A DESIGN FOR VERY SHORT POWERED QUADRUPOLES

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Abstract

Powered optics magnets which could be stacked in a very dense alternating pattern could enable a higher density of focusing in beamlines, with potential use for e.g. muon beams or high-current hadron beams at low energy. Here, we investigate such a design of quadrupole, where the yoke is energised by straight conductors running parallel to the beam, and does not require conductor to pass within the gap between yokes of adjacent magnets of opposite polarity. Suitable shaping and design of the steel yokes allows alternating focusing and defocusing quadrupoles, of arbitrary thickness, to be positioned with only the spacing required for constraining fringe fields. We investigate multiple thicknesses/sizes, and the use of thin field clamps to further reduce the required spacing between quadrupoles.

INTRODUCTION

Reducing the length of a large-aperture focusing/defocusing (FODO) cell in a particle beamline can allow better constraining and more rapid focusing of sparse or high-current beams. The use of permanent magnets to construct very short, high-gradient quadrupoles has offered many advantages [1, 2]. However, their limited magnetic field means that such quadrupoles cannot provide similar gradients for larger apertures, and may also suffer degradation if placed close to beamlines with a high radiation load [3]. Optics elements overcoming these difficulties could be extremely useful for low energy applications such as e.g. sparse post-target beams for research or e.g. high-current hadron beams for nuclear power production or transmutation.

In this research, we have developed a design for a quadrupole based on (super)conductors oriented parallel to the beam, with multiple steel yokes inserted to direct the flux into focusing or defocusing quadrupole fields in the beam aperture. Although distinct from the design in Ref. [4], this results in a similar ability to set an arbitrary separation between yokes, yoke thickness and choice of aperture (albeit with higher field gradient).

We use the pole shape providing a high-purity quadrupole with good-field apertures of 100 mm and 80 mm to investigate the effects of yoke separation, thickness, coil current, field clamps and the use of superconducting shields between yokes on the on-axis quadrupole gradient.

We find this design of quadrupole to be effective for gradients in the range 4-7 $\mathrm{T\,m^{-1}}$ for apertures 90-110 mm. We note that the absence of conductor passing between adjacent yokes allows for increased instrumentation and pumping capacity in the beamline, making this a highly versatile design.

DESIGN

The design used here is intended to provide any distance between yokes of quadrupole magnets. However, we note that the lower limit of separation between magnets of different fields is tied to the aperture (as at lower separations, magnetic flux travels between adjacent yokes, rather than transversely across the beam aperture).

To realise this design goal, we use straight conductors oriented longitudinally, parallel to the beam. The yokes of focusing/defocusing quadrupoles must then pass these conductors on opposite sides, to induce flux in opposite directions and direct it to/from the beamline. At either end of the magnet/assembly, the conductors each split and return on either sides of the yoke poles. The resulting loops resemble those of an elongated octupole magnet. The design is shown in Fig. 1 (single, lone yoke) and Fig. 2 (three FODO cells).

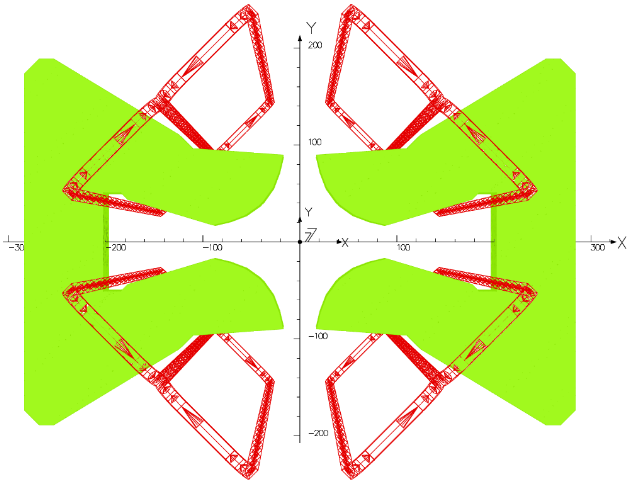

Figure 1: Design of the quadrupole viewed from the beam axis, showing a single, lone yoke assembly (in green) with coils (in red) extending longitudinally. The direction of the current in the coils is shown. The yokes of opposite quadrupole polarity are identical, rotated by 90°.

The half-yoke design is chosen due to the geometry of the coils through which each pole must pass, resulting in the shortest path for a closed magnetic field loop. We note that this design choice also reduces the required steel, though a non-magnetic material may be required to mechanically fix both half-yokes together.

The coil cross-section of 5×10 mm was chosen to produce a square cross-section (10×10 mm) in the conductor passing between focusing and defocusing yokes. This size also allows for a reasonable current density of 300 $\mathrm{A\,mm^{-2}}$ to saturate the yoke steel (as we shall see later).

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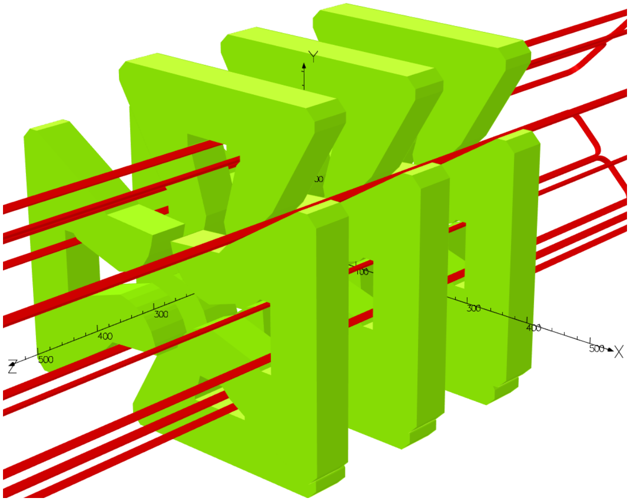

Figure 2: A view of three 110 mm-aperture (good-field aperture of 100 mm) FODO cells with yokes separated by 40 mm, showing the 60 mm-thick yokes (in green) with coils (in red).

The absence of conductor passing between yokes would allow for additional beamline instrumentation (e.g. vacuum pumps, beam position monitors) to be attached, if the coil fields allow. This design may also require less conductor than individually-powered quadrupoles.

Field clamps [5] of thickness 1.25 and 2.50 mm, and superconducting shields [6] between yokes (although much less practical) were also included in the design as options.

SIMULATION

To find the multipole decomposition of the field, we simulated a single, lone yoke of 110 mm aperture in Opera3D [7] with conductor loops extending 500 mm beyond either end (as in Fig. 1, chosen to eliminate the effects of the loop ends for simplicity in these studies). The field was sampled at 100 points azimuthally at $r = 50$ mm around the beam axis within Opera, and a multipole decomposition performed. The pole tip shape was adjusted for the highest purity of quadrupole component whilst retaining symmetry about each pole tip center. We present the obtained multipoles in Table 1.

Table 1: Multipole components up to $n = 6$ (12-pole), sampled at 100 points around the beam axis at $r = 50$ mm in the centre of a single, lone yoke with 110 mm aperture.

n	Normal	Skew	n	Normal	Skew
1	-.00005	.00010	4	-.00026	-.00013
2	.21816	.00001	5	-.00009	-.00007
3	-.00002	-.00019	6	-.00131	-.00010

This configuration was used to study the effect of total coil current on the on-axis field gradient, results for which are shown in Fig. 3. We see yoke saturation effects beginning at total currents around 10 kA-Turns. However, to maximise field while retaining contingency to later choose normal-conducting coils (the latter requiring a larger, but feasible cross-section), we use 15 kA-Turns (corresponding to 300 A mm^{-2}) for the studies here.

The single-yoke configuration was also used to analyse the effect of yoke thickness, for which we simulated yoke thicknesses between 10 and 120 mm.

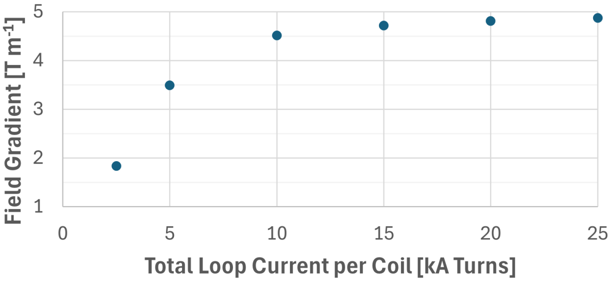

Figure 3: On-axis field gradient of a single, lone 110 mm-aperture yoke, for total loop currents between 2.5 and 25 kA-Turns (conductor current densities between 50 and 500 A mm^{-2}). We see a substantial reduction in benefit above 10 kA-Turns (200 A mm^{-2}), due to saturation of the steel adjacent to the coil. To incorporate some contingency into the conductor design, we use 15 kA-Turns (300 A mm^{-2}) in the other studies presented here.

A set of three FODO cells was also simulated for a yoke-thickness of 60 mm, with a uniform inter-yoke separation (as in Fig. 2). This was repeated for different inter-yoke separations and yoke apertures of 90 and 110 mm, with the conductor loops again extending 500 mm beyond either end.

The optional field clamps (of thickness 1.25 and 2.50 mm) were simulated with 60 mm-thick yokes of 110 mm aperture. We also simulated simplified, Meissner superconductor shields (with same central aperture as the yokes) placed between yokes in the three-FODO, 110 mm aperture configuration.

RESULTS

We present the single-yoke quadrupole properties in Table 2, where we see the expected improvements in peak field and effective length for the 90 mm aperture as compared to the 110 mm aperture.

Table 2: Properties of the quadrupole, for a single, lone yoke, for yoke apertures of 110 mm and of 90 mm.

Yoke Aperture	110 mm	90 mm
Good-Field Aperture	100 mm	80 mm
Yoke Length	60 mm	60 mm
Yoke Size W×H	560×372 mm	560×372 mm
Field: Peak Gradient	4.72 T m^{-1}	6.82 T m^{-1}
Field: Effective Length	125 mm	111 mm
Coil: Ampere Turns	15 kA Turns	15 kA Turns
Coil: Current Density	300 A mm^{-2}	300 A mm^{-2}

The effect of yoke thickness on integrated gradient and peak on-axis gradient are shown in Fig. 4. We see that the gradient increase with thickness reduces substantially for thickness from 60 to 120 mm. We choose the 60 mm thickness here to retain compactness.

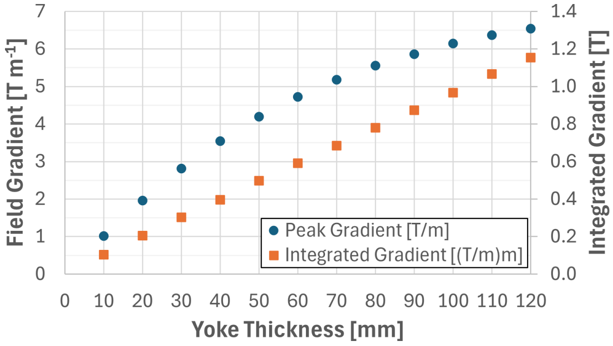

Figure 4: On-axis field gradient (blue circles, left axis) and integrated field gradient (orange squares, right axis) of a single, lone yoke of different thicknesses, found for a 110 mm-aperture yoke with 15 kA-turns in each coil. We see less gain in peak gradient with thickness above thicknesses of ≈40-60 mm. However, the integrated gradient appears to increase linearly, so there is no particular preference for any yoke thickness. We choose 60 mm as an effective yet compact thickness, for the majority of studies performed here.

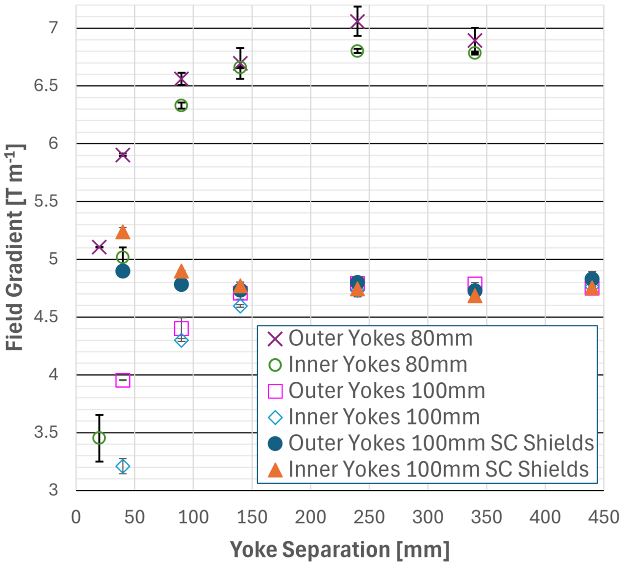

Figure 5: On-axis field gradient taken at the midpoint of each yoke, of inner and outer yokes, plotted against separation of yokes. This is plotted for three FODO cells with all 60 mm-thick yokes equidistant (as in Fig. 2), with good-field apertures of 80 mm and of 100 mm, the latter with and without superconducting shields between yokes. We see the gradient drops notably for yoke separations of less than 100 mm, and inner yokes have a greater drop than the yokes at either end of the assembly (outer yokes). We also see that placing the superconducting shields closer to the yokes enhances the peak gradient.

In Fig. 5 we plot peak on-axis field gradient as a function of yoke separation, and see the same increase in gradient with reduced aperture as presented in Table 2. For reduced yoke separation, we see a reduction in gradient as flux more readily travels between adjacent poles. This effect is more pronounced for the yokes with other yokes on both sides (referred to as "inner" yokes).

Also visible in Fig. 5 is the effect of superconducting shields reducing longitudinal fields between adjacent pole yokes, increasing the transverse field in the beam aperture more for smaller separations. Prior to inclusion of these shields, the longitudinal fields were up to 0.3 T within the shield volumes, which suggests such shields may be feasible.

For the field clamp studies, we found that the 125 mm effective length of the quadrupole was unchanged for the 1.25 mm clamps, but increased to 127 mm for the 2.50 mm clamps. We also found the peak gradient decreased by 0.2 T m^{-1} for each 1.25 mm added to the clamp thickness.

CONCLUSION

The studies (coil current, yoke thickness, yoke separation, yoke aperture, effectiveness of field clamps and superconducting shields) were chosen to effectively characterise this new design of quadrupole. These results should be sufficient to inform future investigation and application of the design.

The results suggest gradients of 4.7 T m^{-1} can be achieved for a yoke aperture of 110 mm with 150 mm yoke separation. Smaller separations are achievable at the cost of gradient, preferable for e.g. beams of low energy produced by a target, or with very high current, where such a design could increase the amount of beam captured.

The use of superconducting shields at smaller yoke separations appears promising, increasing peak gradient for smaller separations. We note operation below H_{c1} (a Meissner superconductor) is preferred for this application, and that the feasibility of using such a shield with high radiation load (typical for the suggested use cases) requires consideration.

Using field clamps for independent positioning of yokes reduced performance. However, thorough characterisation of fields with respect to yoke separation using an FEA code could allow tuning of yokes in close proximity, without the need for field clamps.

For further studies, we suggest a normal-conducting structure (utilising more space between poles), and the possibility of tuning yokes using a steel screw inserted radially through the center of each pole from the radial outside of the yoke. Effects of conductor ends (not studied here) would also be a good candidate for further research. However, beam simulations (particularly for the suggested cases) would most effectively indicate the usefulness of this design.

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