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Addison A. Lake

October 1969

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DESIGN AND FABRICATION OF THE SEPTUM COIL OF THE BEVATRON EXTRACTION MAGNET M1 MARK 4

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ABSTRACT

This report covers the design and fabrication of a narrow septum magnet installed in the LRL Bevatron external proton beam resonant extraction system. It describes the sizing of the copper conductor, the testing of insulating materials, and the choice of metallized ceramic as the structural insulator. Magnetic-field-induced stresses in the septum are calculated for the conductor and insulator. The report also reviews alternative designs and the reasons for their rejection. Fabrication of rectangular conductor from round tubing is described. The procedure is given for the joining by vacuum brazing of the conductors and insulators. Coil operating data are listed.

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INTRODUCTION

This bending magnet is the fourth in a series installed in the Bevatron East Tangent Tank.[1] The first and second magnets were essentially identical C types with a septum approximately 1 in. wide. The first magnet developed severe radiation damage on the septum and was replaced. The third, designed as a developmental resonant-extraction study magnet,[2] has a pole-face gradient coil, a septum coil for bending, and a two-turn bump coil. The septum consists of 14 turns of 0.255-in.-square conductor, water-cooled and wrapped with insulators. The total septum width is approximately 0.335 in. All coils are potted in an alumina epoxy mix. The magnet was completed and installed in May 1967. It is presently stored.

Design was started on the fourth magnet ("Mark 4") in late summer of 1968. The aim was to reduce the septum to 3 mm wide (0.12 in.), and use a more radiation-resistant material to secure the conductors.[3] To satsify the requirements of the narrower septum and radiation margin, it was decided that metallized ceramic insulators brazed between thin conductors would be the solution. This magnet was installed in the Bevatron in July 1969. This report covers the septum coil of the magnet.

DESIGN

The coil consists of 14 turns of OFHC copper hollow conductor 0.262×0.118 in. with a 0.035-in. wall. The straight section of the coil is approximately 35 in. long by 4.3 in. high. The unsupported vertical gap between gradient coils is approximately 3.4 in. The top and bottom of the septum are potted in grooves left for this purpose in the potted gradient coil. This is a fixed-end beam design, and it reduces the field-induced bending moment on the coil below that on a simply supported beam, the usual septum design. The peak magnetic field of 3.22 kilogauss in the gap produces a uniform horizontal coil loading of 6 psi. This is an insulator stress of 2410 psi, a copper stress of 2680 psi.

The method selected for providing structural support and insulation between conductors was to use metallized ceramic strips vacuum-furnace-brazed to the copper conductor. The strips are 0.12 in. wide × 0.042 in. thick × 1.0 in. long. The change in length in going from brazing temperature to room temperature for these materials is approximately 0.0008 in./in., or 0.0004 in. for the length selected. The 94% alumina insulators are molybdenum-manganese coated and nickel plated on two sides. The four edges are free of coating. Strips of 0.002-in.-thick Cusil (72% Ag, 28% Cu) are used as brazing filler. The insulators are spread along the conductors with a 0.04-in. gap between ends. Published data give 10 000 psi as the tensile strength of the bond between the ceramic and copper. Our tests verified this.

The coil is designed with one-half turn per water circuit for a total of 28 circuits in parallel. Two water manifolds at each end of the coil are provided for cooling water. The water manifolds at one end are also

used for current supply to and from the coil. Suitable bus bars and connectors are used to carry current and to distribute water from the manifolds to the coils from turn to turn.

In the development of the septum many other ideas were considered on paper but not used. A few of them were:

(a) A coil of two turns instead of 14. Each turn would be supported by means of a T slot in the pole face and cantilevered in the gap. This would be a water-cooled unit made from strips of copper forming tension and compression members separated by shear-carrying spacers running the length of the coil. Assembly would be by electron beam welding. Another similar design would use a solid T-shaped bar with a water hole at the base of the T slot. Seven times as much current as used in the coil selected would have been required to power this magnet. The plunging system probe tube could not be redesigned easily to carry this current.

(b) A multiturn arched septum. The arch would be designed for minimum bending stresses imposed by the magnetic field. The conductor would be extruded, with a water hole and male and female dovetails. On assembly the dovetails would be insulated with small ceramic strips used in compression. Lack of field uniformity and low strength of the dovetail are problems in this design.

(c) Various ceramic cements to bond and insulate the conductor. None proved satisfactory.

(d) Various thermal expansion joints. We managed to keep the coil temperatures low on the final design and did not look for a solution for this.

TESTING

The ceramic-bonded insulator was tested in several ways to prove the brazing system as well as bond strengths and thermal stability. Many samples were made, consisting of approximately eight pieces of conductor 1 in. long, brazing strips, and seven insulators. These assemblies were evaluated by mounting on a suitably machined fixture and sealing the edges with sponge rubber and sealant. Uniform load was applied by evacuating the sealed volume by a vacuum pumping stystem. The vacuum was selected to provide a beam stress duplicating the design load on the coil. Electronic timing equipment and an electrically operated solenoid air valve were used to give a repetition rate of 80 cycles per minute. The samples broke at the joint, usually near the span center. Failed units were then subjected to a cantilever beam load to failure on each remaining good joint.

Failure occurred at random: at the bond, across the ceramic, or across both bonds. The average ultimate bending stress was 9100 psi. From this testing we found that to get maximum-strength joints extreme care should be taken to clean the parts, machine the surfaces to be bonded, and supply adequate contact pressure during brazing.

Two samples were cycled without failure at 200% load for 100 cycles and 100% equivalent design load for 5×10^6 cycles. At this point, we felt we had a good technique. A 33-in.-long sample of three conductors and two rows of insulators brazed together was dipped alternately in cold and 180°F water, and then dipped in liquid nitrogen and hot water, with no apparent failure. Figure 1 shows a piece from this sample.

Horizontal deflection of septum coil assembled in the magnet was 0.003 in. measured on the center line of the gap at 2000 A input current.

FABRICATION

We formed the conductor from 0.25-in. o. d. × 0.035-in. wall OFHC copper tubing, since time did not allow investigation and buying of nonstandard extruded conductor. The forming was done by internally pressurizing 6-ft lengths of dead soft tube to 200 psi (approximate) and then shaped to the desired rectangular section on a 15-ton press brake. Special tooling was designed and built for the purpose. Large horizontal forces are developed in this operation and the tooling must be very rigid. The sealed hydraulic circuit was pressurized to 800 psi peak during forming. Pressurization of the tubing and control of the brake stroke were required to get flat surfaces and sharp corners on the conductor. Stroke adjustments had to be made to 0.002 in. Even then, 0.002 in. had to be machined from two surfaces to assure a flat and parallel bonding surface on the copper. The corners were sharpened up by this procedure and thus the beam depth was increased. The tubing was then partially bent at the ends and ultrasonically cleaned.

Figure 2 shows the conductor, insulators, and filler material assembled in the tooling in the vacuum furnace. Figure 3 shows the cover installed. Vacuum brazing temperature was approximately 800 °C. Uneven heating and heat losses at the ends caused problems in brazing, and repeated runs were necessary to correct this. No damage was incurred by this repetition. The final overall joint-brazing efficiency was estimated at 95%. Cleaning with a dental sandblast unit was required after brazing to remove flashing and copper deposited on the insulators.

The next procedure was to bend the leads and solder the bus bars to the two half coils, as shown in Fig. 4. The blocks for mounting the thermal protection switches were hard-soldered at this time.

The water manifolds and a fiberglass insulator between were attached to the bus bars with epoxy bonding film. Figures 5 and 6 show this. This was not an ideal solution but time did not permit further development work. We are now investigating metallized ceramic insulators for the manifolds.

Figure 7 shows the assembly of the coil to the alumina oxide epoxy-potted gradient and trim coils. The completed magnet is shown in Figs. 8 and 9.

The entire magnet, with the exception of the metallized insulators, was produced in the LRL shops.

Septum Coil Data

Conductor size	0.274×0.118×0.035-in. wall
Number of turns	14
Field	3.22 kG peak
Current	1810 A dc
Maximum power	134 kW at 38°C temp rise
Water flow	13.4 gal/min at 60 psi differential at magnet
Hydraulic circuits	28
Gap	4.32 in. steel to steel
Core construction	Low-carbon steel, sheet bonded layer to layer with epoxy film and oven cured.

This work done under the auspices of the U. S. Atomic Energy Commission.

REFERENCES

1. W. A. Wenzel , Bevatron External Proton Beam, UCRL-10868, July 8, 1963.

2. R. Allison, H. Grunder, and G. Lambertson, Handling Field Linearity in Bevatron Resonant Extraction, UCRL-19213, Aug. 1969.

3. Addison Lake, Bevatron Proton Beam Extraction Magnet M1 Mark 4 Design Calculation, UCRL Engineering Note M4192, June 20, 1969.

FIGURE CAPTIONS

Fig. 1. Typical conductor and insulator cross section.

Fig. 2. Coil installed in tooling.

Fig. 3. Cover installed on tooling.

Fig. 4. Bus bars and manifold.

Fig. 5. Completed coil.

Fig. 6. Completed coil.

Fig. 7. Assembly of septum coil to gradient coil.

Fig. 8. Septum coil in magnet.

Fig. 9. Completed magnet.

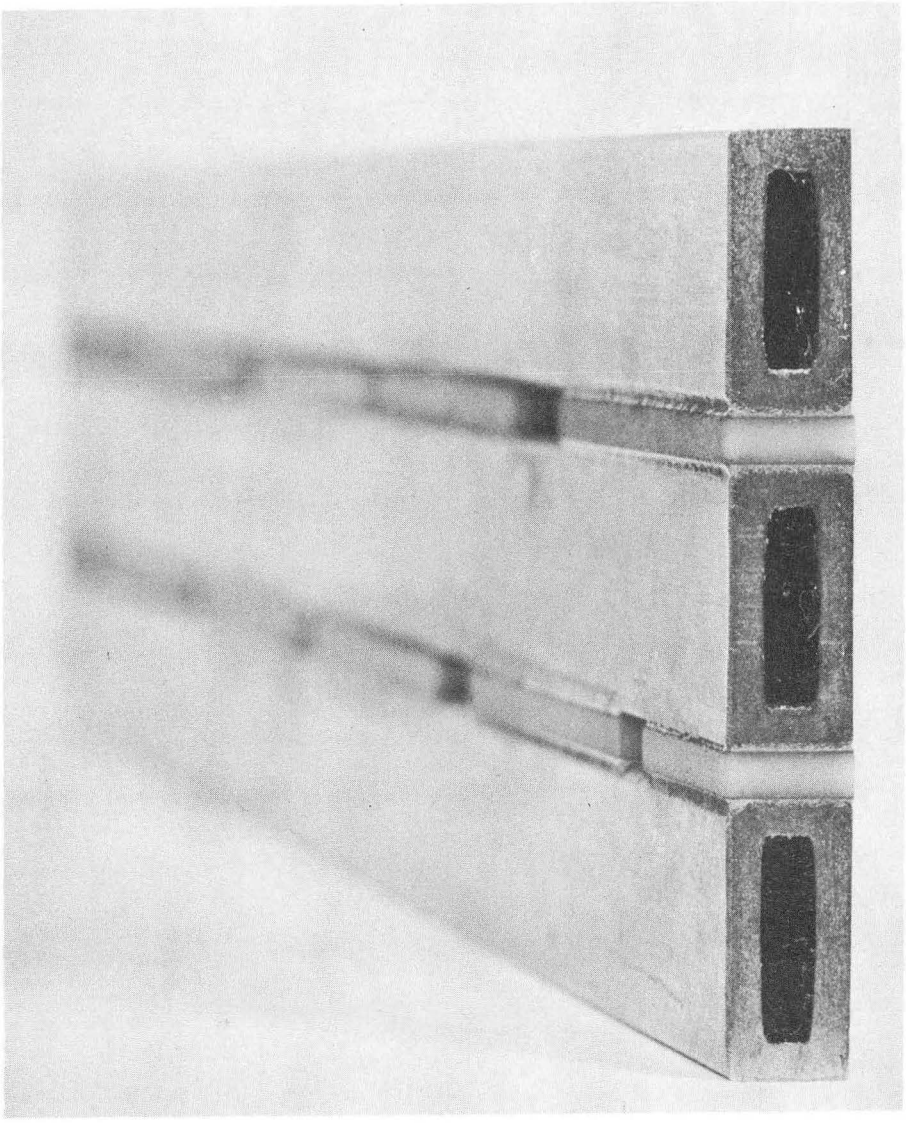

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Fig. 1

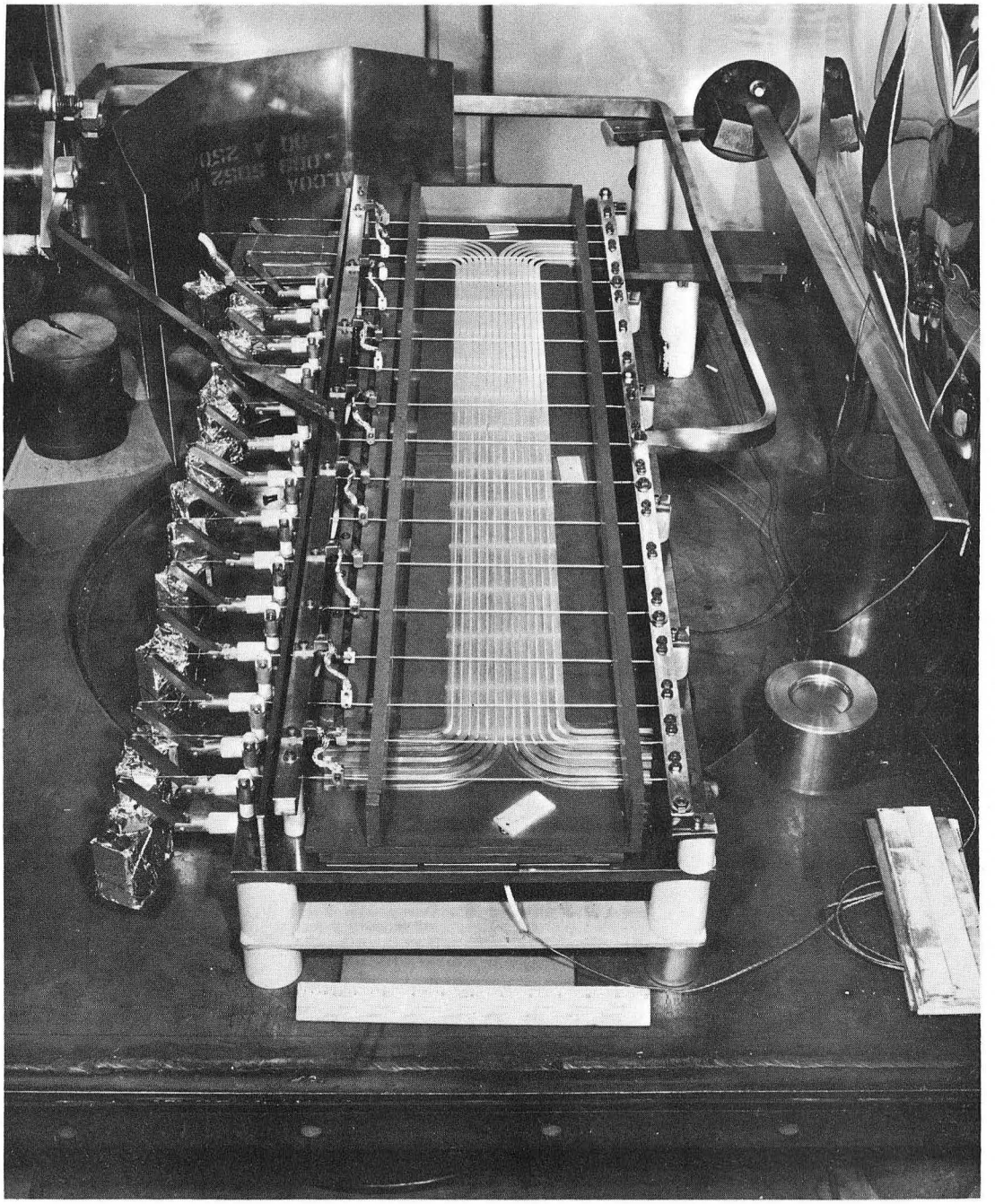

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Fig. 2

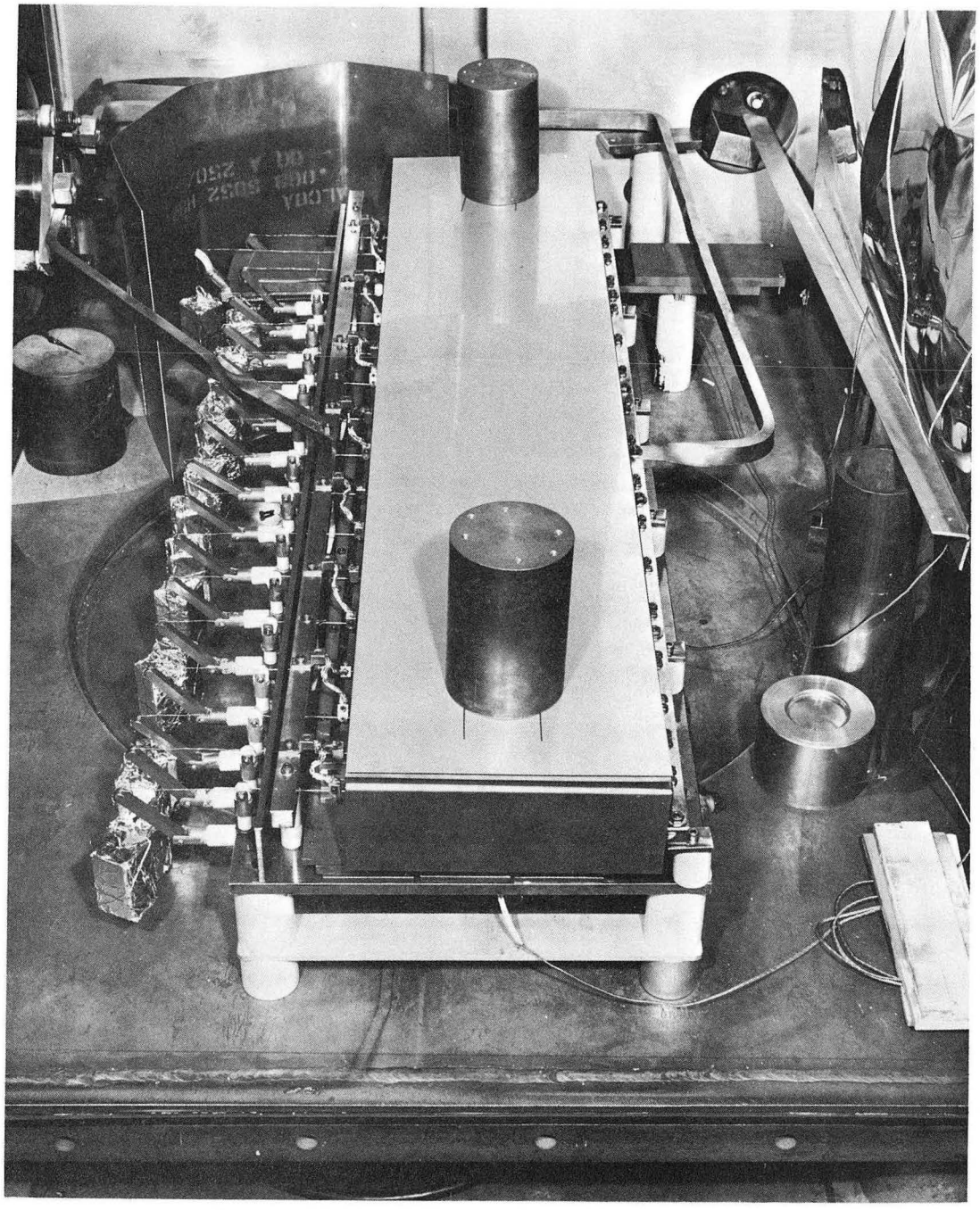

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Fig. 3

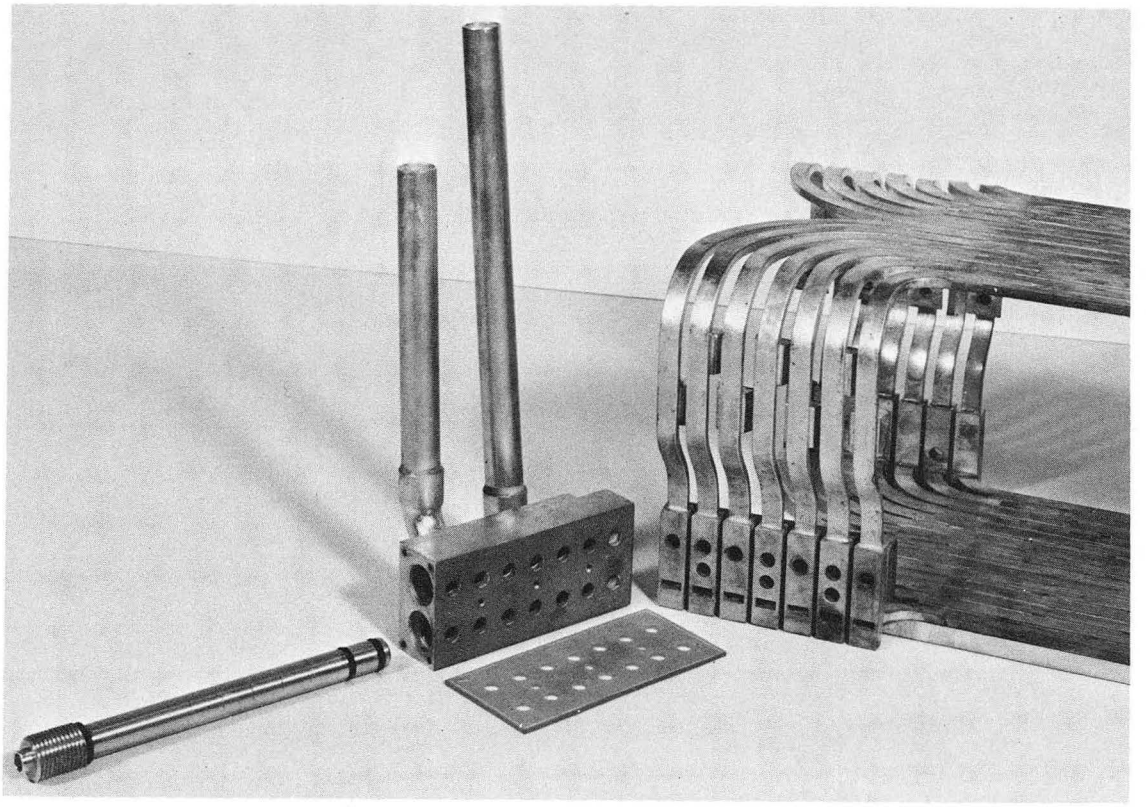

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Fig. 4

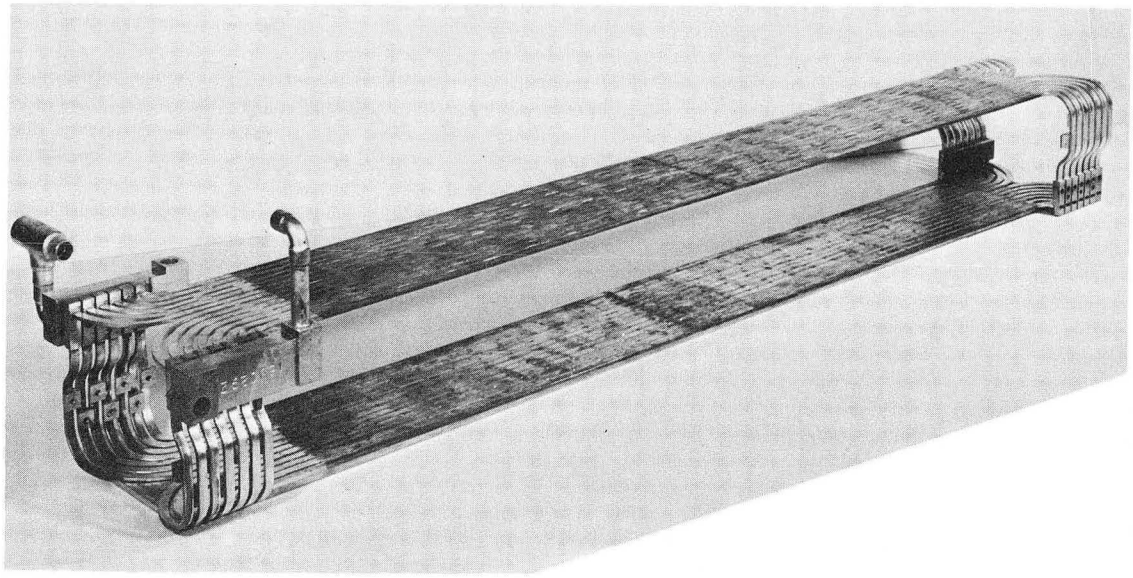

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Fig. 5

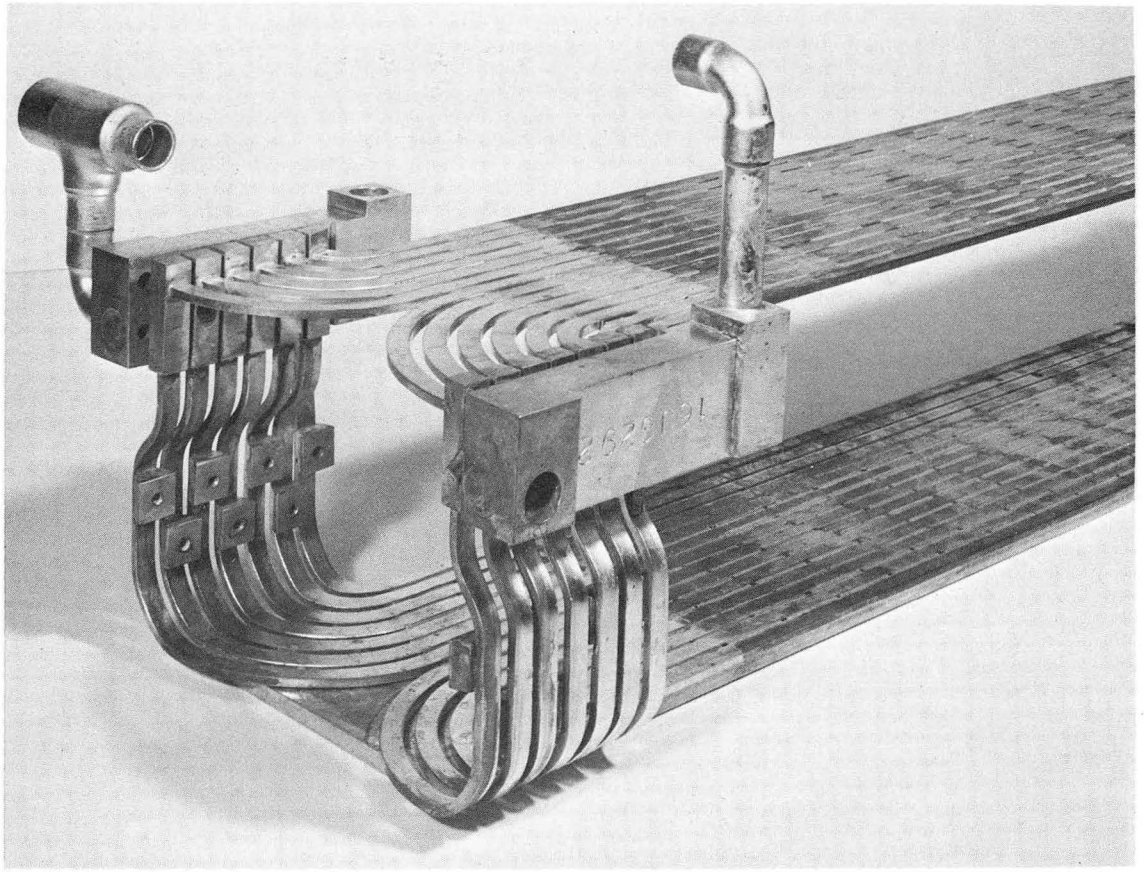

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Fig. 6

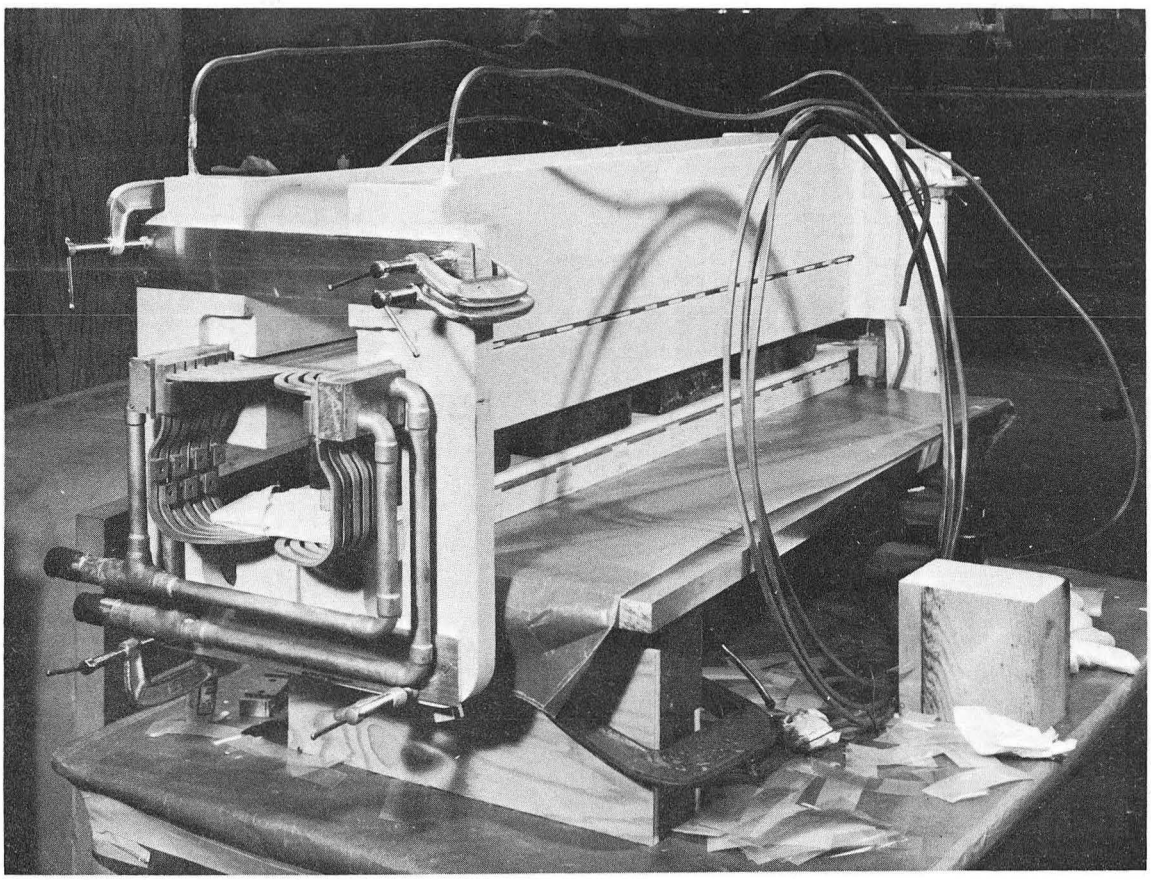

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Fig. 7

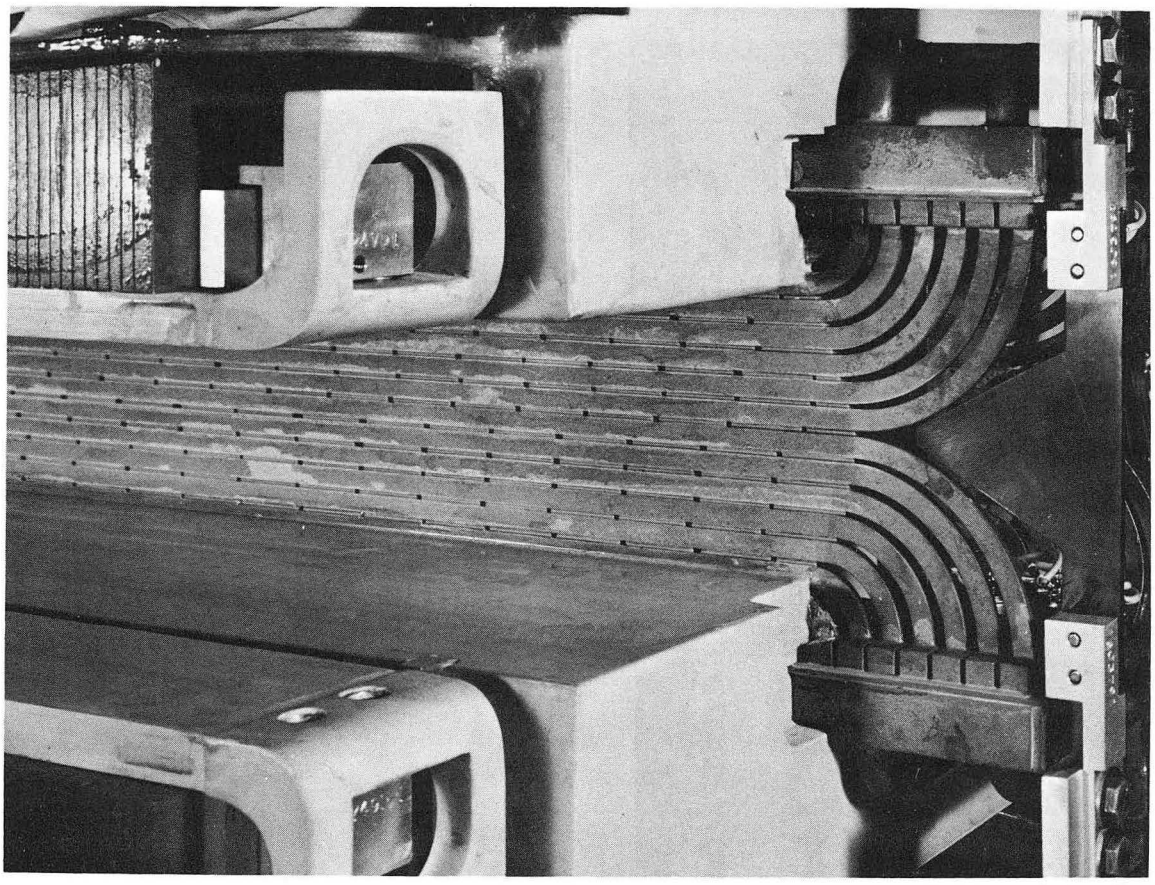

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Fig. 8

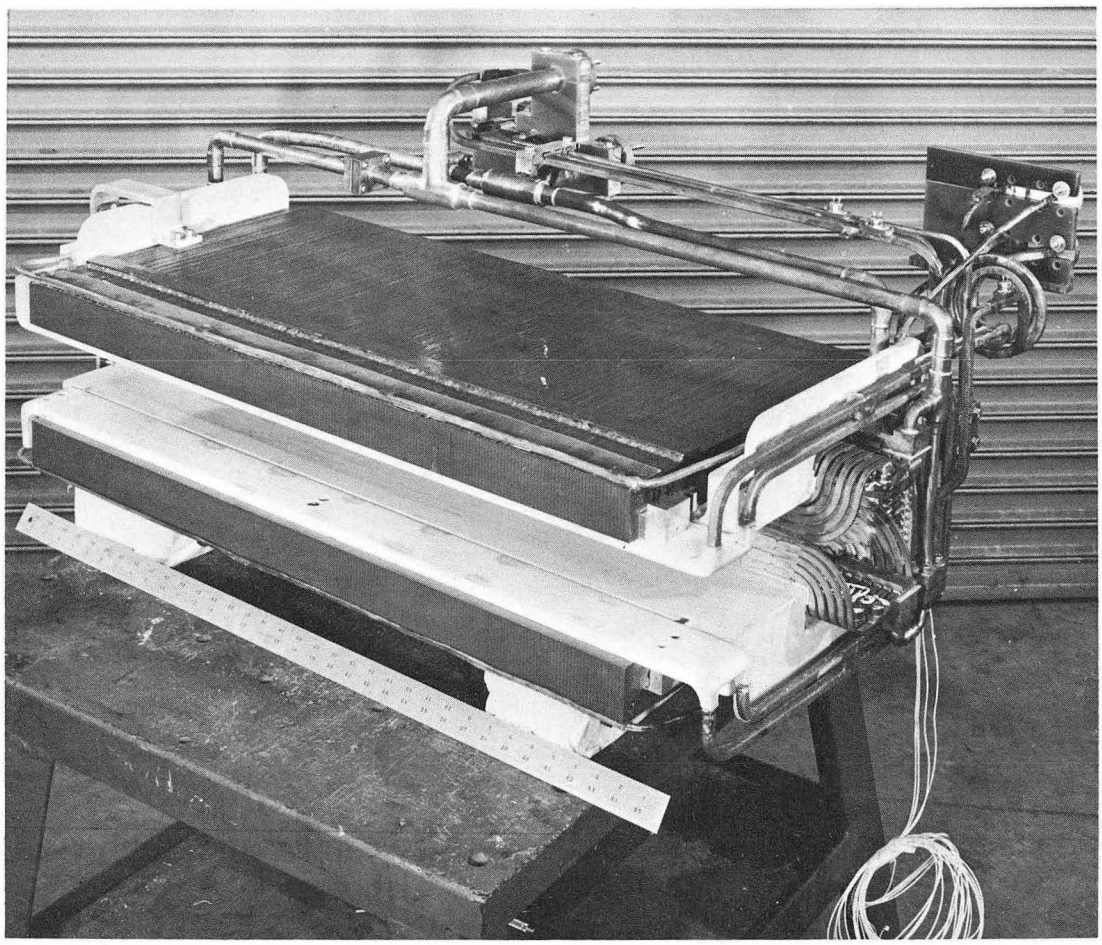

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Fig. 9

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