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COLLINS QUADRUPOLE MAGNETS AND Sextupole MAGNETS
FOR A 200-GeV PROTON SYNCHROTRON

Robert A. Kilpatrick
August 26, 1965
In the preliminary design of a 200-GeV proton synchrotron, new designs have been conceived for "Collins" quadrupole and sextupole magnets. These achieve savings in cross section, power consumption, and core complexity in comparison with more conventional designs.

Collins Quadrupole Magnets

The Lawrence Radiation Laboratory is preparing preliminary designs of a 200-GeV proton synchrotron. The proposed ring configuration includes 12 "Collins" straight sections. Each of these requires two quadrupole magnet units with a relatively large focusing strength.

Conventional quadrupole magnet design has considered the aperture to lie wholly within a circle tangent to the pole-tip vertices. Magnets designed to this philosophy can become very large and thus incompatible with the space limitations occurring at a number of locations in this accelerator. These limits are imposed by the following considerations: At one location, the injected proton beam and associated plumbing must clear the magnet. If antiprotons are to be accelerated, another location may be affected. At several locations, the external proton beam plus beam tubes must be accommodated. At still another location, following a proposed internal target, clearance must be provided for small-angle positive and negative secondary-particle beams. In other straight sections, space is restricted by the necessary length of rf accelerating cavities.

Realization that the gradient-magnet cross section is really a truncated portion of a quadrupole magnet, with the major portion of the working aperture outside the tangent circle, has led to a less inhibited quadrupole design. (See Fig. 1 and Table I for a comparison of the conventional and new designs.) Diametral pole spacing has been appreciably reduced by allowing the elliptical aperture to extend into hitherto forbidden territory. Associated reductions in excitation and total flux allow a marked reduction in cross section. Of course, total flux would be further reduced if the external portions of the coil were placed closer to the pole tips, but the need for clearance near the median plane has overruled this possibility.

### Table I: Comparison of conventional and new Collins quadrupole magnet designs.

<table>
<thead>
<tr>
<th></th>
<th>New</th>
<th>Conventional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gradient X length</td>
<td>454</td>
<td>454</td>
</tr>
<tr>
<td>Peak gradient</td>
<td>3.83</td>
<td>2.97</td>
</tr>
<tr>
<td>Radius to pole vertex</td>
<td>1.90</td>
<td>2.48 in.</td>
</tr>
<tr>
<td>Field at pole vertex</td>
<td>7.2</td>
<td>7.38 kG</td>
</tr>
<tr>
<td>Effective length</td>
<td>118</td>
<td>153</td>
</tr>
<tr>
<td>Peak excitation</td>
<td>15000</td>
<td>20000 ampere</td>
</tr>
<tr>
<td>Assembly weight</td>
<td>8</td>
<td>17 tons</td>
</tr>
</tbody>
</table>

Further explorations within this relaxed view of quadrupole design are evidenced by cutoff of the pole tips, in the vertical direction, closer to the vertex than in the conventional design. There is really no need to supply good field outside the relatively flat, elliptical proton beam aperture except possibly at the magnet ends. However, the effective lengths of the end fringing fields will be a small fraction of the total effective lengths of these 10-ft-long units. Errors introduced in the end leakage fields by this contour cutoff should be easily corrected after they have been determined in model tests.

A very important result of the pole cutoff in the vertical direction is the allowance of a reasonably wide slot between poles for installation of the coils. Several undesirable options would follow the choice of a lesser width: For equal current density, equal numbers of coil subassemblies, and equal core reluctance, the coil-slot depth would increase, forcing an increase in magnet height, width, and weight. For equal current density and core reluctance, and approximate maintenance of core weight, the coil would have to be installed in smaller subassemblies. Coil costs, extensions at ends of the magnet, and assembly labor would all increase. Or, a four-piece core could be specified. The attainment of precise register between the core subassemblies would be more different than with a two-piece core.

Since writing this report, I have found that members of the National Laboratory of Frascati, Italy, presented a quadrupole design incorporating asymmetrical pole contours: *Proceedings of the International Conference on High Energy Accelerators* (published in Moscow, 1964).
Preliminary shaping of the pole contours, with the aid of computer programs "SLYBY" and "TRIM", results in a maximum variation of gradient along the horizontal and vertical axis of approximately 0.5%. Indications are that these variations can be further reduced without reducing the pole-gap width through which the coils must pass.

The 200-GeV accelerator will be a pulsed machine. During the injection and accelerating portion of a pulse the focusing strengths of the Collins quadrupole and main gradient magnets must remain at a constant ratio.

$$\beta = \frac{FS_Q}{FS_M} = \frac{BM^Q}{BM^M}$$

(1)

where $B'$ is a spatial gradient and $L$ is effective length. The requirement is that $\beta = 0$.

The excitation equations for the two magnets are

$$N_{LQ} = 1.01 A_Q B' a_Q^2$$

(2)

$$N_{LM} = 2.02 A_M B'M^M g_M$$

(3)

in the gauss-inch-ampere system of units, where $A_Q$ and $A_M$ are dimensionless factors that account for the NI drops through the cores, $a_Q$ is the radius of the circle tangent to the quadrupole tips, $g_M$ is the vertical gap at the orbit center line of the gradient magnet and $B'M^M$ is the flux density at the orbit center line of the gradient magnet. It is convenient to define a normalized gradient for the main gradient magnets as

$$k_M = 1 \frac{B'M^M}{B'O^M}$$

(4)

Combining Eqs. 1 through 4 gives

$$\beta = \frac{g_M}{a_Q^2} \left( \frac{A_M}{A_Q} \right)^2 \frac{1}{k_M} \left( \frac{N_{LQ}}{N_{LM}} \right)$$

(5)

To achieve $\beta = 0$, it is at present most convenient to try to make each bracketed term independent of magnet excitation. The first term will be independent except for the small reductions in gaps due to the magnetically induced elastic deformations of the cores. The second term will be made constant with excitation by shaping the quadrupole pole bases and back leg to give $A_M \approx A_Q$ at all times during the significant portions of a pulse. Much effort has gone into the design of the gradient magnet to arrive at a minimum change of $k_M$ with excitation; that change which still remains at injection and peak fields will be compensated for by auxiliary magnets in the ring. The third term can therefore be taken as constant. The ratio of effective lengths will change during a pulse. Our present thought is that the change will be small enough to allow correction by a programmed excitation of small trimming coils in the quadrupole (see Fig. 2), or back leg windings in the gradient magnet, or both. This part of the problem is complicated by the fact that the two $(\Delta L)$s will not be constant throughout the two apertures. A full solution will probably not be assured until model test results are available.

The last term in Eq. 5 can be treated in two steps: first, by specifying that the quadrupole coils be connected in series with the main gradient coils, $A_Q = A_M$; then using Eqs. 2 and 3, and remembering that $A_Q = A_M$, to get the design equation

$$N_{OQ} = B' \frac{N_{LO}}{N_{LM}}$$

The gradient magnet factors have been fixed at

$$N_{LO} = 16 \text{ turns,}$$

$$B'O = 15.1 \text{ kG,}$$

$$g_M = 2.44 \text{ in.}$$

The numerator factors are all independent variables but subject to the following constraints: the tangent circle radius $a$' should be small, as allowed by the external shape of the vacuum envelope; the gradient should be large for minimum magnet length, but it must be less than that value at which saturation in a portion of the pole contour would compromise either precision of the aperture field or attainment of $A_Q = A_M$; and of course these two factors must combine in the above equation to make $N_O$ an integer. The best set of values is

$$N_O = 3 \text{ turns per pole,}$$

$$a_O = 2.48 \text{ in,}$$

$$B'O = 3.83 \text{ kG per in.}$$

The peak flux densities at the pole vertex and at the pole corners near the median plane are 7.3 kG and about 18 kG respectively. With a specified focusing strength of 454 kG, the effective length of the quadrupole field is 118 in.

Since the Collins quadrupoles are to be in series with the gradient magnets, there will be two circuits through the main excitation coils. A schematic circuit diagram is shown in Fig. 3. One circuit will consist of the upper left and lower right coils in series, the other circuit of the remaining two coils. This connection scheme will minimize shifts in the magnetic center line due to possible small differences in the two currents. Either exciting current will enter at one end of the magnet and leave at the other end. The necessary asymmetries in location of the currents are confined to those conductors outside the core; the effects on the aperture field shape are expected to be nil. This arrangement offers savings in bus-bar capital and operating costs as well as appreciable reduction in enclosure clutter.

A fair portion of these units will be exposed to radiation dosages estimated to be around $10^{10}$ rads for 10 years. The insulation system will be based on the glass, epoxy, and alumina materials discussed in Ref. 3.
The apparent low space factor in the coil-window results from the desire to limit the extensions of the coil past the ends of the core. Single-layer coils minimize these extensions.

The core will be laminated. The lamination material will be a very-low-carbon steel (denoted by $C_{\text{max}} = 0.003\%$), 0.062 in. thick. The side bars and fastenings will necessarily be of nonmagnetic material, stainless or manganese steel. We are considering the use of nonmagnetic stainless steel end plates in order to minimize the remanent and eddy-current components of the end leakage fields. A high-precision die and stacking fixture will be needed for production of the core. The upper and lower core subassemblies will be held together by two subassemblies so they can be installed

Large excitation differences result from relatively small radius ratios because of the cubic dependence.

In the design presented here (see Fig. 4) the elliptical aperture is allowed to extend outside the traditional tangent circle as in the Collins quadrupole. The coils have been designed to have approximately uniform clearance from the beam tube while giving an integral value to the excitation ratio. This ratio is 5:1. The near poles, at 90 and 270 deg, each carry a five-turn coil, while each of the other four poles is excited by 25 turns. The 25 turns must be divided into two subassemblies so they can be installed through the narrow gap between pole tip corners. The five turn coils must be installed after the larger coils are in place. The small size of the 5 turn coils is the feature that makes the two piece core feasible.

The equation of a sextupole magnetic equipotential is

$$|r| = a [\sin 3\theta]^{-1/3}.$$
large increases in core weight.

Table II. Comparison of conventional and new sextupole magnet designs.

<table>
<thead>
<tr>
<th></th>
<th>New</th>
<th>Conventional</th>
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<tbody>
<tr>
<td>$B^*$</td>
<td>2.58</td>
<td>2.58</td>
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<tr>
<td>Radius to far pole tips</td>
<td>2.221</td>
<td>2.56</td>
</tr>
<tr>
<td>Radius to near pole tips</td>
<td>1.30</td>
<td>---</td>
</tr>
<tr>
<td>Effective length</td>
<td>11.8</td>
<td>11.8</td>
</tr>
<tr>
<td>Peak NI for far poles</td>
<td>9520</td>
<td>14600</td>
</tr>
<tr>
<td>Peak NI for close poles</td>
<td>1940</td>
<td>---</td>
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<tr>
<td>Total excitation</td>
<td>41900</td>
<td>87600</td>
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<tr>
<td>Duty factor</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>rms current density</td>
<td>2000</td>
<td>5000</td>
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<tr>
<td>$I^2R$</td>
<td>1.4</td>
<td>7.5</td>
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<td>Assembly weight</td>
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</table>

Footnote and References

6 Work done under auspices of the U. S. Atomic Energy Commission.


Comparison of Conventional & New Collins Quadrupole Magnet Designs

Figure 1
Primary Ring Magnet Elements
Collins Quadrupole Magnet

Figure 2
Collins-Quadrupole Wiring Diagram

Figure 3

MUB-7629
Conventional Sextupole Magnet

Figure 4
Secondary Ring Magnet Elements
Sextupole Cross Section

Figure 5

MUB7631
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