Письма в ЭЧАЯ. 2014. Т. 11, № 4(188). С. 760–767

ФИЗИКА И ТЕХНИКА УСКОРИТЕЛЕЙ

CRYOGENICS FOR THE FUTURE ACCELERATOR COMPLEX NICA AT JINR

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The NICA cryogenics will be based on the modernized liquid helium plant that was built in the early 1990s for the superconducting synchrotron known as the Nuclotron. The main goals of the modernization are: increasing of the total refrigerator capacity from 4000 to 8000 W at 4.5 K, making a new distribution system of liquid helium, and ensuring the shortest possible cool-down time. These goals will be achieved by means of an additional 1000 l/h helium liquefier and «satellite» refrigerators located near the accelerator rings. This report describes the design choices of NICA, demonstrates helium flow diagrams with major new components, and briefly informs of the liquid nitrogen system that will be used for shield cooling at 77 K and at the first stage of cooling down of three accelerator rings with the total length of about 1 km and «cold» mass of 290 t.

Криогенная система комплекса NICA создается на базе модернизированной установки по производству жидкого гелия, построенной в начале 1990-х гг. для сверхпроводящего синхротрона — нуклотрона. Основные цели модернизации — повышение общей холодопроизводительности от 4000 до 8000 Вт на температурном уровне 4,5 K, создание новой системы распределения жидкого гелия, а также обеспечение кратчайшего времени охлаждения. Эти цели достигаются посредством ввода в эксплуатацию дополнительного 1000 л/ч гелиевого ожижителя и «сателлитных» рефрижераторов, расположенных рядом с ускорительными кольцами. В статье описаны проектные решения по криогенике NICA, представлены схемы гелиевых потоков с новыми главными компонентами, а также дано представление о системе жидкого азота, используемой для охлаждения теплозащитных экранов при 77 K и на первом этапе охлаждения всех трех ускорительных колец общей протяженностью около 1 км и «холодной» массой 290 т.

PACS: 07.20.Mc

INTRODUCTION

Since 1993, the largest Russian liquid helium plant for the superconducting accelerator Nuclotron has been operating at the Joint Institute for Nuclear Research in Dubna near Moscow. The concept of its cryogenic system includes a large number of technical ideas and solutions never used before. The most significant of these solutions were the following: fast cycling superconducting magnets, cooling by the two-phase helium flow, an unusually short period of time for cool down till the operating temperature, parallel connection of about 150 cooling channels of the magnets, «wet» turbo expanders, screw compressors with a pressure rise of more than 25, and jet pumps for liquid helium. These technical solutions allowed one to construct an efficient and reliable cryogenic system.

The plans for further development of the basic installations at the JINR Laboratory of High Energy Physics are to build new accelerators: Booster and Collider, both using magnets with superconducting windings cooled to the liquid helium temperatures. These two accelerators together with the existing Nuclotron will be united into the NICA complex [1].

The newly created accelerator complex will require additional refrigeration capacity at 4.5 and 80 K. For the cryogenic system upgrading, we will use screw helium compressors with a new design, an additional 1000 l/h helium liquefier, and a distribution system of cooling capacity based on the helium «satellite» refrigerators. Besides, a new 80 K refrigerating system will be made on the basis of nitrogen turbo compressors.

1. GENERAL VIEW OF THE NICA CRYOGENICS

A detailed description of the existing Nuclotron cryogenic system can be seen in [2–4]. New installations, which will appear while updating and building of the NICA complex, are shown in Fig. 1. The main technical characteristics of the NICA helium cryogenic system are listed in Table 1.

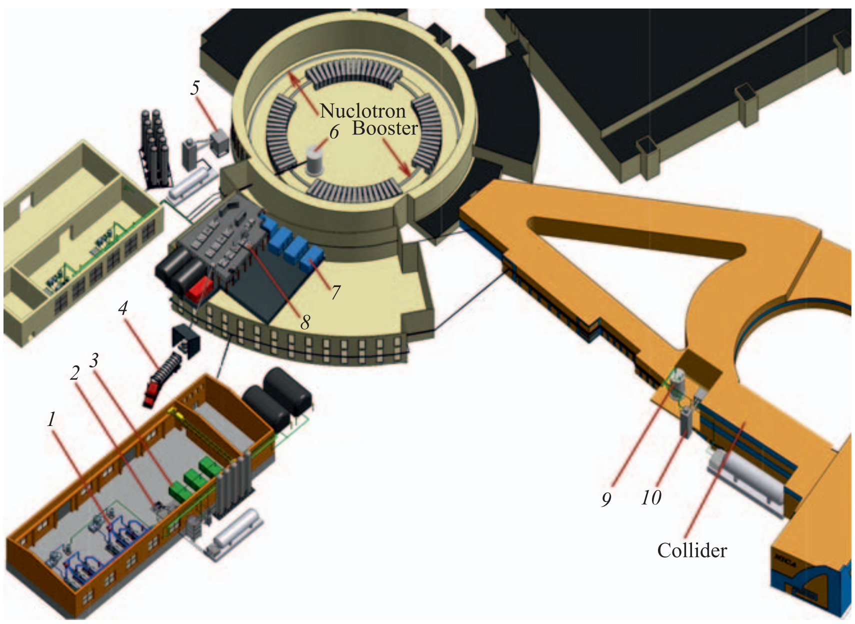

Fig. 1. The general view of the cryogenic system for the NICA complex. New units for the NICA accelerators: *1* — 6600 Nm^3/h screw compressors Kaskad-110/30; *2* — 1300 kg/h nitrogen liquefier OA-1.3; *3* — nitrogen turbo compressors; *4* — liquid helium tank; *5* — 500 kg/h nitrogen recondenser RA-0.5 of the Booster; *6* — «satellite» refrigerator of the Booster; *7* — draining and oil-purification units; *8* — 1000 l/h helium liquefier OG-1000; *9* — «satellite» refrigerator of the Collider; *10* — 500 kg/h nitrogen recondenser RA-0.5 of the Collider

Table 1. **Basic parameters of the NICA helium cryogenics**

Operating temperature, K	4.5
Refrigerating capacity at 4.5 K, W	8000
Total capacity of compressors, Nm^3/h	30420
Total power of electric motors, kW	7400
Flow rate of cooling water, m^3/h	355
Cold mass, t	290

The cryogenic systems of the future accelerators (Booster and Collider) will consist of the central helium liquefier and «satellite» refrigerators (*6, 9*) located near the accelerator rings. The «satellite» refrigerators operate using the liquid helium obtained from the central liquefier. It makes it possible to manage each of «satellite» refrigerators by using minimum of equipment. In this case, this refrigerator, which consists only of heat exchangers, is highly reliable. Less reliable elements requiring more attention of the personnel will be located in one place — on the central liquefier. It is necessary to stress that this system needs minimum of cryogenic pipes but high thermodynamic efficiency is preserved.

Main installations of the existing cryogenic structure at the Nuclotron — two helium refrigerators KGU-1600/4.5 of capacity 2 kW at 4.5 K — were specifically designed by Joint-Stock Company «NPO GELIYMASH» for superconducting magnets of the JINR accelerators and have already been successfully operating for more than 25 years. Using this experience, the company has designed and now is manufacturing 1000 l/h helium liquefier OG-1000 (*8*), which represents the next generation of the Russian large-scale helium cryogenics. Its description will be given below.

We have got similar positive operation experience with helium screw compressors designed and manufactured by the Kazan Joint-Stock Company «NIITURBOKOMPRESSOR». The first machine Kaskad-80/25 was purchased by JINR in 1990. This machine was made in a two-stage version with the outlet pressure of 2.5 MPa. Currently, the Nuclotron cryogenic system uses two of these compressors with helium flow rates of 5040 Nm^3/h each. To refrigerate new NICA accelerators, we have ordered two additional compressor units modified to increase the outlet pressure and capacity. This compressor modification named Kaskad-110/30 (*1*) will be discussed in Sec. 3 of the paper.

2. HELIUM LIQUEFIER OG-1000

In 2011, the helium liquefier OG-1000 was specially designed to meet the needs of the NICA complex by Joint-Stock Company «NPO GELIYMASH». At present, this company is manufacturing hardware. The flow diagram of the liquefier is shown in Fig. 2 (point *4*). Its thermodynamic cycle consists of two gas-expansion turbines, a vat of liquid nitrogen, two- and three-flow heat exchangers, and a «wet» expansion turbine. The liquefier is composed of six basic units (Fig. 3), each enclosed in its own thermally insulated vacuum jacket and connected to the others by means of thermally insulated tubing. Impurities are removed from the helium at liquid nitrogen temperatures in two switchable units *1* and *2* containing charcoal adsorbers.

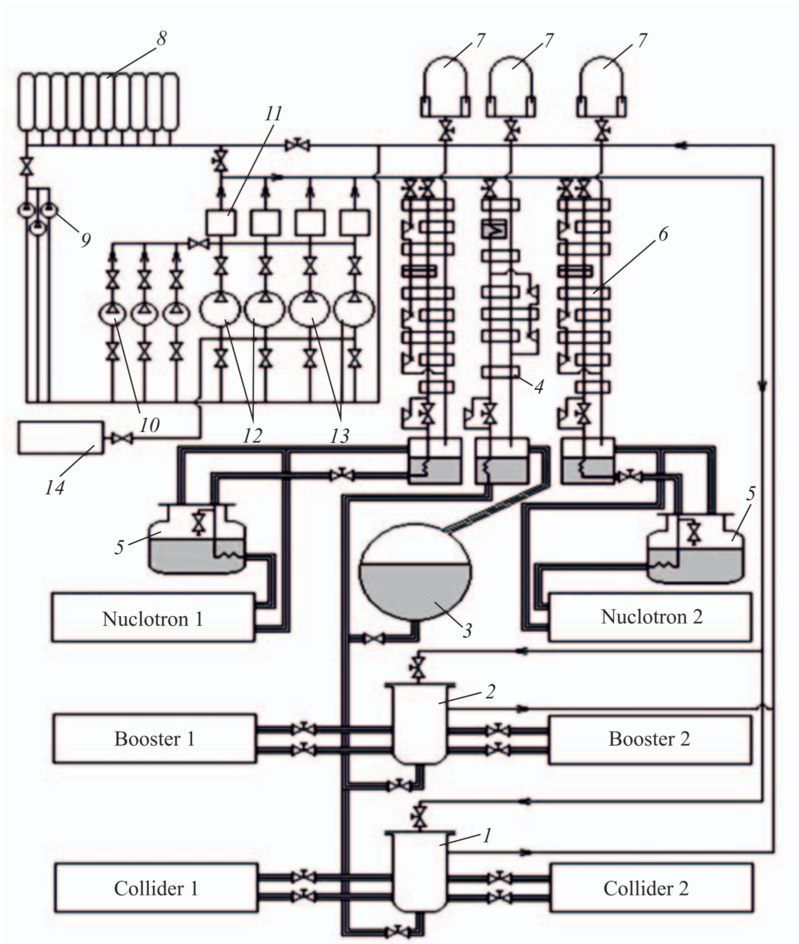

Fig. 2. Schematic flow diagram of the cryogenic helium system for the NICA complex: *1* — «satellite» refrigerator of the Collider; *2* — «satellite» refrigerator of the Booster; *3* — liquid helium tank; *4* — 1000 l/h helium liquefier OG-1000; *5* — liquid helium separators; *6* — KGU-1600/4.5 helium refrigerators; *7* — gas-holders; *8* — compressed-helium reservoirs; *9* — 45 Nm^3/h piston compressors 1VUV-45/150; *10* — 1200 Nm^3/h piston compressors 305NP-20/30; *11* — draining and oil-purification units; *12* — 6600 Nm^3/h screw compressors Kaskad-110/30; *13* — 5040 Nm^3/h screw compressors Kaskad-80/25; *14* — 100 m^3 intake reservoir

When one unit is operating, the other is being regenerated. This is done by heating with a hot gas followed by vacuum pumping. Besides, the picture shows two units *3* and *4* consisting of two- and three-flow twisted heat exchangers, an expansion turbine unit *5*, and a liquefaction unit *6* with a liquid helium collector of about 1000 l in volume. The expansion turbines are constructed following the design described in [5]. Basic parameters of the liquefier OG-1000 and technical characteristics of the turbo expanders are listed in Tables 2 and 3.

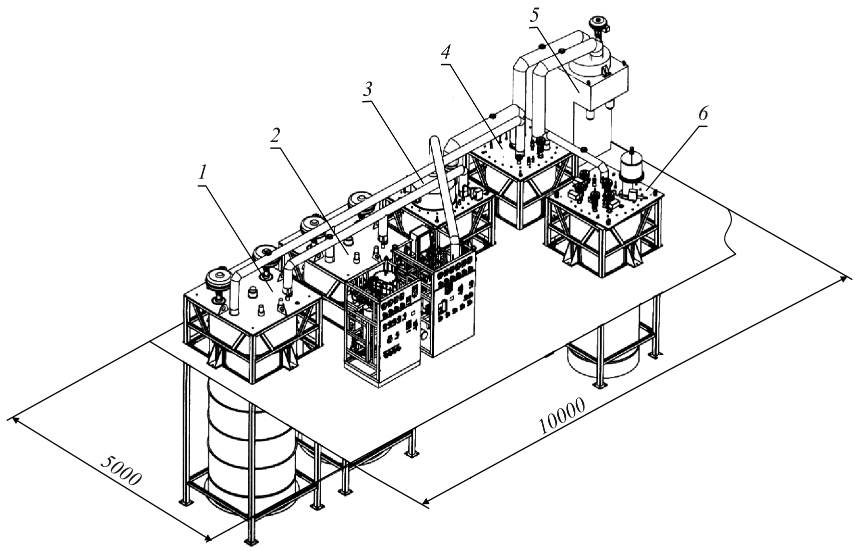

Fig. 3. Helium liquefier OG-1000: *1*,*2* — purification units; *3*,*4* — heat exchangers units; *5* — expansion turbine unit; *6* — liquefaction unit

Table 2. **Basic parameters of the liquefier OG-1000**

Capacity, l/h	1100 ± 100
Liquid nitrogen consumption, kg/h	$\leqslant 560$
Energy consumption, kW	1760
Compressed-helium pressure, MPa	2.5
Compressed-helium flow rate, Nm^3/h	6600
Total mass, kg	14000
External dimensions, m	$5 \times 5 \times 10$

Table 3. **Technical characteristics of the expansion turbines**

Parameters	Turbine 1	Turbine 2	«Wet» turbine
Mass flow rate, kg/s	0.2238	0.2226	0.1094
Inlet pressure, MPa	2.29	1.16	2.21
Outlet pressure, MPa	1.18	0.131	0.21
Inlet temperature, K	54	22.3	7.98
Outlet temperature, K	45	12.3	5.1
Expected isentropic efficiency	0.72	0.75	0.65
Output power, kW	10.9	10.9	1.25
Speed, rpm	130 000	90 000	145 000
Impeller diameter, mm	35	50	15

3. HELIUM COMPRESSORS OF THE NICA COMPLEX

The cryogenic system of NICA will use compressors of various types and modifications. Technical characteristics of the machines are listed in Table 4. The main ones are four oil-lubricated screw compressor aggregates Kaskad-80/25 and Kaskad-110/30. For the stage-by-stage regulation of the flow rate and storage of compressed helium, smaller-capacity 305NP-20/30 and 2GM4-12/31 piston compressors are used. The evacuated helium is

Table 4. **Technical characteristics of the helium compressors in the NICA cryogenic system**

Characteristics	Kaskad-80/25	Kaskad-110/30	305NP-20/30	2GM4-12/31	1VUV-45/150
Number	2	2	3	4	4
Type	Screw	Screw	Piston	Piston	Piston
Capacity, Nm^3/h	5040	6600	1200	840	45
Outlet pressure, MPa	2.5	3.0	3.0	3.1	15
Total power of electric motors, kW	1430	1600	200	160	22
Voltage, V	6000	6000	380	380	380
Number of compression stages	2	2	3	3	3
Speed, rpm	2970	2970	500	710	620
Flow rate of cooling water, m^3/h	60	78	15	7.2	1.5

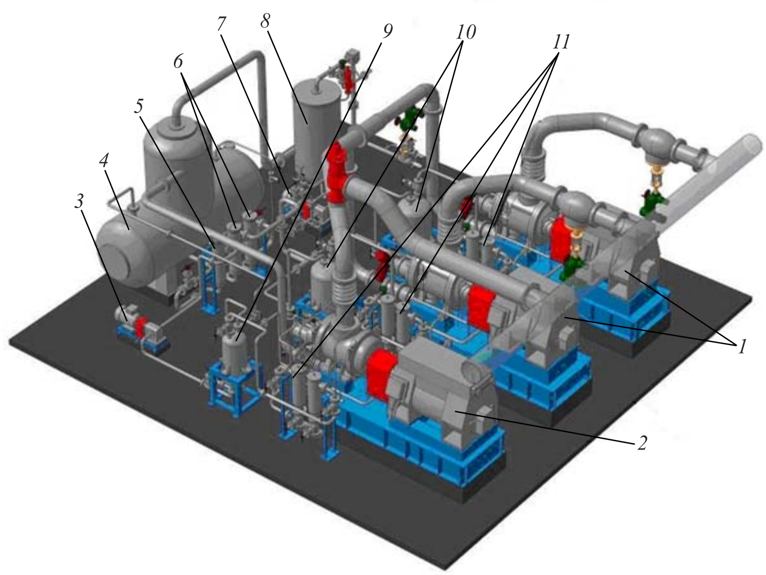

Fig. 4. The general view of the helium screw compressor aggregate Kaskad-110/30: *1* — two primary screw compressors; *2* — screw compressor of the second stage; *3* — oil pump; *4* — oil reservoir; *5* — preliminary oil-purification unit of the second stage; *6* — preliminary oil-purification units of the first stage; *7* — start-up oil pump of the primary screw compressors; *8* — oil separator; *9* — oil cooler of the second stage; *10* — two oil coolers of the first stage; *11* — fine purification oil filters

pumped into the reservoirs by small 1VUV-45/150 piston compressors, operating at higher outlet pressures.

At the present time, two Kaskad-80/25 compressors have been installed in the cryogenic system of the Nuclotron, and there are plans to install two new compressors named Kaskad-110/30 by 2013. The total capacity of the helium compressors, located in the Nuclotron machine room, the installed power, and the flow rate of cooling water are 17220 Nm^3/h, 4.19 MW, and 200 m^3/h, respectively. After new machines are put into operation, these values will increase to 30420 Nm^3/h, 7.4 MW, and 356 m^3/h.

The Kaskad-80/25 consists of three basic units: the first stage, the second stage, and the oil-cooling unit [4]. The first stage contains two compressors operating in parallel, driven by a single electric motor of power 0.8 MW with a voltage of 6 kV. The second stage consists of a single screw compressor. All aggregates have a single oil separator and an oil system common to the compressors of the first and second stages.

In comparison with Kaskad-80/25, the first step of the new machine (Fig. 4) includes two compressors; each of them is placed on a separate frame and driven by its own motor of

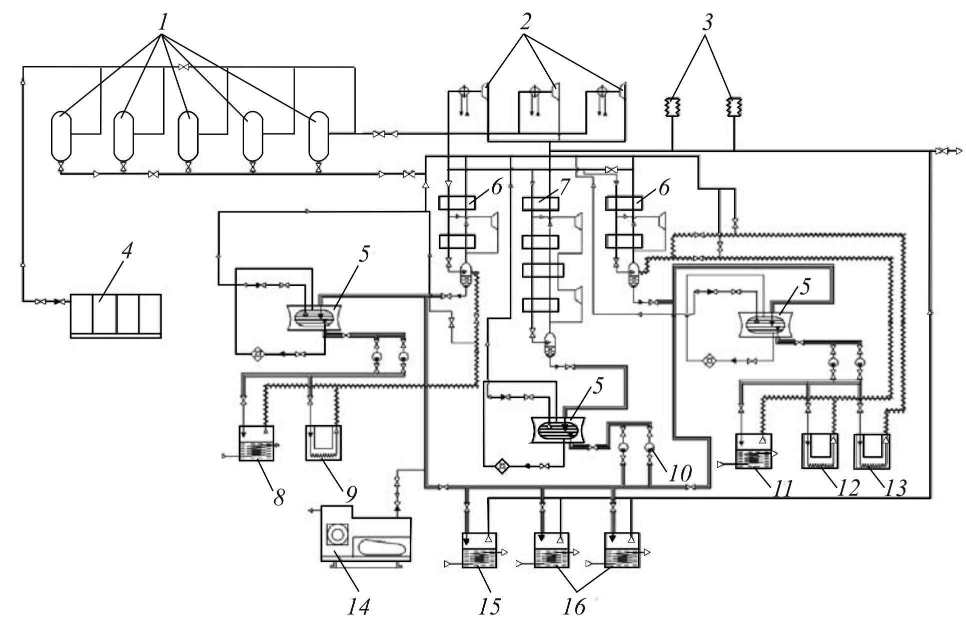

Fig. 5. Flow diagram of the NICA liquid nitrogen system: *1* — five 20 m^3 compressed-nitrogen reservoirs; *2* — three turbo compressors; *3* — two 198 m^3 gas-holders; *4* — adsorption nitrogen plant; *5* — three 30 m^3 liquid nitrogen tanks; *6* — two 500 kg/h nitrogen recondensers; *7* — 1300 kg/h nitrogen liquefier; *8* — vat of liquid nitrogen of the helium «satellite» refrigerator for the Collider; *9* — nitrogen shield of the Collider cryostat; *10* — six liquid nitrogen pumps; *11* — vat of liquid nitrogen of helium «satellite» refrigerator for the Booster; *12* — nitrogen shield of the Booster cryostat; *13* — nitrogen shield of the Nuclotron cryostat; *14* — vacuum pump; *15* — vat of liquid nitrogen of the helium liquefier OG-1000; *16* — vats of liquid nitrogen of the helium refrigerators KGU-1600/4.5

power 0.4 MW. The oil coolers for each compressor are located directly on the compressor unit. This solution together with using of the slide valves allows one to adjust the compressor capacity from 100 to 20% of the nominal value.

The primary oil separation consists of a horizontally installed cylindrical vessel, which also serves as the oil reservoir. The next stage is composed of a vertical oil separator and internal oil-coalescing filter cartridges in parallel. The final oil separation is composed of three filters and one oil adsorber containing active charcoal.

4. LIQUID NITROGEN SYSTEM

To cool down the superconducting magnet system from ambient to operating temperature and to refrigerate the insulating shields at 77 K, it will be necessary to produce about 2300 kg/h liquid nitrogen. The new closed-cycle cryogenic system for producing and distributing of liquid nitrogen is specially designed and will be constructed.

As is shown in Fig. 5, this system is based on a nitrogen liquefier (*7*) with capacity of 1300 kg/h and two 500 kg/h nitrogen recondensers (*6*). Three compressors Samsung Techwin SM-5000 are used for circulation of gaseous nitrogen. Inlet and outlet pressures are 0.12 and 1.8 MPa, respectively.

The nitrogen liquefier has thermodynamic cycle based on two gas-expansion turbines, where the compressed gas expands step-by-step from 1.8 to 0.12 MPa. Both recondensers have identical thermodynamic cycle based on a single gas-expansion turbine.

The work was partially supported by JINR grant No. 13-103-05.

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Received on October 16, 2013.