

STUDY OF THE QUENCH PROCESS IN A FAST-CYCLING DIPOLE FOR THE SIS300 RING

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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

The study of the quench process has 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:

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

where J is a current density, $J_c = J_c(T, B)$ is the critical current density, $r_m = r_m(T, B)$ 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 [2]. 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:

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

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 [3].

Simulation of the quench was performed for three dipole designs [4], which have been considered and analyzed in frame of development of main magnet design for the SIS300 ring. Table 1 specifies the main parameters of the magnets, which are necessary for numerical simulation. The resistance of a dump resistor is chosen so that the voltage across the dump resistor remains below 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
Heater delay time, ms	80	80	80

It was assumed that after quench detection at 1 V threshold, the power supply is switched off with 50 ms time delay and then one of following events takes place:

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 heater, which is placed on external surface of the outer layer and its time delay before firing is 80 ms,
3. A dump resistor absorbs the stored energy of one single magnet.

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. 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 results in a hot spot maximum temperature that is ≤ 100 K. Thus, this protection method is very suitable for use during the testing of a single magnet. As for the other considered cases which are of interest for series connected dipoles, the main conclusion is the following: the magnet is not "self-protecting" and an active quench protection heater, covering the surface of the outer layer of the coil, will be 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.

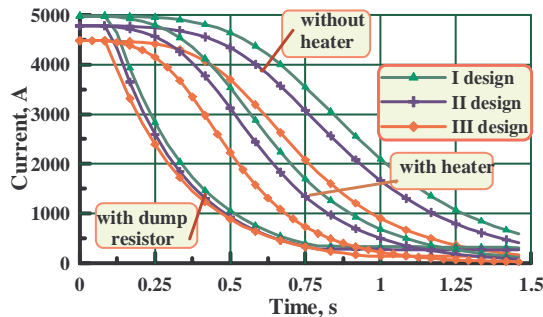


Figure 1: Current decay during quench.

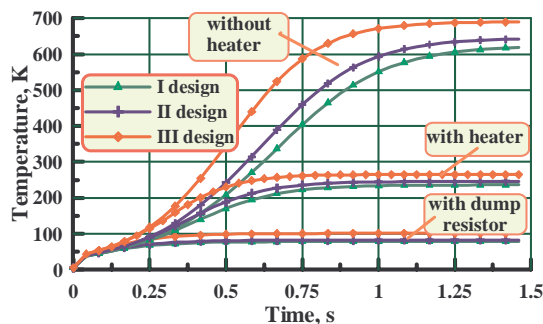


Figure 2: Time evolution of temperature during quench.

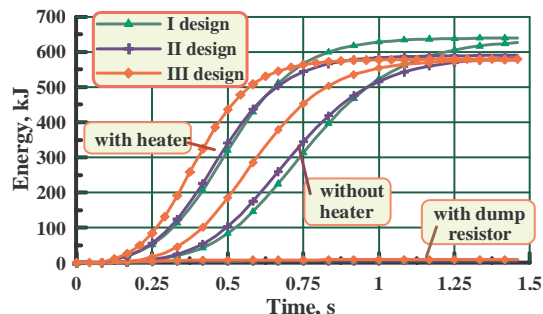


Figure 3: Energy dissipation in coil during quench.

RING FEEDING AND PROTECTION

The main ring for the SIS300 consists of 120 dipoles. Table 2 presents the main parameters at 6-T maximum field and 1-T/s ramp rate for three designs of the SC dipole. The SC ring stores a total magnetic energy of 70÷76 MJ. Inductive voltage on the dipoles reaches up to 43 V, and overall ring voltage reaches almost 5.2 kV.

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 superperiod, 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

Figure 4 gives a schematic representation of a possible excitation circuit for the SIS300 dipole magnets. Magnetic structure is subdivided into six super periods of twenty magnets each. Power supplies, along with dump resistors, are connected into breaks of the magnet string. Briefly enumerated main requirements of the power supplies are: operating current of 5 kA, ramp voltage of 900 V, peak power of 4.5 MVA and allowable current ripple of 10^{-4} .

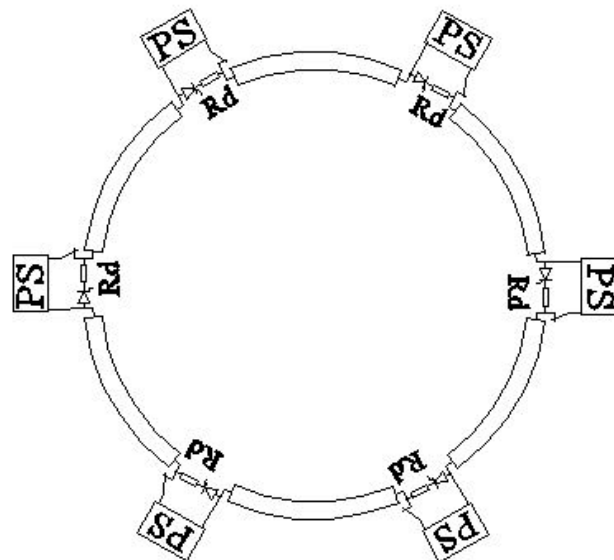


Figure 4: Possible scheme of SIS300 ring powering. PS is a power supply and RD is the dump resistor.

General actions for quench protection of a SC ring should be the following: (1) to detect the quench as soon as possible, (2) to turn off the power supply and redirect the current to bypass the quenching magnets, (3) to fire the quench protection heaters, (4) to discharge the magnet string with the power supply or with an energy absorbing resistor.

So, after detection of a quench, it is necessary to remove the stored energy from the entire series-connected string as rapidly as possible. For quenching magnets, the standard ring de-excitation by power supply with the nominal ramp rate is most suitable for this purpose in the overwhelming majority of cases. This method is faster than energy extraction by a dump resistor, but the last is necessary in case of failures of the current supply or power grid. Current is diverted (by the opening of SCR switches) 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 twenty-magnet string and Rd is a resistance of dump resistor. The time constant of exponential current dumping is about 5 s. 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.

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. For this purpose, cold diodes, which have been success-

fully used on RHIC, HERA and have been approved for LHC [5-7], could be used. Each bypass switch is located inside the cryostat and contains several diodes, connected in series. So, the switch turn-on voltage must exceed over the inductive voltage of 41 V during dipole excitation (see Fig. 5). Internal protective heaters are mounted in each magnet, but a heater is fired only in the quenching magnet.



Figure 5: Magnet string with the cold diodes.

Turn-on voltage for diffusion diode is about six times higher than for epitaxial diodes [8]. 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 absorption of about 1.1 kJ for epitaxial or 0.4 kJ for 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, deposited in diodes, is about two times higher for epitaxial diodes or about the same for diffused diodes as the energy, stored in dipole. Thus, the heat dissipation into the helium, caused by a quench, increases. The primary requirement for such diodes is that they should be radiation resistant. Expected neutron fluence is $4.9 \cdot 10^{12}$ neutron/cm²/year [9]. 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 diode number (taking into account their periodic replacement) can reach of 8500 diffusion or 4500 epitaxial diodes. This number is significantly more than proposed for the LHC (~ 2500), which is much larger than the SIS300 machine.

An alternative scheme (similar to that used in FNAL [10]) uses SCR switches, which are connected in parallel to the groups of magnets, named quench protection cells (QPC). In our case it could contain four dipoles, see Fig. 6.

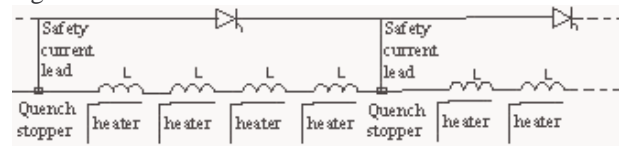


Figure 6: Magnet string with the SCR.

This switch is 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 a quench will not exceed 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 in a time of less than 0.5 seconds. Other part of magnets does not pass into a normal state. Current of these magnets decreases with the time, at a ten times lesser rate.

CONCLUSIONS

These 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. Maximum voltage relative ground has a safe level of ± 500 V. Using protective heaters mounted on dipoles 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 search for, or develop, new diodes with characteristics similar to existing diffusion diodes, but with higher turn-on voltage and with greater radiation hardness.

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