ENTHALPY MARGIN AND STABILITY OF FAST-CYCLING DIPOLE FOR SIS300 RING

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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] is under development at the GSI, Darmstadt. One of the main requirements to SC magnet is its stability. The stability of SC magnet can be estimated by means of temperature margin ΔT_m, enthalpy margin ΔH_m, and the minimum quench energy (MQE). The numerical calculations of the heat losses in the superconducting coil during the SIS300 operating cycle, which cause a coil heating, and the solution of the non-stationary equation of heat balance in the coil and wound by cable with 36 SC strands of 0.825-mm diameter with different RRR and magnetoresistance of wire copper were calculated. Possible ways to increase the stability of the SC magnet are discussed.

DESIGN OF SC DIPOLE AND COIL COOLING

The SC dipole cross section is shown in Fig. 1. The collars will be made thick enough to restrain the coil during assembly. The thickness of the collar laminations is 30 mm. The yoke and the skin together with collars must be used as a part of the coil support structure. The thickness of the yoke is 138 mm.

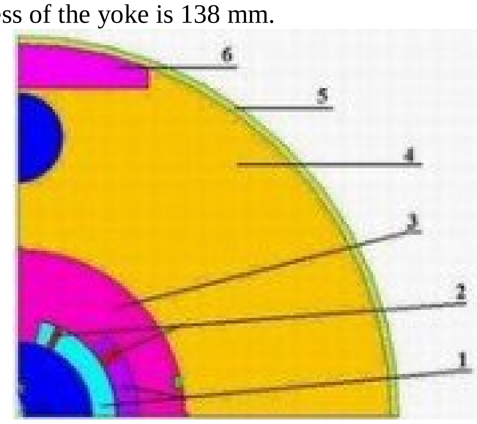


Figure 1: 1 – coil, 2- wedges, 3-collar, 4 – iron yoke, 5 – outer shell, 6 – clamp.

The two-layer coil will be cooled by one phase helium, at 2.5 bar, 4.4 K inlet temperature in the magnet string. Fig. 2 shows the layout of the coil cooling in the cross section of the SC dipole. 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 and 4-mm wide glass-cloth laminate spacers, located at distance of 4 mm from each other. The channels and spacers are arranged at the angle of 45° in the involute (plane R-Θ-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.

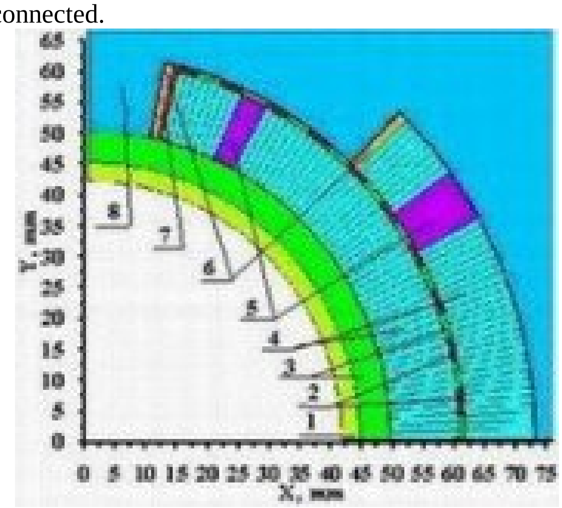


Figure 2: Cooling scheme of the coil of SC dipole in the cross section: 1 - beam pipe, 2 – glass-cloth laminate spacers, 3 - helium channels, 4 - coil, 5 - wedges, 6 – shims, 7 – stainless steel spacers with helium channels, 8 – collars.

COMPUTATIONAL MODEL

A computer code QUEN3 has been developed for analysis of transient thermal processes in the SC dipole. The code is based on simultaneous numerical solution of the equations of thermal conductivity for beam tube, coil, wedges, and collars as well as of the energy equation for each helium flow. This code is described in [2].

Standard equations [3] are used for calculations of hysteresis and coupling losses in the coil. The network model [4], 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 distributions of magnetic flux density $B(r, t)$ and of $B_r(r, t)$, $B_\theta(r, t)$ components in the coil are calculated with the help of the code MULTIC [5].

CRITICAL TEMPERATURE AND AC LOSSES

Field cycle with B_{min} = 1.6 T, B_{max} = 6 T and dB/dt = 1 T/s, corresponding to trapezoid time cycle 4.4 – 11.00 – 4.4 - 0 s (ascent–plateau–descent–pause) was considered. The SC strand has filaments with 5-mm twist pitch and 3.5-μm diameter, copper/SC ratio is 1.38 and critical current density is 2.7 kA/mm^2 (5 T, 4.2 K). We consider two cases of effective transverse resistivity of copper with different RRR and magnetoresistance of copper in cable.

A. $\rho_{et} = (4.0 + 1.3\,B)\times10^{-10}\ \Omega\times m$

B. $\rho_{et} = (1.0 + 0.2\,B)\times10^{-10}\ \Omega\times m$

RRR is 70 for the case A, and 200 for the case B. The cable of Rutherford type has the keystone shape, crossover resistance R_c is 20 mΩ, and adjacent resistance R_a is 200 μΩ.

The dependence of the minimal critical temperature T_c in the coil versus number of wires in the cable is shown in Fig. 3. One of the main requirements to this magnet is 1 K temperature margin. Taking into account this requirement critical temperature must be close to 5.8 K, therefore the number of wires in the cable is 36.

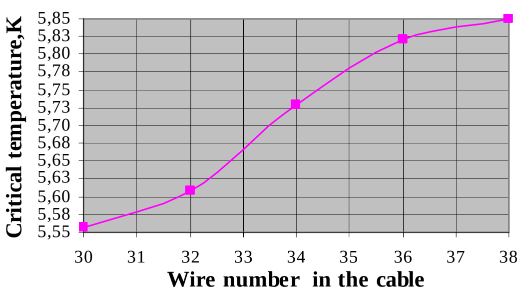


Figure 3: Minimal critical temperature in the coil versus number of wires in the cable.

The distribution of the critical temperature $T_c(B)$ at operating current in turns of the coil for 36 strands in the cable 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).

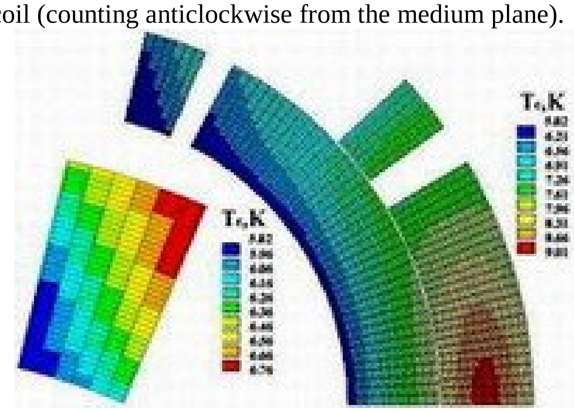
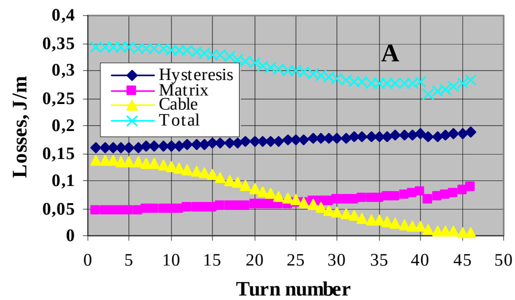


Figure 4: Distribution of the critical temperature in the coil of SC dipole.

The distributions of AC losses per cycle over turns in the inner layer are shown in Fig. 5 (case A) and Fig. 6 (case B) for the first quadrant. The turns are counted off from the median plane.



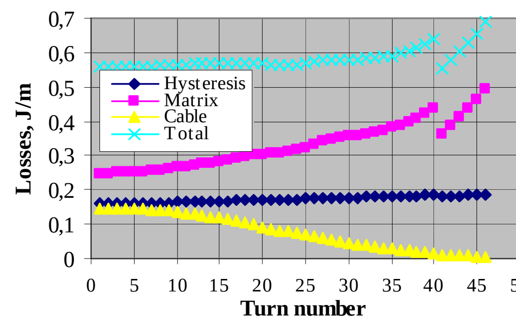


Figure 5: (case A) and Figure 6 (case B). AC losses per cycle in turns of the inner layer (the first quadrant).

The detail distributions of AC power losses per cycle in the last turn of the inner layer are shown in Fig. 7 (case B). It is seen that the cable losses in the last turn are of a negligible value.

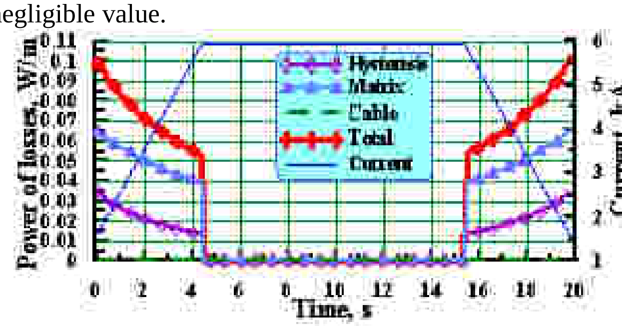


Figure 7: Power of losses in the last turn of the inner layer and operating current versus time of cycle (case B).

Table 1 presents components of AC losses per cycle in the coil for two cases and total losses.

Table 1: Components of AC losses per cycle in the coil.

	A	B
Hysteresis, J/m	46.9	46.9
Matrix, J/m	15.2	73.5
Cable, J/m	15.0	15.0
Total losses, J/m	77.1	135.4

Table 1 shows that the total losses are 1.8 times higher in case A than in case B, losses in last turn are 2.4 times higher in case A than in case B, as it is shown in Fig. 5 and Fig. 6.

STABILITY MARGIN

The helium flow rates in circular channel and inlet temperature of helium in the last dipole of the string U_{in}, were determined by cryogenic conditions like for UNK [6,7], are presented in Table 2.

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

	A	B
Helium flow rate, g/s	47.0	55.0
U_{in} in the last dipole, K	4.66	4.70

The temperature margin of SC magnet is the difference between the critical and operating temperatures of the coil under the worst conditions, depending on the applied magnetic field, temperature, and the transport current. The simulation method for determination of the temperature margin of SC dipole is described in [2]. The value of ΔT_m is found in the last turn of the inner layer.

The calculation of temperature distribution in the coil versus time has been made for sequence of operating cycles. Thick lines in Fig. 8 (case A) and Fig. 9 (case B) show the calculated variation 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 bulk 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.

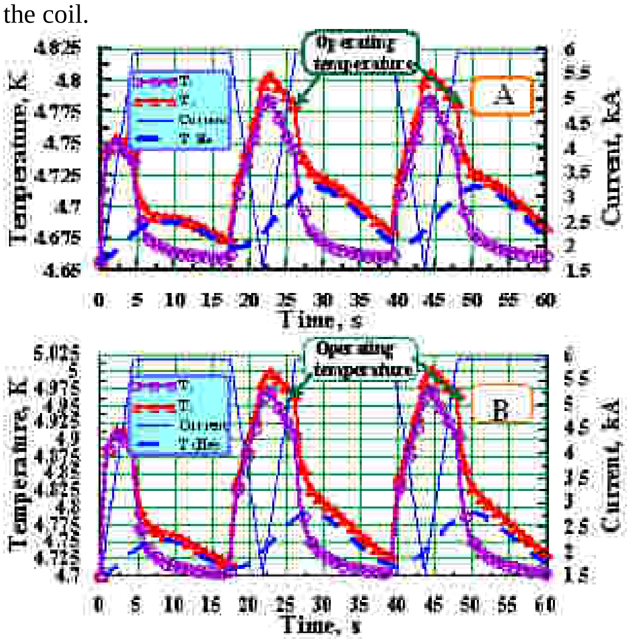


Figure 8 and Figure 9: Temperature in the last turn of the inner layer in the last dipole of the string: thick violet line (o) shows temperature T_1, in the place of inlet helium, thick red line (Δ) is shows the temperature T_2 in the place of outlet helium. Blue dashed line shows the bulk temperature *T(He)* of outlet helium from the last dipole in the string and thin blue line shows the operating current.

Fig. 8 and Fig. 9 show that the thermal process in the coil is stabilized after two cycles. These Figures also show the operating temperature value for calculation temperature and enthalpy margin.

Enthalpy margin and MQE are calculated in one dimension approximation [3] including 2% volume fraction of helium around the SC strands. MQE for acceleration magnet is about 1 mJ [8].

Table 3 presents temperature conditions and stability characteristics of the SC dipole.

Table 3: Temperature conditions and stability characteristics.

	A	B
Critical temperature, K	5.82	5.82
Operating temperature, K	4.78	4.96
Temperature margin, K	1.04	0.86
Enthalpy margin, kJ/m^3	35	30
Minimum quench energy, mJ	0.9	1.1

Temperature and enthalpy margin can be increased by:

- Decrease of matrix losses in the coil.
- 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.

CONCLUSION

The numerical model for transient thermal processes study of SC dipole has been developed. Stability characteristics of SC dipole are calculated. Temperature margin of 1 K and minimum quench energy of 1 mJ are reached at 36 SC strands in the cable of Rutherford type (keystone shape). Matrix losses in SC wire visibly influence these values therefore the losses are to be decreased to as low level as possible.

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