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Lawrence Livermore Laboratory

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ABSTRACT

The MFTF-B central-cell solenoids are a set of twelve closely coupled, large superconducting magnets with similar but not exactly equal currents. Alternative methods of connecting them to their power supplies and dump resistors are investigated. The circuits are evaluated for operating conditions and fault conditions. The factors considered are the voltage to ground during a dump, short circuits, open circuits, quenches, and failure of the protection system to detect a quench. Of particular interest are the currents induced in coils that remain superconducting when one or more coils quench. The alternative connections include separate power supplies, combined power supplies, individual dump resistors, series dump resistors and combinations of these. A new circuit that contains "coupling" resistors is proposed. The coupling resistors do not affect normal fast dumps but reduce the peak induced currents while also reducing the energy rating of the dump resistors. Another novel circuit, the series circuit with diodes, is discussed in detail.

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INTRODUCTION

The MFTF-B magnet system[1] consists of a large number of superconducting magnets that interact magnetically and structurally. The design of the system has raised unique problems not encountered in the design of single magnets.

The protection system for the twelve central-cell solenoids presents a particularly interesting challenge. The solenoids are closely coupled magnetically and since they have similar currents are most economically operated as a group. The problem is a new one and little guidance can be found from past examples. In this report a number of alternative methods of connecting the solenoids are investigated.

The alternative circuits are evaluated for their performance in normal and in fault conditions. Costs are also compared. Analytical methods are used when possible, but for the more complex issues reliance is placed on computer simulations using the Sceptre code[2].

Two new circuits are described for the first time: the circuit with parallel dump resistors and coupling resistors, and the circuit with series dump resistors and diodes. Both were originated by the authors, although a reference to the series circuit has since been found.[3]

A DESCRIPTION OF THE SOLENOIDS

Twelve solenoids, mounted coaxially, form the central field region of the MFTF-B tandem mirror machine. Each coil has 600 turns of niobium-titanium conductor with a mean diameter of 5 m. The maximum operating current is 2800 A producing a field of about 1.5 T. The self-inductance of the coils is 3.6 H and the mutual inductance between coils is substantial, 1 H between adjacent coils. A complete description of the electrical properties is given in Appendix A.

In the planned operating modes the current in the end coils is slightly larger than the current in the center coils. However, the required on-axis fields can be obtained by dividing the four coils at each end into two pairs, each with the same current. The four coils at the center have the baseline, or smallest current flowing through them.

The coils are supplied from thyristor power supplies with freewheeling parallel diodes that allows the current to freely circulate in the forward direction but which block reverse flows. The magnets are charged over the course of several hours. There are two modes of discharge, a slow dump and a fast dump. A slow dump, which takes a number of hours, is used for normal discharges. A fast dump is used under fault conditions. The purpose of a fast dump is twofold: to remove energy that might otherwise heat the magnet; and to eliminate low resistance paths through the power supplies. The speed of the dump is limited by the voltage to ground caused by the dump. This voltage depends on the connection used.

The power supplies, coils, breakers and dump resistors are connected using standard cables. The resistance of the connections, which is the order of milliohms, is an important factor in some of the fault conditions.

CONDITIONS THAT ENDANGER THE COILS

The coils can be damaged by excessively high temperature, voltage, or current.[4,5,6]

A high temperature can melt the solder, cause deterioration of the electrical insulation, or even melt the conductor. Temperatures below 200°C are not dangerous. However, it is prudent to limit the design temperatures to a maximum temperature of 0°C or lower in order to avoid excessive thermal stress in a restricted region of the coil.

High voltage to ground or between one part of the coil and another can damage the electrical insulation. The coils are tested to 2000 V between the coil and ground in one atmosphere helium gas at 300 K. However, 500 V to ground is used as the maximum design voltage.

The electromagnetic forces are proportional to the squares of the currents. The hoop stress in a coil depends on the current in the coil itself. Transverse forces on the structures supporting the coils depend on the magnetic interaction between the coils. The structure is designed to withstand all possible combinations of forces, including forces generated when some coils are on and some are off. Determination of the worst-case combination is a complex subject. However, from the standpoint of the electrical designer, the imperative is to reduce the maximum currents in the coils to a minimum.

A current larger than the operating current can be induced in a superconducting solenoid when the field changes rapidly due to a quench of neighboring coils. The size of the induced current depends on how the coils, dump resistors, and power supplies are connected. One of the purposes of this study is to find a circuit that minimizes the peak current in the coils.

FAULT CONDITIONS

SHORT CIRCUITS

A coil can be shorted either by an internal short within the superconducting coils or an external low resistance short. An internal short can be across all or only part of the coil. A turn-to-turn or layer-to-layer short can be caused by a manufacturing defect, an electrical breakdown, or a mechanical failure. Extensive testing minimizes the probability of a manufacturing defect. Electrical breakdown occurs if the insulation is overstressed either by a single high voltage or a series of lower voltages that create a conducting path. Mechanical failure of the insulation can be caused either by overheating or by excessive mechanical stresses.

The most probable cause of a short of the entire coil is insulation failure of the current leads or lead-in conductors of the coil. These failures can occur if the leads are not properly supported or insulated from each other or from the ground.

The current induced in a superconducting coil with a short can be calculated without resorting to computer simulations. A shorted superconducting coil acts like a memory element, storing flux changes in the form of a current. If all of the currents in the surrounding coils are decreased, the current in a shorted solenoid increases, reaching a peak when all of the other currents are zero. The peak does not depend on the rate of decay, only on the initial current in the coils, the self-inductance of the shorted coil, and the mutual inductance between the shorted coil and the other coils.

$$I_j(\infty) = \frac{1}{L_{jj}} \sum_{k=1}^{n} L_{jk} \, i_k(o) \ .$$

$I_j(\infty)$ = the maximum current in the shorted coil j, at infinite time.

L_{jj} = the self-inductance of coil j.

L_{jk} = the mutual inductance between coils j and k.

$i_k(o)$ = the initial current in coil k.

The current induced in a shorted coil of the MFTF-B central-cell solenoids is roughly twice the normal operating current. A complete listing of the short-circuit peak current values is given in Appendix A.

It is likely that a shorted coil would quench before the peak current is reached. The nominal critical current for the solenoid conductor is 3296 A at 3.1 T. However, the field is not uniform throughout the conductor. Furthermore, the conductor is designed to be cryostable, therefore it is not known how much conductor must turn normal before a quench of the entire coil is induced. As a result, the exact induced current at which a quench of the entire coil occurs depends on the location of the normal zone. Once a quench does take place, the resistance of the coil rapidly rises, the current peaks, and then decays.

A coil can also be shorted externally, across the dump resistors or along connecting cables. A short of this kind could only occur because of an accident or an operational mistake.

The peak current induced in a coil when the short is resistive is less than when it is superconducting. The inductive buildup of current in the shorted coil is accompanied by dissipation of energy as the current flows through the resistive short. If the resistance is large enough there is no peak at all. However, simulations show that for shorts in the milliohm range, the resistance of the power supply loop, there is substantial peaking.

OPEN CIRCUITS

The open circuits that pose a danger are those in the path of the inductive current. An open circuit in the coil, current leads, or in the dump resistor during a dump are in this category.

An inductive current cannot be decreased instantaneously for this implies an instantaneous dissipation of the energy stored in the inductor. Therefore, a voltage is generated in the inductor of whatever size is necessary to maintain the current. There are two hazards: overvoltage of the coil and heating, fire, and melting at the site of the open circuit.

An open circuit can be caused by a manufacturing mistake or an accident during operation. The possibility of an open circuit is remote.

Open circuits do not lend themselves to analysis. The size of the voltage induced depends on the rapidity with which the current is interrupted and can be, in the extreme, very large.

QUENCHES

A quench of a coil is defined as a change of its conductors from the superconducting to the normal state. Since the coils are cyrostable, a quench should not occur in spite of thermal and magnetic disturbances unless the cooling fails. The conductor contains sufficient copper and there is sufficient cooling to cause a normal zone to diminish and eventually disappear. However, failure of the cooling will trigger a quench.

A quench results in a rapid buildup of the coil resistance and decay of the coil current. The decay is roughly an order of magnitude faster than the decay during a fast dump. There are two dangers to the coils. The temperature of a quenched coil may become too hot. And second, a quenching coil or group of coils may induce relatively large currents in neighboring coils. These currents are responsible for the peak mechanical stresses in the coils and the supporting structures.

Developing a mathematical model for a quench is difficult. The growth of a normal zone is complex, depending on the three-dimensional thermal properties of the coil and the circumstances triggering the quench. Rather than attempt to model a quench exactly, two conservative models are used in the simulations. In a few simulations the quench is modelled by a fixed resistance equal to the resistance of a quenched coil at the final temperature of the coil. In most cases a growing resistance is used. The entire superconductor is assumed to go normal at the same time, shifting the bulk of the current from the superconductor to the copper at 4.2 K. All of the heat generated is assumed to be stored in the metallic mass. The temperature rise of the copper is calculated taking into account the dependency of the resistivity and specific heat on temperature. Heat stored in the insulation or lost to the coolant is neglected. The result is a quench that resembles an actual quench, but is more rapid. A full description of the model, which is called the adiabatic model, is given in Appendix B.

The adiabatic model can be used to calculate the coil temperatures that result from a quench. A simultaneous quench of all coils accompanied by a fast dump causes a final temperature of about 75 K. Higher temperatures can result if the energy is transferred to a coil from the other coils either by magnetic induction or by electrical conduction. An upper limit is reached if all of the energy stored in the twelve coils is transferred to one quenched coil. A simulation shows this maximum temperature to be 252 K.

If only a portion of the coil quenches and the rest remains superconducting there is no limit to the temperature rise, at least according to the adiabatic model. Decreasing the size of the normal zone decreases the mass of material available to absorb the energy. However, the appropriateness of the adiabatic model decreases as the normal zone shrinks. For a small normal zone, heat loss to the surroundings is the predominant effect.

FAILURE OF THE QUENCH PROTECTION SYSTEM

One of the purposes of a fast dump* is to reduce the peak currents in the coil by removing the low resistance paths through the power supplies. A quench of one or more coils induces voltages in the remaining superconducting coils that tend to sustain or increase the current. The current that results depends on the resistance of the available conducting paths. In general there are two conducting paths, through the dump resistors and through the power supplies. The paths through the power supplies have, by far, the lower resistance. Therefore, the peak currents occur when the coils quench and the protective system fails to remove the power supplies from the circuit.

A method of reducing the peak induced current, if the protection system fails, is to increase the resistance of the power supply loops. However, power lost in the power supply is a continuing expense. The cable designs are based on National Electrical Code requirements.

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*Another purpose is to remove energy from the coil during a quench. However, an adiabatic simulation shows that during a quench of all coils accompanied by a fast dump only about one-third of the stored energy is absorbed by the dump resistors, if the maximum coil voltage is 500 V.

The peak currents are affected by the way in which the coils are connected to the power supplies and the dump resistors. If each coil has its own supply the supply is directly connected across the coil. However, in other connections, additional coils, resistors, and diode paths can be interposed between the coil and the low resistance paths through the power supplies. One of the purposes of this study is to examine circuits that limit the flow of current through the power supplies.

Every effort is made to prevent the failure of the protective system to remove the power supplies following a quench by using redundant methods and equipment. The breakers and quench detectors are redundant. In addition, the breakers are tripped if the current in a coil increases unexpectedly. The breakers are independently equipped with overcurrent trip devices set at the maximum operating current.

A CLASSIFICATION OF THE SOLENOID CONNECTIONS

Many ways of connecting the solenoids have been proposed and considered. The major features of these circuits are encompassed in the nine circuits shown in Figures 1 through 9 and listed below. The circuits are divided into three groups which have similar functional and physical properties.

Coils with individual, parallel dump resistors

1. One set of breakers
2. Coupling resistors
3. Breakers for groups of four
4. Separate supplies

Coils with combined, parallel dump resistors

5. One group of twelve coils
6. Three groups of four coils

Coils with series dump resistors

7. With diodes, breakers for each coil
8. With diodes, breakers and resistors for groups
9. Without diodes, breakers for each coil

In the first category, each coil has its own dump resistor permanently connected in parallel with it. In the second category, individual dump resistors are not used; a dump resistor serves a number of coils connected in series. In the third category, the dump resistors are connected in series with the coils instead of in parallel and a breaker shorts out the resistors during normal operation. There are two subgroups in this category, circuits with diodes and circuits without diodes. The diodes are used to provide a closed path around each coil and dump resistor during a fast dump.

In order to facilitate comparison between circuits, each circuit is shown with the minimum number of breakers needed to interrupt the low resistance paths through the power supplies. The final design will contain additional, redundant breakers.

COILS WITH INDIVIDUAL PARALLEL DUMP RESISTORS, ONE SET OF BREAKERS

Early in the study the circuit with individual parallel dump resistors, which is shown in Figure 1, became the baseline circuit against which others are compared. Its structure and operation are simple and it combines the advantage of individual dump resistors with a minimum number of power supplies, cable runs and breakers.

A main power supply provides the current shared by all twelve coils. The additional current in the two pairs of end coils comes from smaller trim supplies arranged to minimize the current and power rating of each supply. The supply encompassing the outer four coils supplies the current common to those four coils. The additional current in the two end coils comes from another supply.

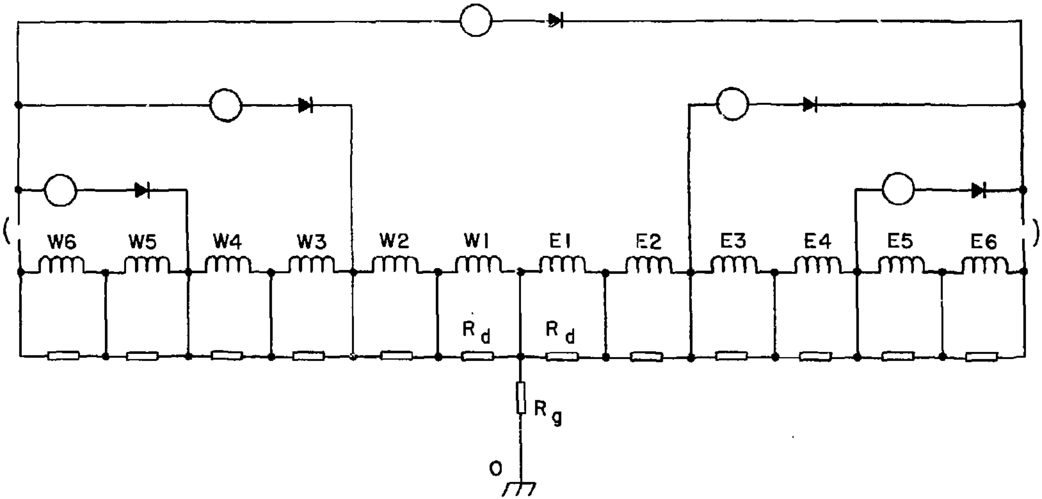

FIGURE 1

Coils with individual, parallel dump resistors, one set of breakers

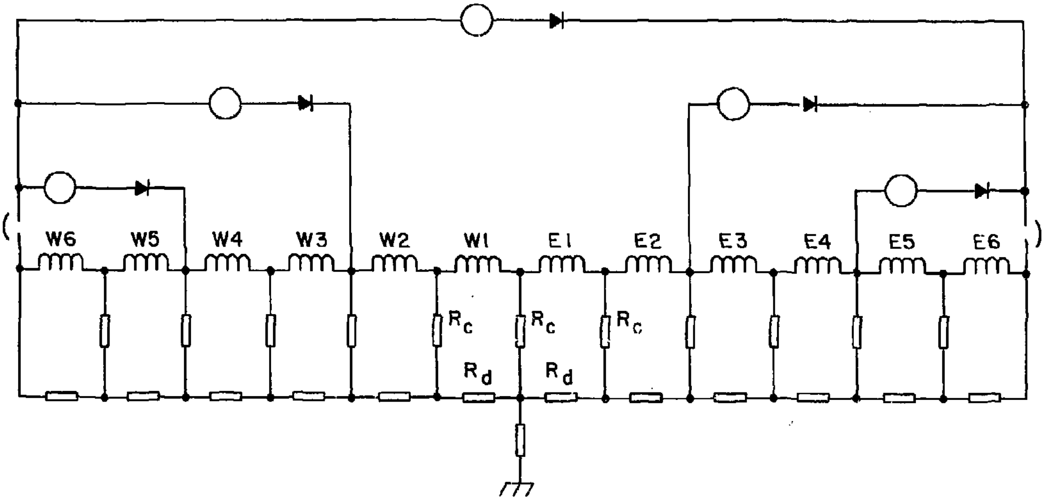

FIGURE 2

Coils with individual, parallel dump resistors, with coupling resistors

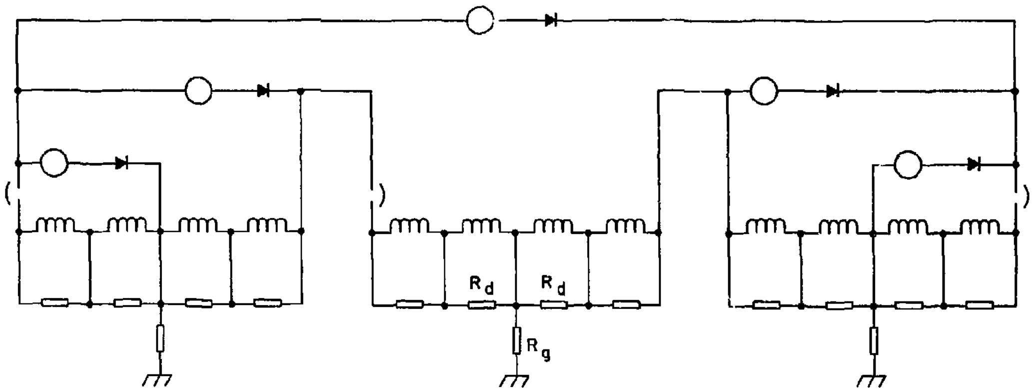

FIGURE 3.

Coils with individual, parallel dump resistors, breakers for groups of four

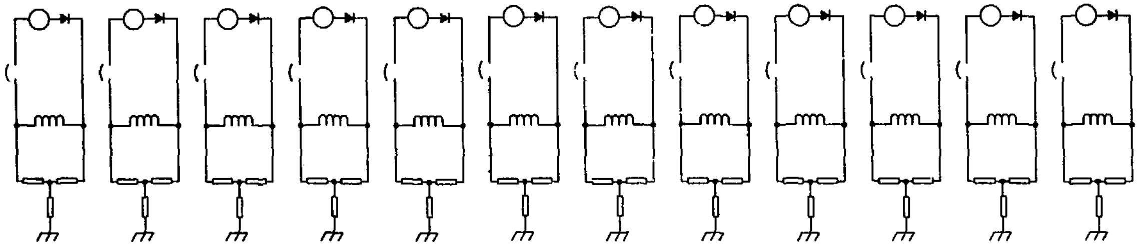

FIGURE 4.

Coils with individual, parallel dump resistors, separate supplies

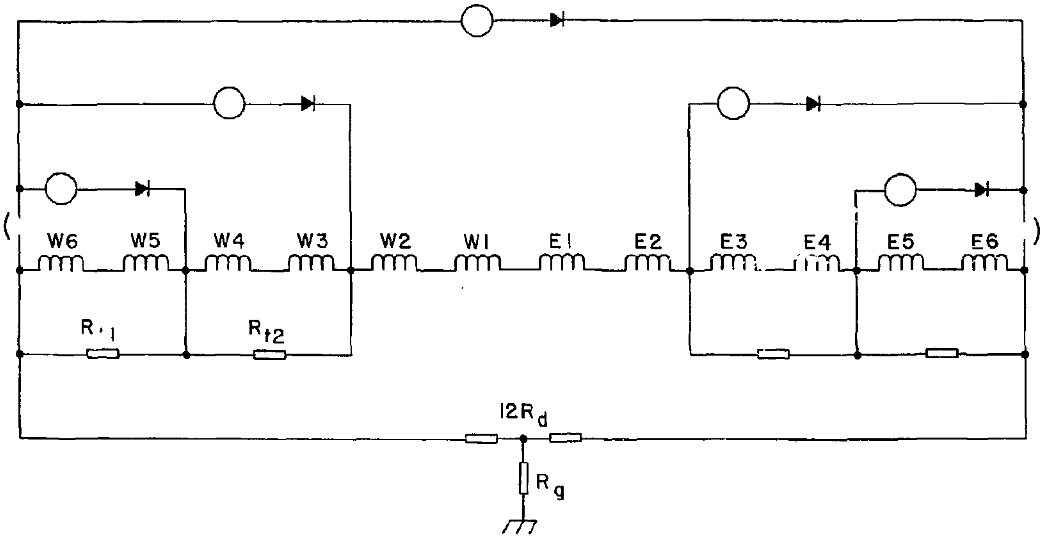

FIGURE 5.

Coils with combined, parallel dump resistors, one group of twelve coils

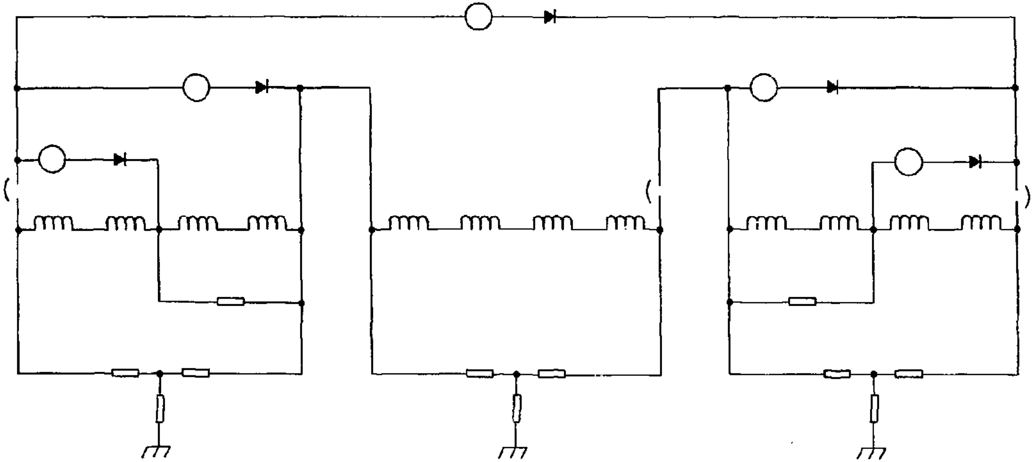

FIGURE 6.
Coils with combined, parallel dump resistors, three groups of four coils

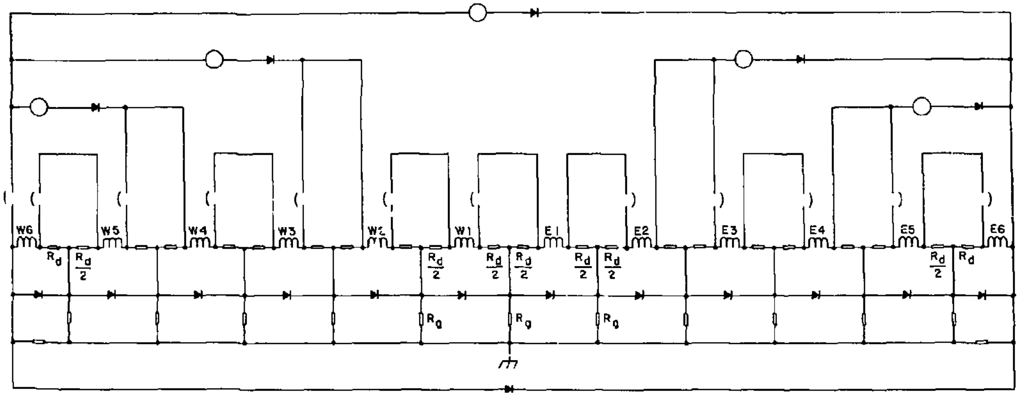

FIGURE 7.

Coils with series dump resistors, with diodes and breakers for each coil

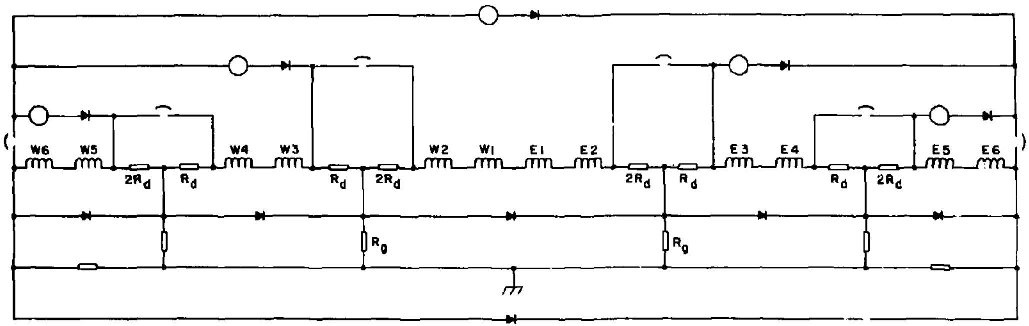

FIGURE 8.

Coils with series dump resistors, with diodes, breakers and resistors for groups

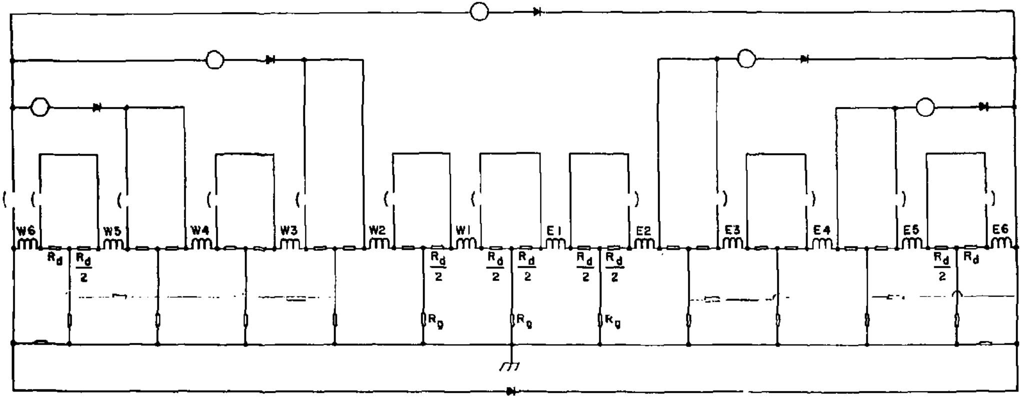

FIGURE 9.

Coils with series dump resistors, without diodes, breakers for each coil

This circuit requires two breakers. It cannot be guaranteed that they will open simultaneously; therefore the consequences of one opening before the other must be considered. The first breaker to open interrupts the current through the eight coils at its end. The current through the four coils at the other end can still flow through the trim supplies. Opening the second breaker interrupts this path.

The maximum voltage to ground is the voltage caused by a fast dump. This voltage occurs just after the first breaker opens. At this moment the voltage from the ground resistor to one end of the series string of coils is 6 V_c, where V_c is the coil voltage. Therefore, the maximum voltage to ground is 6 V_c.

TABLE I.

The maximum induced current, maximum coil temperature, and maximum energy absorbed by a dump resistor during a fast dump and for critical fault conditions for the circuit with individual, parallel dump resistors.

The complete results are tabulated in Appendix C.
Dump resistance = .0291 ohms.

	the maximum peak current / operating current	The maximum final temperature K	The maximum energy absorbed by a dump resistor MJ
FAST DUMP			
all coils superconducting	1.00	4.2	27.8
all coils quench	1.00	67	3.3
all except W1 quench	1.12	66	36.0
POWER SUPPLIES CONNECTED			
all except W3 quench	1.47	76	25.3
all except W5 and W6 quench	1.31	76	1.7
only W1 quenches	1.11	80	117.6

The other two factors that affect the safety of the coils are temperature and peak current. Table 1 is a summary of simulation results that are tabulated in Appendix C in more detail. Included in the table is the maximum energy absorbed by a dump resistor. While not a factor in the coils' safety, the dump resistor energy is a factor in the cost of the protective system.

As Table 1 shows, the critical values of peak current, temperature, and energy absorbed by a dump resistor occur when the power supplies are connected. The fast dump results are included for comparison purposes.

For a fast dump with all coils either quenched or all coils superconducting there is no current peaking. The maximum current during a fast dump occurs when all coils except W1 or E1 quench. W1 and E1, positioned as they are at the center of the string of coils have the maximum coupling to the other coils. The currents induced in coils further away from the center, when all other coils quench, is less.

The additional energy transferred to W1 by its quenching neighbors must eventually be absorbed by its dump resistor. As a result, the maximum energy absorbed by a dump resistor during a fast dump is the energy absorbed by the W1's dump resistor when all other coils quench. This energy is 30 percent greater than that absorbed during a fast dump with all coils superconducting.

If the protective measures fail, and the power supplies remain connected during a quench, the low resistance paths through the power supplies cause the induced current to be higher than during a fast dump. The exact result depends on a complex combination of the available conduction paths and the mutual coupling between the superconducting and quenched coils. Coils near the center have the largest coupling. However, the coils at the end have conductive paths through the trim power supplies.

When the power supplies are connected the maximum current occurs when the superconducting coil is coil 3. During a fast dump, coil 1 has the maximum induced current. Another critical situation occurs when the two end coils, coils 5 and 6 remain superconducting and the remainder quench. These two coils are virtually short-circuited by the outer trim supply. Although the coupling between them and the other coils is not as large as for other pairs, the peak currents are larger.

The maximum energy absorbed by a dump resistor occurs when the power supplies remain connected and only one coil quenches. As the quench resistance builds up, the current is forced from the coil to the alternative path through the dump resistor. The final quench resistance is an order of magnitude greater than the dump resistance, consequently most of the current is diverted to the dump resistor.

The maximum energy is absorbed by a dump resistor when one of the four center coils quenches and the other coils remain superconducting. The quench attenuates the current in the center four coils. However, the currents in the two groups of four end coils are free to circulate through the trim supplies and are not attenuated. The energy stored in the center four coils is absorbed by the quenched coil and its dump resistor. Simulations show that the temperature of the coil rises to 80 K, the largest temperature encountered in this circuit when an entire coil quenches. The energy absorbed by the dump resistor is roughly four times the energy absorbed by a dump resistor during a fast dump with all coils superconducting.

TABLE 2.

The relationship between the fast dump voltage to ground, the maximum induced current and the dump resistance.

The maximum current is induced when all coils except W3 quench and the power supplies are connected. The power supplies contain diodes.

Dump resistance ohms	peak current / operating current	Time of peak current S	Voltage to ground V
.5 x .0291	1.64	88	250
.0291	1.47	73	500
2 x .0291	1.32	60	1000

In choosing the resistance of the dump resistor there is a tradeoff between induced current and voltage to ground during a fast dump. Increasing the dump resistor decreases the induced current by increasing the resistance of the path around which the current flows. However, increasing the resistance increases the voltage to ground. Table 2 shows the nature of the tradeoff for the solenoids. The voltage to ground is proportional to the resistance. However, since the resistance of the power supply is the dominant factor, the induced current is only weakly dependent on the dump resistance. Therefore, increasing the dump resistance is a relatively ineffective way of reducing the induced current.

COILS WITH INDIVIDUAL, PARALLEL DUMP RESISTORS, COUPLING RESISTORS

This circuit, which is shown in Figure 2, is similar to the previous one except that resistors, called coupling resistors, are placed between the coils and the dump resistors. The purpose of the coupling resistors is to decrease the peak induced current in the coils.

The effect of the coupling resistors can be understood by examining Figure 10. When the currents in the two coils are equal, the coupling resistors have no effect. If the current in one coil is larger than the other, a voltage is produced across the coupling resistor that tends to decrease the larger current and increase the smaller one. In effect, energy is transferred from the loop with the larger current to the loop with the smaller current.

During a fast dump the coil currents are equal except for the small trim currents. Coupling resistors adjacent to the coils with equal current have no effect on the dump, while those at the trim power supply lines have only a small effect.

During a quench the current in a quenched coil decays rapidly, causing it to be smaller than the current in adjacent coils. The coupling resistors tend to sustain the current in the quenched coil and decrease the current in the adjacent superconducting coils. This decreases the peak induced current at the price of increasing the energy absorbed by the quenched coil.

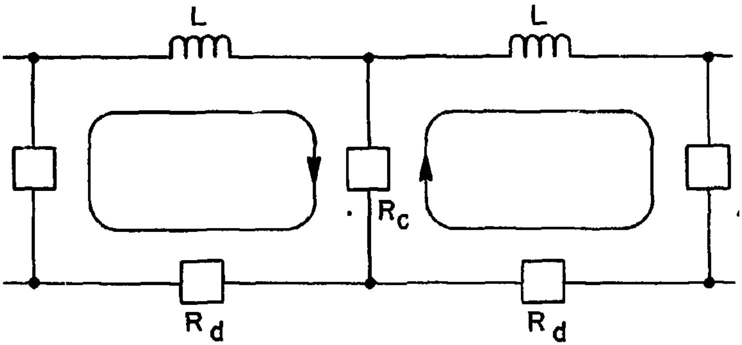

FIGURE 10.

The effect of a coupling resistor on the current in two adjacent loops

The effect of coupling resistors is illustrated by the results in Table 3 which shows the induced current, temperature and energy to resistors for a circuit in which the coupling resistance equals the dump resistance. Table 3 can be compared with Table 1, a similar table for the same circuit without coupling resistors. A more complete tabulation of simulation results is found in Appendix D.

As Table 3 shows, the coupling resistors have little effect during a fast dump for the two cases: all coils remain superconducting or all coils quench. Under these circumstances the current in all of the coils at any time is the same except for the trim currents and differences due to differing mutual inductance. However, if there is a fast dump when all coils quench except coil W1 the effect of the coupling resistor is appreciable. The coupling resistors eliminate the peak current induced in coil W1. In addition, the energy absorbed by coil W1's dump resistor is greatly reduced. Without the coupling resistors the energy absorbed is 1.30 times that absorbed during a fast dump when all of the coils are superconducting. With the coupling resistors it is only .72 times the energy when all coils are superconducting.

The highest induced currents and temperatures occur when the power supply remains connected. As a comparison of Table 1 and 3 shows, the use of coupling resistors reduces the hazard. The maximum energy absorbed by a dump resistor is also greatly reduced.

Table 4 shows the effect of the size of the coupling resistor on the current induced in coil W3 when all of the other coils quench. In the circuit without coupling resistors this peak, which is 54 percent higher than the operating current, is the highest current encountered in this circuit when the protection system fails. Coupling resistors equal to the dump resistors reduce the peak to 21 percent higher, while coupling resistor five times the dump resistor virtually eliminate the peak. The price paid for this reduction in an increase in the final temperature of the quenched coils adjacent to coil W3. However, the increases are well within the allowable limits.

The coupling resistors are not as effective in reducing the peaks in coils W5 and W6 when this pair remains superconducting. Only a single coupling resistor links the rest of

TABLE 3.

The maximum induced current, maximum coil temperature, and maximum energy absorbed by resistors during a fast dump and for critical fault conditions; for the circuit with coupling resistors equal to the dump resistor.

	the maximum peak current / operating current	The maximum final temperature K	The maximum energy absorbed by a dump resistor MJ	The maximum energy absorbed by a coupling resistor MJ
FAST DUMP				
all coils superconducting	1.00	4.2	27.4	0.0
all coils quench	1.00	67	8.3	0.0
all except W1 quench	1.00	68	19.9	4.3
POWER SUPPLIES CONNECTED				
all except W3 quench	1.21	79	6.0	12.2
all except W5 and W6 quench	1.24	76	6.0	0.8
only W1 quenches	1.11	88	18.3	20.0

TABLE 4.

The effect of coupling resistance on the peak current and final temperature when all coils except W3 quench

The power supplies are connected with diodes to ensure unidirectional current flow. The peak current occurs in W3. The maximum temperature rise is in W4. R_d = .0291 ohms.

Value of coupling resistance	peak current / operating current	Final temperature of W 4 K
0	1.54	74
$.5\ R_d$	1.30	76
R_d	1.21	79
$2\ R_d$	1.12	83
$3\ R_d$	1.07	85
$5\ R_d$	1.03	87

the coils to the pair, which is shorted by the outer trim supply. As Table 5 shows, the peak in these two coils is 15 and 31 percent above the operating current when there are no coupling resistors. Increasing the coupling resistance does two things, it equalizes the current in the two coils and lowers the peak. However, a lower limit is reached at about 21 percent above the operating current.

The peak current in coils 5 and 6 can be decreased by increasing the resistance of the trim power supplies. Ordinarily, increasing the resistance of a power supply is prohibitively expensive because the operating current must flow through the additional resistance causing substantial energy losses. However, the trim currents are small and the expense is tolerable. Table 6 shows the effect of the trim supply resistance. Over much of the range studied the relationship is almost logarithmic, a doubling of the resistance reduces the peak by three percent.

The use of coupling resistors substantially reduces the physical size and cost of the dump resistors. The size is fixed by the maximum energy absorbed by a dump resistor. As explained in the previous section, the maximum energy is absorbed by the dump resistor of one of the four center coils, when this coil quenches, the other coils remain superconducting, and the power supplies are connected. Since the resistance of the dump resistor is much less than the quenched resistance of the coil, the current tends to flow through the dump resistance. Except for the resistance of the cables the quenched coil and its dump resistance are the only dissipative elements in the circuit. Therefore, a portion of the energy stored in all of the coils is deposited in the dump resistor.

Placing coupling resistors in the circuit increases the resistance of the alternative path for the current. The current can flow either through the coil itself or through a series combination consisting of a coupling resistor, a dump resistor, and a coupling resistor. Consequently, more of the current tends to flow through the coil and less through the dump resistor. The result is that the final temperature of the coil is higher but the energy absorbed by the resistors is less.

TABLE 5.

The effect of coupling resistance on the peak current and final temperature when all coils quench except W5 and W6

The main end trim power supplies are connected with diodes to ensure unidirectional current flow. R_d = .0291 ohms

Value of coupling resistor	peak current / operating current		Time of peak current		Final temperature	
	for W5	for W6	W5 S	W6 S	W4 K	W3 K
0	1.31	1.15	94	130	67	73
R_d	1.24	1.22	84	118	69	72
2 R_d	1.22	1.22	86	111	69	72
5 R_d	1.21	1.22	92	102	70	72

TABLE 6.

The effect of trim supply resistance on the peak currents when all coils quench except W5 and W6

The main and trim supplies are connected with diodes to ensure unidirectional current flow. The resistances of the outer trim supplies are the variable resistances, the resistances of the inner trim supplies are fixed at .0065 ohms. The coupling resistors are equal to the dump resistors (.0291 ohms)

trim supply resistance (ohms)	maximum current / operating current	
	W5	W6
.0065	1.24	1.22
2 x .0065	1.21	1.19
8 x .0065	1.18	1.16
16 x .0065	1.14	1.13
32 x .0065	1.11	1.11

TABLE 7.

The effect of coupling resistance on the maximum energy absorbed by the dump and coupling resistors.

The maximum occurs when coil 1 quenches and all of the other coils remain superconducting. The power supplies are connected. The dump resistance is .0291 ohms.

Coupling resistance	Final temperature of coil K	Energy absorbed by coupling resistor MJ	Energy absorbed by dump resistor MJ	Total energy absorbed by pair of resistors MJ
0	80	0	117.6	117.6
R_d	88	20.0	18.3	30.2
$2\ R_d$	94	20.4	10.2	30.2
$5\ R_d$	102	17.0	3.4	20.4

Table 7 shows the effect of the coupling resistance on the maximum energy absorbed by the resistors. The energy absorbed by a dump resistor and an adjacent coupling resistor has been listed. A complete tabulation of the simulations is given in Appendix D. Without coupling resistors the energy absorbed by the dump resistor is 117.6 MJ. With the coupling resistance equal to the dump resistance the energy absorbed by a pair of resistors consisting of a dump resistor and a coupling resistor is 30.2 MJ. The pair of resistors, dump resistor and coupling resistor, is roughly a third of the physical size and cost of the dump resistor needed if no coupling resistors are used.

Two factors affect the choice of coupling resistance, the allowable peak current and the cost of the dump resistors. The coupling resistors have no affect on the dump voltage. Although the final temperature of the quenched coils is increased by increasing the coupling resistance, in this application the temperatures are well within acceptable limits.

For several reasons it was decided to make the coupling resistance equal to the dump resistance. For this choice the peak current when all coils except coil W3 quench is 1.21 times the operating current, a value just acceptable to the structural designers. The peak current in coils W5 and W6 when they remain superconducting is slightly more than the acceptable value. However, regardless of the choice of coupling resistance this peak must be reduced by increasing the resistance of the trim supplies. For a choice of coupling resistance equal to the dump resistance the physical size of the dump resistance is governed by the energy absorbed during a fast dump when all of the coils are superconducting. The energy absorbed when only one of the central solenoids quenches is less.

COILS WITH INDIVIDUAL, PARALLEL DUMP RESISTORS, BREAKERS FOR GROUPS OF FOUR

As Figure 3 shows, the solenoids can be divided, during a fast dump, into three groups of four coils by means of a single switch. However, on closer examination the apparent advantage of doing so proves to be spurious.

It might appear at first that dividing the solenoids into groups decreases the voltage to ground during a fast dump. However, the breakers do not open at exactly the same time and it must be assumed that the additional circuit breaker opens last. Therefore, its presence does not decrease the voltage to ground which remains at 6 V_c. Similarly, dividing the solenoids into smaller groups does not reduce the voltage to ground.

In addition, neither the peak induced current nor the energy to a dump resistor is reduced. These critical conditions occur during a failure of the protective system to trip the breakers, consequently the number of breakers is of no account.

COILS WITH SEPARATE SUPPLIES

Providing each coil with a separate supply, as shown in Figure 4, allows the greatest flexibility in the adjustment of the individual currents. In addition, the voltage to ground during a fast dump is only one half the coil voltage. However, these advantages are overshadowed by two serious disadvantages. The cost is high. Furthermore, the separate supplies form a low resistance path across each coil, causing the peak induced current to approach the current that flows in a shorted coil.

COILS WITH COMBINED, PARALLEL DUMP RESISTORS

Instead of having individual dump resistors, a number of coils can share the same dump resistor. In the most extreme application of this concept, all twelve coils, which are connected in series, share the same dump resistor as shown in Figure 5. Since the two pairs of end coils have slightly different currents, it is necessary to connect separate dump resistors across these pairs. The resistance of these trim dump resistors is high, and their effect on the circuit is small.

The circuit is simple and inexpensive, but the main reason for considering it is the low peak induced current. When eleven coils quench, the remaining superconducting coil is in series with the quenched coils. Except for the small trim currents, the current in all coils is the same. As a result, there is no peaking of the current, even when the power supplies remain connected.

Unfortunately, the connection has several disadvantages. An open circuit in any of the coils, the connecting wires, or the dump resistor affects all coils. A less obvious disadvantage is that a quench of one or two coils causes both a high temperature in the quenched coils and a high voltage to ground.

The high temperature is a direct result of the series connection of the coils. The current, which flows through all coils, transfers energy from the superconducting coils to the quenched coils, raising the temperature of the quenched coils. The worst-case occurs when any one of the coils quench and the rest remain superconducting. The results of simulations are given in Appendix E.

A high voltage to ground is also induced by a quench of a small number of coils. A quench places a large resistance in the series path, causing the rate of change of current to be high. The reactive voltages across the superconducting coils, $L\frac{di}{dt}$, are large and add together. The highest voltage to ground is produced by a quench in the coils at one end of the string of solenoids. For the values used, simulations show that the largest voltage to ground is produced when two coils quench. A quench of either one or three produces a smaller voltage. The results of these studies are shown in Appendix E.

The peak voltage to ground and the temperature rise are reduced by using a grouping of less then twelve coils. One such grouping, in which four coils are connected in series to share a dump resistor, is shown in Figure 6. Although three main dump resistors are needed, the number of trim dump resistors is reduced from four to two.

The circuit was not simulated, but some of its properties are evident. Since four instead of twelve coils are in series, the circuit is not as effective in reducing the peak induced current in the center coils. In addition, current peaking is made possible by separating the outer four coils from the central coils. The outer four coils are virtually shorted by the trim power supply.

On the plus side, an open circuit affects fewer coils and the peak voltage and temperature is less than when twelve coils are in series.

COILS WITH SERIES DUMP RESISTORS AND DIODES

Figure 7 shows a circuit in which the dump resistors are connected in series with the coils and diodes are connected across each coil-resistor group. During charging and normal steady-state operation, all of the breakers are closed, shorting the dump resistors. The current flows from the main supply and through the twelve coils in series. The reactive voltages of the coils during charging and the resistive drops during normal operation back bias the diodes, causing them to act like open circuits.

Opening the breakers removes the shorts across the dump resistors and the low resistance paths through the power supplies. The current is constrained to flow through the dump resistors and the diodes, which act like short circuits.

An advantage of the circuit is that, during a fast dump, the voltage to ground is as low as possible, only half the coil voltage. After the breakers have opened the voltage rise across each coil is opposed by the voltage drop across the resistors on each side of the coil. As a result, the voltage from one coil-resistor combination to another is almost zero. The grounding resistors constrain the voltage at the midpoints of the dump resistors to be zero. Therefore, the voltage at the center of the coils is also zero, with the maximum voltage of $\frac{Vc}{2}$ at the ends of each coil.

In contrast to the circuits with parallel resistors, the voltage to ground does not depend on the order in which the breakers open. Figure 11 shows the circuit just after the first breaker, arbitrarily chosen at the center of the string, opens. Opening the breaker places a half dump resistor in series with each of coils E1 and W1. If the trim currents are neglected the initial current in each coil is the same. Therefore, no current flows through the dump resistors not affected by the breaker opening. The current flows through the twelve coils and the dump resistors at W1 and E1 and returns through the power supply or through the outside diode. The inductive voltages across the W1 and E1 are less than the voltage drop across the dump resistors. Consequently, the diodes associated with these coils are back biased and open. The voltage across the other coils forward biases the diodes causing them to act like short circuits, which constrains the voltage across the coils to be close to zero. The voltage to ground at the ends of W1 and E1 is $\pm\frac{IR_d}{2}$, or half the fast dump coil voltage.

In the short time during which the breakers are in the process of opening, the current in the coils does not change perceptibly. Therefore, the current path consists of the coils, the dump resistors that have been activated by the opening of the breakers, and a return path through the outside diode. The voltage to ground is never more than $\frac{IR_d}{2}$.

After all the breakers are open the unbalance between the inductive and resistive voltages that force the diodes to open no longer exists and all of the diodes conduct. The circuit degenerates into twelve virtually disjoint loops each consisting of a diode, the dump resistor to the right of the coil, the coil, and the dump resistor to the left.

The small voltage to ground is a prime advantage of the circuit with series dump resistors as compared with the one with parallel dump resistors. The voltage to ground in the circuit with parallel dump resistor is 6 IR_d or twelve times the voltage to ground in the series circuit.

Another advantage of the circuit with series dump resistors is the reduced stress placed on the circuit breakers. As each breaker opens, it has across it a voltage equal to the voltage IR_d. Each switch, therefore, interrupts or redirects the energy stored in a single coil. This is in marked contrast to the circuit breakers in any of the circuits with

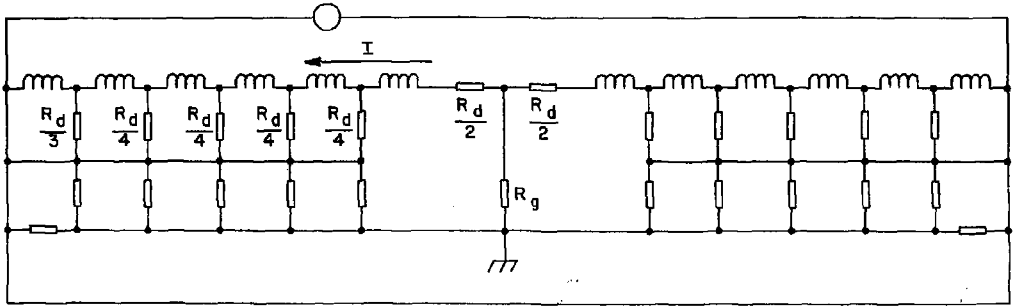

FIGURE 11.

The circuit with series dump resistors and diodes (Figure 7) just after the breaker at the center opens. The diodes associated with that breaker are nonconducting, while the other diodes are all conducting.

parallel dump resistors. In these circuits the first circuit breaker to open must redirect most of the energy stored in all twelve coils. Therefore, in theory at least, smaller circuit breakers can be used in the circuit with series dump resistors and diodes.

Yet another advantage of series dump resistors over parallel dump resistors is that the power supply can have a smaller power rating. In the parallel circuit, current flows through the dump resistors when the magnet current is being changed. In the series circuit the dump resistors are shorted by the breakers and absorb no power.

The power rating of the power supply is the sum of three components, the power supplied to connecting cables, the power needed to charge the coil, and in the case of parallel dump resistors, the power supplied to the dump resistors during charging. The power supply has the maximum power output when the maximum current to the coil is changed. Increasing the rate of charge of current increases the maximum power required.

For the series circuit,

$$\text{Maximum power} = I_m V + I_m^2 R_c$$

where I_m = the maximum operating current in the coil

$V = L \frac{di}{dt}\Big|_m$

$\frac{di}{dt}\Big|_m$ = the maximum rate of change of current required at I_m

R_c = the resistance of the connecting cables.

For the parallel circuit

$$\text{Maximum power} = I_m V + \frac{V^2}{R_d} + \left(I_m + \frac{V}{R_d}\right)^2 R_c$$

$$= I_m V\left(1 + \frac{2R_c}{R_d}\right) + \frac{V^2}{R_d}\left(1 + \frac{R_c}{R_d}\right) + I_m^2 R_c$$

where R_d = resistance of dump resistor

The main difference between the power required for the series and the parallel circuit is the term $\frac{V^2}{R_d}(1 + \frac{R_c}{R_d})$ in the maximum power for the parallel circuit. This is the power absorbed by the dump resistor during the change of current and the additional power loss in the cables caused by the dump resistor current. Since the power depends on the square of V, the importance of this power loss is very much dependent on how fast the current must be changed. For the choice of values used in the solenoids the circuit with parallel dump resistors requires a power supply approximately 15 percent bigger than that needed for the series circuit.

The induced current during a fast dump is the same as the induced current in the circuit with parallel dump resistors. After all of the breakers are open, the series circuit consists of a number of disjoint loops. Each loop contains a coil connected to the dump resistors on either side of it by a conducting diode. This electrical configuration is exactly the same as the circuit with parallel resistors during a fast dump.

The behavior of the series circuit when the protection system fails and the power supply remains connected is entirely different from its fast dump behavior and the behavior of the other circuits. Closing the circuit breakers changes the circuit configuration of the series circuit. A simplified diagram of the circuit, in which the trim supplies are omitted, is shown in Figure 12. The short across a dump resistor pair caused by a closed breaker places the two resistors in parallel. Together they form a path, with half the dump resistance, between the coil and the diodes.

During normal conditions, with the supply operating and all coils superconducting, the resistive drops in the connections between the coils back bias the diodes and keep them nonconducting. A quench causes a decrease in current, generating inductive voltages that can forward bias the diodes causing them to conduct. The examples in Appendix F show the behavior to be quite complex.

For two critical cases, a quench of eleven coils and a quench of one coil, the behavior is simple over the range of interest. If all the coils except coil 1 quench, all of the diodes conduct, resulting in the circuit shown in Figure 13(a). The short from one end of the circuit to the other is a combination of the main supply and the outside diode. The circuit resembles the circuit with coupling resistors in which the dump resistors have zero

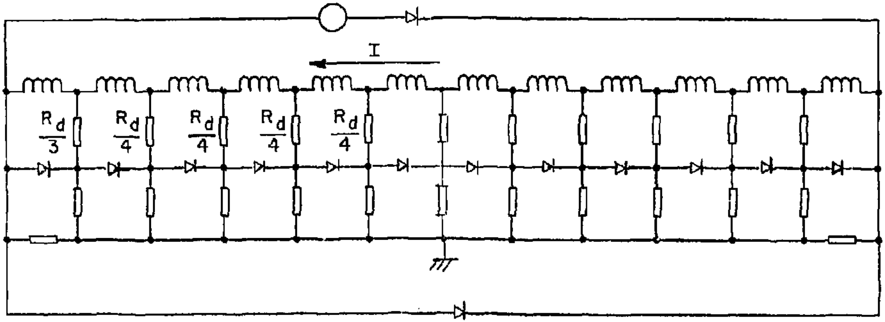

FIGURE 12.

A simplified drawing of the coils with series dump resistors with the breakers closed. Only the main power supply is shown.

FIGURE 13(a)

A simplified circuit diagram of the circuit with diodes when all coils except W1 quench. All diodes conduct.

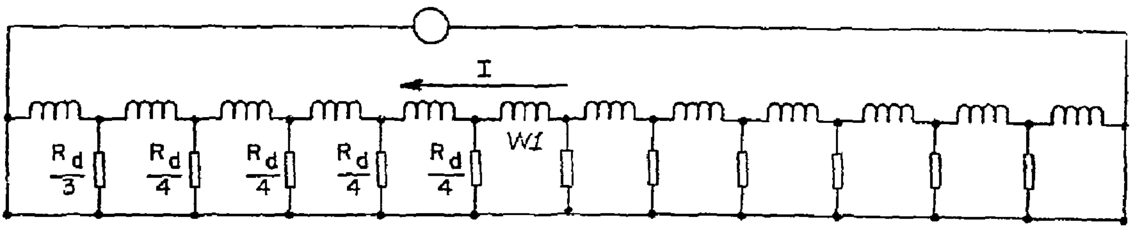

FIGURE 13(b)

A simplified circuit diagram of the circuit with diodes when only W3 quenches. All diodes conduct except the diode associated with W3.

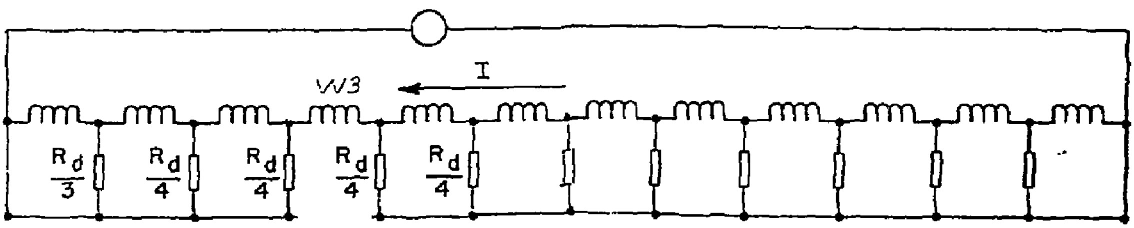

TABLE 8.

A comparison of the peak current when the power supplies remain connected for the circuit with parallel, individual dump resistors and the series circuit with diodes.

The results are from simulations that contain the main and trim supplies with diodes to ensure a unidirectional current. W1 remains superconducting and the other coils quench.

	Dump Resistance (ohms)	Peak Current / Operating Current in W1	Time of Peak S
parallel	.0291	1.47	73
series	.0291	1.57	72
	2 x .0291	1.53	70
	12 x .0292	1.13	48

resistance. If only one coil quenches as in Figure 13(b), the diode associated with that coil opens. This divides the circuit into two parts, each similar to the circuit with coupling resistors.

Table 8 shows a comparison of the peak current induced in coil W1 when all other coils quench for the series circuit with diodes and the circuit with individual, parallel dump resistors. For the same dump resistance, the current induced in the series circuit is higher. However, the dump voltage to ground for the parallel circuit is 6 IR_d while for the parallel circuit it is $\frac{1}{2}$ IR_d. Therefore, the dump resistance in the series circuit can be twelve times the dump resistance in the parallel circuit. When a comparison is made, taking this fact into account, the current induced in the series circuit is less.

Another fault condition, the quench of all coils except the two end, while the circuit breakers remain connected, may also cause current peaking. In the series circuit, as in all of the other circuits, the two end coils are shorted by a trim supply. When the breakers are closed, the series circuit resembles the circuit with coupling resistors. Although a thorough study has not been carried out, it is expected that behavior of the series circuit is similar to the circuit with coupling resistors. The coupling resistors have limited effectiveness in suppressing this peak, which must be controlled by increasing resistance of the trim power supply.

The energy rating of a dump resistor in the parallel circuit is determined by the energy absorbed when one coil quenches and the others remain superconducting. Much of the energy in the coils connected to the quenched coil is dissipated in the quenched coil's dump resistor. In the series circuit the effect of a quench of a single coil is much different. As Figure 13(b) shows, the diode associated with the quenched coil becomes nonconducting while the other diodes conduct. The current in the quenched coil decays rapidly along with the current in the diode-power supply path that connects one end of the solenoid to the other. The quenched coil divides the remaining coils into two almost disjoint circuits, one to the right of the quenched coil, the other to the left. Initially, the current in each of these circuits circulates around the perimeter of the circuit, through the coils and the outer two resistors. During this first moment, the outside coils provide all of the inductive voltage, the inner coils have zero voltage across them. Gradually, the pattern of current and voltage shifts, causing all of the resistors to participate in the discharge of the coils. A complete study of this behavior has not been made; however, it is clear that the series circuit places a smaller energy burden on the dump resistor than does the parallel circuit.

COILS WITH COMBINED SERIES DUMP RESISTORS AND DIODES

The series circuit contains a large number of diodes and circuit breakers. One way of reducing the cost is to group the coils, using only one diode and circuit breaker for each group. Figure 8 shows one such grouping. The choice of groupings is constrained by the need to provide trim current paths for the outer two pairs of coils.

A disadvantage of grouping the coils is that an open circuit in a group affects all coils in the group. Another penalty is an increase in the fast dump voltage to ground. The fast dump voltage in this circuit is four times the voltage in the series circuit with individual resistors.

Grouping the coils eliminates the current peaking when all but one of the central coils quench. The current in the central four coils must be the same. Therefore, there is no peaking when only one remains superconducting. However, there is current peaking in the two end coils when the power supplies remain connected and all of the other coils quench. These two coils are shorted by the trim supply. Although the circuit was not simulated, it is expected that because of the coupling action of the dump resistors, the peak current is somewhat less than the peak current in the circuit with individual dump resistors.

COILS WITH SERIES DUMP RESISTORS, WITHOUT DIODES

In this circuit, which is shown in Figure 9, individual dump resistors are connected in series with the coils, but no diodes are used. During normal operation and charging, the circuit breakers are closed, shorting the dump resistors. A fast dump is initiated by opening the breakers. The current is forced to flow through the series resistors, returning by way of the outside diode. This one diode can be eliminated if the supply is simply turned to zero voltage and allowed to remain in the circuit. A path for the trim current is provided by parallel trim dump resistors of relative high resistance.

The circuit has some of the properties of the diode circuit and some of the properties of the circuit in which the twelve coils have a combined dump resistor.

During a fast dump, with all coils superconducting, the induced voltage of each coil is balanced out by the voltage drop across the neighboring resistors. Therefore, the maximum voltage to ground is $\frac{1}{2} IR_d$. In this respect, the circuit is like the diode circuit.

With respect to the induced current, the circuit is like the twelve coils with a combined dump resistor. Except for the trim currents, which are small, the current is the same in all coils. Therefore, current peaking is eliminated. The currents all decay together, regardless of how many coils quench.

The circuit also shares two disadvantages with the circuit with one combined dump resistor: a high temperature and a high voltage to ground when only one or two coils quench. The high temperature is produced because the quenched coil absorbs much of the energy of its neighbors. The high voltage results from the high inductive voltages in the superconducting coils. However, the voltage is somewhat less than in the circuit with combined, parallel dump resistors. In the series circuit, the voltage drops across the dump resistors are distributed throughout the circuit rather than being concentrated in one place. The drops across the resistors are in opposition to the inductive voltages. However, since the drops across the dump resistors are much smaller than the inductive voltages, the reduction in voltage to ground is small.

COMPARISON AND SUMMARY

Tables 9, 10, and 11 summarize the major properties of the circuits considered. Circuits 3 and 4, individual parallel dump resistors for groups of four, and combined parallel resistors for groups of four, which have characteristics similar to related circuits have been omitted from the tabulation.

COST

The first item in Table 9 gives a cost estimate for the nine connections. The major items in the cost are the power supplies, the breakers, and the cable runs. The cable runs are costly because the power supplies and breakers must be located outside the vault, at a distance from the coils, where the magnetic field and radiation are at acceptable levels.

The cost of the baseline circuit, parallel, individual, dump resistors with one set of breakers, is about a third of a million dollars. Although the use of coupling resistors increases the number of resistors, the total energy rating of the resistors is actually decreased. Therefore, the circuit with coupling resistors costs less than the circuit without them.

A circuit with separate supplies is the most expensive, roughly four times as expensive as the baseline circuit. This circuit requires not only a large number of supplies, but also a cable run and a breaker for each supply.

The circuit with one combined dump resistor in parallel with a series string of the twelve coils is the least expensive, and the least complicated.

Using series dump resistors and diodes doubles the cost. The estimate is based on placing the breakers and diodes in the vault; otherwise, the number of cable runs is excessive. Placing the diodes and breakers in the vault causes technical problems that have not been worked out in detail. The diodes must be shielded from radiation and the electromagnetic trip mechanism must be either shielded or replaced with a device insensitive to magnetic fields.

The major part of the estimated cost is due to the large number of breakers required. Since the breakers in the series circuit interrupt a smaller energy than those in the parallel circuits, it might be expected that less expensive breakers could be used. However, in general, the size of conventional breakers in superconducting magnet circuits is determined by the steady state current rating, not the interrupting capacity. In conventional power systems, the current that must be interrupted is much larger than the operating current. In a superconducting magnet circuit, the operating current is the largest current that must be interrupted. Since breakers are designed for power system applications, a breaker that will carry the operating current continuously has an interrupting capacity far greater than that needed in any of the circuits proposed. Therefore, a conventional circuit breaker used in the series circuit with diodes is the same size as one used in the other circuits.

The cost estimates for the series circuit with diodes and with the coils grouped is based on placing the breakers and the diodes outside the vault area. Grouping the coils reduces the cable runs to a number that is allowable. The series circuit without diodes also has fewer cable runs and can have its breakers outside the vault.

THE RESISTANCE OF THE DUMP RESISTOR

Three factors affect the choice of the resistance of the fast dump resistor: the final temperature of the coil following a worst case fault and a fast dump, the voltages during a fast dump, and the effect of the resistor on the induced current. The first of these conditions, final temperature, places a lower limit on the resistance; the second, voltage, an upper limit.

TABLE 9.

		Cost Above Baseline	Fast Dump Voltage to Ground	Power to Dump R's During Charge	Short Circuit		Open Circuit	
					Coil	Dump Resistor	Coil	Dump Resistor
PARALLEL RESISTORS	1. parallel dump resistors, one breaker	Baseline $402K	6 V_c	yes		similar to short of a coil		
	2. parallel dump resistors, coupling resistors	-21K	6 V_c	yes		coupling resistors must also short	one coil affected	no discharge path for one coil
	4. separate supplies	+855K	$\frac{V_c}{2}$	yes	A current 2.1 times the operating current is induced in the shorted coil, regardless of how the current is decreased in the other coils	similar to short of a coil		
COMBINED PARALLEL	5. combined parallel resistors, group of 12	-64K	6 V_c	yes		small increase in current caused by end coils	all 12 coils affected	no discharge path for 12 coils
SERIES RESISTORS	7. series supplies	+269K (diodes and breakers in vault)	$\frac{V_c}{2}$	no			one coil affected	
	8. series resistors in groups with diodes	+175K (diodes and breakers in vault)	2 V_c	no		coil current not affected, possible heating of remaining resistors	four coils affected	no discharge path if breaker across resistor opens
	9. series resistors without diodes	+185K	$\frac{V_c}{2}$	yes			all 12 coils affected	

TABLE 10.

		FAST DUMP					
		QUENCH OF ONE COIL			QUENCH OF ELEVEN COILS		
		Peak Current / Operating Current	Final Temp. K	Comments	Peak Current / Operating Current	Final Temp. K	Comments
PARALLEL RESISTORS	1. parallel dump resistors, one breaker	1.00	56		1.12	66	
	2. parallel dump resistors, coupling resistors, $R_c = R_d$	1.00			1.00	68	
	4. separate supplies	1.00	56	similar to circuit 1	1.12	66	similar to circuit 1
COMBINED PARALLEL	5. combined parallel resistors, group of 12	1.00	166	voltage to ground is 1550 V for two end coils quench	1.00		
SERIES RESISTORS	7. series resistors with diodes	1.00				100	
	8. series resistors in groups, with diodes						
	9. series resistors without diodes			similar to circuit 5 except voltage to ground much lower			

TABLE 11.

POWER SUPPLIES CONNECTED

		Quench of one or two coils			Quench of ten or eleven coils		
		Peak Current / Operating Current	Final Temp. K	Comments	Peak Current / Operating Current	Final Temp. K	Comments
PARALLEL RESISTORS	1. parallel dump resistors, one breaker	1.11	80.3	dump resistor must absorb 4.2 times energy absorbed in a fast dump	1.47	76	
PARALLEL RESISTORS	2. parallel dump resistors, coupling resistors, $R_c = R_d$	1.13	102	dump resistor and coupling resistor absorb less energy than in a fast dump	1.21	76	slightly higher peak when all except end two coils quench
PARALLEL RESISTORS	4. separate supplies	high			2.1		peak current approaches short circuit values
COMBINED PARALLEL	5. combined parallel resistors, group of 12	1.00	172	voltage to ground is 2871 V if two coils quench			
SERIES RESISTORS	7. series resistors with diodes				1.13		for same value of dump resistors as circuit 1 the peak current is higher
SERIES RESISTORS	8. series resistors in groups, with diodes						
SERIES RESISTORS	9. series resistors without diodes			voltage to ground and final temp. are slightly less than circuit with group of 12			

The effect of the dump resistor on the maximum current induced is more complex. Decreasing the dump resistance slows down a fast dump and decreases the induced current during a fast dump. This fact augers for a small dump resistance. However, the maximum current is induced when some coils quench, the others remain superconducting, and the power supplies are connected. Increasing the dump resistance increases the resistance of the inductive paths available to the current. Therefore, in this application, as high a dump resistance as possible is desirable.

Two factors then, induced currents and temperature, call for the choice of as high a dump resistance as possible. The upper limit is fixed by the dump voltage to ground, which has been set at a maximum of 500 V.

The lower limit set by temperature is far below the choice of resistance dictated by the fast dump voltage. The thermal design of the coils is conservative. All of the energy stored in the solenoids could be absorbed by a single coil without raising its temperature beyond an acceptable limit. Therefore, in this application, the primary value of a fast dump is not to extract energy from the coil, but to limit the induced currents.

The effect of the circuit on the fast dump voltage to ground is shown in the second column of Table 9. Except for the circuit with separate supplies, all of the circuits with parallel dump resistors have a maximum voltage to ground of six times the fast dump voltage of a coil. The circuit with separate supplies and the two circuits with individual series dump resistors have a voltage to ground of half the coil voltage.

SHORT CIRCUITS

For some types of short and open circuits, one circuit is better than the others. However, there is no circuit that protects against a superconducting short of all or part of the coil. If an entire coil is shorted, a current 2.1 times the normal operating current is induced in it when the currents in the other coils are brought to zero, regardless of how the currents are decreased.

In circuits with individual parallel dump resistors, a short of a dump resistor is similar to a superconducting short of a coil except that an external short has some resistance. If coupling resistors are used, the coupling resistors, as well as the dump resistors must be shorted in order to short the coil.

In the circuit with a dump resistor for the twelve coils in series, a short of the dump resistor is also a short of the entire string of twelve coils. This short circuit would have substantial resistance since it encompasses the connections between the coils. Induced currents would arise from the mutual coupling between the end coils and the solenoids, which is less than the coupling between the solenoids themselves. Therefore, it is unlikely that a short of this kind would endanger the coils.

In the circuits with series dump resistors, a short of a dump resistor is not similar to the short of a coil. A short of a dump resistor simply prevents the resistor from participating in a fast dump. A second resistor on the other side of the coil remains. Therefore, a fast dump will proceed, but without the shorted resistor. The remaining resistors must have sufficient energy rating to carry the increased load.

OPEN CIRCUITS

If each coil has its own dump resistor, an open circuit in a coil affects only that coil. Even if the current path is broken, the other coils can discharge through their dump resistors. Grouping the coils with a common dump resistor causes an open circuit in one coil to imperil all of the coils in the group.

In the series connection with diodes, each coil has, in effect, its own dump resistor. An open circuit in a coil causes the other coils to fast dump through their dump resistors and local diodes. On the other hand, the series connection without diodes acts like a group of twelve coils. If the current is interrupted, there is no alternative path and all coils are affected.

An open circuit in a fast dump resistor during a fast dump is similar to an open circuit of a coil. Damage can be averted if the rise in voltage across the coil is rapidly detected and the circuit breakers closed, ending the fast dump. In the circuits with series dump resistors, onlv the breakers associated with the open-circuited dump resistor need be closed. The fast dump can continue with the remaining resistors, provided their energy rating is adequate to withstand the increase in load caused by the loss of some of the resistors.

INDUCED CURRENTS

The maximum mechanical forces occur when currents larger than the operating currents are induced in a coil or coils by the decay of current in neighboring coils. A fast dump causes current peaking in some circuits; however, the largest peaks are caused by a quench accompanied by a failure of the protection system that leaves the power supplies connected. The power supplies provide low resistance paths for the induced current. The other conduction paths are through the dump resistors. Therefore, the peak currents can be controlled by changing the resistance of the power supplies and the dump resistance. Resistance added to the power supplies exacts a heavy penalty in increased energy costs. The maximum value of dump resistance is fixed by the allowable dump voltage to ground.

The induced current also depends on the circuit. Two of the circuits, the circuit with a combined dump resistor for all twelve coils and the series circuit without diodes, have no current peaking. Except for the small trim current, the current is the same in all coils. The circuits with smaller groupings reduce, but do not necessarily eliminate, current peaking. The circuit with separate power supplies has the highest current peaks. In this circuit, each coil is virtually shorted by a power supply.

In the other circuits, there are two critical fault conditions that can lead to a peak current when the power supplies are connected: a quench of all coils except one of the center ones, and a quench of all coils except the end two. A quench of all but a center coil is critical because the center coils have the largest mutual coupling to their neighbors. A quench of all but the two end coils is important in some cases, because the two end coils are shorted by a trim power supply.

In the circuit with individual, parallel dump resistors, the maximum current is induced when all but a center coil quenches. Coupling resistors reduce this peak. However, coupling resistors are less effective in reducing the induced current in the two end coils. This peak must be reduced by increasing the resistance of the trim supply.

The behavior of the series circuit with diodes is not as easily characterized as the other circuits. Instead of one circuit configuration, there are many, depending on which diodes conduct and which do not. However, for the two critical fault conditions, the circuit configuration resembles the circuit with coupling resistors. For the same dump voltage, the current peaks are less than in the circuit with individual dump resistors.

COIL TEMPERATURE AND VOLTAGE TO GROUND CAUSED BY A QUENCH

If an entire coil quenches, the temperature rise is never excessive. In fact, if all of the energy stored in the twelve solenoids is absorbed by one coil, the final temperature is 252 K. However, if only part of the coil is normal, there is no limit to the temperature rise. Therefore, it is prudent to disqualify, or at least demerit a circuit with a high temperature rise.

The highest temperature rise occurs in the circuit with a single dump resistor for the twelve coils when only one coil quenches and the power supplies are connected. The series circuit without diodes is a close second.

These two circuits also generate the highest voltage to ground. It occurs when two of the end coils quench and the power supply is connected. The voltage to ground in the circuit with one dump resistor is 2871 V, high enough to disqualify this circuit.

CONCLUSIONS

Putting aside economic considerations, the series circuit with diodes is the best circuit. It has as low a voltage to ground as is possible, an open circuit affects a single coil, the power supply can have a smaller power rating than in other circuits, a smaller strain is placed on the breakers, and the induced current is smaller than in the circuit with individual, parallel dump resistors. However, the cost is high.

All of the project requirements can be met by a more economical solution, the circuit with individual parallel dump resistors and coupling resistors. The dump resistors are chosen to give the highest allowable voltage to ground. Coupling resistors of the same size reduce to an acceptable level the maximum current induced in a center coil when all other coils quench and the power supplies are connected. The current induced in the two end coils is also reduced. However, resistance must be added to the trim power supply to bring this current to an acceptable level. The coupling resistors also reduce the energy absorbed by a dump resistor when only one coil quenches and the power supplies are connected. In fact, the physical size of a dump and coupling resistor pair is less in the circuit with coupling resistors than it is in the circuit without them.

Grouping the solenoids is an effective way of reducing the current peaking. However, an open circuit affects all of the coils in the group. High voltages to ground and high coil temperatures are also a consequence of grouping. For these reasons, the circuits in which the coils are grouped, and the series circuit without diodes which has many of the characteristics of these circuits, were rejected.

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APPENDIX A

THE ELECTRICAL PROPERTIES OF THE SOLENOIDS

The solenoids are coaxial with a number of other coils, the end coils. For most purposes, the effect of the end coils on the solenoids must be taken into account. Therefore, the properties of the end coils are also listed in the appendix.

TABLE A1.

The mutual and self-inductances of the coils. The values are for version L-72.

	M2	M1	T2	T1	A20	A21	A1	S6	S5	S4	S3	S2	S1
M2	11.1067												
M1	0.5294	11.1067											
T2	0.0290	0.2516	2.6842										
T1	0.0027	0.0065	0.0531	0.8543									
A20	0.0095	0.0200	0.0259	0.2085	6.9632								
A21	0.0029	0.0060	0.0082	0.0834	2.4761	4.5596							
A1	0.0054	0.0098	0.0076	0.0188	0.4550	0.1565	6.9632						
S6	0.0082	0.0139	0.0088	0.0142	0.2076	0.0655	0.7777	3.6086					
S5	0.0064	0.0104	0.0059	0.0080	0.1056	0.0331	0.3894	0.9965	3.6086				
S4	0.0051	0.0080	0.0042	0.0049	0.0587	0.0180	0.1854	0.4435	0.9965	3.6086			
S3	0.0042	0.0063	0.0030	0.0032	0.0353	0.0106	0.0953	0.2275	0.4435	0.9965	3.6086		
S2	0.0034	0.0050	0.0023	0.0022	0.0227	0.0068	0.0537	0.1277	0.2275	0.4435	0.9965	3.6086	
S1	0.0028	0.0041	0.0018	0.0016	0.0153	0.0046	0.0327	0.0772	0.1277	0.2275	0.4435	0.9965	3.6086

The mutual and self-inductances for the Kelley and Mars modes are listed in Table A1. Since the string of coils is symmetrical about the center, it is only necessary to show the values for one end. The solenoids are labelled S, the transition coils T, the yin-yang coils M, and the Axicell coils, A.

TABLE A2.

THE OPERATING AND SHORT CIRCUIT CURRENTS

FOR THE THREE MODES OF OPERATION FOR VERSION L-72.

Coil	Operating Current A	Short Circuit Current A
	KELLEY MODE	
M2	4403	4614
M1	3833	4200
T2	5874	6465
T1	5427	7217
A20	4542	5499
A21	1500	4192
A1	626	1613
S6	2866	4814
S5	2866	5349
S4	2778	5497
S3	2778	5988
S2	2742	5615
S1	2742	5647
	MARS MODE	
M2	4403	4614
M1	3833	4200
T2	5874	6465
T1	5427	7217
A20	4542	5499
A21	1500	4191
A1	4010	4755
S6	1763	3873
S5	1763	3745
S4	1690	3582
S3	1690	3528
S2	1669	3491
S1	1669	3484
	TARA MODE	
M2	4412	Not Calculated
M1	3850	
T2	5874	
T1	5427	
A20	4542	
A21	1500	
A1	4392	
S6	0	
S5	1710	
S4	1639	
S3	1639	
S2	1616	
S1	1616	

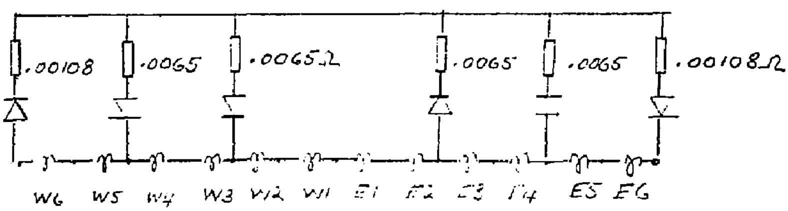
Three modes of operation are proposed for MFTF-B, the Kelley, Mars, and Tara modes. Table A2 lists the normal operating current for each mode, and the currents that result from a perfect short circuit of a coil. The short circuit current is generated if one coil has a superconducting short and the current in the other coils is reduced to zero.

The currents in the solenoids are largest for the Kelley mode. Therefore, unless stated otherwise, the calculated and simulated results are for the Kelley mode.

The fast dump resistors have a resistance of .0291 ohms, giving a coil voltage during a fast dump of 83.4 V for a current of 2866 A. For the circuits in which the maximum voltage to ground is six times the coil voltage, the maximum voltage to ground is approximately 500 V.

The grounding resistors prevent high voltages with respect to ground and aid in the detection of ground faults in the circuit. The resistance of these resistors is approximately 100 ohms. Consequently, they have little or no effect on the distribution of currents during a quench or a fast dump.

The resistances of the power supplies are estimates based on the projected lengths of the cable runs. The values and the circuit used to simulate the power supplies is shown below:



APPENDIX B
THE ADIABATIC QUENCH MODEL

Assumptions on which the model is based:

(a) Superconductivity is lost simultaneously by each part of the coil over a short period of time.

(b) Once normal, the initial resistance of the coil is the resistance of the copper winding at 4.2 K.

(c) All generated heat is stored in the copper, raising its temperature. The heat stored in the helium and insulation and heat lost is not taken into account.

(d) The conductivity and specific heat of the copper depend on temperature.

The calculation is:

power generated = power stored

$$i^2 p(T)\frac{L}{A} = q(T)\, W\frac{dT}{dt}$$

i	= current, A
T	= temperature, K
t	= time, s
L	= length = 2 x 2.5 x 60 m
W	= weight = 5277.87 kg
A	= area = 6.25×10^{-5} m^2
p(T)	= resistivity, a function of temperature
q(T)	= specific heat, a function of temperature

The numerical values given are for one of the solenoids.

The following values are from the Handbook on Materials for Superconducting Machinery, National Bureau of Standards, 1974.

T °K	ρ(T) ohm meter x 10^{-8} for RRR = 97
4	.016
20	.017
32	.020
40	.029
50	.040
60	.100
80	.200
100	.370
150	.760
200	1.000
300	1.700

T °K	q(T) $J\ kg^{-1}K^{-1}$
4	.1
6	.23
8	.46
10	.85
13.5	2
17	4
22	10
28	20
40	60
60	140
80	200
200	360
300	380

The transition of the coil's resistance from zero resistance to the resistance of the winding at 4.2 K is made using the following relationship:

$$R_{coil} = \rho(T)\ \frac{1}{A}\left(1 - 2e^{\frac{-(t - t_q)}{2}} + e^{\frac{-(t - t_q)}{2}}\right),$$

where t_q = the time at which a quench begins.

The predominant time constant is two seconds. Therefore, the transition is virtually complete in six to eight seconds.

Figures A1 and A2 show the rise of resistance and temperature due to an adiabatic quench of one coil, when all of the energy stored in the mutual and self-inductance of the solenoids and their neighbors is deposited in that one coil. The simulation was made to calculate an upper limit to the temperature rise in a coil, but has no counterpart in any of the proposed circuits. In the simulation, the quench resistance of one coil is the only dissipative element in a circuit consisting of all coils in series with one return path.

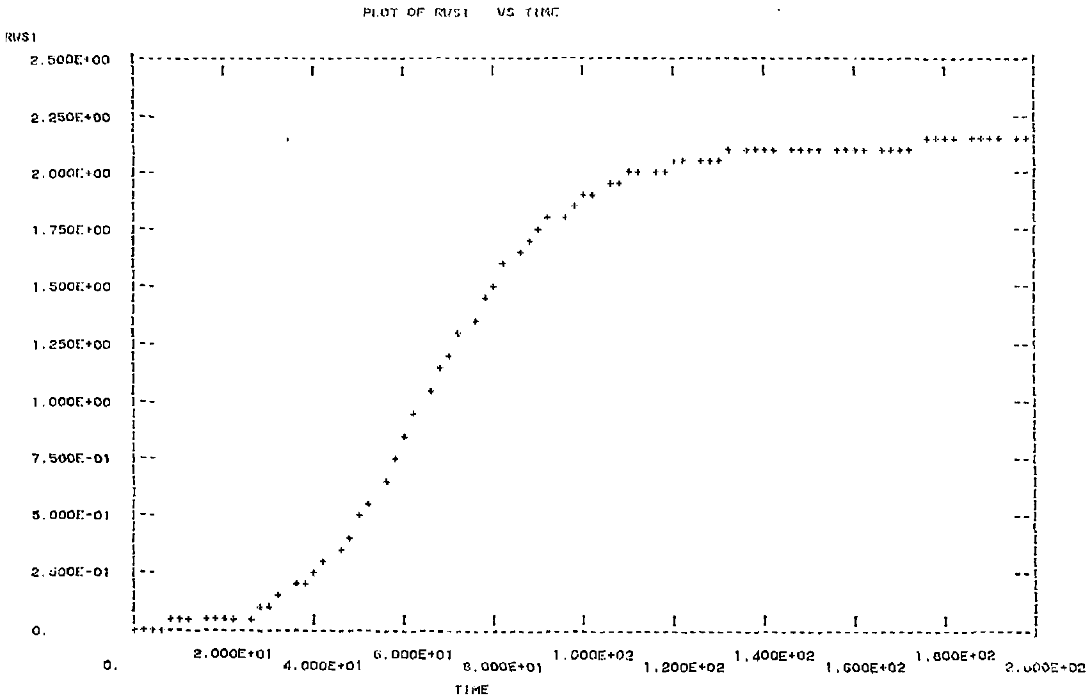


FIGURE A1.

The build-up of resistance in a quenched coil when all of the energy stored in the twelve solenoids is deposited in that coil. Calculated using the adiabatic model.

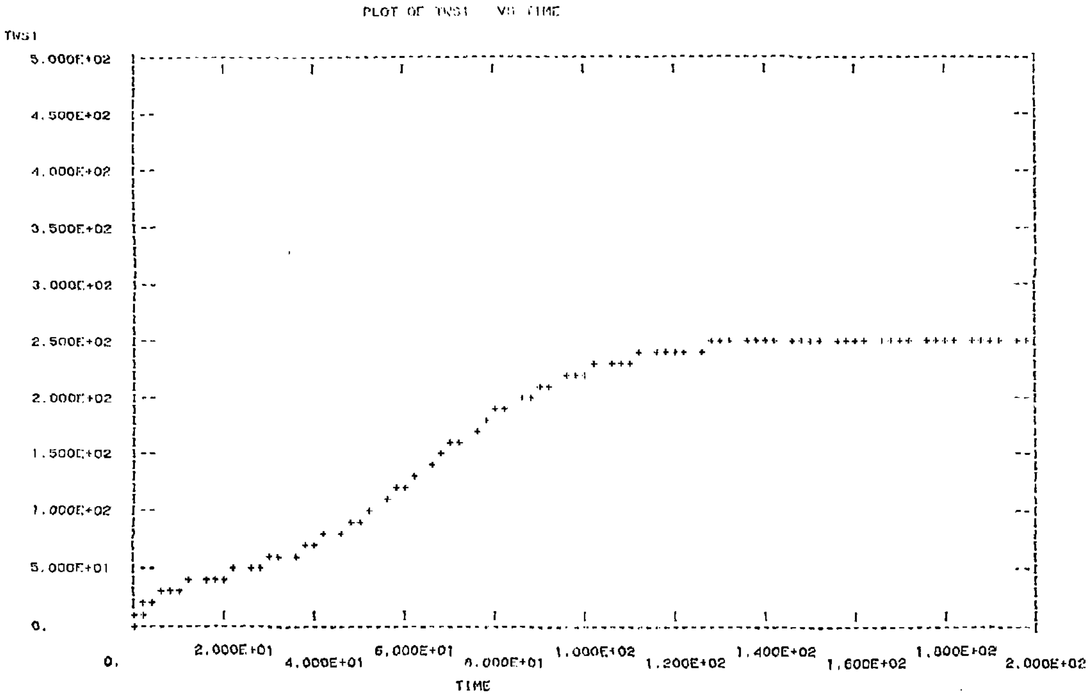


FIGURE A2.

The build-up of temperature in a quenched coil when all of the energy stored in the twelve solenoids is deposited in that coil. Calculated using the adiabatic model.

APPENDIX C
SIMULATION RESULTS, INDIVIDUAL, PARALLEL DUMP RESISTORS

Table A3 gives a complete listing of results that are summarized in the text. The peak operating current, time of peak, final temperature of the coil, and energy absorbed by the dump resistors are tabulated. Several normal and fault situations are included.

Figures A3 to A8 give a sampling of the computed current and temperature waveforms. Figures A3 and A4 show a typical coil current during a fast dump for all coils superconducting and all coils quenched. Figure A5 shows the temperature rise when all coils quench and the circuit is fast dumped. The peak induced current, which occurs when all coils except W3 quench and the power supplies are connected; coils except W3 quench and the power supplies are connected, is shown in Figure A6. Figures A7 and A8 show another critical set of currents, the currents in W5 and W6 when all other coils quench.

TABLE A3.

THE PEAK CURRENTS, FINAL TEMPERATURES, AND ENERGIES ABSORBED BY DUMP RESISTORS FOR THE CIRCUIT WITH INDIVIDUAL, PARALLEL DUMP RESISTORS

For the first two cases only the west values are listed, the east are symmetrical. The power supplies contain diodes to ensure undirectional flow of current. The quenches are adiabatic.

Coil	Peak Current / Operating Current	Time of Peak Current S	Final Temperature of Coil K	Energy Absorbed by Coil's Dump R MJ
All coils superconducting, fast dump				
W6	1.00	0	4.2	23.0
W5	1.00	0	4.2	26.9
W4	1.00	0	4.2	27.3
W3	1.00	0	4.2	27.8
W2	1.00	0	4.2	27.4
W1	1.00	0	4.2	27.2
All coils quench, fast dump				
W6	1.00	0	62	7.68
W5	1.00	0	66	8.17
W4	1.00	0	67	8.24
W3	1.00	0	67	8.29
W2	1.00	0	67	8.26
W1	1.00	0	67	8.23
All coils except W1 quench, fast dump				
W6	1.00	0	62	7.69
W5	1.00	0	65	8.11
W4	1.00	0	60	8.13
W3	1.00	0	65	8.06
W2	1.00	0	62	7.68
W1	1.12	68	4.2	36.00
E1	1.00	68	62	7.66
E2	1.00	68	65	8.02
E3	1.00	68	66	8.18
E4	1.00	68	66	8.18
E5	1.00	68	65	8.18
E6	1.00	68	56	7.68

TABLE A3. (continued)

Coil	Peak Current / Operating Current	Time of Peak Current S	Final Temperature of Coil K	Energy Absorbed by Coil's Dump R MJ
All coils except W3 quench, power supplies connected				
W6	1.06	0	71	2.38
W5	1.06	0	74	2.27
W4	1.06	0	71	1.98
W3	1.47	73	4.2	25.30
W2	1.00	0	69	.0
W1	1.00	0	73	.0
E1	1.00	0	74	.0
E2	1.00	0	75	.0
E3	1.00	0	76	.0
E4	1.00	0	76	.0
E5	1.00	0	75	.0
E6	1.00	0	71	
All coils except W5 and W6 quench, power supplies connected				
W6	1.15	130	4.2	.3
W5	1.31	94	4.2	1.7
W4	1.00	0	67	.4
W3	1.00	0	73	.3
W2	1.00	0	74	.1
W1	1.00	0	75	.0
E1	1.00	0	76	.0
E2	1.00	0	76	.0
E3	1.00	0	76	.0
E4	1.00	0	76	.0
E5	1.00	0	75	.0
E6	1.00	0	71	.0
W1 quenches, power supply connected, energy and temperature at 677 s				
W6	1.01	161	4.2	.2
W5	1.01	82	4.2	.1
W4	1.04	250	4.2	.2
W3	1.07	217	4.2	.4
W2	1.11	71	4.2	3.0
W1	1.00	0	76*	44.6*
E1	1.11	71	4.2	3.5
E2	1.01	60	4.2	2.2
E3	1.05	251	4.2	.4
E4	1.03	239	4.2	.2
E5	1.00	0	4.2	.1
E6	1.01	82	4.2	.2

* At t=50,000 s, when almost all stored energy is dissipated, the energy absorbed by the dump resistor of W1 is 117.6×10^6 J, the temperature of the coil is 80.3° K.

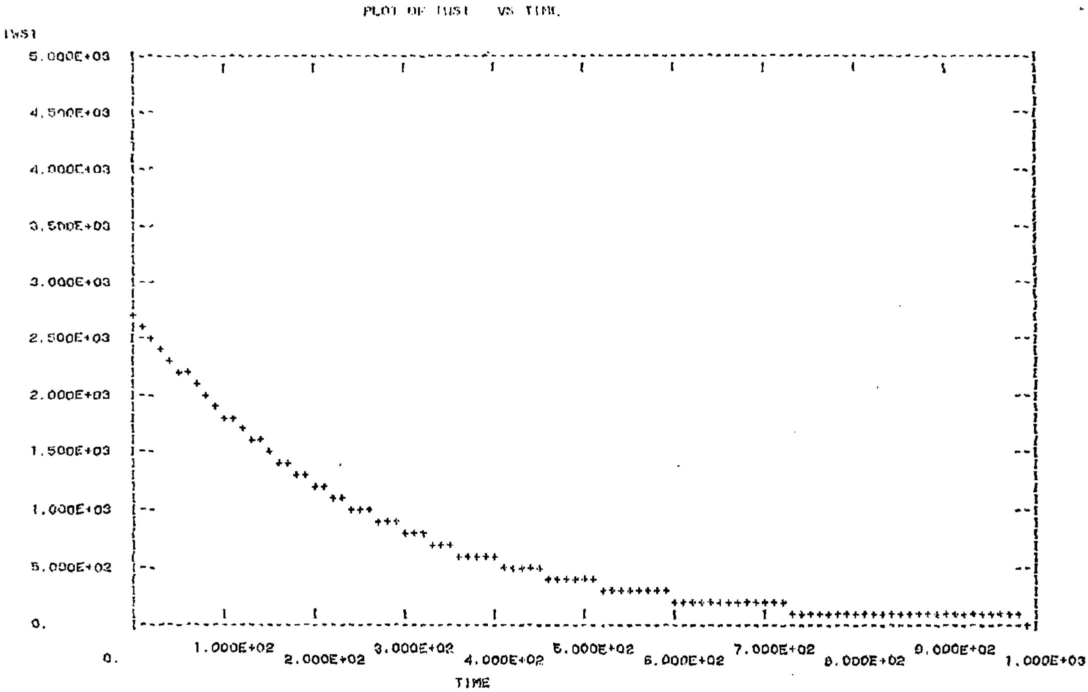


FIGURE A3.

The current in solenoid W1 following a fast dump with all coils superconducting for the circuit with individual, parallel dump resistors.

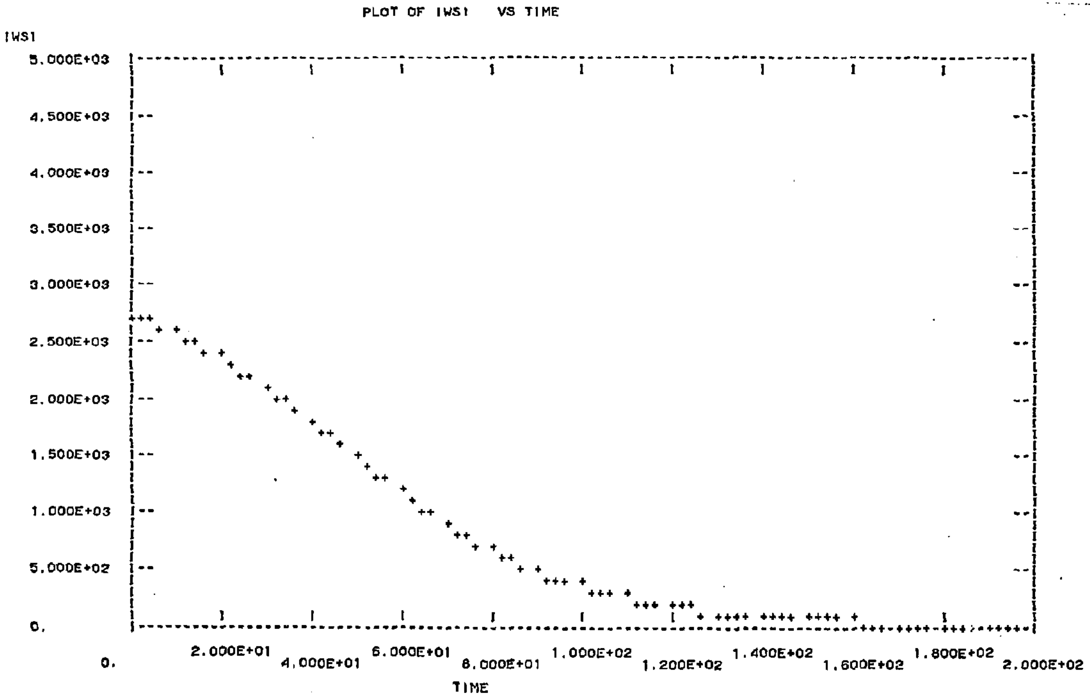


FIGURE A4.

The current in solenoid W1 following a fast dump with all coils adiabatically quenching.
The circuit with individual parallel dump resistors.

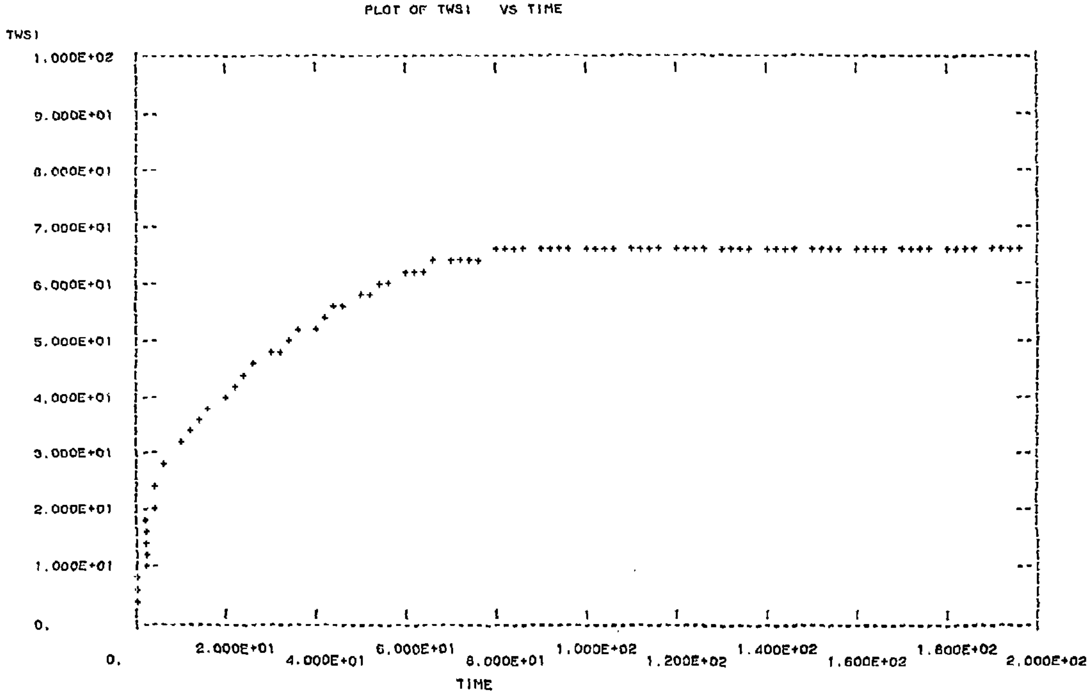


FIGURE A5.

The temperature in solenoid W1 following a fast dump with all coils adiabatically quenching.
The circuit with individual, parallel dump resistors.

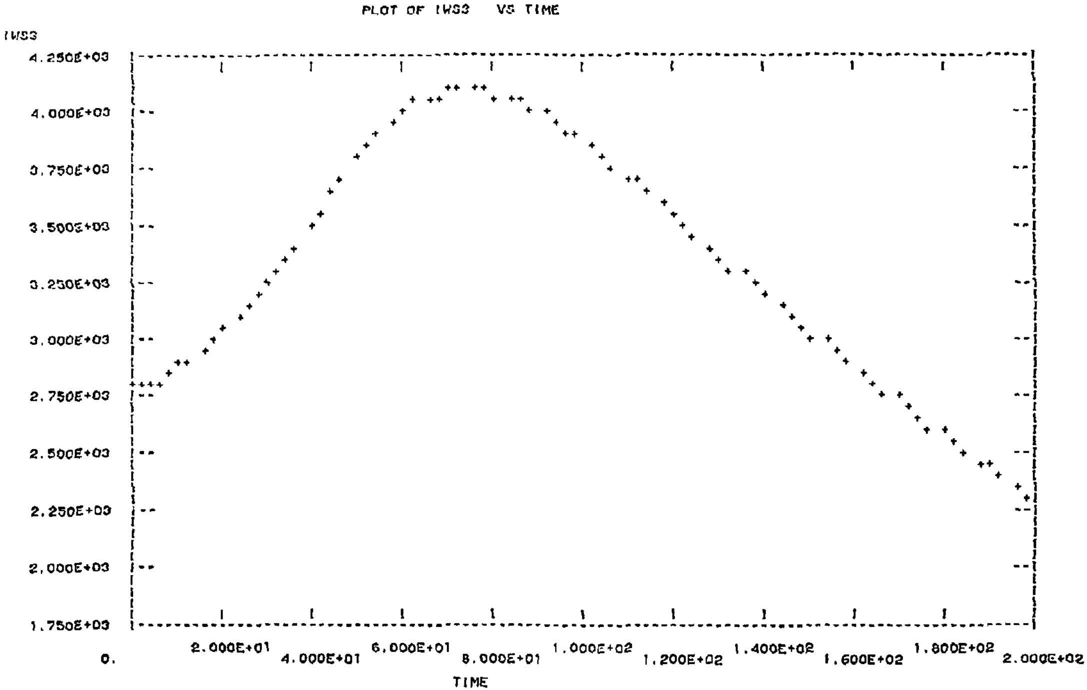


FIGURE A6.

The current in W3 when all coils except W3 adiabatically quench and the power supplies remain connected; for the circuit with individual, parallel dump resistors.

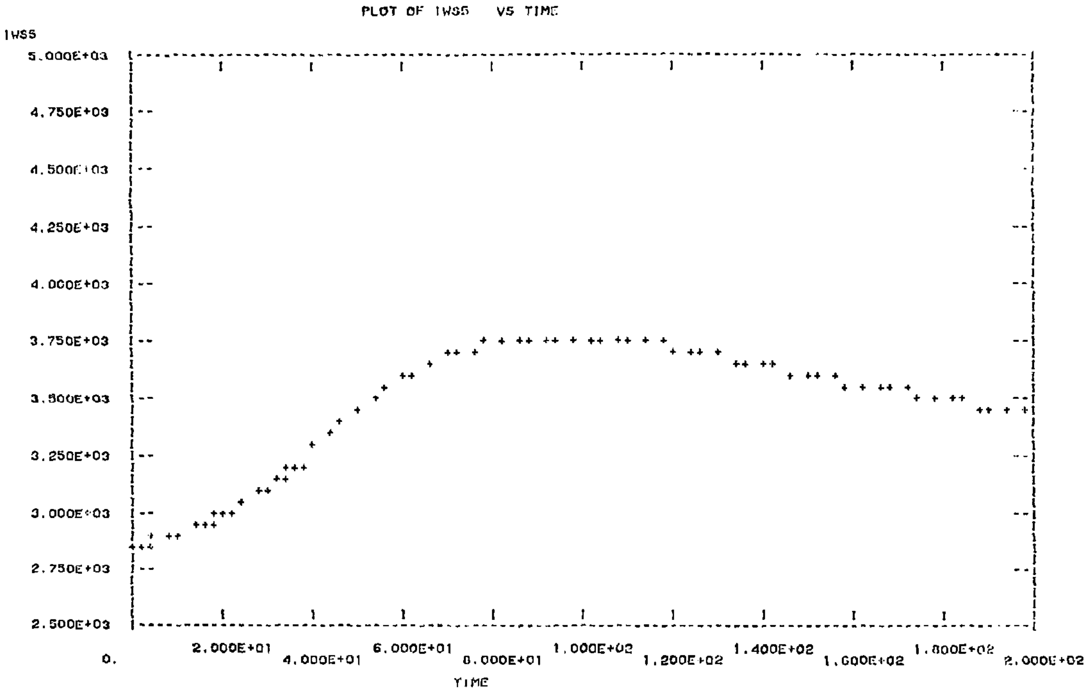


FIGURE A7.

The current in solenoid W5 following a quench of all coils except W5 and W6 with power supplies connected for the circuit with individual, parallel dump resistors.

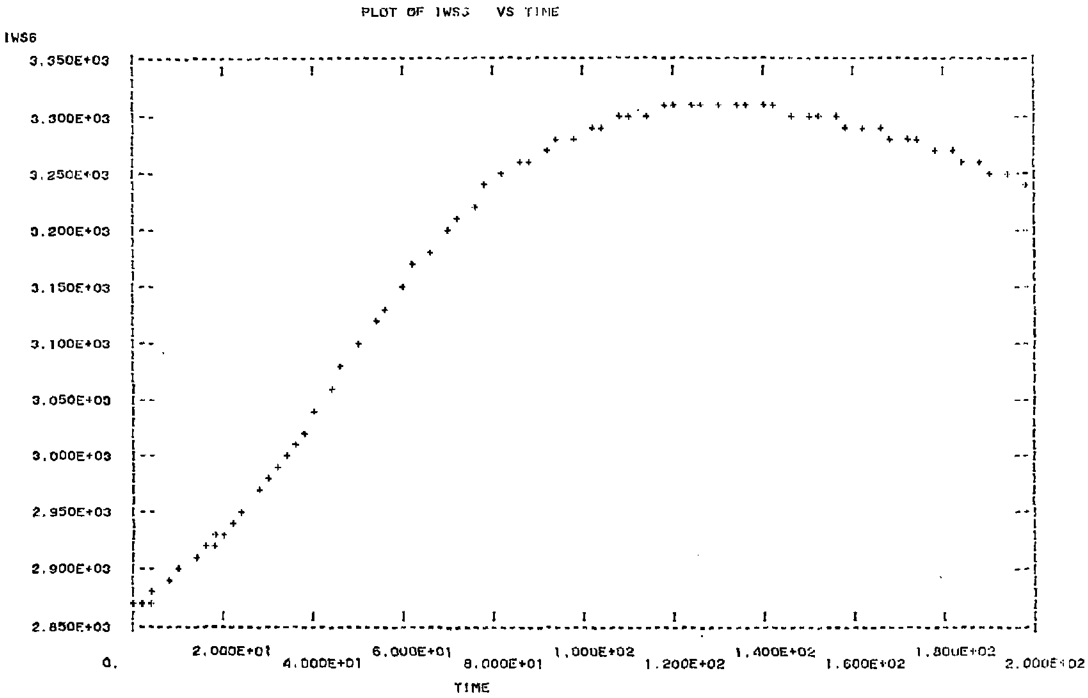


FIGURE A8.

The current in solenoid W6 following a quench of all coils except W5 and W6 with power supplies connected for the circuit with individual, parallel dump resistors.

APPENDIX D
SIMULATION RESULTS, COUPLING RESISTORS

Table A4 gives a complete listing of results that are summarized in the text. The organization of the table parallels that of Table A3, allowing the circuits with and without coupling resistors to be compared.

TABLE A4.

THE PEAK CURRENTS, FINAL TEMPERATURES, AND ENERGIES ABSORBED BY THE DUMP AND COUPLING RESISTORS FOR THE CIRCUIT WITH COUPLING RESISTORS

Coil	Peak Current / Operating Current	Time of Peak Current S	Final Temperature of Coil K	Energy Absorbed by Coil's Dump R MJ	Energy Absorbed by Coupling R to Right of Coil MJ
All coils superconducting, fast dump, $R_c = R_d$					
W6	1.00	0	4.2	24.2	0.1
W5	1.00	0	4.2	26.1	0.0
W4	1.00	0	4.2	27.0	0.0
W3	1.00	0	4.2	27.4	0.0
W2	1.00	0	4.2	27.4	0.0
W1	1.00	0	4.2	27.3	0.0
All coils quench, fast dump, $R_c = R_d$					
W6	1.00	0	62	7.7	0.0
W5	1.00	0	65	8.1	0.0
W4	1.00	0	67	8.2	0.0
W3	1.00	0	67	8.3	0.0
W2	1.00	0	67	8.3	0.0
W1	1.00	0	67	8.2	0.0
All coils except W1 quench, fast dump, $R_c = R_d$					
W6	1.00	0	62	7.7	0.0
W5	1.00	0	65	8.1	0.0
W4	1.00	0	66	8.1	0.0
W3	1.00	0	66	8.1	0.0
W2	1.00	0	68	8.4	4.3
W1	1.00	0	4.2	19.9	4.3
E1	1.00	0	68	8.4	0.0
E2	1.00	0	66	8.1	0.0
E3	1.00	0	66	8.2	0.0
E4	1.00	0	66	8.2	0.0
E5	1.00	0	66	8.1	0.0
E6	1.00	0	62	7.7	0.0
All coils except W3 quench, power supplies connected, $R_c = R_d$					
W6	1.00	0	72	2.0	0.0
W5	1.00	0	75	1.8	0.1
W4	1.00	0	79	1.1	12.2
W3	1.21	54	4.2	6.0	3.9
W2	1.00	0	74	0.2	0.0
W1	1.00	0	73	0.1	0.0

TABLE A4. (continued)

Coil	Peak Current / Operating Current	Time of Peak Current S	Final Temperature of Coil K	Energy Absorbed by Coil's Dump R MJ	Energy Absorbed by Coupling R to Right of Coil MJ
All coils except W3 quench, power supplies connected, $R_c = R_d$ (continued)					
E1	1.00	0	74	0.1	0.0
E2	1.00	0	74	0.1	0.0
E3	1.00	0	76	0.0	0.0
E4	1.00	0	75	0.0	0.0
E5	1.00	0	74	0.0	0.0
E6	1.00	0	71	0.0	0.0
All coils except W5 and W6 quench, power supplies connected, $R_c = R_d$					
W6	1.22	118	4.2	0.5	0.1
W5	1.24	84	4.2	0.5	0.8
W4	1.00	0	69	0.0	0.0
W3	1.00	0	72	0.0	0.0
W2	1.00	0	74	0.0	0.0
W1	1.00	0	75	0.0	0.0
E1	1.00	0	76	0.0	0.0
E2	1.00	0	76	0.0	0.0
E3	1.00	0	76	0.0	0.0
E4	1.00	0	76	0.0	0.0
E5	1.00	0	75	0.0	0.0
E6	1.00	0	71	0.0	0.0
W1 quenches, power supply connected, $R_c = R_d$ AT 875 s*					
W6	1.03	267	4.2	0.3	0.0
W5	1.04	255	4.2	0.3	0.0
W4	1.08	210	4.2	0.4	0.1
W3	1.10	135	4.2	0.3	0.8
W2	1.02	26	4.2	0.3	16.8
W1	1.00	0	88	18.3	20.0
E1	1.02	26	4.2	0.3	1.5
E2	1.02	54	4.2	2.0	0.3
E3	1.11	210	4.2	1.2	0.1
E4	1.06	266	4.2	0.7	0.0
E5	1.01	289	4.2	0.4	0.0
E6	1.01	37	4.2	0.3	

*At 875 s there is 1.57 MJ stored in the central four coils.

TABLE A4. (continued)

Coil	Peak Current / Operating Current	Time of Peak Current s	Final Temperature of Coil K	Energy Absorbed by Coil's Dump R MJ	Energy Absorbed by Coupling R to Right of Coil MJ
W1 quenches, power supply connected, $R_c = 2R_d$ AT 1000 s**					
W6	1.05	243	4.2	0.3	0.0
W5	1.05	232	4.2	0.3	0.0
W4	1.09	187	4.2	0.3	0.2
W3	1.10	119	4.2	0.1	1.4
W2	1.00	15	4.2	0.3	15.7
W1	1.00	0	94	10.2	20.4
E1	1.00	15	4.2	0.3	2.5
E2	1.00	45	4.2	1.3	0.4
E3	1.12	175	4.2	1.0	0.2
E4	1.08	232	4.2	0.7	0.1
E5	1.02	279	4.2	0.5	0.0
E6	1.02	309	4.2	0.4	
W1 quenches, power supply connected, $R_c = 5R_d$ AT 1000 s**					
W6	1.07	203	4.2	0.2	0.0
W5	1.07	192	4.2	0.2	0.6
W4	1.10	158	4.2	0.1	0.3
W3	1.10	113	4.2	0.0	1.4
W2	1.00	3	4.2	0.2	10.9
W1	1.00	0	102	3.4	17.0
E1	1.00	3	4.2	0.1	3.1
E2	1.00	14	4.2	0.6	0.5
E3	1.13	136	4.2	0.6	0.3
E4	1.10	180	4.2	0.5	0.1
E5	1.05	231	4.2	0.4	0.0
E6	1.05	253	4.2	0.4	

** At 1000 s there is, for these two circuits, a negligible amount of energy stored in the four central coils.

TABLE A5. THE PEAK CURRENTS INDUCTED IN THE SOLENOIDS FOR A COUPLING RESISTANCE EQUAL TO THE DUMP RESISTANCE, WHEN ALL BUT ONE OR TWO COILS ADIABATICALLY QUENCH

Coils that do not quench	Peak Current / Operating Current
1	1.16
2	1.16
3	1.21
4	1.16
5	1.17
5, 6	1.22, 1.24

APPENDIX E

SIMULATION RESULTS, COMBINED DUMP RESISTORS

TABLE A6.

THE MAXIMUM VOLTAGES TO GROUND FOR THE COILS WITH COMBINED, PARALLEL DUMP RESISTORS

There were no trim power supplies or trim dump resistors in the simulations, the same coil current was used in all coils.

Coils that Quench	Condition	The Maximum Voltage to Ground	Location
W6	fast dump	1391 V	right side W6
W6, W5	fast dump	1550 V	right side W5
	supply connected	2871 V	right side W5
W6, W5, W4	fast dump	1478 V	right side W4
	supply connected	2739 V	right side W4

TABLE A7.

THE MAXIMUM VOLTAGES TO GROUND AND FINAL TEMPERATURES WHEN W6 and W5 QUENCH, AND MAIN POWER SUPPLY IS CONNECTED

There were no trim power supplies or trim dump resistors in the simulations. The same coil current was used in all coils.

Coil	Maximum Voltage	Time of Maximum	Final Temperatures
W6	1457	67 S	172 K
W5	2871	67	172
W4	2584	67	4.2
W3	2287	67	4.2
W2	1984	67	4.2
W1	1683	67	4.2
E1	1381	67	4.2
E2	1079	67	4.2
E3	782	67	4.2
E4	495	67	4.2
E5	222	67	4.2
E6	-1.4	0	4.2

APPENDIX F

SIMULATION RESULTS, SERIES DUMP RESISTORS WITH DIODES

It is not obvious which diodes conduct and which are nonconducting when one or more coils quench and the breakers remain closed. A change of a diode from a conducting state to a nonconducting state changes the circuit configuration and affects the maximum current induced. Simulation studies were made to determine the way in which the diodes change state. In order to conserve computer time, a fixed quench resistor was used rather than an adiabatic one.

Some representative results are shown in Table A8. The table shows which coils quench at zero time, and the time periods the diodes conduct. The diodes are labelled in accordance with their associated coils except for the diode spanning all of the coils, which is labelled T.

As the table shows, the behavior cannot be characterized in a simple way. However, when only a few of the coils quench, the tendency is for the diodes associated with them to become nonconducting while the others conduct. On the other hand, when almost all of the diodes quench, all of the diodes tend to conduct.