NUCLOTRON CRYOGENIC SYSTEM: STATUS AND RECENT DEVELOPMENT

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ABSTRACT

The Nuclotron is the first fast cycling superconducting synchrotron intended for the acceleration of high-energy nuclei and heavy ions. The accelerator was put into operation eleven years ago at the Joint Institute for Nuclear Research in Dubna near Moscow. The cryogenic system of the Nuclotron includes three helium refrigerators. Each of them has a nominal capacity of 2000 W at 4.5 K. These refrigerators cool the accelerator ring, which has a perimeter of 251.5 m and a "cold" mass of about 80 tons. The new technical ideas used at the Nuclotron have provided low cost of its refrigeration, high reliability, good thermodynamic efficiency, and the ability to regulate the refrigeration capacity. The long-term experience and novel technical solutions of the Nuclotron cryogenic system are described.

INTRODUCTION

The plans for the development of the basic installations at the Joint Institute for Nuclear Research (JINR) Laboratory of High Energies provided for the successive building of new accelerators based on magnets with superconducting windings cooled to liquid-helium temperatures as fundamental elements. Compared to thermal magnets operating at the temperature of the ambient medium, superconducting magnets have several advantages. First, the capital required to build them and the metal content is significantly reduced. Second, the operating expenses, most of which are due to the cost of electrical energy, are also greatly lowered. Another obvious advantage is the large decrease in the size of the magnet system, which allows practically all its elements to be prepared at a simple workbench of ordinary dimensions. This results in high accuracy and, in the end, a magnetic field of good quality. The possibility of building such small-scale objects at the Institute itself, instead of having to resort to expensive commercial production, is also very important.

The Nuclotron, whose basic parameters are listed in Table 1, is designed to accelerate heavy nuclei and multiply charged ions. It was installed at the JINR Laboratory of High Energies during 1987-1992. The planned energy of the charged particles with charge-to-mass ratio Z/A = 1/2 is 6 GeV/nucleon. The accelerator parameters have been described by Baldin *et al* (1994) and (1995). Agapov *et al* (1996a) developed the cryogenic system of the Nuclotron.

In accordance with the plans for the development of the accelerator complex at the Laboratory of High Energies, the Nuclotron ring is located in the ground floor of the synchrophasotron (Fig. 1). The perimeter of the new accelerator is 251.5 m.

The refrigeration of the accelerator ring imposed the following requirements on the cryogenic system:

1. The refrigerating capacity at helium temperature in the operating mode must range from 1750 to 4620 W, including: compensation of heat leaks of 1750 W from the ambient medium; compensation of dynamical heat releases of up to 2870 W at a magnetic field frequency of 0.5 Hz.

2. In addition, it is necessary to produce up to 120 1/h of liquid helium, which is withdrawn from the cryostat to cool the current leads.
3. It is also necessary to cool the 80-ton magnet system from the temperature of the ambient medium to 4.5 K during a period of no more than 80-100 h.

1 CRYOGENIC SYSTEM OF THE NUCLOTRON RING

A general view of the basic design of the cryogenic system for the accelerator is given in Fig. 2. The system is based on three KGU-1600/4.5 refrigerators (Krakovskii and Pron'ko, 1979). Each of these consists of three gas-expansion turbines Tl, T2, and T3, vats of liquid nitrogen, two- and three-flow heat exchangers, a "wet" turbine T4, and a liquid-helium collector of volume of about 1000 l. After leaving the compressors, the compressed helium, purified of oil and moisture, is split into two parts at the input to each KGU-1600/4.5 refrigerator. One part, so called "turbine flow" after the valve V5, is subsequently expanded in the three gas-expansion turbines from 2.5 MPa to 0.13 MPa. The second part – "primary flow" - is fed through valve V6, cooled by heat exchange with the back helium flow to a temperature of 5.5-8.5 K, and then expanded in the "wet" expansion turbine from pressure 2.5 MPa to 0.13-0.17 MPa. Then, part of the "primary flow" is drawn off to a liquid-helium collector (valve V4), and the rest (valve V2) is fed via thermally insulated tubing to an intermediate separator 8. After being cooled in the latter, it is led to the supply header 3 of the cryostat system of the Nuclotron.

Each of two KGU-1600/4.5 refrigerators is connected to its own half-ring. The third is on reserve. It is designed to operate in the liquefaction mode with liquid helium fed through valve V3 via thermally insulated tubing to either of the devices connected directly to a half-ring of the accelerator. When liquid helium is supplied by the reserve KGU-1600/4.5, each of the other two refrigerators can be switched to so-called "satellite mode". In this case using liquid helium obtained from the reserve liquefier, the refrigerator can operate without turbines. This ensures the continued circulation of the needed amount of liquid helium in the corresponding half-ring of the Nuclotron during shut-downs of the expansion turbines due to their breakdown or nonoperation for other reasons. Moreover, switching on the reserve KGU-1600/4.5 ensures increased refrigerating capacity of the entire system as a whole when needed.

Table 1: Basic parameters of the Nuclotron.

1	Maximum design energy of particles, GeV/nucleon	6
2	Perimeter, m	251.5
3	Maximum magnetic field, T	2.0
4	Stored energy, MJ	2,35
5	Temperature, K	4,6
6	Total static heat leak, kW	1,75
7	Maximum dynamic heat releases at 0.5 Hz, kW	2,9
8	Repetition rate, Hz	up to 1
9	Total "cold" mass, tons	80
10	Time to cool down to operating temperature, h	80

2 FAST CYCLING MAGNETS AND REFRIGERATION BY TWO-PHASE HELIUM FLOW

The most interesting feature of the Nuclotron magnets is their capability for very fast cycling (Table 1). It is really unusual for superconducting magnets to operate with the repetition rate up to 1 Hz. That is why in our case dynamic heat releases are larger than the value of static heat leaks. The Nuclotron magnets therefore had to have very reliable conditions of their cooling. These conditions are possible due to using a two-phase helium flow and a hollow superconductor. The superconducting cable represents a 5 mm diameter copper-nickel tube,

inside which a two-phase helium flow proceeds. This tube is coated with epoxy compound and wrapped with 31 wires 0.5 mm in diameter. Each wire contains 1045 NbTi filaments of 10 microns in a copper matrix. Such a design provides a good thermal contact of superconducting wires with a cooling helium flow (Baldin *et al.*, 1995).

The ring consists of 96 dipole magnets each 1.5 m long, 64 quadrupole lenses each 0.45 m long, and 28 multipole correctors (0.31 m) with three or four types of winding in each. The dipole magnets have a superconducting cable 62 m long. The mass of the dipole magnet is 500 kg, the static heat leaks are 6.6 W. Dynamic heat releases depend on the frequency of magnets. In case of 0.5 Hz, they are 21 W. Quadrupole magnets have a superconducting cable 24 m long. The mass of the quadrupole magnet is 200 kg, the static and dynamic heat releases (f = 0.5 Hz) are 5.2 W and 12 W, respectively.

The energy input and output for the main magnets are provided by twelve, 6 kA current leads, cooled by cold helium vapor. The temperatures around the ring perimeter are measured by about 600 cryogenic thermometers.
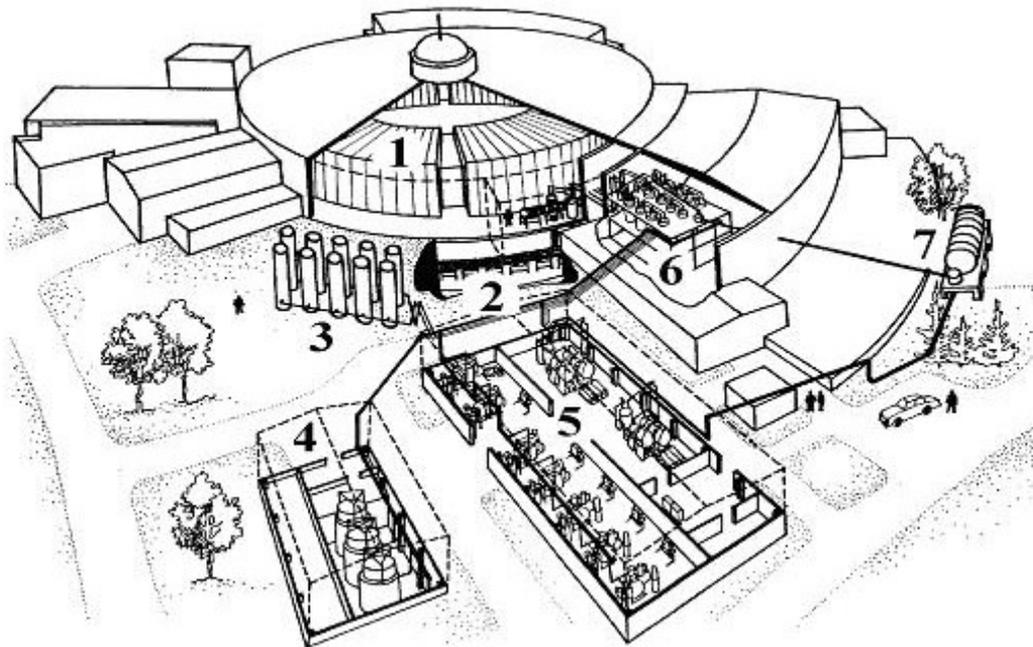

Figure 1 - General view of the cryogenic system for the Nuclotron: (1) synchrophasotron; (2) ring of superconducting magnets of the Nuclotron; (3) compressed-helium reservoirs; (4) gas-holders; (5) compressor plant; (6) KGU-1600/4.5 refrigerators; (7) liquid-helium tank

3 PARALLEL CONNECTIONS OF ALL COOLING CHANNELS

As shown in Fig. 2, each of the dipole and quadrupole magnets is fed with liquid helium from the supply header extending along the entire length of the accelerator. In the standard operating mode, helium with a mass vapor content of about 0.35 leaves the superconducting cable and then cools the iron yoke of the corresponding magnet. After this it is drawn off (with a vapor content of 0.9) to the return header.
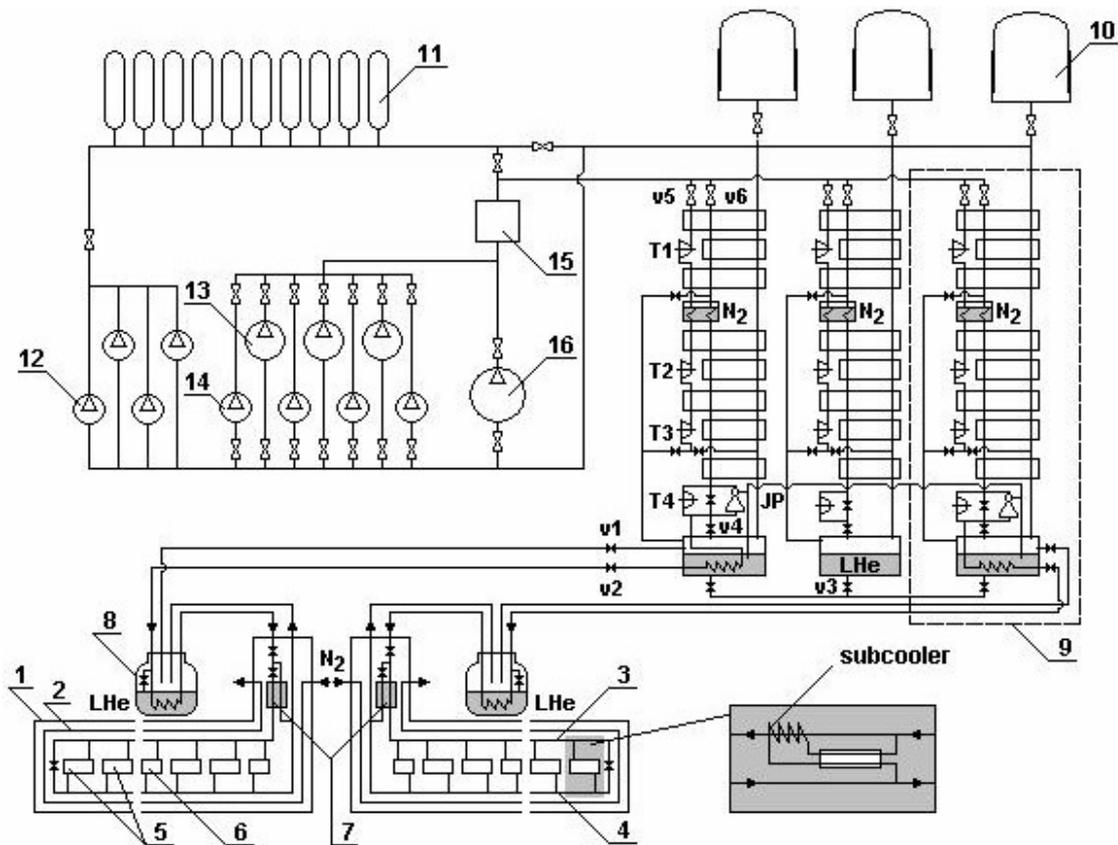
Figure 2 - Basic design of the cryogenic helium system for the Nuclotron: (1) vacuum jacket; (2) thermally shielding screen; (3) supply header; (4) return header; (5) dipole magnet; (6) quadrupole magnet; (7) supercooler; (8) separator; (9) KGU-1600/4.5 refrigerator; (10) gas-holders; (11) compressed-helium reservoirs; (12) 45 Nm^3/h piston compressors; (13) 1200 Nm^3/h piston compressors; (14) 900 Nm^3/h piston compressor; (15) MO-800 draining and oil-purification unit; (16) 5000 Nm^3/h screw compressor "Kaskad-80/25"

The magnets of the accelerator, along which the helium headers of the direct and back flows, are located in a ring cryostat formed by horizontal cylindrical segments of stainless steel (Fig. 3). In addition, there is a heat-shielding screen cooled by liquid nitrogen around the entire perimeter of the ring cryostat. The lengths of the cylindrical segments correspond to the lengths of the magnets, and the full assembly corresponds to unified magneto-cryostat units, connected to each other by syphon decouples.

At the first stage of designing, we were thinking rather carefully of the system, in which the magnets are piped in parallel resulting in about 100 channels in each half-ring returning two-phase helium flow. There were at least two reasons for that. First, it was not obvious whether it was possible to satisfy the required distributions of cooling helium flows in such a large number of different channels. Second, the probability of fluctuations of bubbling helium streams was not excluded. The following ways were accepted to avoid such bad consequences:

- the hydraulic resistance of the cooling channels of the dipole and quadrupole magnets is performed so that the mass vapor content of helium at the outlet of the magnets is equal (90%).

- to be quite sure that there is only the liquid at the inlet of each of the magnets, 62 subcoolers are constructed in each half-ring for keeping helium in a liquid state inside the supply header.

But these actions were not always sufficient. At the difference in pressure between supply and return helium headers less than 0.02 MPa the refrigeration of the magnets was not stable. We observed transitions of superconducting windings in a resistive condition in multitude. To increase the pressure drop higher than 0.02 MPa, it was necessary to raise greatly a helium flow through the valve 6 (Fig. 2). It resulted in the large extra energy consumption because of

operating of additional compressors. Additionally, the refrigerator efficiency reduces due to deviation from optimum modes.

In order to increase liquid helium flow directed to superconducting magnets, jet pumps are used. This appliccations of the jet pump was suggested by Agapov *et al* (1978). The article describes theoretical and experimental studies that permit one to determinate main geometric dimensions of the jet pumps. Using these results, we designed the apparatus presented in Fig. 4. The nozzle has been made by drilling with a minimum diameter of 0.8 mm. Such an apparatus is extremely simple. It costs nothing, and its operational reliability is very high.

Figure 3 – Photograph of the ring cryostat of the Nuclotron
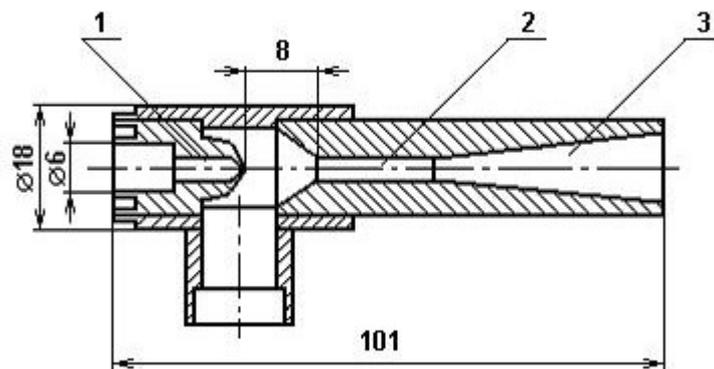

Figure 4 – Liquid helium jet pump: (1) nozzle; (2) cylindrical mixing tube; (3) inlet diffuser
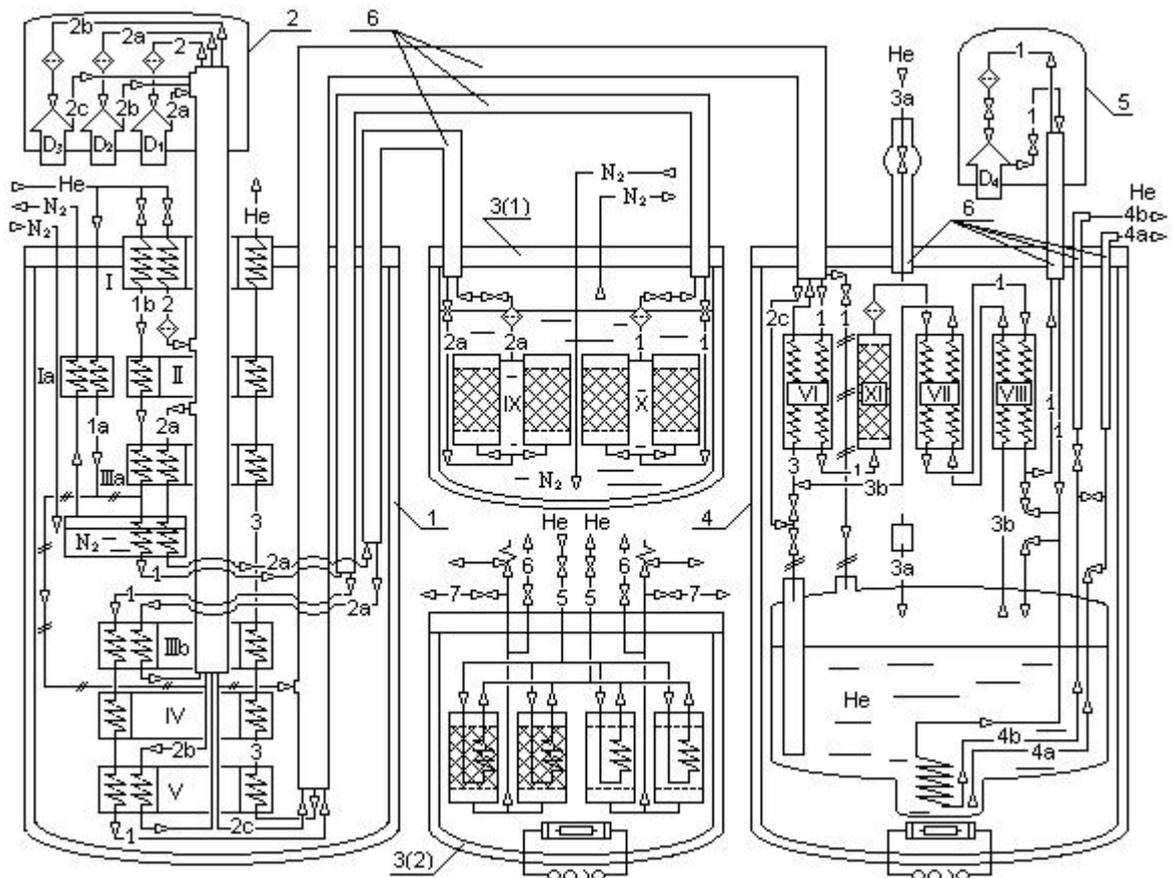
Figure 5 - Schematic diagram of the KGU-1600/4.5 refrigerator: (1) main heat-exchanger unit; (2) gas-expander unit; (3) units for cleansing from N_2 and O_2 impurities; (4) liquefaction unit; (5) "wet" expander unit

The flow diagram is shown in Fig. 2. The "wet" turboexpander T4 and liquid helium jet pump JP have parallel connection. The high pressure stream flows from the last heat exchanger of the refrigerator and splits into two parts. One part (about 90%) is led to the expander T4. The jet pump flow (10%) increases its velocity by means of the nozzle, and then carries away the stream of liquid helium from the 1000 l collector of the refrigerator. The mixed stream, which about five times more than the nozzle flow, joins the outlet stream of the "wet" expander.

Of course we have a small decrease of the refrigerator capacity due to 10% bypass of the "wet" expander. But it allows one to have the pressure drop between supply and return helium headers of the Nuclotron more than 0.025 MPa. In this case the superconducting magnets operate very stably. As well the electrical energy consumption is greatly lowered (about 600 kW) because of not operating of additional compressors.

4 THE KGU-1600/4.5 HELIUM REFRIGERATOR

The KGU-1600/4.5 cryogenic helium refrigerator was specially designed to meet the needs of the JINR Laboratory of High Energies by the Research and Production Association NPO GELIYMASH. The first model, the testing of which began in 1980, was designed for the refrigeration of the superconducting model synchrotron and for the liquefaction of helium to supply various experimental groups at the JINR working both on superconducting magnets as part of the Nuclotron program, and on other problems. Three more such refrigerators were eventually installed in the cryogenic complex of the Nuclotron.

The KGU-1600/4.5 refrigerator is composed of five basic units (Fig. 5), each enclosed in its own thermally insulated vacuum jacket and connected to the others by means of thermally insulated tubing. Unit 1 is a chain consisting of two- and three-flow twisted heat exchangers, from the locations of which run, along the central vacuum housing, three pairs of tubes for the inflow and

outflow of the helium of the gas-expansion turbines of the preliminary cooling stage. The gas-expansion turbine of unit 2 is located in the upper part of unit 1.

Nitrogen and oxygen impurities are removed from the helium at liquid-nitrogen temperatures in two switchable units (3(1)) and (3(2)) containing carbon adsorbers. When one unit is operating, the other is being regenerated. This is done by heating with a hot gas followed by vacuum pumpdown. The adsorber removing Ne and H_2 impurities is located inside the liquefaction unit (4). Its regeneration during operation was not provided for; as a rule, this is done in the warm device before each long operating run. In addition, the liquefaction unit (4) includes a liquid-helium collector of about 1000 1 in volume, heat exchangers, and a low-temperature valves for controlling the device and distributing liquid helium among the users. The liquefaction unit adjoins the unit containing the "wet" turbine (5).

5 VERY SHORT COOL DOWN TIME

For the Nuclotron magnets described above, there are practically no constraints on the cooling time arising from thermal gradients and stresses in the structural elements themselves. All the structural elements have undergone tests for a time of cooling to helium temperatures of no more than 10 hours. It was therefore decided to cool the entire magnet system of the accelerator in the minimum possible time. Analysis showed that the best time in our case was 80-100 hours. This is a record cooling time compared to similar installations. The schematic solution uses a forced flow of gaseous helium, cooled in KGU-1600/4.5 refrigerators by the evaporation of about 80 m^3 of previously supplied liquid nitrogen.

The cooling process does not involve the use of any additional equipment, only the usual helium refrigerators. The forward and back flows are in the same directions as in ordinary operation in the nominal mode, i.e., in refrigeration of the magnets at helium temperatures. However, to speed up the cooling, the KGU-1600/4.5 refrigerators are equipped with bypass lines (Agapov *et al.*, 1996a).

6 "WET" TURBOEXPANDERS

In order to raise the efficiency of cryogenic refrigerators and liquefiers, it is very important to replace the JT process, which involves large losses of exergy, by the improved process of adiabatic expansion. The replacement of a JT-valve by an expander was proposed and realized first in the hydrogen liquefaction cycle at the Joint Institute for Nuclear Research (Balandikov et al., 1966). 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, Collins (1971) made it. Piston-type machines were used in both cases.

Piston expansion devices were used instead of JT-valves in the original version of the Nuclotron helium refrigerators KGU-1600/4.5. A rather large increase of efficiency (about 70%) was obtained as compared to the JT-valve mode. However, the operating team expected to use turbines owing to their greater reliability. Along with the problem of reliability, this modernization also manages to resolve serious operational difficulties arising when piston machines break down. As a rule, such breakdowns lead to a large rise of the pressure of the compressed gas at the refrigerator input and an enormous momentary disturbance of the control system. This unwelcome consequence does not occur in the case of spontaneous shutdown of a turbine-type machine: the nozzle continues to pass the required amount of helium, i.e., it is as though the turbine is transformed into the JT-valve.

So we attempted to replace a piston-type machine of the KGU-1600/4.5 refrigerator by a "wet" turbine (Davydov et al., 1986). The positive experience that we gained using a "wet" helium expansion turbine in the first model of the KGU-1600/4.5 refrigerator allowed us, in further studies of the Nuclotron design, to give up expansion machines of the piston type completely. Long operating experience has demonstrated an entire absence of any technical problems, which

might have been expected in the modes where the expansion process is completed in the two-phase liquid-vapor region.

The test results (Agapov *et al*., 2001) of the second-generation "wet" turboexpander for the Nuclotron helium refrigerators are given in Fig. 6. The isentropic efficiency is calculated to be about 65%. It fits very well the expected efficiency. As a result of using the new "wet" turbines, the capacity of the Nuclotron helium refrigerators increased from 1600 to 2000 W, and the compression work per unit of refrigeration capacity (figure of merit) lowered to about 290 W/W.
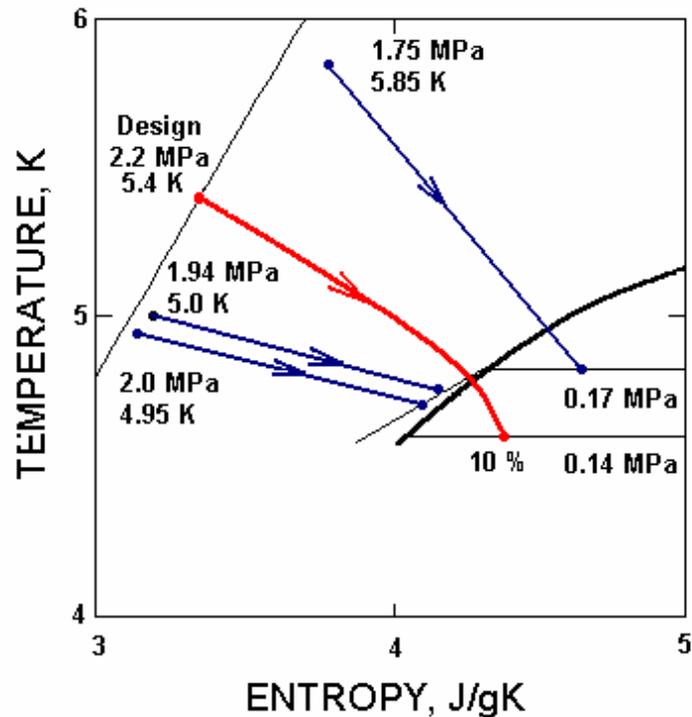

Figure 6 - The test results of the second-generation "wet" turboexpander
for the Nuclotron helium refrigerators

It is of fundamental importance that, despite the absence of any way of regulating the flow cross section of the turbine nozzle, efficient operation of the KGU-1600/4.5 refrigerator is ensured in both the refrigeration and the liquefaction modes. This "self-regulation" of the flows in variable modes arises because for the maximum flow rate of helium through the turbine (the refrigerator mode), the optimal temperature at the input is a minimum and equal to 5.0 K. Upon switching over to the liquefaction mode, the required helium flow rate in the final cooling stage is considerably decreased, but this is compensated by the increase of the optimal temperature at the input of the turbine, which in this case reaches 8.5 K. This temperature rise at the input reduces the flow rate of helium through the "wet" turbine so much that the flows are effectively redistributed.

CONCLUSION

The first cooldown of the entire Nuclotron ring after assembling all the elements in the tunnel and complex testing of the subsystems was started on 17 March 1993. After 100 hours all the elements had reached a temperature of about 4.5 K. On 26 March the first revolutions of the beam in the ring were recorded, and this is the date generally accepted as that on which the new superconducting heavy-nucleus accelerator began operation.

After the first startup of the full ring, regular runs were performed at the Nuclotron. During these runs the cryogenic system operated for more than 10000 hours. In addition, at the request of other users it operated for about 5000 hours for a yearly output of up to 1 million liters of liquid

helium. No breakdowns leading to interruption of the planned operation were recorded during this time.

In summary, it must be said that the cryogenic system of the Nuclotron represents a rather daring project involving a large number of technical ideas and solutions never used before. This system is described in such fundamental terms as "fast cycling superconducting magnets," "refrigeration by a two-phase helium flow," "very short time for cooldown to the operating temperature," "parallel connection of all the magnets," "wet expansion turbines," and "liquid helium jet pumps." These technical solutions have allowed the creation of not only a very efficient and reliable system, but also one which is unusually inexpensive.

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