An overall personal reflection (design to demo – existing or new)

- On RHIC project, I worked closely with accelerator physicists and magnet engineers to use conventional cosine theta designs in many magnets. During this period worked with the team to take features of these designs to a new level, supervised to see that those features got successfully implemented (many of them are now used worldwide). Similarly on SSC magnets, I worked with other labs (e.g., Fermilab) and industry (e.g., GA) on SSC dipoles.
- Invented many new designs (some very different from conventional), got them funded (convinced community and wrote successful proposals), developed and managed programs to see them demonstrated at low cost.
- Above required a wide-ranging skills. My working style is based on clarity and open communication. I developed relations and trust with many collaborators – within magnet division and worldwide. It also required environment within the division and in the lab (confidence and support from colleagues, freedom and support from the management).

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RHIC Magnet Program – Leading development of specific techniques

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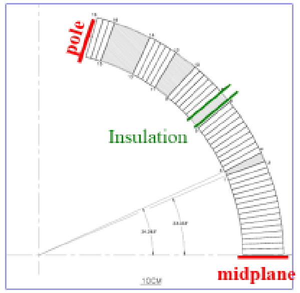
A Flexible Design from the Beginning

Design Philosophy:

- Start out with a design that allows significant adjustability for field harmonics and mechanical parameters (cable thickness, wedges, etc.).
- A flexible design is generally economical, efficient and produces magnets with better performance. I think it's a prudent approach.



Geometric: Start with a larger than required shim and midplane cap. Then adjust it, as required without changing the cross-section of the cured coil. One can also adjust the layers of wedge/cable insulation, if needed. These three parameters can adjust the first two allowed harmonics and pre-stress or cable insulation. This approach was used extensively in various RHIC magnets.

Saturation: Start out with holes in the yoke and fill them with magnetic iron rods later. Or, punch holes in yoke laminations later.

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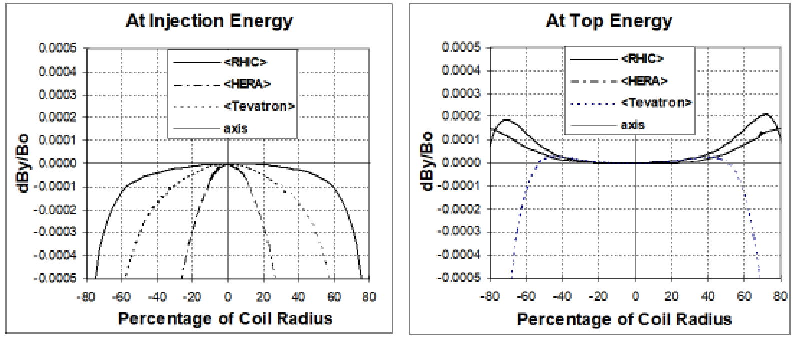
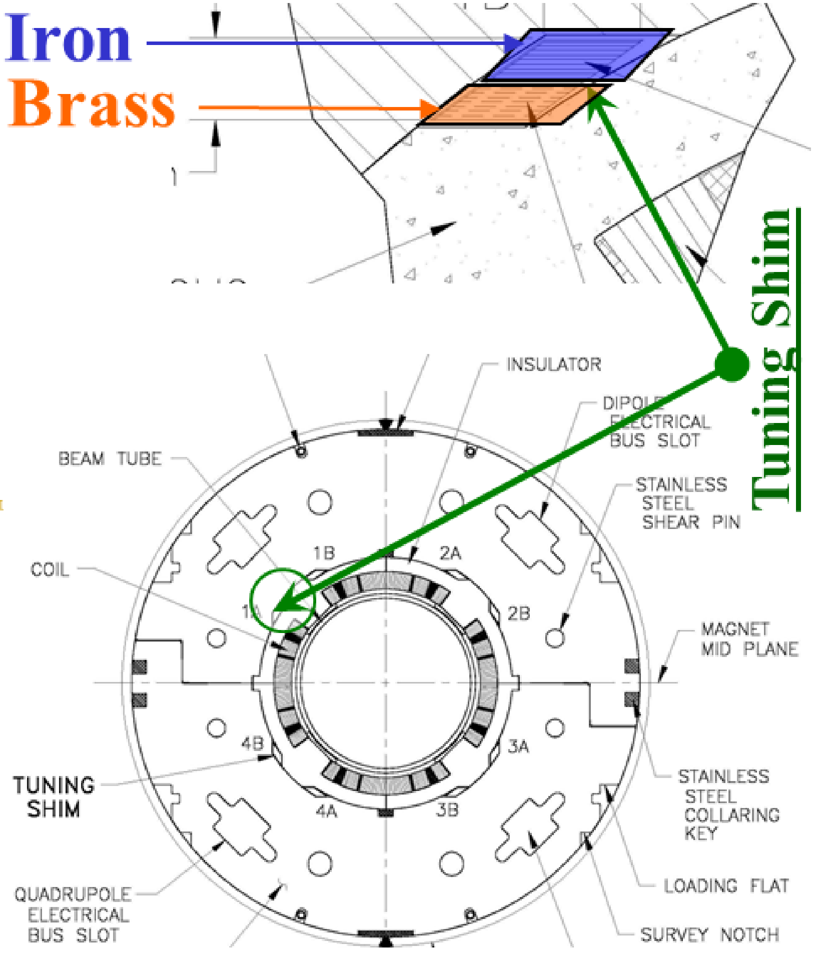
Average Field Errors on X-axis

COIL ID : RHIC 80 mm, HERA 75 mm, Tevatron 76.2 mm



- Warm-Cold correlation have been used in estimating cold harmonics in RHIC dipoles (~20% measured cold and rest warm).
- Harmonics b_1-b_{10} have been used in computing above curves.
- In Tevatron higher order harmonics dominate, in HERA persistent currents at injection. RHIC dipoles have small errors over entire range.

Tuning Shims for Very High Field Quality IR Quad



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Saturation in RHIC Arc Dipoles

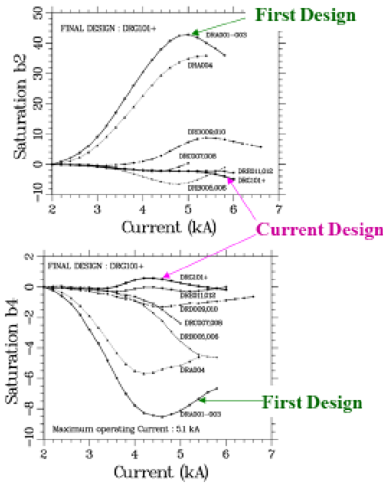
In RHIC dipoles, iron is closer to coil and contributes ~ 50% of the coil field:

3.45 T (Total) ~ 2.3 T (Coil) + 1.15 (Iron)

That's good.

But the initial designs had bad saturation, as conventionally expected when iron yoke is so close to the coils and contributes such a large fraction of coil field.

This course will teach you several techniques to reduce the current-dependence of field harmonics.



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Lecture VIII

Field Quality as a Tool to Monitor Magnet Production

Ramesh Gupta
Superconducting Magnet Division
Brookhaven National Laboratory

ARIZONA STATE UNIVERSITY

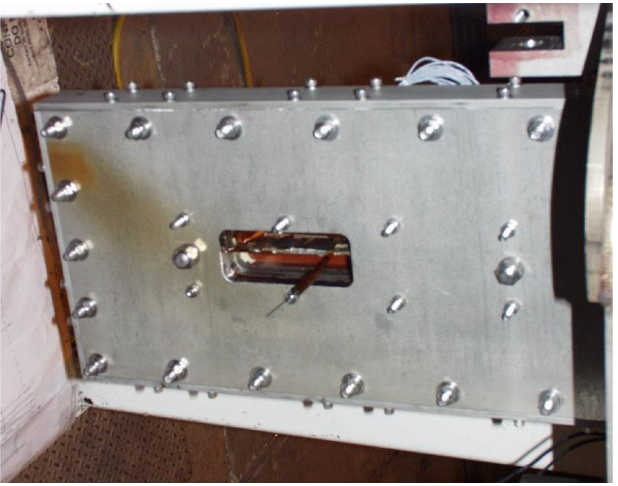
US Particle Accelerator School
Arizona State University
Phoenix, Arizona
January 16-20, 2006

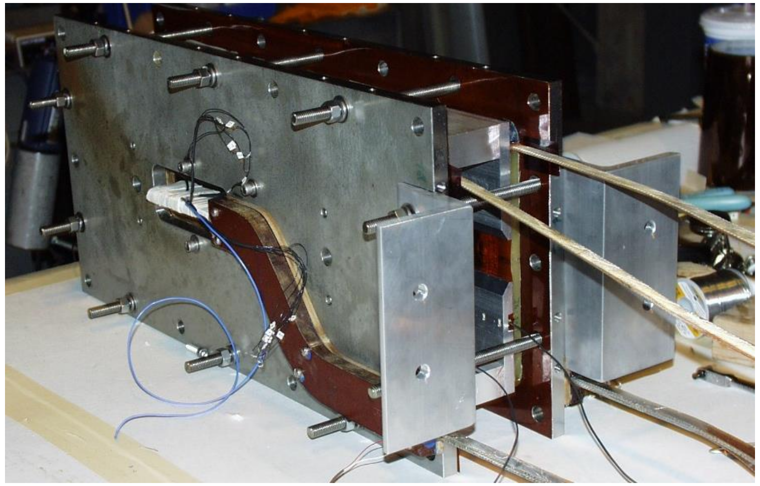
Led from the invention to the demonstration

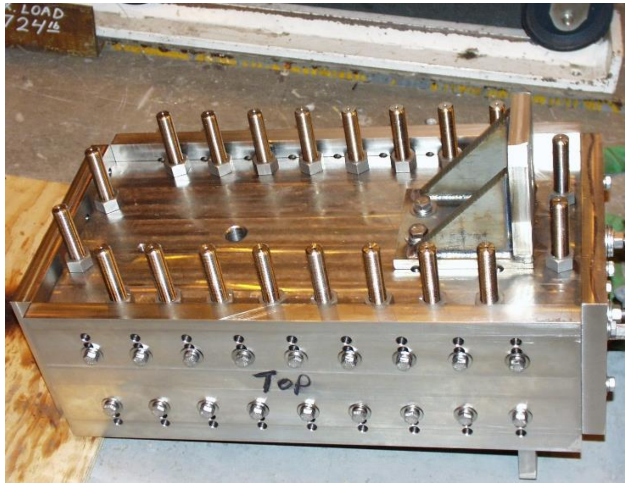
Specific R&D Program Led (example: within BNL with broader impact)

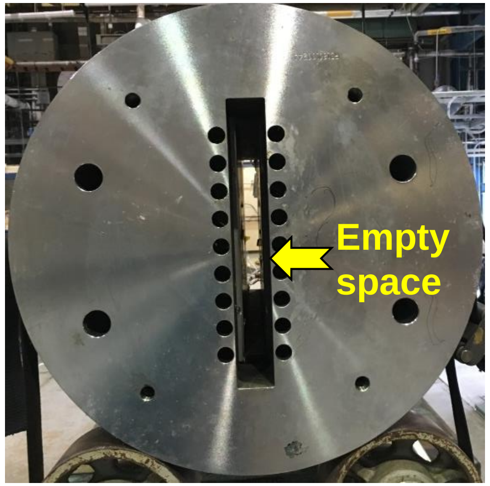
Common Coil

- Developed and supervised new design and new type of R&D program at BNL with a series of magnets (see below - DCC017 was the last magnet of that series)
- Technology developed/implemented – "React & Wind" Nb_3Sn, "React & Wind" Bi2212 (these required working and getting feedback from number of experts), demo of "HTS/LTS hybrid magnet technology", and new rapid-turn-around R&D
- Invented and led the development of common coil design and R&D philosophy, convinced community to fund and build at many places (BNL, FNAL, IHEP, etc.)









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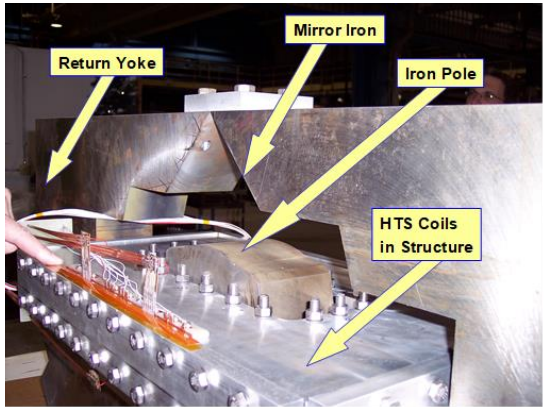
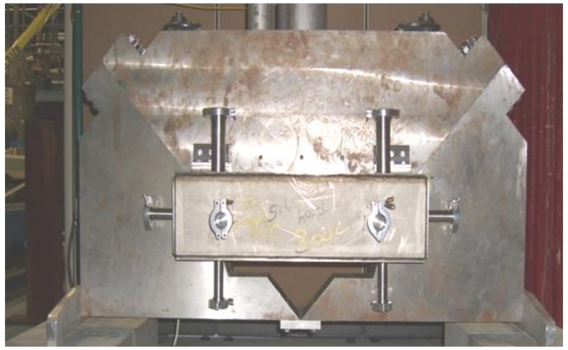
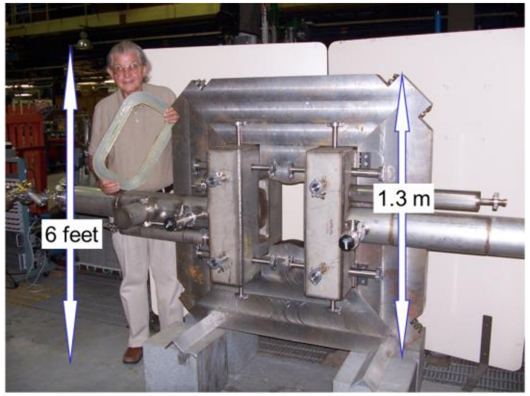
Specific Program and Design Led (with/for outside Lab)



Mirror cold iron



Mirror warm iron

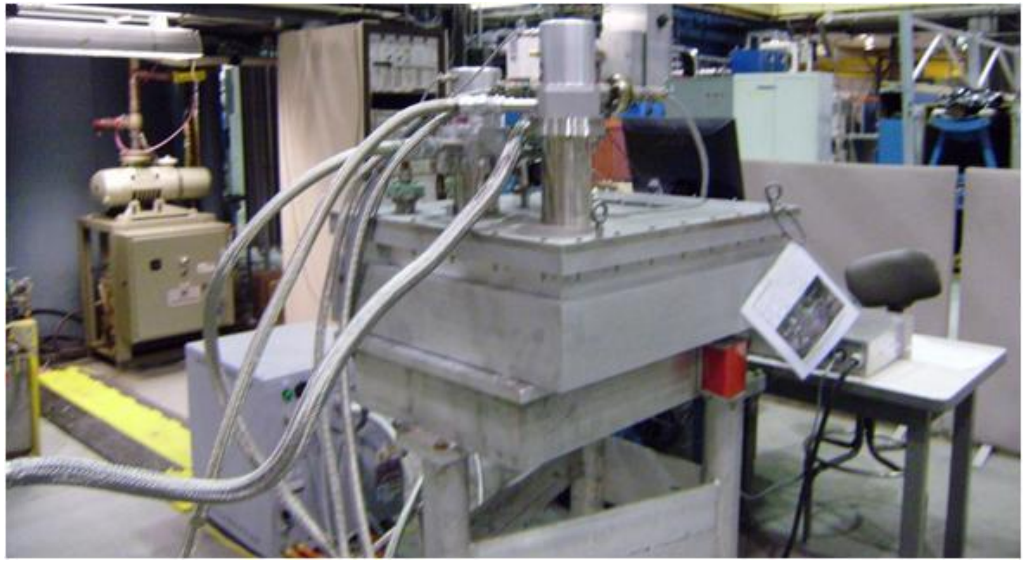


Warm Iron Design to Reduce Heat Load

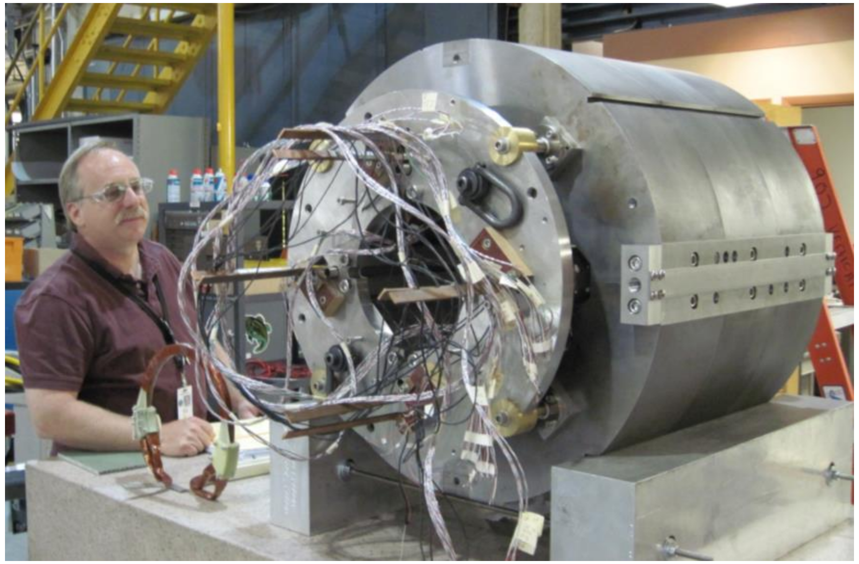
1G HTS, warm iron design

FRIB/RIA HTS quadrupole

- Three technologies, three designs (plus three variations of the first design), three shades of funding (DoE to BNL => to MSU/FRIB, transitional, DoE to FRIB => to BNL)
- Managed collaboration with MSU/FRIB and with HTS vendors when conductor was in early stages of development



Conduction-cooled design



2G HTS, cold iron design

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Magnet Projects with External Collaborators

(as an inventor and/or as a PI/leader of a new R&D project)

- **Common coil dipole**
- **Optimum integral design**
- **Overpass/Underpass magnets**
- **Open midplane dipole**
- **Modular quadrupole design**
- **HTS dipoles/quadrupoles/curved magnets**
- **High field HTS solenoids for many applications (muon collider, SMES, Axion search, neutron scattering)**
- **Superconducting shielding**
- **Recent fusion and HEP research with rapid-turn-around R&D facility with uniquely designed and built magnet DCC017**

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Managing a Variety of Programs with Multiple Collaborators together

There was no specific program, group or funding at BNL to develop HTS magnet technology. Creating such a diverse program (listed on left), required managing multiple programs from diverse funding sources and multiple collaborators. It also required flexibility, clarity and strategies to deal with conflicts.

Since HTS itself was expensive (very expensive), managing and obtaining conductor at "no-cost" (such as significant amount of Bi2212 Rutherford cable where first wire was obtained, then cable was made, and then reacted in very specialized and control furnace) and MgB2 or "reduced-cost" (such as from ASC, SuNAM, SuperPower) required skills and respect.

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Highlights of the HTS Magnet Program at BNL

- First US national lab to start HTS magnet R&D (over 20 yrs ago)
  - Opted the approach of demonstrating capabilities of HTS to create new opening and create excitement, rather than waiting for the conductor to get matured before starting magnet R&D
- A wide ranging HTS magnet R&D at BNL
  - High field, high temperature and the middle course
  - Solenoid, racetrack, cosine theta, curve coils, clover-leaves, ...
- Number of HTS coils and magnets designed, built and tested
  - Well over 150 HTS coils and well over 15 HTS magnets
- HTS used: Bi2223, Bi2212, ReBCO, MgB_2 – wire, cable, tape
- Amount of HTS acquired: Over 60 km (4 mm tape equivalent)

PI/Leader of a Variety of Many HTS Projects

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A List of HTS Programs at BNL (old slide)

- 25 T, 100 mm HTS solenoid for IBS, Korea (Work for Others)
- Hybrid Dipole with CORC® Cable (Phase II SBIR)
- High field solenoid for Neutron Scattering (Recent SBIR)
- Passive shielding for Electron Ion Collider (Phase I SBIR)
- Modular racetrack coil quadrupole for EIC (Phase I SBIR)
- 100 mm aperture "12.5 T @27 K" HTS SMES (arpa-e)
- High field collider dipole (Phase II STTR)
- Curved ReBCO tape dipole (Phase II SBIR)
- MgB_2 solenoid (Phase II SBIR)
- High field open HTS midplane dipole (Phase I SBIR)
- High radiation HTS Quadrupole for FRIB (Collaboration)

2019 IWC-HTS @ Oct 15-17, 2019 BNL experience with HTS magnets and coils -Ramesh Gupta

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Completed HTS Magnet Programs

- 25 mm aperture 16 T HTS solenoid (SBIR)
- 100 mm aperture 9 T HTS solenoid (SBIR)
- HTS quadrupole for RIA (Collaboration with MSU)
- Bi2223 HTS tape common coil dipole (funded by DOE)
- Bi2212 Rutherford cable Common Coil Collider Dipole (DOE)
- HTS solenoid for Energy Recovery Linac (BNL project)
- HTS magnet for NSLS (BNL Project)
- Cosine theta dipole with 4 mm YBCO/ReBCO tape (SBIR)
- Cosine theta dipole with 12 mm YBCO/ReBCO tape (SBIR)
- …and a few others.

(older slides, not updated for recently)

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A Partial List of Collaborators (with whom either working now or worked significantly in past)

Research Institutions

- MSU/FRIB
- CERN
- KEK, Japan
- University of Kyoto, Japan
- IBS, Korea
- RISP, Korea
- PSI, Switzerland
- IHEP, China
- University of Houston
- Texas A&M
- LBNL
- Fermilab
- SSC
- ….

Businesses

- Particle Beam Lasers, Inc. (PBL)
- Muons, Inc.
- HyperTech
- General Atomics (GA)
- Commonwealth Fusion Systems (CFS)
- Renaissance Inc., USA
- Solid Material Systems (SMS)
- Columbus Superconductor, Italy
- Showa, Japan
- SuperPower, US
- American Superconductor Corporation
- Advanced Conductor Technology (ACT)
- ABB
- …

… and many others with whom just had collaborative relationship, but no significant work or funds involved yet (proposals may have been written but not funded)

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**
18. A New Medium Field Superconducting Magnet for the EIC. DE-SC0021578 **April 2022** **$1,1500,000**

-Ramesh Gupta, 2022

Ongoing Projects with Ramesh Gupta as PI

- Very High Field Magnet R&D, US Magnet Development Program
- A collaboration framework to advance high-temperature superconducting magnets for accelerator facilities, U.S.-Japan Science and Technology Cooperation Program In High Energy Physics
- Low Temperature Testing of New Lower Cost Magnum-NXTM HTS Cable for Fusion, INFUSE Program with Solid Material Solutions, LLC (SMS)
- In-field Performance Testing of a Novel HTS CICC for Fusion Magnets, INFUSE Program with General Atomics (GA)
- Pulsed High Temperature Superconducting Central Solenoid Model Coil for Plasma Current Drive and Control in High-Field Compact Commercial Fusion Power Plants, arpa-e Grant with Commonwealth Fusion Systems (CFS)
- A new medium field superconducting magnet for the EIC, Phase II STTR with Particle Beam Lasers, Inc. (PBL)
- CORC® cable based high field hybrid magnets for future colliders, Phase II STTR with Advanced Conductor Technologies (ACT)