QUENCH PROCESS IN FAST-CYCLING SUPERCONDUCTING DIPOLE FOR SIS300

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Abstract

The computer simulation of quench evolution in the coil of SIS300 superconducting dipole with magnetic field of 6 T in 100-mm aperture was made. The most essential variants of quench conditions, which correspond to different basic protection schemes of string of magnets, are considered. The results of calculations are presented. On this base the aptitudes and limitations of possible quench protection schemes are considered.

INTRODUCTION

Superconducting (SC) magnets must be well protected during a quench. Accepted rules are the following: maximum coil temperature should not exceed room temperature (T_{max} < 300 K) and voltage should not be excessive (U_{max} < 1000 K) [1]. The aim of this work was to obtain preliminary data about the quench evolution in the coils of the high induction ramping SIS300 dipoles, and on the basis of these data to outline the general guidelines for design of a ring quench protection system. Variants, which can be realized in protection schemes for single magnets or series-connected magnets in the ring, were modelled in calculations.

COMPUTER SIMULATION

Simulation of the quench was performed for three dipole designs [2], which have been considered and analyzed in frame of development of main magnet design for the SIS300 ring. Three cases was considered:

1. A single magnet dissipates its own energy in the coil.
2. The magnet's stored energy is dissipated in the coil, but the process is accelerated by a strip heater, which is placed on external surface of the outer layer of coil.
3. A dump resistor absorbs the stored energy of dipole.

The cases 1 and 2 are of interest for series connected dipoles in accelerator ring, whereas the case 3 is usually realized at single magnet tests. Table 1 specifies the main parameters of the magnets. The resistance of a dump resistor is chosen so that the maximum voltage is 1 kV.

Table 1: Main magnet parameters

Dipole design	I	II	III
Magnet length, m	2.6	2.6	2.6
Stored energy, kJ	637	587.1	581.4
Inductance of the magnet, mH/m	19.8	19.8	22.3
Operating current, kA	4.98	4.78	4.48
Resistance of dump resistor, Ω	0.20	0.21	0.22

The power supply is switched off with 50 ms time delay after quench detection at 1 V threshold. Heater time delay before firing is 80 ms.

Calculations have been done with help of the computer codes QUEN and QUEN1. The code QUEN simulates a quench process by a set of heat balance equations for the coil of a SC dipole with AC losses taken into account. The internal heat generation in the conductor cable during the quench process is given by:

$$Q_i(t,x) = \begin{cases} \dfrac{J^2\rho_m}{f_m}, & T > T_c, \\ \dfrac{J(J-J_c)\rho_m}{f_m}, & T_h < T < T_c, \\ P_{AC}, & T < T_h, \end{cases}$$

where J is a current density, $J_C = J_C(T,B)$ is the critical current density, $\rho_m = \rho_m(T,B)$ is a matrix resistivity, P_{AC} is AC losses, T_c and T_h are critical and current-sharing temperatures, f_m is the filling factor of copper matrix in wire.

The code QUEN1 models a quench process similarly to the Wilson treatment [3]. The algorithm is based on an adiabatic assumption, which allows one to calculate the maximum temperature of a quenched superconductor from the quench integral, by an iteration process:

$$I^2\Delta t = S_m S_t \int_{\Delta t} \frac{C}{\rho_m} dT \cdot$$

The quench integral has to be recalculated with each time step Δt, $C = C(T, B)$ is specific heat of the cable, S_m is the matrix area and S_t is the total cable area. An evolution of the quench process is described in terms of time dependent longitudinal quench velocities and transverse turn-to-turn quench jump steps.

The currents during a quench are calculated in both codes by solving a set of circuit equations using the Runge-Kutta method. The local magnetic field in the coil is calculated, using the code MULTIC [4].

Results of calculations are presented in Figures 1-3. Figure 1 shows the current decay in magnets during quench. Figure 2 presents the time evolution of the hot spot temperature. The values of the stored energy, dissipated in the coil during quench, are presented in Fig. 3.

As for the case, when magnet dissipates its own energy in the coil, the main conclusion is the following: the 100-mm aperture dipole for SIS300 is not "self-protecting". For this reason a strip heater, covering the surface of the outer layer of the coil, is required in order to spread the resistive zone throughout the quenching coil rapidly and to keep the hot spot temperature as low as possible. In this case, the hot spot temperature is close to 250 K, whereas without a heater the temperature reaches an inadmissible level of more than 600 K. In both cases the maximum voltage on the resistive part of coil does not exceed 400 V.

Only a small part of the stored energy is deposited in the coil in case of the protection of a single magnet with a dump resistor. The use of dump resistor provides the evacuation of about 97% of energy stored in single magnet and limits a maximum hot spot temperature at a level ≤100 K.

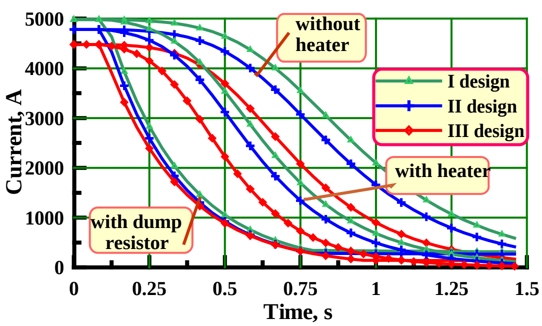

Figure 1: Current decay during quench

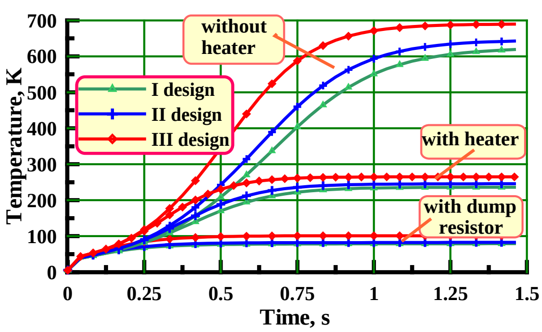

Figure 2: Time evolution of temperature during quench.

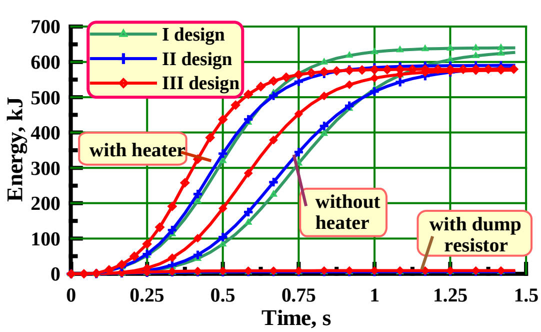

Figure 3: Energy dissipation in coil during quench.

RING FEEDING AND PROTECTION

Figure 4 gives a schematic representation of a possible excitation circuit for the SIS300 dipole magnets. The main ring for the SIS300 consists of 120 dipoles. Power supplies PS, along with dump resistors Rd, are connected into breaks of the magnet string. Thus the magnetic structure is subdivided into six sextants of twenty magnets each. Table 2 presents the basic load specification of SIS300 ring at maximum field of 6 T and ramp rate of 1 T/s for three designs of the SC dipole. A total magnetic energy stored in the ring is 70÷76 MJ. During ring excitation the overall voltage reaches almost 5.2 kV, whereas inductive voltage on each dipoles reaches up to 43 V. Main requirements to the power supplies are: operating current is 5 kA, ramp voltage is 900 V, peak power is 4.5 MVA and allowable current ripple is 10^{-4}.

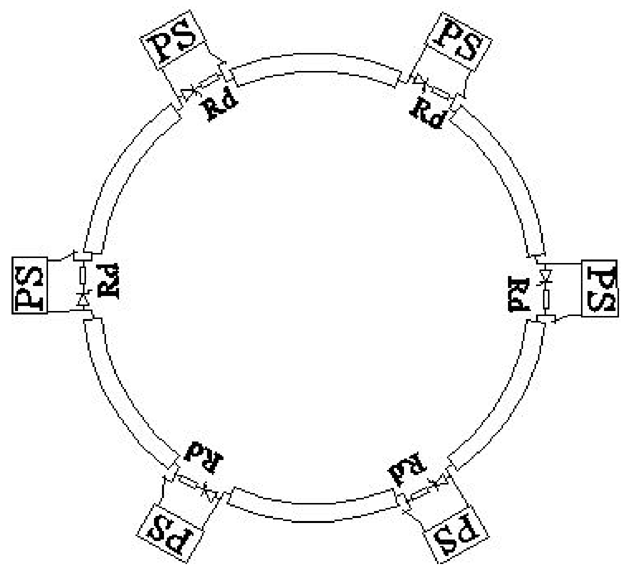

Figure 4: Possible scheme of SIS300 ring powering

Table 2: Basic load specification of SIS300 ring

Dipole design	I	II	III
Operating current, A	4980	4778	4483
Current ramp rate, A/s	830	796.3	747.2
Stored energy per dipole, kJ	637	587.1	581.4
Total stored energy, MJ	76.4	70.5	69.8
Inductance per dipole, mH	51.48	51.48	57.98
Inductance per sextant, H	1.03	1.03	1.16
Total ring inductance, H	6.178	6.178	6.958
Inductive voltage per single dipole, V	42.73	41	43.32
Inductive voltage per sextant, V	854.6	819.9	866.4
Dump resistor, Ohm	0.201	0.209	0.223
Time constant of dump, s	5.13	4.92	5.20
Maximum current dumping rate, A/s	971	971	862

After detection of quench, it is necessary to remove the stored energy from the ring as soon as possible. For this purpose dump resistors are used. By the opening of SCR switches the current is diverted into external heat absorbing dump resistors, which dissipate the stored energy and exponentially reduce current to zero with the time constant $\tau = L/Rd$, where L is inductance of sextant and Rd is a resistance of dump resistor. The time constant of exponential current dumping is about 5 s. Maximum voltage relative ground has a safe level of ± 500 V. The maximum current dumping rate exceeds the nominal ramp rate by less than 22 % (see Table 2) and it will not cause the magnets to quench. Standard ring de-excitation by power supply with the nominal ramp rate can be used too. In our case this method is faster, and hence it is preferable than energy extraction by a dump resistor. But this method is disabled in case of failure of the current supply or power grid. For this reason the dump resistor should be present at the powering scheme necessarily.

The current of the non-quenching magnets is bypassed around the quenching magnet, by the turning on the switches, connected in parallel to the quenching magnet. Either cold diodes [5-7] or SCRs [8] can be applied as such switches.

SCR switches are connected in parallel to the groups of magnets, named quench protection cells (QPC). In our case such cell could contain four dipoles, Fig. 5.

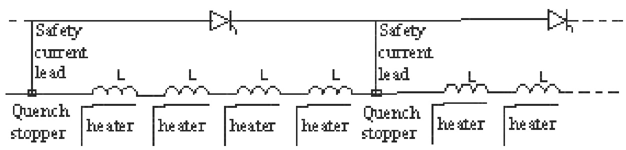

Figure 5: Magnet string with the SCR.

These switches are located outside of the cryostat at room temperature, and therefore additional current leads are needed. These current leads are connected to the SC cable between adjacent QPCs. Safety current leads should be made from stainless steel, which would result in a relatively small additional heat leak into the helium region, of ~0.8 W per each current lead. At that the maximum current lead temperature during quench is less than 380 K. A quench stopper is mounted at the locations, where these current leads are connected to the SC cable. It is made from copper and serves as a terminator of normal zone propagation, due to its large thermal capacity.

After the detection of a quench the by-pass SCR is turned on and power supplies of protective heaters are switched on in all magnets of a QPC module, which contains the quenched magnet. The stored energy is dissipated uniformly in the coils of all dipoles belonging to one QPC. Other part of magnets does not pass into a normal state.

When cold diodes are used, a bypass switches are connected in parallel to the each magnet and are located inside the cryostat, Fig. 6. Each switch contains several diodes connected in series. Protective heaters are mounted in each magnet too, but a heater is fired only in the quenching magnet.

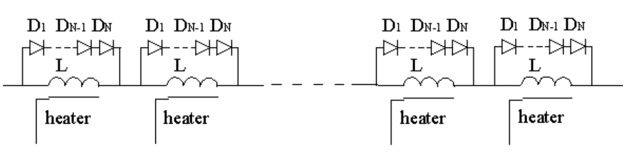

Figure 6: Magnet string with the cold diodes.

The switch turn-on voltage must exceed over the inductive voltage of 41 V during dipole ramping. Turn-on voltage for diffusion diode is about six times higher than for epitaxial diode [9]. Thus, for each dipole 34 epitaxial diodes or 6 diffusion diodes would be required. These diodes should absorb a peak current about 5 kA, which decays exponentially with a time constant of ~5 s. This results in energy liberation of about 1.1 MJ in the epitaxial diodes or 0.4 MJ in the diffused diodes, and requires copper heat sinks of 37 kg or 13 kg, respectively. A large number of diodes and additional heat absorbers strongly complicates a design and reduces reliability. The energy, released in diodes, is about two times higher for epitaxial diodes or about the same for diffused diodes as the energy, released in dipole. Thus, the total heat release into the helium region is increased. The primary requirement for cold diodes is that they should be radiation resistant. Expected neutron fluence is $4.9 \cdot 10^{12}$ neutron/cm^2/year [10]. Radiation hardness of diffusion diodes is about ten times lower than for epitaxial diodes, which have a life-time ~30 years under SIS300 conditions. With continuous operation, the total number of diodes (taking into account their periodic replacement) can reach of 8500 diffusion or 4500 epitaxial diodes. Large number of required diodes is a great disadvantage of this protection scheme.

CONCLUSIONS

SIS300 dipoles are not self-protecting. Quench detection and extraction of stored energy from them is obligatory. For discharging the circuit, the power supply or dump resistor should be used. The resulting maximum current decay rate is comfortably below the level, where quench-back will occur. The using of protective heaters mounted on dipole coils limits the maximum hot spot temperature to a value of ~250 K.

There are no restrictions on using of magnet bypass circuit with warm SCRs, whereas in order to use the advantages, provided by cold diodes, it is necessary to develop the new diodes with improved characteristics such as the turn-on voltage and the radiation hardness.

REFERENCES

[1] L. Rossi, “Superconducting Magnets for Accelerators and Detectors”, Cryogenics v.43, no.3-5, 2003, pp.281-301.

[2] L. Tkachenko et al. “Comparative Analysis of Wide Aperture Dipole Designs for SIS300 Ring”, This conference.

[3] M.N. Wilson, “Superconducting Magnets”, Oxford University Press, 1983.

[4] Tkachenko L.M. “Code Package MULTIC for Calculation of Magnetic Field with an Arbitrary Configuration,” IHEP preprint 92-28, 1992, pp.48.

[5] BNL proc. no. RHIC-MAG-R-7401.

[6] K.H. Mess, “Quench Protection for HERA”, Proc. of the 1987 IEEE Particle Accelerator Conference, p.1474.

[7] K. Dahlerup-Petersen et al. “The Protection System for the SC Elements of the LHC at CERN”, PAC’99, New York, 1999, pp.3200-3202.

[8] R. Stiening et al. “A Superconducting Synchrotron Power Supply and Quench Protection Scheme”, IEEE Transaction on magnetics, v. MAG-15, no.1, 1979, pp.670-672.

[9] D. Hagedorn, “Cold Diodes for the Protection of the Superconducting Magnets in the LHC”, QPS review, 5-7 Dec. 2001, http:// lhc-div-icp.web.cern.ch/lhc-div-icp/ICPPAGES /Talks/Dieter.pdf.

[10] E. Mustafin. “Energy Deposition and Neutron Fluence into Protection Diodes for SIS300 Superconducting Dipoles”, 2003, http://www-linux.gsi.de/~mustafin/sis300diode.pdf.