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FEATURES OF NON-DESTRUCTIVE BEAM INSTRUMENTATION AT THE INR RAS HIGH-INTENSITY HYDROGEN IONS LINAC*

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Abstract

The linac of INR RAS is a high-intensity accelerator of protons and H-minus ions, which is used for a complex of neutron sources, isotope production, proton irradiation and investigations in proton flash therapy. A non-destructive beam instrumentation plays a key role in the linac tuning. The general peculiarity of this multi-component system is that all detectors are home-made devices with a wide operation range and can be used at different ion linacs with a minimum adaptation to beam parameters. Beam current transformers for standard and in-air measurements, resonance and capacitive position and phase monitors, BIF-monitor for 1D and beam cross-section monitor for 2D non-destructive profile diagnostics. Different operation features and manufacturing peculiarities are presented in this paper. Results of implementation, operation and continuous upgrade are discussed. Also, typical scalable designs of some detectors are described.

INTRODUCTION

Multipurpose research complex (MRC) [1] of INR RAS, based on the linac, includes four beam outlets: three neutron facilities of neutron investigations laboratory (time-of-flight Radiation Experiment, pulse neutron source IN-06, lead neutron slowing-down spectrometer LNS-100) and research Complex of Proton Therapy, which is a part of medical physics laboratory. Also, there are isotope production and proton irradiation facilities at the linac (Fig. 1). So, depending on beam user requirements, the linac has to provide beam parameters in a wide range of values: beam energy 20÷305 MeV, pulse current 0.001÷10 mA, pulse repetition rate 1÷50 Hz, pulse duration 0.3÷150 µs.

Moreover, these parameters can be changed several times during a shift for different research groups, that needs not only reliable operation of the linac in different duty cycles, but also a beam instrumentation available for routine control in a wide range of parameters.

Last years the linac non-destructive diagnostic system has been supplemented and upgraded with new instrumentation, software and tuning procedures. In particular, the system of beam current transformers (BCT) was enhanced by several new detectors, including device for in-air measurements, a new beam-induced fluorescence (BIF) monitor was installed at H+ injection channel, an operation of Beam Cross Section Monitor (BCSM) based on ionization principles was improved by a new software. Meanwhile some types of detectors, such as phase monitors, neutron and γ-detectors continued to work confidently in routine operation without significant upgrade.

BEAM CURRENT TRANSFORMERS

There are about 40 BCTs (ACCT-type) at the accelerator complex. They are mainly based on ferrite rings installed in vacuum with different design and electronics. Standard BCTs with preamplifiers, based on AD810 op-amps, are used for routine range of beam parameters. Three sensitive BCTs with OPA827 and ADA4627 – for medical beams with pulse currents down to 10 µA. Four fast BCTs with low input impedance preamplifiers, based on AD844 – for short-pulses down to 0.3 µs for RADEX and LNS-100.

Current signals and calibration signals of all BCTs are transmitted in differential mode by twisted-pair cables, so interferences are minimized, and preamplifiers can be distant for hundreds of meters from a control room.

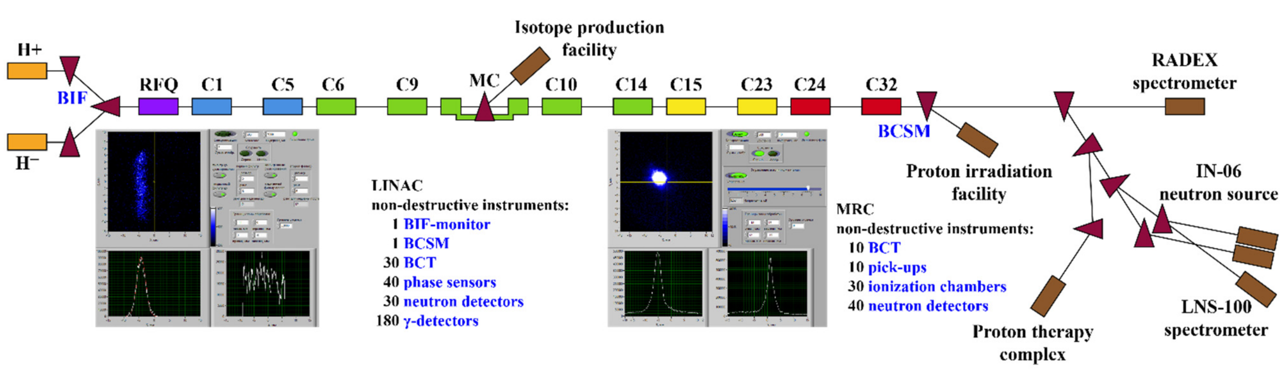

Figure 1: INR RAS accelerator complex layout.

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A new BCT design is based on the high-μ ferrite ring inside double magnetic shield: one – in-vacuum case, second – in-air case (Fig. 2).

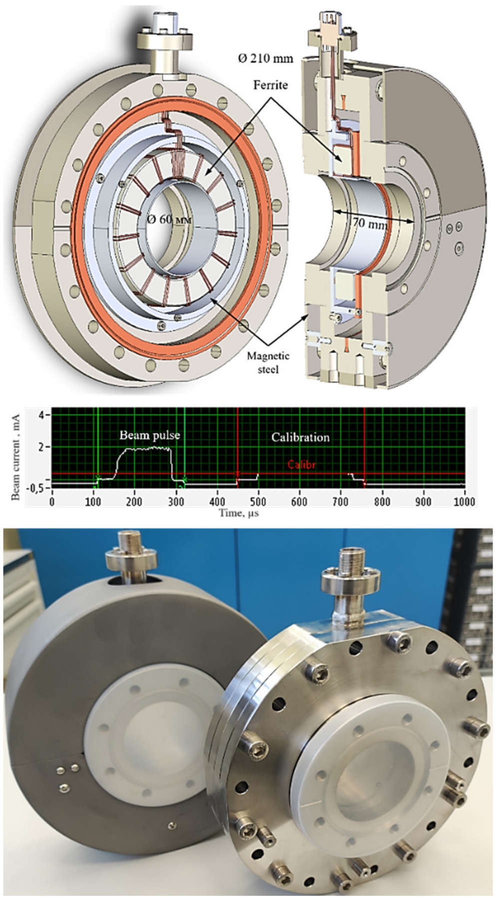

Figure 2: Upgraded INR BCT: 3D-model, photo and measured signal.

At facilities for in-air proton beam irradiation internal vacuum part of BCT is used as in-air devices for beam current control. A well-known problem of BCT in such operation mode is a distortion of the measured current signal due to air ionization: electrons move through the ring together with a proton beam and decrease the current, and ions move by inertia and form a long tail. This problem was resolved by installation of several magnets around aperture to decline trajectories of ionization products and measure actual beam pulse with a systematic error ~15% compared to Faraday cup (FC) in the whole current range (Fig. 3).

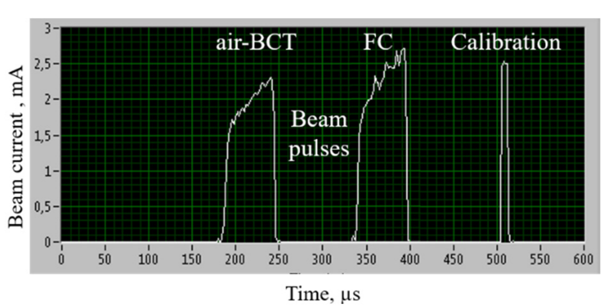

Figure 3: Measured beam pulses at air-BCT and FC.

Also, BCTs play a crucial role in the linac operation with high-intensity beams. A so-called system ΔBCT registers an absolute value of beam losses by a beam current difference between the linac exit and entrances to the research facilities. BCT signals from every beam macropulse are read-out and compared by special electronics, which turns off a beam directly through the chopper in case of specified difference threshold (about 1÷5 % typically) is exceeded in three successive pulses. In addition, this system holds on 1 Hz tuning mode as long as the difference remains.

PHASE AND POSITION MONITORS

Phase and position monitors are presented by ~40 resonant harmonic sensors with capacitive loops and 10 linear-cut electrostatic pick-ups (Fig. 4).

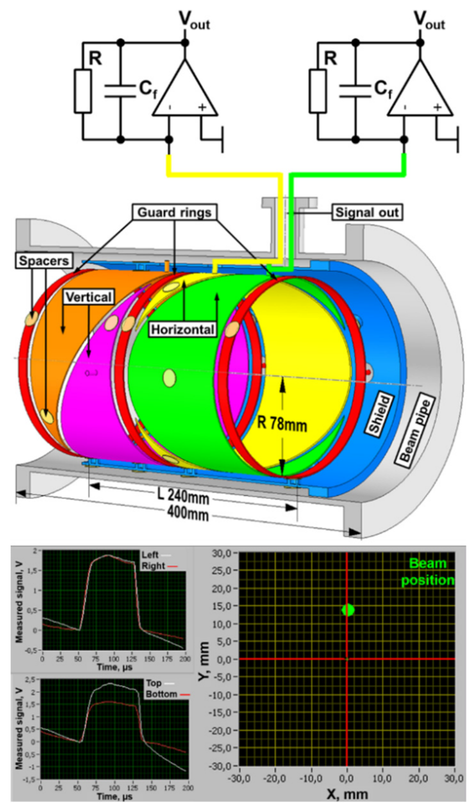

Figure 4: 3D-scheme of electrostatic pick-up and window with measurement and processing results.

The main peculiarity of electrostatic pick-up system is an operation with a debunched coasting beam [2] in long (100÷200 m) transporting channels of MRC. Signal-to-noise ratio is limited by the total detector capacitance, therefore it is necessary to use a voltage or charge preamplifier, connected to pick-up with a short cable. A charge amplifier is more convenient, because its output signal is independent of total detector capacitance and pick-up calibration can be performed with arbitrary cable length. For typical beam parameters pick-ups enable to measure beam center-of-mass position with the resolution about 0.1÷0.2 mm, which corresponds to about 0.1% of the aperture. The initial accuracy can be worse by an order of magnitude and is mainly determined by mechanical tolerances.

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BIF-MONITOR

A beam-induced fluorescence monitor was installed at a low-energy proton injection channel with beam energy 400 keV, pulse current 50÷70 mA, pulse repetition frequency 50 Hz and pulse duration 0.3÷200 µs. The results confirmed the possibility to use BIF-monitor with standard CCD machine vision cameras without extra gas inject and image amplifiers for such low-energy injection channels of high-intensity proton beams.

The installed monitor (Fig. 5) consists of a vacuum chamber with an aperture of 50 mm with two standard borosilicate windows at CF35 flanges. To minimize parasitic reflections the inner surfaces of the chamber are coated with a thin matte conductive layer of graphite. The operating pressure in the injection channel is ~ 10^{-7} ÷ 10^{-6} mbar, while the residual gas mainly consists of water vapor (H_2O ~ 40%), hydrogen (H_2 ~ 18%), nitrogen (N_2 ~ 7%) and also contains carbon monoxide (CO ~ 7%) and methane (CH_4 ~ 10%) due to the historically pumping with oil forevacuum pumps followed by high-vacuum ion-getter pumping. The glow of the gas is recorded by two typical black-and-white PoE CCD machine vision cameras from BASLER and LEO series. To suppress the external optical illumination, the CCD cameras and vacuum windows were closed with a blackened aluminum foil, and lead sheets were used for radiation protection from the parasitic gamma background of the proton injector located nearby.

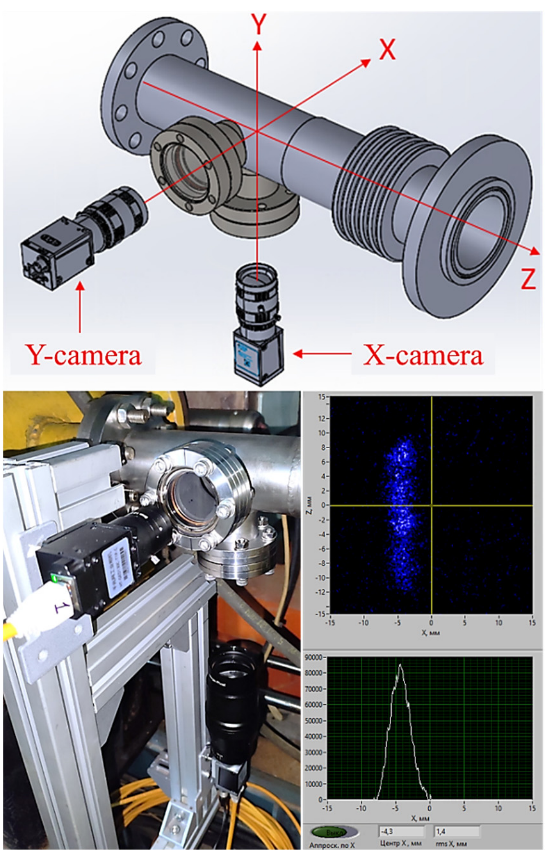

Figure 5: INR BIF-monitor: 3D-model, photo and registered picture with processing beam profile.

The threshold sensitivity of the monitor is limited by the noise of the CCD-matrix, in particular caused by its non-uniform heating, background illumination, hot pixels and parasitic reflections inside the vacuum chamber. Post-processing with a frame summation and median filter of images allows to reduce most of these noise components.

A significant contribution to the measurement error of the beam size is defined by the displacement of the beam axis from the focal plane of the lens. When the beam is shifted relative to the focal plane, the scale of the observed image changes, for example, shift by 10 mm from the focal plane leads to a relative change in scale ~4%. However, a shift of the beam position along one axis determines the displacement of the beam relative to the focal plane along the second axis, so this data can be used to estimate the error of the beam size along this second axis.

BEAM CROSS-SECTION MONITOR

For a proper matching with the linac-MRC transition sector. In-flight beam diagnostics at the linac exit is provided by Beam Cross Section Monitor [3]. The monitor uses a residual gas ionization to observe 2D beam cross section, beam position and profiles, as well as transverse emittance, which can be reconstructed [4] from beam profiles data during linear transformations in phase space by variation of fields in upstream quads.

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

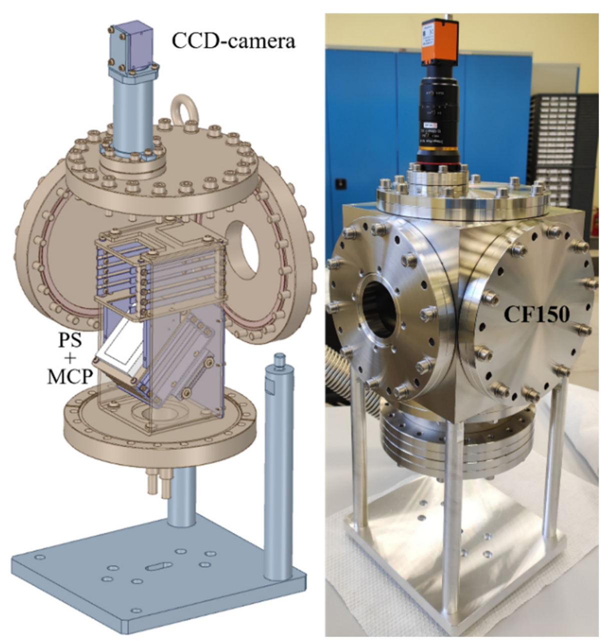

Figure 6: Upgraded BCSM: 3D-model and photo.

The main problem in operation is radiation background of the accelerator. Both γ-quanta and neutron fluxes cause

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damages and functional disruptions of radiation sensitive BCSM electronics (CCD-camera, 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 10^5 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.

BCSM is a 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 (10 µA, 1 µs ÷ 10 mA, 100 µs at vacuum ~10^{-7} mbar) 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. Our long experience shows, that during normal operation, the shape of the beam cross-section is close to the elliptical one and is stable in time. Normally the invariance of the cross-section indicates the stability of the accelerator parameters, that is why BCSM also can be used as a tool for a control of a general beam quality, especially during accelerator tuning (Fig. 7).

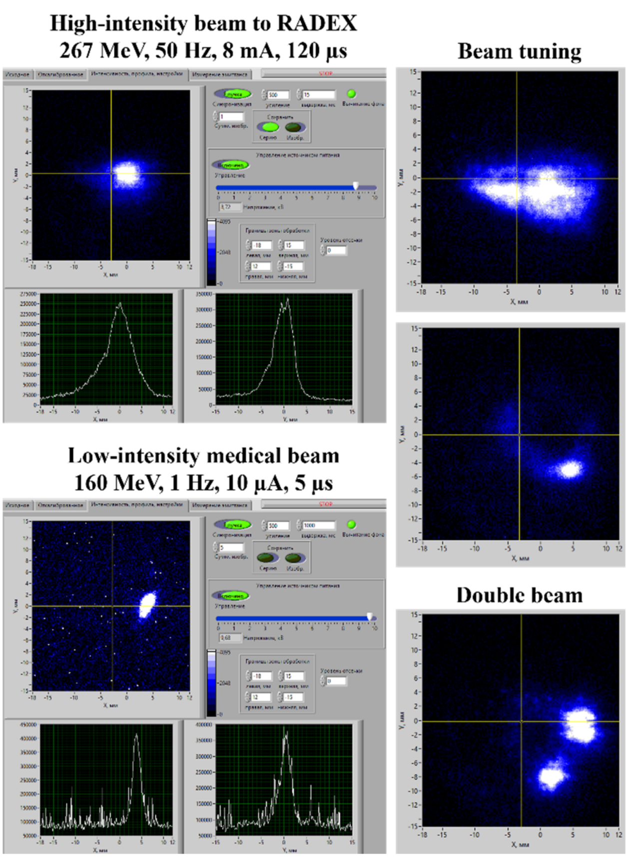

Figure 7: Examples of 2D beam images registered with BCSM in different operation modes.

CONCLUSION

The accelerator complex of INR RAS based on high-intensity hydrogen ions linac is equipped by lots of beam instrumentation, including different non-destructive diagnostic devices.

Beam current transformers with high-µ ferrite toroids in vacuum chambers with magnetic shield are used not only for the pulse current control, but also as a part of a fast machine protection system for pulse-to-pulse measurements of the beam current difference between two BCTs at crucial parts of the linac and transporting channels.

Beam phase control is realized with resonant phase sensors, meanwhile electrostatic pick-ups with charge pre-amplifiers are used for a position monitoring of debunched coasting beams in the research complex.

BIF-monitor with simple machine vision CCD-cameras is used successfully at low-energy transporting channel for position and profile control.

Beam Cross Section Monitor provides truly 2D transverse diagnostics at the exit of the linac in full range of the beam parameters, including extreme modes with low intensities as well as short pulse durations, and plays a role of the tool for a general beam quality control during the linac tuning and operation.

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REFERENCES

[1] L. v. Kravchuk *et al.*, “Multipurpose research complex based on INR high intensity proton Linac”, in *Proc. RUPAC’12*, Saint-Petersburg, Russia, Sep. 2012, paper WEYCH02, pp. 90-94.

[2] S. Gavrilov *et al.*, “Electrostatic pick-ups for debunched beams”, *IEEE Open J. Instrum. Meas.,* vol. 9, no. 10, pp. T10007-T10007, Oct. 2014. doi: 10.1088/1748-0221/9/10/T10007

[3] S. Gavrilov *et al.*, “Two-dimensional non-destructive diagnostics for accelerators by Beam Cross section Monitor”, *Journal of Instrumentation,* vol. 9, no. 01, pp. P01011-P01011, Jan. 2014. doi: 10.1088/1748-0221/9/01/P01011

[4] A. I. Titov et al., “Beam transverse phase space portrait tomography at the high-intensity linear accelerator of hydrogen ions”, *Instrum. Exp. Tech.*, vol. 66, no. 1, pp.1–18, Feb. 2023. doi: 10.1134/s0020441222060185