Open Midplane HTS Dipole SBIR for Muon Collider

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Open Midplane Designs With HTS (High Temperature Superconductors)

- HTS magnets could be designed to operate at very high fields.

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

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

What could be in the SBIR ?

Phase I

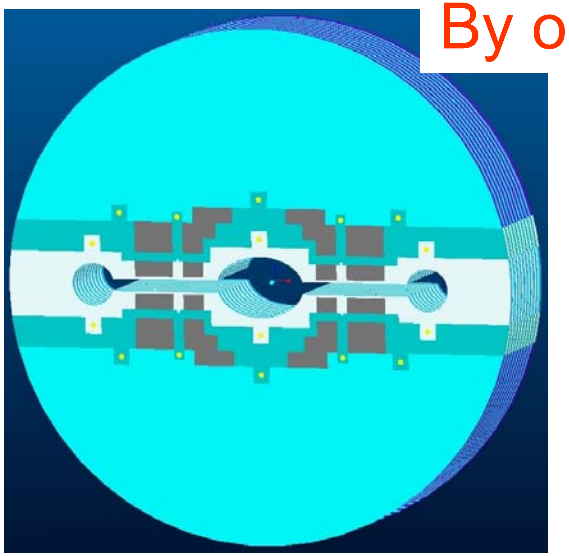
- Machine studies and target field parameters
- Feasibility of Open Midplane Dipole design with HTS
- Examine design options – hybrid, all HTS, operating temperature, etc.
- Preliminary energy deposition calculations
- Examination of support technology (such as Roebel cable)

Phase II

- Design, build and test hardware – R&D magnet and coils that demonstrates and/or addresses key technical issues
- Detailed energy deposition studies
- Machine design that is based on such design
- Other machine issues related to this proposal

A True Open Midplane Design

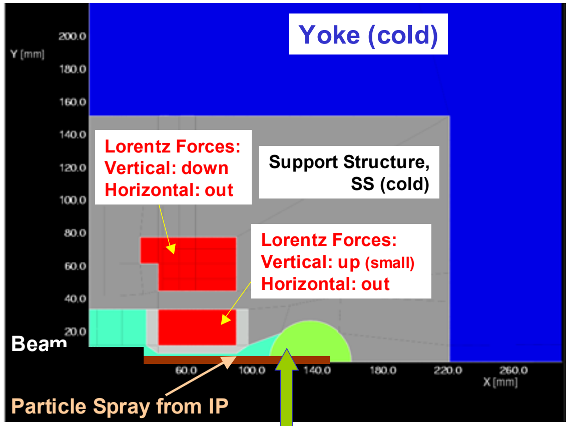
By open midplane, we mean truly open midplane:



- 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.

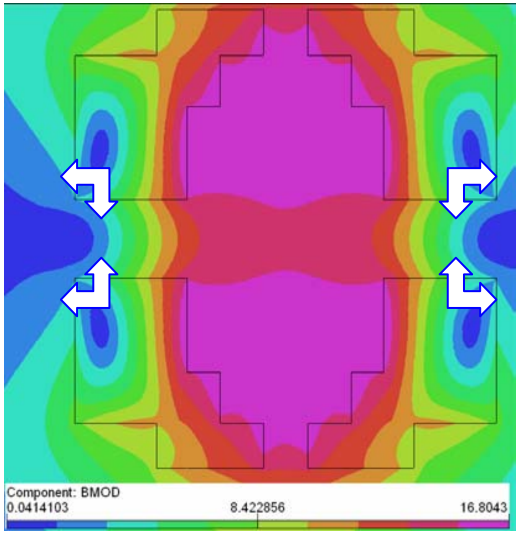
- In earlier "open midplane designs", although there was "no conductor" at the midplane, but there was some "other structure" between the upper and lower halves of the coil. Secondary showers from that other structure deposited a large amount of energy on the superconducting (s.c.) coils.

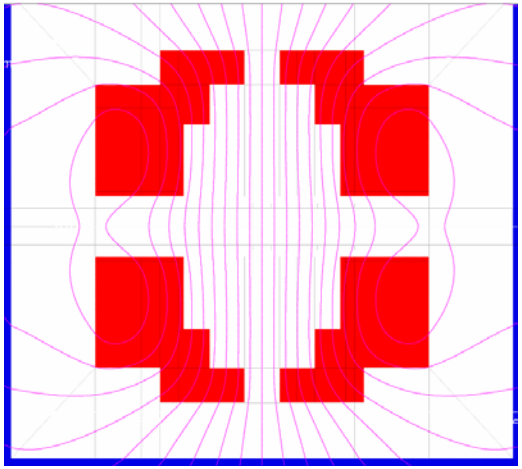
- Earlier designs, therefore, did not work so well in protecting s.c. coils against energy deposition.



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 and Previous Work at BNL





#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.

- **These challenges have been addressed (to some extent successfully) thru design and simulation work in :**
  - **(a) 4 T (NbTi) and 8 T (Nb3Sn) dipole for neutrino factory thru BNL LDRD funding and**
  - **(b) 10-13 T Nb_3Sn dipole thru LARP funding.**

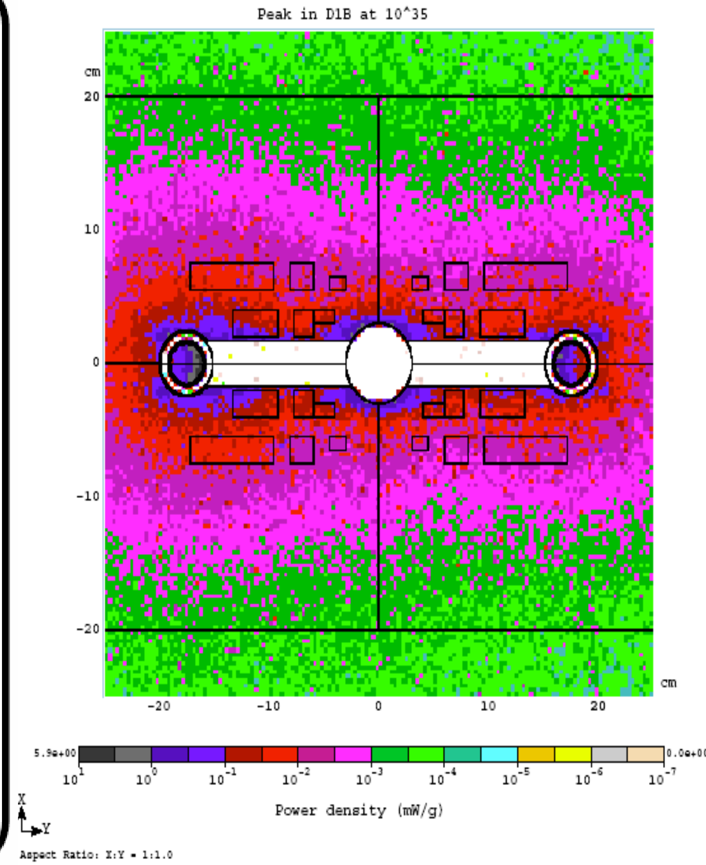
Energy Deposition Calculations in LARP

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

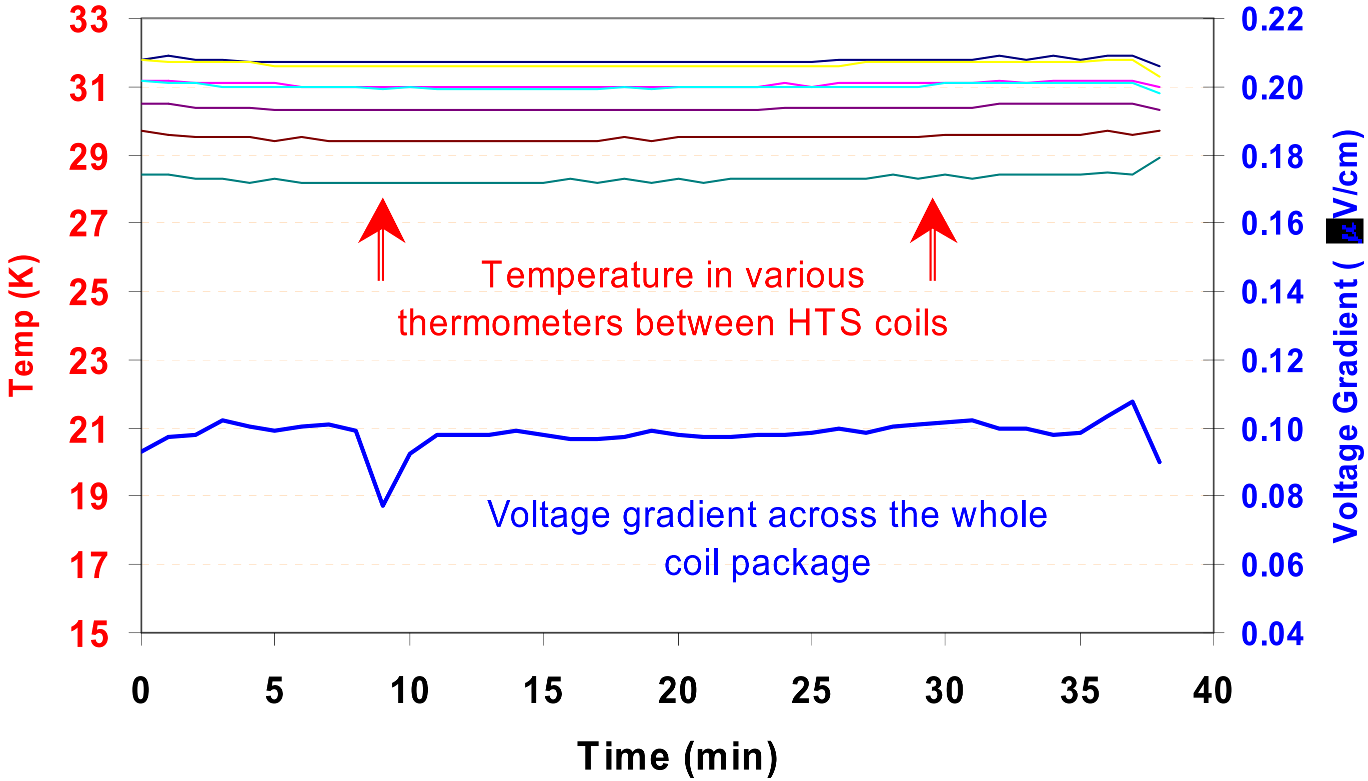
N. Mokhov



(Nikolai Mokhov 04/05)

Large Energy Deposition Experiment

Goal was to demonstrate that the magnet can operate in a stable fashion at the expected heat loads (5mW/cm^3 or 5kW/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).



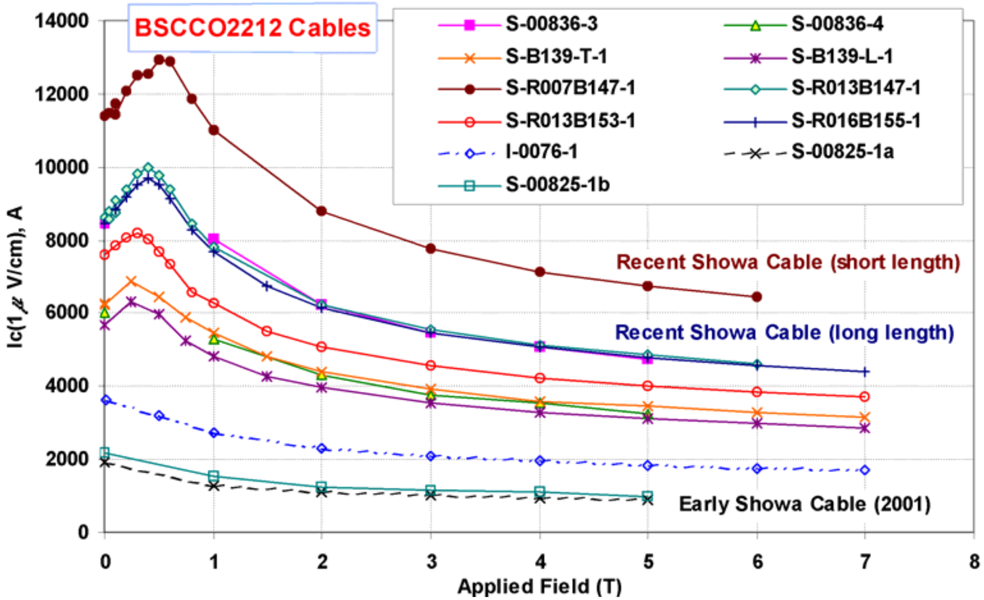
Stable operation for ~40 minutes

- 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

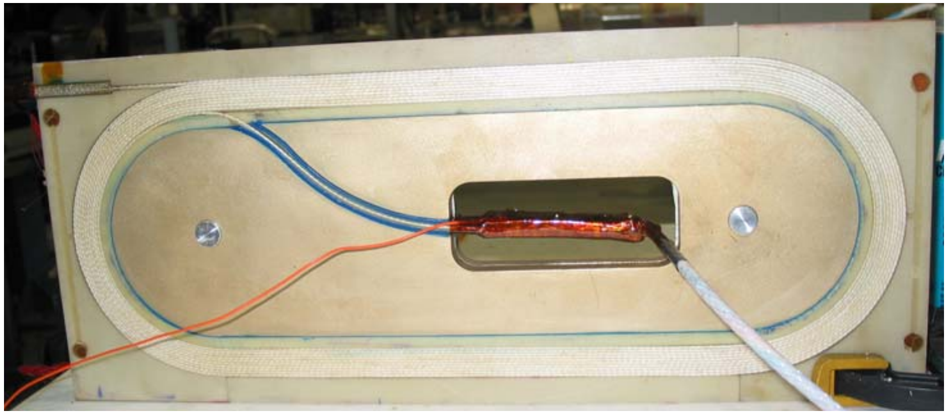
Cables (high current) for HTS Magnets

HTS for High Field Magnets with Bi2212 (1G) Rutherford Cable

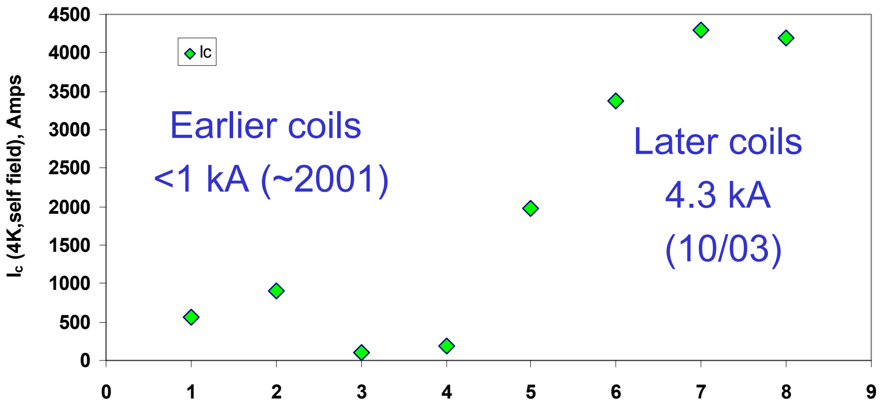


Cable made at LBL, reacted at Showa, tested at BNL

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



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

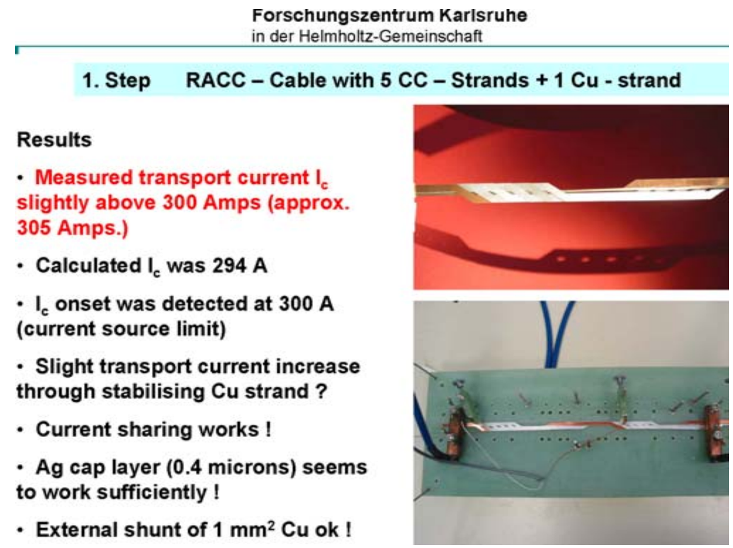


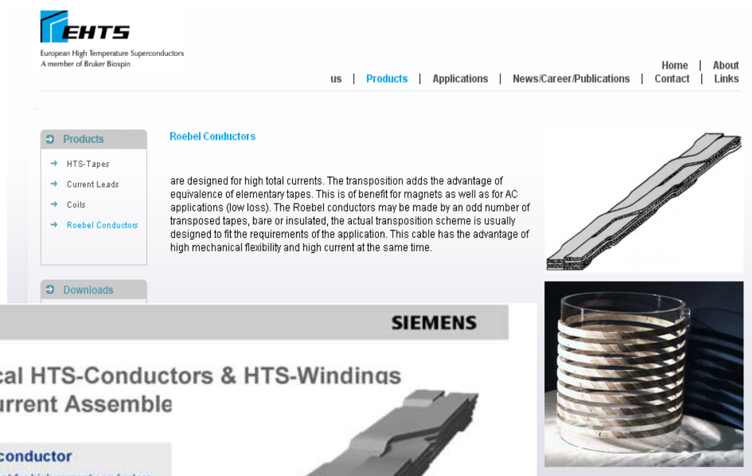
Self-field <0.05 T

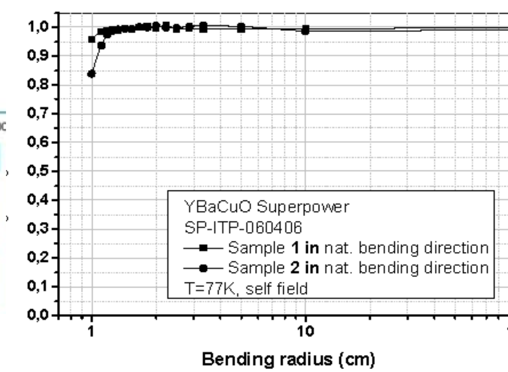
Self-field ~ 1.85 T

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







BNL background on Open Midplane Dipole (in addition to HTS)

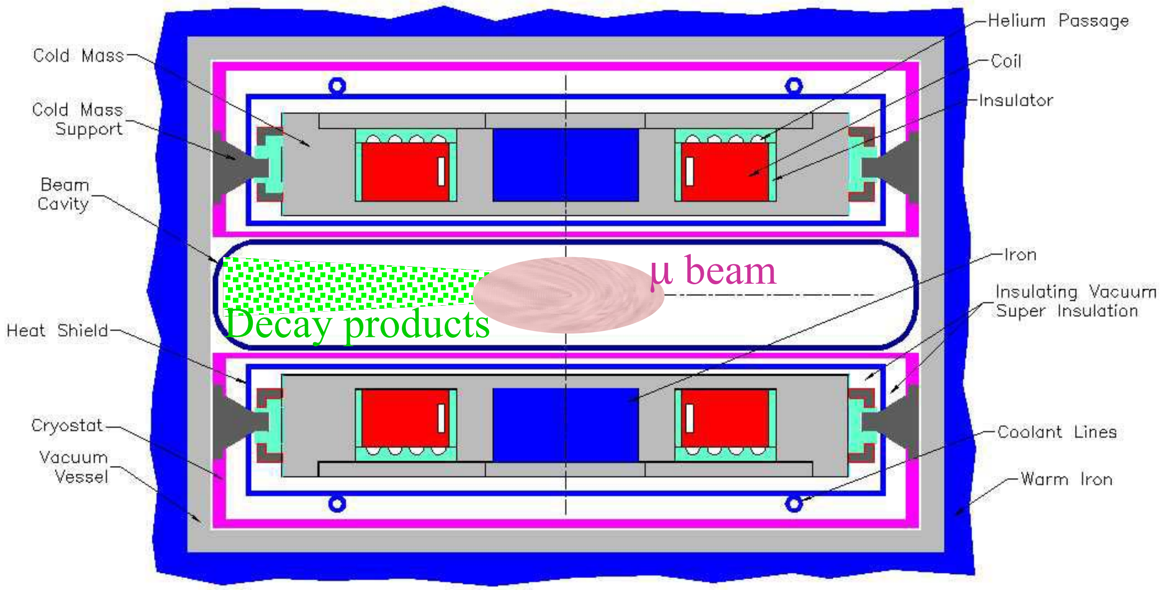
- LDRD
- LARP

BNL LDRD on Open Midplane Magnet Design for Neutrino Factory

- **4 T design with NbTi**
- **8 T design with Nb_3Sn**

Decay products clear superconducting coils

Compact ring to minimize the environmental impact

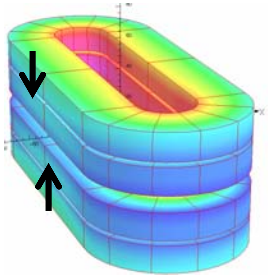


Storage ring magnet design

(simple racetrack coils with open midplane)

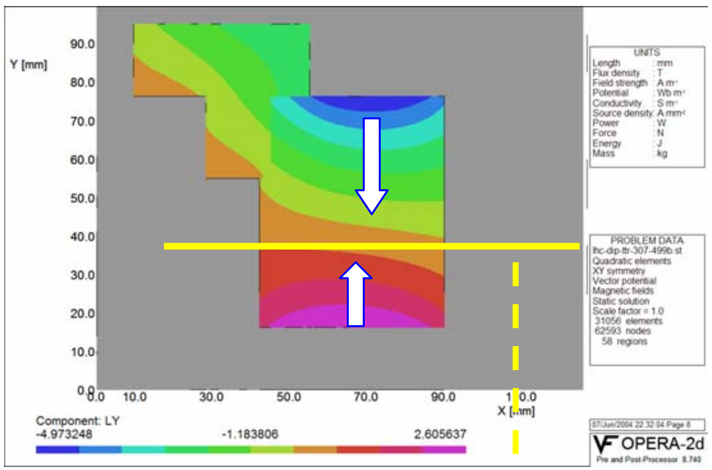
Challenge #1: Lorentz Forces between coils

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.

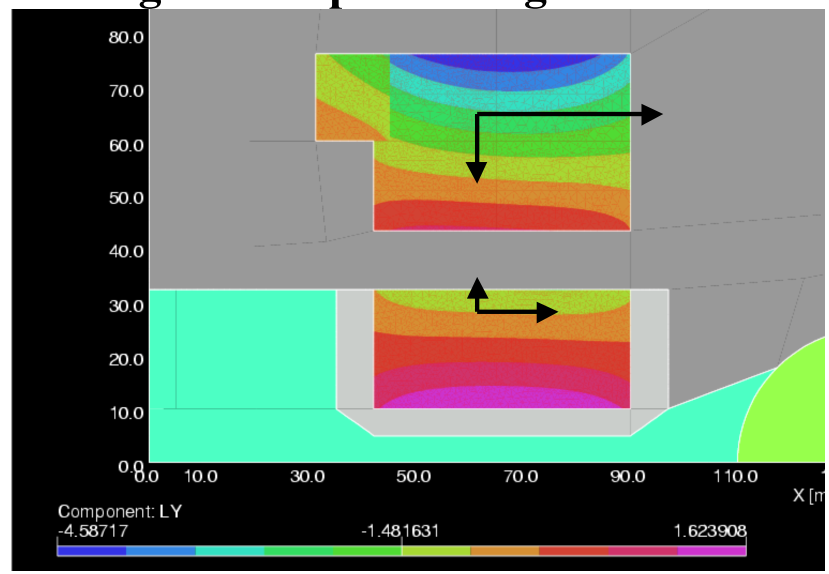
Original Design



Zero vertical force line

Lorentz force density (Vertical)

New Design Concept to navigate Lorentz forces

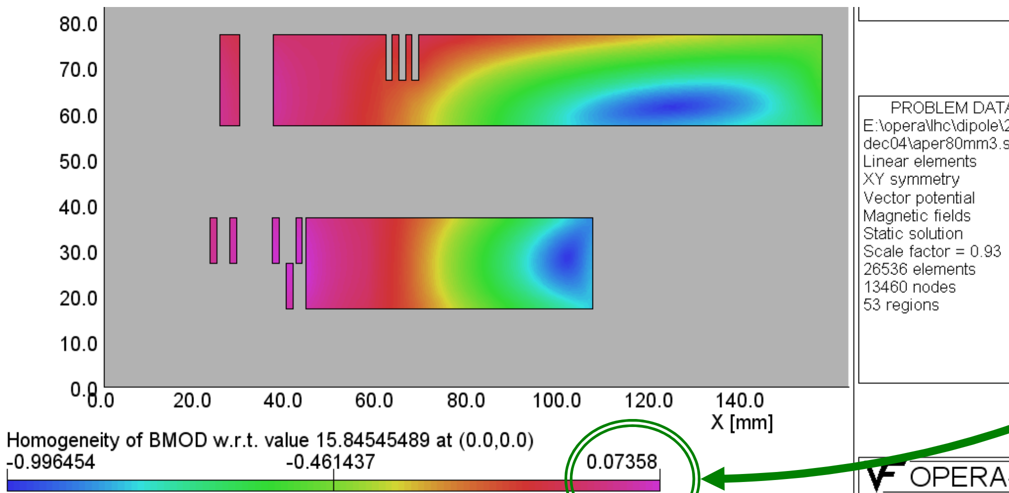


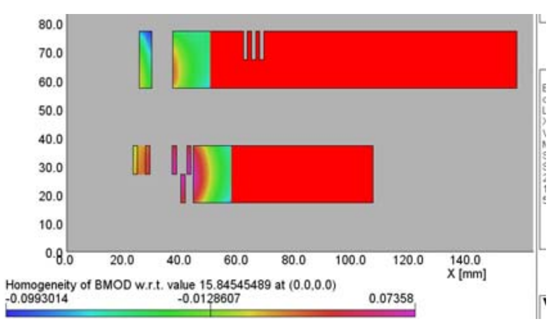
Since there is no downward force on the lower block (there is slight upward force), we do not need much support below if the structure is segmented. The support structure can be designed to deal with the downward force on the upper block using the space between the upper and the lower blocks.

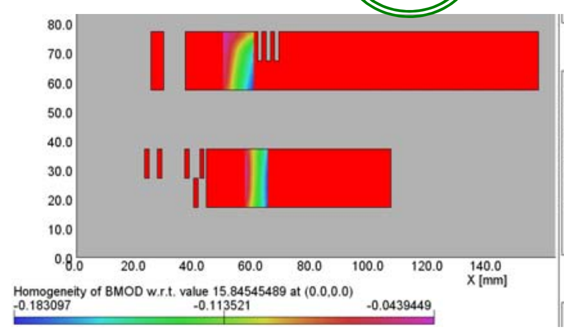
Challenge #2: Peak Field

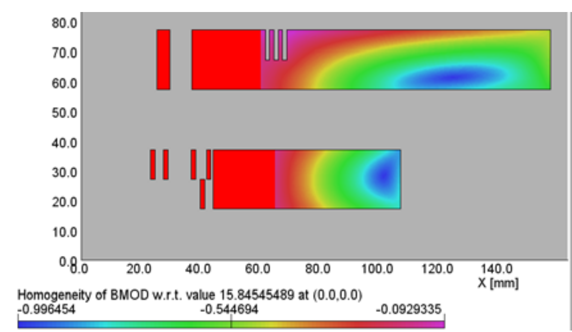
Several designs have been optimized with a small peak enhancement: ~7% over B_o

Relative field enhancement in coil over the central field









Quench Field: ~16 T with J_c = 3000 A/mm², Cu/Non-cu = 0.85

Quench Field: ~15.8 T with J_c = 3000 A/mm², Cu/Non-cu = 1.0

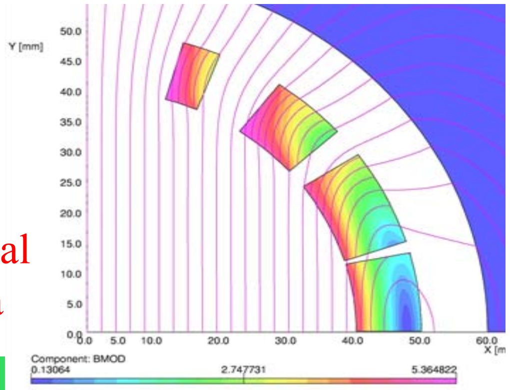
Challenge #3: Field Quality

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

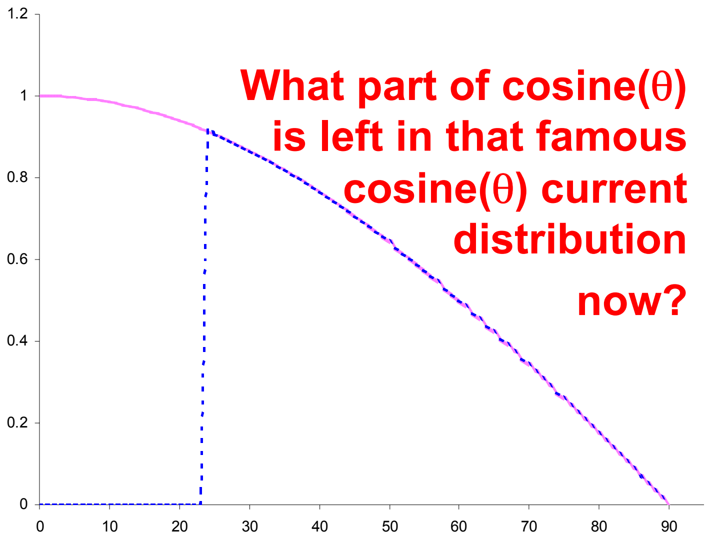
Horizontal aperture = 80 mm

⇒ Vertical gap is > 42% of horizontal aperture

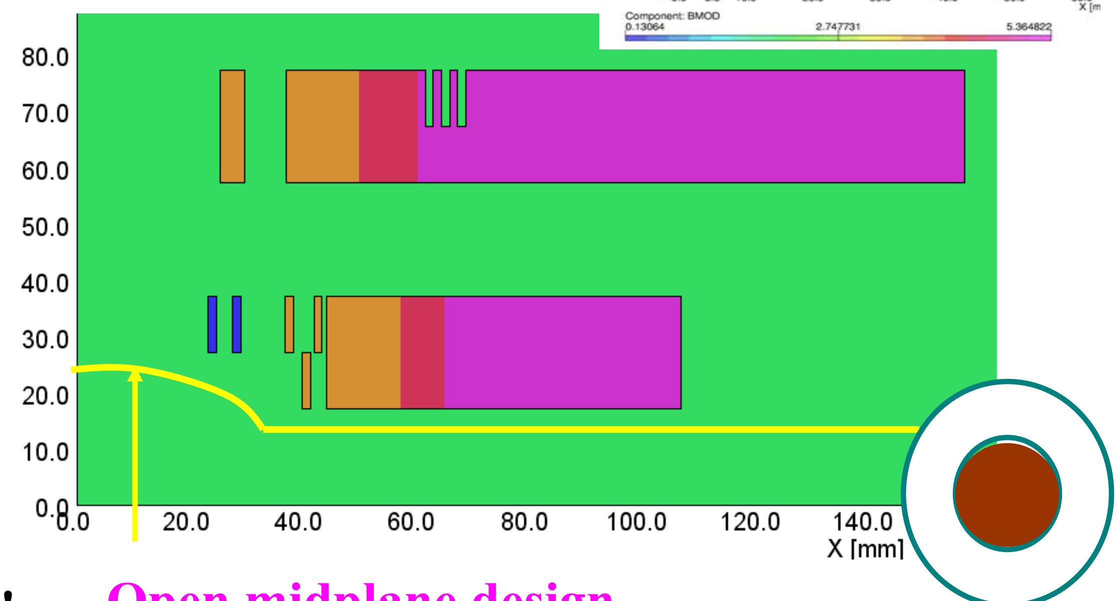
(midplane angle: 23°)



Conventional cosine theta



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



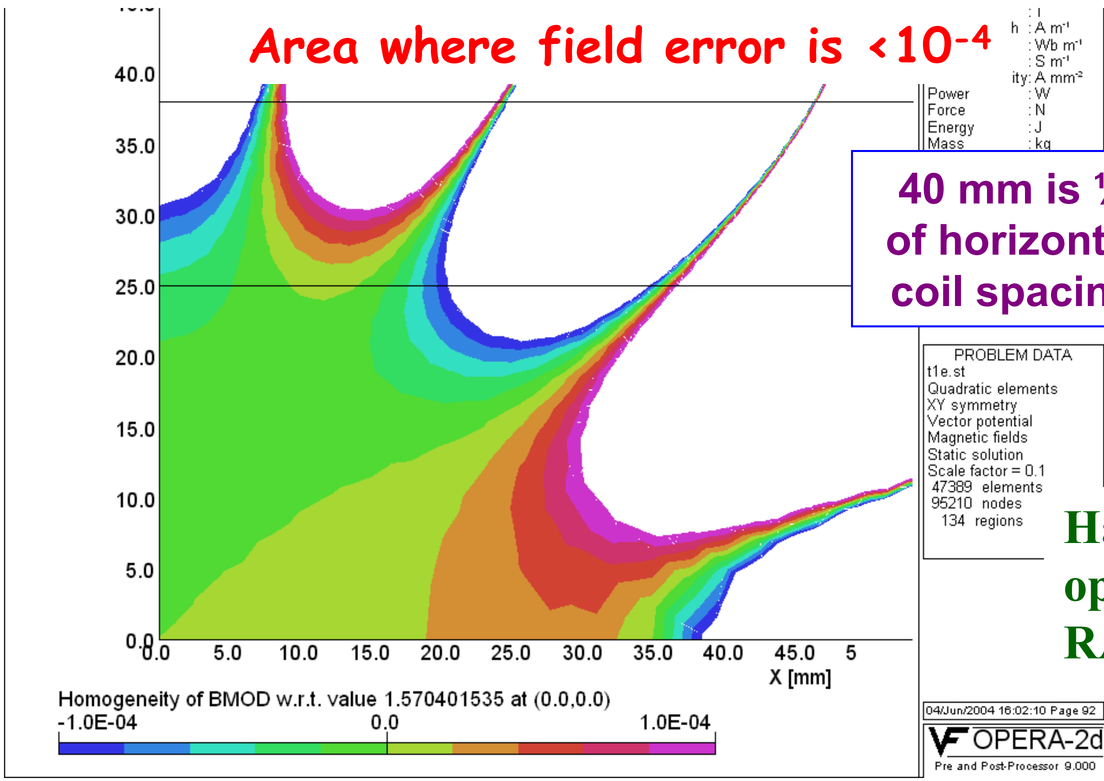
This makes obtaining high field and high field quality a challenging task !

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:



Harmonics optimized by RACE2dOPT

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

(Max. radial beam size: 23 mm)

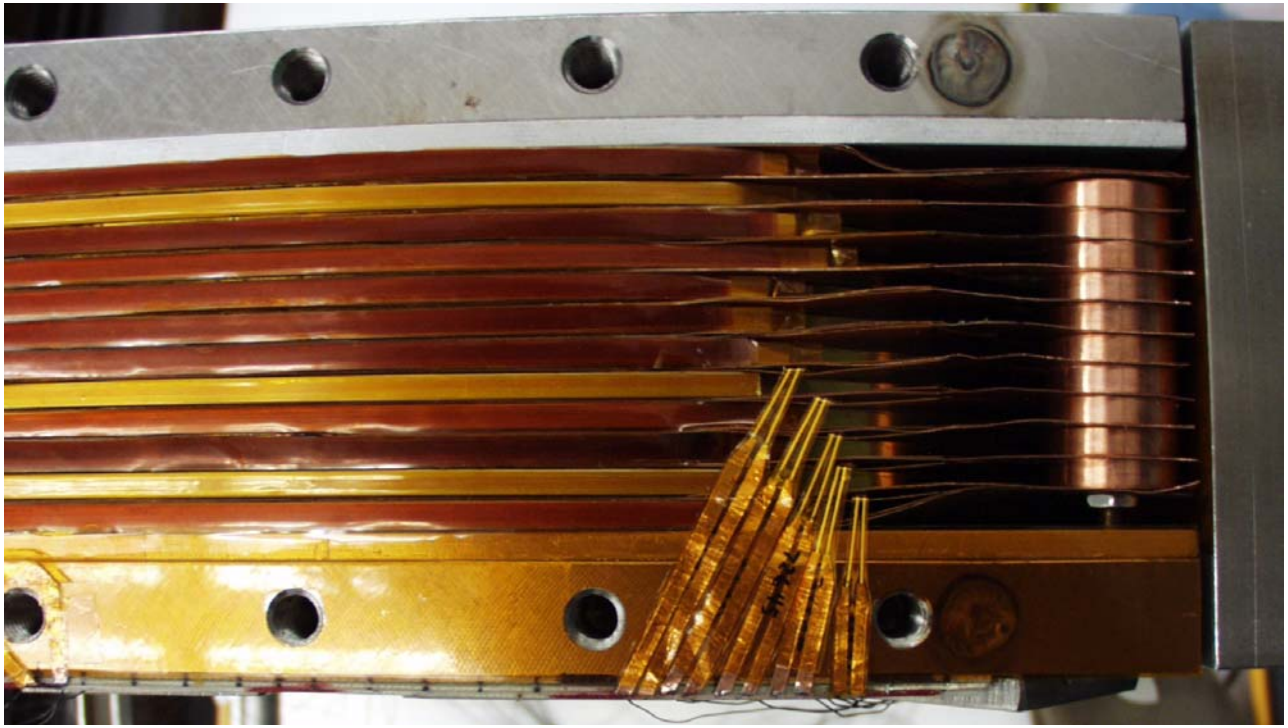
Geometric Field Harmonics:

	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.

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.**

Summary Presented at an Earlier Muon Collider meeting

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.

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.

What to do next on PBL/BNL Phase I SBIR on HTS Open Midplane Dipole ?

My following first notes are still valid:

(including the need to refine them)

- **In this SBIR, we are proposing development of the design of HTS dipole (if hybrid, HTS in coils to the midplane) and demonstration of design and test of key components.**
- **What to demonstrate – TBD (at least coils in a simple mechanical structure with open midplane dipole)**
- **Design Field – TBD.**
- **Include energy deposition simulation – how much – TBD.**
- **Make machine design work as a part of this SBIR perhaps using the model of HTS solenoid SBIR. PBL with its consultants does AP work (including energy deposition simulations), buys conductor and some engineering; BNL does detailed design, construction and test.**