DISTORTIONS OF PROTON BEAM 2-D IMAGES AND PROFILES DUE TO BEAM SPACE CHARGE

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Abstract

The special residual gas ion cross section monitor is used at Proton LINAC INR RAS output to provide measurements of beam parameters. There are distortions and errors of measurements which are caused by various external and internal factors during the formation of beam cross section images. Below estimations of these distortions and results of numerical simulation of registration process of images are resulted, resolution of the detector and accuracy of measurements are discussed.

INTRODUCTION

Beam cross section monitor (BCSM) of accelerated protons is installed at an output of INR linac about in 4 m behind last accelerating resonator. It gives the possibility to observe the next beam parameters during adjustment and exploitation of the linac: form of beam cross section (BCS), form of current impulse, beam position and its displacement concerning linac axis. Besides due to computer processing of images BCSM allows to observe distribution of density of the accelerated particles in BCS and beam profiles. Double dimension distribution of accelerated beam particles in BCS is more informative characteristic in comparison with profiles of a beam [1].

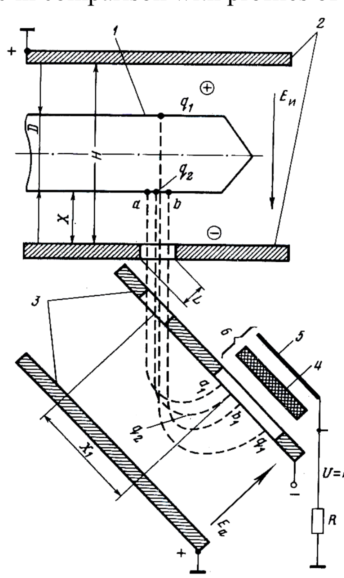

Fig. 1. Configuration design of the monitor:
1) Investigated beam 2) Condenser extracting ions
3) Analyzer of ions 4) Microchannel plates
5) Phosphor screen 6) Electro-optical converter

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The beam of the accelerated protons moves in the vacuum chamber of the accelerator and ionizes residual gas. Formed positive ions are extracted by homogeneous field of flat electrostatic condenser (extracting condenser) through a special slit in lower electrode of the condenser (Fig. 1). Accelerated gas ions pass the slit and form the taped beam. Then ions are rotated by a field of electrostatic energy analyzer (analyzing condenser) which electrodes are placed under 45 degrees to a direction of extraction of ions and to the plane of the extracting electrode. After that ions get to a double microchannel plate (MCP) of the electro-optical converter (EOC) with the coordinates depending on coordinates of an ionization point, creating the image of beam cross section registered TV-camera. Calculation of ion motion trajectory in homogeneous electrostatic fields shows that all kinds of positive ions compose the image [2].

THEORETICAL DESCRIPTION OF IONS DYNAMICS

Indeed nascent positive ion is under the influence of several kinds of fields (Fig. 2):

1) electrostatic field of the extracting condenser E_{ext} = 1,2 kV/cm (force F_{ext})
2) electromagnetic field of the beam which consists of radial electric field E_b (force F_E) and azimuth magnetic field B_b (force F_B).

The vector of the resultant force F_{Ion} isn't perpendicular to axis Y that causes broadening of BCS image (ΔY) along this axis under the influence of the beam space charge. In addition it is necessary to take into account ΔY-errors because of the finite width of the slit and nonzero initial velocities of the ions.

In our case the proton beam coasts at the interval L and expands significantly (by several digits) in a longitudinal direction under the law $\Delta\varphi = \frac{360 \cdot L}{\lambda \cdot \beta \cdot \gamma^2} \frac{\Delta p}{p}$ because of different value of impulses of accelerated particles $\Delta p / p \approx \pm 2 \cdot 10^{-3}$.

Therefore the beam length σ_z is much large than the transverse radii σ_x and σ_y. The appropriate charge distribution in this case is a Gaussian distribution in two dimensions with the constant line number density n:

$$\rho(x, y) = \frac{nq}{2\pi\sigma_x\sigma_y} \exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right).$$

In case of such azimuthally symmetric beam with two-dimensional charge Gaussian distribution the approximate formula for unique nonzero radial component of force acting upon an ion in a beam electromagnetic field was received in work [3]:

$$F_r(r) = \frac{nqQ\left(1 \pm \frac{v_0\beta}{c}\right)}{2\pi\varepsilon_0 r}\left[1 - \exp\left(-\frac{r^2}{2\sigma^2}\right)\right],$$

where the sign depends on a relative direction of speeds of an ion v_0 and a beam.

The beam in the detector point has the elliptic form with parameters $\sigma_x \approx 2$ mm, $\sigma_y \approx 1$ mm, $\beta = 0{,}575$, $n \approx 3{,}625 \cdot 10^8$ protons/m.

In this connection we shall assume that initial resultant force acting upon an ion from the beam has exclusively radial direction, but the absolute magnitude of this force is estimated in view of existing X, Y-axes normal distributions of charges. Such simplifications allow to execute the most realistic simulation in using of azimuthally symmetric beam model with two-dimensional Gaussian distribution of charge.

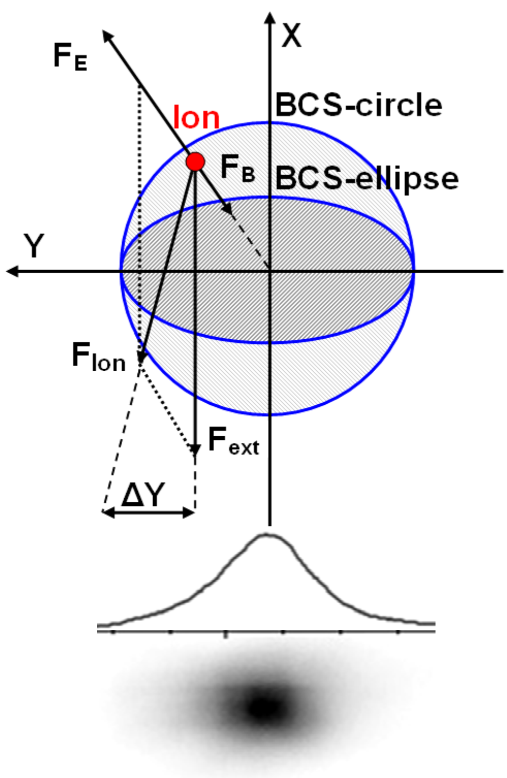

Fig. 2. Forces acting upon an ion and BCS with profile

The formed ions have various energy from 0 up to 0,025 eV. During modeling we shall assume, that initial velocities of hydrogen ions are evenly distributed to X, Y, Z-axes in the interval (–500 m/s, 500 m/s).

Besides we shall consider motion of only positive hydrogen ions (protons), because errors appearing at variation of weight and charge of an ion are negligibly small (around 0,1 percent at transition from a proton to fully ionized atom of nitrogen).

In our case force of the beam magnetic field is less than force of the beam electric field by six digits, therefore its influence on formed ions can be neglected.

Subject to using of various Gaussian distributions in calculations we shall consider, that the zone of ions formation in the residual gas is limited by 3σ.

Taking into consideration all foregoing approximations we shall consider that there are two forces acted upon a formed ion in the extracting condenser:

$$F_x(x,y) = -qE_{\text{ext}} + \frac{nq^2}{2\pi\varepsilon_0}\frac{x}{\left[x^2+y^2\right]}\left[1 - \exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right)\right],$$

$$F_y(x,y) = \frac{nq^2}{2\pi\varepsilon_0}\frac{y}{\left[x^2+y^2\right]}\left[1 - \exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right)\right],$$

which define distortions BCS images under influence of the beam space charge.

NUMERICAL SIMULATION

Program IonTrace with classical numerical Runge-Kutt method of 4-th order of accuracy and adaptive step was written for simulation. As required solutions are smooth enough adaptive step control provides the calculation of an approximate solution at fine mesh when solution changes quickly, and at crude mesh when it changes slowly. It allows to raise accuracy and to reduce time required for solution of the equations.

The primary goal of the program is an estimation of the errors in received BCS image in relation to the ideal image when there is no influence of a beam space charge and all initial velocities of ions are equal to zero.

Let's consider Y-axis distortions. We shall accept that during simulation Z-coordinate of all ions is equal to zero at birth. Final ΔY-distortions depending on ions birth coordinates in the vacuum chamber in case of nonzero initial velocities are presented in fig. 3 (Y-direction deflections up to ±160 μm).

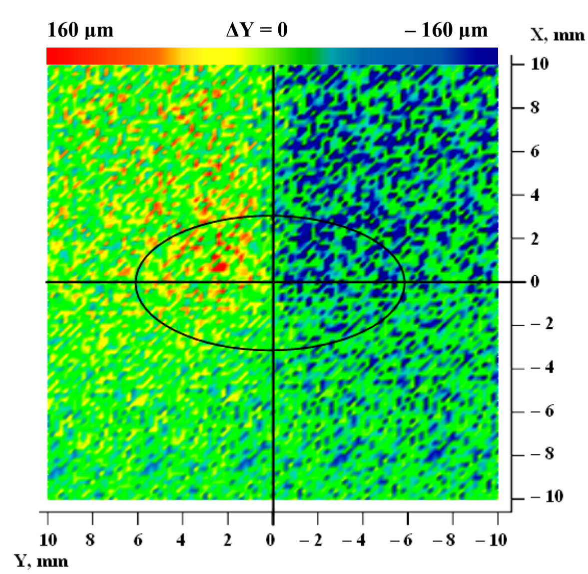

Fig. 3. Y-direction deflections ΔY of ions subject to born coordinates (X, Y)

The color spectrum from green to red corresponds to increasing of the deflections ΔY in a positive Y-direction, from green to violet – in a negative Y-direction, that is color in figure characterizes final deflection of the formed ion with birth coordinates X, Y. Such gradation of colors allows to allocate zones of the least and the greatest deflections of ions at MCP depending on their birth coordinates in relation to the center of a proton beam (marked by ellipse). Average deflections at Y-axis because of influence of the beam space charge are in the range of 100÷150 microns.

The maximum Y-deflection about 160 microns corresponds to an ion with birth coordinates from the zone of the greatest deflections and the worst vector of velocity (500, – 500, – 500) that is when the ion moves upwards against a beam motion that increases time of its staying in the detector.

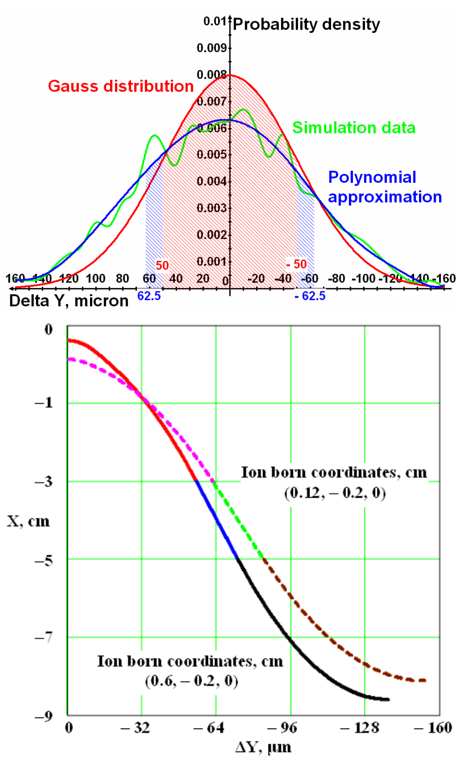

Fig. 4. Ions trajectories with max ΔY subject to born coordinates (X, Y)

Now we shall consider Z-axis errors. According to simulation average total time of an ion motion in the detector is less than 180 ns and time of motion in the extracting condenser is around 80 ns.

For such times ions with thermal velocities are shifted by Z-direction no more than 100 microns. However as shown in fig. 1 the finite width of the slit causes making of two parallel layers «a» and «b» of extracted ions.

Thus we receive several BCS imposed each other. Nevertheless as shown in [4] from the point of view of statistics, it gives small error under the law $\sigma^2_{measured} = \sigma^2_{beam} + L^2/12$, where L – width of the slit (L = 1 mm in the present version).

Resolution of the image is defined by resolution of a chevron MCP assembly in EOC (Fig. 5) which is estimated around 50 micron [5]. Thus we visual recognize final images of two ions if their hit coordinates at MCP differ in 50 microns at X, Y-axes.

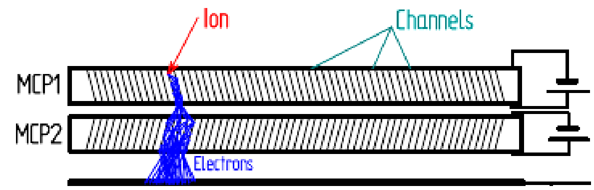

Fig. 5. Image formation mechanism in EOC

CONCLUSION

Considering the simulation data it is possible to tell with confidence that upper limit of the total error in BCS image received on MCP assembly doesn't exceed 30 microns. It is mainly defined by three independent parameters: a beam space charge, initial velocities of formed ions of residual gas and the split influence.

Thus Beam cross section monitor allows to register BCS images with inaccuracy around of 1% that is quite admissible result for the decision of problems of the operative visual control, diagnostics and correction of various parameters of a beam. Possible reduction of the slit size down to 0,1 mm will allow to receive BCS images similar to ideal: at a level of errors less than 1% and final image resolution of 50 microns.

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