LDRD 22-013

BROOKHAVEN NATIONAL LABORATORY
PROPOSAL INFORMATION QUESTIONNAIRE
LABORATORY DIRECTED RESEARCH AND DEVELOPMENT PROGRAM

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DEPARTMENT/DIVISION	**C-AD**	**DATE**	**2/3/21**
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TITLE OF PROPOSAL **TYPE B**	**High-Gradient Permanent Magnets for Emerging Accelerator Applications**		
PROPOSAL TERM (month/year)	From **10/2021**	Through **10/2023**	

SUMMARY OF PROPOSAL

Description of Project:
Magnetic gradients in the range 50 to 250 Teslas per metre are of interest for several applications of particle accelerators. In hadron cancer therapy gantries they enable a novel design by Trbojevic [1] that can transmit a wide range of energies within a fixed-field magnetic pattern, allowing faster energy scanning within the patient. In light sources, a section of high-gradient magnets including a dipole field, termed a "complex bend" [2], can be used as the main bending element in an electron storage ring to produce the lowest equilibrium beam sizes yet achieved, which in turn produce diffraction-limited X-ray beams. Other applications include beam focussing in laser plasma accelerators [3].

At high gradients and small apertures, the scaling of permanent magnets becomes better than electromagnets because the permanent magnets act as 2D current sheets at their boundary whereas copper energising coils are 3D current blocks. Thus, permanent magnets are under investigation for all of the above applications. Recent design modifications also allow the midplane to be clear so that synchrotron radiation can escape without hitting the magnet in light sources and other high-energy electron rings.

C-AD has experience with the CBETA project, in which a large number (200+) of medium-gradient (~10T/m) permanent magnets were built and successfully transmitted beam. As part of this project, tuning methods and software were developed that could reduce the magnetic error content by roughly a factor of 8 from the bare magnet [4]. The project also saw the first use of combined-function Halbach permanent magnets producing both a dipole and quadrupole field at the same time.

It is proposed that these techniques from CBETA are applied to the applications above, while being adapted to higher gradients, smaller magnet apertures, and open midplane geometries.

Expected Results:
Several test magnets will be built, measured and tuned. The magnetic field measurement system will provide information on the field uniformity across the aperture, data which is also used for cancelling out field errors with small iron wires during tuning. The CBETA field uniformity criterion was better than 1 part in 1000, so similar levels will be aimed for in these magnets. After tuning, the magnets will be re-measured to confirm the final field quality, with additional tuning iterations if required.

Field strengths and apertures for the test magnets will be chosen representative of magnets from the applications. The magnets with open midplanes require mechanical support against the magnetic forces trying to close the gap, which will be tested with an engineering prototype.

If time allows, an oval-aperture variant of the Halbach quadrupole, recently designed by Brooks, will also be tested. This is predicted to allow 30% higher gradients with the same amount of magnetic material, for beams that are larger horizontally than vertically, as is the case in the hadron therapy gantry.

PROPOSAL

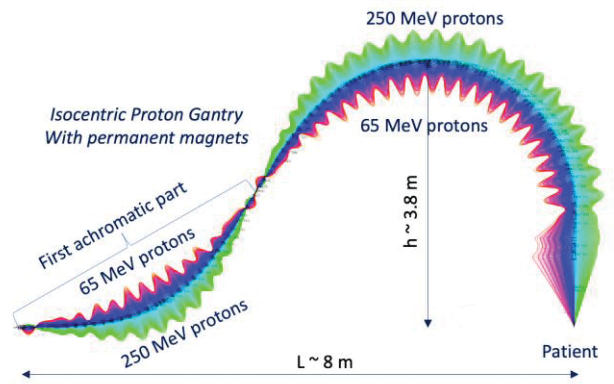
Application Requirements and Magnet Parameters

The magnet parameters for six of the relevant applications are given in Table 1. The magnets in the hadron therapy gantry and CEBAF designs transmit particles with a beam excursion that depends on energy (see Figure 1). The gantry uses protons so does not require a midplane gap for synchrotron radiation, so may be constructed best using the oval aperture quad design. Increasing the field is always beneficial here because it reduces the overall gantry size, thus R&D for maximum field will be of interest.

Table 1. Magnet parameters for main repeating cells of: the recent hadron therapy gantry design from [1], the "Complex Bend II" NSLS-II upgrade light source lattice [2], the PETRA-IV light source, the JLAB CEBAF 20GeV upgrade working design using a fixed-field multi-energy arc, and the ILC damping ring.

Project and magnet name	**Dipole at x=0 (T)**	**Gradient (T/m)**	**Beam half-excursion (mm)**	**Aperture radius (mm)**	**Needs open midplane?**
Gantry QF [1]	0	155	8.8	13.8	No (protons)
Gantry BD	1.8	-97	7.5	12.5	No (protons)
CBII-F [2]	0.26	250	<0.5	5	Yes
CBII-D	0.49	-250	<0.5	5	Yes
Plasma accel. [3]	0	100 to 500	0	3 to 12.5	No
PETRA-IV quads	0	50 to 95	0	12.5	Yes
'' combined func.	0.1976, 0.2861	25.83, 38.94	0	12.5	Yes
CEBAF 20GeV F	0.8827	321.05	3.2	5	Yes
CEBAF 20GeV D	0.8827	-187.47	3.2	5	Yes
ILC-DR quads	0	15	0	32.5	Yes

Table 1 also shows the parameters for next-generation light source magnets. These magnets do not need to accommodate horizontal beam excursion but need a slot for synchrotron radiation to escape (Figure 2). This slot introduces a defect that must be cancelled carefully by the magnetisation direction of the other pieces, so magnet field quality will be a focus of R&D for this application.



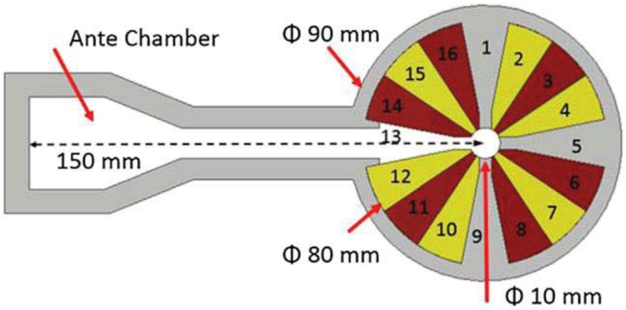


Figure 1 (above left). Transversely exaggerated trajectories of protons over the 65-250MeV energy range being transmitted through the hadron therapy gantry [1] to a focal point within the patient at bottom right. Figure 2 (above right). Schematic cross-section of permanent magnet and vacuum chamber for the NSLS-II upgrade [2]. Synchrotron radiation escapes through a slot, requiring a missing magnet segment.

Magnet Construction and Design Innovations

The typical method of construction of iron-free (Halbach-like) permanent magnets is to first order blocks or wedges of magnetised material from a supplier. The strongest commonly-used material is NdFeB but SmCo exhibits up to 10^4 times better radiation resistance, so it depends on application environment. A non-magnetic housing, typically aluminium for production or plastic for small R&D magnets, is machined and the blocks are forced into place using alignment channels while replacing non-magnetic blanks. Finally the magnets can be epoxied into place if additional restraint is needed.

This proposal will include some novel elements into the designs. Figure 3 shows the performance of an oval aperture quadrupole for horizontally extended beams, which produces 30% more gradient for the same quantity of magnetic material. Figure 4 shows a combined function dipole plus quadrupole magnet: this design can replace an offset quadrupole and needs less material for the same useful aperture because the offset quadrupole creates field in areas where there is no beam.

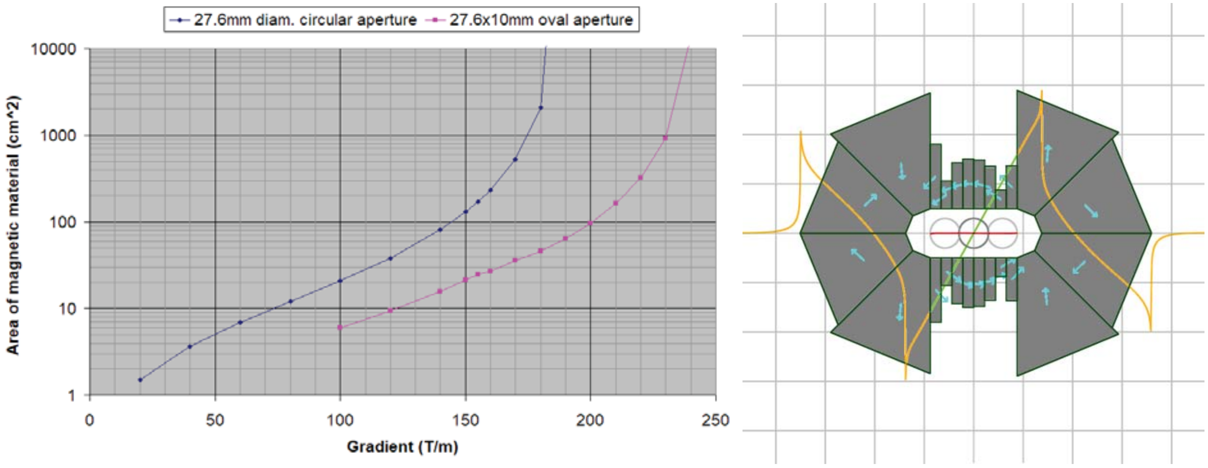


Figure 3. (left) Performance comparison of circular aperture Halbach quadrupoles with oval aperture quadrupoles with the same horizontal beam width. (right) Optimiser-produced design of an oval aperture permanent magnet quadrupole.

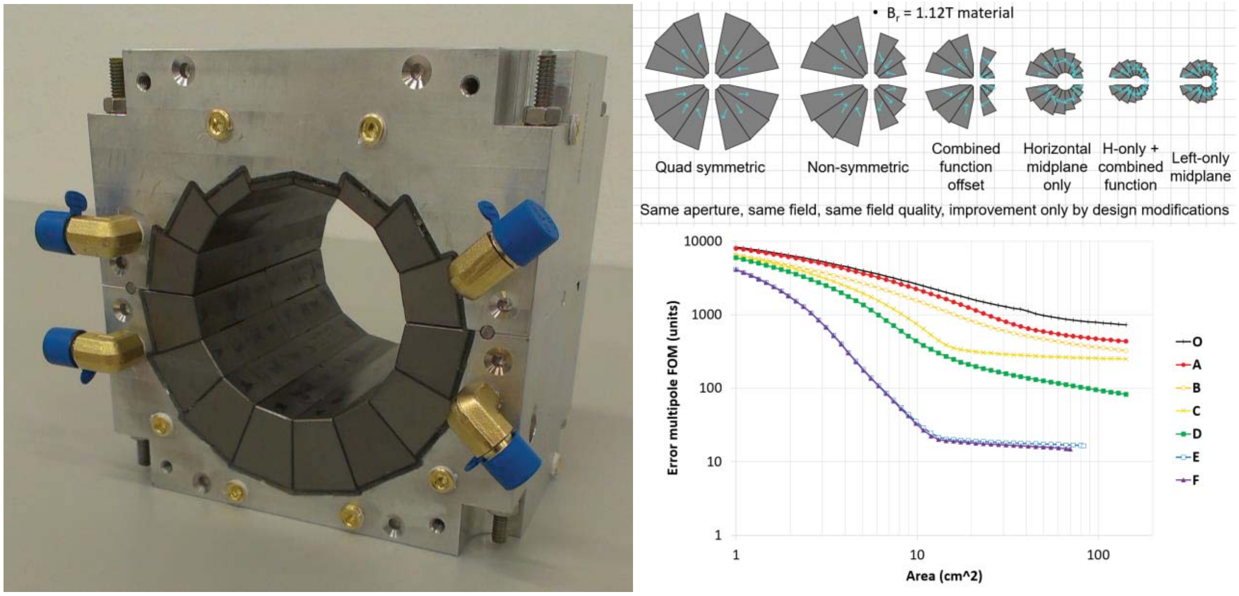
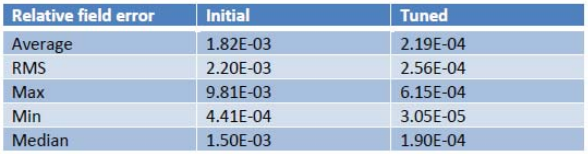


Figure 4. (left) Combined-function Halbach magnet used in CBETA, rotated 90°, low field region at top. (upper right) Design options for the CBII-D open-midplane magnet that produce the same field and field quality around the beam position; grid is cm^2. (lower right) Area vs. field quality comparison of options.

Iron Wire Tuning Method

Permanent magnet blocks typically have a ~1% strength variation when obtained from a supplier and this will be reflected in magnet field quality unless something is done about it. Traditional ways include block sorting or simply throwing away blocks that are outside a certain strength range. For CBETA, a field correction method was developed [4] that allows the use of all blocks and corrects the magnet field inside the aperture using small iron wires, as shown in Figure 5. This results in an ~8× decrease in field errors.

It is expected this method will be developed further for the smaller-aperture magnets in this proposal. The plastic wire holder takes up valuable aperture space, so may be replaced with small wires adhered between two pieces of tape. The wires may be placed accurately using a comb-like aligner and a negative comb to press them all onto the adhesive tape, which is then bent around the inside of the aperture.



Relative field error	Initial	Tuned
Average	1.82E-03	2.19E-04
RMS	2.20E-03	2.56E-04
Max	9.81E-03	6.15E-04
Min	4.41E-04	3.05E-05
Median	1.50E-03	1.90E-04

Figure 5. (left) Permanent magnet with tuning pack inserted. Variable length iron wires are visible in slots. (right) Summary statistics from field tuning of 216 magnets in the CBETA project.

Another option for placing the tuning wires recalls that for apertures as small as this, the vacuum pipe is highly integrated with the magnet, so grooves on the outside of the vacuum pipe itself may house wires.

Magnetic Field Measurement

For previous magnets, the Superconducting Magnet Division's rotating coil (Figure 6) was used for field harmonic measurements but in this proposal most of the apertures are too small for those rotating coils. NSLS-II has a spinning wire measurement system that is designed for small aperture magnets, which it is hoped to use. Other options include a vibrating wire with a variable offset to get a field profile across the magnet, or a small Hall probe scan to generate a field map. However, care must be taken with scannable probes that the position uncertainty does not dominate. The SMD rotating coil is accurate to 10^{-5} of the level of the main field component and typically magnets are corrected to 10^{-3} or 10^{-4}.

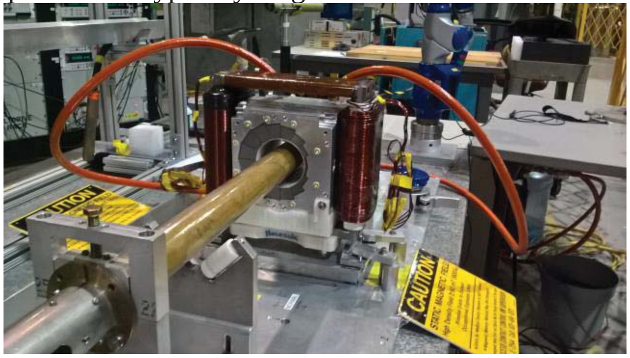


Figure 6. One of the tuned CBETA magnets being measured on BNL magnet division's rotating coil.

Prototypes Build Sequence

The open-midplane quadrupoles are the most requested design, so these can be built first. (1) A magnet around 50T/m would still have a large enough aperture to use the SMD rotating coil and could be an intermediate step before (2) constructing very small magnets up to 250T/m. Finally (3) an oval aperture gantry magnet could be built if time remains.

Each of these designs can first be built into (A) a magnetic field error and tuning demonstrator with a plastic-filled midplane for easier construction, followed by (B) an engineering prototype with real open midplane and its mechancial support, epoxy-glued magnets and water channels for temperature stabilisation. (C) Finally, a radiation damage test of the magnets can be conducted by placing them on the RHIC beam dump along with dosimeter foils, then remeasure.

Schedule and Milestones

1. Dec 2021. Complete designs for first round of prototypes and order magnet material pieces.
2. Mar 2022. Assembly of first magnet (without correction) completed.
3. Jun 2022. Magnet measurement system online and initial test.
4. Sep 2022. Measurement of first magnet completed and attempt at correction.
5. Dec 2022. Second round of designs complete, for more advanced magnets, improvements (NB: some applications require coordination with collaborators).
6. Jun 2023. Measurements of more advanced magnets.
7. Sep 2023. Concluding report including characterisation of all magnets.

References

[1] Dejan Trbojevic *et al.*, "Permanent Halbach Magnet Proton and Superconducting Carbon Cancer Therapy Gantries" Proc. IPAC2017; doi:10.18429/JACoW-IPAC2017-THPVA094 available from http://jacow.org/ipac2017/papers/thpva094.pdf

[2] G. Wang, T. Shaftan *et al.*, "Complex bend. II. A new optics solution", Phys. Rev. Accel. Beams **22**, 110703 (2019); doi:10.1103/PhysRevAccelBeams.22.110703

[3] Amin Ghaith *et al.*, "Permanent Magnet-Based Quadrupoles for Plasma Acceleration Sources", Instruments **2019**, 3, 27; doi:10.3390/instruments3020027

[4] Stephen Brooks *et al.*, "Permanent magnets for the return loop of the Cornell-Brookhaven energy recovery linac test accelerator", Phys. Rev. Accel. Beams **23**, 112401 (2020); doi:10.1103/PhysRevAccelBeams.23.112401