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ZERO GRADIENT SYNCHROTRON COIL FAILURES IN 1970-71, ANALYSIS AND SUBSEQUENT REMEDIAL ACTION*

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Introduction

The main magnet of the Zero Gradient Synchrotron (ZGS) consists of eight 53-ft long coils numbered around the ring sequentially beginning at the point of injection of the 50 MeV proton beam from the linac. On April 21, 1970, octant 2 coil failed after 41 million pulses. On January 9, 1971, octant 3 coil failed after 45 million pulses. Operation of the ZGS started in August 1963.

Somewhat after the failure of the second coil, a committee consisting of the authors of this paper was formed to determine why the coils failed, to predict the future relative to coil failures, and later to make recommendations for specifications for new spare coils and protective measures against further coil failures. This paper consists of a summary of the committee efforts and a coordination of several papers which have been written dealing with parts of the findings and actions taken.

The Coil Failures

In Fig. 1 is shown a drawing of the cross section of a coil. The failure in octant 2 involved turns 1, 1A, 8, and 9 and the adjacent anchor plate about 10 ft from the long straight section end. The failure in octant 3 involved turns 16 and 24 and slightly the anchor plate about 14 ft from the long straight section. The failures developed to catastrophic proportions in one ZGS pulse and consisted of much arc damage to the copper coils and epoxy embedded G-10 insulation which was 0.041 in. thick between layers and turns. The coil layers nominally have 300 V between them during a magnet pulse. The potential across an entire octant peaks at 1200 V. The stainless steel anchor plate adjacent to turns 1, 8, 16, and 24 is tied through a 50 Ω resistor and a 1/2 A fuse to ground. In neither case did the fuse burn out.

The arrangement of the magnet, its power supply, and protective circuitry is described elsewhere. 1, 2An examination of the impedance of an octant coil revealed resonances at 3 kHz, 15 kHz, 36 kHz, 84 kHz, and higher with Q-values of 2.5 to 10. An examination of the attenuation characteristic of the magnet power supply filter when measured at the terminals of the octant coils is shown by the upper curve in Fig. 2.

It was common knowledge among those working

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†Present Address: National Accelerator Laboratory, Batavia, Illinois with the ZGS that sizable electrical transients existed in the magnet system.² Initially, the ground resistor of 50 Ω connected between the junction of octants 3 and 4 and ground had in series with it a current trip. It tripped annoyingly often and its current disturbed beam stability; hence, it was removed. The voltage trip at this point was raised to 700 V to prevent an excessive trip rate. The spark gaps connected across octant pairs were originally set for 3000 V. This adjustment was raised to 5000 V to prevent a high breakdown rate. Contributing to this situation are arc-back and arc-through faults in the power supply which often create rather high transients. Statistically, they occur at a rate of roughly once per day.

Physical examination of the two coils which failed revealed certain characteristics. The coils had been assembled using an epoxy wet layup of G-10 and glass fiber cloth. The bond to the inside surface of the anchor plate was lost over much of its area. The outside glass wrap was unbonded in sizable patches. The continuous layer of G-10 between coil layers was sound, but was unbonded from the copper in spots. The same is true for the bond between the copper and the G-10 layers between turns. There was evidence of bubbles and a black granular material in the epoxy, particularly at the corners of the square copper conductors. There was no evidence of copper failure except for flakes of copper stuck to the epoxy in a few places. Except for the observations noted, the coils appeared to be very strong, sound, and in good repair with no signs of radiation damage.

Analysis of Coil Failures

It is not possible to identify the cause of the coil failures with certainty. It may be beneficial to attempt an analysis of the circumstantial evidence.

It seems clear that the failures were due to electrical breakdown of the insulation and not mechanical failure of conductors or insulators, except in the way which will now be examined. The voids and black granular material in the epoxy resin insulating material likely provide focal points for high electrical stress and corona discharges. The arrangement of the power supply filter prior to the coil failures was such as not to provide good protection against power supply transients. The peculiar combination of the 84 kHz resonance and the filter characteristic may explain the nearly identical location of the two coil failures. Due to the way the coils were installed, the electrical position of turns 1 and 8 in octant 2 is identical to that of turns 16 and 24 in octant 3. The 84 kHz resonant mode would produce voltage maxima at these turn combinations.

Recommendations and Predictions

Recommendations were made and have been carried out l, 2, 3, 4 as follows:

1. Repair of damaged coils and construction of any new coils should employ the same techniques as were used in the original coils with special care to eliminate voids and foreign matter.

2. The power supply filter should be revised for a much better attenuation characteristic. (See the lower curve in Fig. 2 which resulted.)

3. A fast-acting crowbar facility should be attached to all four phantom ground points between octant pairs. l

4. A technique should be developed for identifying corona onset voltages between turns and layers of the octant coils. 3

5. The corona measuring technique should be used to routinely monitor the corona health of the octant coils. $^{\rm 4}$

The predictions are that ZGS operators can keep a log of the corona onset voltages for each octant coil and anticipate their longevity. If the corona threshold does not decrease, the coils will survive insulation breakdown a long time. If the threshold is observed to steadily decrease, some extrapolation to ultimate failure may be possible. With this technique available, ZGS operators can set the level of the power supply voltage with more confidence. With the utilization of improved filter characteristics and transient protective devices, the electrical integrity of the ZGS coils should be considerably enhanced.

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