APPENDIX E

CONDUCTOR STABILITY

E.1 Conductor Stability

The DØ magnet conductor is stabilized with high-purity aluminum and sufficient stabilizer has been included to limit the final peak temperature in the event of a quench, as described in Chapter 11. Because the stored energy of the magnet is smaller than e.g. the Aleph detector solenoid [1] a smaller amount of pure aluminum is required for this purpose than was used for the Aleph conductor. Thus although the current density averaged over the conductor is larger for the DØ magnet, the figure of merit pertaining to quench safety, total magnet cold mass divided by magnet stored energy, for the DØ magnet (Figure E.1) is not largely dissimilar from Aleph and other thin solenoids.

The amount of high purity aluminum included directly affects the stability of the conductor however. Because the radiation length thickness of the DØ magnet was not required to be especially thin as much high purity aluminum as possible was incorporated in the design of the conductor as was permitted by the thickness budget of the magnet and as was judged consistent with overall windability of the conductor given the rather small radius of the DØ magnet. Given that the conductor current density remains higher than other larger magnets, it is particularly useful to compare the resulting stability margins of the magnet with that of other thin magnets to ensure that the reduction in stabilizer has not jeopardized the performance of the coil.

E.2 Steady-State and Transient Heating

Steady heating in the magnet is not the concern. By assumption such heating, from e.g. conductor joints, or heat radiation and conduction from the cryostat, has been made sufficiently small such that the cooling available to the coil is more than adequate to remove this heat and maintain the coil at the desired low temperature. Care in the design and manufacture of the coil and cryostat, and in the specification of the cryogenic system, can justify this assumption.

Transient heating however can easily degrade the performance of the magnet so that at worst it never reaches its design operating current or, less seriously, enables the magnet to reach full field only after extensive "training". Transient disturbances, stemming from e.g. energy released by cracking epoxy or inelastic motion of a section of conductor, are generally believed to be the sources of energy that can cause coil performance to be degraded.

As is well understood, if a quantity of energy is absorbed by a conductor, the final temperature of the conductor is limited only by its enthalpy and any cooling effects available to the conductor. The critical current of the conductor falls with increasing temperature so that if the temperature begins to rise due to the absorption of heat, at some point the conductor can no longer carry the full current without losses and an increasing fraction of the current begins to generate ohmic heating. This "current sharing" process cascades (unless there is sufficient cooling to prevent it) until the conductor is entirely quenched, ie. has been driven completely normal.

In the absence of any cooling the specific energy sufficient to drive a bare superconductor normal is extremely small. The exact margin is given only by the fraction of the critical current the conductor is carrying before the disturbance occurs. If the conductor is carrying 100% of its critical current it can tolerate no disturbances at all without entering the current sharing mode.

E.3 The MPZ Theory

Superconductor stabilized against flux jumping is typically prepared in a matrix of normal-conducting metal. In addition to providing a low-resistance parallel path for the current in the event that some or all of the current is driven out of the superconductor, this metal adds to the stability of the conductor in two ways. First, it increases the enthalpy available to absorb heating, and second, it provides a conduction path for heat to be carried away from a hot spot into cooler portions of the windings.

This second mechanism is exploited by the MPZ ("minimum propagating zone") theory of Wipf [2], Martinelli and Wipf [3], and Wilson and Iwasa [4], to explain the stability margins observed in actual magnets.

The MPZ theory postulates that for all disturbances below a certain critical energy, a transient normal zone in the magnet is created which thereafter decreases in size because the heat generated in the windings driven into the current sharing mode by the disturbance is conducted away from the zone by the stabilizer of the conductor. The initial normal zone created by the disturbance is smaller than the MPZ and does not propagate. For disturbances greater than this critical energy, the normal zone grows in size without limit because the heat generated by the normal windings exceeds the cooling provided by the stabilizer. The zone exceeds the MPZ and propagates.

The theory is relatively straight forward to apply to a winding design that does not involve helium coolant in direct contact with the conductor [5] The magnet windings are approximated by an anisotropic continuum of metal and insulator, the temperature-dependent properties of the materials and the critical properties of the superconductor are supplied, and the size of the largest stable (elliptical) zone where the superconductor has been driven into the current-sharing mode, plus the surrounding shell where the temperature is decreasing back to the bulk of the magnet, is found. The summed energy in the two parts of the windings is then calculated by integrating the specific heat of the windings involved over the temperature range specified. This is the minimum energy pulse, the E_{mpz}, capable of creating an expanding normal zone in the magnet.

The MPZ energy of an magnet made with a typical Cu:NbTi conductor without extra normal-metal stabilizer and potted into a winding structure is quite small(see figure **E**.2).

A winding design made with a conductor deliberately stabilized with extra normal metal can have an MPZ energy much larger than that measured in Figure **E**.2. Following the notation of Wilson we calculate the MPZ of the **DØ** magnet:

$$E_{mpz} = E_{tot} = E_o \times (\varepsilon_g + \varepsilon_h)$$

where $E_o = \frac{4}{3}\pi\alpha^2 R_g^3 \gamma H_o$. The normalizing factor E_o is just the enthalpy of the winding in the elliptical-shaped "generation" region at θ_o, where R_g is the major axis of the ellipse and $\alpha = (k_r/k_x)^{1/2}$, with k_r and k_x the thermal conductivities in the radial and longitudinal directions in the winding, so that αR_g is the minor axis of the zone, and γH_o is the enthalpy in the winding at the temperature θ_o (γ is the density). The dimensionless terms ε_g and ε_h are integrals from θ_o to θ_g in the "generating" zone and the "halo" zone of the MPZ. The "generating" zone lies inside the radius R_g which contains the conductor driven into the current sharing regime beyond θ_g and the "halo" zone lies outside the radius R_g out to a "cold boundary" radius at θ_o.

Wilson presents the solution for the sum $\varepsilon_t = \varepsilon_g + \varepsilon_h$ as a function of $\beta = (\theta_o - \theta_g)/\theta_o$ in Figure **E**.3

E.4 Applying The MPZ Theory

By evaluating β for a given conductor [where one assumes J_c falls linearly with temperature so that $\theta_g = \theta_c - (\theta_c - \theta_o)J_m/J_c$, and so $\beta = (\theta_c - \theta o)J_m/J_c$] one finds ε_t from Wilson's curve, and calculates E_o from the parameters appropriate to the magnet in question so that the MPZ energy follows immediately. In what follows α is used to describe the radial thermal conductivity ratio and ϵ the axial thermal conductivity ratio since these are so dissimilar in the **DØ** magnet. Wilson's term α^2 is then replaced by $\alpha\epsilon$.

Before inserting numbers, it is helpful to examine the MPZ formula to see how this quantity can be maximized. One notes that ε_t increases nearly linearly with $\beta = (\theta_c - \theta o)J_m/J_c$ so that one wants to operate the magnet at a temperature θo as far below the critical temperature of the conductor as practicable, and one wants to minimize the ratio J_m/J_c i.e. operate at as low a fraction of J_c as practicable. These results are intuitively obvious.

The quantity E_o is maximized by making $\alpha\epsilon$ large, by making R_g large, and by making γH_o large. A winding design with high turn-to-turn (and layer-to-layer) heat transfer is exceedingly advantageous in increasing α and ϵ.

Now

$$R_\phi = \pi\left(\frac{k_r(\theta_c - \theta_\phi)}{\lambda_w G_c}\right)^{1/2},$$

where λ_w is the fraction of the windings occupied by conductor and $G_c = \rho\lambda^2 J_m^2/(1-\lambda)$. λ is the fraction of superconductor in the conductor and J_m is the current density in the superconductor.

Note R_ϕ is maximized by maximizing k_r/ρ; selecting high purity aluminum (so that its RRR $\geq$ 1000) one can increase this ratio by an order of magnitude over that for OFHC copper in a 2T field.

In Table **E**.1 are the values of the various terms evaluated for the CDF test magnet [6], the **CLEO I** thin solenoid [7], and the **DØ** magnet. Because the CDF test magnet is just a single layer coil and the MPZ radial dimension αR_ϕ is so much greater than the coil radial thickness, we use a two-dimensional elliptical volume just as thick as the winding, $\pi\epsilon\alpha \times R_\phi^2 \Delta r$, rather than the fully spheroidal volume given by Wilson in E_c above.

E.5 Conclusions

The CDF test magnet was quenched at a current of 5000 amperes with a fast energy pulse of 13 Joules. The agreement between this value and the MPZ prediction is instructive; the MPZ result, involving as it does estimations of the various parameters actually pertaining to the coil, cannot be considered more accurate than a factor of two or so, but it can clearly predict the "neighborhood" of stability of a winding design, as it did for the coil in Figure **E**.2.

We note that the MPZ calculations predict a smaller stability margin for the **DØ** magnet than the CDF test magnet; such is the consequences of a two-layer winding design where a significant thermal barrier must be placed between winding layers. An examination of the results from the **CLEO I** calculation can reassure us that this reduction is not likely to be critical.

From the table we see that the **CLEO I** magnet has an MPZ typical of marginally stabilized magnets like that shown in Figure **E**.2. The **CLEO I** parameters were evaluated for the magnet operating at 1.0 **T**, and from the fact that it operated at this level routinely it can be concluded that the spectrum of transients to which it was exposed never exceeded the MPZ energy given in the table. Since it is hard to see how thin magnets which have added stabilizer would be subject to larger transients, assuming they are as carefully made as was **CLEO I**, they are evidently stable against transients many times larger (evidently by many orders of magnitude) than they actually experience. The successful operating experience with the many aluminum-stabilized solenoids in particle detectors that have been built supports this conclusion; evidently we may conclude that the **DØ** magnet is sufficiently stabilized for proper operation at full design current.

References

[1] J.M. Baze, *et.al.*"Design, Construction and Test of the Large Superconducting Solenoid Aleph", IEEE Transactions on Magnetics, Vol 24, No. 2, 1988.

[2] Wipf, S.L, Los Alamos Scientific Laboratory Report LA 7275, 1978.

[3] Martinelli, A.P. and Wipf, S.L., Proceedings of the 1972 Applied Superconductivity Conf, Annapolis, IEEE, New York, p 331.

[4] Wilson, M.N., and Iwasa, Y. "Stability of Superconductors Against Localized Disturbances of Limited Magnitude", Cryogenics 18, 1978, p 17.

[5] Wilson, M.N., "Superconducting Magnets", Clarendon Press, Oxford, 1983.

[6] S.Mori, et.al., "Construction and Testing of Superconducting Solenoid Magnet Model for Colliding Beam Detector", Advances in Cryogenic Engineering Vol 27, p 151, Plenum, New York, 1982.

[7] D. Andrews, et.al., "A Superconducting Solenoid for Colliding Beam Experiments", Advances in Cryogenic Engineering, Vol 27, p143, Plenum, New York, 1982.

Table E.1: MPZ Calculation			
Parameter	CDF Test Magnet	CLEO I Magnet	DØ Magnet
I_m [A]	5000	1500	4825
J_m [$10^5 A/cm^2$]	1.68	1.36	1.35
λ	0.04	0.20	0.062
I_{op}/I_c	0.63	0.43	0.57
ρ [$10^{-8} Ohm-cm$]	4.0	19.5	5.0
G_c [W/cm^3]	0.198	90.2	0.373
k_r [W/cmK]	23	0.5	18
k_z [W/cmK]	23	0.035	0.153
k_n [W/cmK]	0.092	0.071	0.022
α	1.0	0.265	0.092
ϵ	0.063	0.377	0.035
λ_w	0.97	0.92	0.86
$\theta_c(B)$ [K]	8.7	8.8	8.3
θ_o [K]	4.5	4.6	5.1
R_p [cm]	55.4	0.33	31.6
E_o [J]	1.6	2.8×10^{-5}	0.59
e_L	9	7	6
E_{mpz} [J]	14	2×10^{-4}	3.5

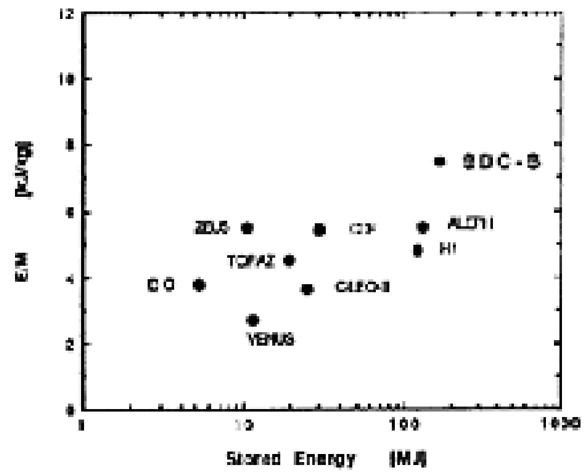

Figure E.1: Stored Energy per Unit Cold Mass vs. Stored Energy for Various Detector Magnets.

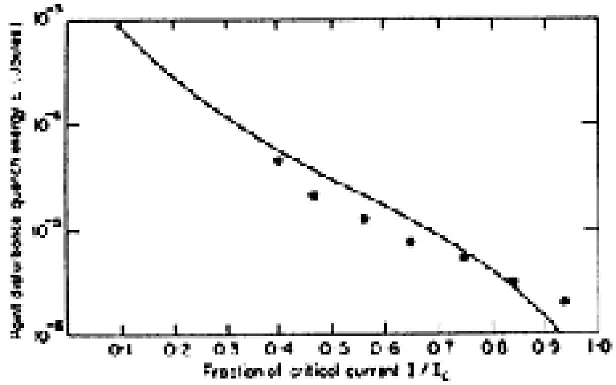

Figure E.2: MPZ energy for an epoxy-filled magnet. The points are measured values, the curve is the MPZ theory.

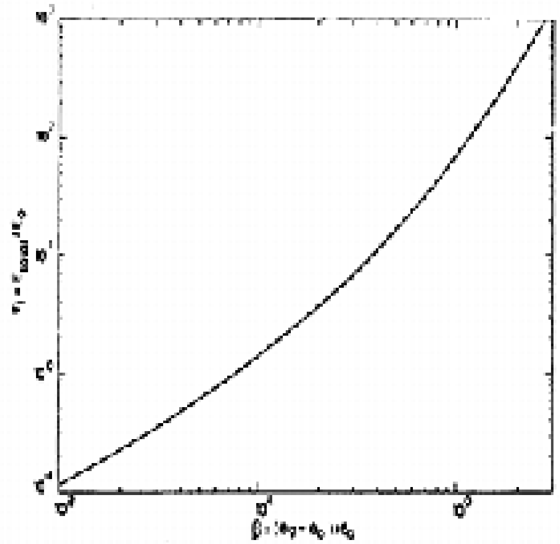

Figure E.3: Unnormalized MPZ Energy as a Function of Temperature Parameter β.