STABILITY OF FAST-CYCLING DIPOLE FOR THE SIS300 RING

V. Zubko, L.Tkachenko, I. Bogdanov, S. Kozub, P, Shcherbakov, S. Zintchenko,
Institute for High Energy Physics (IHEP), Protvino, Moscow region, Russia, 142281
M. Kauschke, G. Moritz, Gesellschaft für Schwerionenforschung (GSI), Darmstadt, Germany

INTRODUCTION

The superconducting (SC) dipole with 100-mm aperture, 6-T magnetic field amplitude and 1-T/s field ramp rate for the SIS300 accelerator [1], now under development at the GSI, Darmstadt. A higher enough field ramp rate causes large AC losses in the magnet, to ensure stable operating mode it is necessary to provide enough temperature margin. The temperature margin of SC magnet is the difference between the critical and operating temperatures under the worst conditions of the applied magnetic field, temperature, and the transport current. Simultaneous solutions of the non-stationary equations of heat balance both in the coil and in a single-phase helium flow and numerical calculations of heat losses in the SC coil, which cause a coil heating, allow one to simulate transient thermal processes in the magnet during the SIS300 operating cycle. Analyses of temperature operating conditions were made with help of computer simulation for three designs [2] of the SC dipole for the SIS300 ring. These designs have been considered and studied in order to choose optimal design, satisfying both field quality and minimal heat losses in the magnet. Possible ways to increase the temperature margin are discussed.

DIPOLE COOLING

Fig.1 shows the layout of the dipole cooling in the cross section of the SC dipole.

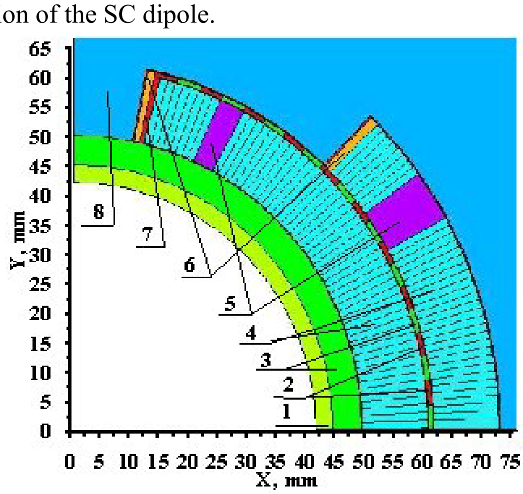

Figure 1. Cooling scheme of the SC dipole in the cross section: 1 - beam pipe, 2 – glass-cloth laminate spacers of helium channels, 3 - helium channels, 4 - coil, 5 - inter-turn spacers, 6 – shims, 7 – spacers for helium channels, 8 – collars.

The coil is cooled by single-phase helium flowing through the channels (3). The circular channel is formed between the beam pipe (1) and the inner layer of the coil. There are also channels between the coil layers, which are formed with the help of 0.5-mm thick glass-cloth laminate and 4-mm wide spacers, located at distance of 4 mm from each other. The channels and spacers are arranged at the angle of 45^o in the involute (plane $R\Theta$-Z), so they have a shape of helical line on the inner layer (so-called "herring bone"). These helical lines are located in the opposite direction in the first - second quadrants and in the third - fourth quadrants. The spacer in the inner layer (7) has 0.5×2 mm^2 grooves, by which the circular and interlayer channels are connected. These grooves allow one to improve cooling in the outer layer.

COMPUTATIONAL MODEL

A computer code QUEN3 has been developed for analysis of transient thermal processes in the most critical magnet (the last dipole of the string).

The code is based on simultaneous numerical solution:

- of the equations of thermal conductivity for beam tube, coil, inter-turn spacers and collars:

$$c\rho\frac{\partial T}{\partial t} = div(\lambda\vec{\nabla}T) + Q\,, \qquad (1)$$

where $c = c(T, B)$ is the specific heat capacity, $\rho = \rho(T)$ is the specific density, $\lambda = \lambda(T,B)$ is the thermal conductivity, $Q = Q(T,B)$ is the density of the heat generation, determined by AC losses in the coil and in other materials of the dipole;

- of the energy equation for each helium flow:

$$(c_p G)\left(\frac{1}{w}\frac{\partial U}{\partial \tau} + \frac{\partial U}{\partial z}\right) = (\alpha P)(T - U), \qquad (2)$$

where U is temperature of helium flow, z is the coordinate along helium channel, c_p is heat capacity of helium, G and w are flow rate and a speed of the helium, (αP) characterizes a convective heat transfer (forced-convection) from the coil to the helium through their common boundary.

These equations are solved with the initial conditions:

$$T\,(r)\Big|_{t=0} = T_0\,, \qquad U_j\Big|_{z=0} = U_{in}\,. \qquad (3)$$

Here T_0 is the initial distribution of temperature in the dipole, U_{in} is the inlet temperature of helium in the last dipole and interlayer channels. G and U_{in} were calculated in circular channel from a model, describing the string behavior as a quasi-stationary approximation [3], and in interlayer channels as published in [4].

Standard equations [5] are used for calculations of hysteresis and coupling losses in the coil. The network model [6], based on solving Faraday's and Kirchhoff's equations, is used for calculations of cable losses and corresponding inter-strand coupling currents. These equations are solved numerically in the developed code. Spatial distribution in the coil of magnetic flux density *B(r, t)* and of $B_r(r, t)$, $B_\theta(r, t)$ components are determined with the help of the code MULTIC [5].

AC LOSSES

Field cycle with B_{min} = 0.48 T, B_{max} = 6 T and dB/dt = 1 T/s, corresponding to trapezoid time cycle 5.52 – 11.00 – 5.52 - 0 s (ascent – plateau – descent – pause) will be considered further as a main one. The coils use SC strand of 0.65-mm diameter, 3.5-μm filaments and 4-mm twist pitch. Copper/SC ratio is 1.38 and critical current density is 2.7 kA/mm^2 (5 T, 4.2 K) [2]. The cable loss components are presented in [8]. Further all figures will be presented for the design II. The main specific results for other geometries will be listed in tables. The distributions of AC losses per cycle over turns in the inner layer are shown in Fig. 2 for the first quadrant. The turns are counted off from the median plane.

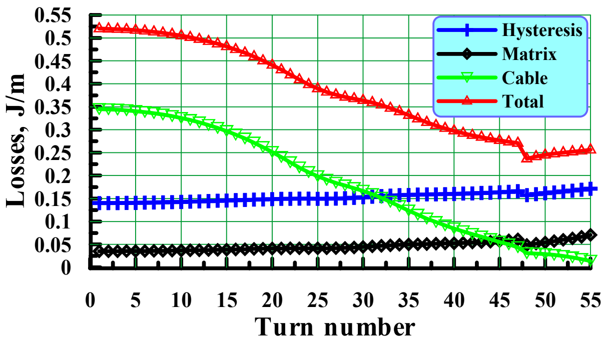

Figure 2. AC losses per cycle in turns of the inner layer (the first quadrant).

The detail distributions of AC power losses per cycle in the last turn of the inner layer are shown in Fig. 3. It is seen cable losses in the last turn are a negligible value.

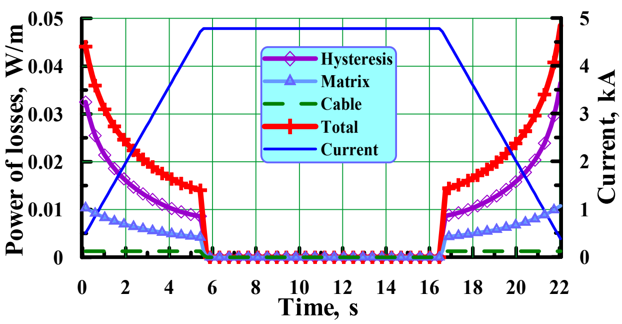

Figure 3. Power of losses in the last turn of the inner layer and operating current versus time of cycle.

Table 1 presents total components of AC losses per cycle in the coil for all designs.

Table 1. Components of AC losses per cycle in the coils.

Design	I	II	III
Hysteresis, J/m	52.4	48.2	42.1
Matrix, J/m	13.1	12.4	10.8
Cable, J/m	65.5	43.2	18.9
Total losses, J/m	131.0	103.8	71.8

CRITICAL TEMPERATURE AND TEMPERATURE MARGIN

The distribution of the critical temperature $T_C(B)$ at operating current in the coil is presented in Fig. 4. The last block of the inner layer is shown enlarged inside of the magnet aperture. The maximal field B_{max} and corresponding minimal critical temperature T_c in the central cross section of the magnet are found in the last turn of the inner layer of the coil (counting anticlockwise from the medium plane). The distributions of the critical temperature for other geometries are almost the same.

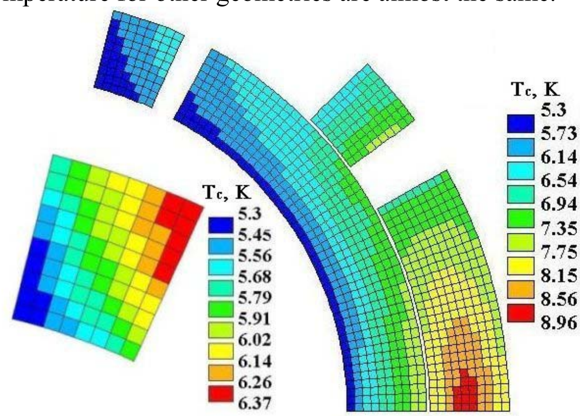

Figure 4. Distribution of the critical temperature in the coil for the design II of SC dipole.

The helium flow rates in circular channel and inlet temperature of helium in the last dipole of the string, determined by cryogenic conditions [3], are presented in Table 2. The inlet temperature in the first magnet of the string is 4.4 K.

Table 2. Helium flow rates in circular channel and inlet temperature in the last dipole of the string.

Design	I	II	III
Helium flow rate, g/s	47.0	40.7	34.3
U_{in} in the last dipole, K	4.66	4.63	4.60

The critical temperatures and AC losses are not homogenous over turns and their magnitudes vary in time during accelerator cycles. So it is necessary to determine the operating $T_o^k(t)$ and minimal critical $T_c^k(t)$ temperatures in each k-th turn of the inner and outer layers during accelerator cycles. At first it is necessary to determine the minimal difference between critical and operating temperatures for each turn: $\Delta T_{\min}^k = \min\left(T_o^k(t) - T_c^k(t)\right) = \min(\Delta T^k(t))$, k is the number of turn. The temperature margin of SC dipole is $\Delta T_m = \min\left(\Delta T_{\min}^k\right)$, *k = 1,…, N, N* is the number of turns.

The calculation of temperature distribution in the coil versus time has been made for sequence of operating cycles. Thick lines in Fig. 5 show the calculated change of temperature during several operating cycles in the last turn of the inner layer at the helium inlet (T_1) and outlet (T_2) in the last dipole of the string. Blue dashed line shows the temperature *T(He)* of outlet helium from the last dipole. The second right axis and thin blue line show the operating current in the coil. Fig. 5 shows that the thermal process in the coil stabilizes during two cycles. Fig. 5 also shows the operating temperature value for calculation of the minimal difference between critical and operating temperatures in the last turn.

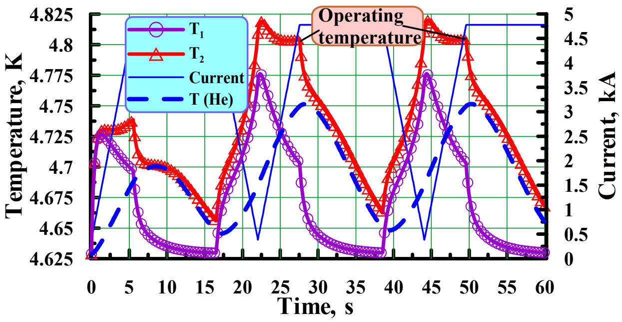

Figure 5. Temperature in the last turn of the inner layer in the last dipole of the string: thick violet line (o) shows temperature *T1*, where is an inlet helium, thick red line (Δ) shows the temperature *T2* in the place of outlet helium. Blue dashed line shows the temperature *T(He)* of outlet helium from the last dipole in the string and thin blue line shows the operating current.

Fig. 6 shows difference between critical and operating temperatures and ΔT_{min} for the last turn of the inner layer.

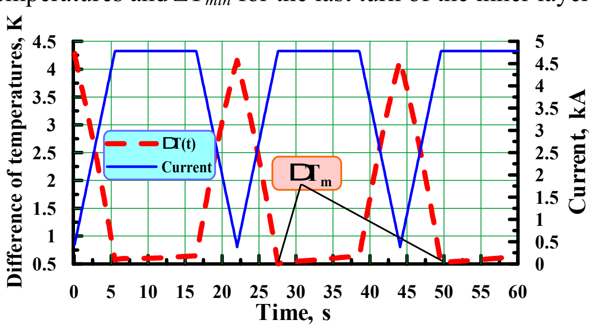

Figure 6. Difference between critical and operating temperatures for the last turn of the inner layer.

Fig. 7 shows the critical and operating temperatures corresponding to minimal differences (Fig. 8) between critical and operating temperatures in turns of the inner layer. All values of ΔT_{min} are larger than 1.5 K in turns of the outer layer. The value of ΔT_m is found in the last turn of the inner layer. Table 3 presents the temperature conditions for all designs.

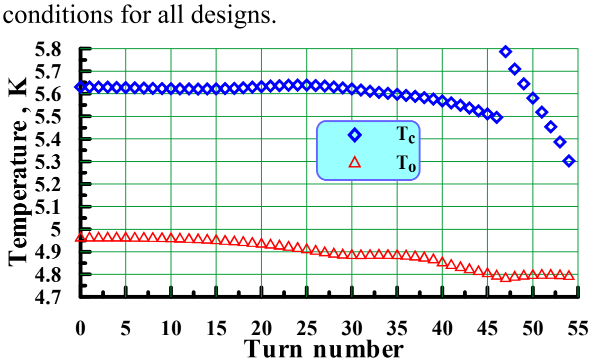

Figure 7. Critical (T_c) and operating (T_o) temperatures in turns of the inner layer corresponding ΔT_{min}.

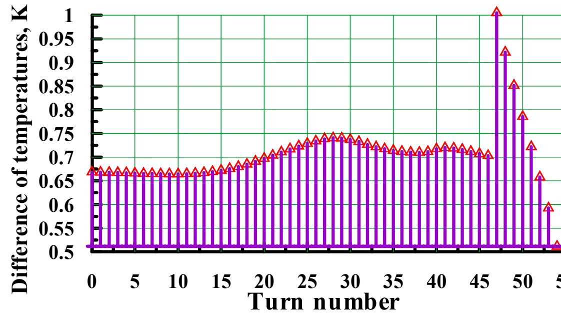

Figure 8. Minimal difference between critical and operating temperatures in turns of the inner layer.

Table 3. Temperature characteristics for all designs.

Design	I	II	III
Critical temperature, K	5.36	5.30	5.22
Operating temperature, K	4.85	4.80	4.74
Temperature margin, K	0.51	0.50	0.48

Temperature margin can be increased by:

- Decreasing helium refrigerator operating temperature below 4.4 K (necessary to have the compressor suction pressure lower than atmospheric).
- Incorporating a number of recoolers into the magnet ring to reduce the helium temperature rise.
- Increasing the helium mass flow rate with the help of liquid helium pumps to reduce the helium temperature rise despite of this way is incompatible with the concept to throttle helium flow at the end of the magnet string.
- Increasing minimal critical temperature in the coil.
- Decreasing AC losses in the coil [8].

CONCLUSION

The numerical model for transient thermal processes study of SC dipole has been developed. Temperature margin of the SC dipole for three designs [2] is about 0.5 K. The full final analysis of the transient thermal processes in the string has to be made only when the SIS300 lattice will be defined in basic.

REFERENCES

[1] http://www.gsi.de/GSI-Future/cdr/
[2] L. Tkachenko et al. “Comparison of Three Designs of Wide Aperture Dipole for the SIS300 Ring”, This conference.
[3] M. Morita et al. “Stability Analysis in Cryogen-Free Superconducting Magnets during Current Excitation”, Proceedings of MT-15, Beijing, China, Vol. 2, 1997.
[4] A.I. Ageyev et al. “Development of Cryogenic System for UNK”, Proceedings of Workshop on Superconducting Magnets and Cryogenics. Brookhaven, USA, 1986.
[5] S.S. Kozub et al. “The Study of Interlayer Channel Effects on the Temperature Conditions of Superconducting Coil for the UNK”, MT-12, IEEE Trans. on Magnetics, v.28, 1992.
[6] A.P. Verweij “Electrodynamics of Superconducting Cables in Accelerator Magnets. PhD Thesis”, University of Twente, Enschede, 1995.
[7] L.M. Tkachenko “Code Package MULTIC for Calculation of Magnetic Field with an Arbitrary Configuration,” IHEP preprint 92-28, 1992.
[8] L. Tkachenko et al. “ Methods for Reduction Cable Losses in Fast-Cycling Dipoles for the SIS300 Ring”, This conference.