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SAFETY LEADS

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INTRODUCTION

The current plan for the Fermilab superconducting synchrocyclotron (Energy Doubler) calls for the installation of approximately 1000 superconducting magnets in the 6 km tunnel of the Main Ring accelerator. Its 3×10^8 Joule emergency energy dump system[1] is based on "safety leads" between 4K and 300K situated after every fifth magnet. With this system, when a quench is detected the power supply is turned off and a 0.5Ω air cooled "energy fountain" resistor is switched into the coil buss at each of six energy transfer stations. This causes the magnet current to decay with a time constant of 10 seconds. This decaying current has to be diverted from the developing quench, and this is done by shunting the current out from the group of five magnets containing the quench by means of the "safety leads". Protection for these magnets is achieved by firing their internal heaters which spread the normal zone to a safe size. The magnetic energy of these five magnets is dumped in the helium and mechanically vented.[2]

DESIGN CONSIDERATIONS

The above described particular use for these current leads and the large number required, justify an optimized design. Considerable

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capital savings in room temperature plumbing is achieved by dry (instead of vapor cooled[3]) leads. Advantage can be taken from the infrequent nature of their use to minimize their inactive state heat leak load. The lead itself can be allowed to get hot when carrying current but its junction to the magnets must remain superconducting otherwise the quench will propagate out of the confined five magnet cell. To satisfy this condition the coldest part of the lead (the "quench stopper") has a large contact area to liquid helium.

High voltage to ground (several kV) might develop between the lead and the cryostat, requiring good electrical isolation and making heat sinking to 78K impractical. The lead will conduct heat directly from 300K to 4K through the thermal insulation vacuum space. Several materials were considered for the hot going section of the lead. Numerical calculations for the expected temperature rise of a small segment of lead as function of time were carried out for these materials in the adiabatic approximation. In this approximation, the rate of temperature increase, $\frac{dT}{dt}$, of an element of cross section s and unit length of the lead is determined only by the electric power, $I^2\rho/s$, dissipated in it and its heat capacity μcs:

$$\frac{dT}{dt} = I^2(t)\ \frac{\rho(T)}{\mu c(T) s^2} \tag{1}$$

where $\rho(T)$, $c(T)$ and μ are the resistivity, specific heat and density of the material. In this approximation cooling effects are neglected. Our maximum expected current

$$I = 4.6\times e^{-t/10}\text{kA} \quad \text{(t in seconds)}$$

will cause the element to reach a maximum final temperature, T_{max}, which depends on its initial temperature, $T_{initial}$, and the quench load

$$F = \mu s^2 \int_{T_{initial}}^{T_{max}} \frac{c(T)}{\rho(T)}\, dT = \int_0^{\infty} I^2 dt = 106\times10^6 \text{ J}/\Omega \qquad (2)$$

A new material property, the quench load capability f, can be defined as:

$$f = \frac{F}{s^2} = \mu \int_{T_{initial}}^{T_{max}} \frac{c(T)}{\rho(T)}\, dT \qquad (3)$$

For maximum quench load per heat leak, one should maximize the ratio:

$$\frac{F}{\dot{Q}} = \frac{s^2 f}{\frac{s}{\ell}\int_4^{300} \kappa(T)\, dT} = s\ell z \qquad (4)$$

where $\kappa(T)$ is the thermal conductivity and $z = f/(\int_4^{300} \kappa(T)\, dT)$ is an index-of-merit of the material. Table I presents calculated values for f and z of selected materials for a conservative $T_{initial} = 300K$ and a practical $T_{max} = 514K$.

TABLE I

LOAD CAPABILITY AND INDEX-OF-MERIT OF SELECTED MATERIALS FOR A HEATING EXCURSION FROM 300K TO 514K

MATERIAL	f $\frac{MJ}{\Omega\ cm^4}$	z $\frac{sec}{u\Omega\ cm^3}$
Copper	314	!0
Nickel	56	.26 or .09
Constantan	17.2	.33
Stainless	10.4	.34
Niobium	22.	.14
Titanium	8.4	.08

Constantan was selected instead of stainless for its electrical characteristics as well as for its availability as a well characterized material. The value of f, equations (2) and (3) determine $s=2.5\ cm^2$. This cross section, the specification of an allowable heat leak of .5W and the thermal conductivity integral of constantan (516 W/cm from 4 to 300K) determine $\ell=258$ cm. The known resistivity of constantan ($3.6\times10^{-5}\Omega$ cm) permits an easy estimate of the maximum voltage drop ($4.6\times10^3\times258\times3.6\times10^{-5}/2.5 = 17$V) across the lead, a value needed for electrical considerations.

QUENCH STOPPER DESIGN CONSIDERATIONS

This liquid helium immersed part of the lead cannot be treated in the same adiabatic approximation, a term expressing the heat transferred to the liquid is essential:

$$\mu s\, c(T) \frac{dT}{dt} = I^2(t) \frac{\rho(T)}{s} - h\, p\, (T-T_L)$$

where h is the heat transfer coefficient, p is the perimeter of the quench stopper cross section and T_L the temperature of the liquid.

Numerical solutions of this differential equation for several materials using heat exchange coefficients found in the literature[4] indicated that a copper conductor/radiator 25.4 cm long with 8 cm^2 cross section and a surface area of 5000 cm^2 was suitable. These calculations were based on copper properties that will probably be different for the copper actually used. To overcome this difficulty an actual test of the performance of such a quench stopper was carried out and is described after the construction details.

CONSTRUCTION DETAILS

A five magnet unit is composed of four dipole magnets and one quadrupole magnet. The quadrupole magnet cryostat contains a service volume to house various components necessary for the operation and protection of the system. Relief lines for the helium and nitrogen shield, instrumentation, correction coil power leads, vacuum relief and pumpouts, beam sensors, and transition piping are among those services contained therein. The available space for these components is approximately 36 cm high, 46 cm wide and 51 cm long.

The safety lead is also incorporated in this area. Its dry part was formed from a cable of constantan wire to a shape compatible with the available space. Cable was chosen over solid stock for ease of forming and availability. Nineteen strands of 0.411 cm diameter wire were needed to satisfy the required cross section. This cable was then formed to the shape shown in Fig. 1. Electrical insulation is provided by or .ayer of Kapton followed by one layer of glass cloth tape. Connection at both ends, one to the quench stopper, the other to an extended cable, is via ceramic vacuum feedthroughs. Internal support and standoff is by G-10 saddle pieces.

As previously indicated the quench stopper is a copper conductor with large heat exchange area. To comply with the low profile required by space limitations, this device was made of readily available copper strips 25.4 cm long, 1.27 cm high and .079 cm thick. These were assembled as shown in the insert of Fig. 2, stacked 80 across and furnace brazed to form the assembly shown in Fig. 2. The resulting unit is 25.4 cm long, 1.27 cm high and 12.7 cm wide.

Unlike the safety lead cable which lies in the insulating vacuum space, the quench stopper is in a space flooded with single phase liquid helium (see Fig. 1). During a quench, potentials as high as 5kV could develop between this assembly and ground (the single phase box). Insulation must be provided which will not only withstand this potential difference but will allow the free flow of helium across the "fins" of the quench stopper.

NEMA G-10 pieces surround the finished assembly at all points where it is in close proximity to the walls of the single phase box, as shown in Fig. 1. The placement of quench stopper is in an active cooling region; i.e., directly over the relief line opening. Relief valves are activated at the time of quench detection to prevent overpressure. Helium flowing past the quench stopper fins maintains the splice end of the assembly below the superconducting transition temperature.

QUENCH STOPPER TEST

The first prototype was instrumented with precalibrated carbon resistor thermometers: T_2 near the constantan junction and T_3 near the superconducting cable splice. This prototype was installed after a vacuum encapsulated 76 cm long section of constantan cable. Care was taken to get a reasonably good simulation at the junction between the constantan and the quench stopper. To insure that T_2 and T_3 measured the temperature of the copper, they and some immediate length of their CuNi alloy leads were varnished in a hole drilled in the copper and covered with epoxy to isolate them from the liquid. Another carbon thermometer, T_1, monitored the temperature of a spot in the constantan. A superconducting cable completed the circuit. Figure 3 shows this arrangement. Seven pulses of current simulating quenches, Q1 through Q7, were fired. Shown in Fig. 4 are events Q3, Q6 and Q7 with the resultant temperature excursions of T_2 (top of quench stopper) and T_3 (bottom of quench stopper). Q6 corresponds to a typical maximum quench and Q3 to common weaker quenches. Q7 was a final long held pulse which also had minimal effect in raising the temperature of the bottom of the quench stopper.

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NOTATION

c = specific heat

F = quench load (see eq. (2))

f = quench load capability (see eq. (3))

h = heat transfer coefficient

I = electrical current

ℓ = length of conductor

p = perimeter of cross section

$\dot{Q}$ = heat leak

Q1-Q7 = events simulating quenches

s = cross section of conductor

t = time

T = temperature

$T_{initial}$ = initial temperature of a lead section

T_L = temperature of liquid helium

T_{max} = maximum temperature of lead

T_1-T_4 = thermometers used in the test or their temperatures

z = index of merit

κ = thermal conductivity

μ = density

ρ = resistivity

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3. Transients in vapor cooled leads have been studied by M.C.Jones, V.M.Yeroshenko, A.Starostin and L.A.Yaskin, Cryogenics 18, 337, (June 1978).

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FIGURES

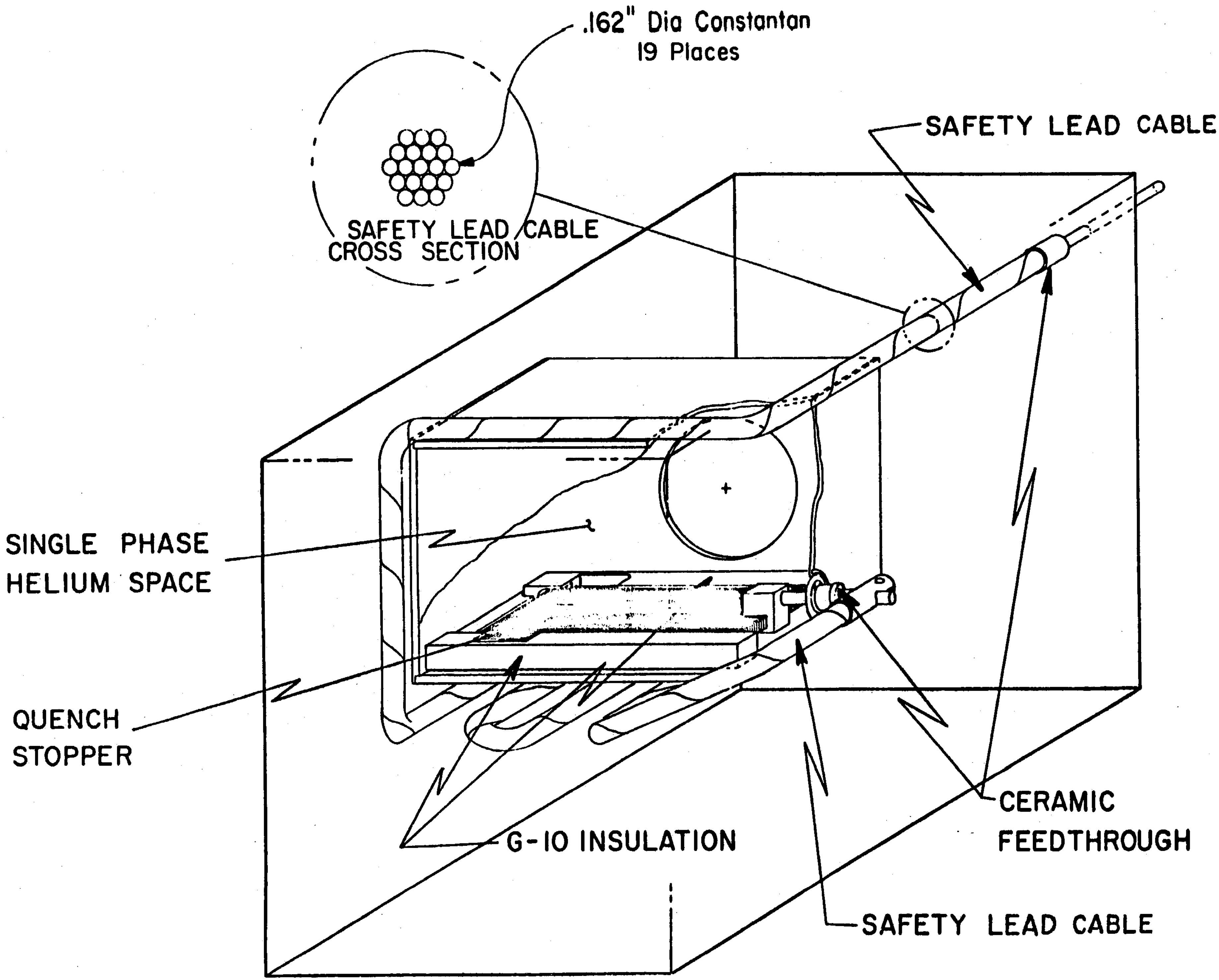

FIGURE 1.

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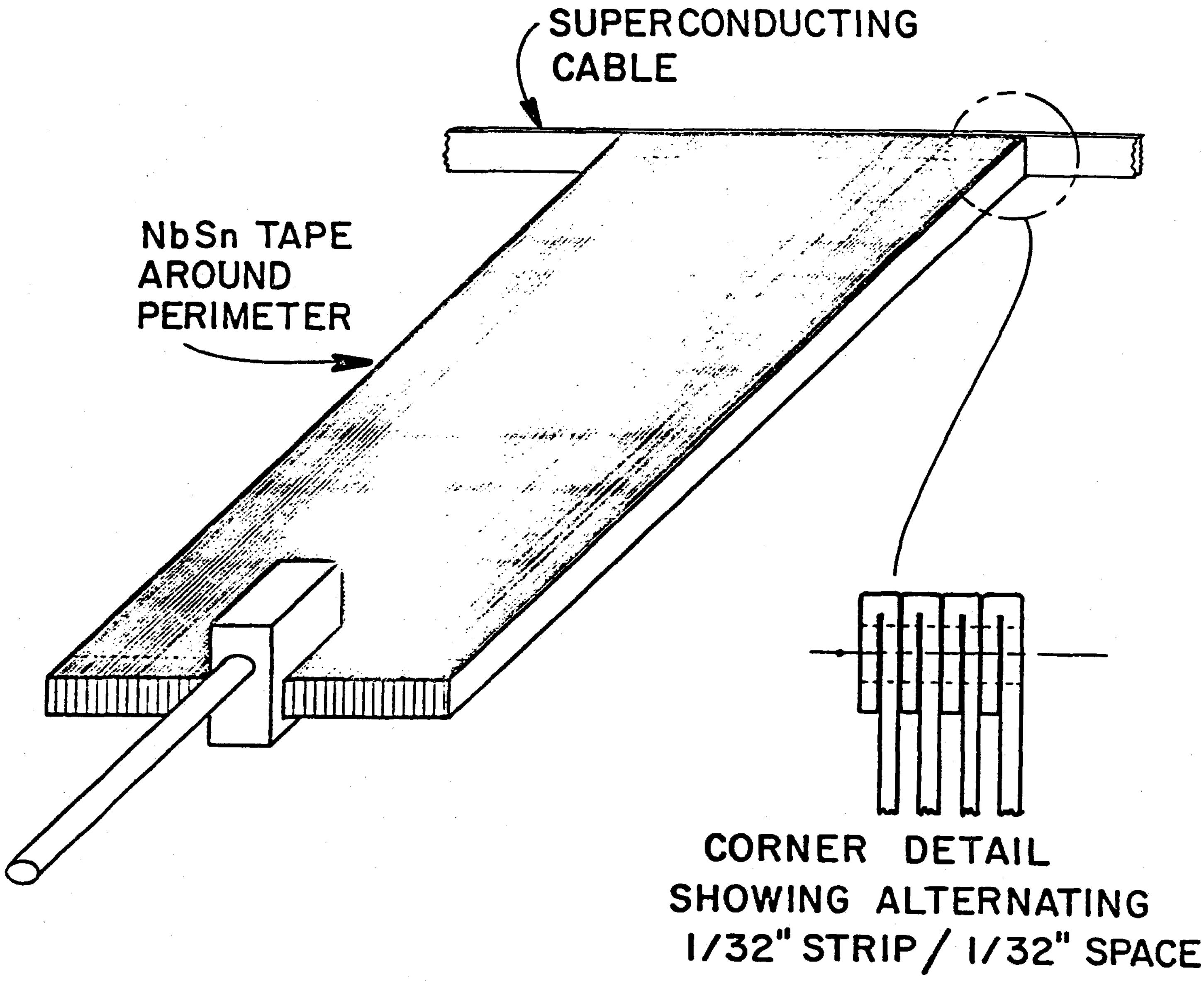
SUPERCONDUCTING
CABLE
NbSn TAPE
AROUND
PERIMETER
CORNER DETAIL
SHOWING ALTERNATING
1/32" STRIP / 1/32" SPACE

FIGURE 2

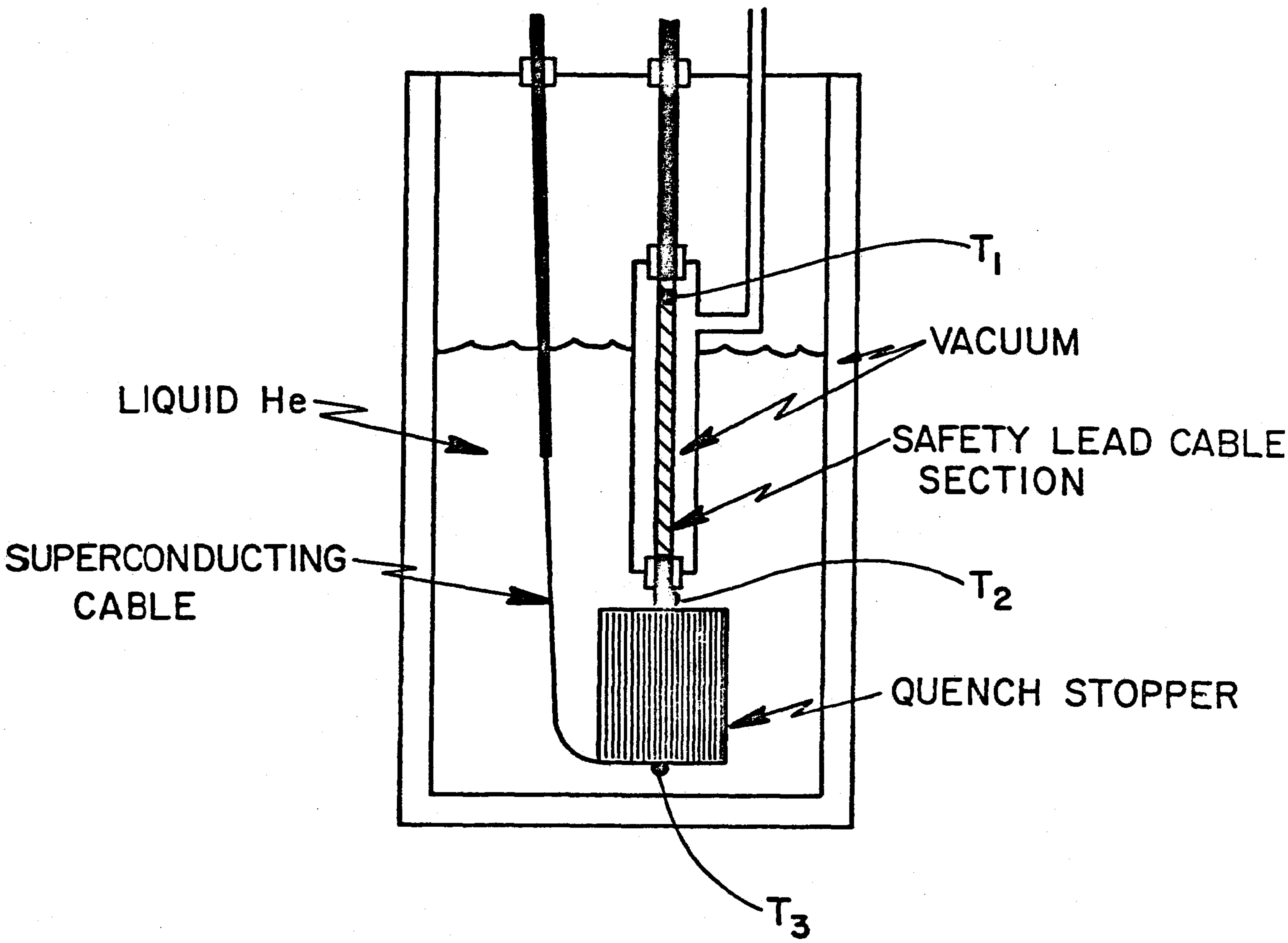
T1
VACUUM
LIQUID He
SAFETY LEAD CABLE SECTION
SUPERCONDUCTING CABLE
T2
QUENCH STOPPER
T3

FIGURE 3

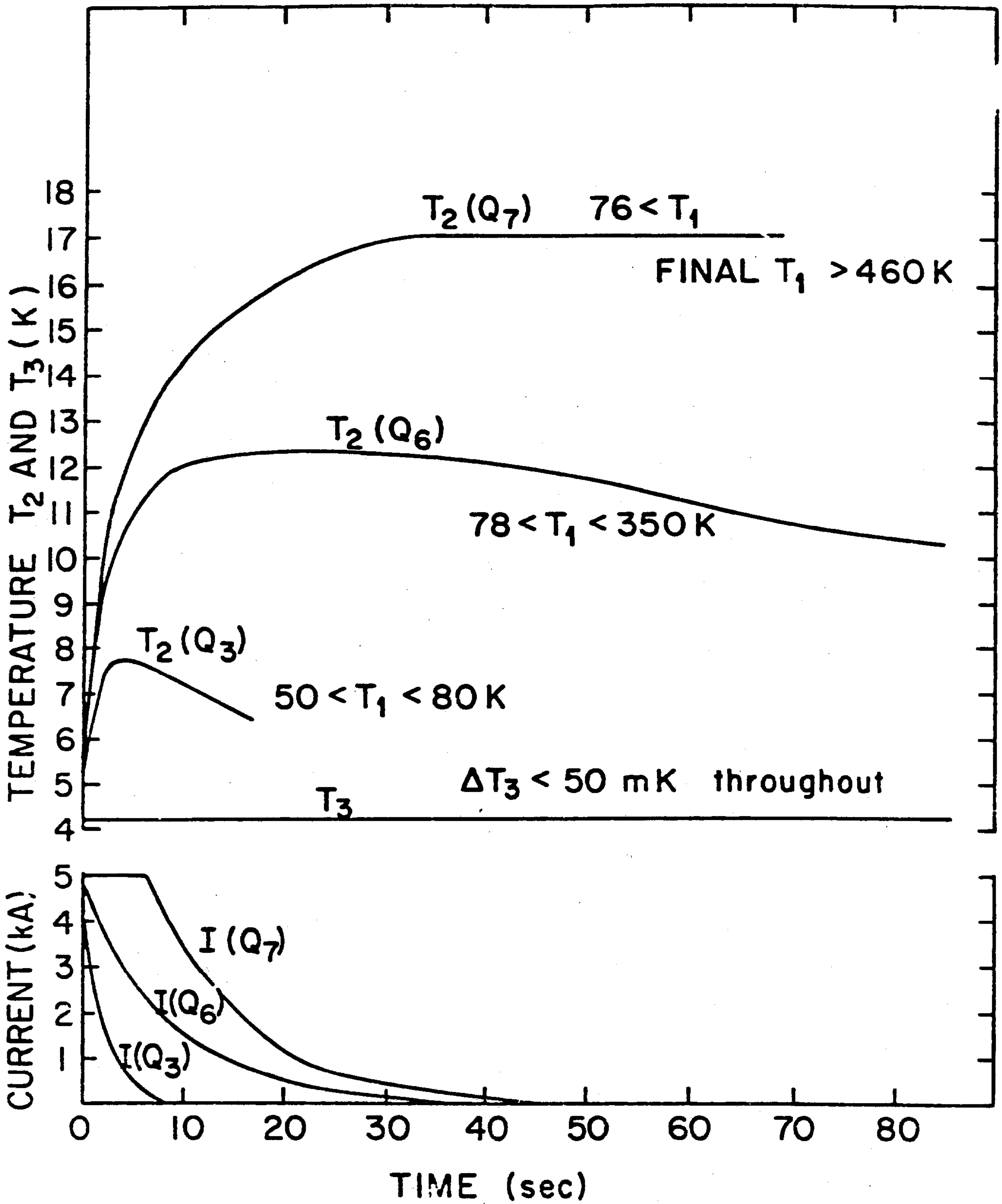
TEMPERATURE T_2 AND T_3 (K)
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
$T_2(Q_7)$ $76 < T_1$
FINAL T_1 > 460 K
$T_2(Q_6)$
$78 < T_1 < 350$ K
$T_2(Q_3)$
$50 < T_1 < 80$ K
$\Delta T_3 < 50$ mK throughout
T_3
CURRENT (kA)
5
4
3
2
1
$I(Q_7)$
$I(Q_6)$
$I(Q_3)$
0
10
20
30
40
50
60
70
80
TIME (sec)

FIGURE 4