MAGNETIC FIELD MEASUREMENT OF HIGH GRADIENT $SmCo_5$ PERMANENT QUADRUPOLE MAGNETS

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ABSTRACT

Three different types of high gradient $SmCo_5$ permanent quadrupole model magnets were constructed and tested for the focusing system of the injector linac of the GEMINI synchrotron. The results of the field quality of the magnets and the method are presented. The attainted maximum field gradient was 16 kG/cm and the pole tip field was 12 kG, which is the world highest field strength in the permanent magnet. The adjustment of the field strength was demonstrated to be possible by a mechanical rotation without introducing an appreciable distortion in harmonics.

INTRODUCTION

Recent investigations of a small drift tube linear accelerator precipitated renewed interest in permanent quadrupole magnets. Among others, samarium cobalt is one of the most promising material as a permanent magnet. In addition, a field strengths of anisotropicaly magnetized magnet is reinvestigated and fabricated by K. Halbach[1,2,3,6,7] in LBL and by N.V. Lazarev[4] in ITEP. In these schemes anisotropicaly magnetized sectors are positoned along a circumference so that quadrupole field, or any other multipole, is generated at the central bore. The surprising fact of this scheme is that the maximum field strength is able to be reached higher than the remanent field B_r of the material of the magnet itself. Actually, this fact dates back to the discovery by Blewett in 1965[11]. Theoretical limit for the maximum field for the ideal material may reach 4 times field strength of the remanent field of the material.

After Halbach, we have constructed the segment type quadrupole magnet, which we call Mark II. In addition to the segment type magnet, a conventional iron pole tip magnet[6] where exciting coil is replaced by the samarium cobalt called Mark III is fabricated and tested. Further increase of the field strength was intended and realized by replacing the bottom part of the iron pole with samarium cobalt, which we call Mark I. Three model magnets are shown in Fig. 1. The attained field strength and the field gradient of the Mark I was 7.7 kG and 12.8 kG/cm, which is slightly higher than that in circular pole[16] permanent magnet at Los Alamos, where the material of the pole is a samarium cobalt and the maximum field strength and the gradient 6.6 kG and 11.1 kG/cm or circular rod type anisotropically oriented magnet with 7.13 kG and 6.2 kG/cm at ITEP.

The field strength and the field quality were measured with a very small Hall probe and harmonic coils. The driving system of the rotatin of the coil is provided by Linac group[18], which is the modified version of that of Kobayashi[10]. The calibration of the Hall proble was performed with NMR in the standard dipole permanent magnet.

REQUIRED FIELD GRADIENT

The design goal of the strength of the field gradient was given by a technical limit of the state of the art of the permanent magnet rather than by an optimum value. The maximum field gradient of g = 15 kG/cm was chosen rather emperically as a design goal. The relation between the field gradient and the acceptance was calculated[17] numerically by the computor code. According to this calculation the normalized acceptance of the Linac is 5.75 π mm mrad which is 65 % of the maximum acceptance.

Now it would be much convenient if one can obtain an analytical expression of the required field gradient and the acceptance rather than some of the results by the numerical method. It turns out that this is possible if one emploies a thin lens approximation. Let a phase advance of a FODO lattice be μ, a ratio of the quadrupole magnetic length to the cell length L be F, Courant Snyder envelope function $\bar{\beta}$, relativistic parameters be β and γ, an aperture of the drift tube be a, velocity of light be c, RF frequency be f and rest mass energy of the proton be E_0 (in GeV), and assume the cell length L is twice the RF wavelength λ, then one can obtain the field gradient g and the normalized acceptance A_n as follows,

$$g(T/m) = \frac{E_0 \sin\frac{\mu}{2}}{0.15\ F} \left(\frac{f}{c}\right)^2 \frac{\gamma}{\beta} \quad , \tag{1}$$

and

$$A_n \equiv \beta\gamma \frac{a^2}{\bar{\beta}_F} = \frac{\gamma\ a^2 \sin\frac{\mu}{2}}{2(1+\sin\frac{\mu}{2})} \frac{f}{c} \tag{2}$$

Putting μ = 90°, F = 0.67, f = 400 MHz, β = 0.046 (T = 1 MeV), γ = 1.00106, E_0 = 0.93826 GeV, a = 5 mm, one has,

$$g \simeq 247\ T/m \simeq 24.7\ kG/cm \quad \text{and} \quad A_n \simeq 8.7\ \pi\ mm\ mrad \quad ,$$

where the deviation from the numerical calculation is small. Note that the field gradient scales as square of the RF frequency f and scales as inverse of the relativistic β.

In Fig. 2, the required field gradient for a given kinetic energy where the phase advance is 90°, is plotted for two typical frequencies, 200 MHz and 400 MHz. It is seen that the minimum exists around the kinetic energy of 400 MeV. For a given phase advance the required field gradient is 4 times higher at 400 MHz than at 200 MHz. It should also be noted that as the aperture scales as the inverse of the RF frequency the required field strength which gives a technical upper limit scales as the RF frequency linarly;

$$B_{max} \simeq g \cdot a \propto \frac{\gamma}{\beta} f \quad .$$

Normalized acceptance scales as the inverse of the RF frequency f,

$$A_n \propto \frac{\gamma}{f} \quad .$$

MEASURING APPARATUS

The magnetic field strength was determined with the Hall probe (STE-0104 F.W. BELL Inc.) and the Gauss meter (Type 811 F.W. BELL Inc.). The size of the Hall probe was 0.38 mm in thickness and 2 mm in width and the active area is 0.8 mm^2. The calibration was checked with our permanent dipole magnet where the absolute field strength had beeen measured with NMR. A field homogeniety of 4 poles, axial field distribution and field leakage were measured with this probe.

A dipole component which results from various error sources and higher harmonic components were measured with a conventional harmonic coil. The fundamental component from the pick up coil was a quadrupole component rather than a dipole component[10,18] or higher multipoles[9,12,13,14] (higher than quadrupoles).

Two coils, short and long coil were fabricated. The inner and outer radius and the axial length of the short coil are, r_1 = 0.8 mm, r_2 = 3.7 mm, ℓ = 5.4 mm, respectively. The same parameter for the long coil are, r_1 = 0.8 mm, r_2 = 4.2 mm, ℓ = 60.4 mm.

Azimuthal component B_θ instead of a radial component B_r is picked up in this coil. The output voltage V of the harmonic coil is written as,

$$V = \int \dot{B}_\theta \, dA$$

$$= \omega N \ell \sum_{n=1} C_n \cos(n\theta + \alpha_n)(r_2^n - r_1^n) \qquad (3)$$

where ω is an angular frequency of a rotation, N is a number of turns of the harmonic coil, ℓ is the length of the coil and C_n is a coefficient of the harmonic component we want to determine. A phase difference α_n is not known in this system and a separtion between normal and skew components is not able to be done. A rotation frequency of the coil is 20 Hz and the induced voltage V given by eq. (3) is directly connected to a spectrum analyzer via sealed mercury rotatry connector (Mercotac inc.). The harmonic coil is driven by the driving system of the LINAC group10),18).

FIELD QUALITY

(i) Field strength

The attained field gradient were 12.8 kG/cm, 16.1 kG/cm, 7.6 kG/cm for Mark I, Mark II and Mark III respectively. The field gradient of 16.1 kG/cm gives the corresponding pole tip field of

$$B_{\text{pole tip}} \equiv g r_1 = 12 \text{ kG} \quad ,$$

which is the world highest field strength in the permanent magnet ever published. For Mark II, we have attained the pole tip field of 7.7 kG, whereas upto now iron pole magnet had been limited to about 6 kG3),5). The material of the Mark I is Hicorex-22A and that of Mark II and III are Hicorex-30. An effective length, an integrated field gradient, geometrical length are presented below. The effective length of Mark I and II are 26.3 mm and 22.4 mm respectively. It should be emphasized that the effective length of Mark I is longer than that of Mark II by 3.9 mm. In other words, the effective length of the segment type iron-less magnet is not long compared to that of the iron pole magnet. In the numerical calculation, we have assumed the effective length to be 24.3 mm. Thus the difference in the integrated field gradient is only 4 % between Mark I and Mark II. Axial distribution of the gradient is shown in Fig. 4.

	g_0	ℓ_G	$\int g(s)ds$	material	ℓ_{G0}	B_{pole}
Mark I	12.8 kG/cm	22.26 mm	33.72 kG	H-22A	20 mm	7.7 kG
II	16.1	22.38	34.75 ∿ 36.0	H-30	20	12.1
III	7.6	24.71	16.9 ∿ 18.73	H-30	18	4.55

(ii) Off center

The difference between the beam center and magnetical-center results in the momentum kick of the beam. Thus some amount of residual random momentum kicks from 233 units of quadrupoles may not be avoidable. It could shown quantitatively to estimate the reduction of the acceptance either by a computer simulation or by an analytical closed form.

Observation of the off center may be performed by watching a ratio of the dipole component to the quadrupole component. The observed quantities from the long harmonic coil are 0.4 %, 1.3 %, 0.8 % for Mark I, II and III respectively. These quantities corresponds to the off center between the harmonic coil and the magnetic center of 17 μm, 55 μm, 34 μm for Mark I, II and III. The sign and the phase of these quantities are not known at the present system.

(iii) Higher harmonic

In a quadrupole magnet families of 4 m (m = 1,2,3 ....) poles are allowed to exist intrinsically. Families of 2(2m-1) poles are generated by asymmetric errors. In the following, we present only the deviations of dominant allowed terms of the integrated terms and others are shown in Fig. 5.

	8 pole	12 pole	16 pole
Mark I	0.8 %	4.7 %	1.3 %
II	0.8	1.7	0.1
III	1.5	2.1	0.5

The deviations shown are normalized by the quadrupole component at $r = r_2$ and has a dimensionless unit. Again the phase and the sign of these deviations are not known. There is a possibility that some terms may cancel with other terms. The pole shape of Mark III is hyperbolic whereas that of Mark I not. Mark I has the richest harmonics and Mark II has the modest harmonics.

In any case except at the central field of Mark II, 12 pole component is the highest one.

(iv) Adjustment of the strength of the field gradient

Adjustment of the strength of the field gradient with mechanical rotation8) proposed by K. Halbach was shown to work without appreciablly deteriorating the harmonic components. This test was performed by adding a quadrupole ring to Mark III. The magnet size in the ring was modest. The direction of the orientation was azimuthal and not like radial8) like the one by Halbach. Adjustment of the strength of ± 10 % was observed as shown in Fig. 6.

DISCUSSION

In spite of the highest gradient segment type Mark II magnet, there is a discrepancy between the observed and the predicted value by about 3 kG. This may be due to the nonlinear B-H characteristic of H-30 material, but further investigation is necessary. For much higher field gradient, the reduction of the inner radius r_1 from 7.5 mm to 6 mm and a new material such as NbFe might push up the pole tip field and the field gradient to 16 kG and 26.8 kG/cm.

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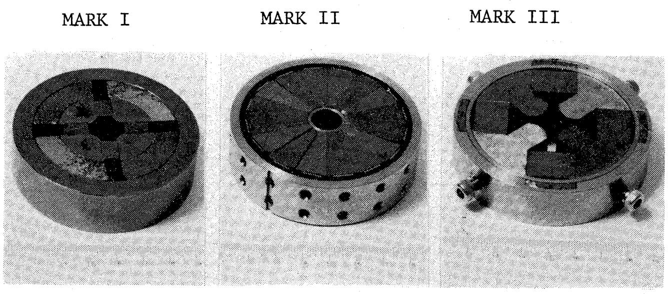

Fig. 1 Three types of Model quadrupole magnets, Mark I, Mark II, and Mark III.

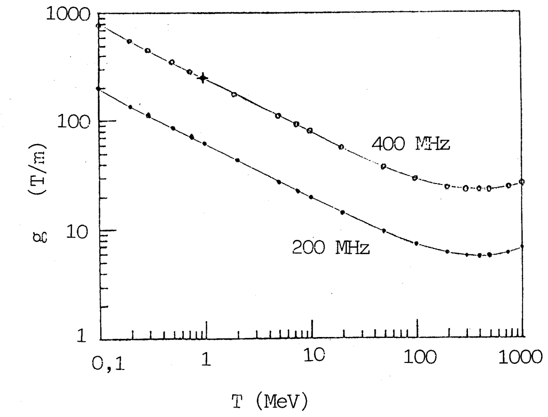

Fig. 2 Required field gradient vs injection kinetic energy with RF frequency of 200 MHz and 400 MHz. Phase advance is 90°

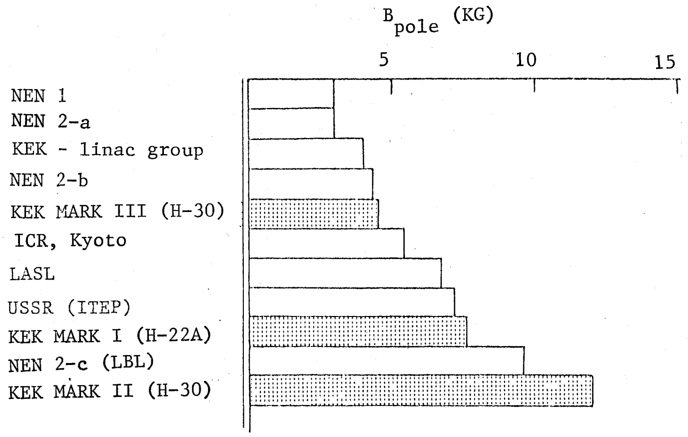

Fig. 3 Maximum field strength B_{pole} at various laboratories.

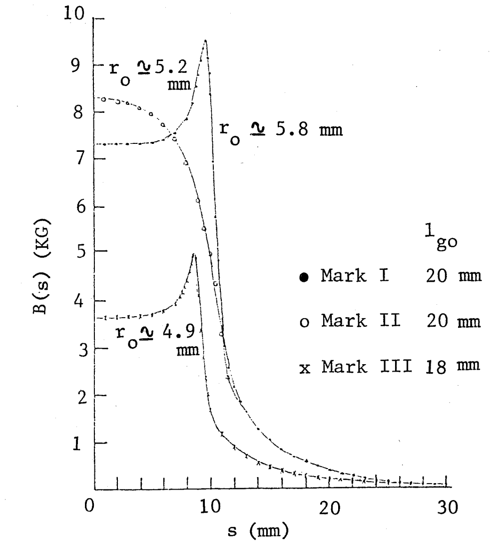

Fig. 4 Axial field distribution at $r=r_o$

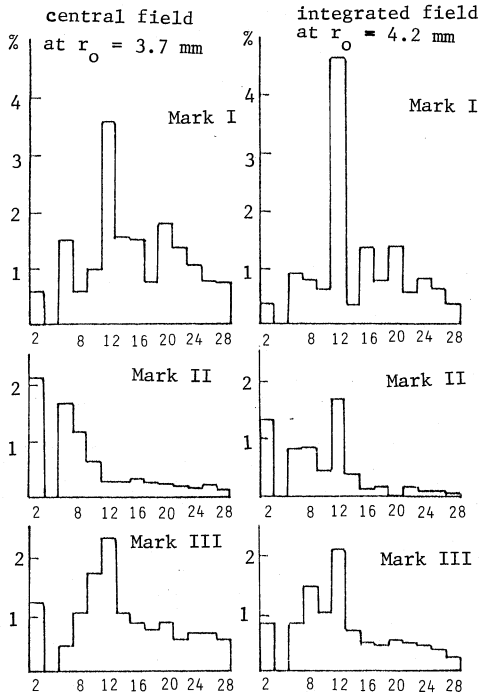

Fig. 5 Deviation of harmonic components normalized by quadrupole component.

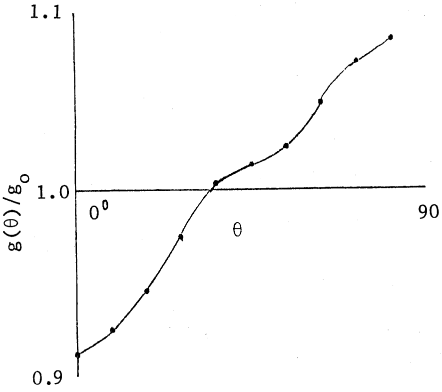

Fig. 6 Adjustnent of the strength of the field gradient.