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**CRYOGENIC SYSTEM OF THE PROTOTYPE
OF THE SUPERCONDUCTING MAGNET
FOR DC-1**

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Development and construction of the superconducting magnet for the deuteron cyclotron DC-1 (SCM DC-1) is the first stage in implementation of the project of the deuteron cyclotron facility of the energy up to 2000 MeV ^{/1/}. The cryogenic system (CS) is designed for cooling, cryostatting and warming the superconducting magnetic system of the SCM. Earlier the results of analysis of different CS designed for the same purposes were published ^{/2/}.

This paper deals with the results of development of the chosen CS with a satellite refrigerator, which is being constructed in the Joint Institute for Nuclear Research. Systems of this type have been successfully operating in recent years, and new ones are being designed ^{/3-8/}. Their main advantage against other circulation CS is high reliability, which is of special importance for accelerator operation. Besides, they are simple in operating, can be automated and allow easy switching to different modes.

Fig. 1 shows a lay-out of the CS. It consists of the following main parts: a commercially produced liquefying refrigerator with the output 40 l/hour of liquid helium, or 150 W at 4.5 K, - LR (1), a satellite refrigerator (4), a cryostat of the SCM (5), two 500-litre vessels for liquid helium - VLH (2,3), nitrogen tanks of capacity 0.5 m³, 5 m³, 8 m³ - VLN (13, 14, 15 respectively), a 1200-m³ gas storage tank for helium (20), a system to monitor parameters (21), a block of preliminary cooling (22). The LR has been modified for operation as a part of the CS: one more system of helium purification has been added to ensure continuous operation during preparations and carrying out SCM experiments, a possibility to drain liquid helium and supply it from the LR collector through one of refrigerator inputs in the cold block of the satellite is ensured, this allows alternately draining helium in the cryostat of the satellite and in VLH, since the output of the LR in the liquefying mode exceeds the amount of liquid helium consumed by the satellite. The satellite refrigerator comprises a compressor two helium purification systems, a cold block and a vessel for liquid helium. The LR and the satellite have piston compressors of the same type with the output pressure

Fig. 1.

3 MPa and a capacity $360 \text{ m}^3/\text{hour}$. They are combined into a compressor station which also includes a reserve compressor. The helium purification system of the satellite is of the same type as that of the LR. The superconducting coil is cooled by two-phase helium supplied to the SCM cryostat from the cold block of the satellite. The flow of two-phase helium is divided into two parts in the SCM cryostat. One flow is throttled and sent to the heat exchanger of overcooling and then to current inputs to cool them. The other flow passes through the heat exchanger of overcooling, then it is divided and sent to cooling channels of the superconducting coil and current reconnection units of the superconductor. This type of helium distribution ensures a possibility of a wide and somewhat independent control over mass consumption of helium in cryostated elements of the SCM with different heat load. Another advantage is lower mass consumption of helium or smaller mass content of steam in the helium flow at the output of cooling channels owing to helium overcooling at the input. This leads

to reduction of hydraulic losses in cooling channels of the superconducting coil and current reconnection units, and to higher hydrodynamic stability of the two-phase helium flow; besides, uneven distribution of the steam phase over channels is excluded at the division of the helium flow. One long channel has been chosen on the basis of calculations performed to choose an optimum geometry of cooling channels of the superconducting coil; it allows avoiding difficulties at the distribution of helium over parallel channels and increasing thermal hydraulic stability of the system ^{/10/}. The channel is a copper tube of inner diameter 10 mm placed in such a way that it shields the superconducting coil against external heat input, ensures even cooling of the mass to helium temperature and small values of temperature gradients in sections of the superconducting coil. The total length of cooling channels is about 150 m. The cold block of the satellite is a cryostat 700 mm in diameter with a heat exchanger, overcooler, accessories, parameter-measuring devices, supply of liquid helium (200 l). A throttle type of the satellite refrigerator has been chosen as the most reliable and simplest one. It has one throttle valve. Intermediate throttling must, of course, reduce consumption of liquid helium and compressed gas, but the present accuracy of calculations of satellite heat exchangers is quite low ^{/6/}; as a result, the intermediate throttle valve is connected at a non-calculated temperature level, which reduces the thermodynamic efficiency of the system. An operating satellite must take off a heat load of 20-30 W from the cryostated object and cryogenic helium lines between the SCM cryostat and the cold block of the satellite. When running in the forced mode, it must ensure cold production of 100 W. The choice of the optimum pressure in front of the throttle valve is based on minimisation of the additional supply of liquid helium to the cryostat of the satellite. According to ^{/9/}, the pressure is 2 MPa. The pressure in the cryostat of the cold block of the satellite is 0.12 MPa, that in the line of gas storage tanks - 0.103 MPa. There is a filter in the liquid helium supply line; it captures solid particles. In case the filter is blocked up during the experiment, a relief valve will allow the helium flow through. According to ^{/9/} and with allowance for heat exchange in the overcooling heat exchanger and for hydraulic resistance of the coil cooling channels, a 20-W heat load can be taken off without overcooling helium at the input of channels of the superconducting coil and current reconnection units of the superconductor, the high-pressure helium rate through the heat exchanger of the satellite 2.1 g/s, the rate of liquid helium evaporated in the cryostat being 0.31 g/s, the rate of gaseous helium to cool current inputs being

0.18 g/s. Heat input of 30 W at higher heat inputs (e.g. after long operation when the degree of blackness of surfaces affected by low temperature increases owing to residual gas and oil vapour condensation from isolating vacuum) requires the following helium rates under the same conditions: helium through the heat exchanger of the satellite - 3.1 g/s, liquid helium - 0.58 g/s, for current inputs - 0.38 g/s. If one needs overcooled helium to be supplied to the inputs of channels of the superconducting coil and current reconnection units of the superconductor (in order to reduce helium rate or vapour content in the helium flow at the outputs of the channels), one has to increase the helium rate through current inputs and, consequently, additional supply of liquid helium. If the heat load is 20 W, the helium rate through current inputs is 0.33 g/s and the liquid helium rate is 0.46 g/s; for 30 W the rates are 0.58 g/s and 0.78 g/s respectively. The evaporation rate of liquid helium due to heat supply to the cryostat of the cold block of the satellite is 0.14 g/s. The liquid helium production rate of the LR is 1.32 g/s, which is more than enough to compensate evaporation. Additional supply of liquid helium comes to the satellite from the VLH (the vapourability is 0.007 g/s) or directly from the LR operating in the liquefying mode. In the former case liquid helium from the LR is poured out into the VLH which is then carried to the cold block of the satellite and is connected to it. In the latter case liquid helium directly flows from the cold block of the LR to the cryostat of the satellite, and both VLH can be filled up by means of a more powerful liquefier. The SCM can be cryostated by the LR alone, when it works in the combined liquefying and refrigerating mode. In this case helium is supplied from the cold block of the LR directly to the cryostat of the SCM. The mass of the structures to be cooled to helium temperatures is about 7 tonnes. The SCM will be cooled in three stages. At first it is cooled to 80 K by means of the preliminary cooling block which is a cryostat containing a heat exchanger of preliminary cooling and a coil pipe in the liquid nitrogen bath designed for cooling high pressure helium coming from the satellite compressor. Then it is cooled to 10 K by means of the LR operating in the combined mode. At the last stage it is cooled by the satellite operating in the forced mode at the expense of liquid helium stored in VLH in advance or due to additional supply of liquid helium directly from the cold block of the LR. The total cooling time will be about 7.5 days. The CS is warmed to the environment temperature by circulating helium warmed by special heaters in high pressure pipelines. The main cold parts of the CS- the cold block of the LR, the cold block of the satellite,

the superconducting coil of the SCM - can be warmed element by element. Isolating vacuum is produced in the cryostat of the SCM by the stationary connected high-vacuum oil-vapour pumps (the main pump and the reserve one). The evacuation rate of each pump is 840 l/sec in the pressure range from $1.3 \cdot 10^{-1}$ Pa to $1.3 \cdot 10^{-3}$ Pa, the maximum residual pressure being $6.6 \cdot 10^{-5}$ Pa. The pump is switched off after the preliminary evacuation. A high-vacuum pump is used to avoid possible helium leakage and to minimise soiling of the reflecting surfaces with frozen residual gases. To control the CS and various investigations, the CS is equipped with all necessary transducers and sensors monitoring pressure, temperature, mechanical stresses, level, consumption.

Fig. 2.

The lay-out of the CS equipment is shown in Fig. 2. The experimental hall houses the SCM (5) and its auxiliary systems (not shown in the Fig.), cold blocks and helium purification systems of the satellite (4, 11, 12) and of the LR (1, 9, 10), vessels for liquid helium VLH (2, 3), a 500-litre vessel for liquid nitrogen VLN (13), a parameter-measuring system (21), a block of preliminary cooling (22). The machine room houses the satellite and LR compressors with the oil purification and control systems (7, 6), two gas holders of

capacity 6 m^3 each (16, 17), and a compressor for pumping helium into the gas storage tank (18). In other halls there are a reserve compressor (8) and an additional compressor for helium (19). The helium storage tank (20) and VLN of capacity 5 m^3 and 8 m^3 are outdoors near the experimental hall. Now the LR is installed and is able to work; calculations and designing have been completed; the cryostat chambers and elements of the superconducting coil of the magnet are being made.

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Криообеспечение прототипа сверхпроводящего
магнита ДЦ-1

Изложены результаты разработки системы криогенного обеспечения (СКО) прототипа магнита дейтронного циклотрона со сверхпроводящей обмоткой. Выбранная СКО состоит из ожижителя-рефрижератора с производительностью 40 л/час жидкого гелия или 150 Вт снимаемой мощности на температурном уровне 4,5 К, сателлитного рефрижератора, криостата сверхпроводящей обмотки магнита и емкостей для хранения жидких азота и гелия. В настоящее время смонтировано вспомогательное оборудование и изготавливаются основные части магнита.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.
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Cryogenic System of the Prototype
of the Superconducting Magnet for DC-1

The results achieved in designing a cryogenic system for the superconducting magnet of the deuteron cyclotron BC-1 are described. The cryogenic system consists of a liquefier-refrigerator with the output 40 l/hour, or 150 W of power taken off at 4.5 K, a satellite cryostat, a cryostat of the superconducting magnet coil and vessels for liquid nitrogen and helium. Now auxiliary equipment is being mounted, and the main parts of the magnet are being manufactured.

The investigation has been performed at the Laboratory of Nuclear Physics, JINR.

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