FOUR-DIMENSIONAL EMITTANCE METER FOR DC ION BEAMS EXTRACTED FROM AN ECR ION SOURCE*

S. Kondrashev[#], A. Barcikowski, B. Mustapha, P. N. Ostroumov, ANL, Argonne, IL 60439, U.S.A.
N. Vinogradov, Northern Illinois University, De Kalb, IL 60115, U.S.A.

Abstract

We have developed a pepper-pot, scintillator-screen probe to measure the emittance of low-energy DC beams extracted from ECR ion sources. Different scintillators have been tested, and CsI (Tl) was chosen due to its high sensitivity, wide dynamic range and long life-time. A fast vacuum shutter with a minimum dwell time of 18 ms has been employed to reduce the scintillator degradation by ion beam irradiation. A CCD camera with shutter speed adjustable from 1 μs to 65 s has been used to acquire pepper pot images. The linearity of both the scintillator and the CCD camera has been studied. On-line emittance measurements are performed by an application code developed on the LabVIEW platform. The sensitivity of the device is sufficient to measure the emittance of DC ion beams with current densities down to about 100 nA/cm^2. The emittance of all ion species extracted from the ECR ion source and post-accelerated to an energy of 75-90 keV/charge have been measured downstream of the LEBT. Because of the two-dimensional array of holes in the pepper-pot, this emittance meter can be used to observe and study four-dimensional emittance correlations in beams from ECR ion sources.

INTRODUCTION

Ion beams extracted from ECR ion sources have a complicated structure in 4-D phase space [1]. The ion motion in the horizontal and vertical planes is strongly coupled due to the magnetic field configuration inside the source and extraction regions. Widely used slits and Alison type emittance scanners only provide 2-D projections of the beam emittance. A pepper pot emittance probe is the most suitable device to study 4-D ion beam emittance. Another significant advantage of the pepper pot probe is its short measurement time. 4-D emittance data can be obtained in less than 1 s on-line, allowing ECR ion source tuning to minimize emittance of the extracted ion beam. Previously, different scintillators were used to measure emittance of intense ion beams extracted from pulsed ion sources [2, 3]. However, there is almost no data on emittance measurements of DC ion beams with moderate intensities, which are typical for ECR ion sources, using a pepper-pot device coupled to a scintillator probe. The main challenge is the choice of a viewing screen that provides high sensitivity, a long life time, good linearity and a wide, dynamic range of measurements.

*This work was supported by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357.
[#]kondrashev@anl.gov

Our first tests of the pepper pot coupled to a CsI (Tl) crystal [4] have shown that the sensitivity of the probe is high enough to measure the emittance of DC ion beams with energy 75 keV per charge state for a variety of ion species from protons to heavy ions with current densities below 1 μA/cm^2.

DESIGN OF THE EMITTANCE PROBE

The structure of the pepper pot emittance meter is shown in Fig. 1.

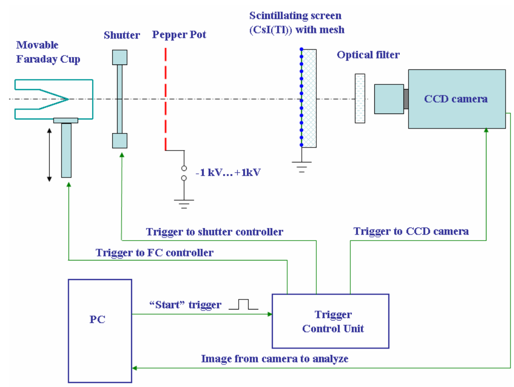

Figure 1: Emittance meter structure.

It consists of a movable Faraday cup (FC) equipped with a negatively biased suppression ring. The diameter of the FC input aperture is 46 mm. A compressed air cylinder drove the FC between two positions: in and out of the beam. The time required to complete the movement in both directions is about 1 s. The FC was used both as a detector of the ion beam current at the input of the emittance meter and as a beam blocker to protect the normally closed iris-type fast shutter from long time irradiation by a DC ion beam with a power of about 10 W. The normally closed iris-type UNIBLITZ-CS65S fast shutter with 65 mm aperture had an adjustable dwell time with a minimum of 18 ms and serves to protect the CsI (Tl) scintillator screen from possible degradation caused by DC ion beam irradiation. The tantalum pepper pot (PP) plate with a diameter of 70 mm and thickness of 380 μm had an aperture array over the whole area with 100 μm diameter holes with 3 mm spacing between them. An optical certification has shown that the diameters of all 415 holes were within the 100 – 104 μm range. The pepper pot plate was isolated from the ground and its potential can be varied in the range of ±1 kV to study the effect of secondary electrons on the emittance measurements. The CsI (Tl) scintillator screen with a diameter of 80 mm and thickness of 3 mm was placed at a distance of 100 mm downstream of the pepper pot plate.

To prevent charge build-up caused by the ion beam, a grounded fine nickel mesh with 88.6% transparency and 200 μm cell size was attached to the crystal surface being irradiated by ions. A CCD camera connected to a PC was used to acquire and save pepper pot images. Fig. 2 shows the time diagram of the FC, fast shutter and CCD camera triggering.

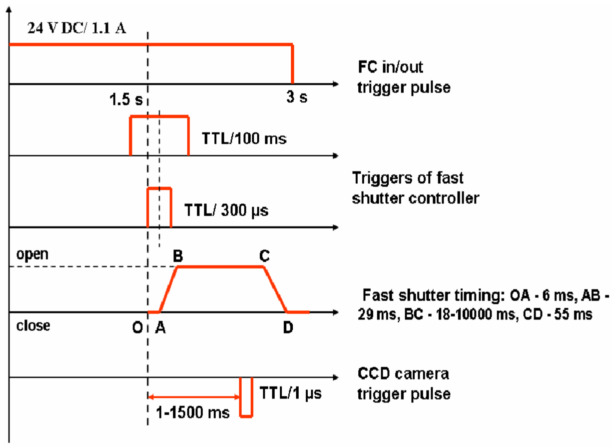

Figure 2: Emittance meter timing.

The operational cycle of the device consists of the following steps. First, the FC moves out of the beamline to allow the beam to pass to the closed iris of the fast shutter. Next, the shutter controller opens the iris for 100 msec to expose the PP plate. The image produced by the array of active beamlets on the crystal is acquired by the CCD camera and sent to the control PC for analysis. The cycle is completed by closing the fast shutter iris and returning the Faraday Cup back into the beam line. The overall cycle period is about 3 seconds and restricted by the time delay for moving the massive FC body. The actual time of acquiring the beam signal is defined by the camera settings (66 ms for the most of measurements). Processing of the acquired image is based on an algorithm similar to the one described in [5]. So far, two-dimensional codes are used for the data analysis while four-dimensional codes (x, y, x', y') will be developed in the future to take a full advantage of the 4-D pepper pot emittance probe.

The emittance probe has been used to measure the emittance of ion beams extracted from a high-intensity ECR ion source. The probe was placed at the end of the injector. The injector consists of an ECR ion source, a 100-kV platform and an achromatic LEBT system based on two 60° bending magnets [6]. The ECR ion source was built using all permanent magnets and is described elsewhere [7].

CCD CAMERA AND SCINTILLATOR LINEARITY

The sensitivity of the emittance meter can be significantly enhanced by increasing the CCD camera gain and the shutter speed. The CCD camera shutter speed was normally kept unchanged during emittance measurements and the gain was varied depending on the ion beam intensity. The dependence of the emittance values on the CCD camera gain is shown in Fig. 3. The number of saturated CCD camera pixels depending on the CCD camera gain is plotted in Fig. 3 as well. One can see that the emittance increases with increasing CCD camera gain both below and above the saturation limit. The saturation limit corresponds to a CCD camera gain that is equal to 300 in Fig. 3. It is explained by the fact that low intensity tails of the ion beam phase space distribution become more and more visible to the emittance meter with increasing CCD camera gain. The emittance value will be not "true" in both regions below and above the saturation limit of the CCD camera. The most accurate emittance value should be found just at the boundary between saturated and non-saturated ranges (CCD camera gain is equal to 300 in Fig. 3). For all emittance measurement described below, a criteria for the number of saturated pixels to be between 1 and 10 was used.

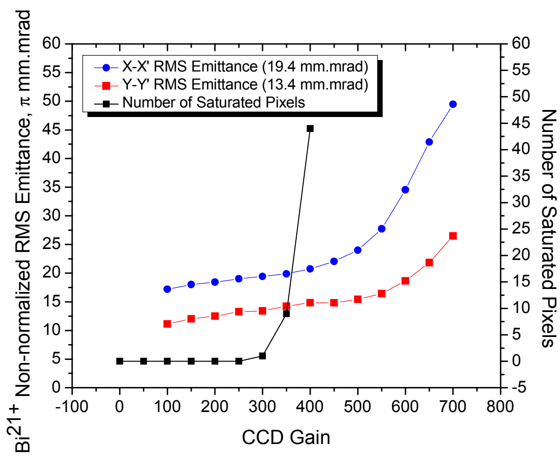

Figure 3: Emittance and number of saturated pixels as a function of CCD camera gain.

A special calibration PP plate was used to check the linearity of the CsI (Tl) scintillator. This plate has a 4x4 array of holes with diameters of 10 and 20 μm up to 300 μm (in 20 μm steps) with 5 mm spacing between them in both directions. If the diameters of the holes are much less than the diameters of their beam images (this condition was satisfied in our case) and ion beam distribution is homogeneous enough across the area occupied by the holes (15x15 mm^2 in our case), the diameters of the images are defined by the ion beam emittance and should be approximately the same for all holes. The ion current density at the scintillator surface should also be proportional to the square diameter of each hole. If the scintillator has a linear response, both maximum and integrated intensity of light recorded by the CCD camera should follow this relation too. The main challenge in these measurements was obtaining a homogeneous irradiation of the calibration PP plate. First the pepper pot with 100 μm holes was irradiated by beams of different ion species to study the homogeneity of the beams themselves. Very large spatial fluctuations in ion beam intensity (3 – 10 times over 15x15 mm^2 central area) were found for focused ion beams of different ion species. Homogeneity was improved to about 40 – 50% in the best cases by switching off all electrostatic quads along LEBT. At the same time, ion current density dropped by about a factor of 5 at the entrance of the emittance meter.

The dependence of integrated light intensity on the diameter of the calibration pepper pot holes for a Bi^{20+} ion beam is presented in Fig. 4. As one can see, no evidence of saturation was found. Fluctuations around the expected curve are within homogeneity of irradiation. Similar dependence was found for an O^{6+} ion beam. The obtained results also show that the CsI (Tl) crystal dynamic range is better than 50.

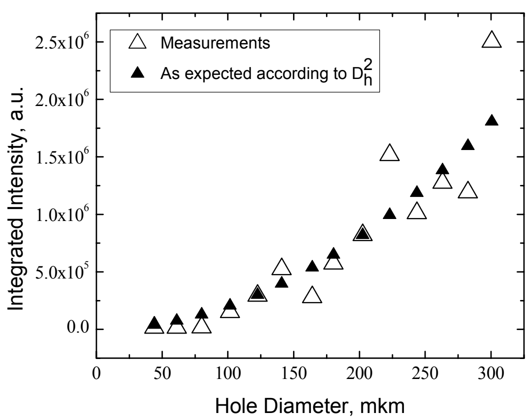

Figure 4: Integrated intensity as a function of hole diameter for Bi^{20+} ion beam irradiation (energy – 1.5 MeV, current density at pepper pot plate – 0.4 μA/cm^2).

EMITTANCE MEASUREMENTS FOR ALL ION SPECIES EXTRACTED FROM ECRIS

The dependence of the normalized x-x' and y-y' rms emittance on the mass to charge state ratio are presented in Fig. 5 for all ion species extracted from the source.

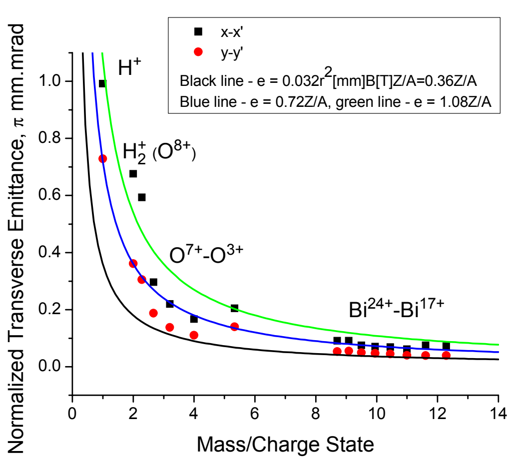

Figure 5: Normalized x-x' and y-y' rms emittance as a function of mass-to-charge-ratio for different ion species extracted from the source.

The black line in Fig. 5 shows the expected emittance dependence under the assumption that emittance is fully defined by beam rotation (angular momentum) induced by the ion source magnetic field [8]. The blue and green lines are the results of multiplication of this dependence by a factor of 2 and 3, respectively. The emittance significantly decreases with an increase in ion mass or a decrease in ion charge state and the measured values are typically ~2 times the angular momentum limit.

CONCLUSION

A 4-D emittance meter based on a pepper pot - scintillator screen has been developed for on-line measurements and was used to study the emittance of DC ion beams extracted from an ECR ion source. Special attention was paid to the linearity of the emittance measurements:

- No saturation of the CsI (Tl) scintillator was found for typical ion current densities of ECR ion sources
- Emittance measurement errors can be minimized by choosing a CCD camera gain and shutter speed just at the boundary of CCD saturation.

The emittance was measured for several ion species extracted from the ECR ion source and it was found that:

- The dependence of emittance on ion mass-to- charge-state ratio follows qualitatively well the dependence due to beam rotation induced by a decreasing ECR axial magnetic field
- The measured emittance values can not be explained by angular momentum effects only; contributions due to ion temperature in the plasma, non-linear electric fields, or non-linear space charge are comparable
- The emittance increases with charge state for both oxygen and bismuth ions

ACKNOWELEDGEMENT

The authors are grateful to R. H. Scott for his help with the ECR ion source operation, to M. Anthony, P. Wilt and S. I. Sharamentov for their electronics support, and to A. Pikin for discussions about the pepper-pot technique.

REFERENCES

[1] P. Spadtke, et al., Rev. Sci. Instr. 79, 02B716 (2008).
[2] R. Scrivens, Extraction of an Ion Beam from a Laser Ion Source, Ph.D. thesis, Physics Department, University of Wales Swansea, May 1999.
[3] A. Sidorov, et al., Rev. Sci. Instr. 79, 02A313 (2008).
[4] S. Kondrashev, et al., "Experimental results on multi-charge-state LEBT approach," PAC'07, Albuquerque, June 2007, TUPAS003, p. 1658 (2007); http://www.JACoW.org.
[5] A. Pikin, A. Kponou, J. Ritter, V. Zajic, Pepper pot emittance meter, BNL note C-A/AP/#244, July 2006.
[6] P. N. Ostroumov, et al., Submitted to Phys. Rev. Lett.
[7] D. Z. Xie, Rev. Sci. Instr., 73(2), 2002, p.531.
[8] D. Leitner, et al., Nucl. Instr. And Meth. In Phys. Res. B, v. 235, 1-4, p. 486.