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LONGITUDINAL IMPEDANCE OF THE NICA COLLIDER RING AND ION BEAM STABILITY

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Abstract

The report presents the results of optimization of the longitudinal coupling impedance of the NICA collider ring using numerical simulation of its individual elements by the CST Studio. Based on the obtained results, analytical estimates of the stability of the ion beam in the ring are obtained for one value of the ion mode energy – 3 GeV/u.

INTRODUCTION

The project of the Nuclotron-based Ion Collider fAcility (NICA) accelerator complex [1] is being developed at JINR. The ion Collider, which is the main part of it, will allow us to study the collision processes of gold ions with a kinetic energy of 1 – 4.5 GeV/u (√s ≤ 11 GeV/u) and polarized protons with energy of 2 – 12.6 GeV (√s ≤ 27 GeV). One of the criteria determining the stability of the motion of charged particles inside the beam chamber is the value of its impedance, which is most important for high-intensity beams.

The interaction of the charged particle beam with the accelerator beam chamber leads to the appearance of electromagnetic fields induced in the chamber (wake-fields) and their reverse effect on the beam, leading to coherent instabilities in the longitudinal and transverse directions. The value $W_{||}(r_1,s)=\frac{1}{q_1}\int_{-\infty}^{\infty}E(r_1,z,t)_{t=(s+z)/c}dz$ is called the longitudinal Wake potential. Its transverse component can be found according to the Panofsky-Wenzel theorem: $W_{\perp}(r_1,s)=-\nabla_{\perp}\int_{-\infty}^{s}W_{||}(r_1,s')ds'$. The coupling impedance is the Fourier image of the Wake potential

$$Z_{\parallel}(\omega)=\frac{\int_{-\infty}^{\infty}W_{\parallel}(s)e^{-i\omega s}ds}{\int_{-\infty}^{\infty}\lambda(s)e^{-i\omega s}ds}$$
$$Z_{\perp}(\omega)=i\frac{\int_{-\infty}^{\infty}W_{\perp}(s)e^{-i\omega s}ds'}{\int_{-\infty}^{\infty}\lambda(s)e^{-i\omega s}ds} \quad (1)$$

where λ (s) is the charge distribution normalized by q_1.

The longitudinal and transverse impedances can excite instabilities of the beam particle motion in the Collider. In addition, the real part of the longitudinal impedance determines the contribution to the growth of energy dissipation in the walls of the vacuum chamber, which, with a high-intensity beam, can cause significant heating of individual elements of the superconducting Collider.

Each of the Collider rings (Fig. 1) is a racetrack type accelerator and consists of two rotary arches and two long straight sections. The perimeter of the Collider 503.04 m is equal to two perimeters of the Nuclotron.

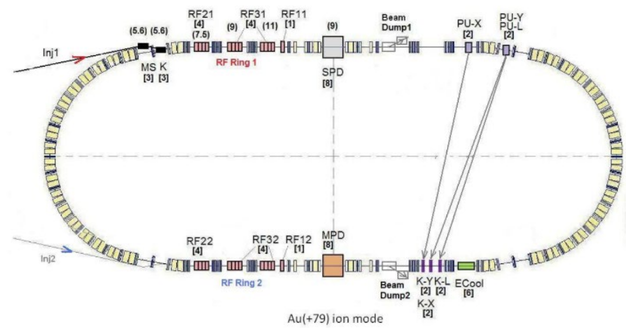

Figure 1: Scheme of the Collider ring. Here Inj1, 2 – injection channels; RFij – RF-stations with i – number of station, j – number of the ring; SPD – spin physics detector, MPD – multipurpose detector, PU-X,Y,L and K-X,Y,L – pick-up stations and kickers for stochastic cooling; ECool – electron cooling system; MS – septum magnet; K – injection kicker.

CALCULATION OF IMPEDANCE

After the initial calculation, changes were made to its design for each element to minimize the value of $Z_{\parallel}$ /n, where n is the circulation frequency harmonic.

In this work, the calculation of Wake-potentials was performed in the CST Studio program. To minimize the contribution of the impedance to the particle dynamics, it is possible to change the design of the element to reduce the amplitude of low-frequency resonances, or to shift them up in frequency. In other words, changes were made to minimize the value of $Z_{\parallel}$ /n. The choice of a design change is helped by the wakefield picture calculated by CST Studio, which displays the excitation of the electromagnetic field in various cavities of the chamber elements.

The biggest changes were made to the collimator unit, kicker of feedback system and pick-up stations in Collider arches (Beam Position Monitor – BPM).

Collimator Unit

The collimator unit consists of scraper and absorber, having a similar design, so we will limit ourselves to considering changes in the design only on the example of a scraper (Fig. 2).

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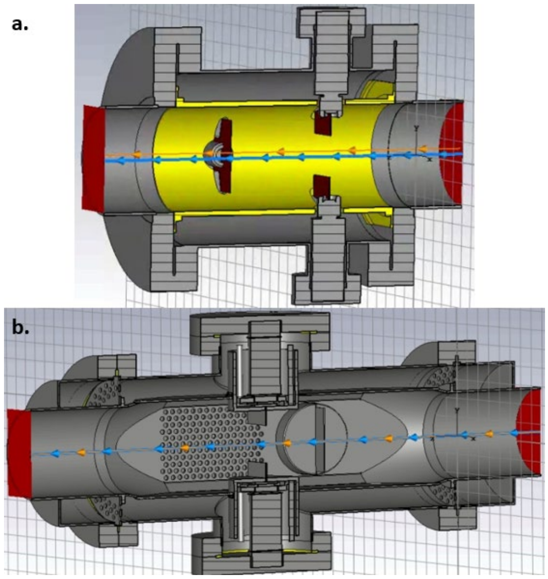

Figure 2: The design of the scraper a) initial model and b) modified.

Shielding “cups” were installed around the scraper plates, connected to the aperture insert by a sliding contact to avoid the penetration of an electromagnetic field into the volume of the vacuum chamber. For the same purpose, end screens were added. The total length of the structure increased from 230.8 mm to 400 mm, due to the expansion of the pipes of the stepper mechanism (for placing "cups"). To ensure the necessary vacuum conditions, a pumping pipe was added (located in the horizontal plane and not visible in the figure) and a perforation was made in the aperture insert. All this made it possible to shift the resonant frequencies upwards (Fig. 3).

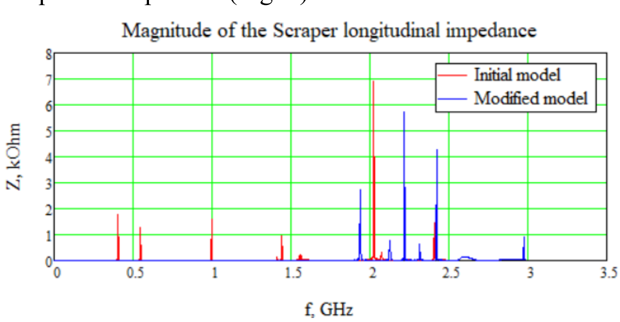

Figure 3: The longitudinal impedance of the scraper for the collimation mode before (red curve) and after (blue curve) design changes.

Kicker of the Feedback System

The feedback kicker (Fig. 4) should work in the frequency band 0.7 to 3.2 GHz. Therefore, in this case, it was necessary not only to reduce the values of $Z_{\parallel}/n$, but also to prevent resonances from entering the kicker's working frequency band (Fig. 5).

The kicker plates were elongated and bent at the edges right next to the flange, which in the updated design has a beveled face. All this ensured the suppression of the resonant amplitudes by 30 or more times in a given frequency band.

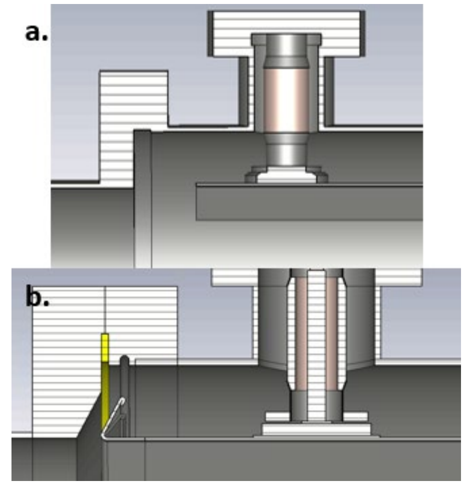

Figure 4: The design of the feedback kicker a) initial model and b) modified.

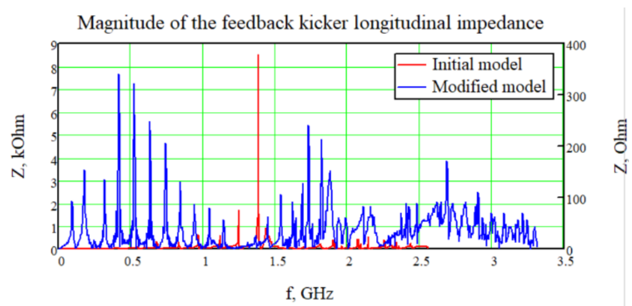

Figure 5: The longitudinal impedance of the feedback kicker before (red curve) and after (blue curve) design changes.

Beam Position Monitor

In total, 46 BPMs are installed in the arches of one Collider ring – 23 horizontal and vertical (4 for betatron oscillation period). Each BPM (Fig. 6) has a measuring electrode 1 of elliptical cross-section with a diagonal cut, which is separated on both sides from the rest of the beam tube by guard electrodes 2. Each BPM is located in a common vacuum chamber with a pumping pipe and bellows.

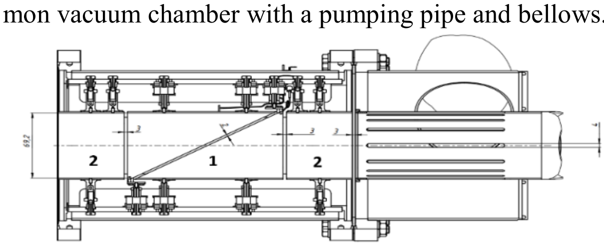

Figure 6: Sketch of the initial BPM and pumping pipe.

The main changes added to the design of the BPM are shielding “clamps” that close the gaps between the measuring and guard electrodes, and end screens with cooper ”springs” installed on the guard electrodes and closing the gaps between them and the bellows chamber and the pumping pipe unit, respectively (Fig. 7). This made it possible to get rid of all resonant frequencies, except for one arising from the diagonal cut in the measuring electrode (Fig. 8).

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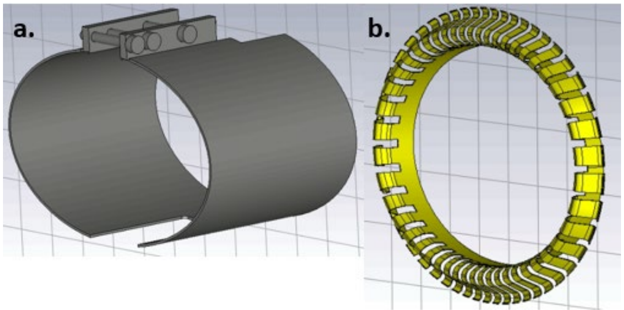

Figure 7: a) Shielding “clamp” and b) “springs”.

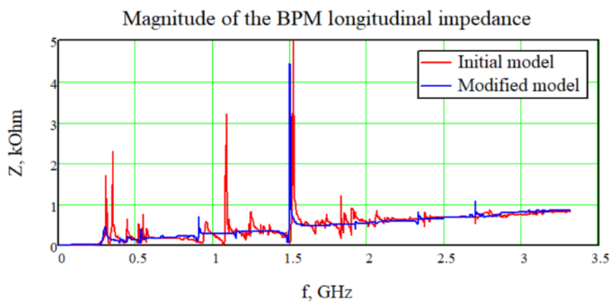

Figure 8: The longitudinal impedance of BPM in Collider arches before (red curve) and after (blue curve) design changes.

ANALYSIS OF ION BEAM STABILITY

The total impedance of the ring consists of the impedances of its individual elements. The total impedance of the NICA Collider ring is represented by Fig. 9 for two operating modes – the beam collimation mode (collimators are put in working position) and the mode when collimators are in retracted position. For both modes, the results are presented for the initial and shielded design of BPM.

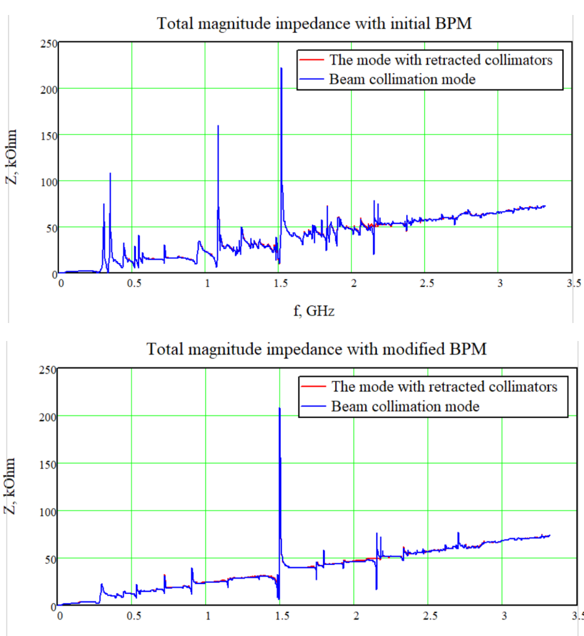

Figure 9: Total impedance of the ring with initial (top) and modified (bottom) BPM design.

As can be seen from the Fig. 9, the main contribution to the total impedance is given by BPM and there is practically no difference between the collimation mode and the mode with retracted collimators, therefore we will limit ourselves in the future only to the collimation mode.

Using the results published in CERN Accelerator School [2], a function was obtained that determines the boundary of the region of stable longitudinal motion for a coasting beam in the ring of the NICA Collider.

The real and imaginary values of the ring impedance are superimposed on this graph and are added to the impedance of the spatial charge and the resistive wall (Fig. 10). The beam motion is stable if the point is located inside the region.

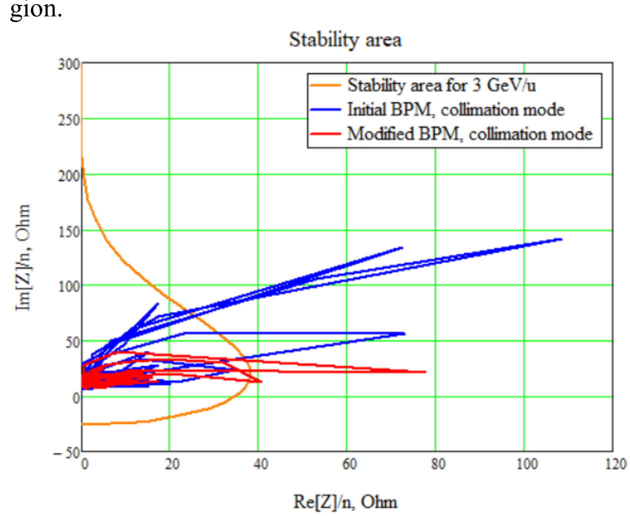

Figure 10: Influence of the initial and shielded BPM model on the beam stability.

Thus, application of the RF shielding of the BPMs reduces impedance contribution to the instability of the beam motion.

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