Preliminary Design of HTS Dipoles for NSLS2

Ramesh Gupta

Contents

- The basis of present HTS magnet design

  Why it is being developed the way it is (based on our unique experience)

- Challenges for HTS magnets as compared to room temperature magnets

  Technical plus *cost, cost and cost !!!*

- Status of present magnet design (based on parameters as understood)

  Please give your input/feedback

- Summary

For more background on HTS magnet designs and technology and BNL experience visit:
http://www.bnl.gov/magnets/Staff/Gupta/scmag-course/uspas06/RG06/rg-uspas06-lecture09.pdf

Challenges with HTS Magnets and Our Approach

- HTS materials are very brittle

  Work on magnet designs ("conductor friendly designs").

  We have developed many such designs for a variety of applications. We have a number of success stories. They will not be discussed today.

- HTS materials and magnets with cryostat are very expensive

  The cost of HTS (per amp meter) is coming down continuously.

  Develop designs such that the conductor requirement and cost of magnet goes down. A number of ideas/approach have been developed here.

  A major topic of discussion today.

  Also consider the cost of ownership (capital + operating cost).

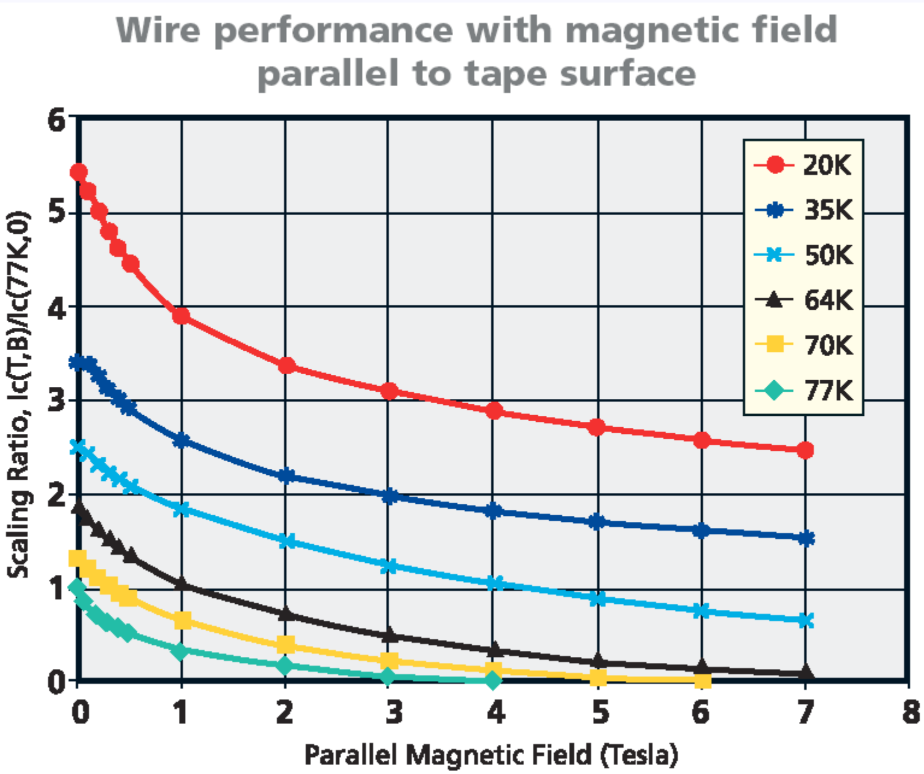
- Unknown issues (field quality, lifetime, etc.)

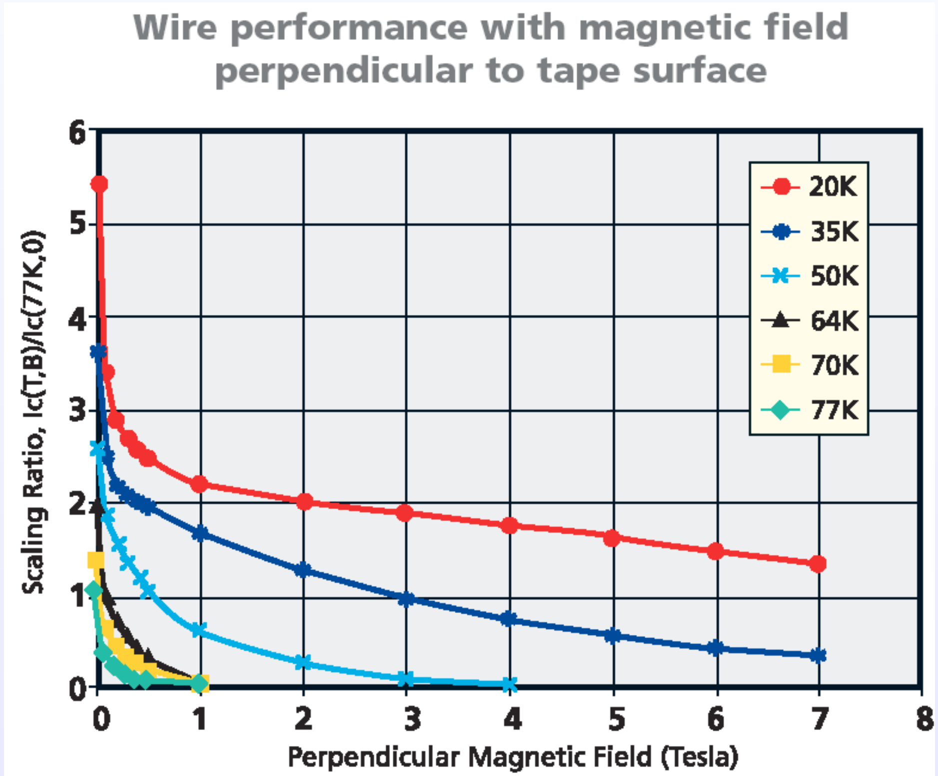
  There are no short cuts. We have to design, build, test and prove.

  Also work on the magnet designs.

Critical Current of BSCCO 2223 Tape As a Function of Field At Various Operating Temperatures

HTS current carrying capacity is quoted at 77 K, self field. Multiply by scaling factor to obtain at any T & B





American Superconductor
REVOLUTIONIZING THE WAY THE WORLD USES ELECTRICITY

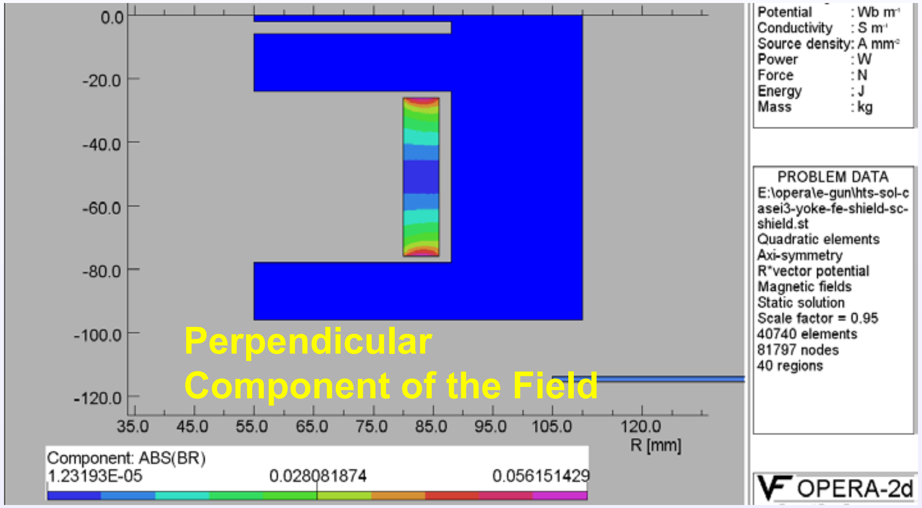
Current carrying capacity of HTS depends on:

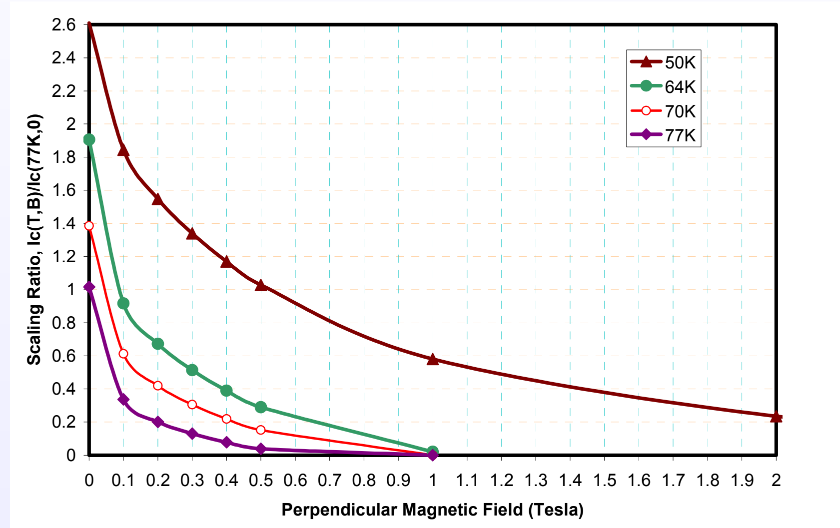
- Temperature
- Magnitude of the field

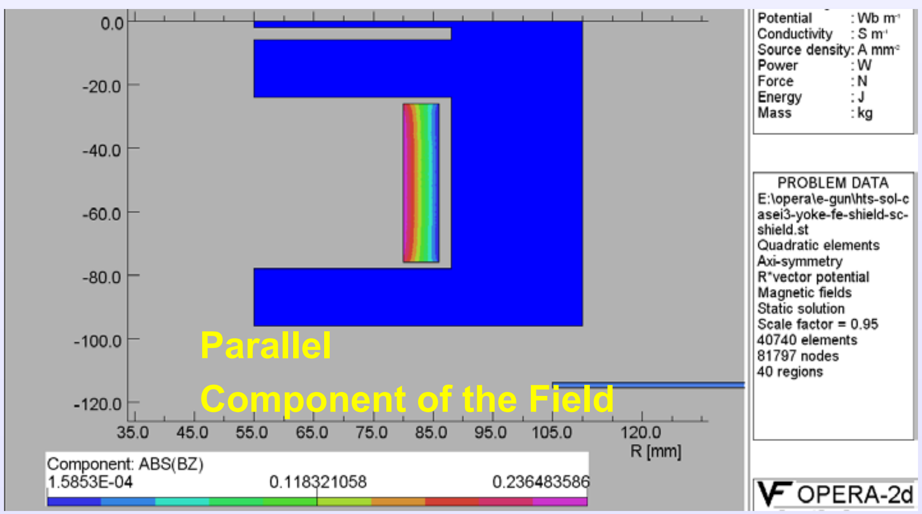
→ **and also on the direction of the field**

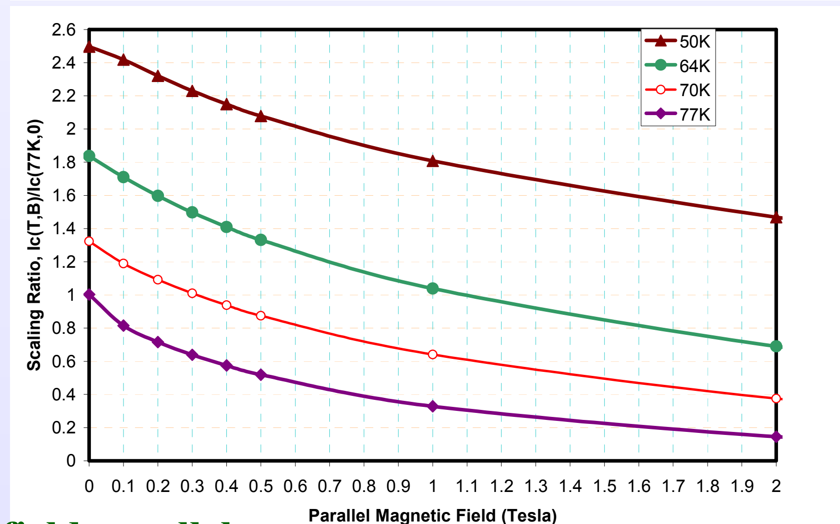
HTS Solenoid Design With Iron Yoke Over Coil

Magnetic model has been optimized to reduce the perpendicular field in the superconductor



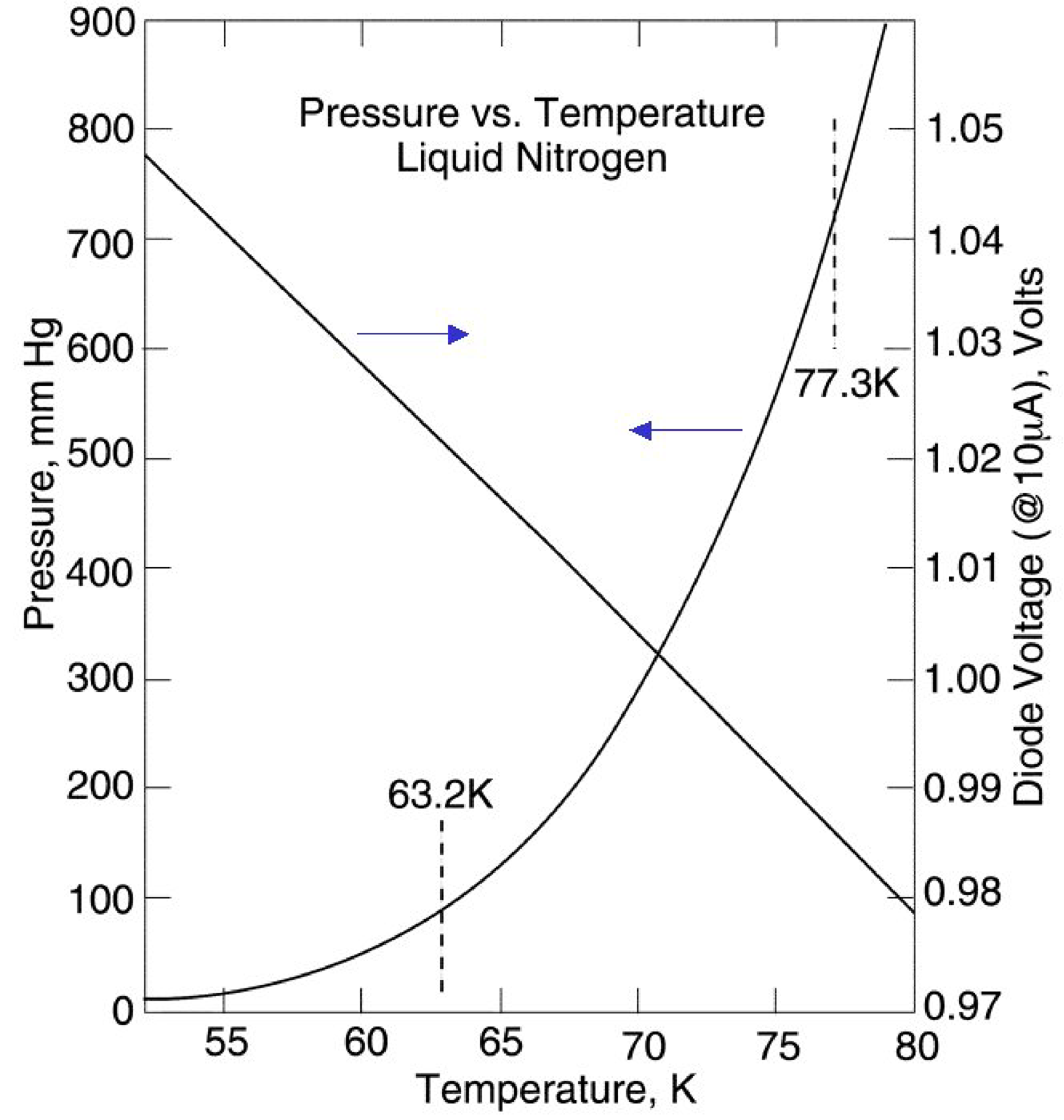






Note: Perpendicular component is less than ¼ of field parallel

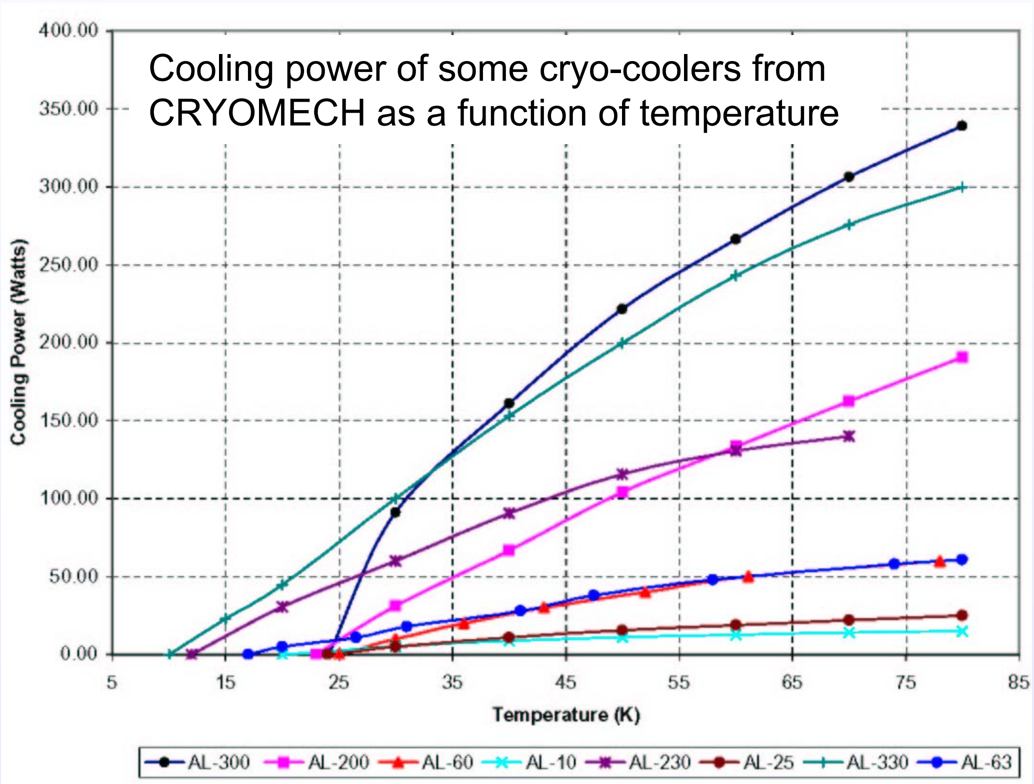
HTS magnets Based on Nitrogen (Temperature Can Be Lowered by Pumping)

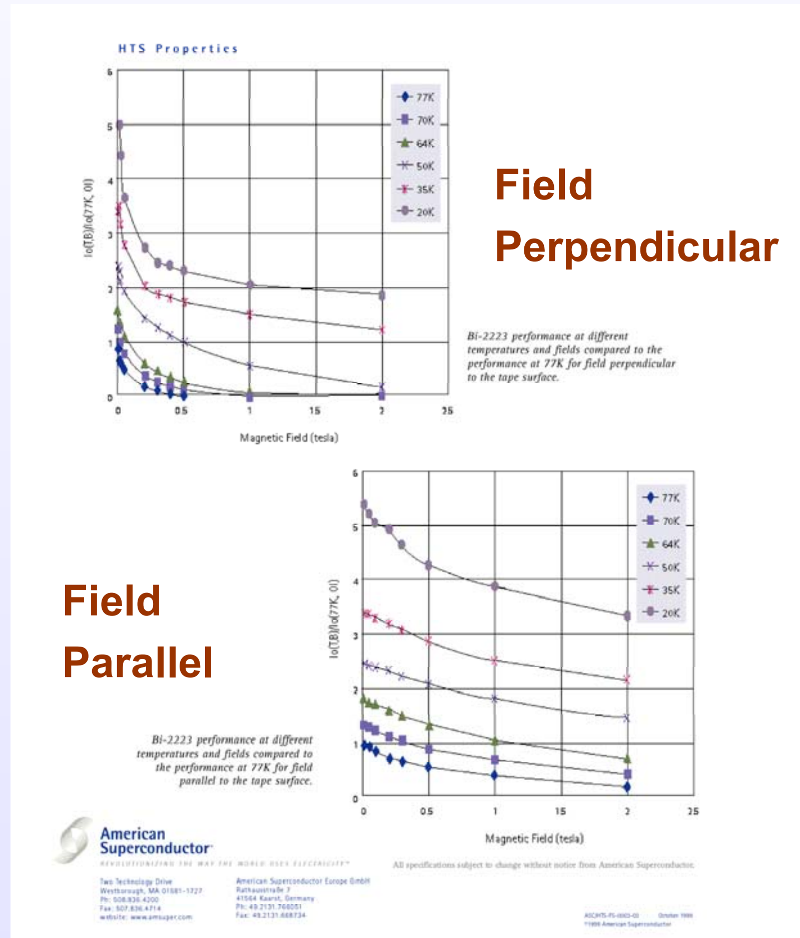


- In some low field applications, one can perhaps operate HTS magnets with nitrogen only.
- One can reach significantly lower temperature than 77 K by reducing the pressure.
- This means that the superconducting (HTS) magnets can be operated without helium.
- This is a major advantage in many situations.

HTS Magnets with Cryo-coolers

In some application (and/or places) it is advantageous to design a magnet system with cryo-coolers.





Operating temperature is an important parameter in cost optimization. A good magnet design with lower field on conductor (in particular lower perpendicular field may significantly reduce conductor amount).

HTS LS2 Dipole Design is Based on the Design Developed for the Neutrino Facility Proposal

DRAFT – BNL Proposal to Conduct Accelerator R&D - DRAFT
for a Future U.S. Neutrino Physics Program
Brookhaven National Laboratory
August XX, 2005

[Version: August 30, 2005]

Executive Summary

This is a proposal submitted by Brookhaven National Laboratory (BNL) to the U.S. Department of Energy (DOE), Office of High Energy Physics (OHEP), to conduct ***Accelerator R&D*** focused on the improvement of accelerator systems and capabilities needed for effective realization of future accelerator-based sources of ***intense neutrino beams***. Our proposal emphasizes the most pressing R&D needs required by the ***'Super Neutrino Beam'*** concept identified in the 2004 Office of Science Future Facilities Intiative[1]. The proposed R&D work will be central to the future effectiveness of the U.S. Neutrino Oscillations Program using accelerator sources of neutrinos. We outline a program that is structured to evolve over a three-year period, indicating technical goals, requested OHEP support levels and staffing levels to meet these national objectives. The proposed R&D topics are described in detail in the Main Text sections below. A prioritized list of topics and proposed support levels is provided here.

Our 1st priority is directed to generic high-power, proton target and integrated target/horn meson-focusing systems R&D. This proposed R&D work will be needed by *any accelerator source* that proposes to advance the capabilities of the U.S. in future accelerator-based neutrino experiments. We also observe that, beyond the neutrino-less double beta-decay and high-precision reactor neutrino experiments currently under consideration for near-term approval, the future effectiveness of neutrino oscillation research will depend upon the development of Megawatt-class target sources and Megaton-class detectors, hence the need for the high power proton target and horn R&D. Our 2nd R&D priority is for development of proton beam transport magnets using high temperature superconductors, a development that will significantly reduce electrical power costs during the operations period of a super neutrino beam program. Our 3rd priority is for the development of novel, Fixed-Field, Alternating-Gradient (FFAG) conceptual accelerator designs that could provide a less costly, high-power proton driver for neutrinos than the present superconducting linac approach. The potential applications of a successful FFAG R&D program extend beyond the improvement of future neutrino beam facilities into the regime of general application to new, high-power proton accelerators for a variety of new scientific applications.

Although there were other quite compelling R&D projects and tasks that we considered adding to this proposal, we felt that the program presented here needed to be held to the requested funding levels. We felt that this dollar level could be supported by DOE OHEP, even under very stringent budgets.

We supply here, a Table of proposed Accelerator R&D projects listed in BNL's priority order.

Table of BNL Accelerator R&D Topics and Budgets by Fiscal Year

Project Name	BNL Priority	FY06 ($K)	FY07 ($K)	FY08 ($K)	Total ($K)
Target Materials & Target/Horn Integration	1	820	970	290	2080
High Temperature Superconducting Magnets	2	363	321	0	684
FFAG Accelerators For Neutrino Physics	3	351	487	385	1223

We will seek an opportunity to discuss these ideas with DOE-OHEP at a meeting to be scheduled in Germantown in the near future.

[1] "Facilities for the Future of Science, A Twenty-Year Outlook", U.S. DOE Office of Science, Nov 2003.

2.0 High Temperature Superconducting Magnets: R. Gupta, PI

High Temperature Superconducting Magnet R&D for Neutrino Physics Application

Continued magnet R&D on cryogen-free super-ferric magnets (Fig. 1) based on High Temperature Superconductors (HTS) is proposed as a way to significantly reduce the operating cost and also potentially reduce the construction costs of the future Super Neutrino Beam Facility identified as part of the DOE Office of Science's 2003 Future Facilities Plan. The present proposal is built upon the recent success of the proof-of-principle HTS magnetic mirror model developed at BNL as part of the Rare Isotope Accelerator (RIA) R&D program [1]. Design concepts are being further developed so that these magnets, fabricated using commercially available HTS tape, become comparable in cost to room temperature water-cooled copper magnets requiring a field over 1.5 Tesla. Moreover, since HTS dipoles can generate significantly higher fields (~2.5T) than room temperature dipoles, this approach would also improve the technical performance of the targeting system, resulting in a more compact primary proton beam transfer line, thereby allowing a longer decay length and/or a shorter, cheaper tunnel.

A primary proton beam transport constructed from such HTS magnets, operating at a temperature of ~35K, will be much more compact than room temperature magnets and will be cooled by plug-in cryo-coolers; hence, no cryogenic plant will be needed. HTS magnets will significantly reduce or potentially eliminate the beamline cooling water system. The magnets will operate below 300 amps, a factor of ten lower than the current required for room temperature magnets. The development of these magnets would not only reduce the operating cost (and perhaps overall construction cost) of the Super Neutrino Beam,

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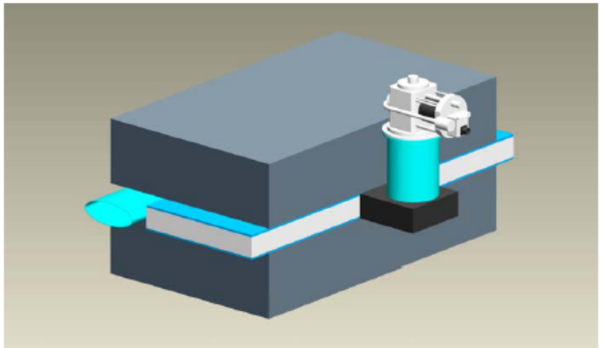
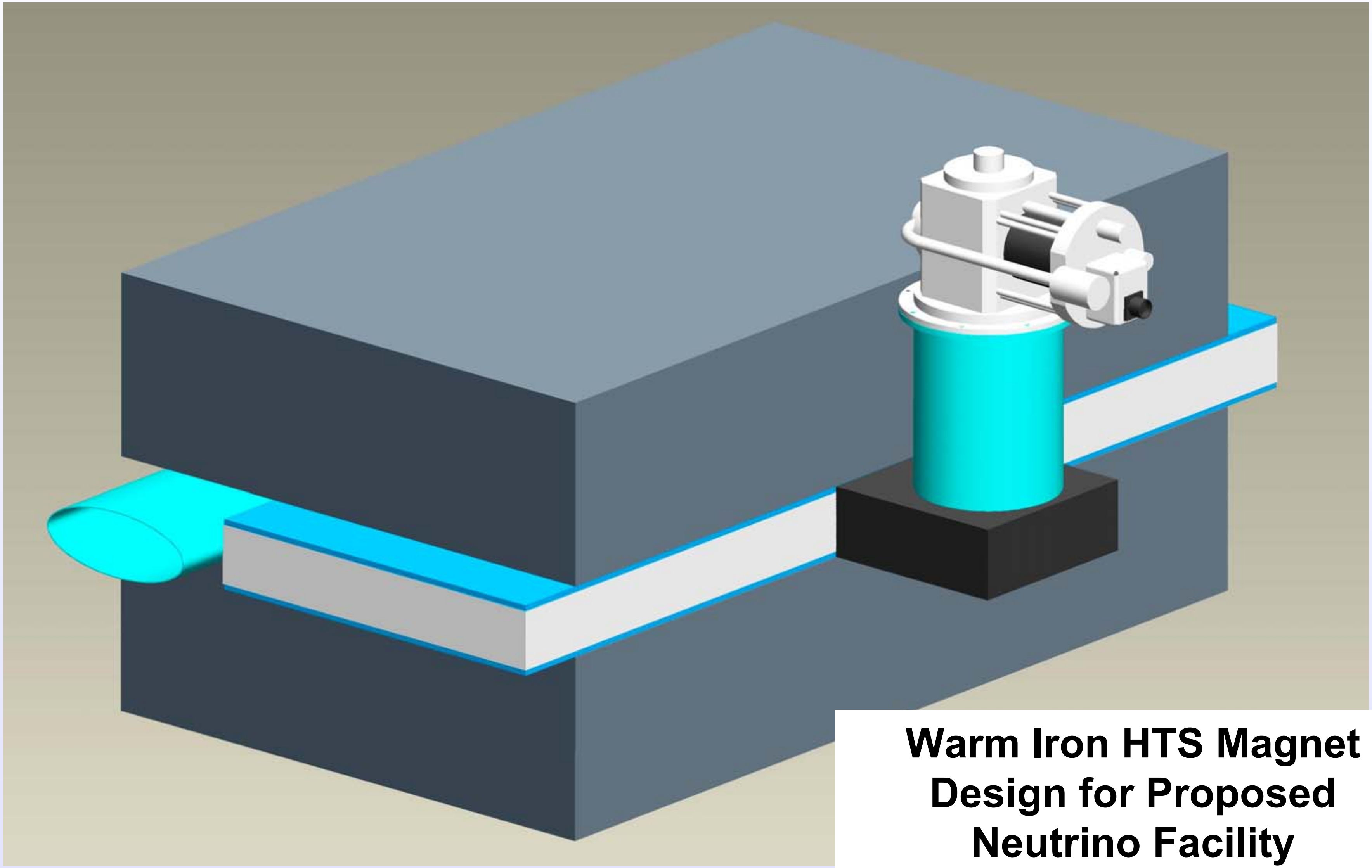


Fig. 1: *Conceptual design of HTS magnet with cryo-cooler for Super Neutrino Beam Line at AGS*

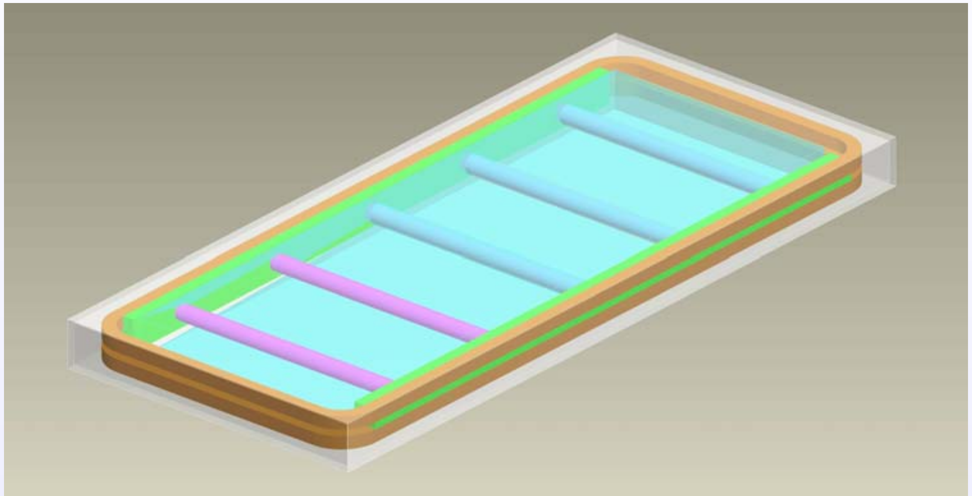
Magnet Concept with Cryo-cooler

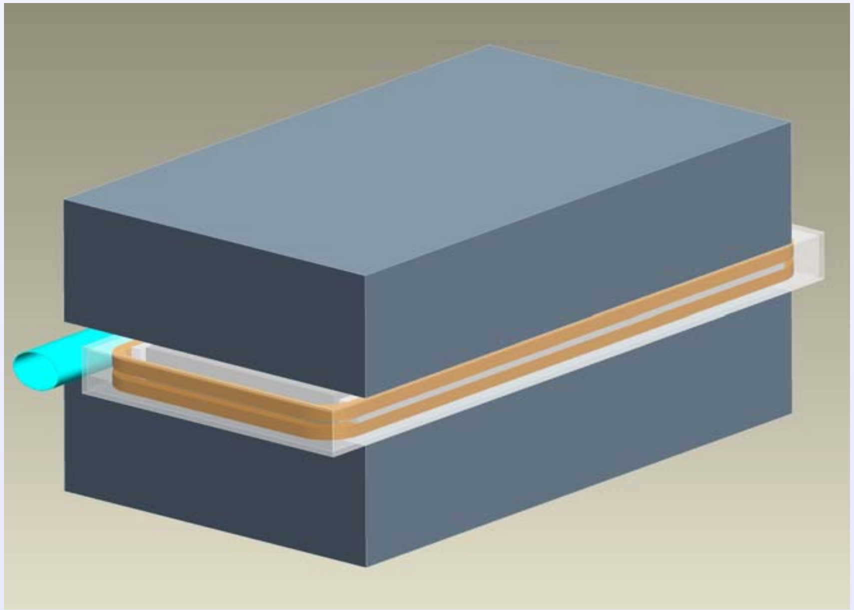


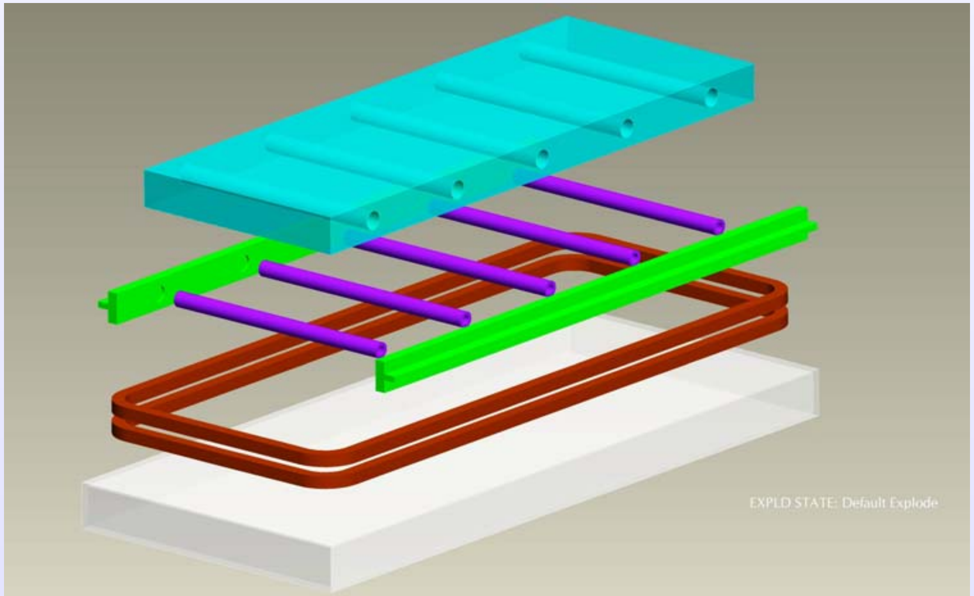
Warm Iron HTS Magnet Design for Proposed Neutrino Facility

Cooling and Support Structure Concepts for Neutrino Facility LONG Magnet

In longer magnet, copper rods were placed (a) to provide much shorter cooling path to coil on the opposite side and (b) to contain forces within cold structure and hence minimize heat leak. Magnetic circuit can be made to accommodate these rods.

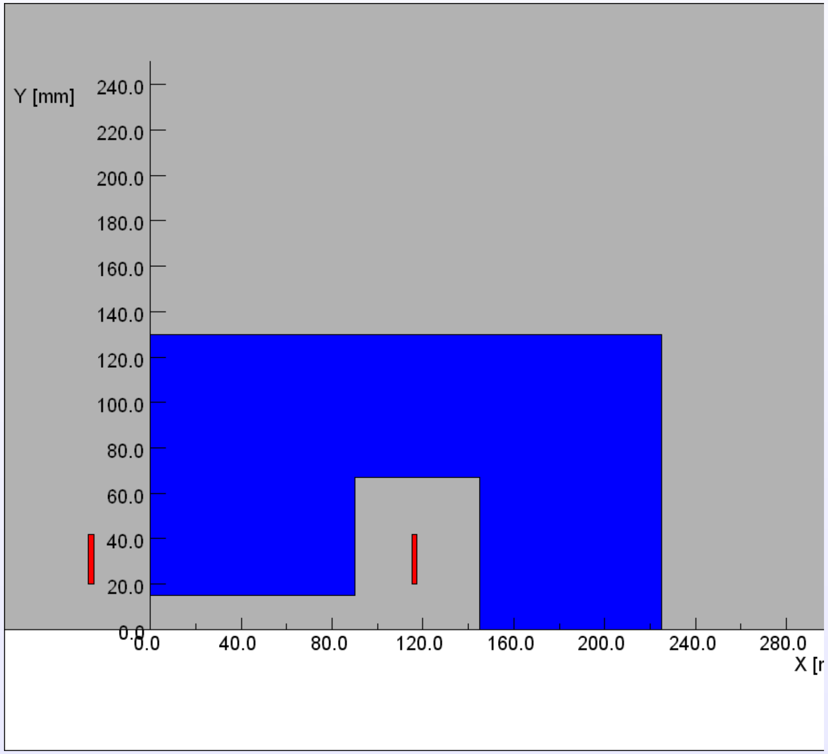


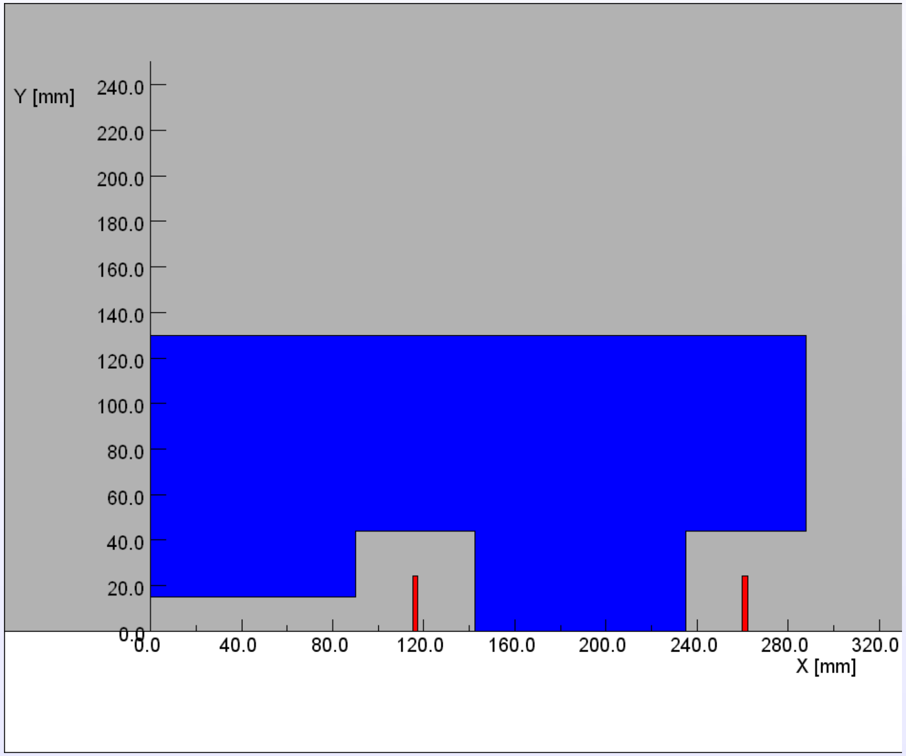




Cooper plate inside the coil is made of high strength cooper. This also serves dual purpose – (a) distribute/contain forces (they are small) and distribute cooling.

Two Magnet Styles

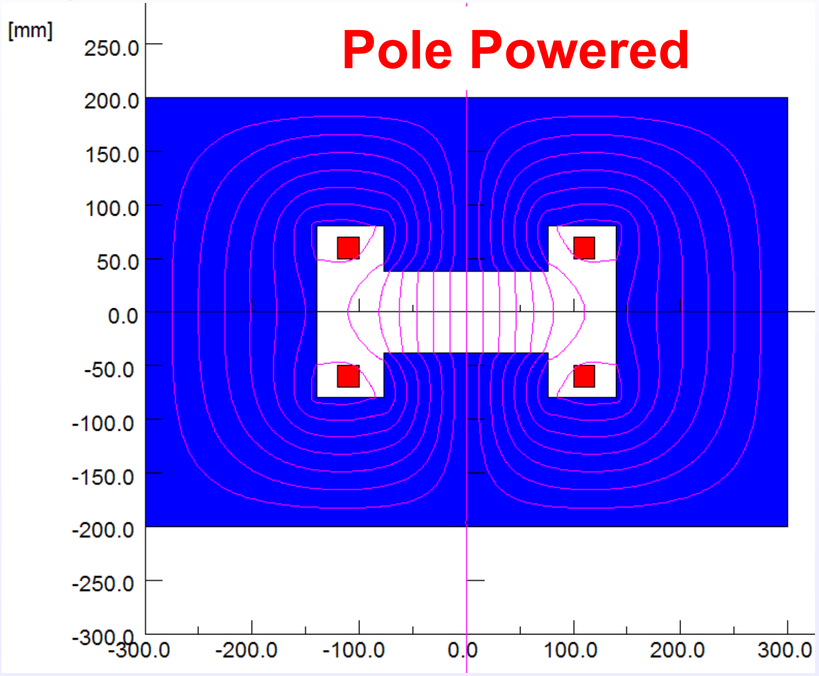


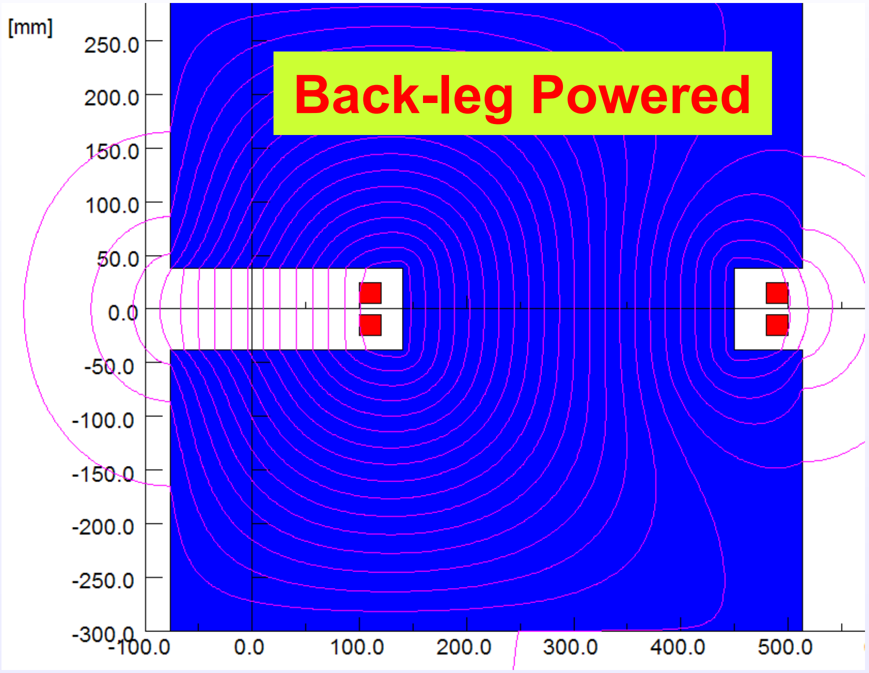


Pole Powered
(earlier referred to as H magnet)

Return Leg Powered
(earlier referred to as C magnet)

Two Types of Basic Designs





We prefer back-leg powered over pole powered to produce lower cost HTS magnets

(a) Needs one cryostat instead of two

(b) Simpler and cheaper support structure because no need to deal with vertical forces

(c) Heat leaks will be lower

(d) Need much less superconductor because field is parallel to superconductor surface

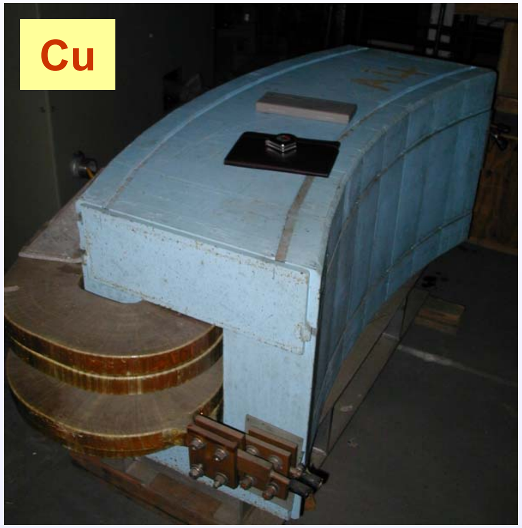
(e) Need for reverse bend in coil winding because of sagitta, can be eliminated

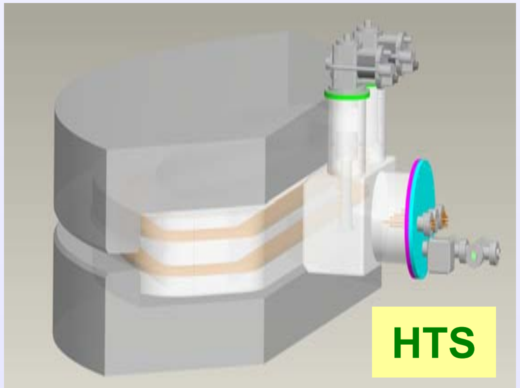
(f) Should facilitate a simpler and cheaper cryostat design

A Case Study for Cost Comparison of Copper and HTS Dipole for Neutrino Facility (This is NOT LS2)

Design Parameters:
- B = 1.55 T
- L = 3.73 m
- Pole width = 153 mm
- Pole gap = 76 mm

Copper Magnets:
- Better known costs (estimated : ~150k$ each for this magnet)
- Cost of individual components like coil, yoke, etc., is well understood
- High operating costs (estimated ~3 MW total)
- Low thermal conductivity water cooling plan
- Higher current (a few kA) power supply (higher cost)
- Maintenance issues (cost, downtime): water leak etc.





Desired cost of support structure and cryostat in this HTS magnet: < 20 K$

HTS Magnets:
- Develop designs to reduce cost (goal : ~150k$/magnet for equivalent integral field)
- Cost of HTS as per present price: ~35 k$ (only ~1/4, lower in future)
- Need to include cost of other components like iron (low and well understood), support structure, cryostat (major driver unless better designs developed)
- Lower operating costs (wall power of cryo-cooler?)
- Cost of cryo-coolers (compare with infrastructure cost of Low Thermal Conductivity Power Plant)
- Lower current (a few hundred Amp) power supply (cheaper)
- Maintenance issues (cost, downtime): cryo-coolers

With this background we move to HTS magnet design for LS2/NSLS2

The purpose of giving this background was to help you appreciate why we are doing things the way we are. (at least we tried!)

Some LS2 Dipole Parameters

The current working LS2 dipole parameters are :

Maximum magnetic field – ~3.3 kG (3.5 is a good round number)

Gap ~ 35 mm

Saggitta ~ 30 mm

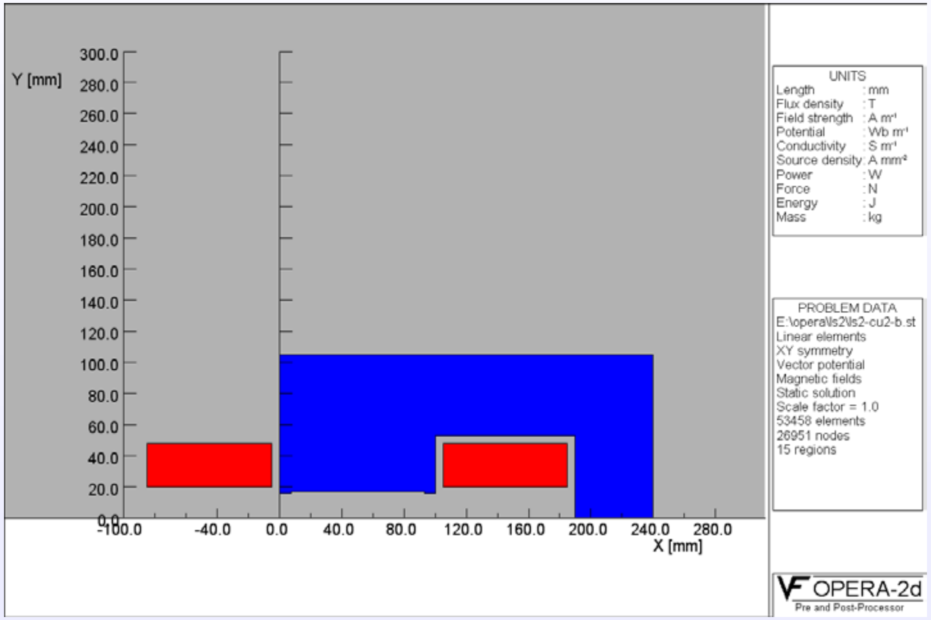
Horizontal aperture - ± 30 mm
(60 mm in curved magnet, 90 mm in straight magnet)

There is no high field (1 T) section at this stage

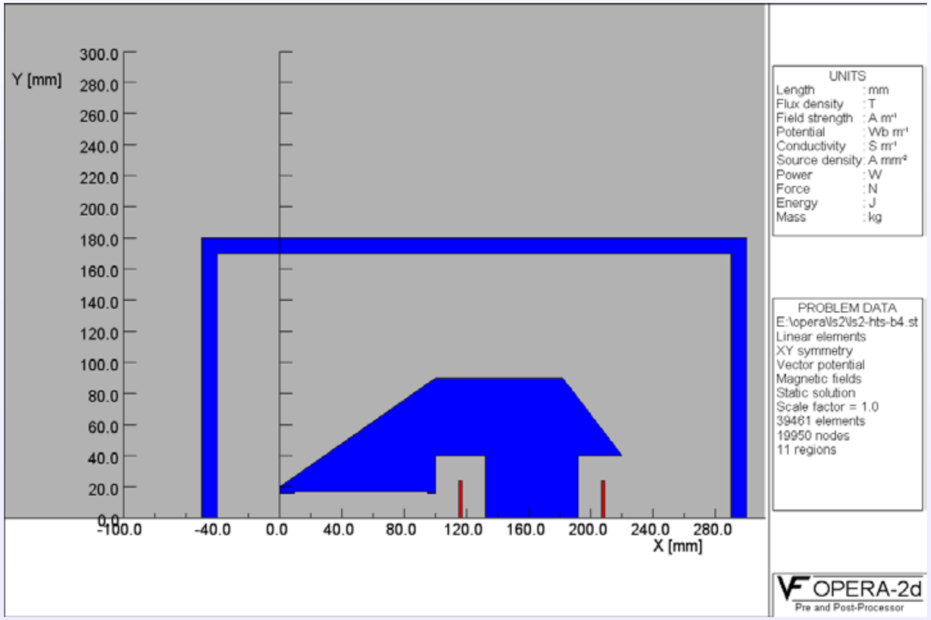
Magnetic design studies will be made for both a “1 T high field section in the middle” and a “0.1 T low field section” in one end. But no detailed engineering design will be made.

This is a good time to make suggestions/corrections.

Magnetic Models of 3 kG Magnet Designs for Light Source 2 (LS2)



Water-cooled copper magnet
(Pole powered)
Current Density = 2 A/mm^2



HTS magnet with shield
(Back-leg powered)
Current Density = 50-100 A/mm^2

How Ampere's Law Is Satisfied and Fringe Field is Kept Low

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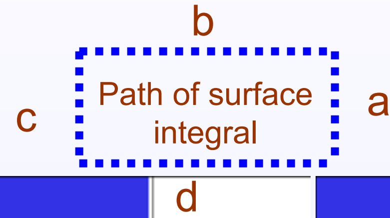
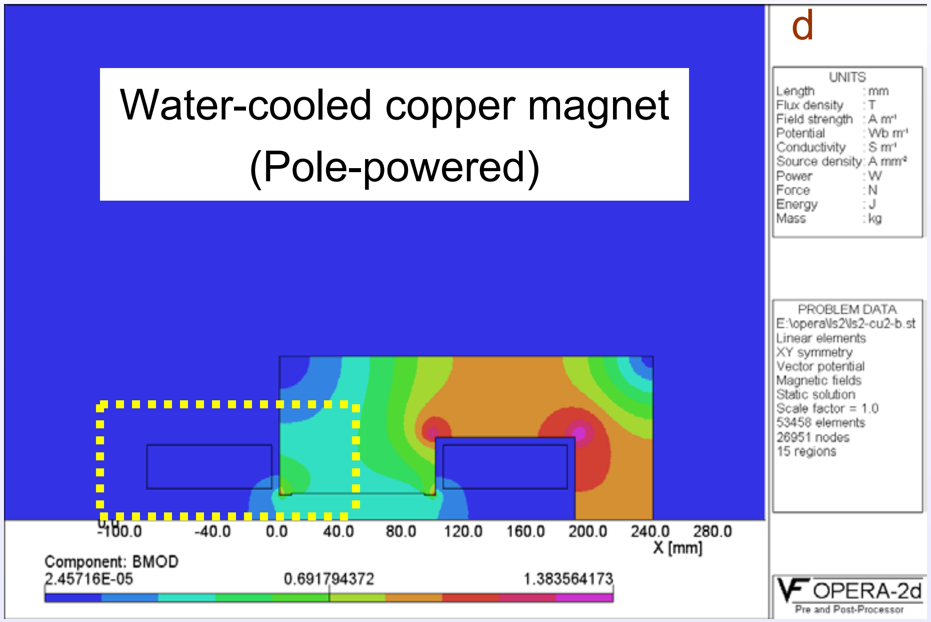
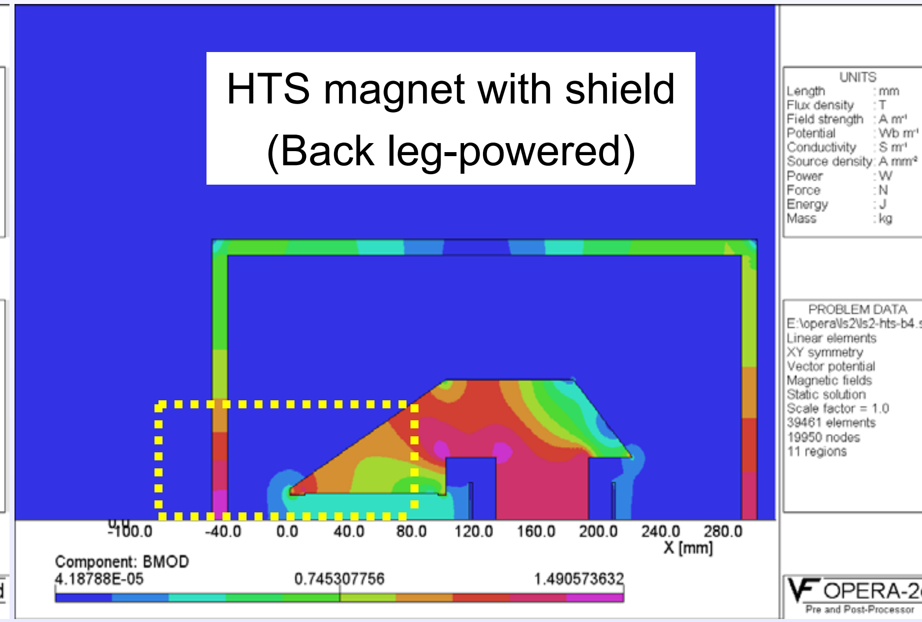
$$\oint H \cdot dL = N \cdot I$$



With a properly designed shielding, Ampere's law does not come in the way of low fringe field outside the shield





Only significant contribution comes from H (B_y/μ_o) in gap (*g*) region. One can obtain:

$$B_y . g \,/\, \mu_o = N \,.\, I$$

- Fringe field ***"c"*** can be small !

Significant contributions come from H_y in gap (g) and H_x separation (*s*) between shield and iron region. Fringe field can be small if:

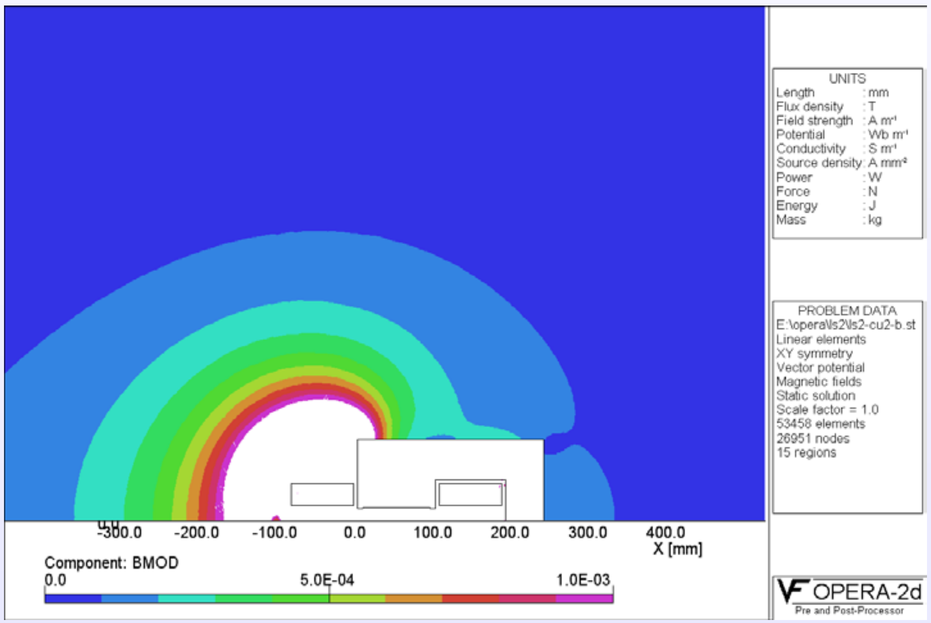
$$H_y . g \sim -H_x . s$$

- Fringe field ***"c"*** can be small !

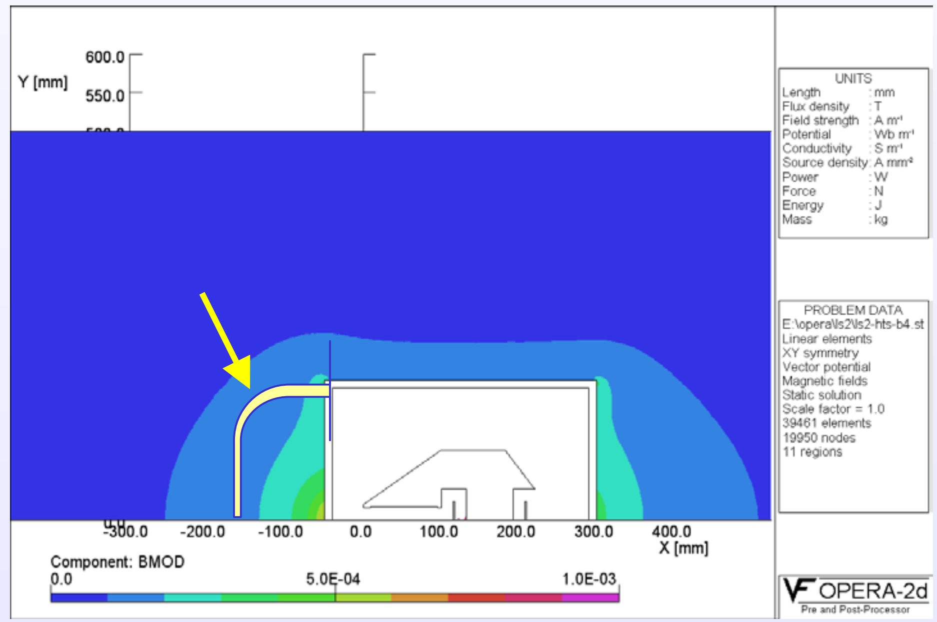
Fringe Fields in Magnet Cross-section

Note: Fringe field is significantly lower at a similar distance (as compared to conventional pole-powered water-cooled magnet) from magnet center in back leg powered HTS magnet with appropriate shield (maximum width 10mm).

There are a variety of simple and practical ways to incorporate this shield.



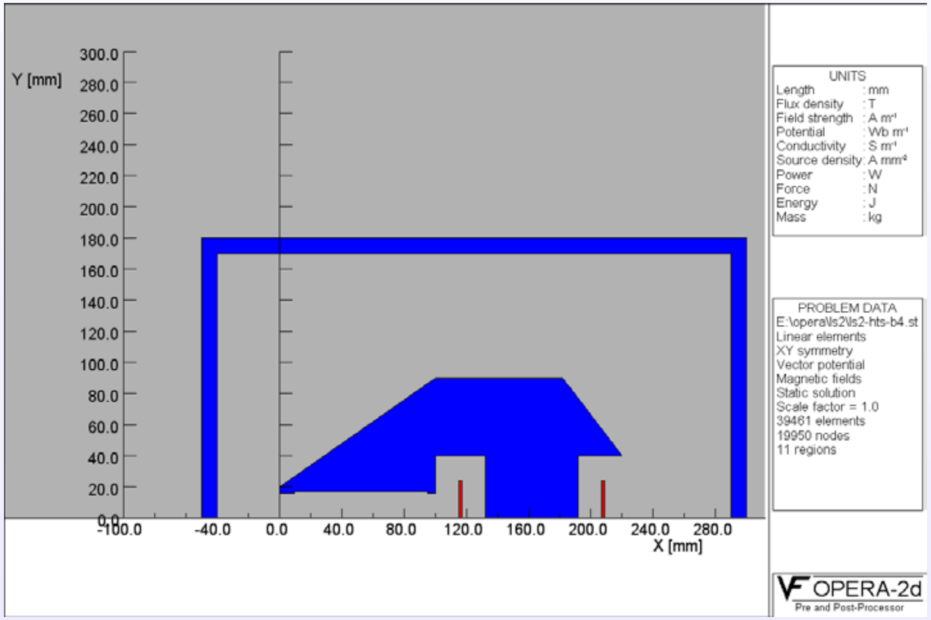
Water-cooled copper magnet
(Pole-powered)

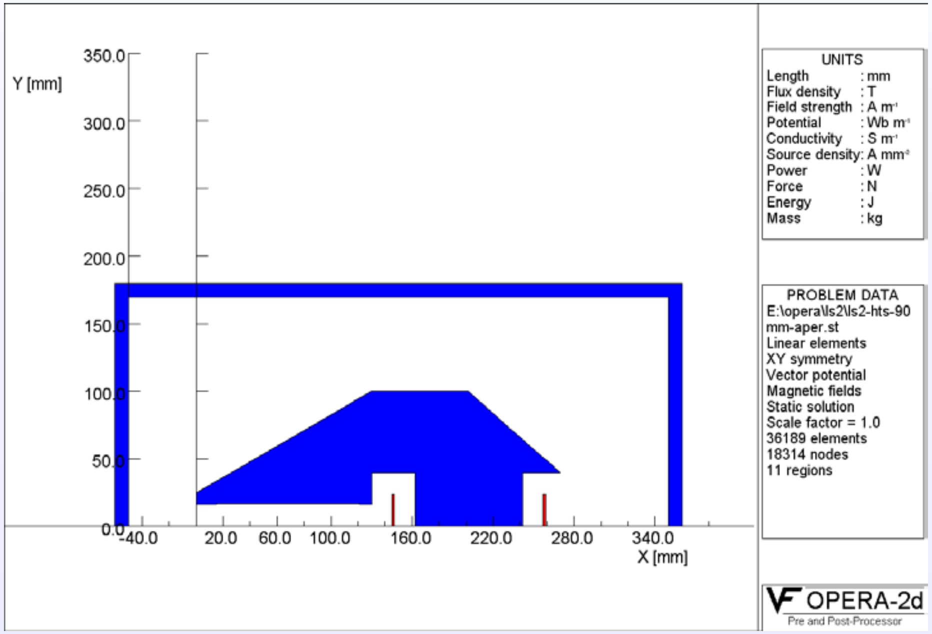


HTS magnet with shield
(Back leg-powered)

Maximum scale 10^{-3} T (10 G); Pacemaker limit: 5 G
Field is much lower a certain distance away from the shield.

Magnetic Models of 3 kG Magnet Designs for Light Source 2 (LS2)





HTS 60 mm good field aperture (curved)

HTS 90 mm good field aperture (straight)

Our baseline design for CDR is straight magnet (as per guidance from Vladimir)

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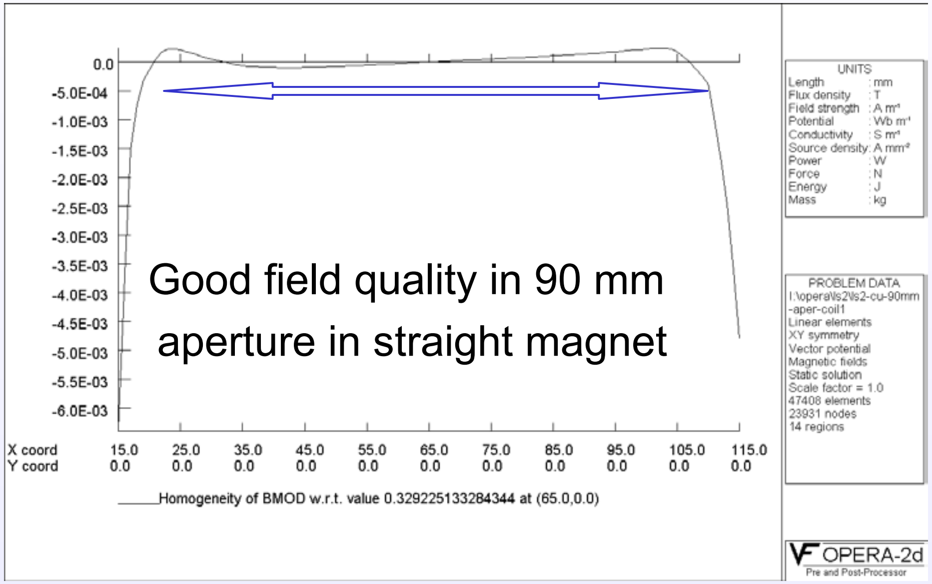
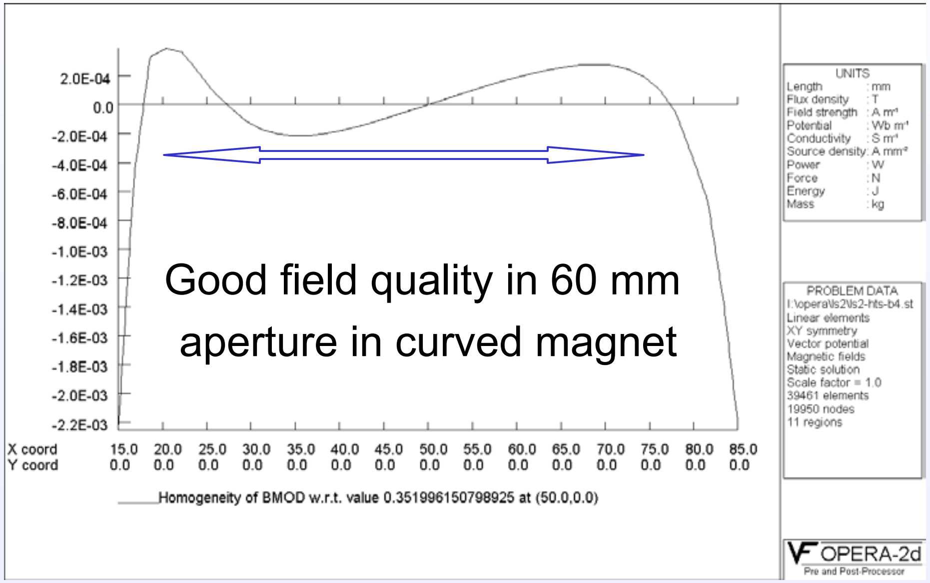
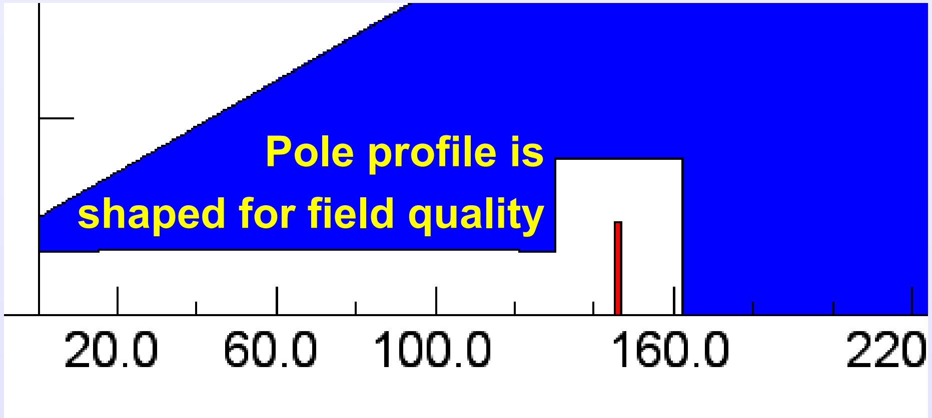
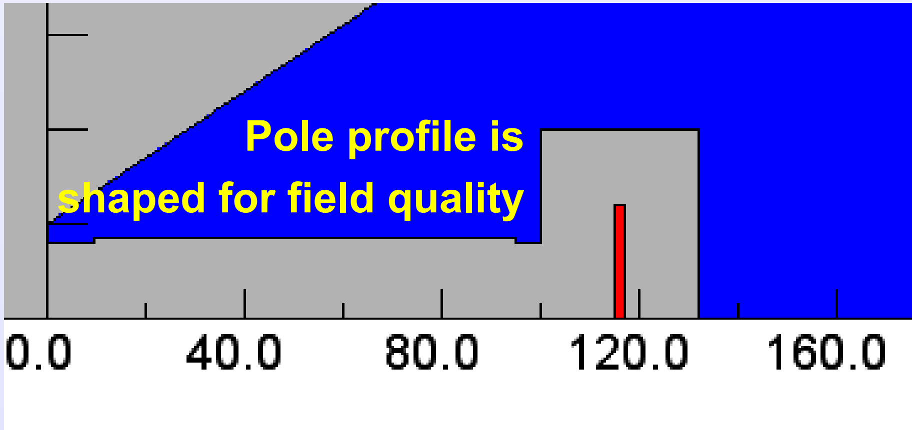
Field Quality in Preliminary Design



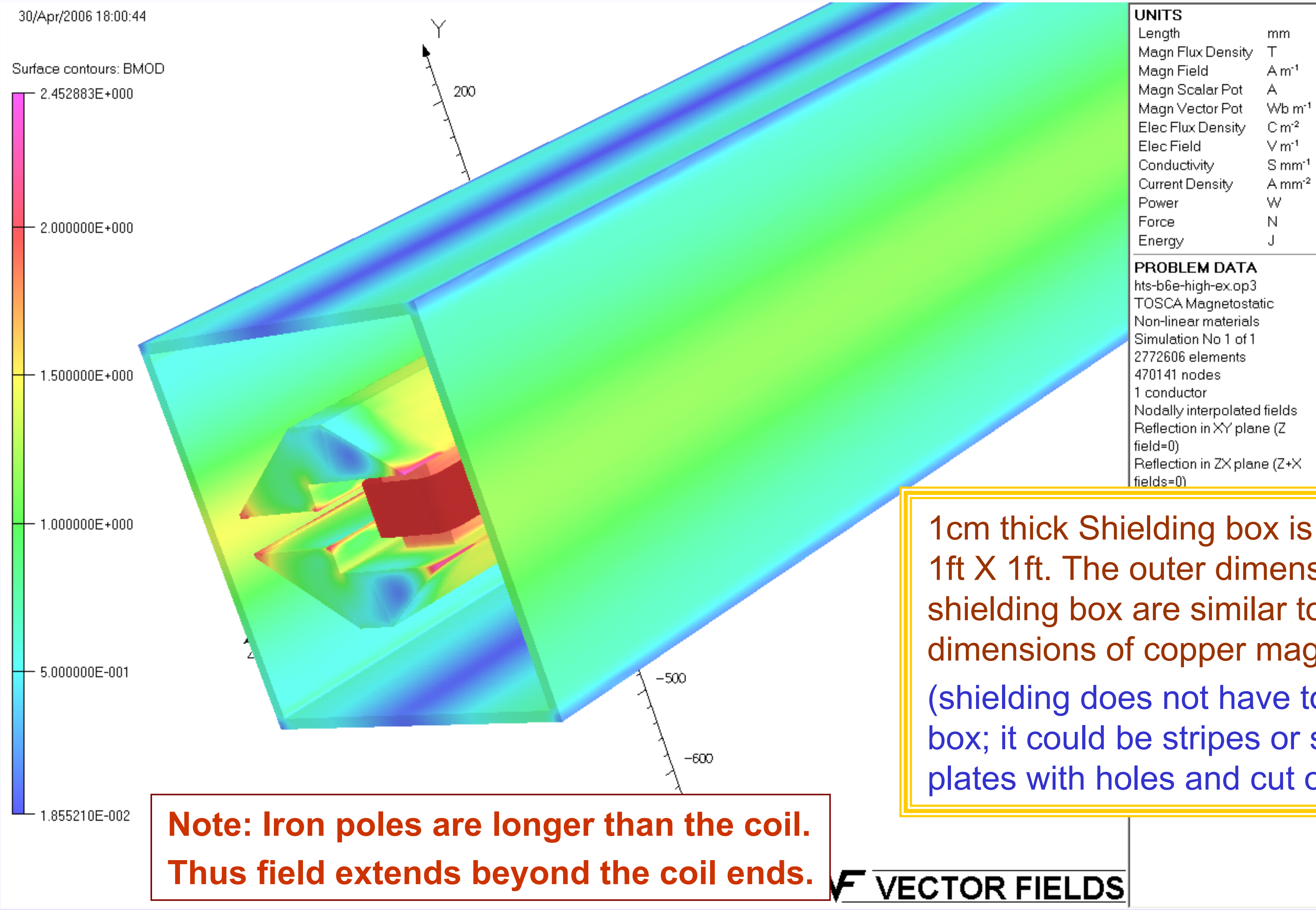


These are preliminary conceptual designs. Nevertheless the field quality requirements of a few parts in 10^{-4} have been obtained by shaping the pole (0.5 mm max, vertically).





HTS Back-leg Powered Magnet (Without End Shields)

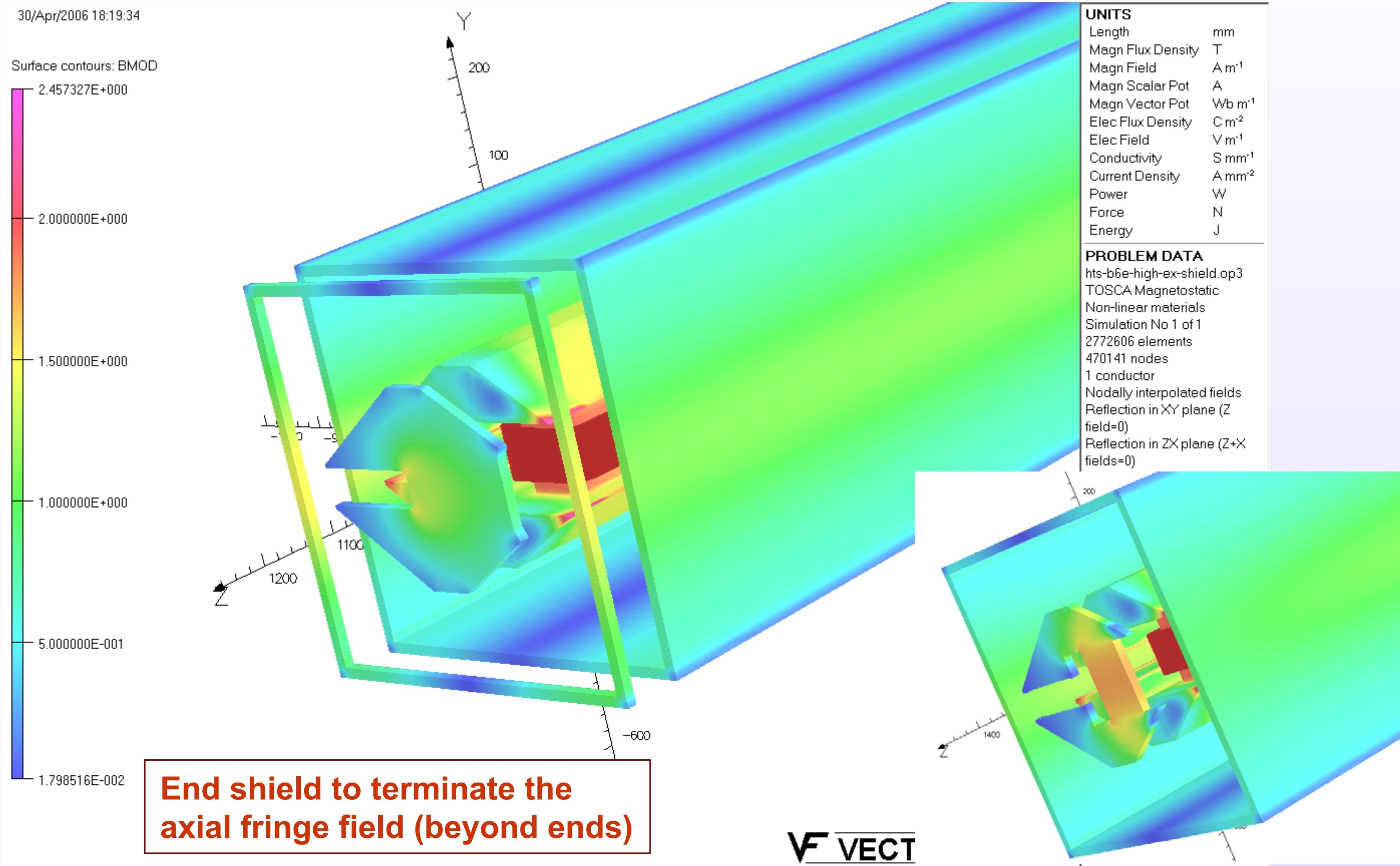


1cm thick Shielding box is about 1ft X 1ft. The outer dimension of shielding box are similar to overall dimensions of copper magnet.

(shielding does not have to be a box; it could be stripes or simple plates with holes and cut out, etc.)

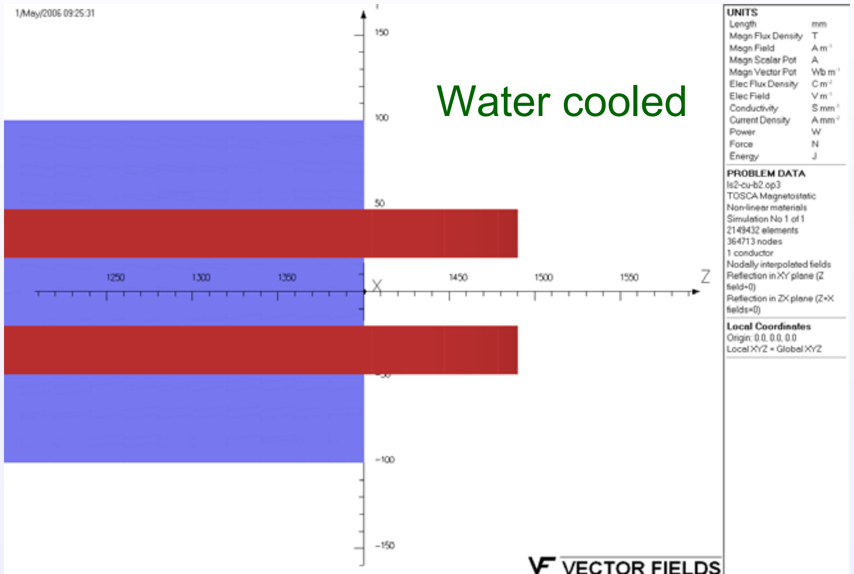
Note: Iron poles are longer than the coil. Thus field extends beyond the coil ends.

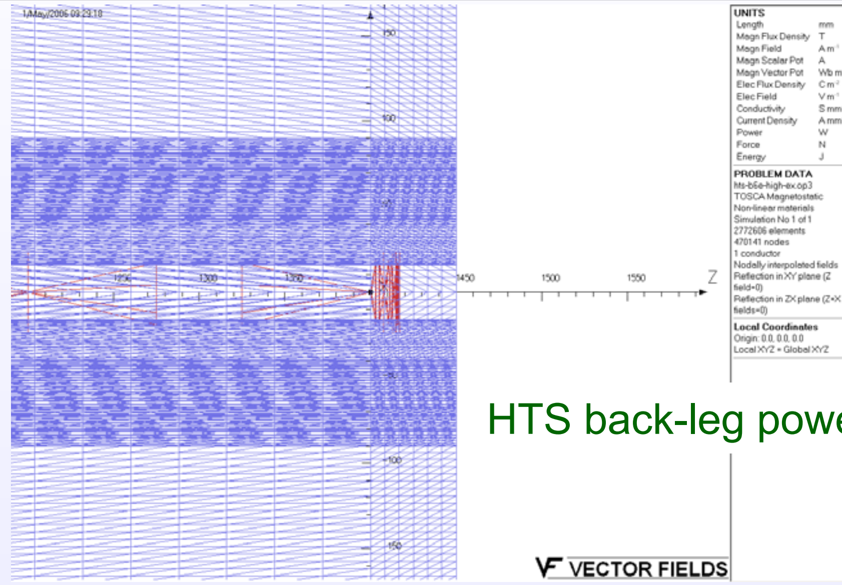
HTS Back-leg Powered Magnet (With End Shields)

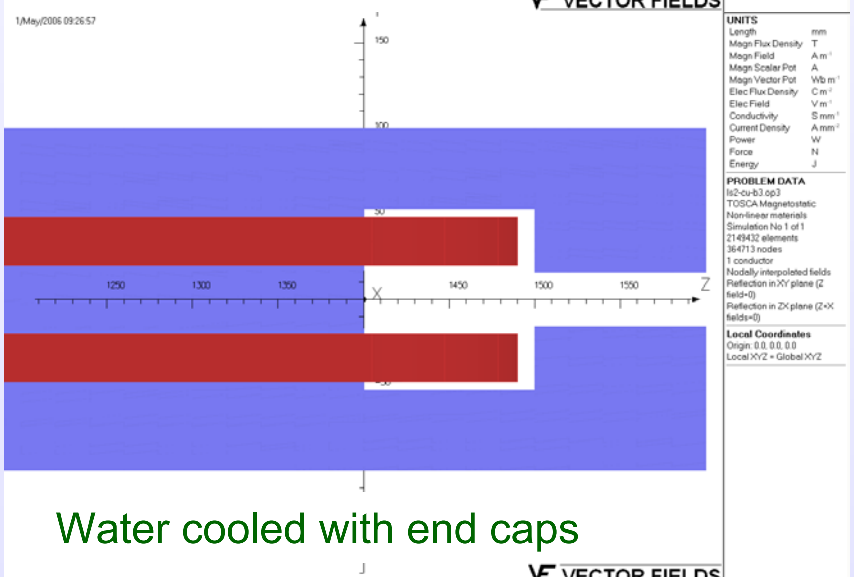


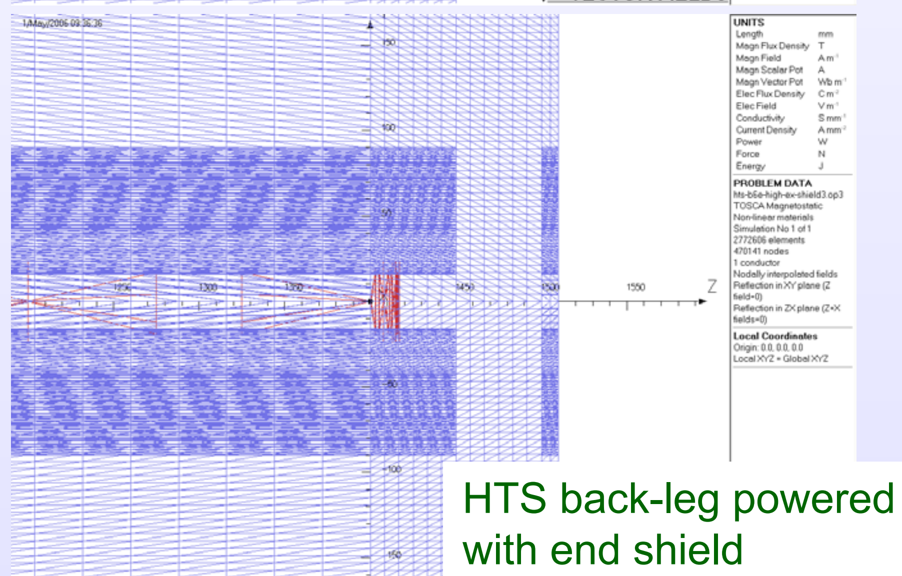
End shield to terminate the axial fringe field (beyond ends)

Fringe Field Beyond the Magnet Ends
(All designs have same inner coil length)

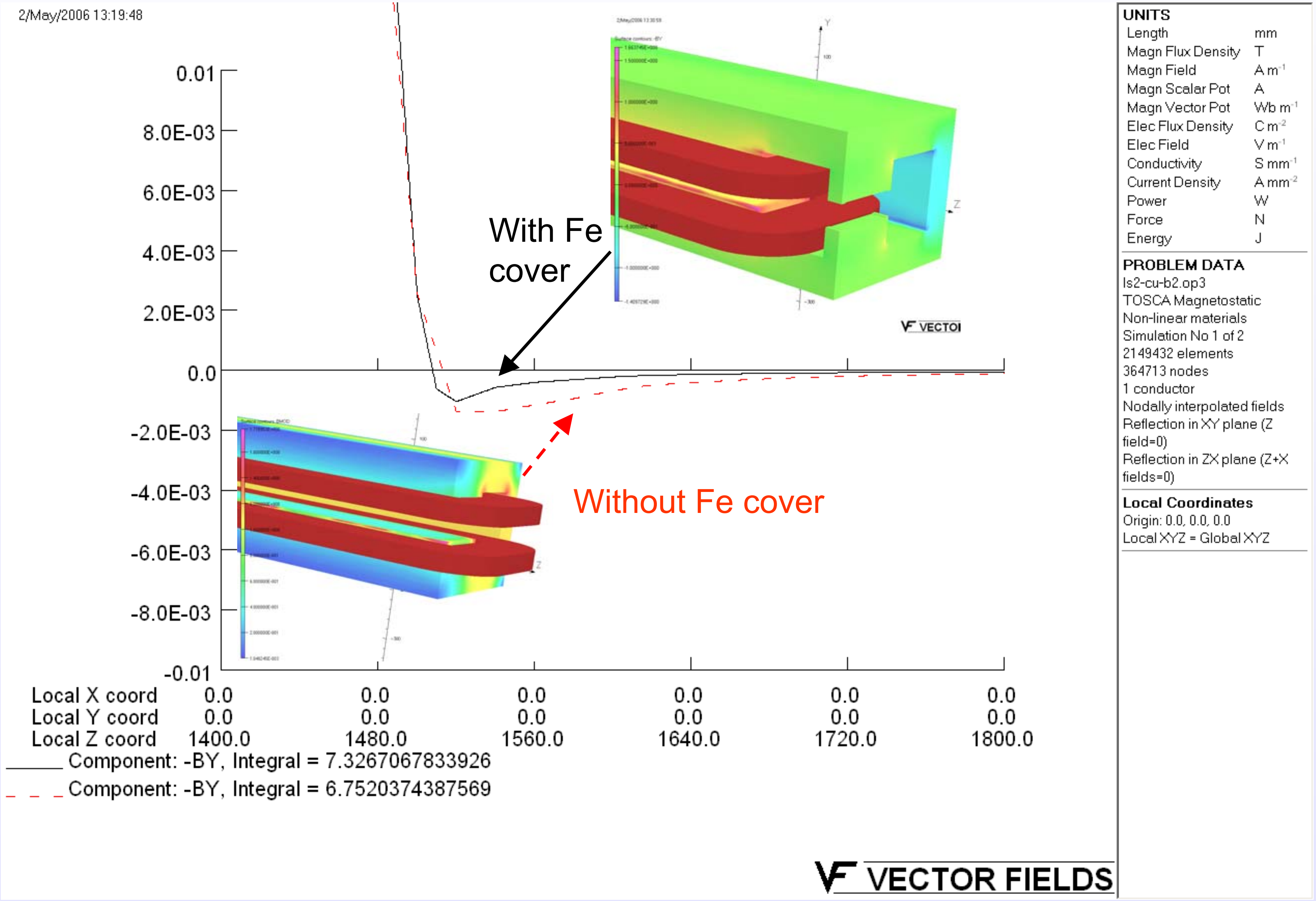




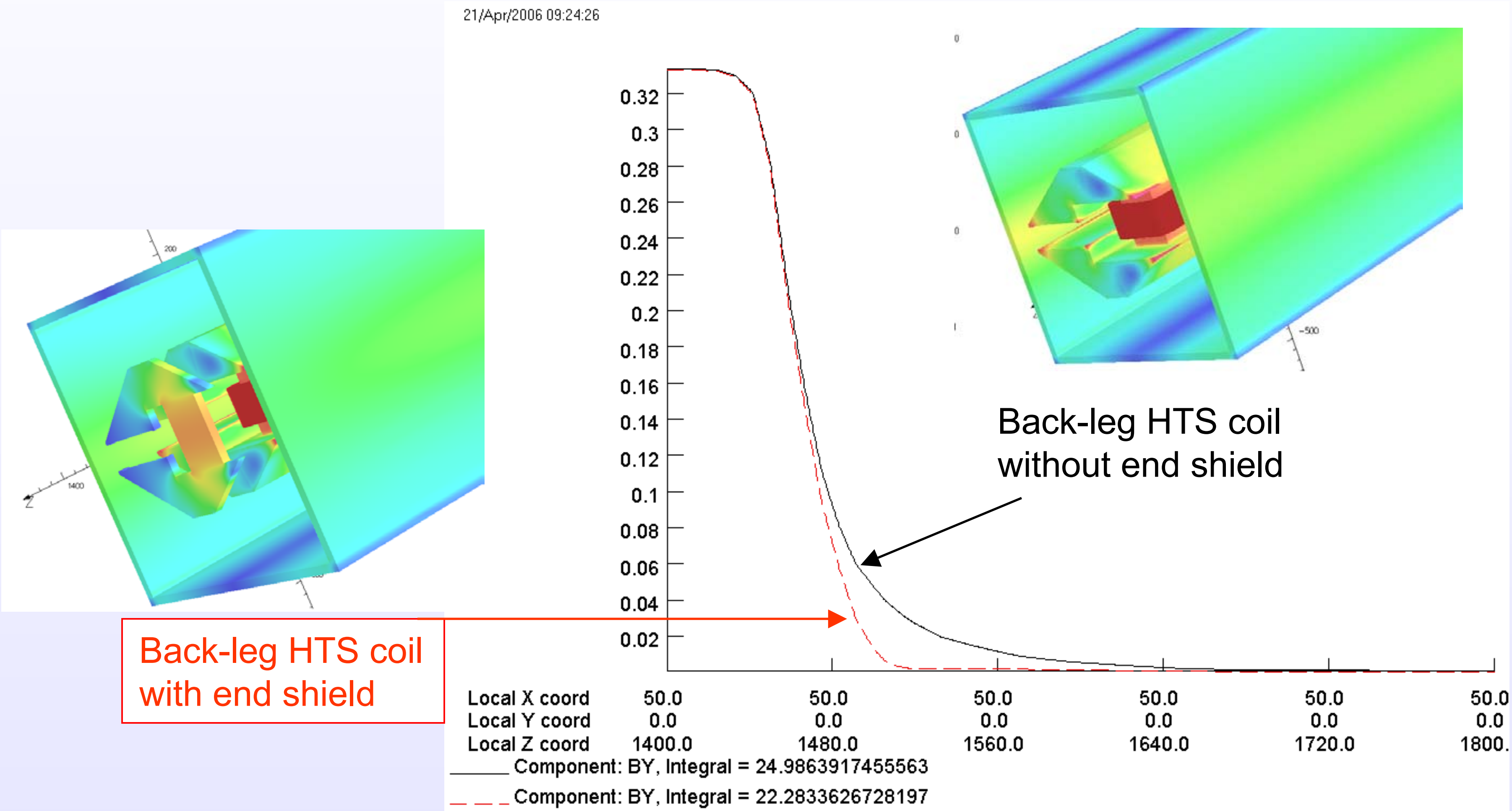




Field Away From Magnet With and Without Fe Cover in Copper Magnet



Field Beyond Ends in HTS Magnets



The field beyond shield in HTS magnet is similar to Cu magnet with 1 cm shield (can be made smaller with thicker end shield, if desired).

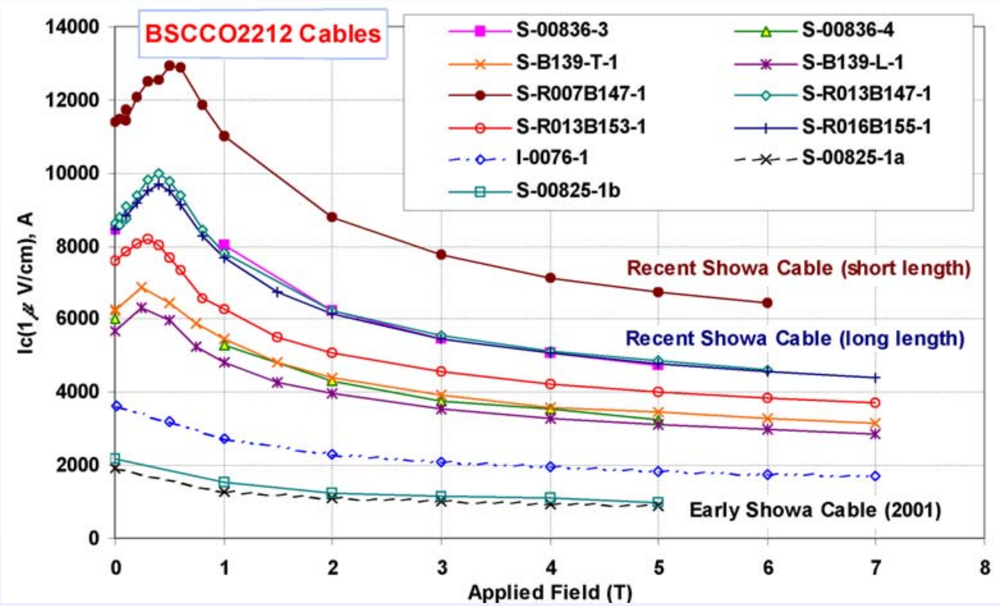
Summary

- Preliminary investigations of HTS dipole design has been made.
- We hope that there is a better understanding of why we are doing tings the way they are.
- We can move forward to finish this design study with some guidance.

Extra Slides

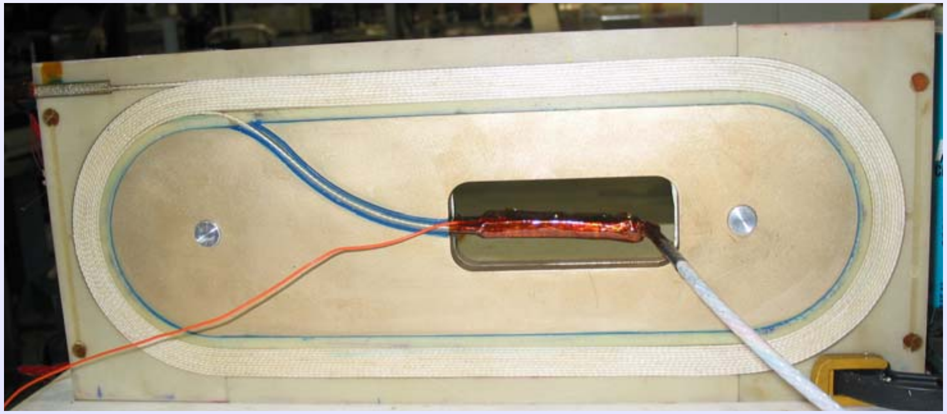
Superconducting
Magnet Division

High Field HTS Coils and Magnet at BNL with Rutherford Cable

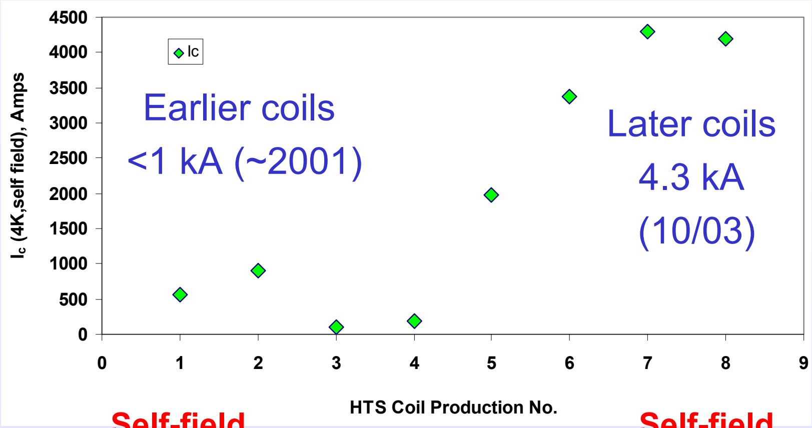


Cable made at LBL, reacted at Showa, tested at BNL

Modern HTS cables, coils & magnets can carry a significant current.



HTS coil wound and tested in a common coil magnet at BNL



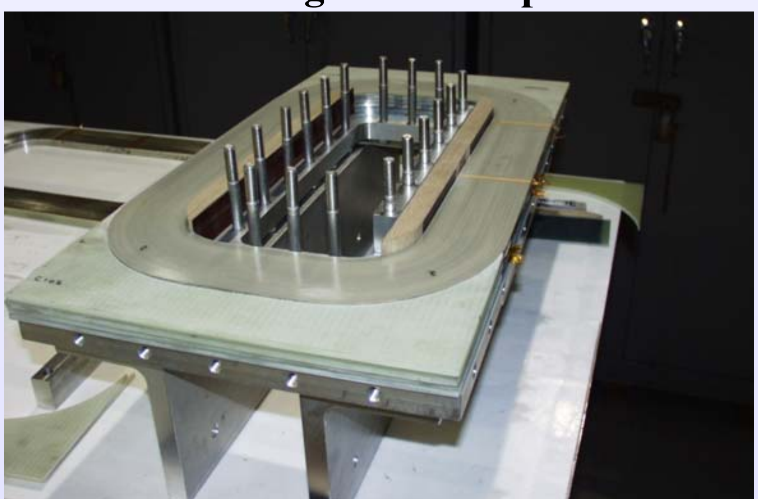
Self-field <0.05 T

Self-field ~ 1.85 T

RIA HTS Quadrupole At Various Stages of Construction and Testing

HTS coil winding with SS tape insulator

Warm iron magnetic mirror test with twelve coils



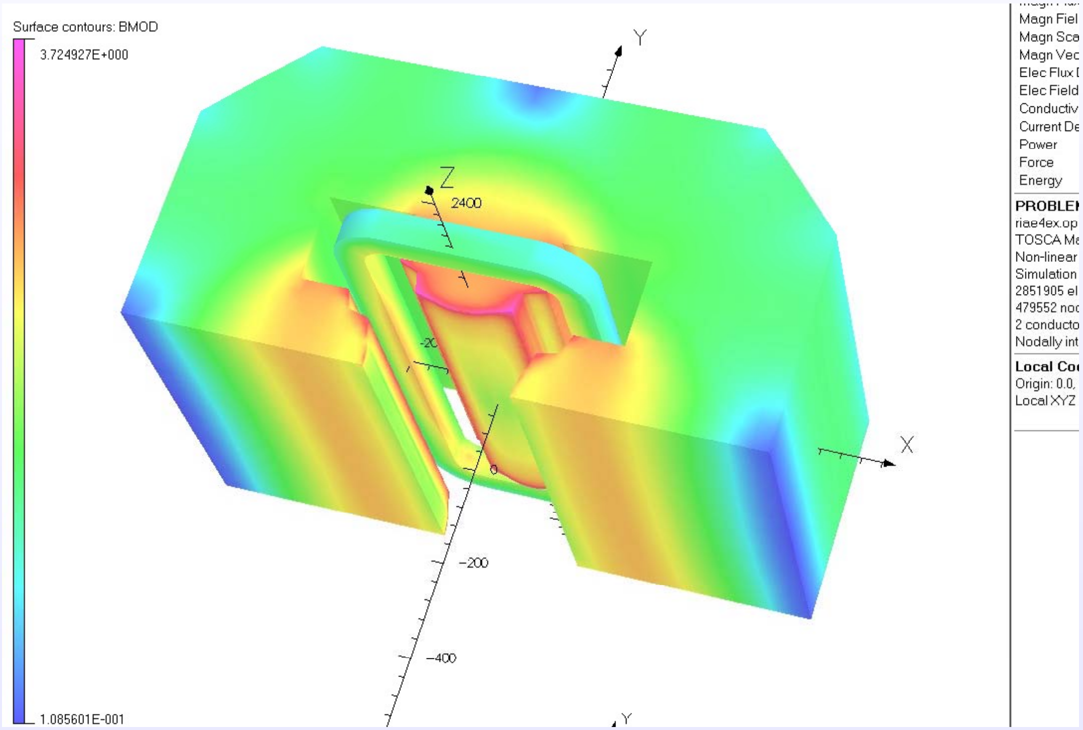
HTS coils during magnet assembly

Cold iron magnetic mirror test with six coils

- We have been doing HTS magnet design and R&D from last 10 year. BNL/Magnet Division is the leading laboratory in the world on HTS Magnets.
- We designed the magnets around the conductor and around the specific situation, rather than just pointing out the difficulties with the conductor and the magnet design.

Superconducting
Magnet Division

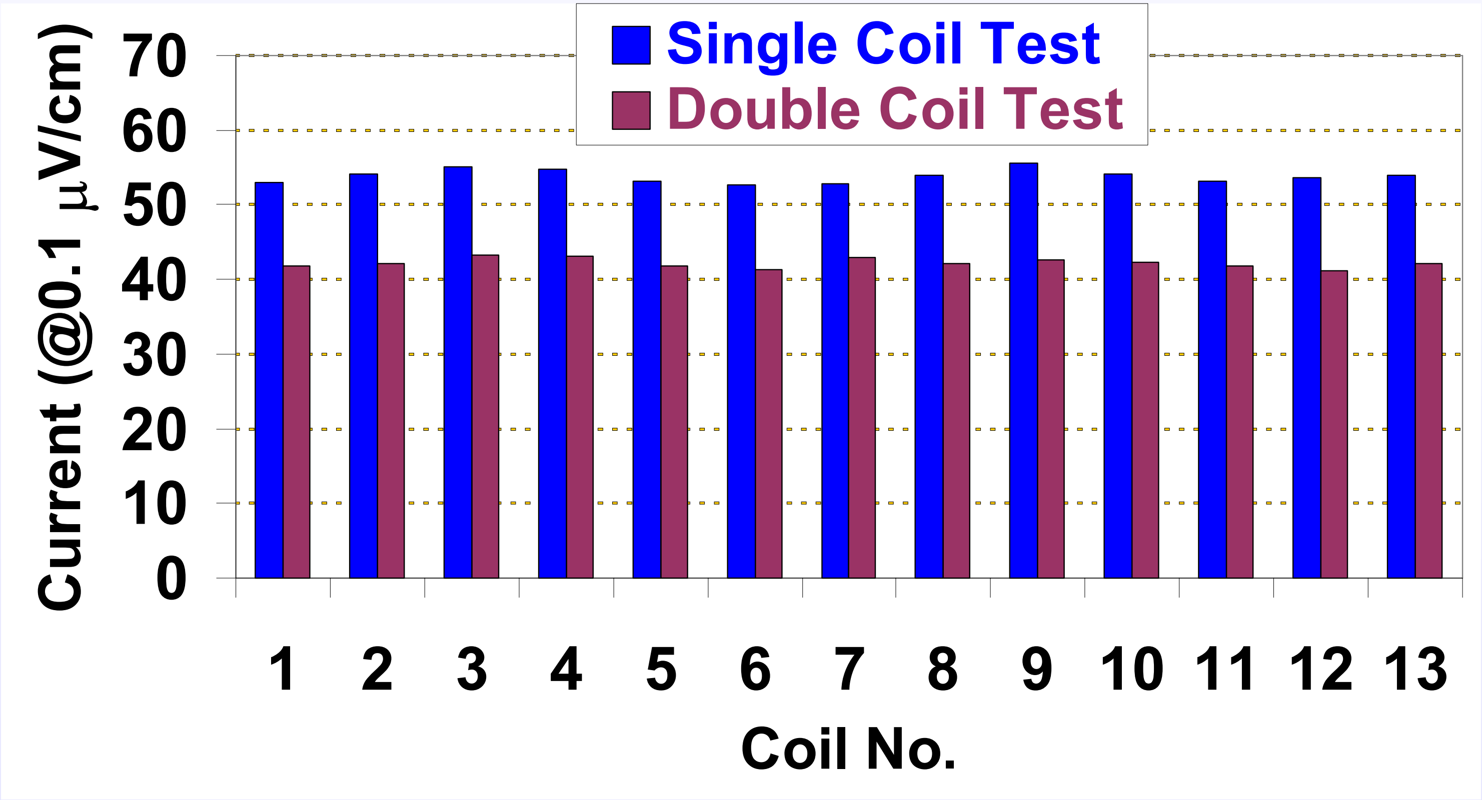
3-d Model of RIA Quad



An OPERA3d model of the 280 mm aperture super-ferric quadrupole design for RIA. Color indicates the field intensity on the surface of coil and iron regions. The model shows only one symmetric half the complete magnet. The magnet is designed such that two coils create the quadrupole symmetry.

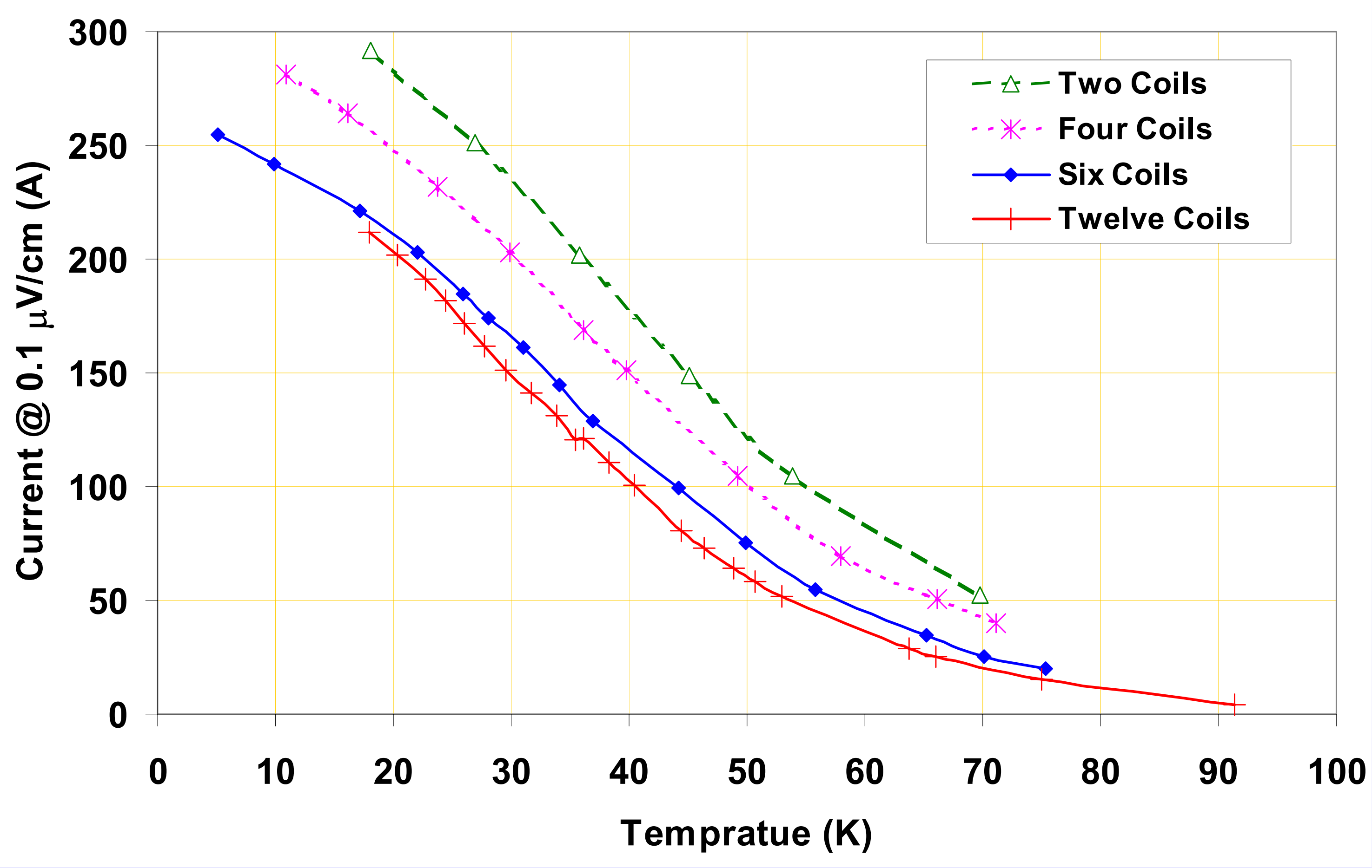
Performance of 13 HTS Coils (Each made with ~220 meter of tape)

Coils can be made without damaging or degrading conductor. Also note the uniformity in performance of coils made with commercially available HTS.



The current at a voltage gradient of 0.1 μ V/cm (10 μ V/meter) over the total length of the coils at 77 K.

RIA HTS Model Magnet Test Results for Various Configurations



More coils create more field and hence would have lower current carrying capacity

A summary of the temperature dependence of the current in two, four, six and twelve coils in the magnetic mirror model. In each case voltage appears on the coil is closest to the pole tip. Magnetic field is approximately three times as great for six coils as it is for four coils.