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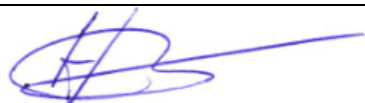
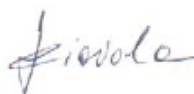
Report on emittance meters building

Dissemination level: *PP*Issued by: *KVI*Reference: *EURONS-D-J07-4*Status: *Final***Summary:**

This report is intended to describe in some details the design, construction and operation of a pepperpot emittance meter. This instrument can measure the full 4D transversal phase-space distribution of low-energy heavy-ion beams. Comparison with emittance measurements performed with an Allison scanner shows good agreement. In addition the pepperpot device also allows to measure phase-space correlations between the transversal planes.

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Report on emittance meters building

1 Introduction

In the framework of ISIBHI and the KVI-GSI collaboration we have designed and built a versatile pepperpot emittance meter capable of measuring the 4-dimensional emittance of intense low-energy heavy-ion beams. This information is important for understanding and improving the beam formation and transport of intense, multiply-charged ion beams extracted from electron cyclotron resonance ion sources. The instrument can be installed at different locations where the expected shape of the phase-space distribution is highly variable. In order to be able to measure the emittance of an ion beam at the EIS test bench of GSI Darmstadt, where in the horizontal plane the beam has a waist and a large divergence and in the vertical plane a large width and small divergence, we use a combination of the pepperpot method in the vertical direction and scanning method in the horizontal direction. In this way an acceptable accuracy is reached in both orthogonal planes. This report contains a description of the pepperpot emittance meter, its main characteristics and the measurement procedure, the analysis method used to extract the 4-dimensional phase-space distribution from the measured beam images and some typical examples of emittance measurements.

2 The pepperpot emittance meter

The pepperpot emittance meter is designed to be able to measure four-dimensional phase space distributions with in the horizontal plane a maximal divergence of ± 50 mrad and a narrow width and in the vertical plane a maximal beam width of 40 mm and a small divergence. In order to realize an acceptable resolution in both orthogonal planes we have adopted a hybrid technique in which a vertical array of holes is stepped in the horizontal direction through the beam. At each step a two-dimensional image is taken of the beamlets transmitted through the holes in the pepperpot plate. The four-dimensional phase-space distribution of the incident ion beam can be extracted from the entire data set. The principle of the pepperpot emittance meter is shown in Fig. 1. The pepperpot plate with a vertical array of holes is mounted on a translation stage which allows the plate to be stepped horizontally through the beam with an accuracy of less than 10 μm . The minimum displacement of the plate is also 10 μm . The pepperpot plate is made of a 25 μm thick tantalum foil with a vertical row of 20 holes of $\text{\O} 20$ μm diameter, machined by laser cutting, with a pitch of 2 mm. This foil is mounted on a water-cooled copper block. By changing the geometry of the hole pattern the instrument can be adapted to different phase space distributions.

The ions transmitted through the holes in the pepperpot plate are detected with a position sensitive detector which is mounted a distance $L = 59.3$ mm downstream of the pepperpot plate. The detector consists of two multi-channel plates (MCP) in chevron configuration and a phosphor screen both with an effective diameter of 41.5 mm, purchased from El-Mul. The MCP has a maximum gain of up to 5×10^7 and is capable of detecting individual ions. The phosphor screen converts the charge cloud produced by the impinging ions to visible light with a typical decay time of 1.2 ms. Finally, the 2D light-intensity distribution from the phosphor screen is imaged with a mirror ($\text{\O} 50$ mm) and a lens system (PENTAX C2514M) onto a SONY XCL-U1000 CCD camera mounted outside the vacuum. The CCD camera has 1600×1200 pixels of 4.4×4.4 μm and is capable of taking 15 frames per second. Its shutter time can be varied from 0.07 to 10^{-4} s. The optical transmission from the phosphor screen to the CCD has a slight position dependence, which is easily corrected by incorporating a digital filter in the analysis software.

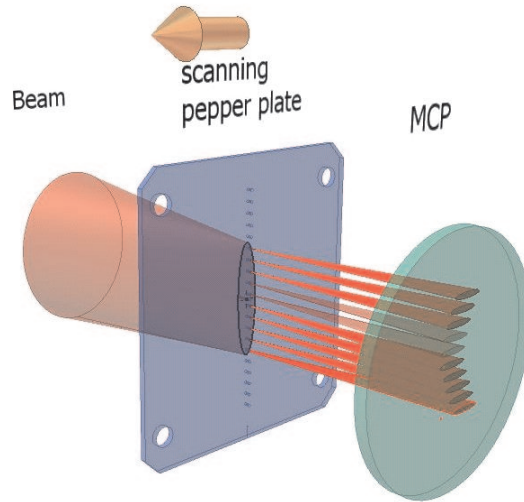


Figure 1: Principle of the pepperpot emittance meter.

The MCP, phosphor screen and mirror are mounted on a table which can be moved in and out of the beam. The whole system is mounted on a CF150 flange, can be baked out and is suitable to operate in a 10^{-9} mbar vacuum. A schematic view of the instrument, indicating its main components, is shown in Fig. 2.

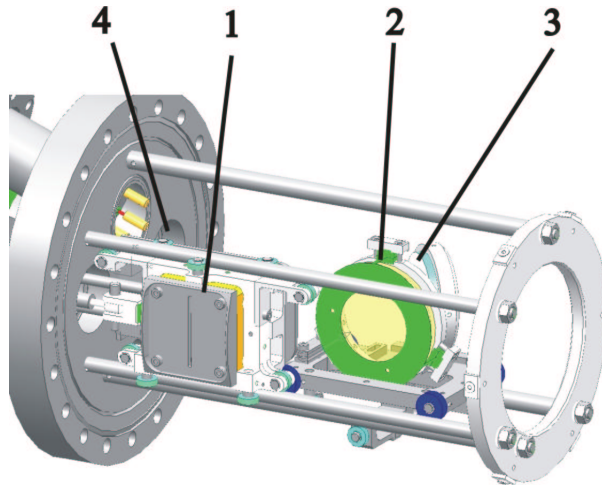


Figure 2: Layout of the emittance meter: 1) pepper plate, 2) multi channel plate, 3) mirror, 4) view port to CCD camera.

3 Main characteristics and measurement procedure

In this section we will discuss the single-ion response of the detection system, the measurement procedure and determination and subtraction of the background signal.

3.1 Single-ion response

The single-ion response of the MCP + phosphor screen determines the ultimate angular resolution that can be reached, independent of the geometrical dimensions and the imaging system. The single-ion response has been determined using a very low-intensity, defocused beam of O^{7+} ions impinging on a 1 mm diaphragm placed in front of the MCP. The light from the phosphor screen is focused onto the CCD camera with a single lens with magnification $M = 0.28$. The CCD shutter time was set at a value of 35 ms. The ion flux incident on the MCP was determined by measuring the MCP count rate. Rates down to 100 s^{-1} were easily produced.

Figure 3 shows a CCD image of an 84 keV O^{7+} beam at a count rate of 400 s^{-1} . Individual ion impacts can easily be distinguished. This is also shown in Fig. 3 where at the right an intensity distribution is plotted of six ions hitting the MCP along the vertical line through the middle of the CCD image. The single-ion responses can easily be fitted with Gaussians, whose positions are determined with a standard deviation of 2 pixels. The 3σ accuracy of the impact location of an ion hitting the MCP corresponds to a spatial uncertainty of $\approx 100 \mu\text{m}$ on the phosphor screen. The spatial binning of the imaging optics is $44 \mu\text{m}$, which thus is not a limiting factor for the intrinsic spatial resolution. The corresponding angular resolution is 1.9 mrad. It should be pointed out that the resolving power of the spatial intensity distribution is determined by the sampling, i.e. the hole distance in the pepperpot plate for the y direction and the step size for the x direction.

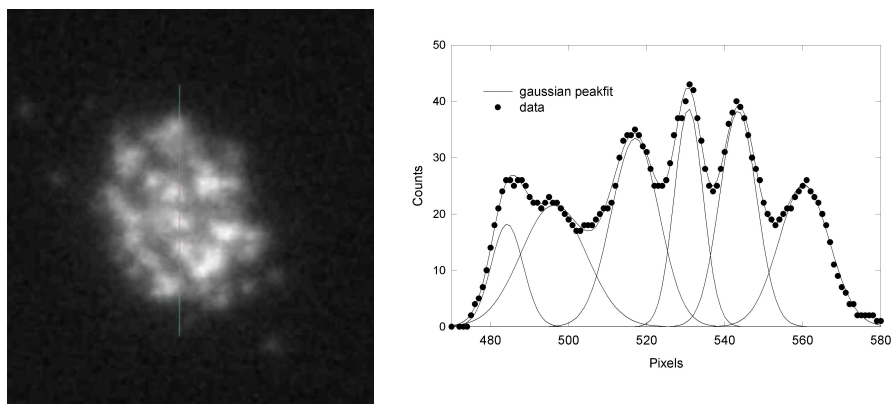


Figure 3: Left: CCD image of 87 keV O^{7+} ions at a MCP count rate of 400 s^{-1} . Right: Intensity distribution along a vertical line through the middle of the CCD image.

3.2 Measurement procedure

An emittance measurement is performed by stepping the pepperpot plate through the beam while taking a CCD image of the transmitted beamlets at each step. This procedure is controlled by a LABVIEW program and results in a data set from which the various 2D projections of the full 4D phase space distribution can be extracted. An example of such a data set for a 84 keV Ne^{7+} beam is shown in figure 4. Each column in the figure is an image of the beam transmitted through the pepperpot plate located at a well-defined horizontal position. The horizontal step size in this measurement was set at $130 \mu\text{m}$. An emittance measurement takes approximately 5 minutes.

3.3 Background subtraction

The grey value of each pixel in the data set consists of beam related, background and noise components which have to be separated. The background and noise components originate in both the MCP and CCD camera. The background component is eliminated by subtracting from each CCD image an image taken without beam. The noise component is eliminated by determining

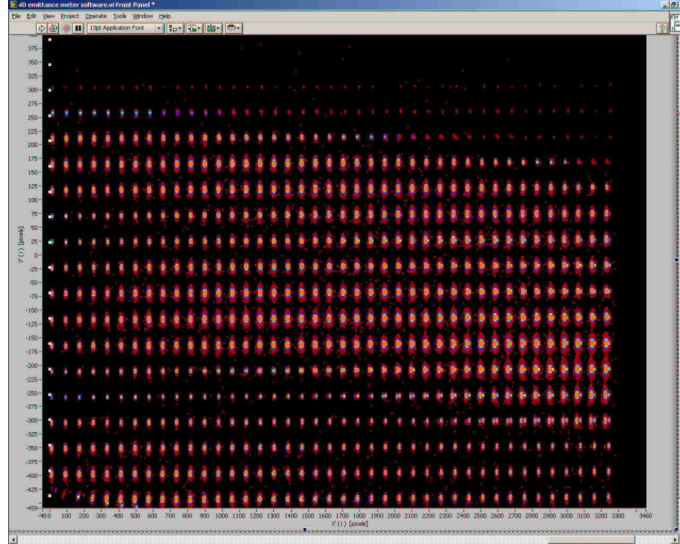


Figure 4: Example of a raw image file of an emittance measurement for a $6 \mu\text{A}$, 84 keV Ne^{7+} beam. In this measurement the spatial step size was set at $130 \mu\text{m}$.

the frequency distribution of the integrated pixel content. An example of this is shown in figure 5. The frequency distribution consists of a Gaussian representing the noise component superposed on a tail which represents the beam-related component. We simply separate the beam-related component from the noise by considering all grey values smaller than three standard deviations of the Gaussian distribution as noise. This procedure overestimates the noise component to some extent.

4 Data analysis

The transversal phase-space distribution $\rho(x, y, x', y')$ of the ion beam is proportional to the number of ions in the 4D volume-element $dx dy dx' dy'$ at the phase-space position x, y, x' and y' . It can be determined from the full data set shown in figure 4. The analysis procedure is best illustrated by first discussing how a partial (vertical) phase-space distribution $\rho(x = 0, y, x' = 0, y')$ is extracted from a single CCD image of the transmitted beamlets when the pepperpot plate is positioned at the horizontal position $x = 0$. The corresponding image is shown in the left half of figure 6 for a 84 keV Ne^{7+} beam. The vertical positions of the holes in the pepperpot plate are indicated as white dots. As can be seen, the individual beamlets are clearly separated. It is interesting to note that this single image already shows a clear correlation between x' and y , a feature that can not be detected with an Allison-type emittance meter. From this image a partial y - y' phase-space distribution at $x = 0$ and $x' = 0$ has been calculated by determining the grey value of each pixel in the vertical column $x = 0$. The vertical coordinate y is given by the vertical position of the corresponding hole in the pepperpot plate. The vertical angle y' is given by $y' = (y_p - y)/L$, with $y_p - y$ the vertical distance between a pixel in the $x = 0$ column and the vertical position of the corresponding hole. The resulting partial y - y' phase-space distribution is shown in the right half of figure 6.

The full phase-space distribution $\rho(x, y, x', y')$ can be obtained in a similar way from the entire data set. Finally, various 2D cross sections through the 4D phase-space distribution $\rho(x, y, x', y')$ are calculated by integrating away the complementary degrees of freedom, e.g.

$$\rho(x, x') = \iint \rho(x, y, x', y') dy dy' . \quad (1)$$

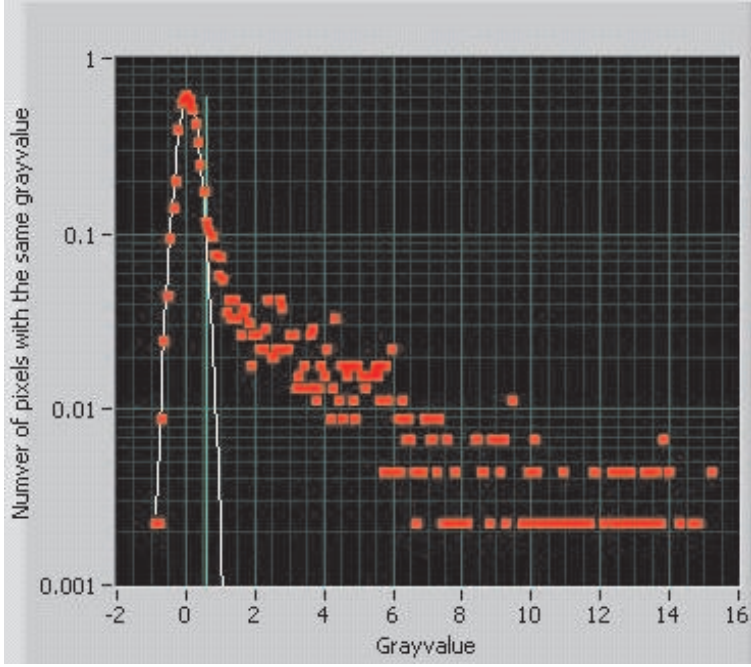


Figure 5: Frequency distribution of the integrated pixel content. The white curve is a Gaussian fit and represents the noise component.

5 Results

The initial commissioning of the emittance meter has been performed at the injection beam line of the AGOR facility at KVI using heavy-ion beams produced with the KVI-AECR ion source [1]. To illustrate the possibilities of the pepperpot emittance meter we show here a comparison with an Allison emittance scanner and a more detailed investigation on the substructure of the phase-space distribution of an ion beam extracted from an ECRIS. These measurements were performed with the A-Phoenix ECRIS at LPSC Grenoble. Figure 7 shows $x-x'$ phase-space distributions of a 210 keV Ne^{6+} beam measured both with the pepperpot emittance meter and an Allison scanner. Note that the pepperpot device was installed 30 cm behind the Allison scanner which explains the smoother shape of the pepperpot measurement. The normalized RMS emittances were 0.15 ± 0.01 and $0.18 \pm 0.02 \pi\text{-mm-mrad}$ determined with the pepperpot and Allison meters, respectively.

Unlike the Allison scanner, however, the pepperpot emittance meter allows to investigate substructures of the 4D phase-space distribution. To illustrate we show in figure 8 a partial $x-x'$ phase-space distribution of the 210 keV Ne^{6+} beam discussed above, but now only for vertical angles y' in the interval $-13 < y' < -11$ mrad. As can be seen, in this angular range the horizontal phase-space distribution consists of two horizontally displaced S-like substructures. Further analysis of the data shows that the left S-structure originates from the upper half half of the beam and the right S-structure from the lower half of the beam, see the middle and right parts of figure 8. This phase-space fractionation probably originates from plasma effects in the ion source itself. With the pepperpot emittance meter we can investigate how this fractionation depends on the ion source tuning and hopefully learn more about ECRIS physics.

6 Conclusions and outlook

This report describes an emittance meter based on the pepperpot principle that is capable of determining the full transversal phase-space distribution of low-energy heavy-ion beams in a few

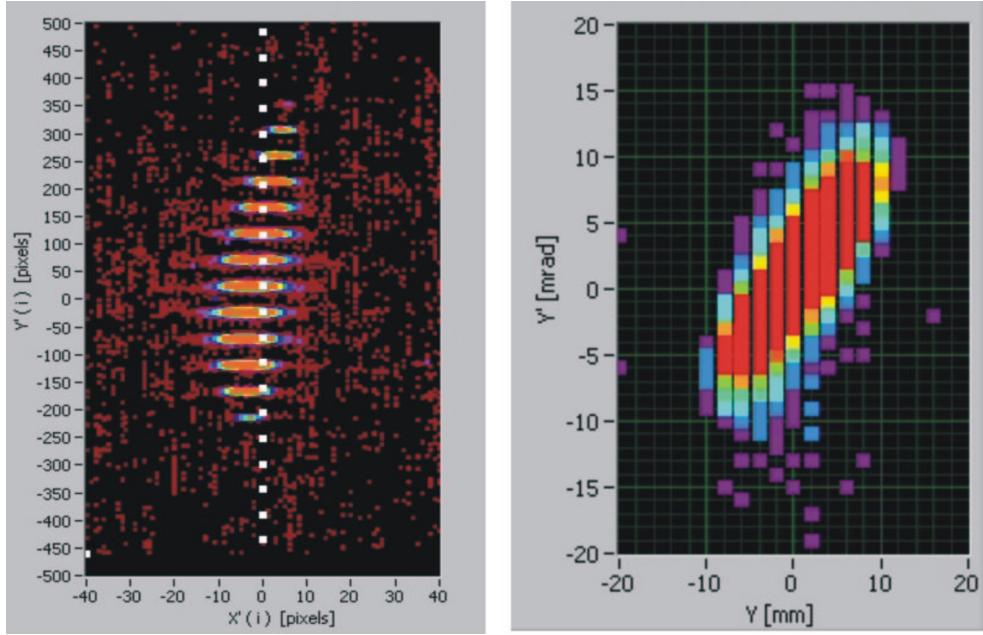


Figure 6: Left: Two-dimensional spatial profile of a 84 keV Ne^{7+} beam with the pepperpot plate positioned at $x = 0$. Right: A partial $y-y'$ emittance for $x = 0, x' = 0$ of the image shown on the left.

minutes. The instrument is mounted on a standard CF150 flange and can easily be installed behind an ion source to measure its emittance. Comparison of the pepperpot emittance meter with an Allison scanner at the A-Phoenix test stand at LPSC Grenoble shows good agreement. The added value of the pepperpot device is clearly displayed by showing the beam fractionation in the 4D phase-space which can not be seen with an Allison scanner. The attractive features of the pepperpot emittance meter, i.e. determination of the full 4D phase-space distribution including correlations between both transverse planes and short measuring times, will be very useful to study and improve the extraction and transport of low-energy and high-intensity heavy-ion beams.

References

- [1] H.R. Kremers, J.P.M. Beijers, S. Brandenburg, Proc. DIPAC2007, JACoW (2007)

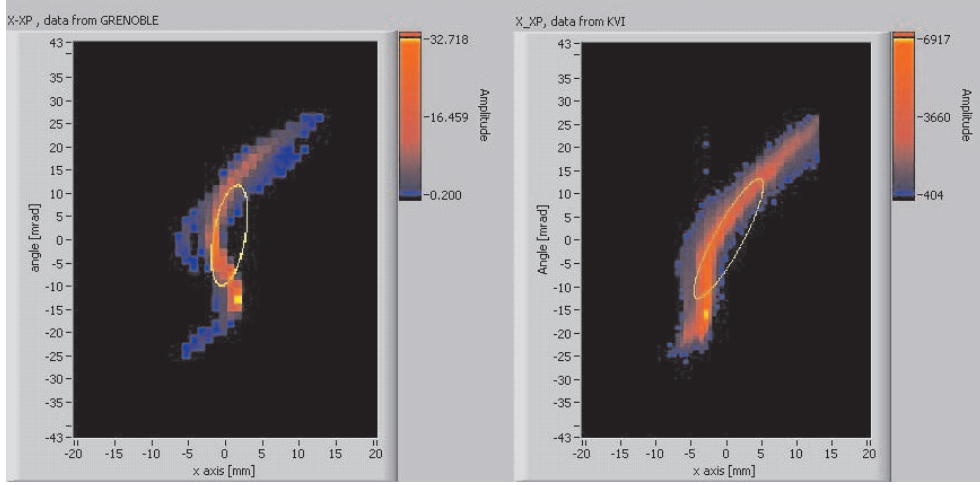


Figure 7: x - x' phase-space distributions of a 210 keV Ne^{6+} beam measured with an Allison scanner (left) and pepperpot emittance meter (right).

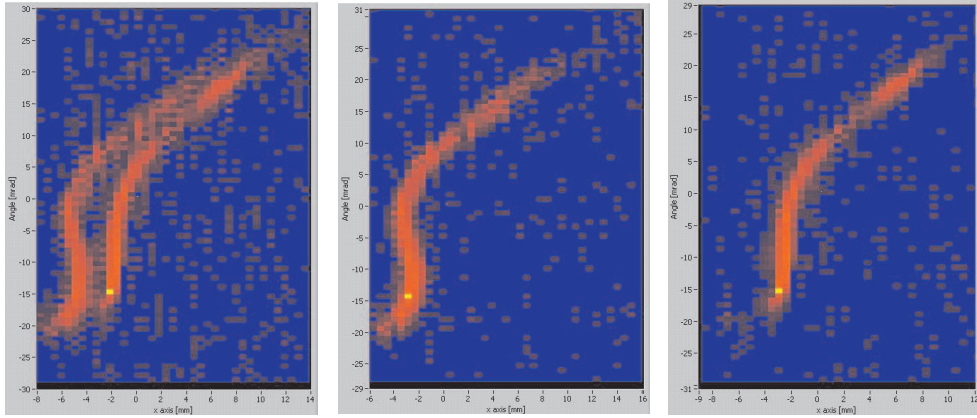


Figure 8: Left: Partial x - x' phase-space distribution of a 210 keV Ne^{6+} beam in the vertical angular range $-13 < y' < -11$ mrad. Middle: Same as left picture, but only for $0 < y < 20$ mm. Right: Same as left picture, but only for $-20 < y < 0$ mm.