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Vacuum System of the NICA Project

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Abstract—This paper presents the progress of development of the NICA project vacuum system. The main vacuum requirements in the chain of accelerators and the current status of work are described. Special attention is paid to the problems of achieving ultra-high vacuum in the booster. The test bench for the study of most efficient pumping tools for the beam chamber of the superconducting fast cycling synchrotron has been designed and built for this purpose in cooperation with the VakuumPraha Company (Prague, Czech Republic). The vacuum distribution in the superconducting accelerators with "warm" chamber parts at room temperature was simulated using specialized software. The simulation showed that it is necessary to install additional pumping equipment along the booster perimeter. To solve this problem, the original design of a titanium sublimation pump operating at cryogenic temperatures is under development in collaboration with the Budker Institute of Nuclear Physics (Novosibirsk, Russia).

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INTRODUCTION

The main requirement for vacuum conditions in charged particle accelerators is the reduction of particle losses at molecules of residual gas. The loss rate is determined by both the beam parameters and the residual gas composition. As the beam is accelerated and accumulated in the sequence of accelerators, the requirements for the residual pressure value change.

The NICA accelerator complex [1] consists of two linear accelerators, the booster synchrotron, the Nuclotron accelerator, two collider rings (Table 1), and the beam lines. Particles travel through the linear accelerators just once; therefore, a pressure of 10^{-4}–10^{-5} Pa is sufficient. Then particles enter the booster via the beam line. The injection energy for Au^{31+} ions is just 3.2 MeV/u, which requires an ultrahigh vacuum in the booster on the order of 10^{-9} Pa. The interaction cross section for scattering on nitrogen molecules at the injection energy is $\sigma = 68 \times 10^{-22}\ \mathrm{m}^{-2}$. Then, for a pressure of 10^{-9} Pa we obtain a beam lifetime of about 20 s, which is comparable with a particle acceleration cycle in the booster of about 5 s.

After acceleration in the booster to an output energy of about 600 MeV/u, particles go to the beam line with the stripping target on which gold ions lose all electrons and are injected into Nuclotron, where fully stripped ions are accelerated; therefore, the vacuum requirements are much lower than in the booster. Then particles are transferred to the collider rings, in which the beam lifetime should be at least 1 h, which requires a high vacuum on a level of 10^{-9} Pa.

It should be noted that, in order to achieve the required beam lifetime upon injection energy in the booster, it is necessary to solve the problem of obtaining ultrahigh vacuum. The main problem in the collider is the suppression of secondary electron emission from the chamber walls, which results in the electron cloud effect [2]. The estimate of dynamic vacuum, taking into account secondary ion emission from the chamber walls, which results in the local vacuum

Table 1. Vacuum systems of the accelerators in the NICA project

Accelerator	Length	Pressure, Pa	Pump	Status
LU-20	20	10^{-4}	turbo + cryo	Upgraded
HILAC	11.5	10^{-5}	turbo + ion	Tested
Booster	211	10^{-9}	ion + getter	Equipment is being shipped
Nuclotron	251.5	10^{-7}	turbo + ion	Upgraded
Collider	503	10^{-9}	ion + getter	Design

worsening, shows that this effect is inessential in all accelerators of the complex.

BOOSTER VACUUM SYSTEM

The booster vacuum system consists of four superconducting arcs operating at cryogenic temperatures and four straight sections at room temperature. At present, the vacuum volumes of two straight sections have been shipped to JINR: those of the RF stations and the electron cooling system. Both volumes were manufactured at the Institute of Nuclear Physics (INP). The required vacuum conditions on a level of 2×10^{-9} Pa [3] were achieved during the assembly and testing of the electron cooling system.

The straight section of the injection system is at the stage of manufacture; it will be shipped to JINR in 2018. The straight section of the beam extraction system from the booster together with the beam line to Nuclotron are being manufactured at INP. Titanium sputtering devices in combination with ion pumps are used in all warm sections as the final method of vacuum pumping. The nonevaporated getters [4] are used as the additional pumping tools.

The design of the vacuum chambers for the superconducting arcs is almost finished, and the prototypes of different chambers operating at cryogenic temperatures were manufactured. At present, vacuum testing of the beam chambers for the bent magnets manufactured in cooperation with FRAKOTERM company (Chorzów, Poland) is in preparation. The main component of residual gas ions in the superconducting arcs is expected to be hydrogen molecules and atoms; therefore, the vacuum stations of the booster will be equipped with titanium sublimation pumps.

Due to the low vacuum conductivity of the chambers and large distances between the vacuum stations in the superconducting arcs (about 9 m), it is necessary to install additional pumping elements operating at cryogenic temperatures. The pumping rate of nonevaporated getters drop sharply with reducing temperature [5]. A good solution to this problem is the application of cryosorption pumps. This approach, however, requires strong changes in the cryogenic system of the superconducting magnets, which is impossible at this stage.

Therefore, it was decided to develop vacuum pumps based on titanium sublimation devices and install them in all gaps between the superconducting magnets. In this case, it would be necessary to install additional 40 A current leads in the cryostats of the isolation volume. The application of such pumps would reduce pressure several times and provide the required vacuum conditions in the booster.

VACUUM TEST BENCH

The test bench, which provides heating of all elements to 300°C and achieving the vacuum sufficient for mass spectrometric analysis of the residual gas composition [7], was designed and developed in cooperation with VakuumPraha [6] for testing secondary air pumps, accelerator elements, and materials to be used in the beam chambers.

A vacuum of $<10^{-9}$ Pa [8] was obtained at the test bench in the prototype beam chamber after maintaining a temperature of 280°C for 30 h. The combination of the ion and titanium sublimation pumps was used to achieve this pressure. The vacuum measurements were performed using Bayard–Alpert and Varian vacuum gauges.

A measurement of the mass composition of gases in the chamber showed that, if the requirements of vacuum hygiene are observed, the main component of the residual gas after heating is H_2 (up to 99 mass %).

The second test bench was developed for the studies on achieving the required vacuum under real conditions of the superconducting arcs; it is planned to verify the operation of the vacuum system with combinations of pumps of different types and simulation of real gas loads using the measured gas inlet and a variation of the chamber wall temperature at this test bench (Fig. 1).

The test bench consists of a cross bar to which the pumping and measurement equipment is connected. Various types of studied pumps can be connected to the cross bar to investigate their performance. The test bench design provides its connection with the beam chamber of the test magnet for testing the operation of different equipment configurations [9].

To achieve the working pressure in the chamber ($<1 \times 10^{-9}$ Pa), a device for baking all elements of the test bench to 280°C with a temperature growth and reduction rate of no higher than 50°/h was developed. In the course of baking, the pumping is performed using the tandem of turbomolecular pumps (nos. *2*, *6*), which provides a prompt response to the variation in the vacuum conditions using the gauge (no. *5*). The pressure is measured using a high vacuum gauge (no. *15*). The leak valve (no. *11*) is installed at the opposite end of the pumping station. It is possible to supply the test gas through the leak valve, thus simulating the conditions of various gas loads.

At the first stage of operation on the test bench, the tested chamber will be at room temperature. Later, it is planned to assemble a part of the cold section of the accelerator, cool it down to the working temperatures, and perform experiments under conditions close to real ones.

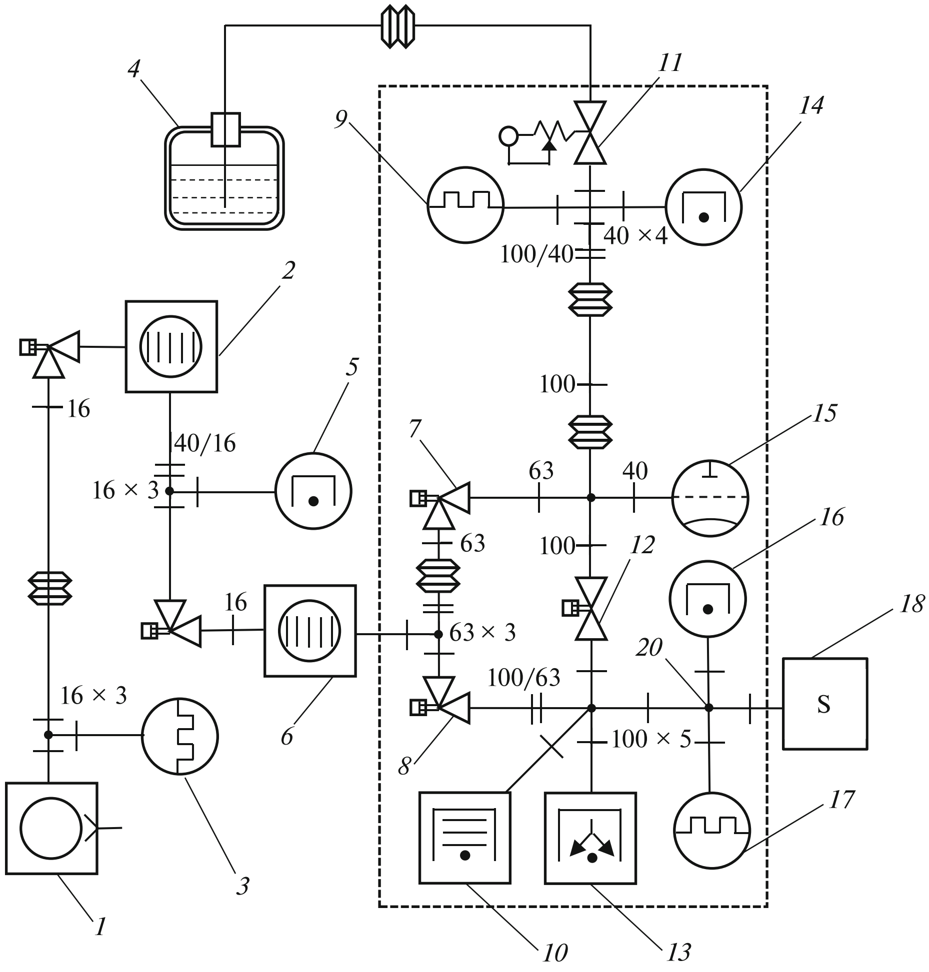

Fig. 1. Schematic diagram of the high vacuum station. (*1*) Dry oil-free spiral pump, (*2*) auxiliary turbomolecular pump, (*3*, *9*, *17*) thermoresistive vacuum gauge, (*4*) Dewar vessel with liquid nitrogen, (*5*, *14*, *16*) cold cathode vacuum gauge, (*6*) turbomolecular pump with increased compression for light gases, (*7*, *8*) all-metal angle valve, (*10*) ion pump with titanim sublimation pump, (*11*) leak valve, (*12*) all-metal gate valve, (*13*) nonevaporated getter pump, (*15*) hot cathode (Bayard–Alpert) vacuum gauge, and (*18*) mass spectrometer.

SIMULATION OF VACUUM CONDITIONS

The specific feature of vacuum conditions in the NICA project is the alternation of beam chambers at cryogenic and room temperatures. The application of fast-cycling superconducting magnets results in additional chamber heating inside the magnets, which yields substantial temperature distribution inhomogeneity in the beam chambers along the accelerating rings, especially in the booster.

A code that takes the temperature distribution along a chamber into account was developed to simulate pressure distribution along beam chambers. The code is based on the software BETACOOL applied for the simulation of beam dynamics in a charged-particle storage ring [6].

It should be taken into account that, upon the transition between the chambers with different temperatures, the concentration and pressure change in the following way:

$$n_1\sqrt{T_1} = n_2\sqrt{T_2}, \quad P_1\Big/\sqrt{T_1} = P_2\Big/\sqrt{T_2}.$$

Then the equation of dynamic pressure distribution with respect to the longitudinal coordinate with account for the temperature difference between the neighboring chambers can be written as:

$$\frac{\Delta P_j}{\Delta t}V_j = C_j\left(P_{j+1}\sqrt{T_j/T_{j+1}} - P_j\right) - C_{j-1}\left(P_j - P_{j-1}\sqrt{T_j/T_{j-1}}\right) - S_jP_j + Q_j,$$

where P_j is the pressure in the jth chamber, V is the volume of the vacuum chamber, C is the conductance of the vacuum chamber, S is the pumping rate, and Q is the total inleakage. It is convenient to define the initial values, normalized to the unit length of the chamber, in the simulation. It should be considered, however,

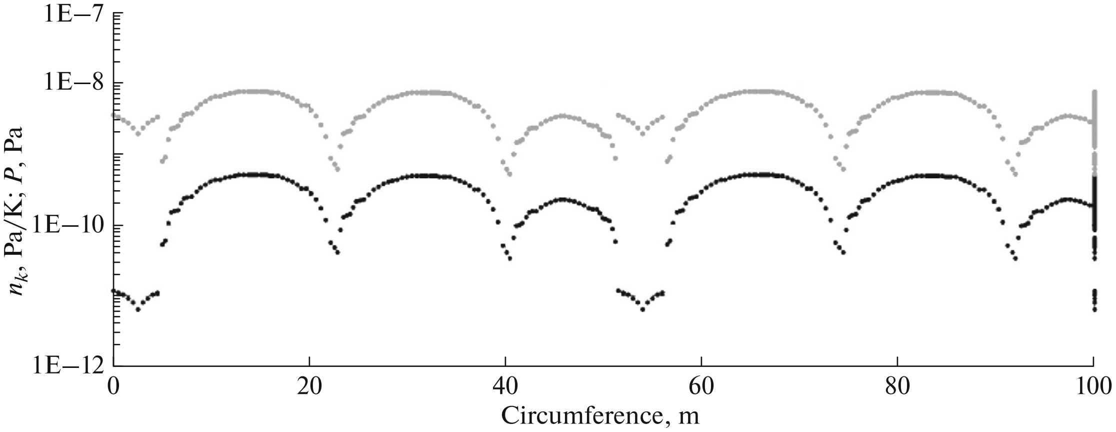

Fig. 2. Pressure distribution along the booster chamber (half-ring, beginning from the "warm" section). Pressure is shown at the top and molecule concentration at the bottom.

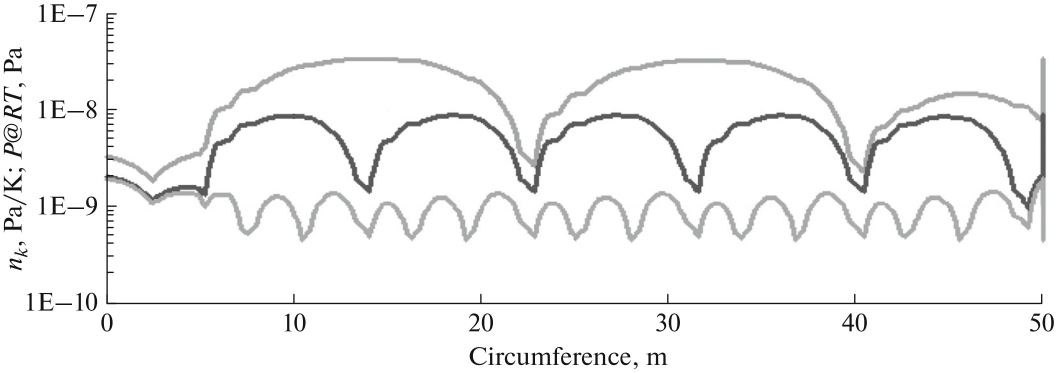

Fig. 3. Pressure distribution at the vacuum gauges at room temperature (1/4 of the booster). The first stage of pumping with turbo-pumps is shown at the top, the second stage using all 24 pumping stations is shown at the middle, and the application of additional sublimation pumps between all magnets is shown at the bottom.

that the chamber conductance is determined per unit length; i.e., in order to obtain the conductance of a particular chamber, the value should be divided by the section length, rather than multiplied by it, as is done for the other initial parameters (volume, pumping rate, and inleakage).

Figure 2 exemplifies the calculation for the booster chamber structure. The pressure is shown at the top and the concentration in Pa/K is shown at the bottom. It can be seen from the plots that the pressure is lower and the molecule concentration is higher at the cold sections. In order to avoid these discontinuities in the plots, it is better to plot the pressure distribution depending on the readings from vacuum gauges at room temperature (Fig. 3, top line).

At the first stage of booster pumping, 8 pumping stations (two for each arc) based on turbomolecular pumps alone were installed; this provides a pressure on a level of 10^{-8} Pa (Fig. 3, top line). Further, the installation of all 24 pumping stations in the superconducting arcs at a distance of 9 m from each other would improve the vacuum conditions several times (Fig. 3, middle line). The required vacuum conditions on a level of 10^{-9} Pa would be achieved after the installation of the additional sublimation pumps between all magnets of the booster (Fig. 3, bottom line).

The calculations for the collider show (Fig. 4) that, for achieving a pressure on a level of 10^{-9} Pa, it is sufficient to use the standard pumping stations in the quadrupole lenses situated at a distance of 6 m from each other in the superconducting arcs. It should also be taken into account that the vacuum requirements in the collider are less strict than in the booster, since the collider operates at much higher energy and fully stripped gold ions and the ion lifetime exceeds the required experiment time by more than one order of magnitude.

It should be noted that, for simulating instability development due to the dynamic vacuum, when secondary ions locally worsen the vacuum conditions, we

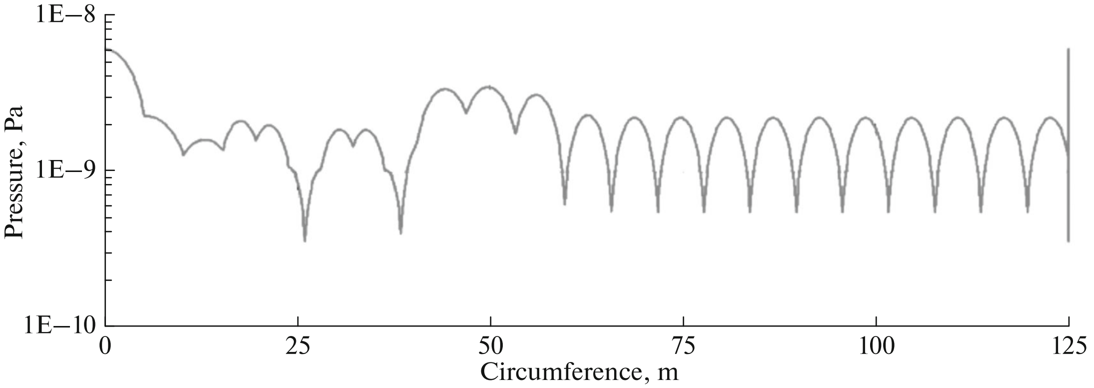

Fig. 4. Pressure distribution for 1/4 of the collider, beginning from the collision point.

used a simple model in which all ions that interacted with the molecules of residual gas at the considered section hit the chamber walls and locally produce secondary ions. The calculations showed that this effect does not substantially influence the vacuum conditions in the booster and the collider. Only if the beam intensity increases by two orders of magnitude, when compared to the design value, the instability related to the dynamic vacuum begins to be manifested.

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