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# DESIGN OF SPLIT PERMANENT MAGNET QUADRUPOLES FOR SMALL APERTURE IMPLEMENTATION*

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*Abstract*

Permanent magnet quadrupoles are ideal for strong focusing in compact footprints. Recent research in the use of permanent magnet based quadrupole magnets has enabled very high-gradient uses approaching 800 T/m in final focus systems. However, in order to achieve high quality field profiles with strong fields, small diameter bore magnets must be used necessitating in vacuum operation, or very small beampipes. For small beampipe geometry, we have developed a hybrid-permanent magnet quadrupole, with steel and permanent magnet wedges, that is able to maintain high quality fields but also readily machinable in a separable design. The split design allows for accurate and reproducible reconfiguration on a beam pipe. In this paper, we will discuss the design, engineering, fabrication and first measurements of the split permanent magnet quadrupole.

## BACKGROUND

Modern Ultrafast Electron Microscopy (UEM) techniques allow for angstrom resolution and can image individual atoms. A major milestone in the field is to reach the capability of probing atomic dynamics that are on the timescale of 10 fs [1]. Using high-brightness electron beams for UEM is a way to probe ultra-short time-scales with exceptional resolution. The main drawback is that at low energy, high-brightness electron beams have non-negligible space charge forces, which act to decrease the optimum resolution of the machine in two ways: angular broadening and energy spread aberration. In order to alleviate the problem, it is possible to use ultra-relativistic electrons. However, at high energies, stronger focusing magnetic optics are required to achieve the desired microscope lens properties for a given machine.

Permanent magnet quadrupoles (PMQs) are one of the most robust ways to produce high-gradient magnetic focusing optics for relativistic particle beams [2] and they have successfully been used in UEM recently [3]. PMQs can meet the high-gradient and small footprint requirements of UEM machines using ultra-relativistic electron beams.

## DESIGN

In this study, we set out to design an objective lens composed out of PMQs that are strong enough for 3 MeV electron beams. The initial step in the design process was to investigate the benefits of a quadrupole doublet, triplet, and quintuplet as an objective lens. We settled on using a symmetric quintuplet. Then we leveraged a multi-objective genetic algorithm (MOGA) to incorporate physics (beam dynamics), engineering, and manufacturing constraints into the design of the optic and the individual quadrupoles. The details of this work are presented by Gerard Andonian - MOPAB139 [4].

### *Optimized Optic*

The quintuplet optic design that performed best in the MOGA optimizer requires PMQs with competing properties: short length, large aperture, and high gradient. In Fig. 1, the quintuplet's gradient profile along the magnetic axis is shown. The peak gradients of the individual quadrupoles for this particular optic are presented alongside. It is interesting to note that the design requires a relatively weak magnet in the middle and very short and strong magnets at the ends. This peculiarity is an artifact of the MOGA optimizer and further investigation is in order.

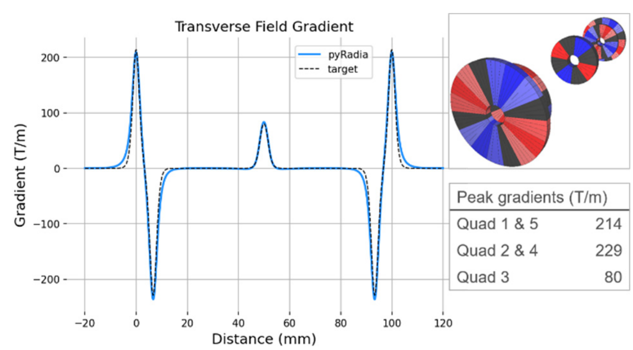


Figure 1: Quintuplet optic design. The on-axis transverse gradient profiles through the optic for an Enge model and that produced by pyRadia are shown on the left. A 3D depiction of the optic is on the right with a list of the peak quadrupole gradients below.

A further complication to the design of the individual PMQs arises from the application's requirement to operate the quadrupoles outside of the electron beam's vacuum chamber while still achieving the high gradients of the design. By incorporating steel wedges and cutting the quadrupole along the steel, it is possible to mount this hybrid-PMQ around a small chamber without breaking vacuum in the electron beamline and thus allow for quick reconfiguration of the beam-line. This "splittable" design is illustrated in Fig. 2.

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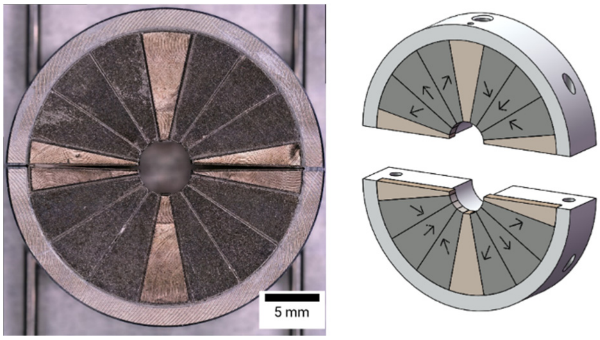


Figure 2: The left picture shows one of the three types of hybrid-PMQs produced and the right graphic is a 3D model.

### 3D Magnetostatic Simulations

The design of the individual quadrupoles was done using the 3D magnetostatic code Radia as implemented in python (pyRadia [5, 6]). The large aperture and short length of the magnets means that the hard-edge model for magnets is not a good approximation to accurately describe the associated electron beam dynamics. Furthermore, the fringing fields increase the harmonic content inside the aperture of the magnets, which leads to undesired chromatic and spherical aberrations in the lens. The effect of the 3D geometry on the gradient profiles can be seen in Fig. 1, where the results of pyRadia simulations are compared to a first order Enge model [7]. The 3D model results have heavier tails than expected by the analytic Enge model.

The initial MOGA optimizations were performed with Enge functions, once 3D models were made in pyRadia, the MOGA optimizer was updated to include the new profile curves.

### Harmonic Content

Introduction of the steel wedges allows for more exotic designs for gradient strength adjustments using a varying external magnetic excitation source such as a coil or rotating permanent magnet [8-10].

The most significant drawback of incorporating steel blocks in the PM assembly is that the harmonic content inside the quadrupole aperture increases. The finished magnet is not a pure quadrupole, but has higher order harmonics. In Fig. 3, the total harmonic content is plotted as a function of the radial distance from the magnetic axis. Specifically:

$$HC\% = 100\% \times \sum_n \frac{b_n(r)}{b_2}$$

The coefficients, $b_n(r)$, are computed at the specified radius, r, and are such that the auxiliary transverse magnetic vector potential can be expanded in the usual way: $F(z) = \sum_n b_n z^n$. The quadrupole moment is $b_2$.

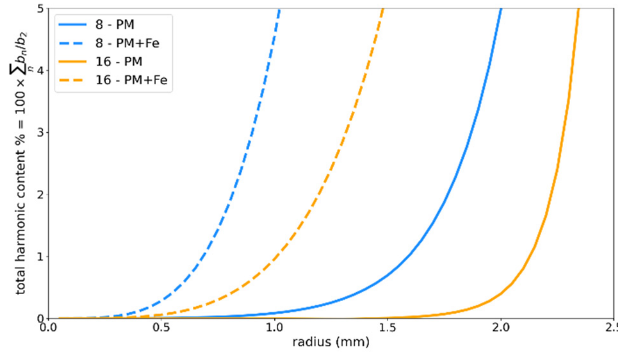


Figure 3: The harmonic content at different radii inside the magnet aperture. The effect of inserting steel in 8-magnet and 16-magnet Halbach assemblies is a large increase in undesired multipoles inside the aperture.

## MEASUREMENTS

RadiaBeam has manufactured the 3 different hybrid-PMQs outlined in the quintuplet optic design. Type 1 of the PMQs is presented in Fig. 2. Hall probe measurements were undertaken to qualify the magnetic characteristics of the quadurpoles.

Measured gradient profiles are presented for 6 samples of hybrid-PMQ type 1 in Fig. 4. The measured peak gradient for the 6 hybrid-PMQs at a physical length of 6 mm is 243.6 ± 13.5 T/m. Unfortunately, this is far below the peak gradient reached in 3D magnetostatic simulations, which is around 500 T/m. The main source of error is expected to be from tolerance stack-up in the manufacture of such small assemblies (including physical dimension errors, magnetization errors of PM wedges, etc.) Nevertheless, the consistency of the gradient profiles over the 6 samples per each type (types 2 and 3 not shown) is encouraging for future development projects.

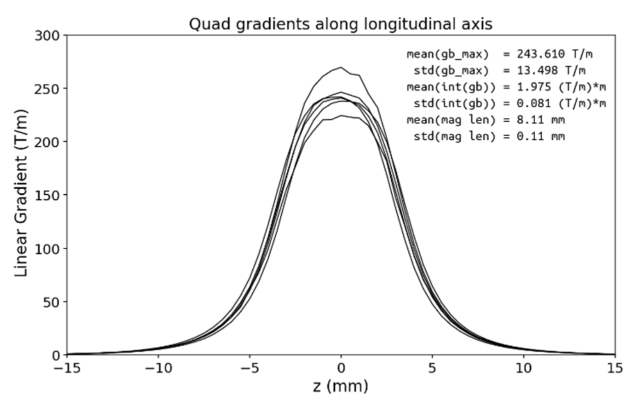


Figure 4: Measured on-axis gradient profiles for 6 hybrid-PMQs of type 1. The text inset highlights the aggregate properties of interest: gb – gradient, int(gb) – integrated strength, mag len – magnetic length.

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## OUTLOOK

We have demonstrated the capability to manufacture a hybrid-PMQ with a large aperture to length ratio that achieves a high gradient. The next steps in our UEM optic design will begin with closing the feed-back loop with our MOGA optimizer by feeding in the measured quadrupole gradients and producing a sensible modification to the original quintuplet design. Next, we will proceed with EDM cutting the hybrid-PMQs to the desired lengths and assemble a self-aligned full quintuplet. Finally, proof-of-concept experimental runs are planned at the Brookhaven National Lab's UED facility.

## ACKNOWLEDGEMENTS

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## REFERENCES

[1] W. Wan, F.-R. Chen, and Y. Zhu, "Design of compact ultrafast microscopes for single- and multi-shot imaging with MeV electrons," *Ultramicroscopy*, vol. 194, pp. 143–153, Nov. 2018, doi:10.1016/j.ultramic.2018.08.005

[2] S. M. Lund and K. Halbach, "Iron-free permanent magnet systems for charged particle beam optics," *Fusion Engineering and Design*, vol. 32–33, pp. 401–415, Nov. 1996, doi:10.1016/S0920-3796(96)00496-6

[3] R. K. Li and P. Musumeci, "Single-Shot MeV Transmission Electron Microscopy with Picosecond Temporal Resolution," *Physical Review Applied*, vol. 2, no. 2, Aug. 2014, doi:10.1103/PhysRevApplied.2.024003

[4] G. Andonian *et al.*, "High Resolution Imaging Design Using Permanent Magnet Quadrupoles at BNL UEM", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, MOPAB139, this conference.

[5] O. Chubar, P. Elleaume, and J. Chavanne, "A three-dimensional magnetostatics computer code for insertion devices," *Journal of Synchrotron Radiation*, vol. 5, no. 3, pp. 481–484, May 1998, doi:10.1107/S0909049597013502

[6] O. Chubar, https://github.com/ochubar/Radia

[7] H. A. Enge, "Effect of Extended Fringing Fields on Ion-Focusing Properties of Deflecting Magnets," *Review of Scientific Instruments*, vol. 35, no. 3, pp. 278–287, Mar. 1964, doi:10.1063/1.1718806

[8] F. Marteau *et al.*, "Variable high gradient permanent magnet quadrupole (QUAPEVA)," *Applied Physics Letters*, vol. 111, no. 25, p. 253503, Dec. 2017, doi:10.1063/1.4986856

[9] M. J. Easton, H. Li, Y. Lu, J. Zhu, and P.-D. Pfister, "Permanent-magnet quadrupoles for an interdigital H -mode drift tube linear accelerator: Optimization code and adjustable magnet design," *Physical Review Accelerators and Beams*, vol. 21, no. 12, p. 122401, Dec. 2018, doi:10.1103/PhysRevAccelBeams.21.122401

[10] S. Brooks, G. Mahler, J. Cintorino, J. Tuozzolo, and R. Michnoff, "Permanent magnets for the return loop of the Cornell-Brookhaven energy recovery linac test accelerator," *Physical Review Accelerators and Beams*, vol. 23, p. 112401, Nov. 2020. doi:10.1103/physrevaccelbeams.23.112401