A PULSED QUADRUPOLE SYSTEM FOR PREVENTING DEPOLARIZATION*

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Summary

A pair of pulsed quadrupoles spaced 180° apart in the Zero Gradient Synchrotron (ZGS) ring was installed to prevent the depolarization of polarized protons during acceleration in the ZGS. These quadrupoles must produce a 50-G/in gradient over a useful aperture of 2 in vertically and 10 in radially. The pulse must have a 10-μs rise time and a 2½-ms flattop. They must be pulsed up to ten times during the 1½-s ZGS acceleration period. The computer calculations and the mechanical and electrical design and fabrication of the quadrupoles and their power supply will be described.

Computer Design of the Magnet

The desired parameters were a quadrupole gradient of 50 G/in over a volume of 2 in vertically, 10 in radially, and 20 in long. A clear aperture of 5.5 in vertically and 36 in radially was necessary in order to match the ZGS vacuum chamber dimensions. It was initially thought that a 1/2-μs rise time was necessary. This dictated a design for minimum inductance to keep applied voltages at a reasonable level. We, therefore, considered a 1-turn coil and a steel configuration to provide the gradient over as small a volume as possible. Further calculations showed that we could go to a 10-μs rise time and a 4-turn coil, provided we still kept the condition for minimum field volume.

Magnets having symmetry about the 45° line would produce the desired gradient over a circular region, as shown in Fig. 1. This region is very much larger than required and such a magnet would have a relatively large inductance. A pole shape as shown in Fig. 2 was determined by using the computer program TRIM to calculate the magnetic fields. Simple machining operations can be used to produce this shape, whereas a smooth curved pole would require more elaborate machining. Furthermore, much less steel is required for this magnet than for one like Fig. 1. The coil was positioned 0.75 in from the steel to reduce the leakage flux around the coil. The calculated fields for this design are shown in Fig. 3.

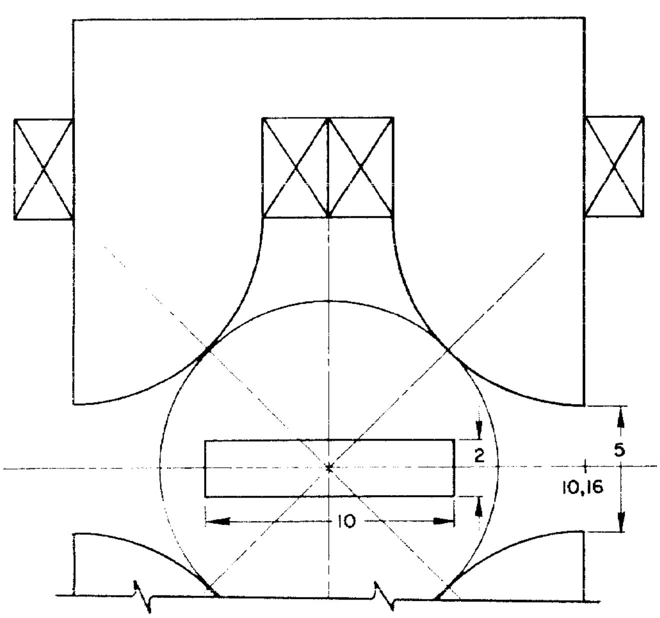

Fig. 1 Quadrupole with 45° Line Symmetry

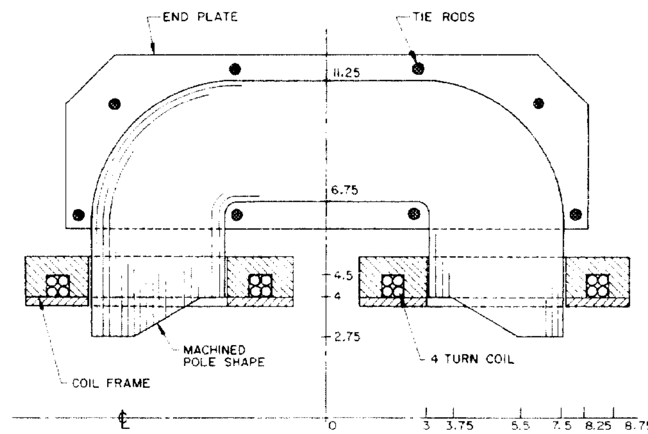

Fig. 2 Pulsed Quadrupole Pole Shape and Coil as Determined from TRIM Computer Program

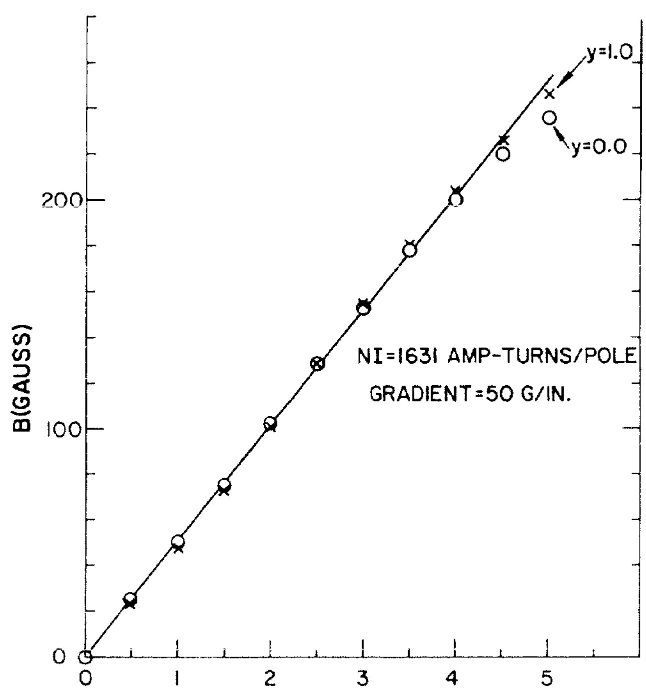

Fig. 3 Calculated Fields for Pulsed Quadrupole

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Core and Coil Design

Various schemes for laminating the core from 4-mil, high silicon content steel with a permeability of < 1000 for field values under 500 G were installed gated. The cost estimate for fabrication of two cores from stamped laminations was about \$18, 000, of which \$5, 000 was for a die. The cost of these cores could be reduced by \$10, 000 if we fabricated them from commercially available tape wound cores of 4-mil laminations. Tape wound cores were purchased in 5-in lengths and assembled to give the desired 20-in length. Actual assembly of tape wound core halves to form a C-core is much simpler and, therefore, less costly than the assembly of 4-mil stamped laminations.

Four tape wound core halves were aligned on a surface plate, insulated from each other by glass cloth, and clamped between 3/4-in thick stainless steel end plates as shown in Fig. 4. The assembly was then vacuum impregnated to bond the units into a 20-in long C-core. After resin curing and cleanup, the pole shape was machined to the required dimensions.

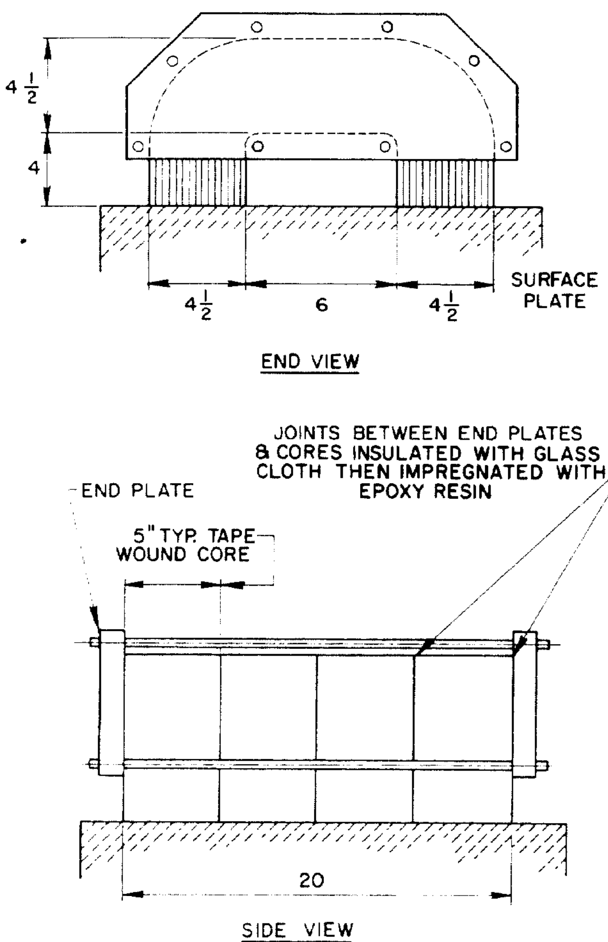

Fig. 4 Assembly of Quadrupole from Tape Wound Cores

The coil consists of four turns of No. 6 (0. 162-in diam) solid copper wire. The wire was insulated with six layers of 3-mil Kapton "H" film and wound into a NEMA grade G-10 mounting frame. It was vacuum impregnated with epoxy resin into the frame. The C-core and coil frame cross section are shown in Fig. 2. The coil frame is attached to the C-core by angle clips mounted to the core end plates.

Electrical System

As noted in the conference paper on "Acceleration of Polarized Protons in the ZGS," an electrical system is required to simultaneously pulse the two quadrupole magnets up to ten times in about 1. 5 s, then rest and repeat the ten pulses some 3 s later when the ZGS cycle again occurs. With the two 4-turn quadrupoles hooked up in parallel, we require 750 A with a 10-μs rise time and a 2½-ms flattop (±20%). Decay time can be about 10 ms. Alternate pulses must have opposite polarities since the correction must compensate for either a sum or difference resonance.

As in any system of this type, a number of trade-offs are possible when establishing operating voltage and current. One of the economic preconditions was the use of a set of 16 ignitrons which was installed and available in the ZGS Main Ring Building. These have an average current limit of 2 A per tube. This led to the choice of a 4-turn coil. The magnets could be connected either series or parallel, but parallel was chosen to keep the nominal operating voltage at about 6 kV. This leaves some reserve voltage capability in case a faster rise time or a larger gradient is desired. All insulation systems, feedthroughs, etc., are designed for a 10-kV operating voltage. Also, parallel magnet connections should make less of a problem with transmission line reflections than a series magnet connection. Figure 5 is a schematic of the electrical system.

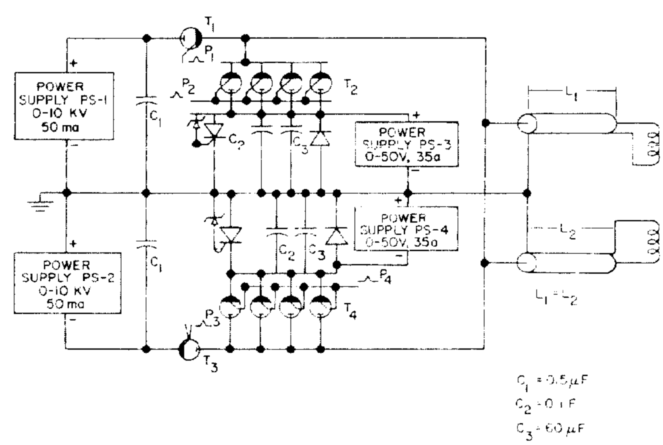

Fig. 5 Schematic of Electrical System for Quadrupole Pulsing

The system is basically a combination of two resonant systems with greatly different resonant frequencies. A somewhat similar technique has been used at the ZGS before.[1] The systems above and below the ground line are images of each other to provide the reverse polarity pulses.

Capacitor C_1 is chosen to resonate with the quadrupoles at 25 kHz. This gives the required rise in 10 μs. The simplest choice for sustaining the current for the required 2 ms is a purely exponential decay provided by commutating the current into a low resistance path through T_2. However, the losses in the tubes force this decay to be too fast. Instead, one must supplement the magnet stored energy with the capacitor bank C_2 and C_3, shown in Fig. 5. As shown, the resonant frequency of C_2 and C_3 with the quadrupoles is about 60 Hz. Control of the width of the time window needed for the ZGS tune shift will be made by voltage control of PS-3, the charging supply for C_2 and C_3. PS-3 is programmed so that it can only charge C_2 and C_3 and not continuously sustain the arc of T_2. Capacitor bank C_2 is a stacked foil electrolytic bank chosen for low inductance. It is rated 50 WVdc. Capacitor C_3, the diode, and the zener-fired SCR are provided to protect C_2 and PS-3 from over and reverse voltage. C_2 should be protected from the accidental discharge of C_1 into C_2 because of the ratio of the values of C_2 and C_1.

The operating sequence is as follows: Capacitor C_1 will be charged to either + or - 6 kV in about 30 ms. Tube T_1 will be fired by pulse P_1 from the ZGS programmer. Ten μs later, at the voltage zero of C_1, tube T_2 will be fired. However, the voltage on C_3 is too small to strike an arc. When the charge on C_1 has reached a negative value of a few hundred volts, T_2 will strike an arc and the current is commutated to the crowbar. Capacitors C_2 and C_3, which had been charged to 40 V, will now discharge through T_2, thus sustaining the magnet currents. At this instant, PS-3 will be voltage limited to 3 V and current limited to about 0.1 A. The current per quadrupole, which will rise to 1.07 I_o at 1 ms, will be I_o again at 2 ms, and will be approximately zero at about 10 ms. Approximately 100 ms after T_2 has turned off, a pulse of opposite polarity is generated with tubes T_3 and T_4.

Reference

[1] W. F. Praeg, Argonne National Laboratory, A Pulsed Beam Shutter for Radio-Frequency Separated Beams at the ZGS, 1973 Particle Accelerator Conference, San Francisco, California, March 5-7, 1973.