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CRYOGENIC SYSTEM OF THE NUCLOTRON — A NEW SUPERCONDUCTING SYNCHROTRON

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INTRODUCTION

The Nuclotron, a new superconducting synchrotron, built at the Laboratory of High Energies over the period of 1987–1992 is intended to accelerate nuclei and multicharged heavy ions. The maximum energy of accelerated particles with the charge to mass ratio Z/A=1/2 is 6 GeV per nucleon. The parameters of the Nuclotron and the program of physics investigations are presented in papers [2, 3]. The perimeter of the accelerator is 251.5 m. The ring of the Nuclotron comprises 96 dipole magnets 1.5 m long, 64 quadrupole lenses 0.45 m long, 28 multipole correctors 0.31 m long with 3 or 4 types of windings in each, twelve 6 kA helium-cooled current leads, 234 leads of 100 A current for correcting windings and special-purpose magnets, 32 special units for beam injection, acceleration, diagnostics, and extraction, and also about 600 sensors of cryogenic temperatures.

MAGNET AND CRYOSTAT

The basic element of the Nuclotron magnetic system is a magnet of the "Dubna" type [4]. That is a pulsed SC magnet with a "cold" iron yoke and a saddle-shaped hollow superconductor winding. The maximum value of the iron-shaped magnetic field in the central bore is about 2 T.

The SC cable represents a 5 mm OD copper-nickel tube which is wrapped by thirty-one 0.5 mm diameter wires. Each wire contains 1045 NbTi filaments of 10 μm in a copper matrix. The tube allows a high helium pressure after quenching or vacuum breaking. The rise of helium pressure is required to decrease the cooldown time.

A high electric strength, a low inductance of the windings and good conditions of their cooling make it possible to provide a high (up to 1 Hz) repetition frequency of accelerating cycles at the Nuclotron. This allows the Nuclotron to be used as a booster for the next accelerator ring in the future.

The cross sections of the dipole and quadrupole magnets are shown in Figure 1. The main characteristics of the magnets are presented in Table 1.

The magnet is fastened in the cryostat by eight suspension parts 9 (see Fig.2) so

Table 1. Main characteristics of the magnets.

DIPOLE	
Mass	500 kg
Number of turns in winding	2×8
Length of SC cable in winding	62 m
Induction at a nominal current of 6 kA	1.98 T
Integral relative inhomogeneity of magnetic field $\Delta B/B$ (B=1.92 T, R=20 mm)	6.6×10^{-4}
Dynamic heat releases at $\dot{B}$=2 T/s, B_{min}=0, B_{max}=2 T and f=0.5 Hz	21 W
Inductance	1.1 mH
QUADRUPOLE	
Mass	200 kg
Number of turns in winding	4×5
Length of SC cable in winding	24 m
Gradient at a nominal current of 5.6 kA	33.4 T/m
Dynamic heat releases at indicated ramp rate	12 W
Inductance	0.44 mH
Helium pressure difference between headers when magnets run at indicated ramp rate and x_0=0, x_2=0.9	20 kPa

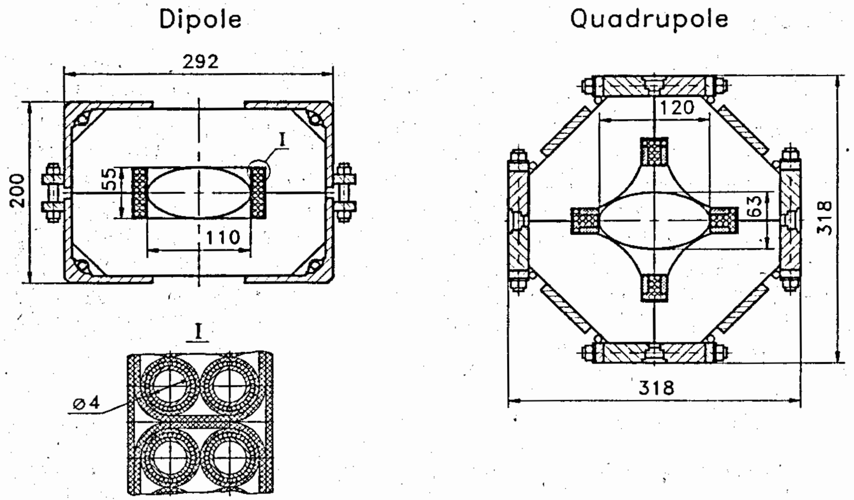

Figure 1. The cross sections of the dipole and quadrupole magnets.

that there is no change of its position after cooling down the magnet.

Flexible bellows 1 are connected to both ends of vacuum shell 8 by means of rotatable flanges. Such a flange allows a unit to be rotated around the axis. The bellows permit the movement of the neighbouring units relative to each other. The unit is placed on support 15 with arrangements for adjusting. The vacuum shells of the units are connected by demountable sleeves 5. There is no helium vessel. So it's easier to provide all interconnections between the magnets.

The magnetic system [5] is assembled of three types of magnet-cryostat units with dipole, focusing, and defocusing magnets, respectively. Before installation in the tunnel, each unit was individually tested at a special-purpose test facility. At the test facility the following parameters were measured: hydraulic resistance of the helium cooling channels, insulation voltage of the winding, field quality in the operating aperture, effective length of the magnet, quench current and training quenches, dynamic heat release and static heat leak, vacuum leaks of helium and nitrogen at room and operating temperatures. Helium headers 2, tubes for liquid nitrogen 7, beam pipe 4, and sleeves 5 of the vacuum shell from the neighbouring units are connected under assembling the magnet system (Fig.2).

COOLING OF THE MAGNETS

A two-phase helium flow was chosen as a coolant after tests of the prototype magnets [6, 7, 4]. In comparison with two-phase helium, a single-phase coolant (liquid helium) leads to a substantial increase of the helium flow through the magnet, a rise in cooling temperature, and a drop in the stability of the SC winding to heat loads. An additional reason for this choice is the fact that a main heat load for the Nuclotron magnets is caused by the iron yoke. The mass vapour contents $x_1 = 0.35$ and $x_2 = 0.9$ at the outlets of the winding and the magnet, respectively (see Fig.3). This fact allows one to provide operational conditions even under substantial discrepancies between the values of hydraulic resistance and heat load for the cooling channels of the magnets. A refrigeration scheme of the Nuclotron magnets is presented in Figure 4. Heat shield 2, supply 3 and return 4 helium headers are placed inside vacuum shell 1. The liquid helium, entering the supply header of the half-ring cryostat, is distributed over the cooling channels of individual units, which are connected in parallel. In each unit (Fig.3) the two-phase helium flow passes through the cooling channels of the SC buses, the winding, and the tubes for cooling the supply header and the iron yoke. The mass vapour content of helium varies from 0 at the inlet of the unit to 0.9 (on the average, for all units of the half-ring) at its outlet.

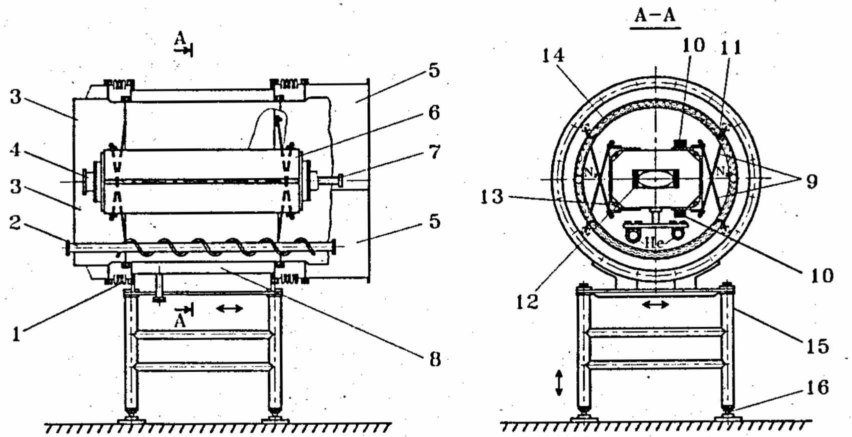

Figure 2. Layout of the magnet-cryostat unit. 1 – bellows; 2 – helium headers; 3 – heat shield; 4 – beam pipe; 5 – sleeve; 6 – yoke; 7 – tubes for liquid nitrogen; 8 – vacuum shell; 9 – suspension parts; 10 – SC buses; 11 – cold bridge; 12 – winding; 13 – tube for cooling the yoke; 14 – superinsulation; 15 – support; 16 – jack.

The temperature of the helium flow entering the return header is monitored by a thermometer and characterizes the conditions of cooling the magnet. The temperature sensors [8] are also placed at the inlet and outlet of the windings of each dipole and quadrupole magnet.

CRYOGENIC SUPPLY SYSTEM

The cryogenic supply system (Fig.4) is based on three KGU-1600 refrigerators [9] of a nominal capacity of 1600 W at 4.5 K each. The total cooling power is provided by two refrigerators; each of them is connected to its half-ring and runs independently. The third one is installed for redundancy reasons. It is aimed to run in the liquefaction mode with liquid helium fed to any refrigerator in the case of failure. Each refrigerator includes three gas turboexpanders T1, T2, T3, a liquid nitrogen bath, double- and triple-flow heat exchangers, wet turboexpander T4 and a liquid helium receiver with a volume of 1000 L. After oil and water removal, the compressed helium is divided into

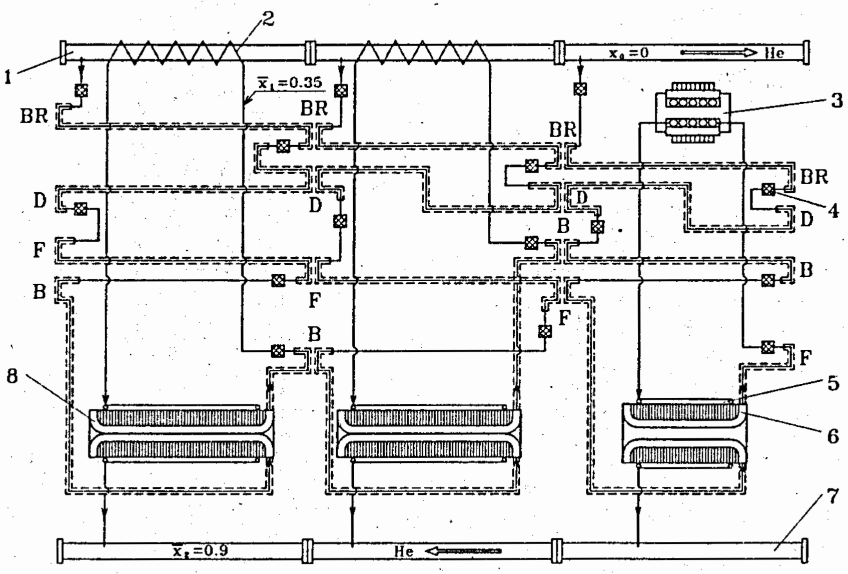

Figure 3. Schematic diagram of electric and helium communications of the magnet-cryostat unit. 1 – supply header; 2 – tube for cooling the header; 3 – multipole corrector; 4 – insulating bush; 5 – tube for cooling the iron yoke; 6 – quadrupole winding; 7 – return header; 8 – dipole winding; B, F, D – SC bus of the bending, focusing, and defocusing magnets, respectively; BR – return bus of the dipole magnets; $\bar{x}_1$, $\bar{x}_2$ – average mass vapour content in the helium flow at the outlet of the winding and the yoke, respectively; x_0 – mass vapour content in the supply header.

main and turbine streams at the entrance of each refrigerator. The turbine stream is expanded step-by-step in the three turbines from 2.5 MPa to 0.13 MPa. The optimum temperatures of helium at the input of the turboexpanders are 150 K, 50 K and 19 K. The main stream after cooling in the heat exchangers to a temperature of 5.5 K – 7.5 K is expanded in the wet turbine from 2.5 MPa to 0.17 MPa. Then one part of the main stream is removed to the liquid helium receiver, and the other part is directed to a half-ring of the Nuclotron after liquid-vapour separation in the phase separator.

The basis of the compressor system is a screw compressor [10] CASCADE-80/25. There are piston compressors with a relatively smaller capacity for step-by-step variation of the compressed helium stream and its redundancy. The main parameters of the helium compressors are given in Table 2. Each of the screw compressors is supplied by an oil and water purifier MO-800. Final oil vapour purification is performed in the purifier by two charcoal adsorbers with a duty cycle of 2500 hours each. After the time is over, the adsorbers are interchanged, and the used charcoal is renewed. Water purification is performed in two ceolite adsorbers of the purifier. The running time of each adsorber is 10 days, and then it is regenerated.

The water removal of compressed helium from the piston compressors is performed by three parallel switched-on purifiers with a flow rate of 3×1200 nm^3/h. Gaseous helium is stored in 10 vessels of a 20 m^3 capacity each with a maximum

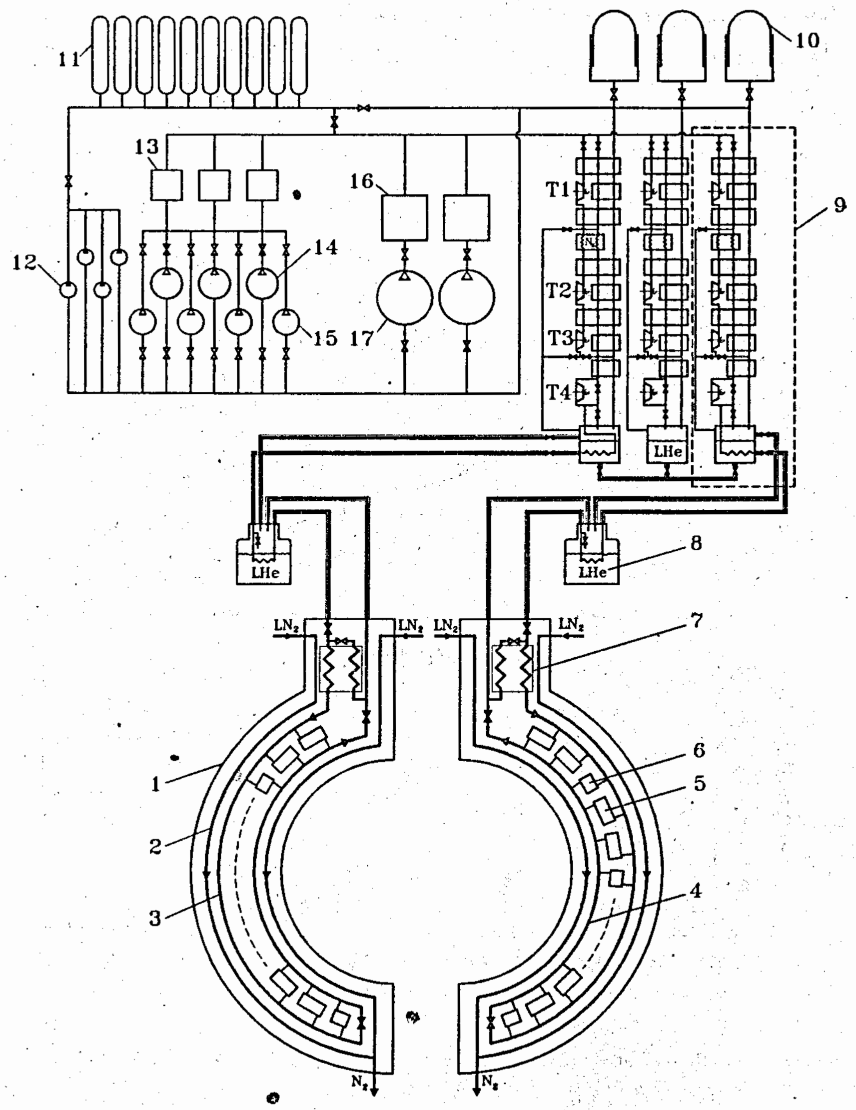

Figure 4. General scheme of the Nuclotron cryogenics. 1 – vacuum shell; 2 – heat shield; 3 – supply header; 4 – return header; 5 – dipole magnet; 6 – quadrupole magnet; 7 – subcooler; 8 – separator; 9 – refrigerator; 10 – gas bag; 11 – storage vessel; 12, 14, 15, 17 – compressors; 13, 16 – purifiers.

pressure of 3 MPa and in 3 gas bags of a 20 m^3 capacity each.

Table 2. Main parameters of the helium compressors.

Component	CASCADE-80	305NP-20	2GM4-12	1VUV-45
Number	2	3	4	4
Type	screw	piston	piston	piston
Capacity, m^3/h	5040	1200	900	45
Discharge pressure, MPa	2.5	3.0	3.1	15.0
Number of compression stages	2	3	3	3
Power of electric motors, kW	2×630	200	160	22
Voltage of electric motors, V	6000	380	380	380

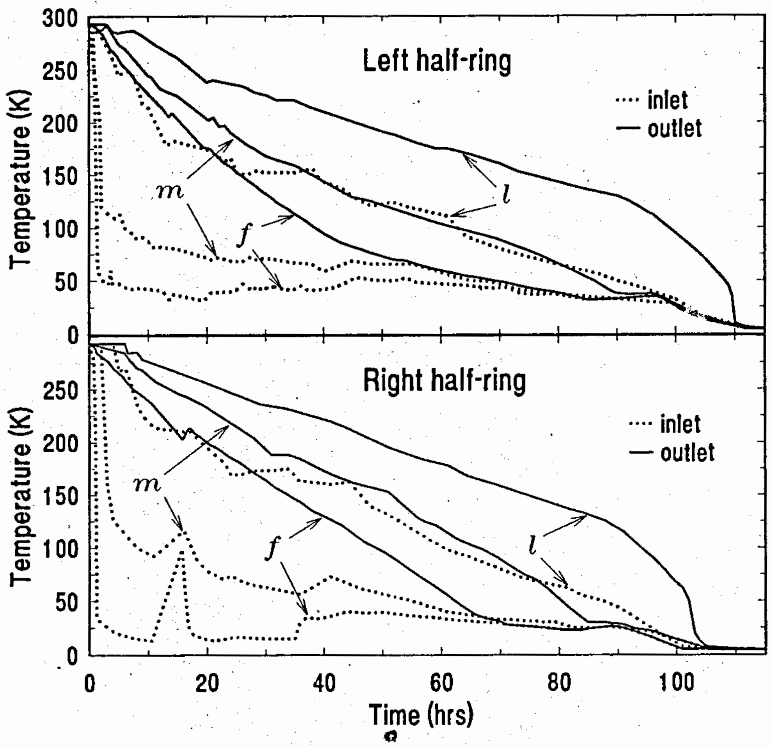

Figure 5. Cooldown history of the Nuclotron half-rings during the pilot run. *f*, *m*, *l* – the first, fortieth, and eightieth magnet on the way of helium, respectively.

COMMISSIONING OF THE NUCLOTRON RING

The stand tests of a string of 12 dipole magnets and 4 quadrupole lenses were performed in the February of 1990. The time spent on cooldown of the string of magnets with a total cold mass of 7 tons from room to LHe temperature was about 46 hours. The time difference between cooling down the first and the last magnets to LHe temperature was 17 hours.

The cooling was performed by a KGU-1600 refrigerator at a mean helium flow rate of 0.45 g/s through each magnet. The first spontaneous quench current was 5.9 kA, the second one 6.4 kA (an operating current of 6 kA). Several tens of quenches were initiated during the run. No breakdowns were observed in the energy evacuation system. Recovery from a quench takes less than 5 minutes. When the windings were excited by current pulses of triangular shape with an amplitude of 6 kA, a pulse duration of 2×1.55 s, and a pulse repetition period of 3.55 s, the measured energy losses in the magnets were 140 W. The heat leak from the surroundings to the magnet string and two cryostats for the current leads was 100 W. The helium flow rate per one current lead was 0.37 g/s at a constant current of 6 kA. The mass vapour content of helium in the supply header, reliably measured by means of a void fraction sensor [11], was controlled close to zero with the aid of a subcooler. The pressure difference between the supply and return headers was kept equal to 9 kPa. In this case the mass vapour content of helium in the return header was about 1 and the helium temperature approximately 4.5 K. The cooling and operation of the magnets were stable. No flow rate oscillations were observed in the parallel cooling channels. In the indicated operating mode the magnets ramped 192 hours (2×10^5 excitation cycles). The operation of the magnets was also stable at significant deviations of cooling parameters from nominal ones. The pressure difference between the supply and return headers was decreased to 6 kPa. In this case the superheated vapour, having a temperature from 5.1 K for the magnet with the least hydraulic resistance to 7.8 K for the magnet with the largest hydraulic resistance of the cooling channels, went out of the channels for cooling the yoke.

The first quadrant of the Nuclotron was installed in the accelerator tunnel in February, 1992, and its test commissioning was performed. It took about 84 hours to cool down 28 dipoles and 11 quadrupoles to LHe temperatures. The cooldown was performed at a mean helium flow rate of 0.34 g/s through each magnet. Cooling of the magnets was stable. The pressure in the vacuum chamber of the accelerator was less than 1×10^{-7} Pa. The injection of a beam of polarized deuterons with an energy of 5 MeV/nucl. was performed at an intensity of 2×10^9 part./pulse, and the beam was transported through 1/4 of the ring.

The Nuclotron ring assembling in the tunnel was finished on January 13, 1993, and the first run of cooling and operation with a beam was carried out on March 17-26. Both half-rings of the Nuclotron with a total cold mass of 80 tons were cooled down simultaneously. The cooling down was performed at a mean helium flow rate of 0.16 g/s through each magnet. The cooldown time of the left and right half-rings was 103 and 110 hours, respectively (see Fig.5). All systems of the accelerator were tested, and the first turns of the deuteron beam in the ring were obtained for an injection energy of 5 MeV per nucleon. The pressure in the beam pipe was better than 2×10^{-7} Pa. The system of 26 oil diffusion vacuum pumps, having a capacity of 0.5 m^3/s each and aimed to control helium, nitrogen, and air leakages, was unnecessary and switched off. The vacuum in the insulation volume was kept no worse than 2×10^{-3} Pa only by two 2.5 m^3/s booster pumps. The flow rate of liquid nitrogen for cooling the shields after cooling down was equal to 0.186 kg/s. The cooldown times were 61 and 64 hours for the nitrogen shields of the left and right half-rings, respectively.

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Балдин А.М. и др. E9-93-273
Криогенная система нуклотрона —
нового сверхпроводящего ускорителя

Сверхпроводящий ускоритель релятивистских тяжелых ионов успешно прошел испытания в марте в Дубне. Была получена циркуляция пучка дейтронов. Полная охлаждаемая масса составила 80 тонн. Магнитная система с «холодным» железным ярмом и сверхпроводящими трубчатыми обмотками охлаждалась потоком двухфазного гелия. Все 160 магнитов запитаны параллельно от вводных и выводных гелиепроводов длиной около 250 метров. Система криогенного обеспечения состоит из трех ожижителей гелия полной мощностью 4,8 кВт при 4,5 К. Представлены результаты испытания криогенной системы.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

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Baldin A.M. et al. E9-93-273
Cryogenic System of the Nuclotron —
a New Superconducting Synchrotron

The superconducting relativistic heavy ion accelerator was commissioned the last week of March in Dubna, and the first deuteron beam was circulated in the ring. The total cold mass of the magnetic system is about 80 tons. The magnet with a «cold» iron yoke and a hollow superconductor winding is refrigerated by a two-phase helium flow. All 160 magnets are connected in parallel with supply and return helium headers about 250 meters long. The cryogenic supply system is based on three helium refrigerators with a total capacity of 4.8 kW at 4.5 K. The results on the commissioning of the cryogenic system are presented.

The investigation has been performed at the Laboratory of High Energies, JINR.

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