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Highly charged ion beam diagnostics at the mVINIS Ion Source

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Abstract. In order to determine position, dimensions and intensities of multiply charged ion beams at the mVINIS Ion Source, a novel method was developed based on a fluorescent screen and a commercial digital TV camera. The spatial characteristics of multiply charged ion beams (for example the ionization states of Ar^{2+} to Ar^{10+}) have been precisely measured and analyzed at the TESLA Accelerator Installation for the first time. In this work, we discuss in details the characteristics of Ar^{8+} ion beams. The obtained ion beam characteristics were compared with the results of previously applied conventional methods of ion beam diagnostics.

1. Introduction

In the 'Vinča' Institute of Nuclear Sciences, the TESLA Accelerator Installation consists of an isochronous cyclotron (VINCY), a positive and negative ion source for obtaining light ion beams (pVINIS), a multiply charged heavy ion source (mVINIS), and several low energy and high energy experimental channels [1].

The mVINIS Ion Source, a room temperature electron cyclotron resonance ion source (ECRIS), was designed and constructed in the joint cooperation with the Flerov Laboratory of Nuclear Reaction, JINR in Dubna, Russia [2], [3]. For almost ten year operation, it has been producing ion beams from gases (He, N_2, O_2, Ne, Ar, Kr, Xe) [4] as well as from solid materials (B, C, Fe, Zn, Pb, Hf etc) [5]. A very important part of our accelerator installations is the ion beam diagnostics at low energy (up to 500 keV) as well as at the high energy sides (up to 60 MeV).

The measurements of ion beam characteristics were based on standard elements of diagnostics (Faraday cup, moving slits, profile-meters etc.). For optimizing the beam transport from the ion source either to the low energy experimental channels or to the cyclotron, a high-quality measurements of ion beam characteristics emerged. A novel method was developed based on the interaction of ions with new fluorescent materials and data acquisition by CCD cameras. We present in this work the measurements of positions, dimensions and intensities of multiply charged ion beams.

2. Experimental set-up

A Faraday cup was used mostly in old set-up for the ion beam diagnostics. It provides only information about the current of a positively charged particle beam, i.e. about the intensity of a part of a beam, which passed through the circular aperture. In this way, we can measure the beam currents in

the range from 10 nA to 2 mA. We use the standard Faraday cup of aperture of $\varnothing$=20 mm with a "bias" electrode at the negative potential (-120 V) and the calibrated linear preamplifier (DANPHYSIK model 537/548 System 5000). A moving slit in X direction defines the maximum beam width in the focal plane. The transversal X-Y profiles were recorded by scanning wire probe. This instrument provides a rough data about shape, dimensions and position of an ion beam. It was not possible to measure the important ion beam characteristics - the transversal emittance - by using already existing diagnostic tools.

The ion beam spatial characteristics are essential for high-quality adjustment of the ion source and the ion beam transport efficiency at low-energy channels. The main problem at the experimental channel L3A for the modification of material is a low transmittance of multiply charged ions (30%) [4], so that gives rise to additional development of the advance diagnostic methods.

We present a novel method for the high resolution digital measurements of spatial dimension of multiply charged ion beams at the mVINIS Ion Source. The ion beams from the source are being directed to a new diagnostic box. In this diagnostic box a fluorescent screen of KBr salt is mounted at 45 degrees with respect to the direction of ion beam propagation. When the multiply charged ions hit the screen, bromine atoms are being strongly excited in salt crystals. Light at 45 degrees with respect to the screen and at the right angle with respect to the incident ion beam propagates trough a vacuum window of diagnostic box and it is recorded by a digital camera (see figure 1(a)). The commercial CCD video camera Sanyo VCC-5984 was put in front of the glass vacuum window. The distance between the screen and the CCD chip was 390 mm. The image resolution was (H x V) 520 x 350 TV lines. The ratio signal/noise (S/N) for video signal of 48 dB enables us to distinguish 256 levels of light intensity [6]. The image magnification and sharpness were adjusted by a COMPUTAR lens of the variable focal length 5-50 mm. A camera exposure time can be selected by electronic shutter settings from 1/10000 to 1/60 seconds. A PC TV card Pixel View digitalizes incoming analogous signal from camera. Its software enables the acquisition of the individual images or video sequences (30 frames per second).
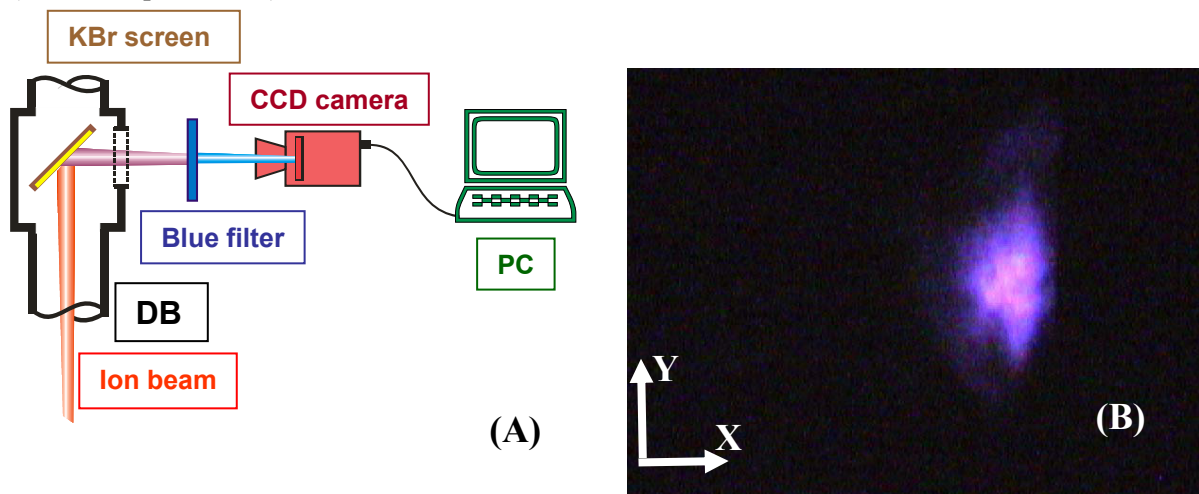

Figure 1. (A) Experimental setup of the new method of measuring beam characteristics consists of: DB diagnostic box, fluorescent screen, blue filter, CCD camera and PC. **(B)** Unsaturated 2D digital image of Ar^{8+} ion beam (E = 120 keV and I = 50 eμA) recorded at the KBr screen in the blue range of visible spectrum for the exposure time of 1/60 sec. Vacuum pressure of 1×10^{-6} mbar was unperturbed.

During first experiments, we noticed in the images a large area with maximum intensity (saturated CCD detector). In the interaction of multiply charged ions and solids of fluorescent screen of a large number of discrete atomic states is excited. In spectral range of 300 – 850 nm, bromine radiates 79 very intensive lines [7]. The band pass filter in the range of 400 to 480 nm, placed in front of the

camera, enables us to detect only 13 Br I lines. Due to small relative intensities, the 11 potassium spectral lines can be ignored [8]. This enables us the ion beam detection up to 300 eμA (figure 1(b)).

3. Results

An applicative program in the MATLAB software package was developed to process a recorded images or whole movie up to 30 seconds (or 900 frames per sequence). This program performs complete analysis of ion beam characteristics for a loaded image (movie). First, it converts the color palette of a taken image from "true color" (2^{24} colors) into "grayscale" (2^8 shades of gray). Each image is processed as 2D matrix with each element corresponding to the image pixel. The value of every element presents the light intensity of the corresponding pixel. In the case of movie processing, our program arranges results of one image analyses into new sequences and it creates new movies of results (for example the calibrated 2D or 3D ion beam spectra recorded at the fluorescent screen).

Before the characterization of multiply charged ion beams, it was necessary to perform additional measurements in order to estimate the level of background noise, the magnification of optical system, the X-Y coordinate system origin, the calibration and reliability of the light intensity versus ion beam intensity, ion kinetic energy, charge states etc.

3.1. Ion beam position and dimensions

The resolution of recorded images (H x V) of 681 x 510 pixels was arbitrary selected and was kept constant during experiments. The spatial parameters were first calculated in pixels and then recalibrated in millimetres (see figure 2(b)). The amplification of optical system M, determined on the known values of different parts of fluorescent screen, was $M = 19.2 \pm 0.5$. Camera resolution of 520 x 350 TV lines defined the absolute error of measurement of all dimensions at CCD detector: Δu = 4.8 mm / 520 = 9.2 μm; Δv = 3.6 mm / 350 = 10.3 μm (pixel size 6.4x7.4 μm). The ratio of values at CCD detector (in micrometers) and values in image (in pixels) was k = 7.0 μm/pixel. The value k was constant throughout the whole measurement. Absolute errors of measurement of ion beam spatial characteristics (ΔX and ΔY) are obtained based on the error propagation law (1):

$$\Delta X = M \cdot \Delta u + p \cdot k \cdot \Delta M \qquad \text{and} \qquad \Delta Y = M \cdot \Delta v + q \cdot k \cdot \Delta M \qquad (1)$$

where p and q are quantities from a digital image (pixels), respectively in X and Y-axis. Absolute errors of measurement predominantly depend on absolute error of optical system magnification ΔM. Digital ion beam profiles were fitted with Gaussian functions using Levenberg-Marquardt method. The estimated characteristics of Ar^{8+} ion beam are presented in table 1.

3.2. Ion beam intensity

In our experimental setup, during the image acquisition, a D/A and A/D conversion were done and they both generated the noise. This noise contribution is dominant in comparison with the noise characteristic for a CCD detector (photon noise, readout noise etc). At recorded images, the light intensity was expressed in the range of 0 to 255 and an average noise level was 14. Therefore, we can conclude that from theoretical 8 bits of data on pixel intensity, we have only four reliable bits. That means, we can reliably distinguish 16 gray levels. When the image of an ion beam is transformed into a matrix before being processed, a mean value of noise is subtracted from each element. Summation of all matrix elements gives a measure of ion beam intensity. A three-dimensional image of Ar^{8+} ion beam is shown in figure 2(b). Total integral of light intensity I_{light} over all pixels is 6.06 rel.units.

By processing images of beams of differently charged Ar ions (Ar^{2+} to Ar^{10+}), a measure of light intensity for individual beams was obtained. The calibration of light intensity (relative unit obtained from image) into the beam current I_{beam} (in μA) was done by means of consecutively recorded currents in ion spectrum with Faraday cup. The data analysis data gave a conversion factor $C = I_{light} / I_{beam} /E_i$ where E_i is ion kinetic energy ($E_i=qU_{ext}$). Based on the argon ion beam measurements, we obtained the value of factor C= (1.03 ± 0.17) x10^{-3} rel.unit/μA/keV. It is possible to reduce relative error of 20%, introduced by conversion constant C in measuring current intensity from obtained images, reducing

the level of background noise, reducing screen roughness etc. A detailed study of multiply charged ion interaction with KBr crystals and excited light radiation will be expanded in future with ion beams of noble gases Kr ($q_{max} = 15+$) and Xe ($q = 9+$ to $24+$).

Table 1. Measurement results of Ar^{8+}ion beam characteristics.

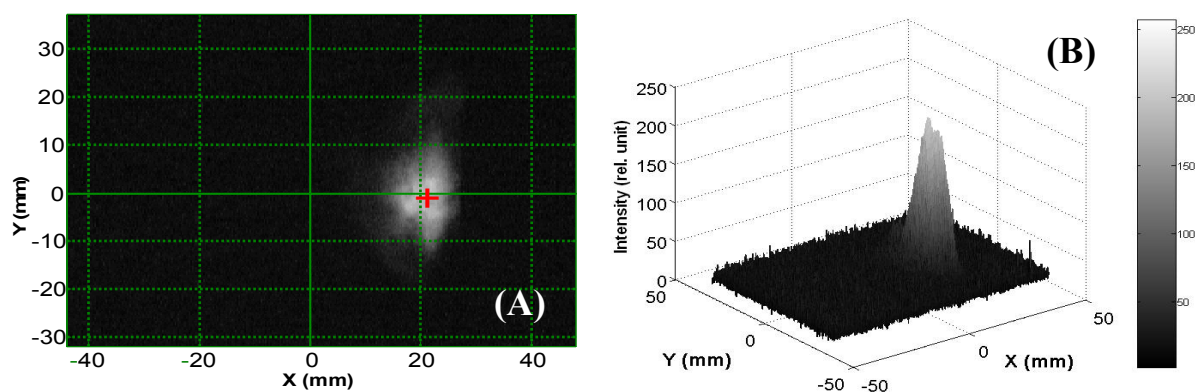| Characteristics	Value
Centroid (X_C)	(20.6 ± 0.7) mm
Centroid (Y_C)	(-0.5 ± 0.2) mm
FWHM (W_X)	(7.4 ± 0.4) mm
FWHM (W_Y)	(12.3 ± 0.6) mm
Beam area (A)	(71.5 ± 7.3) mm^2
Beam density (J)	(44 ± 4) eμA/cm^2
Particle density (J_p)	(5 ± 0.5) pμA/cm^2

Figure 2. (A) Two-dimensional image of Ar^{8+} ion beam with calibrated axes (in mm). The centroid of beam is marked by (+). **(B)** Three-dimensional image of Ar^{8+} ion beam intensity distribution.

4. Conclusion

For the first time, at the TESLA Accelerator Installation, the spatial characteristics of multiply charged ion beams were measured and analyzed in details. Measurements were carried out with different multiply charged ion beams but in the work only results obtained for Ar^{8+} beam are discussed. A new method has been developed for measuring position, dimensions and ion beam intensities, in order to improve the beam transmittance to low energy experimental channels. It offers also the possibility of indirect determination of ion beam emittance based on variable quadropole gradients. The application of described method will enable direct the high resolution measurement of beam transversal emittance.

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