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ABSTRACT

A detailed description of the mechanical construction of the trim coils is presented. It includes selection, optimization and application of a suitable electrical conductor for use under severe radiation conditions, brazing considerations for a very large furnace brazing job, and a discussion of some of the problems encountered during the fabrication procedures.

TRIM-COIL CONSTRUCTION FOR
THE BERKELEY 88-INCH CYCLOTRON†

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1. Introduction

Two types of trim coils are installed in the Berkeley 88-inch cyclotron: circular coils for control of the magnetic field radial profile, and valley coils for control of field harmonics. No flutter coils are provided. This paper is concerned only with the mechanical design and construction of the trim coils; their performance is described elsewhere¹).

All trim coils are wound with mineral-insulated cable. This cable consists of an outer copper sheath, an inner copper conductor, and magnesium oxide insulation between the sheath and the conductor. In the case of the circular trim coils, the conductor is hollow—to provide a passage for cooling water. In the case of the valley coils the conductor is solid, and cooling is provided by conduction to water-cooling circuits.

2. Design Considerations

Four basic factors were considered in the mechanical design of the trim coils. In approximate order of importance these are: (a) reliability, (b) precision of placement of individual conductors, (c) vacuum properties, and (d) space factor. These factors are briefly discussed below.

† Work done under the auspices of the U.S. Atomic Energy Commission.

‡ On leave at Rutherford High Energy Laboratory, Harwell, England.

Reliability is obviously of extreme importance. In this regard, two points stand out: (a) the trim coils are absolutely essential to the operation of the machine, and (b) in case of failure the trim coils would be extremely difficult, if not impossible, to remove after the machine has become active. The trim coils are in the very heart of the machine and their removal would entail the removal of the roof shielding, the rf system, the vacuum system, and, finally, the partial dismantling of the complex array of trim-coil leads.

For these coils, reliability evolves into resistance to radiation damage and resistance to mechanical damage (overheating due to momentary water failure, scraping during installation, etc.). Resistance to radiation damage is the strongest reason for the selection of mineral-insulated cable. As far as is known, magnesium oxide will suffer no significant damage for the life of the machine in the expected radiation fluxes. It is certainly difficult to conceive of a more rugged cable construction. This cable will operate at red heat and may be flattened to a thickness of less than a quarter of its diameter without developing shorts between the sheath and the center conductor.

The space factor (the ratio of the cross-sectional area of the conductor proper to the area occupied by the coil) of mineral-insulated cable is admittedly quite poor. This might be improved somewhat by "squaring up" the cable or by reducing the thickness of the mineral insulation. To help counteract the poor space factor the circular trim coils are combined with the rf pole liner. This results in a considerable saving of gap space, compared to a construction in which the pole liner (with its cooling tubes) is separated from the trim-coil package.

As first conceived, the circular trim coils were of mineral-insulated cable with a solid conductor rather than a hollow one. In this case, cooling water tubes would be occasionally interspersed with the cables. This construction proved, however, to involve high temperature gradients across the

insulation, and also led to alternate hot and cold zones in the copper sheet. These hot and cold zones could cause buckling into a shape similar to that of the diaphragm in an aneroid barometer. Consideration of these problems led us to the hollow conductor.

It will immediately be recognized that there is an optimum cooling-water hole size to maximize the current for a given conductor under given conditions²). Assume that the following parameters are fixed: conductor outer diameter, water temperature rise, water pressure drop, and length of conductor for one water path. Starting with a very small hole, it will be seen that the current is limited by the flow of cooling water. Going to a very large hole will, of course, increase the water flow, but now the current is limited by the reduced copper area. An optimum hole size for maximum current exists between these two extremes. However, as the hole size increases, the required power increases rapidly. Therefore, it will be found desirable to operate with a hole somewhat smaller than that required for maximum current. To take a specific example: with our conductor diameter of 0.460 in. (sheath diameter 0.699 in.) the hole size selected is 0.300 in. By increasing the hole size to 0.350 in., the optimum for maximum current, the allowable current would be increased by only 6% but the required power would be increased by about 50%.

3. Construction Details

An estimate of the number of circular coils required and the currents necessary in them was derived from graphical studies of data obtained from model magnet and model trim coil measurements. The actual number of circular coils is greater than the number indicated by the above estimate. The radial space allotted for coils could not be used for any other purpose and so was completely filled. This procedure cost very little more and provided an extra safety factor.

The circular coils consist of 17 separate circuits, with from two to four turns in each circuit. The outer six coils are of two turns each and are designed for a current of 2000 A. The inner 11 circuits are designed for a current of 750 A (fig.1).

The valley coils are superimposed over the circular-coil leads; they are in two tiers (fig. 2). Each valley is divided into five separate radial zones, with a separate circuit for each zone. Information on design currents and number of turns is given later in this paper.

Figure 2 shows a complete trim-coil assembly for the upper pole tip. The lower trim-coil assembly is a mirror image of the upper assembly.

It was necessary to position the circular coils very accurately, especially in regard to concentricity with the center of the machine. For example, when the center of a single turn carrying 2000 A on one pole is displaced by 0.010 in., the resultant first harmonic amounts to 0.2 G³).

To meet the concentricity requirements described above, the circular coils were wound into close-fitting concentric grooves machined into a 3/8-in.-thick OFHC-copper base plate. There are a total of 49 grooves. Their radii from the machine center vary from 5.250 in. to 42 in. Tolerances of less than ± 0.005 in. were held. In the appropriate areas the lands between grooves were machined off to provide crossovers between turns.

The base plate, which is also the rf pole liner, is approximately 107 in. wide by 105 in. long. To provide structural strength and stiffness, superstructure was added where vertical space allowed. The base plate, coils, and superstructure were all furnace-brazed together. People in the brazing business have said that this is possibly the largest copper brazing job ever attempted.

The combination of copper-sheathed cable and furnace brazing under conditions where no flux is used provides a clean assembly for vacuum use.

The sheaths on the leads are brazed into plates that are fastened to the dee tank with metal gaskets.

The method used for holding the circular coils securely in their grooves prior to brazing is shown in fig. 3. The valley-coil conductors were held in a similar fashion. The twisted brads were snipped off where necessary, after brazing.

Our assembly-shop workers devised methods and fixtures for bending the conductors to the proper contours.

The valley coils required about the same amount of time for fabrication as the circular coils. Five bending forms were made, representing the five radial zones, for winding the 30 coils. Special three-dimensional wooden forms representing the contour the valley-coil leads would take allowed us to shape the leads without waiting for the circular coils to be completed. Very careful layout work was necessary to ensure accurate placement of the valley coils on the circular coils. There were many possibilities for interference between the valley coils and the hills on the poles, but no difficulty was experienced at assembly.

Because of the fact that all components were to be brazed together, more than ordinary cleanliness was required in handling them. Just before final tying together of components, all parts were bright-dipped and thoroughly rinsed. From that time until brazing was completed, cotton gloves were used for handling the components.

The brazing alloy used was selected as a result of fabrication tests, and also because the constituents have good vacuum characteristics. The alloy is made of 60% silver, 30% copper, and 10% tin. The flow point is 1325° F. Approximately 2000 troy ounces of alloy were used (51.6 kg).

Placement of the alloy was found to be quite important. In most cases where tolerances would permit, the alloy was placed between parts to be

joined (the place where the braze would form). This placement worked well except for the circular coils, which would not permit this arrangement because of the close tolerances previously mentioned. The coils had to be held tightly in place without any solder in the joint area. The alloy was placed by melting it and letting it flow into the space between two adjacent turns of conductor, where it solidified. This method placed the alloy close to the joint, and at the same time, because of the geometry of the conductors with respect to the base plate, provided a keying action which prevented displacement during shipping to brazing facilities (this was a major concern). The alloy was melted by running a wire of it through a modified metallizing gun at a rate which would produce a continuous stream of droplets. The gun was pivoted at the center of the assembly so that consecutive circular passes could be made.

The plates that the leads come through were fabricated in two steps. They consist of a stainless steel plate with a copper insert. The stainless steel provides a surface for the metal gasket seal, and the copper insert provides a copper-to-copper joint for the leads. At the relatively low temperature of our copper-brazing cycle stainless is difficult to braze to copper. Therefore a preliminary high-temperature copper to stainless joint was made and vacuum checked prior to installation on the main assembly.

The brazing of the assembly took place in a large heat treating furnace in Alhambra, California. This furnace, although not ideal for brazing, had been used for brazing in the past, and it appeared to be capable of doing the job. There were no standard brazing furnaces available to us that were large enough.

Our specifications required that the brazing operation take place in an atmosphere of hydrogen. The hydrogen provides a reducing atmosphere and cleans the assembly so that no flux is required. The hydrogen atmosphere

also requires that all copper in the assembly be oxygen-free. Copper containing oxygen is embrittled when it comes in contact with hydrogen.

The hydrogen atmosphere was obtained by enclosing the assembly in a gas-tight retort or tank. Inlet and outlet tubes provide a method of circulating the gas around the assembly.

Thermocouples were placed at strategic points on the assembly, and the leads were brought out through a special fitting. The leads terminated at a recorder. Temperature was regulated by observing the recorder, then manually changing furnace controls to compensate for undesirable effects.

Flatness of the assembly during brazing was controlled by the platform upon which it rested. The retort wall was so thin as to be negligible in causing distortion. The platform was a 1-ft-thick "egg crate" made of mild steel that had been annealed and machined after welding. It has been found that flatness during brazing is not critical, since straightening afterwards is relatively easy.

The brazing cycle was specified so as to keep to a minimum the time that the assembly was in the solder-melting range. It appears that a long brazing cycle has a bad effect on the braze quality. This effect apparently results from the brazing alloy forming new compounds with the copper and changing its characteristics. The furnace heating capacity is important.

The first trim-coil assembly was run through its brazing cycle. Most of the specified requirements were met, and the braze quality was quite good. There was some straightening to be done, but it was not difficult. Dimensionally the part was very good. No significant changes were noted in dimensions.

The second assembly did not fare quite so well, although ultimately we did end up with an acceptable braze. The first major incident occurred when the brazing contractor introduced acetylene gas into the retort during

a leak-detecting procedure. (This was not their standard procedure, and it was done with intention of saving time.) A helper, in a thoughtless moment, applied a soldering torch to one of the inlet tubes and an explosion resulted. The explosion was not severe and no one was injured, but our assembly was covered with an unbelievably thick layer of black soot. It was necessary to ship the assembly back to Berkeley, partially dismantle it, and scrub it clean with dishwashing detergent and an ultrasonic transducer "scrub brush."

The second incident occurred during the height of the brazing cycle. The retort opened up with a large leak and the cycle was barely completed. As stated previously, however, the braze, though not as good as the first assembly, was quite acceptable. Again the dimensional stability was very good.

In spite of the difficulties encountered, the brazing of large complicated assemblies such as ours seems to be quite feasible. The problems encountered would not be difficult to avoid in the future.

The trim-coil leads at the lead plate were trimmed to size after brazing. Then they were fitted with a specially designed high-temperature seal to keep moisture out of the magnesium oxide insulation, and to withstand hard solder temperatures when the internal leads were joined to the external leads (fig.4).

The external circular-coil leads are made of square hollow water-cooled conductor of two sizes. The 2000-A conductors are 0.814 in. square with a 0.503 in. diam hole. The 750-A conductors are 0.640 in. square with a 0.402 in. hole. These leads for the upper and lower coils are carried from their junction at the internal leads to the ends of the magnet. The 750-A leads are on one end and the 2000-A leads are on the other. A series connection is made between upper and lower coil pairs at the ends of the magnet, to help keep lead lengths as short as possible. The two remaining leads from each coil

pair are terminated on cross-connect boards in the pit below the magnet. The coil power supplies are connected to the cross-connect boards. Since there are fewer power supplies than coil circuits, the cross-connect boards provide a means of connecting the coil circuits in the desired way.

The valley-coil external leads are 1/2-in. -square solid copper conductors. They are convection cooled. The leads go from the lead plates, down the sides of the magnet into the pit. The necessary cross-connections between coils are made in the pit terminal area. Power supplies are some distance away beneath the control room, so flexible leads carry power from the control room to the terminals in the pit.

Some general information regarding the trim coils follows:

Circular Coils⁴⁾

The circular trim coils are numbered from the center outward: The center coil is No. 1 and the outermost is No. 17.

Conductor: mineral-insulated, 0.699 in. sheath diam, 0.460 in. conductor diam, 0.300 in. hole.

Design current, coils 1 to 11: 750 A.

Design current, coils 12 to 17: 2000 A.

Min mean coil diam: 12 in.

Max mean coil diam: $83 \frac{1}{4}$ in.

Conductor lengths: vary, 30 to 61 ft.

Total conductor length: 2500 ft.

Max calculated temperature rise in cooling water: 30° C.

Total calculated power required: 344 kW (with coils at design current).

Total calculated cooling-water flow: 52 gpm.

Valley Coils⁵⁾

The valley coils are also numbered from the center outward: No. 1 is innermost and No. 5 is outermost.

<u>Coil</u>	<u>No. turns</u>	<u>Design current (A)</u>
1	5	200
2	5	200
3	5	130
4	6	225
5	8	250

Total conductor length: 1260 ft.

Conductor: mineral-insulated, 0.340 in. sheath diam, 0.162 in. conductor diam.

Total calculated power: 27 kW (with coils at design current).

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FIGURE CAPTIONS

Fig. 1. Circular trim coils wound in place on the base plate.

Fig. 2. Complete trim-coil assembly for the upper pole tip.

**Fig. 3. Typical cross section of the circular trim coils
and base plate, showing method used for holding conductors
in place prior to brazing.**

Fig. 4. Junction of external and internal trim-coil leads.

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Fig. 3

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