EMITTANCE MEASUREMENTS OF ION BEAMS EXTRACTED FROM HIGH-INTENSITY PERMANENT MAGNET ECR ION SOURCE*

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Abstract

A pepper-pot – scintillator screen system has been developed and used to measure the emittance of DC ion beams extracted from a high-intensity permanent magnet ECR ion source. The system includes a fast beam shutter with a minimum dwell time of 18 ms to reduce the degradation of the CsI(Tl) scintillator by DC ion beam irradiation and a CCD camera with a variable shutter speed in the range of 1 μs to 65 s. On-line emittance measurements are performed by an application code developed on a 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. As the mass-to-charge ratio of ion species increases, the normalized RMS emittances in both transverse phase planes are reduced from 0.5-1.0 π mm·mrad for light ions to 0.05-0.09 π mm·mrad for highly charged ^{209}Bi ions. The dependence of the emittance on ion's mass-to-charge ratio follows very well the dependence expected from beam rotation induced by decreasing ECR axial magnetic field. The measured emittance values can not be explained by only ion beam rotation for all ion species and the contribution to emittance of ion temperature in plasma, non-linear electric fields and non-linear space charge is comparable or even higher than the contribution of ion beam rotation.

INTRODUCTION

During the last few years it became evident that ion beams extracted from ECR ion sources have complicated structure of both spatial and phase space distributions [1]. The ion motion in the horizontal and vertical planes is strongly coupled due to the magnetic field configuration inside the source and extraction region. Slits and Alison type emittance scanners, which were widely used previously, can not provide full information about such distributions. 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 the very short time of measurements. 4-D emittance data can be obtained in less than 1 s on-line, allowing ECR ion source tuning to minimize the emittance of extracted ion beams. Different scintillators were used previously to measure the emittance of intense ion beams extracted from pulsed ion sources [2, 3]. However, there are almost no data on emittance measurements of DC ion beams with moderate intensities typical for ECR ion sources using a pepper pot coupled to a scintillator probe. The main challenge is the choice of the viewing screen to provide high sensitivity, long life time, linearity and wide dynamic range of measurements. In most cases these parameters are unknown or not well known.

Our first tests of a pepper pot coupled to a CsI (Tl) crystal [4] show that the sensitivity of the probe is high enough to measure 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 even below 1 μA/cm^2. The simple COHU 2600 [www.cohu.com] monochrome CCD camera with shutter speed 60 frames per second has been used in these measurements. It is obvious that the sensitivity can be significantly enhanced using a CCD camera with longer integration time and higher gain. In this paper we describe recent developments of the pepper pot emittance probe based on a CsI (Tl) scintillator. A fast in-vacuum shutter with a minimum dwell time of 18 ms was employed to reduce the scintillator degradation by DC ion beam irradiation. A PC connected IMI TECH IMB-147FT 12-bit Firewire Monochrome [www.imi-tech.com] digital CCD camera with shutter speed variable in the range of 1 μs to 65 s and adjustable gain was used to acquire and save pepper pot images. On-line emittance measurements were performed by an application code developed on LabVIEW [www.ni.com] platform. The linearity of the emittance meter was studied. The emittance meter was used to measure the emittances of all ion species extracted from the high intensity permanent magnet ECR ion source.

EXPERIMENTAL SETUP

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

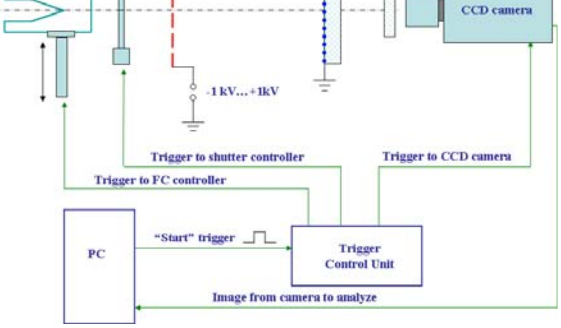

Figure 1: Emittance meter structure.

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It includes a movable Faraday cup (FC) equipped with negative voltage suppression ring. The FC is shielded from secondary particles by outer grounded cylinder. The diameter of FC input aperture is 46 mm. The FC was driven by a compressed air cylinder. The time required to insert or remove the cup is about 1 s. The FC was used both as a detector of ion beam current at the input of the emittance meter and as a slow shutter to protect the normally closed iris-type fast shutter from long time irradiation by the DC ion beam with a maximum power of about 10 W. The normally closed iris-type UNIBLITZ-CS65S fast shutter with aperture 65 mm has an adjustable dwell time of 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 plate with diameter 70 mm and thickness 380 μm has an aperture array over the whole area with holes 100 μm diameter and 3 mm spacing. Optical certification has shown that diameters of all 415 holes were within 100 – 104 μm range. The pepper pot plate was isolated from ground and its potential can be varied in the range of ±1 kV to study the effect of secondary electrons on the emittance of ion beam. A CsI (Tl) scintillator screen with diameter of 80 mm and thickness of 3 mm is placed at a distance of 100 mm downstream of the pepper pot plate. A grounded fine Nickel mesh with transparency 88.6% and cell size of 200 μm was attached to the crystal surface irradiated by ions to prevent charge build-up caused by ion beam. The 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. The time structure of the fast shutter opening and closing is shown in Fig. 2 as well. The scintillator screen pre-irradiation time (time between beginning of DC ion beam screen irradiation and pepper pot image acquiring) can be varied up to 1.4 s.

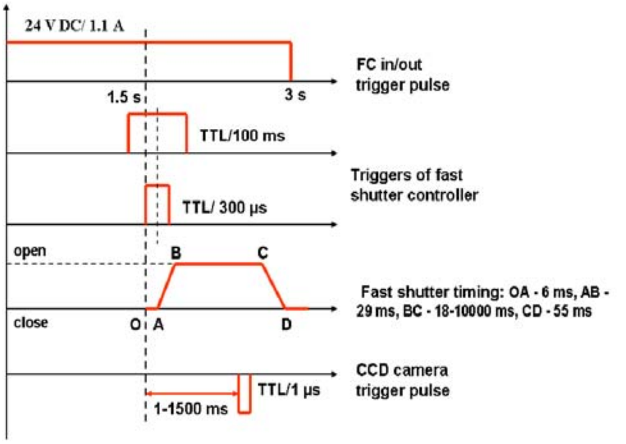

Figure 2: Emittance meter timing.

The operational cycle of the device consists of few steps. First, the Faraday Cup moves from the beamline axis to allow the beam to the closed iris of the fast shutter. Next, the shutter controller opens the iris for 100 msec to expose the scintillator to the beamlets from the PP plate. The image produced by the array of active beamlets on the crystal is acquired by 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 most measurements).

The results on emittance probe linearity and influence of pepper pot potential and scintillator pre-irradiation time on emittance measurements are presented in the paper "Development of a novel emittance probe and its application for ECR ion beam studies" submitted to Nuclear Instruments and Methods.

The emittance probe was used to measure the emittance of ion beams extracted from a high-intensity permanent magnet ECR ion source. The probe was placed at the end of the injector shown in Fig. 3.

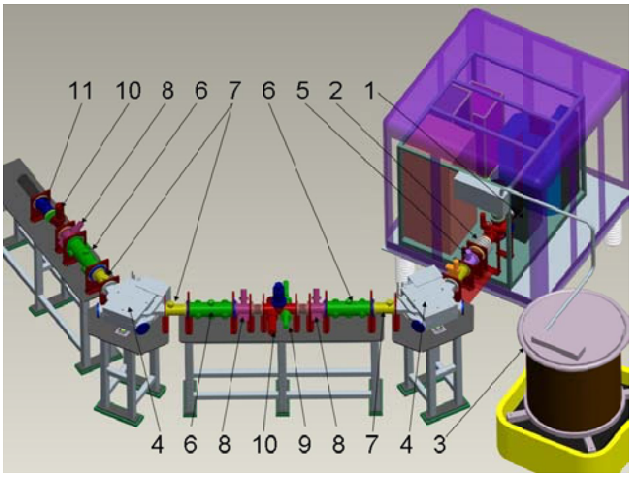

Figure 3: General view of the injector. 1- All permanent magnet ECRIS installed on HV platform, 2- 75-kV accelerating tube, 3- isolation transformer, 4- 60° bending magnet, 5- Einzel lens, 6- electrostatic triplet, 7- electrostatic steering plates, 8- rotating wire scanner, 9- horizontal slits, 10- Faraday cups, 11- emittance probe.

The injector consists of an ECR ion source, a 100-kV platform and an achromatic LEBT system based on two 60° bending magnets. The ECR ion source is built using all permanent magnets and it is described in more detail elsewhere [5]. The main parameters of the source are listed below:

- Axial peak field (injection region) – 13 kG
- Axial field at extraction – 6.6 kG
- Axial central magnetic field – 4.2 kG
- Maximum radial field (at chamber wall) – 11 kG
- Aluminum plasma chamber: length – 17.5 cm, diameter – 6.4 cm
- Extraction aperture – 8 mm
- Heating: 2 kW/14 GHz klystron + 700 W/12.75-14.5 GHz TWT RF amplifier
- Extraction potential – up to 25 kV

- HV platform potential – up to 75 kV

The high voltage (HV) platform accelerates all ion species extracted from the ECR source to higher energy to reduce the influence of space charge effects in the LEBT. Ion beam focusing along the LEBT is provided by electrostatic Einzel lenses and quadrupole triplets. Rotating wires are used for beam profile measurements and ion beam alignment. The injector allows us to accelerate all ion species up to q×100 keV total kinetic energy, where q is the charge state of the ion.

Our injector differs from any other ECR source on HV platform currently used in various applications worldwide. Specifically, we extract all ion species available from the ECR source and analyze them after acceleration by the platform potential. A bismuth ion beam was produced using an oven heated to about 550°C. The ECR is equipped with two RF amplifiers set to 12.8 GHz and 13.8 GHz with total available RF power up to 2.7 kW. Oxygen is used as a support gas to enhance the intensity of higher charge states of ^{209}Bi ions.

CURRENTS OF DIFFERENT ION SPECIES

For all the measurements described below the bismuth ion beam is first extracted by applying a 15 kV source potential and then accelerated by a 60 kV platform potential. To analyze the beam, a 36 mm aperture Faraday cup (FC1) equipped with a suppression ring is installed downstream of the first 60° magnet to record the beam current. After few days of source conditioning and tuning, we were able to obtain stable ion beam. Figs. 4 and 5 shows the currents of all ion species extracted from the source and zoomed currents of bismuth ions with different charge states respectively.

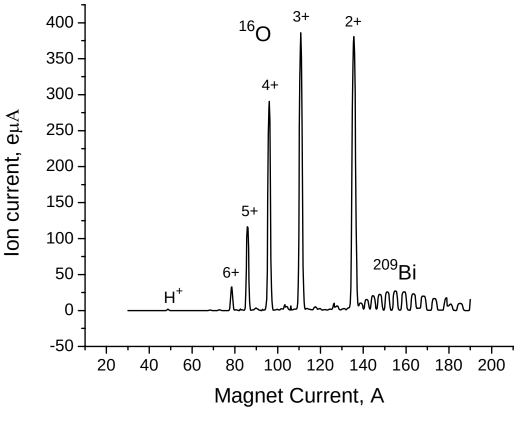

Figure 4: Currents of all ion species measured downstream the first bending magnet.

The currents of all ion species extracted from the source and measured downstream from the first magnet are summarized in Table I.

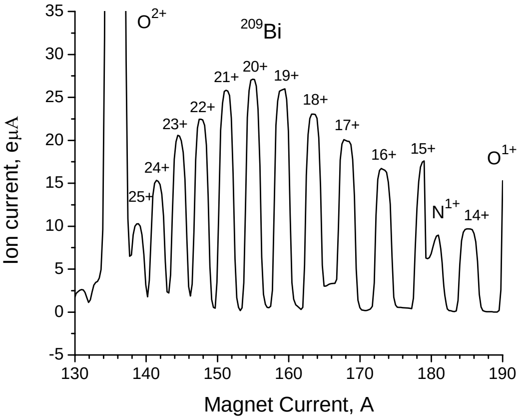

Figure 5: Currents of bismuth ions measured downstream the first bending magnet.

The sum of all currents in Table I is equal to 1.8 mA (current of O^{1+} ions is supposed to be 370 μA according to tendency of oxygen ions distribution). The total ion current extracted from the source is equal to 3.8 mA. It means that the total transmission from the source exit to FC1 can be estimated to be about 47%. Transmissions from FC1 to FC2 for all ion species extracted are shown in Fig. 6.

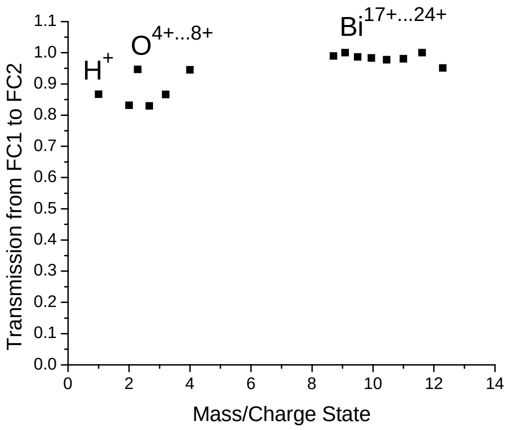

Figure 6: Transmission from FC1 to FC2 for different ion species.

FC2 is installed downstream of the second 60° magnet in front of the emittance probe. Using these data, the total transmission from the source exit to the emittance probe can be estimated to be in the range of 40 – 47% for all ion species. All the results of emittance measurements presented and discussed in this paper were obtained for these transmitted fractions of ions.

Table I: Currents of all ion species measured downstream the first bending magnet

El.	Hydrogen		Oxygen						Bismuth											
Ion	1+	2+	7+	6+	5+	4+	3+	2+	25+	24+	23+	22+	21+	20+	19+	18+	17+	16+	15+	14+
I, μA	2	0.6	1.0	32	118	292	387	378	10	15	21	23	26	27	26	23	20	17	12	10

EMITTANCE MEASUREMENTS FOR DIFFERENT ION SPECIES

The emittance was measured for all ion species listed in Table I. The following procedure was implemented for all ion species before each measurement:

- Beam was centered along LEBT by adjusting both bending magnets
- Slits were scanned to measure the spatial distribution of different ion species
- Slits were set to select a single ion specie.

An example of slit scan for Bi ions with charge states 22+ -24+ is presented in Fig. 7.

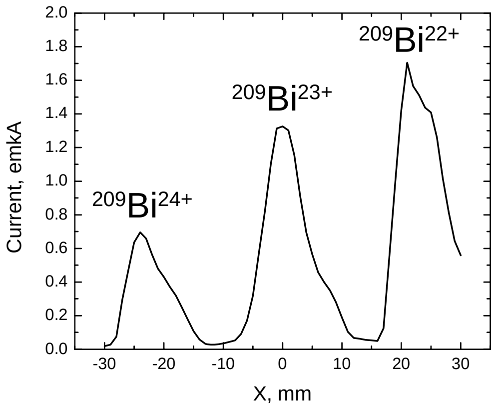

Figure 7: Slit scan for Bi ions with charge states 22+ - 24+.

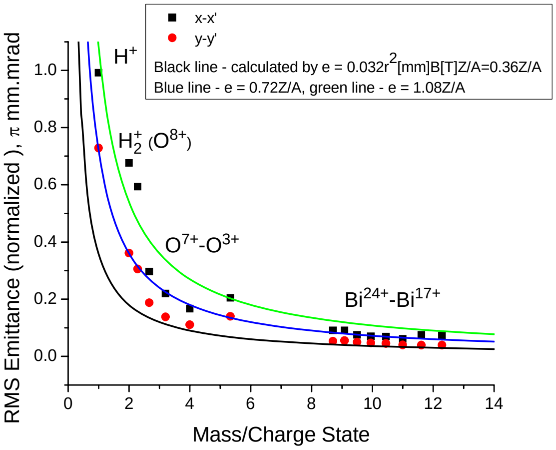

Figure 8: Dependences of normalized x-x’ and y-y’ rms emittance on mass to charge state ratio for all ion species extracted from the source.

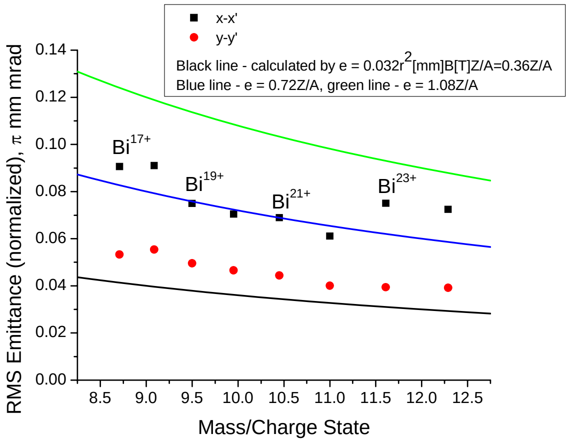

Figure 9: Enlarged fragment for highly charged Bi ions.

One can see that spatial resolution is good enough to select the single charge state (23+ in this case) by adjusting slit positions. The spatial resolution was better than the one shown in Fig. 7 for all other ion species extracted from the source. Each ion specie was easily separated from all others for emittance measurements.

The dependence of the normalized x-x’ and y-y’ rms emittances on the mass-to-charge ratio is presented in Fig. 8 for all ion species extracted from the source. An enlarged fragment of this dependence for highly charged Bi ions is shown in Fig. 9. Taking into account the transmission from source exit to the emittance meter estimated above, emittance of 40 – 48% of each ion species extracted from the source was measured. The black line in Fig. 8 shows the expected emittance dependence under the assumption that emittance is fully defined by beam rotation induced by the decreasing ion source magnetic field [7]. The blue and green lines are the results of multiplication of this dependence by factor 2 and 3. One can see that emittance decreases significantly with increasing ion mass or with decreasing ion charge state. The experimental dependence of emittance vs mass-to-charge state follows very well the dependence defined by beam rotation only. One can conclude that ion beam rotation has very strong influence on the emittance of ion beams extracted from ECR ion sources. But, the measured emittances are 2 – 3 times higher than predicted by ion beam rotation. The contributions to the emittance of ion temperature in plasma, non-linear electric fields and non-linear space charge are comparable or even higher than the contribution of ion beam rotation. The measured x-x’ emittances are always higher than y-y’ emittances for all ion species extracted from the source. This can be explained by both higher x-x’ acceptance of the first bending magnet and asymmetric ion beam distribution at ECR exit.

DEPENDENCE OF EMITTANCE ON BIASED DISC POTENTIAL

The influence of biased disc potential on the emittance was studied for the Bi^{20+} ion beam. The dependences of emittance on biased disc potential are presented in Fig. 10.

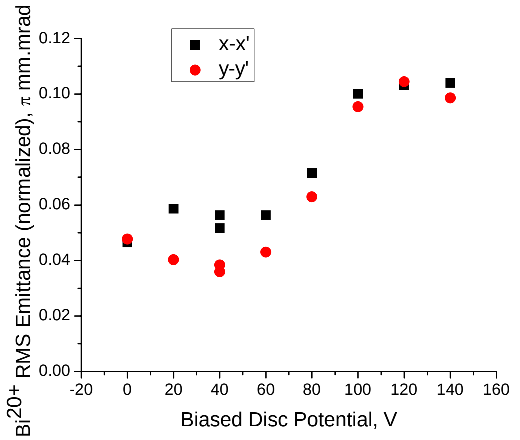

Figure 10: Dependences of Bi^{20+} ion beam emittance on biased disc potential.

The dependences of Bi^{20+} ion beam current at the entrance of emittance meter and total current extracted from the source on the biased disc potential are shown in Fig. 11. All values for biased disc potential equal to -40 V were measured twice: in the beginning and in the end of measuring cycle. The emittance is minimal and Bi^{20+} ion beam current is maximal for biased disc potential equal to -40 V. It means that the brightness of Bi^{20+} ion beam is well peaked for -40 V biased disc potential. The ratio of x-x' and y-y' emittance values depends on the biased disc potential as well.

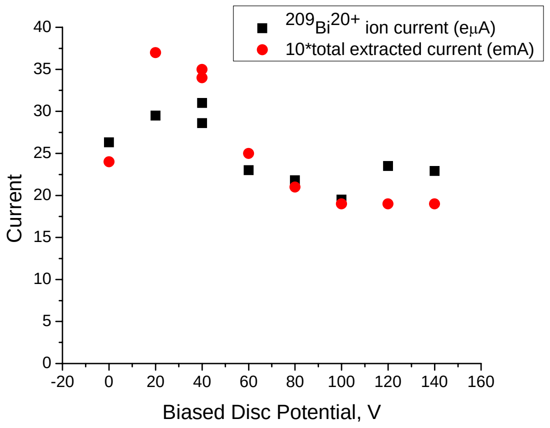

Figure 11: Dependences of Bi^{20+} ion beam at the entrance of emittance meter and total current extracted from the source on biased disc potential.

CONCLUSION

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

The emittance was measured for about 40 – 48% of each ion species extracted from ECR ion source and it was found that:

- Dependence of emittance on ion mass over charge state ratio qualitatively follows very well the dependence due to beam rotation induced by decreasing ECR axial magnetic field
- Measured emittance values can not be explained by only ion beam rotation for all ion species and contributions to emittance of ion temperature in plasma, non-linear electric fields and non-linear space charge are comparable or even higher than the contribution of ion beam rotation
- Emittance increases with increasing of charge state for both oxygen and bismuth ions
- Emittance and brightness can be optimized by biased disc potential

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