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MAGNET EXCITING COILS

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Summary

Magnet exciting coils which have been built at the Cambridge Electron Accelerator are described. The paper gives the indices used in designing the coils, and evaluates the properties of various types of insulation.

The fields obtained in bending magnets and in quadrupole magnets have been measured, and the magnetic efficiencies of the flux circuits are recorded. Designs of some unique coils will be shown, which include the following: The exciting coils on the alternating gradient magnets of the accelerator, the coils on the choke that powers the accelerator, a bending magnet, a quadrupole magnet, and the large solenoid coil on a spark chamber magnet.

Exciting Coils on the CEA Machine

One hundred and ninety six coils, each with two layers of stranded cable, are used to excite the alternating gradient magnets of the Cambridge Electron Accelerator. The cable contains 91 strands of Formvar coated copper wire. Each strand has a bare diameter of 0.0523 inch, after Formvar coating a diameter of 0.0541 inch, and the 91 strands produce a cable with a maximum external diameter of 0.635 inch. Two parallel cables have a combined net copper cross-section of 0.39 square inch. The cables are cast in epoxy resin, with a 5/16 inch water cooled tube in the central portion of the coil. Power losses in the conductor will raise its temperature above the temperature of the surrounding resin. Heat flow from a linear foot of parallel cables to the encased water tube is through a resin barrier about 12 square inches in cross-section and 1/16 inch thick.

The coils are excited with current in the form of a biased sine wave at 60 cycles per second. At maximum excitation, about 13 watts are dissipated in each linear foot of a pair of cables. If a heat transfer coefficient of 0.15 Btu/(hr)(ft^2)(^{o}F per ft) is assigned to epoxy resin, calculations indicate that there will be a 20^{o}F temperature differential between the exciting coils and the adjacent water cooling tube.

The coils were fabricated by the National Electric Coil Company. The cables and the water cooling tube, complete with glass insulating barriers, were wound onto a steel form. The free ends of the electrical cable and the water cooling tube were hard soldered to terminal blocks. A steel cap was then bolted onto the winding form to produce a vacuum tight coil form. Air was pumped from the top of the coil form, and epoxy resin was flowed into the bottom of the form until all crevices in the coil were filled with resin. The coil and coil form were then placed in an oven and cured at a temperature of 160^{o}F for a period of three hours.

After the coil was removed from the casting form, mica insulated glass tape, impregnated with partially cured epoxy resin, was hand wrapped around the outside of the coil to form the ground insulation. Each coil was baked a second time to fix the ground insulation, which was then tested by applying 10,000 volts rms, 60 cycles, for a period of one minute. The coils are operated at a maximum potential of 4000 volts to ground.

Pulsed coils often fail due to stress embrittlement of the copper. The Cambridge Electron Accelerator has been operating since August, 1962, and no stress embrittlement in the machine exciting coils has been observed. Only one coil has failed, and this failure occurred at a point where the ground insulation had been chafed by the steel of the magnet frame. The burned insulation was removed to inspect the coil windings, which are shown in Fig. 1.

Choke Coils

The choke is shown in Fig. 2. Twelve choke core blocks of laminated steel are separated by 2-1/2 inch thick micarta spacers. At maximum excitation each of the spacers is compressed by a force of about 100 tons, which generates 60 cycle vibrations. All coil supports which have been devised to date transmit some vibration to the coils. Of the twelve coils that were originally installed, six have failed.

The coils form a girdle around a core block. Each girdle is made up of two secondary coils and one primary coil, cast into a single form to enhance the mechanical strength of the assembly. New coils were installed about nine months ago, with the thin primary winding cast in place between the heavier secondary windings. As of this date, none of the new coils has failed. Two core blocks, each with extra coils in place, are retained as spares. If a coil fails, it can be replaced with a spare in a period of about six hours.

The choke conductor is solid rectangular cable with water cooling through a pierced hole in the center of the conductor. The operating parameters of the magnet and the choke coils at maximum excitation are recorded in Table I.

Coils with Pierced Conductors

All coils at the Cambridge Electron Accelerator, with the single exception of the machine exciting coils, are cooled by flowing water through a pierced hole in the central portion of the conductor. Observers have shown that the coefficient of heat transfer at a water-metal interface increases with the 0.8 power of the water velocity.[1] With a water velocity 5 feet per second through a tube of 3/8 inch internal diameter, heat transfer at the water-metal interface will take place at a rate of about 1200 Btu/(hr)(ft^2)(°F).

As an example of a typical conductor, consider a copper bar 5/8 inch square, with 3/8 inch diameter water hole. The conductor has a net cross-section of 0.281 square inch. A linear foot of the conductor has a wetted area of 0.0985 square feet and an electrical resistance of 3.25×10^{-5} ohms at 50°C. The temperature gradient at the wetted surface is directly proportional to the heat generated in the conductor. At a current density of 2000 amperes per square inch, the temperature gradient at the metal-water interface is 0.3°F; at 20,000 amperes per square inch the temperature gradient is 30°F. Small coils, where total power consumption is of little interest, may well employ high current densities. In large apparatus, where power consumption is a matter of importance, coils are operated at relatively low current densities.

The design parameters of some of the magnets now in use at the Cambridge Electron Accelerator are shown in Table II.

Water Flow

A typical "H" magnet is shown in Fig. 3, and a quadrupole in Fig. 4.

The velocity of water flow through a long tube can be calculated by the equation:

$$V = \sqrt{\frac{g \cdot D \cdot \Delta p}{2 \cdot f \cdot \rho \cdot L}}$$

When the water velocity is of the order of 5 feet per second, the flow will be turbulent, and the value of the friction factor, f, will not exceed 0.01.[2] In the CEA laboratory, Δp, the differential pressure between water inlet and water outlet is about 160 psi.

A multiplicity of parallel water passages must be used to deliver a sufficient volume of cooling water to the larger magnets. The spark chamber magnet is shown in Fig. 5. Here each separate winding is made with four parallel strands of conductor, and a total of 22 windings comprise the finished coil. Water flows through 88 parallel passages, each of which is electrically isolated by rubber hose connections at the terminals. Water flows through the spark chamber magnet at the rate of 120 gallons per minute.

Costs

Pierced copper coils, both for bending magnets and for quadrupole magnets, were purchased at unit costs in the price range of $2.00 to $2.50 per pound of copper. The 220 machine exciting coils were purchased at a unit cost of $1.75 per pound of stranded conductor. The unit cost of the choke coils, which are complex with high voltage insulation, was $3.50 per pound of conductor.

Costs on steel magnet frames, including the material and fabrication, have been as low as 22¢ per pound for simple bending magnets and 32¢ per pound for quadrupole magnets. The laminated blocks that comprise the alternating gradient sectors on the machine were purchased at a unit cost of 41¢ per pound.

References

1. W.H. McAdams, "Heat Transmission," McGraw-Hill Book Company (1954); p. 219.

2. Ibid, p. 156.

TABLE I

PULSED MAGNETS

	Air Gap	No. Turns	Exciting Coils			D.C. Resis-tance	Operating at 6 BeV			
	Ht. Wd. Lg.		Conductor Cross Sect.	Conductor Length	Coil Cross Sect.		D.C. Current	D.C. Power Loss	A.C. Power Loss	D.C.+A.C. Power Loss
	Inches		in^2	ft.	% Copper	Ohms	Amps	kw	kw	kw
Choke Coil (Power to two machine magnets)	2-1/2 x 30 x 60	48	0.233	850	57	0.032	400	5	27	32
Two Alternating Gradient Machine Magnets (8 coils)	2 x 6-1/2 x 262	80	0.390	2100	36	0.048	400	8	20*	28
							Power Loss for 1 Circuit		=	60
							Power Loss for the 24 Circuits on the Machine		=	1440

*NOTE: Alternating rms potential at peak excitation across four coils connected in series equals 3600 volts.

TABLE II

D.C. MAGNETS

Magnet Type	Air Gap Ht. Wd. Lg. (Inches)	EXCITING COILS: No. Turns	Conductor Cross Section (in^2)	Coil Cross Sect. (% Copper)	Resistance Coil (Ohms)	Operating Conditions: Current Flow (amps.)	Current Density (amp/in^2)	Power (kw)	ΔT Cooling Water (°F)	Measured Magnetic Flux in Air Gap (Kgauss)	Magnetic Efficiency (%)
H	3 x 10 x 72	420	0.100	57	0.695	309	3100	66	34	18.0	84
H	3 x 12 x 42	400	0.131	52	0.334	327	2500	36	25	18.0	84
H	4 x 15/45 x 58	384	0.161	58	0.498	415	2600	86	32	18.0	91
H	10 x 22 x 48	960	0.170	58	1.030	458	2700	216	33	18.0	83
H	11 x 17 x 48	928	0.170	62	0.926	494	2900	226	36	18.0	87
Quad	12 x 48	496	0.136	60	0.538	459	3400	114	38	12.0	91
Quad	8 x 36	428	0.160	63	0.241	491	3100	58	32	12.0	92
Spark Chamber	40 x 40 x 60	1232	0.498	70	0.450	1110	2200	550	30	16.0	95

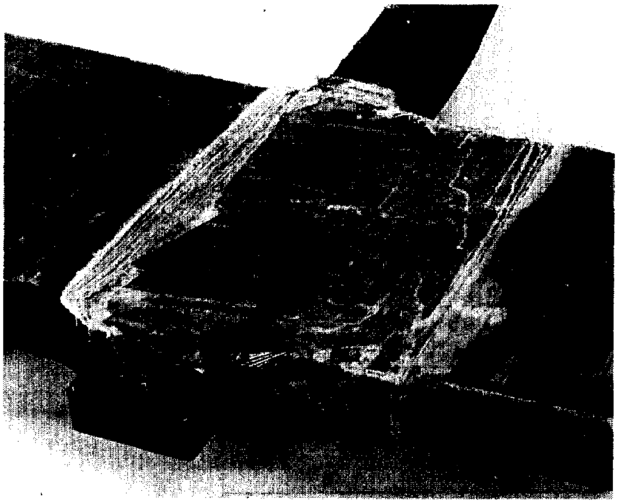

Fig. 1. Machine exciting coil.

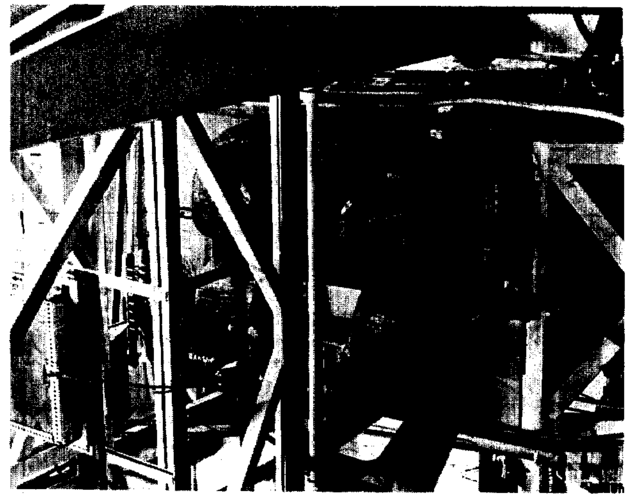

Fig. 3. Bending magnet.

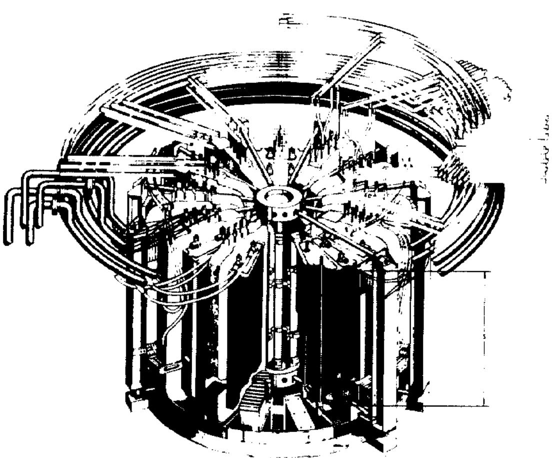

Fig. 2. Choke.

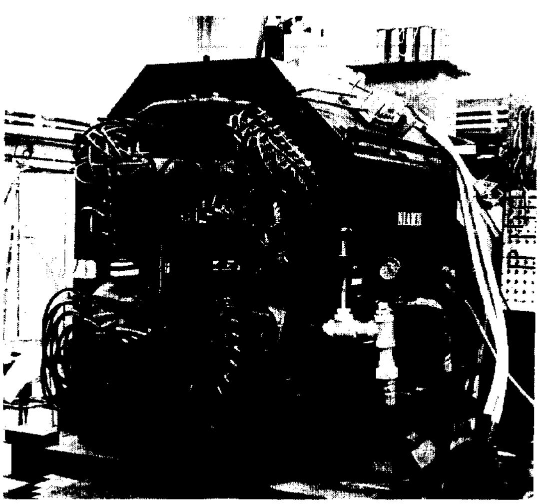

Fig. 4. Quadrupole magnet.

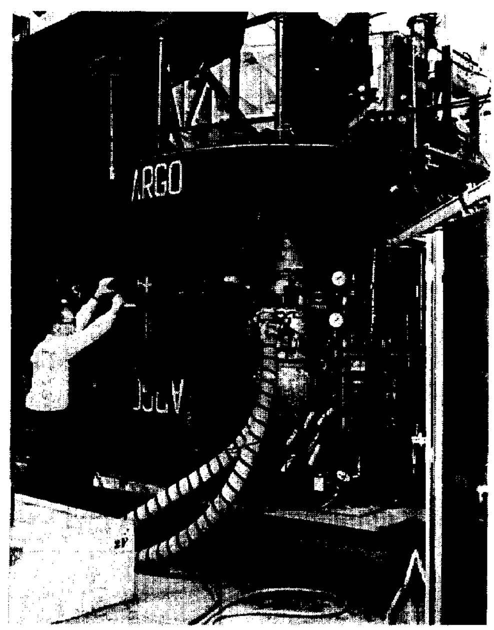

Fig. 5. Spark chamber magnet.