# PERMANENT QUADRUPOLE MAGNETS*

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## Summary

A family of quadrupole magnets using a soft iron return yoke and circular cross-section permanent magnet poles were fabricated to investigate the feasibility for use in ion or electron beam focusing applications in accelerators and transport lines. Magnetic field measurements yielded promising results. In fixed-field applications, permanent magnets with sufficient gradients would be a low cost substitute for conventional electromagnets, eliminating the need for power supplies, associated wiring, and cooling.

## Introduction

Quadrupole magnets have become the standard in the area of focusing devices since their invention.[1] The theoretically ideal pole tip has a hyperbolic cross section (Fig. 1); however, conventional quadrupole magnets driven electrically have truncated poles (Fig. 2) to provide coil space, compromising the field quality. Naturally, electromagnets require power supplies, controls, interlocks, bus bars and a wiring system. Cooling is required in the higher powered magnets with the associated pumps, plumbing and water treatment. Hollow magnet conductor with an adequate passage for cooling has a relatively large cross section requiring higher current, larger bus and more massive power supplies.

Permanent magnets are typically fixed field devices and do have magnetic field gradient limitations. Periodically, permanent magnets have been reinvestigated [2] (Fig. 3), and in some cases have actually been placed in service [3] (Fig. 4).

Two major limitations of permanent magnets in the past have been their relatively low magnetic gradients and the reluctance on the part of designers to give up the variable field capabilities of electromagnets.

Linear accelerator design capabilities have progressed to the point that the required quadrupole gradients can be determined with sufficient accuracy that fixed field focusing magnets can be used.

Recent investigations of a small drift-tube linear accelerator precipitated renewed interest in permanent quadrupole magnets. With the small size required, permanent quadrupole magnets appear to offer a low cost, simple solution that would be expensive and difficult to execute using conventional electromagnet techniques.

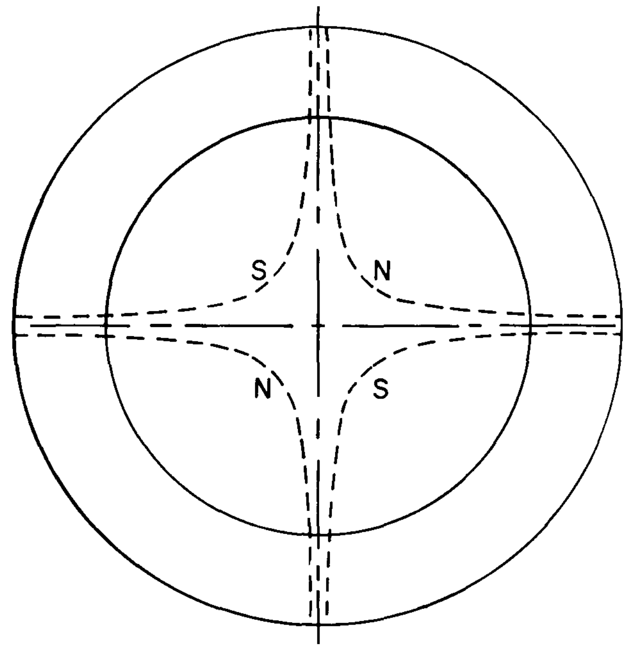


Fig. 1. Ideal Quadrupole Magnet

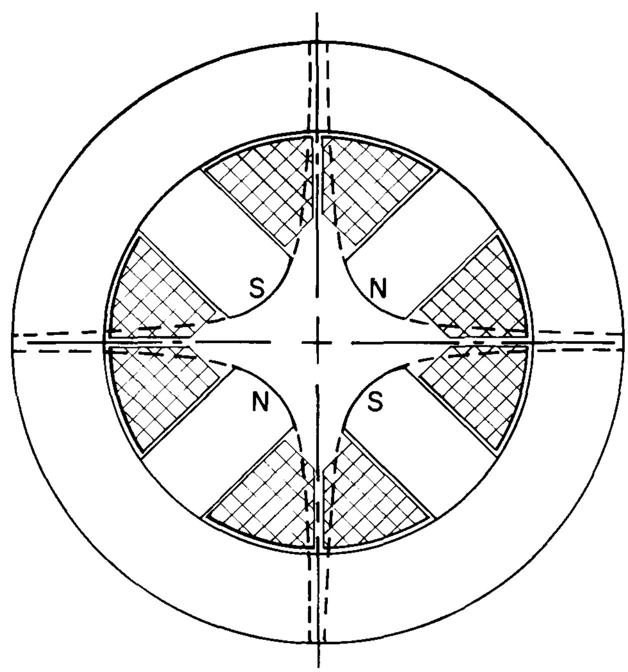


Fig. 2. Conventional Quadrupole Magnet

*Work performed under the auspices of the Energy Research and Development Administration.

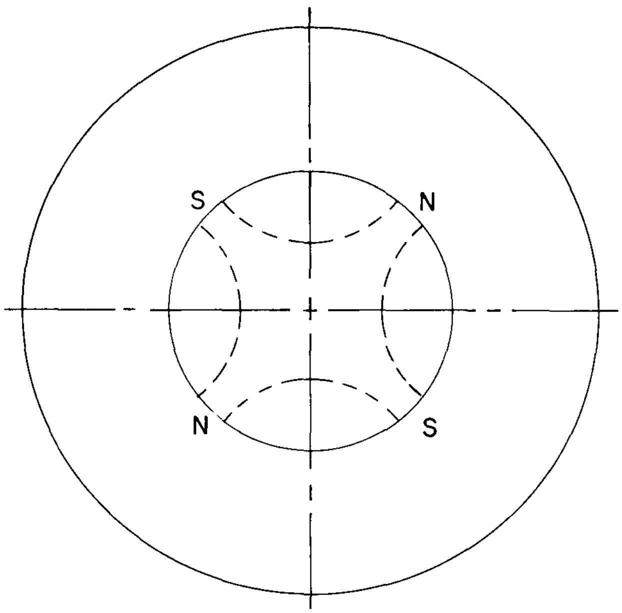


Fig. 3. Cylindrical Permanent Quadrupole Magnet

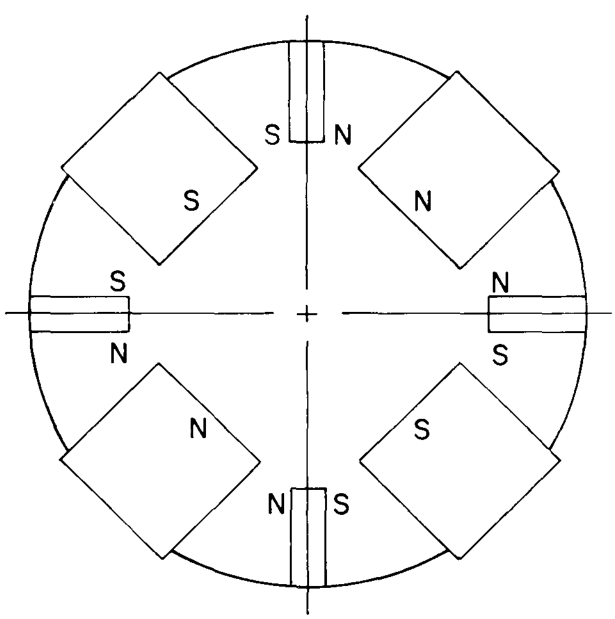


Fig. 4. Rectangular Pole Permanent Quadrupole Magnet

## Permanent Quadrupole Magnet Models

Our first magnet was fabricated with four pre-charged alnico-V magnets with truncated poles and a circular pole tip cross section. A soft iron yoke served to complete the magnetic circuit (Figs. 5 and 6). This configuration was dictated by the availability of suitable magnet material. Magnetic field measurements performed on this magnet indicated further studies were in order.

The second generation model was further simplified by using an array of four magnets of circular cross section and magnetized across the diameter. Again, a soft iron yoke was used to provide the magnetic return path (Fig. 7). For years, the ideal hyperbolic pole shape has been approximated by using a circular cross section introducing less aberration than that caused by the truncation required to provide coil space in conventional magnets.[4]

Oriented alnico-V and barium ferrite Grade 5 ceramic magnets, fabricated, charged and stabilized in the open circuit condition by the vendor, were utilized in the studies described.

Circular approximations of the ideal hyperbola have a pole-radii to bore-radii ratio of:

$$R_P/R_B = 1.15$$

The yoke assembly consists of a soft iron outer ring and an interference fit insert of nonmagnetic stainless steel. A family of yoke assemblies, (Fig. 8) with $R_P/R_B$ ratios of 1.00, 1.15, 1.30 and 1.45 were fabricated to experimentally determine the effect of the ratio because the effective pole edge of a permanent magnet is not necessarily at the physical edge.[2]

## Magnetic Field Measurement Instrumentation

Axial and transverse magnetic field surveys were performed with a Bell Model 240 Hall-type gaussmeter. The probe was positioned and scanned by three mutually perpendicular slides mounted on a black granite surface plate (Fig. 9). The field and displacement were plotted by a Hewlett-Packard X-Y recorder.

Harmonic measurements[4] were made with a single-turn coil, driven by a 60-rps, 1/20 horsepower hystersis synchronous Bodine motor (Fig. 10). One leg of the coil sweeps near the poles and the other leg is positioned on axis by minimizing the subharmonic voltage output to locate the magnetic center. A Hewlett-Packard Model 302 wave analyzer was used to select the harmonic number of interest and display it on a Hewlett-Packard Model 1200-A, dual trace oscilloscope.

## Harmonic Measurements

The raw data are recorded for each harmonic n = 1 through n = 8 (n = 2 being the quadrupole

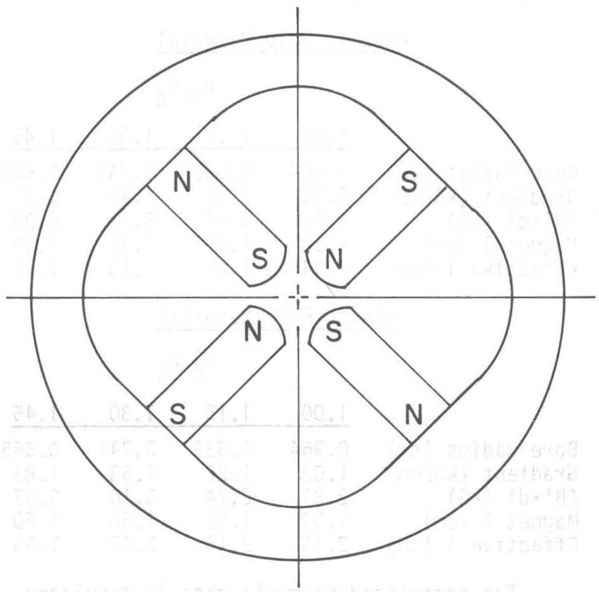


Fig. 5. Circular Truncated Pole
Permanent Quadrupole Magnet

Fig. 6. Circular Truncated Pole
Permanent Quadrupole Magnet

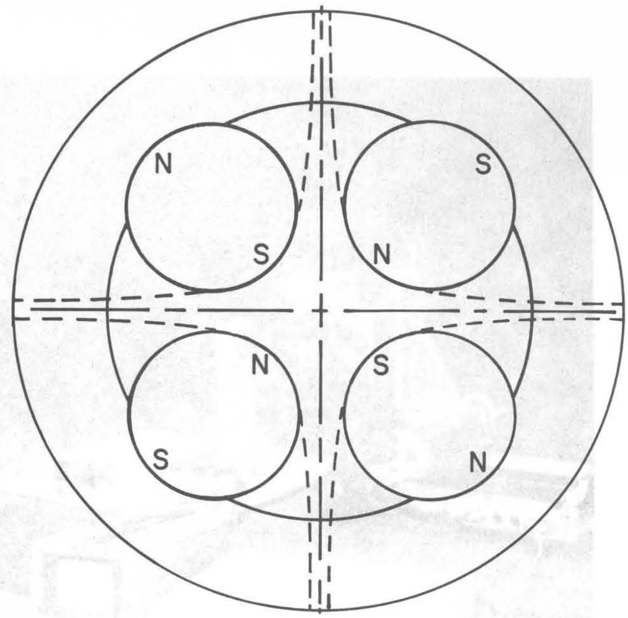


Fig. 7. Circular Pole Permanent Quadrupole Magnet

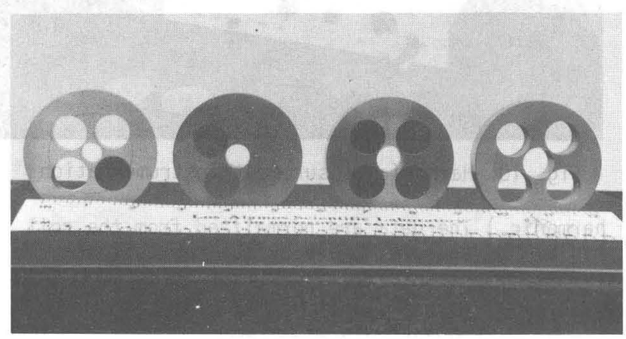

Fig. 8. Circular Pole Permanent
Quadrupole Magnet Models

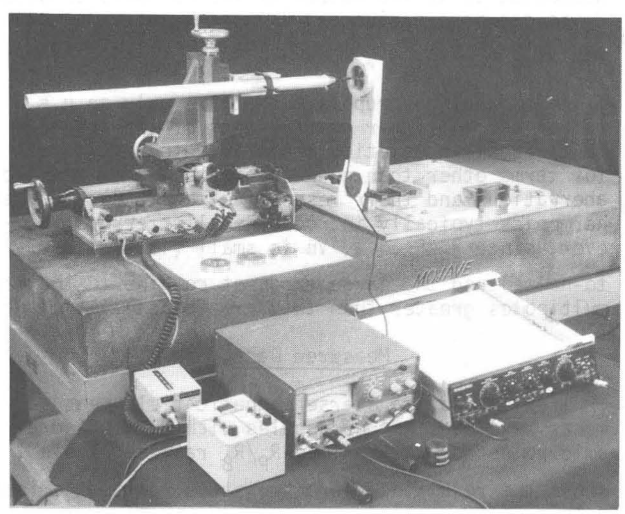

Fig. 9. Magnetic Field Measurement Instrumentation

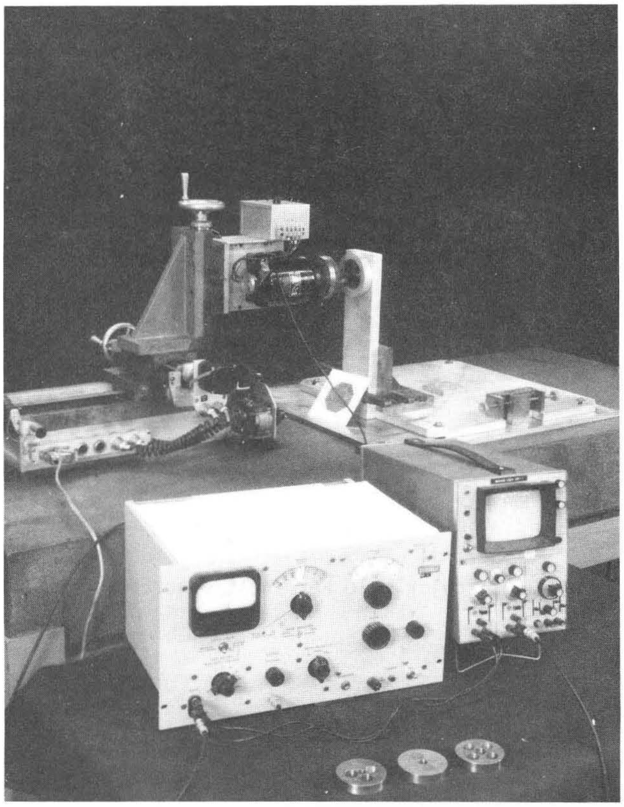

Fig. 10. Harmonic Measurement Instrumentation

harmonic.) The data are normalized from the coil radius to the bore radius by the expression

$$\% \text{ Quadrupole} = \frac{Vn}{V2}\left(\frac{R_B}{R_C}\right)^{n-2}$$

where V2 is the voltage output of the quadrupole harmonic, Vn is the output of the harmonic selected, $R_B$ is the bore radius and $R_C$ is the rotating coil radius.

An ideal quadrupole magnet has only an n = 2 output and all other coefficients of the solution to the Laplace equation vanish. Output voltages for terms other than n = 2 indicate magnetic field aberrations and their respective magnitude. Higher harmonics typically introduce smaller errors; however, since $R_B/R_C > 1$, Vn is small (lower signal-to-noise) and the large exponent combine to indicate multipoles greater than they are in actuality.

## Measured Data

Axial and transverse magnetic-field measurements were made on quadrupoles with alnico and ceramic poles for the various $R_p/R_B$ ratios. Table I shows the resulting characteristics for the various magnet configurations.

TABLE I

PERMANENT QUADRUPOLE MAGNET CHARACTERISTICS

Ceramic Pole Material

| | $R_p/R_B$ 1.00 | 1.15 | 1.30 | 1.45 |
|---|---|---|---|---|
| Bore Radius (cm) | 0.964 | 0.838 | 0.741 | 0.665 |
| Gradient (kG/cm) | 1.95 | 2.45 | 2.95 | 3.51 |
| $\int B' \cdot dl$ (kG) | 3.78 | 4.44 | 5.12 | 6.05 |
| Magnet l (cm) | 1.50 | 1.50 | 1.50 | 1.50 |
| Effective l (cm) | 1.94 | 1.81 | 1.73 | 1.72 |

Alnico Pole Material

| | $R_p/R_B$ 1.00 | 1.15 | 1.30 | 1.45 |
|---|---|---|---|---|
| Bore Radius (cm) | 0.964 | 0.838 | 0.741 | 0.665 |
| Gradient (kG/cm) | 1.02 | 1.27 | 1.53 | 1.83 |
| $\int B' \cdot dl$ (kG) | 2.21 | 2.74 | 3.10 | 3.57 |
| Magnet l (cm) | 1.50 | 1.50 | 1.50 | 1.50 |
| Effective l (cm) | 2.16 | 2.16 | 2.03 | 1.95 |

The normalized harmonic data is tabulated (Table II) for multipoles through n = 8.

TABLE II

PERMANENT QUADRUPOLE MAGNET HARMONIC DATA

Ceramic Pole Material

| Harmonic No. n | $R_p/R_B$ 1.00 | 1.15 | 1.30 | 1.45 |
|---|---|---|---|---|
| 2 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| 3 | 0.0066 | 0.0029 | 0.0082 | 0.0049 |
| 4 | 0.0118 | 0.0106 | 0.0129 | 0.0103 |
| 5 | 0.0044 | 0.0024 | 0.0012 | 0.0028 |
| 6 | 0.1486 | 0.1133 | 0.0859 | 0.0651 |
| 7 | 0.0040 | 0.0026 | 0.0028 | 0.0015 |
| 8 | 0.0063 | 0.0042 | 0.0024 | 0.0014 |

Alnico Pole Material

| Harmonic No. n | $R_p/R_B$ 1.00 | 1.15 | 1.30 | 1.45 |
|---|---|---|---|---|
| 2 | 1.0000 | 1.0000 | 1.0000 | 1.000 |
| 3 | 0.0158 | 0.0198 | 0.0178 | 0.0185 |
| 4 | 0.0076 | 0.0119 | 0.0083 | 0.0066 |
| 5 | 0.0200 | 0.0158 | 0.0136 | 0.0130 |
| 6 | 0.1366 | 0.1031 | 0.0742 | 0.0534 |
| 7 | 0.0084 | 0.0048 | 0.0062 | 0.0049 |
| 8 | 0.0078 | 0.0072 | 0.0050 | 0.0047 |

It can be seen that several of the multipoles are rather large, although many of the multipoles are less than those in some conventional quadrupole magnets that are presently in service.

The dodecapole, n = 6, 12-pole harmonic is large and can be caused by mechanical perturbations; pole truncation and symmetrically radial displacement errors of all four poles. Circular approximation would introduce some apparent truncation, seen in Table II. The multipole n = 6 decreases as the ratio $R_p/R_B$ increases, indicating that the apparent pole edge is at a greater radius than the physical pole edge, a characteristic noted by Blewett.[2]

The data reported here represent the results of our first attempt at permanent quadrúpole magnet design. Higher gradients can be achieved by optimizing the magnetic circuit geometry, and lower harmonics can be accomplished by selecting the appropriate $R_p/R_B$ ratio and by modification of the pole sides.

## Permanent Magnet Characteristics[5,6]

Permanent magnets possess both advantages and disadvantages. The two magnet materials investigated were chosen primarily because of their low cost and ready availability. Alnico has a much higher residual field than barium ferrite ceramic but suffers a more rapidly diminishing field with increased air gap than the ceramic. Properly designed permanent magnet circuits (which might at first appear to border on the "black arts") have a geometry chosen to permit magnet operation near the maximum energy product for a particular material. Physical limitations may preclude optimum geometric design, in which case a permanent magnet material must be selected with a load slope characteristic approximating that required by the magnetic circuit geometry. Another solution is to further maximize the magnet mass for a given air gap. Applied to our magnets, it would consist of utilizing a permanent magnet yoke.

It is standard practice in the permanent magnet industry to use oriented (anisotropic) magnet material to maximize flux output in a particular plane. The material is then demagnetized for ease of fabrication. The completed assemblies are then charged and stabilized to the desired field. This technique eliminates the open-circuit condition of a charged magnet which causes "knockdown" or a reduction in the residual flux.

## Time Stability

A freshly charged permanent magnet does lose a certain amount of flux as a function of time. Barium ferrite ceramic loses essentially zero flux in 100,000 hours while alnico-V amounts to $\sim$ 1%. This loss can be essentially eliminated by partial demagnetizing (stabilizing) after charging in an amount of 7% to 15%.

## Temperature Stability

Barium ferrite ceramic suffers no irreversible field effect between 350°C and -60°C. However, it does have a negative 0.19% per °C field variation which is reversible. Alnico-V suffers an irreversible 1.3% field loss when exposed to a temperature of 350°C, then returned to room temperature, and a 2.5% loss when cycled to -60°C. Alnico-V has a reversible temperature coefficient $\sim$ 1/10 as great as ceramic magnets.

## Radiation Stability

Most alnico and ceramic magnets can withstand radiation intensities of $2 \times 10^{18}$ neutrons per $cm^2$ without flux changes and less than 10% flux loss when subjected to $3 \times 10^{19}$ neutrons per $cm^2$.

## Production Fabrication

Ideally, quadrupole magnets should be fabricated from oriented, uncharged magnet material. The magnet design should provide space for charging coils, and the charging system should incorporate a rotating coil. The completed magnet could then be charged and stabilized to the desired field as determined by the n = 2 voltage output from the rotating coil. While it is a fixed-field magnet after fabrication, charging capabilities would permit recharging to other field gradients within the limits of the magnet design.

## Conclusion

Based on these preliminary tests, it can be seen that permanent quadrupole magnets can offer a low cost, reliable solution in applications requiring small, fixed-field focusing devices for use in ion or electron-beam transport systems. Permanent magnets do require special considerations in design, fabrication, handling, and service that are different than encountered in conventional quadrupole magnets. If these basic conditions are satisfied, the resulting beam-focusing device would be stable, maintenance free, with virtually an indefinite lifetime.


## Acknowledgements

Several people contributed in the construction and testing of this series of magnet models. In particular, I am indebted to Donald A. Swenson for his ideas leading to the initial concept of utilizing the full circular pole cross section and to Edward J. Schneider for his assistance in setting up the instrumentation and interpreting the harmonic measurements.


## References


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5. R. J. Parker and R. J. Studders, Permanent Magnets and Their Applications (John Wiley and Sons, Inc., New York, 1962).

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## DISCUSSION

J. Claus, BNL: Does the harmonic distribution you gave, refer to point measurements or to $\int \partial B/\partial L \cdot d\ell$ measurements?

Bush: It's the integrated distribution measured with a long coil. I might add one other point. The technique in the past has been to use the approximation of loss measurements for permeance coefficient or flux meter measurements for actual permeance coefficient measurements. The new DIRECT program can handle permanent magnets or even oriented permanent magnets, although it hasn't been applied yet.