DESIGN AND TESTS OF A SUPERCONDUCTING MAGNET WITH A CRYOCOOLER FOR THE ION SOURCE DECRIS-SC

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Abstract

A superconducting magnet system (SMS) for the multicharged ion source DECRIS-SC was designed and manufactured at the Joint Institute for Nuclear Research. Successful tests of the SMS were conducted in late 2003 – early 2004. The peculiarities of this system are stipulated by the use of a cryocooler 1 W in power for the cryostabilization of the magnet, and also by a special configuration of the magnetic field demanded for the source of ions.

Four coils ensure induction of a magnetic field on the axes of the source of up to 3T (the mirror ratio of ~ 6) which considerably extends possibilities of the ion source from the point of view of producing intense highly charged ion beams. The problem of compensating large forces of interaction between the coils and surrounding iron yoke in this magnet has been successfully solved, and a reliable suspension of the magnet in a cryostat realized. For compounding of the windings working in vacuum at indirect cryostabilization prepreg is used. There has been applied a new technology of the superconducting magnet protection with the help of sectionalization of the windings, using passive elements of the protection based on "cold" diodes and resistances, as well as a new technology of active protection with normal zone detectors and heaters.

INTRODUCTION

A new “liquid He-free” superconducting Electron Cyclotron Resonance Ion Source DECRIS-SC [1] to be used as an injector for the IC-100 compact cyclotron has been designed and manufactured at the FLNR and LHE (JINR).

IC-100 is a compact cyclotron with a pole diameter of 100 cm. It is intended for the research in solid state physics, materials science and new industrial technologies. After modernization the cyclotron will be able to accelerate such ions as Kr^{15+}, Xe^{22+} up to energies of about 1 MeV/n and in the future - Kr^{20+} and Xe^{30+} ions - up to 2 MeV/n [2].

The high enough requirements on charge and intensity of accelerated beams (Kr^{15+}, Xe^{22+}) demand the necessity of using the ion source with the large mirror ratio and a strong magnetic field. From our point of view, the use of superconducting coils is optimal in the creation of demanded distribution of the axial magnetic field at rather low power consumption.

MAGNET CONSTRUCTION

The axial magnetic field is created by a set of four solenoid coils. At the nominal excitation, this magnetic system allows one to reach peak mirror fields of 3 T in the injection and those of 2 T in the extraction regions on the axis.

Figure 1 shows the electrical coil connection and axial magnetic field distribution with a nominal current of 60 A. In this case external coils are connected in series and the central one is working with a reverse current.

Parameters of the coils are presented in Table 1.

![Fig. 1: The axial magnetic field distribution and electrical coil connection.](image-url)
steel, which is free-floating fixed inside a vacuum casing (7) with the help of glass textolite supports (6).

<table>
<thead>
<tr>
<th>Name</th>
<th>Unit measures</th>
<th>Value</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of a solenoid</td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Inner diameter of the winding</td>
<td>mm</td>
<td>281</td>
<td>280</td>
<td>280</td>
<td>281</td>
</tr>
<tr>
<td>Outer diameter of the winding</td>
<td>mm</td>
<td>397</td>
<td>396</td>
<td>396</td>
<td>350</td>
</tr>
<tr>
<td>Length of the winding</td>
<td>mm</td>
<td>80</td>
<td>81</td>
<td>50</td>
<td>80</td>
</tr>
<tr>
<td>Maximal operating current</td>
<td>A</td>
<td>60</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of Ampere-turns</td>
<td>MA</td>
<td>0.549</td>
<td>0.562</td>
<td>0.345</td>
<td>0.318</td>
</tr>
<tr>
<td>Current density in the winding</td>
<td>A/mm²</td>
<td>118.4</td>
<td>119.6</td>
<td>118.8</td>
<td>115.1</td>
</tr>
<tr>
<td>Maximal induction on the axes</td>
<td>T</td>
<td>2.06</td>
<td>3.0</td>
<td>2.8</td>
<td>0.56</td>
</tr>
<tr>
<td>Maximal induction in the winding</td>
<td>T</td>
<td>4.0</td>
<td>5.0</td>
<td>4.6</td>
<td>2.6</td>
</tr>
<tr>
<td>Inductance</td>
<td>H</td>
<td>33.6</td>
<td>33.6</td>
<td>12.2</td>
<td>11.4</td>
</tr>
<tr>
<td>Stored energy</td>
<td>kJ</td>
<td>60.5</td>
<td>60.5</td>
<td>22</td>
<td>20.5</td>
</tr>
<tr>
<td>Mass at 4.5 K</td>
<td>kg</td>
<td>~280</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compound material</td>
<td></td>
<td>Prepreg</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The framework and the windings are connected with the second stage of the cryocooler by a high-purity aluminum tape. The copper plates are screwed to the framework. "Cold" diodes (12) and damp ohmic resistances (13) are located on the plates. The copper screen is fastened to supports (6). Six HTSC current leads (9) are posed around the cryocooler head. The pumping of the vacuum casing is performed by forevacuum and turbomolecular pumps.

**ELECTRICAL POWER SUPPLY AND SAFETY SYSTEM**

A block diagram of the coil power supply and safety system is shown in Fig.3.

The safety system contains three sensor units of transition in the normal state, "cold" diodes, dumping ohmic resistors and eight resistive heaters, installed at the windings. The detectors have a bridge scheme of measuring the voltage arising in the normal zone of the winding wire or in the HTS insertion of current lead at their transition in the normal state or breaking. The obtained signal passes an amplitude-time analyzer, an

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Fig. 2: Design of the magnet (longitudinal section): 1 - superconducting solenoids; 2 - framework of solenoids; 3 - heat screen; 4 - multilayer screen-vacuum isolation; 6 - support of cold masses; 7 - vacuum casing; 8 - magnetic shield; 9 - current lead; 10 - cryocooler; 11 - heat pipes; 12 - "cold" diodes; 13 - damp resistors; 15 - nitrogen heat interchanger.

The casing (7) is surrounded with an iron yoke (8). The framework with windings is protected by a reflective aluminium shield (15) and copper screen (4) which is cooled by the first stage of the cryocooler (10). The copper screen is covered with a multilayer screen-vacuum isolation.

Fig. 3: An electrical circuit of the power supply and protection of solenoids: 1, 2, 3, 4 – windings; 5, 6, 7 - current sources of the windings; 8 – HTSC current lead; H1, H2 – heaters of the windings; CD - "cold" diodes; R - damp resistors.
amplifier and turns to switch off the power supply and to switch on a supply unit of the heaters. The "cold" diode opens at a voltage of ~ 7 V and closes the circuit of the winding sections through a 1 Ohm resistor. The aim protection consists in preventing excessive local heats of the windings and temperature strains, and also in preventing breakdown of electrical insulation. Such protection also allows one to reduce the probability of damage of HTS current lead insertions in accidents. The simultaneous heating of all the windings allows one to avoid the arising of excessive attractive forces between the framework of windings and the magnetic yoke. Such forces can reach a magnitude of more than a ton and can result in breaking the supports for "cold" masses.

The control of electric power supplies for the windings as well as monitoring the status of the whole superconducting system is carried out by a PC. The charging and discharging of current in the windings are carried out at a speed from 0.005 A/s to 0.015 A/s. In the cold zone of the magnet 16 thermometers are located. TVO carbon resistors are used as thermometers [3]. A scheme of the thermometer location and the readings in one of magnet test runs is shown in Fig. 4.

![Fig. 4: A layout of thermometers and their readings in one of sessions of the magnet trials at a current of 45 A:](image)

A cooling-down period of the magnet was approximately 120 hours (Fig.5).

![Fig.5: One of cooling-down periods of the magnet. A layout of T1-T6 is shown in Fig 4.](image)

A temperature rise of 0.1-0.2 K was observed during charging a current in the windings. Any aberrations from the normal operation were detected which allows us to conclude that conditions for the operation of this magnet system were good.

**RESULTS OF THE TEST**

The temperatures T1-T6 (cryocooler’s second stage, four coils and the framework) do not exceed 4 K (see Fig. 4) which demonstrates availability of some reserve capacity of the cryocooler’s second level. It is determined experimentally that this reserve capacity is about 0.5 W. The windings 3 and 4 are tested by a current of 60 A. The current of 45 A was charged in all the windings simultaneously after adjusting the safety system.

![Graph](image)

**CONCLUSION**

1. Joint influxes of heat are close to the estimated values. The total influx of heat is close to 0.5 W, thus the temperatures of windings and current leads are optimal.

2. The task of floppy thermal linkage between magnetic elements and the second level of the cryocooler using high-purity aluminum tapes is fulfilled. Thermal contacts and heat wires have sufficient thermal conduction, however, it is possible to improve them in the future.

3. The task of compensating the forces in the windings is successfully fulfilled, and a reliable support of the magnet system is realized.

4. Passive protection (compartmentation, diodes, resistors) and active protection using sensor units of the normal zone and heaters of the winding are realized.

**REFERENCES**

[1] A.A.Efremov et al. in Proc. of the 15th Intern. Workshop on ECR ion sources
