ANALYSIS OF MEASUREMENT ERRORS OF INR LINAC IONIZATION BEAM CROSS SECTION MONITOR*

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Abstract

Residual gas ionization beam cross section monitors (BCSM) are installed at LEBT and HEBT of INR RAS proton linac to measure cross section, profiles and position of the beam. BCSMs provide two-dimensional non-destructive real-time beam diagnostics at linac operation with repetition frequency from 1 to 50 Hz, pulses duration from 0.3 to 200 µs and wide range of amplitudes, particle energy 400 keV and 209 MeV.

The analysis of systematic measurements errors (accuracy) because of nonuniform electrostatic fields, determined by BCSM design features, is presented. New detector model, minimizing these nonuniformities, is shown. Besides that, the analysis of statistical errors (precision) due to the method features, in particular, ions thermal motion and a beam space charge, is done.

The simulation results make it possible to estimate measured cross sections size, profiles and beam positions and to draw conclusions about the reliability of BCSM results for beams with various parameters.

INTRODUCTION

BCSM was proposed in [1, 2]. Configuration design and image processing system, realization features and some experimental results at INR linac were described in detail in [3, 4]. Secondary ion flux after extraction and subsequent energy analysis reproduces a beam cross section (BCS) at electron-optical converter. The image is optically transmitted to a CCD-camera.

BCSM is intended for measurements of the two-dimensional beam density distribution:

$$L(x,y,t) = \iint \rho(x,y,z,t)dzdt,$$

where x and y are transverse coordinates, z is a longitudinal one, $\rho(x,y,z)$ – is a beam density distribution, t – time. Integrating $L(x,y,t)$ over one of the transverse coordinates one can get a conventional beam profile along the other coordinate which is normally measured with wire scanners or one-dimensional ionization profile monitors.

BCS image is forming vertically (X-axis) and horizontally (Y-axis) under the different influence of the same factors, therefore it is necessary to describe each axis separately. Besides, the key measurable parameters are position of beam gravity center and rms beam size $\sigma_{measured}$. It is measurement errors of these parameters that determine accuracy, precision and consequently spatial resolution of the Monitor.

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NONUNIFORMITIES OF THE FIELDS

Formerly it was assumed that extracting and analyzing fields in the detector were uniform, but in fact because of BCSM design features these electrostatic fields always have some nonuniformities, which lead to errors in measurable coordinates of ions.

For X-axis systematic error is:

$$\delta X^{Fields}_{Gravity\ center} = X_{real} - X_{ideal},$$

where X_{real} – observed ion coordinate in case of real fields, X_{ideal} – ion coordinate in case of uniform fields.

Analysis of ions motion in real fields shows beam gravity center offset which is defined by initial coordinate at slit plane in extracting condenser (Fig. 1), however there is no influence on $\sigma_{X\ measured}$.

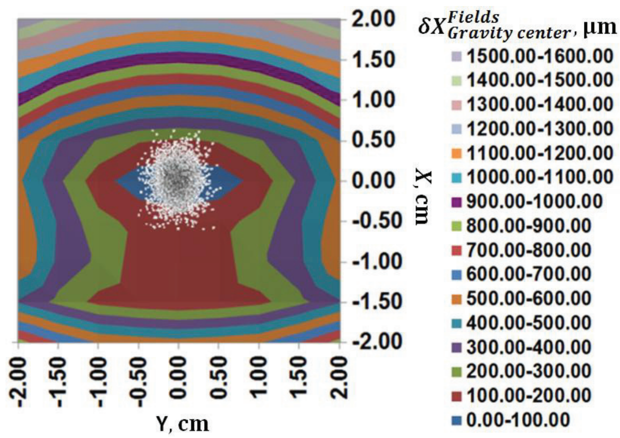

Figure 1: Beam gravity center offset depending on initial coordinates X/Y at slit plane in extracting condenser. Also beam region is shown in the center of this plane.

In case of Y-axis fields nonuniformities influence depends on not only initial coordinate, but also on rms beam size. Ions observed coordinates obtain systematic offset from condenser edges to Y-axis, that corresponds to effective decreasing ($\Delta Y^{Fields}_{rms\ size} = |Y_{real}| - |Y_{ideal}| < 0$) of observed rms beam size (Fig. 2):

$$\sigma_{Y\ measured} = \sqrt{\sigma^2_{Y\ real} - (\Delta Y^{Fields}_{rms\ size})^2}.$$

In order to minimize these errors new design of the Monitor was proposed (Fig. 3) and now being developed for operation in JINR project NICA at LU-20 and HILAC.

New design contains extra correction electrode, and also general Z-axis symmetry of extracting condenser is provided. Fields simulation results with different field components for both designs are shown in Fig. 4.

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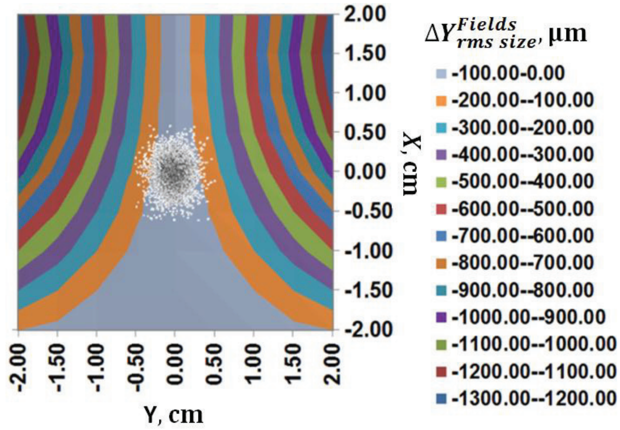

Figure 2: Decreasing of observed rms beam size depending on initial coordinates X/Y at slit plane in extracting condenser. Also beam region is shown in the center of this plane.

Uniformity of the field in analyzing condenser is especially important since there are ions moving in two planes simultaneously, and fields nonuniformities lead to BCS image distortions both axes. New design provides uniformity improvement and consequently decreases the distortions by an order of magnitude. Moreover such uniformity is reached with wider aperture: 9 cm to 6 cm in previous design.

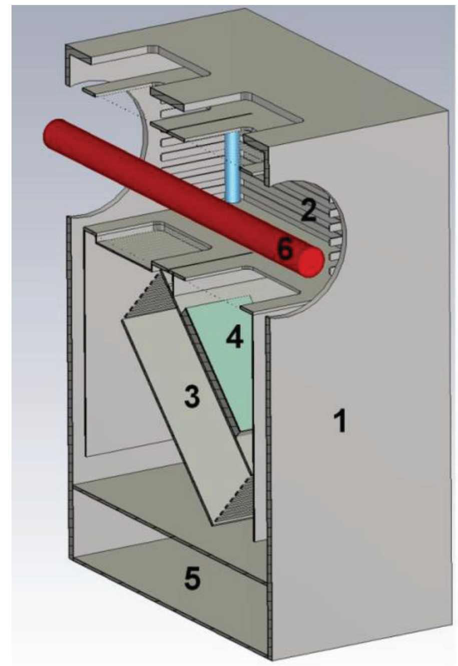

Figure 3: 3D-design of BCSM proposed for NICA. 1 – high vacuum box, 2,3 – extracting and analyzing condensers respectively with correcting electrodes, 4 – electron-optical converter, 5 – forevacuum region for electronics, 6 – analysed beam.

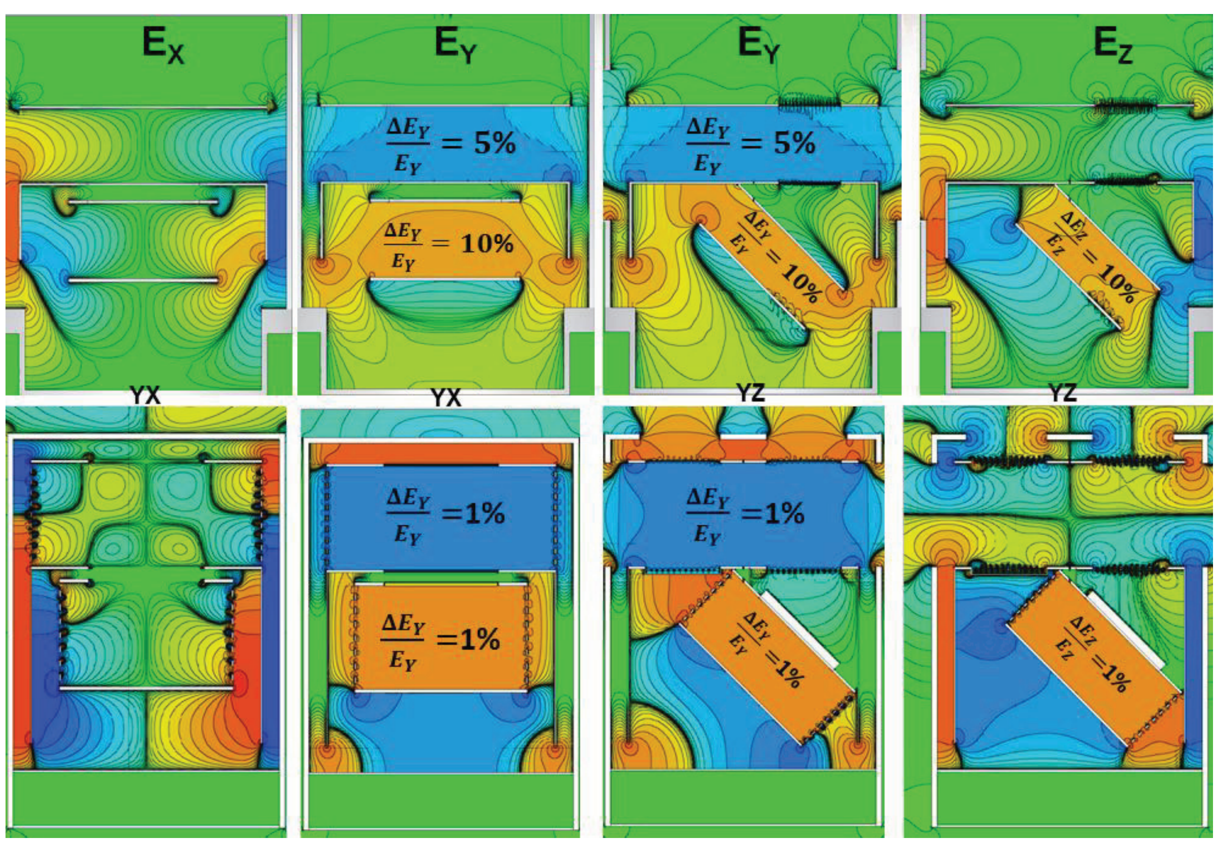

Figure 4: Fields simulation for old BCSM design (top row) and new one (bottom row). X, Y, Z-components of fields are shown in different planes (Z-axis correspond to beam direction). New design provides fields uniformity improvement by an order of magnitude.

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SLIT FILTER

The finite width of the slits determines one effect: Z-distribution of ions is transformed to X-distribution in analyzing condenser, leading to systematic spreading of X-peculiarities in image fine structure to segments with width equals slits width L_{slit}. At the same time rms beam size is: $\sigma_{X\,measured} = \sqrt{\sigma_{X\,real}^2 + \frac{L_{slit}^2}{12}}$, where $\frac{L_{slit}^2}{12}$ – variance of continuous uniform distribution.

In order to reduce this spreading it is necessary to minimize slits width, that leads to decreasing of BCSM sensitivity. Therefore slits size is a compromise between spatial resolution and sensitivity of the Monitor.

In Y-direction there is not any influence of slit filter.

ELECTRON-OPTICAL CONVERTER AND CCD-CAMERA

Typical resolution of electron-optical converter with two microchannel plates and phosphor screen R_{MCP+Ph}~50 μm is defined by size and position of channels and also phosphor grain size. Besides, it should be taken into account, that converter is placed under 45 degrees to X-axis, and therefore X-resolution is improved by $\sqrt{2}$ times.

The Monitor resolution also depends on CCD-camera resolution R_{CCD}, which is better than ~30 μm for up-to-date cameras.

IONS THERMAL MOTION

A contribution of ions thermal motion to X-errors is negligible, but for Y-axis there is BCS image spreading, which is defined by the ions tracking time in extracting and analyzing condensers, which in turn depends on the Monitor geometry, fields value and residual gas type. For INR linac with water vapor as residual gas (Fig. 5) and existing BCSM design this error is ~250 μm.

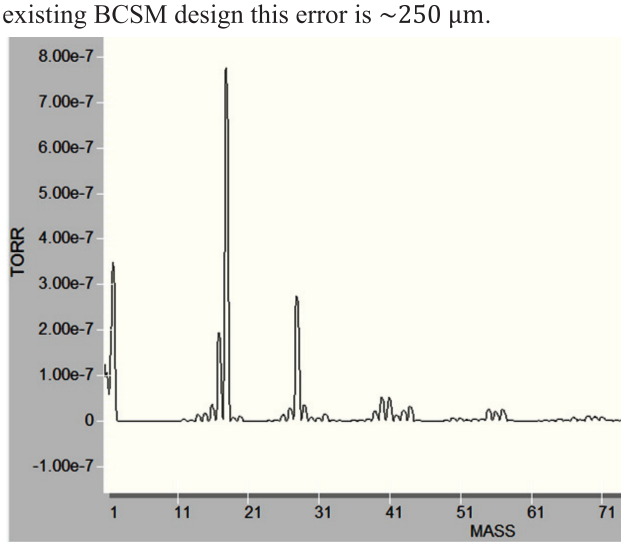

Figure 5: Mass spectrum of residual gas in BCSM region at INR linac. Water vapour dominates.

BEAM SPACE CHARGE

For simulation of space charge effects it is necessary to take into account not only beam parameters, but also ions thermal motion as initial conditions, because ions with different velocities move in different fields of analyzed beam, i.e. thermal motion and space charge are dependent quantities and have nonzero correlation coefficient. Space charge, like other factors, influences differently at X/Y-axes of BCS measurements.

For X-axis error is beam gravity center offset:

$$\delta X_{Gravity\ center}^{Space\ charge} = X_{real} - X_{ideal}.$$

Besides, there is asymmetric separation of BCS image. It is a distinctive feature of two-dimensional ionization diagnostics, that is specified by asymmetric configuration of beam and BCSM own fields in extracting condenser. This effect appears when the beam field exceeds the extracting field. An example of such separation is shown in Fig. 6 as simulation for U-70 IHEP, where field of the beam with $1.7 \cdot 10^{13}$ protons per pulse is 6 times greater than BCSM probable field (5 kV/cm) [5].

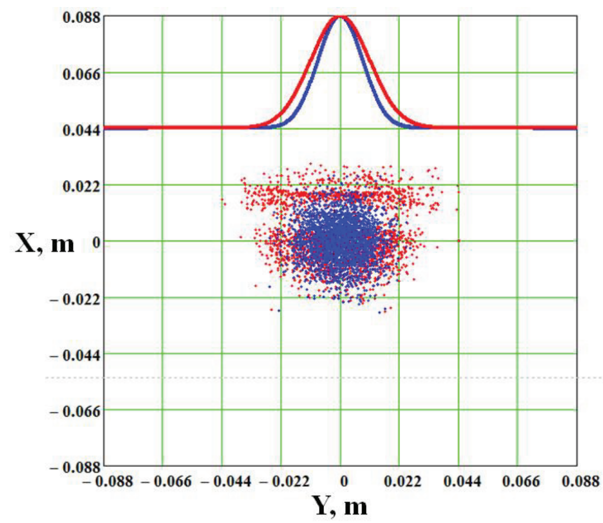

Figure 6: BCS image and profiles simulation for U-70 IHEP. Analyzed beam (blue) with $1.7 \cdot 10^{13}$ protons per pulse and measured BCS image (red) at 5 kV/cm extracting field. Y-profile spreading is 45%.

In case of Y-axis the beam space charge spreads measured rms beam size by $\Delta Y_{rms\ size}^{Space\ charge}$, and depending on the sign of charge of analyzed beam particles and utilized component of ionized residual gas this quantity defines both broadening effect ($\Delta Y_{rms\ size}^{Space\ charge} > 0$) and narrowing effect ($\Delta Y_{rms\ size}^{Space\ charge} < 0$) on BCS Y-axis profile, for instance for beam of negative ions or utilization of electron component of ionized residual gas.

INR linac beam is debunched in BCSM installation point at the output of the linac. In this case, for the proton beam with following parameters: W = 209 MeV, I_{pulse} = 15 mA, τ_{pulse} = 120 μs, σ_X = 2 mm, σ_Y = 1.5 мм – beam rms size errors are: $\sigma_{X\,errors} = 300$ μm, $\sigma_{Y\,errors} = 270$ μm, that corresponds to relative errors ~1%.

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For bunched beam at the output of the last accelerating resonator beam rms size errors are: $\sigma_{X\ errors} = 300$ µm, $\sigma_{Y\ errors} = 300$ µm, and consequently in case of INR linac ions thermal motion is a key contribution in comparison with beam space charge and is comparable with errors because of BCSM fields nonuniformities.

Beam gravity center offset $\delta X^{Space\ charge}_{Gravity\ center} = 200$ µm in both cases.

For estimations of rms beam size errors in new BCSM design for NICA beam with following parameters was simulated: Au^{32+}_{197}, W = 5 MeV/nuclon, I_{pulse} = 10 mA, τ_{pulse} = 10 µs, acceleration frequency 145 MHz, rms phase extent 20°, $\sigma_X = \sigma_Y$ = 3 мм. In this case, with extracting field 3 kV/cm, measurements errors are comparable with errors at INR linac: $\sigma_{X\ errors} = 300$ µm, $\sigma_{Y\ errors} = 320$ µm, $\delta X^{Space\ charge}_{Gravity\ center} = 200$ µm, that with a glance of beam size is visually unobserved (Fig. 7).

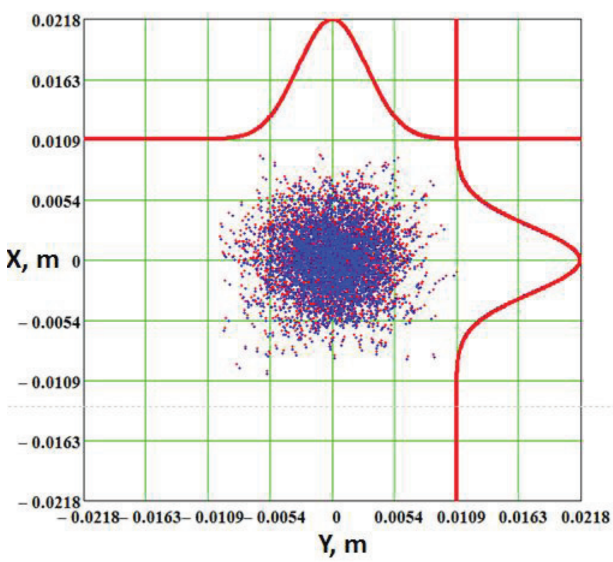

Figure 7: BCS image and profiles simulation for LU-20 NICA JINR. Analysed beam (blue) and measured BCS image (red) at 3 kV/cm extracting field. Relative errors of measurements of rms beam size and position of beam gravity center are ~1%, and profiles difference is indistinguishable.

CONCLUSIONS

Beam space charge simulation and analysis of electrostatic fields nonuniformities, determined by BCSM design features, show the necessity to take into account the correlations between BCS measurement errors with different nature and to describe effects on X/Y-axes separately.

For X-axis rms beam size, measured by BCSM is:

$$\sigma_{X\ measured} = \sqrt{\sigma^2_{X\ real} + \sigma^2_{X\ errors}},$$

$$\sigma^2_{X\ errors} = \frac{L^2}{12} + \left(\frac{R_{MCP+Ph}}{\sqrt{2}}\right)^2 + R^2_{CCD},$$

and observed offset of beam gravity center is:

$$\delta X_{Gravity\ center} = \delta X^{Fields}_{Gravity\ center} + \delta X^{Space\ charge}_{Gravity\ center}.$$

Besides, there is a distinctive feature of two-dimensional ionization diagnostics – asymmetric separation of BCS image, when beam field exceeds extracting field.

For Y-axis rms beam size, measured by BCSM is:

$$\sigma_{X\ measured} = \sqrt{\sigma^2_{Y\ real} + \sigma^2_{Y\ errors}},$$

$$\sigma^2_{Y\ errors} = -\left(\Delta Y^{Fields}_{rms\ size}\right)^2 \pm \left(\Delta Y^{Space\ charge}_{rms\ size}\right)^2 + R^2_{MCP+Ph} + R^2_{CCD},$$

where the sign for beam space charge contribution depends on the sign of charge of analyzed beam particles and utilized component of ionized residual gas.

This allows to describe accurately both broadening effect ("+") and narrowing effect ("-") for BCS Y-axis profile. There are no horizontal offsets of beam gravity center.

Hence the Monitor resolution for two Gaussian beam images is:

$$R_X = 2.355 \cdot \sigma_{X\ measured} + L,\ R_Y = 2.355 \cdot \sigma_{Y\ measured}$$

and corresponds to threshold response, when BCS envelope of two beams has no local minimum.

The resolution for image fine structure is:

$$R_X = L + \frac{R_{MCP+Ph}}{\sqrt{2}} + R_{CCD},$$

$$R_Y = \Delta Y^{Fields}_{rms\ size} + \Delta Y^{Space\ charge}_{rms\ size} + R_{MCP+Ph} + R_{CCD}.$$

Obtained estimations for BCSM measurement errors are confirmed in experiments at INR linac and indicate possibility to use the Monitor for real-time two-dimensional beams diagnostics at Nuclotron and Buster injectors in NICA project.

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