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Summary

An ultra-narrow, high-quality quadrupole magnet has been designed for use in the Bevatron experimental area. Several magnets have been fabricated and tested. Pertinent dimensions are: aperture = 8.244", core width x height x length = 12" x 24" x 24", overall width x height x length = 13" x 41" x 32" (including adjustable stand, terminals and water manifolds but excluding supply and return piping). This corresponds to a width/aperture ratio of ~ 1.5 compared to previously reported "narrow" ratios of 2.5 to 3.0 and common ratios of 5 or more. This narrow magnet permits significant improvement in beam target utilization by permitting more beam lines and/or moving closer to the target to achieve greater particle acceptance. In spite of its small size, the magnet can achieve field gradients up to 5000 G/in.. The measured field quality generally equals or betters that of full-size quads, which is surprising considering the ultra-narrow width and the simple hyperbolic pole shape. A compact cooling circuit arrangement contributed to achievement of these results within such a small volume.

Introduction

Quadrupole magnets commonly[1] have a ratio of overall width to clear aperture (diameter) of $w/d > 4.5$. Previously-reported narrow quadrupole magnets and their width/aperture ratios are LRL 8-inch High Power[1] (w/d= 3.0), BNL-AGS 8-inch Narrow[1] (w/d = 2.7), CERN Split-pole[2] (w/d = 2.5), CERN Figure-of-eight[2] (w/d = 2.75), and LRL 8QN & 12QN[3] (w/d = 2.91 & 2.83). Our goal was to achieve a significantly narrower 8-inch quadrupole magnet even though sacrifices in magnet quality, power, and maximum gradient might be required.

Magnetic Design

A typical magnetic cross-section of our new magnet, designated 8QS, is shown in Figure 1 together with the cross-sections of the narrow 8QN and conventional 8QB quadrupole magnets, all drawn to the same scale. All three magnets have identical apertures of 8.244 inch. The smaller size of the 8QS is readily apparent. The principal parameters of the three magnets are given in Table I. The coil cross-section is 1.56" square and consists of 9 turns/pole of 0.467" sq. x 0.275" dia. hollow conductors carefully positioned within a few mils. The pole profile is a simple hyperbola terminating at the coil window. The core width is 12 in. giving w/d = 1.46. Side bars providing mechanical support between core halves give an overall width of 13 inch. Not all side bars are mandatory; some can be removed if required for clearance from adjacent objects.

The magnetic performance of the 8QS magnet was computed using the two-dimensional magnetostatic program LINDA. The computed magnetic gradient along the x and y axes is shown in Figure 2 for several excitation levels. Somewhat surprizingly, the 8QS field quality at moderate excitation is comparable to our best quadrupoles and is superior at high excitations. Even at the extreme excitation of 5.0 kG/inch, the gradient error $\leq$ 1% within almost half the useful aperture volume. This performance appears paradoxical until one realizes that leakage flux through the coil in most quadrupole magnets exceeds the useful flux. Also, pole corner saturation is less of a problem, since the pole corner (hyperbola-coil intersection) is located ~ 65% back on the coil where less than half the ampturns are linked.

Computer optimization of pole contour[3] was not undertaken because LRL experience indicated that unanalyzed errors (e.g. magnet end effects, hysteresis) would likely overshadow any further reduction in computed errors.

Power and Cooling

The users anticipated that the 8QS magnet would normally operate at gradients of 1.0 to 3.0 kG/inch. The nominal rated performance was arbitrarily set at 3.4 kG/inch, where saturation effects are still small. In case a user might desire extreme excitation, the magnet is capable of 5.0 kG/inch operation (Ref. Table I), but the power requirements are prodigious and boosted water pressure is required. In spite of this, some applications may justify this extreme operation.

There are six water cooling circuits per pole. A compact water manifold arrangement as shown in Figure 3 contributes to a small overall magnet size. The vertical connecting pipes can be located on either side of the magnet or, alternatively, can be omitted and replaced with separate water connections to upper and lower halves.

Performance

Two 8QS magnets have been built and tested with more under construction. They have performed satisfactorily at excitations from 1000 A to 6800 A (~ 3.5 kG/inch) which was limited by the spare power supplies then available. Magnetic measurements were made both of the field integrated over the central 8" of axial length and of the total field, including end effects, measured over a length of 72 inches.[5] The fields over the central 8" agreed well with the computed values. The total field including end effects deviated by about the amount anticipated and had harmonic coefficients (normalized at r = 3.668" to the quadrupole component b_2) of

Central	Harmonic Coef. b_n(% of b_2)			
Gradient	n = 4	n = 6	n = 8	n = 14
0.6 kG/in	-.26	-.02	-.03	-.08
2.4 kG/in	-.28	+.03	-.03	-.09
3.5 kG/in	-.39	+.30	-.08	-.09

with other harmonic magnitudes at each gradient level being even smaller. Adjustments[5] which should substantially reduce the b_4 and b_6 components are planned for the remaining magnets.

Conclusion

This design results in a quadrupole magnet of very narrow width, with excellent field quality, and capable of very high gradients. The power requirements are large, but should be justifiable for many applications.

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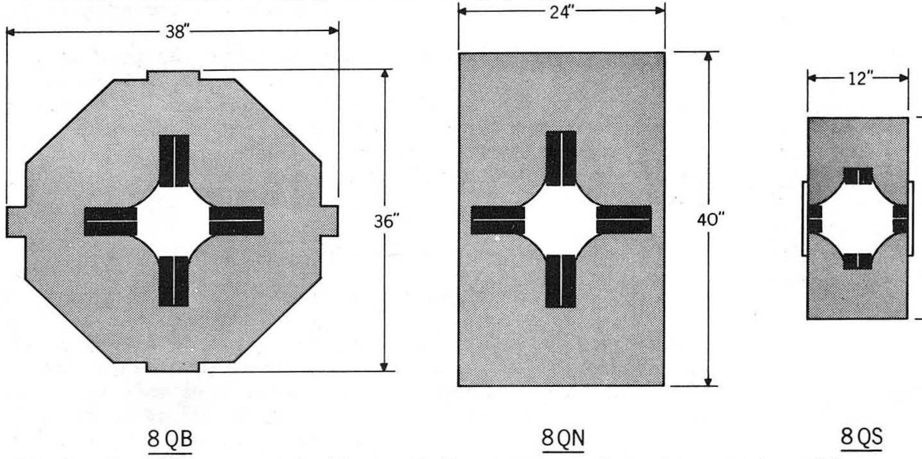
Table I - Principal Parameters of 8QB, 8QN & 8QS Quads

	8QB32 Nominal	8QN32 Nominal	8QS Nominal	8QS Extreme
Gradient, kG/in.	3.64	3.64	3.4	5.0
Field at Pole Apex, kG	15.0	15.0	14.0	20.6
Turns/Pole	24	24	9	9
Current, kA	2.75	2.75	6.5	11.6
Density, kA/in^2	13.4	13.4	41.4	74
Voltage, V	92	92	89	158
Power, kW	254	254	580	1840
Water:				
Circuits/Pole,	3	3	6	6
Total flow, gpm	69	69	76	243
Δp, psi	60	60	22	167
Temp. Rise, C°	33	33	30	30
Core Dimensions:				
width, in.	38	24	12	12
height, in.	36	40	24	24
length, in.	32	32	24	24
Overall dimensions:*				
width, in.	38	24	13	13
height, in.	55	46	41	41
length, in.	39	41	32	32
Aperture Dia., in.	8.244	8.244	8.244	8.244
Core Width/Aperture	4.61	2.91	1.46	1.46

* Includes adjustable stand, terminals and water manifolds. Excludes supply and return piping.



8 QB 8QN 8QS

Figure 1. Core cross-sections of three LRL quadrupole magnets, all with aperture of 8.244 inch.

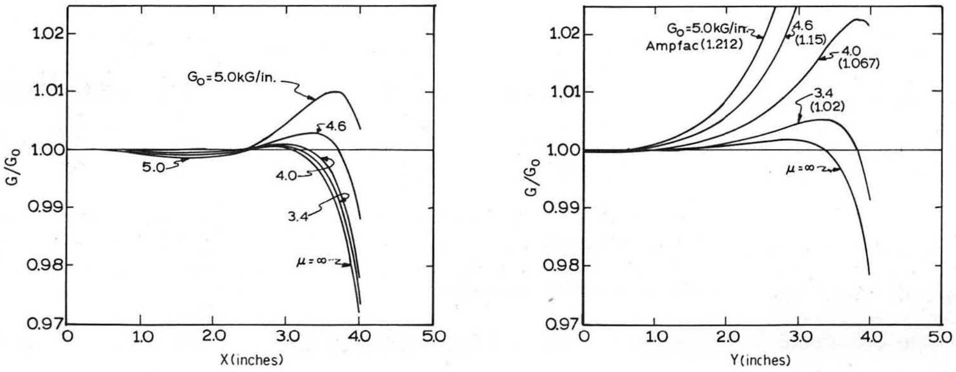


Figure 2. Computed field gradients on x and y axes normalized to central gradient. Ampfac (in parentheses) is ratio of computed amp-turns to the amp-turns for infinitely permeable iron and is a measure of core saturation.

Acknowledgements

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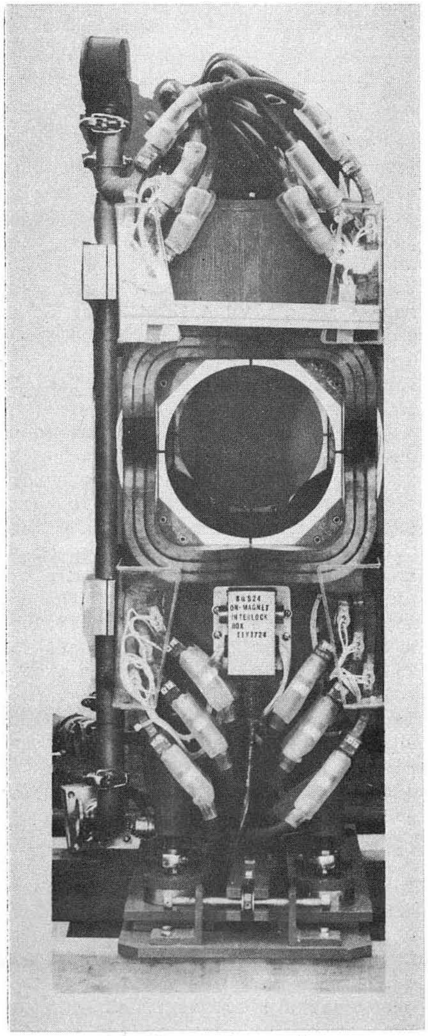

Figure 3. Photo of 8QS magnet.

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