Quench Analysis of the Energy Deposition in the SSC Magnets and Radiation Shielding of the Low-β IR Quadrupoles

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Abstract

The temperature rise in the superconducting coil because of the energy deposition is estimated, as is the quench threshold for periodic, continuous, and accidental particle losses in the ring. Radiation shielding in the interaction region is analyzed along with its implications on the beam luminosity for the Superconducting Super Collider (SSC).

I. Introduction

One of the major concerns in designing and constructing a high-energy superconducting (s.c.) accelerator is the study of the energy deposition in the s.c. coil and associated radiation effects in its components due to particle losses in the ring. These losses can be due [1, 2] to beam-gas scattering, interaction of protons with other elements (scrapers, septum, bend crystal, lambertson magnets), instabilities in the particles, and accidental or catastrophic losses. In particular, the study of radiation-induced quenches in the s.c. magnets receives special attention. Here, the quench threshold for the s.c. magnets is determined and is used as a reference point of safety level.

The quench threshold for the s.c. Tevatron magnets was widely analyzed [3], and the experience obtained from these magnets is used as the quench level for the SSC magnets [2, 5]. It will be seen below that the above analysis suggests that the sensitivity of the SSC magnets is lower than these estimations; however, the general conclusions about the quench analysis given with these estimations remain. To give a different feeling of the events involved in the losses, these will be divided into accidental, periodic, and continuous losses.

II. Periodic And Continuous Losses

Assume that a periodic or continuous event happens such that there is a density of energy, ζ, deposited uniformly along the length of a s.c. wire in the magnet. This uniformity assumption is based on the fact that whenever there is a loss of a high-energy particle, the peak of the energy deposition changes smoothly with respect to the longitudinal direction. The cooling time is quite long in comparison with the time of energy deposition of the events, so there will be an increase in the temperature in each event until a stationary temperature is reached because of the cooling process [1]. This stationary temperature, θ_s, will determine whether the magnets will quench in a periodic or a continuous loss. To calculate this stationary temperature and the time taken to reach it, assume that the event occurs at a frequency f. Then, the heat transferred to He in the time $1/f$ is given by $\sqrt{\pi}\xi H_n(\theta-\theta_o)/\sqrt{A}f$, and the temperature variation of the s.c. wire in the ith-event will be given by

$$(\delta C)\Delta\theta_i = -\frac{\sqrt{\pi}\xi H_n(\theta-\theta_o)}{\sqrt{A}f} + \zeta \, , \tag{1}$$

where a cylinder shape conductor has been assumed and the thermal conductivity of the materials is ignored; (δC) is the average over the s.c. wire components of the density multiplied by the specific heat; θ is the temperature of the wire; θ_o is the batch temperature; ξ (about 0.8) is the fraction of the s.c. wire perimeter in contact with He; A (about 0.5127 mm^2) is the cross section area of the wire, and $H_n(\theta-\theta_o)$ is the heat transfer function. Its stationary temperature, θ_s, will be given naturally by the solution of the algebraic equation

$$\zeta - \frac{\sqrt{\pi}\xi H_n(\theta_s-\theta_o)}{\sqrt{A}f} = 0 \, . \tag{2}$$

Safer situations will be those of lower frequencies, althought most of the periodic events in the SSC occur at the collision frequency $f = 1/\tau_* \simeq 60$ MHz.

It is possible to use the same equations (1) and (2) for some continuous events by selecting a proper time scale, τ_*, for the event. For example, in the beam gas scattering events it is possible to consider the revolution time, $\tau_* = 2.9\times10^{-4}$ sec, as the scale in which the events occur (similarly, the synchrotron radiation damping is studied), the evolution of the temperature in s.c. wire as a function of the number of turns can be calculated using the above equations. Assuming that the energy deposition in the s.c. wire per turn is $\zeta = (1.4\times10^5)\times(1.149\times10^{-7})\times(50\ \mathrm{Gev/cm}^3)$, where $(1.4\times10^5)\times1.149\times10^{-7}$ is the number of proton losses per turn in 1 cm, and 50 $\mathrm{Gev/cm}^3$ is the density of energy deposited in this 1 cm of wire per proton of interaction.[1] The result of the integration indicates that

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[1] This value is about the double estimated by reference 2.

the temperature of the s.c. wires will not increase more than 1/1000 of the batch temperature in about 10^5 turns. So, this continuous event is quite safe with respect to inducing quench in the s.c. coil. For energy deposition in the first low-β IR quad ($\tau_* = 1.66 \times 10^{-8}$ s and $\zeta =$ 0.18 Gev/cm^3), the results bring about a quench safe margin of about five orders of magnitude in energy deposition.

The slow beam spill is another continuous event which is of particular interest in slow resonant extraction. In this case, it is possible to assume that there is a dc-pulse of protons of time length τ_*, uniformly distributed, which delivers a constant power, $\epsilon_p\ dN_p/dt$ (where ϵ_p is the density of energy deposition per proton), when the protons strike the s.c. coil; dN_p/dt is the number of protons spilled per unit time; and the spilling time, τ_*, is normally between 0.5 sec and 1.0 sec. Because of these long times, the thermal conductivity $k(\theta)$ should be taken into account for the evolution of the temperature of a s.c. cable. However, the maximum stationary temperature will occur in the region where the change of heat flow is zero, and this one is given by the same relation (2) (changing f by dN_p/dt). It will be seen below that the minimum specific energy deposition needed for a quench in the s.c. coil for the SSC dipole magnets is about 0.2 mJ/g, so it is expected that a slow spill of 10^6 protons will cause a quench. The power threshold to cause a quench in these events would be between 0.2 mW/g and 0.4 mW/g for spill times between 0.5 sec and 1.0 sec. These estimated values contain uncertainties in cooling effects, energy deposition, and characteristics of the magnet itself, so beam-induced quench experiments with the SSC dipole magnet are required to obtain a more realistic threshold.

III. Accidental (Or Fast) Events

These events are characterized by the fact that some fraction of the beam suddenly strikes the beam pipe and deposits a great deal of energy in the s.c. coil, raising the temperature of the s.c. wires to the quench level. The process occurs so fast that there is no chance for any cooling effect or thermal conduction, so the effective density of energy, ζ, needed to raise the temperature of the coil from batch temperature, θ_o, to the quench temperature, θ_g, is given by

$$\zeta = \int_{\theta_o}^{\theta_g} (\delta C)(\theta) d\theta \;, \qquad (3)$$

where generating temperature θ_g and the average of the density times the specific heat (δC) are given by

$$\theta_g(B) = \theta_c(B) - (\theta_c(B) - \theta_o) J_o / J_{co}(B) \;, \qquad (4a)$$

and

$$(\delta C) = \frac{\lambda}{1+\lambda}(\delta C)_{Cu} + \frac{1}{1+\lambda}(\delta C)_{NbTi} \;, \qquad (4b)$$

where J_o is the operational current density; θ_c and J_{co} are the critical temperature at zero current and the critical current density at batch temperature, respectively. They are calculated using expressions given in Reference [4], and λ is the copper to s.c. ratio. For the SSC threshold estimate, the conductor chosen was that of the midplane of the SSC dipole magnets, and the magnetic field was calculated as a function of the operational current with the help of the POISSON program. In accidental losses the maximum energy deposition occurs just in the inner edge of the inner coil. For the 40 mm-aperture SSC dipole magnet, the magnetic field is about 6.6 T at high field, so the heat-generating temperature is about 4.8 K, and the specific energy threshold quench is about 0.13 mJ/g. This threshold is about one order of magnitude lower than the Safer Doubler Magnet. If the peak specific energy deposition per proton [5] is about 6 Gev/g, losses of about 10^6 protons will cause a quench in the magnet. For the 50-mm-aperture SSC dipole magnet, the peak specific energy deposition [2] is about 2 Gev/g with the magnetic field the same, but its operation point is 75% of the short sample (10% less than 40 mm magnet). Its heat-generating temperature is about 5 K, so its specific energy threshold is about 0.24 mJ/g. Therefore, losses of about 8×10^6 protons will cause a quench in this magnet.

IV. Radiation Dose And Shielding

The radiation dose threshold is well known for several materials [6], and this one gives the maximum radiation dose that the material can support before serious damage may happen. From the quench point of view, the interest is directed toward the radiation effects in the s.c. coil. Here, the Kapton and Expoxy materials which insulate the s.c. cables receive the same radiation dose as the coil. Fortunately, these organic materials are the most resistant under radiation exposure. Nevertheless, there is some concern about this since the radiation levels are somewhat high in some regions of the accelerator. For example, in the low-β interation region (IR) the peak specific energy deposited in the first quadrupole [2] is 0.02 Gev/g, bringing about a lifetime of about one year for this magnet, for a peak Luminosity of 10^{34} and an operational time per year of 10^7 sec. The radiation dose in these quadrupoles is quite high and may cause disturbances in the operation of the accelerator. So the idea is to design a collimator which absorbs part of the energy and reduces the energy deposition on these magnets. This study was done with the help of the computer programs MARS10 [7] for energy deposition, and ISAJET [8] for generation of collision events at the interation point.

The geometry of the quadrupoles in the low-β IR are given elsewhere [9]. The results with 4-cm-aperture magnets suggest the following optimum collimator parameters: material Fe; inner radius 4 mm; outer radius 10 mm; effective length 4 m (1 m smooth-tapered); and location as close as possible to the first IR quad. A detailed view of the energy deposition with this collimator in the quadrupoles of the Low-β IR is shown in Figure 1, where the energy deposited in the inner coil for the azimuthal an-

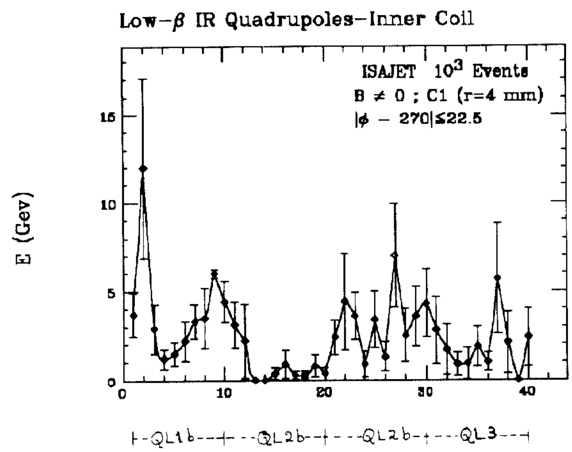

Figure 1: Energy Deposition in the Low-β Quadrupoles (the mass factor for the first one is 2300 g).

gle $|\phi - 270| \leq 22.5$ is given. The total mass of the effective 4-m-long (1 m smooth-tapered), 0.4-cm-inner-radius, and 10-cm-outer radius iron collimator is about 985.7 Kg.

Given the Luminosity, L, the inelastic pp interaction cross section, σ_{inel}, and the operation time of the machine in a year, T_{year}, the annual dose in the s.c. coils can be estimated from [2] by the following expression:

$$\dot{D} = \zeta L \sigma_{inel} T_{year} \ , \quad (5)$$

where ζ is the effective specific energy deposition in the s.c. coil. For radiation damage study in the components of the coil, it is most important that the maximum dose corresponds to the maximum specific energy deposition. This value is about 0.02 Gev/g [2] for the QL1b quadrupole in the low-β IR, and in accordance with 4.1, this value can be reduced by a factor of 10 only by using an optimum collimator shielding. Keep in mind that the maximum dose per year allowed in the s.c. coil must be 5000 Mrad (Kapton threshold). Using σ_{inel} = 90 mb, $T_{year} = 10^7$ s, and $L = 10^34$ cm^{-2}s^{-1}, the dose in the first Low-β IR quadrupole is about 2500 Mrad/year without shielding and 200 with the above collimator shielding. Without shielding, the lifetime of this quadrupole is about one year (using a safety margin); if the above shielding is used, the lifetime may be about 10 years.

V. Conclusions

The results of Section 2 suggest that there are no quench problems because of the direct energy deposition in the s.c. coil of the SSC magnets due to beam gas scattering (which is consistent with Reference 2) or pp collision at the interaction points. The results of Section 3 suggest that the threshold quench limit for fast spill is 0.2 mJ/g which is much lower than that for the Tevatron magnets, so calculations based in the Doubler threshold limits (1 mJ/g for fast losses, 8 mW/g for slow losses) might result in underestimated. In Section 4, the lifetime of the quadrupoles close to the interaction point in the low-β IR was estimated with and without shielding. This lifetime could be much lower if weaker materials against radiation damage are needed in these magnets, and if because of many uncertain factors, the IR quadrupole magnets have to be protected. The above calculations suggest that the maximum reduction in energy deposition in low-β s.c. magnets is one order of magnitude using an 8-mm-diameter, 4-m-long iron collimator. This aperture would be used only during the collider operation. Studies of wake field effects and scraper behavior of the collimator are still needed in order to define the minimum diameter allowed.

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