PERMANENT QUADRUPOLE MAGNETS FOR DRIFT TUBES OF 20 ∿ 40 MeV LINAC

Eiichi TAKASAKI, Sadayoshi FUKUMOTO, Takao KATO and Tateru TAKENAKA
National Laboratory for High Energy Physics
Oho-machi, Tsukuba-gun, Ibaraki-ken, 305, Japan

Shinji MACHIDA
Department of Physics, The University of Tokyo
Hongo, Bunkyo-ku, Tokyo, 113, Japan

ABSTRACT

The permanent quadrupole magnets were designed with bore radius of 17.0 mm, core length of 160 mm and the maximum field gradient of 25 T/m. These magnets were fabricated with ALNICO-9 magnets, with poletips and with yorks made of the soft iron. The field measurements were done with the rotating coils. Some results of permanent quadrupole magnets are presented.

INTRODUCTION

At KEK, the second linac tank has been designed and negative hydrogen ions are to be accelerated from 20 MeV to 40 MeV[1]. It was decided that permanent quadru- pole magnets are installed in its drift tubes.

Permanent magnets possess both advantages and disadvantages. The main disadvantage is how to get the same operating points on the demagnetization curves in order to reduce the dipole component. Usually, variation of the magnetic characteristics of ALNICO-magnets would be ± 5 %. It is very difficult problem. However, the permanent magnets require no sophisticated pulsed power supplies and simplify operation and maintenance of the linac. We selected ALNICO-9 as a material of a permanent magnet.

ALNICO-9 quadrupole magnets have the windings for magnetization and yield the necessary field gradient of 20 ∿ 21 T/m. With these windings,the field gradient is variable in some region after installation into the tank. After demagnetization, electron beam welding can be applied to fabrication of drift tubes without the special caution.

In this article, the results of field measurements on ten ALNICO-9 quadrupole magnets are given.

CHARACTERISTICS OF PERMANENT QUADRUPOLE MAGNETS

The main parameters of the permanent quadrupole magnets are given in Table I. The maximum field gradient is about 25 T/m. The core length is 160 mm. The effective length of 175 mm would be obtained with this core length.

The cross-sectional view is shown in Fig. 1. The material of a permanent magnet is ALNICO-9. The magnet size seen in Fig. 1 was chosen with the following method.

The important parameter of a quadrupole magnet is the leakage coefficient, which is defined with the useful part of the full magnetic flux generated by a permanent magnet. The useful part means the field within R_B at the median plane in the quadrupole magnet. Therefore, the leakage coefficient is

$$\alpha = \frac{B_m w_m}{G R_B^2} .$$

On the other hand, the magnetic field strength along the magnetic flux is connected with the field gradient by the equation

$$H_m \ell_m = \frac{G R_B^2}{2\mu_0}$$

where H_m and B_m are the magnetomotive force and the magnetic flux in the operating point on the demagnetization curve, respectively. ℓ_m and w_m are length and width of a permanent magnet bar. G is the field gradient and R_B is a bore radius. Usually, the operating point must be chosen near the region corresponding to the maximum density of the magnetic energy. From our experiments with the model quadrupole magnet, the leakage coefficient α of about 5 was observed.

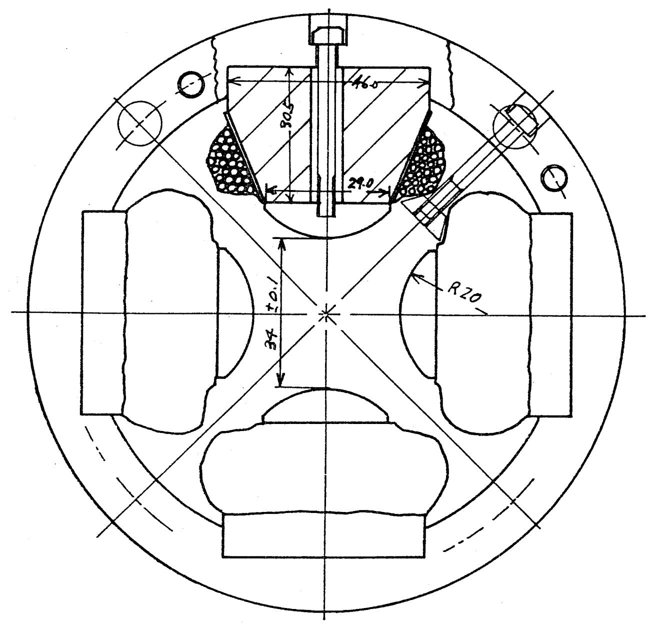


Fig. 1 Cross-sectional view of the permanent quadrupole magnet.

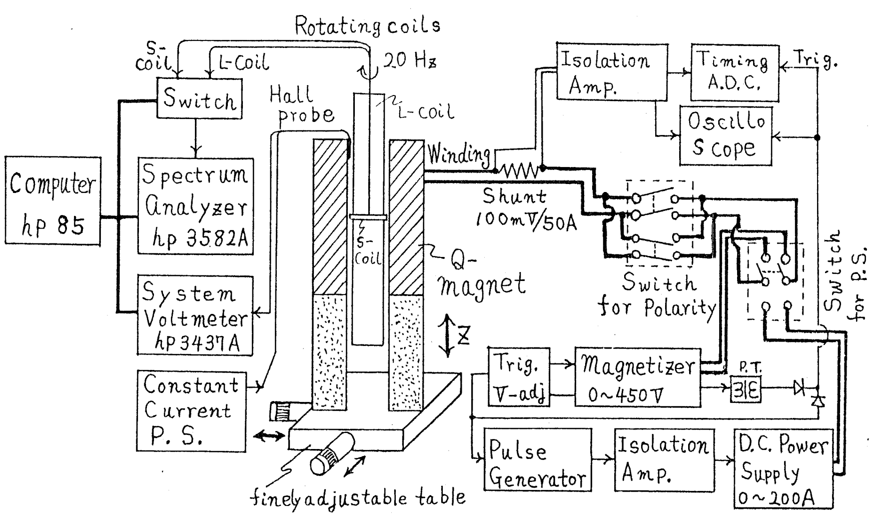


Fig. 2 Block diagram for magnetic field measurements and mag./demag. system.

Table I

Parameters of the permanent quadrupole magnet

bore radius	$17.0 \begin{smallmatrix} +0.1 \\ -0 \end{smallmatrix}$ mm
outer diameter	$135 \begin{smallmatrix} +0.0 \\ -0.02 \end{smallmatrix}$ ϕ
core length	$160 \begin{smallmatrix} +0.1 \\ -0.0 \end{smallmatrix}$
poletip radius	20.0 ± 0.05
full size of magnet	< 190
maximum field gradient	25 T/m
material of permanent magnet	ALNICO-9
material of poletip and york	soft iron
coil for magnetization	25 turns/pole

Considering the required maximum field gradient of 25 T/m and an area occupied with coils, which were used for fully magnetizing the permanent magnet, the size parameters of ℓ_m and w_m were chosen as seen in Fig. 1. The coil was impregnated and welded to the permanent magnet with epoxy resin.

Circular approximation was used for machining poletips. Usually, this has a pole-radii (R_p) to bore-radii ratio of R_p/R_B = 1.15 for the ideal hyperbolic poletip. However, R_p/R_B = 1.18 for our permanent quadrupole magnet was selected to decrease the 12-th component without changing the other higher components.

Variation of the total magnetic flux among 4-permanent magnets (ALNICO-9) was selected to be within 1 %.

FIELD MEASUREMENT AND MAGNETIZATION-DEMAGNETIZATION

Figure 2 shows the block diagram for magnetic field measurements and magnetizing/demagnetizing system. Hall probe seen in Fig. 2 was used for checking the polarity of the quadrupole magnet.

The magnetic field was measured with the rotating coils[2] driven by 20 Hz, which was chosen for separation of the net field from the external fields (mainly 50 Hz field). The long coil for measurement of the integrated field strength and the small coil for the magnetic field strength at the center of a magnet were prepared. The long coil has 260 mm in length, 22 turns and 24.02 mm in width. The small coil has 10.0 mm in length, 2 turns and 26.29 mm in width. The distance between the rotating axis and the geometrical axis of the search coils are 0.85 mm for the long coil and 0.47 mm for the small coil.

The data were calculated from the coil size to the bore radius by the equation

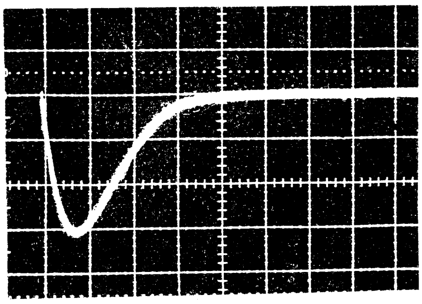
$$\left(\frac{B_n}{B_2}\right)_{\text{at } R_B} = \frac{\varepsilon_n}{\varepsilon_2} \times \frac{X^2 - (-1)^2 X'^2}{X^n - (-1)^n X'^n} \times R_B^{n-2}$$

where ε_2 and ε_n are the voltages of the quadrupole component and the selected harmonic component, respectively. X and X' are distances between the rotating axis and the search coil. For example; X = 12.86 mm and X' = 11.16 mm for the long coil, X = 13.61 mm and X' = 12.68 mm for the small coil.

The permanent quadrupole magnet was mounted on the table with the finely adjustable stage. The reproducibility in this adjusting mechanism was within ± 3 µm.

Full magnetization; this was done by flowing the current with the pulsed power supply (magnetizer seen in Fig. 2). The typical current pattern is shown in Fig. 3. Excitation curves are shown in Fig. 4. As seen in Fig. 4, the excited field gradients are dependent upon the initial state of the permanent magnet. Above 500 A, the saturation effect is seen. Therefore, for fully magnetizing the permanent magnet, the pulse currents of 750 A flowed two ∿ four times. The field gradient of 25.3 T/m was obtained.

Reduction of magnetization; this was done with D.C. power supply. This power supply produced the long pulse current pattern with 1 sec in width, 100 msec in the rising time and 800 msec in the falling time. The effects of the magnetic viscosity were not observed. The field gradient vs. a reduction current is shown in Fig. 5. Reproducibility of the field gradient at the same reduction current was within 0.3 %.



V; 240A/Div.
H; 5msec/Div.

Fig. 3 Current pattern for magnetization.

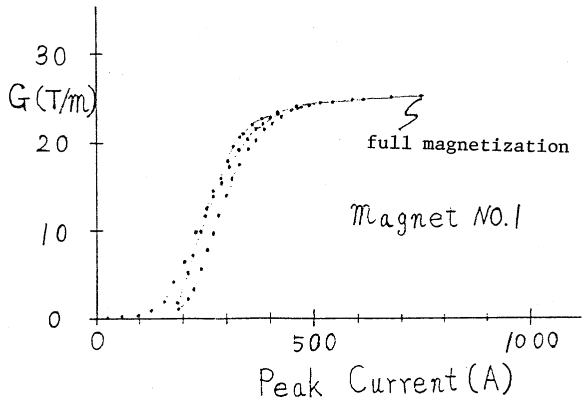


Fig. 4 Excitation curves for magnetizing the Q - magnet NO. 1.

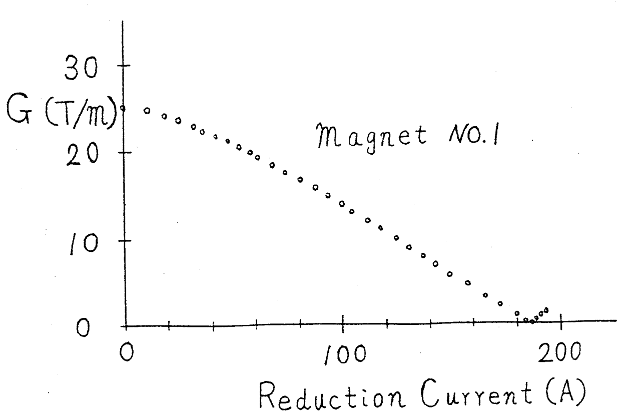


Fig. 5 Field gradient at the center vs. reduction of magnetization. D.C. power supply was used.

Demagnetization; this was very troublesome steps because of the effect of a saturation of the soft iron and demangetization of the ALNICO-9. In order to weld drift tubes by the electron beam, the no residual magnetic field is desired. The following process was taken for demagnetization. After full magnetization, the opposite current alternately flowed decreasing the current amplitude and then the field strength was monitored with the rotating coil. After demagnetization, the dipole component at the center of magnet was below 0.2 Gauß and the integrated dipole component was below 6 Gauß·cm.

THE RESULTS AND CONCLUSION

The field distribution along the longitudinal axis (Z-axis) was measured with the small coil. The 12-th component is shown in Fig. 6. The effective length of 175 mm was estimated.

The discrepancy between the dipole minimum and the mechanical center of the permanent quadrupole magnet was measured with the reduction of magnetization. The results are shown in Fig. 7. As seen in Fig. 7, this discrepancy is dependent upon the field gradient. This is due to the different operating points of 4-permanent magnets.

In Fig. 8, variation of this discrepancy at about 20 T/m between 10 permanent quadrupole magnets is shown. Maximum discrepancy is about 0.07 mm. If the displacements of the quadrupole magnets have the random sign and be 0.07 mm, the increase ΔX_{rms} of the amplitude of transverse oscillation would be about 1.6 mm. Tolerances of the drift tubes alignment, which were determined mainly from technical problems, would be 0.1 mm[3]. Therefore, the final ΔX_{rms} would be as large as 2.9 mm.

In Table II, comparison of higher components between the permanent quadrupole magnet and the conventional quadrupole magnet used in 20 MeV Proton Linac are given. Table II shows the permanent quadrupole magnets have the small multipole components. In particular, the 12-th component, which can be caused by mechanical perturbation, is smaller than that in the conventional magnet.

Table II

Comparison of the multipole components (B_n/B_2) at R_B

	Conventional quadrupole	Permanent quadrupole
n = 1	0.22 (%)	0.18 (%)
n = 2	100.	100.
n = 3	0.09	0.06
n = 4	0.72	0.35
n = 5	0.10	0.01
n = 6	4.60	0.09
Bore radius	11.0 mm	17.0 mm
field gradient	44 T/m	20.8 T/m

ACKNOWLEDGMENTS

The authors would like to express their gratitude to SUMITOMO special metal Co., LTD. for fabrication of the quadrupole magnets.

REFERENCES

1) S. Fukumoto et al., "Linac Upgrading and P to H$^-$ Conversion", Proc. 1984 Linear Accelerator Conf., Darmstadt, 1984.
2) M. Kobayashi et al., Japan J. Appl. Phys. 10 (1971) 1195.
3) M. Kobayashi, KEK-73-4.

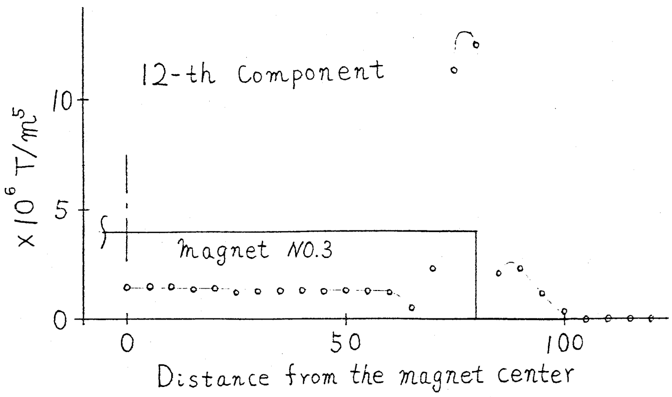


Fig. 6 12 - th component of Q - magnet NO.3.

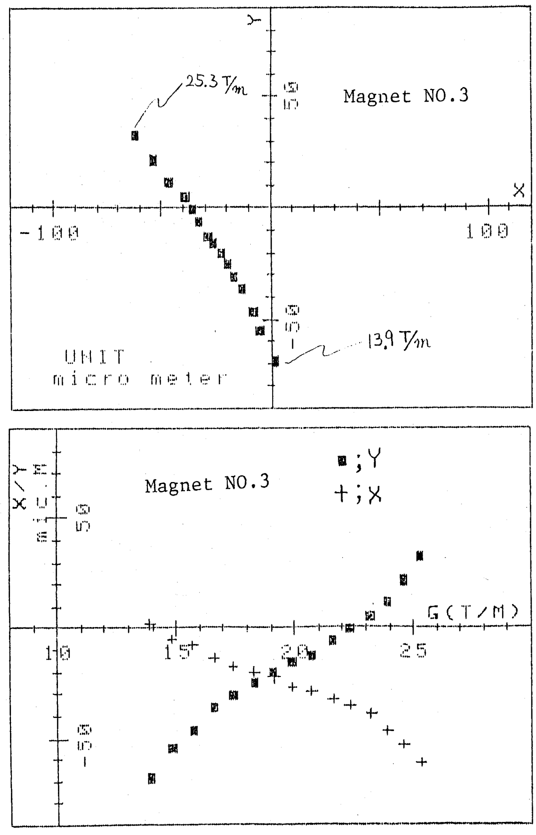


Fig. 7 Discrepancy between the dipole minimum and the geometrical axis of Q - magnet NO.3.

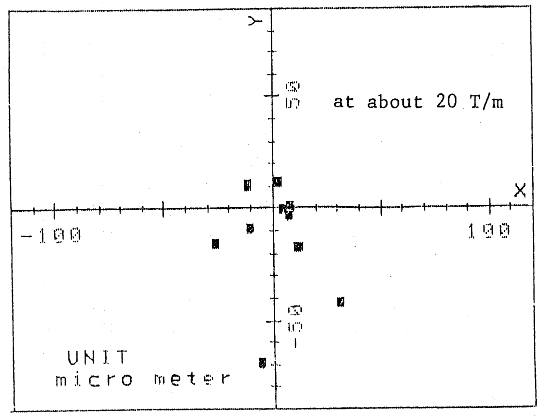


Fig. 8 Variation of discrepancy among 10 permanent Q - magnets.