PROGRESS IN THE NICA DESIGN AND CONSTRUCTION

Dubna, JINR, 1 January 2015

Introduction

Last session of the NICA Machine Advisory Committee took place at JINR (Dubna) in October 17-18, 2013. As result MAC formulated concrete recommendations concerning further project development. For the next MAC meeting the designer team has to provide the following works:

- to examine improvement the momentum acceptance up to +-1%,
- to provide the scheme of the vertical dispersion correction,
- to present full report about instabilities, specifications of the RF system together with feed-back for the beam load compensation, functional specification of the feed-back systems – transverse and longitudinal,
- to consider the possibility to use the turbines instead of the Joule-Thompson valves in the nitrogen liquefier and in the nitrogen,
- to present concepts of machine and radiation protection system for NICA,
- to present work-chart distribution of various responsibilities, assigned personal to specific tasks starting with the project chef engineer, the work on time table development has to be continued and the results have to be presented to the next MAC in details.

For the start-up configuration of the NICA collider MAC recommends the following minimal set of equipment

- no electron cooling
- reduced version of stochastic cooling, however the longitudinal cooling id mandatory,
- reduced RF system has to include BB cavity and minimum 2 cavities of RF2 or RF3 per ring,
- no feed-back systems.

Start-up configuration and harmonic number of RF2, RF3 systems has to be chosen together with start-up configuration of MPD. Chosen start-up (and beam dynamic simulation for it) has to be presented to the next MAC meeting.

The stochastic cooling is one of the key technical issues for the NICA project, and the further study of stochastic cooling at the Nuclotron, especially for the bunched beam cooling is mandatory.
Concept of the Stochastic Cooling System (SCS) system was presented, but conceptual design is in a preliminary stage. The work has to be intensified with the help of outside leading experts. The conceptual design has to be presented to the next MAC meeting.

This report is concentrated at the answers for the MAC requests and includes the following chapters:

PARAMETERS OF THE COLLIDER CORRECTION SYSTEM

SPECIFICATION OF THE INSTABILITIES AT THE NICA COLLIDER

START-UP CONFIGURATION OF THE NICA COLLIDER. BEAM PARAMETERS UNDER LONGITUDINAL STOCHASTIC COOLING

STOCHASTIC COOLING SYSTEM FOR NICA

POWER SUPPLY AND QUENCH PROTECTION SYSTEM OF THE NICA COLLIDER

THE QUENCH DETECTOR FOR SUPERCONDUCTING ELEMENTS OF THE NICA ACCELERATION COMPLEX

VACUUM CONTROL AND PROTECTION

BEAM LOSS MONITOR SYSTEM FOR THE NICA COLLIDER

INJECTION COMPLEX, BEAM TRANSPORT, INJECTION/EXTRACTION SYSTEMS

COMMISSIONING OF THE BOOSTER RF STATIONS

STATUS OF WORK ON THE DEVELOPMENT AND MANUFACTURE OF SUPERCONDUCTING MAGNETS FOR THE NICA PROJECT AT DECEMBER 2014

The stable circulation of the particle beams requires to have the profound systems of magnetic field corrections in the collider lattice. The following set of the correction chains is considered in the each ring: closed orbit distortion correction; linear betatron tune shift correction; transversal coupling correction; compensation or correction of the natural chromaticity of tunes; correction of amplitude dependent tune spread from sextupoles. The ring optics structure was slightly changed in order to increase interaction region in accordance with MPD demands. The lattice functions of the current structure are shown in the Fig. 1, 2.

Figure 1. Betatron amplitude functions in the collider ring.
Figure 2. Dispersion functions: horizontal $D_x$, vertical $D_y$ (before/after correction).

The updated general parameters of the collider ring are compiled in Table 1, in particular, bunch parameters and corresponding approximately equalized IBS growth times and luminosities.

**Correction of the closed orbit distortions.** For the realized random tolerances on the alignment of the magnetic elements and guiding field imperfections [MAC2013 report], maximal required number of the dipole kickers ($n_{corr} = 40$, maximal correction kick $\theta_{corr} \leq 0.01 \cdot \theta_{dip}$) provides the corrected orbit $\sigma_{x/y} = 0.1$ mm and the correction quality of 30.
Table 1. General parameters of the collider ring.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference of the ring, m</td>
<td>503.04</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>22</td>
</tr>
<tr>
<td>R.m.s. bunch length, m</td>
<td>0.6</td>
</tr>
<tr>
<td>$\beta$-function in IP, m</td>
<td>0.35</td>
</tr>
<tr>
<td>Betatron frequinces, $Q_x/Q_y$</td>
<td>9.44/9.44</td>
</tr>
<tr>
<td>Chromaticities, $Q'_x/Q'_y$</td>
<td>-33/-28</td>
</tr>
<tr>
<td>Acceptance of the ring, $\pi$ mm·mrad</td>
<td>40</td>
</tr>
<tr>
<td>Momentum acceptance, $\Delta p/p$</td>
<td>±0.010</td>
</tr>
<tr>
<td>Critical energy factor, $\gamma_{tr}$</td>
<td>7.088</td>
</tr>
<tr>
<td>Energy of $^{79}$Au, GeV/u</td>
<td>1.0</td>
</tr>
<tr>
<td>Number of ions per bunch</td>
<td>$2.0 \cdot 10^8$</td>
</tr>
<tr>
<td>R.m.s. momentum spread, $\Delta p/p$</td>
<td>$0.55 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>R.m.s. emittance, $\pi$ mm·mrad</td>
<td>1.1/0.95</td>
</tr>
<tr>
<td>Luminosity, cm$^{-2}$ s$^{-1}$</td>
<td>$0.6 \cdot 10^{25}$</td>
</tr>
<tr>
<td>IBS growth time, s</td>
<td>160</td>
</tr>
</tbody>
</table>

**Quadrupole correction of betatron tunes.** Power supply system of the collider rings has the same main supply current over the lattice quadrupoles up to $I_{\text{max}} \approx 11$ kA. Optics of the bending arcs is “fixed” due to the constant phase advance per cell ($\mu_{x,y} = 90^0$) and $D_x$ - dispersion suppression. The variation of betatron tunes, matching conditions and beam parameters in IPs are produced in the long straight sections by the trim quadrupoles that have the separate low current power supplies ($I_{\text{trim}} = \pm 1$ kA). In the Figure 3 the possible working points of the collider are shown together with resonance lines. Two parts of the long straight section (on both sides of IPs) for top or bottom ring are matched separately taking to account the antisymmetric connection of final focus triplets about IPs. For instance, the straight setting are given in Table 3 for 2 working point of the collider: $Q_{x,y} = 9.44/9.44, 9.10/9.10$. Tuning is provided by trim quadrupoles.

**Skew quadrupole correctors.** The main sources of coupling of the betatron oscillations in the collider rings, MDP detector solenoid ($B_s=0.66$ T) and ECool solenoid ($B_s=0.2$ T), and random roll of quadrupoles (up to 0.1 mrad expected), will cause the effects of tune shifts and x/y-coupling for unequal transverse emittances. There are 4 skew quadrupole families (separate power supplies) required for simultaneous correction of the nearest coupling resonances $Q_x$-
\( Q_y = 0 \) and \( Q_x + Q_y = 19 \). Four correction elements are located in dispersion-free region and designed for the maximal gradient of 1 T/m.

Correction of the vertical dispersion \( D_y \) could be provided by at least 2 additional skew quadrupole families located in arcs near maxima of \( D_x \)-dispersion (8 correctors, \( G_{\text{max}} = 1 \) T/m) (Fig. 2).

**Sextupole correction of chromaticity.** The large value of natural tune chromaticity \( (Q'_{x,y} \approx -30) \) caused by the large variation of \( \beta \)-functions at IP region (Fig. 4) leads to the unallowable tune spread \( \Delta Q_{x,y} \approx 0.7 \) in the range of momentum acceptance \( (\Delta p/p = \pm 0.01) \) and resonances intersections. The sextupole correctors are located in the dispersion arcs and divided into 4 families. The betatron phase advance between the correctors of one family is \( \mu_{x,y} = 180^0 \). The given scheme is allowed to suppresses the sextupole influence on DA in second order and to control the second order chromaticity \( \Delta Q_{x,y} = Q'_{x,y}(\Delta p/p) + Q''_{x,y}(\Delta p/p)^2 \). The correction is shown in Fig. 4 for the condition of \( Q'_{x,y}(\Delta p/p=0) = -1.5 \). The peak gradient required is 150 T/m².

![Figure. 3. Range of betatron tunes. Resonances of betatron oscillations up to 9-th order, collider working points.](image1)

![Figure. 4. Betatron tunes vs momentum before (1) and after (2) correction of chromaticity working points.](image2)

**System of octupole correctors.** Due to the low–beta insertions the collider rings require the large sextupole strength to control the chromaticity that it is necessary to consider the second order effects in sextupoles. That is the betatron tune shift dependence on amplitude of betatron oscillations: \( \Delta Q_x = a_{xx}J_x + a_{xy}J_y \), \( \Delta Q_y = a_{yx}J_x + a_{yy}J_y \). At least 2 families of octupole correctors required for compensation of tune spread. There are 10 corrector coils in each family which are placed in relative maximum of \( \beta_x^2, \beta_y^2 \) in the bending arcs and produce the peak gradient of...
about 400 T/m³. From the other hand the same octupole system could introduce the controllable betatron tune spread to compensate head-tail instability in the beam by the Landau-damping: 
\[ \Delta Q_{x,y} = \Delta Q_{x,y,coh} - \Delta Q_{x,y,SC} - \Delta Q_S , \]
where \(\Delta Q_{x,y,coh}\) – coherent tune spreads, \(\Delta Q_{x,y,SC}\) and \(\Delta Q_S\) – transversal and longitudinal spreads due to the space charge. The another requirement for damping is the small and negative first order chromaticity.

**Dynamic Aperture calculations.** The investigation and comparison the methods of numerical simulation of charged particles tracking in the electromagnetic fields of the structural elements of the collider and evaluation of long-term DA have been carried out (A.Bolshakov, P.Zenkevich). Two methods of numerical integration of the movement of charged particles in external fields realized in code MAD-X have been used. The first one, thin-lens model, transforms each magnetic element into the sequence of slices, or, by default, in a zero-length element located in the centre of the thick element. The second method, Polymorphic Tracking Code (PTC) is an another attempt of the symplectic integration of particle movement. In this approach the ring elements are described symplectically to a certain extent, which is defined by the user and the computer's performance. Thin-lens model unlike PTC algorithm does allow to consider the space charge and beam-beam forces in particle tracking. In both approaches the following factors were included: uncompensated \(D_y\), RF3 cavity is on, chromaticity correction is on, expected systematic and random nonlinearity of the dipole magnets. Beam dynamics was tested for \(N_{\text{turn}}=10^5\) - number of turns and \(N_{\text{part}}=10^3\) - number of particles. The results of PTC shown in Fig. 5 and Fig. 6 represent the region of the survived particles and envelope of this region.

The long-term DA is evaluated by the Giovannozzi approach: the data of the numerical experiments are fitted by the law \(\sqrt{D(N)} = \sqrt{D_\infty}(1 + b/[\log(N)]^k)\), where \(D_\infty\) - asymptotic DA, \(b\) and \(k\) parameters are defined from the DA-number of turns dependency \(D(N)\). The
corresponding approximations for PTC and thin-lens methods are given in Fig. 7. In both cases asymptotic DA for the chosen working point \(Q_{x,y} = 9.44/9.44\) is larger than the collider acceptance of \(A_{x,y} = 40\pi\) mm·mrad: \(D_\infty = 98\pi\) mm·mrad (PTC), \(58\pi\) mm·mrad (thin-lens).

Figure. 7. Dynamic aperture (PTC, thin-lens methods and approximations) vs number of turns \(N_{\text{turn}}\).

Table 2. Characteristics of the multipole corrector. \(L=0.3\) m. Pole tip radius \(R=66\) mm.

<table>
<thead>
<tr>
<th>Multipole component</th>
<th>Function</th>
<th>Max. parameter of magnetic field</th>
<th>Max. parameter of power supply [kAturns]</th>
<th>Number of correction coils</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole</td>
<td>Steering and closed orbit correction</td>
<td>0.15 T</td>
<td>8.0</td>
<td>40</td>
</tr>
<tr>
<td>Quadrupole</td>
<td>Betatron tune correction</td>
<td>2.2 T/m</td>
<td>3.8</td>
<td>12</td>
</tr>
<tr>
<td>Skew quadrupole</td>
<td>Coupling compensation; (D_y)-correction</td>
<td>1.0 T/m</td>
<td>1.7</td>
<td>4; 8</td>
</tr>
<tr>
<td>Sextupole</td>
<td>Chromaticity control</td>
<td>150 T/m²</td>
<td>5.7</td>
<td>48</td>
</tr>
<tr>
<td>Octupole</td>
<td>Second order control</td>
<td>400 T/m³</td>
<td>3.8</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 3. Tuning of the ring with trim quadrupoles (an example for half of the straight section).
<table>
<thead>
<tr>
<th>L [m]</th>
<th>I [kA]</th>
<th>G [T/m]</th>
<th>K1 [1/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Qx/Qy=9.44/9.44**

**Arc quads**

<table>
<thead>
<tr>
<th>QFA</th>
<th>0.46</th>
<th>11.0</th>
<th>23.4</th>
<th>0.52</th>
</tr>
</thead>
<tbody>
<tr>
<td>QDA</td>
<td>0.46</td>
<td>11.0</td>
<td>-23.4</td>
<td>-0.52</td>
</tr>
</tbody>
</table>

**Straight quads**

<table>
<thead>
<tr>
<th>QFAL1</th>
<th>0.41</th>
<th>11.0</th>
<th>23.4</th>
<th>0.52</th>
</tr>
</thead>
<tbody>
<tr>
<td>QDAL1</td>
<td>0.57</td>
<td>11.0</td>
<td>-23.4</td>
<td>-0.52</td>
</tr>
<tr>
<td>QFAL2</td>
<td>0.39</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>QDAL2</td>
<td>0.46</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>QFAL3</td>
<td>0.42</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>QDAL3</td>
<td>0.38</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>QFAL4</td>
<td>0.39</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>QDAL4</td>
<td>0.47</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**Trim quads**

<table>
<thead>
<tr>
<th>QDT5</th>
<th>0.3</th>
<th>1.0</th>
<th>2.2</th>
<th>0.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>QFT5</td>
<td>-</td>
<td>-</td>
<td>-2.2</td>
<td>-0.05</td>
</tr>
<tr>
<td>QDT6</td>
<td>-</td>
<td>-</td>
<td>-2.2</td>
<td>-0.05</td>
</tr>
<tr>
<td>QFT6</td>
<td>-</td>
<td>-</td>
<td>2.2</td>
<td>0.05</td>
</tr>
<tr>
<td>QDT7</td>
<td>-</td>
<td>-</td>
<td>-2.2</td>
<td>-0.05</td>
</tr>
<tr>
<td>QFT7</td>
<td>-</td>
<td>-</td>
<td>2.2</td>
<td>0.05</td>
</tr>
</tbody>
</table>

**Final quads**

<table>
<thead>
<tr>
<th>QFF1</th>
<th>0.85</th>
<th>11.0</th>
<th>18.45</th>
<th>0.41</th>
</tr>
</thead>
<tbody>
<tr>
<td>QFF2</td>
<td>1.60</td>
<td>11.0</td>
<td>-18.45</td>
<td>-0.41</td>
</tr>
<tr>
<td>QFF3</td>
<td>1.0</td>
<td>11.0</td>
<td>18.45</td>
<td>0.41</td>
</tr>
</tbody>
</table>

**Qx/Qy=9.10/9.10**

**Trim quads**

<table>
<thead>
<tr>
<th>QDT5</th>
<th>0.3</th>
<th>1.0</th>
<th>2.2</th>
<th>0.050</th>
</tr>
</thead>
<tbody>
<tr>
<td>QFT5</td>
<td>-</td>
<td>0.2</td>
<td>-0.4</td>
<td>-0.009</td>
</tr>
<tr>
<td>QDT6</td>
<td>-</td>
<td>0.8</td>
<td>-1.8</td>
<td>-0.040</td>
</tr>
<tr>
<td>QFT6</td>
<td>-</td>
<td>0.3</td>
<td>-0.6</td>
<td>-0.013</td>
</tr>
<tr>
<td>QDT7</td>
<td>-</td>
<td>1.0</td>
<td>2.1</td>
<td>0.048</td>
</tr>
<tr>
<td>QFT7</td>
<td>-</td>
<td>1.0</td>
<td>-2.2</td>
<td>-0.050</td>
</tr>
</tbody>
</table>
# Specification of the Instabilities at NICA Collider

A. Sidorin, P. Zenkevich, V. Zhabitsky

<table>
<thead>
<tr>
<th>Type of instability</th>
<th>Driven by</th>
<th>Limiting parameter</th>
<th>Importance</th>
<th>Cures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robinson instability</td>
<td>Wide-band cavity</td>
<td>$Z_{cav}(\omega) = \frac{R_s}{1 + iQ(\frac{\omega}{\omega_R} - \frac{\omega_R}{\omega})}$</td>
<td>not so important: - large SC impedance - long bunch</td>
<td>standard cures limiting contribution of different chamber elements in shunt impedance</td>
</tr>
<tr>
<td>Transverse MCW</td>
<td>Equilibrium with Landau damping</td>
<td>$N_{lim}^{tr} \leq \beta t \sqrt{2\pi} \frac{U_p}{Z_t c} \frac{A_i}{</td>
<td>Z_{\perp}</td>
<td>R c Z_t} \gamma^3 \beta^2</td>
</tr>
<tr>
<td>Longitudinal MCW</td>
<td>Equilibrium with Landau damping</td>
<td>$N_{lim}^{long} \leq \frac{2\pi}{c \beta \gamma} \frac{A_i}{</td>
<td>Z_{</td>
<td></td>
</tr>
<tr>
<td>TMCI</td>
<td>wake</td>
<td>$N_{lim}^{tm} \leq \frac{\beta t c \delta Q Q_{s}(\Omega_0)^2}{\pi r_0 e^2 W_0}$</td>
<td>$N_{lim}^{tm} \sim 10^{12}$</td>
<td>Not dangerous in the total energy range</td>
</tr>
<tr>
<td>LMCI</td>
<td>wake</td>
<td>Threshold for LMCI is higher than for TMCI</td>
<td>Not dangerous in the total energy range</td>
<td></td>
</tr>
<tr>
<td>Weak head-tail instability</td>
<td>chromaticity</td>
<td>$\lambda_i = \frac{1}{\omega_0} \frac{1}{1 + l A_i 4 \gamma E_p} \sqrt{\frac{2}{\omega_0 \tau_p} \frac{</td>
<td>Z_{\perp}(\omega_0)</td>
<td>Re[F_i(\chi)]}}$</td>
</tr>
</tbody>
</table>
In context of a transverse feed-back system (TFS) the theoretical studies are started taking into account stabilization of high intensity beams in regimes for tunes close to a half integer. It was observed at SPS CERN that high intensity beams at these regimes can be stabilized if a fast feed-back system is used. **The fast TFS** consists of two pick-ups and two kickers shifted by 90 degrees for betatron phase advances. This system can detect all betatron phases of the beam trajectory and consequently has no disadvantages for fractional tunes close to a half integer. These theoretical studies are being implemented in collaboration with the damper team from CERN. The digital fast TFS has been installed at SPS in 2014.

<table>
<thead>
<tr>
<th>Instability Type</th>
<th>Description</th>
<th>Formula</th>
<th>Stability Conditions</th>
<th>Feedback System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole longitudinal one-bunch instability</td>
<td>Loss of longitudinal Landau damping due to shift between incoherent spectrum and frequency of coherent oscillations</td>
<td>$N_{b}^{lim} = \frac{nZ_0 \gamma(Q_s)^2 R}{</td>
<td>Z</td>
<td><em>{sc}} \frac{1}{2r_i \eta q^3} k</em>{lim}^n$</td>
</tr>
<tr>
<td>Transverse Multi-bunch instability</td>
<td>Resistive wall impedance</td>
<td>$1 \tau_{ms} = -\frac{1}{1 + m \frac{Z_i e M_I b}{4 \pi \gamma Q A_1 \eta E_0}} Re Z_{RW}^{R}(\omega_p) f_m^r(\omega_p \tau_L - \chi)$</td>
<td>$f_{inst} \sim 440$ turns</td>
<td>Transverse Feedback</td>
</tr>
<tr>
<td>Longitudinal Multi-bunch instability</td>
<td>Resonant elements</td>
<td>$\lambda_{long} = \frac{r_i \eta \gamma p r_s R_s}{\beta^2 \gamma T_0 Q_s \gamma Z_0}$</td>
<td>Most dangerous at ~ 3 GeV/u</td>
<td>Longitudinal feedback system, control impedance of high frequency HOM</td>
</tr>
</tbody>
</table>
START-UP CONFIGURATION OF THE NICA COLLIDER. BEAM PARAMETERS UNDER LONGITUDINAL STOCHASTIC COOLING

I.Meshkov, G.Trubnikov, A.Sidorin

15 of January 2014 at the NICA Coordination Committee the start up configuration of the collider equipment was discussed. Two regimes have been compared:

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harmonics</td>
<td>66</td>
<td>22</td>
</tr>
<tr>
<td>Bunch number</td>
<td>66</td>
<td>22</td>
</tr>
<tr>
<td>R.m.s. bunch length, cm</td>
<td>40</td>
<td>121</td>
</tr>
<tr>
<td>Hour-glass factor</td>
<td>0.67</td>
<td>0.34</td>
</tr>
<tr>
<td>Luminosity, $10^{25}$</td>
<td>4.8</td>
<td>7.2</td>
</tr>
</tbody>
</table>

(at $\Delta Q = 0.01$ and $E_{ion} = 3.5$ GeV/u)

The both regimes provide comparable level of the luminosity. The first regime (66 harmonics) provide concentration of the luminosity in the central part of the detector, however it leads to two parasitic collisions inside the detector area. The MPD start-up configuration does not include the inner tracker. For the detector it is preferable the second regime.

As result the start-up configuration of the RF system was determined as follows:

<table>
<thead>
<tr>
<th></th>
<th>Total set</th>
<th>Start-up version</th>
</tr>
</thead>
<tbody>
<tr>
<td>BB cavities</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>RF2 resonators</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>RF3 resonators</td>
<td>16</td>
<td>0</td>
</tr>
</tbody>
</table>

Stochastic cooling consists of two chains instead of six: only longitudinal for each ring.

No electron cooling.

No feedback system.

The luminosity required for test of the detector systems is $5 \cdot 10^{25} \text{cm}^{-2}\cdot\text{s}^{-1}$.

Energy range for first experiments chosen from 3 to 4.5 GeV/u. Operation scenario will be started with stacking with BB RF system + longitudinal stochastic cooling. At maximum emittance the bunch intensity corresponding to the luminosity of $5 \cdot 10^{25} \text{cm}^{-2}\cdot\text{s}^{-1}$ is about $7 \cdot 10^8$
ions. The beam stacking time is less than 150 s. Expected beam emittance at the exit of the Nuclotron is below 0.3 π-mm-mrad and this value can be adjusted by electron cooling in the Booster. There are no reasons to expect sufficient increase of the emittance during the short stacking period.

After completion of the stacking the bunching will be provided to form 22 bunches with the length of about 1.2 m (instead of 0.6 m). The bunching procedure is realized by the same way as in the final collider configuration. The difference is only smaller number of particles. It was shown in numerical simulations that the bunch length of 1.2 m can be achieved with stochastic cooling during adiabatic increase of the RF voltage up to 50 kV, which corresponds to maximum voltage at 22 harmonics at start-up configuration. The bunch momentum spread as function of energy is shown at the Fig. 1.

![Figure 1](image1.png)

**Fig 1.** The rms momentum spread corresponding to 1.2 m of the bunch length at RF voltage of 50 kV, harmonics number = 22 as function of the beam energy.

Due to small value of the momentum spread the filter method instead of Palmer will be used. The method was already tested for cooling of bunched beam at the Nuclotron.

The maximum SC tune shift corresponds to minimum energy (3 GeV/u). At 7·10⁸ ions it is about 0.009. Beam-beam parameter is about one order less. More serious restriction of the beam intensity is related to longitudinal microwave instability (because of small momentum spread). The threshold particle number (Fig. 2) is about 3 times larger than the required bunch intensity.

![Figure 2](image2.png)

**Fig. 2.** Threshold particle number in accordance with Keil-Shnell criterion for microwave longitudinal instability as function of the beam energy.
To avoid weak head-tail instability the collider will be operated at small negative chromaticity, the high order modes will be suppressed by use of octupole families.

At the small momentum spread the bunch is fare from thermal equilibrium between transverse and longitudinal degrees of freedom. The relaxation due to IBS leads to fast heating of the longitudinal degree of freedom. The horizontal heating time is more than order of magnitude longer than the longitudinal one, at the same time the vertical emittance decreases due to so called “simpathetic” cooling. For instance at 3 GeV/u and at emittance of 0.48 $\pi$ mm-mrad the horizontal heating time is of the order of 1000 s when the vertical IBS time has exact the same value but the negative sign. At the collider operation at coupling resonance at equal horizontal emittances the transverse heating rate can be estimated as mean value of the horizontal and vertical rates without coupling. For the example above if the longitudinal heating is compensated by the stochastic cooling the transverse emittance is stabilized at the value of $0.48 \pi$ mm-mrad. Such an “equilibrium” transverse emittance as function of the beam energy is shown in the Fig. 3. At energy of 4 GeV/u and larger the stabilization of the beam emittance takes a place at the value larger than 1.1 $\pi$ mm-mrad (ring acceptance limitation) and at the plot the last three points correspond to slight growth of the emittance.

![Fig. 3. Equilibrium emittance as function of energy.](image)

The bunch intensity corresponding to the luminosity of $5 \cdot 10^{25}$ cm$^{-2}$s$^{-1}$ (Fig. 4) lies in the range from $5 \cdot 10^8$ to $7 \cdot 10^8$. The longitudinal heating time varies from 30 sec at 3 GeV/u up to about 500 sec at 4.5 GeV/u (Fig. 5). The transverse heating rate has exact zero value up to about 3.8 GeV/u (Fig. 6). At the energy of 4.5 GeV the transverse heating time at the emittance corresponding to the acceptance limit is about 15 hours. The IBS heating times were calculated in accordance with Bjorken model (S.Nagaitsev, V.Lebedev), the simulations with the Betacool program give slightly more optimistic results.
Fig. 4. The particle number per bunch corresponding to $5 \cdot 10^{25}\text{cm}^{-2}\text{s}^{-1}$ of the luminosity as function of the beam energy.

Fig. 5. Longitudinal heating time as function of the beam energy.

Fig 6. Transverse heating rates as function of the beam energy.

At the energy about 4 GeV/u the longitudinal heating time is about 200 s. Such a cooling time is achievable with the designed stochastic cooling system. At the final collider configuration the cooling system is to provide the cooling time of 1250 sec (see the next chapter). In the start up configuration the bunch intensity is about 4 times less, the bunching factor is two times less, correspondingly the equivalent particle number is about 8 times less than in the final configuration. At optimum rate the cooling time is scaled linearly with the particle number. Thus during the experiment the momentum spread will be stabilized by stochastic cooling, the transverse emittance will be stabilized at the value slightly smaller than the acceptance limit by sympathetic cooling of the vertical degree of freedom.
STOCHASTIC COOLING SYSTEM FOR NICA

N.Shurkhno, A.Sidorin, G.Trubnikov

Stochastic cooling in the collider is primarily aimed at preserving of the required luminosity level during operation at higher energies. The main source of the luminosity degrading is IBS heating effect, therefore stochastic cooling systems must provide cooling rates higher than IBS growth rate.

1. Cooling strategy

The present NICA parameters which are of interest for the stochastic cooling are listed in the following table:

<table>
<thead>
<tr>
<th>Energy [GeV/u]</th>
<th>Initial dp/p \times 10^{-3}</th>
<th>Intensity \times 10^{10}</th>
<th>Eta full</th>
<th>Eta PU-K</th>
<th>IBS rate [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.62</td>
<td>0.6</td>
<td>0.215</td>
<td>0.199</td>
<td>160</td>
</tr>
<tr>
<td>2</td>
<td>1.00</td>
<td>1.0</td>
<td>0.082</td>
<td>0.067</td>
<td>300</td>
</tr>
<tr>
<td>3</td>
<td>1.25</td>
<td>5.3</td>
<td>0.037</td>
<td>0.021</td>
<td>460</td>
</tr>
<tr>
<td>4</td>
<td>1.65</td>
<td>4.8</td>
<td>0.016</td>
<td>0.00061</td>
<td>1250</td>
</tr>
<tr>
<td>4.5</td>
<td>1.65</td>
<td>4.8</td>
<td>0.0099</td>
<td>-0.0057</td>
<td>1800</td>
</tr>
</tbody>
</table>

Numerous calculations (independently carried out by L. Thorndahl/CERN, T. Katayama/GSI and N. Shurkhno/JINR) show that cooling is only possible for energies higher than 3GeV/u. At lower energies cooling cannot be achieved because local and full slip-factors become large (which slows or fully stops cooling) while required cooling times due to IBS growth-rate become very short.

*Palmer method* is currently foreseen for longitudinal cooling because it provides high performance and widest energy range 3-4.5 GeV/u, compared to other traditional comb-filter and ToF methods. Palmer cooling requires high dispersion at the pickup while maximum ring dispersion is only 2.5m, which is quite low. That is not important for calculations, but in principle it can sufficiently complicate real cooling, so for highest energies (>4GeV/u) switching to filter-method could be advantageous and is considered as an alternative. Moreover, the possibility of implementation of new method (initially proposed by D. Mohl) that utilizes
differential signal from two pickups is being investigated. This is dispersion-free method and it does not reduce significantly momentum range available for cooling, comparing to filter method. Preliminary calculations show that this method is most advantageous, but since it has not been yet tried out, it requires further detailed theoretical and experimental studies.

The parameters of the cooling systems are summarized in the table:

<table>
<thead>
<tr>
<th>Energy, GeV/u</th>
<th>3</th>
<th>4 - 4.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>IBS growth-rate, s</td>
<td>700</td>
<td>1500-2000</td>
</tr>
<tr>
<td>Longitudinal method</td>
<td>Palmer</td>
<td>Palmer/filter</td>
</tr>
<tr>
<td>Cooling time, s</td>
<td>&lt; 500</td>
<td></td>
</tr>
<tr>
<td>Gain, dB</td>
<td>&lt; 90</td>
<td></td>
</tr>
<tr>
<td>Power for the kicker, W</td>
<td>&lt; 50</td>
<td></td>
</tr>
<tr>
<td>Power for the beam, W</td>
<td>&lt; 500</td>
<td></td>
</tr>
</tbody>
</table>

2. Location

In order to fight three-dimensional IBS heating for each ring of the collider there are foreseen three cooling systems (longitudinal, horizontal and vertical), thus six in total. The planned location of the systems is presented in Fig. 1:

![Fig. 1 NICA stochastic cooling systems placement, bottom ring (red), top ring (blue)](image)

Cooling systems for both rings will be located reflection symmetric. Longitudinal and transverse systems will be spatially separated in each ring. Transverse systems – horizontal and
vertical - will use same pick-ups and kickers. Such arrangement corresponds to using Palmer method for longitudinal cooling, which demands high dispersion at pickup, while horizontal cooling needs zero dispersion in order to avoid cross-heating. The lattice functions are shown in Fig. 2:

![Fig. 2 Lattice functions at pickups](image)

Longitudinal pick-up is located in region with highest dispersion, simultaneous horizontal and vertical pick-up is located in region with small dispersion and high horizontal beta-function. The transverse pick-up is placed in the region with non-zero dispersion in order to avoid interference with electron cooling system. Such disposition allows to have proper phase advance for both transverse and horizontal systems - $\Delta \Psi / \pi = 3.5 \pm 0.1$.

3. Hardware

The main elements of the stochastic cooling systems, which should be considered beforehand are pickup and kickers, amplifiers, delays and notch-filters (if used).

Slot-ring couplers will be used as *pick-ups and kickers* (Fig. 3). The devices were tested in at COSY (FZ Juelich) and Nuclotron (JINR) facilities and showed excellent performance. It is planned to use same pick-ups and kickers for horizontal and vertical systems by appropriate combination of electrodes (Fig. 4).

Initially the devices were developed for the stochastic cooling systems of HESR, and in the coming year it is planned to optimize the structures for the NICA: reduce the aperture from 90mm to 70mm (NICA aperture), determine the required number of electrodes in each ring, etc.
Fig. 3 Slot-ring coupler with 16 rings (used at Nuclotron)

Fig. 4 Combination of electrodes for horizontal (blue) and vertical (red) signals.

It is planned to use solid-state *amplifiers* because they have best amplitude and phase behavior. The achievable power from one device with proper characteristics is approx. 60-70W, thus to obtain the required 500W power it is planned to feed the power separately to each kicker unit (8-10 in total). The other strategy could be using the lower power amplifiers separately for each electrode (or groups of electrodes). This will significantly reduce the final costs of the amplifiers, but considers the identical amplifiers’ responses. The approach is going to be tested during next Nuclotron run in Feb 2015.

The optical system delays and optical notch-filter developed and tested at Nuclotron have demonstrated excellent performance and are planned to use at NICA.

4. Software

Software for the stochastic cooling system is developing in two directions: control and automation of measurements and adjustments. Presently the algorithms for automation of system delay (open-loop measurements) and comb-filter adjustments are developed and tested, several realizations of control software were also experimentally tested. Further, it is planned to develop the single integrated software for the Nuclotron cooling system, which can be easily extended for controlling and adjustment of all six NICA cooling channels and has a possibility of integration into the general NICA control system based on TANGO.

5. Stochastic cooling system for the start version of NICA

Start-up configuration of the NICA collider uses reduced energy range 3.0 - 4.5 GeV/u, 1/4 of the design intensity (approx. $5 \times 10^8$ instead of $2 \times 10^9$ ions per bunch) and 1/3 of the
design momentum spreads. As soon as collider will start to operate at fixed energy (comparatively high) the electron cooling system is not considered. Stochastic cooling system for start version is significantly simplified – only longitudinal filter cooling is considered. Such initial set-up makes the system very similar to the one used currently at Nuclotron.

6. Results of stochastic cooling during 48-49 runs

During 48 run (Dec 2013) longitudinal cooling of coasting and bunched beams of C6+ was tried out in the experiment. The system was carefully reassembled anew. Besides numerous minor changes, all variable delays and main amplifier were changed (previously used 17W main amplifier was substituted with 60W amplifier). This allowed getting much better cooling rates. Due to a number of technical problems the beam intensity was limited to 1-2×10^8, which is not sufficient for working with the transverse signal from the pick-up. Experimental parameters are listed in the table:

<table>
<thead>
<tr>
<th>Ions</th>
<th>C6+</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy, GeV/u</td>
<td>2.52</td>
</tr>
<tr>
<td>Flattop time, s</td>
<td>20</td>
</tr>
<tr>
<td>Initial dp/p</td>
<td>1-2×10^-4</td>
</tr>
<tr>
<td>Intensity</td>
<td>2×10^8</td>
</tr>
<tr>
<td>Rev. frequency, MHz</td>
<td>1.15</td>
</tr>
<tr>
<td>Phase-slip factor</td>
<td>0.068</td>
</tr>
<tr>
<td>Cooling system</td>
<td>Long., notch filter</td>
</tr>
<tr>
<td>Gain, dB</td>
<td>&lt;120</td>
</tr>
<tr>
<td>Power (amplifier), W</td>
<td>60</td>
</tr>
</tbody>
</table>

Cooling of the coasting beam was observed with cooling times 25-50s for different gains. The experimental results with cooling time approx. 46s is presented at Fig. 5-6. During experiment the momentum spread was reduced from 0.18×10^-3 to 0.11×10^-3.
The first attempt of working with *bunched beams* was carried out. Nuclotron had not worked before with long flattops with switched on RF-cavities, and the process of machine adjustment exposed a number of problems, the achieved parameters are listed in the table:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF voltage, $kV$</td>
<td>2</td>
</tr>
<tr>
<td>Bunch length, $m$</td>
<td>4.2</td>
</tr>
<tr>
<td>Bunching factor</td>
<td>4.8</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Fractional number of bunches means that due to unbalanced injection first two bunches were captured properly and the third one contains lower number of particles. The bunched beam of C6+ has been being cooled within 20s, the momentum spread was reduced from $0.2 \times 10^{-3}$ to $0.13 \times 10^{-3}$ and calculated cooling time is approx. 64s. The experimental results are presented in Fig. 8-9.
Strong RF-activity was observed only once during the process of Nuclotron adjustment for long flattops:

Fig. 10 Longitudinal signals from bunched beam
POWER SUPPLY AND QUENCH PROTECTION SYSTEM OF THE NICA COLLIDER

V.Karpinsky

POWER SYSTEM (PS)

The Collider consists of 2 independent rings. The current supply of each of the 2 rings is from their sources. At design of the collider power supplies system (fig. 1) the requirement of consecutive connection of structural dipole magnets M (total inductance 36 mH), quadrupole focusing F (total inductance 4.6 mH) and defocusing D (total inductance 4.6 mH) lenses is accepted for a basis. The main powerful source PS1 of the power supply system forms a demanded current with the required magnetic field ramp in the general chain according. PS1 have nominal output parameters 55V x 11kA, that allows to receive the magnetic field of 1.8T and field ramp of 0.1T/s. The peak power of a source is 605kW. Two additional power supply sources PS2 and PS3 of essentially smaller power are intended for flexible adjustment of a working point of the accelerator. One of them allows changing simultaneously a field gradient in focusing and defocusing lenses, another only in defocusing ones.

The power supply system includes also equipment of regulation, management and diagnostics.

Fig. 1. The power supply system of the Collider.

QUENCH PROTECTION SYSTEM (QPS)
The "switches" connected consistently with a chain of magnets and lenses are applied to evacuation of the accumulated energy from superconducting elements in case of superconductivity quench. They are controlled by a signal from detecting system that reacts on the occurrences of a normal phase in a superconductor. On the arrival of a control signal the switch is disconnected, and the energy, which has been saved up in the magnets, dissipates in resistors of the field dump, connected in parallel to the switches (fig. 1). The dipole magnets (4 chains 1/4M) and quadrupole lenses (F and 2 chains 1/2 D) are connected through the switches of energy evacuation (thyristor switch TS, breaker B) to a source under the symmetric scheme concerning voltage supply. Inductance of groups and nominal resistance of dumping resistors are chosen so that the voltage on the current feed through concerning the ground potential have not exceed 500 V at the moment of energy evacuation. Resistors of the field dump and the total inductance of the magnetic system corresponds to the evacuation process characteristic time of 170 ms. It is sufficient from the safety requirements.

At the moment a structural modeling of the thyristor switch is developed (fig. 2a). A model TS (fig. 2b) for test stand for the NICA SC magnets of the booster and Collider was made. The parameter of the model TS are the current 15kA and time of output current 0.5 sec. This model is a prototype TS for QPS of collider.

![a) model](image1)
![b) prototype](image2)

Fig.2. 15 kA thyristor switch.
THE QUENCH DETECTOR FOR SUPERCONDUCTING ELEMENTS OF THE NICA ACCELERATION COMPLEX

E. Ivanov

The Nuclotron quench detection system is based on a comparison of voltage across identical galvanically coupled inductive elements. Either the half windings of a single controlled element (magnet or lens) or the neighboring identical elements are used for comparison, while, as the measuring instrument, the bridge circuit is used at which the difference voltage appears when the resistive constituent arises in one of the bridge arms (Fig. 1). This voltage after amplification and processing is the indication of quench. The bridge method for measuring is applied almost at all SC accelerators owing to reliability, the large dynamic range of compared quantities, and insensitivity to ionizing radiation due to the absence of active elements in the bridge circuit. With the obvious advantages of bridge circuit, the following fundamental limitation in its application should be noted - the elements under control should form a galvanically coupled pair. These should be either neighboring elements in the accelerator ring or an element having a midpoint tap. A solitary element cannot be controlled.

![Bridge circuit quench detections](image)

Fig.1 Bridge circuit quench detections. R1,2,3 protecting resistors, Rbal- balance resistor, QD- quench detections block.

The NICA facility will include a few new SC elements operated in different regimes. The Booster is a fast cycling synchrotron similar to the Nuclotron. The beam transfer line from the Booster to the Nuclotron, SC solenoids of MPD and collider electron cooling system will be operated in continuous mode. The collider will be operated at constant magnetic field, however slow acceleration (or deceleration) of the beam is presumed as a reserve option. Additional quench detection system is necessary for the facility for Assembling and Testing of SC Magnets. In some cases more effective method of the quench detection is based on separation of resistive constituent in the voltage measured across the controlled element and reference signal.
To realize both methods of the quench detection the universal quench detector was designed for new superconducting accelerators of the NICA accelerator facility (Fig. 2). Two digital inputs permit to use the detector for comparison of voltage at two nearest elements with a bridge scheme and for detection of resistive part of the voltage at the element under control as well.

Fig.2. Circuit Diagram of the universal quench sensor.

There are places in the accelerator ring where one can note large noise level of the detector input signal. It is due to large power-consuming loads located close to accelerator ring and other facilities interfering with input signal and communication lines. To suppress these noises, the method of digital filtering for input signal is used in the new detectors (Fig. 3).

Fig. 3. Suppression of noises. Y-axis: ADC-bits, max equals to 3,3VX-axis: milliseconds Yellow line – before suppression, blue line –after suppression.
Prototype of the new detector was tested during the Nuclotron run #49 (December 2013). For the detection of resistive part of the voltage at the element under control the detector was used at the facility for Assembling and Testing of SC Magnets (Fig. 4).

Fig. 4. Application of the direct measurement for testing the straight current leads.

Production of the first batch of the detectors that will be tested on the Facility for Assembling and Testing of SC Magnets is scheduled for 2015.
Vacuum automatic control system (VACS) has aims to control of the vacuum system and to prevent as the vacuum as the user hardware from the damage in the case of the fast vacuum failure and bad vacuum conditions. VACS should provide two level of the vacuum protection. First level is realizing on the base of simple electronic elements and using for the protection of user hardware: RF stations, high voltage potentials, etc. First level should work properly even the second level is completely destroyed.

Second level is used for the control and protection of vacuum system elements: pumps, gauges, valves, bake out. Second level can be realized on the base of SCADA Zenon (http://www.copadata.com/, Figure 1). The JINR vacuum group has an experience in the modernization of Nuclotron accelerator complex in the collaboration with Vakuum Praha and FOTON companies (Czech Republic).

Figure 1. Zenon ACS of the vacuum system of the Nuclotron injection complex
Requirements for VACS:

- Unified design and operation
- Integration into the common Accelerator Control System
- Universally valid Time Stamp (ACS)
- Historical Data
- Vacuum zones able to operate stand alone
- Safe Mode during power outages
- Ability to recover from defective devices until next shutdown
- Reaction time <200ms

Vacuum Failure Protection System (VFPS) has the aim to protect the beam pipe and cryostat volume from the damage in the case of fast leakages from the atmosphere, liquid nitrogen system and liquid helium system. Copper pipes of superconducting magnets can withstand a high pressure of the liquid helium flow and the most dangerous situation exists for the fast leakages from the atmosphere. Helium gets intense boiling caused by the heat leakage from liquid air condensing on the outer surface of the superconducting magnets. Pressure in the cryostat volume rises to the atmospheric pressure and then safety valves open. Parameters of safety valves were calculated on the base of the algorithm which was used for the design of safety valves for the Nuclotron cryostat volume. The following assumptions made in the direction of increasing the estimated value of the required flow area of the safety valve:

- pressure rises to atmospheric pressure instantly and remains constant;
- temperature of liquid helium after the opening of the safety valve is constant and equal to the saturation temperature.

The required flow area of the dipole magnet is $3.8 \times 10^{-3}$ m$^2$, for the quadrupole magnet is $0.88 \times 10^{-3}$ m$^2$. For the one arc of the collider ring (40 dipoles and 24 quadrupoles) the required flow area is about 0.16 m$^2$ what is corresponds to two safety valves with the nominal diameter DN300. The required flow area for other “cold” sections is much smaller and the nominal diameter of safety valves will be defined by the design of the cryostats between “warm” sections.
The main functional characteristics of the *ideal* Beam Loss Monitor System are the following [1]:

- Radiation detector with high dynamic range to be used for both regular (low) loss and irregular (high and fast) loss;
- Not sensitive to radiation caused not by beam loss;
- Ability to find out amount of beam lost (conversion from radiation intensity to actual number of primary particles);
- Ability to resolve time structure and spatial distribution of loss;
- Ability to separate intentional loss (wire scanners, scrapers, collimators, etc.) and unintentional loss (beam size, residual gas scattering, not ideal beam alignment, instabilities, etc.) is highly desirable.

Four types of detectors are considered as the beam loss monitors for Collider [1, 2, 3, 4]:

1. **Short ionization chamber** (Fig. 1, Fig. 2).

![Ionization Chamber Diagram](image)

Fig.1. Examples of the ionization chambers design.
2. **PIN - diode (Bergoz Instrumentation, Fig.3).**

   **Working principle**
   - About $10^4$ $e^-$-hole pairs are created by a Minimum Ionizing Particle (MIP).
   - A coincidence of the two PIN reduces the background due to low energy photons.
   - A counting module is used with threshold value comparator for alarming.

   → **small and cheap detector.**

   ![PIN diode image](image)

   **Fig.3. PIN - diode detector.**
3. Scintillator detector (Fig.4).

Fig.4. Examples of the scintillator detector design.

4. Neutron detector BDKN-96 (SPC “Doza”, Fig.5).

Detector:
- He-3 counter in polyethylene moderator
Measurement range:
- Dose rate $H^*(10)$ for Pu-Be: 0.1 $\mu$Sv/h $\div$ 0.1 Sv/h
- Dose $H^*(10)$ for Pu-Be: 0.1 $\mu$Sv $\div$ 1.0 Sv
Energy range:
- 0.025 eV $\div$ 14 MeV
Overall dimensions, weight:
- Detector: Ø 100x300 mm, 2.0 kg

Fig.5. External view and some features of the neutron detector.

Four neutron detectors were successfully tested during Nuclotron runs as the beam loss monitors (Fig.6).

Fig.6. Display of the beam loss time structure (the first flattop - beam interaction with internal target, the second flattop - beam slow extraction).
References


INJECTION COMPLEX, BEAM TRANSPORT,
INJECTION/EXTRACTION SYSTEMS
A.Butenko, V.Monchinsky, A.Govorov, A.Tuzikov, V.Mikhailov

KRION-6T heavy ion source

The ion source was optimized for production of ions with charge to mass ratio of \( q/A \geq 1/3 \) in order to provide complex test of all its systems at operation on existing injection facility. In May 2014 the source was installed at high-Voltage (HV) platform of the LU-20 fore-injector (Fig.1) and used during Nuclotron run #50 in June. The main goal for future two years is to reach the project parameters of KRION-6T for \( \text{Au}^{31+} \) beam.

Figure 1: Krion-6T at high-voltage platform of LU-20 fore-injector. The Nuclotron Run #50.

Low energy beam transport channel

1) Lattice of the LEBT channel has been designed. Technical designs of the channel elements are being developed.

*Short description of the LEBT channel.* The ion source is situated on high-voltage platform (up to 150 kV). The channel (Fig. 2) begins from electrode with potential \( U_0 \), after which a DN 250 vacuum valve is installed. In initial part of the channel (IPC) the focusing electrodes with potentials \( U_1 \) and \( U_2 \) are located. IPC ends the tube with potential, falling off from \( U_3 \) up to 0. Two solenoids, placed after initial part, form beam at the input of RFQ.
2) Simulations of multi-component ion beam transportation along the channel were fulfilled. Electrostatic field inside IPC and magnetic field of solenoids were calculated by the POISSON program [1]. Optimization of the channel parameters to achieve required beam parameters at the RFQ entrance was performed by MCIB04 code [2]. The code takes into account the aperture of the channel and the effects of the space charge of the multi-component beam. Two different variants of possible initial charge state spectrum of the gold beam are used in simulations.

Estimates of the transfer efficiency from the ion source into the RFQ acceptance were obtained for different ion charge states and different beam currents corresponding to different schemes of the beam injection into the Booster ring (one-turn and multi-turn injection schemes). Results of the simulations were shown that the proposed variant of the channel is suitable for transportation of Au\(^{31+}\) beam from the KRION source and injection of ions into RFQ acceptance. The Au\(^{31+}\) beam rms emittance at RFQ entrance is about 10 \(\pi\text{-mm}\cdot\text{mrad}\) at 3.5 mA.

**HILAC**

1) During 2013-14 all three cavities of the HILAC were fabricated. The RFQ section and its RF amplifier have been delivered already (Fig. 3). The IH1 tank is at present at the copper plating workshop and will be followed by IH2 (Fig. 4). Quadrupole lenses for the transverse beam focusing along the HILAC are under fabrication.
2) Beam diagnostic elements such as capacitive pick – up probes and current-transformers were developed in collaboration with INR, Troitsk. They have been delivered already.

3) Low level RF system of the HILAC has been developed by ITEP.
**The LLRF system description.** LLRF system of HILAC is shown in Fig. 5. A single-board reference generator G produces five generally independent sinusoidal signals (exciting three accelerating cavities, rebuncher and debuncher).

![Figure 5: Structure of the HILAC LLRF system.](image)

In normal operational mode those signals have a common frequency and a predetermined phase difference between channels. Feedback signals fb1…fb5 may be used for additional stabilization of phases (and amplitudes in the case of A or AB-class amplifiers Ai). Right side of Figure 5 shows a resonant frequency control loop, implemented for each resonator of the HILAC. Detuning is determined using the relation between the signal from the resonator \( r \) and the forward wave signal calculated as combination of properly scaled electric and magnetic components of EM-field in the RF feeding line \( u = e + m \).

Figure 6 shows a simplified structure of the multichannel reference generator G. Sinusoidal signals produced by precisely in-time adjusted DDS microchips. Basic parameters, like the frequency tune word (FTW), amplitude and phase are written to DDS’s registers by ARM microprocessor. Same microprocessor receives the measured data in form of amplitude and phase arrays using one of direct memory access channels. This allows performing of slow feedback and a general system monitoring. Buffered raw data from any of eight channels of the ADC is also available for testing purposes. An ADC, working in IF mode digitizes the control signals of the resonators with a rate of 34.6 MSPS per channel. Detector Det filters incoming data, decimates and calculates an amplitude and phase of control RF signals. This data is available for subsequent analysis and for fast feedback loop based on the digital controller C.

![Figure 6: Simplified structure of the reference generator.](image)
4) Bldg. EG-5 was prepared for the HILAC installation. The HILAC equipment placement in the Bldg. EG-5 is being designed. Longitudinal support for the HILAC has been designed, manufactured and is already installed (Fig. 7).

![Figure 7: Support for the HILAC in the Bldg. EG-5.](image)

**HILAC – Booster beam transport channel**

1) Shape of the channel geometry with two bends has been chosen instead of straight line geometry (Fig. 8). Several variants of the channel lattice are considered. Lattice optimization is in progress. The goal of optimization is to find locations of the channel devices (dipoles, quadrupoles, steerers, a debuncher, a chopper, beam diagnostics etc.) that satisfy all conditions on ion beam optics along the channel in the best way. It has been shown that the considered lattices provide optional retuning used for different schemes of the beam injection into the Booster ring.
Short description of the HILAC – Booster channel. The HILAC – Booster channel is divided by two dipole magnets on three straight line sections. Ion optics is provided by quadrupole lenses (from 8 to 10 lenses for different lattice variants). The debuncher is placed at the end of first long straight line section to produce the beam debunching in non-dispersive region with maximal effectiveness. The correcting dipole magnet is located at the end of the channel (Fig. 9) to vary the beam trajectory at the entrance of a septum of the Booster injection system that is used for different schemes of the beam injection. Absorbers for separated ion charge states are situated in second and third straight line sections of the channel. Beam diagnostic devices and steerers are
distributed along the whole channel. Location of the chopper is not defined yet and will be chosen after choice of final variant of the channel lattice.

Results of the beam dynamics simulations are presented in Fig. 10.

Figure 9: Final part of the HILAC – Booster beam transport channel (one of the considered variants).

Figure 10: Lattice, apertures and beam envelopes (one of the considered variants). Positive values on x/y axis represent horizontal (x) coordinates, negative values represent vertical (y) coordinates.

2) Longitudinal support for the 1st straight line section of the channel as well as the HILAC has been designed, manufactured and installed. A frame intended to pass the channel through the Synchrophasotron yoke is almost designed.
**Booster injection system**

1) New concept of the electrostatic septum has been chosen. The septum is divided into two sections. Each section has a pair of curve electrodes.

2) Development of technical designs of the electrostatic septum (Fig. 11) and the electric kickers is started. Final determination of the system devices’ parameters is near completion.

![Preliminary design of the electrostatic septum.](image)

3) Septum thickness in the new concept is more than it was used in previous simulations of the beam injection into the Booster. New calculations have been performed to estimate emittances of the stored beam for different schemes of the injection. Their results show that for all previously proposed schemes of the injection the beam emittances do not exceed the Booster acceptance.

**Booster extraction system**

Technical design of the magnetic kicker is being developed. End date is the first half of 2015.

**Booster – Nuclotron beam transport channel**

1) Designs of a frame insertion into the Synchrophasotron yoke and a through passage in the floor of Bldg. 1 are being developed.

2) New simulations of ion stripping are fulfilled. Although we suppose that a conventional stripping target will be designed later we are finding out new ideas to improve ion stripping efficiency. One of such ideas is to use a foil made of carbon nanotubes. Simulations are shown that the efficiency of Au ion stripping (to bare nuclei state) at the energy of about 600 MeV/u is increased from 70% (for a conventional carbon foil) up to 95%.
**Nuclotron fast extraction system**

Revision of the beam transfer from the Nuclotron to the Collider rings has shown that for previously specified angle of the beam deflection in the magnetic kicker of the extraction system the beam passing the lattice quadrupole (located after the Lambertson magnet) partially hits its yoke. This fault has been corrected by increasing the magnetic field inside the kicker (and the kick angle respectively) up to level of the field of the analogous kickers of the Collider injection system.

**Nuclotron – Collider beam transport channel**

1) Suppression of vertical dispersion of the beam in the channel was examined. The best solution of this task is to provide achromatic transfer of the beam from Nuclotron to median planes of the Collider rings. But lattice variants which meet condition of achromatic transfer have not been found.

Vertical dispersion can be also suppressed by means of optical sections with vertical bending magnets located in branches of the channel. The most preferable locations of dispersion suppressors are long straight line sections of the channel branches. Three variants of vertical profile of the channel providing dispersion suppression have been proposed. Two of them seem to be more preferable.

*Description of method of vertical dispersion suppression named as “Variant 7”*. The beam in common part of the channel (Fig. 12) is lifted up onto the average plane of the Collider rings. Optical system of the common part is tuned to minimize vertical dispersion invariant \( I_{Dy} = \gamma_y D_y^2 + 2\alpha_y D_y D'_y + \beta_y D'_y^2 \) which is critical for this method of suppression. Pairs of vertical dipole magnets (Fig. 13) are used as dispersion suppressors which are placed in each branch of the channel so that the beam is lifted or lowered onto the plane of the receiving Collider ring. Low values of vertical beta functions are required inside the suppressors to obtain zero vertical dispersion at their exits.

![Figure 12: Common part of Nuclotron – Collider channel (Variant 7).](image1)

![Figure 13: Dispersion suppressor (Variant 7).](image2)
Description of method of vertical dispersion suppression named as “Variant 9”. The beam in the common part of the channel (Fig. 14) is lifted up onto the plane of the upper Collider ring. Minimization of vertical dispersion invariant by means of optical system of the common part is not necessary. Two pairs of vertical dipole magnets with quadrupole doublets (Fig. 15) are used as dispersion suppressors which are placed in each branch of the channel so that the beam is transferred onto the plane of the receiving Collider ring. There are no limitations on values of vertical beta functions inside suppressors. Vertical dispersion suppression is provided by tuning betatron phase advance between two parts of the suppressor.

![Figure 14: Common part of Nuclotron – Collider channel (Variant 9).](image)

![Figure 15: Two parts of dispersion suppressor (Variant 9).](image)

2) The channel variant without vertical dispersion suppression was also considered. Growth of the beam emittance due to dispersion mismatch has been estimated as insignificant. Final decision on vertical dispersion in the channel has not been made yet.

3) Revision of the channel geometry (its horizontal projection) has been fulfilled and some changes in the beam trajectory have been done in order to bring it into line with the project of new building designed for the Collider rings and the channel. Shape of embranchment section of the channel has been chosen. Straight line sections of the channel have been aligned to walls of a tunnel assigned for the channel installation. Angles of the beam entrance into the Collider rings have been decreased. Short arc is added at the end of the left branch of the channel. The beam trajectory inside Bldg. 1 has not been fixed yet.

4) Preliminary composition of the channel (including magnetic elements, their power supplies, beam diagnostic devices, vacuum equipment, cable routing) has been obtained on basis of
several considered lattice variants. Conditions on the channel tunnel and other rooms assigned for allocation of the channel equipment are determined.

**Collider injection system**

Decreasing of angle of the beam entrance into the Collider leads to decrease of the magnetic septum length. Simulations of the beam injection with new septum have been performed.
Two RF accelerating stations of the Booster were constructed at BINP. In May 2014 the stations were assembled and tuned in Novosibirsk with participation of JINR specialists. In October 2014 the stations were delivered to Dubna, consequently assembled and tested (Fig. 1). Using imitator of the magnetic field cycle the parameters satisfied to technical requirements were demonstrated in the total frequency range. The development of the station control electronics necessary for integration into the NICA control system and feed-back application was discussed.

Fig. 2. The Booster RF station during commissioning at test bench at JINR.
STATUS OF WORK ON THE DEVELOPMENT AND MANUFACTURE OF SUPERCONDUCTING MAGNETS FOR THE NICA PROJECT AT DECEMBER 2014
H. Khodzhibagiyan

* A pre serial dipole magnet for the booster was made and successfully passed cryogenic tests.

* A first phase of the system for the magnetic measurement of the dipole magnets for the booster was put in operation.

* The first "warm" and "cold" measurements of characteristics of the magnetic field in the aperture of the bended dipole magnet for the booster were successfully carried out.

* The repeatability of characteristics of the magnetic field in the aperture of the dipole magnet after its assembly / disassembly into two halves was experimentally confirmed, which makes it possible to install the beam pipe after the magnetic field measurements.

* A doublet of the quadrupole magnets for the booster was made and prepared for testing.
* A yoke for the pre serial dipole magnet for the collider was manufactured.

* The first stage of the test facility for the assembly and cryogenic test of superconducting magnets was put in operation.
* Serial production of magnets and cryostats for the booster started.

* The contract for the production of thin-walled curved beam pipe for the magnets of the booster has been concluded. Operations for the production of beam pipe are made in companies in Poland, Germany and Sweden. The first six beam pipes for testing will be made in March - April 2015.
CONCERNING THE CHOICE OF THE JOULE-THOMPSON VALVES IN THE NITROGEN LIQUEFIER AND IN THE NITROGEN REFRIGERATORS (RELIQUEFIER)

N. Agapov

In order to raise the efficiency of cryogenic refrigerators and liquefiers, it is very important to replace the Joule-Thompson process by the improved process of adiabatic expansion. In 1965, the replacement of a JT-valve by an expander was proposed and realized in the hydrogen liquefaction cycle at JINR. The output of the hydrogen liquefier was 50-60 per cent higher with an expander than with a JT-valve. As for a helium liquefier, S. Collins (USA) made it in 1970. Piston-type machines were used in both cases. The first successful experience to use a turbine was gained by NPO GELYMASH and JINR together in 1985. After modernization, using turbines instead of JT-valves increased the capacity of Nuclotron helium refrigerators from 1 to about 2 kW.

But at nitrogen liquefaction, application of expansion machines is not so useful for two reasons. At first, in contrast to liquid helium, liquid nitrogen is an almost incompressible fluid, so the effect from the application of the expansion machine is practically absent. Secondly, because of the very large difference in the densities of the liquid and gaseous phases of the nitrogen, two-phase flow in the turbines will have significant fluctuations, which will inevitably lead to mechanical breakdowns of expansion machines.