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SUPERCONDUCTING CYCLOTRON MAGNET COIL SHORT*

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Abstract.-In February 1981, a short circuit appeared in the superconducting coil of the K500 cyclotron. The short is resistive in character and therefore has no effect on steady state operation of the magnet. The resistance of the short varies, sometimes being below the threshold of detection as a heat load on the cooling system and sometimes being significant. The resistance under certain conditions shows approximately cyclic phenomena with time constants in the range of seconds and other approximately cyclic phenomena which correlate with gross operating parameters of the magnet (shifting current from one coil to another at high field and lowering and raising the liquid helium level). A number of diagnostic studies of the short have been made, using 1) an array of flux sensing loops to sense the magnetic effect of the short, 2) voltage comparisons between upper and lower sections of the coil, 3) comparisons of forces in the nine member coil support system and 4) the effect of the short on the thermal characteristics of the coil. Insulation failure or a metal chip shorting out turns have been explored in some detail but a convincing determination of the exact cause of the short may never be available, (even the extreme step of unwinding the coil having a significant probability that an imperfection with the observed characteristics would pass unnoticed). Analysis of the characteristics of the short indicated that the most serious consequence would be failure of the coils mechanical support system in the event that the magnet was quickly discharged, as in a dump or quench. To deal with this hazard, the support system has been modified by installing solid supports which prevent the coil from moving by an amount sufficient to damage the support system. We have also reexamined the data and calculations used in he original coil design and have made some additional measurements of the properties of the materials (yield strength, friction coefficient, Young's modulus) used in the coil construction.

1. Introduction.-In the winter of 1980-81, the final magnetic field measurements of the K500 cyclotron were being completed. A prescribed operating procedure, running the magnet to full excitation and then to a measuring point to minimize magnetic hysteresis effects,[1] was being executed when an imbalance between the voltage within the coil was detected and at the same time an anomalously high helium boiloff rate was observed. A diagnostic program was immediately initiated and in the following sections we describe the results so far obtained.

2. Detection of coil short.-Figures 1 and 2 are simplified drawings of the coil physical layout and the electrical circuit diagram.[2] The most enlightening data have been obtained with two magnetic flux pickup single turn wire loops ("$\dot{B}$ coils") located between the small and large coil, above and below the magnet symmetry plane (see Fig. 1). Additional measurements have been made with multiple $\dot{B}$ coils placed external to the coil vacuum jacket and two solenoids mounted around the top and bottom coil sets. The data gathered with these detection devices are presently unclear because of limited use. Figure 3 shows a transient $\dot{B}$ event. The cyclotron magnetic field at 4T is decreasing at a constant rate. The upper and lower $\dot{B}$ coils detected changes of opposite polarity in the magnetic flux. Figure 4 shows an intentional short, connected through 36Ω, across the voltage tap of the small coil and carrying 0.2 amps (~200 ampturns), (see Fig. 2) while the magnet is being charged, which closely reproduces the observed transient event of Fig. 3. (An ambiguity exists in that the large coil might recouple the $\dot{B}$ coils in the opposite sense from the small coils in which case the signal would indicate that the short is in the bottom large coil.)

A hard short, the condition of a continuous short, could be produced in the coil by charging the magnet up to maximum field with 800 amperes in the small coil and 600 amperes in the large coil and then swapping current between the large and small coil. The swapping of current results in a small change in magnet field, but a large change in forces on conductors. An example of the $\dot{B}$ data for a hard short is shown in Fig. 5 and indicates large flux deviations of up to 10,000 ampere turns. Figure 6 is a $\dot{B}$ measurement made at the beginning of charging the magnet with a hard short present. The asymmetry in the $\dot{B}$ data is larger when charging the large coil and there is a time lag in the upper $\dot{B}$ loop relative to the lower; these data then support a "short-in-the-upper-large-coil" hypothesis.

3. Coil short force.-The coils are suspended by nine fiberglass links and the force on each link is monitored by strain gauges. In the hard short condition, the forces were detected and had an appearance of possible runaway when the magnet was charged or discharged at full voltage.

An axial force between coil and iron of course comes from the interaction of the current in the shorted superconducting loop with the radial component of the magnetic field in the iron. This is awkward to calculate since the dominant component of B_r is due to the coil itself and this component of course produces no net force on the total coil. A series of relaxation calculations were run with several gross assumptions for the distribution of ampere turns in the short, the coil field was subtracted, and the net force between coil and iron was then calculated by integrating the interaction

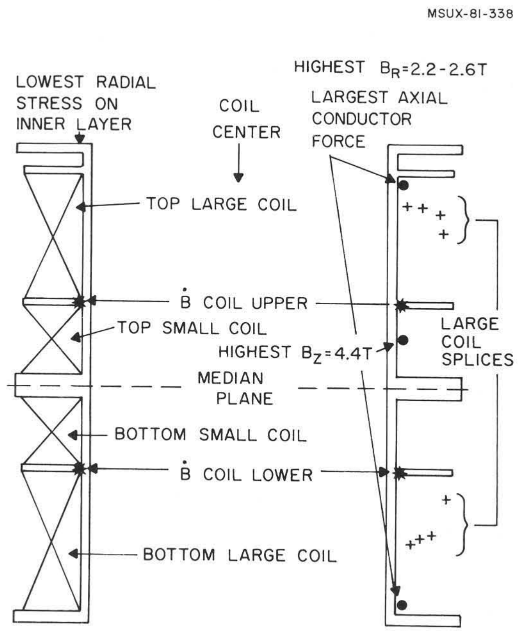

Fig. 1: A schematic drawing of the K500 cyclotron superconducting coil is shown. The complete coil has two large and small coils placed symmetric to the cyclotron median plane. The + denote wire splices within the large coils. The positions of the small coil splices were not recorded. The position of the flux sensing loops are shown. The maximum axial conductor force occurs in the large coils at the inside corner furthest from the median plane. The lowest radial pressure occurs for the inner layer of both small and large coils.

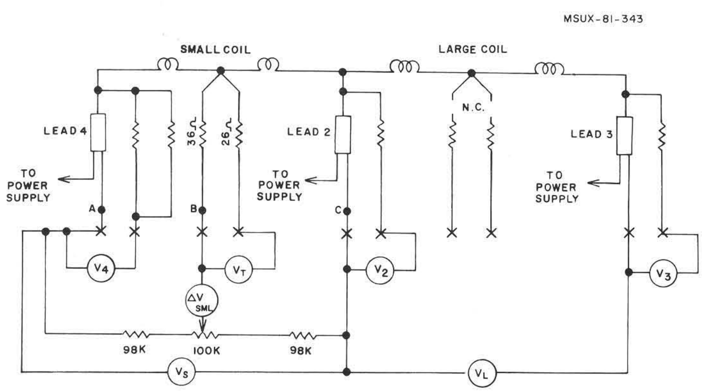

Fig. 2: The voltmeter connections are the following:
V_S =small coil total voltage
V_L =large coil total voltage
Δ_{SML} = small coil, upper/lower difference
V_2 =current lead 2 voltage drop
V_3 =current lead 3 voltage drop
V_4 =current lead 4 voltage drop
V_T =center tap short test meter
Points A, B, C, are the positions where intentional shorts across the coil were made. (The center taps of the large coil (N.C.) were burned out in a very early failure of the magnet current lead (1); at that time the magnet coils were connected to a common center lead (2)).

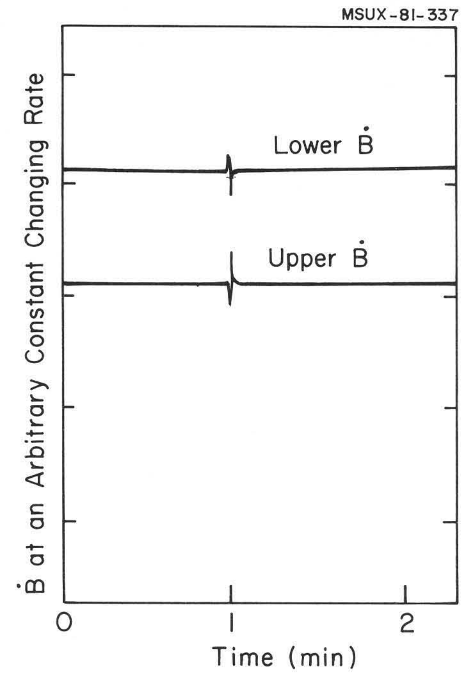

Fig. 3: The recorded signals of the $\dot{B}$ coils, position indicated in Fig. 1, are shown. The magnet is charging at a constant rate, (the power supply can be adjusted to produce a constant current ramp of up to 10 amp/sec. in the large and small coils subject to voltage limitation at low fields). A transient short event is detected and gives an opposite sign in the flux rate of change between the bottom and top $\dot{B}$ coils.

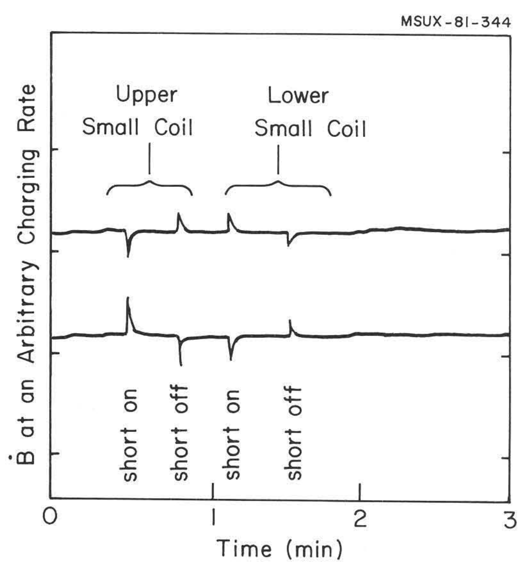

Fig. 4: The upper and lower $\dot{B}$ coils are shown for a constant magnet charging rate. The detected $\dot{B}$ signals occured when a deliberate short was made across the upper and lower small coils. The polarity direction of the upper coil simulated short has the same sign as the transient short events observed in the magnet.

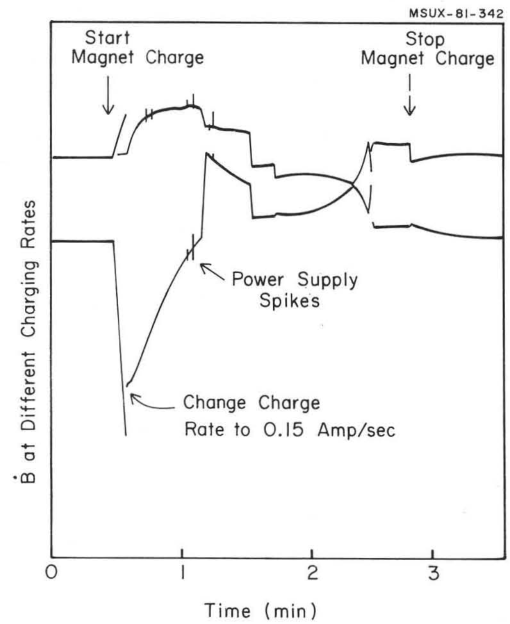

Fig. 5: The Ḃ coils are shown for the case of a "hard" short in the magnet coil. Large flux changes are detected as the magnet is charged. Models of superconducting loops being driven up to the current sharing mode and then decaying can be proposed for these fluctuations and also for the geneation of a heat load on the liquid helium bath. The hard short effects can be altered by changing the magnet charging rate and by stopping and letting the superconducting flux loops decay.

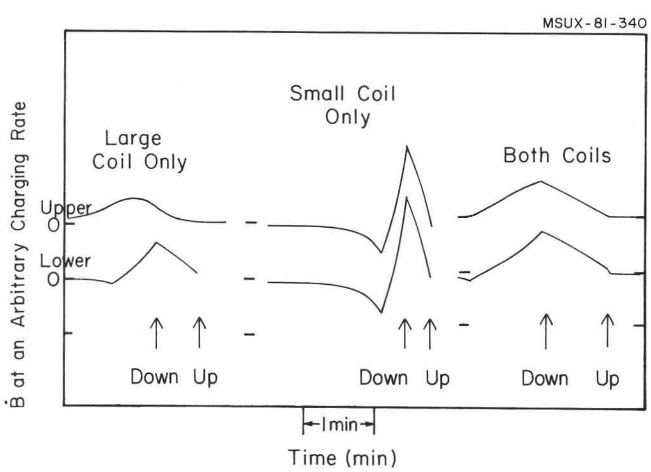

Fig. 6: The Ḃ coils are shown for three charging cases of the magnet, starting with the current at zero ampere. The small coils give an almost symmetric pattern whereas the large coil shows a very asymmetric pattern. The upper B signal appears to initially resist charging as the current is increased in the large coil and then after charging stops and the current is decreasing to zero the upper Ḃ coil shows the short acting to maintain the flux before finally decaying. For both coils charging, the asymmetry is still detectable. These results support the hypothesis that the hard short is in the upper large coil. Increasing time is to the left.

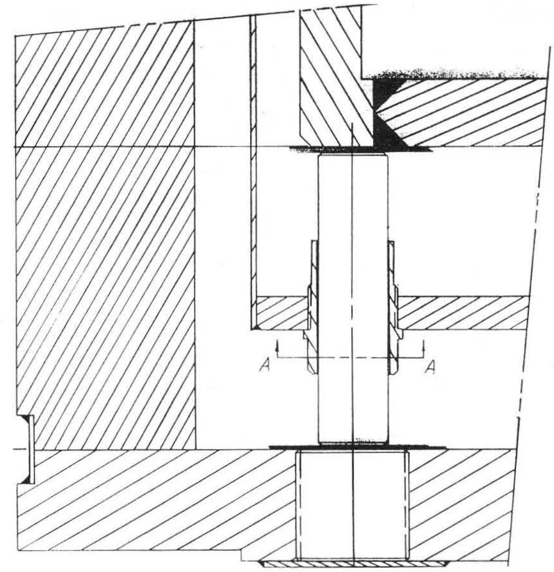

Fig. 7: The mechanical drawing of a lower bumper is shown. The bumpers are made of titanium and are in sliding contact with the liquid nitrogen shield. Coil motion is limited by the bumpers therefore protecting the relatively fragile fiberglass links on the main coil support system from excessive loads.

of the B_r from the iron with the currents in the coil. This analysis agreed with the hypothesis of a short in the upper coils and its magnitude was in fairly good agreement with the observed force imbalance of ~4000 lbs.

If the short were driven by a large voltage such as in a quench or if additional turns were to short, it is conceivable that the force imbalance could exceed the breaking strength of the support link system. To guard against this a backup "bumper" system has been installed in the coil. Figure 7 is a drawing of a typical bumper, the system is designed to come into contact with the coil and take over the support load before the links exceed their breaking points.

4. Review of coil design.-The magnet coil stress calculations[3)] and many of the material parameters used in the coil design and construction have been recalculated and measured. The stress calculation indicates that the maximum axial force on the conductor occurs in the large coil. Therefore the material properties that cause slippage that might produce a short have been measured. It has been found that the contraction value of G-10 used in the original coil design calculations is about one-half the value appropriate for G-10 in its normal-to-the-weave direction.[4)] This change reduces the calculated radial compression in the coils by about 10%, so the coil should still stay bound and not slip. Coefficient of friction measurements of a conductor stack yield a value of 0.3 at room and liquid nitrogen temperature to be compared with the previously estimated value of 0.2; hence the force needed to move the conductor is larger than previously calculated. Young's modulus measurements of the coil wire give a value of 10.4×10^6 psi, where 16.6×10^6 psi, the value of copper, was assumed for the azimuthal Young's modules in the original stress calculation. The Young's

modulus used in the stress calculation was then varied over a wide range; for one extreme value (1×10^5 psi) the coil does have the potential of slipping. An apparatus for measuring the radial Young's modulus of the actual coil stack samples is being constructed to clarify this point.

Transient stress forces on the coil conductor and its aluminum banding have been investigated. In coil cooldown and warmup it is possible to overstress the aluminum banding, but a review of the thermocouple data from various cooldowns indicates that the coil temperature distribution never approached the extreme temperature gradients necessary to overstress the banding, i.e. the banding at 100 K and the coil at room temperature. Calculation shows transient stress due to eddy current flow in the aluminum banding during a magnet dump also increases the banding stress load, but it is several thousand psi below the aluminum yield strength for the most extreme assumptions.

The compressive yield strength of mylar in a coil stack has been measured at liquid nitrogen temperature and found to be 15,000 psi, a magnitude above the expected forces it is subjected to in the coil. Fatigue failure tests at pressures of 2000 to 8000 psi caused the mylar to fail after 1000 cycles at the 8000 psi level. The failure of the insulation due to over-pressure and fatigue then seems unlikely and the short therefore appears most probably to be caused by some miscellaneous metal chip which has drifted into the winding.

5. Coil operations, future plans, conclusions.-The preponderance of the described coil short diagnostic data indicate that the superconducting coil short is most probably located in the large upper coil and a metal chip seems the most likely specific cause, a model based on this assumption being able to explain both the short term transient shorts, such as in Fig. 3, the persistent hard short as in Fig. 4 and 5, and the clearing of the hard short which has twice reproducibly occurred in a cycle of removing and refilling the coil with liquid helium. After careful study of all these data, we conclude that safe operation of the coil is possible in all normal operating conditions now that the support link bumper system has been installed to protect the support system against the large forces which might be associated with the currents induced in the short circuit in a dump or quench. We expect the transient short to continue to reproducibly appear when the magnet is operated above 4T and the hard short to reproducibly appear in the process of making a current swap at 5T. Since the short is resistive in nature, its effect of course completely disappears in any steady state operating condition and the only impairment in operating characteristics is then an enhanced helium boil off when the field is being changed at a high charging rate; from a cyclotron operating standpoint this might slightly slow the process of making a major energy change. In view of this and to guard against the possibility of some more severe coil difficulty, a decision has been made to construct a duplicate coil and cryostat as a low priority effort. This coil will then become a spare part which can be rather quickly substituted (~2 weeks) for the existing coil in the event some more serious coil difficulty should develop. It appears that the detailed cause of the present coil short will not be definitively established unless the coil is disassembled at some future time and even in that eventuality, it must be accepted as rather likely that the real cause of such a small short circuit might slip by unnoticed. The short does emphasize the vulnerability of open-lattice, bath-type coils with their large areas of bare conductor surface in relatively close proximity; this emphasizes a need for exercising even greater caution than in a normal coil to guard against the introduction of metal chips into the coil in the winding and fabrication process.

References

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