Superconducting Magnets for Particle Accelerators

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OVERVIEW

- Superconductivity and Superconducting Magnets
- Review of SC Magnet Design for Accelerators
- HTS Magnets and their Applications
- Summary

Superconductors

Superconductors

- Discovered 100 years ago
- Essentially zero electrical resistance
- Facilitate electro-magnets with high fields that are not practical with magnets made with copper coils while conserving electrical power

Conventional Superconductors

- Most applications require operation at ~4K (-269 C, *liquid helium*)
  - Thus also called Low Temperature Superconductors (LTS)

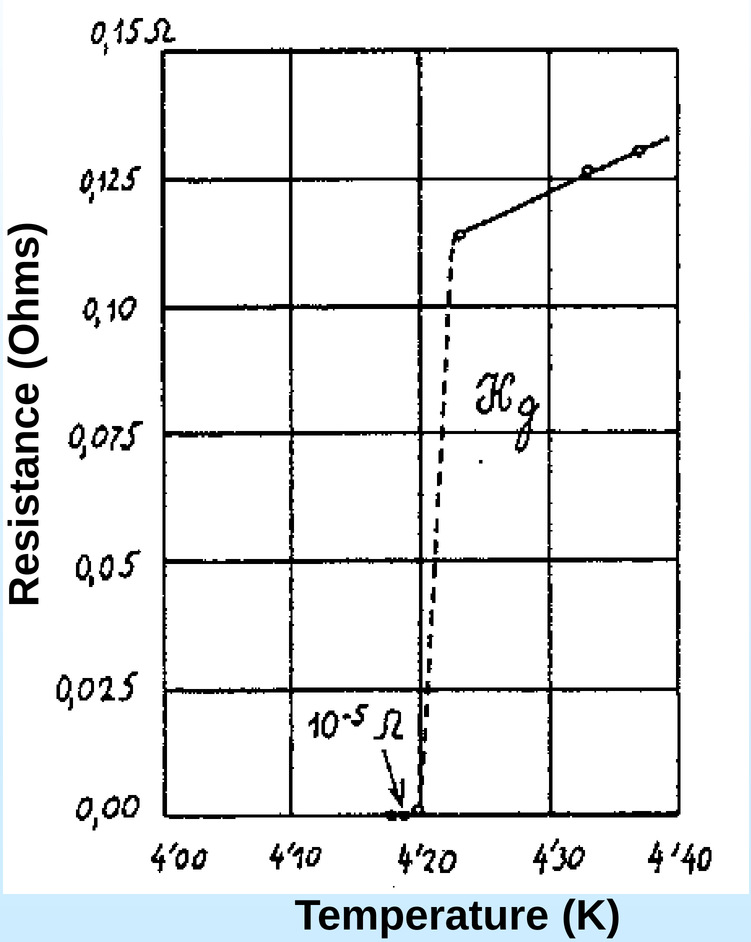
High Temperature Superconductors (HTS)

- Materials that are generally superconducting at ~77 K (-196 C, *liquid nitrogen*)

Conventional Low Temperature Superconductors (LTS) and New High Temperature Superconductors (HTS)

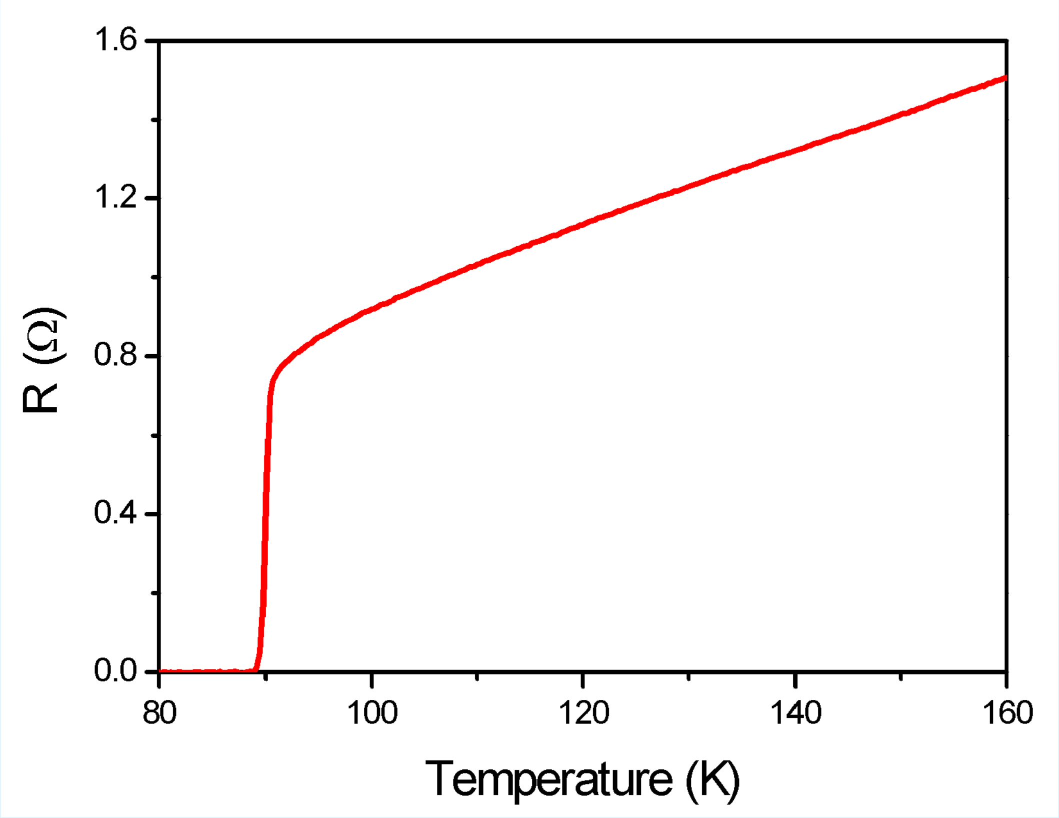
Low Temperature Superconductor(1911)

Resistance of Mercury falls rapidly at very low temperature



High Temperature Superconductors (1986)

New materials (ceramics) loose their resistance at NOT so low temperatures (Liquid Nitrogen)!



Critical Surface of Nb-Ti

Critical Surface

The surface on 3-d (J,T,B) volume within which the material remains superconducting.

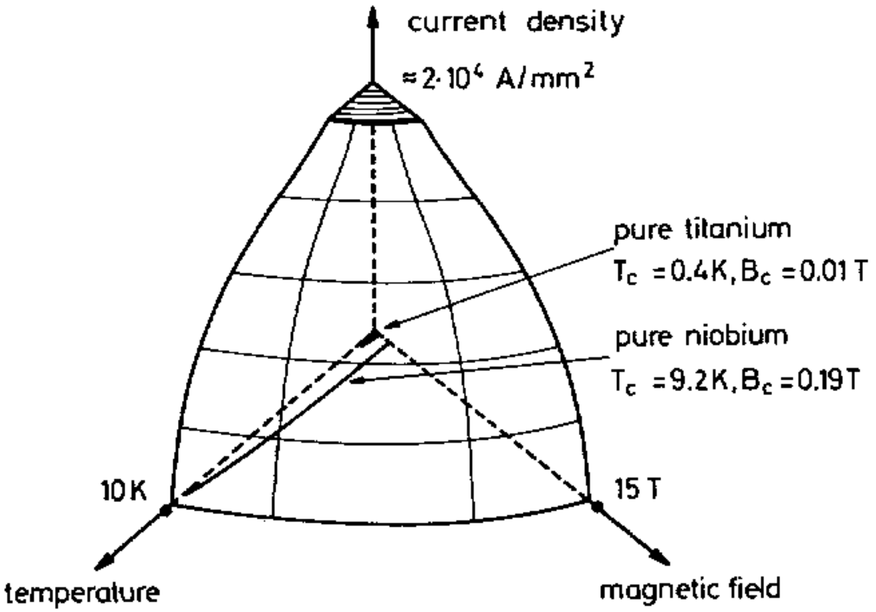
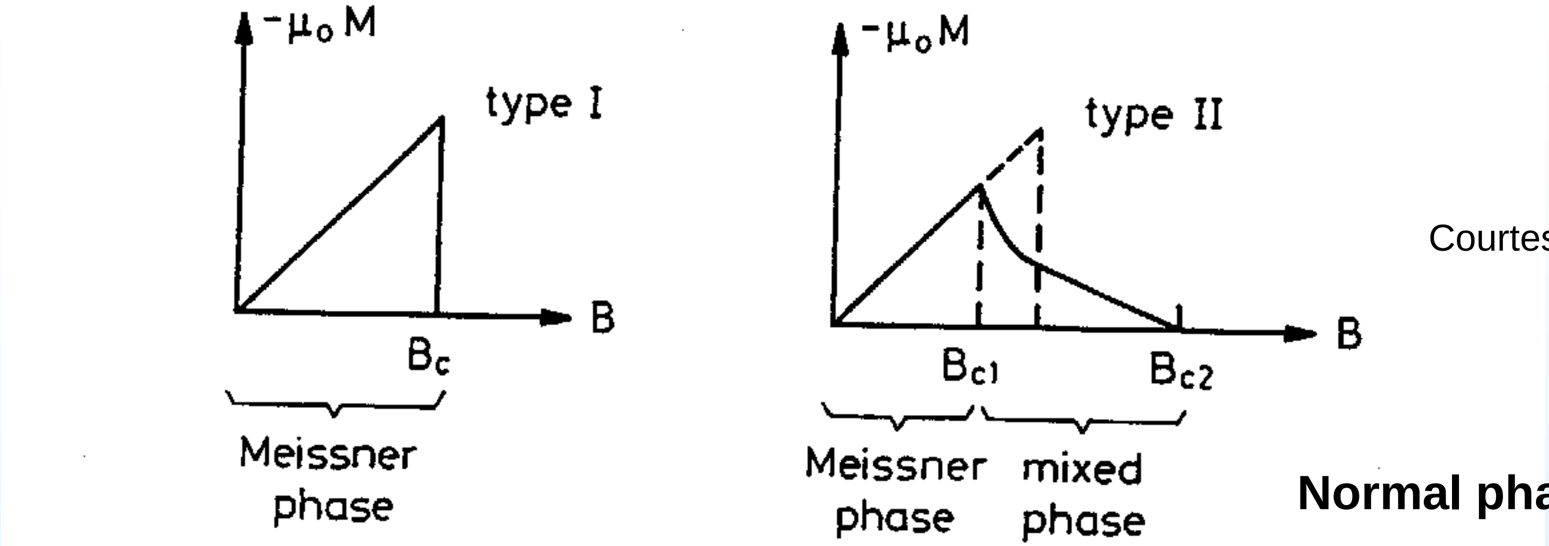


Figure 2.11: Sketch of the critical surface of NbTi. Also indicated are the regions where pure niobium and pure titanium are superconducting. The critical surface has been truncated in the regime of very low temperatures and fields where only sparse data are available.

In a magnet, the operating point must stay within this volume with a suitable safety margin!

Courtesy: Schmuser/Wilson

Type I and Type II Superconductors



Courtesy: Schmuser

Normal phase

Figure 10: Magnetisation of type I and type II superconductors as a function of field.

Type I:

Also known as "soft superconductors".

Completely exclude flux lines (Meissner Effect).

Allow only small field (<< 1 T).

Not good for accelerator magnets.

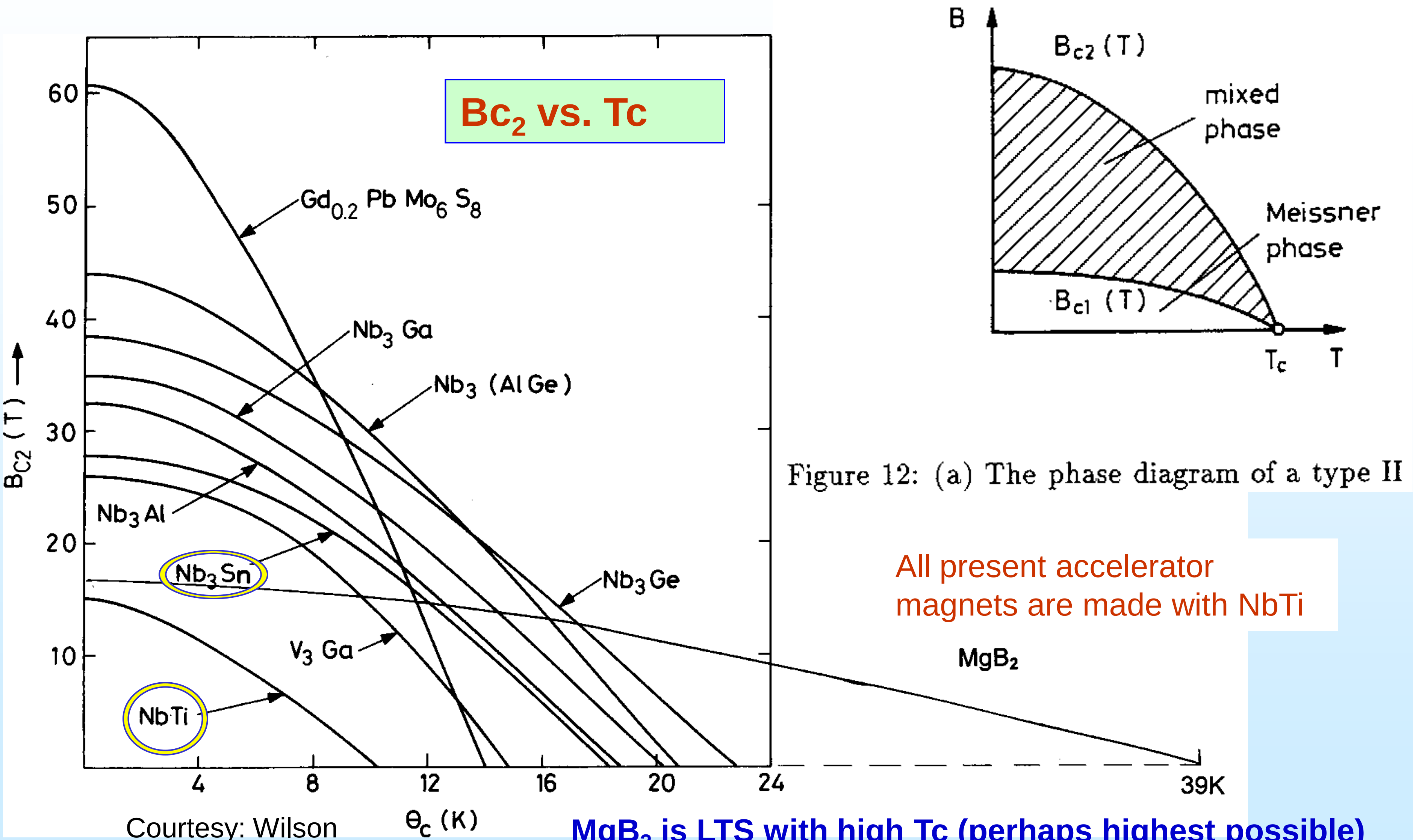
Type II:

Also known as "hard superconductors".

Completely exclude flux lines up to Bc_1 but then part of the flux enters till Bc_2

- Important plus: Allow much higher fields.
- These are the one that are used in building accelerator magnets.

Critical Field as a Function of Temperature in Low Temperature Superconductors



Bc$_2$ vs. Tc

Figure 12: (a) The phase diagram of a type II

All present accelerator magnets are made with NbTi

Courtesy: Wilson

MgB$_2$ is LTS with high Tc (perhaps highest possible)

Common Superconductors

Critical temperatures (T_c) of popular superconductors:

LTS

NbTi: ~ 9 K

Nb_3Sn: ~ 18 K

HTS

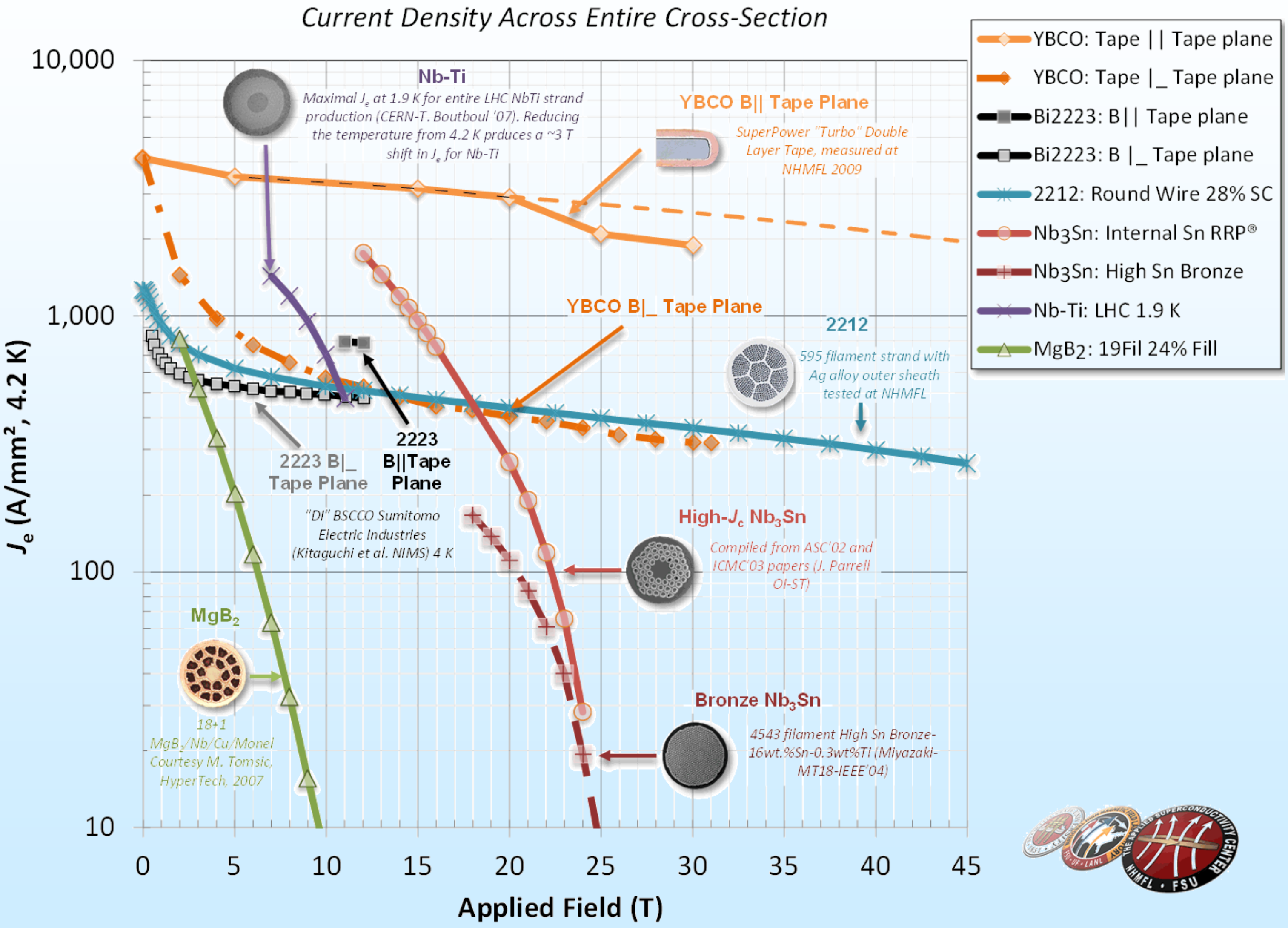
BSCCO2223: ~ 110 K

BSCCO2212: ~ 85 K

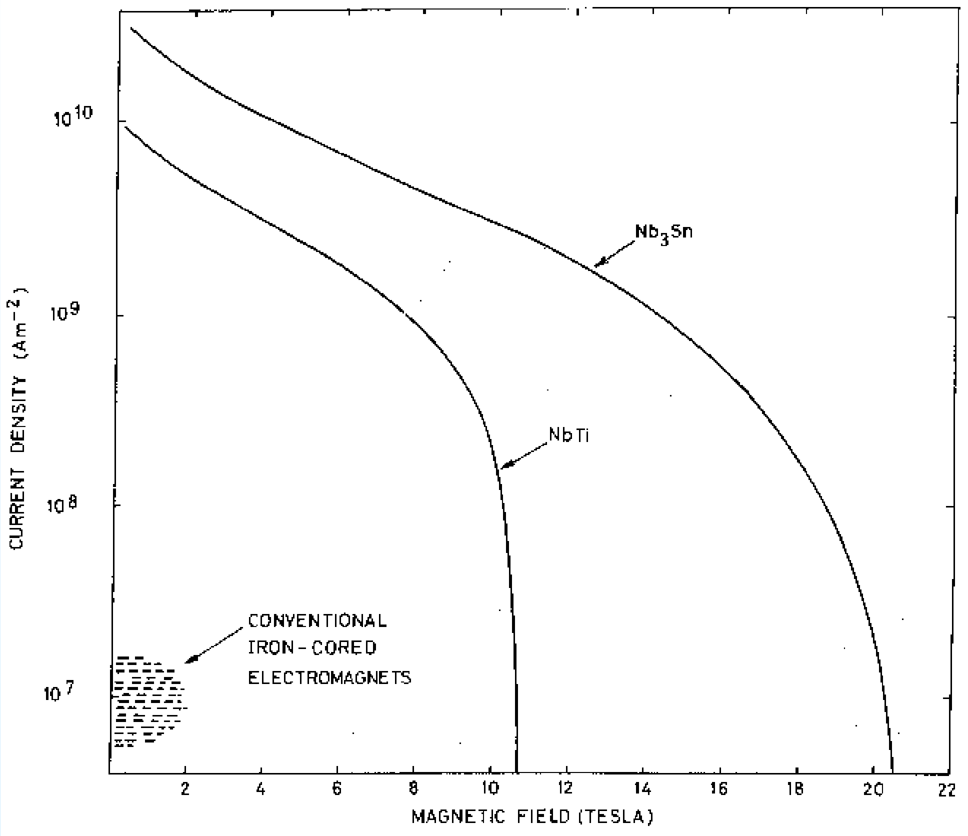
YBCO/ReBCO: ~ 90 K

MgB_2: ~39 K

Critical Current Density as a Function of Field in LTS & HTS



Copper and Superconducting Magnets



Courtesy: Martin Wilson

Room Temperature Magnets:

Current density in copper coils of conventional magnets:

- Air cooled (max) ~1 A/mm^2
- Water cooled ~ 2-10 A/mm^2

Typical fields: ~1.2 T.

Superconducting Magnets:

Current density in coils of superconducting magnets:

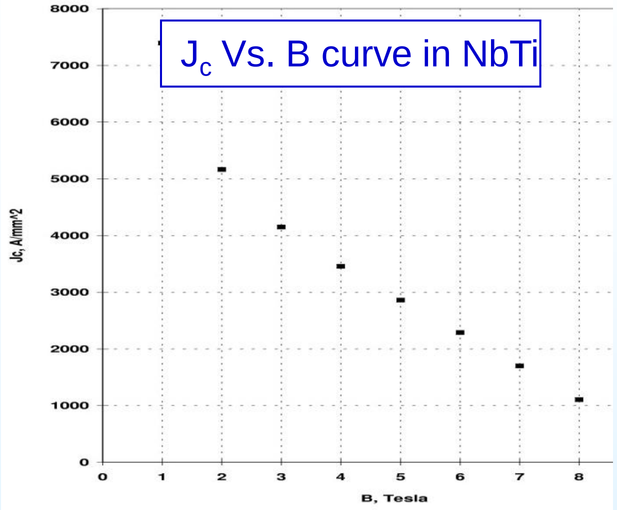
- 100- 1000 A/mm^2

Typical fields:

- Iron dominated: 2-3 T
- Conductor dominated: 3 - 10 T
  - ➢ R&D for even higher fields

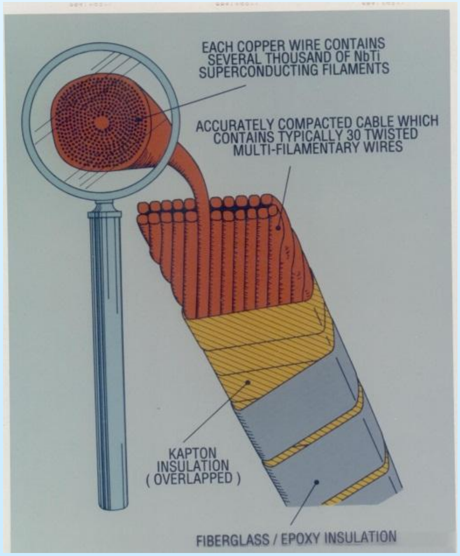
Current Density in Superconductor Vs. Available Current Density in Coils

Even though the superconductor may be capable of carrying a current density of 3000 A/mm^2 or so, only a fraction of that is available to power the magnet.



Here is why?

- There should be enough copper within the wire to provide stability against transient heat loads and to carry the current in the event the superconductor turns normal (quench).
- Usually the % of copper is more than % of superconductor. In medium field NbTi production magnets, the maximum current density in copper is generally <1000 A/mm^2 at the design field.
- The coil consists of many turns. There must be a turn-to-turn insulation taking ~15% of the volume.
- Thus with all included, in most cases Jo could be ~500 A/mm^2 (much less than 3000 A/mm^2).



Superconducting Magnets in Accelerators

Major reasons for using superconducting magnets in the accelerators:

Cost advantage

- Superconducting magnets reduce the size of and often cost of advanced machine.
- Superconducting magnets also lower the power consumption and hence the cost operating cost.

Performance advantage

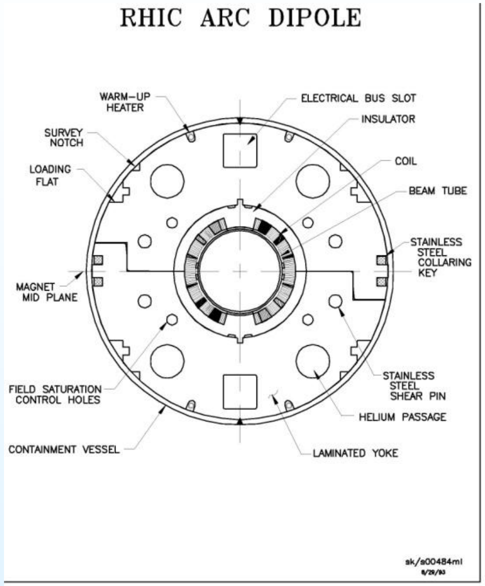
- A few high field magnets may significantly enhance the performance of the machine.
- Thus even if the cost of a few magnets is high, the overall return of the investment to experimentalists may be impressive and highly cost-effective.
- Some time there is no option but to use high field superconducting magnets to obtain the desired performance.

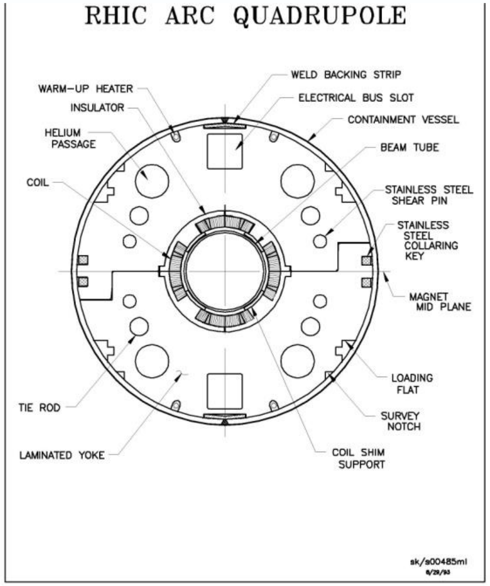
Superconducting Magnets
The Impact on the Modern Accelerators

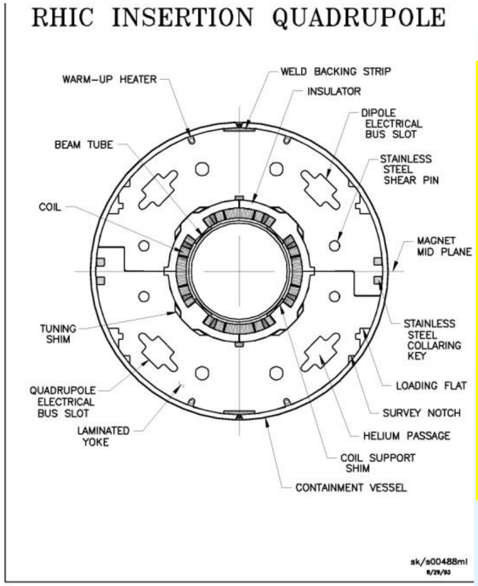
- Without “energy saving” superconducting magnets, the power bill of many accelerators would have been so large that they would not have been built
- Without “powerful” superconducting magnets, the size of those machines would have been so large that it may hardly have fit in the space available
- Without “high gradient ” superconducting magnets, the desired luminosity would not have been possible (RISP in Fragment Separator, included)

Relativistic Heavy Ion Collider (RHIC) at BNL

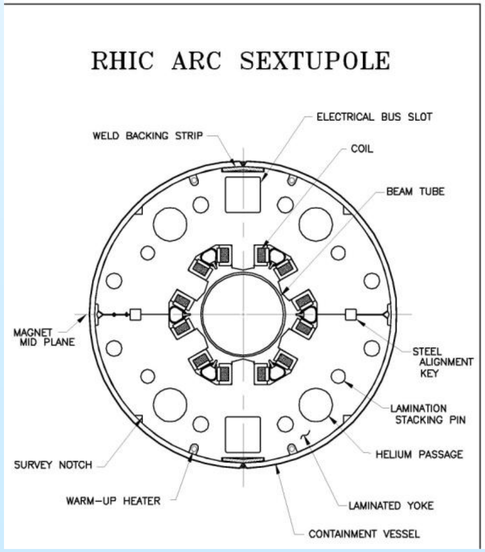
Variety of Superconducting Magnets in RHIC (all magnets in RHIC are superconducting)

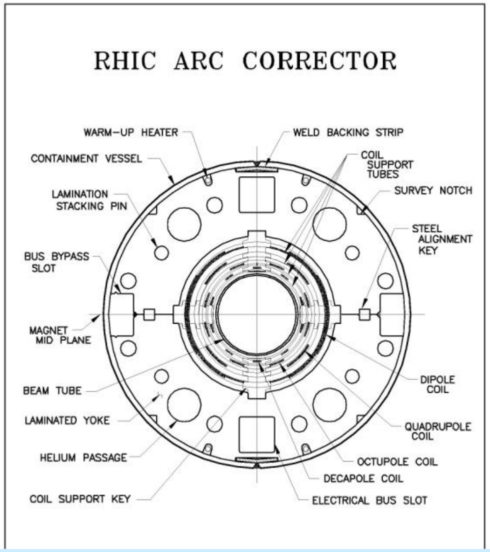






Conductor dominated (cosine theta) and iron dominated (super-ferric) magnets





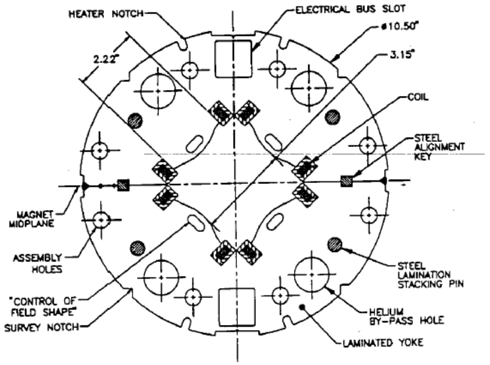
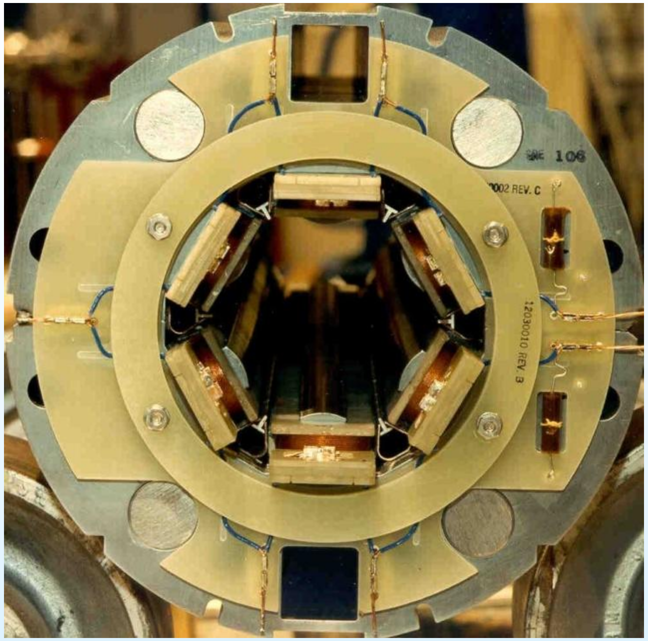


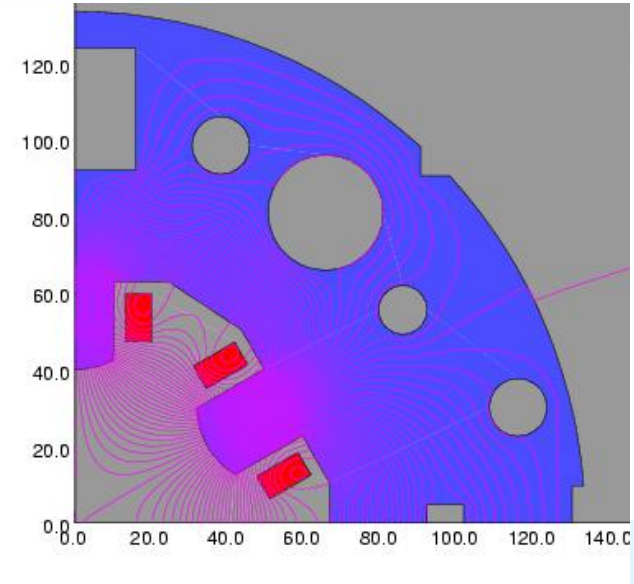
Fig. 1-16. Cross section of the trim quadrupole cold mass. All lamination dimensions outside the pole area are identical to those in the sextupole lamination.

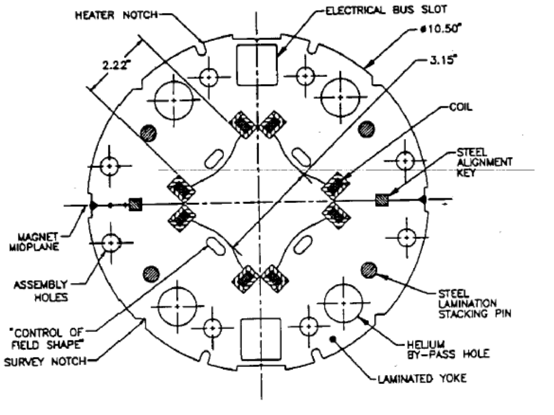
Cosine Theta (conductor dominated) Magnets for RHIC, SSC and LHC

RHIC dipole coldmass during assembly

Super-ferric (iron dominated) Magnets in RHIC







RHIC uses Super-ferric Trim Quadrupole and Sextupole Magnets

FRIB (and hopefully) RISP will also use super-ferric Magnets

Overall Magnetic Design

Magnet Aperture

- Usually comes from accelerator physicists
- However, an interaction between accelerator physicists and magnet scientists may produce a more optimized system design.

Design Field

- Higher fields may improve the performance of machine and/or reduce cost. However, higher field also make magnets more complicated
- The value of field determines the choice of conductor

Superconducting Magnet Design (1)

- The magnet should be designed in such a way that the conductor remains in the superconducting phase with a comfortable margin.

- Superconducting magnets should be well protected. If the magnet quenches (conductor loses its superconducting phase due to thermal, mechanical, beam load, etc.), then there should be enough copper in the cable to carry the current to avoid burn out.

- The cryogenic should be able to cool and maintain the low temperature (roughly at 4 K in LTS, higher in HTS). It should be able to handle heating caused by the beam, either by radiation or by decay particles.

Superconducting Magnet Design (2)

- The magnet cost should be minimized.

- There are large Lorentz forces in superconducting magnets. The coil should be contained in a support structure that can handle these large forces and minimize the conductor motion.

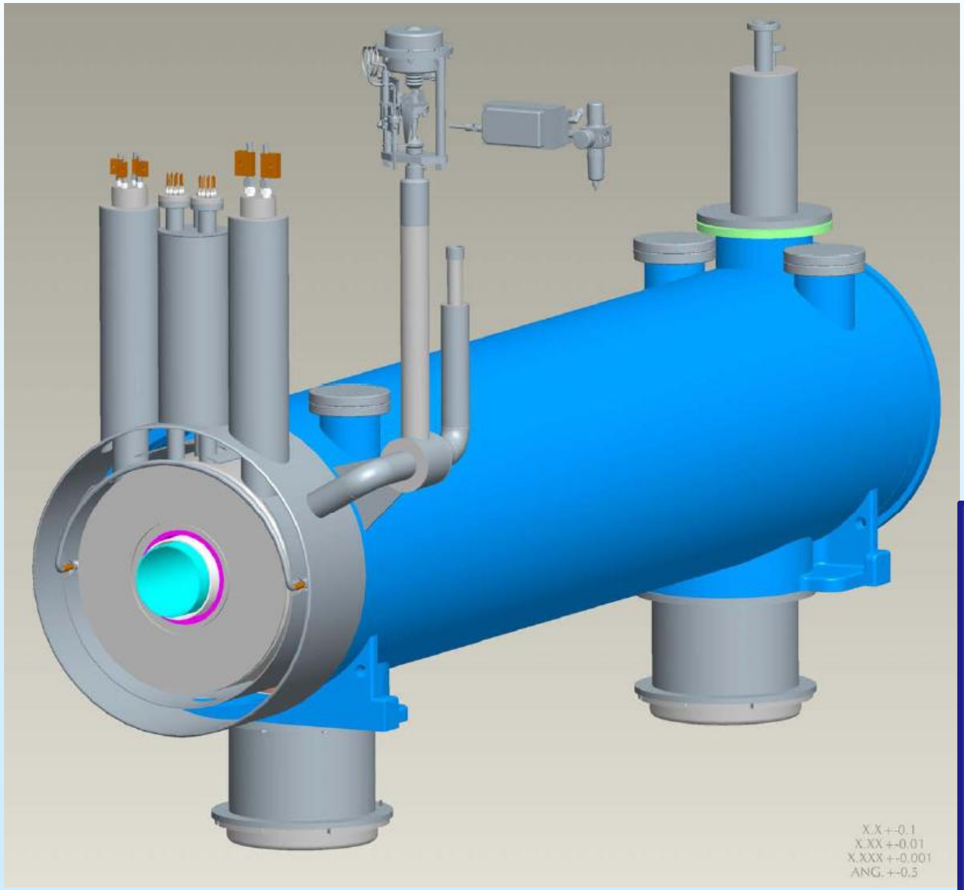
- The magnets should be designed in such a way that it is easy to manufacture (very important).

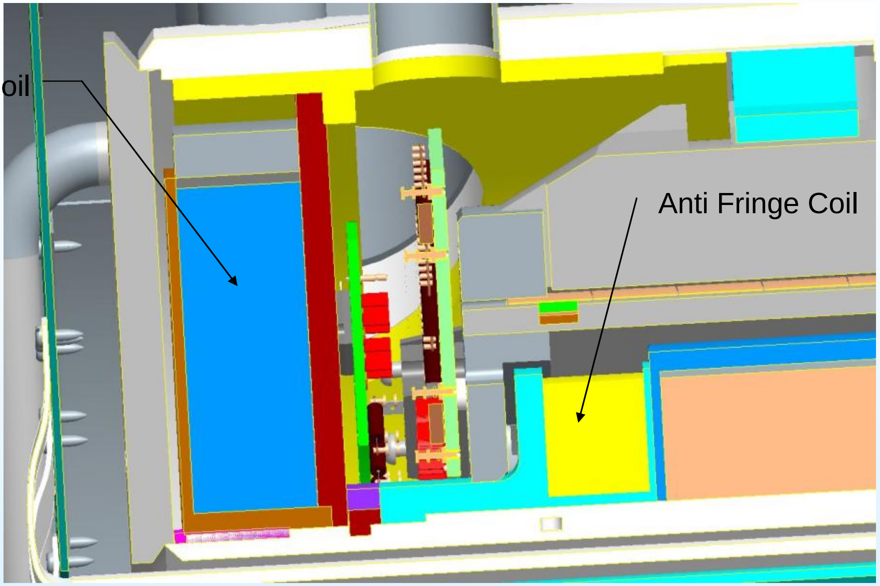
- It must meet the field quality (uniformity) requirements.

Designing Conductor Dominated

Superconducting Magnets

BNL 200 mm aperture 6 T NbTi Solenoid for RHIC e-lens system

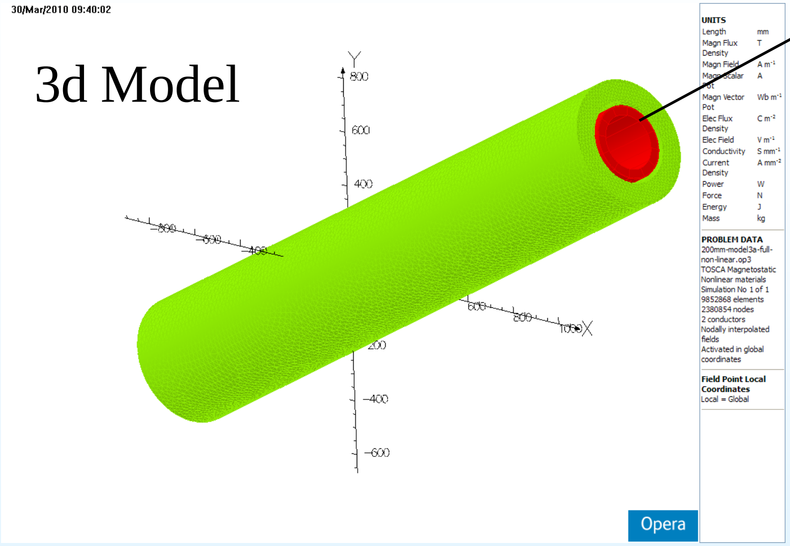




Breaking news (last week):

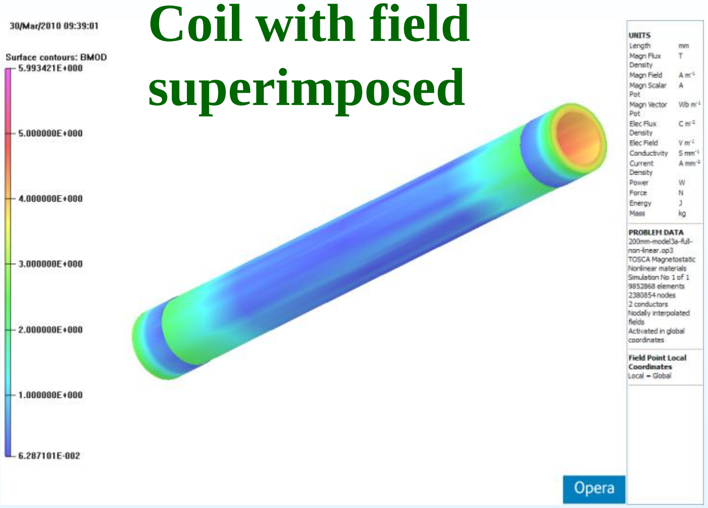
Two solenoid systems (each consisting of many coils) were recently built and tested at BNL with >10% margin.

Computer Models of a Solenoid



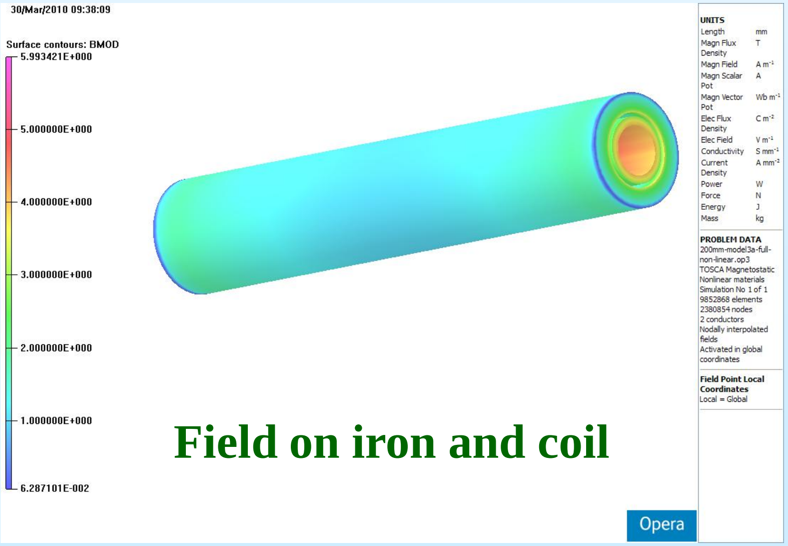
3d Model

z-axis

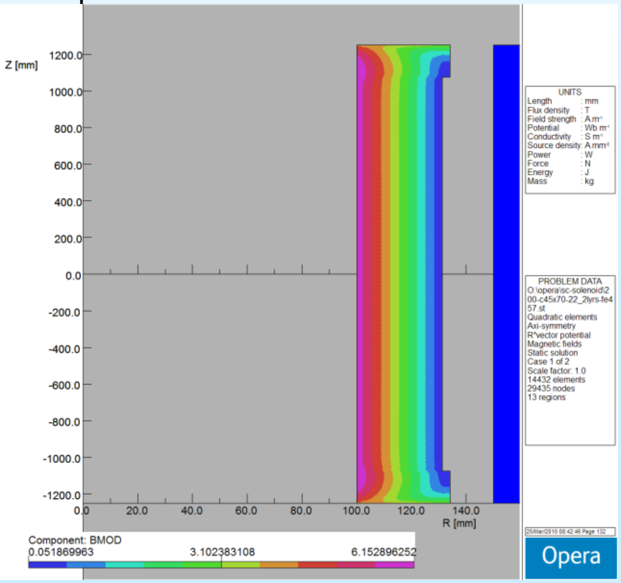


Coil with field superimposed

z-axis



Field on iron and coil

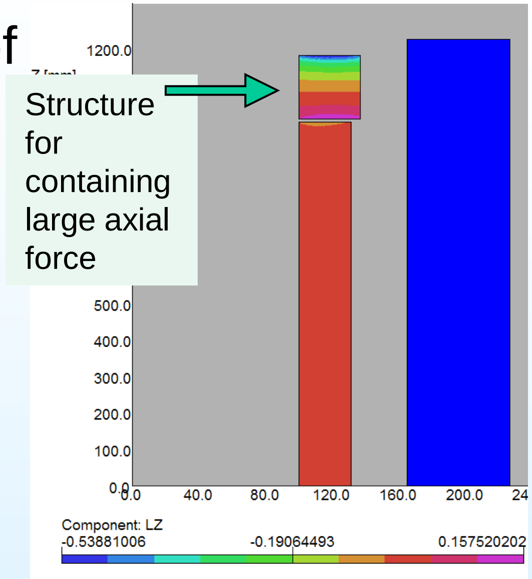


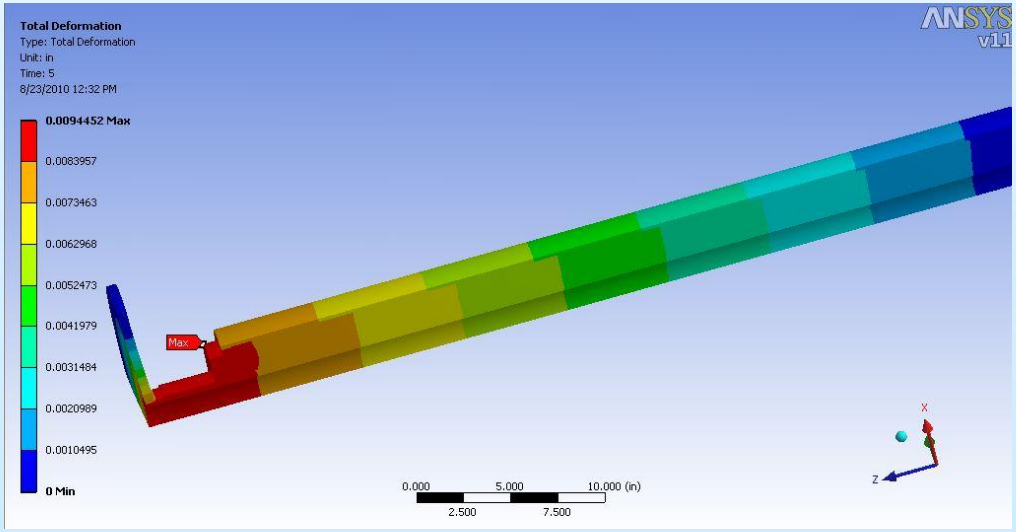
2d Model
(more accurate
and faster
calculations in
many cases)

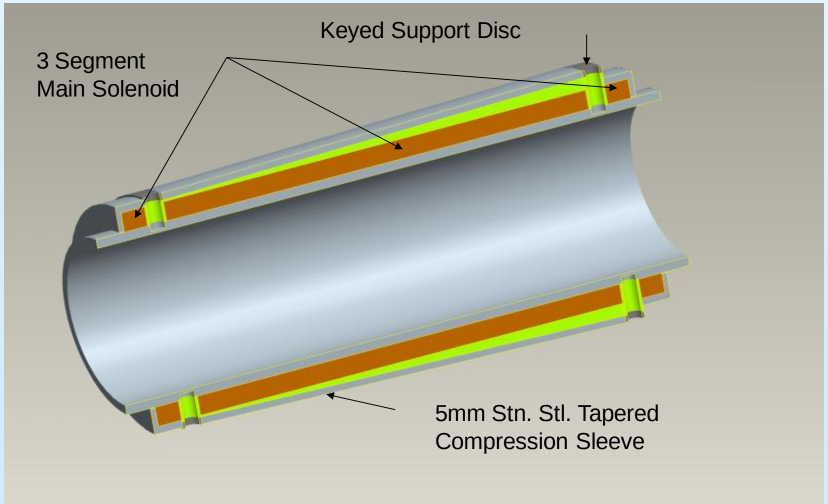
Mechanical Structure and Analysis

- A good mechanical structure is the key to the success of a superconducting magnet.
- An advanced support structure developed after the conceptual and a detailed engineering design analysis.
- In this case, the mechanical structure is consisted of stainless steel outer support tube and intermediate stainless steel plates to contain complex Lorentz forces.

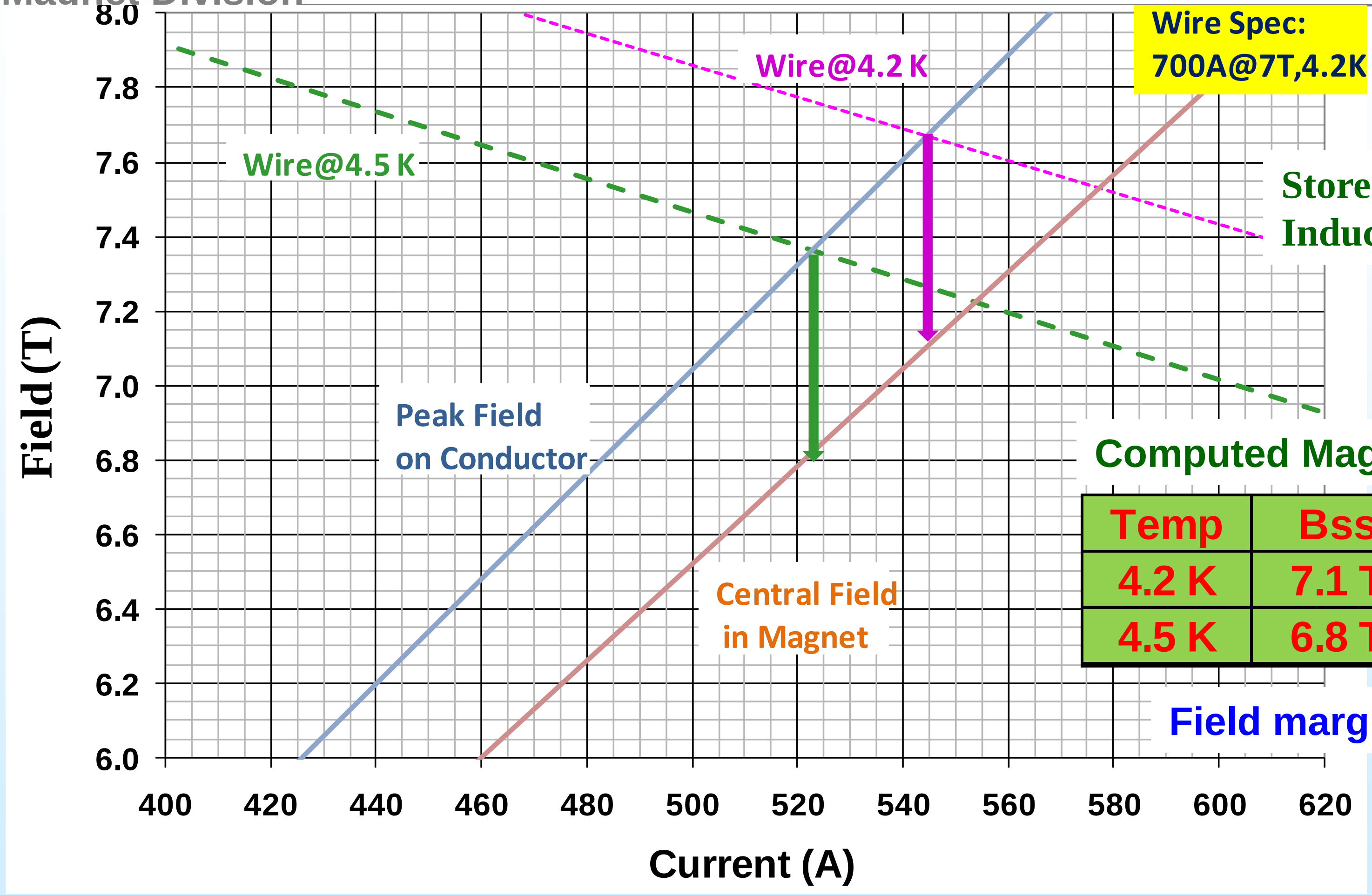
Courtesy: A. Marone


Structure for containing large axial force





Solenoid Wire and Magnet Performance (Load Line and Peak Field)



Wire Spec: 700A@7T,4.2K

Design Field: 6 Tesla

Stored Energy: ~1.4 MJ, Inductance:~14 Henry

Computed Magnet Performance:

Temp	Bss	Bpk	I(A)
4.2 K	7.1 T	7.65 T	545 A
4.5 K	6.8 T	7.35 T	523 A

Field margin@4.5 K: ~13%

Peak field line corresponds to the maximum field on the conductor (determines how much current one can put in), and Load line refers to the field in the aperture (determines field available to beam)

Quench Protection

Total MIITs in the circuit:

$$\int I^2\,dt \quad : \quad \sim 1.5 \text{ MIITs}$$

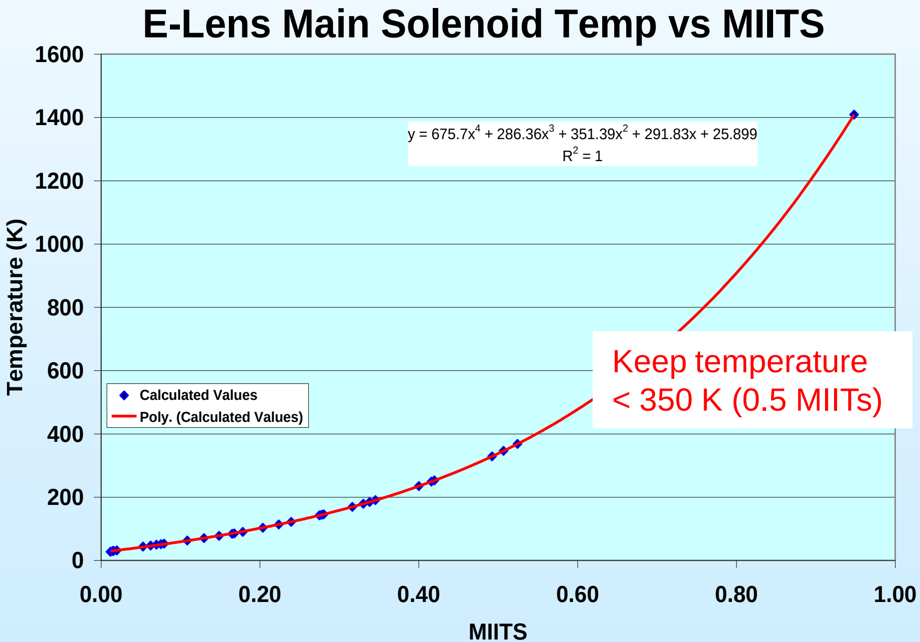
(for I=~500 A, L=~14 H, R_{dump}=~1.2 Ω; giving time constant: ~ τ= ~12 sec)

Diodes are across segments of the coil to limit the energy deposited in the coil segment (< 0.5 MIITs).

Bus & diodes are designed to handle a much higher MIITs than the coil conductor (> 1.5 MIITs).

Energy extraction is used to limit the maximum MIITs in the bus & diodes

Energy extraction and quench protection diodes are used to control temperature rise in the coil in the event of a quench



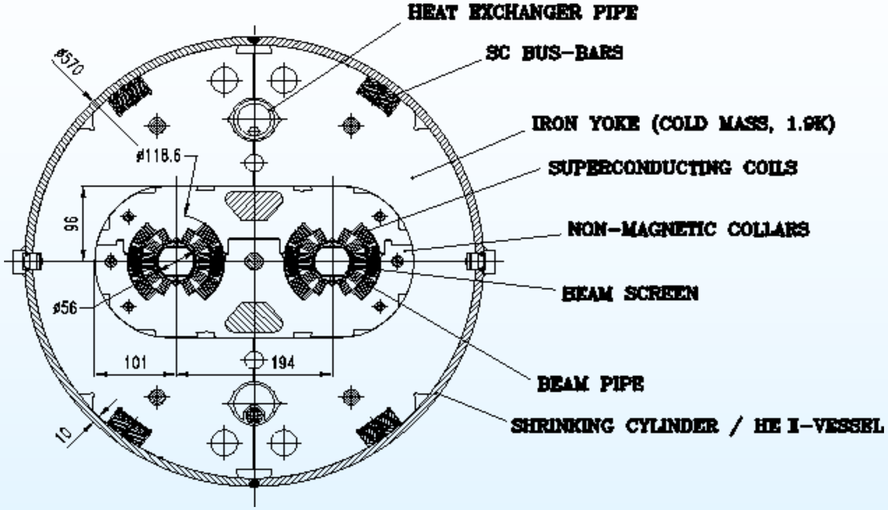
Keep temperature < 350 K (0.5 MIITs)

Courtesy
Joe Muratore
George Ganetis

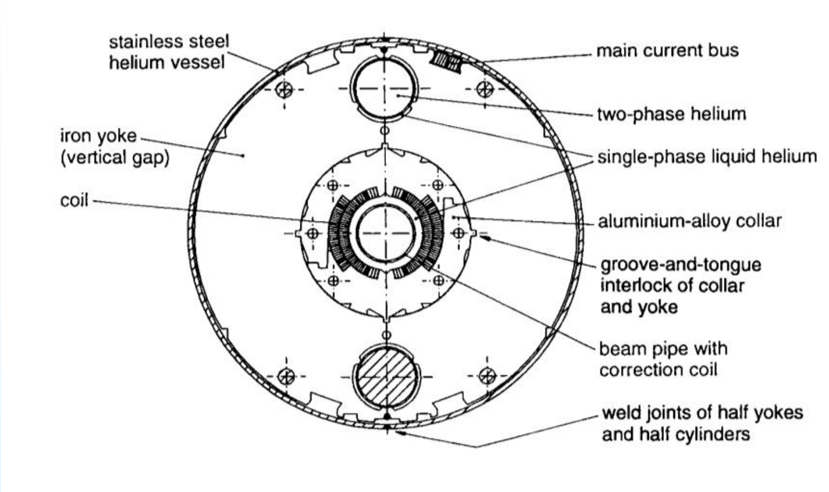
- **This is safe as temperature remains well below 350 K**

Coil Designs for High Field Dipoles Magnets of Modern Accelerators

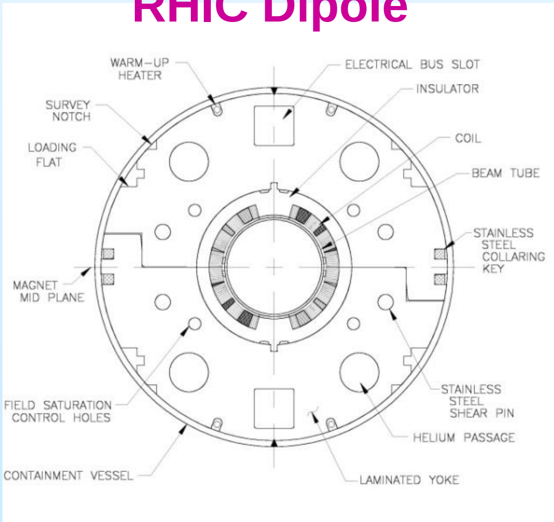
LHC Dipole



HERA Dipole



RHIC Dipole



Tevatron Dipole

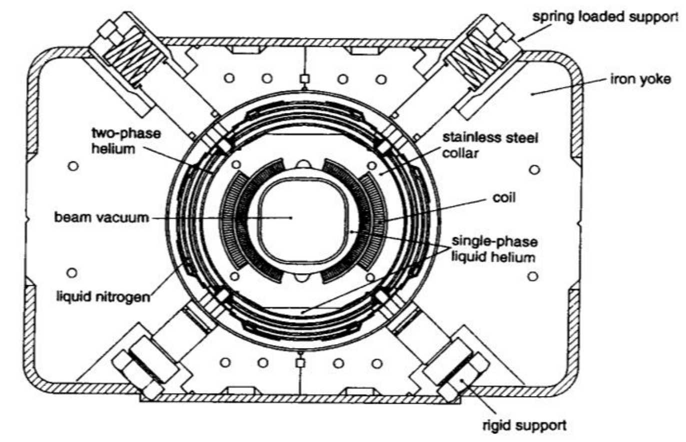
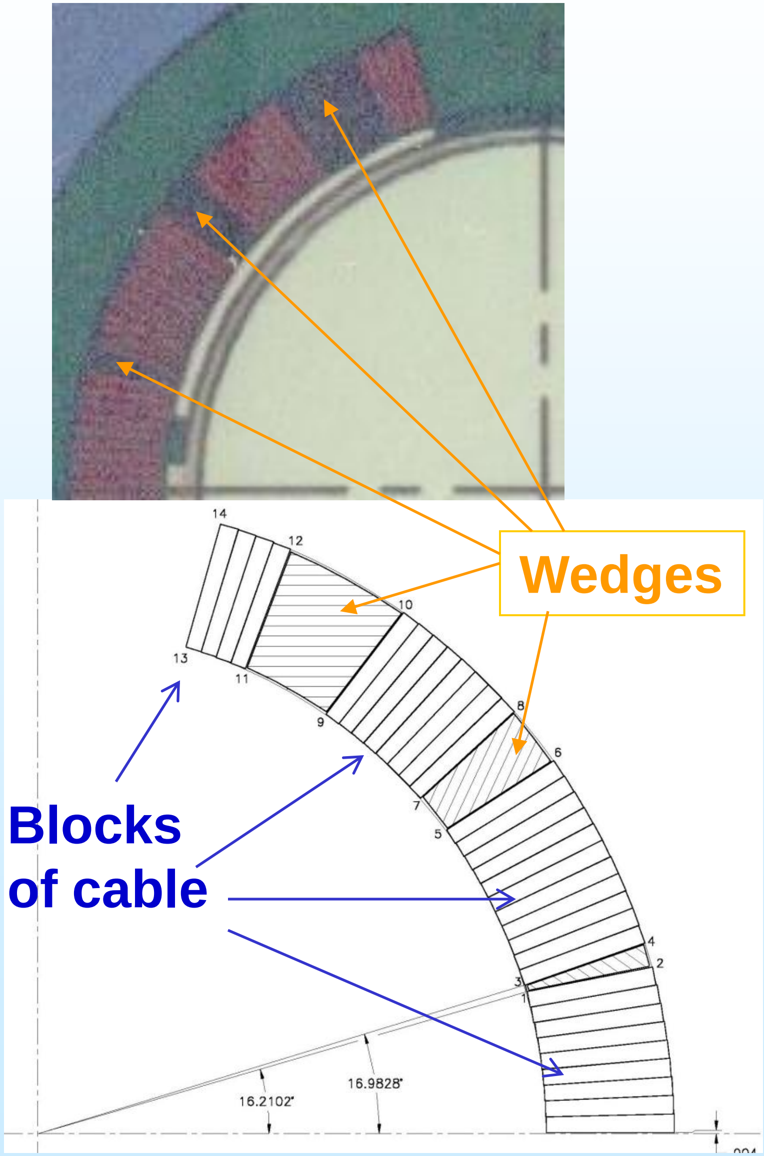


Figure 4.9: The Tevatron 'warm-iron' dipole (Tollestrup 1979).

- **All magnets use NbTi Superconductor**

- **All designs use cosine theta coil geometry**

Optimizing Coil Geometry



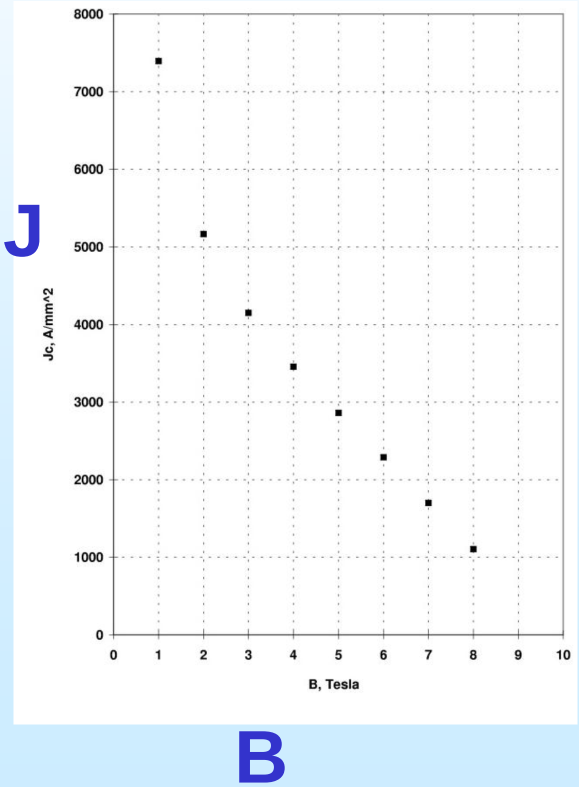
Coil geometry is optimized with special codes to minimize field errors and maximize the operating fields (parameters- wedges and turns).

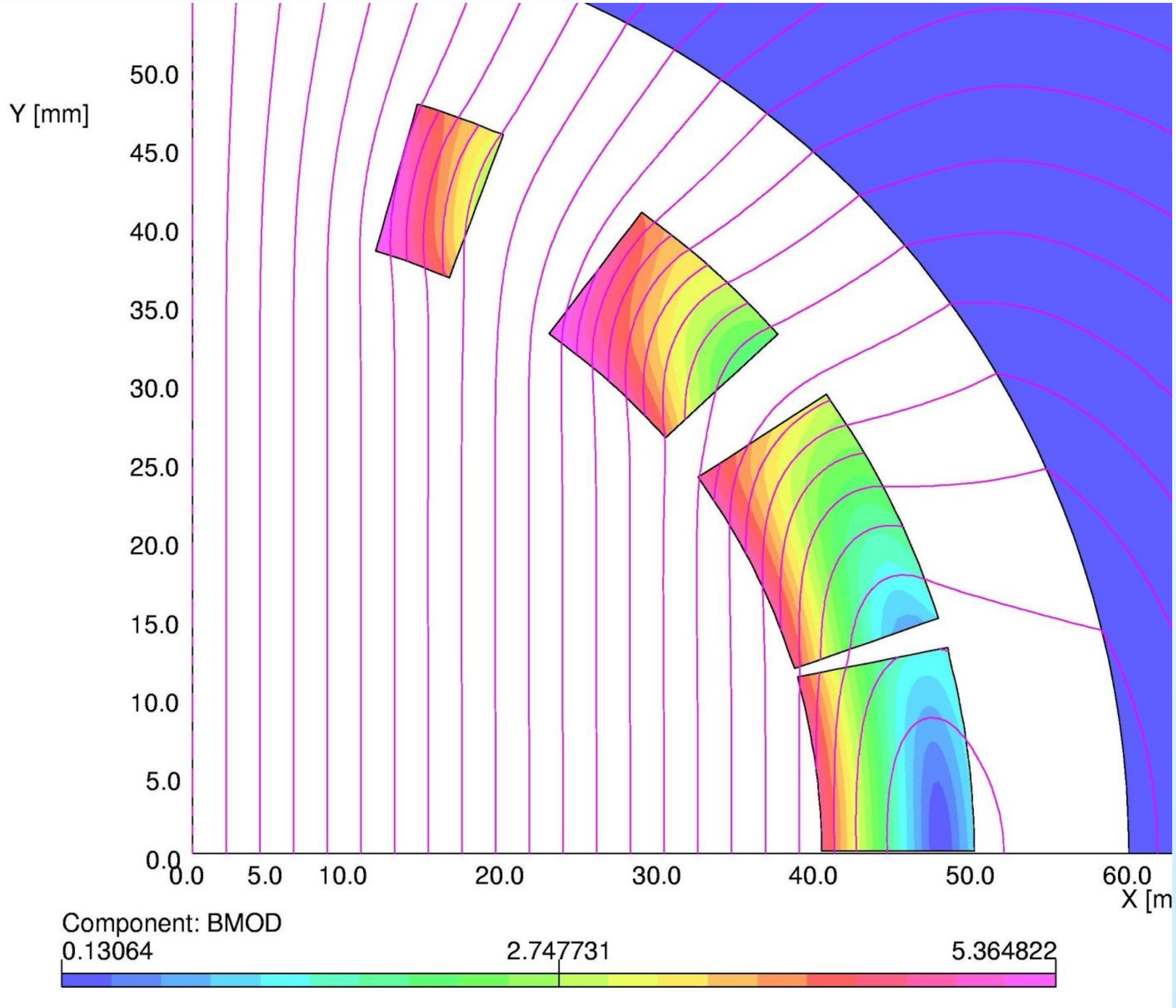
Such coil geometry is commonly referred to as "cosine theta geometry".

The conductor placement error should generally be within 50 μ*m.*

Field in the Superconducting Coil in the RHIC Arc Dipole Magnet

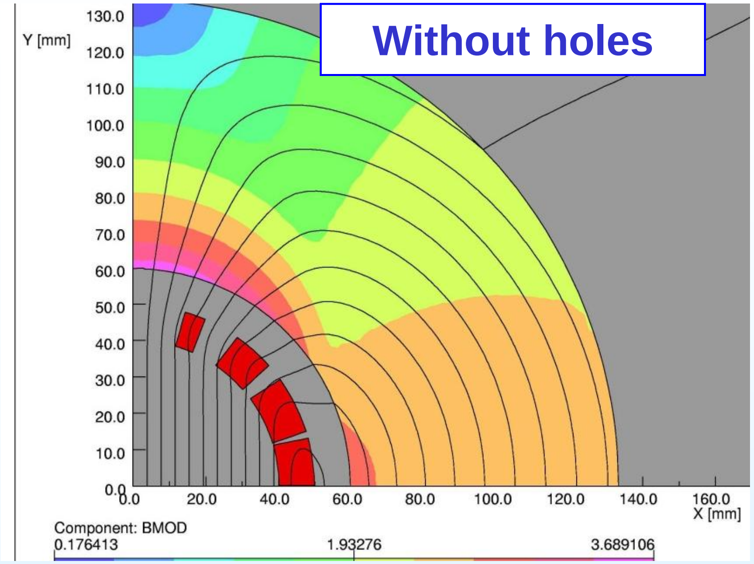
The field is high in the pole block and lower on other blocks, particularly on the outside.

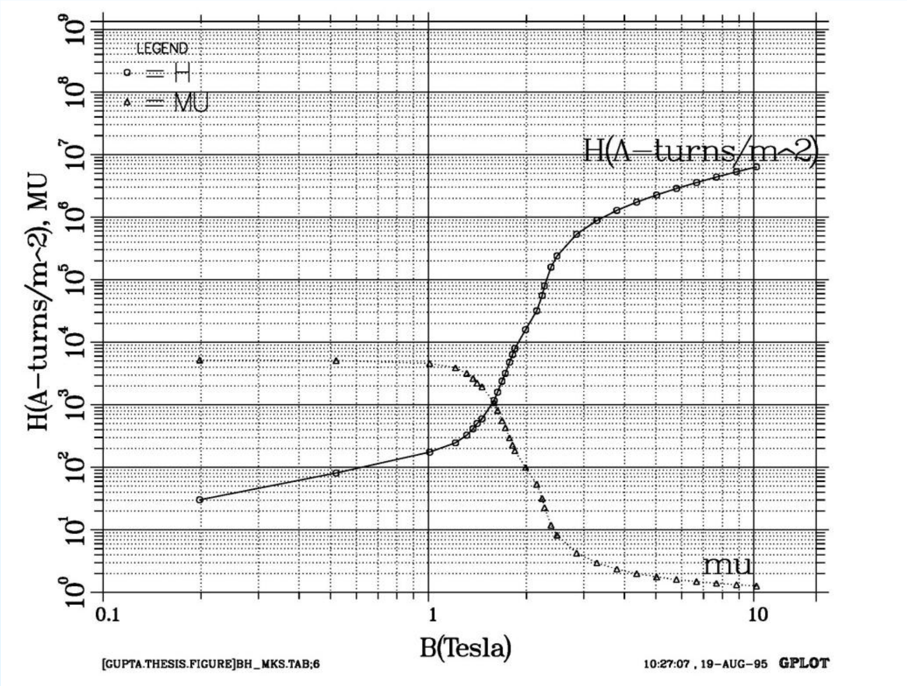


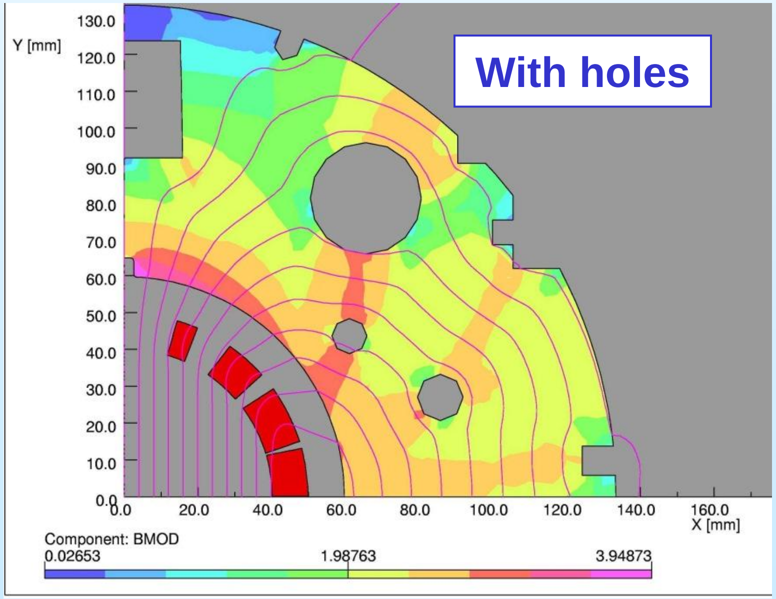


Non-linear Iron Saturation

- Non-linear properties of iron can create field errors at high field even if they were not present at low fields
- Magnet designs for more uniform saturation
- Important issue in super-ferric magnets also







$$B = \mu H$$

Designing Iron Dominated

Superconducting (Super-ferric) Magnets

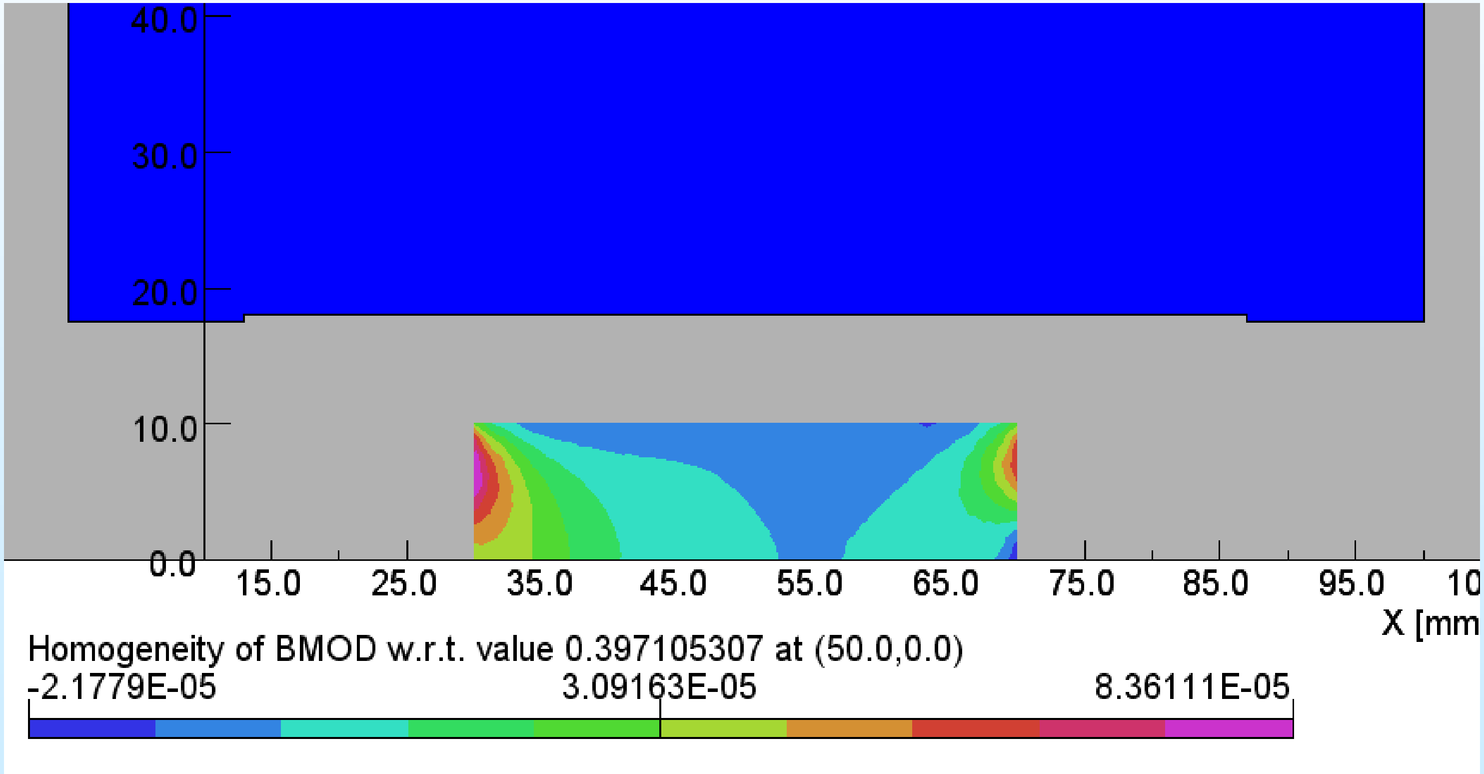
Magnetic Modeling

The primary purpose of the magnet modeling at early stage of the program is to:

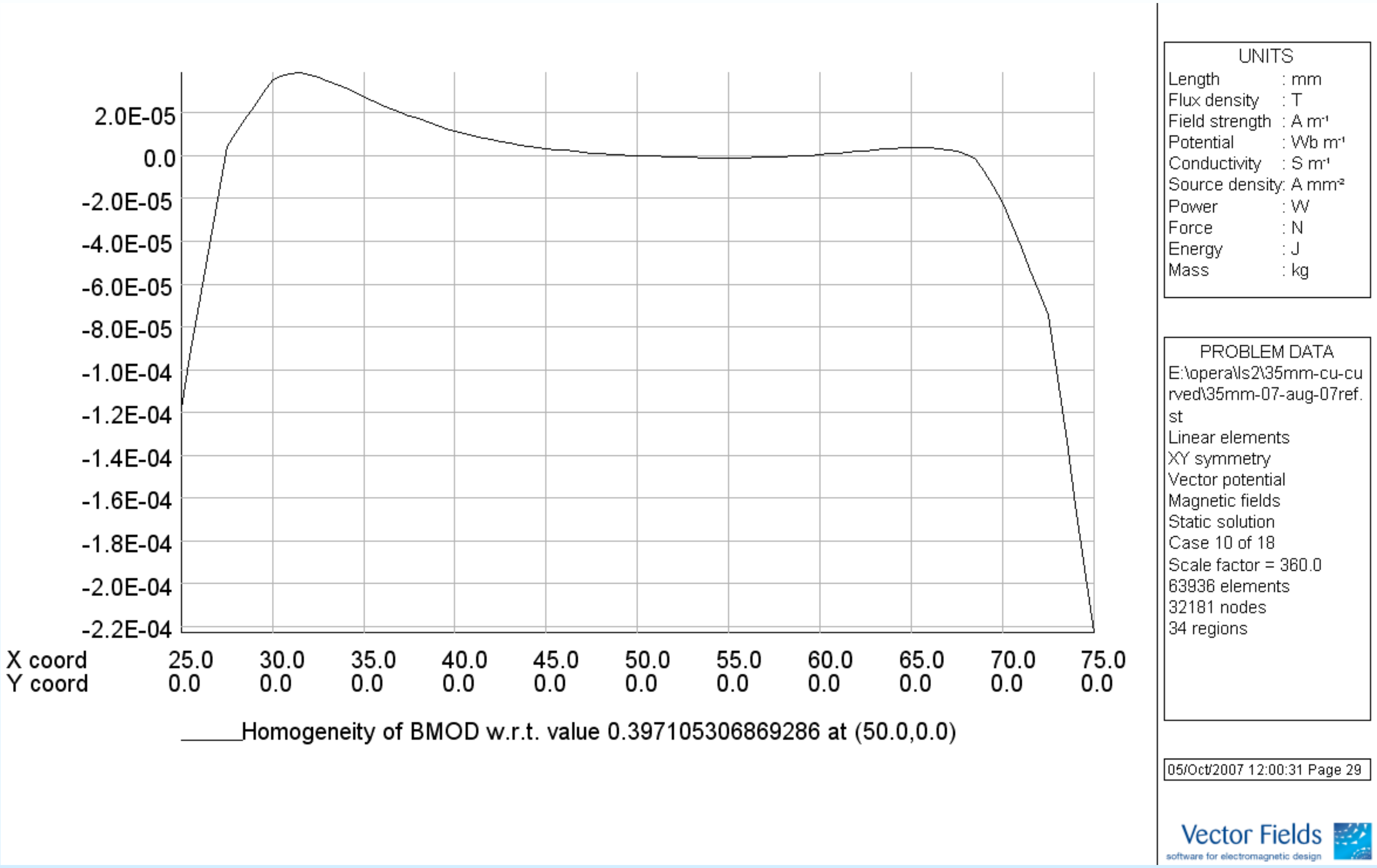
- **Produce designs that meet or exceed the machine requirements**
- **Give feed back to machine physicists on what errors to expect, and also what is the level of our confidence in those calculations, so that they can use this information in designing the machine**

2-d Magnetic Design of Dipole

- Pole bumps are used for field shaping.
- Adjust width and height of the bump to obtain a good field quality.
- Vertical size of the bump is kept small to minimize a decrease in the pole gap.



Relative Field Error On Midplane



Homogeneity of BMOD w.r.t. value 0.397105306869286 at (50.0,0.0)

UNITS

Length	: mm
Flux density	: T
Field strength	: A m⁻¹
Potential	: Wb m⁻¹
Conductivity	: S m⁻¹
Source density	: A mm⁻²
Power	: W
Force	: N
Energy	: J
Mass	: kg

PROBLEM DATA
E:\opera\ls2\35mm-cu-curved\35mm-07-aug-07ref.st
Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 10 of 18
Scale factor = 360.0
63936 elements
32181 nodes
34 regions

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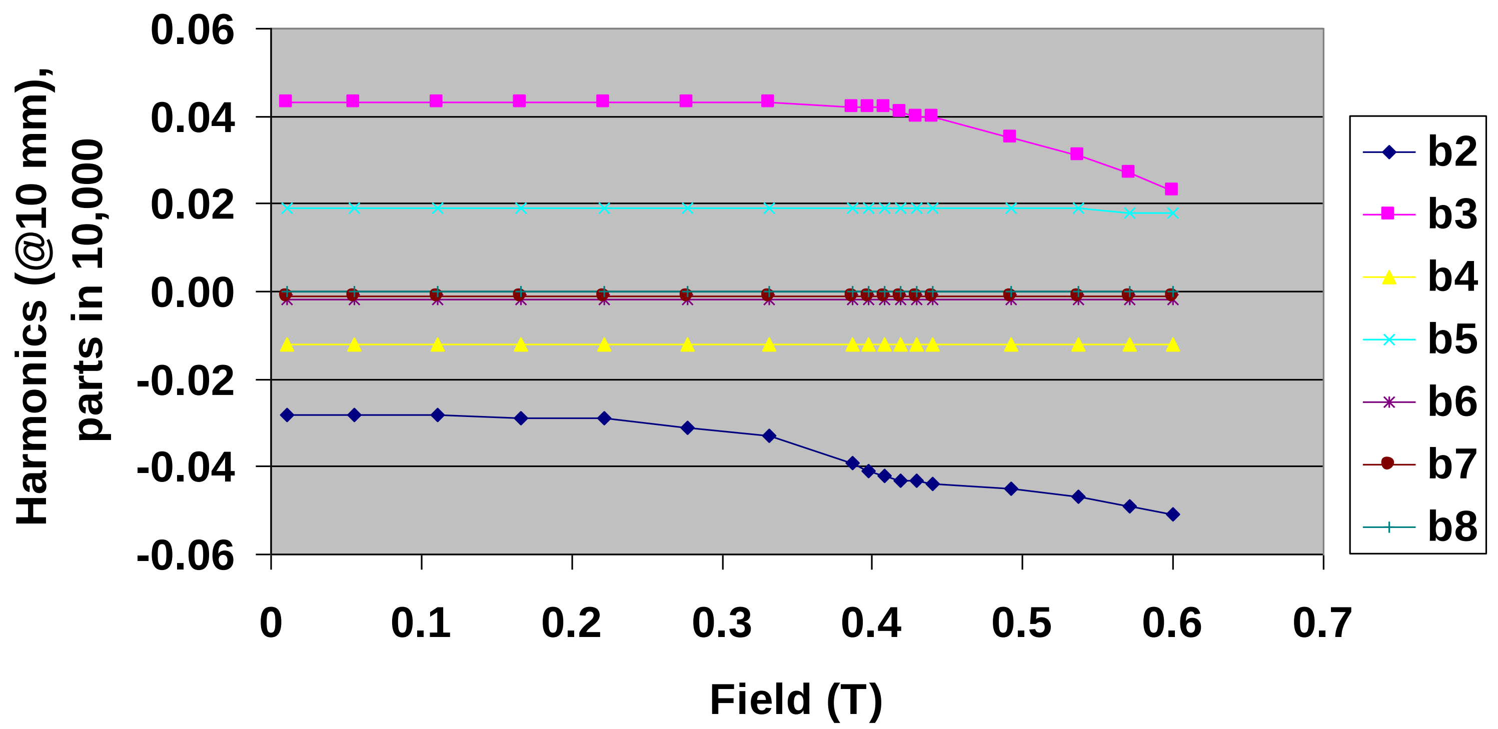
Needed good field quality (a few part in 10^4) in +/-20 mm (40 mm total width); above design has a range of 50 mm

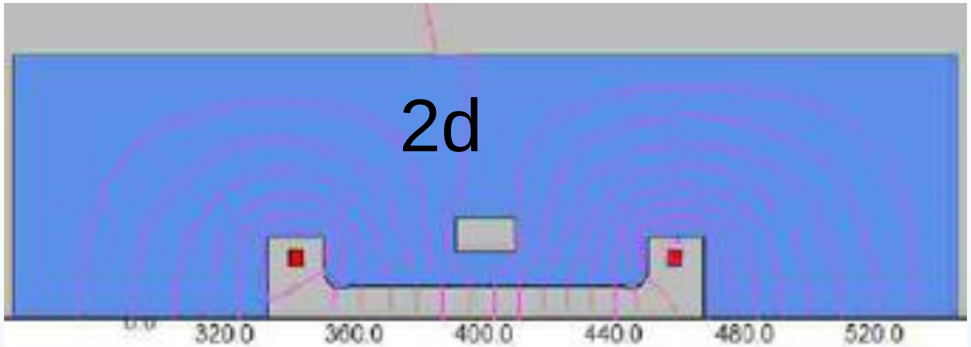
Computed 2-d Harmonics in 35 mm Dipole

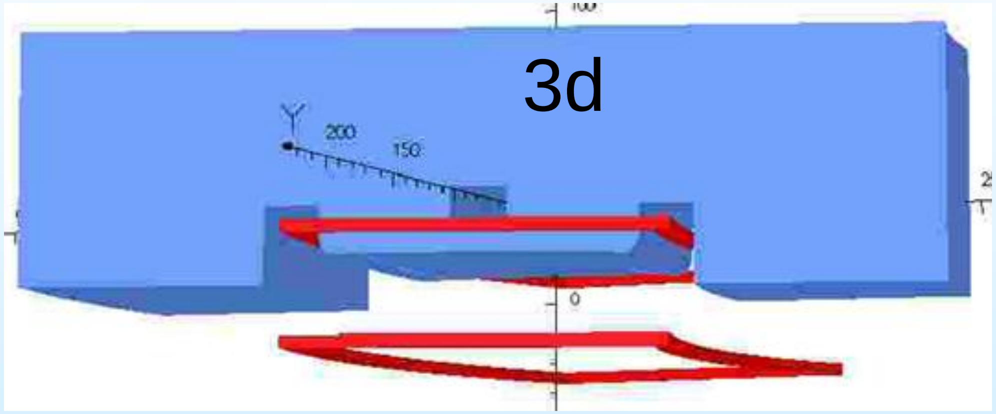
Field harmonics are normalized to fundamental harmonic and are given in the units of 10^{-4}. b2 is quadrupole.



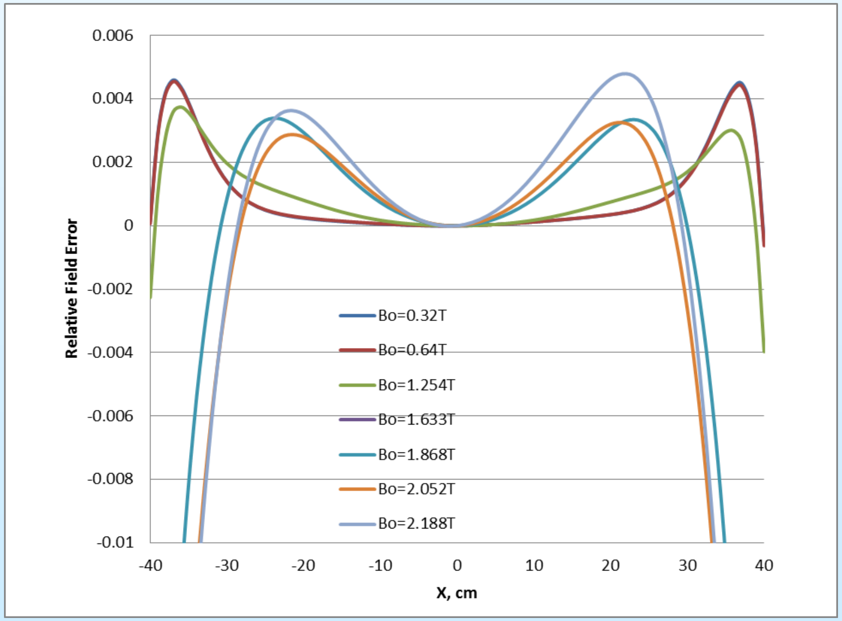
All harmonics are very small (given in units of 10^{-4}). They are only a few parts in 10^5 even at 20 mm reference radius. Therefore, the good field requirements are met both in terms of harmonics (see above) and in terms of the good field region (last slide).

Iron Yoke Optimization - Dipole





- Pole shape must be optimized to minimize field errors at low fields
- Cutout/holes can be used to minimize field errors at high fields when iron properties become non-linear (similar to that as in conductor dominated magnets)



From IPAC2012 Paper

Muons, Inc.

High Radiation Environment Nuclear Fragmentation Separator Dipole Magnet

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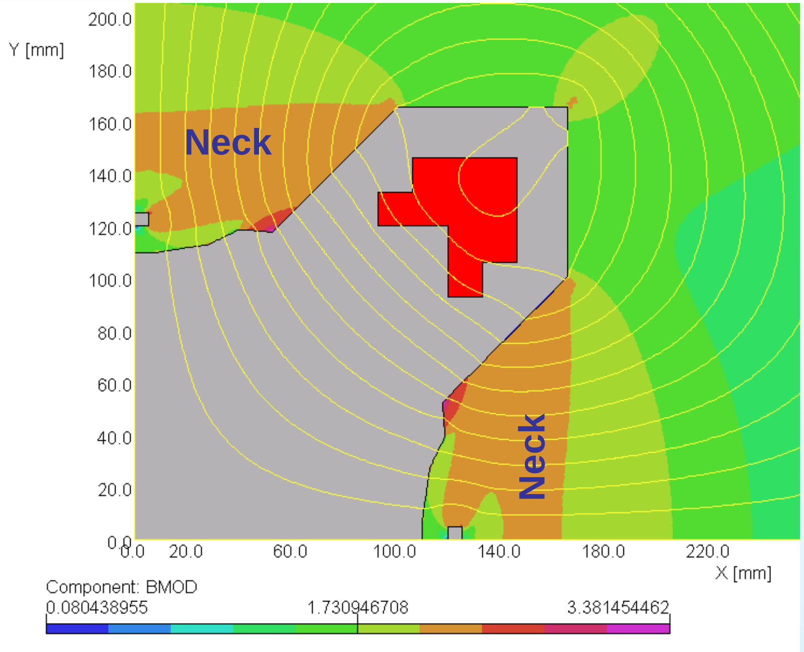
Iron Yoke Optimization - Quadrupole

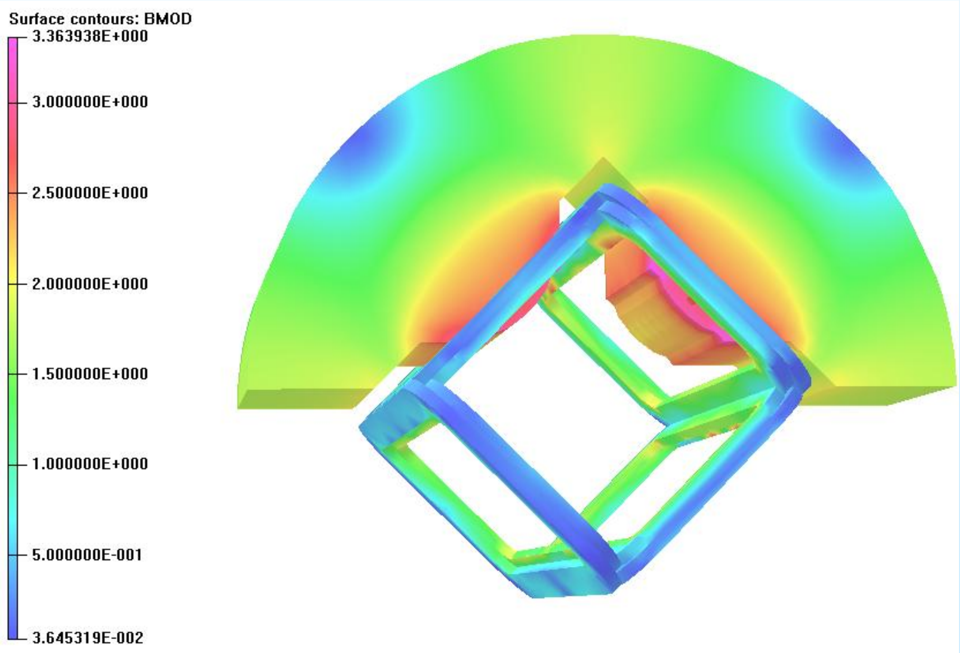


- Space needed for cryostat minimized by carefully designing a cryo-mechanical structure.
- Space yoke in neck area is maximized to minimize iron saturation at high currents.
- Cutout for good field quality at all fields.
- In addition, both quadrupole and dipole yokes are also optimized for reducing peak field (in particular, perpendicular field)

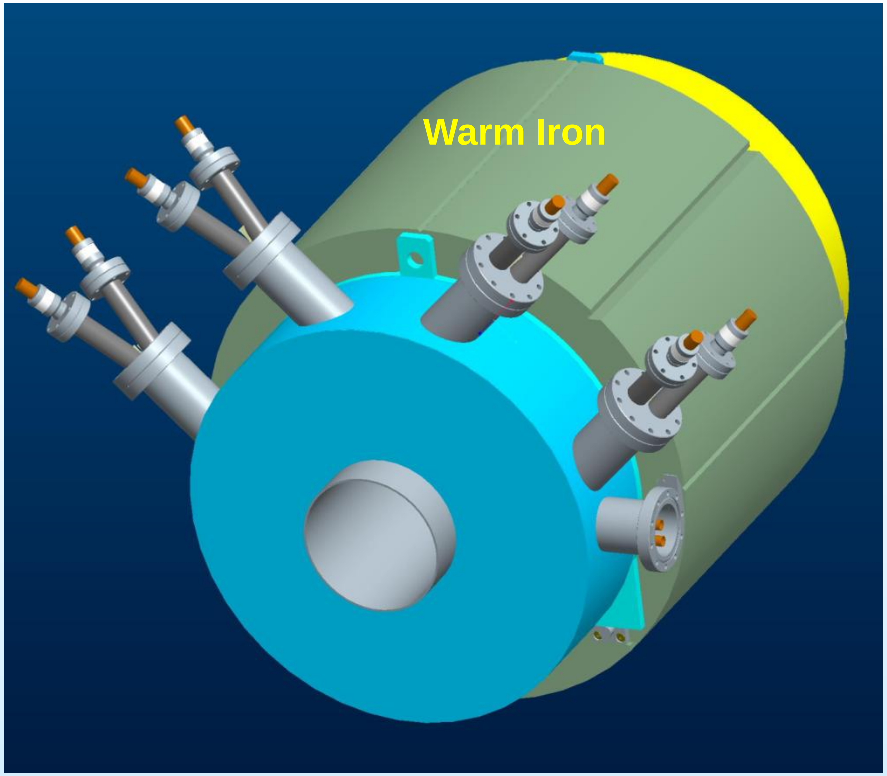
Second Generation HTS Quadrupole for FRIB

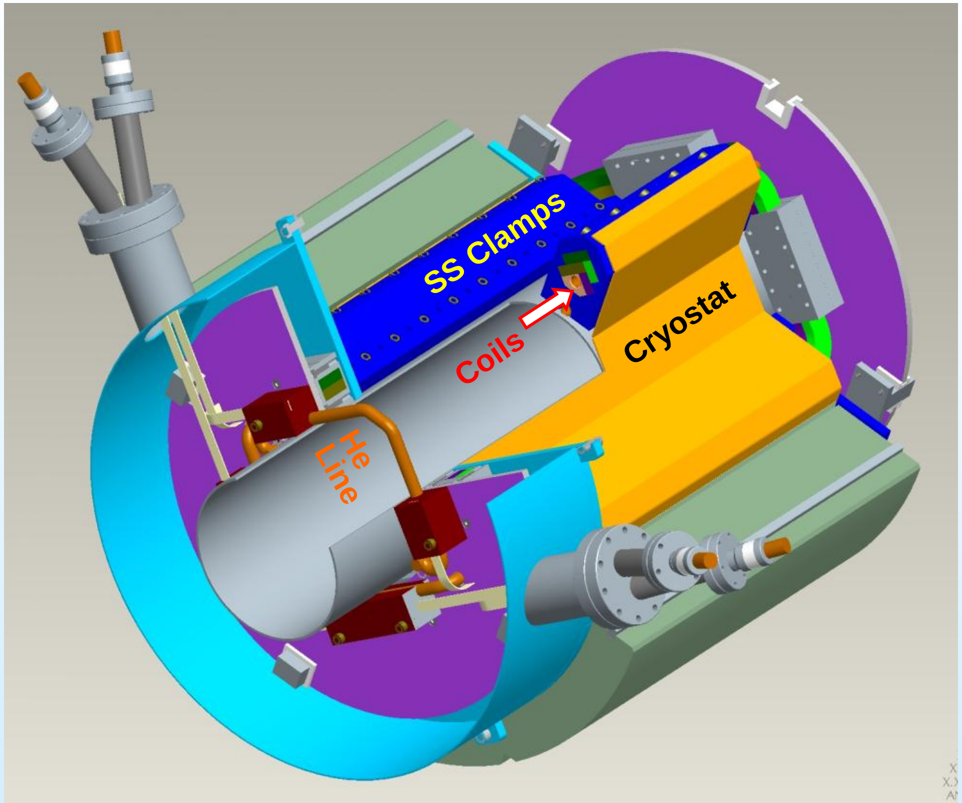
R. Gupta, M. Anerella, G. Ganetis, A. Ghosh,
G. Greene, W. Sampson, Y. Shiroyanagi, P. Wanderer
Brookhaven National Laboratory

A. Zeller, Senior Member IEEE
Michigan State University



Cryo-mechanical Structure



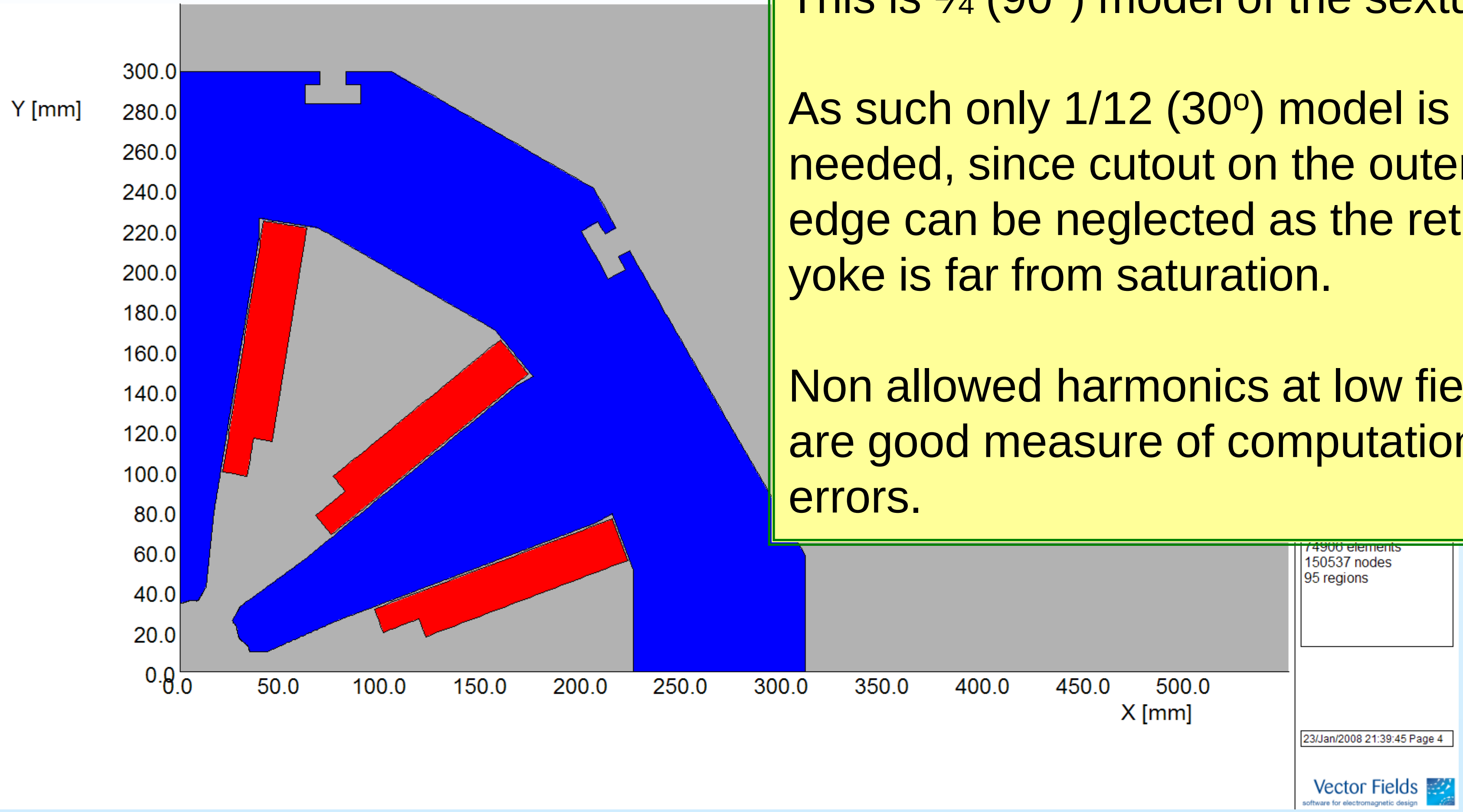


R&D Magnet in cryostat
(allows independent testing of four HTS coils)

Cut-away isometric view of the assembled magnet
(compact cryostat allowed larger space for coils and reduction in pole radius for higher gradient)

From ASC 2010 Paper

2-d Modeling Case Study – NSLS2 Sextupole



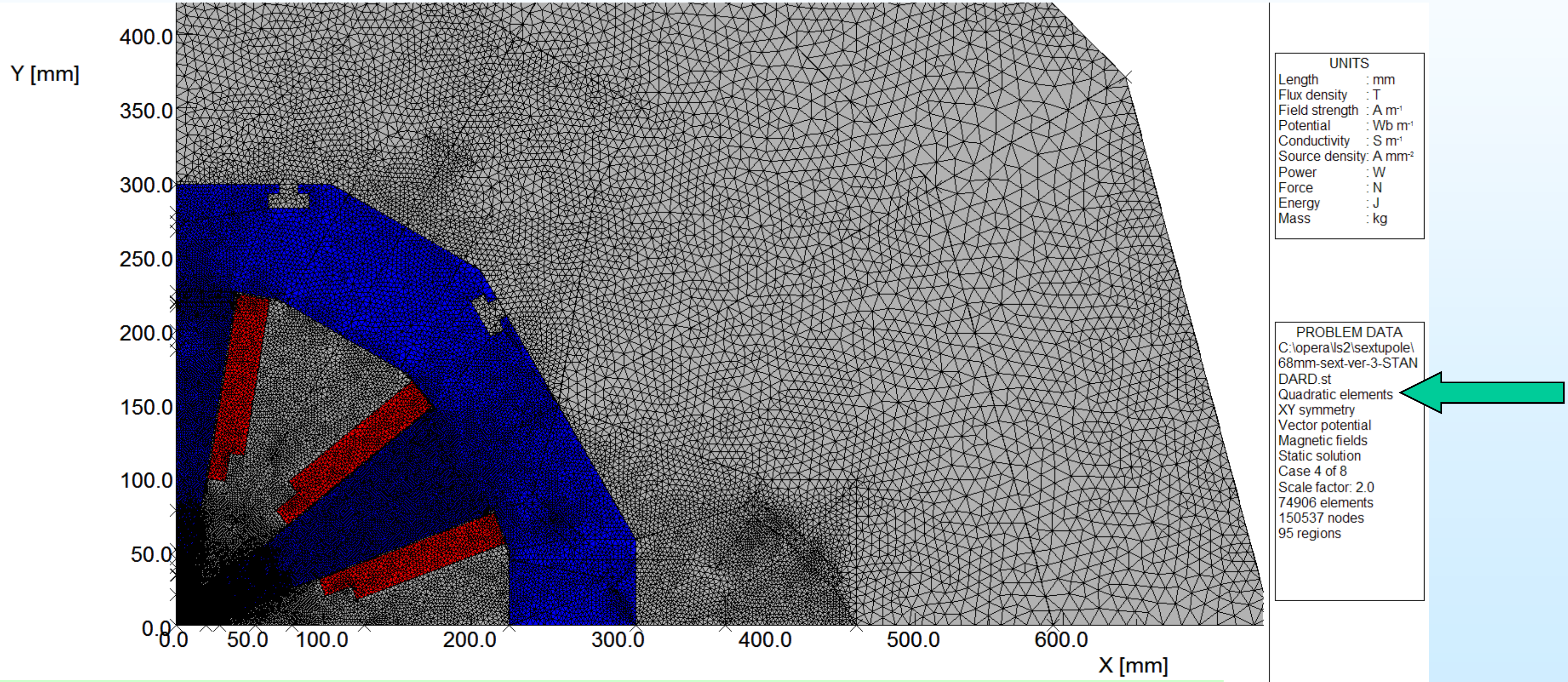
This is ¼ (90º) model of the sextupole.

As such only 1/12 (30º) model is needed, since cutout on the outer edge can be neglected as the return yoke is far from saturation.

Non allowed harmonics at low fields are good measure of computational errors.

Finite Element (OPERA 2d) Model of Sextupole

Use quadratic elements. This increases accuracy of calculations significantly in quadrupoles and sextupoles. Linear elements are OK in dipoles where vector potential changes linearly.



UNITS

Length	: mm
Flux density	: T
Field strength	: A m^{-1}
Potential	: Wb m^{-1}
Conductivity	: S m^{-1}
Source density	: A mm^{-2}
Power	: W
Force	: N
Energy	: J
Mass	: kg

PROBLEM DATA
C:\opera\ls2\sextupole\68mm-sext-ver-3-STANDARD.st
Quadratic elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 4 of 8
Scale factor: 2.0
74906 elements
150537 nodes
95 regions

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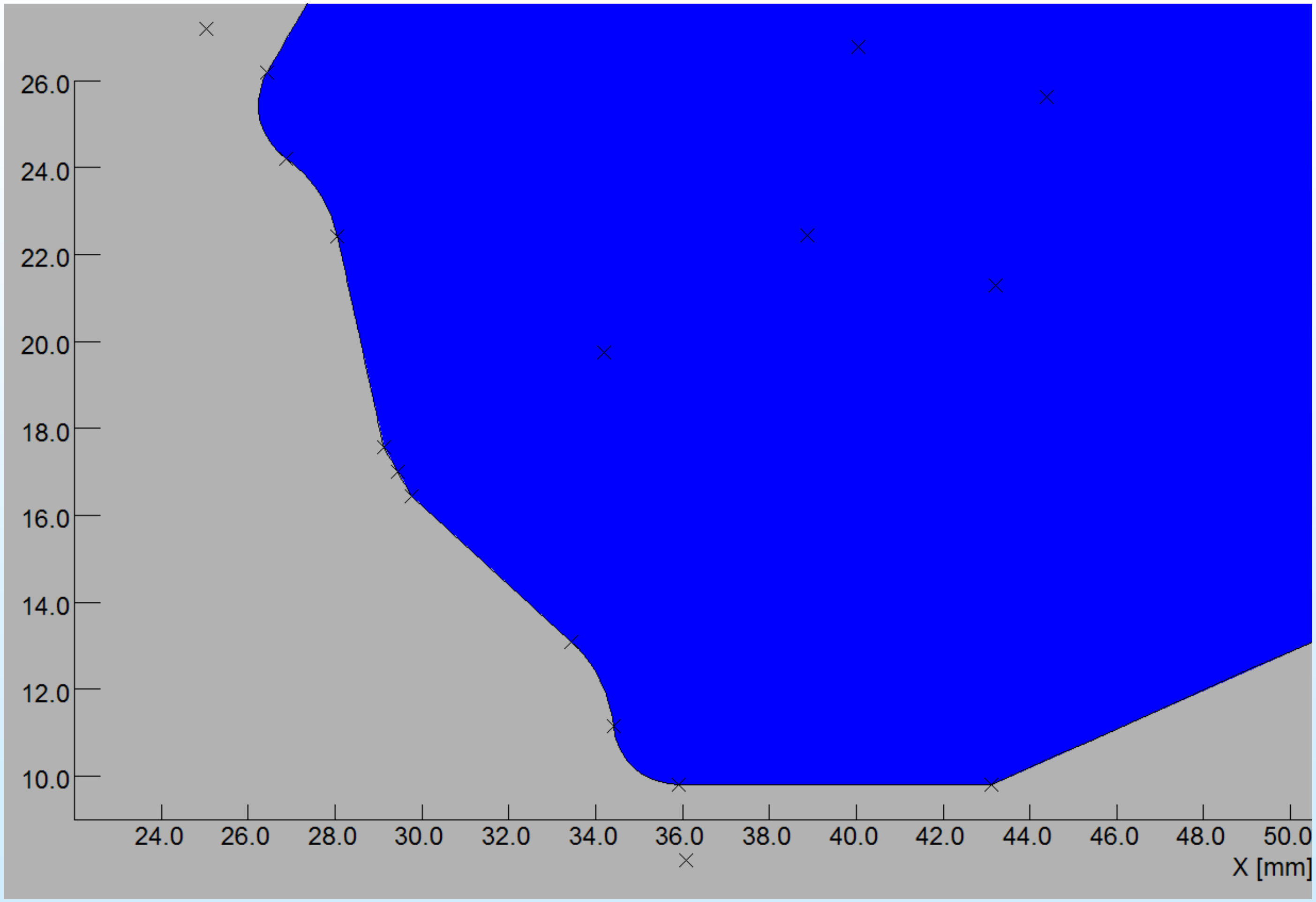
Vector Fields

Higher mesh density in the region where higher relative accuracy is needed for computing field harmonics

Magnetic Optimization of Pole Profile

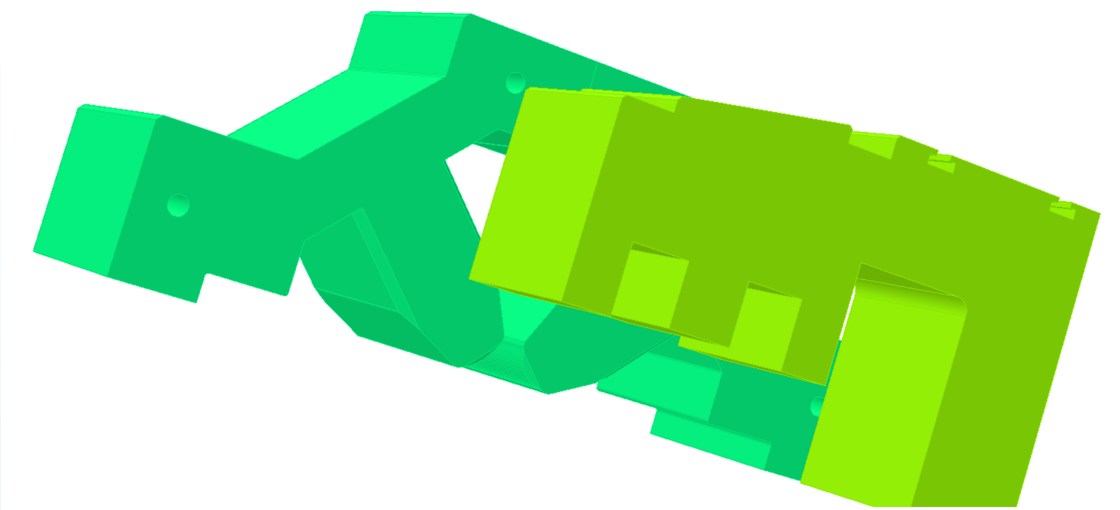


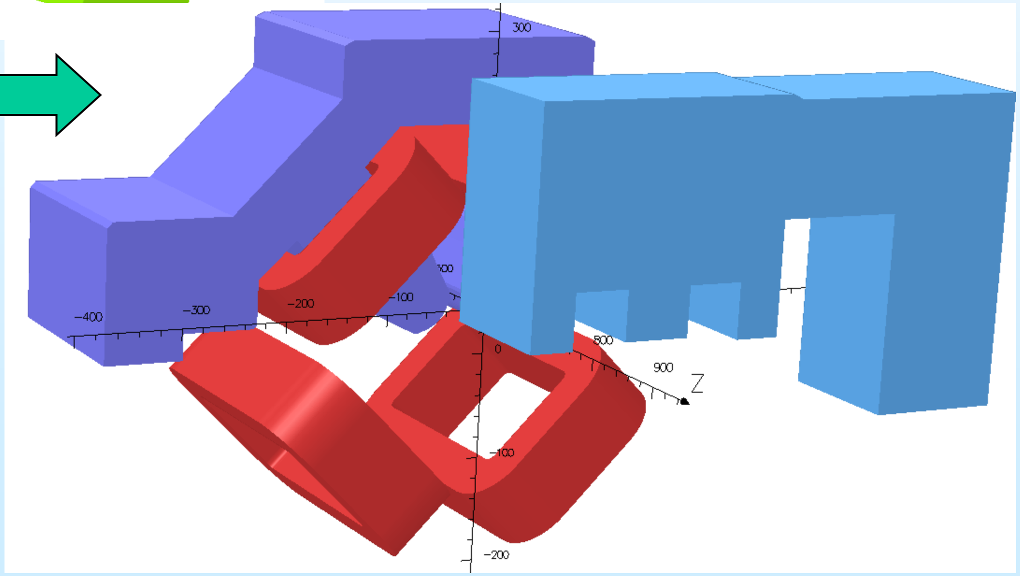
Six points (position) and two radii were used in optimizing pole profile to obtain low allowed harmonic while satisfying geometric constraints.

3-d Modelling of the Sextupole

Ends are chamfered to minimize integral harmonics.

Simplifying the Model

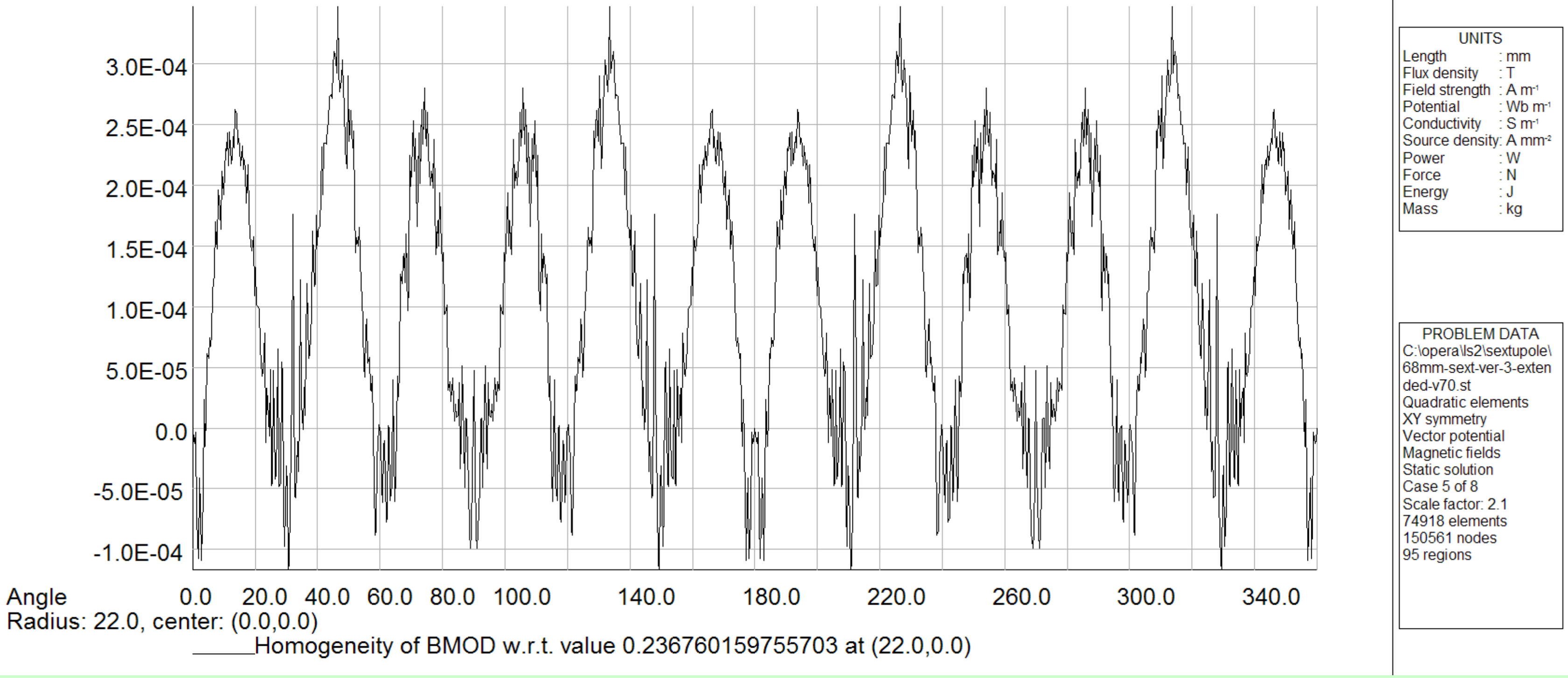




Simplifying certain details of iron structure does not decrease the accuracy of the calculations of the interference harmonic but significantly reduces the computational time.

Understanding Errors in Field Computations (2d)

Relative field errors on a circular arc are computed with respect to its value at x=R



Radius: 22.0, center: (0.0,0.0)
Homogeneity of BMOD w.r.t. value 0.236760159755703 at (22.0,0.0)

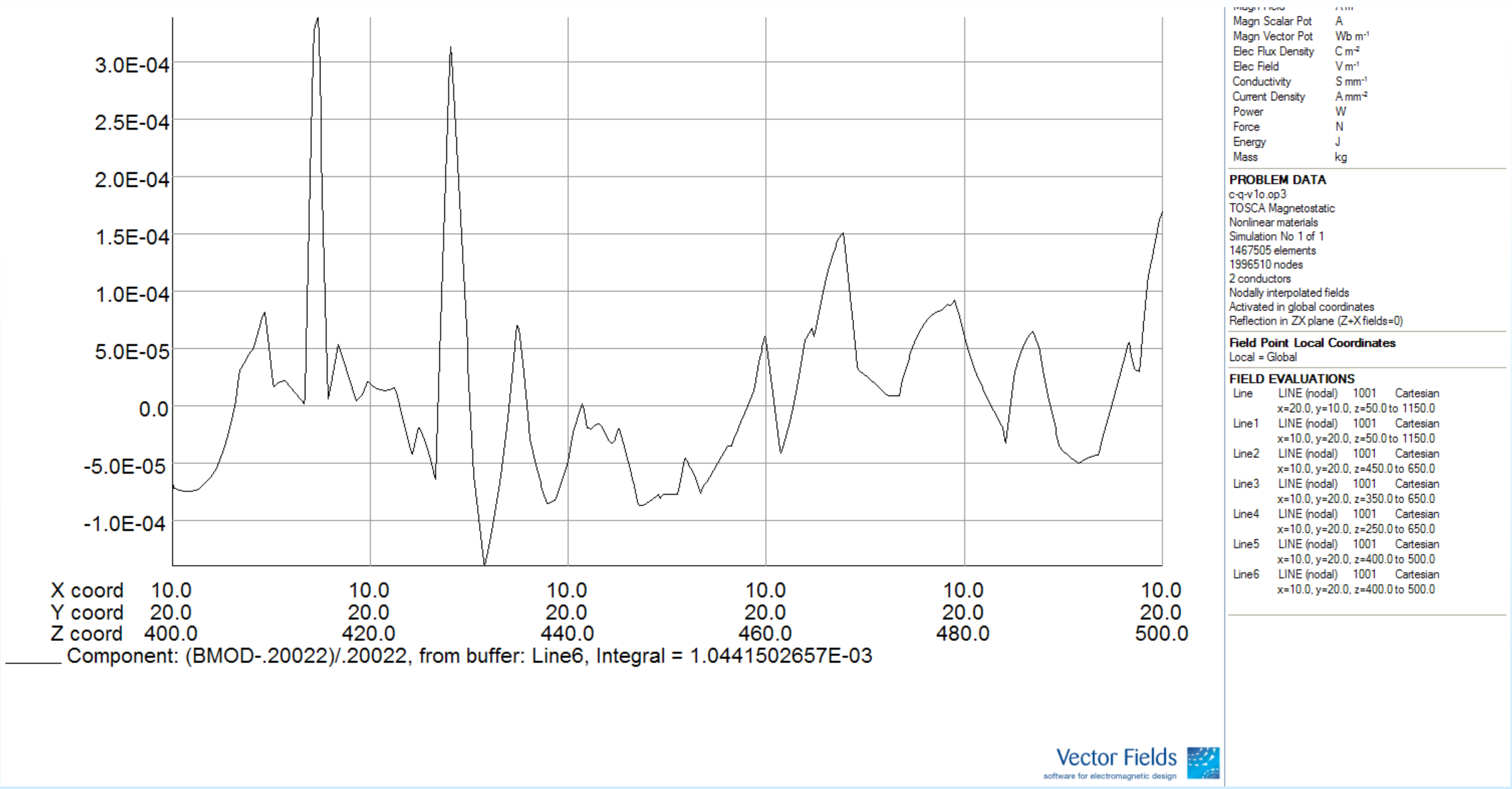
UNITS

Length	: mm
Flux density	: T
Field strength	: A m^{-1}
Potential	: Wb m^{-1}
Conductivity	: S m^{-1}
Source density	: A mm^{-2}
Power	: W
Force	: N
Energy	: J
Mass	: kg

PROBLEM DATA
C:\opera\ls2\sextupole\68mm-sext-ver-3-extended-v70.st
Quadratic elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 5 of 8
Scale factor: 2.1
74918 elements
150561 nodes
95 regions

- Smooth variation (parts in 10^4) may be due to inherent harmonics in the model.
- Noise (a few parts in 10^5) may be due to errors in field calculation.
- This suggest that the calculations should be reliable to a few parts in 10^5.
  - ➢This seems to be a reasonably good model giving reasonably good results.

Relative Error in Field Calculations (3d)
Magnitude of Field Parallel to z-axis



Component: (BMOD-.20022)/.20022, from buffer: Line6, Integral = 1.0441502657E-03

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

PROBLEM DATA
c-q-v1o.op3
TOSCA Magnetostatic
Nonlinear materials
Simulation No 1 of 1
1467505 elements
1996510 nodes
2 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)	1001	Cartesian
	x=20.0, y=10.0, z=50.0 to 1150.0		
Line1	LINE (nodal)	1001	Cartesian
	x=10.0, y=20.0, z=50.0 to 1150.0		
Line2	LINE (nodal)	1001	Cartesian
	x=10.0, y=20.0, z=450.0 to 650.0		
Line3	LINE (nodal)	1001	Cartesian
	x=10.0, y=20.0, z=350.0 to 650.0		
Line4	LINE (nodal)	1001	Cartesian
	x=10.0, y=20.0, z=250.0 to 650.0		
Line5	LINE (nodal)	1001	Cartesian
	x=10.0, y=20.0, z=400.0 to 500.0		
Line6	LINE (nodal)	1001	Cartesian
	x=10.0, y=20.0, z=400.0 to 500.0		

For most part relative error is 1 part in 10^4.
This is unusually good for 3-d for chosen mesh density.

Questions???

HTS Magnets and their Applications

A quick overview – detailed can be discussed off-line

New Possibilities with HTS in Superconducting Magnet Technology

HTS can function at high temperature

- That makes helium free superconducting magnets operating at high temperature possible as never before (> 20 K)

HTS can carry substantial currents at high fields

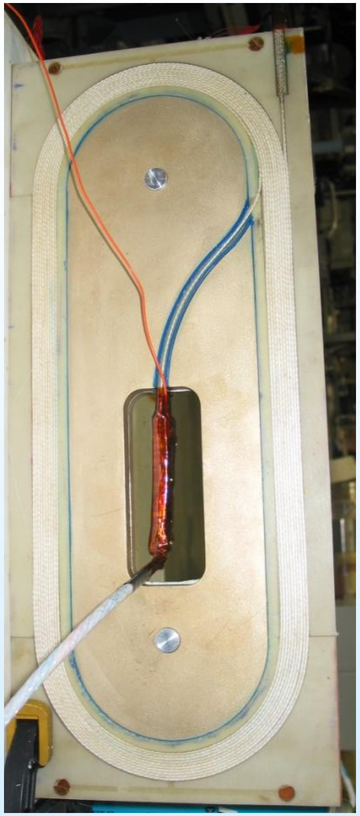
- That makes very high field superconducting magnets possible as never before (>20 T)

Even one of above is sufficient to revolutionize the field

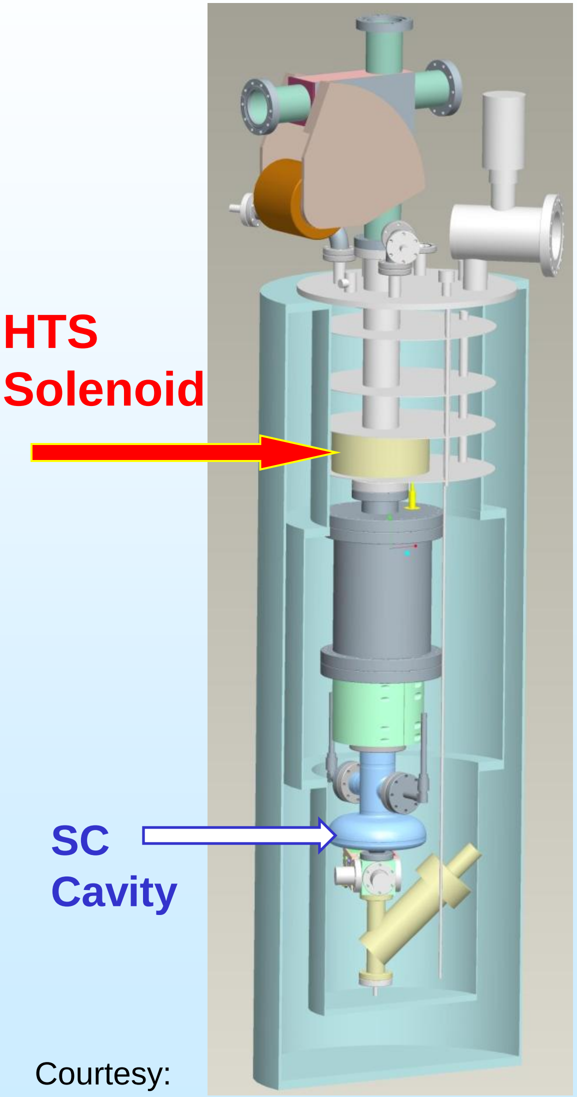
- ➢ Here we have two ! !

Magnets Made with HTS (offer a range of possibilities)

- ☐ High temperature, low field
  - ➢ Already in use in R&D programs at BNL
- ☐ Medium field, medium temperature
  - ➢ Potential for large scale cryogen-free applications
  - ➢ Solving critical problem of large heat loads as in **RISP**
- ☐ Very high field magnets
  - ➢ Dipoles for energy upgrade of particle accelerators
  - ➢ Quadrupoles for interaction region upgrade
  - ➢ Solenoids (>30 T) to make Muon Collider possible



HTS Solenoid for Superconducting Electron Gun

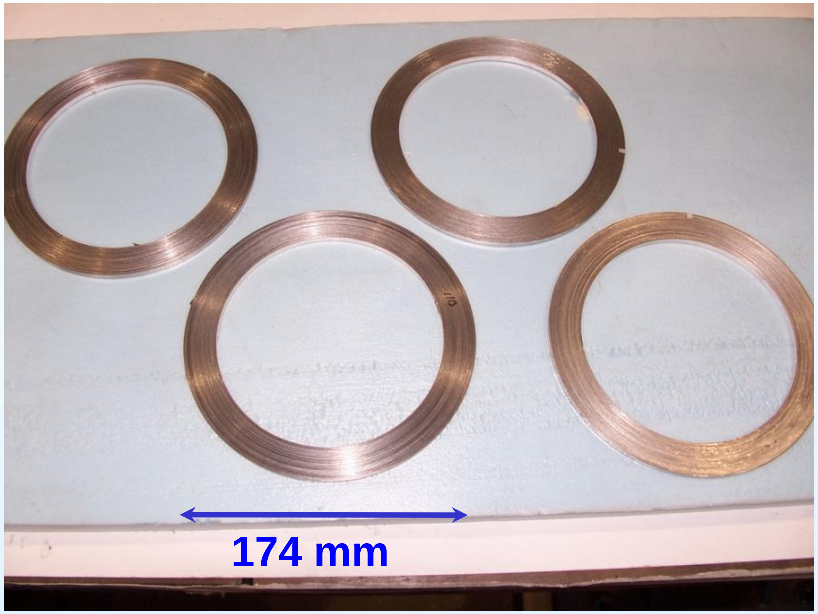


Courtesy:
Ben-Zvi, Kewisch

Produces intense electron beams with focusing from HTS solenoid

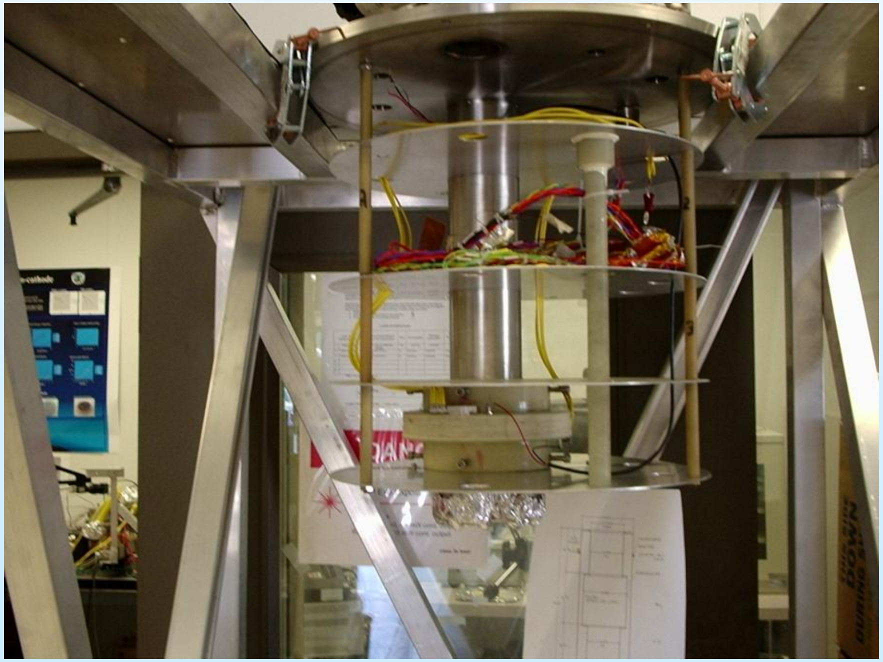
- No room for LTS solenoid in Liquid Helium
- Copper solenoid would generate ~500 W heat as against the ~5 W heat load of the entire cryostat
- Temperature between baffles ~20 K **– *NO LTS***
- **HTS solenoid provides a unique solution**

Hardware of HTS Solenoid Built as a Part of LDRD



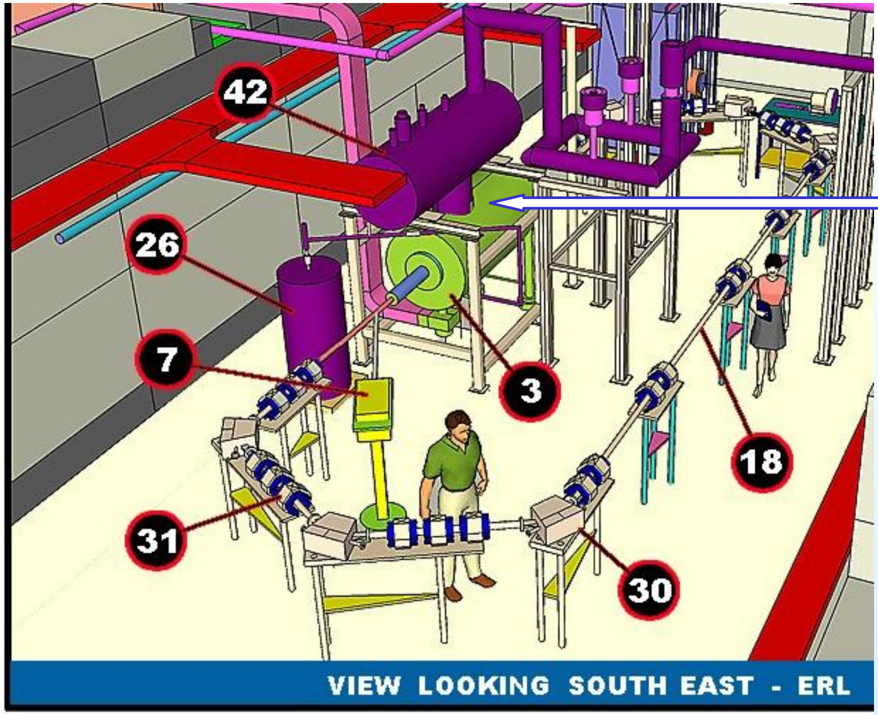
- Conductor cost: ~ a few k$
- Compact size
- Low current (<20 A) operation with household wiring

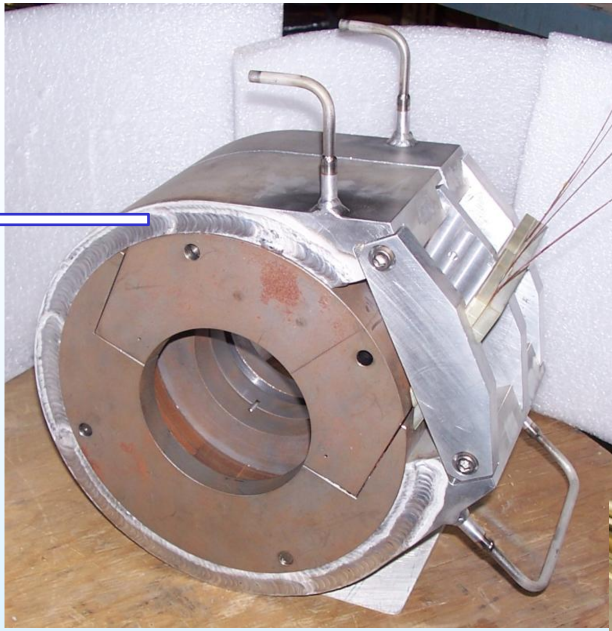
- Testing at ~77 K in LN_2 is much cheaper than testing at ~4 K in LHe
- **HTS provided an economically better (design + build + test) and technically superior solution**

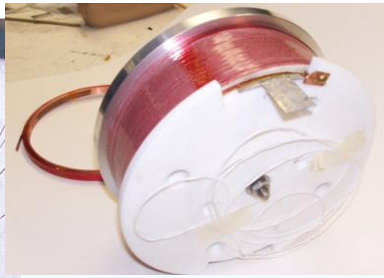


Courtesy/Contributions: Dilgen, Ince

HTS Solenoid with Superconducting Cavity for the Energy Recovery Linac at BNL







HTS solenoid is placed in cold to warm transition region after the superconducting cavity where neither LTS or copper solenoid would work

A unique BNL solution that other labs are adopting

Medium Field HTS Magnet Programs

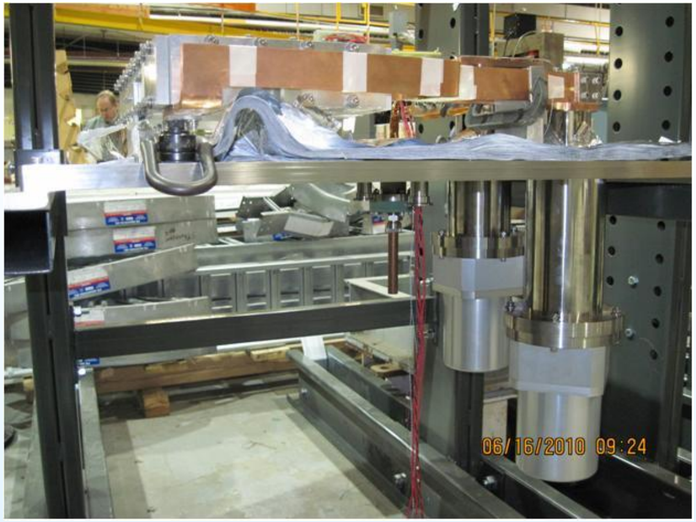
1. **General Purpose (for accelerators & medical applications)**

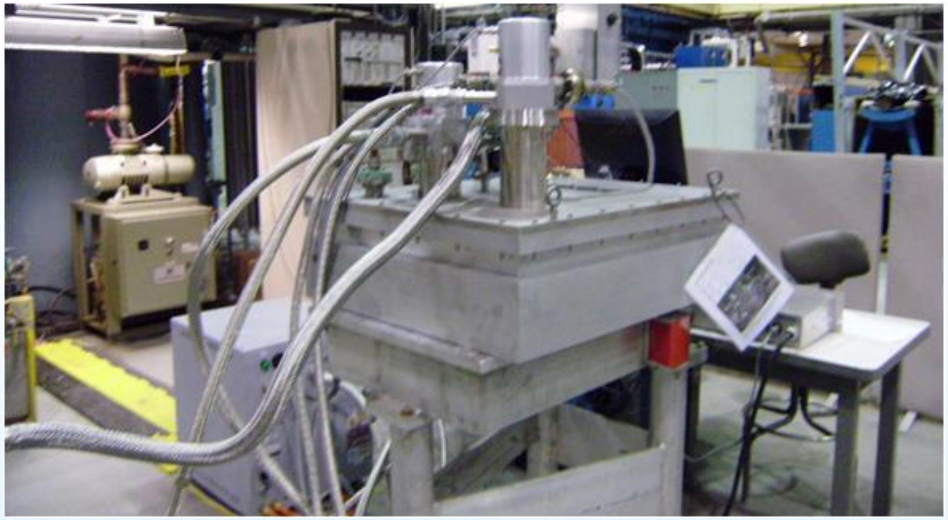
- Must compete with two established technologies:
  - Magnets powered with water-cooled copper coils
  - Super-ferric magnets with conventional superconductors (NbTi)

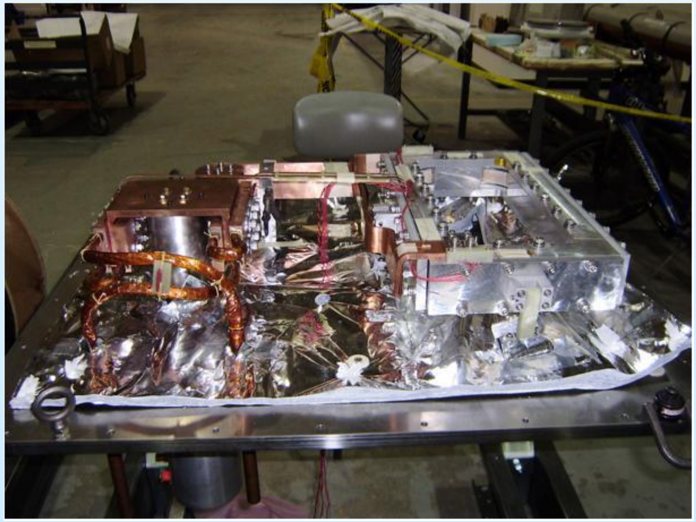
2. Special Purpose Magnets:

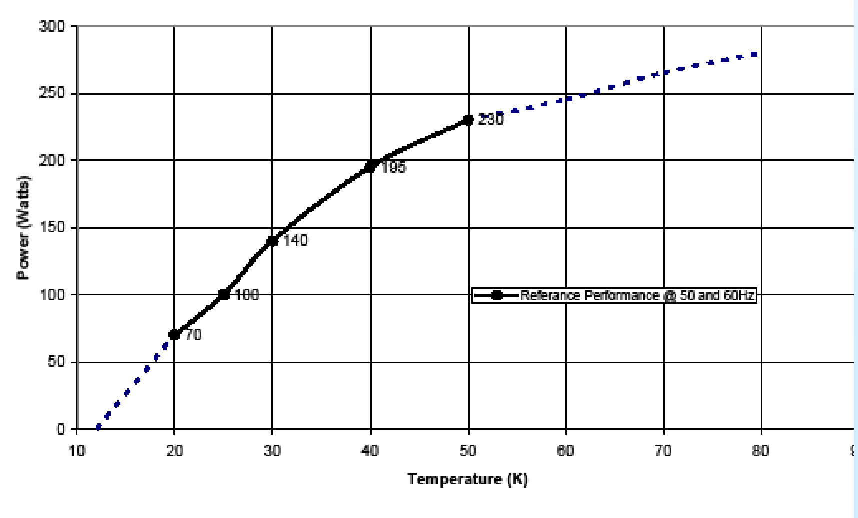
- HTS magnets solve critical technical problems
- Example: Large energy deposition in FRIB, RISP, etc.

HTS and Cryo-coolers
(a promising marriage)









Evening: Switch ON; Morning: Fully COLD

HTS Magnet Development Program for Facility for Rare Isotope Beams (FRIB)

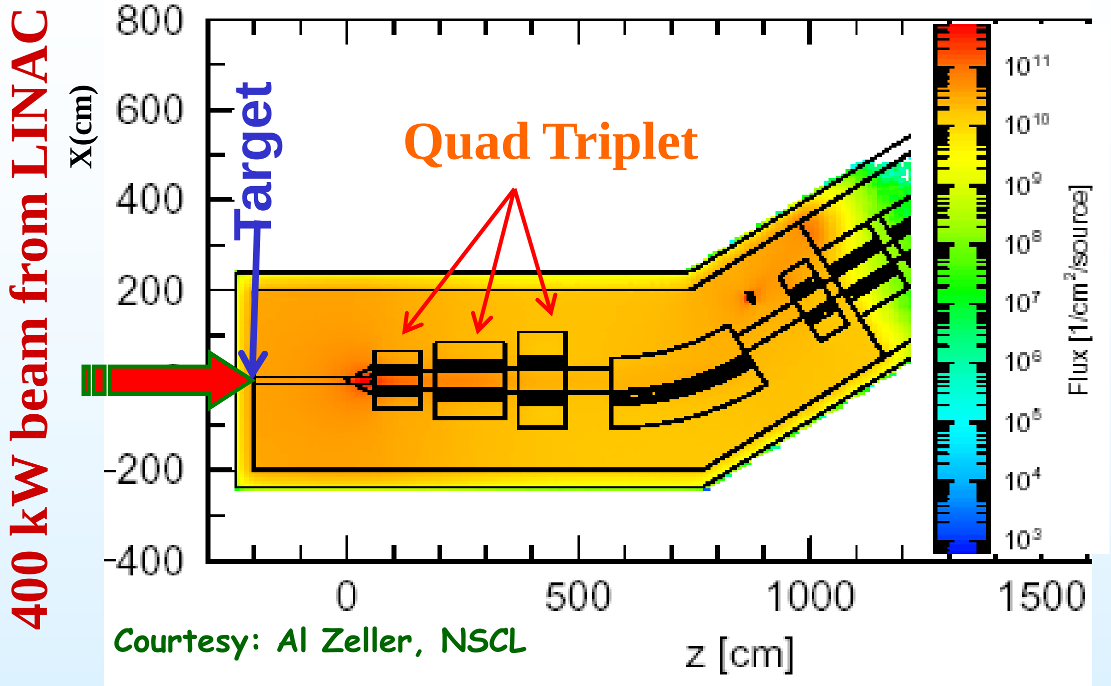
Will create rare isotopes in quantities not available anywhere

- Michigan State University

HTS Magnets for RISP:

Discussed in details in the HTS/RISP seminar

Technical Advantage of HTS Magnets in FRIB



Courtesy: Al Zeller, NSCL

- ➢ High power beam (~400 kW) hits the target to create intense rare isotope beams
- ➢ Magnets are exposed to very high radiation and heat loads (~15 kW in the first)
- ➢ HTS magnets remove this heat more efficiently at 30-50 K than LTS at ~4 K
- ➢ HTS magnets have a large temperature margin, can tolerate a large local increase in temperature and allow a robust cryogenic operation in presence of large heat loads

Very High Field HTS Solenoids

- **The most demanding program yet**
- **High fields create large forces, large stored energy, etc., etc., etc.**
- **Will test the limit of the conductor and of structure**

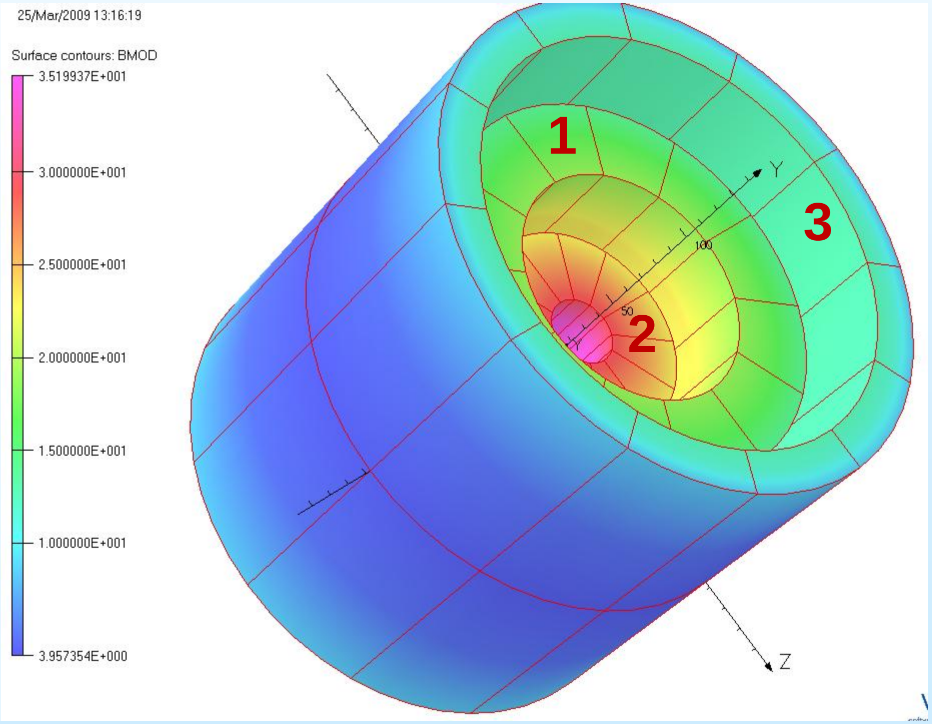
Two ambitious programs:

- **24-30 T HTS solenoid for magnetic energy storage**
- **30-40 T HTS+LTS (hybrid) solenoid for cooling in muon colliders**

Both would be the highest field HTS magnets ever built!

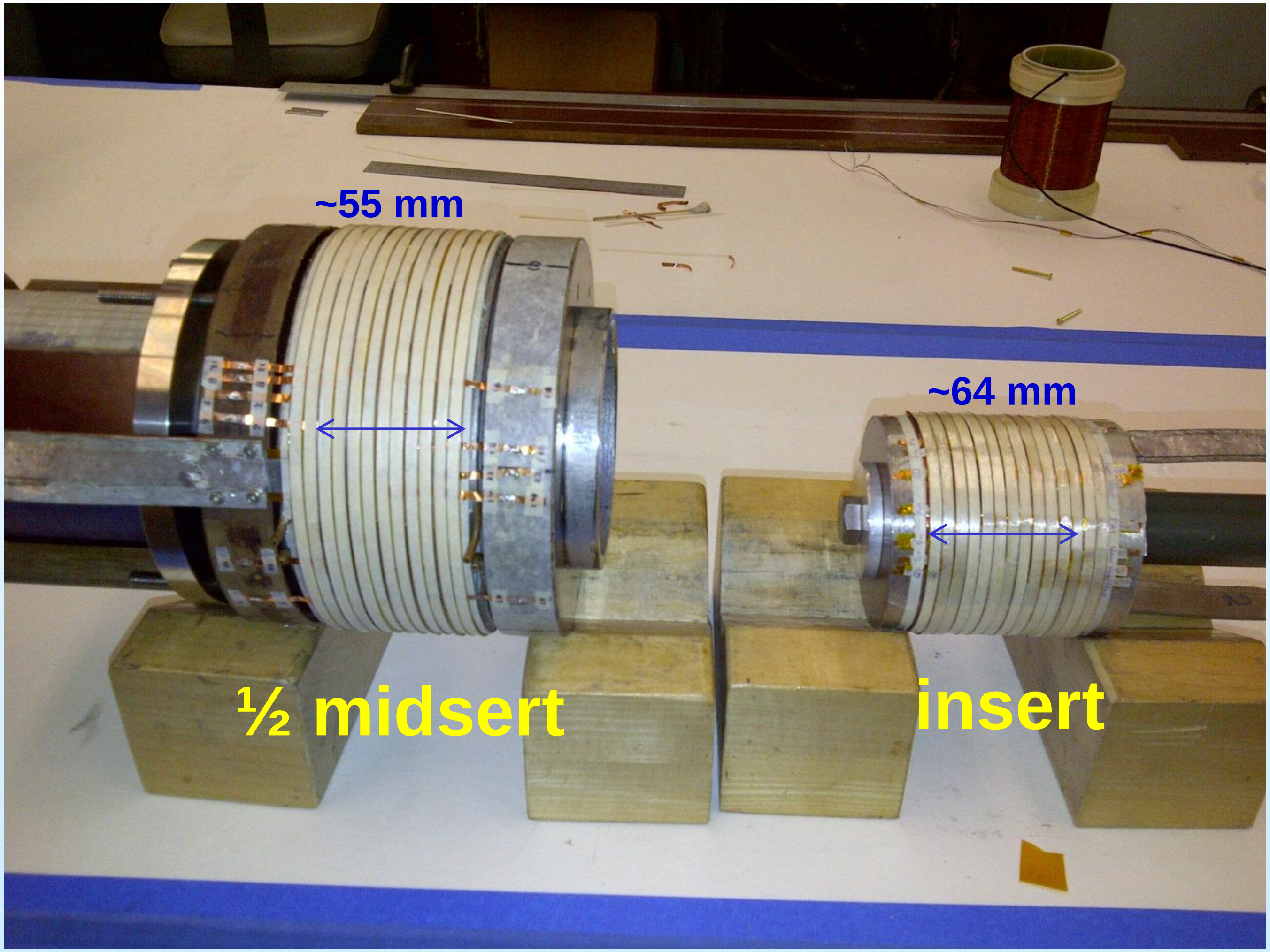
High Field Solenoid for MAP

- Ambitious R&D to develop SC magnet technology for 35-40 T
- Significant demonstrations so far:
  - ➢ **Highest field (>15 T) HTS magnet ever built**
  - ➢ **Large use (1.2 km) of HTS in a high field magnet**



SBIR with PBL

High Field HTS Solenoids for MAP

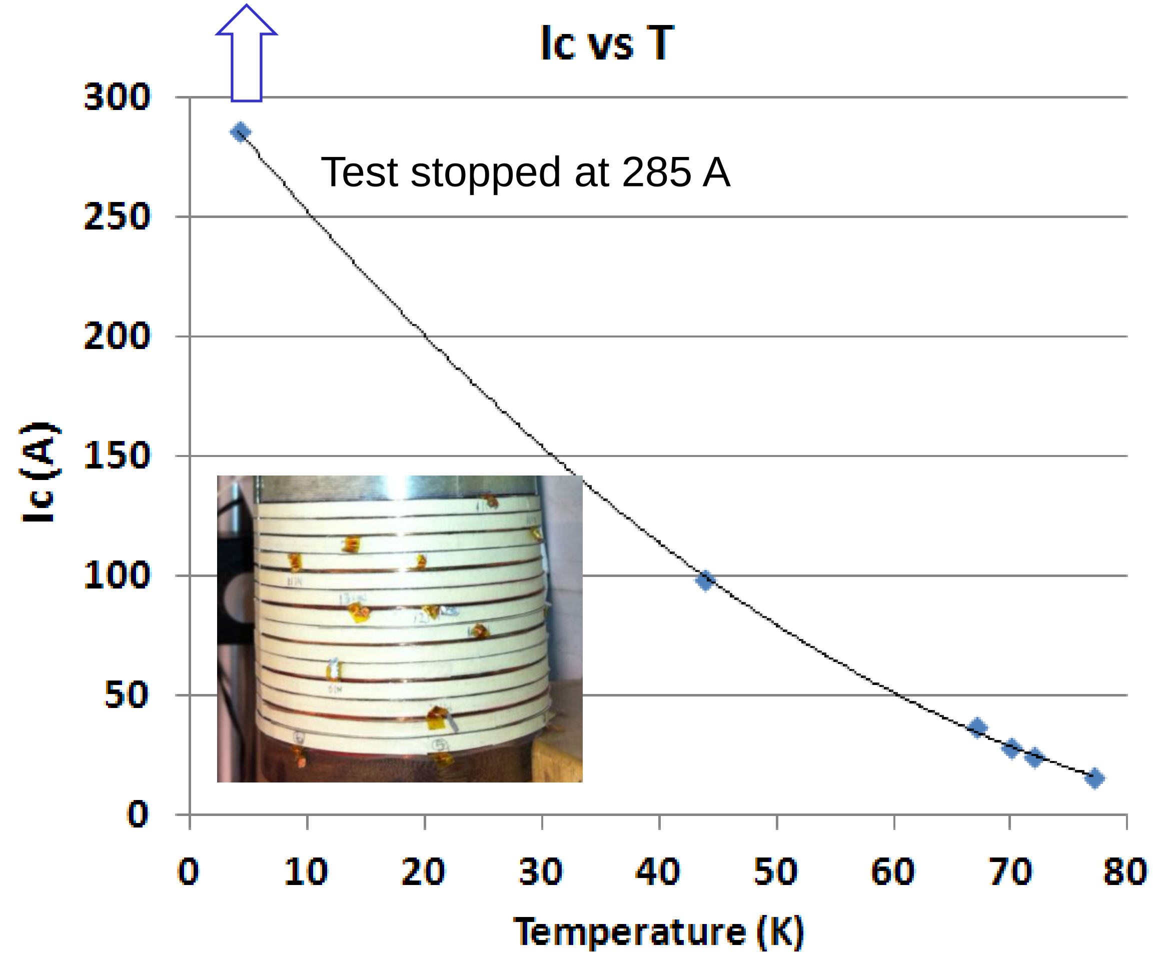


Two significant construction and tests

Conductor:
High strength 2G HTS from SuperPower with ~45 μm Copper

SBIR with PBL

High Field HTS Test Results (magnet #1)



Field on axis:

- over 15 T

Field on coil:

- over 16 T

Real demo of 2G HTS to create high field

Highest field in an all HTS solenoid (previous best SP/NHMFL ~10.4 T)

Overall J_o in coil:

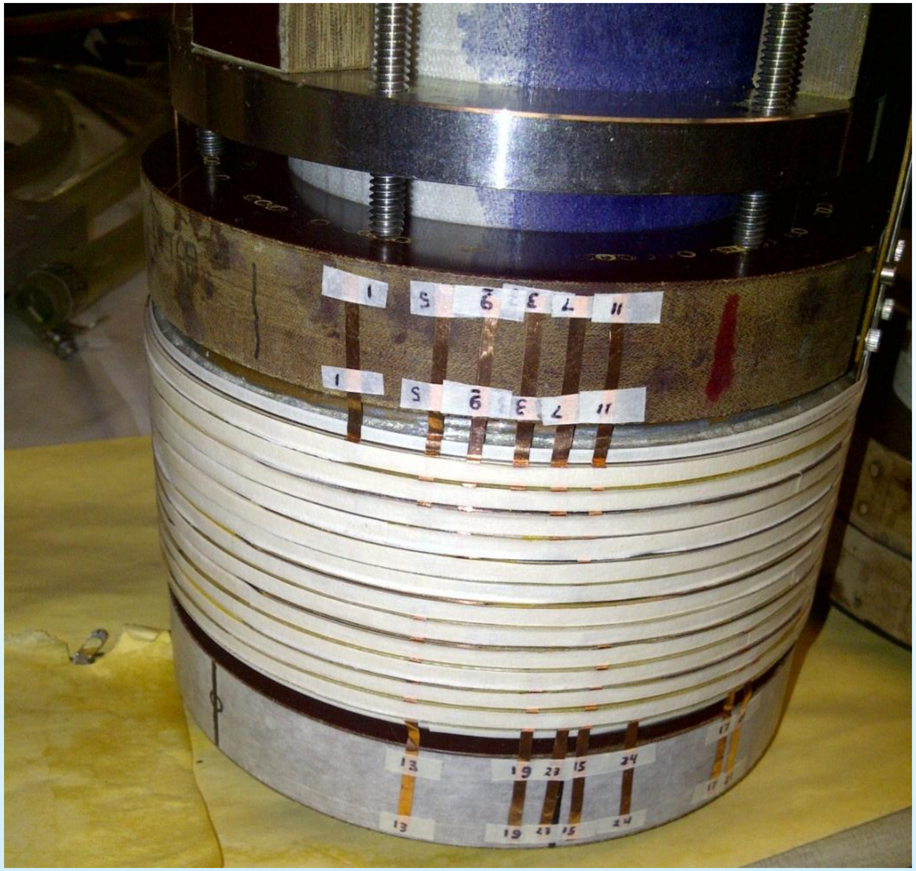
>500 A/mm^2 at 16 T

(despite anisotropy)

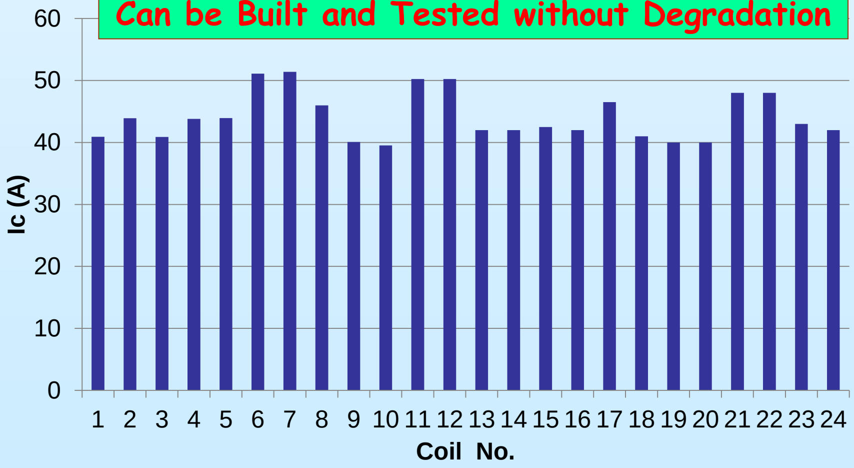
24 pancake coils with ~25 mm aperture

SBIR with PBL

Test Results of ~100 mm HTS Coil (magnet #2 - half length midsert)



Proof That A Large Number of 2G HTS Coils Can be Built and Tested without Degradation

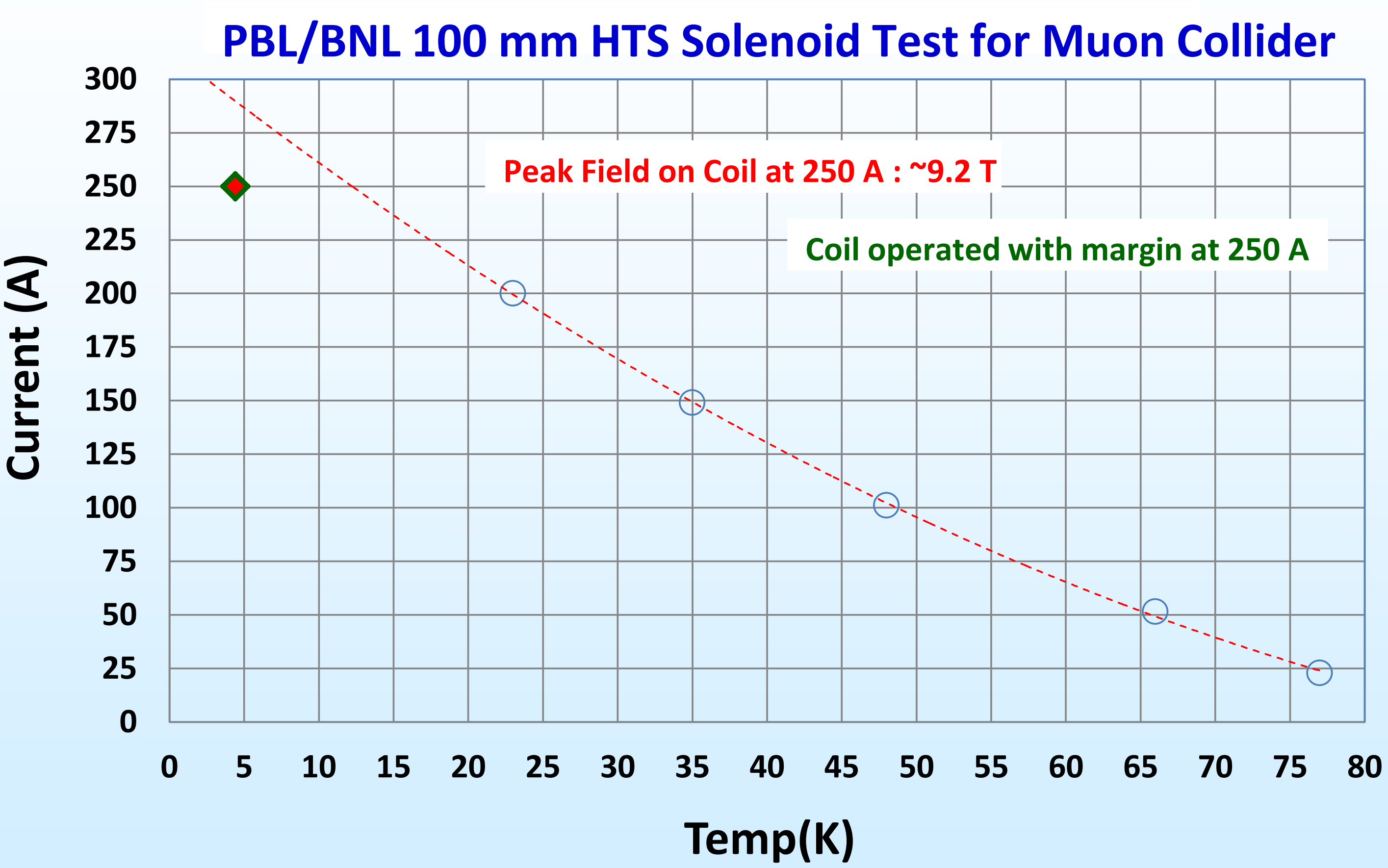


- Intermediate test with 12 pancakes
- Full solenoid will have 24 pancakes

(each coil built with 100 m SP HTS)

Test Results of ½ Midsert Solenoid

Measured Critical Current As a function of Temperature



250 A ==>
6.4 T on axis
9.2 T on coil

Coil could have reached above 10 T, but we decided to hold back to protect our electronics

SBIR with PBL

Status and Future Prospects of Very High Field Solenoid Program

- 25 mm and 100 mm solenoids will be merged together and should be ready for test in a few months
- Expected field: 20-25 T (would be a remarkable result)
  - Highest field in an all HTS magnet (beating 15 T just achieved)
- Proposal to build a NbTi outsert to above to enhance the field to over 25 T when all powered together.
- Proposal to add more modular coils to enhance the combined to ~35 T as needed for Muon Accelerator Program (MAP)

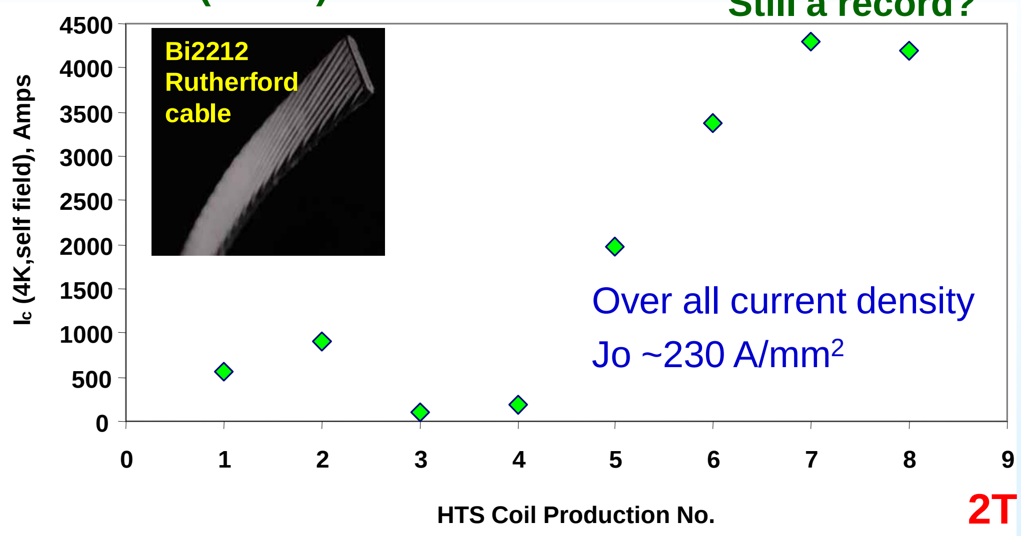
HTS Common Coil Dipole with Bi2212 Rutherford Cable

8 Coils and 5 Magnets built at BNL with Rutherford Bi2212 Cable

Coil / Magnet	Cable Description	Magnet Description	I_c (A)	J_e(sf)[J_e(5T)] (A/mm^2)	Self-field, T
CC006 DCC004	0.81 mm wire, 18 strands	2 HTS coils, 2 mm spacing Common coil configuration	560	60 [31]	0.27
CC007 DCC004	0.81 mm wire, 18 strands		900	97 [54]	0.43
CC010 DCC006	0.81 mm wire, 2 HTS, 16 Ag	2 HTS coils (mixed strand) 74 mm spacing Common coil	94	91 [41]	0.023
CC011 DCC006	0.81 mm wire, 2 HTS, 16 Ag		182	177 [80]	0.045
CC012 DCC008	0.81 mm wire, 18 strands	Hybrid Design 1 HTS, 2 Nb_3Sn	1970	212 [129]	0.66
CC023 DCC012	1 mm wire, 20 strands	Hybrid Design 1 HTS, 4 Nb_3Sn	3370	215 [143]	0.95
CC026 DCC014	0.81 mm wire, 30 strands	Hybrid Common Coil Design 2 HTS, 4 Nb_3Sn coils (total 6 coils)	4300	278 [219]	1.89
CC027 DCC014	0.81 mm wire, 30 strands		4200	272 [212]	1.84

Earlier coils
<1 kA (~2001)

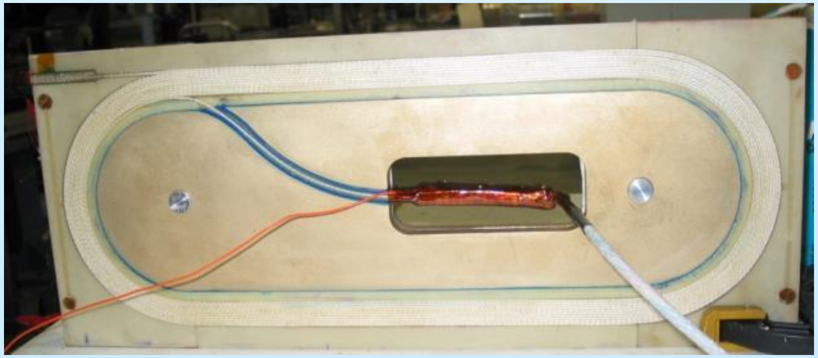
Later coils
4.3 kA (2003)
Still a record?

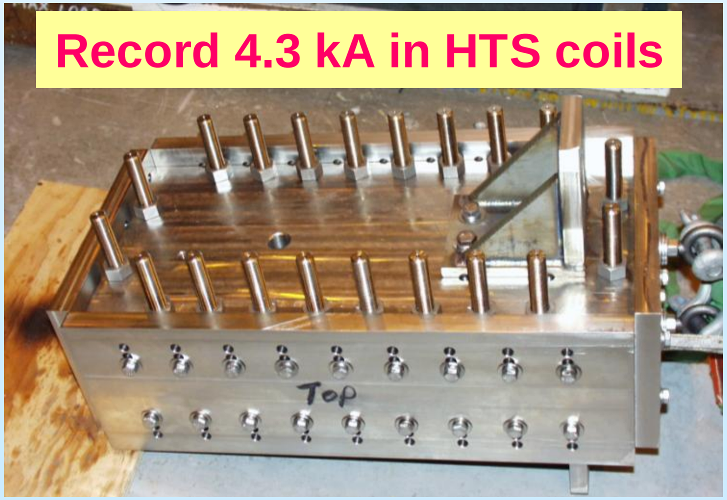


Over all current density
Jo ~230 A/mm^2

2T

Racetrack HTS coil with Bi2212





Record 4.3 kA in HTS coils

Thank you for your attention.

Questions?