PULSED DRIFT TUBE QUADRUPOLE MAGNETS WITH HIGH PRECISION

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Abstract

The drift tube quadrupole magnets for KEK 20 MeV injector linac are described. New manufacturing processes of pulsed quadrupole magnets were developed to obtain such a high field gradient as 11 kG/cm, a high reliability and a high precision. The core of the magnet was divided into four quadrant cores. The core leaves were punched by a high precision die set, stacked on a jig and epoxidized to form a quadrant core block. The coils, instead of a wire-winding method, were made of copper blocks by a machining. Four quadrant cores and a coil assembly were assembled on a jig. The deviations of the magnetic centers from the bore center were within 0.02 mm for 90 magnets.

Introduction

Drift tube quadrupole magnets should satisfy such requirements as a high field gradient, a high mechanical precision, a high reliability, a compact structure, and a facility for the manufacturing. The coils should have sufficient mechanical strength, good electrical insulation, and high cooling efficiency, because of high field gradient and high current density under pulsed operations.

The inner surface of the bore tube was chosen as the reference for alignment of the drift tubes. Therefore the deviation of the magnetic centers from the bore centers should be as small as possible. To satisfy this requirement, two methods were considered.

1. Fine adjustment at the time of setting of the quadrupole magnets into the drift tubes.

2. Quality control of the parts and manufacturing processes of both the drift tubes and the magnets.

The latter method has an advantage of reliability and reproducibility of the manufactured magnets.

The total ninety magnets are divided into five groups according the core thickness of 25 mm, 35 mm, 50 mm, 75 mm and 100 mm. Corresponding to the increase of the bore diameter at 29th drift tube from 20 mm to 25 mm, there are two different core profiles A and B (Fig.1). Typical parameters of the quadrupole magnets are as follows.

Drift tube number	1	30	50	90
Gradient, kG/cm	11	6.0	4.3	3.3
Magnet length, cm	2.5	5.0	7.5	10.0
Magnet gap radius, cm	1.1	1.35	1.35	1.35
Peak pulse current, A	700	585	412	320
Power loss, Watts. avg.	130	120	60	60
Number of turns of coil per pole	7.5			
Duty factor of pulsed operation	1300 μs. 20 pps.			

Structure

Four poles of a quadrupole magnet should be symmetrical about the two orthogonal planes including the core axis, and the tips of the poles should be fit into the bore tubes with a negligible clearance. As the core was divided into four quadrants, the pole tip profile and butting surfaces of the quadrant cores were required to have a highest precision.

The coils were machined from copper blocks; accordingly, they have accurate dimensions and symmetry. After assembling the cores and coils on a jig, Al-rings were shrunk on the outer periphery of the cores, and a cooling channel was attached to the magnet. The mechanical reference of the magnets is the tips of the four poles (Fig.2).

Punching of the Core Leaves

The fabrication method of the cores depends on the accuracy of punched leaves, the uniformity of the core thickness, and the magnitude of punched burrs. The mechanical tolerance of the punching die set was within 5μ. The leaves were punched from cold rolled silicon steel belts of 0.35 mm thick (Fig.3). The leaf-by-leaf error of the profile was less than ± 2μ. The punching die set was designed to reduce the punched burrs, however, in order to omit the de-burring process completely, and to obtain a uniform thickness of the cores, it was found that the leaves should be stacked in the same direction as the punching process. To memory the direction, a mark was punched at the outer periphery of the leaves (Fig.1). After inspection,the leaves were degreased by vapour of an organic solvent.

Stacking and Epoxy-Impregnation

For the quadrant cores, the following requirements should be satisfied.

1. Orthogonality between the two butting plane surfaces of a quadrant core $< 10''$

2. Flatness of the butting surfaces < 0.01 mm

3. Perpendicularity of the butting surfaces with respect to the reference end-plane $< 10''$

4. Uniformity of the core thickness < 0.015 mm

In order to satisfy these requirements, the degreased leaves were stacked to form a quadrant core on a jig which consists of a base plate, two rigid square blocks forming the orthogonal reference surfaces and two demountable end-plates (Fig. 4a, b). The leaves were pressed against the reference blocks and compressed to the correct thickness by clamping bolts of the end-plates. The assembly of stacked leaves and end-plates was demounted from the jig and preheated to 50°C. Then the lateral surface of the stacked leaves were painted by an epoxy resin. The resin was cured for 3hrs at 165°C. The epoxy resin penetrates about 10 mm inside the spaces between leaves by a capillary action. The quadrant-core block was demounted from the end plates and the superfluous resins were removed (Fig.5). By this method, the uniformity of the core thickness was obtained within the error of 0.015 mm.

Coil

In order to mount a quadrupole magnet into a restricted space of the drift tube and to obtain a large packing factor with high reliability, the coils were machined from copper blocks. The process of coil fabrication consists of several steps.

1. A copper cylinder with a center hole is cut into four quadrant blocks, each of which is finished to a quadrant coil. 2. A radial hole for the magnet pole is cut in the quadrant block by a milling machine, leaving the walls of 4.5 mm thick (Fig.6). 3. On the two rectangular side-walls, seven parallel grooves are cut at the interval of 3.5 mm. The width of grooves is 1 mm and the depth 4 mm. At the one side of the walls the grooves are parallel to the axis of the quadrant, while at the other side they are slanted in order to link a turn of the coil to the next. 4. Four quadrant blocks are mounted on a jig and seven grooves are also cut by a lathe azimuthally on the both up and down walls. The width and the depth of the grooves as well as their intervals are the same as those on the side-walls. 5. These four quadrant blocks soldered together at three points so as to form a coil assembly connected in series. Two lead wires (4 mm x 2.5 mm) are also soldered with the end terminals. 6. Inside the grooves and the space between coil blocks, thin phenolic resin sheets are inserted and an epoxy resin is impregnated. 7. After curing, the inner surfaces of the radial hole for the magnet pole is milled 0.5 mm to separate each turn of the coil by means of the epoxy impregnated grooves (Fig.9).

Fig.10 shows the coil assembly which forms a series connected seven and a half turn coil. The cross-section of each turn is 4 mm x 2.5 mm and the packing factor of the coil is 75 %. After inspection of the inter-turn short circuits by measuring the inductance and the Q-value of the coil, the both end surfaces and the inner surfaces of the radial holes were epoxidized with the thin phenolic resin sheets. Consequently, each turn of the coil was completely insulated from the cores and the surroundings.

Assembling

After a coil was placed on an assembling jig, two diagonal quadrant cores were first bolted to the jig fitting the butting surfaces of the cores and the reference blocks of the jig (Fig.11). The reference blocks were replaced by the other two quadrant cores which were then bolted down. The four quadrant cores were clamped together by shrinking Al-rings around the assembly (Fig.12). This shrinking method was found superior to bolting to the end plates because of simple and reliable construction. Corresponding to different magnet lengths, various rings were used. For 25 mm length magnets, two rings 5 mm thick and 5 mm high were fitted with a shrinkage of 0.15 mm. The shrinkage pressure averaged over the magnet periphery was 13 kg/cm^2. Shrinkage of the cores was found to be 0.02 ± 0.01 mm at the pole gaps. The magnet outer surfaces are completely cylindrical within ± 0.005 mm.

Results

Magnetic field was measured for all the assembled magnets under the maximum pulsed excitation.[2] The magnetic center and the harmonic field contents of each magnet were measured by a search coil under dc excitation.[3] For some magnets sampled, the harmonic field contents were measured at actual pulsed operation in order to check the result obtained at dc excitation. The field gradient as high as 11 kG/cm was obtained for the quadrupole magnet of 25 mm thickness and 12 kG/cm for 35 mm thickness. The deviations of the magnetic centers from the bore centers were within 0.02 mm for all the 90 magnets. The harmonic content, in terms of the ratio of the n-th harmonic component to the main quadrupole component at the pole tip radius, was typically 3.5 % for n=6, 0.4 % for n=4 and less than 0.1 % for the other non-linear components.

A cooling channel was attached to the outer periphery of Al-rings. The complete magnets were mounted into the drift tube shells, then the shells were seamed by electron beam welding. Epoxy resin containing filler was vacuum impregnated inside the drift tubes (Fig.13).

One of the 25 mm quadrupole magnet mounted in the drift tube #2 was excited by d.c. currents of 135A for 8hrs. The dissipated power corresponds to the sum of the ohmic losses and the eddy current losses at a pulsed operation of 900A with 20 pps repetition. The temperature rises of the drift tube surface and the coil were measured flowing the cooling water (25°C, 3 ℓ/min). The maximum temperature rise at the surface of the drift tube was 22°C and that of the coil was 33°C.

Acknowledgments

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Reference

(1) M. Kobayashi, J. Tanaka and S. Yamashita: "Quality control for Stacking and Assembling Drift tube Quadrupole Magnets" (KEK-72-3 NLHEP, 1972).

(2) M. Kobayashi and S. Yamashita: "Precise Measurements of Peak Fields of Pulsed Quadrupole Magnets" Nucl. Instr. Meth. 101 (1972) 187.

(3) M. Kobayashi, J. Tanaka, H. Baba and S. Yamashita: "Precise Center Setting Device for Quadrupole Magnets" Japan. J. appl. Phys. 10 (1971) 1195.

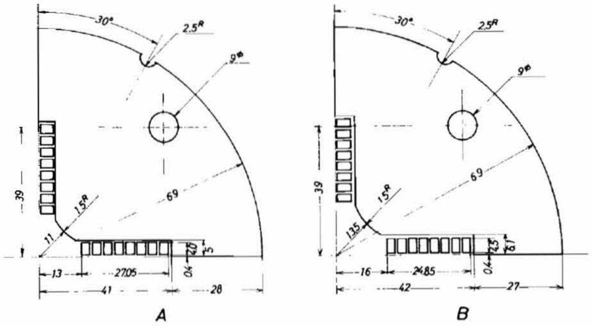

Fig.1 Profiles of punched core leaves.

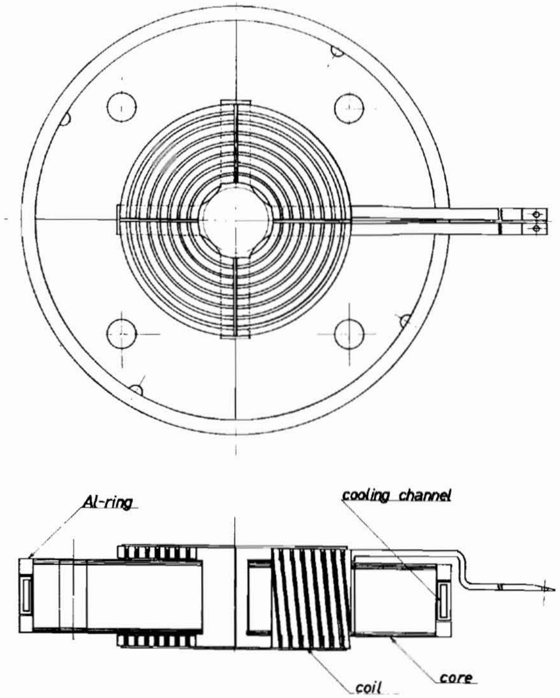

Fig.2 Structure of a quadrupole magnet.

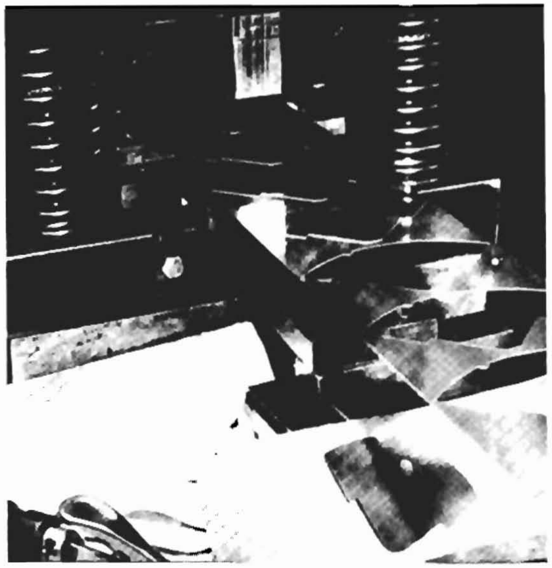

Fig.3 Punching of core leaves.

Fig.4 a,b Stacking of quadrant leaves and the jigs.

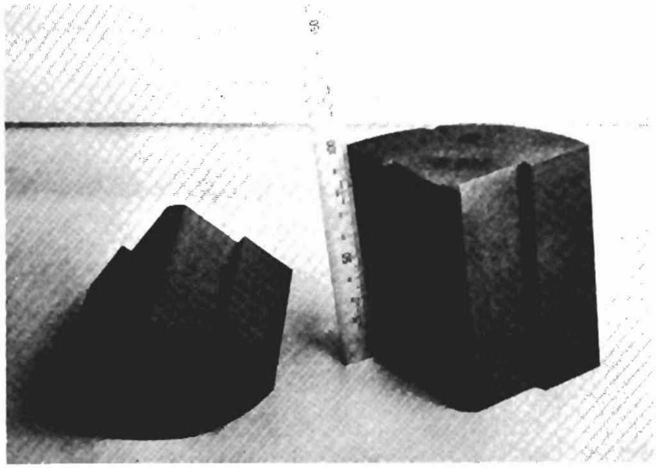

Fig.5 Quadrant core blocks.

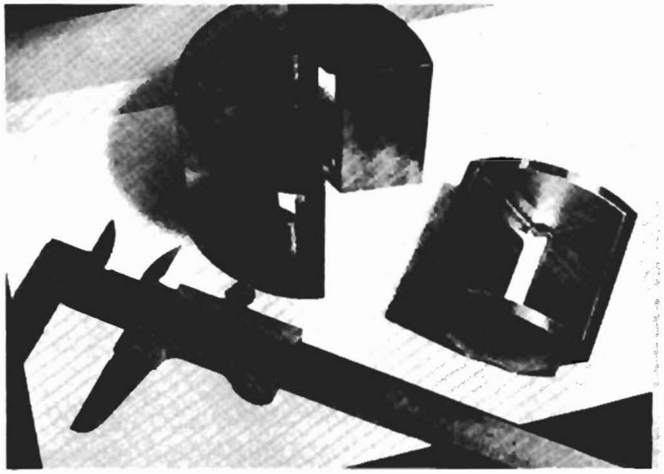

Fig.6 Quadrant coil blocks with the radial hole.

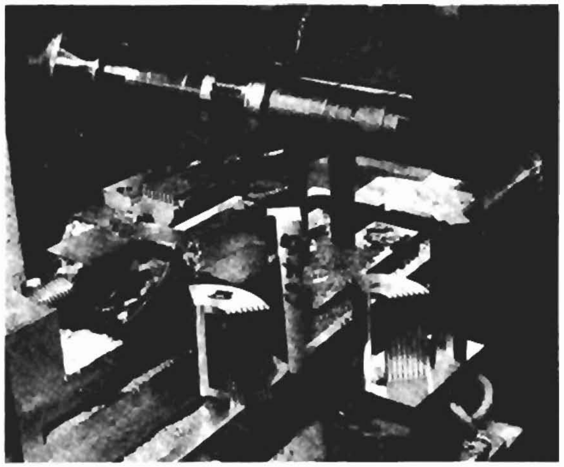

Fig.7 Cutting of the parallel grooves by a milling machine.

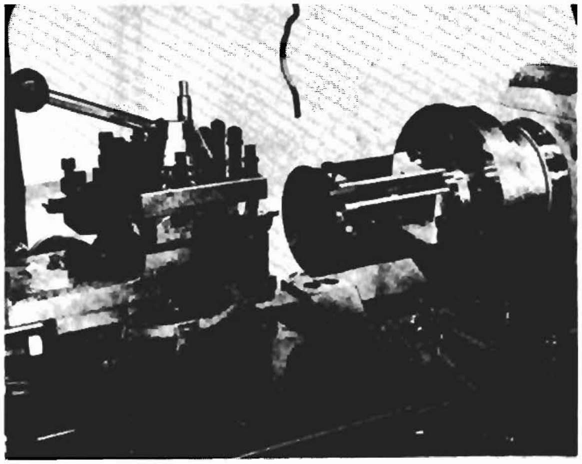

Fig.8 Cutting of the azimuthal grooves by a lathe.

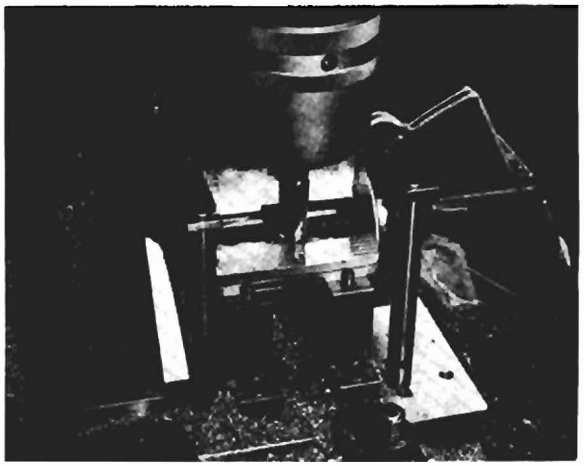

Fig.9 Final machining of assembled coil.

Fig.10 Completed coils.

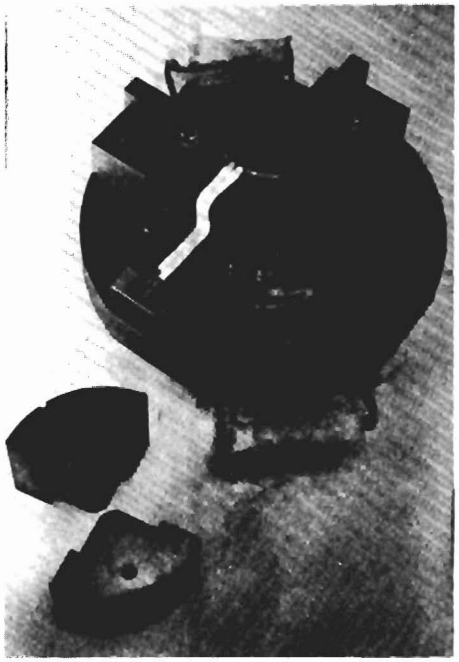

Fig.11 Assembling of the cores and coil on a jig.

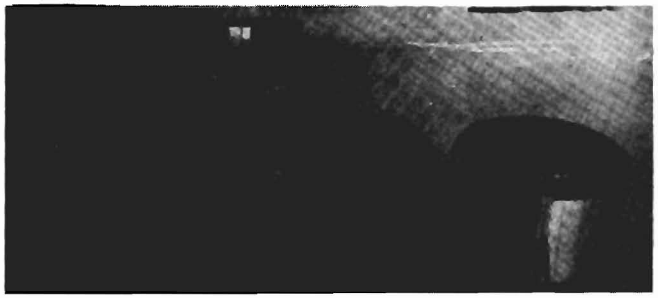

Fig.12 Completed magnet and the components.

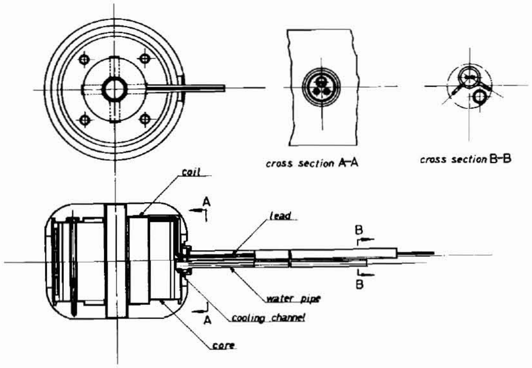

Fig.13 Structure of a drift tube.