ISBN: 978-3-95450-192-2 doi:10.18429/JACoW-IBIC2017-WEPCC17

2D NON-DESTRUCTIVE TRANSVERSE DIAGNOSTICS BY BEAM CROSS-SECTION MONITOR

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Abstract

Beam Cross-Section Monitors implemented at INR RAS proton linac provide an efficient non-destructive registration of real 2D beam cross section, beam position and profiles, phase space ellipses reconstructed from profiles data as well as real-time evolution of these parameters in the entire range of beam energies and intensities. Features of the monitor's design and image processing system are described. Measurement accuracy and precision analysis are discussed. A variety of available experimental results are presented.

INTRODUCTION

The reconstruction technique of a two-dimensional beam density distribution *I(x, y)* through a residual gas ionization was initially proposed by V. Mihailov et al. [1] in Kurchatov institute. Beam Cross-Section Monitors (BCSMs) [2], based on ion components of a residual gas ionization, were implemented later and upgraded at INR RAS linac for in-flight non-destructive diagnostics. The general principle of BCSM has been described many times previously and is clear from Fig. 1.

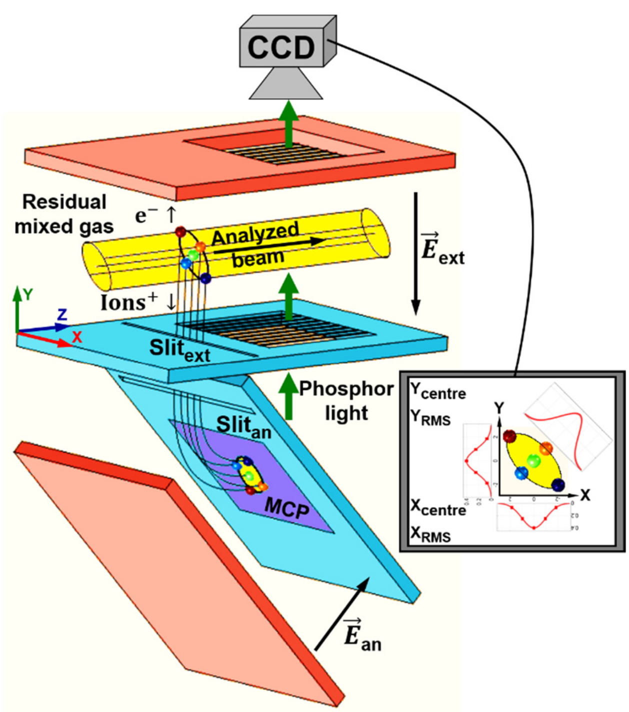

Figure 1: BCSM scheme.

The beam under study passes the area of a quasi-uniform electrostatic field and ionizes molecules of a residual gas. The energy of extracting ions in a double slit filter depends on their original Y-coordinates, so their energy distribution reproduces the transverse density distribution of the analyzed beam along Y-axis, while the distribution of the ions along X-axis keeps the same as that in the beam. Due to a potentiality of electric fields all types of ions, regardless of a specific charge: H_2^+, N_2^+, H_2O^+, etc. contribute to a 2D image formation of particle density distribution in analyzing beam cross-section (BCS).

DESIGN FEATURES

There are four main components of BCSM measurement errors. Two physical: thermal motion of ions and beam space charge and two technical: optical image processing system and internal mechanical design.

The design defines uniformity of extracting and analyzing fields as well as an Y-scale of the BCS image at electro-optical converter (MCP + phosphor). In case of uniform fields, the original distance Y_{ext} from the ion to extracting slit and converted distance L_{an} from the ion image to analyzing slit along the electrode are related as $L_{an} = 2 \cdot Y_{ext} \left({}^{E_{ext}}/{}_{E_{an}} \right)$. The image on the phosphor screen is detected by CCD-camera directed parallel to Y-axis. In case ${}^{E_{an}}/{}_{E_{ext}} = \sqrt{2}$ the detected image is identical to the analyzed BCS.

The fields in a simple, but effective, design (Fig. 2a) can be improved by several times with multiple extra correction electrodes (Fig. 2b), which decrease a non-uniformity of extracting and analyzing fields down to less than 1%. For Z-axis field symmetry extra cuts with special calculated forms can be implemented.

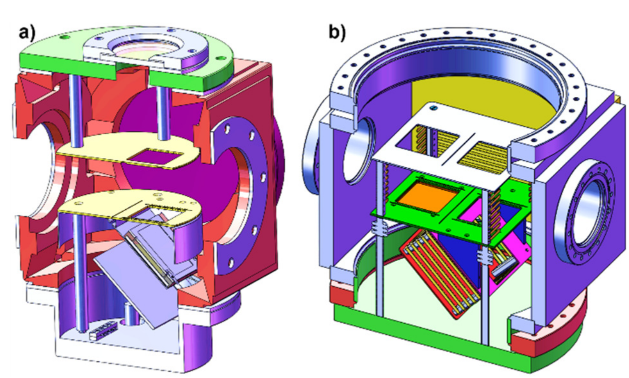

Figure 2: BCSM internal designs: a) used one (initial), b) improved one by extra correction electrodes and cuts.

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EXPERIMENTAL RESULTS

INR RAS linac provides beams for several research facilities: three neutron sources (time-of-flight radiation experiment, pulse neutron source, lead neutron slowing-down spectrometer), complex of proton therapy and proton irradiation facility. Therefore, a universal non-destructive diagnostics is preferable: both for high-intensity beams, which can destroy diagnostic device, and low-intensity beams, which can be destroyed totally during measurements. BCS (Fig. 3) is one of the most informative beam parameters, enabling simultaneous measurements of beam position and beam profiles at any angle.

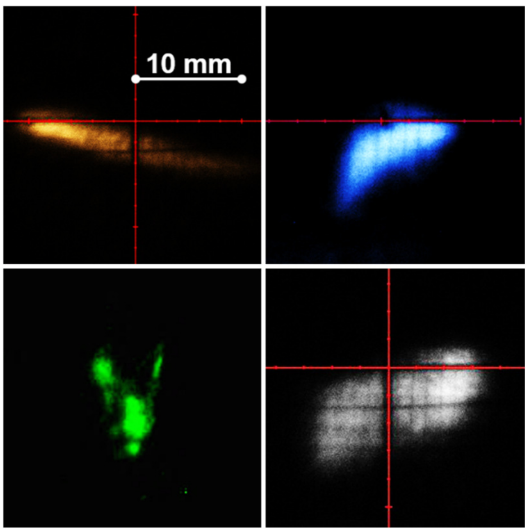

Figure 3: BCS images, registered during the linac tuning.

BCSM provides in-flight measurements in a wide range of beam parameters (Fig. 4) and reproduces as simple as complex beam cross-section images with a resolution about 300 µm. Experimentally tested range at INR linac: 5 µA, 7 µs ÷ 10 mA, 120 µs at energies 74÷247 MeV with the pressure of residual gas about 10^{-7} Torr.

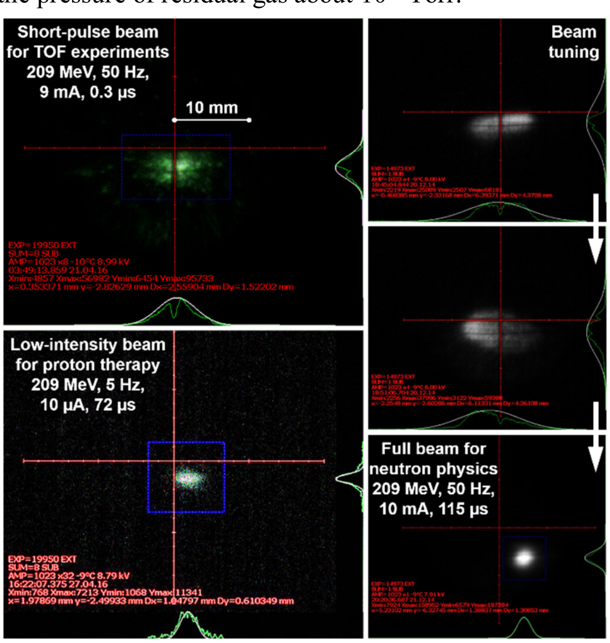

Figure 4: Routine beam measurements by BCSM.

Our experience shows, that during normal operation, the shape of the beam cross-section is close to the elliptical one and is unvaried in time. Typically, the invariance of the cross-section indicates the stability of the accelerator parameters. Besides, the monitor enables to observe beam tails (Fig. 5), which are of importance in high-intensity accelerators in terms of beam losses. That is why BCSM can be used as a convenient tool for in-flight transparent control of a general beam quality.

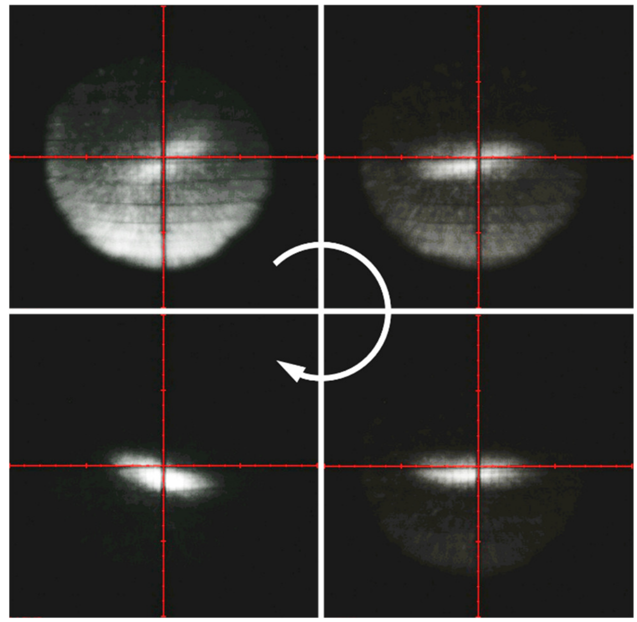

Figure 5: Successive decreasing of beam tails during the beam rotation by a group of quadrupole doublets.

Emittance equivalent phase ellipses, reconstructed from profiles data (Fig. 6) in combination with adjustable beam focusing elements for linear transformations in phase space, can be obtained also with subsequent calculation of the Twiss-parameters.

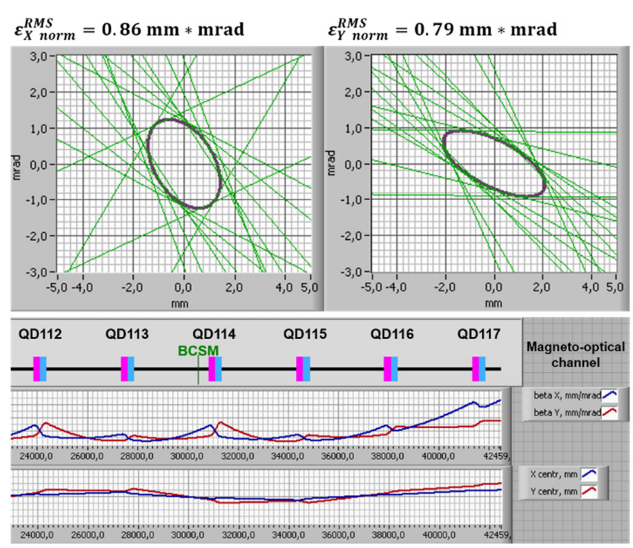

Figure 6: Equivalent phase ellipses of a 127 MeV proton beam, reconstructed from BCSM profile data, and the evolution of beta-function and beam position in the magneto-optical channel.

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IMAGE PROCESSING SYSTEM

A CCD- or CMOS-camera, which are used for direct image detection, can provide simple high-resolution registration. However interactions between beam losses and a beam pipe produce both γ-quanta and neutron fluxes, causing damages and disruptions in a radiation sensitive camera matrix, that leads to decreasing of a signal to noise ratio (Fig. 7) and following irreversible damage of pixels.

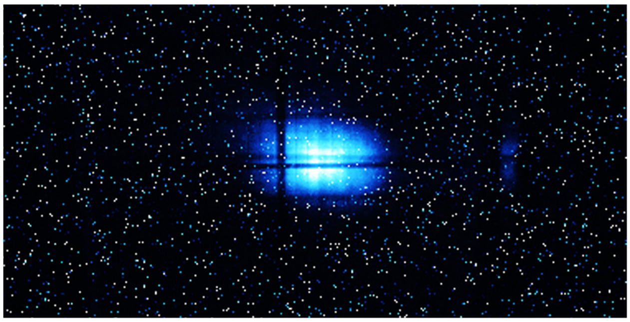

Figure 7: “Hot” pixels (white) and parasitic pixels (shades of blue) from beam losses at CCD-matrix during registration a BCS by the camera installed near beam pipe.

To avoid these problems, catadioptric periscope system is used (Fig. 8). Sizes and optical parameters of lenses and mirrors can be chosen so, that the system will collect and transmit optical radiation from phosphor screen of BCSM to the camera behind 70 cm of a concrete shield of the linac tunnel without significant loss of a light flux.

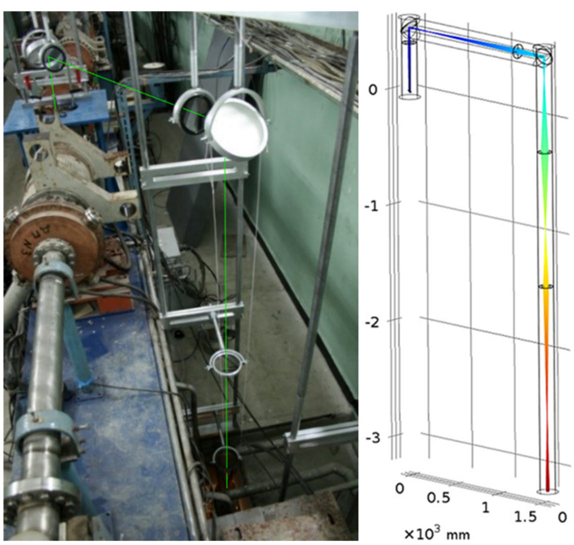

Figure 8: Installed catadioptric system and 3D-model with the light tracing through it.

Unfortunately, as well as every non-compensated optical system with one type of lenses, this one generates errors connected with distortions and spherical aberrations. The type and the absolute value of the resulting effect depend on the final magnification (Fig. 9), i. e. the focal length of a camera lens. Pincushion distortion is associated with long-focal telephoto lenses, while barrel distortion is normal for short focus. Besides, the spherical aberration appears and results in uncompensated defocusing.

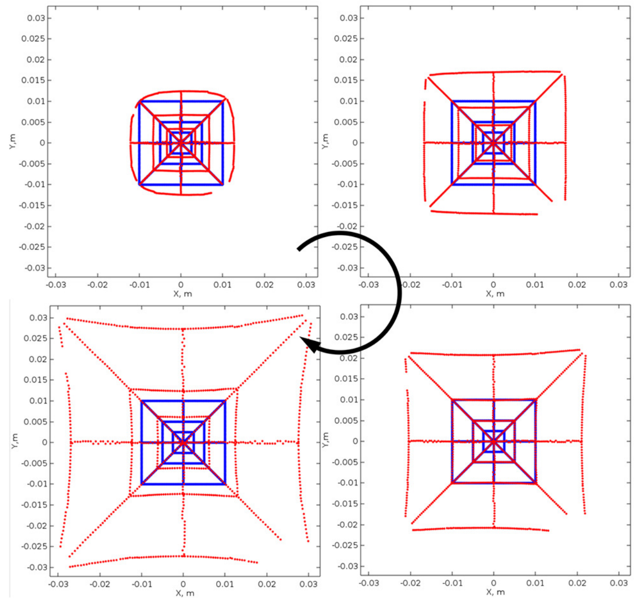

Figure 9. Transmitting of initial image (blue square with diagonals) through the periscope system with different magnifications by variation of a camera lens focal length.

One can note, there is a focal point, where distortions are minimized for working region. Nevertheless, such system demands extra software correction, for example, by using special calibrating mask at the phosphor screen (Fig. 10).

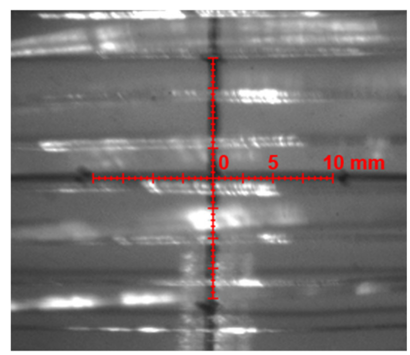

Figure 10. The phosphor screen with physical and software calibration crosses.

CONCLUSIONS

BCSMs, implemented at INR RAS proton linac, provide a unique non-destructive 2D observation and measurements of beam cross-section, position and profiles in a wide range of beam intensities. Used image processing system is an operating example of a simple extension of the camera life-time in an accelerator tunnel on condition of proper alignment and extra software correction, however it needs upgrade for design simplification and further elimination of the standard optical distortions.

REFERENCES

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[2] S. Gavrilov et al., “Two-dimensional non-destructive diagnostics for accelerators by Beam Cross Section Monitor”, 2014 *JINST* 9 P01011.