INR RAS INSTRUMENTATION FOR BUNCH SHAPE AND BEAM CROSS-SECTION MONITORING

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Abstract

Instruments for bunch shape and beam cross-section diagnostics at ion linacs are as important as complicated devices. Widespread Bunch Shape Monitors developed in INR RAS are used during a linac commissioning and optimization of beam dynamics. Beam Cross-Section Monitor implemented at INR RAS linac provide efficient non-destructive beam tuning and control. Features of both monitors investigated in simulations and beam tests are described. A variety of experimental results are presented.

INTRODUCTION

A bunch shape is defined usually as longitudinal distribution of particle intensity in bunches $I(z)$ or $I(\varphi)$, which is one of the most difficult to observe characteristics of a beam at ion linear accelerators.

There are several methods for bunch shape measurements, however low energy secondary electrons are used most extensively because of weak dependence of their properties both on the type of primary particles and on their energy. The technique of a coherent transformation of a temporal bunch structure into a spatial charge distribution of low energy secondary electrons through RF-modulation was initially implemented by R. Witkover [1] for BNL linac. An energy (longitudinal) RF-modulation of secondary electrons was used.

In the Bunch Shape Monitor (BSM) [2], developed in INR RAS, a transverse RF-scanning is used. The general principle of BSM operation is clear from Fig. 1.

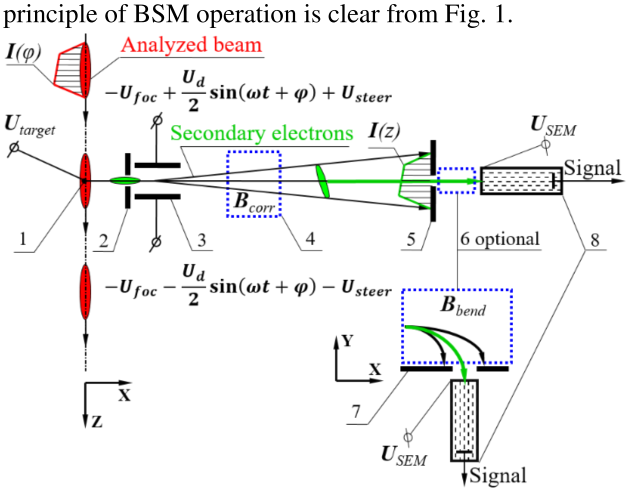

Figure 1: BSM scheme: 1 – tungsten wire target, 2 – inlet collimator, 3 – RF-deflector combined with electrostatic lens, 4 – correcting magnet, 5 – outlet collimator, 6 – optional bending magnet, 7 – registration collimator, 8 – secondary electron multiplier.

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Two-dimensional beam density distribution $I(x, y)$ is one of the most informative beam parameters, enabling simultaneous measurements of beam position, profiles and emittance ellipses reconstructed from profiles data in combination with adjustable beam focusing elements for linear transformations in phase space. Luminescent screens, typical devices for 2D cross-section measurements, have all advantages and drawbacks of destructive diagnostics. More convenient, transparent technique of residual gas ionization, was initially proposed by V. Mihailov et al. [3] and used for both charged particle and synchrotron light beams [4].

The Beam Cross-Section Monitors (BCSMs) [5], based on ion component of the residual gas ionization, were implemented and upgraded at INR RAS linac for in-flight non-destructive diagnostics in the full range of beam parameters. The basic principle of operation is shown in Fig. 2. The energy of the ions at the slit linearly depends on their original coordinates X, hence their energy distribution downstream of the slit reproduces the transverse particle density distribution in the primary beam along X coordinate, while the distribution of the ions along Y coordinate keeps the same as that in the primary beam, similarly to 1D ionization profile monitors. In case of uniform fields the distances X_0 and X_1 are related as $X_1 = 2X_0(E_{ex}/E_a)$, that is independently of charge and mass of residual gas ions, and all types of ions contribute to formation of 2D image of particle density distribution in analyzing beam cross-section.

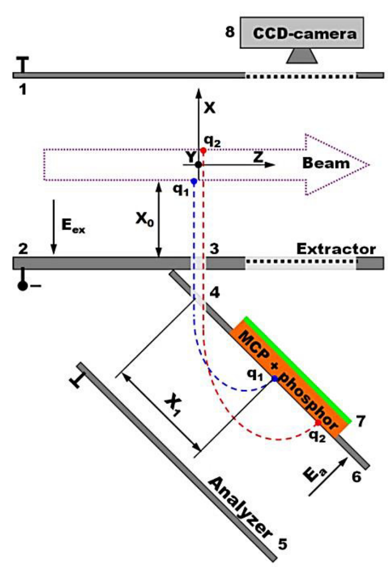

Figure 2: BCSM scheme: 1, 2 – electrodes of extractor, 3, 4 – double slit filter, 5, 6 – electrodes of analyzer, 7 – electro-optical converter, 8 – CCD-camera.

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BUNCH SHAPE MONITOR

The main requirement for bunch shape measurements is a phase resolution. In ion linacs for typical bunch phase durations about several tens of degrees the resolution of 1° looks sufficient, that corresponds to a temporal resolution from several tens to hundreds of picoseconds.

The first BSM, providing such resolution, has been developed and built in INR in the eighties and the first measurements has been done in 1988 during commissioning of INR linac. Since that time various modifications of BSM have been developed and built for several accelerators [6] including SSC Linac, DESY Linac-3, SNS Linac, J-PARC Linac, CERN Linac-2/3/4.

Two groups of electrons passing the deflector with the phase shift of 180° get through the output collimator and their intensity is detected. If the bunch length is bigger than 180° then the signals corresponding to two longitudinal points, shifted by 180°, are superimposed, and the results of the measurements are distorted. Hence the typical phase range of BSM measurements is equal to half a period of the deflecting field. The range of the measurements can be increased to full period if one of the two groups of electrons is blocked. In 2016 BSM with the feature of 360° phase range and with three replaceable RF-deflectors was fabricated and tested for GSI-FAIR accelerators: UNILAC, CW- and proton linacs (Fig. 3).

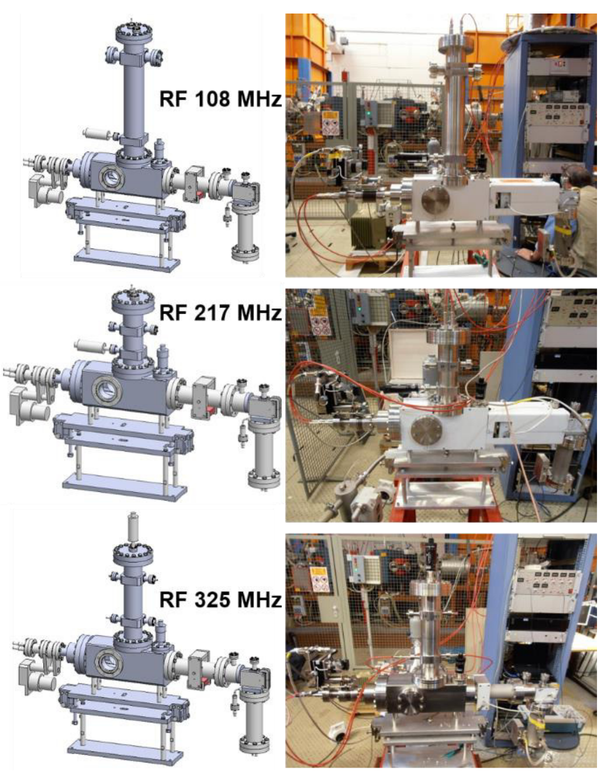

Figure 3: BSM: 108.408 MHz for UNILAC, 216.816 MHz for CW-linac, 325.224 MHz for proton linac.

To do it the flag-type movable curtain was installed at the exit of RF-deflector. Rotating the curtain one can absorb the electrons corresponding to one of the two half-periods of the deflecting field thus avoiding superimposing of the signals from particles shifted by half a period.

Modern ion linacs under construction, such as FRIB MSU or ESS ERIC are foreseen to operate with RMS bunch lengths of about 10÷20 ps at medium energies and even shorter at high energies, and at least 0.5° phase resolution is required for reliable bunch shape diagnostics. To improve the resolution of BSMs for these linacs several modifications, based on long experience, were implemented.

Firstly, to improve the uniformity of both deflecting and focusing fields in Y-direction, thus improving a phase resolution, the new λ-type symmetric RF-deflector has been developed for BSM-ESS (Fig. 4).

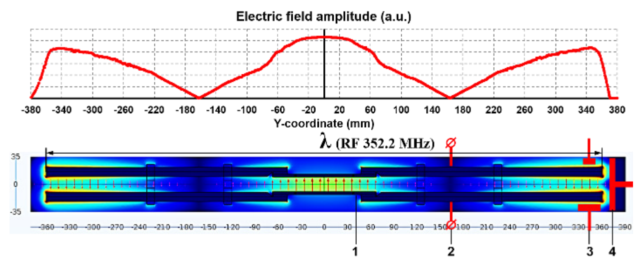

Figure 4: E-field distribution in λ-type deflector.

The symmetric deflector provides resolution about 0.5° (about 4 ps for ESS linac), in case of proper focused and oriented electron beam.

So, the second feature, foreseen for new BSM modifications, is a correcting magnet with the combination of dipole and quadrupole fields (Fig. 5a). The dipole field produced with two coils moves the electron beam along Y-axis. The quadrupole field of another four coils enables to adjust the tilt of the beam image in YZ-plane (Fig. 5b).

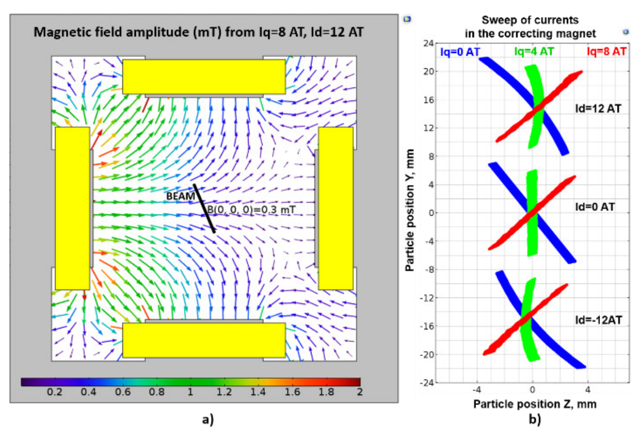

Figure 5: (a) Superposition of dipole and quadrupole fields of the correcting magnet. (b) Cross-sections of the e-beam in the plane of the outlet collimator for different quadrupole Iq and dipole Id coil currents (Ampere·Turns).

The three corrections provide an exhaustive fit of the electron beam and the outlet collimator, thus compensating misalignments and influence of external moderate static magnetic fields. To decrease strong fringe or alternating fields from magnetic focusing elements special magnetic shield is used. Typical BSM shield represents a sectional jacket made of 2 mm low-carbon steel. Additionally, the interior surfaces can be covered with a foil made of an amorphous cobalt-iron alloy with high μ_r.

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BEAM CROSS-SECTION MONITOR

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.

Despite seeming simplicity of ionization method BCSM (Fig. 6) has a variety of realization problems: geometry and alignment of registration box interior, design of optical channel and radiation shield for CCD-camera, multilevel voltage supply for fields uniformity, lifetime of electro-optical converter etc.

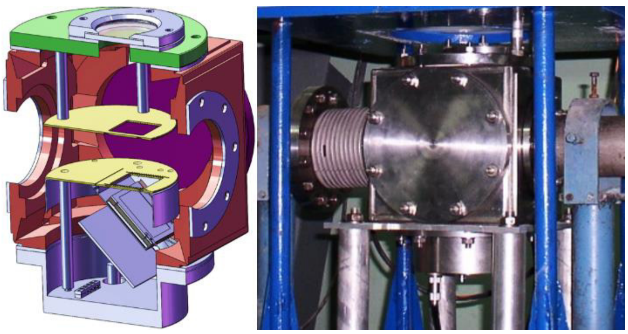

Figure 6: BCSM at the exit of INR Linac.

The main problem of BCSM operation is radiation background at the accelerator (Fig. 7). Both γ-quanta and neutron fluxes cause damages and functional disruptions of radiation sensitive BCSM electronics (CCD camera, memory chips, ADC, MCP). Besides, it is necessary to consider that, for example, reconfiguration process of INR linac for various experiments can change the beam intensity up to 10^4 times, that leads to proportional change of images brightness and losses in the same number of times. Therefore, it is necessary to protect the electronics at high beam intensity, without losing sensitivity in low intensity. So, lens-mirror periscope system was implemented at the linac for realization of these inconsistent requirements.

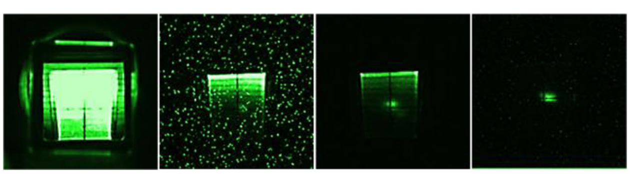

Figure 7: Beam losses decrease during beam tuning.

Now upgraded BCSM is the unique tool for observation and measurements of beam parameters both high and extremely low intensities in the wide range of energy. BCSM has high experimentally tested signal dynamic range (5 µA, 7 µs ÷ 10 mA, 120 µs) and reproduces as simple as complex beam cross-section images and profiles with resolution about 300 µm, that is quite admissible result for in-flight control and diagnostics of various beam parameters (Fig. 8). Our long experience shows, that during normal operation, the shape of the beam cross-section is close to the elliptical one and is unvaried in time. Normally the invariability of the cross-section indicates the stability of the accelerator parameters, that is why BCSM can be used as a tool for control of general beam quality.

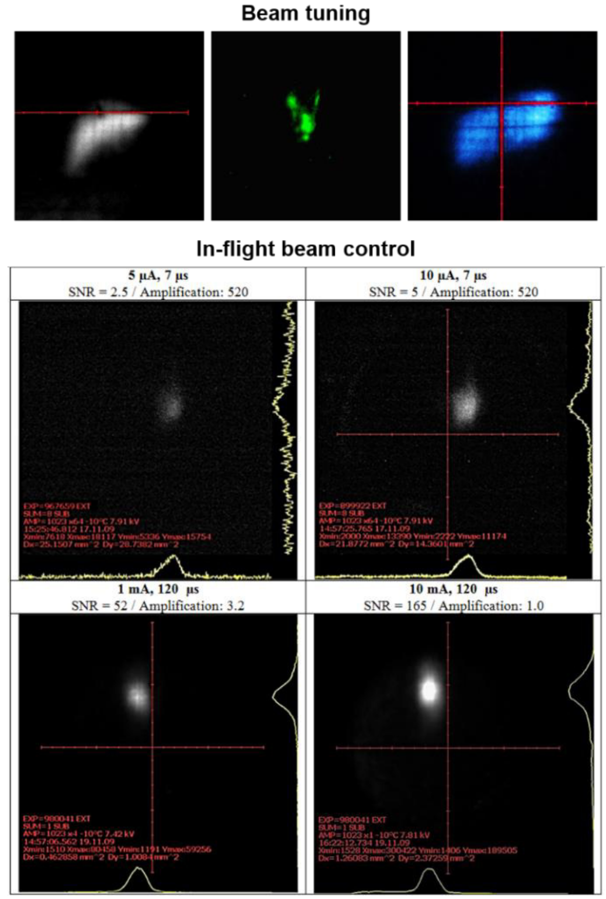

Figure 8: Experimental beam images, registered by BCSM.

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Such complicated beam diagnostics devices as Bunch Shape Monitor and Beam Cross-Section Monitor are tools, which developed and upgraded for years. Many people contribute to this work and it is not so easy to list all of them. Nevertheless, the authors would like to acknowledge those, who made enormous contribution during the resent years: Victor Gaidash, Yuri Gotovtsev, Yuri Kisselev, Yuri Kalinin and Ivan Vasilyev.

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