

OPERATION OF MULTIPLE SUPERCONDUCTING ENERGY DOUBLER MAGNETS IN SERIES

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Summary

In order to understand the operational characteristics of the Energy Doubler, we have started a series of experiments designed to be a practical test of running superconducting accelerator magnets in series. We describe two separate tests in which we have powered two Energy Doubler dipoles in series. Of particular interest are the static losses of the cryostats and the behavior of the coils and cryostats during quenches. The results of the tests show that Energy Doubler magnets can be safely operated near their short sample limit, and that the various safety devices used are adequate to protect the coils and the cryostats from damage.

Introduction

The tests of two Energy Doubler dipoles are part of a program to construct a two cell segment of the Energy Doubler to gain operational experience, and to test the monitoring techniques and safety devices of the superconducting accelerator. The tests consist of connecting two full size (6.6 meters) Energy Doubler dipoles in series, electrically and cryogenically, making cryogenic measurements and exciting the magnets. Since the magnets will quench only near the short sample limit, we have put a heater into each coil so that we can induce a quench at any current. In this way we are able to study the behavior of the system from 1800 amps up to the short sample limit, about 4500 amps.

Data Collection

The data are recorded using a part of the existing accelerator control system. The computer samples up to 40 parameters continuously at two rates; one rate as fast as every five milliseconds and one at a slower rate that is adjustable. When a quench is detected the computer continues to write 200 complete data sets. Typically we are left with data spanning the time of ± 5 seconds from the quench at 5 millisecond intervals and data spanning -0.5 seconds to 19.5 seconds at 100 millisecond intervals. The data consist of voltages and currents in the coils and energy removal circuits, and temperature and pressures in the cryostats. From these data one can reconstruct the power deposited in the helium, the pressure rise, the coil resistance, etc., as a function of time.

Cryogenic Measurements

A schematic representation of the cryogenics is shown in Fig. 1. Liquid helium is taken from a dewar by a turbine pump immersed in the dewar and forced into the magnet in the region containing the coils. At the end of the magnet string the liquid flows through a Joule-Thompson valve and returns to the dewar in a boiling state.

The magnet is constructed like a coaxial heat exchanger with the boiling helium flowing in an annulus inside the region containing the coils and the non-boiling liquid helium. If there is good heat exchange between the two-phase fluid and the liquid, the temperature rise along the string is determined by the pressure drop in the two-phase system. The advantage of

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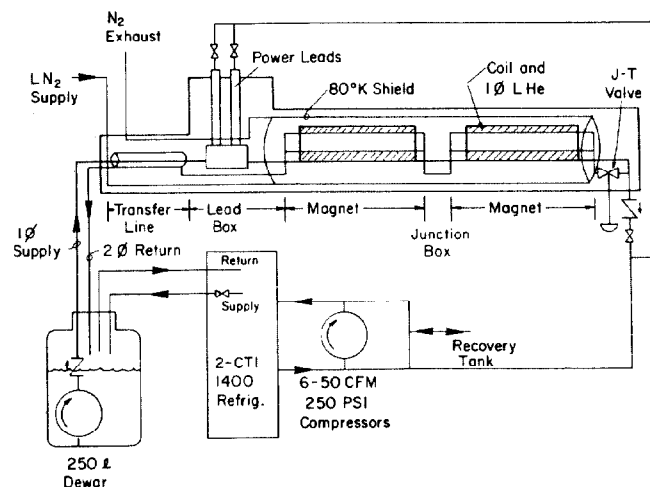


Fig. 1 Cryogenic loop schematic.

of this system is that the temperature rise in a long string of magnets is very small.

Measurements of the heat leak into the 4.6°K region were made on E22-5 and E22-6 and are shown in Table I along with the temperature rise at the normal flow rate of 20 grams/second of liquid helium. These results are adjusted for the load of the safety leads and the power leads. The heat leaks are about a factor of two larger than design for this type of magnet.

TABLE I

Magnet	Heat Leak To 4.6°K	Temperature Rise At 20 g/sec
E22-5	7.0 $\pm$ 2 watts	
E22-6	9.0 $\pm$ 2 watts	0.038°K
E22-5 + E22-6		0.060°K

The uncertainty is due to the power lead end box and JT end box which contribute a maximum of 2 watts. Although accurate measurements were not made for the string E22-8 and E22-9, they appear to be consistent with a heat leak of around 8 or 10 watts.

Magnet Coil Protection

If an Energy Doubler magnet quenches at high current the temperature rise due to ohmic heating would destroy the coil. Hence, it is necessary to detect the start of a quench and to quickly remove as much field energy as possible from the magnet. This is done by using the energization/safety circuit shown schematically in Fig. 2.¹ Normally the SCR's A and B are conducting and current flows in the magnets. When resistive voltage is detected SCR's C and D are turned on commutating A and B off. The current then flows in the circuit consisting of the magnets and the water-cooled dump resistors R_D . Typically $R_D = 0.2\Omega$, giving a L/R time constant of 0.225 seconds and a peak voltage across each magnet of 900 volts at 4500 amps. Figs. 3a and 3b show the current, coil resistance, internal power and the

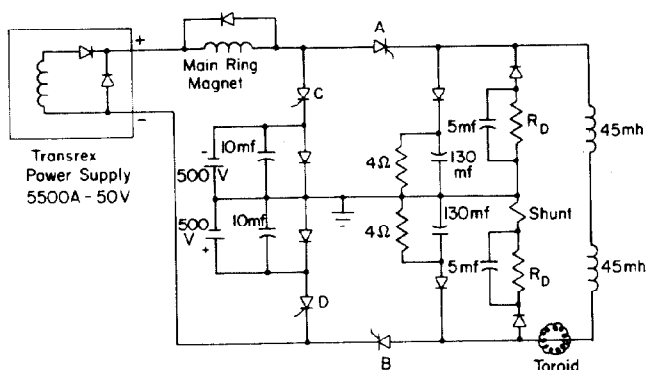
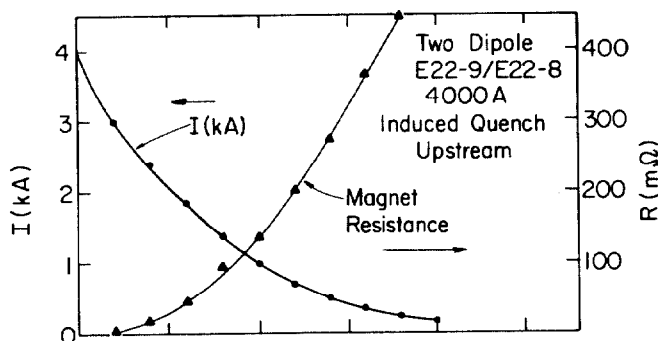
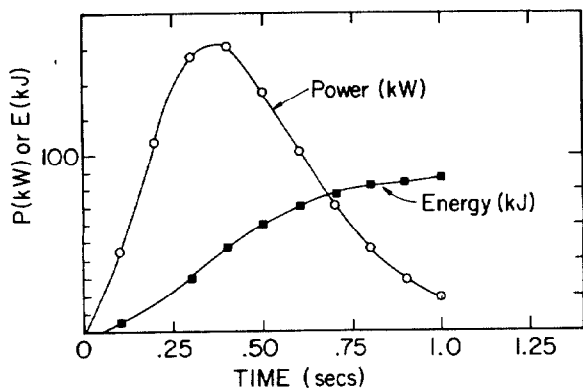


Fig. 2 Magnet energization/safety circuit



3a Current and resistance versus time

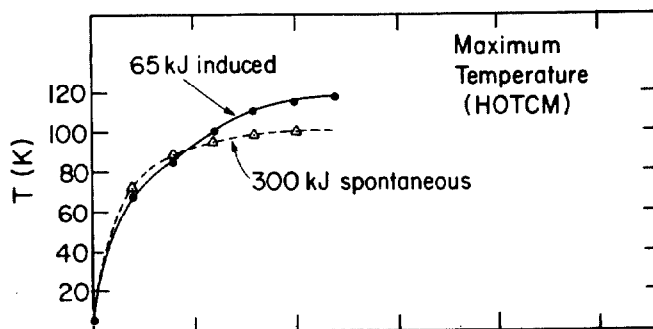


3b Power and energy versus time

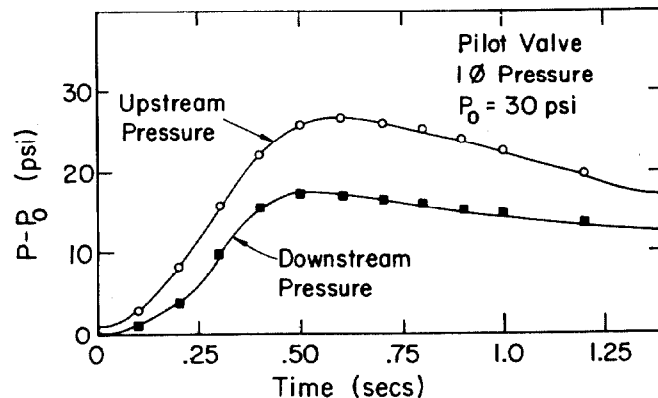
Fig. 3 4000 ampere heater induced quench

energy dissipated in the coil as a function of time for an induced quench at 4000A in E22-8 and E22-9 with each of the dump resistors $R_D = 0.10\Omega$.

In general spontaneous quenches deposit more energy into the coil than induced quenches because they occur in regions of the coil closer to the short sample limit, which makes the velocity of the quench wave higher and hence the development of normal resistance faster. The very fact that more cable goes normal, however, decreases the time constant and increases the heat capacity, and provides a natural limit to the maximum temperature to which the coil will go. Using the computer program HOTCM, which integrates the heat capacity, resistivity, and I^2 under the assumption that there is no cooling, we can estimate the maximum temperature rise in the coil.² This result is shown in Fig. 4a. The solid line shows an induced quench at 4000 amps which deposited 65 kJ into the helium. The dashed line shows a spontaneous quench at 4300 amps which deposited 300 kJ into the helium. Even though the temperature rise was



4a Calculated maximum temperature versus time



4b Pressure rise versus time at either end of the magnet pair. The quench was induced at the upstream end.

Fig. 4 Temperature and pressure versus time

initially faster, the final temperature was lower. Qualitatively we can make the following observations:

1. The safety circuit used adequately protects the magnets during quench.
2. At fixed dump resistance, the energy deposited into the helium for induced quenches is roughly proportional to I^3 .
3. Only one quench out of roughly 30 induced and spontaneous quenches propagated from one magnet to the other. This is true even though most of the induced quenches were started in a region of the upstream coil which was only 50 cm of cable from the downstream coil.
4. All but one of the spontaneous quenches of each of the magnets were at or above the percentage of short sample reached in previous vertical dewar tests adjusted for temperature. The one magnet (E22-6) which did not reach that level on the first quench did make it on the second. All the magnets operated at 96% of short sample or better.

Cryostat Protection

When a quench occurs in a coil, most of the energy is removed by the safety circuit. The energy which is deposited in the coil; however, causes a sudden high pressure rise in the cryostat. In these cryostats the single phase helium is in an enclosed volume, blocked at one end by a check valve and at the other by a restricted J-T valve. In order to relieve the pressure, each

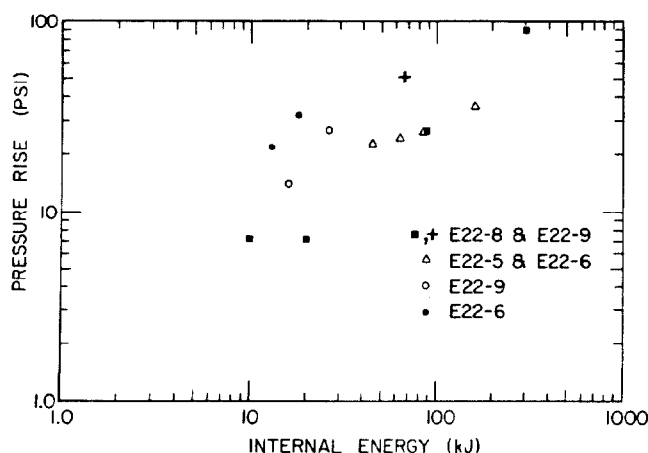


Fig. 5 Peak pressure versus total energy deposited in coil during quench.

magnet has a tube from the single phase to relief valves outside the cryostat. In the tests of E22-5 and E22-6, these tubes were 1.25 cm inside diameter and terminated in spring loaded 2 cm diameter valves set to open at 2.1 atm pressure. In the tests of E22-8 and E22-9 these tubes are 2.5 cm inside diameter, each terminated in two 3 cm diameter spring load valves. In the second case one of the spring loaded valves was replaced by a

5 cm diameter pneumatically operated pilot valve, which was opened when the quench was detected.

Pressure transducers at room temperature were installed on the end of tubes about one meter long connected to the single and two-phase volumes in the lead box and end box. Fig. 4b shows an output from each of the single phase transducers for a 4000A induced quench. This quench was started in the lead box very close to the upstream transducer. From these data, the velocity of the pressure wave is calculated to be about 120 meters/sec, which agrees with the speed of sound at 4.7°K and 2 atm within the accuracy of the measurement.

Figure 5 shows the pressure rise data versus internal energy. What is apparent is that the pressure rise is less severe in the two magnet case than in the one magnet case which is reasonable since liquid helium is a compressible fluid. The anomalously high point for the two magnet case of E22-8 and E22-9 at 65 kJ is the spontaneous quench where both magnets went normal.

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