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**Optimum Copper to Superconductor Ratio in Cables
for Superconducting Magnets at 1.9 K**

R. Wolf

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The duration of the perturbations leading to a quench are estimated from flux measurements made with pickup coils in the LHC dipole models.

The optimum copper to superconducting ratio is then found by studying the minimum quench energy and the influence of the length and the duration of the perturbation and heat transfer to the surroundings. A comparison is made of the behaviour at temperatures of 1.9 and 4.3 K.

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Optimum Copper to Superconductor Ratio in Cables for Superconducting Magnets at 1.9 K

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Abstract - In this paper the optimum copper to superconducting ratio is calculated to prevent quenching for superconducting cables used in accelerator magnets like the LHC dipoles, operating in superfluid helium at 1.9K.

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I. INTRODUCTION

This study was made in the framework of the development of superconducting dipole models at CERN for the large hadron collider (LHC) project [1]. A change of cable design was considered with a smaller copper to superconductor ratio for the strands. This study is similar to other studies made on this subject [3]-[10], but it specifically considers the fact that the superconducting dipoles work in superfluid helium at a temperature of 1.9 K, and takes into account quench measurements on the models itself to establish the time scale and magnitude of the perturbations.

At the moment, the strands in the LHC cables have a copper to superconductor ratio between 1.6:1 and 1.8:1. A number of reasons may exist for not going to a lower ratio like protection during quench or mechanical properties of the cable. This paper tries to find if a lower (say 1.3:1) copper to superconductor ratio could be accepted, by looking at the maximum possible thermal perturbation causing a quench, as function of the Cu:Sc ratio. These calculations were made on a strand by solving the heat balance equation with the following assumptions:

- The Cu:Sc ratio is varied, but the cross-section of the strand is kept constant. This effectively means that the magnet cross-section stays the same and that the load line does not change.
- The transport current is supposed to remain constant, which means that current transfer to neighbouring strands is supposed to be negligible at the onset of the quench.
- The heat balance equation is taken as 1-dimensional at the start of the quench and thermal contact to the surroundings is taken into account by a heat transfer term.

II. EXPERIMENTS ON LHC DIPOLE MODELS.

A. Measurement of Perturbations which Lead to a Quench

Voltage measurements on the magnet coils and flux measurements on pickup coils in the dipole aperture [2] during training of the LHC dipole models have lead to the following conclusions:

- Quenches are often preceded by events of a duration not longer than typically 200 to 300µs, which are interpreted as mechanical movements somewhere in the structure.
- The energy contained in these events calculated from the measured voltages and simple models of mechanical movement is often sufficient to quench a considerable part of the winding.
- The quench does not necessarily start where the event took place. The mechanical perturbation can travel with the speed of sound through the structure and induce the quench somewhere else.

B. Heat Exchange with the Surroundings

Any stability calculation must take into account the heat transfer from the strands in the cable to the superfluid helium. The superconducting cable is insulated with a polyimide tape and a second layer of glass fiber tape, impregnated with epoxy resin. Heat transfer measurements performed at CEA-Saclay [11], have shown that for steady state heat transfer the effective heat transfer is determined by the polyimide layer ($h \sim 50 \text{ W/m}^2$). For pulsed heat transfer, however, the polyimide layer may have to be considered as a 'sponge' penetrated by superfluid helium. Therefore the stability calculations are performed for heat transfer values ranging from 50 W/m^2 to 5000 W/m^2 .

III. CALCULATION OF AN OPTIMUM COPPER TO SUPERCONDUCTING RATIO

A. Method

The method involves solving the one dimensional heat balance equation.

$$\frac{d}{dx} k \frac{dT(x,t)}{dx} O_{cu} + \frac{P_m \cdot I_t}{O_{cu}} I_{cu} - hP(T(x,t) - T_0) + \dot{Q}(x,t) = C \frac{dT(x,t)}{dt} O \quad \dots(1)$$

TABLE I
LIST OF PARAMETERS

Parameter	Description	Unit(SI)
B	magnetic field	T
Bq	quench field on the load line	
C	heat capacity of strand per unit volume	J/m ³
C _{Cu}	heat capacity of copper per unit volume	J/m ³
C _{NbTi}	heat capacity of NbTi per unit volume	J/m ³
Cu:Sc	copper to superconductor ratio in the strands	
f	=I _t /I _q , the transport current relative to the quench current on the load line	
h	linear heat transfer coefficient	W/m ² /K
I _{co}	critical current at operating condition	A
I _{cu}	current in copper matrix	A
J _c	current density in NbTi	A/m ²
I _t	transport current	A
I _q	quench current	A
k	heat conductivity of copper	W/m/K
O	cross section of the strand	m ²
O _{cu}	copper cross-section	m ²
O _{sc}	superconductor (i.e. NbTi) cross-section	m ²
P	strand perimeter	m
Q	heat pulse power per unit length	W/m
Q _p	energy of heat pulse	J
rrr	ratio of copper resistivity at 300K and 4.2K	
T	local temperature	K
T _c	critical temperature	K
T _s	current sharing temperature	K
t	time	s
t _{max}	duration of heat pulse	s
x	position, the heat pulse is always centered on x=0.	m
x ₀	half length of gaussian heat pulse	m
ρ _{cu}	copper resistivity	Ωm

A Kapitza type heat transfer, proportional to $T^n - T_0^n$ with $n \sim 3$ can also be taken into account. See table 1 for the meaning of the parameter names. The current in the copper matrix, I_{cu} , depends on the temperature as $I_{cu} = I_t - I_{c0} * (T - T_0) / (T_c - T_0)$ when $T_s < T < T_c$ while $I_{cu} = 0$ when $T < T_s$ and $I_{cu} = I_t$ when $T > T_c$. The current sharing temperature T_s is defined as $T_s = T_0 + I_t / I_{c0} * (T_c - T_0)$. The heat pulse power $Q(x, t)$ is assumed to be of a gaussian form:

$$Cu/Sc=1.80, RRR=100., H= 0.0W/cm^{**2}/K$$

Fig. 1. An example of temperature profiles after a heat pulse of duration 10 μ s and energy 3.8 μ J over 1 mm which just initiates a quench, with no heat exchange to the surroundings.

$$Q(x, t) = \frac{Qp}{2\sqrt{\pi}} \frac{e^{-\left(\frac{x}{x_0}\right)^2}}{x_0 t_{max}} \quad (2)$$

where $2 * x_0$ is considered the length of the perturbation.

This equation is solved numerically and the energy is determined which just causes a quench. An example of such a calculation giving the temperature rise and electric field over the strand is shown in Fig. 1 and 2.

Fig. 2. The electric field integral over the strand for the example in Fig. 1.

B. Typical Strand Operating Conditions

The calculations are performed at $T = 1.9\text{ K}$ and $T = 4.3\text{ K}$ at various field levels. The magnet operating conditions are imitated by considering a strand with a diameter of 0.835 mm and a Cu:Sc ratio of 1.8, operating with the same current-field relationship as the central dipole field. Some parameters at the usual operating condition at 90% of critical current ($f=0.9$) are listed below.

Parameter	Value at $T=1.9\text{K}$	Value at 4.3K
B	8.59	6.60
I_t	314	241
T_c	5.42	6.43
Cu:Sc	1.8	1.8
rrr	100	100
I_q	349	268
B_q	9.55	7.33
T_s	3.06	4.93
C	631	2650

IV. RESULTS FOR PERTURBATIONS OF LONG LENGTH

There is a fundamental difference between a perturbation spread out over a short or a long length. In the first case the heat conduction along the length of the strand plays an important role due to the large temperature gradient and the short length of the normal region, leading to a higher quench energy. In practice for a long perturbation the current density is so high that the heat conduction at the ends plays no role. From Fig. 3 we see that 'long' means longer than a few millimeters only.

For heat pulses with a duration of up to $200\text{ }\mu\text{s}$ the quenching depends mainly on the heat capacity of the strand and thus favours a low copper to superconducting ratio. The calculations show that only at very high heat transfer rates, of the order of 20000 W/m^2 , not feasible in the LHC magnet, would a copper to superconductor ratio larger than 1.8 be advisable.

V. RESULTS FOR PERTURBATIONS OF SHORT LENGTH

Perturbation of short length would seem the most probable. Local stress release, i.e. due to resin cracking, belongs to this category and even friction due to movement on a larger scale would deposit energy on perhaps many smaller regions. Therefore, the calculations have been usually made for a pulse length of 1 mm , close to strand diameter.

An optimum copper to superconductor ratio could appear because if there is more copper, more heat can be conducted away, however at the same time the quench temperature becomes lower and the enthalpy of the strand goes down.

Fig. 3. Quench energy density as function of the length ($2 \times x_0$) of the pulse at $T = 1.9\text{ K}$, $t_{\text{max}} = 10\text{ }\mu\text{s}$, $h=0$.

A. Influence of the Field

The influence of the field is shown in Fig. 4 for a case with a short pulse and no heat transfer to the surroundings. Note that at $f = I_q/I_c = 0.7$ an optimum appears at Cu:Sc = 0.9.

B. Influence of the Pulse Duration and Heat Transfer to the Surroundings

From Fig. 5 it can be concluded that it is favourable to use a low Cu:Sc ratio at operating conditions.

C. Comparison of $T = 1.9$ and $T = 4.3\text{ K}$

A comparison between the heat needed to quench the strand at 4.3 and 1.9 K shows that about twice as much heat is needed at 4.3 K (Fig. 6). This calculation has been made for a strand operating at 90% of critical current on the load line.

Fig. 4. Quench energy at various field levels at 1.9 K , $t_{\text{max}} = 10\text{ }\mu\text{s}$, $h = 0$. The 'f' indicates the fraction of quench current or field.

Fig. 5. Quench energy at $T = 1.9$ K at 90% of quench current on the load line, for various duration (t , in μ s) of the heat pulse and various heat transfer coefficients (h , in $W/m^2/K$).

VI. CONCLUSIONS

Both for thermal perturbations long in length (>2 mm), of both short and long duration and for thermal perturbation short in length (<2 mm) within the assumed limits of pulse duration ($\leq 200 \mu$ s) and heat transfer ($\leq 5000 W/m^2/K$), the optimum copper to superconductor ratio is rather low (<1) at $T=1.9$ K in high fields. This conclusion that a low copper to superconductor ratio is favourable was also reached by several authors [3]-[6], [8] at 4.3 K.

Fig. 6. A comparison of the heat needed to quench the strand at 1.9 K and 4.3 K operating at 90% of quench current on the load line. Pulse duration (t) in μ s. No heat exchange to the surroundings.

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APPENDIX: MATERIAL PROPERTIES

This appendix lists the material properties used for the calculations.

A. NbTi

$$T_c = 9.2 \left(1 - \frac{B}{14.5} \right)^{0.59} \quad J_c = (J_{c0} - 7.99 \cdot 10^8 B) \left(1 - \frac{T}{T_c} \right)$$

$$C_{NbTi} = 50T^3 + 62BT$$

The thermal and electrical conductivity of NbTi are supposed negligible compared to those copper.

B. Copper

$$C_{Cu} = 96.4T + 6.64T^3 \quad \rho_{Cu} = \frac{1.70 \cdot 10^{-8}}{rrr} + 0.5 \cdot 10^{-10} B$$

For calculating the heat conductivity the Wiedemann-Franz law is supposed to apply: $k_{Cu} = 2.45 \cdot 10^{-8} \frac{T}{\rho_{Cu}}$

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