line (LEBT). There were two types Pepper Pot probe, one is single-pass type [8] that the probe was rapidly insert to the beam center to measure whole beamlet [9] data, the laboratories like LBNL, ANL, RIKEN, BNL are all this type; the other is scanning type [10] that the beamlet data were obtained through probe moving step by step, KVI has designed this type probe and it was used to measure the beam transverse distribution. Most of exist Pepper Pot probes have acquired the beam transverse distribution of LEBT that without the verification, in most case the results of Pepper Pot probe whether reliable is uncertain. In this paper the Pepper Pot probe result was compared to Allison Scanner in order to certify the accuracy.

THE SETUP OF PEPPER POT

The prototype of the Pepper-Pot meter which was recently designed and commissioned is shown in Fig. 1. It contains a Pepper-Pot mask with two copper frames, a square scintillator and a 45 degree stainless steel mirror. The Pepper-Pot mask is a tantalum foil with a thickness of 100 micrometers with holes of 100 micrometers diameter and distance between adjacent holes is 3 mm in both x and y direction. A round potassium bromide (KBr) is used for the scintillator (5 mm thickness) with 50*50 mm available size. The mask is mounted in the copper frame which has one blocked hole in the center to provide an absolute spatial reference for the data processing. There was no additional cooling of the mask because the beam is low energy during the tests. A 45 degree mirror reflects the appearing light pattern to the CCD camera seem like perpendicular at the beam. The exposure time and gain of the camera can be adjusted online via the user interface and a real-time image can be acquired. A code based on the Matlab software is designed for the transverse emittance calculation.

The Pepper Pot probe is located on the LEBT line of the LECR4 platform [11, 12] at IMP. The layout of the LECR4 platform is shown in Fig. 2. It contains a room temperature ECR ion source and a LEBT line which includes two solenoids and a 90 degree analysis magnet to focus and select the expected ion beam to the RFQ. The Pepper Pot probe was mounted in the diagnostic box behind the RFQ, two Allison scanners [13] were recently added to the same cube in order to compare the measurement results between two types device.

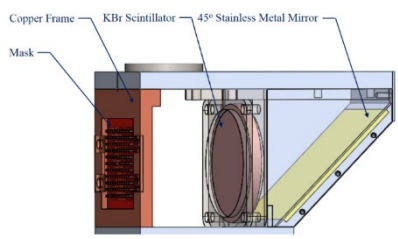

Figure 1: The draw of Pepper Pot probe with KBr scintillator at IMP.

* Work supported by CAS (QYZDB-SSW-JSC025), MOST (contract No. 2014CB845500), and NSF (contract No. 11221064).
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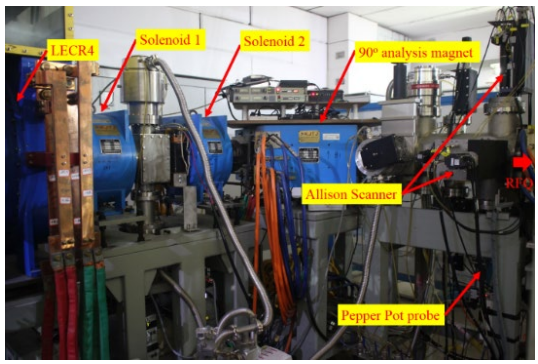

Figure 2: Layout of LECR4 experimental platform.

CONFIGURATION

Angular Resolution

The angular resolution of the Pepper Pot probe depends on the distance between the Pepper Pot mask and the scintillator screen. With increasing the distance, the absolute spot size on the final image increase, but the angular resolution decrease. In practice however, for a given mask, the distance depends on the expected maximum angle that the beam particles have and that beam spot do not overlap but far enough to ensure a good spot resolution. The distance of the Pepper Pot probe at IMP can be varied from 10 up to 40 mm. Table 1 shows the angler resolution for the different distance between the Pepper Pot mask and the scintillator screen.

Table 1: The Angular Resolution of the Probe that the Pixel Size is 52 μm

Distance (mm)	Angular resolution (mrad)
10	5.20
25	2.08
40	1.30

Linearity of the Light Yield

The linearity of the light yield of the different type scintillator were test in world laboratories [14, 15]. The material of scintillator of the Pepper Pot probe at IMP is KBr because of its highest light yield. The linearity of light yield of KBr screen interact with ion beam will be discussed in this section. Figure 3 shows the linearity of the light yield with the O^{5+} ions collision. One can see that nearly linear increase with the total generated light with the incident ion beam current with different threshold value. The light yield dependence means that the KBr scintillator shows a high saturation behind on the hundred micro-ampere ion beam current that the beam emittance measurement is credible, within the measured beam current no saturation effect was found.

IMAGE DATA PROCESSING

One version of the transverse emittance processing code has been developed to analyze the Pepper Pot beam image. The code is capable of extracting the full 4D phase space information from the captured light image. It includes noise treatment, production of the beam distribution matrix, calculation of the transverse 4D sigma matrix and the phase ellipse parameters based on the root-mean-square algorithm [16], and saving the output results. The detail analysis steps of the code are described in the following.

The Noise Treatment

The noise of the Pepper Pot image were reduced including the background subtraction and Gaussian noise flitting. The procedure is that the beam image with beam collision subjects the dark image without beam collision, and both image is under same camera settings. Then pixel gray of the disposed image under the threshold sets to zero and the other pixel gray deducts the threshold. Finally, a 3*3 medial filter which is the effective technique in isolated pixels removing is used to filter the stochastic noise.

The Beam Matrix Calculation

The sensitive image contains whole beamlet collision is cut out by the code. Based on the image, the Decal coordinate (Xp, Yp) of pixels can be defined through the relative center of the beam pattern and the pixel resolution. The beam momentums matrix on the both direction are obtained through the quotation r'=(R-r)/L. L is the distance between the front side of Pepper Pot mask and the detecting side of the KBr light pattern screen, R is the Decal coordinate of pixels, r is the Decal coordinate of the holes of the mask related to the pixels. So the beam distribution matrix ρ(x, x', y, y') can be generated through sorting the data with one direction such as horizontal.

Beam emittance analysis

According to the beam distribution matrix, the phase space ellipse parameters can be calculated through quotation. The 4D emittance will be obtained synchronously. The emittance analysis will be discussed particularly on the next section of this paper.

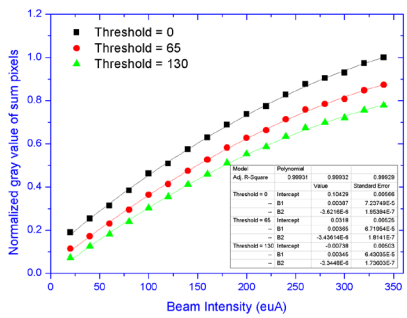

Figure 3: The light yield for the 15 keV O^{5+} beam with the gain is 400 and the exposure time is 1000 ms.

RESULTS CERTIFICATION

The final transverse distribution results of the Pepper Pot probe based on image processing are very sensitive with the external setting. However, there are almost no data on the certification of analysis results of the Pepper Pot probe. The detailed certification of the Pepper Pot results is discussed on this section.

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Phase Ellipse Rotation Angle Comparison

Phase ellipse rotation angle [8] is used to a certification that verify the difference of the twiss parameters between the Pepper Pot probe and Allison Scanner. The ellipse rotation angle θ is shown in Fig. 4. Nine different phase space ellipse has been measured by both the Pepper Pot probe and the Allison Scanners with different focusing solenoids value. The ellipse rotation angle relationship between the Pepper Pot and the Allison Scanner is shown in Fig. 5. It can see that the difference of ellipse rotation angle between the two types emittance meter is less than 1.5% of the both phase space.

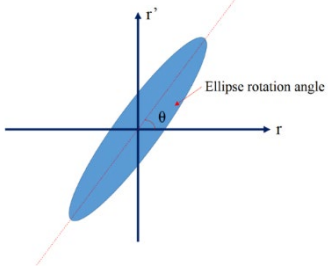

Figure 4: The ellipse rotation angle.

The Ellipse Parameters Comparison

The 2D transverse phase distribution contains the RMS emittance and the twiss parameters are compared to that of Allison scanner to certain the reliability of the results. The verification pattern is shown is Fig. 6, it can be seen that the difference of the RMS emittance is 18.73% in the horizontal and 4.18% in the vertical. The horizontal difference of twiss parameters is 20.22% with α, 18.80% with β and 14.90% with γ, these difference of vertical is 10.95%, 7.10% and 9.08%. The horizontal difference is The largest difference of the Pepper Pot probe results is not larger than about 20%, and the smallest is less than about 4%, so it is a conclusion that the Pepper Pot probe at IMP can be used to measure the beam transverse distribution and its processed results is reliable.

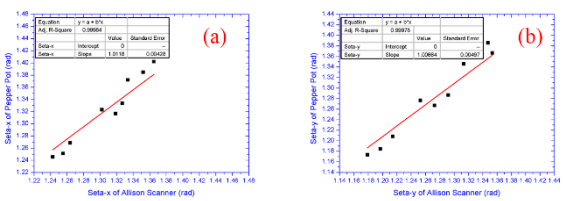

Figure 5: The ellipse angle comparison. The difference of the ellipse rotation angle is related to the slop of the red line in the pattern. (a) The rotation angle of space xx' (b) The rotation angle of space yy'.

4D EMITTANCE

The advantage of Pepper Pot probe in the measurement is the 4D emittance calculation. The 4D emittance results are shown in Fig. 7, it contains the 4D emittance acquired by the Pepper Pot probe, and the products on the two-dimensional emittance that processed by these two meters. One can see that the difference between the 4D emittance and the product of two-dimensional emittance of Pepper Pot probe is lower than that of Allison Scanner, and the products of Allison Scanner is larger than the 4D emittance obviously.

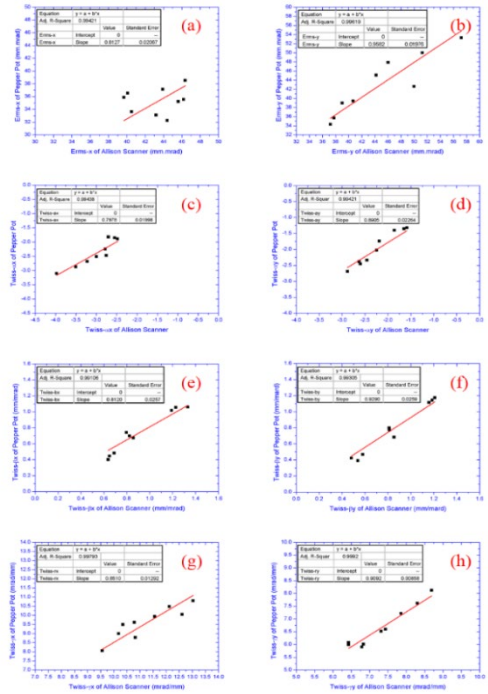

Figure 6: The comparison of the twiss parameters. The difference is related to the slop of the red line in the pattern. (a) The RMS emittance of space xx'. (b) The RMS emittane of space yy' (c) The twiss-α of space xx' (d) The twiss-α of space yy' (e) The twiss-β of space xx' (f) The twiss-β of space yy' (g) The twiss-γ of space xx' (h) The twiss-γ of space yy'.

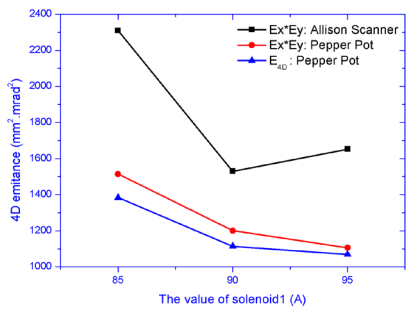

Figure 7: The 4D emittance processed by the Pepper Pot probe on different value of solenoid 1 that the value of solenoid 2 is fixed at 125A.

CONCLUSION

The design of Pepper Pot probe has been completed and the 4D transverse phase space distribution has been clearly demonstrated. The results of Pepper Pot probe is verified to that of Allison Scanner comprehensively. The verification shows a well property of Pepper Pot probe so that the transverse phase distribution base on the image process method is credible. Increasing the detecting range of the mask is the next optimizing work of the Pepper pot probe at IMP.

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