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THERMAL ASPECTS OF A SUPERCONDUCTING COIL FOR FUSION REACTOR*

H. T. Yeh

Thermonuclear Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

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Abstract

Computer models are used to simulate both localized and extensive thermal excursions in a large superconducting magnet for fusion reactor. Conditions for the failure of fusion magnet due to thermal excursion are delineated. Designs to protect the magnet against such thermal excursion are evaluated.

Introduction

To produce net power, fusion reactor by magnetic confinement of plasma is likely to employ superconducting magnets. Thus, the problem of quenching and the resulting thermal excursion in such magnets is intimately related to the question of safety, reliability and the protection of such fusion reactors. This paper studies and evaluates several possible modes of thermal excursion in a large superconducting magnet for fusion reactor. Both localized (section 2) and extensive thermal excursion (section 3) in the magnet are discussed. Design considerations will follow in section 4.

Localized Hot Spot

In principle, high temperature spots (hot spots) cannot exist in a cryostatically stabilized magnet. Liquid helium supposedly can remove heat faster than it can be generated in the magnet, even if all the currents flow in the matrix. In practice, this may not be the case as a result of local defects (e.g., thick insulation, vapor locks). If a local hot spot is formed, since a normal zone cannot propagate very fast, if it propagates at all, in a cryostatically stable magnet, one might get a local burn up before the normal zone gets very far. Furthermore, since the hot spots are localized, they may be difficult to detect. Thus, it is of some interest to evaluate whether hot spots are a potential problem in a large magnet.

Consider a one-dimensional composite conductor surrounded by liquid helium at 4.2K. The steady state heat transfer equation is given by

$$\frac{d}{dx}\left[(K_s A_s + K_n A_n) \frac{dT}{dx}\right] - Ph\,\eta + \frac{I^2 \rho_n r_n}{A_n} = 0 \qquad (1)$$

Here, subscripts s(n) denotes superconductor (matrix). In our calculation, the variation of ρ_n, K, h with temperature and magnetic field are taken into account. Current sharing[1] between superconductor and matrix is assumed. Local defect is simulated by having a helium heat transfer efficiency η_d less than one. η is one outside the defect region.

Eq. (1) is solved on computer for a typical set of fusion magnet parameters (Table I). A given P, η_d and T_{max} fixed the half-width X_o of the defect zone. A parameter study varying p and η_d indicates that a hot spot can be stable (neither shrink nor expand) only under the combination of rather extreme conditions; namely, poor local heat transfer coupled with excellent heat transfer to helium in the surrounding (Fig. 1). To make a hot spot stable, the aspect ratio of the conductor needs to be absurdly large. (>15) For stable hot spots (Fig. 2), the voltage across the normal zone can be calculated once the temperature profile is known. (Table I) We note that the voltage signal is of the order of 0.1 volt and the higher the value of T_{max}, the smaller the size of the normal zone. This is a consequence of the fact that, the bath temperature is fixed at 4.2K. The stable hot spots have defect zone of the order of 10 cm. Our result suggest that localized hot spots are not likely to occur in a large cryostatically stabilized magnet.

Uniform and Non-uniform Quenches

The thermal aspect of the quenching of a superconducting magnet is a rather complex problem in itself. Heat conduction is time-dependent and takes place in an inhomogeneous and anisotropic medium. Material properties are strongly temperature-dependent. Heat transfer coefficient between helium and the conductor follows a hysteresis loop. Thus, various approximation schemes are needed in order to have quick approximate answers.

To focus our attention, let us consider a specific coil design. (Table II) The cross-section of the coil is shown in Figure 3. Conductors are layerwound with thin insulation between them. The whole conductor is then insulated and encased in stainless steel. In a thermal excursion, liquid helium is likely to be expelled as a result of the pressure build up in helium. Thus, our model is conservative in assuming that there is no radiation heat loss and in ignoring the heat transfer to helium. To simulate a very unfavorable quench condition (power supplies not disconnected), the current in the conductor is assumed to be constant.

The thermal conduction equation

$$\rho_m c \frac{\partial T}{\partial t} = \vec{\nabla}\cdot(\kappa \vec{\nabla} T) + \dot{Q} \qquad (2)$$

can be rewritten as the thermal diffusion equation of enthalpy,

$$\frac{\partial H}{\partial t} = \vec{\nabla}\cdot (\kappa \vec{\nabla} H) + \dot{Q} \qquad (3)$$

The thermal diffusivity κ is very different for the three components (conductor, structure and insulation) used in the magnet. (Table III) κ is very large for copper at low temperature, nearly constant (~0.1) for stainless steel and quite small for Teflon. This helps to explain why during a quench, the temperature gradient tends to accumulate in stainless steel or insulation. Analytical solutions of Eq. (2) are possible only under rather special conditions[2] and can be used for making crude estimates.

In order to get a more accurate estimate, a versatile heat transfer computer program HEATING-5[3] was used to solve Eq. (2). For our model, $\dot{Q}$ is just $j^2\rho_n$, the Joule heating rate per unit volume, and

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insulated boundary conditions are assumed. The program has been debugged and tested by its author. We have run a few test cases and checked out the convergence for different time steps and lattice sizes. Because of the very small specific heat of copper at cryogenic temperature, very small time step has to be used initially. Variable time steps was used to cut down the computer time.

To illustrate the different behavior between copper and stainless steel during a quench, let us consider a one-dimensional case with uniform current in copper. (Fig. 4) The solutions with coarse grid lattice agrees well with those obtained by fine grid lattice. The temperature in the copper is nearly uniform and drops very rapidly as one gets into stainless steel. We note that estimates based on 77K[4] (vs. 4K) as the starting temperature gives more conservative (higher temperature excursion) results. The results of Figure 4 is misleading in that actually it is the insulation which sees most of the temperature gradient, as is evident from the temperature contour of a uniform quench of our coil (Fig. 5). Without insulation, the temperature gradient will fail in the first few centimeters of stainless steel. As Teflon has an even smaller thermal diffusivity as compared with stainless steel, the temperature drop across it is even more spectacular. Figure 5 says that a temperature difference of more than 200K will develop across the 0.25 cm of Teflon in only 70 seconds. Clearly, Teflon will see large thermal strain and thermal stress in such a quench and it may soon crack.

One may simulate a non-uniform quench by assuming that only one layer of conductor is normal and has Joule heating. The current will again be approximated as constant. For such a quench, we see both a large local temperature gradient near the edge of the layer which is normal and a temperature gradient in the direction transverse to the layers. (Fig. 6) Our result suggests that, however, very little time (a few seconds) is needed before all the layers went above the transition temperature, hence the quench really should behave quite similar to a uniform quench. Of course, thicker insulation, stainless steel interleaving, and the presence of warm helium gas will tend to slow down the heat conduction between layers.

Design Considerations for Thermal Protection

From the last section, we see that the combination of rather extreme conditions (loss of coolant, protection circuit failure, failure in disconnecting power supplies or other coils after quenching) could lead to large temperature gradients in the magnet and the insulation is likely to crack first. Various means could be used to prevent such damages during a quench. One possibility is to use heat drains.[5] For our design, if a thin layer (0.1 cm) of copper-like material (say, anodized Al) is placed between the conductor and insulation, then the heat input to the insulation during a non-uniform quench is effectively diverted, and the temperature gradient in the insulation is very much reduced. (Fig. 7) Copper coating has been suggested as a heat drain for the heat generated in stainless steel due to neutron capture.[6] Figure 8 shows that such copper coating (0.05 cm outside and in the center of the bottom part of the stainless steel coil case) is not effective in relieving the temperature gradient generated in the stainless steel by a uniform quench.

If power supplies (or other coils) continue to pump energy into a quenched coil, eventually, the temperature of the coil will exceed the melting point of its components. A two components model (copper and stainless steel) showed that for uniform quenching the temperature in copper will exceed 300K in 75 seconds (Fig. 9) and exceed melting point in 200 seconds (Fig. 10).

Hence the single most important factor in thermal protection of fusion magnet is to avoid feeding energy into coil after it has quenched. To achieve this, it is necessary to adopt reliability concepts and principles in the magnet protection circuitry design. For example, manual discharge mechanism should be provided, so the magnet operator would have a chance to intervene in case the automatic protection system failed. Power supplies may be disconnected after the magnet has been charged up, and used only intermittently afterwards. Redundant switches may be used in the protection circuit. (Fig. 11) Provided that no external source can feed energy into a quenched coil, the energy stored in a cryostatically stable fusion magnet could be safely handled by the enthalpy of its copper content alone. (Temperature excursion less than 100K).[7]

In conclusion, our results seem to indicate that the type of thermal excursion which could lead to the failure/rupture of a fusion magnet is not likely to occur and can be prevented.

Acknowledgements

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<u>List of Symbols</u>

A	area (m^2)
B	magnetic field (Tesla)
c	specific heat (J/kg-K)
H	enthalpy at temperature T [$\int_0^T \rho_m c dt$] (J/m^3)
h	heat transfer coefficient between helium and conductor (W/m^2)
I	transport current in conductor (A)
i	current density in conductor (A/m^2)
K	thermal conductivity (J/m-K-s)
P	wetted perimeter of conductor (m)
$\dot{Q}$	heat generation and removal rate (W)
r_n	current sharing factor
S_i, S_i'	switches
t	time (s)
T_c	critical temperature (K)
T_{max}	maximum temperature in hot spot (K)
T	absolute temperature (K)
x	distance (m)
x_o	half-width of the conductor defect zone (m)
η_d	helium heat transfer efficiency
κ	thermal diffusivity ($\frac{K}{\rho_m c}$) (m^2/s)
ρ_m	density (kg/m^3)
ρ_n	resistivity of conductor (Ω-m)

Table I

The Resistive Voltage, Defect Half-Width and Maximum Temperature in Hot Spots*

T_{max} (K)	x_o (cm)	V (volt)
300	7.68	0.13
250	8.57	0.11
200	10.20	0.09
150	13.95	0.07
100	20.4[illegible]	0.06
50	Hot Spot Shrinks	

*System Parameters

B= 8 tesla, I= 6000 A, T_c= 5.4K

A= 1.4* cm^2, P= 10 cm, η= 0.2

Ratio (Cu): Superconductor (NbTi) = 4

Table II

Parameters of the Coil Design

Coil thickness	65.5 cm
Coil width	72.0 cm
Insulation (Teflon) thickness	0.25 cm (outside the conductor)
	0.025 cm (between conductor layers)
Conductor* current density	4 kA/cm^2
Stainless steel (310) thickness	4 cm (side)
	0 cm (top)
	15 cm (bottom)

*Conductor properties are approximated by those of O.F.H.C. copper.

Table III

Comparison of the Thermal Diffusivity* of Copper, Stainless Steel and Teflon (B = 8 tesla)

Material \ Temperature (K)	4	20	80	300
Copper (O.F.H.C.)	3077	361	2.7	1.16
Stainless Steel	0.14	0.73	0.068	0.031
Teflon	0.09	0.04	0.016	0.002

*In unit of cm^2/sec.

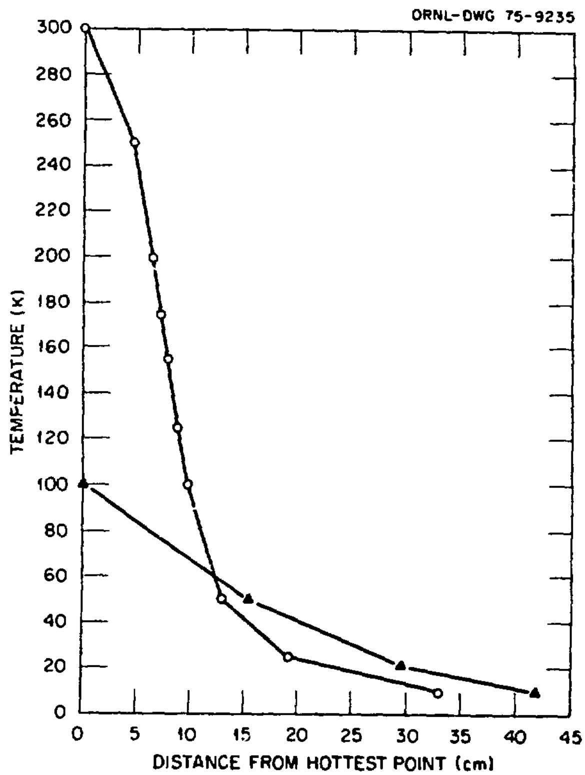

Fig. 1. Parameter study of hot spots (T_{max} = 300K).

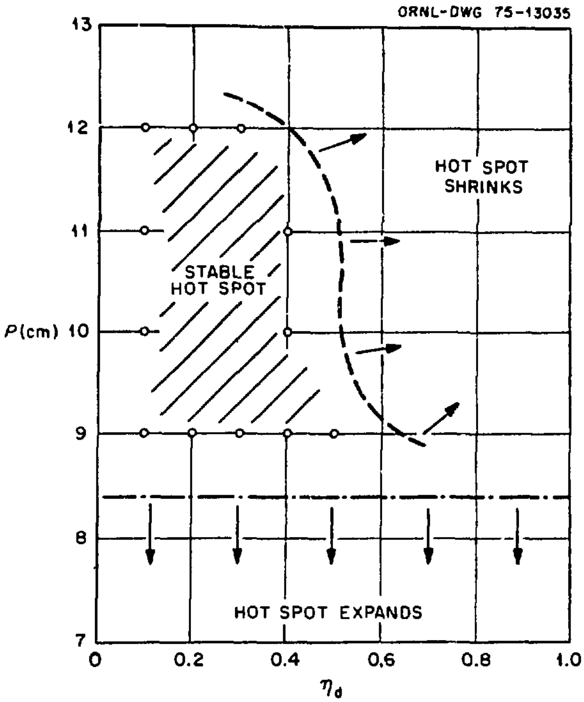

Fig. 2. Hot spot temperature profile ($P = 10$ cm, $\eta_d = 0.2$).

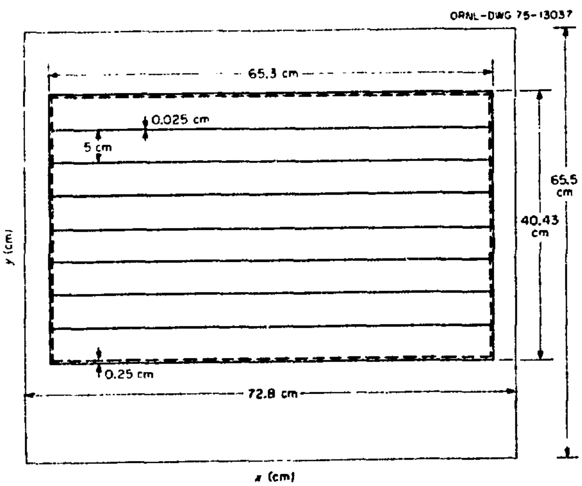

Fig. 3. Cross-section of a coil.

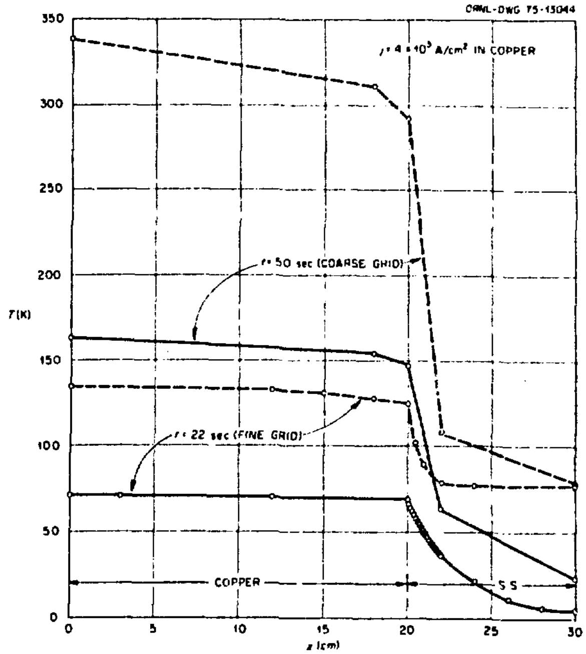

Fig. 4. Comparison of thermal excursions with different initial temperature. (Solid lines 4K, dotted lines 77K).

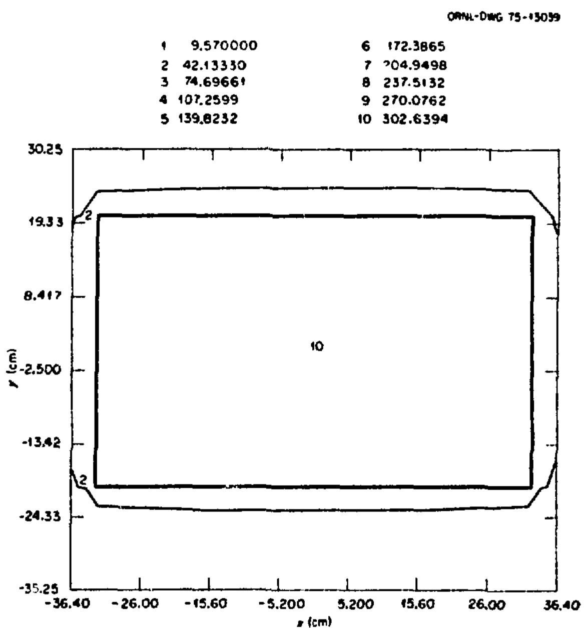

Fig. 5. Temperature contour at $t = 70$ sec. uniform quench, three components (copper, stainless steel, Teflon).

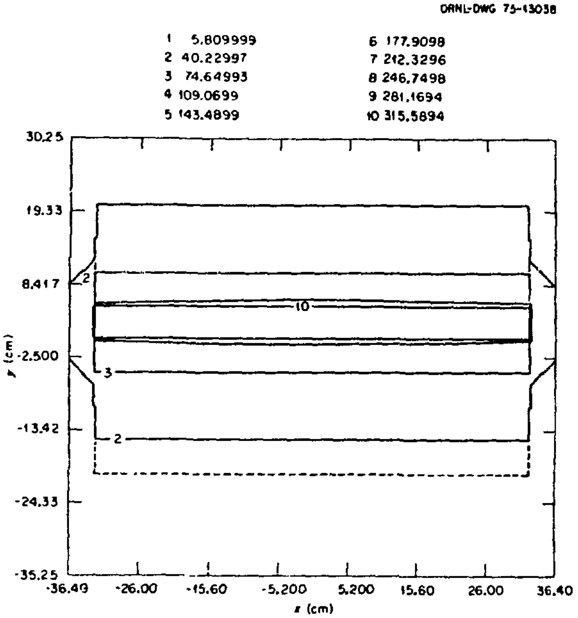

Fig. 6. Temperature contour at t = 100 sec, non-uniform quench, three components (copper, stainless steel, Teflon).

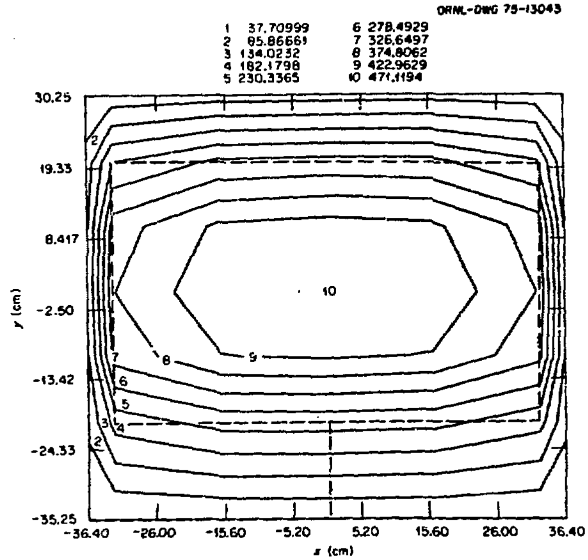

Fig. 8. Temperature contour at t = 95 sec, uniform two components (copper, stainless steel), with heat darin (0.05 cm copper) in stainless steel.

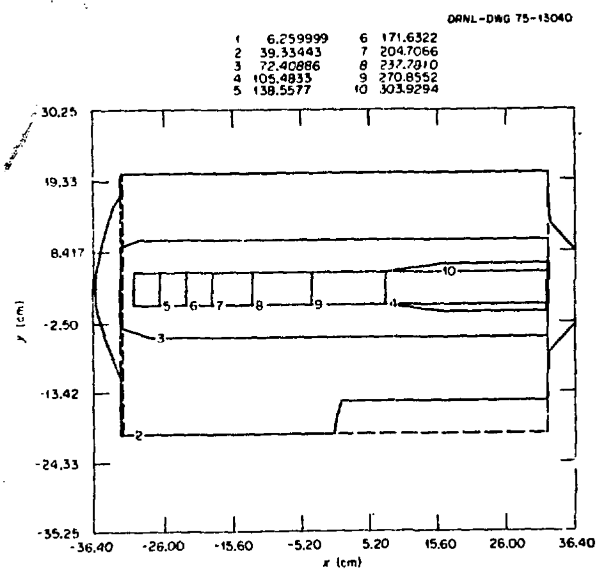

Fig. 7. Temperature contour at t = 100 sec, non-uniform quench, three components (copper, stainless steel, Teflon), with heat drain (0.1 cm copper) inside Teflon.

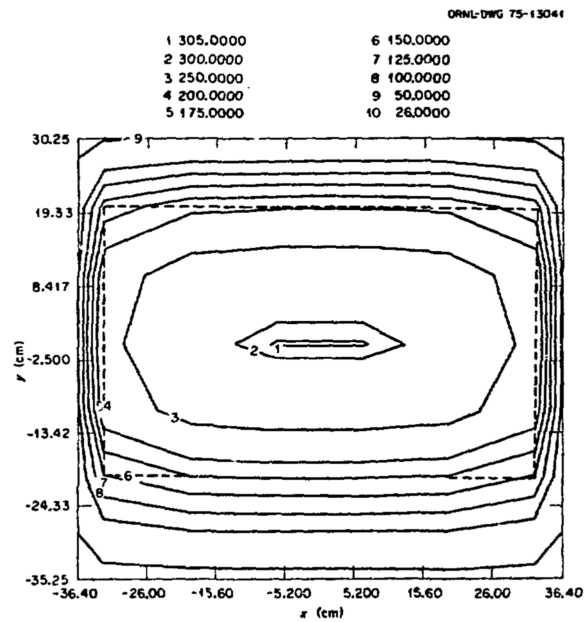

Fig. 9. Temperature contour at t = 75 sec, uniform quench, two components (copper, stainless steel).

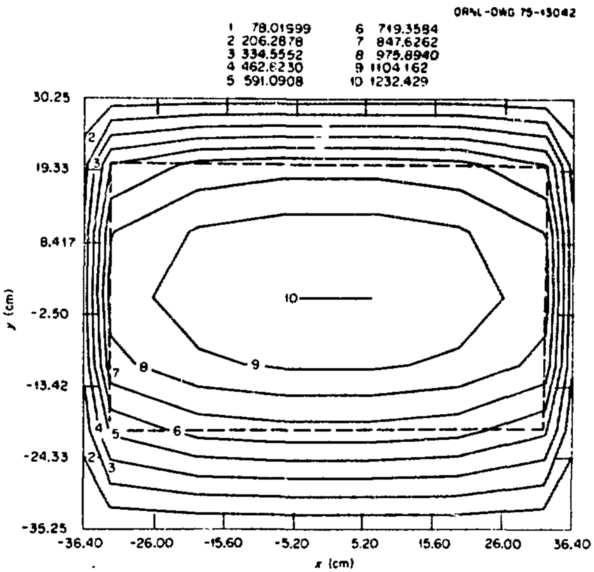

Fig. 10. Temperature contour at t = 200 sec, uniform quench, two components (copper, stainless steel).

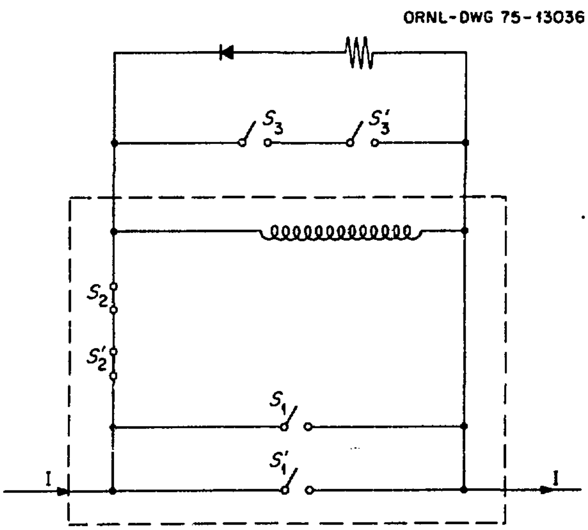

Fig. 11. Redundant switches to improve the reliability of the magnet protection circuit. S_1,S_1' (normally open) and S_2,S_2' (normally closed) are persistent switches inside the cryostat. (dotted line) S_3,S_3' (normally open) are circuit breakers. To discharge during quench, first close S_3,S_3', then close S_1,S_1', then open S_2,S_2', then open S_3,S_3'.