DoE STTR Phase II, Fiscal Year 2019

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PROJECT TITLE: **Novel Design for High Field, Large Aperture Quadrupoles for Electron-Ion Collider**

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TOPIC: **29** SUBTOPIC: **h**

STATEMENT OF THE PROBLEM OR SITUATION THAT IS BEING ADDRESSED

The proposed Electron-Ion Collider (EIC) needs several high-field, large-aperture quadrupole magnets in the interaction region (IR) for the ion or proton beams. These magnets should employ cost effective manufacturing techniques and must be able to accommodate the electron beam, which is close to the ion beam in the IR.

STATEMENT OF HOW THIS PROBLEM OR SITUATION IS BEING ADDRESSED

We are proposing to demonstrate a novel “modular design” concept based on simple racetrack coils. Magnets based on racetrack coils require less tooling and are generally less expensive to build. The modular quadrupole, like the Panofsky quadrupole, allows conductor at the mid-plane to be placed at a radius similar to the cosine two-theta magnets making it efficient. This is crucial to creating the high field gradient in quadrupoles. Although we emphasize the design of the Q1APF magnet as it is one of the most demanding in the EIC, the design technique is applicable to many of the quadrupoles of the IR whether made of NbTi or Nb_3Sn superconductor. In fact, a major advantage of the modular design is that it allows the same coils to be used in demonstrating several model magnets have different apertures.

WHAT WAS DONE IN PHASE I

We developed the modular design technology for high field gradient quadrupoles for the IR of an EIC. We explored two modular design options appropriate for the BNL Q1PF and the JLab QFFB1_US quadrupoles. Our analyses included both magnetic and structural designs.

WHAT IS PLANNED FOR THE PHASE II PROJECT

We plan to design, build and test a model of the Q1APF quadrupole for the EIC based on simple racetrack coils. The RHIC NbTi cable operating at 4.2 K satisfies the design requirements.

COMMERCIAL APPLICATIONS AND OTHER BENEFITS

The investigation of the modular quadrupole design to be done in this project will have an immediate use in the EIC, and it is foreseen to be valuable in the future development of high quality, high field gradient quadrupole magnets. It is expected that the design will facilitate cost effective, rapid-turn-around R&D programs that require feedback before freezing parameters and technologies.

KEY WORDS: superconducting quadrupoles, electron-ion collider, racetrack quadrupoles.

SUMMARY FOR MEMBERS OF CONGRESS

The proposed electron-ion-collider will require special high field quadrupole magnets for ion beams so that the close-proximity electron beams will not be deflected by the fringe field of the quadrupole. This proposal will explore alternative designs that should be less expensive and easier to build than conventional designs.

NARRATIVE SECTION

Novel Design for High Field, Large Aperture Quadrupoles for Electron-Ion Collider

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Proprietary Data Legend – Not Applicable: This proposal contains no proprietary data.

Project Overview

This project designs high-field, large aperture quadrupole magnets in the interaction region (IR) for the ion beam of the proposed Electron-Ion Collider (EIC). The goal of this proposal is to design, build and test a Proof-of-principle quadrupole magnet designed for the EIC based on NbTi racetrack coils within the budget of Phase II. We have chosen to build a short length model of the first IR quadrupole Q1APF, which is closest to the Interaction Point (IP) and is one of the most challenging. The current design requirements of this magnet can be met with NbTi superconductor, even though the modular design is attractive for Nb_3Sn as well. Included with this proposal package is the Phase I Final Report, which describes the analysis for an EIC quadrupole upon which this proposal is based. Also included are papers submitted to the ASC 2018 conference for publication.

Identification and Significance of the Problem or Opportunity

The Nuclear Science Advisory Committee (NSAC) recommended in the 2015 Long Range Plan [1] that an Electron Ion Collider (EIC) be the highest priority for construction in Nuclear Science. Two competitive designs are being considered for the EIC project. The design proposed by Brookhaven National Laboratory, the eRHIC project [2], is to use one of the existing RHIC collider rings for heavy ions or protons and construct a new ring in the existing tunnel for electrons. The design proposed by Jefferson Lab is to use the existing CEBAF ring to accelerate electrons and construct new “figure 8” shaped ion and electron collider rings [3]. Both proposed EIC projects require the development of several new technologies, one of which is the development of high-field-gradient quadrupoles needed to focus the proton and ion beams in order to achieve high luminosity in the interaction region (IR). Fig. 1 on the left shows the forward side (ion downstream) layout of the IR magnets for the baseline design [2]. Table I shows the magnet parameters of the eRHIC preCDR [4]. The separation of the ion and electron beams at the first IR quadrupole (Q1PF) is 15 cm at the upstream end of the magnet and 16.6 cm at the middle of the magnet. Q1PF is the most challenging quadrupole in the eRHIC layout. This magnet must provide a field gradient of ~140 T/m for the ion beam while not exposing the electron beam to a field more than ~10 gauss. Because of its large pole-tip field, the Q1PF quadrupole was planned to use Nb_3Sn superconductor.

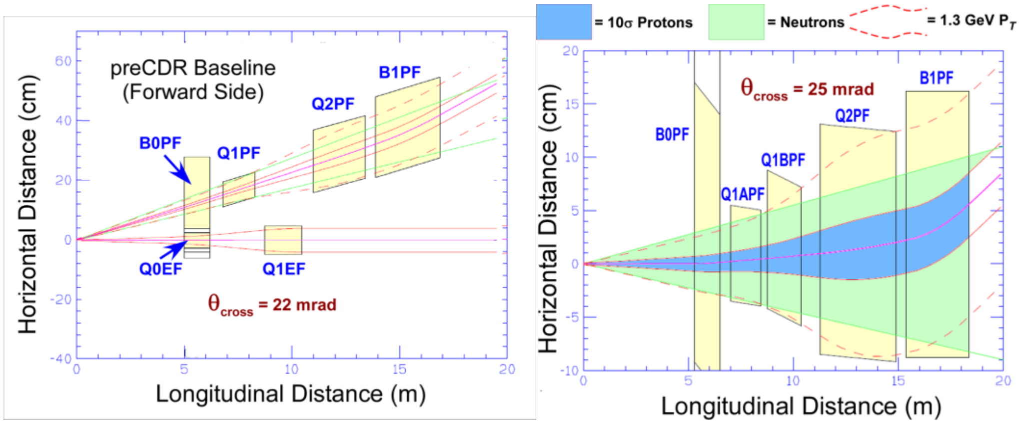
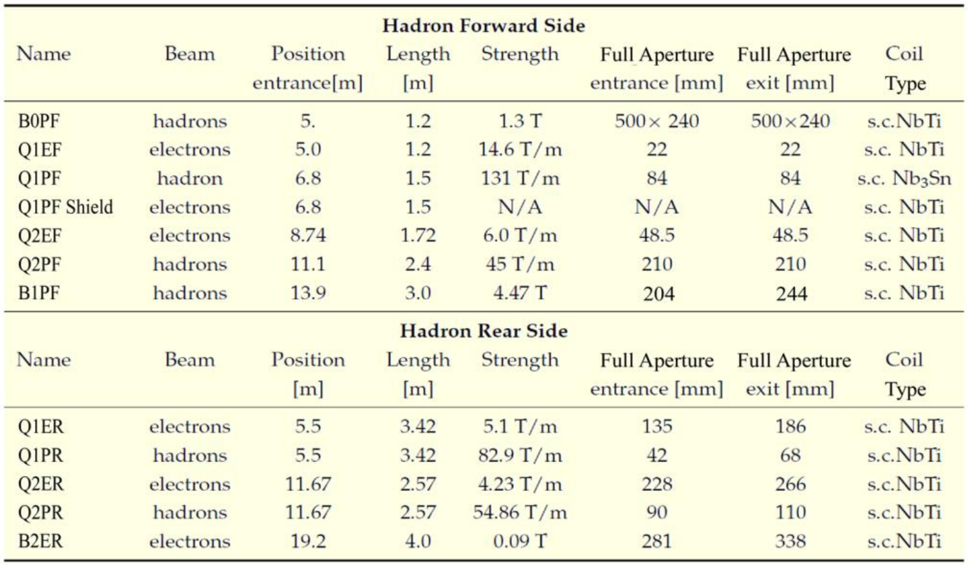


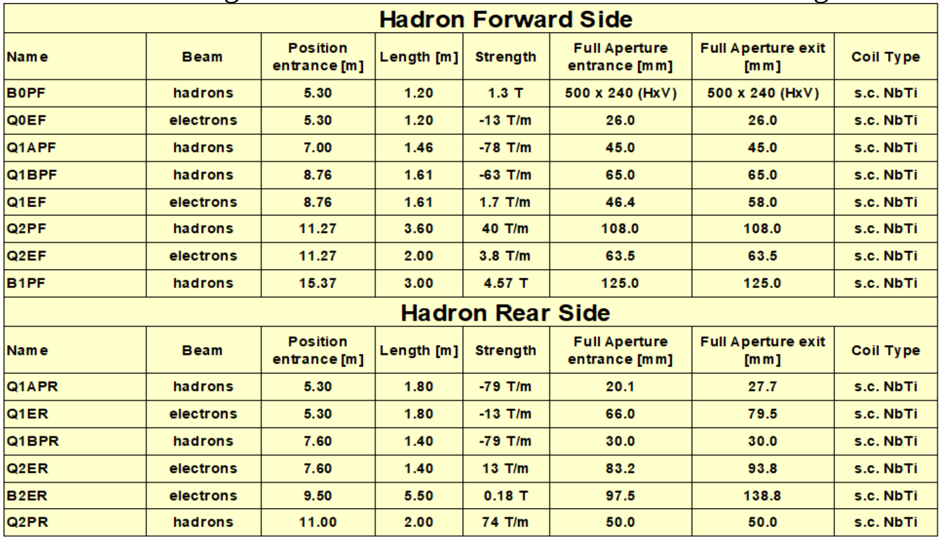
Figure 1: Layout of the upstream (ion beam) IR magnets for eRHIC. Design on the left is from preCDR baseline. On the right is the revised (but not yet released design).

Table I: IR Magnet Table from the eRHIC preCDR (baseline)



Hadron Forward Side							
Name	Beam	Position entrance[m]	Length [m]	Strength	Full Aperture entrance [mm]	Full Aperture exit [mm]	Coil Type
B0PF	hadrons	5.	1.2	1.3 T	500× 240	500×240	s.c.NbTi
Q1EF	electrons	5.0	1.2	14.6 T/m	22	22	s.c. NbTi
Q1PF	hadron	6.8	1.5	131 T/m	84	84	s.c. Nb_3Sn
Q1PF Shield	electrons	6.8	1.5	N/A	N/A	N/A	s.c. NbTi
Q2EF	electrons	8.74	1.72	6.0 T/m	48.5	48.5	s.c. NbTi
Q2PF	hadrons	11.1	2.4	45 T/m	210	210	s.c. NbTi
B1PF	hadrons	13.9	3.0	4.47 T	204	244	s.c. NbTi
Hadron Rear Side							
Name	Beam	Position [m]	Length [m]	Strength	Full Aperture entrance [mm]	Full Aperture exit [mm]	Coil Type
Q1ER	electrons	5.5	3.42	5.1 T/m	135	186	s.c. NbTi
Q1PR	hadrons	5.5	3.42	82.9 T/m	42	68	s.c.NbTi
Q2ER	electrons	11.67	2.57	4.23 T/m	228	266	s.c.NbTi
Q2PR	hadrons	11.67	2.57	54.86 T/m	90	110	s.c.NbTi
B2ER	electrons	19.2	4.0	0.09 T	281	338	s.c.NbTi

Table II: IR Magnet Table for the New eRHIC 25 mrad Configuration



Hadron Forward Side							
Name	Beam	Position entrance [m]	Length [m]	Strength	Full Aperture entrance [mm]	Full Aperture exit [mm]	Coil Type
B0PF	hadrons	5.30	1.20	1.3 T	500 x 240 (HxV)	500 x 240 (HxV)	s.c. NbTi
Q0EF	electrons	5.30	1.20	-13 T/m	26.0	26.0	s.c. NbTi
Q1APF	hadrons	7.00	1.46	-78 T/m	45.0	45.0	s.c. NbTi
Q1BPF	hadrons	8.76	1.61	-63 T/m	65.0	65.0	s.c. NbTi
Q1EF	electrons	8.76	1.61	1.7 T/m	46.4	58.0	s.c. NbTi
Q2PF	hadrons	11.27	3.60	40 T/m	108.0	108.0	s.c. NbTi
Q2EF	electrons	11.27	2.00	3.8 T/m	63.5	63.5	s.c. NbTi
B1PF	hadrons	15.37	3.00	4.57 T	125.0	125.0	s.c. NbTi
Hadron Rear Side							
Name	Beam	Position entrance [m]	Length [m]	Strength	Full Aperture entrance [mm]	Full Aperture exit [mm]	Coil Type
Q1APR	hadrons	5.30	1.80	-79 T/m	20.1	27.7	s.c. NbTi
Q1ER	electrons	5.30	1.80	-13 T/m	66.0	79.5	s.c. NbTi
Q1BPR	hadrons	7.60	1.40	-79 T/m	30.0	30.0	s.c. NbTi
Q2ER	electrons	7.60	1.40	13 T/m	83.2	93.8	s.c. NbTi
B2ER	electrons	9.50	5.50	0.18 T	97.5	138.8	s.c. NbTi
Q2PR	hadrons	11.00	2.00	74 T/m	50.0	50.0	s.c. NbTi

As a cost savings effort the IR magnet layout was redesigned so as not to have to use Nb_3Sn. Figure 1 (right) shows the new IP magnet layout, in which the former Q1PF is now split into two magnets with lower gradient requirements that can use NbTi superconductor. Table II shows the magnet parameters for the new IP layout. The separation of the ion and electron beams at the first IR quadrupole (Q1APF) is 17.5 cm at the upstream end of the magnet and 19.3 cm at the middle of the magnet. With the larger crossing angle the electron beam will clear both the Q1APF and Q1BPF quadrupoles if the standard cosine-two-theta design [4] with active shield for flux return is used.

Table III shows the parameters for the ion beam magnets in the JLEIC IP [5-7]. The upstream ion beam quadrupoles need substantial gradients, which will require Nb_3Sn conductor.

Table III: JLEIC Ion Magnet Parameters

		Requirements					Design				
Magnet Location	Magnet Type	Magnet Strength (T, T/m, T/m^2)	Magnetic length (m)	Good field region radius (cm)	Inner Radius (cm)	Outer radius (cm)	Inner radius (mm)	Coil inner radius (mm)	Coil width in radial direction (mm)	Coil outer radius (mm)	Peak field from VF (T)
Interaction Region (IR) Ion Quadrupole	QFFB3_US	-116	1	3	4	12	40	45.0	18	63.0	8.93
	QFFUS03S ***	-9.9	1		4	12	40	67.0	2	69.0	0.22
	QFFB2_US *	149	1.5	3	4	12	40	45.0	30	75.0	8.0
	QFFUS02S ***	5.30	1.5		4	12	40	77.0	2	79.0	0.2
	QFFB1_US	-141	1.2	2	3	10	30	34.5	18	52.5	7.9
	QFFUS01S ***	-14.4	1.2		3	10	30	57.0	2	59.0	0.24
	QFFDS01S	8.6	0.1		8.5	17.1	85	90.8	10	100.8	1.6
	QFFB1 **	-88	1.2	4	8.5	17.1	85	90.8	43.6	134.4	11.5
	QFFDS02S ***	-3.7	0.1		12.6	24.7	126	133.4	10.0	143.4	1.8
	QFFB2 **	51	2.4	4	12.6	24.7	126	133.4	45.0	178.4	10.3
	QFFDS22S ***	-5.5	0.1		12.6	24.7	126	133.4	10.0	143.4	1.8
	QFFB3	-35	1.2	4	14.8	26.7	148	155.0	38.0	193.0	8.5
	QFFDS03S ***	4	0.1		14.8	26.7	148	155	10	165.0	1.84
*		First Order Electromagnetic Optimization done and optimized design presented in rest of the paper									
**		First Order Electromagnetic Optimization done and optimized design presented in a separate section, magnet interaction is done without optimized design									
***		The peak field values are just for the skew quad alone, this value is higher when operated with the main quad									

Modular Approach

The cosine-two-theta design is efficient for the mass-production of magnets, as for arc quadrupoles. For applications where the requirement is for only one or two magnets of each design, or for an R&D project where one expects the magnet parameters to evolve, the modular design based on racetrack coils may be more cost effective. In mass production the cost of materials dominates the cost; for a limited number of units, the R&D and design costs may dominate. The coil configuration close to the beam is similar to that in the Panofsky quadrupole [8].

For the EIC (and particularly the JLEIC), several magnets have similar, but not identical designs and parameters. It is appealing to have the ability, particularly during the R&D phase, to rearrange the positioning of racetrack coils to adjust parameters such as the beam aperture. Moreover, designs based on racetrack coils are expected to have better quench performance than the more conventional designs, because conventional designs require complex ends to clear the bore tube; these ends are susceptible to quenching problems.

Technical Approach

Our approach is to design and fabricate a high gradient large aperture quadrupole magnet that could be used in the EIC IR to focus ion beams. In the EIC IR the electron and ion beams are in close proximity; the magnets must be designed so that the ion beam magnets don't deflect the electron beam. The electron beam must be in a region that is nearly free of field. We plan to use simple flat racetrack coils that are easier to wind and arrange them to produce a Panofsky style quadrupole. This scheme, which we refer to as "modular design" [9], has coils at minimal radial distance positioned at the mid-plane. Most quadruple designs that use flat racetrack coils use conductor inefficiently, with most of the conductor near the poles rather than the mid-plane [10-12], as can be seen in Fig. 2. These quadrupole designs sacrifice significant field gradient for the same coil width. Modular magnets with racetrack coils are simpler to wind and assemble than cosine-two-theta magnets however, they do require more conductor to achieve the same gradient.

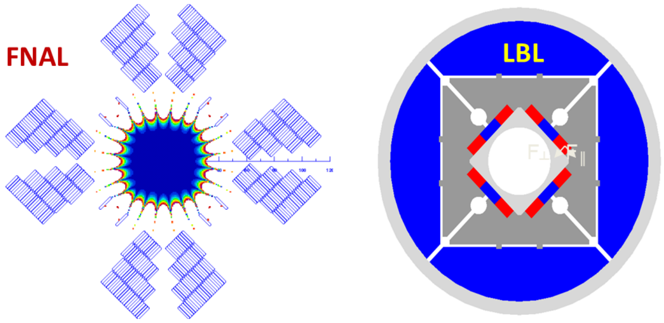


Figure 2: An earlier quadrupole design with flat racetrack coils from Fermilab [11] and LBNL [12]. In such designs, the turns at the mid-plane do not hug the bore tube closely.

Modular Designs

Figure 3 shows two variations of the modular design. The design on the right is the "simpler" model that requires only four racetrack coils; the design on the left is the "symmetric" model, which requires eight racetrack coils. Both of these designs produce similar quadrupole fields inside the inner square aperture. The simpler design lacks the eight-fold quadrupole symmetry in the cross section and consequently produces skew harmonics that are absent in magnets with quadrupole symmetry.

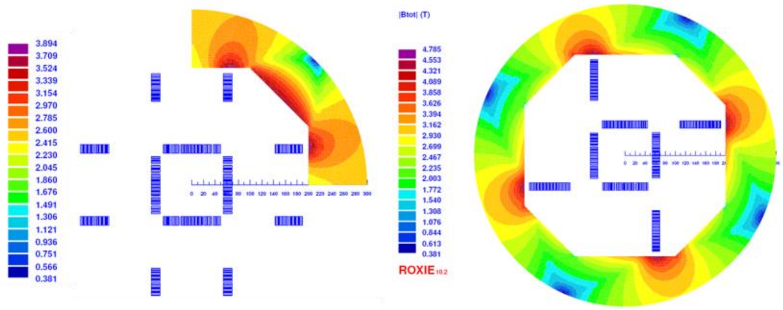


Figure 3: Two versions of the modular quadrupole designs. The one on the left is the symmetric design; the one on the right is the simpler design.

There are advantages and disadvantages to each of these designs. The simpler design requires only four identical racetrack coils. No interleaving between the coil pancakes is required to assemble the magnet. Although the simpler design generates skew harmonics in its natural coordinate system, the skew harmonics can be eliminated by properly optimizing the coil configuration and rotating the magnet when installed. We have shown this to be feasible. For the symmetric model, identical adjacent coils would interfere; adjacent coils must be of lengths sufficiently different to avoid the interference (see Fig. 4). This introduces an octopole harmonic in the end region of the coil. The symmetric design generally has smaller overall dimensions, because the current can return via both two sides.

Electron Beam Shielding

In both EIC projects the electron beam is in close proximity to the ion beam; the magnets closest to the interaction point of the electron beam can be deflected by the magnets for the ion beam. For the Q1PF magnet with the cosine-two-theta design, the magnet is surrounded by an active shield (coils outside the magnet) that buck the field producing a field-free region outside the magnet for the electron beam. In addition to field that punches through the iron there are also fringe fields at the magnet ends that can extend to the electron beam location. The modular design magnets have iron flux return yokes, which increase the outer radius of the magnet. One approach for the modular design magnet is to place the electron beam inside the return yoke, which would supply partial shielding. This is the favored approach for modular magnets, but it does put constraints on the radial size of the magnet. Figure 5 shows a sketch of one of the symmetric design quadrupoles simulated, which shows the cutout inside the yoke for the electron beam. This favors the symmetric design, because returning the current symmetrically on both sides reduces the transverse magnet dimensions. Without additional shielding the field at the electron beam would be 0.3 T, which is much too large. Superconducting shielding or mu metal surrounding the electron beam would be necessary. If the electron beam cannot be placed inside the iron of the return yoke, it could be placed in a low-field position in the magnet interior. Such a position does exist, because of field cancelations; however, design for the low-field position to be at the electron beam places constraints on the coil configuration. This can be overcome by using a superconducting shielding around the electron beam [13]. PBL has an SBIR grant to study shielding with superconducting materials [14].

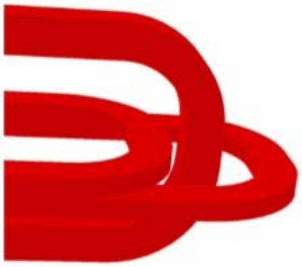


Figure 4: Schematic layout of coils in the end region of the magnet for the symmetric design. The length of each coil pancake is adjusted to accommodate the adjacent orthogonal coil.

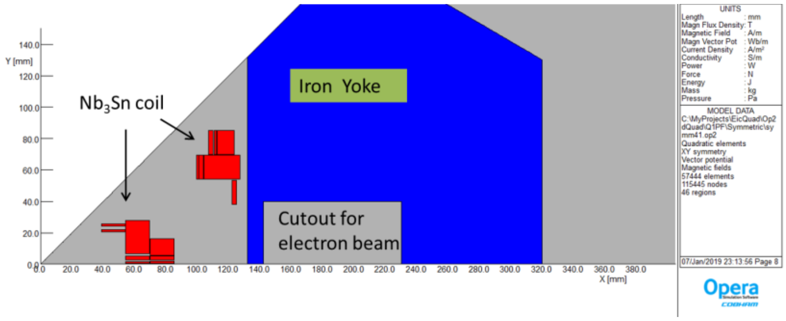


Figure 5: OPERA2d model of an octant of the symmetric modular design (configuration B) with two layers of optimized coils, in addition to a two-turn pole block. Return coil blocks are further away from the aperture. The rectangular cutout in the iron return yoke is for the electron beam pipe.

Quench Margins

Four modular design configurations were analyzed for quench margins. Table IV shows the layer, block and turn configurations for these cases. Figure 6 shows |B| on the inner coils of the symmetric configurations. The peak field is located at the pole regions. Table V shows the peak field for each of the design configurations. The quench field is calculated using Roxie [15] and is based on the LARP cable parameters [12] that were used. The load line percentage is the ratio of the peak field to the quench field. We would like a 15% quench margin—not met by the single layer cases C and D as designed, but attainable with a heftier cable. Improving the quench margin will be part of the Phase II study to improve the magnet cross section.

Table IV: Parameters Describing the Designs Considered.

Case	Layers	Blocks	Turn Configuration	Turns w/ return	Current in turn Amps	Configuration Type
A	2	7	28+28	112	9300	Symmetric
B	2+	8	1+18+16	70	12700	Symmetric
C	1	7	27	54	17000	Symmetric
D	1	5	2×(3+8+7+4+3)	50	17200	Simpler

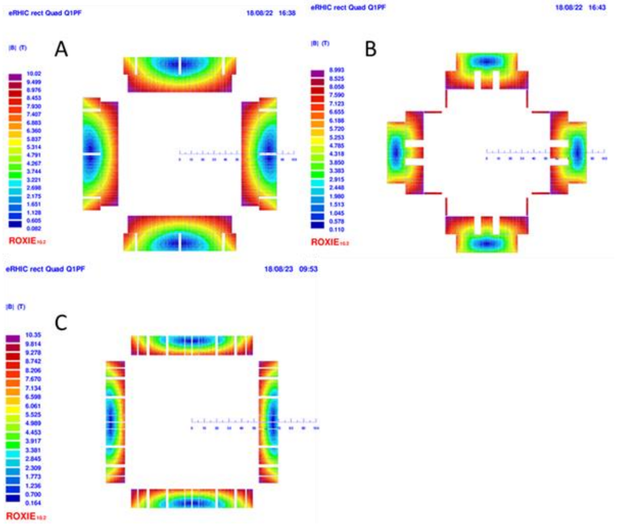


Figure 6: Contour plot of |B| on the inner coils for the symmetric designs, A, B, C.

Table V: Quench Margins for Modular Designs

Design	Current I, Amps	Peak |B|, T	Quench |B|, T	% Load Line	% Short Sample
A, symm	9008	9.7	15.5	62.7	58.6
B, symm	12700	9.1	12.5	72.8	29.4
C, symm	17000	10.4	11.7	88.2	19.4
D, simp	17073	10.4	11.8	88.7	18.7

Anticipated Public Benefits

The proposed modular design consists of simple flat racetrack superconducting coils that can be stacked as cassettes for carrying out systematic and varied magnet R&D within a Modular Program. This modular approach is expected to obtain results similar to the positive results obtained with the common-coil magnet design [18] that facilitated a cost-effective, rapid-turn-around R&D program. Such R&D is particularly useful in the early stages of an accelerator program in which the machine and magnet parameters cannot be frozen without a feedback from proof-of-principal magnets. This is also useful if several magnets of different apertures are needed. The benefit of such an approach is expected to be useful in other fields, such as in accelerators and beam-lines for high energy physics and medical applications.

The proposed project aims to benefit the science of building colliding-beam accelerators for nuclear physics research, so the most immediate beneficiaries are researchers working in nuclear physics around the world. The market for colliding beam accelerators is small when measured in number of units – typically only one or two devices are constructed every 10 to 20 years. However, the market as measured in dollars can be significant, with project costs typically at least hundreds of millions of dollars. Enabling supporting technology for such significant investments is important for the eventual success of the project, to get the most scientific output possible for the money spent.

Degree to which Phase I has Demonstrated Technical Feasibility

The complete results of the Phase I project are presented in the Final Technical Report. These are summarized here:

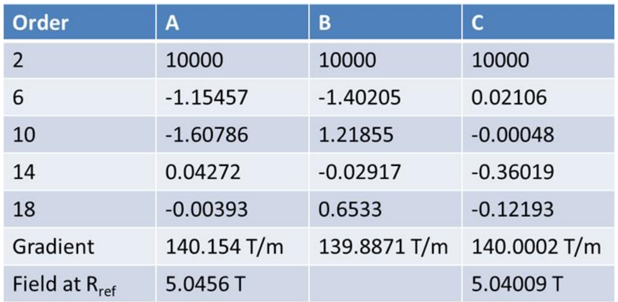
Magnetic design for the Q1PF quadrupole

We have examined the modular designs for both the “simpler” and “symmetric” configurations for the eRHIC Q1PF quadrupole. We have used both the Opera [19] and Roxie [15] electromagnetic simulation software for the analysis.

Roxie calculations

The Roxie program is most powerful in its optimization flexibility. We used Roxie to optimize the 2D cross section for three “symmetric” and one “simpler” configuration described in Table IV. The main differences between the configurations are number of layers and the turns per layer. The optimization varies the gap between coil blocks to minimize the field harmonics higher than the fundamental b_2. Table VI shows the field harmonics for the three symmetric configurations. The harmonics are normalized relative to the fundamental $10^4 \times B_2$. Harmonics of the order of unity are acceptable. Table VII shows the harmonics for the “simpler” case. Column 3 shows that there are large skew terms present. The skew terms can be eliminated by rotating the magnet during installation and minimizing the b_6, a_6 terms during optimization.

Table VI: Harmonics Calculated with Roxie for Symmetric Configurations



Order	A	B	C
2	10000	10000	10000
6	-1.15457	-1.40205	0.02106
10	-1.60786	1.21855	-0.00048
14	0.04272	-0.02917	-0.36019
18	-0.00393	0.6533	-0.12193
Gradient	140.154 T/m	139.8871 T/m	140.0002 T/m
Field at R_{ref}	5.0456 T		5.04009 T

Table VII: Optimized Harmonics for the Simpler Quadrupole

Order	Normal b_n	Skew a_n	Normal b_n'	Skew a_n'
			Rotated	Rotated
2	10000	-1561.86	10000	-0.16669
6	-0.02287	-0.77642	0.00084	0.0001
10	0.28870	-0.15468	0.25315	0.23133
14	-0.01696	0.02706	-0.04202	0.00959
18	-0.06562	0.00872	-0.01032	-0.06104

Opera calculations

We used the Opera program for both 2D and 3D analysis of the Q1PF magnet. The analysis in this section examines the symmetric configuration B. The Nb_3Sn coil cross section was optimized as in Fig. 5 to provide good field quality over the operating range. Figure 6 (left) shows the Opera2d |B| contour plot for the Q1PF. A profile of field along the mid-plane is shown in Fig. 6 (right). In the aperture the field increases linearly with a gradient of 140 T/m. In the yoke cutout for the electron beam the residual field is 0.3 T, which will have to be reduced by additional shielding. A similar analysis was performed for the simpler design.

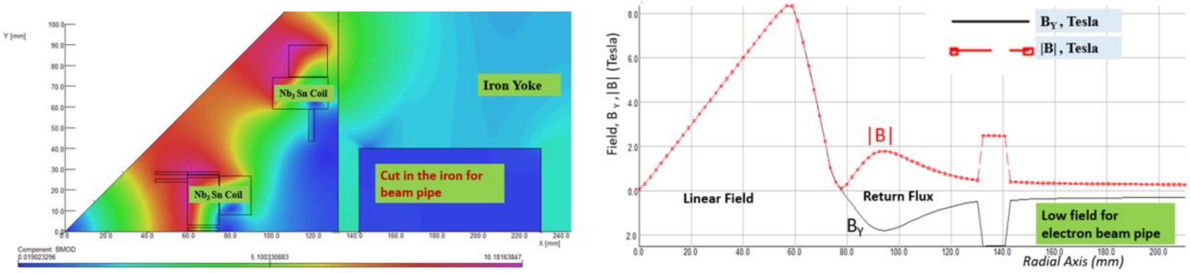


Fig. 6: (left) Contour of |B| for an octant of the symmetric modular design B. (right) Mid-plane profile of |B| and B_Y.

Tosca was used to analyze the 3D behavior of the magnet design, especially the field distribution along the beam axis, the integrated field harmonics, the stray field at the magnet ends, the field along the electron beam pipe, and the peak field. Figure 7 shows a schematic of 3D Q1PF magnet along with a |B| contour on the coil surfaces. In order to avoid interference in the ends of the symmetric coils, adjacent coils differ in length. Figure 8 shows the B_X(90°) and B_Y(0°) at the reference radius, R_{ref}, along the axial position. The integral field strengths, $\int B_{2x} \cdot dL$ and $\int B_{2y} \cdot dL$ at R_{ref} are 8.32 T-m and 8.35 T-m, respectively, a difference of 0.4%. The differencing coil lengths will also add 3 units to the integrated octupole component.

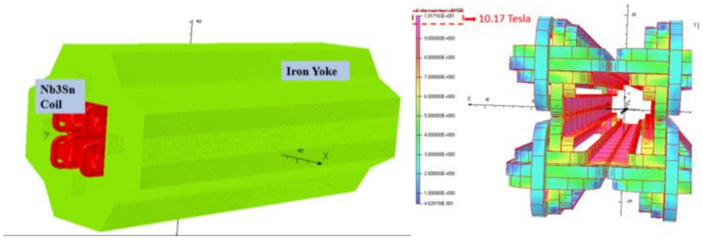


Fig. 7: (left) Schematic layout of Q1PF model used for Tosca. (right) |B| contour on the coil surfaces from Opera3d.

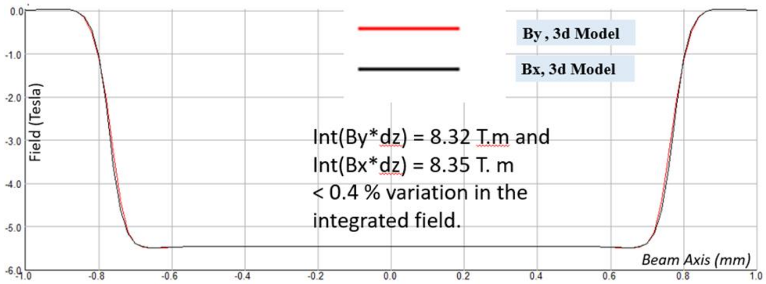


Figure 8: Field profile along the axial axis at R_{ref} = 36 mm.

For the symmetric design the Lorentz forces on the different length coils are 184 kN and 323 kN, respectively, in each quadrant. The unbalanced force toward the yoke is 140 kN in each quadrant. For the simpler model there are large Lorentz forces on each coil, even though the force on the total coil package is zero. The torque, τ_z = 61 MN-m, will be transferred to the yoke, which must be secured to external supports.

Mechanical Analysis and Structural Design

Mechanical analyses using ANSYS was performed independently by BNL engineers and PBL staff. The two analyses found similar results. Models of both the symmetric design A and the simpler design D were performed using finite-element structural codes. ANSYS was used to calculate the magnetic field, as shown in figure 9 for the simpler model. Because the structural simulation will use the same mesh as the magnetic, the forces are known locally.

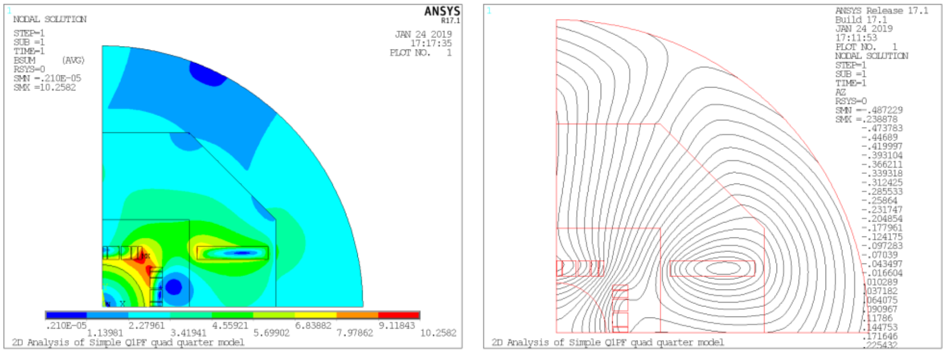


Figure 9: Contour plots of |B| (left) and A_z (right). The A_z contour plot shows the magnetic flux lines.

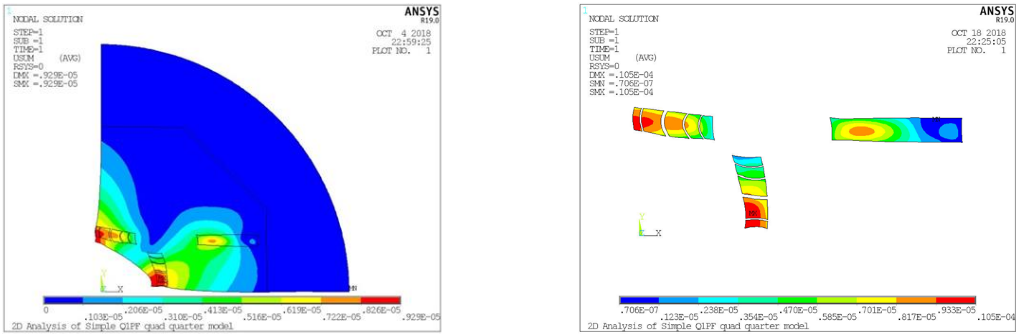


Fig. 10: Contour plot of nodal displacement for (left) simpler design and (right) for its coils.

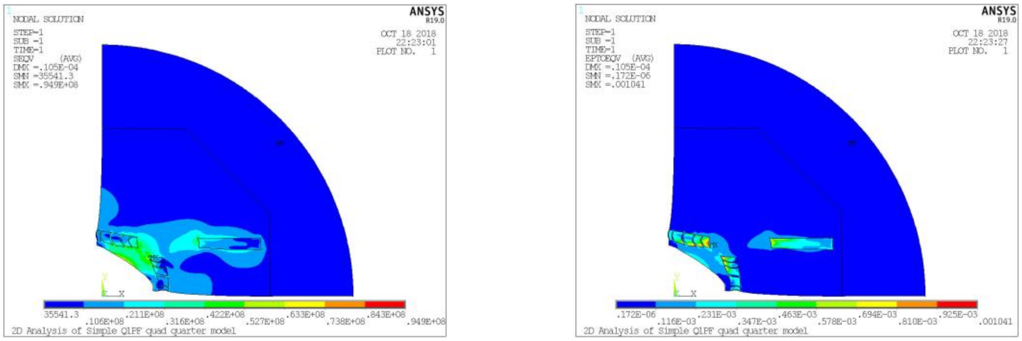


Fig. 11 Contour Plot of the Von Mises stress (left) and strain (right) for the simpler design

Figure 10 shows a contour plot of the distortions (exaggerated) to the magnet from the Lorentz forces. The plot on the right is an enlargement of the distortions of the coils. The maximum displacement is 10.5 μm, at the mid-plane of the coils. A similar analysis was made with the symmetric design, which is contained in the Phase I final report. Table VIII summarizes the maximum values of distortions, stress and strain for the simpler and symmetric designs.

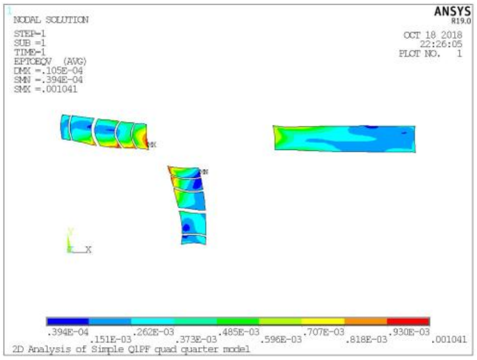
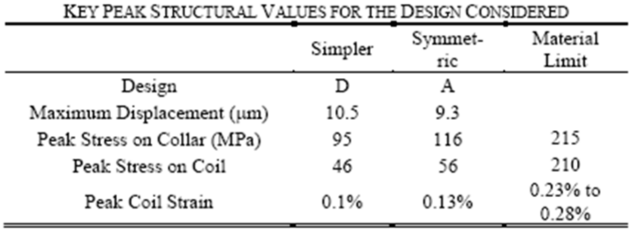


Figure 12: Von Mises strain in the coils for the simpler design.

Table VIII



KEY PEAK STRUCTURAL VALUES FOR THE DESIGN CONSIDERED

	Simpler	Symmet-ric	Material Limit
Design	D	A	
Maximum Displacement (μm)	10.5	9.3	
Peak Stress on Collar (MPa)	95	116	215
Peak Stress on Coil	46	56	210
Peak Coil Strain	0.1%	0.13%	0.23% to 0.28%

Proof-of-Principle Modular Design to be Built in Phase II

In the Phase II section of this proposal we describe a demonstration magnet that we are proposing to build. This magnet will follow the simpler modular design and use NbTi conductor (for budgetary reasons). This magnet will be shorter in length but will meet the other specifications of Q1APF, the first IR magnet in the latest design of eRHIC [5].

Flexible Design Structure for the Modular Design Concept

The modular design also offers a unique possibility to change quadrupole apertures while using the same coil modules. We carried out a simulation in which we moved the coil modules in the

Q1PF magnet design to create the aperture for the JLab quadrupoles QFFB1_US, QFFB2_US, and QFFB3_US, and were able to obtain good field quality. As an example, in the model of the Q1PF without return yoke (Fig. 13, left), coil modules are rearranged and moved towards the center by 10 mm to meet the requirement of JLAB QFFB1_US (Fig. 13, right). A plot of field contours on the surface of the Q1PF (left) and QFFB1_US (right) quadrupole conductor is shown in Fig. 14. The required engineering current density in QFFB1_US is about 85% of Q1PF, whereas the achieved field gradient is 5% higher. The modified model of QFFB1_US provides a field gradient 148 T/m (2.96 T at 0.02m); the peak field in the straight section of the coil is 8.1 T.

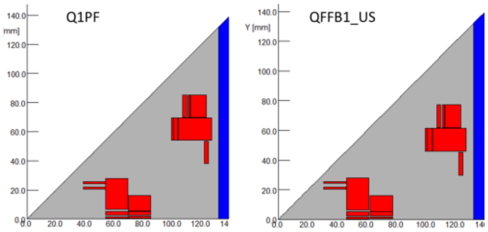


Fig. 13: The Q1PF coils (left) are rearranged inward to satisfy the requirements of QFFB_US.

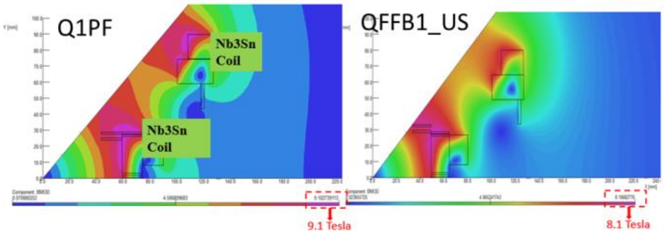


Fig. 14: |B| contour plot of the symmetric Q1PF and QFFB1_US magnets. The peak fields in the conductor is 9.1 T and 8.1 T for Q1PF and QFFB1_US respectively.

The Phase II Project

Technical Objectives

For the Phase II project we wish to design, fabricate and test a prototype of a large aperture high gradient quadrupole magnet that would be suitable for the EIC interaction region. Our Phase I analyses assumed Nb_3Sn conductor, to obtain the highest field gradient consistent with the desired quench performance, but the demonstration magnet coils will use NbTi to limit cost and because the eRHIC project has chosen to modify the IR magnet layout to accommodate the lowered gradient from using NbTi. For the demonstration magnet we will use the same NbTi conductor chosen by eRHIC. In Phase I we studied the symmetric and the simpler modular designs. Both designs would be acceptable, each with its own advantages and disadvantages; for the demonstration magnet we have chosen the simpler design. We will use a single pancake coil and optimize the magnet design to provide both good field quality and good quench margin. The magnet will be rotated during installation as shown in figure 15 to avoid the unwanted skew harmonics present in the simpler magnet design. This choice allows the fabrication of four identical racetrack coils without concern of interference between adjacent coils. This avoids the interference present in the symmetric design that requires adjacent coils to have different lengths, which creates an octupole harmonic at the ends of the coils. We would like to achieve a quench margin of at least 15%.

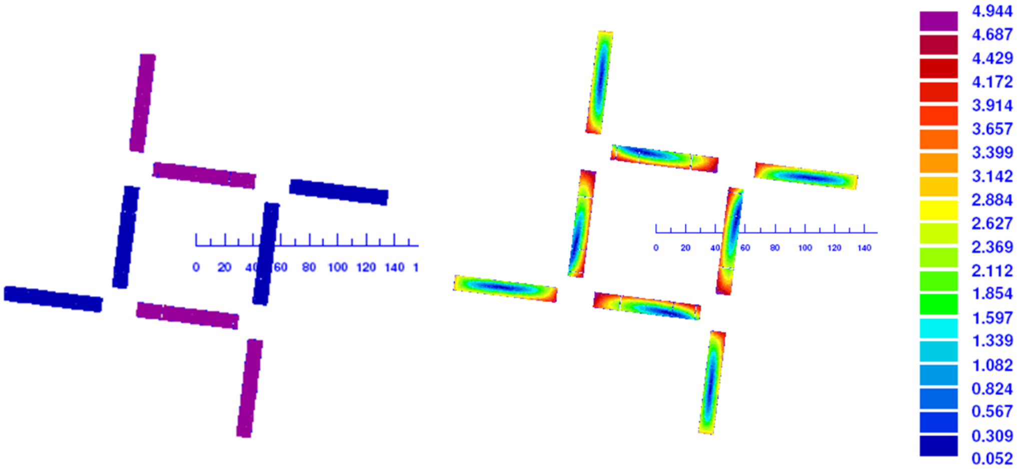


Figure 15: Rotated coils of the single layer simpler design proposed for Phase II. The sign of the current for each coil is shown on the left. The |B| contour at the coils is shown on the right.

The Phase II proposal has several objectives. We need to develop an assembly scheme for the magnet; the collaring scheme that is commonly used with cosine theta magnets is not practical for this design. The design should be developed to deliver the maximum field gradient consistent with a sufficient quench margin for large aperture quadrupole magnets. This R&D will be valuable for future accelerator projects.

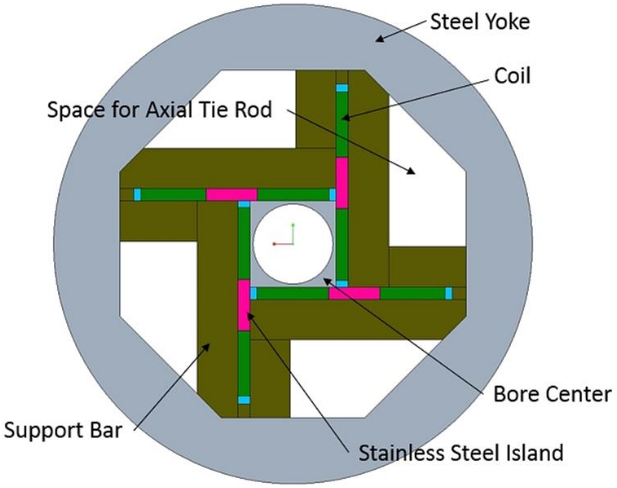


Figure 16: Sketch of the collaring support structure for the simpler magnet design.

Magnet Assembly

Figure 16 shows an initial sketch of a collar plan for the support of the racetrack coils with the simpler design. The design will use four double racetrack coils. Each single coil is wound onto a stainless-steel support piece (called island, magenta in the figure) and mated to a second coil. The inner coil lead splice is located inside cuts in the island. This arrangement simplifies lead design and has been used previously. The coils are easily removed and replaced in this coil support system. Unlike interlocking keyed collar laminations, the supports are a series of solid stainless-steel bars that run the full length of the coil, offering the same radial and azimuthal support to the coil ends as to the straight section. These bars are screwed together through holes in the coil islands. Inner support is offered by the square bore center insert; the coil axial torque is restrained by the octagonal inner surfaces of the steel yoke. The coil assembly is expected to be a precision running fit against the iron yoke, offering additional radial support to the coils. Coil replacement is a simple matter of disassembly involving no pressing, unkeying, or cutting. Coil sets of different dimensions would be accommodated by a different set of support bars dimensioned appropriately. The four large void spaces inside the iron provide space for stainless steel tie-rods attached to the end plates to provide restraint against axial forces.

Magnet Testing Program

The completed magnet will be tested in the magnet test facility at BNL. It will be tested at 4.3 K, to achieve the largest gradient consistent with the quench margin. Field harmonics will be measured at least at room temperature. The measured results will be compared with those calculated.

Phase II Work Plan

To meet the objectives mentioned in the previous section the following work plan for Phase II will consist of the following tasks:

Task 1: Perform a detailed magnetic design of the demonstration magnet.

The demonstration magnet should respond to the general specifications of the eRHIC Q1APF magnet, which is the closest quadrupole to the interaction point. This magnet will have the same beam aperture and will allow for the electron beam, even though in the demonstration there will be no beam and no “additional” superconducting shielding. The demonstration magnet will follow the simpler modular design that we have described, but we will upgrade the magnetic analysis to account for the eRHIC IR design changes. NbTi superconductor will be used for economy. The goal of this task is to optimize the design to provide good field quality and a quench margin greater than 15%. A complete magnetic analysis will be performed. This will be performed by PBL and BNL staff.

Task 2: Continued R&D for high gradient quadrupoles using Nb_3Sn conductor.

Although we do not plan to use Nb_3Sn conductor for this magnet, we will continue at some level to study its use for high gradient magnets. At this time JLEIC has not ruled out its use. Future projects are likely to need higher field and higher gradients. Accumulating the technical knowledge for these magnets is part of the business plan. This task will have lower priority but can be done in parallel to the other tasks. This will be done by PBL staff.

Task 3: Develop a strategic plan for the assembly of the magnet.

A plan of how to support the coils while winding on a mandrel, how to collar the coils, and how to insert the collared coil package into the iron yoke will be made. Figure 15 described above is a preliminary attempt at the assembly plan; this will be refined. Drawings based on the assembly plan will be made. This will be done by PBL and BNL staff.

Task 4: Perform a structural analysis for the demonstration magnet.

We will perform a structural analysis of the magnet consistent with the detailed magnetic design and the assembly plan. This will show deformations, stresses and strains on the yoke, collar and coils. We will use ANSYS for this task. This will be done by PBL and BNL staff.

Task 5: Procure superconductor and other materials.

We plan to use NbTi conductor. We will evaluate whether to use Rutherford style non-tapered cable (currently favored) or use the Direct Wind [20] approach, which might reduce tooling costs. If we use a Rutherford style cable, it is likely to be the same cable as chosen for other eRHIC magnets. The cable, stainless steel and iron along with other materials will be purchased. This will be performed by PBL staff.

Task 6: Finalize the engineering plans.

Make final CAD drawings. Verify the design. This will be performed by the BNL magnet division engineers with participation of PBL staff.

Task 7: Assemble the magnet.

This will be performed by the BNL magnet division technical staff with supervision of PBL staff.

Task 8: Test the magnet cold.

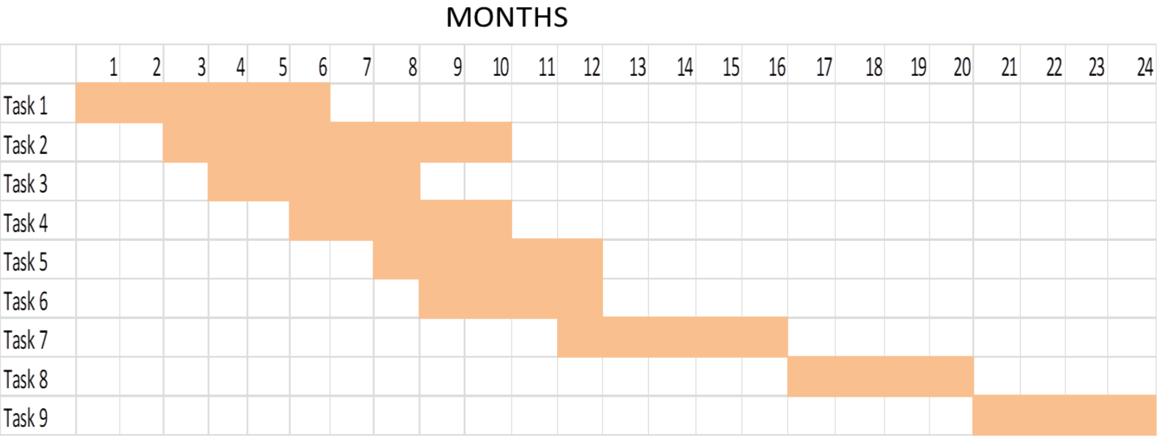
The magnet will be tested in the BNL magnet test facility at 4.3 K. The test program will measure the field harmonics and the quench margin. The test results will be compared to values calculated by the simulation programs. This will be performed by BNL and PBL staff.

Task 9: Document the results.

The results of this project will be documented in the final report. The construction, testing and analysis of the demonstration magnet will be published in journals. This will be done by PBL staff.

Performance Schedule (Tasks and Milestones)

The project duration will be 24 months. The following is the schedule of the tasks corresponding to the objectives listed in the work plan:



MONTHS

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Task 1	■	■	■	■	■	■																		
Task 2			■	■	■	■	■	■	■	■														
Task 3				■	■	■	■	■																
Task 4						■	■	■	■	■														
Task 5								■	■	■	■	■												
Task 6									■	■	■	■												
Task 7												■	■	■	■	■								
Task 8																	■	■	■	■				
Task 9																					■	■	■	■

Responsibilities

PBL, Inc.: The direction of the project is the responsibility of the company and the PI.
BNL: Dr. Ramesh Gupta will be responsible for the BNL sub-grant.

Managerial Controls for a Successful Project

To ensure a successful project, PBL will hold regular technical meetings and compare progress made against the performance schedule above. The technical staff will meet to ensure that important milestones are being met in a timely way. PBL senior management will also travel to participate. During each meeting, the team will identify any problems as well as ensure ways to solve them.

PBL has extensive experience with the DOE SBIR program, having completed several SBIR research efforts over the years. As such, PBL personnel are well versed in the reporting and administrative needs that will be an important part of the project proposed herein.

Related High Field Magnet R&D Engaged by the PBL/BNL Team

Over the years, the PBL/BNL team has been involved in various high field magnet SBIR/STTR R&D projects for high energy physics. The R&D proposed herein directly benefits from the technology generated and experience gained in those earlier SBIR/STTRs. This experience also helps in developing high field magnet technology for wider use. This point has been well recognized by professionals in the field as well as in the comments of various SBIR/STTR reviewers on previous submissions. This section will now highlight some of the important contributions made by the PBL/BNL team.

The PBL/BNL team has established a strong R&D position in HTS superconducting magnet technology [16, 21]. One of the outstanding accomplishments of this effort is the achievement of world record fields in HTS solenoids. One HTS solenoid designed and built through a PBL/BNL SBIR produced a field of ~16 T (a record field at that time), exceeding its nominal field by more than 30% [16]. Another major achievement of this team is the recent demonstration of a significant HTS/LTS dipole magnet [21], whose field remains a record at this time for a hybrid HTS/LTS dipole.

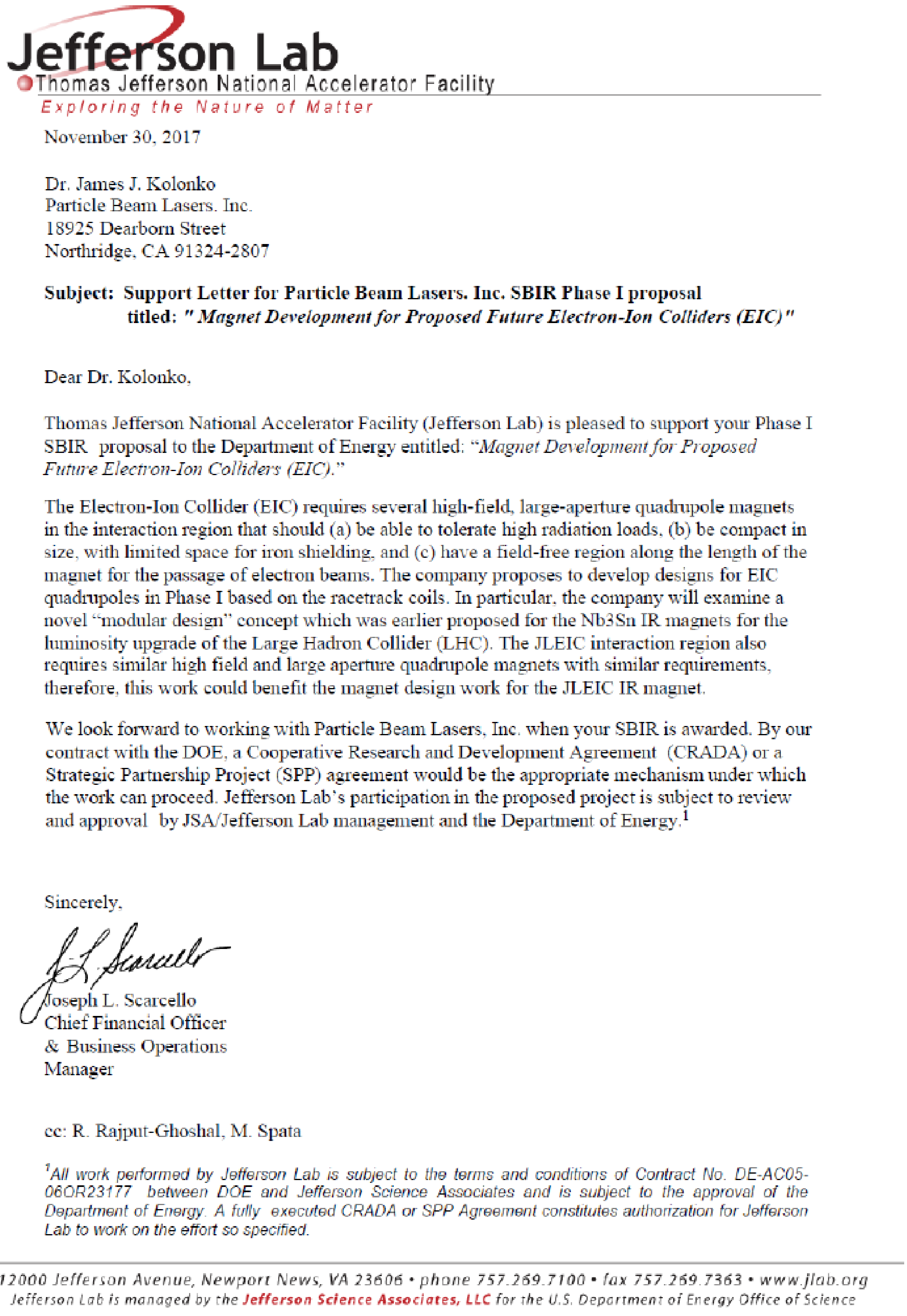
Facilities/Equipment

The Superconducting Magnet Division (SMD) at BNL has been a major force in the development of accelerator magnets for many decades. The Superconducting Magnet Division has extensive facilities for winding demonstration coils and for testing these coils. It also has access to simulation and engineering software tools that will aid in the design of coils and magnets. The design software available includes ROXIE, OPERA2d, OPERA3d and in-house software for magnetic design, ANSYS for mechanical design, and Pro/ENGINEER (PTC Creo Elements/Pro) and AutoCAD for engineering design.

The superconducting magnet division has a staff of about 30, including scientists, engineers, technicians and administrative staff. Construction and test of the pole coils will be carried out in a 55,000 ft^2 multipurpose R&D complex at the SMD. A prominent asset of the complex is an active cryogenic test facility, complete with high-current, high-resolution and high-stability power supplies.

The facility allows testing of a variety of superconductors, coils and magnets from ~2 K to ~80 K. Among the elements of the dedicated equipment in the facility are several computer-controlled, automated coil-winding machines, automated-cycle curing and soldering stations, centralized exhaust-vent systems, and hydraulic presses, all of which are available for use in the construction of superconducting magnetic devices. The building has several large-capacity (>15 ton) overhead cranes. Within the building complex are two machine shops with capacity to manufacture the majority of components needed for the R&D task. BNL also has a central machine shop and a procurement group to handle orders with private companies.

Letter of Support for Jefferson Lab



Jefferson Lab
Thomas Jefferson National Accelerator Facility
Exploring the Nature of Matter

November 30, 2017

Dr. James J. Kolonko
Particle Beam Lasers, Inc.
18925 Dearborn Street
Northridge, CA 91324-2807

Subject: Support Letter for Particle Beam Lasers, Inc. SBIR Phase I proposal titled: "*Magnet Development for Proposed Future Electron-Ion Colliders (EIC)*"

Dear Dr. Kolonko,

Thomas Jefferson National Accelerator Facility (Jefferson Lab) is pleased to support your Phase I SBIR proposal to the Department of Energy entitled: "*Magnet Development for Proposed Future Electron-Ion Colliders (EIC).*"

The Electron-Ion Collider (EIC) requires several high-field, large-aperture quadrupole magnets in the interaction region that should (a) be able to tolerate high radiation loads, (b) be compact in size, with limited space for iron shielding, and (c) have a field-free region along the length of the magnet for the passage of electron beams. The company proposes to develop designs for EIC quadrupoles in Phase I based on the racetrack coils. In particular, the company will examine a novel "modular design" concept which was earlier proposed for the Nb3Sn IR magnets for the luminosity upgrade of the Large Hadron Collider (LHC). The JLEIC interaction region also requires similar high field and large aperture quadrupole magnets with similar requirements, therefore, this work could benefit the magnet design work for the JLEIC IR magnet.

We look forward to working with Particle Beam Lasers, Inc. when your SBIR is awarded. By our contract with the DOE, a Cooperative Research and Development Agreement (CRADA) or a Strategic Partnership Project (SPP) agreement would be the appropriate mechanism under which the work can proceed. Jefferson Lab's participation in the proposed project is subject to review and approval by JSA/Jefferson Lab management and the Department of Energy.[1]

Sincerely,

J.L. Scarcello

Joseph L. Scarcello
Chief Financial Officer
& Business Operations
Manager

cc: R. Rajput-Ghoshal, M. Spata

[1] *All work performed by Jefferson Lab is subject to the terms and conditions of Contract No. DE-AC05-06OR23177 between DOE and Jefferson Science Associates and is subject to the approval of the Department of Energy. A fully executed CRADA or SPP Agreement constitutes authorization for Jefferson Lab to work on the effort so specified.*

12000 Jefferson Avenue, Newport News, VA 23606 • phone 757.269.7100 • fax 757.269.7363 • www.jlab.org
Jefferson Lab is managed by the Jefferson Science Associates, LLC for the U.S. Department of Energy Office of Science

Principal Investigator and Other Key Personnel

Dr. Stephen Kahn will be the project principle investigator. Dr. Kahn has 25 years of experience with superconducting accelerator magnets. He has worked as a PI on four previous SBIR grants. He has worked at the Advanced Accelerator Group at BNL on neutrino factory and muon collider R&D. His previous experience at Brookhaven has been broad, including work on high energy physics experiments (neutrino bubble chamber experiments and the D0 experiment) and superconducting accelerator magnets (for ISABELLE, RHIC, the SSC and the APT). Work to design superconducting magnets included 2D and 3D finite-element field calculations using the Opera2d and Tosca electro-magnetic design programs along with structural finite-element calculations with ANSYS.

Dr. Ramesh Gupta will be the BNL sub-grant Principle Investigator for this grant and will supervise the work performed in the Superconducting Magnet Division (SMD) at the Brookhaven National Laboratory (BNL). Dr. Gupta has more than three decades of experience in the design of superconducting accelerator magnets for various applications. His current interests include developing and demonstrating HTS magnet designs and technology for particle accelerators and beam lines.

Dr. Ronald Scanlan has had 35 years of experience in the field of superconducting magnets and materials at General Electric R&D Laboratory, Lawrence Livermore National Laboratory, and Lawrence Berkeley National Laboratory. From 1995 to 1999, he was Program Head for Superconducting Magnet Development at LBNL, during which time a world-record 13 T Nb_3Sn dipole magnet was built and tested. In 1991, he shared the IEEE Particle Accelerator Conference Award with Dr. David Larbalestier for “the development of NbTi superconducting material for high current density application in high field superconducting magnets”, and in 2011 he received the IEEE Council on Superconductivity award for “Continuing and Significant Contributions in the Field of Applied Superconductivity”.

Robert J. Weggel will be the PBL magnet designer for this Phase I project. He has been PI for PBL on several recent SBIR/STTR projects (see related research section). Mr. Weggel has had over 50 years of experience as a magnet engineer and designer at the Francis Bitter National Magnet Laboratory at MIT and Brookhaven National Laboratory and as a consultant in magnet design. In the course of his career he has authored over 100 peer-reviewed articles concerning resistive and superconducting magnets as well as hybrid high-field versions.

Dr. Erich Willen, a PBL employee, will contribute his expertise in the areas of magnet design and magnetic field quality. Recently, he served as PI on a related SBIR entitled “Magnet Coil Designs Using YBCO High Temperature Superconductor.” Dr. Willen became the head of the Magnet Division at BNL in 1984 and led the development of the SSC and RHIC superconducting magnets.

Consultants and Subcontractors

This grant application involves a formal collaboration between Particle Beam Lasers, Inc. and a research institution, Brookhaven National Laboratory (BNL). As can be found in the attachments found in block 12, what follows is the requested identifying information for this collaboration:
Name and address of the institution:

Brookhaven National Laboratory
Building 460
P.O. Box 5000

Upton, NY 11973-5000
Name, phone number, and email address of the certifying official from the RI:
Erick Hunt
Manager, Research Partnership
(631) 344-2103
ehunt@bnl.gov

Other Consultants and Subcontractors

BNL will be a subcontractor for the Phase II effort. There will be no other consultants or subcontractors on the Phase II effort. The value of the Phase II subcontract is $445000.

References and Bibliography

[1] 2015 NSAC Long Range Plan *"Reaching for the Horizon"*, October 20, 2015. https://science.energy.gov/~/media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf

[2] A. Arno et al., *"eRHIC Pre-Conceptual Design Report"*, Brookhaven National Laboratory, BNL Formal Report, BNL 205809-2018-FORE (2018).

[3] JLEIC Design Update (Oct. 2018) https://jleic-docdb.jlab.org/cgi-bin.public/ShowDocument?docid=273

[4] B. Parker and H. Witte, *"IR Magnet Layout & Design"*, https://www.jlab.org/indico/event/281/session/36/contribution/34/material/slides/0.pptx

[5] T. Michalski, et al., *"IR Magnet Layout/Design—JLEIC"*, https://www.jlab.org/indico/event/281/session/36/contribution/35/material/slides/0.pptx

[6] M. Wiseman, C. Hutton, F. Lin, V.Morozov, R. Rajput-Ghoshal, *"Preliminary Design of the Interaction Region Beam Transport System for JLEIC"*, Proc. of ASC 2018.

[7] R. Rajput-Ghoshal, R. Fair, P. K. Ghoshal, E. Sun, C. Hutton, M. Wiseman, *"Preliminary Design of the Interaction Region Beam Transport Systems for JLEIC"*, Proc. of ASC 2018.

[8] L. Hand and W. Panofsky, *"Magnetic Quadrupole with Rectangular Aperture"*, Review of Scientific Instruments, Vol. 30, No. 10 (1959).

[9] R. Gupta, et al., *"Modular Design and Modular Program for High Gradient Quadrupoles",* IEEE Transactions on Applied Superconductivity, vol. 17, No. 2 (2007).

[10] R. Gupta, et al., "*Next Generation IR Magnets for Hadron Colliders*," IEEE Transactions on Applied Superconductivity, Volume 13, pp. 1351-1354, June 2003.

[11] V.V. Kashikhin, J. Strait, A.V. Zlobin, "*2nd Generation LHC IR Quadrupoles Based on Nb3Sn Racetrack Coils*," Proceedings of the 2004 European Particle Accelerator Conference, Lucerne, Switzerland, July 2004, pp.1774-1776.

[12] P. Ferracin, et al., "*Development of a large aperture Nb3Sn racetrack quadrupole magnet*", IEEE Trans. Appl. Superconductivity, Vol. 15, No. 2, pp. 1132-1135, June 2005.

[13] D. Barna et al., *"NbTi/Nb/Cu multilayer shield for the superconducting shield (SuShi) septum"*,arXiv:1809.04330v1 (2018)

[14] R. Gupta, et al. *"Field Compensation in Electron-Ion Collider Magnets with a Passive Superconducting Shield",* Proc. of ASC 2018, 2LPo2K-08.

[15] Stephan Russenschuck, Roxie magnet optimization program. https://espace.cern.ch/roxie/default.aspx

[16] Gupta, R et al., "*High Field HTS Solenoid for a Muon Collider – Demonstrations, Challenges and Strategies*", IEEE Trans. on Appl. Supercond. 24, Article#: 4301705 (2014).

[17] S. S. Chouhan, et al., "Design and Fabrication of Iron-Dominated Magnets and Cryomodule Magnetic Shielding for the Re-Accelerator Project at MSU," IEEE Trans. On Applied Superconductivity, Vol. 24, No. 3, June 2014.

[18] R. Gupta et al., *"Common Coil Dipoles for Future High Energy Colliders"*, IEEE Transactions on Applied Superconductivity. Vol. 27, No. 4, 4000605 (2017).

[19] Opera Electromagnetic Simulation Software, Cobham Technical Services.

[20] B. Parker et al.,*"BNL Direct Wind Superconducting Magnets",* IEEE Trans. Appl. Supercond. 2012, vol. 22, Issue 3, DOI: 10.1109/TASC.2011.2175693. BNL-96547-2011-CP.

[21] R. Gupta et al., *"Design, Construction and Test of HTS/LTS Hybrid Dipole",* International Conference on Magnet Technology (MT-25), Amsterdam (2017)