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THERMODYNAMIC CHARACTERISTICS OF THE SUPERCONDUCTING QUADRUPOLE MAGNETS OF THE NICA BOOSTER SYNCHROTRON

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Abstract

The Booster synchrotron of the NICA accelerator complex in Dubna is designed for acceleration of heavy ions before injection into the Nuclotron. The first run of the Booster synchrotron was carried out in the end of 2020. This work presents calculated and experimental data of static heat leak and dynamic heat releases for quadrupole magnets of the Booster synchrotron with different configuration of the corrector magnets. Obtained results will be taken into account for development of new superconducting magnets and cryogenic installations.

INTRODUCTION

The magnetic system of the booster synchrotron includes 40 dipole magnets, 16 doublets of quadrupole magnets with dipole corrector magnet (DCM) and 8 doublets of quadrupole magnets with multipole corrector magnet (MCM), a reference dipole and a reference doublet of quadrupole magnets.

Correction magnets are designed to correct the orbit and focus the beam. DCM consists of two dipole coils: horizontal and vertical. MCM has 4 coils: sextupole normal, octupole normal, sextupole skew and quadrupole skew.

The magnets produced at JINR are subjected to cryogenic tests, one of the main stages of which is the measurement of static heat leak and dynamic heat releases.

STATIC HEAT LEAK

The calculated total static heat input to the SC magnet is determined as the sum of the heat input by thermal radiation, thermal conductivity of residual gases and along thermal bridges.

Thermal Radiation

For the considered SC magnets, the heat leak includes radiation from the inner surface of the thermal shield at 80 K to the magnet yoke at 4.6 K and the vacuum shell at 300 K to the magnet yoke through the technological holes in the thermal shield for the magnet suspension system and the vacuum system. The heat transmitted by thermal radiation is calculated using the Stefan-Boltzmann Eq. (1) [1]:

$$Q_l = \varepsilon_n C(T_2^4 - T_1^4)A, \tag{1}$$

where ε_n – emissivity; C – Stefan-Boltzmann constant,W/m^{2}K; T_2, T_1 – temperature of warm and cold surfaces; A– surface area of the thermal radiation, m^2.

Heat Leak by Thermal Conductivity of Residual Gases

The heat leak by thermal conductivity of residual gases for vessels can be calculated using the Eq. (2) [1]:

$$Q_g = 1.82 \cdot 10^5 A_1 \frac{\alpha_1\alpha_2}{\alpha_2+\frac{A_1}{A_2}(1-\alpha_2)\alpha_1}\frac{k+1}{k-1}\frac{p(T_2-T_1)}{\sqrt{MT}}, \tag{2}$$

where A_1, A_2– surface area of the inner and outer vessel, m^2; α_1, α_2– accommodation coefficient for the first and second gas in the vessel; k – adiabatic exponent; p – vessel pressure, Pa; M – molecular weight of gas mixture; T- pressure gauge temperature, K. The mixture of nitrogen and helium is taken as the residual gas in the insulating volume of the vacuum shell.

The calculated value of the heat input by the thermal conductivity of the residual gases is 0.02 W.

Heat Along the Thermal Bridges

Static heat leak through thermal bridges is determined from the heat transfer equation:

$$Q_t = \lambda\Delta T\frac{S}{l}, \tag{3}$$

where λ – thermal conductivity coefficient, W m^{-1} K^{-1}; S – thermal bridge cross-sectional area, m^2; ΔT – temperature difference, K; l – thermal bridge length, m.

The SC magnets of the NICA accelerator complex are fixed in the cryostat using eight rods. After the magnet cools down to operating temperature, a large temperature gradient from 293 K to 4.5 K appears in the rods. Then the calculated static heat leak to the magnet by eight rods is 2.9 W. To reduce this value, thermal bridge to the thermal shield is provided in the design of the SC magnet (see Fig. 1), due to which the temperature gradient in the rods decreases from 82 K to 4.5 K. This reduces static heat leak to the SC magnet from 2.9 to 1 W.

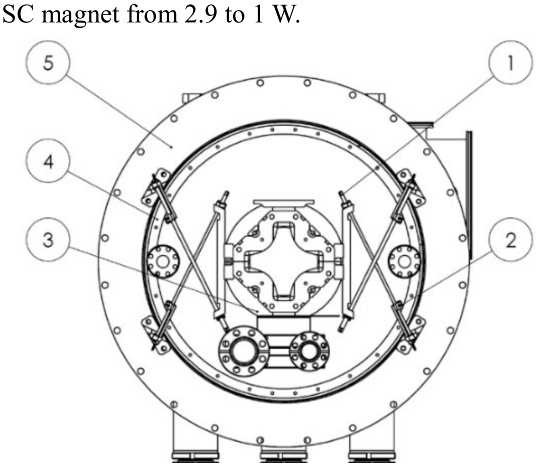

Figure 1: Quadrupole magnet of the booster synchrotron in the cryostat: 1 – rod; 2 – thermal bridge to the thermal shield; 3 – yoke of the SC magnet (4.5 K); 4 – thermal shield (82 K); 5 – vacuum chamber (293 K).

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There are copper current leads in quadrupole magnets with DCM and MCM, which are cooled by means of thermal contact with thermal shield. They bring an additional heat leak to the magnet from four DCM current leads of 0.35 W and from eight MCM current leads of 2 W.

The magnetic field in the magnets is measured using a magnetic measurement probe located in the magnet aperture. At helium temperature of the magnet, the measured value of the probe temperature is about 100 K. The calculated value of the heat leak from the magnetic measurement probe to the magnet is about 1.09 W.

The results of a comparative analysis of the calculated and average experimental values of the static heat leak for quadrupole magnets are shown in Fig. 2.

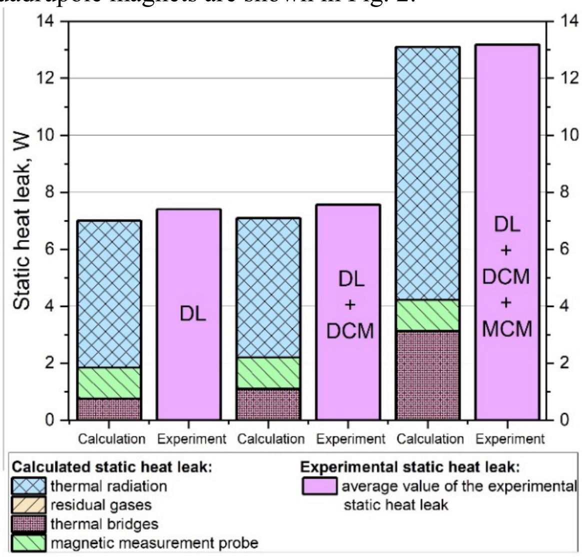

Figure 2: Comparison of the calculated and experimental value of static heat leak for different configurations of the Booster quadrupole magnets.

Figure 2 shows that the calculated and average experimental values of the static heat leak have a slight discrepancy, for quadrupole magnets with DCM – 6 %, with DCM and MCM < 1 %. The heat leak to magnets with and without DCM do not differ much from each other, which is explained by the fact that the DCM is located inside the yoke of quadrupole magnet. Thermal radiation for these configurations of the quadrupole magnet is the same. Therefore, only the DCM current leads determine the difference in static heat leaks.

DYNAMIC HEAT RELEASES

Dynamic heat releases occur in the SC coil and yoke of the magnet. By calculating the heat releases in the SC coil and measuring the total heat releases in the magnet, you can determine the amount of heat releases in the yoke. The Nuclotron type Nb-Ti hollow composite SC cable is used in the coil of the NICA booster synchrotron [2].

The main losses in the SC coil are hysteresis and eddy current losses. Hysteresis losses – magnetization reversal losses of a superconductor. It is possible to reduce the hysteresis losses by decreasing the diameter of the SC filaments. Eddy current losses – ohmic losses that appear as a result of eddy currents flowing in the stabilizing matrix inside the strand. They can be reduced by decreasing the pitch of twisting the SC filaments in the wire and by increasing the ohmic resistance of the matrix material.

The total hysteresis losses in the SC coil can be calculated for one cycle by the relation (4) [3]:

$$Q_G = \frac{8}{3\pi} J_c d_a B_m \lambda V, \tag{4}$$

where Q_G- hysteresis losses, J/cycle; J_c– critical current density, $\mathrm{A/m^2}$; d_a– SC filament diameter, m; B_m – magnetic field amplitude, T; λ – volume fraction of superconducting filaments in a wire; V – wire volume, $\mathrm{m^3}$. For the NICA accelerator complex $B_m = 1.8$ T, the volume fraction of superconducting filaments in the SC strand of λ =0.42. Figure 3 shows the operating cycle of the NICA booster synchrotron. The calculated value of the hysteresis losses for the cycle in Fig. 3 is 1.105 W.

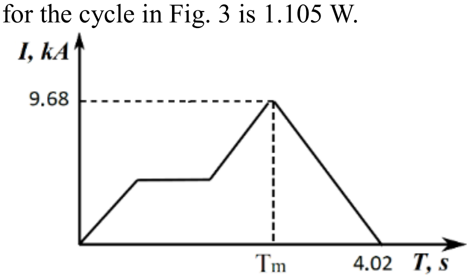

Figure 3: Operating cycle of the Booster synchrotron.

Relation (5) determines eddy current losses [3]:

$$Q_v = \frac{B_m^2}{6\mu_0} \frac{8\tau}{T_m} \lambda V, \tag{5}$$

where Q_v– eddy current losses, J/cycle; τ – time constant of stranded multifilament wire, s (during this time, the screening currents decay after the termination of the change in the external magnetic field); μ_0 – magnetic permeability of vacuum, N/A^2; T_m – field rise time, s. The calculated value of the eddy current losses for the cycle in Fig. 3 is 0.825 W.

The total value of the calculated heat releases in the SC coil is about 1.93 W.

DCM and MCM have current leads on 40 A for DCM and on 80 A for MCM. They are the main source of the dynamic heat releases for DCM and MCM. Detailed calculation and description of their production technology presented in the work [4]. The average experimental value of the dynamic heat releases for the DCM current leads is 0.42 W, and for the MCM is 1.61 W. Figure 4 shows obtained values of heat releases for the quadrupole magnets without DCM and MCM.

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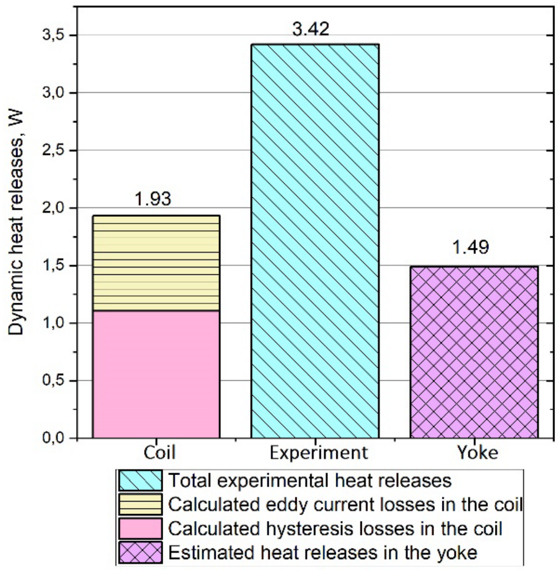

Figure 4: Dynamic heat release of the quadrupole magnets of the Booster synchrotron without DCM and MCM.

From the analysis of the data in Fig. 4 it follows that the yoke accounts for about 44 % of the total dynamic heat releases. It is also seen that hysteresis losses 32 % of the total heat release, prevail over eddy current losses, which equals 24 %.

EXPERIMENT

During cryogenic tests, using the calorimetric method (for more details in [5]), the experimental values of static heat leak and dynamic heat releases in SC magnets are determined.

The static heat leak and dynamic heat releases in the operating cycle of the booster synchrotron for magnets with DCM obtained by the calorimetric method are shown in Fig. 5.

Figure 5 shows that the experimental data have a small scatter, for static heat leak average value equals to 0.6 W and for dynamic heat releases 0.2 W. For static heat leak, this is mainly due to the duration of cooling down and the error of the calorimetric method of about 6 %. Low current leads make the main contribution to the obtained experimental data of dynamic heat releases. Because their technical characteristics have changed.

CONCLUSION

The experimental and calculated values of static heat leak and dynamic heat releases for quadrupole magnets of the Booster synchrotron are presented. The discrepancy between the calculated and experimental mean values for quadrupole magnets with DCM equals to 6 %, with DCM and with MCM <1 %. In addition, based on the analysis of the obtained data, it follows that about 44 % of the released heat falls on the yoke of the SC magnet.

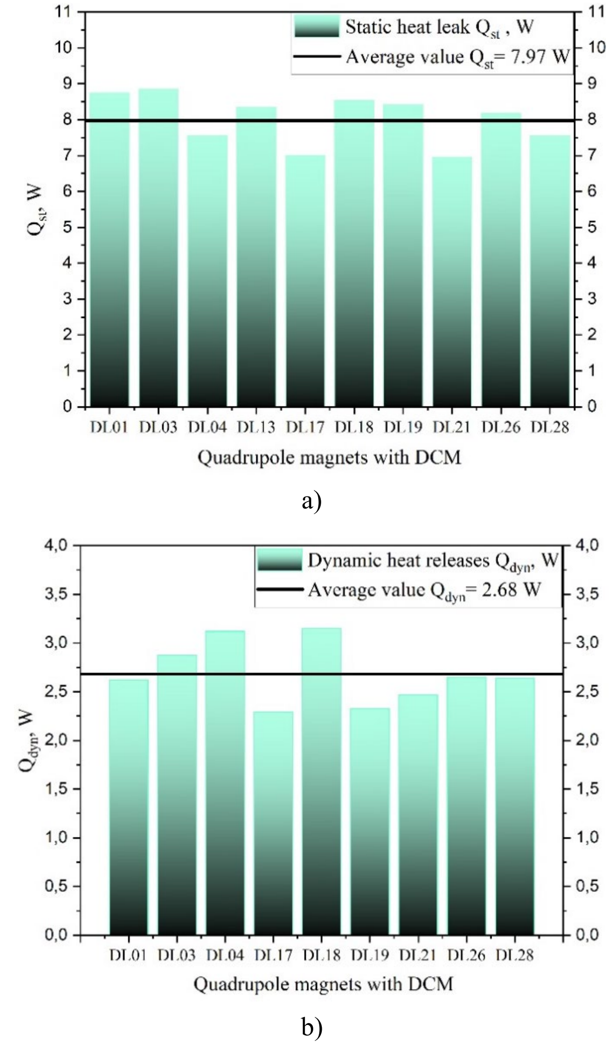

Figure 5: a) Experimental values of heat leak of quadrupole magnets of the Booster synchrotron with DCM; b) Experimental values of dynamic heat releases of quadrupole magnets of the Booster synchrotron with DCM.

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