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. In order to obtain the four-dimensional (4D) characteristic matrix with coupling elements, a Pepper Pot probe was developed and used to obtain the full 4D transverse phase space distribution of the low energy beam extracted from the ECR ion source at IMP. This paper describes the detailed design and image processing procedure of Pepper Pot probe, especially the analysis results verification compared to another type emittance meter. The first 4D transverse phase space distribution measurement data of oxygen beams from the LECR4 experimental platform are presented and discussed.

1. Introduction

Electron cyclotron resonance (ECR) ion sources were widely used in the particle accelerators because of their high performance on producing highly charged heavy ions. During the last few years it became the evident that the ion beams extracted from the ECR ion source exits complicated structure of phase space distributions. The ion beam in the horizontal and vertical planes were strongly coupled due to the strength field of solenoid include extraction coil of the axial mirror magnets and the extraction solenoid. In order to obtain the transverse phase space distribution, some types of emittance device were previously used, like Slit to wire meter, Allison type meter, but these devices cannot provide full transverse 4D 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 so that it can be used to measure the phase space distribution of pulse beam. Pepper Pot probe was widely used to measure both electron and heavy ion emittance of the low energy beam transport line (LEBT). During the last twenty years development, Pepper Pot probe was divided to two types, one is single-pass type that the probe was rapidly insert to the beam center to measure whole beamlets data, for instance, the Pepper Pot probes in laboratories like LBNL, ANL, RIKEN, BNL are all this type. The other one is the scanning type that the beamlets 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 the existing Pepper Pot probes have acquired the beam transverse distribution, however no validation check on whether the final distribution is reliable or not has not been reported. In this paper the Pepper Pot probe results were compared to that of Allison Scanner in order to certify the accuracy.
2. The setup of Pepper Pot probe

The prototype of the Pepper-Pot probe which was recently designed and commissioned at IMP is shown in Figure 1. It contains a Pepper-Pot mask with two copper frames, a round scintillator and a 45 degree tilted stainless steel mirror. The Pepper-Pot mask is a 100 micrometers thickness tantalum foil with holes of 100 micrometers diameter and the distance between adjacent holes is 3 mm in both x and y directions. A round potassium bromide (KBr) disk is used for the scintillator (5 mm thickness) with 50x50 mm available size. The mask is mounted in the copper frames 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 incident beam energy is low during the tests. A 45 degree mirror reflects the appearing light pattern to the CCD camera. 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.

![Figure 1. The draw of Pepper Pot probe with KBr scintillator at IMP.](image1)

The Pepper Pot probe was installed on the LEBT line of the LECR4 platform\textsuperscript{[11, 12]} at IMP. The layout of the LECR4 platform is shown in Figure 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 beams to the diagnostic box. The Pepper Pot probe was mounted in the diagnostic box in front of the RFQ, two Allison scanners\textsuperscript{[13]} were recently added to the same cube in order to compare the measurement results between two types of device.

![Figure 2. Layout of LECR4 experimental platform](image2)
3. Configuration

3.1. Angular resolution

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

| Distance (mm) | Angular resolution (mrad) | Maximum angle (mrad) |
|---------------|---------------------------|----------------------|
| 10            | 5.20                      | 300                  |
| 25            | 2.08                      | 120                  |
| 40            | 1.30                      | 75                   |

3.2. Linearity of the light yield

The linearity of the light yield of the different type scintillator needs to be checked in worldwide laboratories that have developed Pepper Pot probe[14, 15]. The material of scintillator of the Pepper Pot probe at IMP is KBr because of its highest light yield. Figure 3 shows the linearity of the light yield with the O^{5+} ions collision. One can see that nearly linear increase of the total generated light with the incident ion beam current at different threshold values. The linear light yield dependence indicates that the KBr scintillator has no saturation issues in this application for the detection of ~100 euA ion beam, and the obtained signal is credible.

![Figure 3](image_url)

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

4. Image data processing

One version of the transverse 4D emittance processing code has been developed to analyse the Pepper Pot probe 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 characteristic matrix and the phase ellipse parameters based on the root-mean-square (RMS) algorithm[16], and saving the output results. The detailed analysis steps of the code are described in the following.
4.1. 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 subtracts the dark image without beam collision, and both images are under same camera settings. Then pixel grey of the disposed image under the threshold sets to zero and the other pixel grey deducts the threshold. Finally, a 3*3 medial filter which is the effective technique in isolated pixels removing is used to filter the Gaussian noise.

4.2. The beam matrix calculation

The sensitive image contains whole beamlets collision is cut out by the code. Based on the sensitive image, the coordinate (X, Y) of pixels can be defined through the relative centre of the beam pattern and the pixel resolution. The beam momentums matrix on the both directions are obtained through the quotation $r'=(R-r)/L$. L is the distance between the front side of mask and the detecting side of the KBr light pattern screen, R is the coordinate of pixels, r is the coordinate of the holes of the mask related to the pixels. The current of beamlets is related to the pixel grey, so the beam 4D transverse distribution $\rho(x, x', y, y')$ can be generated through sorting the data with one direction such as horizontal.

4.3. Beam emittance analysis

According to the beam 4D transverse distribution $\rho$, the elements of 4D characteristic matrix can be calculated by the RMS algorithm and the 4D emittance will be obtained synchronously. The emittance analysis will be discussed particularly on the next section of this paper.

![Figure 4. The ellipse rotation angle.](image)

![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 phase space xx’ (b) The rotation angle of phase space yy’](image)
Figure 6. The comparison of the twiss parameters. The difference is related to the slope of the red line in the pattern. (a) The RMS emittance of phase space xx'. (b) The RMS emittance of phase space yy' (c) The twiss-α of phase space xx' (d) The twiss-α of phase space yy' (e) The twiss-β of phase space xx' (f) The twiss-β of phase space yy' (g) The twiss-γ of phase space xx' (h) The twiss-γ of phase space yy'
5. Results certification
The final transverse distribution results of the Pepper Pot probe based on image processing are very sensitive to the external settings. However, there are almost no report on the certification of analysis results of the Pepper Pot probe. The detailed certification of the Pepper Pot results at IMP is discussed in this section.

5.1. Phase ellipse rotation angle comparison
Phase ellipse rotation angle is used in the certification that verifies the difference of the twiss parameters between a Pepper Pot probe and an Allison Scanner. The ellipse rotation angle θ is shown in Figure 4. Nine different phase space ellipses have been measured by both the Pepper Pot probe and the Allison Scanner by changing the upstream focusing solenoids strength. The ellipse rotation angle relationship between the Pepper Pot and the Allison Scanner is shown in Figure 5. It can see that the difference of ellipse rotation angle between the two types of emittance meters is less than 1.5% for both of the phase space distribution at the projection planes. It means that the measured rotation angle of the transverse phase ellipse with the Pepper Pot at IMP is consistent and reliable.

5.2. The ellipse parameters comparison
The 2D transverse phase distributions with the RMS emittance and the twiss parameters are compared to those from Allison scanners to validate the reliability of the results. The difference between two types of emittance meters is related to the slop of the fitting line. The verification pattern is shown in Figure 6, which indicates the difference of the RMS emittance is 18.73% in the horizontal plane and 4.18% in the vertical plane. The twiss parameter difference in horizontal plane is 20.22% with α, 18.80% with β and 14.90% with γ, and 10.95%, 7.10% and 9.08% respectively in vertical plane. Obviously, the biggest deviation is in the horizontal plane which is barely around 20%, and the least one is only about 4%, which brings about the conclusion that the Pepper Pot probe at IMP can be used to measure the beam transverse distribution and its results are reliable.

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.

6. 4D emittance
The advantage of Pepper Pot probe for ion beam diagnostics is that it provides the 4D emittance information of the incident ion beam. The 4D emittance results are shown in Figure 7, it contains the 4D emittance acquired with the Pepper Pot probe, and the products of the emittances on the 2 projection
planes with Allison Scanner. One can see that the real 4D emittances obtained with the Pepper Pot probe are lower than the products of $\varepsilon_x*\varepsilon_y$ from both the Pepper Pot and the Allison Scanner. It means that using the products of 2D emittances to describe the 4D emittances is unreasonable especially the beam is strongly coupled. The Pepper Pot probe is the effective device to acquire the right beam 4D emittance.

7. Conclusion
The development of a Pepper Pot probe has been completed and the 4D transverse phase space distribution has been clearly demonstrated. The results of Pepper Pot probe have been verified to those of Allison Scanner comprehensively. The verification shows a well property of Pepper Pot probe that also demonstrates the transverse phase distribution based on the image process method is credible. Increasing the detection range of the mask is the next step work of the Pepper pot probe improvement at IMP.

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