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QUENCH PROTECTION IN THE SLAC LINEAR COLLIDER FINAL FOCUS TRIPLET*

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Abstract

During the testing phase of the implementation of the superconducting final focus for the SLAC Linear Collider, one of the triplets began quenching at a relatively low current. The process of superconductor quenches is discussed, as well as systems used to protect against a quench and the details of the quench we experienced.

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I. Introduction

The SLAC Linear Collider (SLC) shoots 50 GeV electrons and positrons at each other so that the SLC Large Detector (SLD) can study the results. To increase the number of collisions, the 1 mm beams are focused to a spot about 2 μm in diameter. The final focus of each beam for the SLAC Linear Collider consists of a triplet of superconducting quadrupole magnets.[1,2]

Figure 1: SLC.

Superconducting magnets can run very large currents, and they therefore can produce extremely large fields and gradients, but they pose special problems uniquely related to their superconductivity. A "quench" is a sudden change from a superconducting state to a normally resistive state, a change which can produce potentially catastrophic results in large current systems. Such systems must have circuits to detect the onset of a quench, and there must be fast-acting protection devices that can save the magnets. A quench that occurred during the testing phase of the SLD superconducting final focus provides an illustration of the peculiarities of running a superconducting magnet system.

II. The Superconducting Final Focus

The final focus triplet consists of three superconducting quadrupole magnets, referred to as Q1, Q2, and Q3. Q1 is the magnet nearest the interaction point (IP) where the beam is focused so that the beam enters the triplet in Q3 and exits from Q1. The coils of the magnets are all connected in series, so all of the quadrupoles have the same strength, but the current in Q2 is reversed so that its field has the opposite sign, as is necessary for magnetic focusing.

Figure 2: Final Focus configuration.

A cross section of one of the quadrupoles is shown in figure 3. The central aperture through the quad is 5.0 cm, and a 4.6 cm diameter beam pipe extends through this aperture, out of the page in the figure. Superconducting wires carry sheets of current along the beam pipe, coming out of the page on the top and bottom of the figure and going into the page along the sides. Each sheet of current is, in fact, 48 ribbon-shaped superconducting cables, each typically carrying about 4000 A.

Figure 3: Quad cross section.

The superconducting cable itself is made of 23 superconducting wires bundled together into a flat ribbon 7.8 mm wide and averaging 1.2 mm thick. Each individual superconducting wire consists of 570 filaments of 19 μm diameter NbTi type II superconductor immersed in a 0.68 mm diameter copper matrix. The entire triplet is housed in a single liquid helium cryostat that maintains their temperature just above absolute zero, at about 4.3 K.

Figure 4: Cross section of SLC triplet cryostat #6508A3.

In spite of the large current, the superconductor itself generates no heat, since i^2R is 0. But there are myriad ways that heat can enter the system from the outside environment. The liquid helium container that holds the magnets is surrounded by a vacuum contained by a copper vapor shield. The vapor shield is kept cool by helium gas boiloff that is returning from cooling the magnets, and it is further vacuum insulated from the outside containment vessel.[3] Each vacuum space is filled with 10 to 20 layers of superinsulation. With this elaborate cryostat system isolating the magnets, the major heat loss is limited to the 5000 A leads that connect the magnets with their power supply, and even these leads are cooled by cold helium gas to keep the heat load to a minimum.

III. Quenches in Superconducting Magnets

One of the special problems associated with using superconducting magnets is that there might be some sudden change that could cause the superconductors to undergo a transition to a normal resistive state, a quench. Then suddenly and unexpectedly there would be thousands of amperes of current in a wire with non-zero resistance. With i^2R no longer equal to zero, a great deal of heat would be produced, concentrated in a very small area. The temperature there might rise enough to destroy the wire—a catastrophic event.

The superconducting cable itself is highly stable against small, highly local transient quenches, due to the wire's construction from many filaments of NbTi surrounded by copper. Tiny points along the NbTi may go normal, but the current can continue through other filaments and through the copper, which can conduct heat away as well. This quenched point of NbTi, cooled and with a reduced current density, can then return to its superconductive state. The danger occurs when the quench appears rapidly over many filaments, so that the the copper matrix is not able to transmit the heat away quickly enough.

When the quench occurs over several fibers, temperature rise is substantial. The heat from this section of wire can then cause a nearby section to quench, too. Then the resistance from that additional quench causes a further rise in temperature, which causes the section near it to quench, which produces more heat, and so on and on. The quench can travel along the wire with the speed of sound, turning the whole coil resistive. With increased resistance the power supply can no longer maintain the current, and the magnetic field must collapse, releasing its energy and possibly destroying the magnet.

A quench may be initiated by a number of events. Exceeding the critical current density for a particular magnetic field strength, for example, or changing the current too rapidly can bring on a quench. At the magnetic field strength in which our quadrupole magnets are operated, the critical current for the superconducting cable is approximately 7100 A, well above the typical operating current in the SLC final focus of 4250 A.

When superconducting magnets such as these are first manufactured, they will not sustain a current near the critical value for the wire, quenching prematurely. However, if the current is repeatedly ramped up to the point of a quench, it is found that the quench current increases, then levels off at a value near the critical current for the wire. Apparently, the currents and resulting fields produce forces on the coils, which then move slightly, producing a quench. As this continues with higher and higher currents, the coils settle down into “niches,” where substantial movement can no longer occur. The process of increasing the quench current through repeated rampings-to-quench is referred to as “training,” and this is an essential part of the preparation of new superconducting magnets. The quadrupoles used in the SLC superconducting triplets underwent from 15 to 25 training quenches, reaching consistent quench currents in excess of 6500 A.[4]

IV. Quench Protection

The total inductance of the three series connected magnets is 4 mH. At a typical operating current of about 4250 A, the energy stored in the magnetic field is $E = \frac{1}{2} I^2L \approx 36$ KJ. This much energy concentrated in a small region of wire would be devastating to the system. So in actual operation the superconducting magnet system must be protected against the results of an unexpected quench. There must be circuits that somehow sense the onset of a quench, and they must react very rapidly before any damage can be done. And, of course, there must be devices which can somehow prevent a rapid rise in temperature and which can dissipate the stored energy of the magnets safely.

There are several ways that trouble might be detected in the superconducting system. Sensors could look for a rise in temperature or an increased pressure in the helium vapor, for instance. Or changes in voltages or changes in the level of liquid helium in the cryostat could be used. In the SLD superconducting final focus, protection devices are triggered by a change in the level of liquid helium, by the voltages across individual leads, or by an imbalance in the voltage across the different magnets.

The level of liquid helium is determined by a superconducting "dip stick," a superconducting wire that extends into the liquid. A constant current is passed through this wire, and, since it is a superconductor, its resistance is zero as long as it is completely covered in liquid helium. The extent to which its resistance is different from zero, then, tells how much of the "dip stick" is out of the liquid helium, and the voltage across it, therefore, gives an indication of the level. While a change in liquid helium level would not give a fast enough warning to aid in protection against a quench, this sensor does serve to protect the magnets from problems that may occur in the cryogenic system by initiating a slow ramp down of the magnet current.

Each lead that brings current into the cryostat must have one end at room temperature and the other end in liquid helium. Due to the lead's resistance, a voltage is developed between the two ends, and this voltage depends on the temperature of the returning vapor that is being used to cool them. These voltages are monitored, both to detect cryogenic problems that would lead to a slow ramp down of the current and to detect the onset of a quench.

With a 4000 A current, the total voltage across the triplet is typically a few millivolts, due primarily to the resistance of the leads that extend out of the liquid helium. But the voltage across Q1 and Q3 should just match the voltage across Q2. (The center member of the triplet is twice as long, and has twice the inductance of the other two.) Even a small section of the superconducting wire going normal dramatically alters this balance of voltage, and that change is the most reliable signal that a quench is beginning and that protective measures should be invoked.

The SLC superconducting final focus relies on two methods of protection. A primary danger is that, with a small portion of the superconductor system going normal, all of the energy in the magnet will be concentrated at that point and produce a high temperature that will destroy the wire. Many superconducting systems, including the SLC's final focus, have heaters built into the magnets, in strips laid in along the wires. These "quench heaters" can be energized to force the entire magnet to go normal, spreading out the energy over a much greater area. This process takes about 40 to 50 ms.

Figure 5: Power supply circuit.

Of course, as soon as a quench is detected, the power supply must be disconnected from the triplet. To make this possible, the power supply is connected to the magnets through a silicon controlled rectifier, or SCR, a fast-acting switch. (See Figure 5.) An SCR, after being turned on by a momentary signal at its gate, behaves like a normal diode and conducts as long as current continues to flow through it. But when the current drops near zero, the SCR turns off and will not conduct again until it is given an additional signal at the gate. So, at the detection of a quench, a bank of capacitors is fired which applies 400 V backwards across the SCR, shutting off current, turning off the SCR, and effectively isolating the magnet from the power supply. Firing the SCR occurs in about a millisecond after detection.

However, just disconnecting the power supply does not save the magnets. The magnetic field must collapse, and, if the magnets were completely disconnected, the energy stored in them would dissipate as heat generated by eddy currents inside the magnets' wires. This heat could destroy the magnets.

Instead, an alternate path is provided through a 0.015~Ω resistor, R_2 in Figure 5, where the energy can be safely dumped.

The SCR turnoff is fast, and nearly all the energy is dumped safely outside the magnets. The quench heaters, on the other hand, are slower, and, by making the magnets go normal, they dump most of the energy in the magnets themselves. The cryogenic system is then relied upon to remove the heat by the boiling of liquid helium. The resulting drop in the liquid level in the cryostat requires some time to recover before the magnets can be re-energized. The SCR turnoff, then, is seen as the primary protection system, and the quench heaters provide a backup. Quenches have occurred, however, when either of these systems was the only one operating, and the magnets were still well protected.

V. A Quench in the Superconducting Final Focus

The final focus requires two sets of superconducting triplets, of course, one for each beam, electrons and positrons. But since the magnets are unique and irreplaceable, four sets of three magnets were in fact manufactured for SLAC at the magnet lab at Fermilab. With one set of magnets kept in reserve, three complete, functioning triplets were built, providing a spare in case one malfunctioned.

Before being installed, each triplet was tested, aligned, and surveyed off beam. During the testing of "Triplet 2", it was found that a quench would occur whenever the current in the magnets was brought to about 4050 A (± 10 A over approximately 25 quenches). Further tests showed that the cause was inside the cryostat, associated with Q1, and probably due to a faulty soldered splice between two superconducting cables. The final focus commissioning program continued with "Triplet 3," and the superconducting final focus was installed on schedule. Triplet 2 was opened, and the splice was found, verified to be bad, and repaired. It has now been tested to a nominal 5500 A, and serves as the spare.

Figure 6: Voltage across Q1a and Q1b during ramp-up.

When the triplet is energized, the power supply ramps the current upward at about 30 A/s. Figure 6 is a graph, produced by an automatic monitoring system, that shows the sudden increase in voltage across Q1a and across Q1b, two of the four coils (each corresponding to one of the four poles of the quadrupole) in quadrupole Q1. Each of the four coils has an inductance of about 0.25 mH, and the increase in current is producing an induced EMF, $V = L\frac{di}{dt} \approx 7.5\,\mathrm{mV}$ in each coil. An interesting feature is that, unlike most inductors, there is no iR drop reducing the measured voltage—the resistance equals zero, after all.

Figure 7: Voltage across (a) quenching coil Q1a and
(b) superconducting coil Q1c.

Figure 7, on the other hand, records the onset of a quench that occurred in coil Q1a. (The quench actually started in a splice just outside the magnet itself, but the voltage measurements were across the coil and splice together.) The current had been ramped to 4047 A and remained at that current for a few seconds. With constant current, the voltage across the coil was zero. But a gradual rise in voltage indicates an increasing resistance in the coil due to a quench. In order to study the quench in this magnet, the voltage was allowed to rise to 2.0 V, at which point the capacitor bank was fired. This reverse voltage turned off the SCR and removed the power supply from the circuit, forcing current through the 0.01 Ω dump resistor.

In figure 7b, the voltage across coil Q1c is seen to respond. As Q1a begins to go resistive, the voltage available to Q1c drops slightly. But when the SCR fires, the rapid drop in current induces a negative voltage in the coil. Since $V_c = -4.1$ V, the current must be decreasing at $di/dt = V_c/L_c \approx 16\,000$ A/s. And of course the voltage across Q1a, the quenching coil, drops by the same amount, since it has the same inductance. But Q1a already had a voltage across it due to its resistance, 2.0 V, so its voltage at this point is less negative than in Q1c, –2.1 V.

Since the voltage rise in Q1a due to the increasing resistance reaches 2.0 V when the current attains 4000 A, the resistance of the normal section must be $R_a = V_a/i = 0.5$ mΩ. But the resistance continues to rise as the quench moves along the wire, and so, the voltage is seen to rise in Q1a.

As soon as the SCR fired, current was diverted to the 0.015 Ω dump resistor, R_2. A current of 4000 A through the resistor implies a voltage across it of about 60 V. The voltage drop in the resistance must be supplied by the induced EMF in the coils, so this 60 V must be the initial voltage across the magnet, as well. The current could then decay with a time constant of $\tau = L/R \approx$ 4 mH/15 mΩ ≈ 0.3 s. (This would be modified slightly due to the resistance of the leads and the voltage across the diode, D2, but these contributions are relatively small.) The exponential decay can be seen in both coils. After 50 to 100 ms, the rate of decay is seen to change, as the quench heaters fire and the resistance is increased.

If the SCR had not fired, the current would have to decay through the 0.7 mΩ resistor, R_1, and the time constant would instead be nearly 6 s. Since the danger to the magnets is the increased temperature from the energy delivered by the current, $\Delta E = \int P\,dt = \int i^2 R\,dt$, it is important to keep the time as short as possible, implying that the external resistance should be large. However, if the resistance is too large, the initial voltage across it, $V_o = i_o R$, and thus the voltage across the magnet, would be so large that dielectric breakdown would be a danger. R_2 is picked to moderate these extremes.

Table 1 has a summary of values and calculations.

Table 1: **Summary of Values and Calculations**	
Nominal current:	$I_o = 4047$ A
Charging rate:	$\frac{di}{dt} = 30$ A/s
Inductance of individual coil, e.g.:	$L_a = 0.25$ mH
Energy stored in triplet:	$E = \frac{1}{2} I^2 L \approx 36$ KJ
Induced EMF across a coil during charging:	$V = L \frac{di}{dt} \approx 7.5$ mV
EMF induced across a coil during quench, read from graph:	$V_c = -4.1$ V
Initial decay rate of current:	$di/dt = V_c/L_c \approx 16$ KA/s
Resistance of quenching section of Q1a as the SCR fired:	$R_a = V_a/i = 0.5$ mΩ
Voltage induced across magnets:	$V_L \approx V_{R2} = i_o R_2 \approx 60$ V
Time constant for decay:	$\tau = L/R \approx 4$ mH/15 mΩ ≈ 0.3 s

VI. Conclusions

A quench that occurred in the superconducting final focus at the SLAC Linear Collider serves to illustrate the behavior of inductors in a changing DC circuit. This is particularly nice, since superconducting coils are perfect inductors. In addition, the quench is an interesting example of the operation of superconducting magnets, and the systems that are designed to protect them.

VII. Acknowledgements

The superconducting final focus was precisely aligned and indulgently pampered by Jim Ferrie. Bill Burgess designed and implemented the unique cryogenic system. Al McInturff, from Fermilab, provided insight and expertise in superconductor quenches. Hank Cutler is responsible for the power supply and the quench detection system. Special thanks must go to Bill Ash who leads the Superconducting Final Focus group and who has inspired and broadened my teaching and my science. The whole group has been extremely helpful during my stay at SLAC.

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Triplets," SLAC–PUB–1478, revised May 1988; also Tenth International Conference on Magnet Technology, Boston, MA, September 23–26, 1987.

Figure Captions

Figure 1: SLC.

Figure 2: Final Focus configuration.

Figure 3: Quad cross section.

Figure 4: Cross section of SLC triplet cryostat.

Figure 5: Power supply circuit.

Figure 6: Voltage across Q1a and Q1b during ramp-up.

Figure 7: Voltage across (a) quenching coil Q1a and (b) superconducting coil Q1c.

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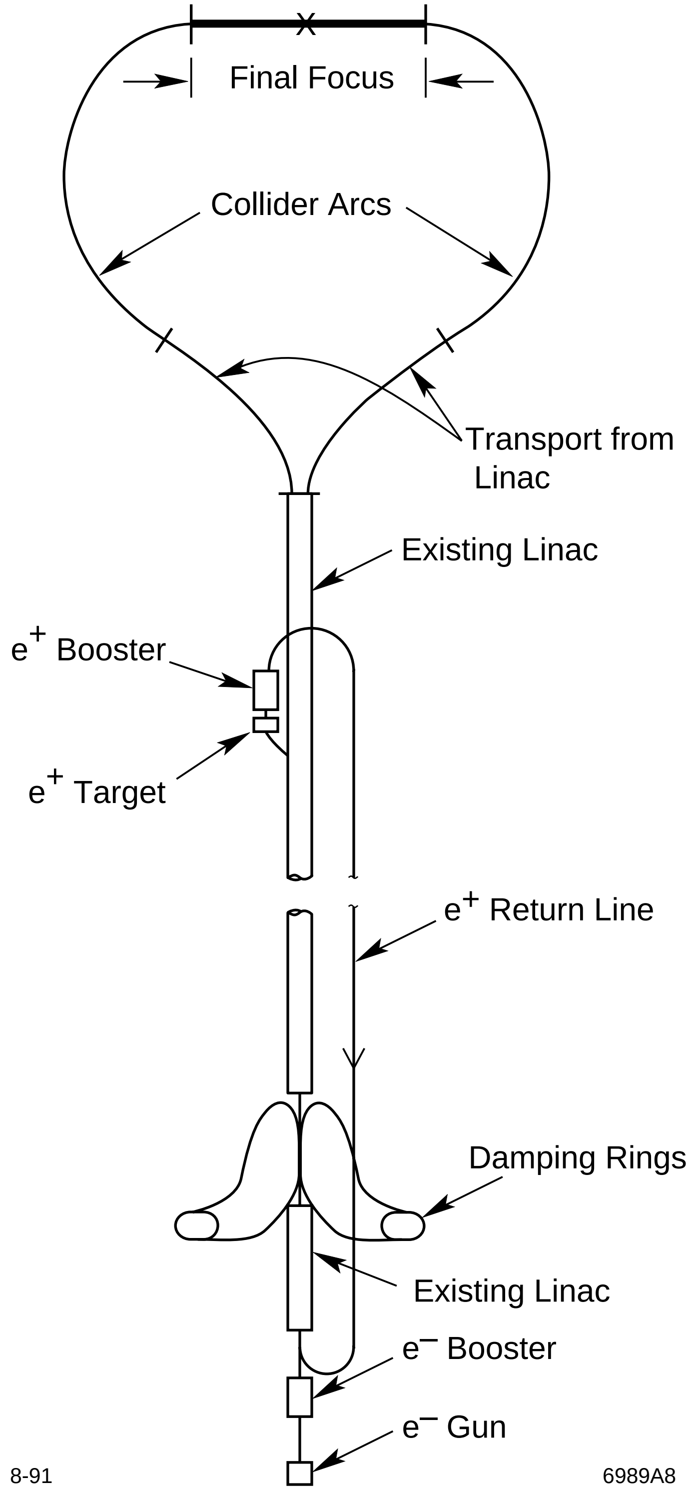


Final Focus
Collider Arcs
Transport from Linac
Existing Linac
e^+ Booster
e^+ Target
e^+ Return Line
Damping Rings
Existing Linac
e^- Booster
e^- Gun
8-91
6989A8

Figure 1

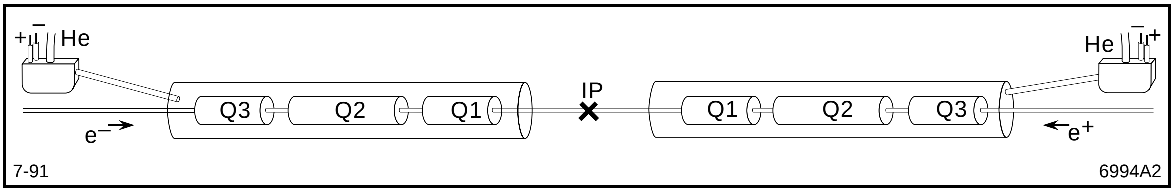


Figure 2

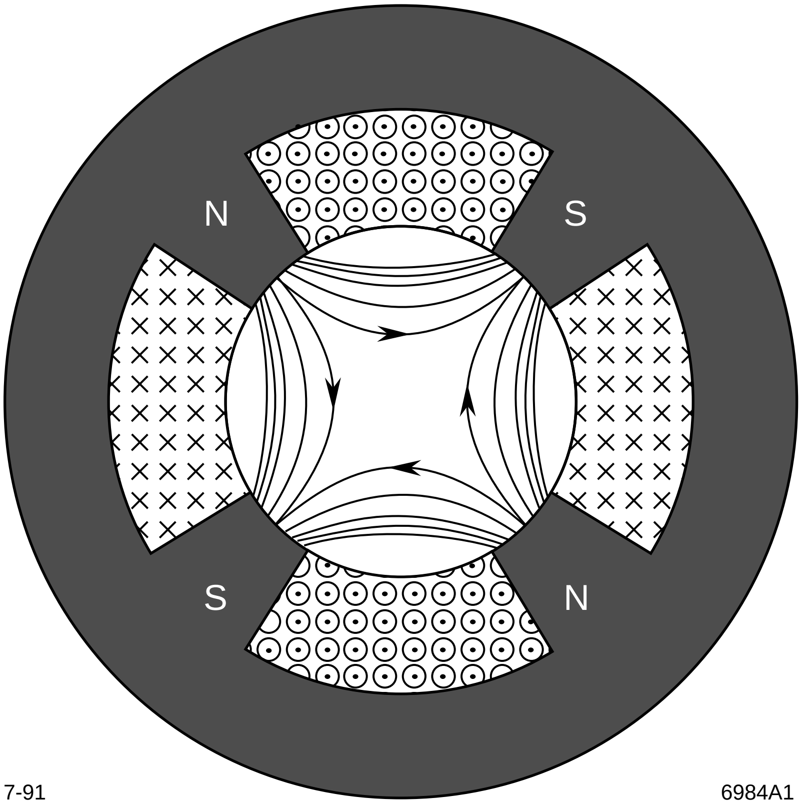
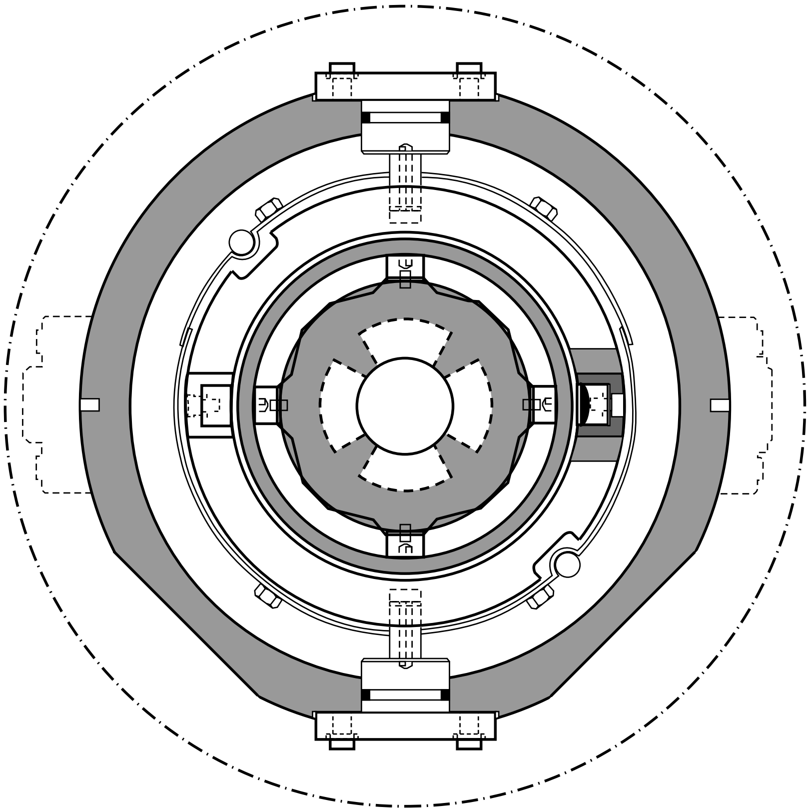


Figure 3



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6508A3

Cryostat Cross-Section

Figure 4

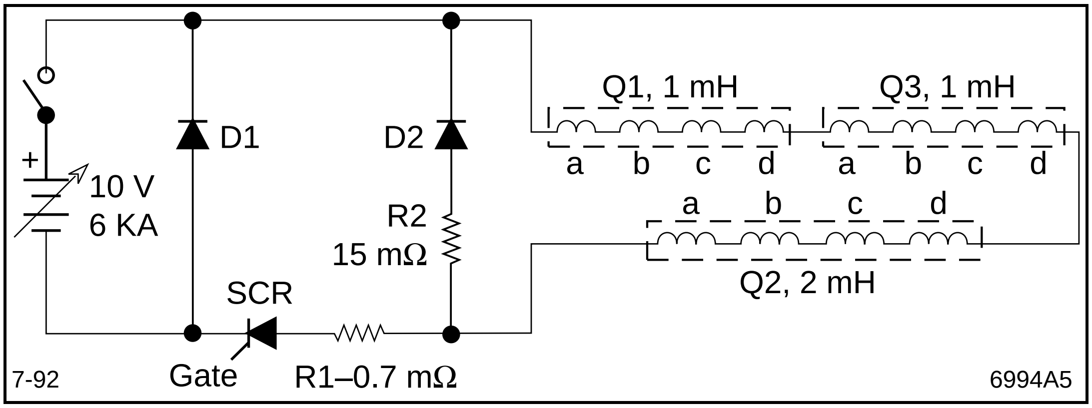
Q1, 1 mH
Q3, 1 mH
D1
D2
a
b
c
d
a
b
c
d
+
10 V
6 KA
R2
15 mΩ
a
b
c
d
Q2, 2 mH
SCR
Gate
R1–0.7 mΩ
7-92
6994A5

Figure 5

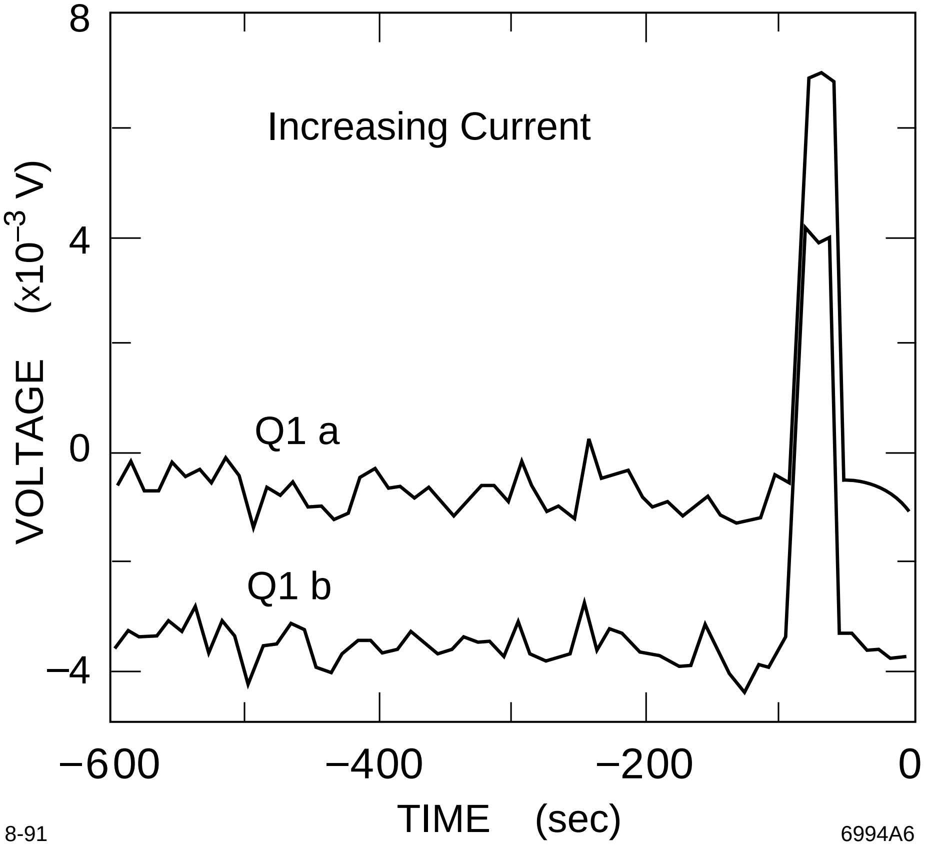
8
4
0
−4
VOLTAGE (×10^−3 V)
Increasing Current
Q1 a
Q1 b
−600
−400
−200
0
TIME (sec)
8-91
6994A6

Figure 6

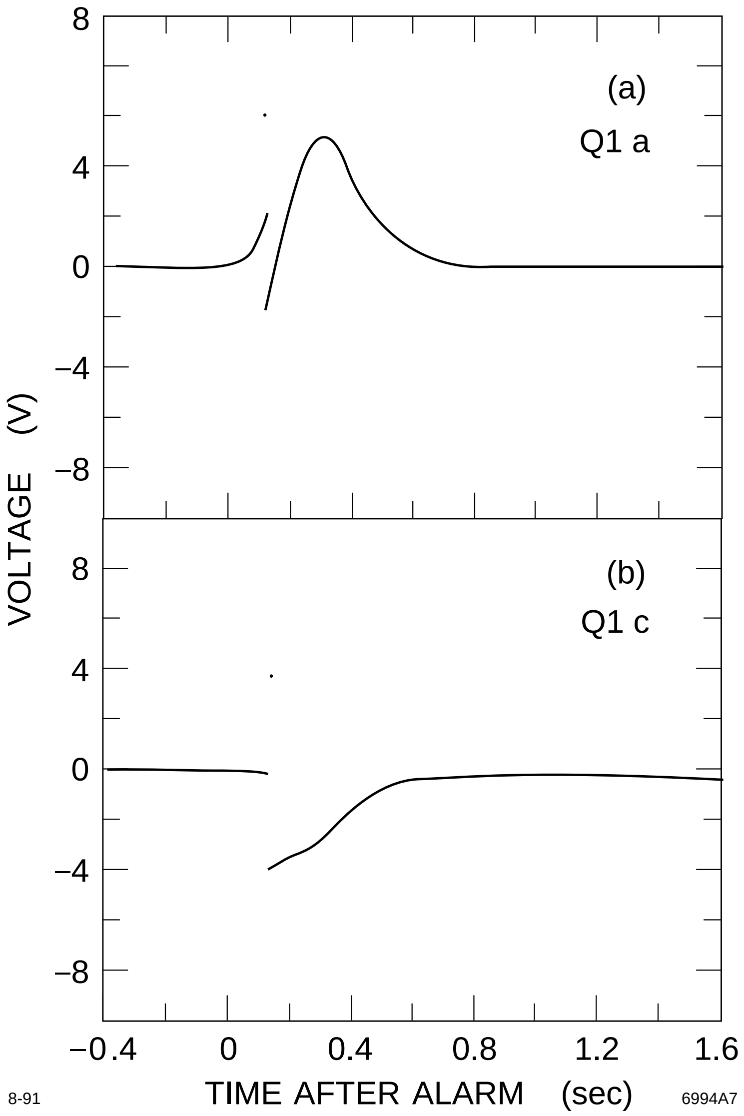
8
4
0
−4
−8
8
4
0
−4
−8
VOLTAGE (V)
(a)
Q1 a
(b)
Q1 c
−0.4
0
0.4
0.8
1.2
1.6
TIME AFTER ALARM (sec)
8-91
6994A7

Figure 7