Open Midplane Magnets

Part 2 - Magnet Design

(Part 1 was presented by Brett Parker)

Ramesh Gupta
Brookhaven National Laboratory

Overview

- Open Midplane Dipole Design
  - Basic design concept and advantages
  - Progress in high field and high field quality magnet designs (LARP work)

✓ Relevance to $\mu^+\mu^-$ collider: Large energy deposition at midplane from decay particles

- RIA HTS Quadrupole
  - HTS coils to withstand and economically remove extremely large heat loads
  - Magnet construction and test results
    - including critical energy deposition experiments

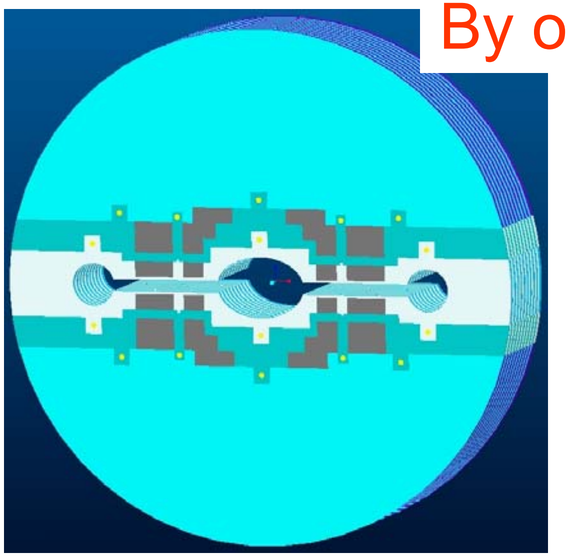
✓ Relevance to $\mu^+\mu^-$ collider: HTS can create high fields and withstand large heat loads

- Combined Function Magnet Designs
  - A brief review of the previous work on neutrino factory combined function magnet design (dipole with skew quad) for a compact machine (B. Parker)
- Summary

Progress in Open Midplane Dipole Design

(work performed under the auspices of LARP)

A True Open Midplane Design

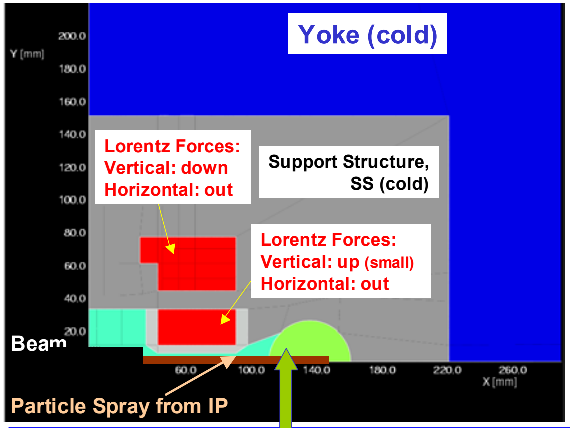


By open midplane, we mean truly open midplane:

- Particle spray from IP (mostly at midplane), passes through an open region to a warm (~80 K) absorber sufficiently away from the coil without hitting superconducting coils or any structure near it.

- In earlier "open midplane designs", although there was "no conductor" at the midplane, but there was some "other structure" between the upper and lower halves of the coil. Secondary showers from that other structure deposited a large amount of energy on the superconducting (s.c.) coils.

- Earlier designs, therefore, did not work so well in protecting s.c. coils against energy deposition.



Yoke (cold)

Lorentz Forces:
Vertical: down
Horizontal: out

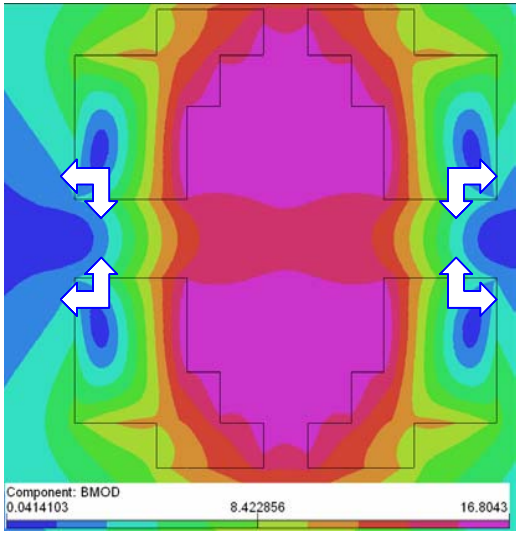
Support Structure, SS (cold)

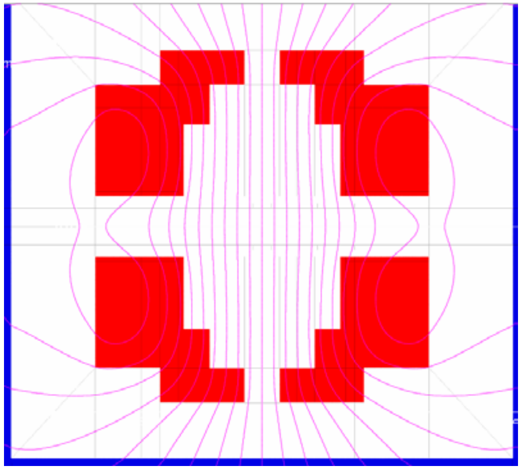
Lorentz Forces:
Vertical: up (small)
Horizontal: out

Particle Spray from IP

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.

Open Midplane Dipole Design Challenges





#1 In usual cosine theta or block coil designs, there are large attractive forces between upper and lower coils. How can these coils hang in air with no structure in between?

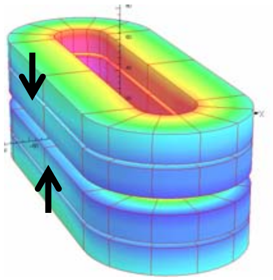
#2 The ratio of peak field in the coil to the design field appears to become large for large midplane gaps.

#3 The large gap at midplane appears to make obtaining good field quality a challenging task. Gap requirements are such that a significant portion of the cosine theta, which normally plays a major role in generating field and field quality, must be taken out from the coil structure.

=> Could there be a solution that can overcome above?

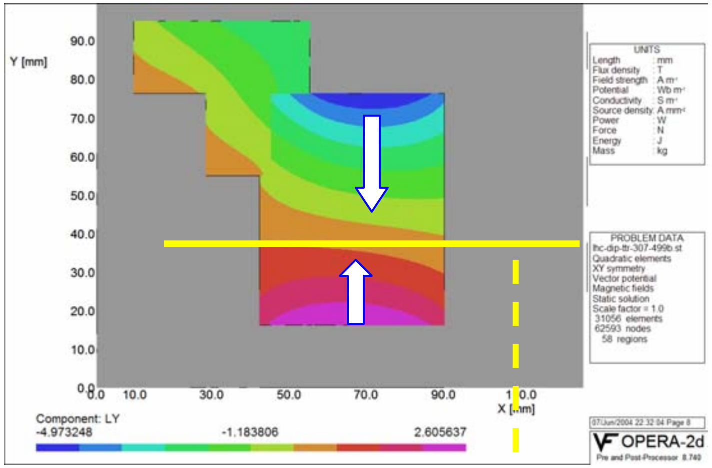
⇨ **With such basic challenges in place, don't expect the design to look like what we are used to seeing in conventional cosine theta magnets.**

Challenge #1: Lorentz Forces between coils
A new and major consideration in design optimization



In conventional designs the upper and lower coils rest (react) against each other. In a truly open midplane design, the target is to have no structure between upper and lower coils. Structure generates large heat loads and the goal is to minimize them.

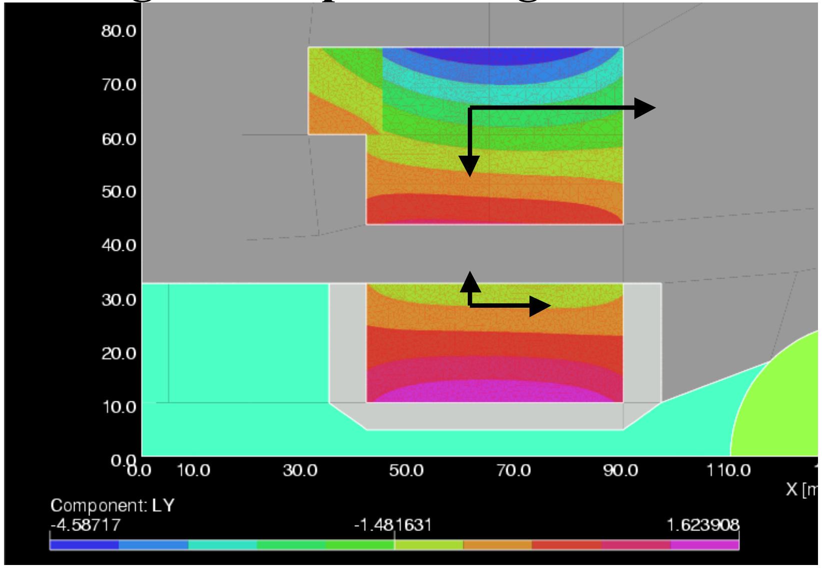
Original Design



Zero vertical force line

Lorentz force density (Vertical)

New Design Concept to navigate Lorentz forces

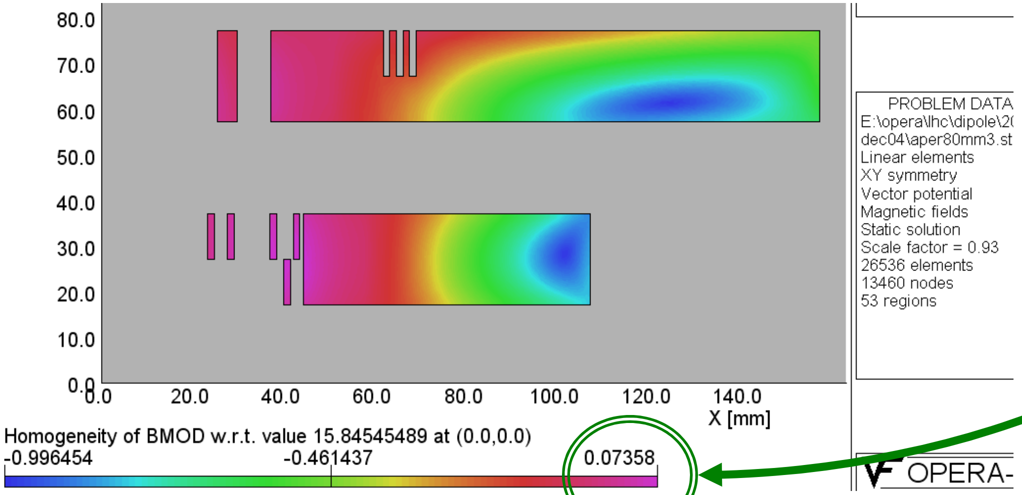


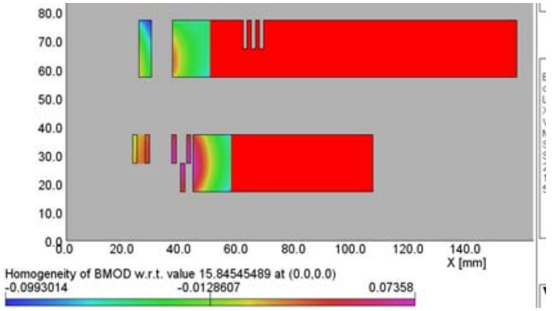
Since there is no downward force on the lower block (there is slight upward force), we do not need much support below if the structure is segmented. The support structure can be designed to deal with the downward force on the upper block using the space between the upper and the lower blocks.

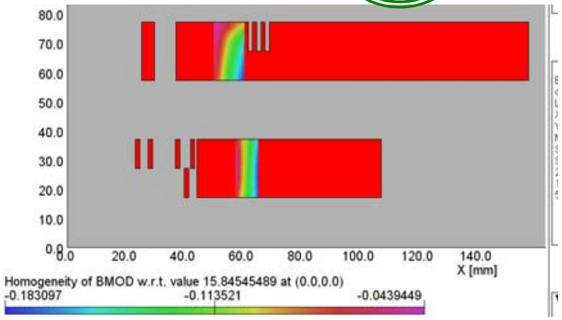
Challenge #2: Peak Field

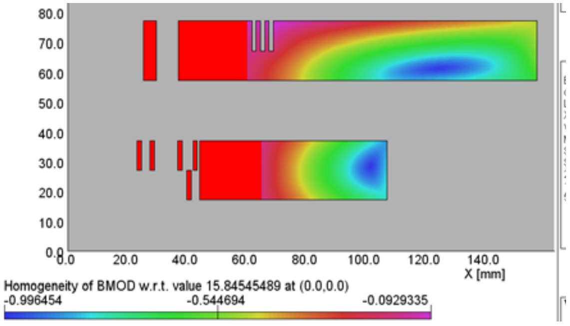
Several designs have been optimized with a small peak enhancement: ~7% over B_o

Relative field enhancement in coil over the central field









Quench Field: ~16 T with J_c = 3000 A/mm^2, Cu/Non-cu = 0.85

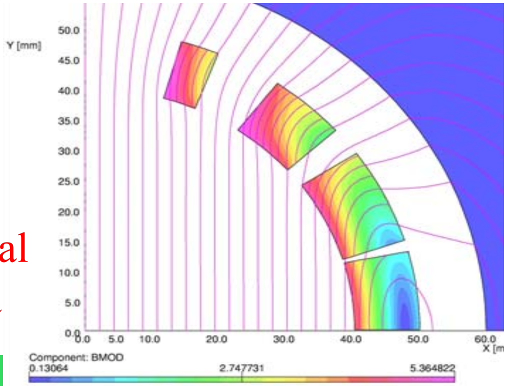
Quench Field: ~15.8 T with J_c = 3000 A/mm^2, Cu/Non-cu = 1.0

Challenge #3: Field Quality

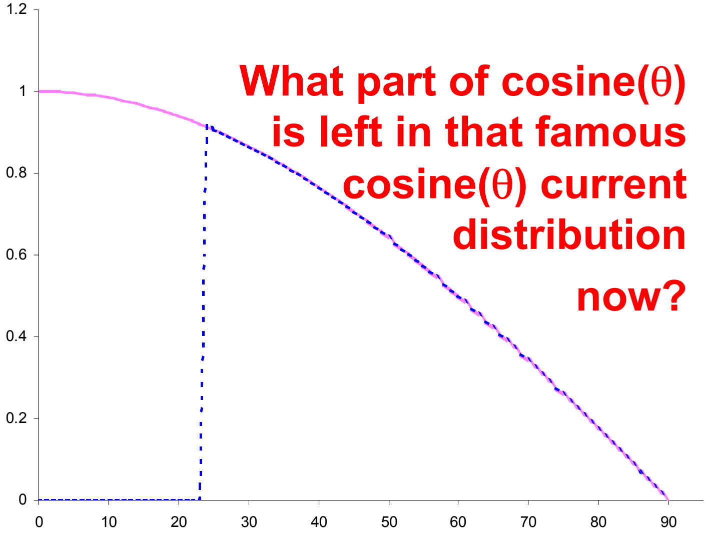
Coil-to-coil gap in this design = 34 mm (17 mm half gap)

Horizontal aperture = 80 mm

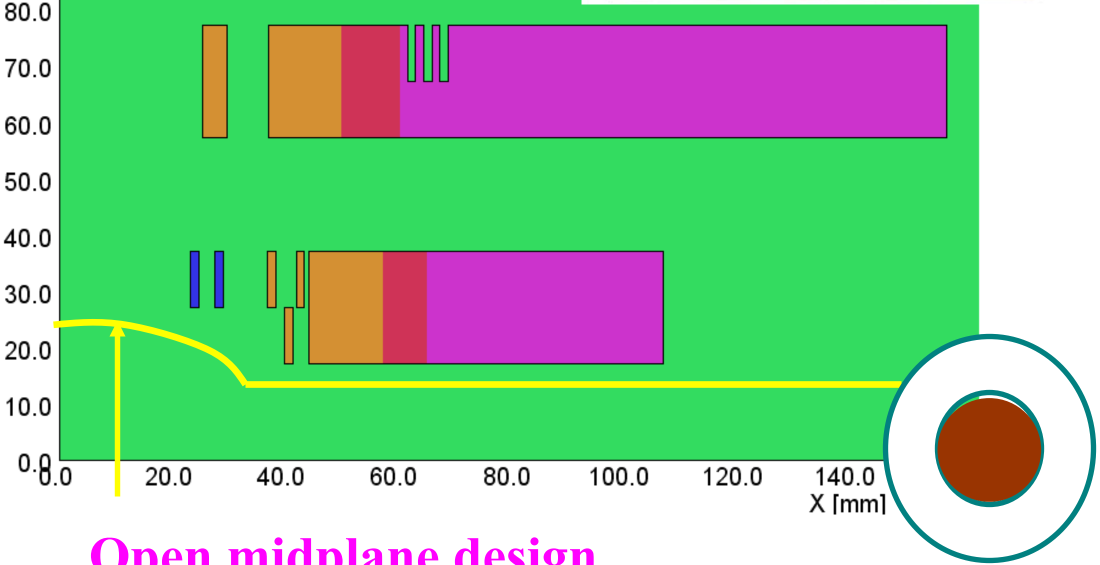
⇒ Vertical gap is > 42% of horizontal aperture (midplane angle: 23°)



Conventional cosine theta



What part of cosine(θ) is left in that famous cosine(θ) current distribution now?



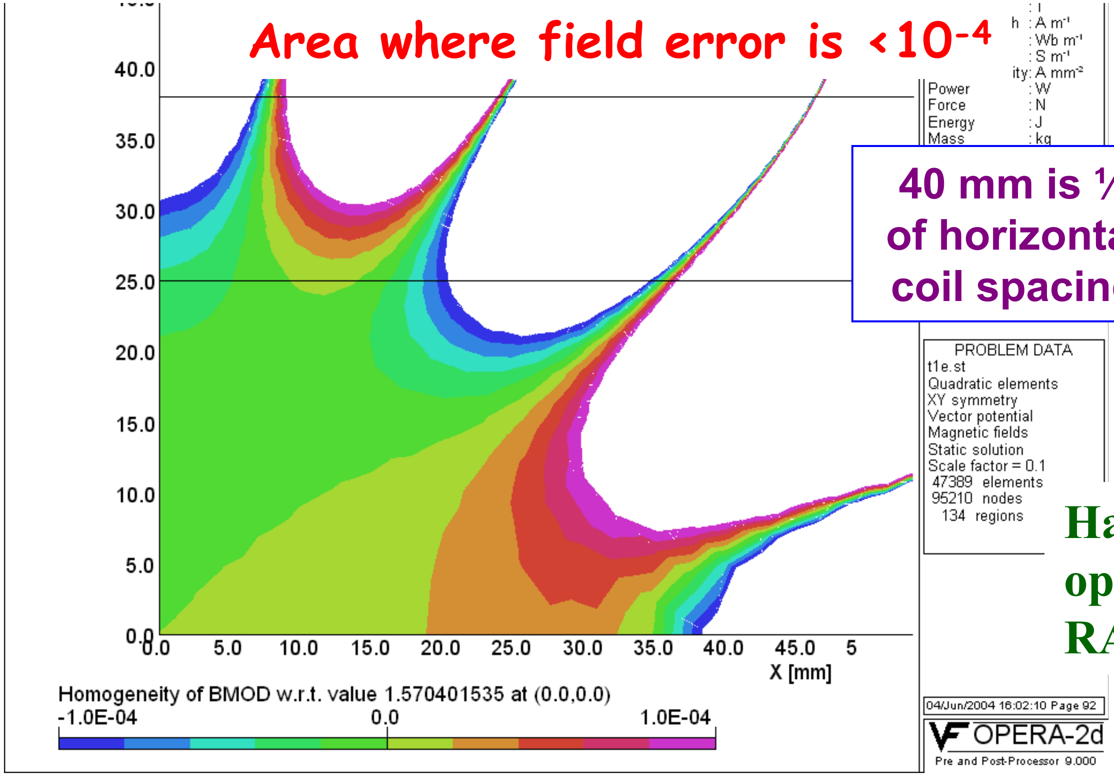
This makes obtaining high field and high field quality a challenging task !

Open midplane design

We did not let prejudices come in our way of optimizing coil - e.g. that the coil must create some thing like cosine theta current distribution !

Field Harmonics and Relative Field Errors in an Optimized Design

Proof: Good field quality design can be obtained in such a challenging design:



Area where field error is $<10^{-4}$

40 mm is ½ of horizontal coil spacing

Harmonics optimized by RACE2dOPT

(Beam @ x=+/- 36 mm at far end)

(Max. radial beam size: 23 mm)

Geometric Field Harmonics:

	Ref(mm)	Ref(mm)
n	36	23
1	10000	10000
2	0.00	0.00
3	0.62	0.25
4	0.00	0.00
5	0.47	0.08
6	0.00	0.00
7	0.31	0.02
8	0.00	0.00
9	-2.11	-0.06
10	0.00	0.00
11	0.39	0.00
12	0.00	0.00
13	0.06	0.00
14	0.00	0.00
15	-0.05	0.00
16	0.00	0.00
17	0.01	0.00
18	0.00	0.00
19	0.00	0.00
20	0.00	0.00

Field errors should be minimized for actual beam trajectory & beam size.

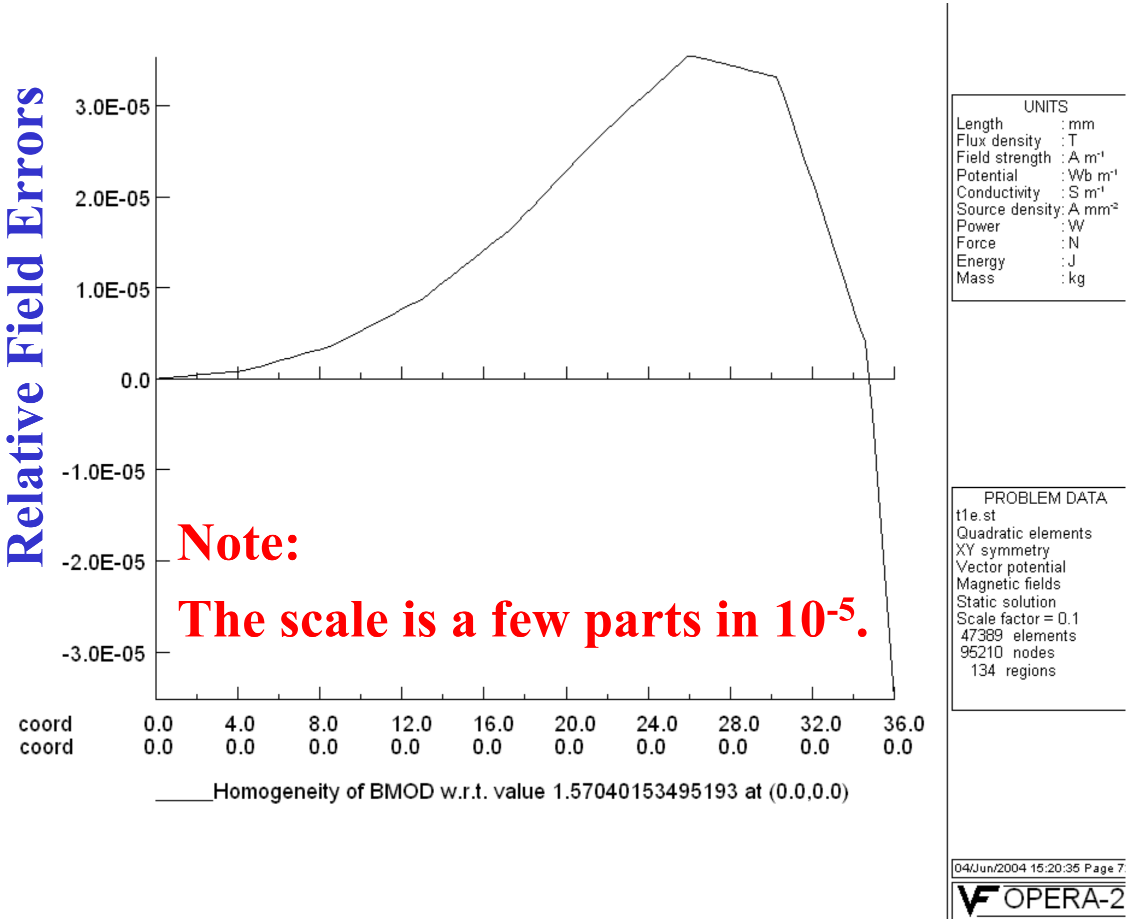
It was sort of done when the design concept was being optimized by hand.

Optimization programs are being modified to include various scenarios.
Waiting for feed back from Beam Physicists on how best to optimize.

However, the design as such looks good and should be adequate.

Field Uniformity in an Optimized 15 T Open Midplane Dipole Design

Proof that good field quality can be obtained in such a wide open midplane dipole design:



Note:

The scale is a few parts in 10^{-5}.

Homogeneity of BMOD w.r.t. value 1.57040153495193 at (0.0,0.0)

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
t1e.st
Quadratic elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Scale factor = 0.1
47389 elements
95210 nodes
134 regions

The maximum horizontal displacement of the beam at the far end of IP is +/- 36 mm.

The actual field errors in these magnets will now be determined by construction, persistent currents, etc.

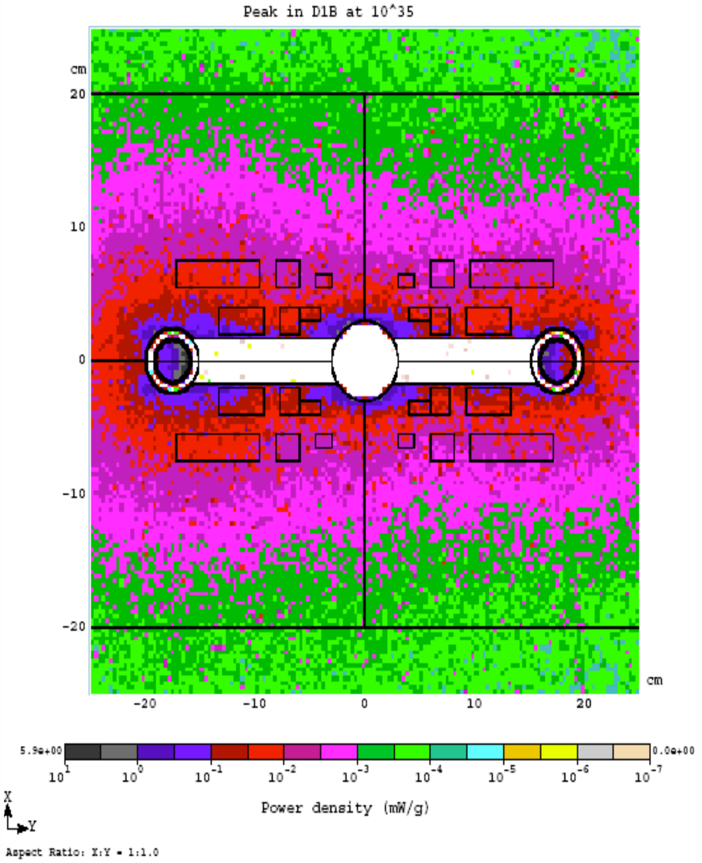
Energy Deposition Summary (Nikolai Mokhov 04/05)

SUMMARY

- The open midplane dipole is very attractive option for the LARP dipole-first IR at $\mathcal{L} = 10^{35}$. The design accommodates large vertical forces, has desired field quality of 10^{-4} along the beam path and is technology independent.
- After several iterations with the BNL group over last two years, we have arrived at the design that – being more compact than original designs – satisfies magnetic field, mechanical and energy deposition constraints.
- We propose to split the dipole in two pieces, 1.5-m D1A and 8.5-m D1B, with a 1.5-m long TAS2 absorber in between.
- With such a design, peak power density in SC coils is below the quench limit with a safety margin, heat load to D1 is drastically reduced, and other radiation issues are mitigated. This is a natural two-stage way for the dipole design and manufacturing.

Fermilab

N. Mokhov



Summary of Optimized Open Midplane Nb_3Sn Dipole Designs for LARP

	A	B	C	D	E	F
H(mm)	84	135	160	120	80	120
V(mm)	33	20	50	30	34	40
V/H	0.39	0.15	0.31	0.25	0.43	0.33
B_o(T)	13.6	13.6	13.6	13.6	15	13.6
B_{ss}(T)	15	15	15	14.5	16	15
J_c(A/mm^2)	2500	3000	3000	3000	3000	3000
Cu/Sc	1	1,1.8	0.85	0.85	0.85	1
A(cm^2)	161	198	215	148	151	125
R_i(mm)	135	400	400	320	300	300
R_o(mm)	470	800	1000	700	700	700
E(MJ/m)	2.2	4.8	9.2	5.2	4.1	4.8
F_x(MN/m)	9.6	10.1	12.3	9.5	10.4	9.6
F_y(MN/m)	-3.0	-6.8	-8.7	-7.0	-5.1	-5.4

For more information (publications + talks): http://www.bnl.gov/magnets/Staff/Gupta/

Open Midplane Designs With HTS (High Temperature Superconductors)

- HTS magnets could be designed to operate at very high fields (16 Tesla and above).

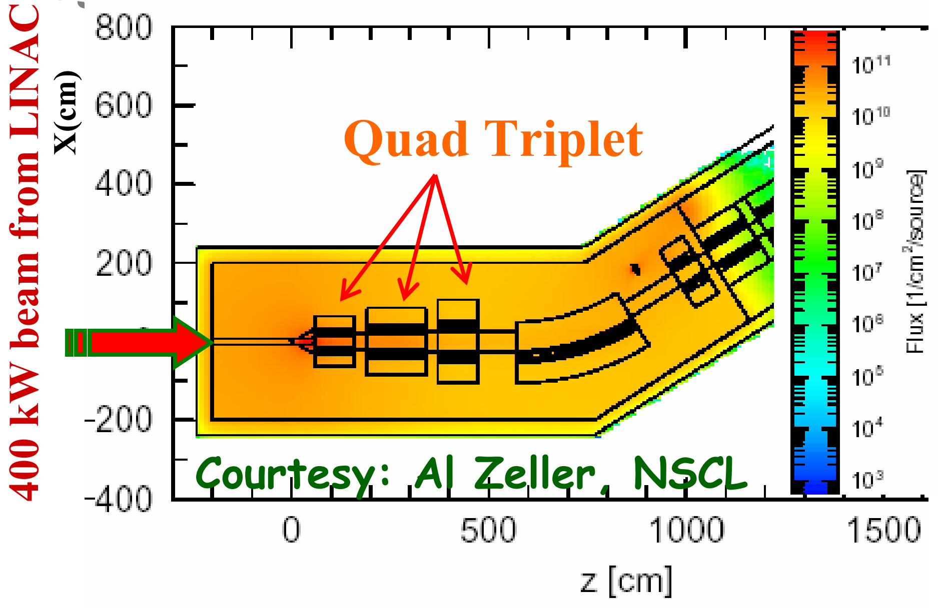
- HTS may be used in a hybrid design with Nb_3Sn coils.

- A significant advantage of HTS is that they could tolerate a large amount of energy deposition.

RIA HTS QUAD

Experience with construction and test of HTS magnet

HTS Quad for RIA's Fragment Separator



Courtesy: Al Zeller, NSCL

- ➢ Up to 400 kW of beam power hits the target producing a variety of isotopes.
- ➢ Fragment separator then select one isotope to transport out; but must deal with a large number of unwanted one.
- ➢ Quad triplet in the fragment separator is exposed to very high level of radiation and heat loads.
- ➢ ~15 kW of the above is deposited in the first quadrupole itself.

Quads in the fragment separator region will live in an environment that was never experienced before by magnets in any accelerator or beam-line.

Basically, RIA needs "Radiation resistant" **magnets that can withstand these extremely large radiation and heat loads and can also operate economically.**

Advantages of using HTS in RIA/FRIB

- Removing these large heat loads (~400 kW in target, ~15 kW in first quad) at ~30 K instead of ~4K is over an order of magnitude more efficient.

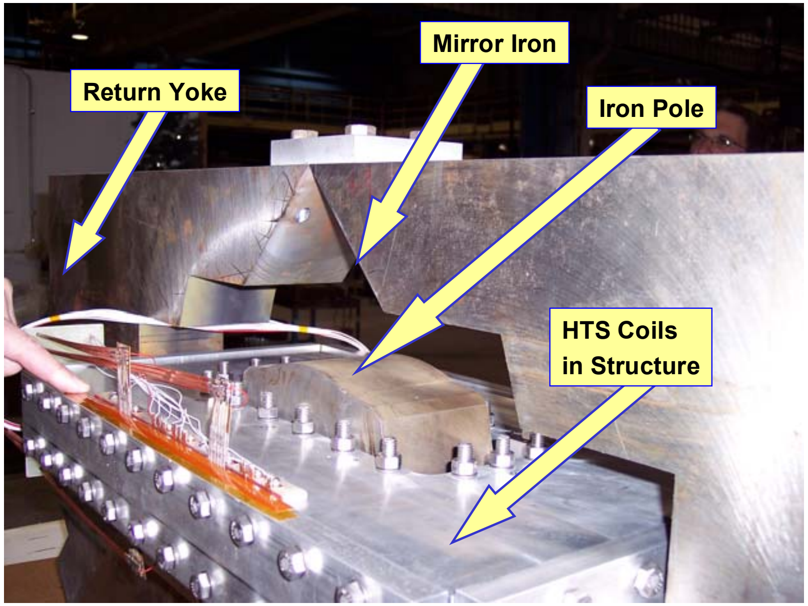
- HTS can tolerate a large local increase in temperature in superconducting coils caused by the non-uniform energy deposition.

- Moreover, in HTS magnets, the temperature need not be controlled precisely. It can be relaxed by over an order of magnitude as compared to that for the present low temperature superconducting magnets (few kelvin rather than a few tenth of a kelvin). This simplifies the design and reduces cost of the cryogenic system.

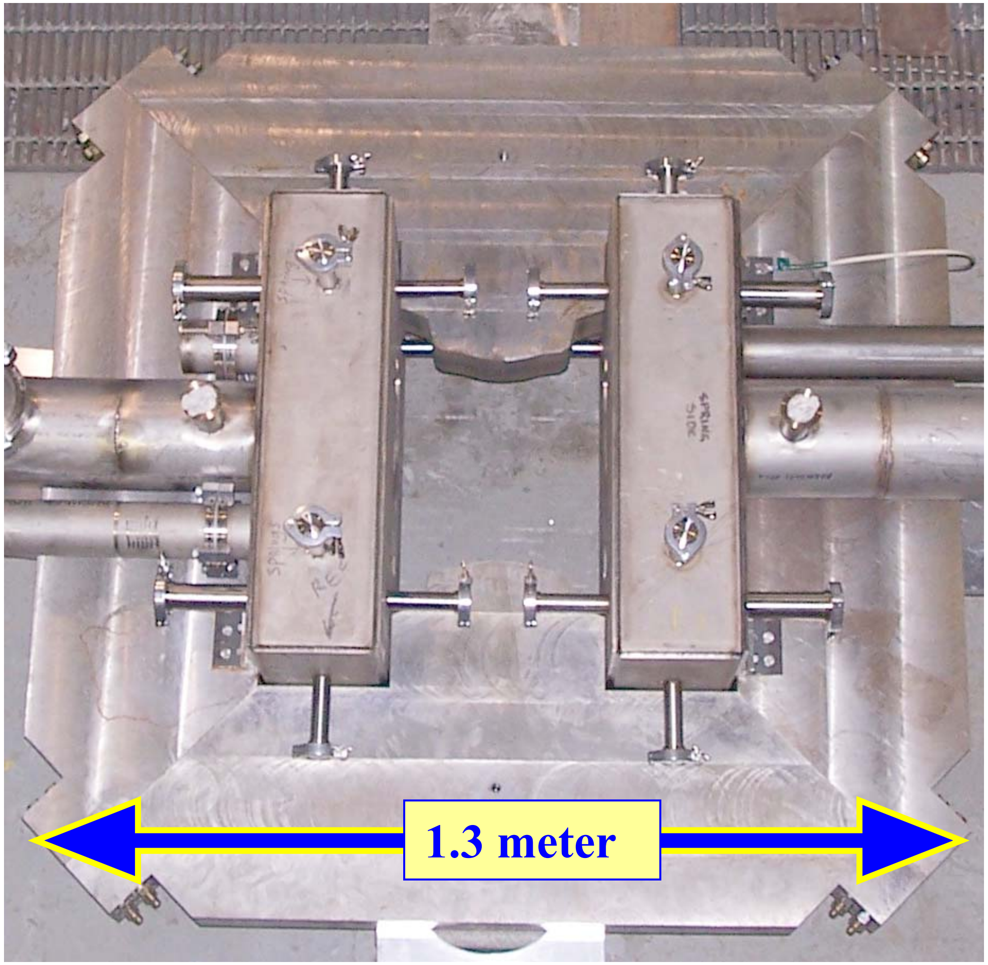
- Therefore, HTS would facilitate a magnet system for fragment separator that will be robust and economical to operate.

RIA HTS Model Quadrupoles

Cold iron mirror model



Warm iron mirror



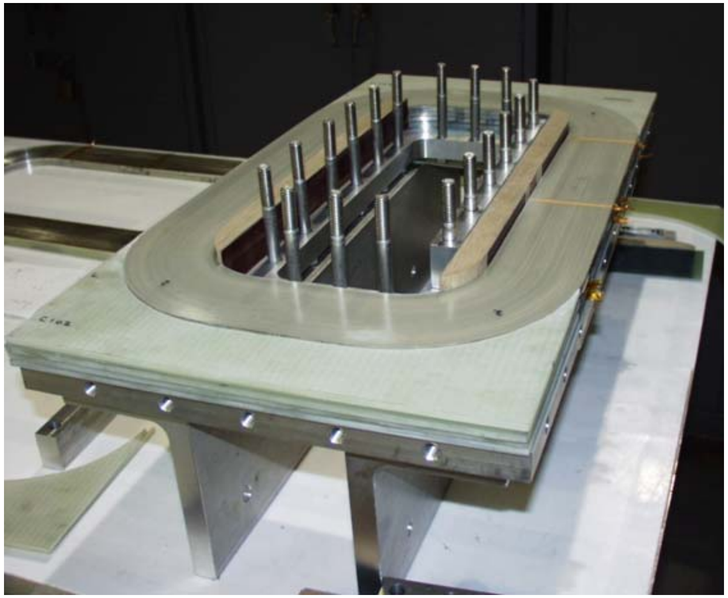
Warm iron R&D quadrupole with twenty four coils in two cryostats

Bi2223 Coils in RIA Quads

RIA coils are co-wound with HTS tape and S.S. tape. In RIA, S.S. tape is used as radiation resistant insulator.

In high field solenoid S.S. tape is used as high strength material (e.g. Muons, Inc./Palmer's proposal and a coil earlier wound by Sampson under an LDRD).

RIA quad is made with 24 coils with each using ~200 meter of commercially available HTS wire (tape).

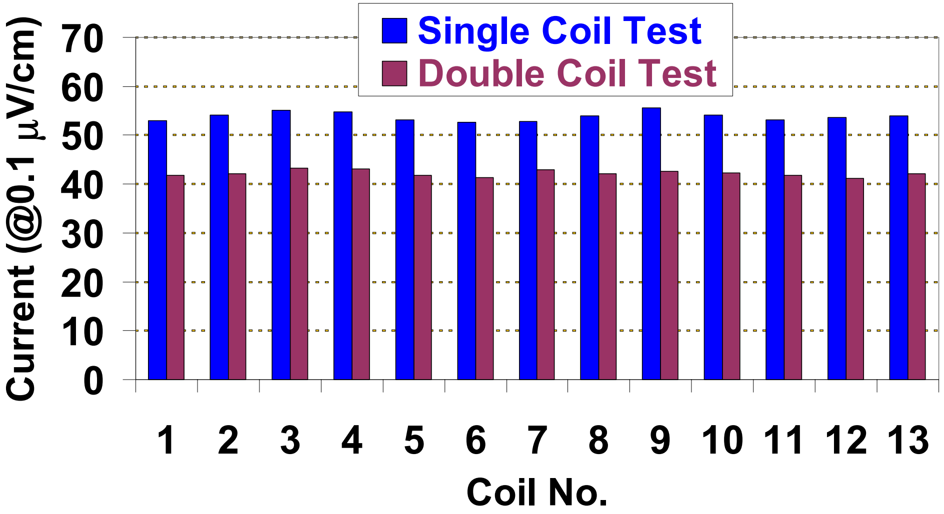


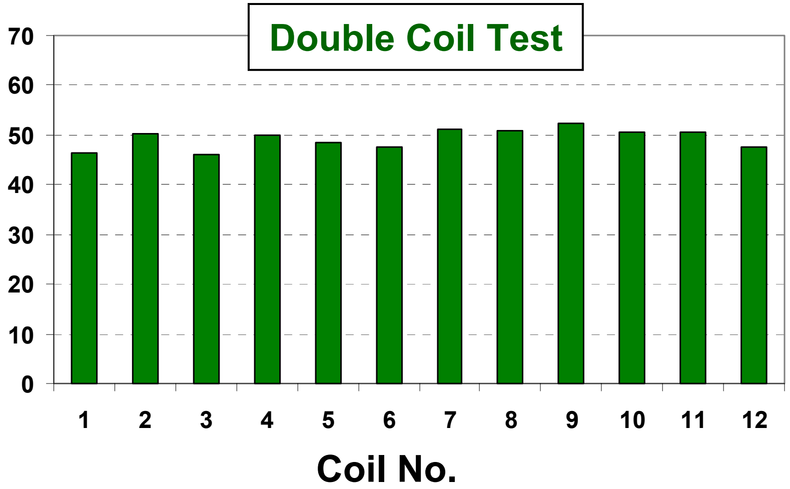
This gives a good opportunity to examine the reproducibility and reliability in performance of number of coils (number grows every year).

LN$_2$ (77 K) Test of 25 BSCCO 2223 Coils

13 Coils made earlier tape
(Nominal 175 turns with 220 meters)

12 Coils made with newer tape
(150 turns with 180 meters)



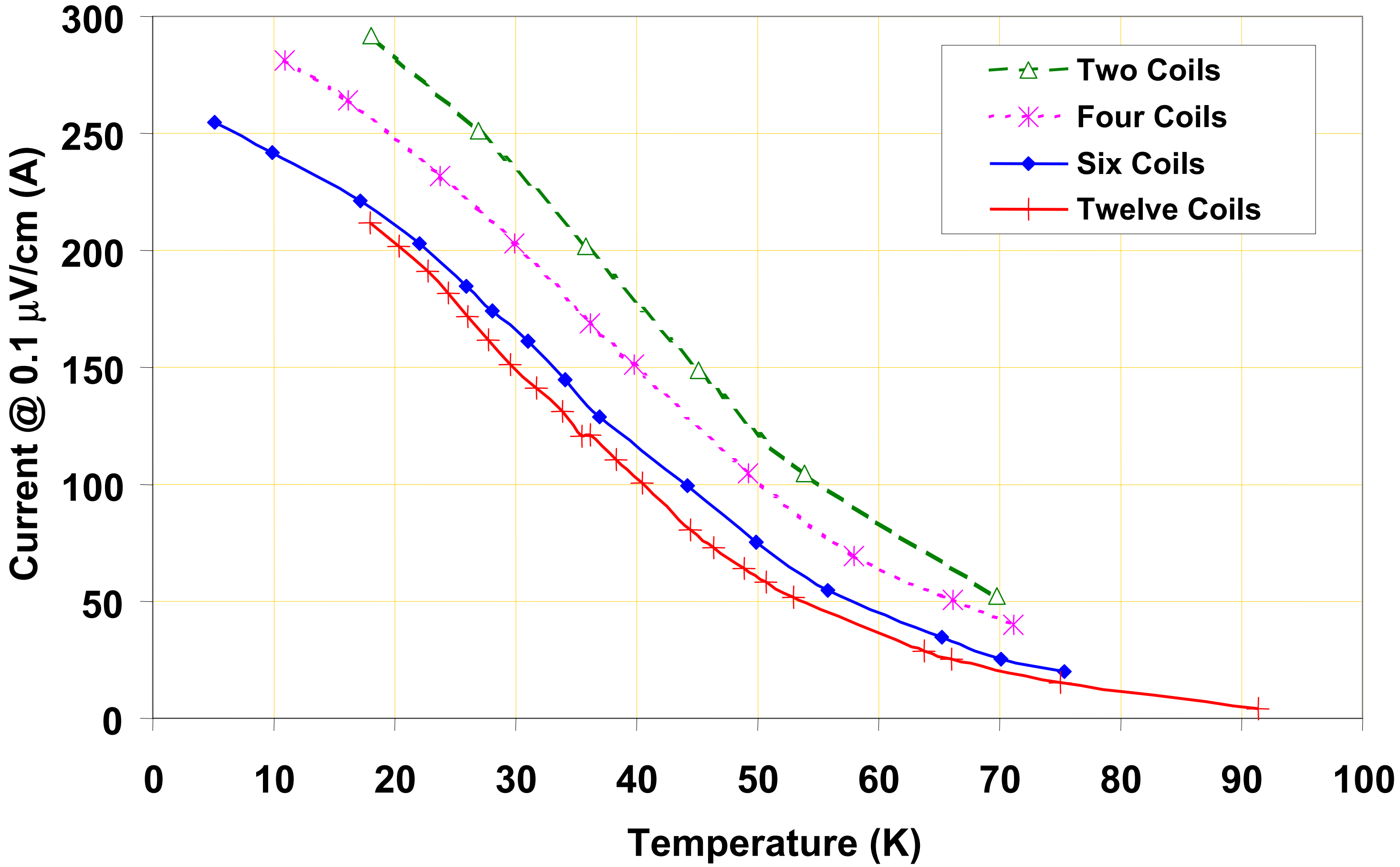


Coil performance generally tracked the conductor performance very well.

Note: A uniformity in performance of a large number of HTS coils made with commercially available superconductor (ASC).

It shows that the HTS technology is now maturing !

RIA HTS Mirror Model Test Results
(operation over a large temperature range)

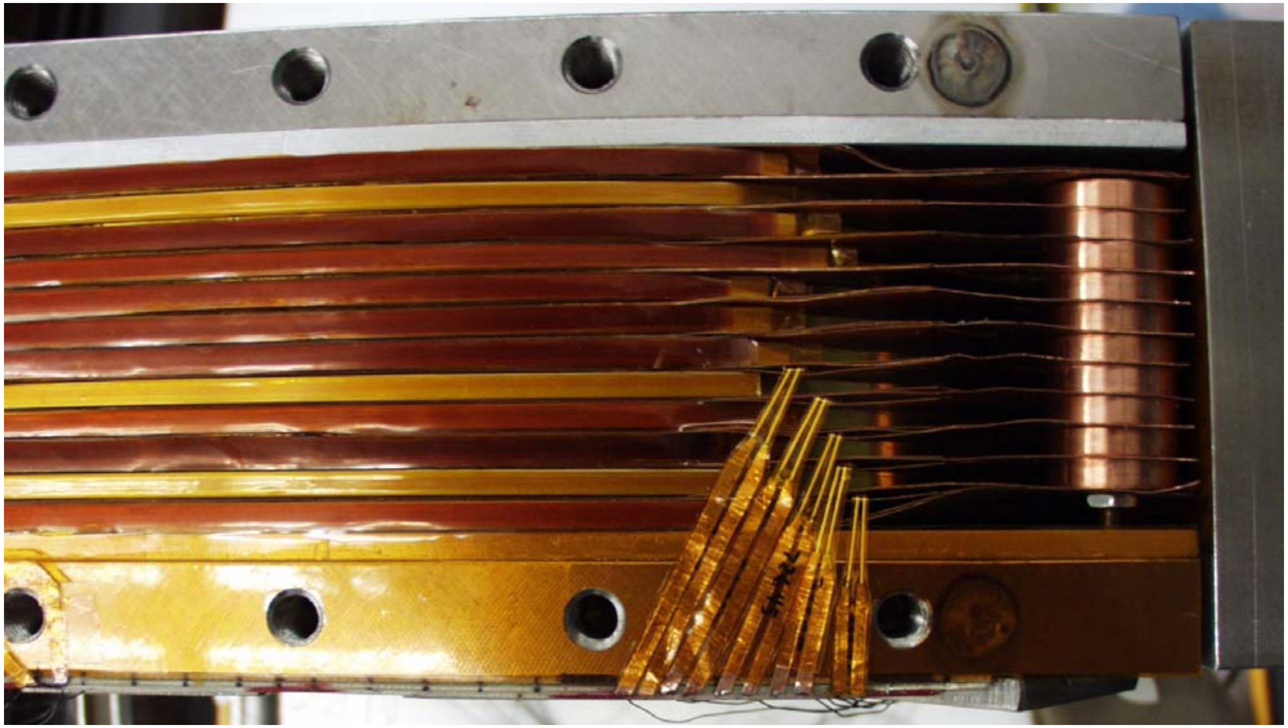


More coils create more field and hence would have lower current carrying capacity

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 first appears on the coil that is closest to the pole tip. Magnetic field is approximately three times as great for six coils as it is for two coils.

Energy Deposition and Cryogenic Cooling Experiments (Direct Vs. Conduction)

Stainless steel tape heaters for energy deposition experiments

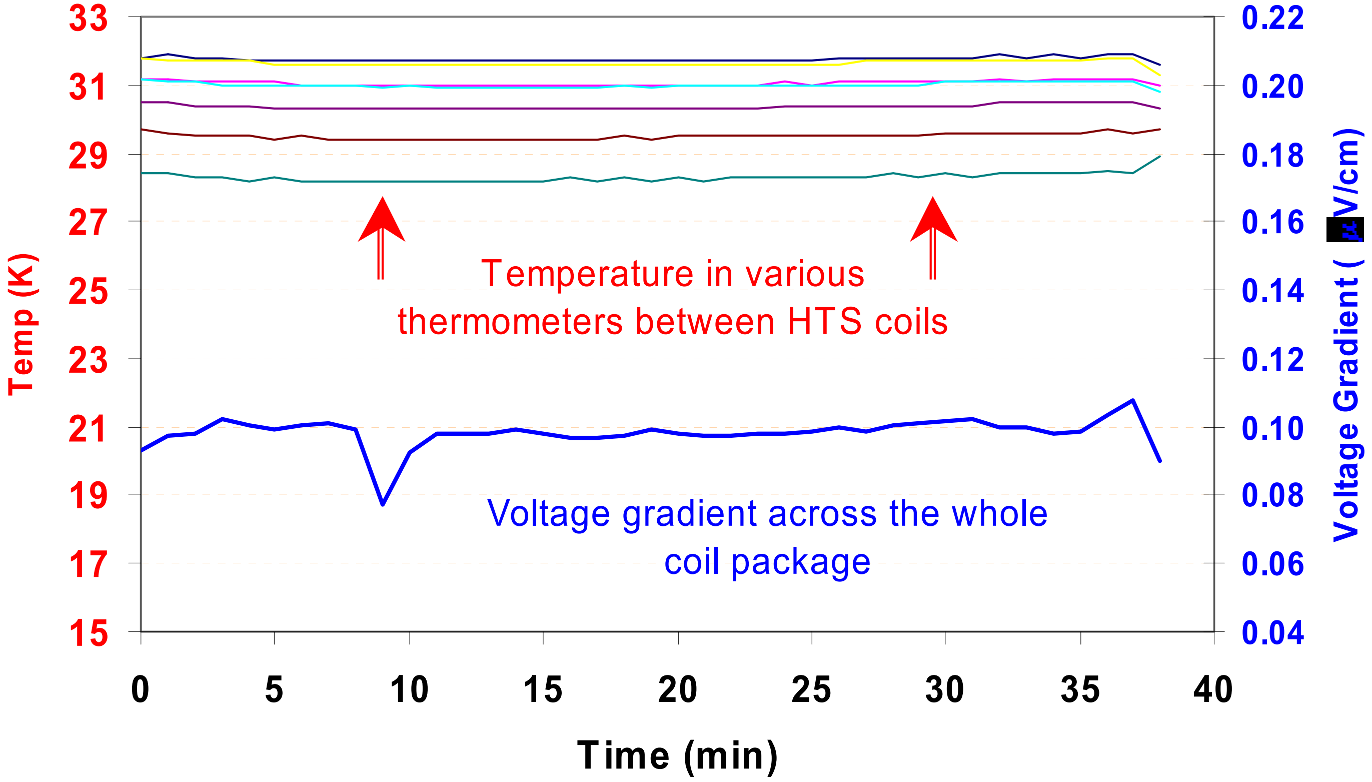


Copper sheets between HTS coils with copper rods and copper washers for conduction cooling

- In conduction cooling mode, helium flows through top and bottom plates only.
- In direct cooling mode, helium goes in all places between the top and bottom plates and comes in direct contact with coils.

Large Energy Deposition Experiment

Goal was to demonstrate that the magnet can operate in a stable fashion at the expected heat loads ($5 mW/cm^3$ or $5 kW/m^3$ or 25 W on 12 short HTS coils) at the design temperature (~30 K) with some margin on current (@140 A, design current is 125 A).



Stable operation for ~40 minutes

- We use 0.1 μV/cm as the definition of I_c.
- Temperature differences may be partly real and partly calibration mis-match.
- As such HTS can tolerate such temp variations with small margin.

Voltage spikes are related to the noise

Current and Future Program

The goal is to move to 2nd generation wire because:

- ➢ 2G is expected to allow operation at 50 K (or above), which would provide even more saving in operation.
- ➢ 2G is expected to be less expensive.

Near Future (04/07-03/08)

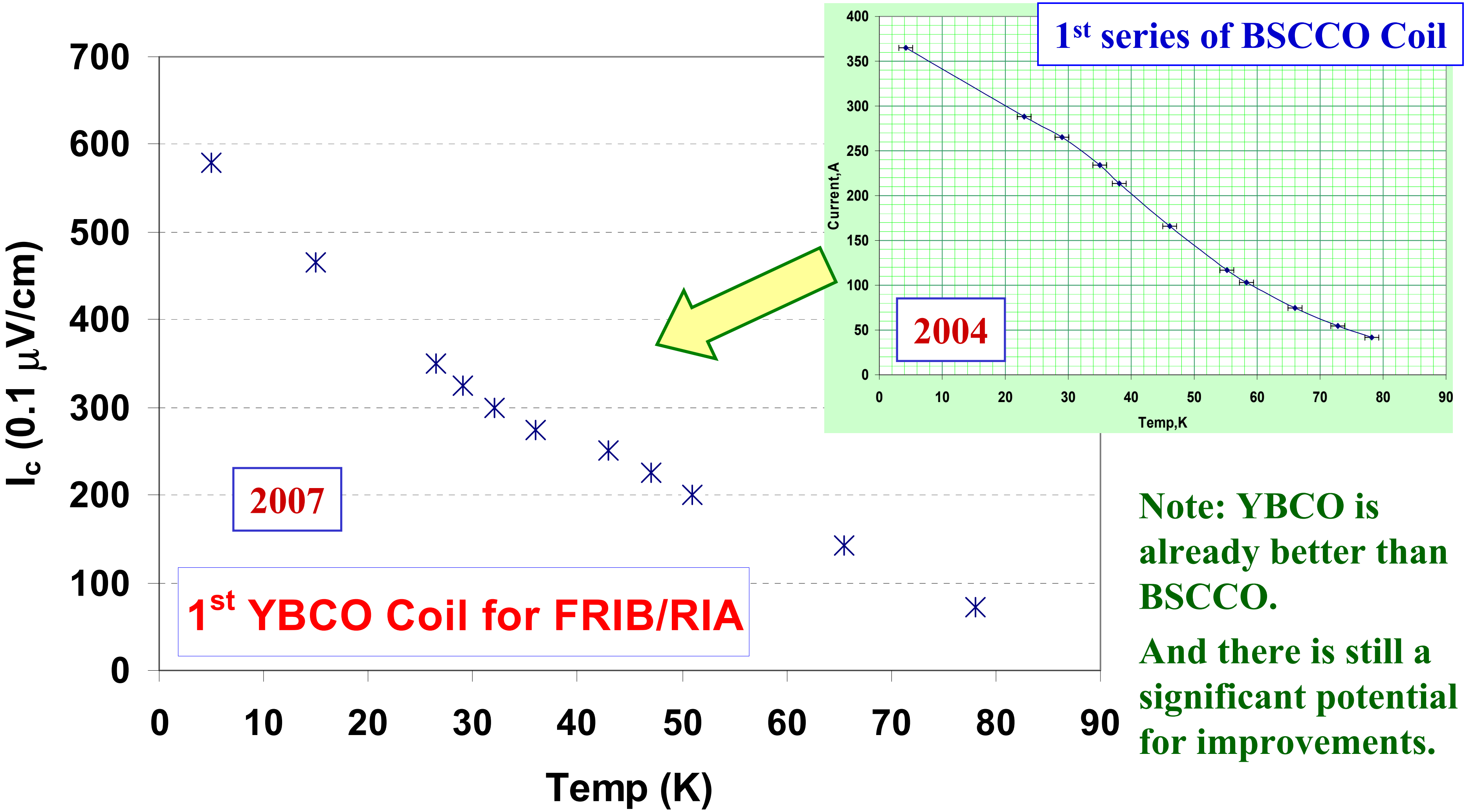
- Make 3 coils each with ~100 m of 2nd generation wire
  - o Two coils with wire from ASC wire and one from SuperPower
- Continue experimental studies on radiation damage on YBCO and BSCCO to determine if one is significantly better than the other.

Intermediate Future:

- Develop design, build and test full length quad based on whichever conductor is better
- Study other critical magnets

Coil made with 2G

I_c Vs. T Over a Large Range of Temperature in RIA Coils Made with YBCO and Bi2223



1st series of BSCCO Coil

2004

2007

1^{st} YBCO Coil for FRIB/RIA

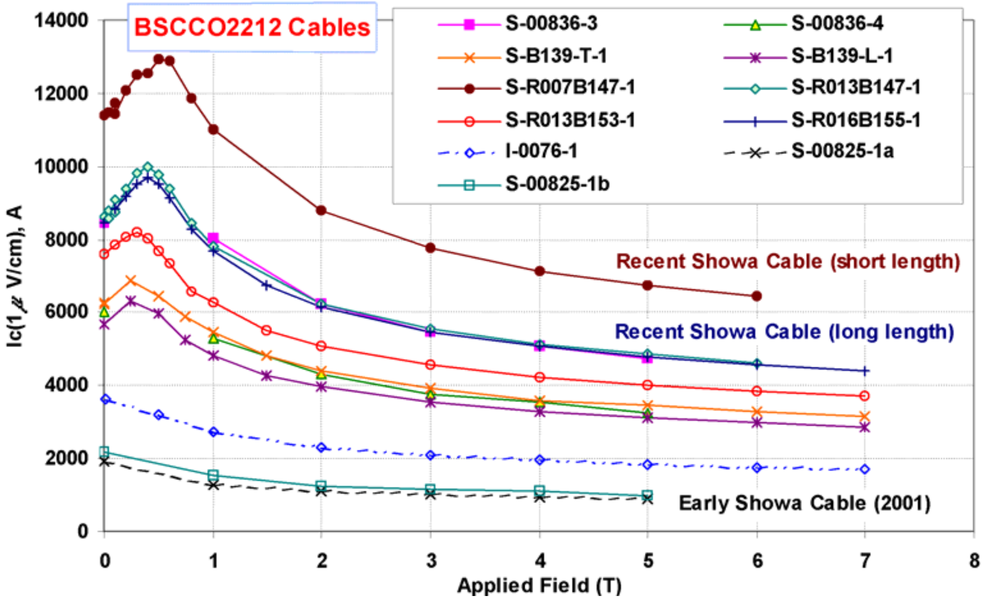
Note: YBCO is already better than BSCCO.

And there is still a significant potential for improvements.

BSSCO and YBCO Tapes from ASC

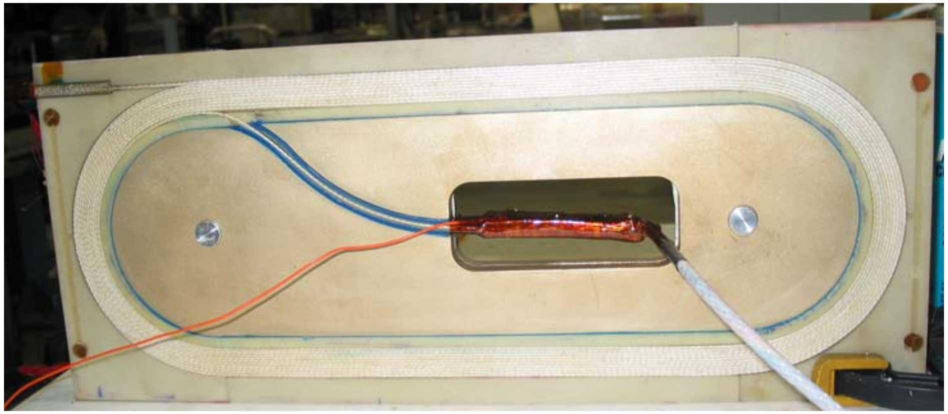
A Few HTS Magnet Topics Directly Related to Muon Collider and/or Neutrino Factory

HTS for High Field Magnets with Rutherford Cable

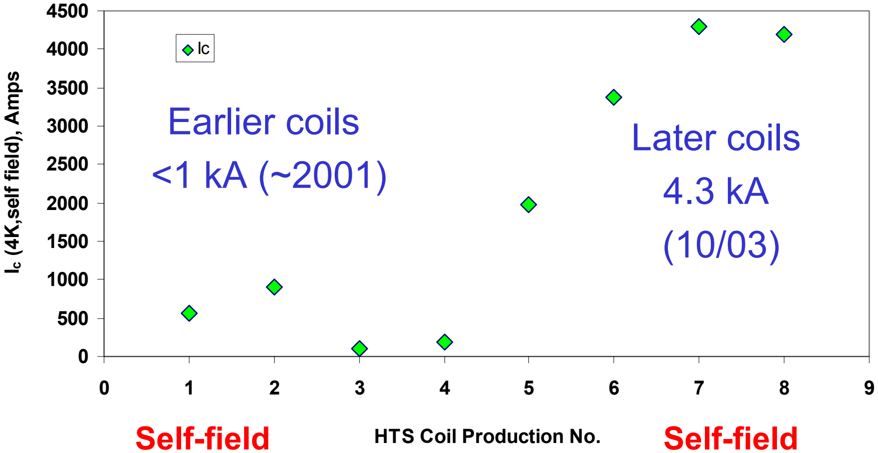


Cable made at LBL, reacted at Showa, tested at BNL

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



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

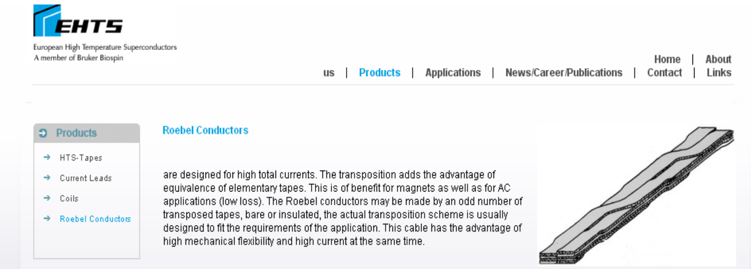


Self-field
<0.05 T

Self-field
~ 1.85 T

ROEBEL High Current Cable

- **Roebel cable allows higher operating current and coupling between a number of wires (somewhat analogous to Rutherford cable with round wires)**
- **Roebel cable may make YBCO tape much more attractive for accelerator and other type of magnets**



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- HTS-Tapes
- Current Leads
- Coils
- Roebel Conductors

Downloads

Roebel Conductors

are designed for high total currents. The transposition adds the advantage of equivalence of elementary tapes. This is of benefit for magnets as well as for AC applications (low loss). The Roebel conductors may be made by an odd number of transposed tapes, bare or insulated, the actual transposition scheme is usually designed to fit the requirements of the application. This cable has the advantage of high mechanical flexibility and high current at the same time.

SIEMENS

CORPORATE TECHNOLOGY

Technical HTS-Conductors & HTS-Windings
High Current Assemble

Roebel bar conductor
- modular concept for high-current conductors
- transposed strands for low ac-loss
- insulated strands - thin coated plastics
- flexibility for coil winding
- long-lengths production - semiautomatic
- developed for HTS transformers
- presently not applicable for YBCO

Laboratory Cabling Facility LARA

Flexible conductor

13-strand conductor, length=160m

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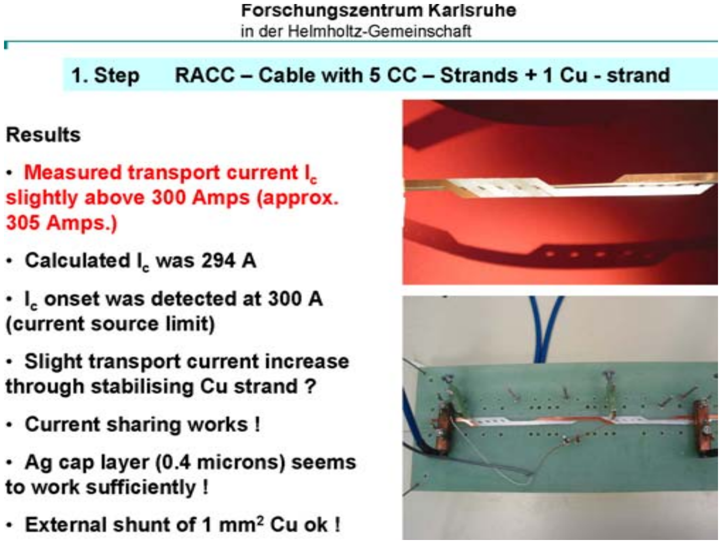
Power & Sensor Systems
Power Components & Superconductivity



Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

1. Step RACC – Cable with 5 CC – Strands + 1 Cu - strand

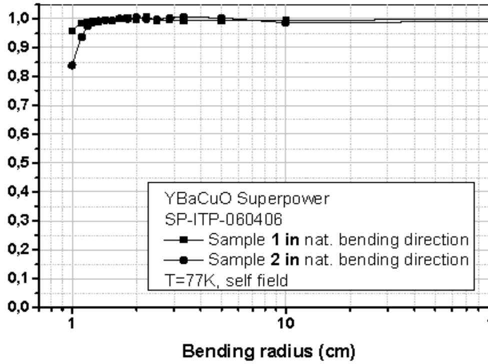
Results

- Measured transport current I_c slightly above 300 Amps (approx. 305 Amps.)
- Calculated I_c was 294 A
- I_c onset was detected at 300 A (current source limit)
- Slight transport current increase through stabilising Cu strand ?
- Current sharing works !
- Ag cap layer (0.4 microns) seems to work sufficiently !
- External shunt of 1 mm² Cu ok !

Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

Institut für Technische Physik, Superconducting materials, Wilfried Goldacker 8-200

2. Step Full 16 strand DyBCO-RACC sample (35 cm length)



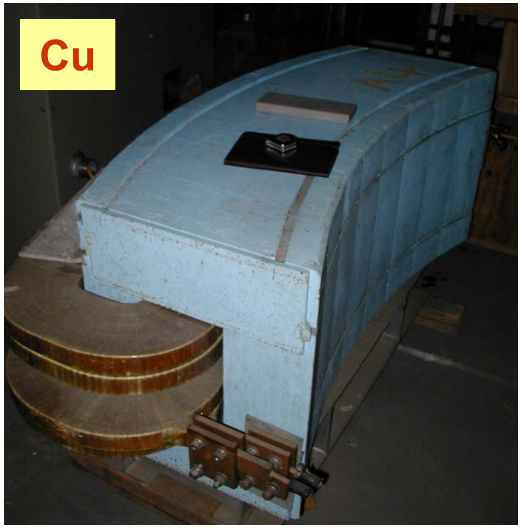
Medium Field HTS Dipole for Super Neutrino Facility
A Case Study for Cost of Ownership (capital+operation)
Comparison between Copper and HTS Magnet

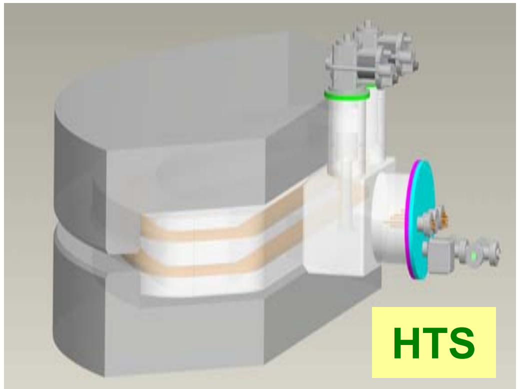
Design Parameters:

- 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.



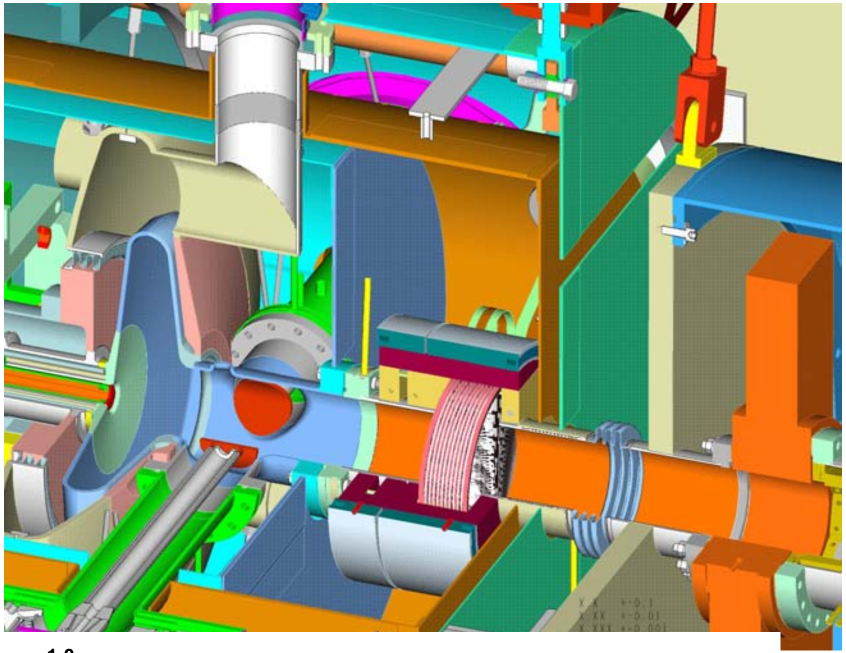


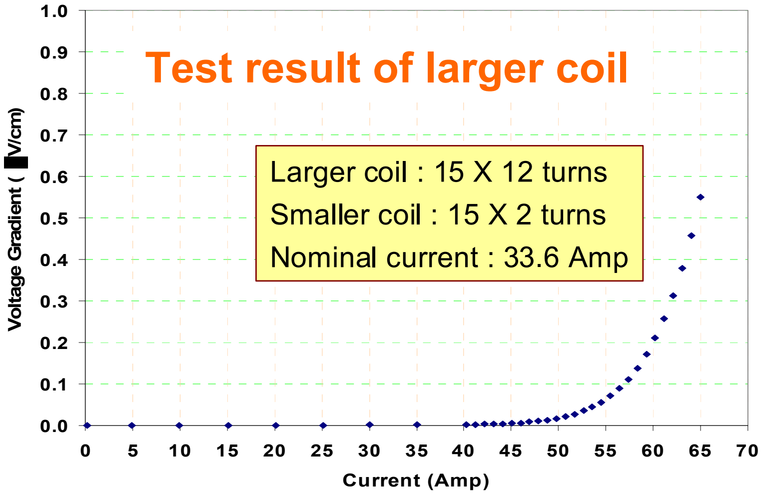
Desired cost of support structure and cryostat in this HTS magnet: < 20 K$

HTS Magnets:

- Develop designs to reduce cost (goal : ~150k$/magnet for equivalent integral field)
- Cost of HTS: ~30 k$ (~1/5 of total magnet cost per present rate)
- 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? Is LN2 possible?)
- 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

HTS Solenoid for Electron Cooling





Test result of larger coil

Larger coil : 15 X 12 turns
Smaller coil : 15 X 2 turns
Nominal current : 33.6 Amp

Combined Function Magnet Design

Dipole and skew quadrupole optics for compact ring (Parker)

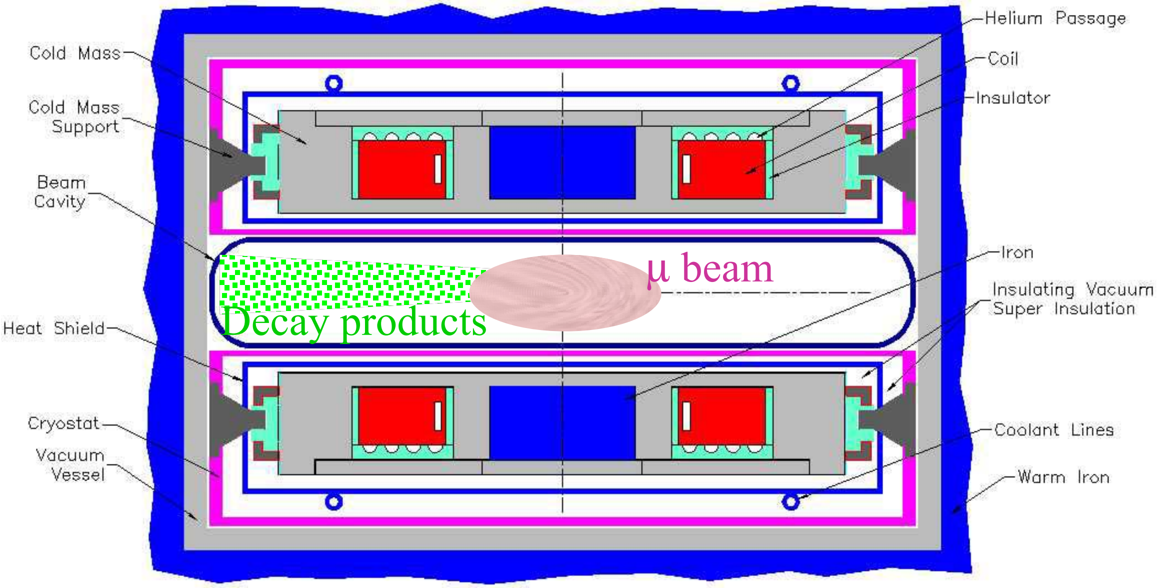
Magnet Design for ν Factory

Design Principles and Requirements:

Decay products clear superconducting coils

Compact ring to minimize the environmental impact (the machine is tilted)

⇨ Need high field magnets and efficient machine design

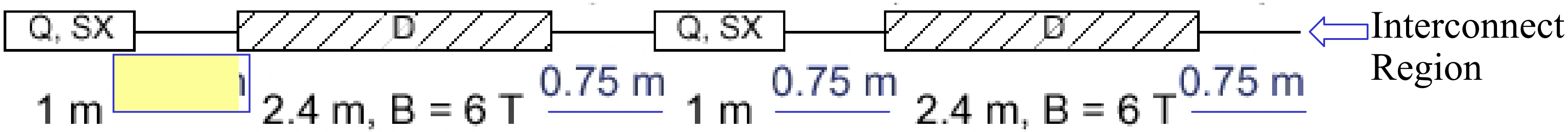


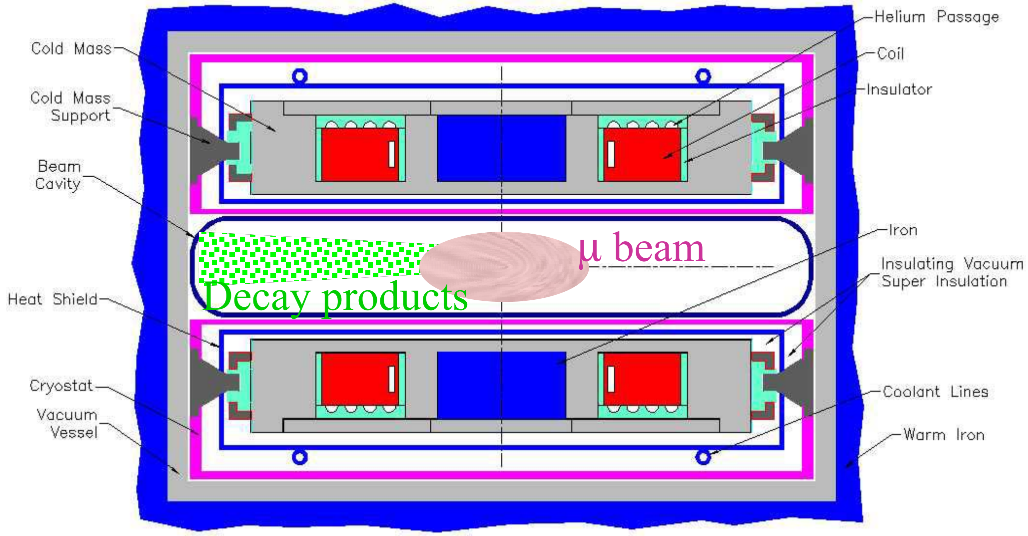
Storage ring magnet design

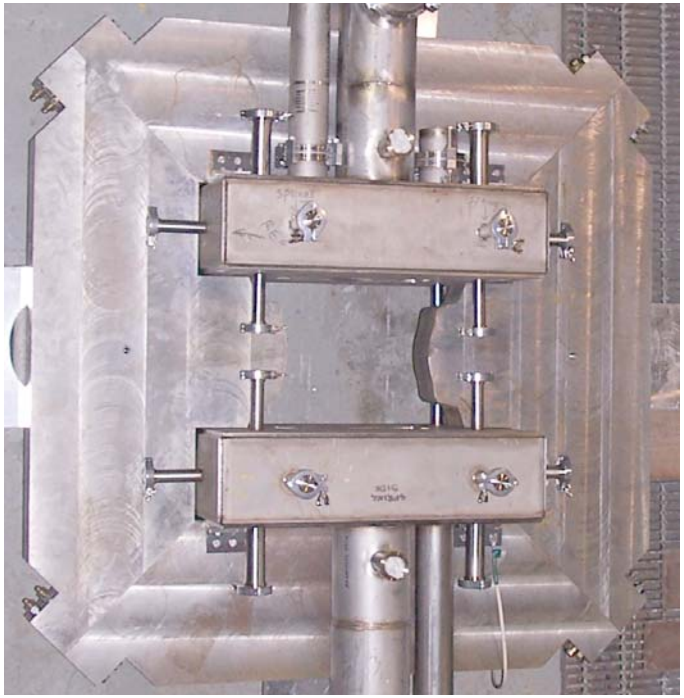
(simple racetrack coils with open midplane)

Compact Ring with Combined Function Skew Quadrupole Lattice

- Skew quadrupole needs NO conductor at midplane (B. Parker)
- In study 1 (50 GeV), ~1/3 space was taken by inter-connect regions



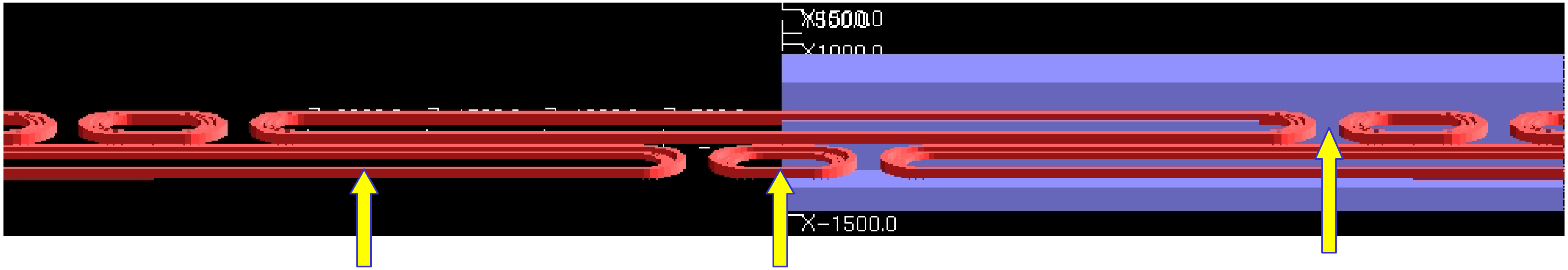




To first order, dipole becomes a skew quad, if the relative polarity of coils is changed.

Note: A 90 degree rotation in RIA Quad brings a close resemblance

Coil Layout for Obtaining A Variety of Magnet Configurations



Normal Coils
Dipole

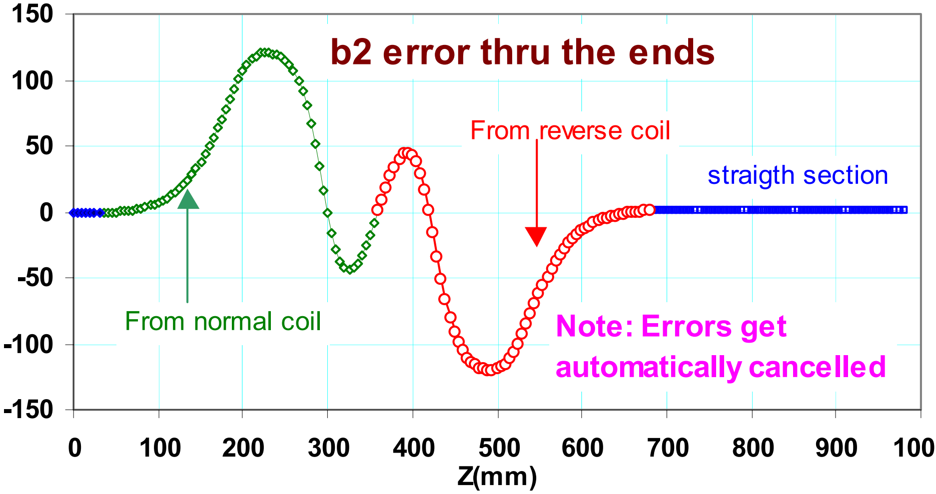
Reverse Coils
Skew Quad

One Coil
1/2 & 1/2

- ➢**New magnet system design makes a productive use of all space !**

Shorter cells ⟹ smaller aperture, improved beam dynamics (Parker)

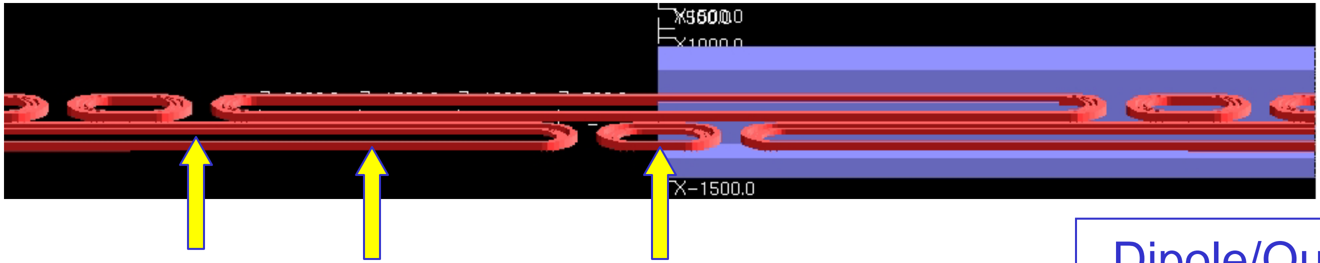
Reverse coils also cancel harmonic errors in the ends



A Possible Magnet Test Setup

Structure to test magnet performance in various configuration:

Magnet system layout in the proposed ν factory storage ring:

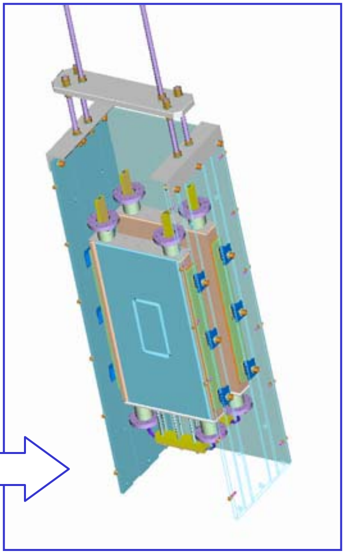


One Coil
D/2 & Q/2

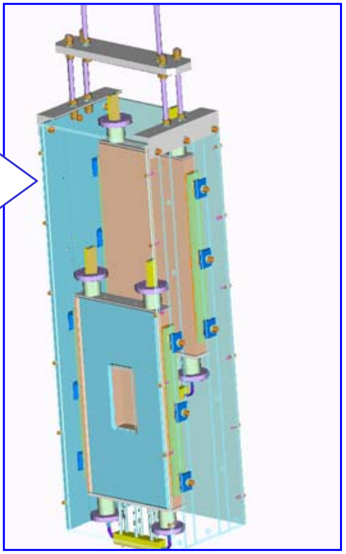
Normal Coils
Dipole (D)

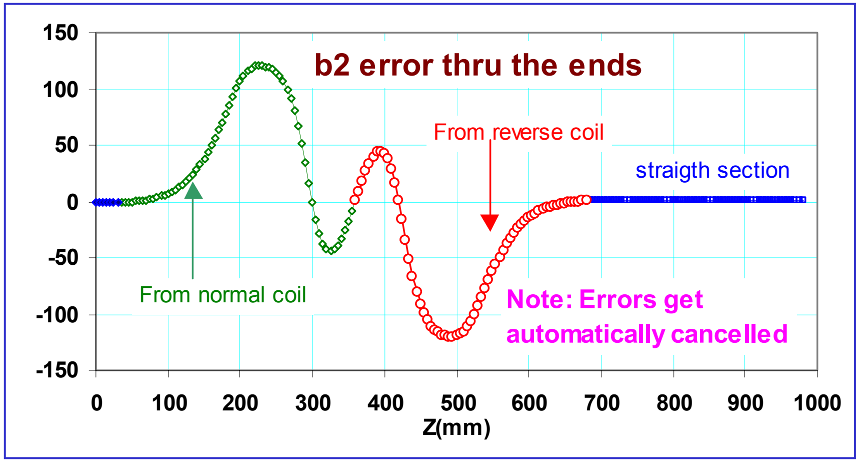
Reverse Coils
Skew Quad (Q)

Dipole/Quad test setup
(switch relative current direction)



Staggered coil setup





Work carried out under a BNL LDRD

Summary

- The development of open midplane design is important to $\mu^+\mu^-$ colliders, as large magnitude of decay particles at the midplane may limit the performance of superconducting coils and increase the operating cost of the machine.
- The design concept has been significantly developed over last few years. Now, we can have a truly "Open Midplane" design with a way to deal with Lorentz forces and have a good field quality, as well.
- HTS is beneficial in a variety of magnets in $\mu^+\mu^-$ colliders. HTS can generate very high fields and can tolerate and economically remove large heat loads.
- It has been shown that HTS magnets can be designed, built and operated in presence of a large heat load environment.
- Second generation HTS makes HTS magnets even more attractive.
- Combined function magnet design with skew quadrupole offers an interesting possibility. Such magnets and lattice can be designed.

Of course, all of above still require a significant amount of work before magnets based on these designs could be inducted in an operating machine.