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CRYOGENIC STABILITY OF HOLLOW S/C CABLES IN A TRANSVERSE MAGNETIC FIELD GRADIENT

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INTRODUCTION

A few magnets, designed for specialized duty, like the thin magnets for High Energy detectors, some magnets for energy storage and the beam magnets for proton accelerators, are wound in one or two layers. Therefore the magnetic field varies across the cable section by a large amount. We think that the conductor stability must be studied and tested, in these cases, taking into account the magnetic environment of the cable in the coil, and not, as usual, with B as a free parameter.

As a consequence of the field gradient, the conductor, above its critical current I_c, will divide in two or three zones, corresponding to the superconducting, current sharing and normal regimes, and the current will distribute across the conductor in a nonuniform way. The study of the conductor stability in these conditions is quite complex, but becomes easier if the cable cross section can be considered onedimensional, as for instance when the cable is in the shape of a tube.

The calculations reported in this paper have been done to study the stability of a forced flow conductor to be used in the GEM magnet for the DELPHI detector at LEP[1] (fig. 1). Our model is appropriate to S/C cables having the following characteristics: 1) the S/C strands or filaments and the stabilizer, form a tube of small thickness/diameter ratio; 2) the S/C components are

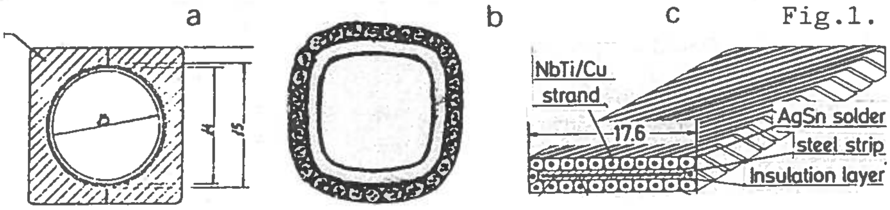

Fig.1. Examples of conductor
a) GEM[2]
b) SULTAN[3]
c) TESPE[4]

helically wound; 3) the thermal conductivity and the thermal and electrical contact between the components are good. We will study the cryostability of the S/C cable under the assumptions made in Stekly[4] theory. A further simplification is indeed obtained since the cable can be considered isothermal and the magnetic field uniform along the cable length.

THE MODEL OF THE CONDUCTOR

Under the given assumptions and in a uniform magnetic field, we describe the tube wall as an homogeneous composite with non-linear and anisotropic electrical properties.

We find, at first, the constitutive equations (E vs J relationship) in a frame which has a "l" (longitudinal) axis parallel to the S/C filaments and a "t" axis transverse to it. In the longitudinal direction the S/C component is electrically in parallel with the matrix. We use the simple model of current sharing which gives

$$E_L = 0 \qquad J_L < J_c \tag{1a}$$

$$E_L = \rho_L (J_L - J_c) \qquad J_L > J_c \tag{1b}$$

$$E_L = \rho_L J_L \qquad J_c < 0 \tag{1c}$$

where the J's are normalized to the total composite area. In the transverse direction the nonlinearity is small and an ohmic law ($E_T = \rho_T J_T$) can be used. If the cable is well stabilized we can neglect also the difference between ρ_L and ρ_T. Indeed we can define a reduced current density $j = J/J_{coo}$ and a reduced electric field $e = E/\rho J_{coo}$ where J_{coo} is the critical current density at some reference conditions.

We assume that the critical current density of the S/C material has a linear J vs T dependence, and a B dependence as given in ref. 5. In reduced form we can write

$$j_c(\tau,B) = J_c(\tau,B)/J_{COO} = (1-\tau-\gamma B)/(1+\gamma B) \qquad (2)$$

where $\tau = (T - T_b)/(T_{CO}-T_b)$ is the reduced temperature, T_b is the bath temperature, T_{CO} the critical temperature in zero magnetic field, J_{COO} the critical current density at T_b and B=0 and γ an adjustable parameter of the order of 1/10 for NbTi.

We calculated in detail the magnetic field of a round tube arranged in a winding of N layers, with a distance "a" between adjacent conductors of outer radius "r". We verified that the changes in the current distribution due to the cable transition hardly influence the magnetic field at the outer radius of the conductor. Here we have almost everywhere the maximum field on any strand (at least for $\theta > 60°$) and we assume that J_c depend on the field modulus at this position. The field of the nth layer, neglecting the small coherence between the disuniformity of different layers, can be written in complex form as:

$$B = i\beta \left[\frac{(2n-1)}{2N} j_{im} - \cot g\left(\frac{\pi r}{a} e^{j_{im} 2(\eta-1)}\right)\right] \qquad (3)$$

where j_{im} is the imaginary unit. Other examples have been carried out, like flattened and squared cables. In these cases we assumed the field to have a linear gradient across the winding complex.

THE POWER DISSIPATION

To obtain the cable characteristics, i.e. the voltage and the power dissipation as a function of the flowing current, we must obtain the distribution of electric field and current density in its section. As said before, due to the nonuniform magnetic field, the conductor will be split, above I_c, in two or three zones, which moves gradually towards the lower field side on increasing the circulating current. Two possible paths are shown in fig. 2, but the three regimes (way 2) can coexist only if the J_c vs B dependence is very steep or if the overall current density in the coil is very high. Under the assumptions of uniform temperature and no y-dependence for B, the fields e and j do not depend on y and the problem is indeed one-dimensional. From the continuity equation for the current density ($\bar{\nabla}.\bar{J}=0$) we obtain that $J_x(x)$ is a constant (J_{xo}) and

$$\Phi_{Jy} = i \qquad (4)$$

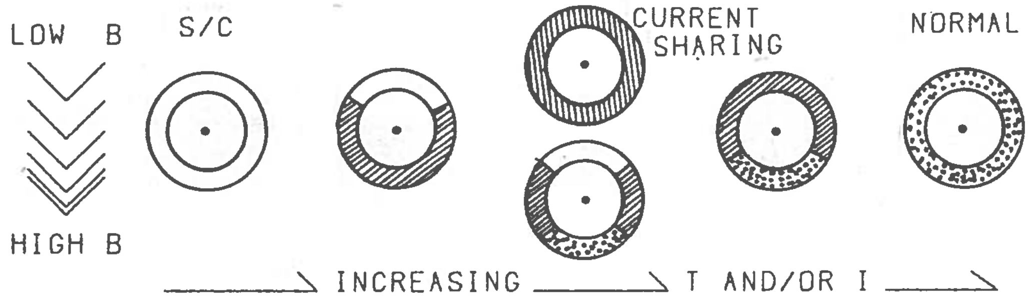

Fig. 2. Possible zoning of the conductor.

From the Maxwell equation ($\bar{\nabla} \times \bar{e}=0$) we find that e_y too is a constant (e_{yo}) and

$$\oint e_x dx = 0 \tag{5}$$

Indeed, only e_x and j_y vary across the cable circumference;in the superconducting zone we have:

$$\begin{bmatrix} e_x \\ j_y \end{bmatrix} = \begin{bmatrix} tg\,\theta & 1/\cos^2\theta \\ 0 & -tg\,\theta \end{bmatrix} \begin{bmatrix} e_{yo} \\ j_{xo} \end{bmatrix} \tag{6a}$$

in the current sharing zone

$$\begin{bmatrix} e_x \\ j_y \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} e_{yo} \\ j_{xo} \end{bmatrix} + j_c(x) \begin{bmatrix} sen\,\theta \\ -\cos\theta \end{bmatrix} \tag{6b}$$

and the same expression, with $j_c(x) = 0$, in the normal zone. So we see that the x dependence is effective only in the current sharing regime and is simply related to the $j_c(B(x))$ dependence. Substituting the above relationships in (4) and (5) we get a linear system for j_{xo} and e_{yo}, whose coefficient depends both on known parameters (i and τ) and on the position of the borders between the various zone, to be determined otherwise. This system can be solved and we obtain:

$$e_{yo}(\eta_{12},\eta_{23}, \int j_c(\eta) d\eta , i) = \frac{(1-\eta_{12})i/2 - \int j_c(\eta) d\eta \; sen\,\theta}{(1-\eta_{12}) + \eta_{12} tg^2\theta} \tag{7a}$$

$$j_{xo}(\eta_{12},\eta_{23}, \int j_c(\eta) dy, i) = \frac{\eta_{12} i/2 \; tg\,\theta + \int j_c(\eta) d\eta \cos\theta}{(1-\eta_{12}) + \eta_{12} \; tg^2\theta} \tag{7b}$$

where η_{12} and η_{23} are the reduced coordinate of the separation lines between S/C (1), current sharing (2) and normal (3) zones. At the border between the S/C and the current sharing zone the current density in the S/C filaments direction is equal to the critical current density

$$j_c(\tau, B(\eta_{12}), i) = j_L(\eta_{12}, \eta_{23}, \int j_c(\eta)\, d\eta, i) \qquad (8)$$

while the critical current density is zero at the border between current sharing and normal zones.

$$j_c\,(\tau\,, B(\eta_{23})) = 0. \qquad (9)$$

B(x) being fixed it is possible to solve (9) for η_{23}, reducing (8) to an equation in η_{12} only.

From the above model we can get a picture of the distribution of currents and electric field in the cable at various circulating currents. In the fully superconducting state the current will flow parallel to the S/C filaments and in the normal state parallel to the cable axis. When two or three zone are present together, the current will flow at an angle $\theta_{S/C}$ between θ and $\pi/2$ in the S/C zone, where the electric field will be perpendicular to the filaments. In the current sharing zone it will curve gradually towards the cable axis and will flow again at fixed angle $\theta_n > \theta_{S/C}$ in the normal zone.

<u>The numerical results.</u>

We solved the above model by computer. In fig. 3 we report the reduced power vs τ , with i as a parameter, for a round cable with r/a=.35, θ =75°, wound in a single layer coil giving 2.4 Tesla at I_c. The graph is divided in three regions corresponding to the coexistence of S/C and current sharing regime, pure current sharing and current sharing-normal regime. At low temperature the power increases more than linearly, due to the reduction of the S/C zone dimension; in the current sharing regime we get a linear behaviour and then a leveling of the power due to the spread of the normal zone. In fig. 4 we compare a round, a square and a flat cable with the same characteristics given above. A second layer is considered, and we note that the curves for the inner layer group together, because the field gradient is less effective.

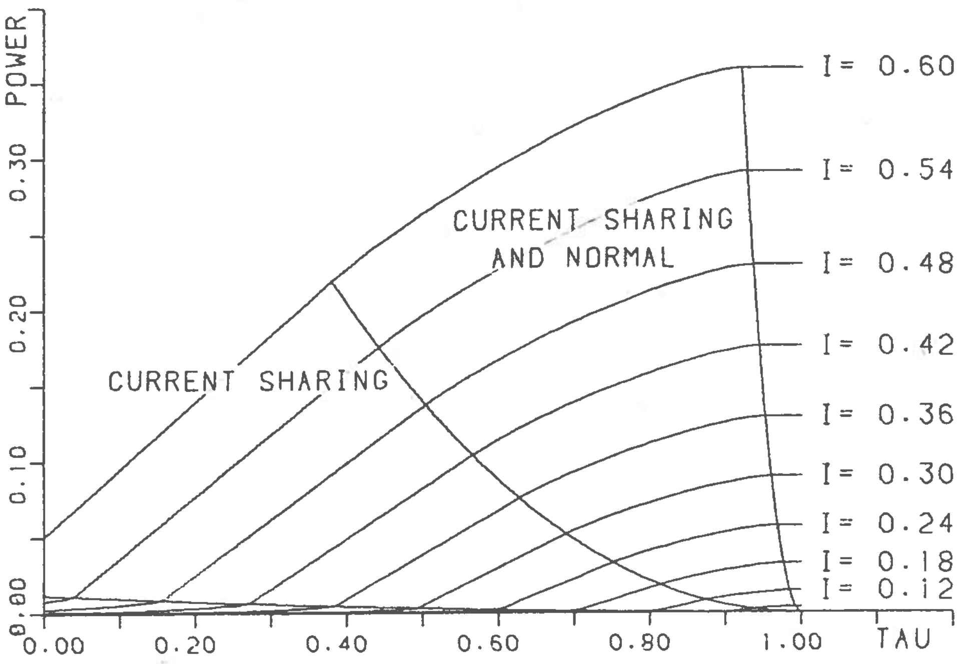

Fig. 3. Reduced power for round cable in single layer 2.4 T coil.

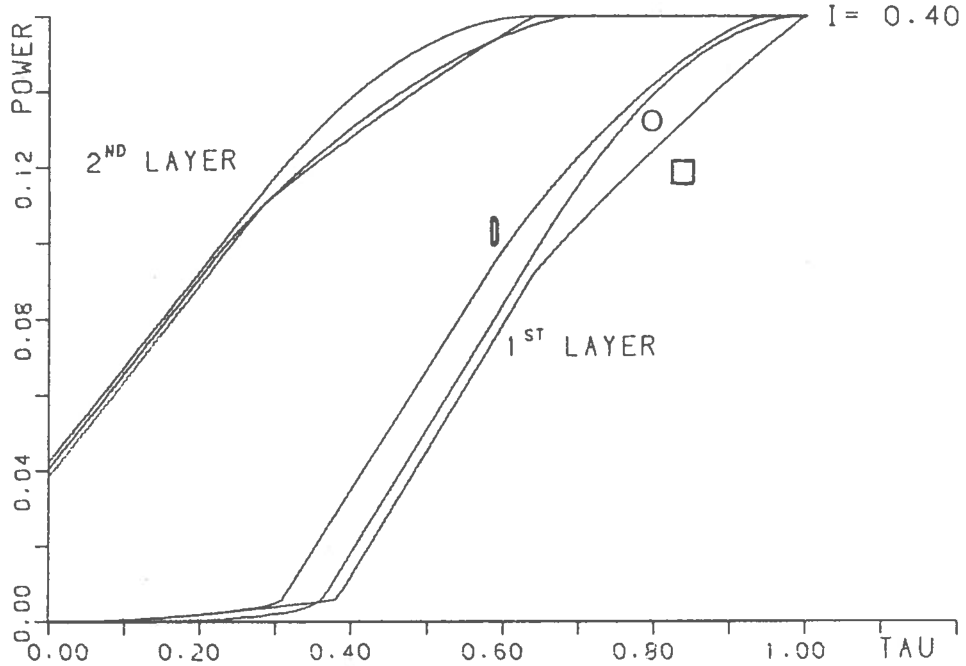

Fig. 4. Comparison between round, square and flat cable.

THE CRYOGENIC STABILITY

To find the cryogenic stability of the conductor we must simply impose a balance between the calculated power dissipation and the heat transfer to the coolant:

$$\alpha_{00} \cdot q(i,\tau) = f(\tau)$$

α_{00} is the well known Stekly parameter calculated at zero field:

$$\alpha_{00} = \frac{\rho A J^2_{c00}}{hP(T_{c0}-T_b)}$$

where A is the stabilizer cross section area, p the cooled perimeter and h the heat transfer coefficient in the nucleate boiling regime. Unlike the standard model, α_{00}=1 is not the limiting condition for complete cryogenic stability.

Results.

The curves of electric field vs circulating current are given in fig. 5a for the 1st and 2nd layer of the same coil as in fig.3. We took α_{00}=.5 and the three regions are clearly seen. The same system, but less stabilized (α_{00}= 3.5) is shown in fig.5b. The main feature that comes out is the existence of a solution partially superconducting above I_c and a second one partially normal in the same current range, even if we assume a linear heat transfer law. In fig. 6a we show the stability plot for an Aluminum stabilized conductor for the GEM coil[1]. The characteristics of this conduc-

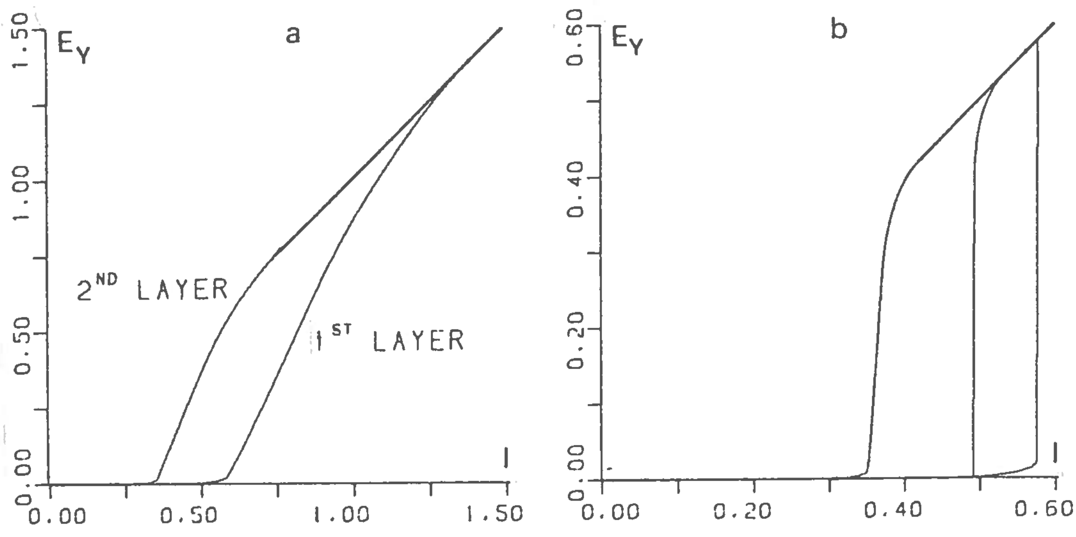

Fig. 5. Cable stability in 2 layer coil. a) α_{00}=.5, b) α_{00}= 3.5

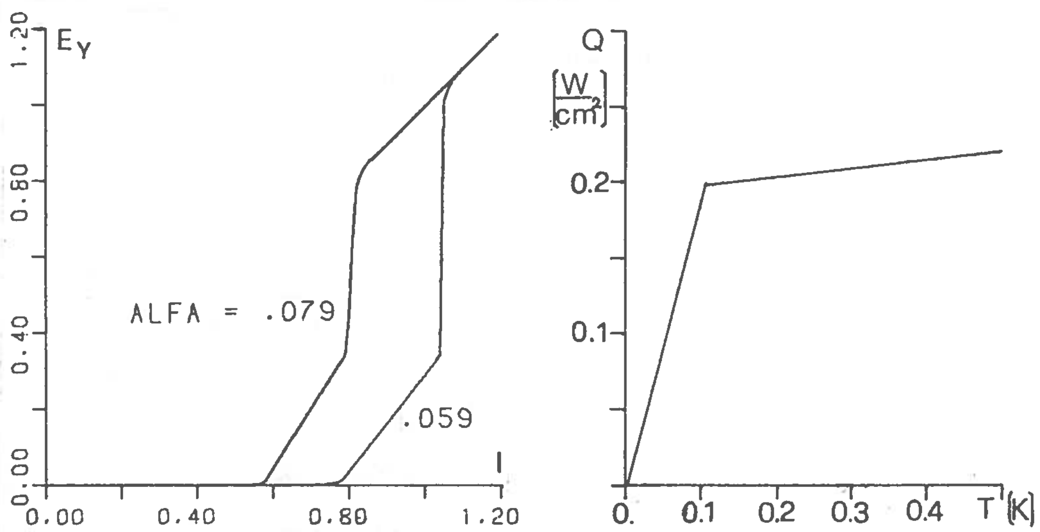

Fig. 6. a) Stability of the GEM cable, b) assumed heat transfer for two phases forced flow.

tor are: I_c=16 kA at 1.2 T and 4.4 K, stabilization by Al of RRR=500 and A=200 mm^2, cooled perimeter p=40 mm, winding angle-75°.The double layer coil will give B=1.2 Tesla at an operating current I=10 kA. The conductor will be cooled by forced flow of subcooled He, at a pressure of 1.7 atm, so we use a nonlinear heat transfer as shown in fig.6b.

CONCLUSION

A simple model has been developed to study the stability of tubular composite cables used to wind coil of a few layers. The effect of the cable shape has been shown. In general the cables result stabler than from a standard analysis in a current range just above their critical current. The characteristics in this region resemble the effect of current transfer and indeed we can describe this way the current rearrangement inside the sample.

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