ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB252

MINIMIZATION OF NICA COLLIDER IMPEDANCE

S. A. Melnikov†, I. N. Meshkov, K. G. Osipov, Joint Institute for Nuclear Research, Dubna, Russia

Abstract

The paper presents the results of the longitudinal impedance minimization for the beam tube section in the arches of the NICA collider ring, consisting of a pumping pipe, a BPM station, and a bellows assembly, and considers the contribution of the impedance of this section to the ion beam stability in the NICA collider ring. To confirm the efficiency of the optimized design, a BPM prototype was fabricated, and a test bench was built for further laboratory measurements.

INTRODUCTION

JINR is developing a project for the Nuclotron-based Ion Collider fAcility (NICA) accelerator complex [1], which has the all-Russian status of a megaproject. The ion collider, which is main part of the complex and will make it possible to study the processes of collision of gold ions with energies up to 4.5 GeV/u / (√s ≤ 11 GeV/u) and polarized protons with energies up to 12.6 GeV (√s ≤ 27 GeV). One of the criteria determining the stability of the motion of charged particles inside the beam tube is the value of the impedance of the last one. In the course of this work, numerical modeling and bench measurements of the impedance values of individual elements of the rings of the NICA collider are carried out in order to minimize it to values that provides the beam stability. For this, changes are made to the design of the elements: – additional screens, elimination of resonance cavities, etc. Based on the simulation, analytical calculations are carried out to assess the stability of the beam dynamics.

BPM DESIGN

The BPM installed in the arches of the collider ring (Fig. 1) has an elliptical measuring electrode 1 (main axis a = 119.3 mm, minor axis b = 69.2 mm) with diagonal cut and separated from the beam tube on both sides by security electrodes 2. Each BPM is located in a common vacuum chamber with a pumping pipe and bellows.

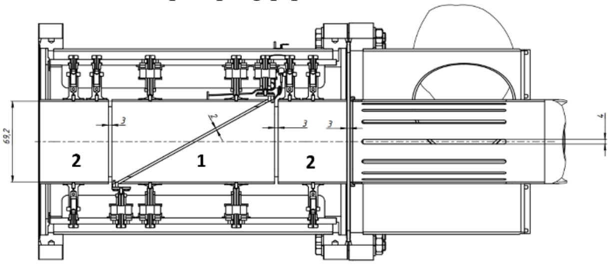

Figure 1: Sketch of initial BPM and pumping pipe.

In total, 46 such sections are installed in the arches of one ring of the collider (4 for betatron oscillation period).

†smelnikov@jinr.ru

IMPEDANCE DEFENITIONS

Space Charge Impedance

In the case of a constant cross-section of the beam tube and perfectly conducting tube walls, the space-charge impedance mode is dominant. If we consider an elliptical cross section in the arches of the ring of the NICA collider, we can assume that b<<a and use the formula for the case of parallel walls:

$$\frac{Z_n}{n} \approx i\, sign(n) \frac{Z_0}{\beta\gamma^2} ln\left(\frac{1.86b}{\sigma_b}\right) \tag{1}$$

where $n \ll \frac{2\pi R_0 \gamma}{b}$ is number of revolution frequency harmonic, $Z_0 = 377$ Ohm, σ_b is the transverse beam size. Numerical coefficient 1.86 corresponds to the elliptical shape of the beam tube (for a round tube it should be replaced by 1.5). This formula is valid for a circular beam with a Gaussian distribution.

Resistive Wall Impedance

In the case of finite conductivity of the chamber walls, a resistive wall impedance appears, which for an elliptical cross section is defined by the expression:

$$\frac{Z_n}{n} = (1 - i\,\mathrm{sign}(\omega_n)) \frac{Z_0 \beta c}{2b\sqrt{2\pi\sigma\omega_n}} F_L \tag{2}$$

where F_L is beam tube form factor: $F_L = 0.98$ for $a/b = 1.71$. σ is conductivity of the chamber material. Even for the first harmonic, where impedance Z_n/n achieves its maximum, the resistive wall impedance is much smaller than the space charge impedance.

Coupling Impedance

The interaction of the charged particle with the accelerator beam tube leads to generation of fields induced in the chamber (wake-fields) and their reverse effect on the beam exciting instability of the particle motion in longitudinal and transverse directions.

By definition $W_{||}(r_1, s) = \frac{1}{q_1}\int_{-\infty}^{\infty} E(r_1, z, t)_{t=(s+z)/c} dz$ is Wake-function. The transverse component of the Wake-function 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 wake impedance is computed by the Fourier-transformation of the longitudinal component of the wake potential, which is divided by the Fourier-transformed charge distribution function $\lambda(s)$:

$$Z_{\parallel}(\omega) = \frac{\int_{-\infty}^{\infty} W_{\parallel}(s) e^{-i\omega s} ds}{\int_{-\infty}^{\infty} \lambda(s) e^{-i\omega s} ds}$$
$$Z_{\perp}(\omega) = i\frac{\int_{-\infty}^{\infty} W_{\perp}(s) e^{-i\omega s} ds}{\int_{-\infty}^{\infty} \lambda(s) e^{-i\omega s} ds} \tag{3}$$

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB252

SIMULATION RESULTS

Initial Model

A simplified 3D model of the ring arch section based on the design sketch (see Fig. 1) was created for calculations (Fig. 2). It includes bellows 1, BPM 2 and pumping unit 3.

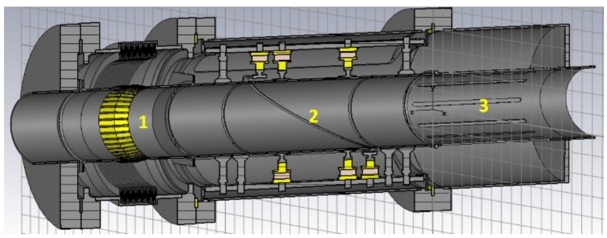

Figure 2: General 3D view of the ring section with BPM.

Numerical simulation of the longitudinal impedance was performed in the CST Studio (Fig. 3). Beam parameters for simulation are: charge q = 1.264e-8, which corresponds to the number of gold ions in the bunch N = 10^9; $\beta = v/c =$ 0.97, (i.e. the beam energy is equal to 3 GeV/u).

Resonances 1, 2 correspond to gaps in the beam tube at the bellows ends, 3 is a gap in the beam tube between the measuring and guard electrodes, 4 is a diagonal cut of the measuring electrodes, 5 is a gap in the tube between the guard electrode and the beam tube of the pumping pipe.

Table 1 shows the amplitude values of the longitudinal impedance modulus depending on number of revolution frequency harmonic n ($f_0 \approx 0.579$ MHz) for the initial model.

Table 1: Amplitude Values of the Longitudinal Impedance Modulus for the Initial Model

f, GHz	n	|Z|/n, Ohm
0.31027	538	4.12
0.35011	607	4.45
1.0851	1882	3.16
1.5196	2636	1.98
1.8325	3178	0.464
1.8994	3294	0.3

Shielded Model

The value of 4 Ohm multiplied by the number of BPM in the ring is significant. To minimize it, the following design changes were introduced to provide RF shielding:

1. Added" clamps " made of stainless steel, covering the gaps between the guard and measuring electrodes.
2. Added end shields and copper springs at the ends of the guard electrodes, providing electrical contact along the entire perimeter of the joint of the guard electrodes with the bellows/pumping pipe.

As a result, we managed to get rid of all large resonant peaks, except for one (see Fig. 3 blue curve): $f =$ 1.532 GHz, $|Z|/n = 1.89$ Ohm.

STABILITY AREA

Using the results published in the lectures of the CERN Accelerator School (CAS) [2] a function that defines the boundary of the stable longitudinal motion region for the coasting beam in the NICA collider ring was obtained (Fig. 4).

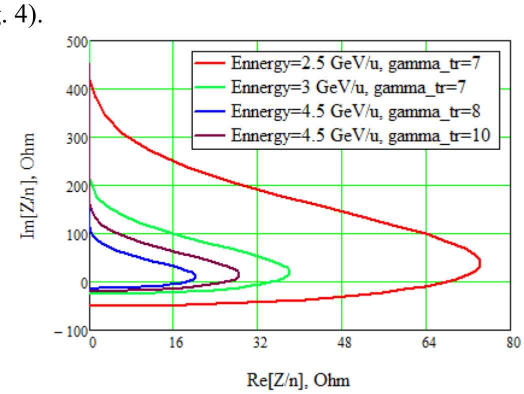

Figure 4: Stability areas for different ion beam energies.

The real and imaginary values of the simulated element impedances are imposed on this graph, multiplied by the total number of these elements in the ring and added to the impedance of the space charge and resistive wall. If the point lies inside the area, then the movement is stable. Taking into account the obtained simulation results, we have the picture (Fig. 5) of impedance influence on beam stability for initial and shielded BPMs.

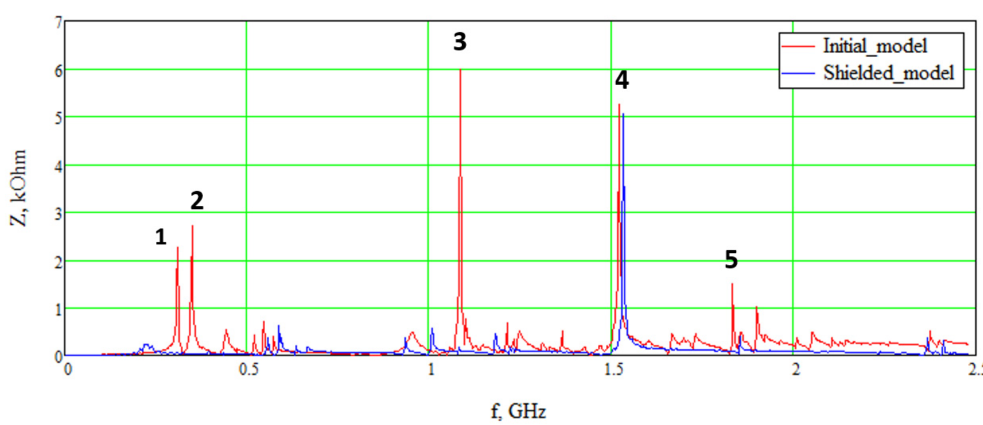

Figure 3: The longitudinal impedance modulus for the original BPM version (red curve) and the shielded one (blue curve).

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB252

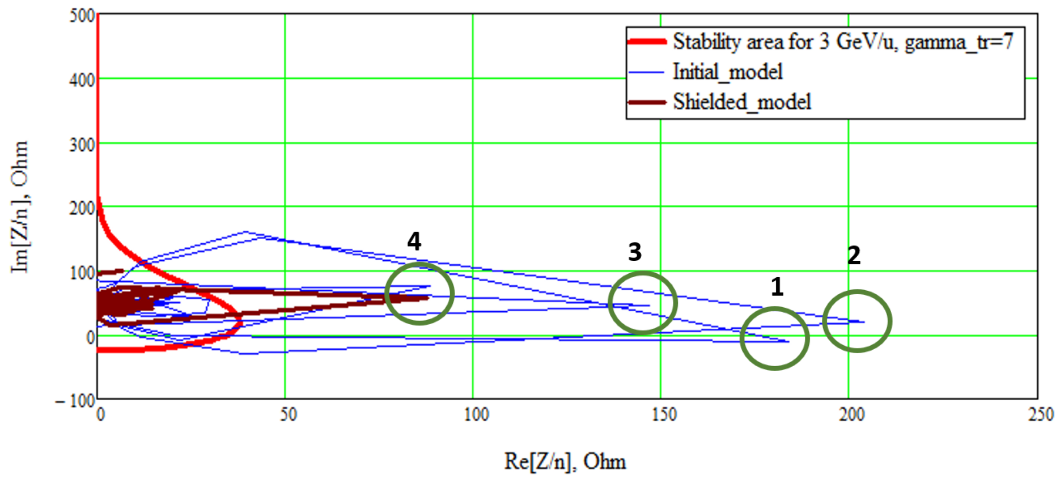

Figure 5: Influence of the initial and shielded model on the beam stability. Numbers at green circles correspond to resonance values of impedances from Fig. 3.

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

LABORATORY MESURMENTS

To confirm experimentally the performance of the developed RF screens, a test bench for measuring the BPM impedance for the initial and shielded versions was constructed. The measurements are being carried out directly only for BPM without pumping pipe and the bellows. To match the BPM impedance with the impedance of the external RF generator and connecting cables, a branch line (two end cones) is used (Fig. 6). Their dimensions are also selected using numerical simulation. The aperture of the cones has a complex geometry, varying from elliptical one at its connection with the guard electrodes to circular at the exit.

Figure 6: BPM prototype for test bench measurements.

Due to the complexity of manufacturing such cones, they were fabricated with polyamide on a 3D printer with subsequent metallization with silver. Measurements are in progress.

REFERENCES

[1] D. Kekelidze *et al.*, “Three stages of the NICA accelerator complex”, *The European Phys. Journal A*, vol. 52, no. 8, 2016. doi:10.1140/epja/i2016-16211-2

[2] J. L. Laclare, “Coasting beam longitudinal coherent instabilities”, in *CERN Accelerator School: Course on General Accelerator Physics*, Jyvaskyla, Finland, Sep. 1992, pp. 349-384.