DRIFT TUBE QUADRUPOLES*

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Introduction

The 200-MeV proton linac injector for the Brookhaven AGS Conversion will have a focusing magnet in each of its 274 drift tubes. A development program has been under way to produce the required quadrupole magnet designs. Both dc and pulsed power prototypes have been fabricated and tested. It was found that the pulsed magnet design achieved substantially higher gradients than the dc powered design. The pulsed magnet design is a scaled-down version of the Danby-Jackson narrow quadrupole.[1] Measurements of harmonic content have been taken by the AGS magnetic measurements group. Thermal tests have been conducted and their results are discussed. All tests were performed on magnets designed to fit into the first full drift tube of the injector.

Core Selection

It has been shown by Chasman,[2] Ohnuma,[3] and Gluckstern,[4] that the ability of linac drift tube quadrupole magnets to limit the growth of transverse oscillations and of beam emittance depends strongly on the magnitudes of the quadrupole field gradients in the low energy portion of the accelerator. The rate of increase of transverse oscillation amplitude with mean proton energy is much less for large values of quadrupole field gradient than for relatively small values. Also, the proton beam emittance grows less rapidly with energy for the relatively large values of quadrupole field gradient. For these reasons, a core design[1] characterized by good quadrupole field quality at relatively large gradients has been selected for installation in the 200-MeV linac drift tubes. A sketch of the cross section of this magnet is shown in Fig. 1. The width of the slots between pole tips is too small to contain copper tubing. With solid copper wire carrying the excitation current, there is a gain in packing factor, but the advantage of being able to cool the copper by flowing water through tubing is lost. The cores will be in good thermal contact with the water-cooled drift tubes, but the copper windings are thermally insulated from the core. For these reasons, the magnets cannot be energized with direct current. A current pulse with a duty factor of about 1% is planned, and the shape of the pulse is such that the cores must be laminated in order to impede the flow of eddy currents.

Mechanical Assembly

The same fabrication methods used in the production of the prototype magnets will be used to produce the final quadrupoles. The low energy drift tube quadrupole cores are made of three basic pieces: two laminated half cores and a clamping ring (see Fig. 2). The laminations used for prototypes were machined but the laminations for finished quadrupoles will be stamped from strip stock. An oxide finish[5] is applied to them for interlamination resistance. The laminations are then degreased and sprayed, one side only, with a laminating epoxy resin and oven dried at 125°F for eight hours. Before stacking, the laminations are dipped into petroleum ether to remove any dust or body oils from the bonding surfaces. The laminations are then stacked, spring-loaded against the mandrel, and the epoxy resin is cured at 320°F for three hours. Next, the stacked half-cores are soaked in an epoxy vapor stripper to remove any excess resin which flows out of the joints during the curing cycle. The half-cores are then masked (OD, pole tips and butt area), heated to 300°F for the fluidized bed application of the coil-to-core epoxy insulation.

The coils are wound using 12 gauge (0.081 in diam) solid copper wire with heavy formvar insulation. Special bobbins have been developed and are motorized. The finished coils are wound in two layers with no extra insulation between turns or layers. After the coils are wound, they are coated with a quick-curing epoxy and are not removed from the bobbin until the resin is cured. This insures that the coils will retain their shape after removal from the bobbin. The coils are then inspected for breaks in the insulation, leads trimmed, and their resistance and inductance measured and recorded. Coils for a particular quadrupole are matched for resistance and inductance in order to insure symmetry. The coils are then placed on the half-cores and the heated clamping ring is placed around the halves for a shrink fit. The coils are then connected and the assembly is made ready for the potting process. The quadrupoles are vacuum-potted with a high thermal conductivity epoxy resin system.

Current Pulse Generator

It would seem that a good choice for the shape of the excitation current pulse would be a trapezoid. The rise and fall times could be chosen such that the coil voltage is a comfortable margin below coil-to-core insulation breakdown. The top of the pulse could be held as flat as is necessary. A disadvantage of this wave shape is that a combination of faults might occur which would result in failure of the pulse to stop rising at the top of the trapezoid. Excessive current flow for an appreciable time interval is possible. Protection of the magnets is a primary consideration in this system because the process

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* Work performed under the auspices of the U.S. Atomic Energy Commission.

of replacing one of them after it has been sealed up in a drift tube is extremely costly in terms of downtime. Therefore, attention has been concentrated on a type of pulse generator which does not need to contain a power source or an energy source of sufficient magnitude to damage a magnet. A charged capacitor bank is switched across the magnet winding with an SCR, and the LC circuit formed in this way goes through one-half cycle of oscillation. Most of the energy stored in the capacitor bank becomes stored in the quadrupole field one-quarter cycle after closing the switch, and the closure is timed such that the peak of the current pulse is coincident with the center of the linac beam pulse. The pulse width, or resonant frequency, is determined by the maximum allowable variation of magnetic field during the time that the beam is present. The maximum pulse width presently expected of this injector is 200 µs. A tentative choice of pulse width is 2.25 ms, which results in a variation of plus and minus 1% about the mean magnetic field level during a 200 µs time interval centered at the peak of the pulse. A circuit capable of generating this pulse shape at 10 pulses per second and of sufficient amplitude to saturate the core has been designed and built. The important circuit details are similar to those of a system developed by Larson[6] and are not repeated here.

Techniques for flattening the top of the sinusoidal current pulse are being explored so that a higher degree of flatness during the linac pulse can be achieved without increasing over-all pulse width.

Thermal Tests

Thermal tests have been performed on prototype magnets. The assembled magnets were placed in a water-cooled jacket (maintained at 75°F) to simulate the cooling conditions of a quadrupole mounted in a drift tube. The present design of the drift tube body incorporates a cooling channel brazed into the body. The drift tube and quadrupole are cooled by the same coolant. The quadrupole depends upon heat conduction across its locating surfaces for its cooling. Dc power was dissipated in the magnet coils and the change of coil resistance as a function of dissipated power was measured. The change in coil temperature was then calculated. Figure 3 shows the results. In the short drift tubes at the low energy end of the linac, where large gradients are required, and where the least cooling area is available, 30 W is expected to be dissipated per magnet. This corresponds to a copper coil temperature of 86°F, which is well below the limits of materials used in the fabrication of the assembled quadrupoles. Higher energy drift tube quadrupoles will require lower magnetic field gradients, thus lower dissipated power levels, and will have larger areas available for cooling surfaces.

Field Measurements

Since some of the magnets are to be used at or near the highest gradients they are capable of providing, the degree of degradation of quadrupole field quality at high gradients is of interest. The harmonic content[7] as measured with a search coil long enough to intercept the full length of the fringe field is taken as a measure of quadrupole field quality. Preliminary measurements have shown that the higher harmonics are all less than one-half of one percent of the quadrupole component, at least up to gradients of 6000 G/cm (Fig. 1). These measurements were made at a radius equal to 80% of the distance from axis to pole tip. This study is to be continued at higher gradients.

Another subject to be investigated is the effects of the flow of eddy currents in the laminated pole tips. The choices of current pulse shape and of lamination thickness may be influenced by the results of this study.

Other field measurements to be made are:

(1) $\underline{B}$ as a function of displacement along lines parallel to the axis, as in Fig. 4.

(2) $\int (\partial B_y)/(\partial x)\, dz$ as measured with a long coil, positioned at known radii.

(3) $\underline{B}$ vs. ampere-turns at various points in the field, as in Fig. 5.

(4) Forces between magnets in neighboring drift tubes.

(5) Position of the center of the quadrupole field with respect to the geometric center of the magnet.

The overlapping fringe fields of neighboring magnets are to be explored with small coils and with small Hall crystals.

The measurements with search coils are made by integrating the voltage which the pulsed field induces in the coil. The output of the integrator is the flux intercepted by the area of the coil, or the average flux density in the region enclosed by the coil.

Acknowledgments

The designers of the magnet's core (G. Danby and J. Jackson) supervised the work reported in Fig. 1 which led to the selection of optimum slot widths. Most of the magnetic measurements have been done by J. Weisenbloom. W. Rasmussen's skill in winding long search coils with hundreds of turns of No. 50 gauge wire has made possible the sixth harmonic content measurements of Fig. 1. Suggestions offered by R. Larson, J. Bittner, J. Sheehan and many others are gratefully acknowledged.

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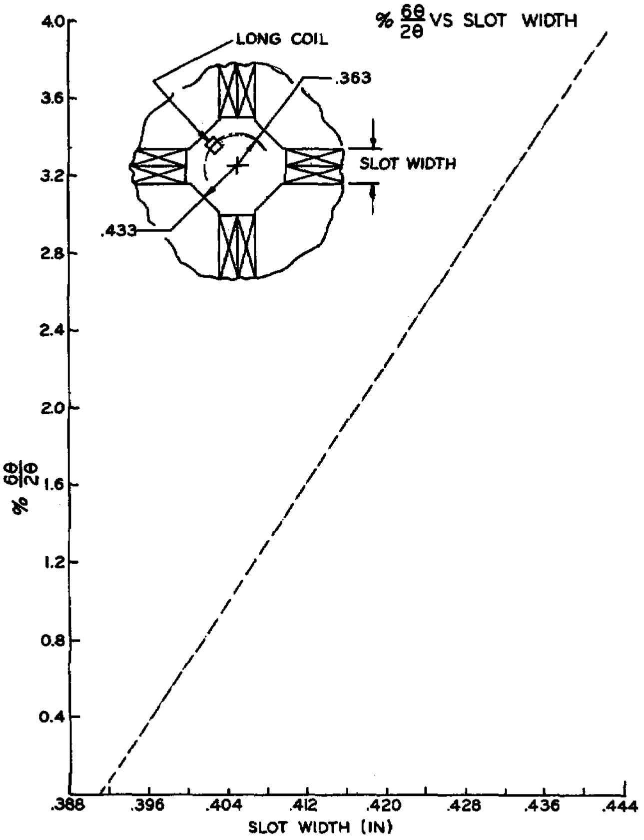

Fig. 1. Sixth harmonic content vs. slot width.

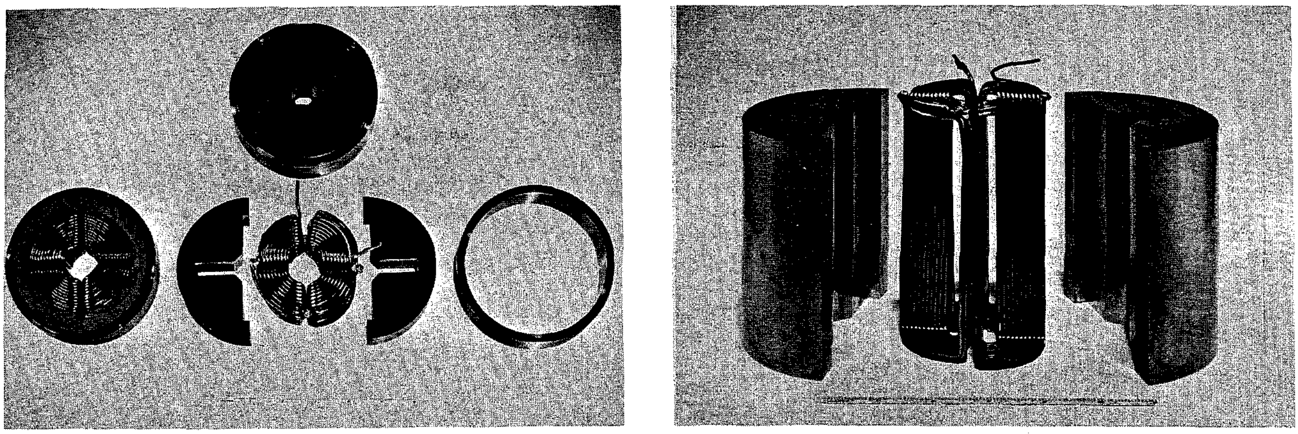

Fig. 2. Magnet components.

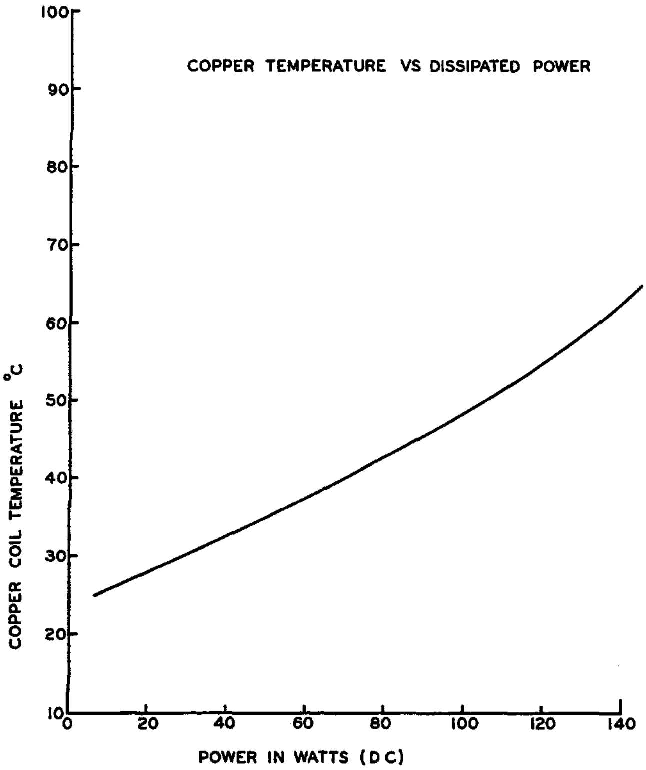

Fig. 3. Copper temperature vs. dissipated power.

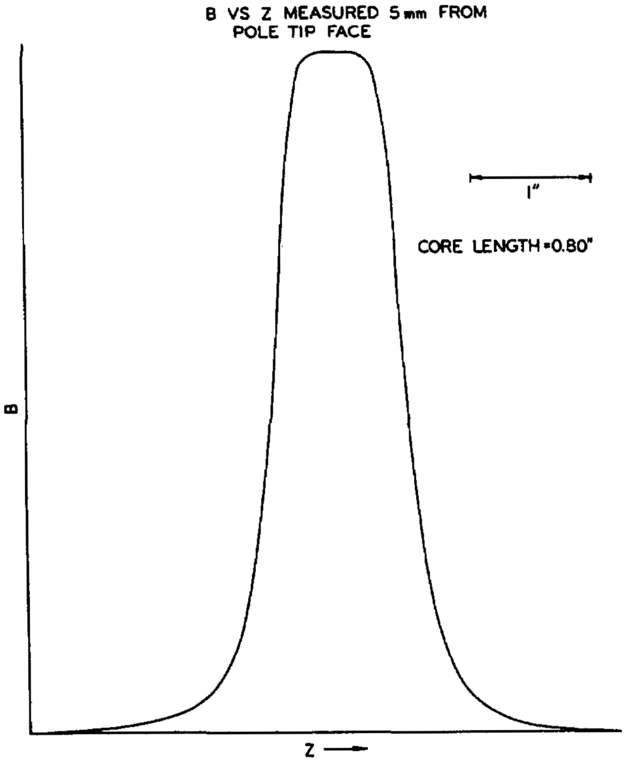

Fig. 4. *B* vs. z.

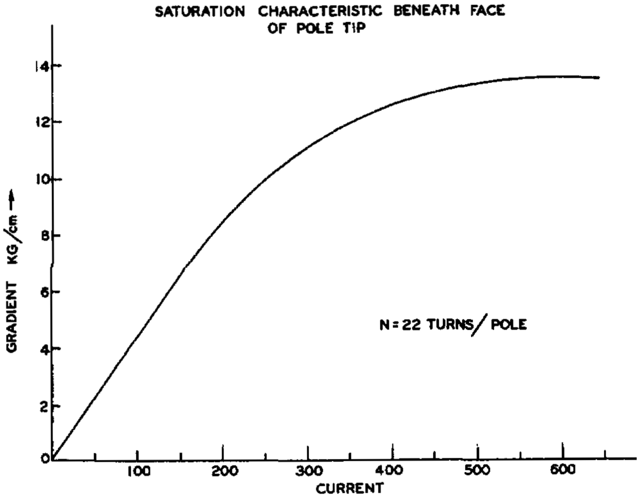

Fig. 5. Pole tip saturation.