Chapter 9.
Cryogenic System

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9.1. Introduction

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Table 9.9.1: The $(g-2)$ Magnet Parameters

9.9. Quench Analysis

The quench analysis is given in $(g-2)$ Note No. 159. [1] and is briefly reviewed here. The magnet parameters relevant for the quench analysis are given in Table 9.9.1. The conductor parameters are given in Table 9.9.2. An important consideration is the cold aluminium mandrel which supports the conductors (see Fig. 9.9.1). A changing magnetic flux enclosed by the mandrels generates an emf which induces current to flow within the mandrel such that it opposes the change in magnetic flux. If the flux changes rapidly enough, the energy dissipated by the eddy currents in the mandrel will drive the entire

Table 9.9.2: The $(g-2)$ Magnet Superconductor

Figure 9.9.1: Quench Protection System

coil normal. This is called "quench-back". Quench-back is desirable if a quench should develop. Since the entire coil goes normal, the heat is dissipated over the whole coil/mandrel assembly. Thus temperature differences are minimized.

The design goals are to cause quench-back quickly once a quench is detected, but to maximize the time constant with which the energy is extracted. The latter requirement is to minimize eddy currents in the iron. These are conflicting requirements. The quench analysis has resulted in a design which gives an acceptable solution for both of these requirements.

The eddy currents generated in the iron [2] create a magnetic field which effectively remains confined to the iron. Therefore, in some places it opposes the main magnetic field, and in other places it reinforces it. It is the latter case that causes a potential problem, since the enhanced magnetic field will put the iron in a new position on the **B** *vs* **H** curve. We can get an estimate of the size of the above effect from the CERN experience. After a power breakdown, the magnetic field changed by 55 *ppm* when the magnet was turned on again. [3]

However, when a turn-on cycling procedure was used [4], the magnetic field was reproducible at the 1.4 *ppm* level. The L/R time constantfor the CERN magnet was $\tau = (0.3H/0.1\Omega) = 3s$. During the cycling procedure, the magnet was ramped to 110% of full current in 100 seconds, and then ramped down in 100 seconds. This was repeated three times. Finally, the current was slowly cycled above and below the set point.

We have chosen a quench protection resistor with a resistance of 0.01Ω based on the above considerations. A schematic of the electrical circuit is shown in Fig. 9.9.1. The current will then decay with a time constant of about 29 seconds. The current and energy ratios as a function of time after quench are shown in Fig. 9.9.2. This time constant is about ten times longer than the CERN value. Therefore the eddy currents in the iron should be about ten times smaller. The effects on the reproducibility of the magnetic field should be acceptable based on the CERN experience. Calculations of the effects of the iron eddy currents with the magnetic field analysis program OPERA are proceeding. We have allotted time for quench-back and field reproducibility studies during the magnetic field shimming process (see Chapter 21). If power is lost, the current will decay with a time constant [5] of about 800 sec. The maximum voltage developed during the quench is:

$$V_m = NA\frac{dB}{dt} = (48)\left(25m^2\right)\frac{1.5T}{29s} = 62\ V$$

The insulation has been tested to over 1 KV.

As can be seen in Fig. 9.9.2, over 60% of the magnet stored energy will be dissipated by the 0.01Ω resistor. The 29 second time constant dominates over the other quench time constants (see Table 9.9.3). The hot spot temperature will be less than $100°K$. The criteria

Figure 9.9.2: Current and Energy Ratios During a Quench

Table 9.9.3: Time Constants

is that the hot spot temperature remain less than $300°K$. Quench-back will occur in less than 2 seconds. This makes every quench effectively identical.

9.10. References

1. M.A.Green, *Muon g-2 Note No. 159*, *Design Parameters for the g-2 Solenoid Power Supply and Quench Protection System*, May 1993.
2. K. Halbach, Nucl. Inst. and Meth. 107, 529 (1973).
3. CERN Logbook 2, 33 (1974).
4. H. Drumm et al., Nucl. Inst. and Meth. 158, 347 (1979).
5. W. Morse, *Minutes of April 13, 1994 Energy Extraction Workshop.*