

Magnetic Design

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Superconducting Magnet Division S&T Committee Program Review

Magnetic Design - Core Competencies

- 2-d and 3-d optimization of conventional designs with a number of codes (some commercial, some public domain and some developed locally).
- Develop design concepts for non-standard applications.
- Iterate magnetic design with accelerator physics and mechanical design.
- Develop interfaces. In many cases coils are wound directly based on the magnetic design ("direct wind") or grooves for laying wires are cut in tubes directly based on the magnetic design (as in helical magnets).

Our resources and our contributions to the development of magnet designs for various projects within the lab and worldwide will be described with the help of a few selected examples.

Magnetic Design and Field Quality

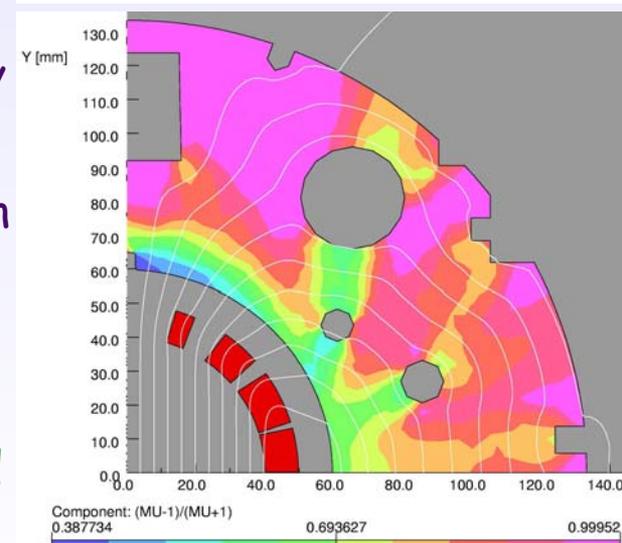
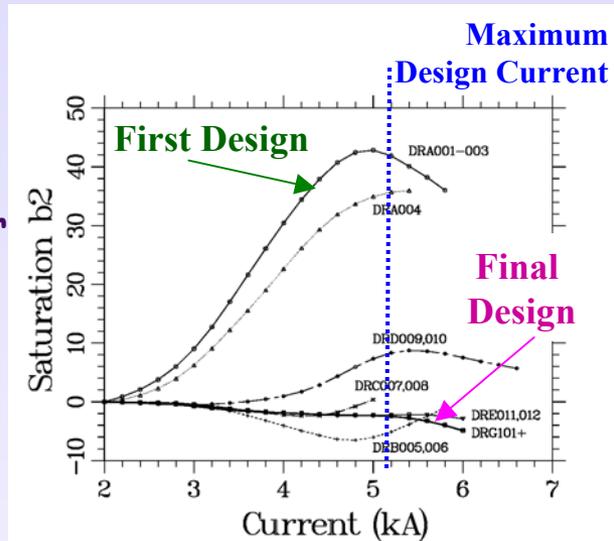
One major goal of the magnetic design is to minimize the field errors. Ideally one would like good field aperture to be as big as the physical aperture. This allows machine performance to be good and size (and cost) of magnets to be small.

Sources of field errors:

- **Iron saturation:** In RHIC dipoles, iron makes a significant contribution to field. Generally one would expect large error harmonics due to non-linear iron saturation. A few examples of what we did to reduce these errors will be given.
- **Coil errors:** The error in conductor position should be within 1-2 mils (25-50 microns). One usually carries out several magnet iterations (each costing time and money) to get the desired field quality. See how we reduced the number.
- **Construction errors:** A few examples of what we did to overcome construction errors. Also one example of what we did to detect a major flaw in magnet construction will be given .

Development of Magnetic Designs to Minimize Field Errors due to Iron Saturation

- In most RHIC magnets iron yoke is very close to coil.
- Yoke enhances coil field by $\sim 50\%$, but at the expense of large saturation-induced harmonics as seen in the **1st design** (see upper figure on right that shows sextupole or b_2 in units of 10^4 of dipole field at $2/3$ coil radius).
- During the RHIC magnet R&D program (spanning over a decade), we developed designs and techniques that brought large reduction in saturation-induced b_2 (see **final design**) and higher harmonics.
- This was achieved by forcing yoke to saturate uniformly by minimizing variation in $(\mu-1)/(\mu+1)$ with holes, etc.
- RHIC may be the only accelerator where field quality in main dipoles remains good not only in the design range but well beyond. This would be useful in case of an "Energy Upgrade" proposal (dipoles have a large quench margin).
- Similar techniques were used in SSC 50 mm dipoles and dipoles made for LHC insertion regions.

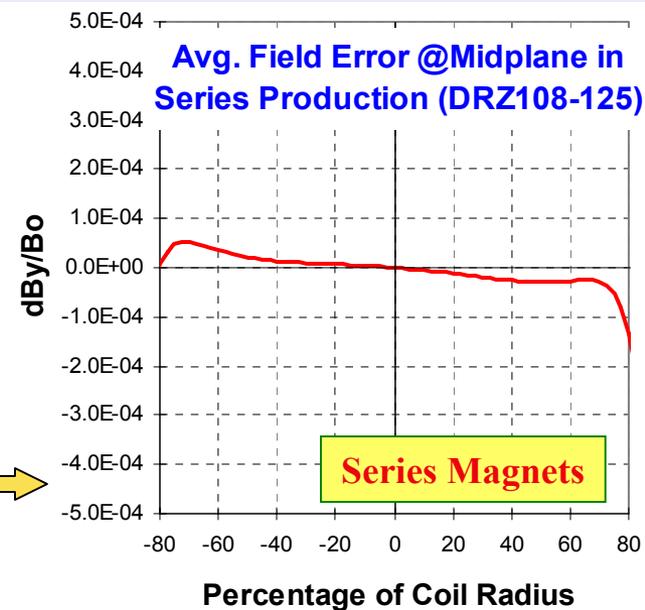
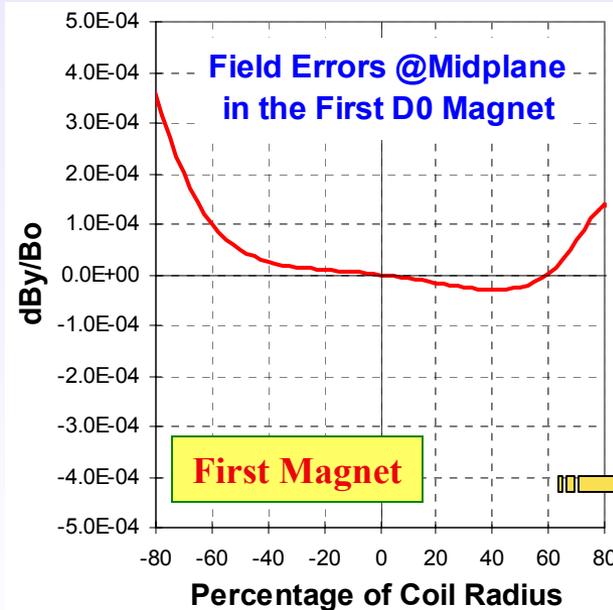
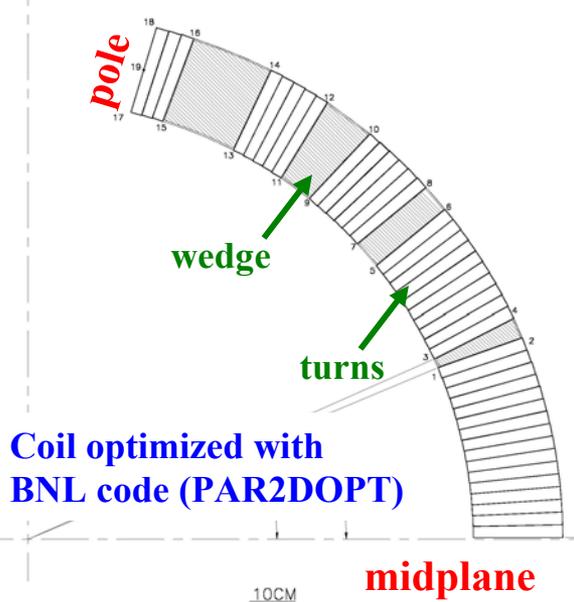


OPERA2d Model

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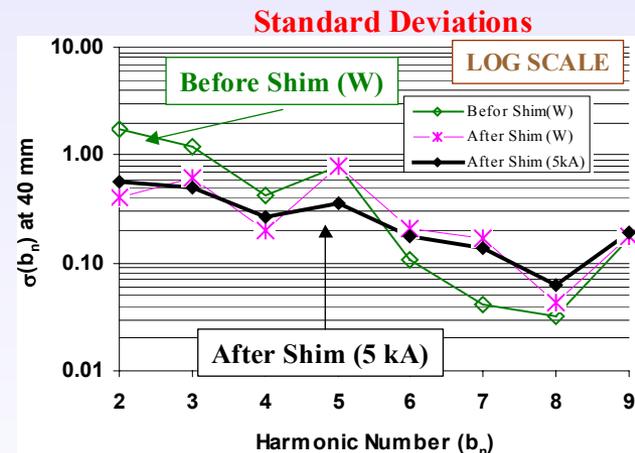
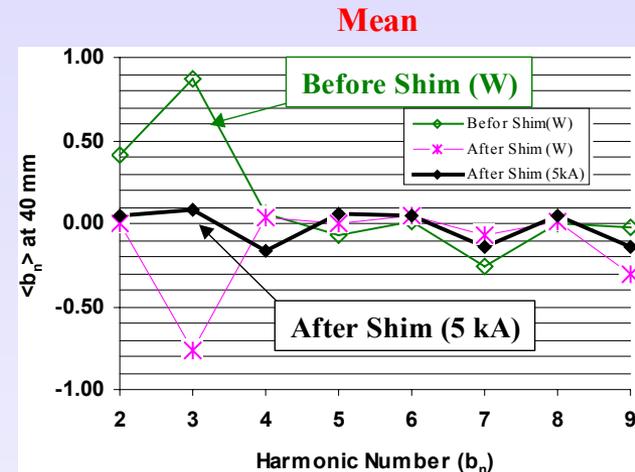
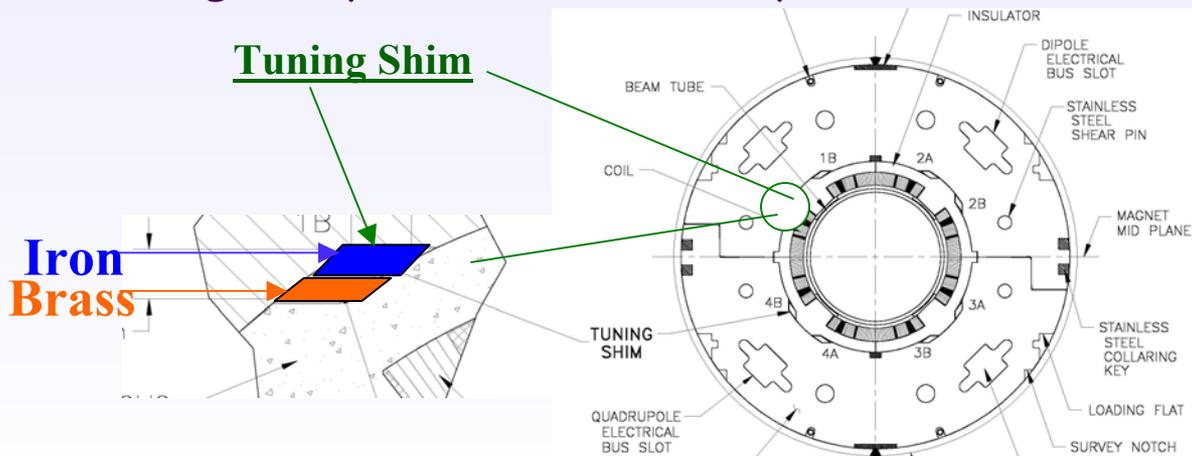
Advances in the Magnetic Design of the Coil Geometry (Example: 100 mm RHIC Interaction Region Dipole)

- Coil X-section and ends were optimized by a series of codes developed at BNL.
- Usually one needs to build a few magnets to obtain a good field quality.
- These magnet iterations results in a significant time and cost penalties.
- We developed techniques that produced accelerator grade field quality in the **very first magnet** (field errors ~ 1 part in 10^4 up to 60% coil radius).
- Flexibility in the design allowed simple magnetic tuning during the production without changing coil or yoke. It resulted in very good field quality magnets - average error < 1 part in 10^4 up to $\sim 80\%$ of coil radius (almost entire vacuum pipe).



High Field Quality in RHIC IR Quads with Tuning Shims

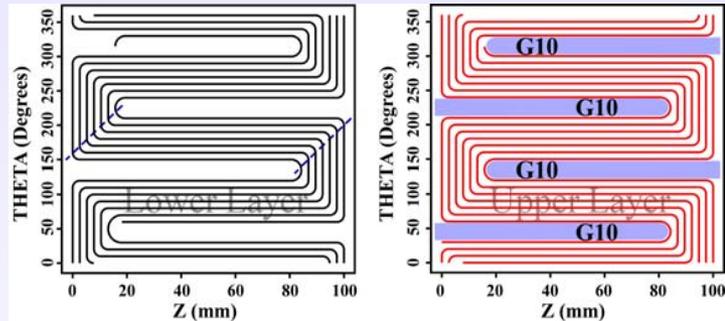
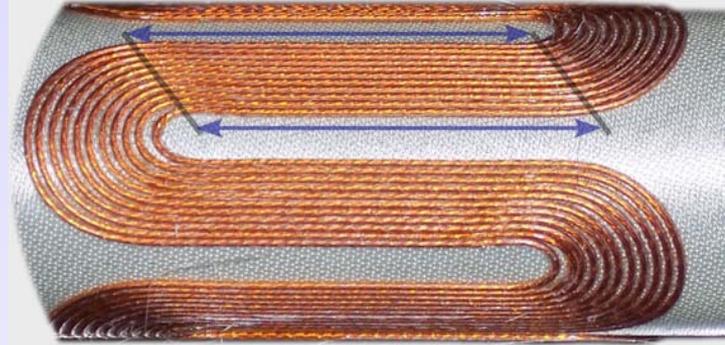
- β^* in RHIC was changed from 2 meters to 1 meter.
- Such changes normally require an increase in the aperture of Interaction Region (IR) quadrupoles as the good field region must increase. That would have been a new and more demanding magnet program.
- Tuning shims (variable amount of Fe) compensate measured harmonics and reduce them to a few parts in 10^5 at 2/3 radius (below normal construction errors).
- Correction applied at the max. design energy (field).
- In RHIC IR/arc beam size ratio is $\sim 7:1$, whereas the IR/arc magnet aperture ratio is only $\sim 1.6:1$.



SHIMCAL series of BNL codes perform non-linear field optimization

Serpentine Technique for Direct Wind Magnets

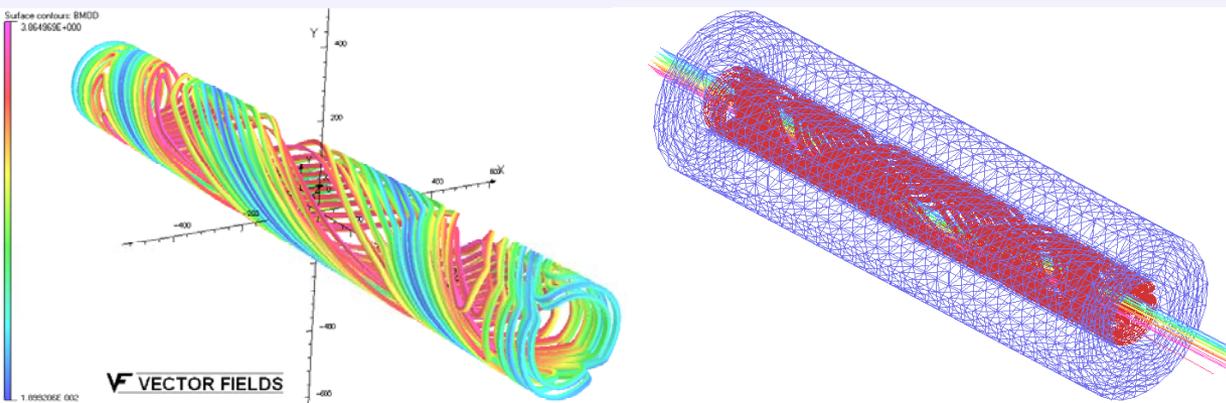
- In a novel Serpentine design (Brett Parker), all poles of a coil layer are continuously wound with no splices since individual turns go on to the next pole instead of returning to the same pole.
- Each turn is the same length so the 2D cross-section defines integral field harmonics. This allows ends to be simple (3D reduced to 2D; trivial adjustment to correct small topological effects).
- Alternating winding direction between coil layers, cancels axial component & reduces peak field.
- Have design freedom of "half a turn per pole" and we can easily extract leads in zero radial clearance.
- Our locally developed CAD/CAM codes yield rapid turnaround, a flexible approach and no new tooling is required.
- Used in the design of magnets for many projects : ALPHA, ATRAP, BEPC-II, ASACUSA, BTeV, DANAE, eRHIC, ILC and J-PARC so far.



A series of of BNL developed codes that do a series of things (3-d magnetic design optimization to direct coil winding on tube)

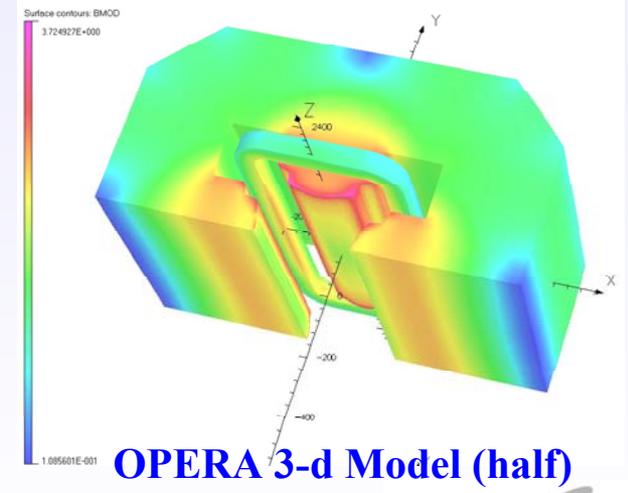
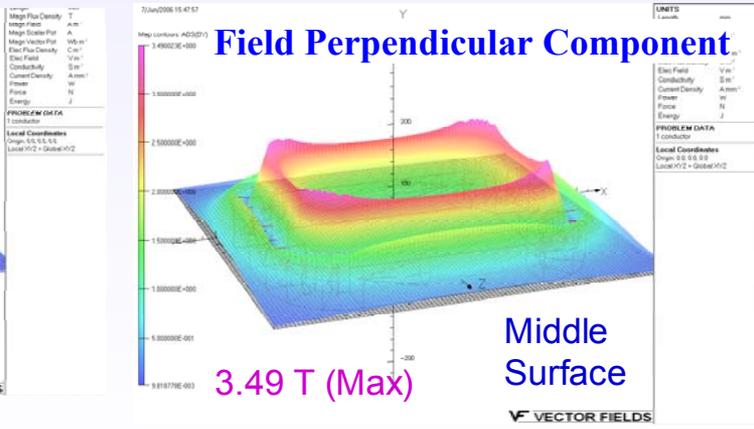
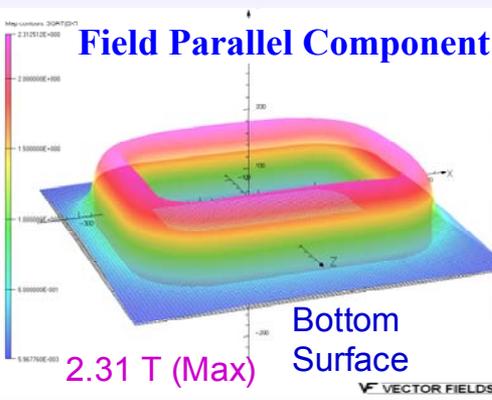
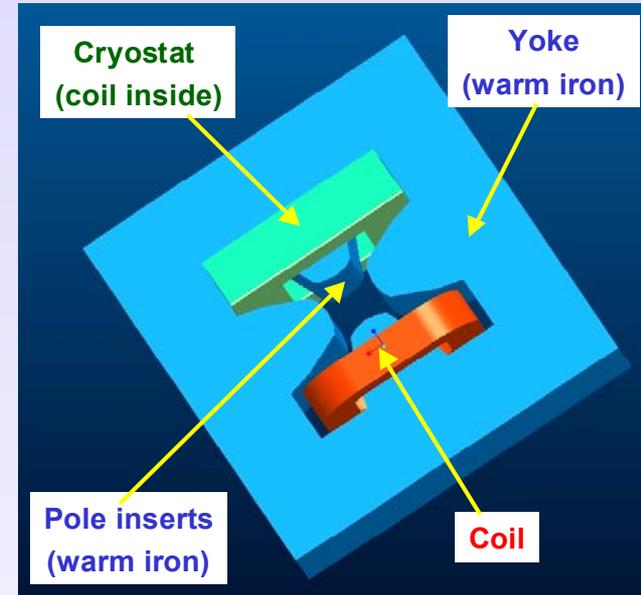
Magnetic Design of AGS Helical Dipole

- For AGS helical dipole, through a series of interrelated codes, we developed an integral approach for (a) Magnetic 2-d and 3-d design, (b) particle tracking, (c) instructions for CAD drawings, and (d) instructions for cutting grooves.
- The above integrated approach allowed many design iterations between magnetic, beam dynamics & mechanical design while assuring that we built what we designed.
- A significant advancement in techniques from RHIC to AGS helical dipoles.
- The complete package included "direct wind" corrector magnets and solenoid which must fit in a limited space. A new "optimum integral design" was developed that allowed compact magnets with high transfer function.



High Temperature Superconductor (HTS) Magnet Design for RIA Quadrupole

- Quads in RIA's Fragment Separator region are subjected to large amount of radiation (~15 kW).
- The requirements cannot be met by a Cu/Fe magnet.
- A super-ferric 2-coil quad design is developed that reduces ~15 kW to ~130 W in cold structure.
- 130 W is still a large amount to be removed at ~4 K.
- We are developing radiation resistant HTS magnets operating at ~35 K to remove this heat economically.
- HTS also allows a large variation in operating temperature and thus a simpler cryogenic system.
- Components (not only magnitude) must be computed since I_c of HTS depends strongly on them (next slide).



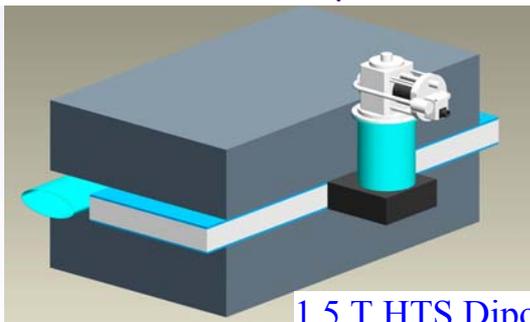
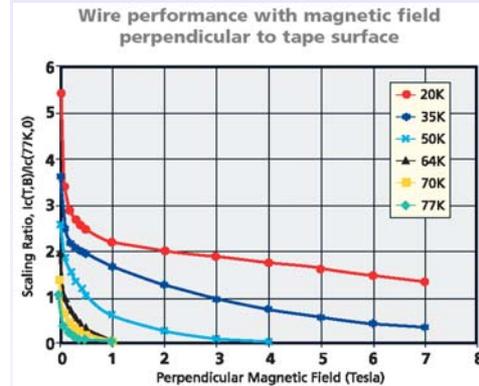
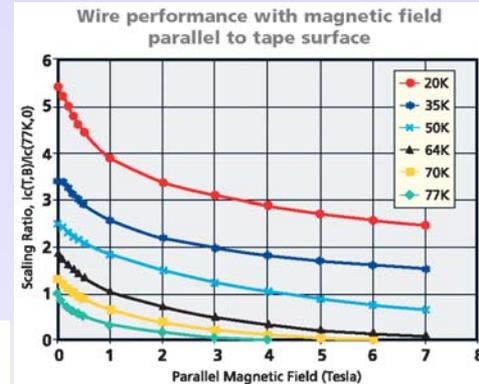
Lower Cost Medium Field HTS Magnet Designs

Vision: Develop “HTS magnets” that can compete in “cost of ownership” with “Copper” or “Low Temperature Superconducting (LTS)” magnets.

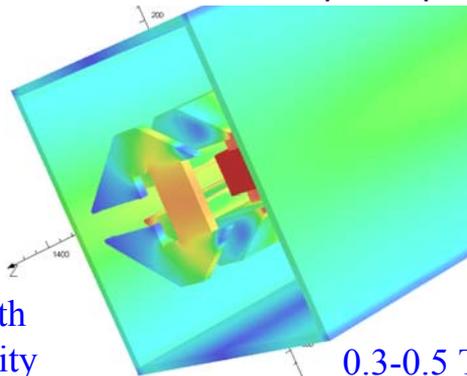
Strategy: Develop an approach that is optimized for HTS rather than simply replacing coils in designs optimized for copper or LTS magnets (first developed for the proposed ~1.5 T AGS Neutrino Facility Dipoles).

We came up with a back-leg powered HTS magnet concept that:

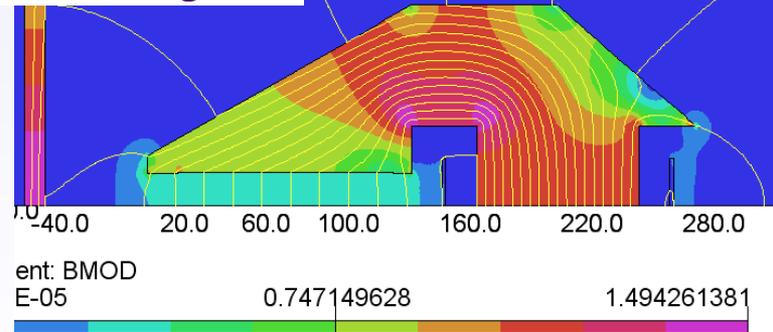
- o needs much less superconductor: ~5k\$ @35 K operation and ~12k\$ at 65 K operation in 3 meter long, 0.33 T NSLS2 dipole (similar savings in other designs). This was achieved by making the maximum field on conductor lower and parallel to the surface.
- o needs simpler and cheaper support structure and cryostat since vertical forces are eliminated. Heat leaks will be lower.
- o needs one cryostat instead of the two in a pole-powered design.



1.5 T HTS Dipole with cryocooler for ν facility



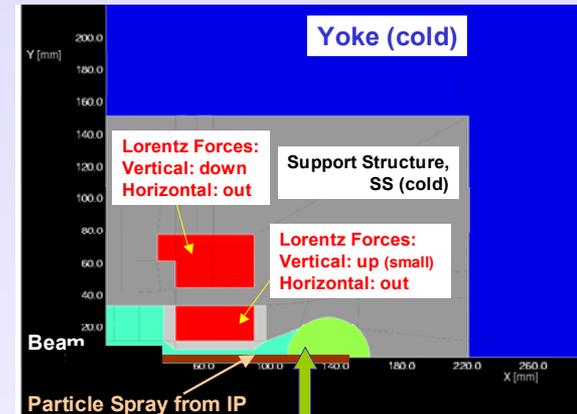
0.3-0.5 T HTS Dipole for NSLS2



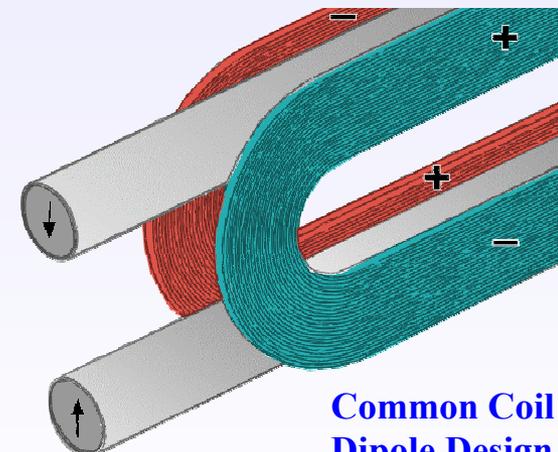
Racetrack Coil Magnets for High Field Superconductors

- High field magnets are being considered for various projects. Large Lorentz forces play a significant role.
- Moreover, most high field superconductors are brittle.
- Magnets based on simple flat racetrack coils provide an interesting alternative to convention $\cos(\theta)$ designs.
- Two designs of special interest:
 - Open Midplane Dipole
 - 2-in-1 Common Coil Dipole
- In addition, large bend radii in these designs allow the use of both "Wind & React" and "React & Wind" technologies. Recently a 10.3 T "React & Wind" Nb_3Sn common coil dipole was tested successfully at BNL.
- Magnetic designs were developed to produce a field quality that is acceptable for accelerator magnets (a few parts in 10^4 at 2/3 coil radius). Coils were optimized with RACE2Dopt (BNL) and ROXIE (CERN); iron with POISSON (public domain) and OPERA (commercial).

Open Midplane Dipole Design



A large amount of particles coming from high luminosity IP deposit energy in a warm (or 80 K) absorber, that is inside the cryostat. Heat is removed efficiently at higher temperature.

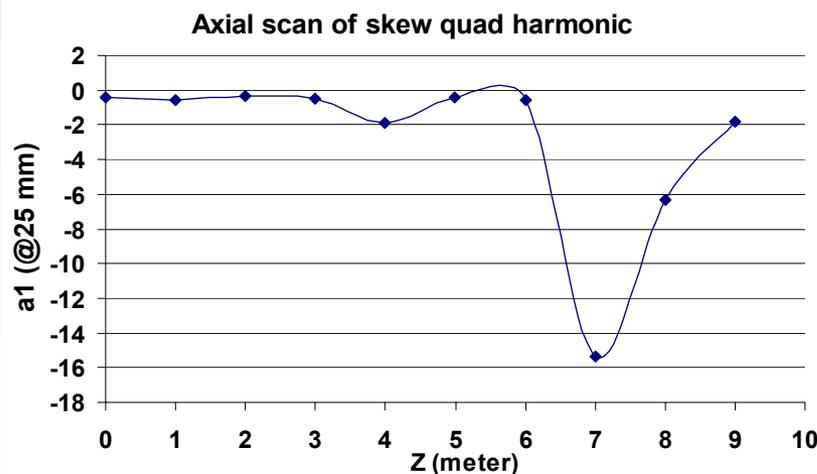


Common Coil Dipole Design

Development of Field Quality As a Tool To Monitor Magnet Production

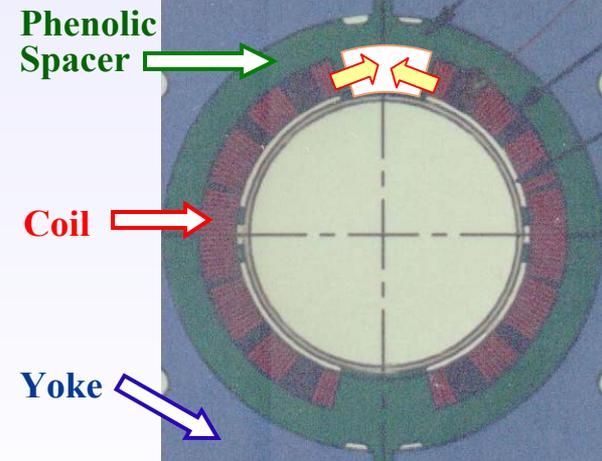
- Warm magnetic measurements are analyzed to not only satisfy machine requirements but also monitor trend or any thing unusual for possible defect.
- For example, large local harmonics in one RHIC dipole were hard to explain.
- A careful analysis of measurements suggested a large physical discontinuity in upper pole region. This was linked to the use of end spacers in the magnet body.
- A magnet with such major flaw would have very poor quench performance.
- Vendor implemented additional checks after notification.
- Without the above analysis, there was the potential of many more such errors.
- The above tool is being used to monitor the production of LHC magnets as well.

Unusual harmonics were used to pinpoint the exact fault (location & associated component)



Measured Integrated Harmonics in unit-meter

n	an	bn
1	-22	0
2	0	-10
3	2.7	0
4	0	1.3
5	-0.9	0
6	0	-0.45
7	0.3	0



Summary

- We are involved in carrying out a variety of magnet designs. Some of them are conventional and some of them are unique or special purpose (more so lately).
- In the case of conventional designs, we have contributed to advancing the state of the art of magnetic design techniques that
 - produce magnets with significantly improved field quality (better machine performance).
 - need fewer (in some cases NO) model magnets to achieve good field quality (savings in cost and time).
 - makes field quality measurements and analysis an important tool to monitor magnet production.
- We have developed several new designs (only a fraction presented here) for new and special applications where the conventional designs are not best suited.
- A good interface has been developed between beam optics, magnet design, mechanical design and CAD software.