PBL

Particle Beam Lasers

Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

A new medium field superconducting magnet for the EIC

PI: Ramesh Gupta, BNL

**PBL Team: James Kolonko, Delbert Larson, Steve Kahn, Ronald Scanlan,
Bob Weggel, Erich Willen, Al Zeller, Richard deHaas**

**BNL Team: Jason Becker, John Escallier, Kathleen Amm, Michael Anerella,
Andy Marone, Thomas Van Winckel, Anis Ben Yahia, Piyush Joshi**

Presentation Date: June 28, 2021 (as a part of Phase I PI meeting)

Overview

- **Particle Beam Lasers, Inc. (PBL) and major contributions of PBL/BNL team**
- **Optimum Integral Design and its benefits to Electron Ion Collider (EIC)**
- **Direct Wind Technology for one-off magnets to save expensive tooling cost**
- **Current status of the program**
- **Summary**

PBL/BNL Team

Current staff of Particle Beam Lasers, Inc. (PBL)

- James Kolonko (President, UCLA retiree)
- Delbert Larson (Senior Scientist, Vice President)
- Steve Kahn (Senior Scientist, BNL retiree)
- Ron Scanlan (Senior Scientist, LBNL retiree)
- Bob Weggel (Senior Engineer, FBNML & BNL retiree)
- Erich Willen (Senior Scientist, BNL retiree)
- Al Zeller (Senior Scientist, MSU retiree)
- Richard deHaas (Engineer and Senior Designer)

BNL staff expected to participate in Phase I & Phase II (if funded)

- Ramesh Gupta, Jason Becker, John Escallier, Kathleen Amm, Michael Anerella, Andy Marone, Thomas Van Winckel, Anis Ben Yahia, Piyush Joshi, and other designers and technicians, as needed

Previous PBL participants:

Fred Mills (FNAL)
Bob Palmer (BNL)
David Cline (UCLA)
Harold Kirk (BNL)
Albert Garren (LBL)
Shailendra Chouhan (MSU)

PBL SBIR/STTR Awards with BNL

1.	A 6-D Muon Cooling System Using Achromat Bends and the Design, Fabrication and Test of a Prototype High Temperature (HTS) Solenoid for the System.	DE-FG02-07ER84855	**August 2008**	**$850,000**
2.	Study of a Final Cooling Scheme for a Muon Collider Utilizing High Field Solenoids.	DE-FG02-08ER85037	**June 2008**	**$100,000**
3.	Design of a Demonstration of Magnetic Insulation and Study of its Application to Ionization Cooling.	DE-SC000221	**July 2009**	**$100,000**
4.	Study of a Muon Collider Dipole System to Reduce Detector Background and Heating.	DE-SC0004494	**June 2010**	**$100,000**
5.	Study of a Final Cooling Scheme for a Muon Collider Utilizing High Field Solenoids: Cooling Simulations and Design, Fabrication and Testing of Coils.	DE-FG02-08ER85037	**August 2010**	**$800,000**
6.	Innovative Design of a High Current Density Nb_3Sn Outer Coil for a Muon Cooling Experiment.	DE-SC0006227	**June 2011**	**$139,936**
7.	Magnet Coil Designs Using YBCO High Temperature Superconductor (HTS).	DE-SC0007738	**February 2012**	**$150,000**
8.	Dipole Magnet with Elliptical and Rectangular Shielding for a Muon Collider.	DE-SC000	**February 2013**	**$150,000**
9.	A Hybrid HTS/LTS Superconductor Design for High-Field Accelerator Magnets.	DE-SC0011348	**February 2014**	**$150,000**
10.	A Hybrid HTS/LTS Superconductor Design for High-Field Accelerator Magnets.	DE-SC0011348	**April 2016**	**$999,444**
11.	Development of an Accelerator Quality High-Field Common Coil Dipole Magnet.	DE-SC0015896	**June 2016**	**$150,000**
12.	Novel Design for High-Field, Large Aperture Quadrupoles for Electron-Ion Collider.	DE-SC00186	**April 2018**	**$150,000**
13.	Field Compensation in Electron-Ion Collider Magnets with Passive Superconducting Shield.	DE-SC0018614	**April 2018**	**$150,000**
14.	HTS Solenoid for Neutron Scattering.	DE-SC0019722	**February 2019**	**$150,000**
15.	Quench Protection for a Neutron Scattering Magnet.	DE-SC0020466	**February 2020**	**$200,000**
16.	Overpass/Underpass Coil Design for High-Field Dipoles.	DE-SC002076	**June 2020**	**$200,000**
17.	**A New Medium Field Superconducting Magnet for the EIC.**	**DE-SC0021578**	**February 2021**	**$200,000**

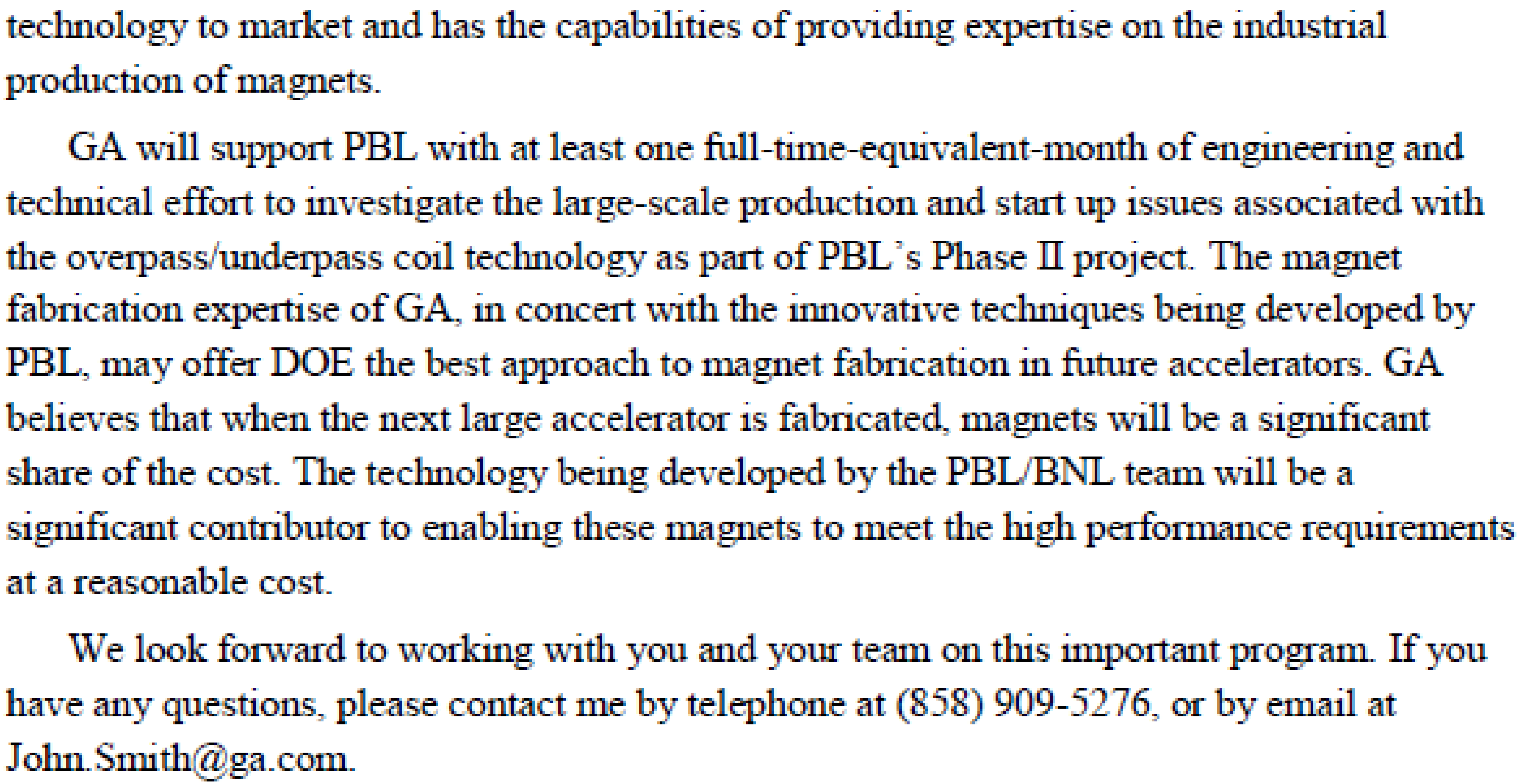
Other PBL Grants and Contracts

1. Design of a Multistage Electron Beam Collector to Enable Free Electron Laser Power Source Development.
   DE-AC02-86ER80388 July 1986 $49,290
2. Superconducting Magnet Development for Compact Storage Rings. DE-FG03-94ER81826
   August 1994 $75,000
3. Feasibility Study of Compact Gas-Filled Storage Ring for 6D Cooling of Muon Beams. DE-FG02-04ER84037
   July 2004 $94,527
4. A 6-D Muon Cooling System Using Achromat Bends. DE-FG02-07ER84855
   June 2007 $100,000
5. Professional Services provided BNL to investigate the energy deposition profile resulting from a 4MW proton beam impinging on the target system envisioned for a Muon Collider or Neutrino Factory. BNL Contract No. 200570
   August 2011 $24,000
6. Professional Services provided BNL to investigate the energy deposition profile resulting from a 4MW proton beam impinging on the target system envisioned for a Muon Collider or Neutrino Factory. BNL Contract No. 228502
   September 2012 $64,332
7. Professional Services provided the Fermi National Accelerator Laboratory for work On Design and Simulations: Front-End and Technology Development: Targets and Absorbers for the U.S. Muon Accelerator Program. Fermilab Purchase Order No. 615151 January 2014 $100,000

Recent Alignment of PBL with General Atomics

(for commercialization and taking technology to the next level)

From a recent letter of support:



technology to market and has the capabilities of providing expertise on the industrial production of magnets.

GA will support PBL with at least one full-time-equivalent-month of engineering and technical effort to investigate the large-scale production and start up issues associated with the overpass/underpass coil technology as part of PBL's Phase II project. The magnet fabrication expertise of GA, in concert with the innovative techniques being developed by PBL, may offer DOE the best approach to magnet fabrication in future accelerators. GA believes that when the next large accelerator is fabricated, magnets will be a significant share of the cost. The technology being developed by the PBL/BNL team will be a significant contributor to enabling these magnets to meet the high performance requirements at a reasonable cost.

We look forward to working with you and your team on this important program. If you have any questions, please contact me by telephone at (858) 909-5276, or by email at John.Smith@ga.com.

Major Contributions of PBL/BNL Team

- **Record field in an all HTS solenoid: 16 T (2012)**
  - ✓ Led to several other SBIR/STTR grants, HTS SMES program at BNL with ARPA-E which produced record high field, high temperature SMES (12 T, @27 K) and major HTS program at BNL
- **Record field in an HTS/LTS hybrid dipole: 8.7 T (2017)**
  - ✓ Led to several other SBIR/STTR grants, US Magnet Development Program (MDP) with DoE at BNL, which produced another record hybrid field of 12.3 T, and HTS background field test program for fusion and HEP community
- **Patents (awarded and in process)**

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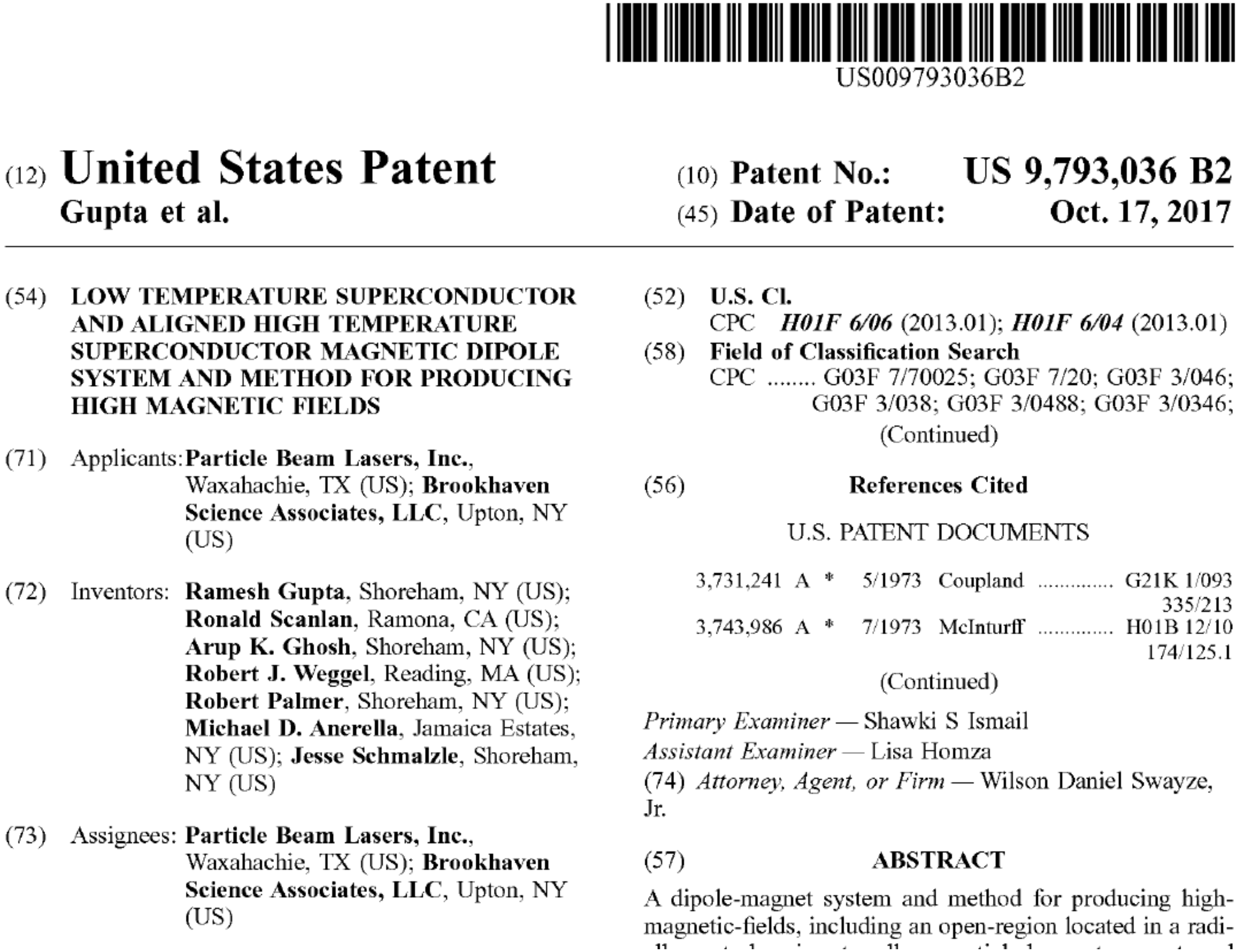
Patent Awarded and Application in Progress



US009793036B2

(12) **United States Patent**
Gupta et al.

(10) **Patent No.:** **US 9,793,036 B2**
(45) **Date of Patent:** **Oct. 17, 2017**

(54) **LOW TEMPERATURE SUPERCONDUCTOR AND ALIGNED HIGH TEMPERATURE SUPERCONDUCTOR MAGNETIC DIPOLE SYSTEM AND METHOD FOR PRODUCING HIGH MAGNETIC FIELDS**

(71) Applicants: **Particle Beam Lasers, Inc.**, Waxahachie, TX (US); **Brookhaven Science Associates, LLC**, Upton, NY (US)

(72) Inventors: **Ramesh Gupta**, Shoreham, NY (US); **Ronald Scanlan**, Ramona, CA (US); **Arup K. Ghosh**, Shoreham, NY (US); **Robert J. Weggel**, Reading, MA (US); **Robert Palmer**, Shoreham, NY (US); **Michael D. Anerella**, Jamaica Estates, NY (US); **Jesse Schmalzle**, Shoreham, NY (US)

(73) Assignees: **Particle Beam Lasers, Inc.**, Waxahachie, TX (US); **Brookhaven Science Associates, LLC**, Upton, NY (US)

(52) **U.S. Cl.**
CPC *H01F 6/06* (2013.01); *H01F 6/04* (2013.01)

(58) **Field of Classification Search**
CPC G03F 7/70025; G03F 7/20; G03F 3/046; G03F 3/038; G03F 3/0488; G03F 3/0346;
(Continued)

(56) **References Cited**

U.S. PATENT DOCUMENTS

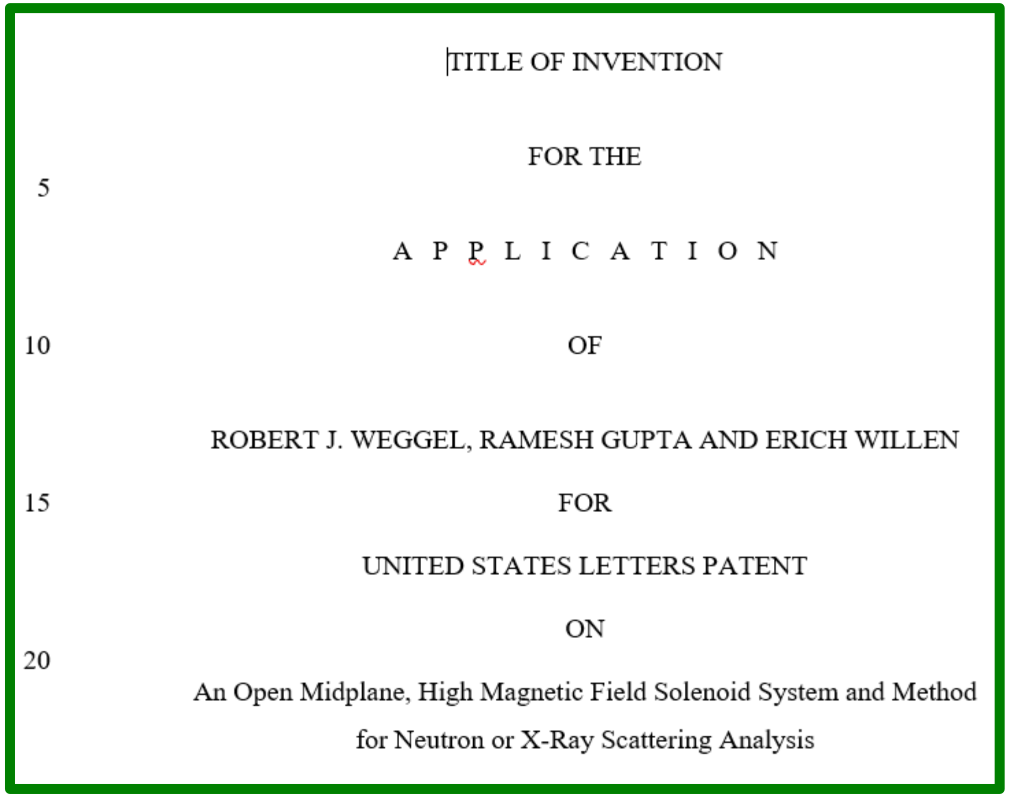
3,731,241	A *	5/1973	Coupland	....	G21K 1/093 335/213
3,743,986	A *	7/1973	McInturff	....	H01B 12/10 174/125.1

(Continued)

Primary Examiner — Shawki S Ismail
Assistant Examiner — Lisa Homza
(74) *Attorney, Agent, or Firm* — Wilson Daniel Swayze, Jr.

(57) **ABSTRACT**

A dipole-magnet system and method for producing high-magnetic-fields, including an open-region located in a radi-



TITLE OF INVENTION

FOR THE

APPLICATION

OF

ROBERT J. WEGGEL, RAMESH GUPTA AND ERICH WILLEN

FOR

UNITED STATES LETTERS PATENT

ON

An Open Midplane, High Magnetic Field Solenoid System and Method for Neutron or X-Ray Scattering Analysis

Contributions of SBIR/STTR Programs

- **Development listed in previous slides would not have been possible (some perhaps even not started) without the support of SBIR/STTR grants**
- **SBIR is facilitating development of those *"innovative designs" that* couldn't proceed without some initial proof-of-principle demonstration**
- **Specifically, DOE/HEP Phase I grant is facilitating a proof-of-principle demonstration of *"OverPass/UnderPass Design",* first presented in a paper in 2002 (now part of CERN's 20 T HTS dipole design).**

  Phase II applied for (award selection pending)

- **DOE/NP Phase I grant (this one) is facilitating a proof-of-principle demonstration of a medium field *"Optimum Integral Design"* first presented in a paper in 2004 (could become part of EIC)**

Optimum Integral Design

Conventional Magnet Design

Step 1: Optimize coil cross-section to obtain cosine theta distribution (spread out turns):

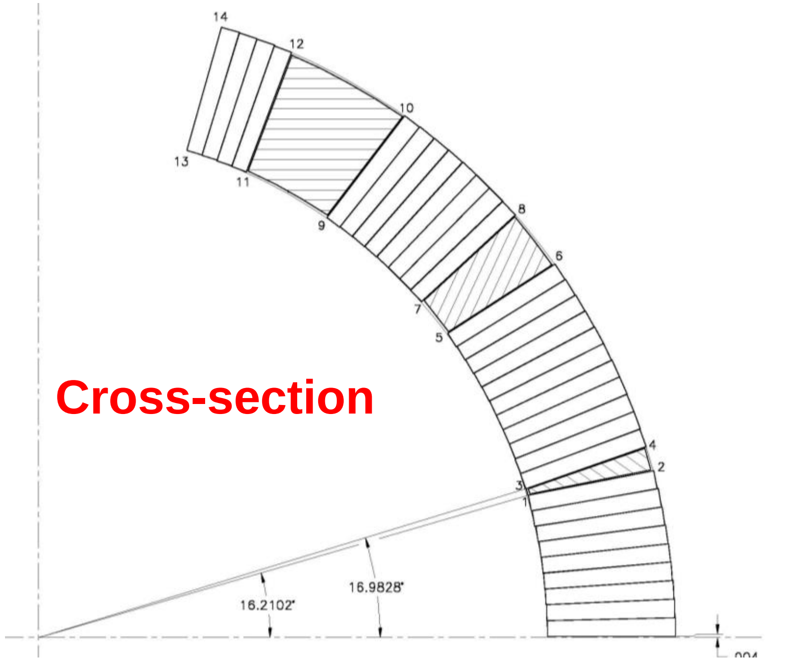
$$I(\theta) = I_o \ . \ \cos(n\theta)$$

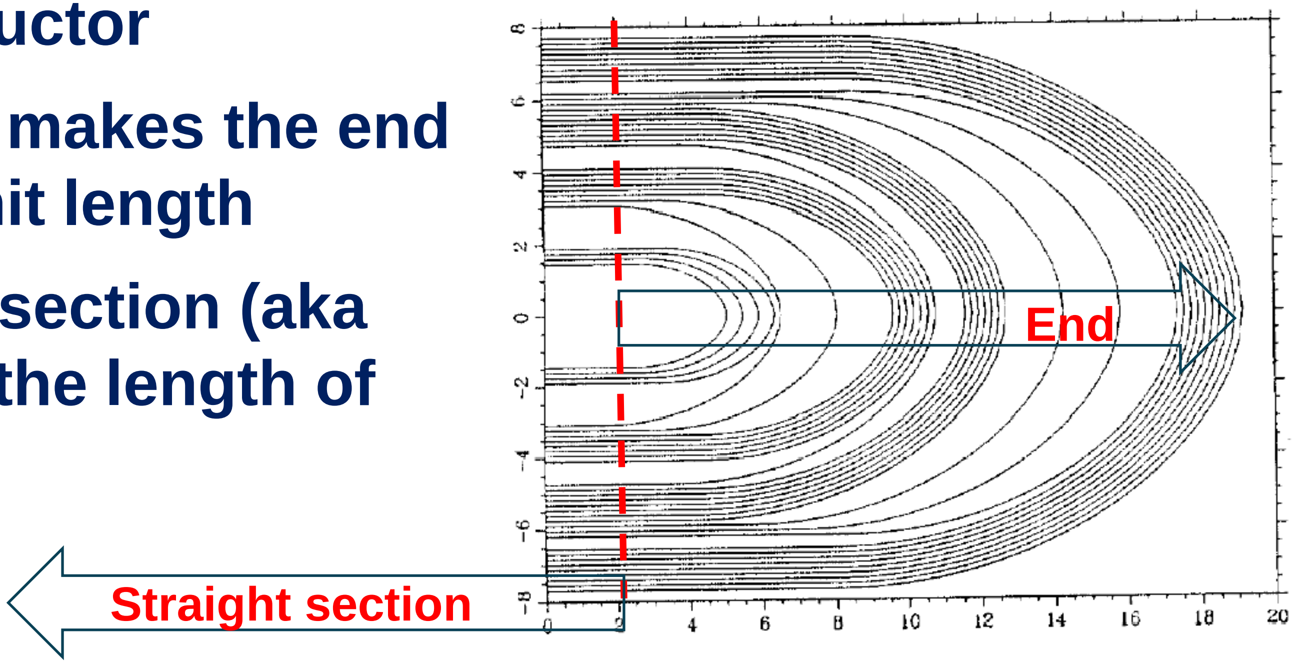
- ➢ **This limits the number of turns in straight section**

Step 2: Optimized ends to reduce integral harmonics, and to reduce peak field on the conductor

- ➢ **This spreads out turns in the ends, makes the end longer, and reduces the field per unit length**

Total coil length is length of the cross-section (aka straight section or magnet body) plus the length of the ends (two), optimized separately





Optimum Integral Design

- **A one step process to get a higher field integral**

Optimize cross-section and ends together to obtain an integrated cosine theta distribution:

$$I(\theta) . L(\theta) = I_o . L_i(\theta) \propto I_o . L_o . \cos(n\theta)$$

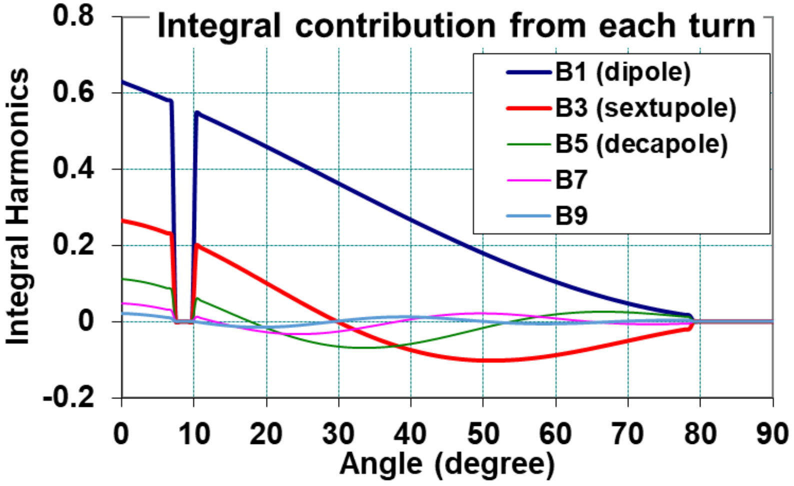
L: length of turn. Dipole and other multipole fields are generated by the length of the current-carrying turns in axial direction (solenoidal field gets cancelled).

Coil length becomes the magnetic length. Ends help in shaping the field rather than causing a loss

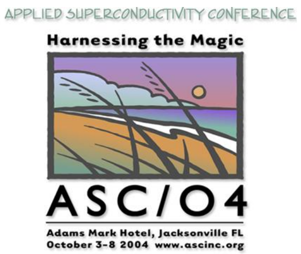
2004: 1st proposed for 0.008 T-meter corrector dipole

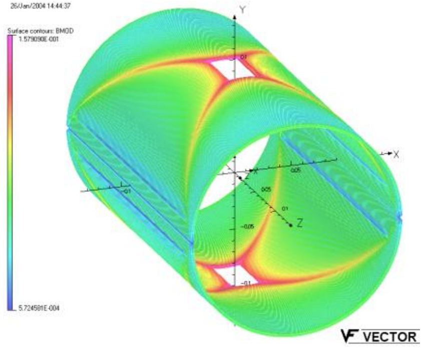
This STTR (2021): A significant dipole for 2 T-meter

- **A good field quality and medium field (3^+ T) required**



1st optimization by hand via excel





OPERA 3d Model

Motivation for the Optimum Integral Design

- In conventional designs, magnet ends take too much space and produce a fraction of the field per unit length of the cross-section (body) of the magnet
- A typical loss for dipole is about one coil diameter
- To compensate for that, the field in the body of the magnet (also in the ends) must be increased
- The relative increase in field becomes significant in short magnets, such as in some EIC magnets
- Optimum integral design overcomes above loss
- The design is well suited for several EIC Interaction Region (IR) magnets. B0APF has a coil diameter of 120 mm and length of 600 mm, means a 20% loss
- The design, however, must be proven before it can be used in any major application. Phase I will do that at a lower field; Phase II, if funded, at the design field

RHIC Coil End (conventional)

EIC Coil End (conventional)

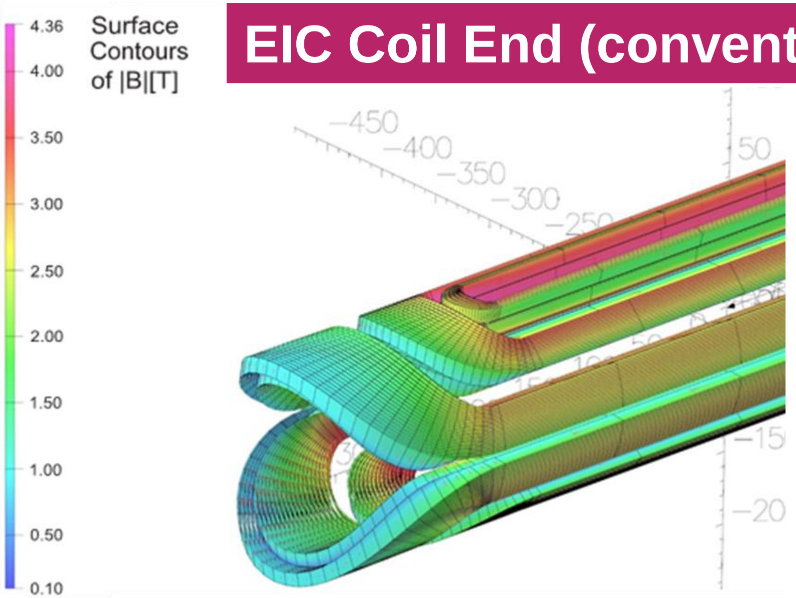
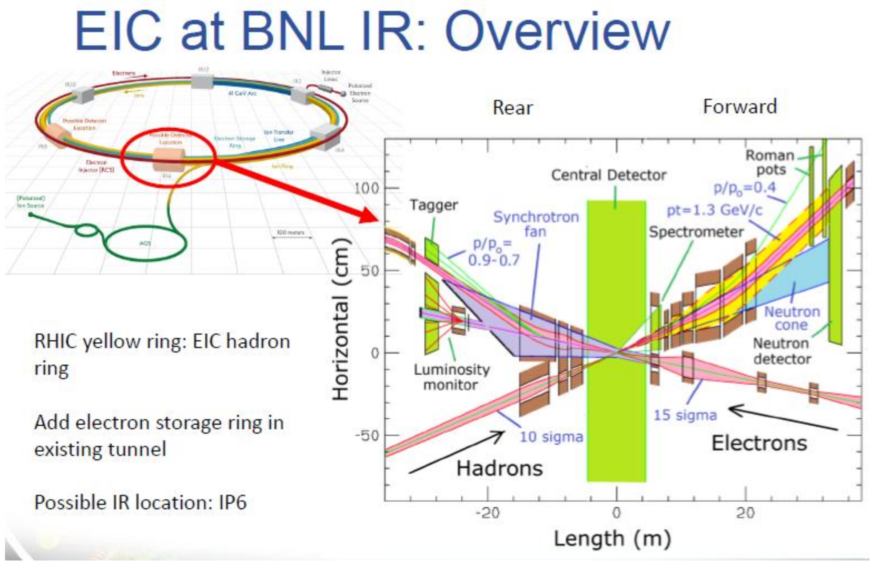


Figure 5: *B0APF coil with field contour*

Benefits of Optimum Integral Design for other EIC Magnets

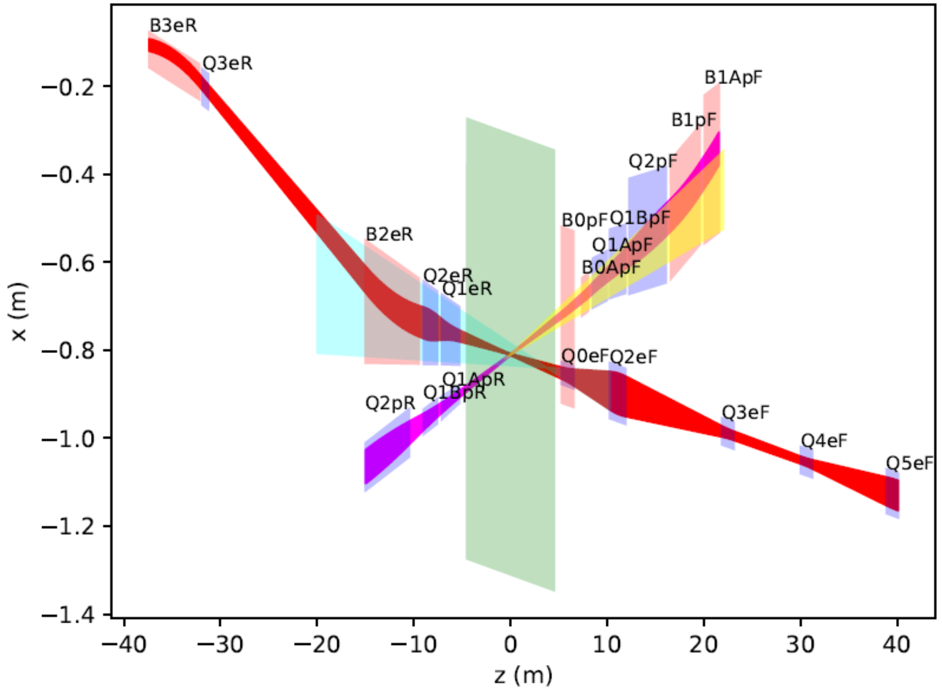
- Many EIC IR magnets; are relatively short and only one-of-a-kind are required
- EIC IR magnets are not trivial magnets as the aperture is large and typical field requirement is 3 T or more (RHIC dipoles operate at ~3.5 T)
- These magnets can greatly benefit from the optimum integral design, since reducing field by 10-20% will make them much less challenging
- Optimum integral design is not part of EIC or any major accelerator program. However, once demonstrated with a proof-of-principle magnet for field, field quality and aperture in the range of interest, the benefits of the design should make it


EIC at BNL IR: Overview

RHIC yellow ring: EIC hadron ring

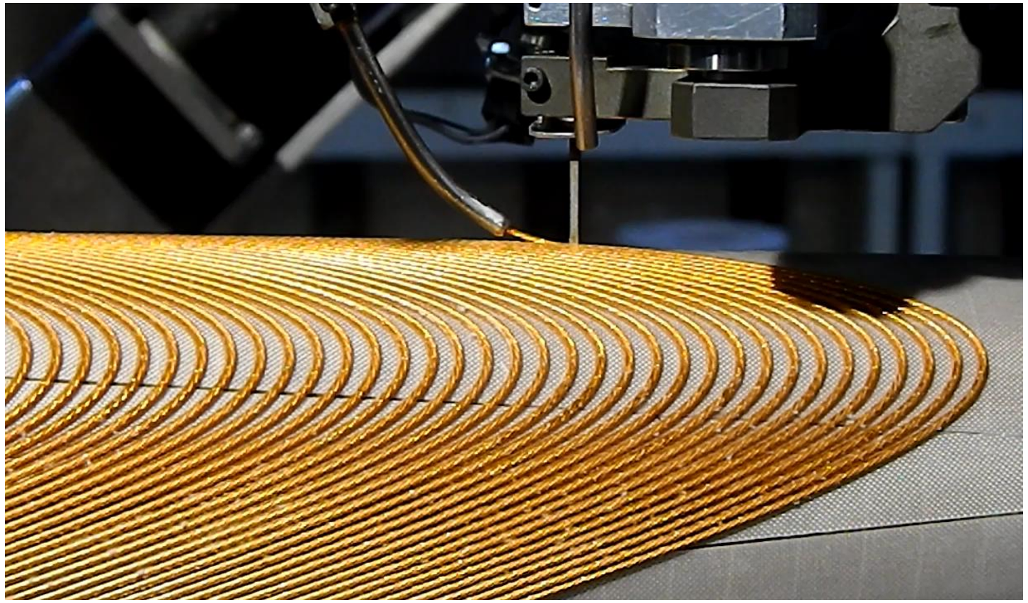
Add electron storage ring in existing tunnel

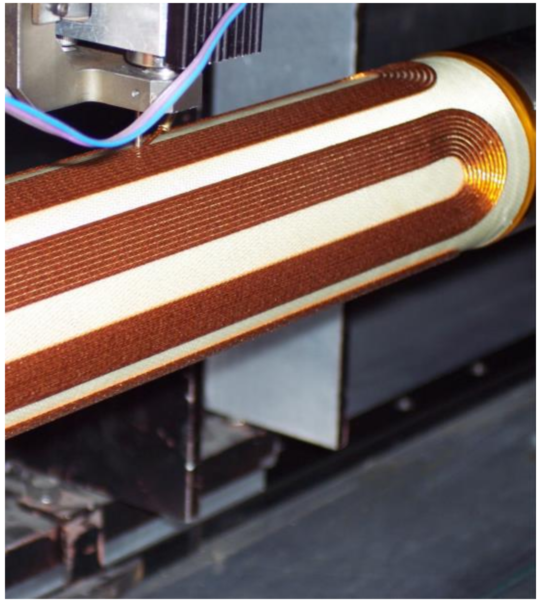
Possible IR location: IP6

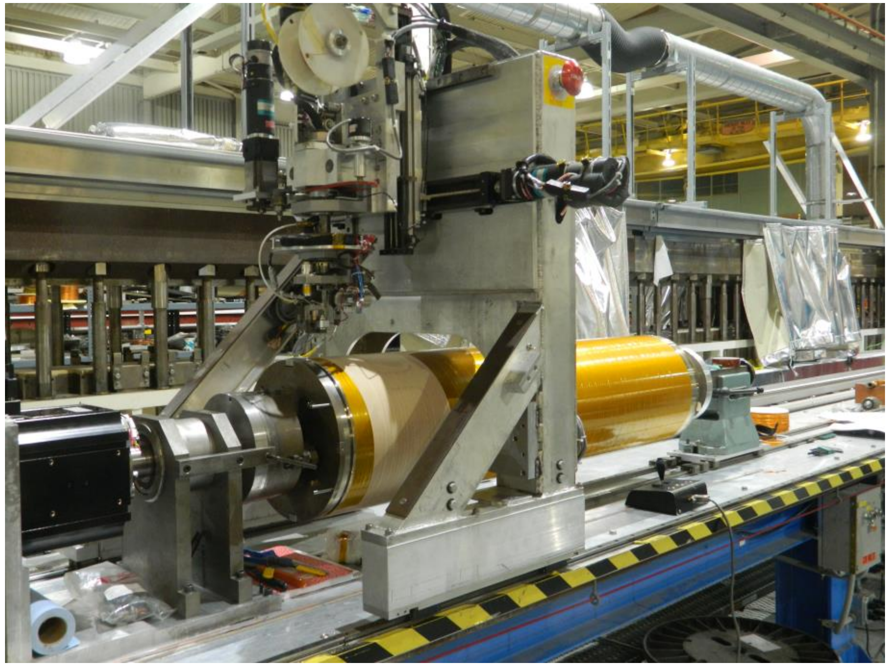


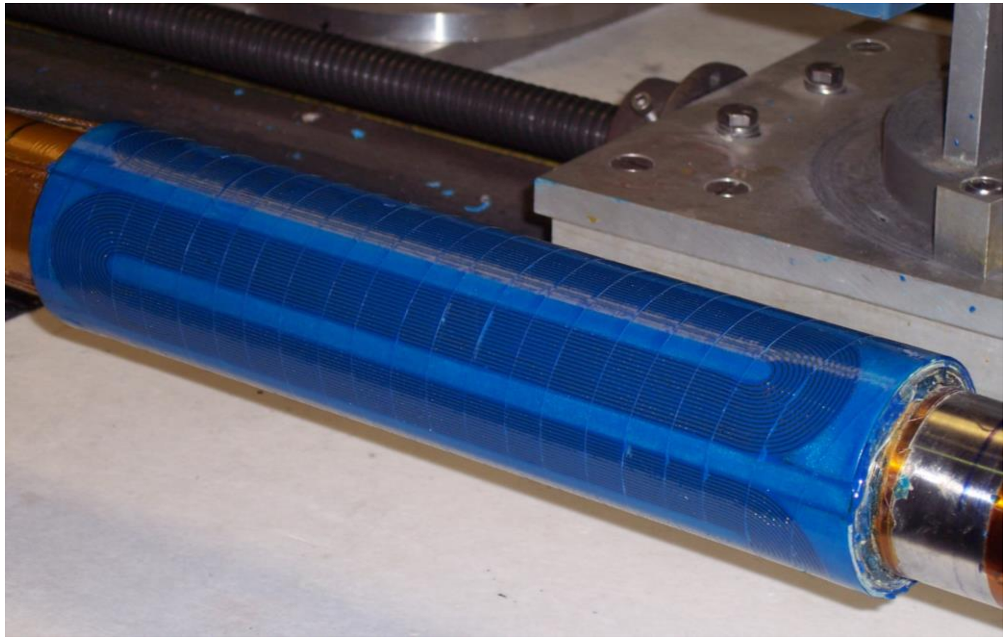
Direct Wind Technology

- Wire is laid directly on the tube and bonded with ultrasound onto a substrate.
- Gaps are filled with matched expansion material
- Pre-stress is applied with S-glass pre-peg roving
- This is an inexpensive technology for one-off magnets. It doesn't require tooling, and design work and has been reliable for low field magnets









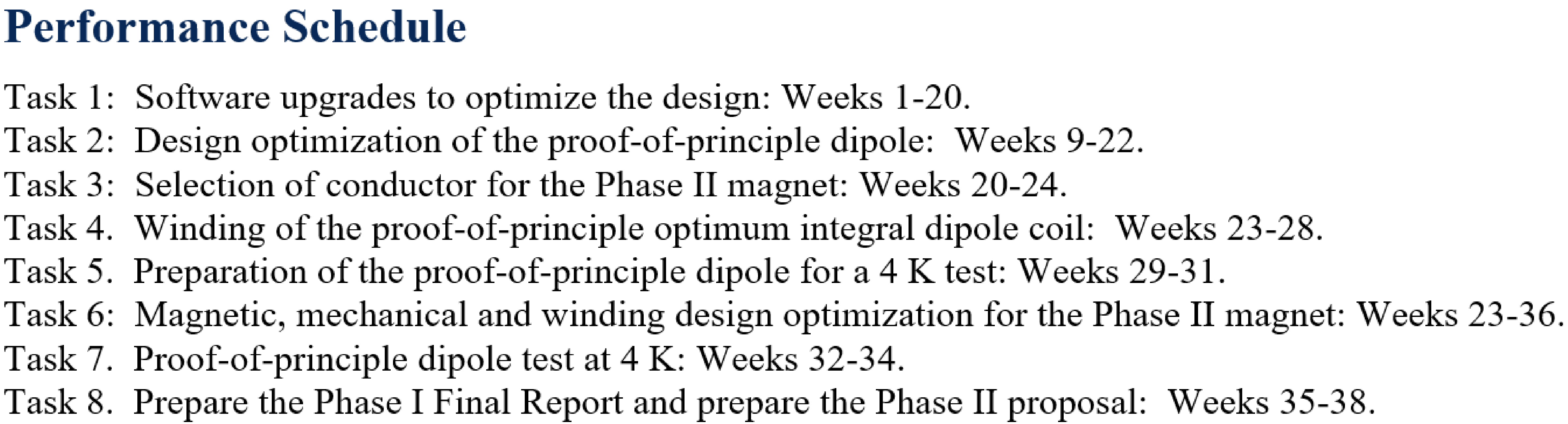
Current Status of the Program

Programmatic Challenges and Mitigation

- PBL/BNL team has proposed to design, build and test a ~2 T superconducting dipole magnet in Phase I itself
- This is very ambitious in a short period of Phase I (~ 6 months after all administrative work done) vs. 2^+ years generally required
- PBL started work before BNL – delivered tube, worked on software
- BNL management approved and gave an advanced bridge loan
- Direct wind technology doesn't require (a) detailed engineering design of the magnet, (b) new magnet tooling and (c) magnet parts
- Thanks to above, we remain confident that we will be able to design, build and test the superconducting dipole as promised in Phase I itself.

Performance Schedule – Plan and Status

Phase I Plan (as proposed)



Performance Schedule

Task 1: Software upgrades to optimize the design: Weeks 1-20.
Task 2: Design optimization of the proof-of-principle dipole: Weeks 9-22.
Task 3: Selection of conductor for the Phase II magnet: Weeks 20-24.
Task 4. Winding of the proof-of-principle optimum integral dipole coil: Weeks 23-28.
Task 5. Preparation of the proof-of-principle dipole for a 4 K test: Weeks 29-31.
Task 6: Magnetic, mechanical and winding design optimization for the Phase II magnet: Weeks 23-36.
Task 7. Proof-of-principle dipole test at 4 K: Weeks 32-34.
Task 8. Prepare the Phase I Final Report and prepare the Phase II proposal: Weeks 35-38.

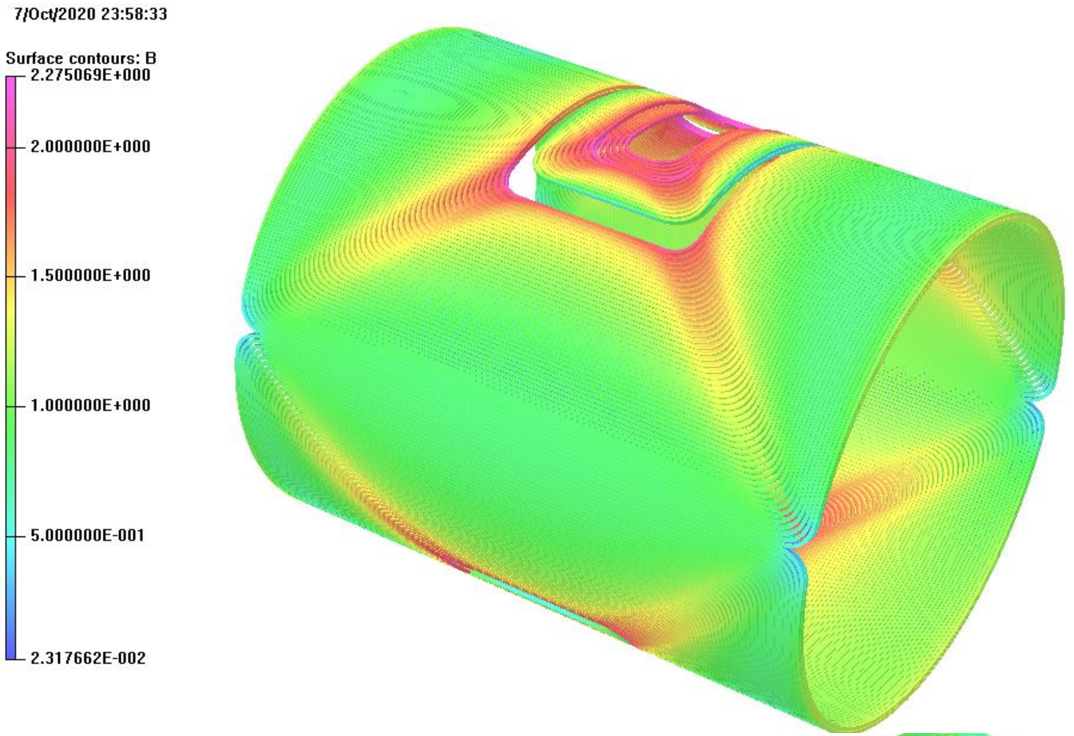
Phase I Current Status

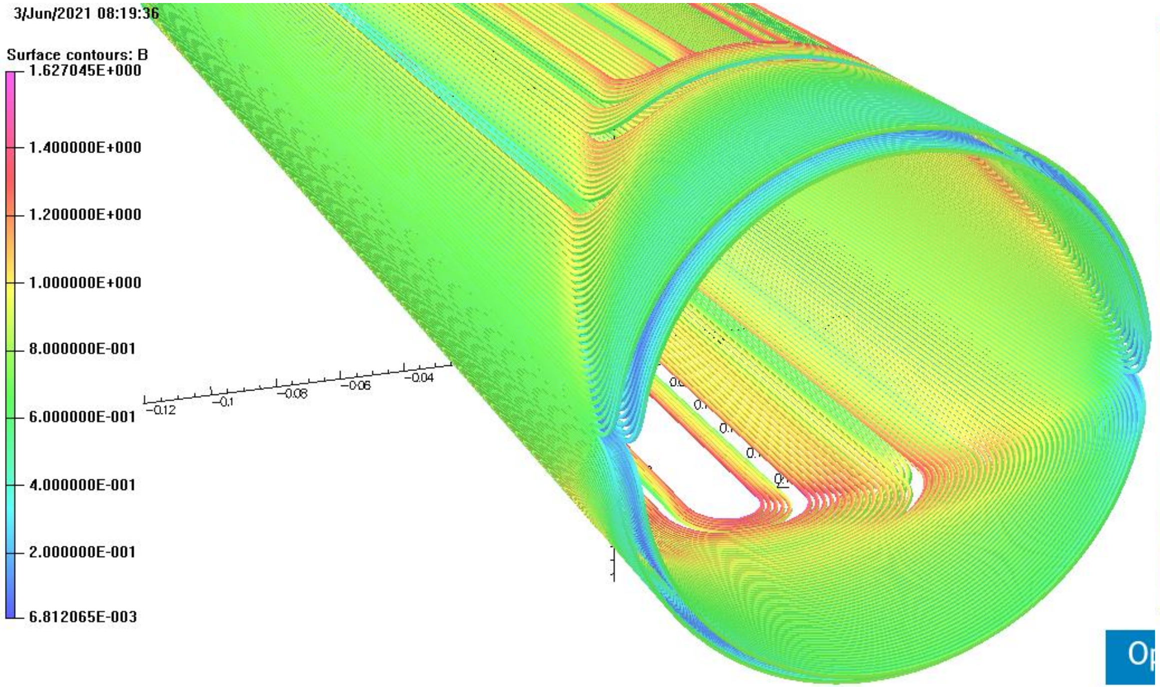
- **Task 1 through task 3 completed.**
- **Task 4 is scheduled to be completed next week.**

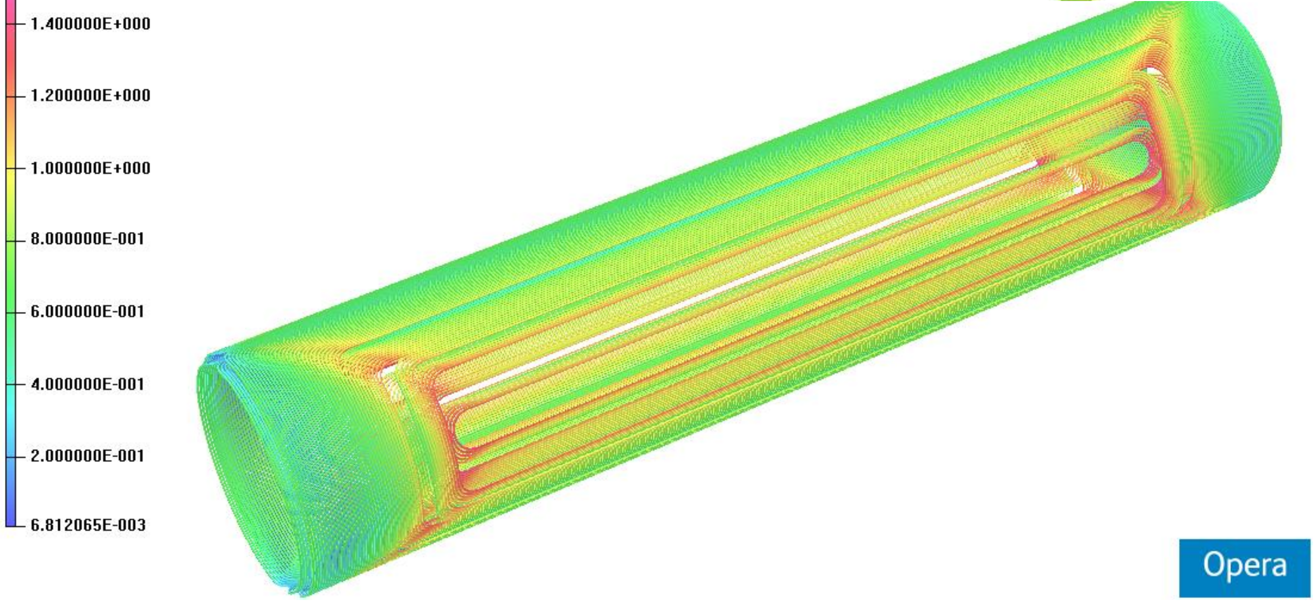
On Schedule

Technical Update

- Phase I proposal had a scaled down 150 mm long dipole, instead of full 600 mm
- Detailed studies found that it wouldn’t be representative for 120 mm coil id
- Current Phase I is making 600 mm long using leftover superconducting wire







Practice Coil Winding – short length (1)

Tube ready for full length windings

Initial short length practice windings of a few turns

Practice Coil Winding – short length (2)

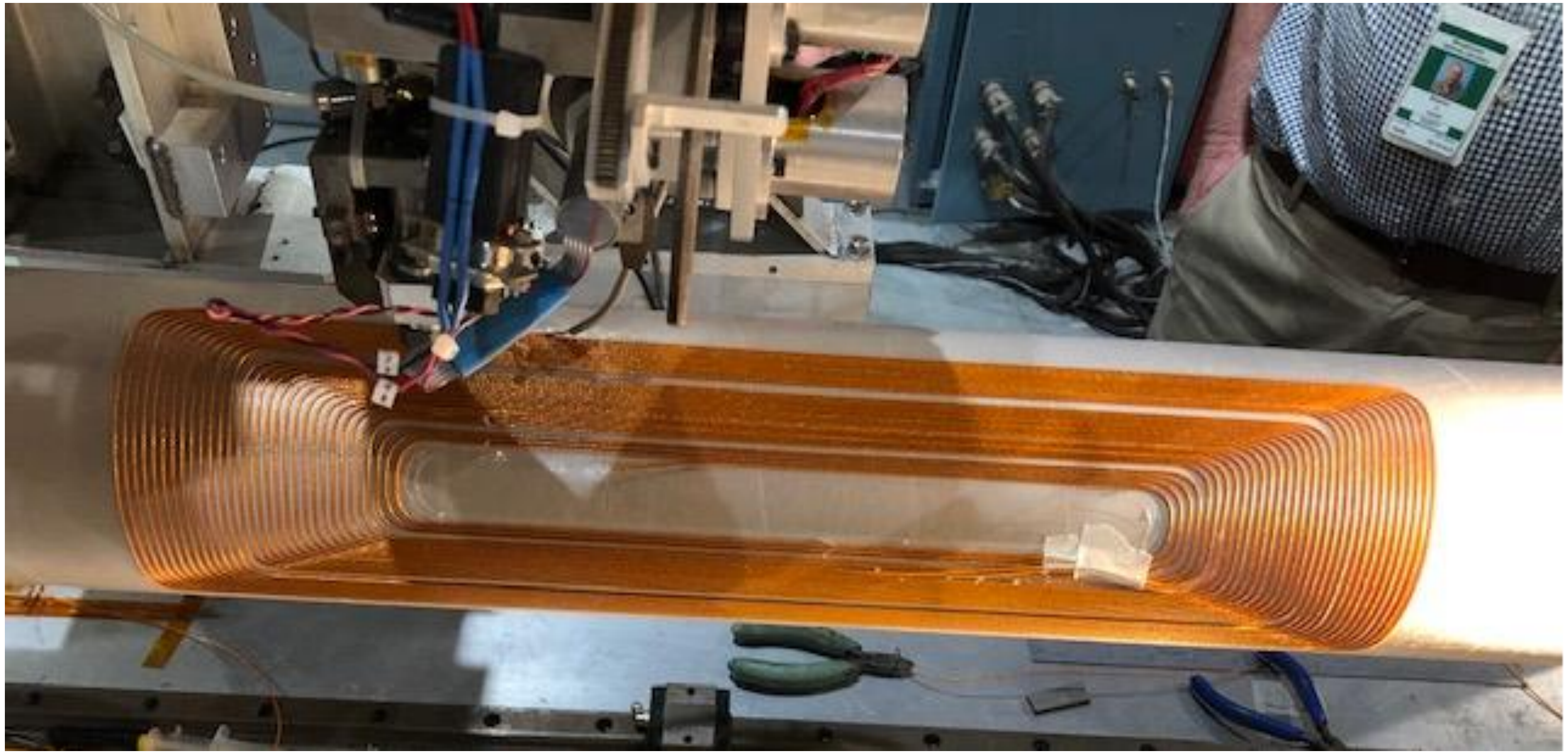
BNL and PBL staff discussing the short length winding

Practice Coil Winding – full length (1)


Tube installed (before winding)

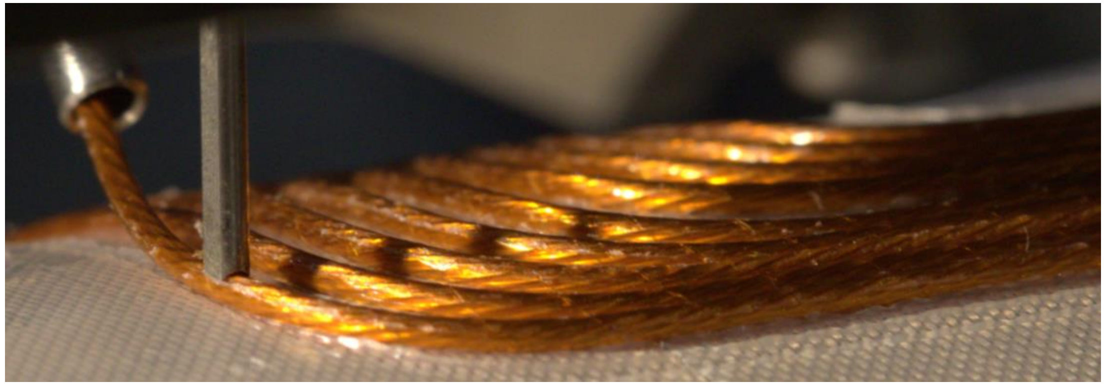
During the winding

(about ½ of one layer on one side wound)



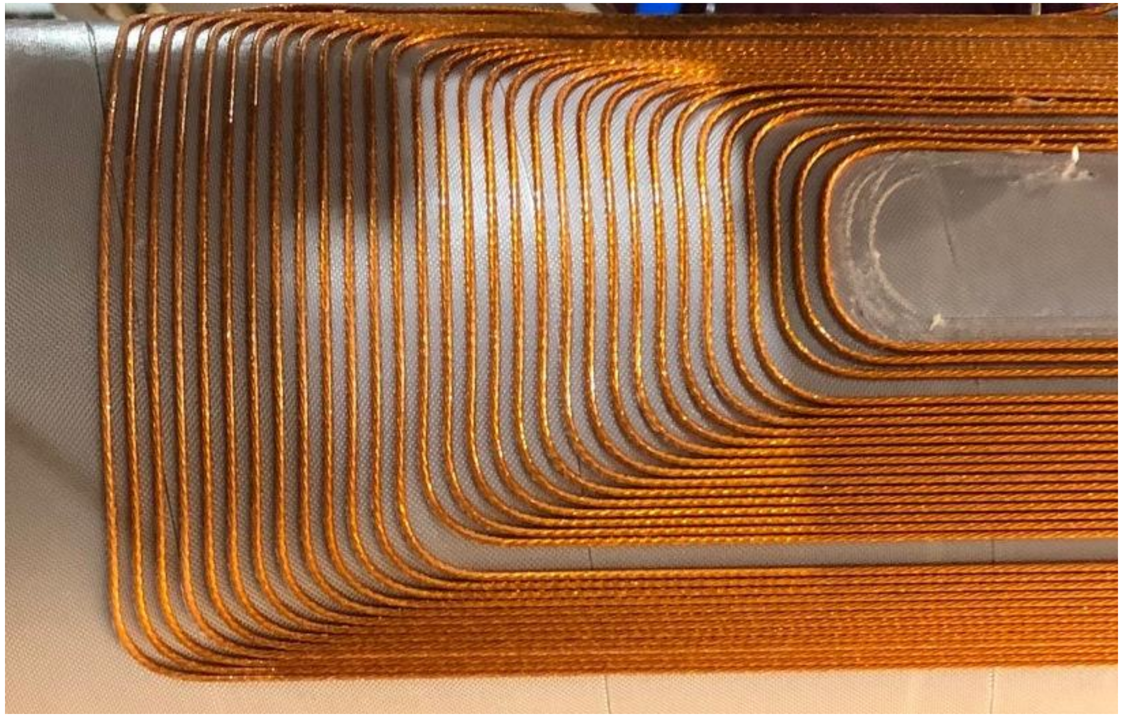
Practice Coil Winding – full length (2)

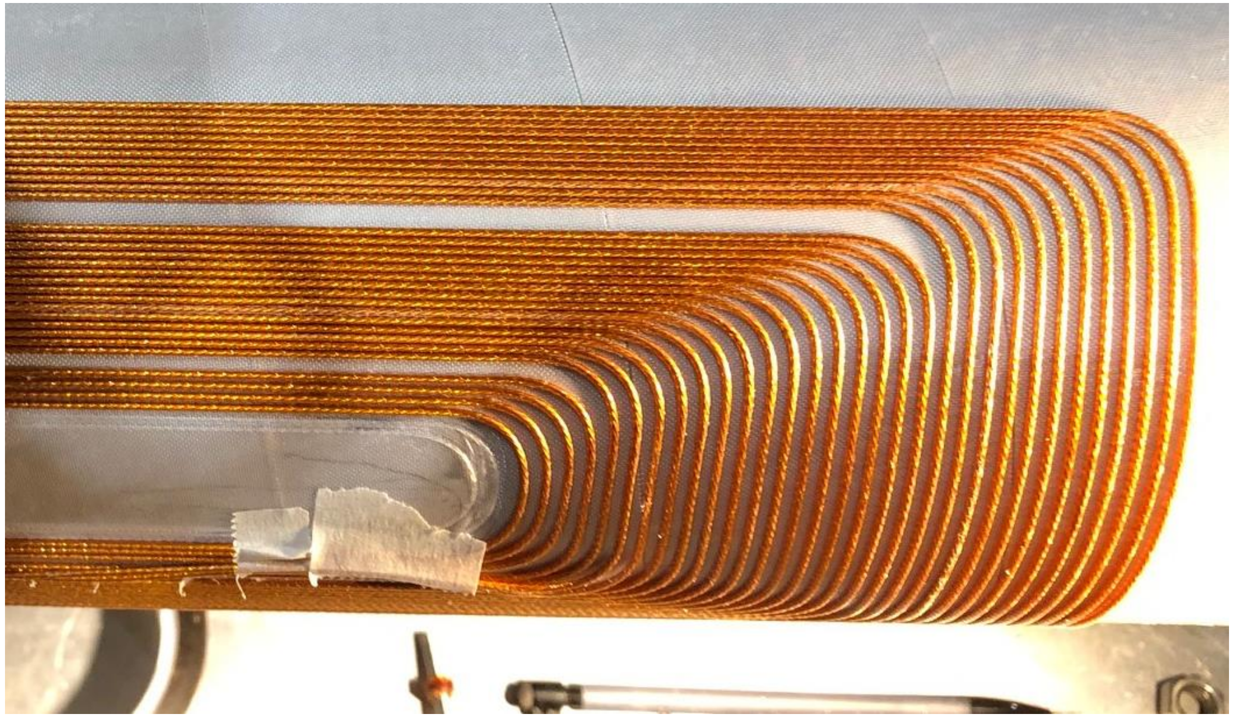
BNL and PBL staff during the initial part of full-length practice winding



Practice Coil Winding – full length (3)

Turns laid down directly on the tube
(two sides of the partially wound practice coil)





Summary

- Optimum integral design is well suited for short magnets, as it essentially makes full use of coil length by avoiding/minimizing the loss in magnetic length at the ends
- PBL/BNL team has made a good progress so far and is on track of achieving the ambitious goal of building and testing a large aperture (120 mm as compare to 80 mm of RHIC main dipoles) superconducting magnet in Phase I itself
- A demonstration of proof-of-principle dipole in a couple of years based on the “Optimum Integral Design” should have an impact on the other EIC IR magnets also
- Though other applications of this design were not discussed in this presentation, this design and technology could be used in many other applications since it makes very short dipole, quadrupole, sextupole, etc., possible, which otherwise would not be

Extra Slides

ASC2004 Paper - Introduction

In short-length conductor dominated magnets, where the mechanical length of the coil is comparable to or a few times the coil diameter (aperture), the ends determine the magnetic design and the length of the magnet itself. In conventional conductor-dominated dipole magnets, loss in the effective magnetic length over the end-to-end coil length is generally of the order of a coil diameter in dipoles, a coil radius in quadrupoles, etc. The physical space taken by the turns in the end itself is of the order of a diameter in typical dipoles and of the order of a radius in typical quadrupoles. Thus, in very short dipoles one would have to significantly reduce the number of turns in the cross-section and hence the integral field that can be achieved. This limits how short a magnet can practically be while generating a sufficient integral field and low field harmonics.

Relevance to SBIR/STTR

- In most dipoles (for example see SSC or RHIC), the combined mechanical length of the two ends is of the order of two diameters and the contribution to magnetic length is about a diameter.
- The serpentine design proposed by Brett Parker does not require an end optimization, as ends contribute none or little to the dipole field.
- However, in both cases (in conventional ends and in serpentine ends), dipole ends waste a length that is of the order of a coil diameter.
- For EIC B0APF, coil id is 120 mm and length is 600 mm. This means a 20% loss, which is significant.

A Particular Magnet of Interest for SBIR/STTR

Innovation and extension of technology of interest for SBIR/STTR:

(a) Optimum Integral Design for a relatively short magnet – this could have wider application well beyond EIC for which this proposal is focused.

(b) Can one make a relatively high field magnets with direct wind technology? This is an inexpensive technology for one of magnets since it doesn't require a lot of tooling, and design work, etc. and these magnets have reached short sample without training quenches. The question is, will it be a good technology for higher field magnets?

(c) Optimum integral design reduces the maximum field by 10-20%. Lorentz forces, stored energy and stresses goes as square of the field. There would be a hesitation for having it as a baseline design for a project like EIC and therefore should be a good topic for SBIR

(d) B0Apf dipole in EIC has an aperture of 120 mm and a total length of 600 mm. The design field is ~3.3 T. This is ideally suited but a challenging magnet for a SBIR/STTR proposal

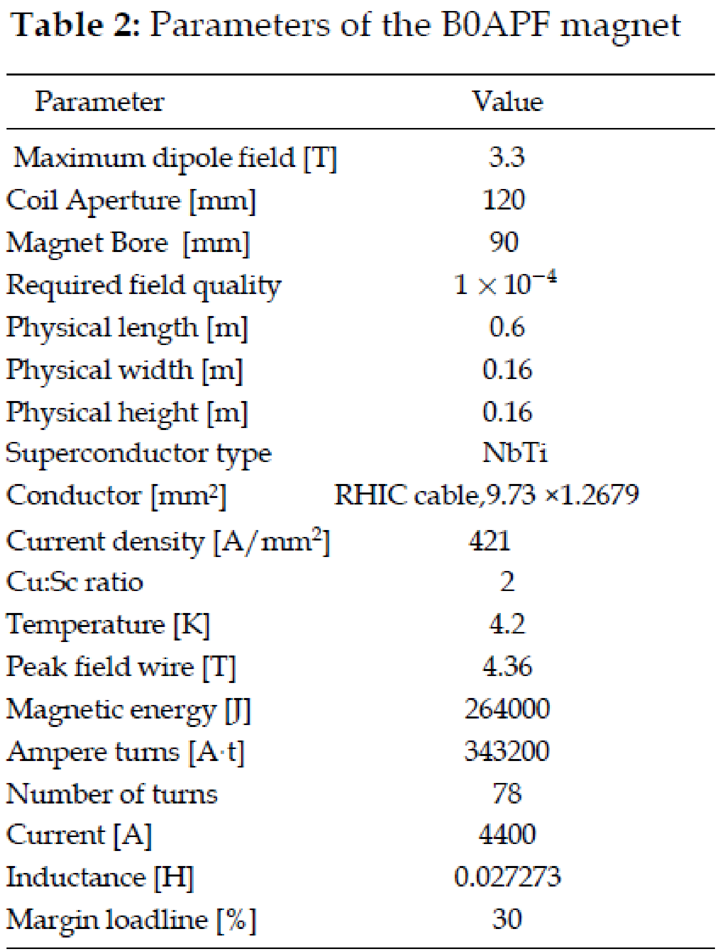


Table 2: Parameters of the B0APF magnet

Parameter	Value
Maximum dipole field [T]	3.3
Coil Aperture [mm]	120
Magnet Bore [mm]	90
Required field quality	1×10^{-4}
Physical length [m]	0.6
Physical width [m]	0.16
Physical height [m]	0.16
Superconductor type	NbTi
Conductor [mm^2]	RHIC cable,9.73 ×1.2679
Current density [A/mm^2]	421
Cu:Sc ratio	2
Temperature [K]	4.2
Peak field wire [T]	4.36
Magnetic energy [J]	264000
Ampere turns [A·t]	343200
Number of turns	78
Current [A]	4400
Inductance [H]	0.027273
Margin loadline [%]	30

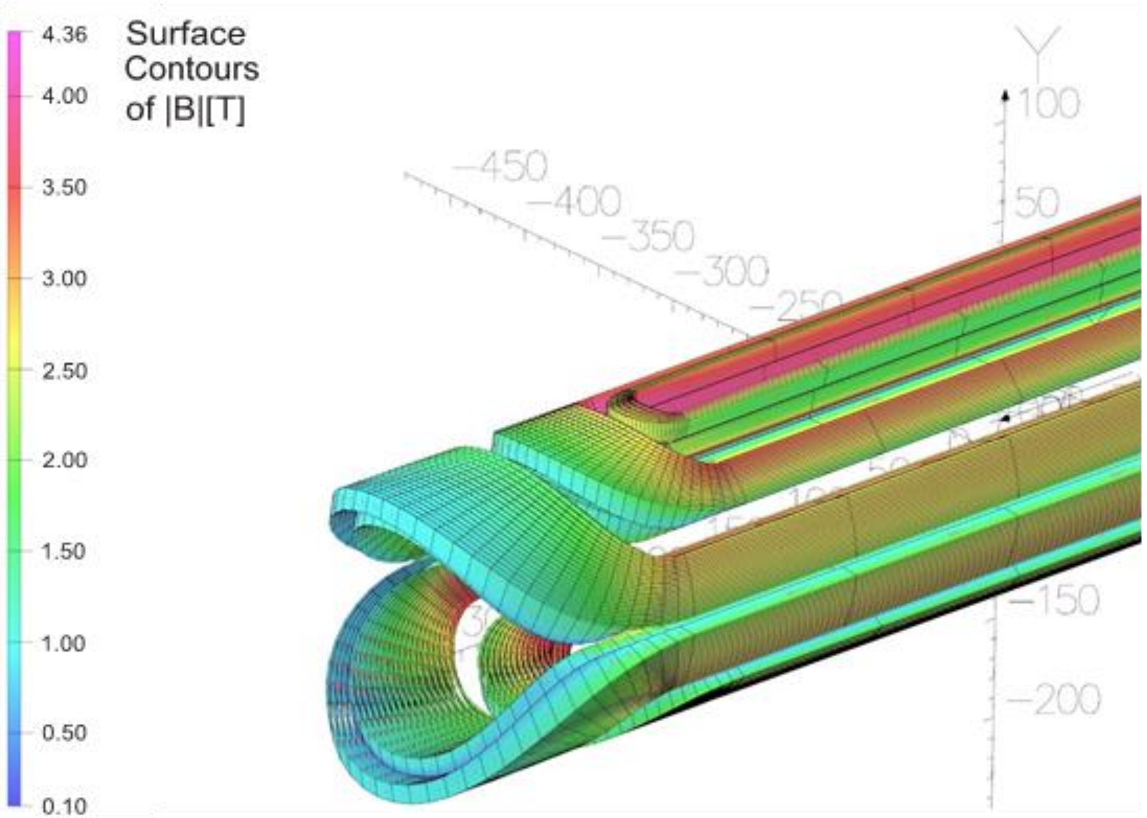
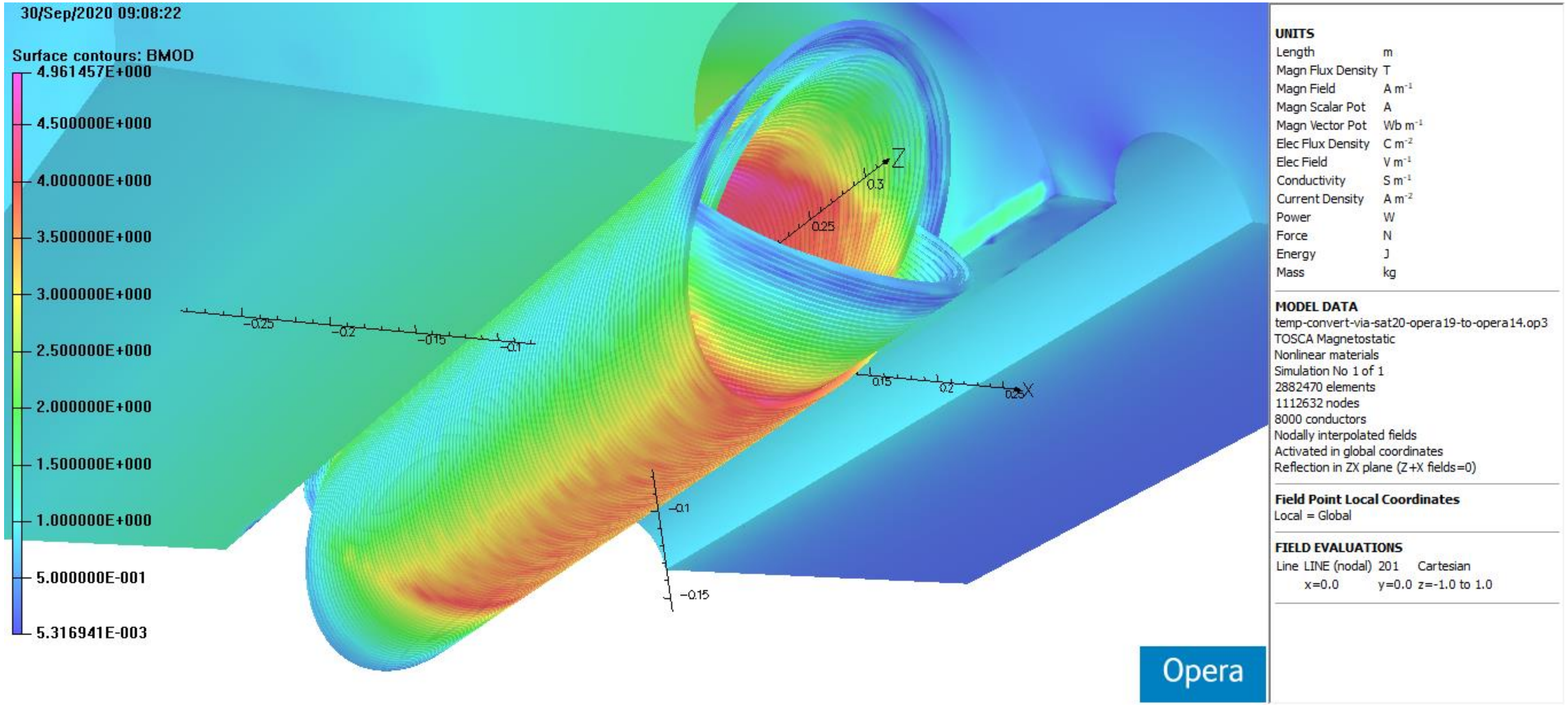


***Figure 5**: B0APF coil with field contour superimposed on the body and ends.*

Peak Field – Double Helix

Peak Field 4.96 T for integral field of 2.04 T.m



UNITS

Length	m
Magn Flux Density	T
Magn Field	$A\ m^{-1}$
Magn Scalar Pot	A
Magn Vector Pot	$Wb\ m^{-1}$
Elec Flux Density	$C\ m^{-2}$
Elec Field	$V\ m^{-1}$
Conductivity	$S\ m^{-1}$
Current Density	$A\ m^{-2}$
Power	W
Force	N
Energy	J
Mass	kg

MODEL DATA

temp-convert-via-sat20-opera19-to-opera14.op3
TOSCA Magnetostatic
Nonlinear materials
Simulation No 1 of 1
2882470 elements
1112632 nodes
8000 conductors
Nodally interpolated fields
Activated in global coordinates
Reflection in ZX plane (Z+X fields=0)

Field Point Local Coordinates

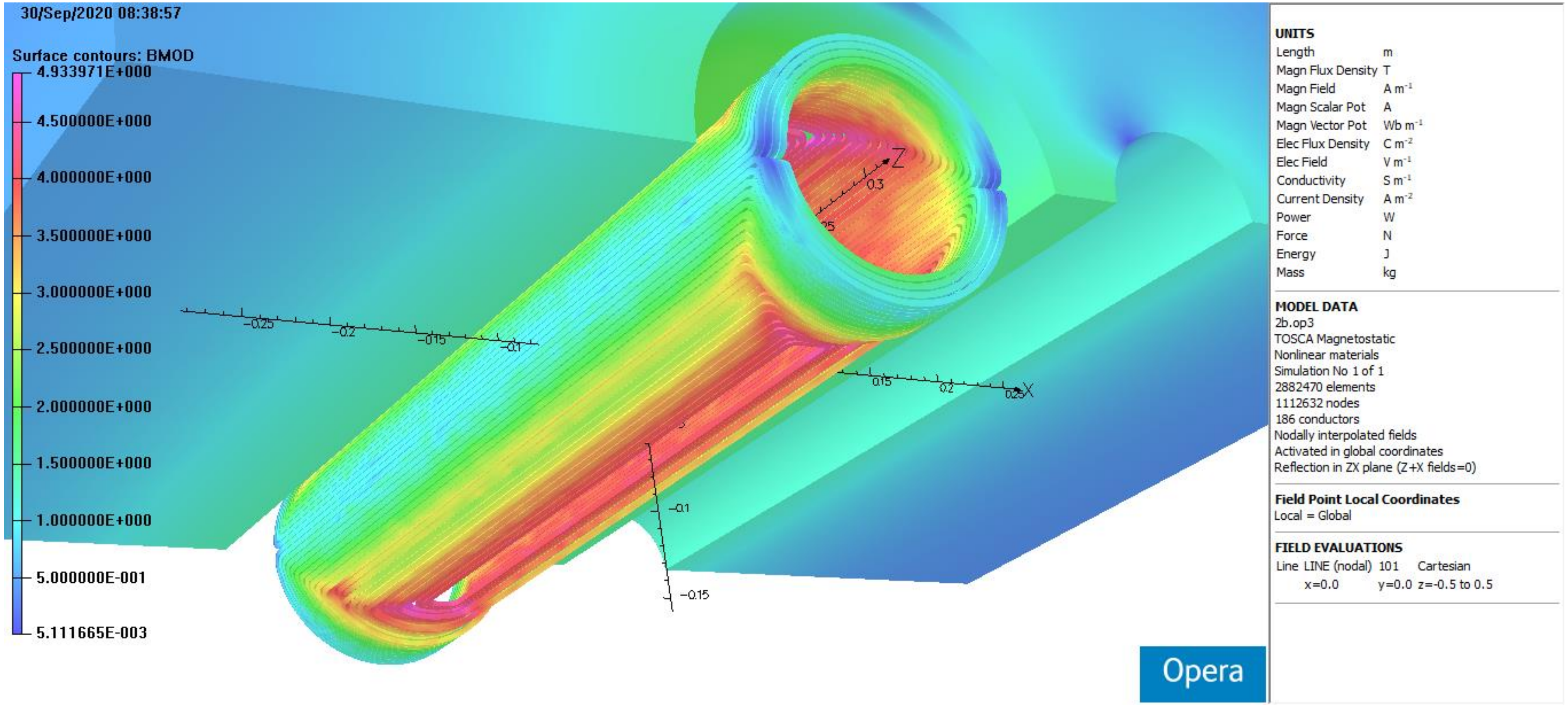
Local = Global

FIELD EVALUATIONS

Line LINE (nodal) 201 Cartesian
x=0.0 y=0.0 z=-1.0 to 1.0

Peak Field – Optimum Integral

Peak Field 4.93 T for integral field of 2.27 T.m



UNITS

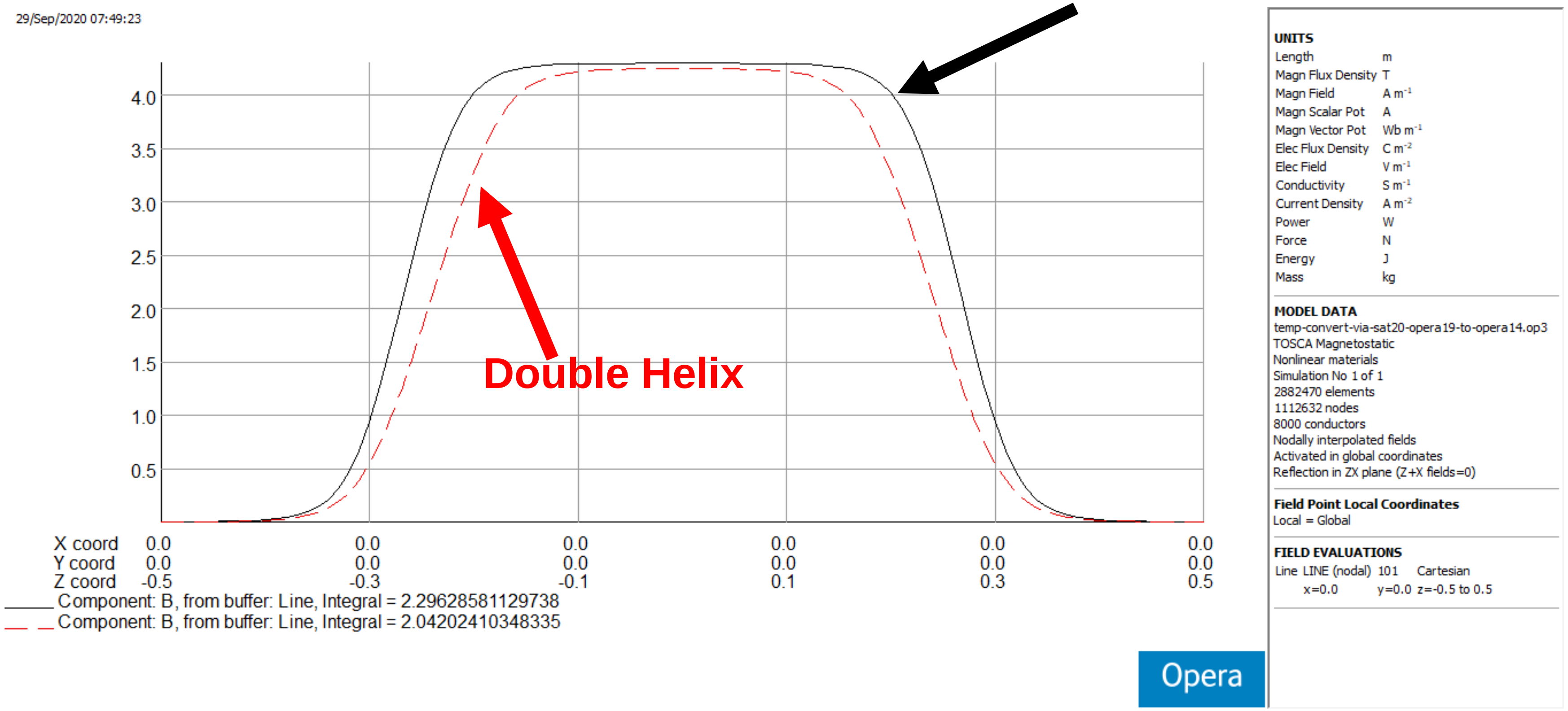
Length	m
Magn Flux Density	T
Magn Field	A m^{-1}
Magn Scalar Pot	A
Magn Vector Pot	Wb m^{-1}
Elec Flux Density	C m^{-2}
Elec Field	V m^{-1}
Conductivity	S m^{-1}
Current Density	A m^{-2}
Power	W
Force	N
Energy	J
Mass	kg

MODEL DATA
2b.op3
TOSCA Magnetostatic
Nonlinear materials
Simulation No 1 of 1
2882470 elements
1112632 nodes
186 conductors
Nodally interpolated fields
Activated in global coordinates
Reflection in ZX plane (Z+X fields=0)

Field Point Local Coordinates
Local = Global

FIELD EVALUATIONS
Line LINE (nodal) 101 Cartesian
x=0.0 y=0.0 z=-0.5 to 0.5

Extending Field Length of B0apF with the Optimum Integral Design



Optimum Integral

Double Helix

_____ Component: B, from buffer: Line, Integral = 2.29628581129738

— — Component: B, from buffer: Line, Integral = 2.04202410348335

UNITS

Length	m
Magn Flux Density	T
Magn Field	A m^{-1}
Magn Scalar Pot	A
Magn Vector Pot	Wb m^{-1}
Elec Flux Density	C m^{-2}
Elec Field	V m^{-1}
Conductivity	S m^{-1}
Current Density	A m^{-2}
Power	W
Force	N
Energy	J
Mass	kg

MODEL DATA

temp-convert-via-sat20-opera19-to-opera14.op3
TOSCA Magnetostatic
Nonlinear materials
Simulation No 1 of 1
2882470 elements
1112632 nodes
8000 conductors
Nodally interpolated fields
Activated in global coordinates
Reflection in ZX plane (Z+X fields=0)

Field Point Local Coordinates

Local = Global

FIELD EVALUATIONS

Line LINE (nodal) 101 Cartesian
x=0.0 y=0.0 z=-0.5 to 0.5