High Field HTS Open Midplane Dipole

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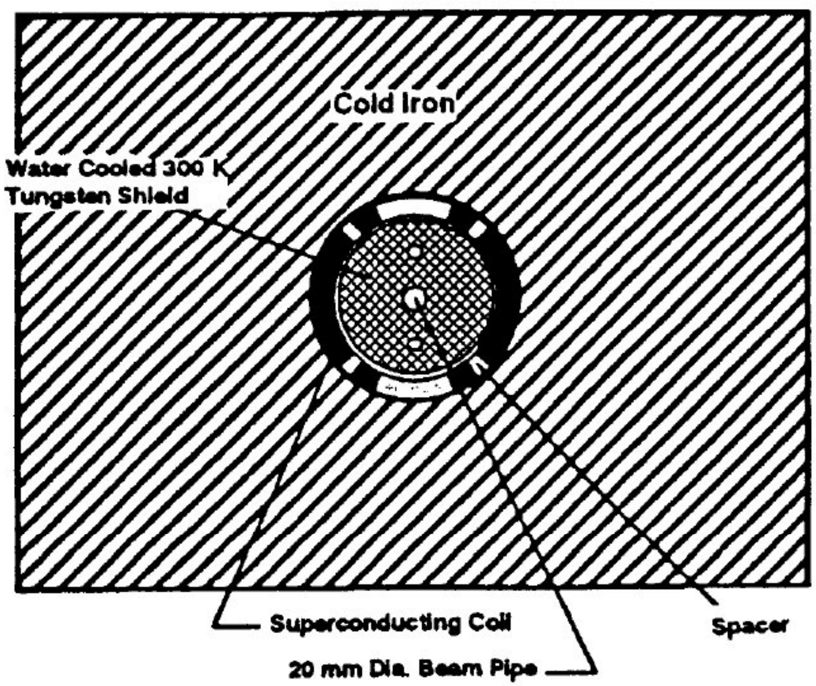
Overview

- Why Open Midplane Dipole design?
- Why HTS?
- Recent radiation damage study on HTS relevant to muon collider
- Energy deposition experiments relevant to muon collider
- Significant development in the Open Midplane Dipole concept (under LARP funding)
- Open Midplane Dipole SBIR for muon collider from PBL
- Work on HTS & high field magnets relevant to muon collider
- Summary

Motivation for Open Midplane Dipole Design



Conventional cosine theta design with Tungesten Liner

- Superconducting coils in muon collider dipoles are subjected to a large number of decay particles (a few kW/m) from short lived muons. One way to protect the coils is to use Tungsten liner. However, that increases size of the magnet.
- Angular distribution of the decay particles is highly anisotropic with a large peak at the midplane (Mokhov). In an "open midplane dipole" design they are trapped in non-superconducting material at the midplane. Different versions of this design have been examined earlier by M. Green and P. McIntyre, etc.

➢ **An ideal or true open midplane design will be with no structure at all the midplane.**

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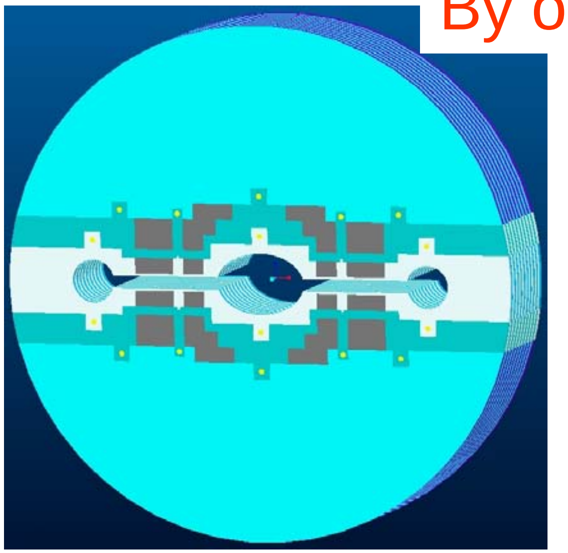
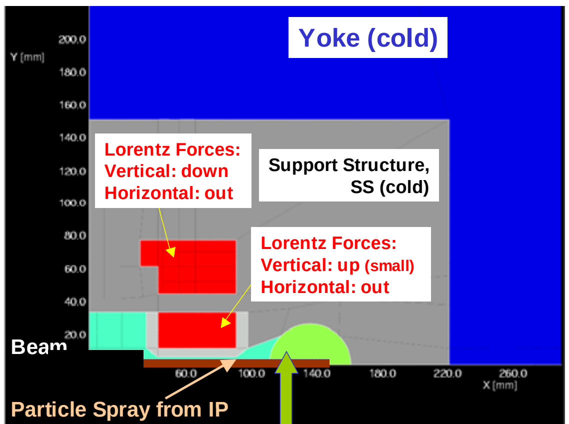
Why a True Open Midplane Design?





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

By open midplane, we mean truly open midplane:

- Particle spray from detector deposit energy in a warm (~80 K) absorber sufficiently away from the superconducting coils and support structure .

- In some earlier "open midplane designs", although there was "no conductor" at the midplane, there was some "other structure" between the upper and lower halves of the coil.

- Those designs, though avoided a direct hit from primary shower, created secondary showers in that other structure. The secondary shower then deposited a significant amount of energy in the superconducting coils.

- Earlier designs, therefore, did not work as well in protecting coils against large energy deposition.

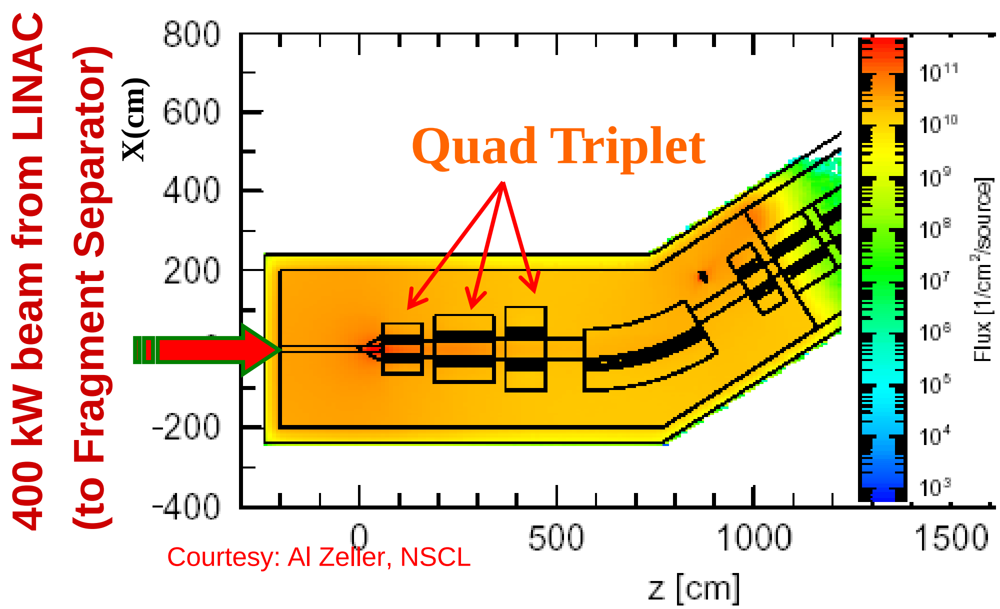
Why High Temperature Superconductors (HTS) ?

Overall machine design (particularly that related to machine detector interface) could benefit significantly from the development of the high field magnets that can reside in high radiation environment. HTS could play a key role there as:

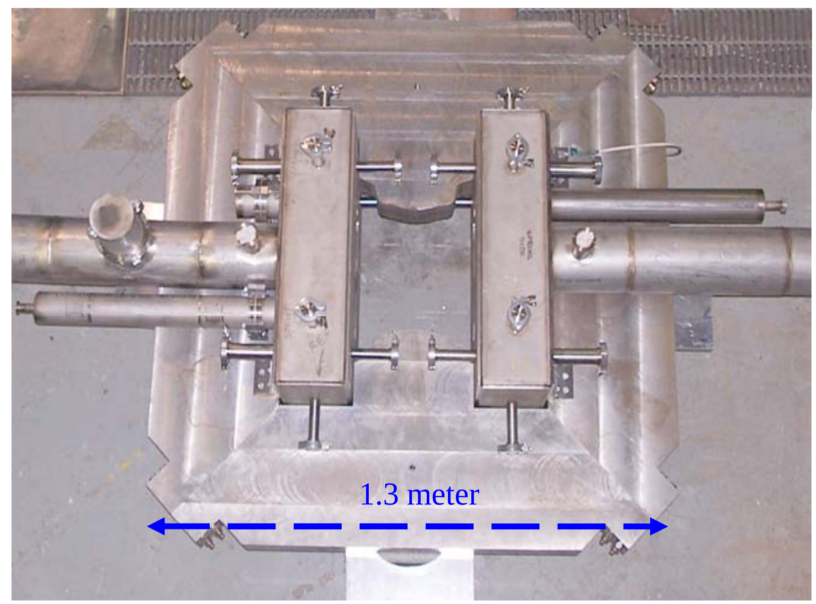
- HTS carry significant current at very high fields. This means that they can be used in building very high field magnets.
- HTS have a high critical temperature. This means that they would be robust against a large local temperature rise caused by energy deposition which is highly anisotropic. HTS can tolerate several degree temperature increase rather than only a few tenth in LTS.
- Recent studies at BNL indicates that *HTS are robust against radiation damage and can tolerate a large energy deposition*.

Motivation for Recent Radiation Damage Studies on HTS

- Radiation damaged studies are being carried for the proposed Facility for Rare Isotope Beams (FRIB) for magnets in the Fragment Separator region. Use of HTS offers several advantages.
- Critical quadrupoles are exposed to unprecedented level of radiation (~20 MGy/year) and heat loads (~10 kW/m, 15 kW in first quad itself).
- **Question:** Can HTS magnets withstand and remove these radiation and heat loads?
- A comprehensive conductor and magnet R&D program was carried out to demonstrate above.
- The results of this program are relevant to other future proposals, such as muon collider.

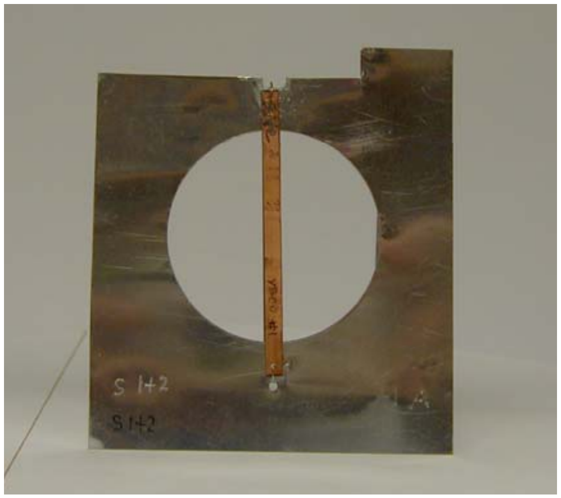


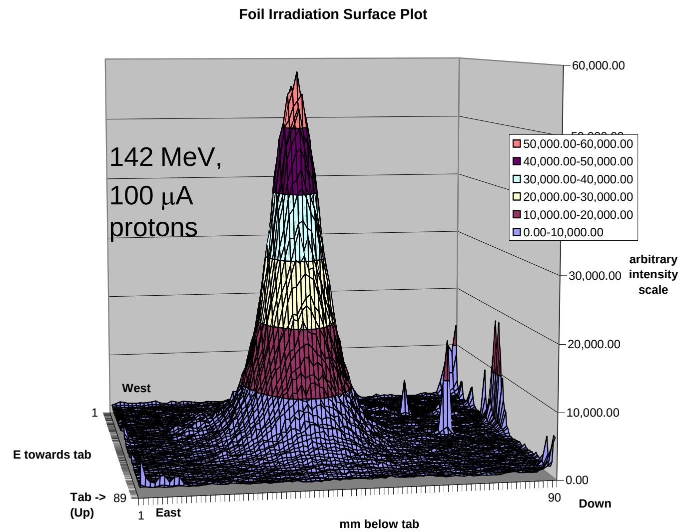
Courtesy: Al Zeller, NSCL

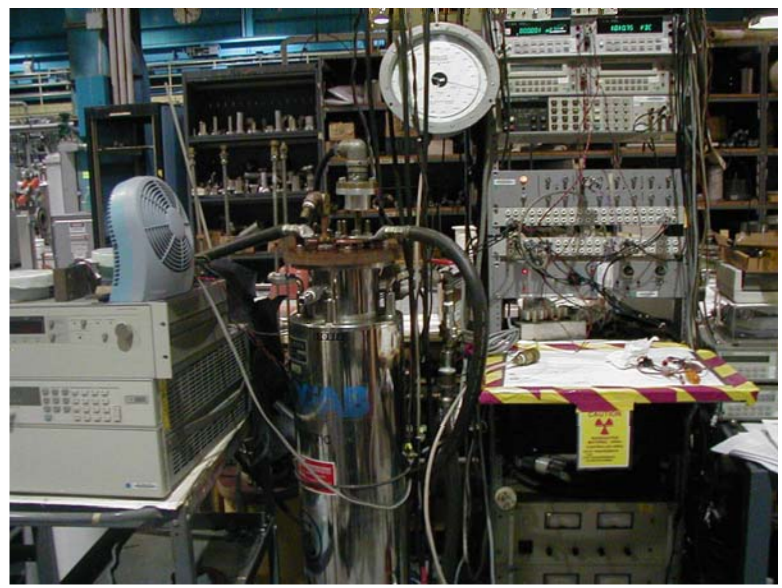


HTS QUAD

Key Steps of Radiation Damage Experiment







Radiation Damage Studies at BLIP

Figure 2. The BLIP facility.

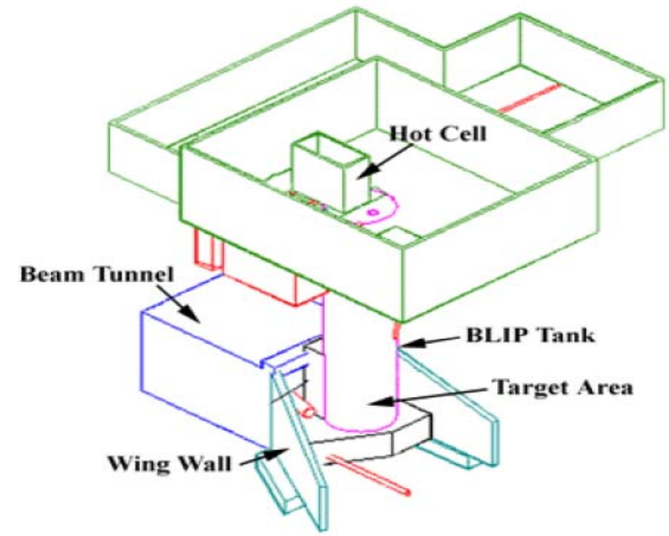


Figure 3. BLIP Beam Tunnel and Target Schematic

From a BNL Report (11/14/01)

The Brookhaven Linac Isotope Producer (BLIP) consists of a linear accelerator, beam line and target area to deliver protons up to 200 MeV energy and 145 µA intensity for isotope production. It generally operates parasitically with the BNL high energy and nuclear physics programs.

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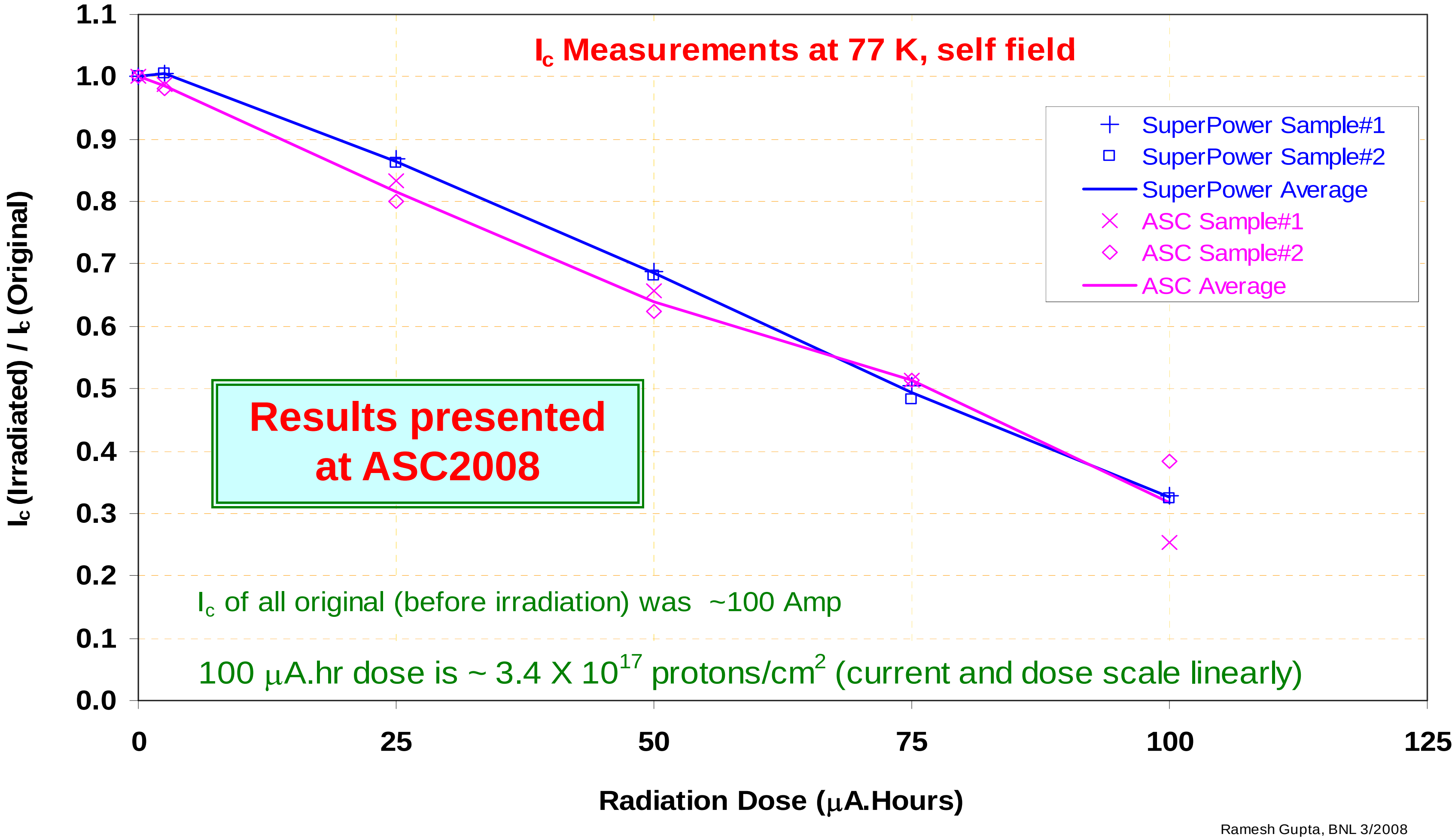
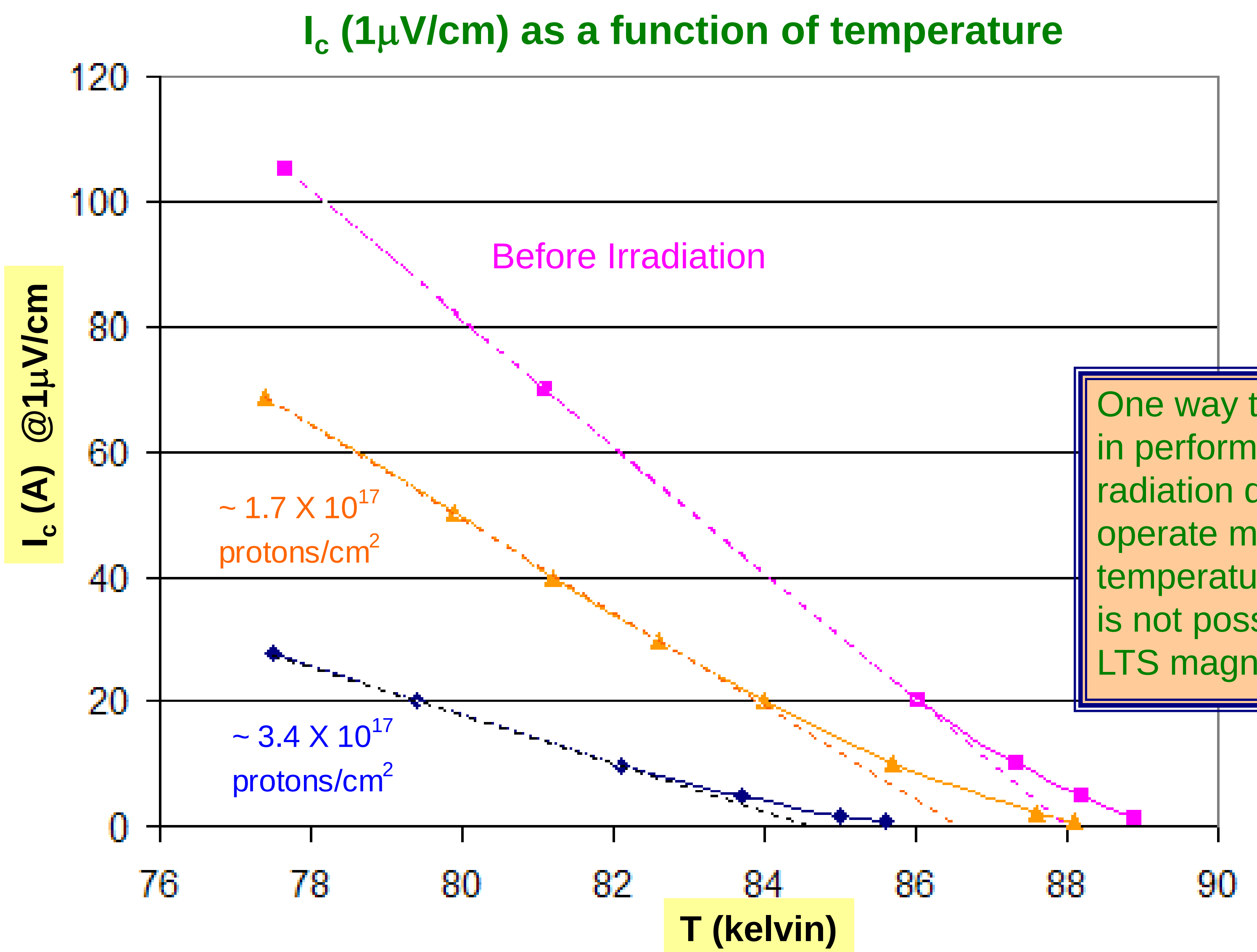
Change in Critical Current (I_c) of YBCO Due to a Large Irradiation

Radiation Damage Studies on YBCO by 142 MeV Protons by G. Greene and W. Sampson at BNL (2007-2008)



Change in Critical Temperature (T_c) of YBCO Due to a Large Irradiation



Note:

Radiation damage has impact on T_c, in addition to that on I_c.

One way to recover the loss in performance due to radiation damage is to operate magnet at a lower temperature – something that is not possible in conventional LTS magnets.

Results were presented at ASC2008.

Impact of Irradiation on HTS

- The maximum dose was 3.4 X 10^{17} proton per sec 100 μA.hr.
- As per Al Zeller, displacement per atom (dpa) per proton is ~9.6 X 10^{-20}.

This gives ~0.033 dpa at 100 μA.hr.

Bottom line:

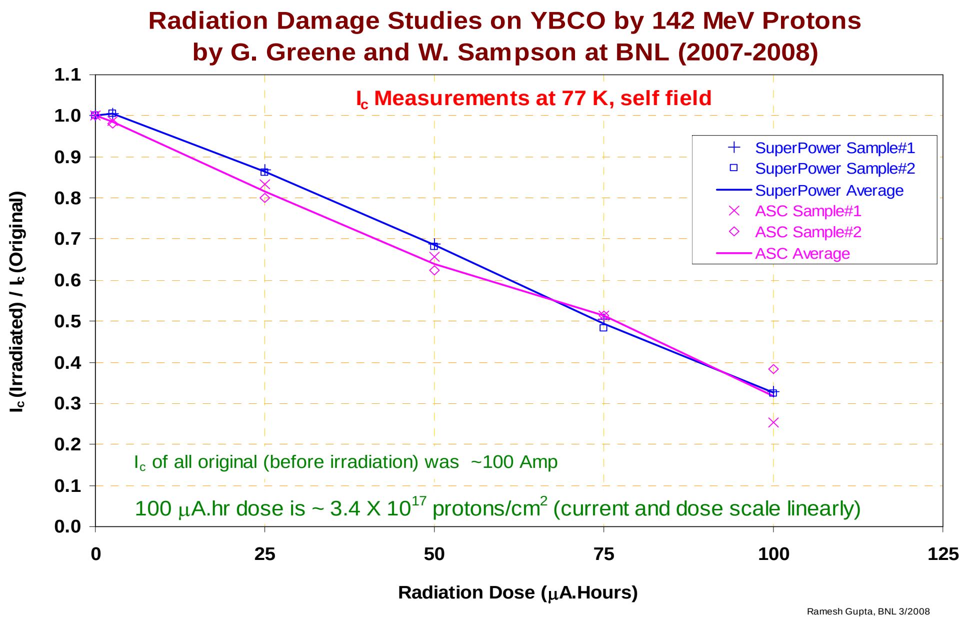
- **I_c performance of YBCO will drop ~10% after 30 years operation.**
- **This is pretty acceptable !!!**

It appears that YBCO is at least as much radiation tolerant as Nb_3Sn is (Al Zeller).

Caveat:

Above is based on 77 K, self-field.

To be completely sure, we are making measurements at lower temperature and in the presence of field.



One needs to normalize the impact of this damage for muon collider magnets

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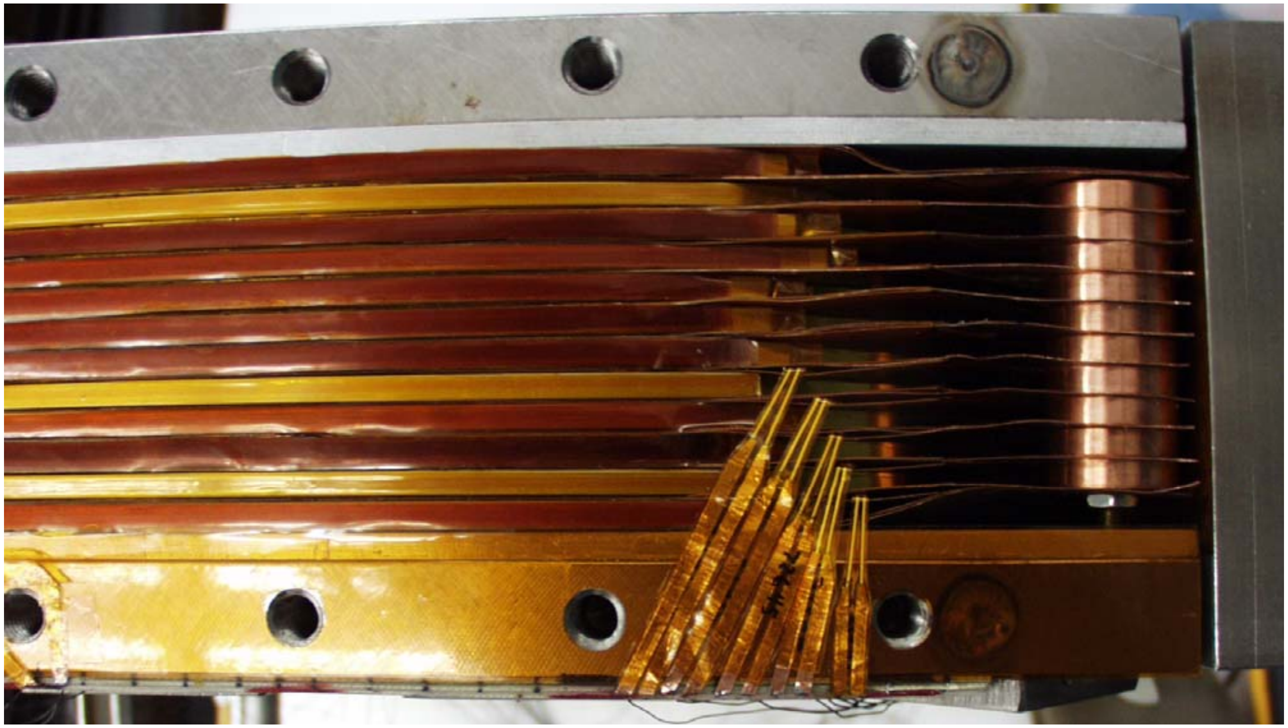
Energy Deposition Experiments for FRIB

- With 15 kW going in first quad (~10 kW/m), energy deposition is a key issue in FRIB.
- We should be able to remove these large heat loads efficiently.
- Magnets should be able to operate in a stable fashion in presence of these loads.
- These experiments are relevant to muon collider magnets next to detectors.

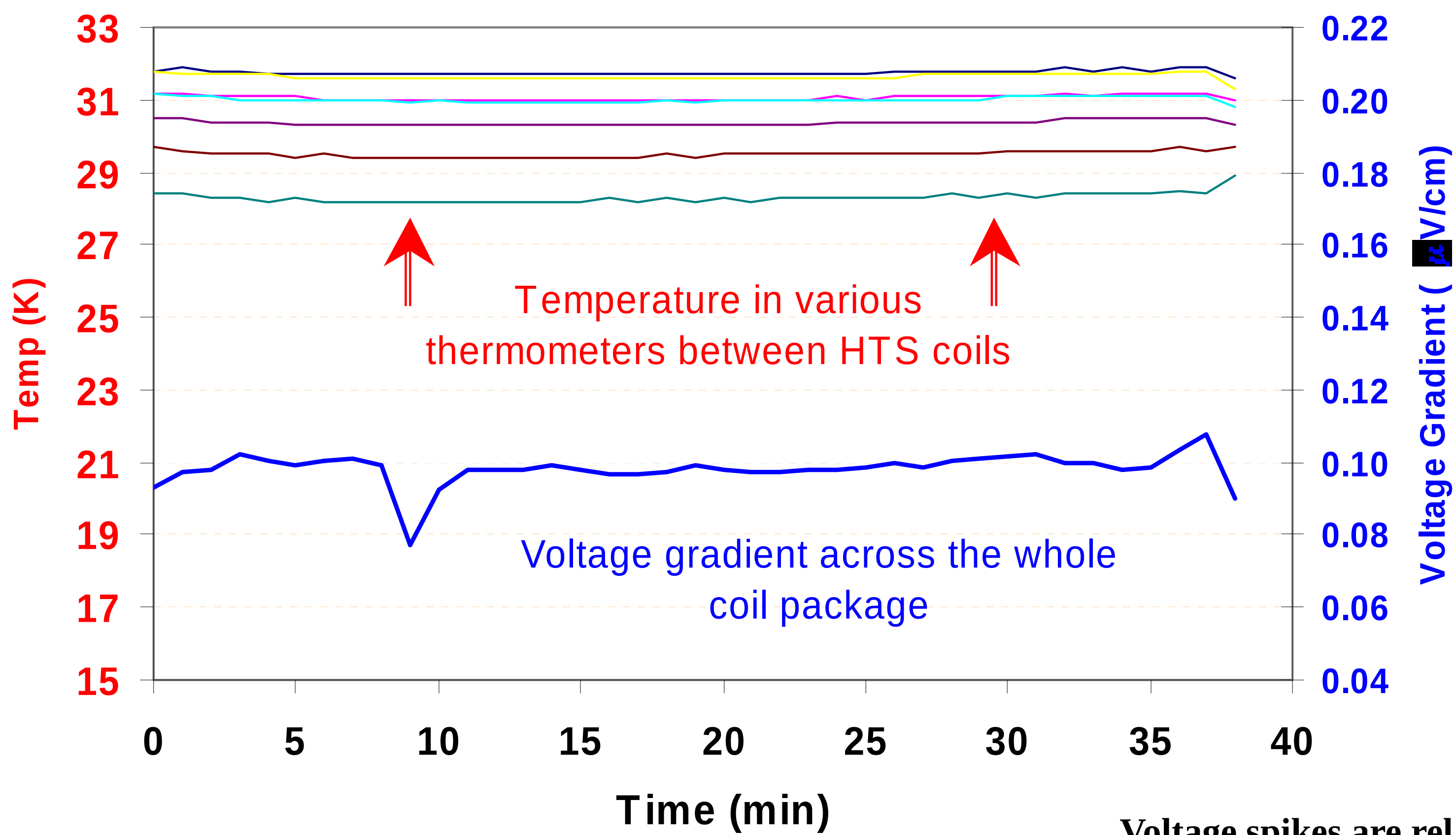
Stainless steel tape heaters for energy deposition experiments



- Controlled energy (heat) is deposited between the coils with these heaters.

Large Energy Deposition Experiment

Goal is to demonstrate that the magnet can operate in a stable fashion with the heat loads expected in FRIB (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

Voltage spikes are related to the noise

Progress in Open Midplane Dipole Design (1)

(work performed under the auspices of LARP)

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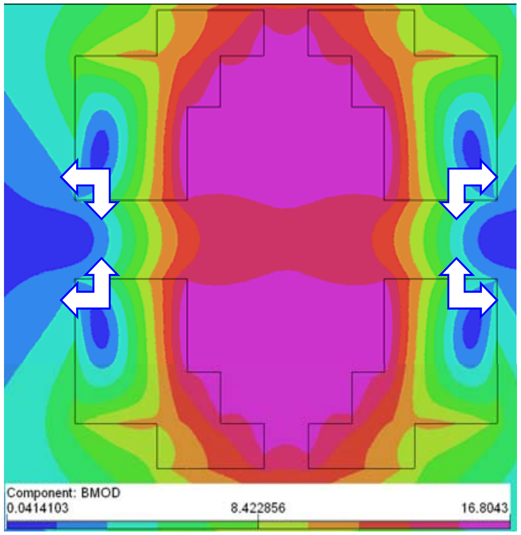
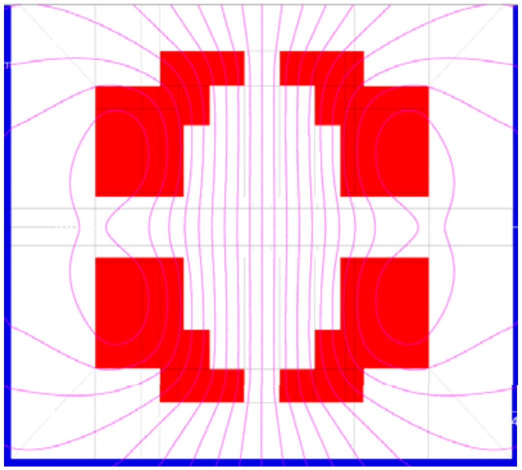
Open Midplane Dipole Design

(challenges with the true open midplane design)





#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?

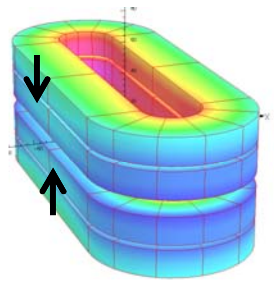
#2 The ratio of peak field in the coil to the design field appears to become large for large midplane gaps.

#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.

⇨ **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.**

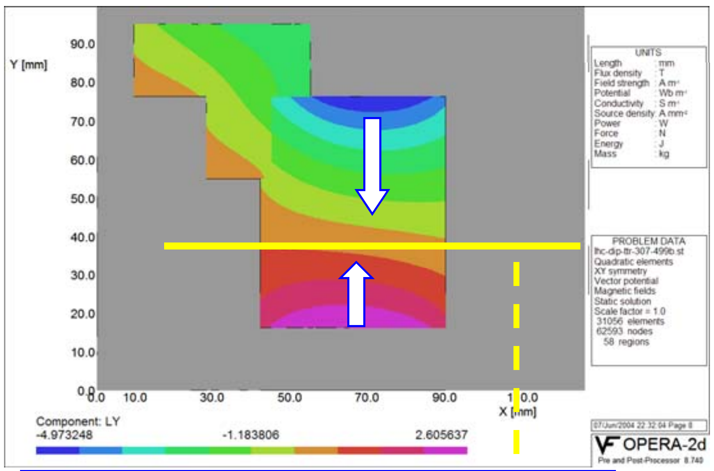
Challenge #1: Lorentz Forces between coils

A new and major consideration in design optimization



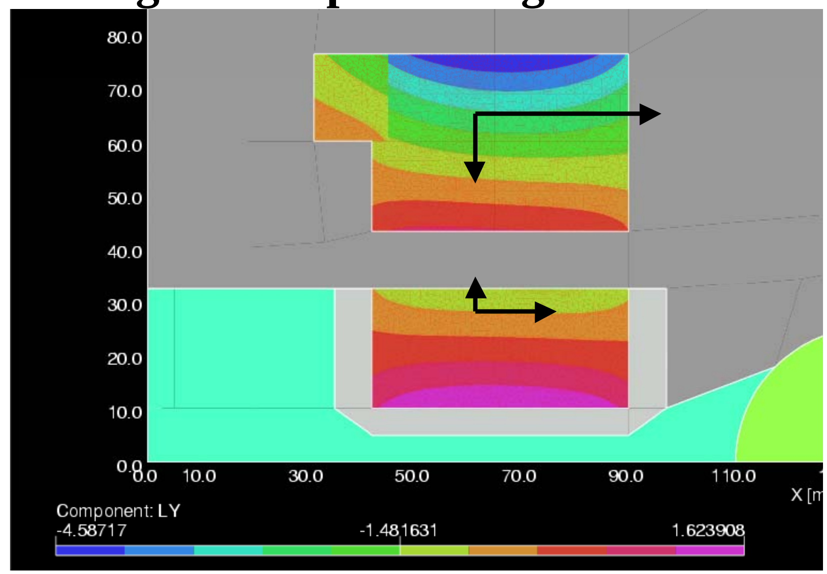
In conventional designs the upper and lower coils rest (react) against each other. In a truly open midplane design, the target is to have no structure between upper and lower coils. Structure generates large heat loads and the goal is to minimize them.

Original Design | **New Design Concept to navigate Lorentz forces**



Zero vertical force line

Lorentz force density (Vertical)



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.

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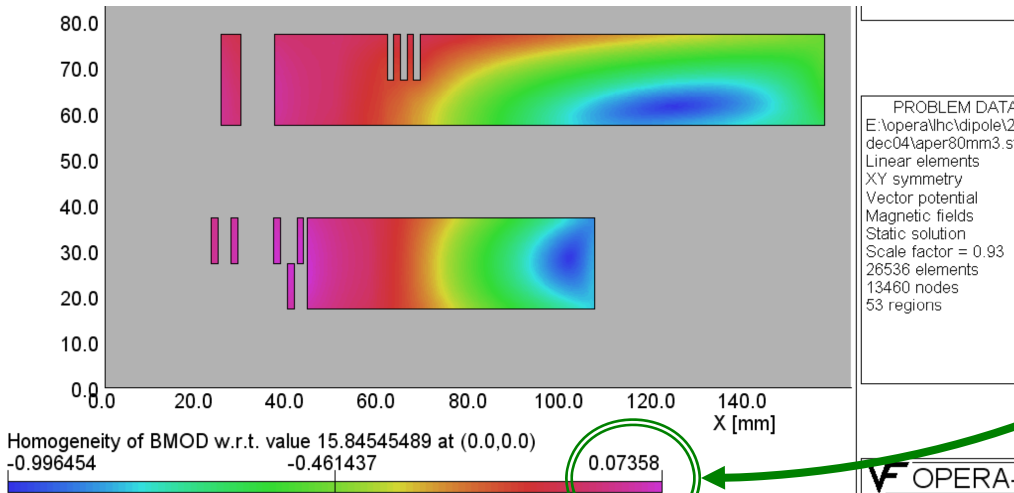
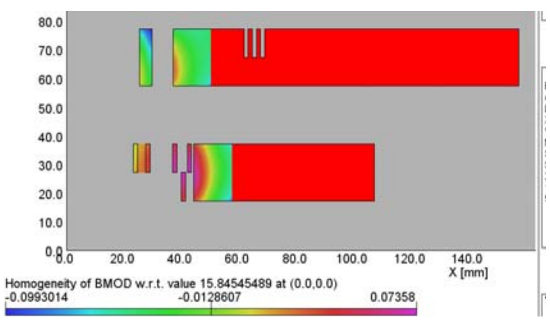
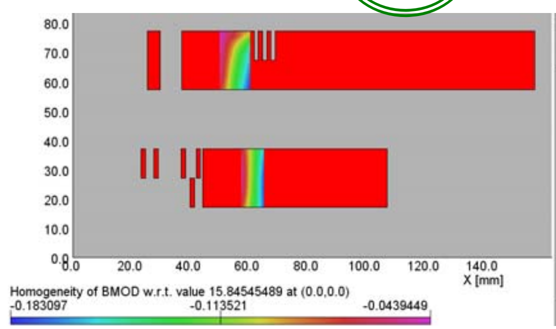
Challenge #2: Peak Field

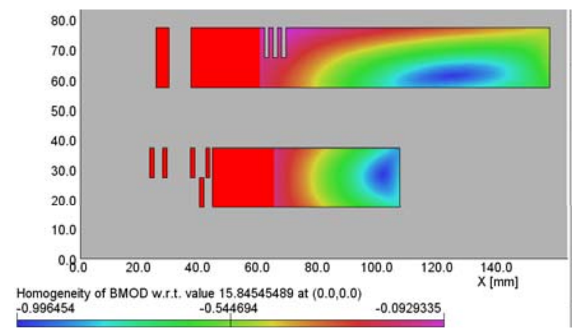
Several designs have been optimized with a small peak enhancement: ~7% over B_o

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

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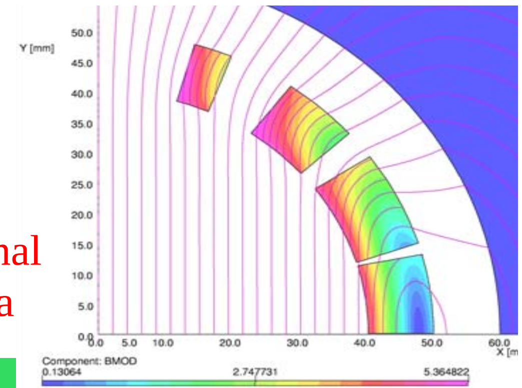
Challenge #3: Field Quality

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

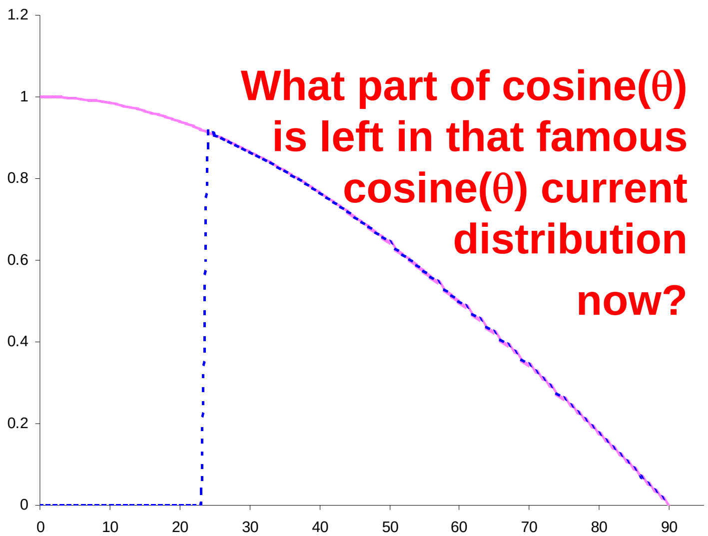
Horizontal aperture = 80 mm

⇒ Vertical gap is > 42% of horizontal aperture

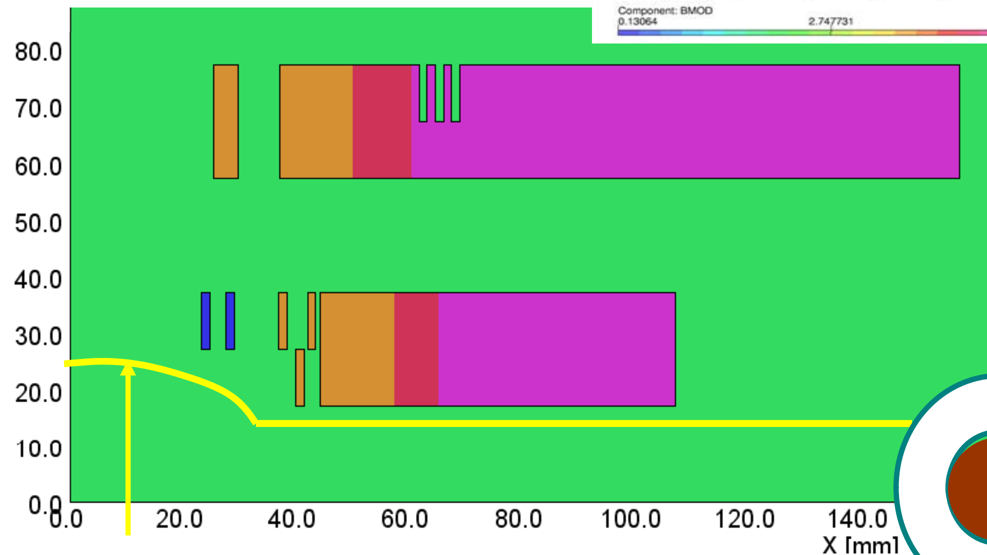
(midplane angle: 23°)

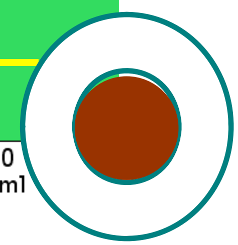


Conventional cosine theta



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





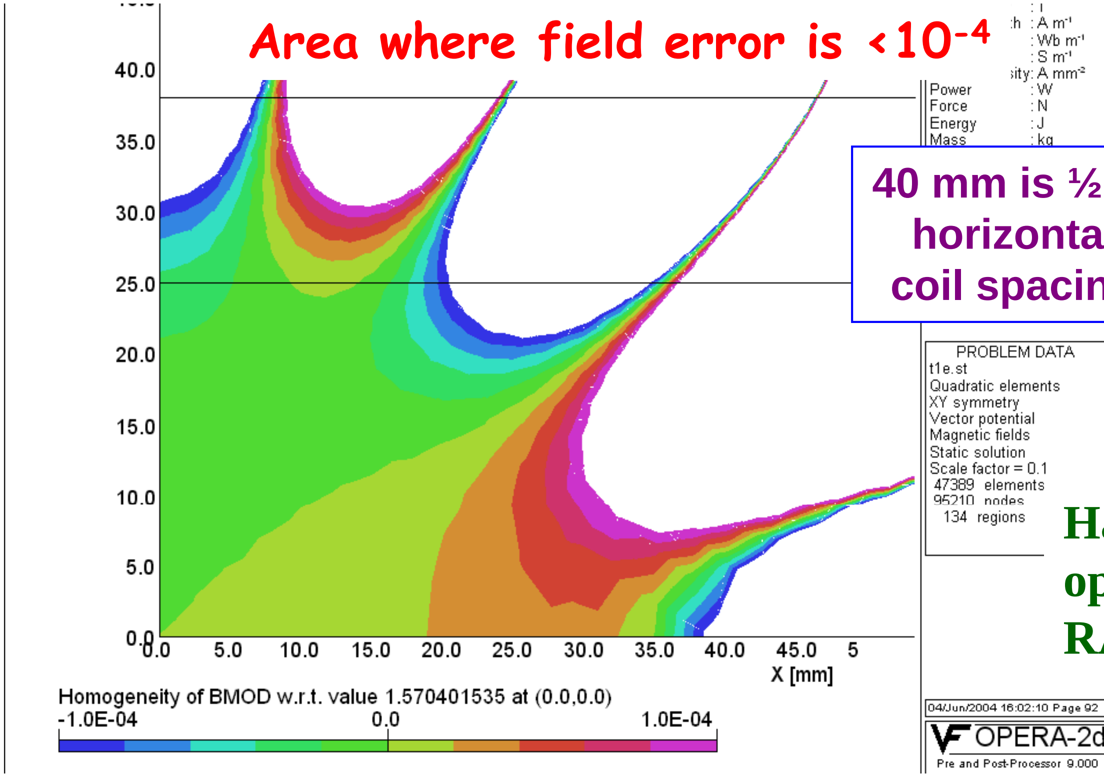
This makes obtaining high field and high field quality a challenging task !

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.

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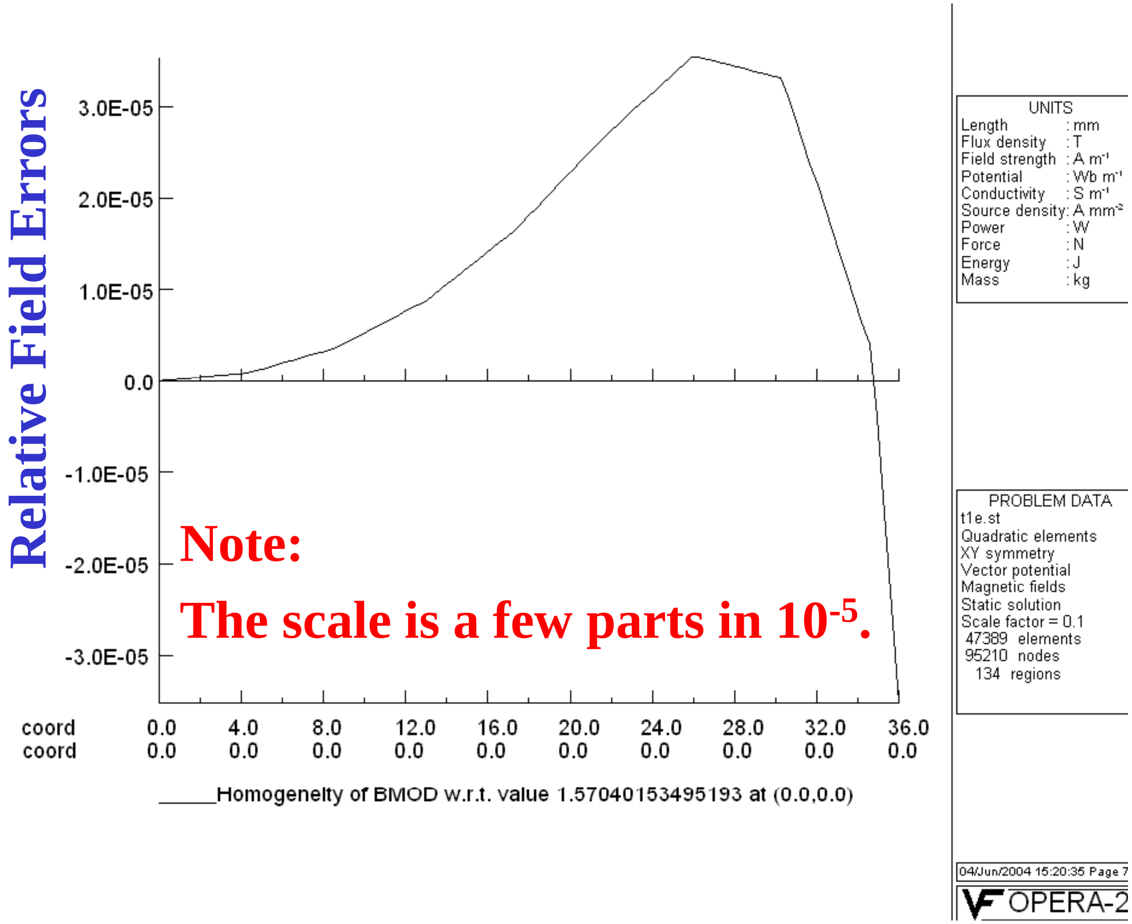
Field Uniformity in an Optimized 15 T Open Midplane Dipole Design

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



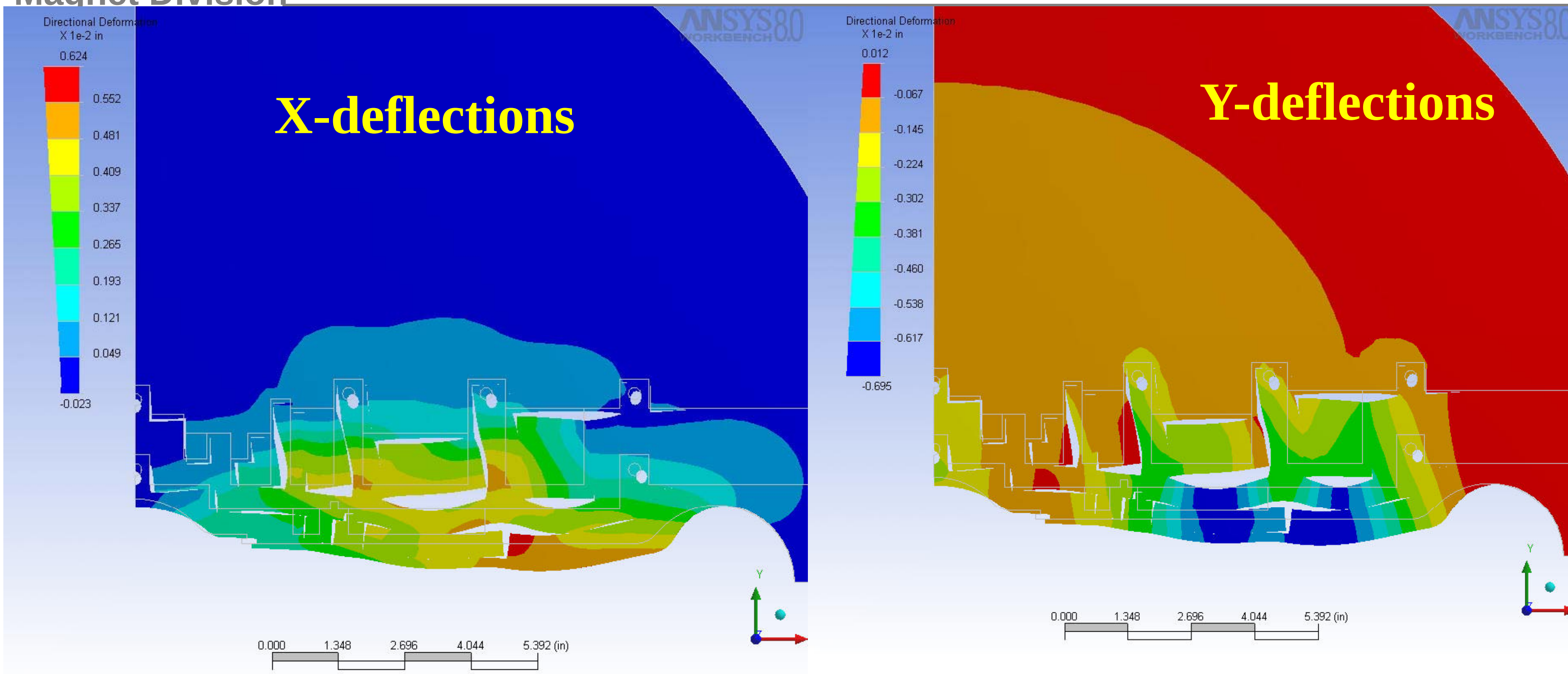
Note:

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

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.

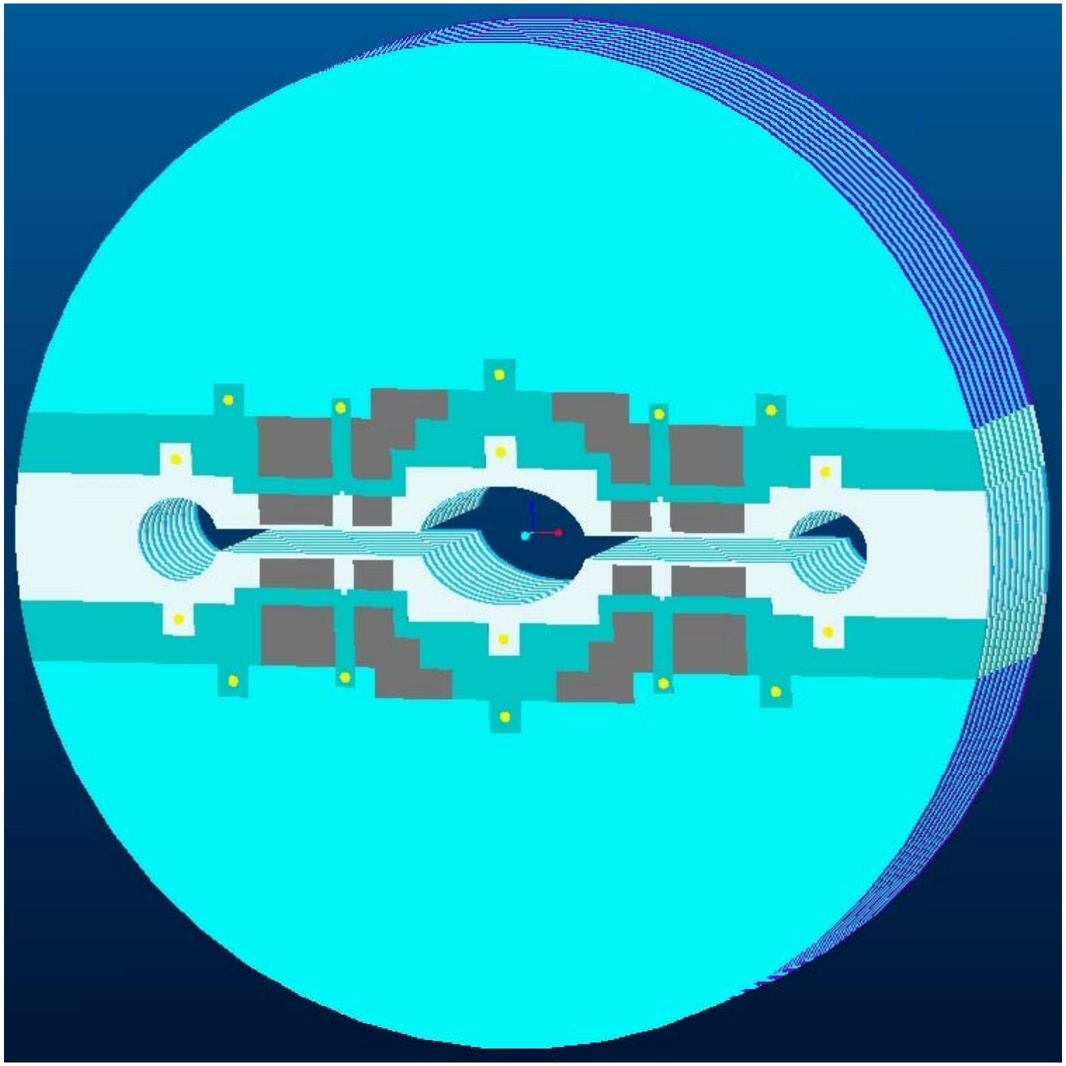
Mechanical Analysis



In the present design the relative values of the x and y deflections are 3-4 mil (100 micron) and the maximum value is 6-7 mil (170 micron).

Above deflections are at design field (13.6 T). They are ~1-2 mil higher at quench field.

Mechanical Assembly



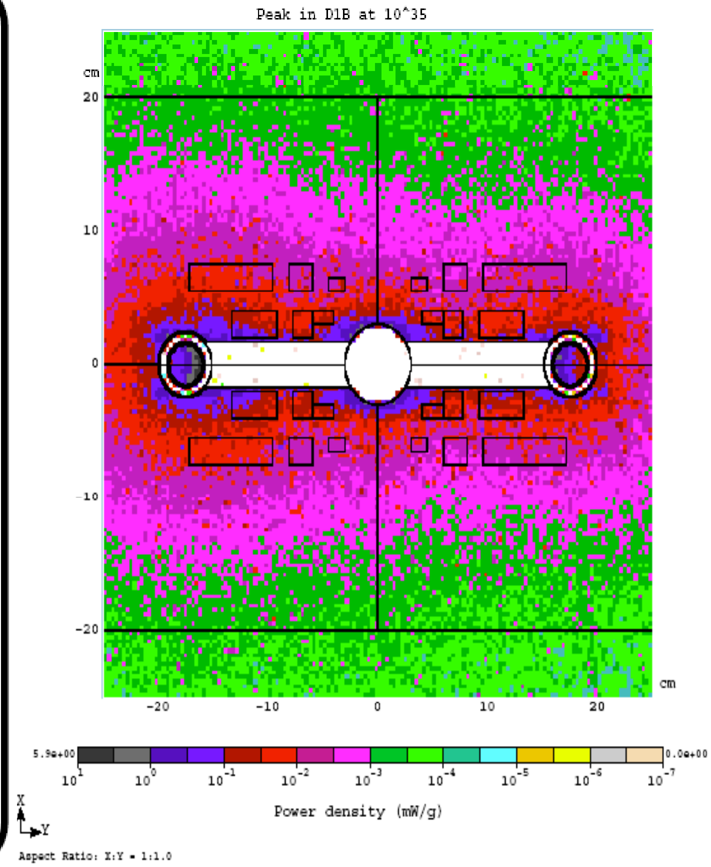
- **Several possible assembly concepts for the open midplane dipole design were examined.**

- **A possible mechanical assembly is shown on the left.**

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

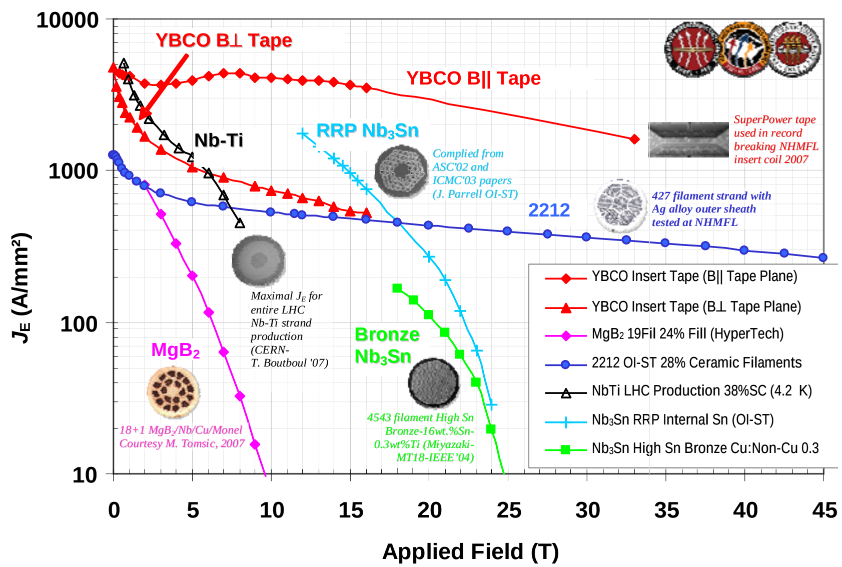
Summary of Optimized Open Midplane Nb_3Sn Dipole Designs for LARP

	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 (say ~20 T).
- HTS may be used in a hybrid design with Nb_3Sn coils.
- Reminder: A further advantage of HTS coils is that they could tolerate a large amount of energy deposition.



Progress in Open Midplane Dipole Design (2)

(combined function dipole design developed under BNL LDRD)

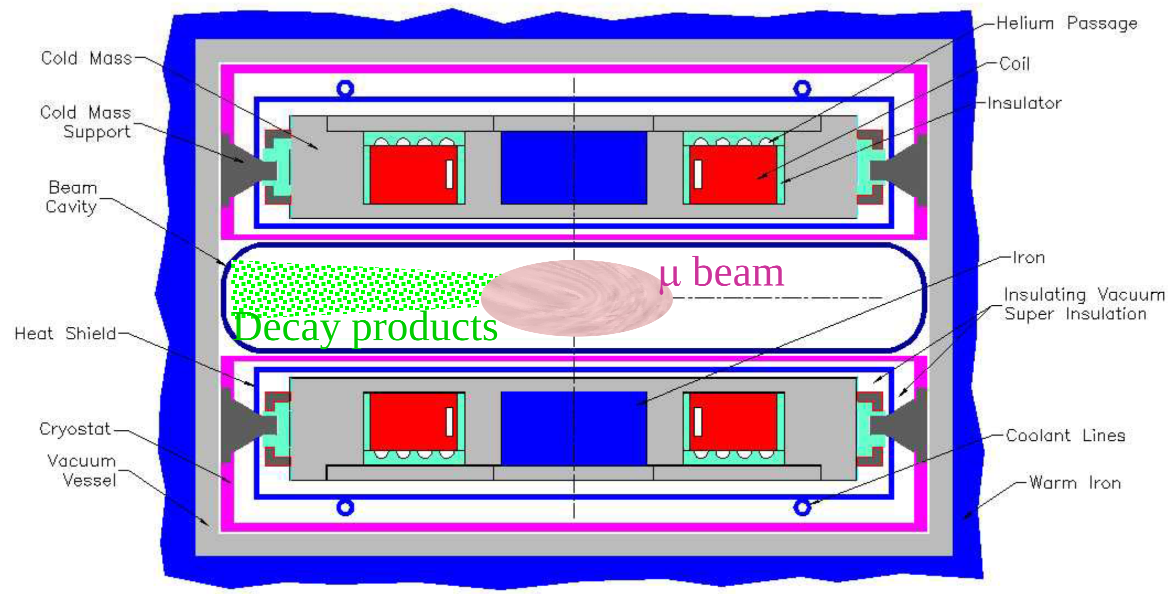
Magnet Design for ν Factory

Design Principles and Requirements:

Decay products clear superconducting coils

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

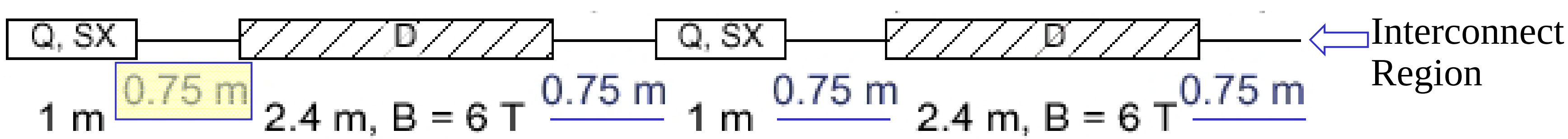
⇨ Need high field magnets and efficient machine design

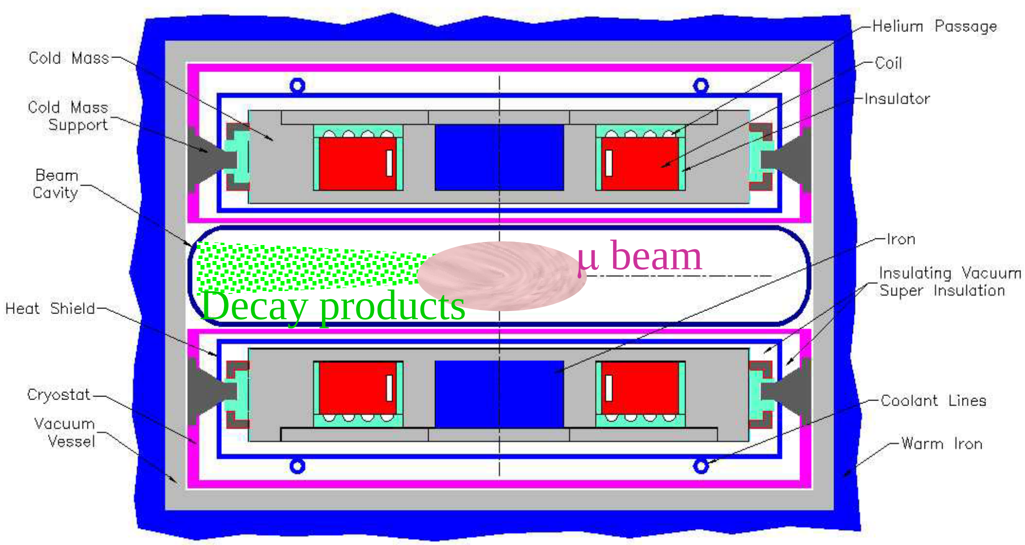


Storage ring magnet design
(simple racetrack coils with open midplane)

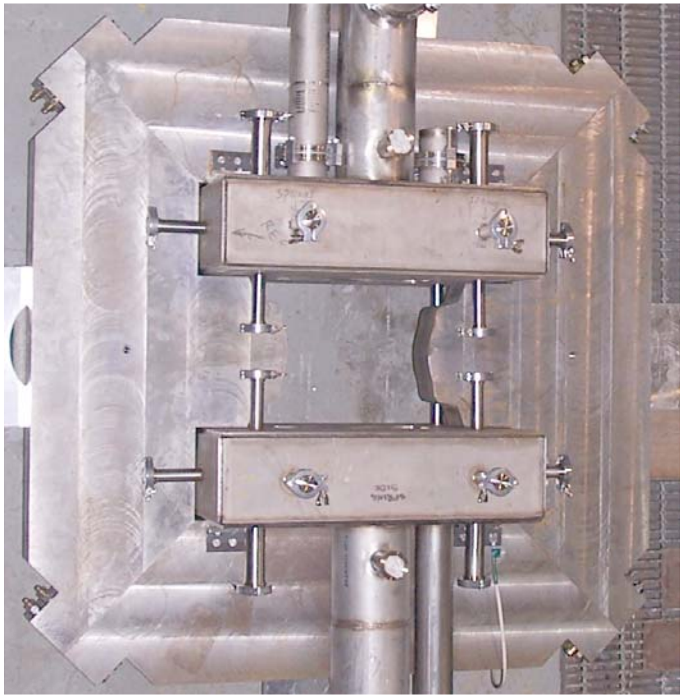
Compact Ring with Combined Function Skew Quadrupole Lattice

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





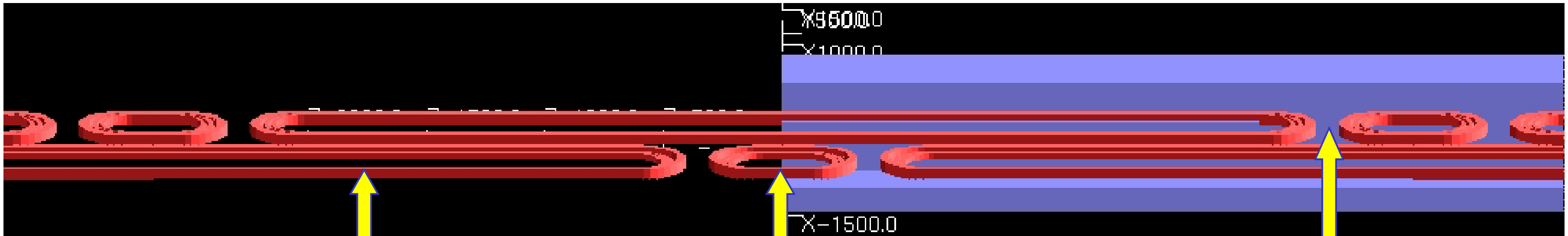
To first order, dipole becomes a skew quad, if the relative polarity of coils is changed.



HTS Open Midplane Dipole

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

Coil Layout for Obtaining A Variety of Magnet Configurations



Normal Coils Dipole

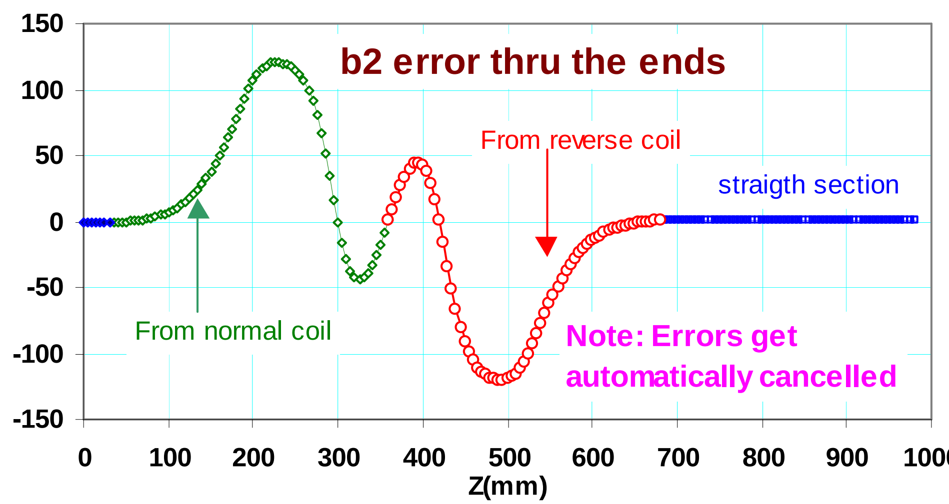
Reverse Coils Skew Quad

One Coil 1/2 & 1/2

- **New <u>magnet system design</u> makes a productive use of all space !**

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

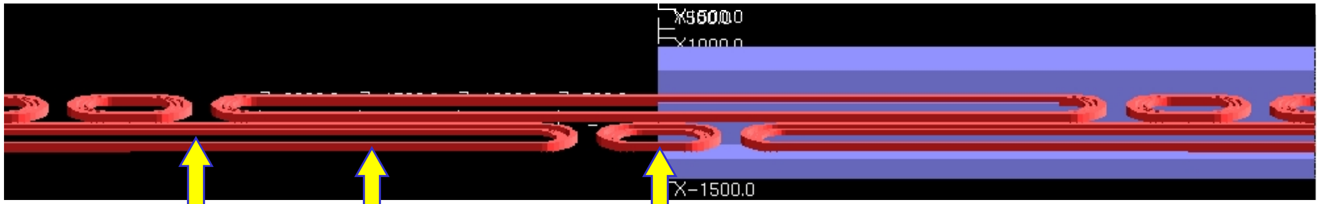
Reverse coils also cancel harmonic errors in the ends



A Possible Magnet Test Setup

Structure to test magnet performance in various configuration:

Magnet system layout in the proposed ν factory storage ring:

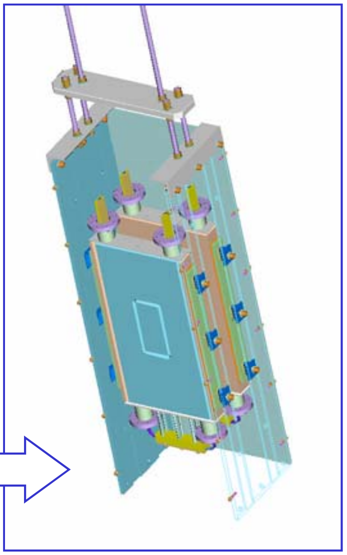


One Coil D/2 & Q/2

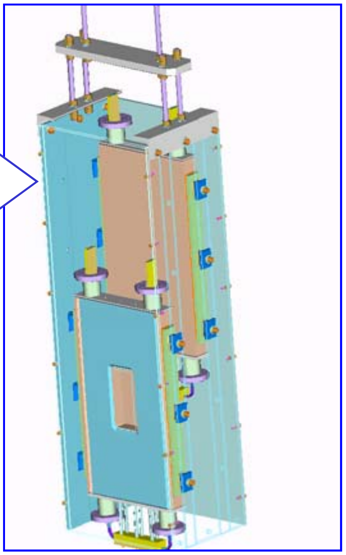
Normal Coils Dipole (D)

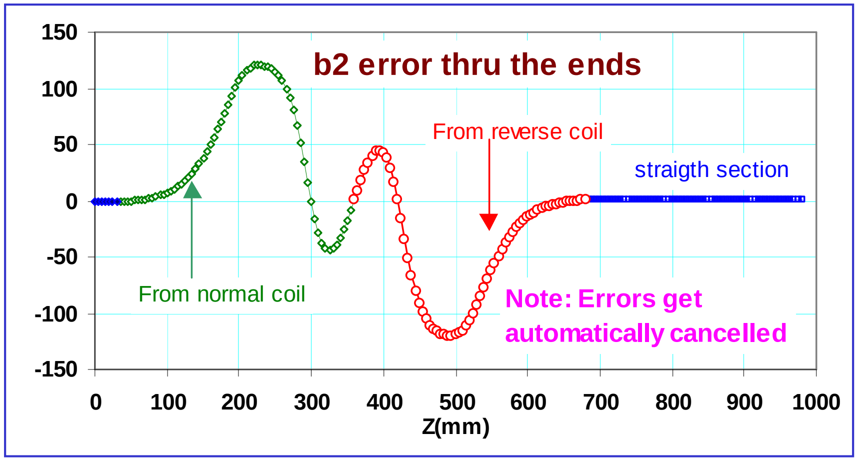
Reverse Coils Skew Quad (Q)

Dipole/Quad test setup (switch relative current direction)



Staggered coil setup





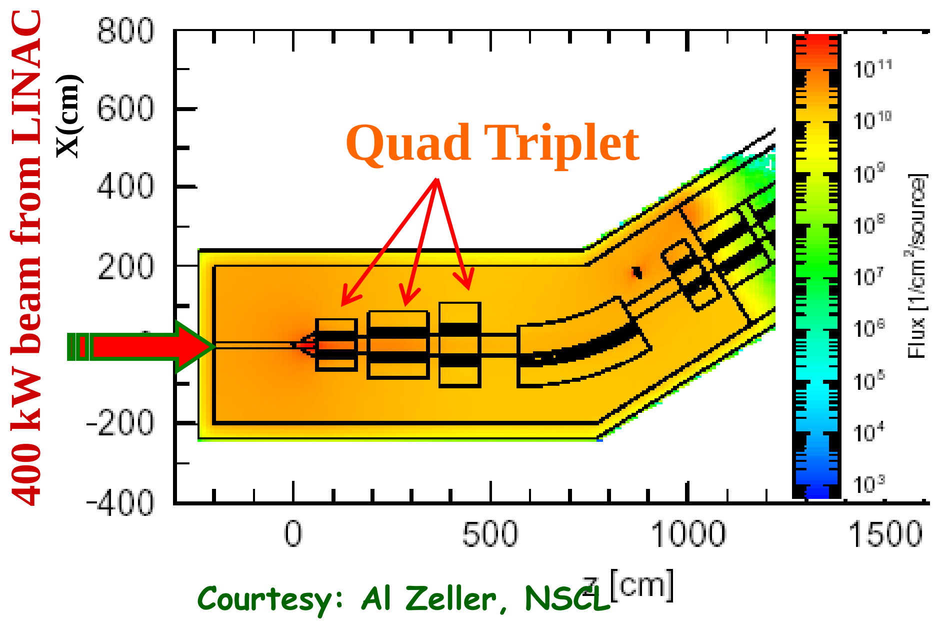
Work carried out under a BNL LDRD

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

FRIB/RIA HTS QUAD Program

Providing significant experience with the construction and test of HTS magnets in high radiation environment

HTS Quadrupoles for RIA/FRIB



Courtesy: Al Zeller, NSCL

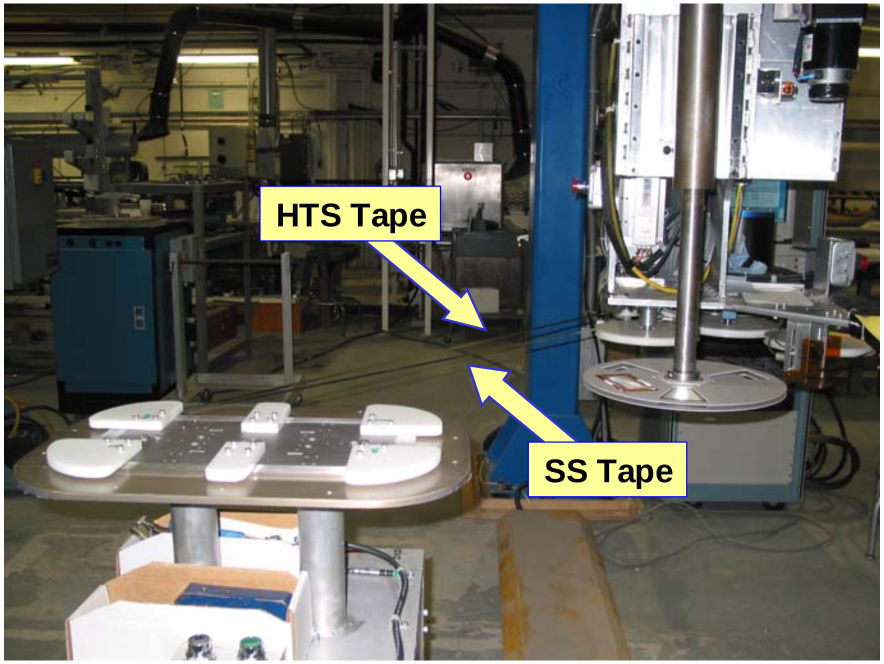
- To create intense beams of rare isotopes, up to 400 kW of beam hits the target before the fragment separator.
- Quadrupole triplet is exposed to very high level of radiation and heat loads (~15 kW in the first quadrupole itself).
- HTS magnets could remove this more efficiently at 30-50 K than LTS at ~4 K.

- **These quads were identified as one of the most critical components of the machine.**
- **We have successfully built and tested a large number of coils and magnets and have performed radiation damage and energy deposition experiments.**

RIA: Rare Isotope Accelerator
FRIB: Facility for Rare Isotope Beams

HTS Coils for RIA/FRIB Magnets

- RIA quad is made with 24 coils, each using ~200 meter of HTS. We have purchased over 5 km of 1G wire for this project (FRIB purchase of 2G wire is separate).
- This gives a good opportunity to examine the reproducibility in coil performance.
- Stainless steel tape serves as an insulator which is highly radiation resistant.



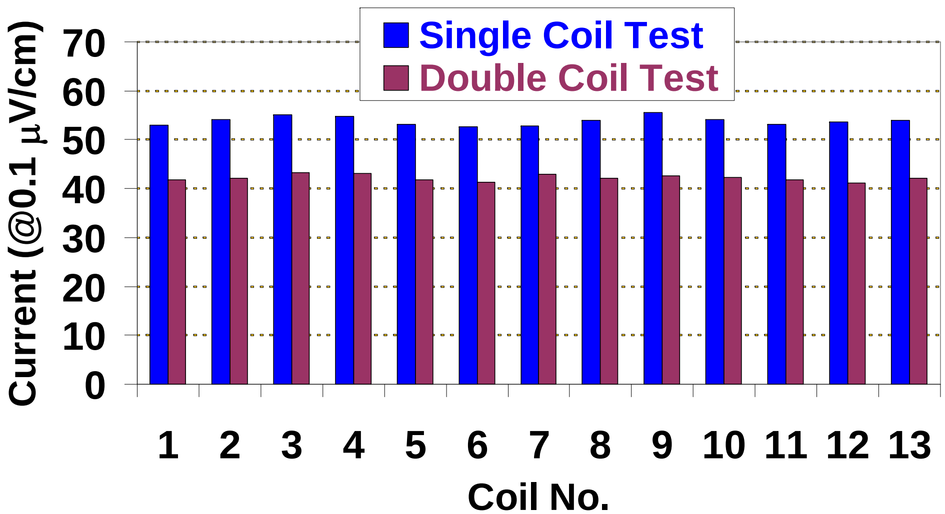
RIA: Rare Isotope Accelerator

FRIB: Facility for Rare Isotope Beams

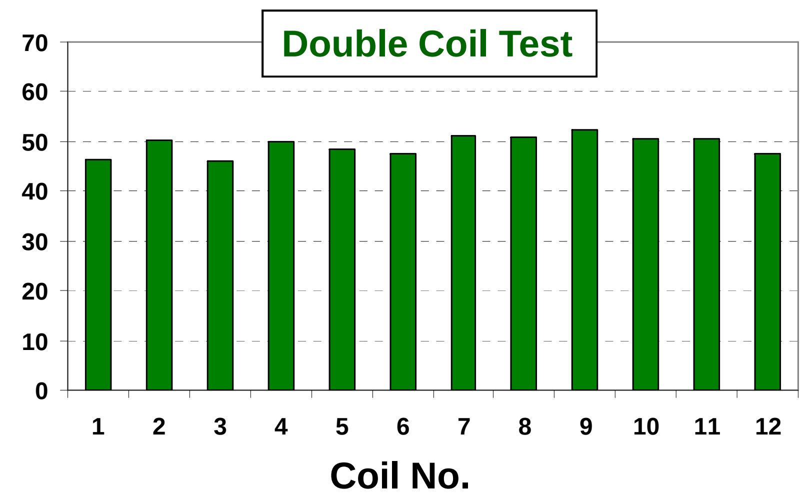
LN_2 (77 K) Test of 25 BSCCO 2223 Coils

Superconducting
Magnet Division

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.
It shows that the HTS coil technology is now maturing !

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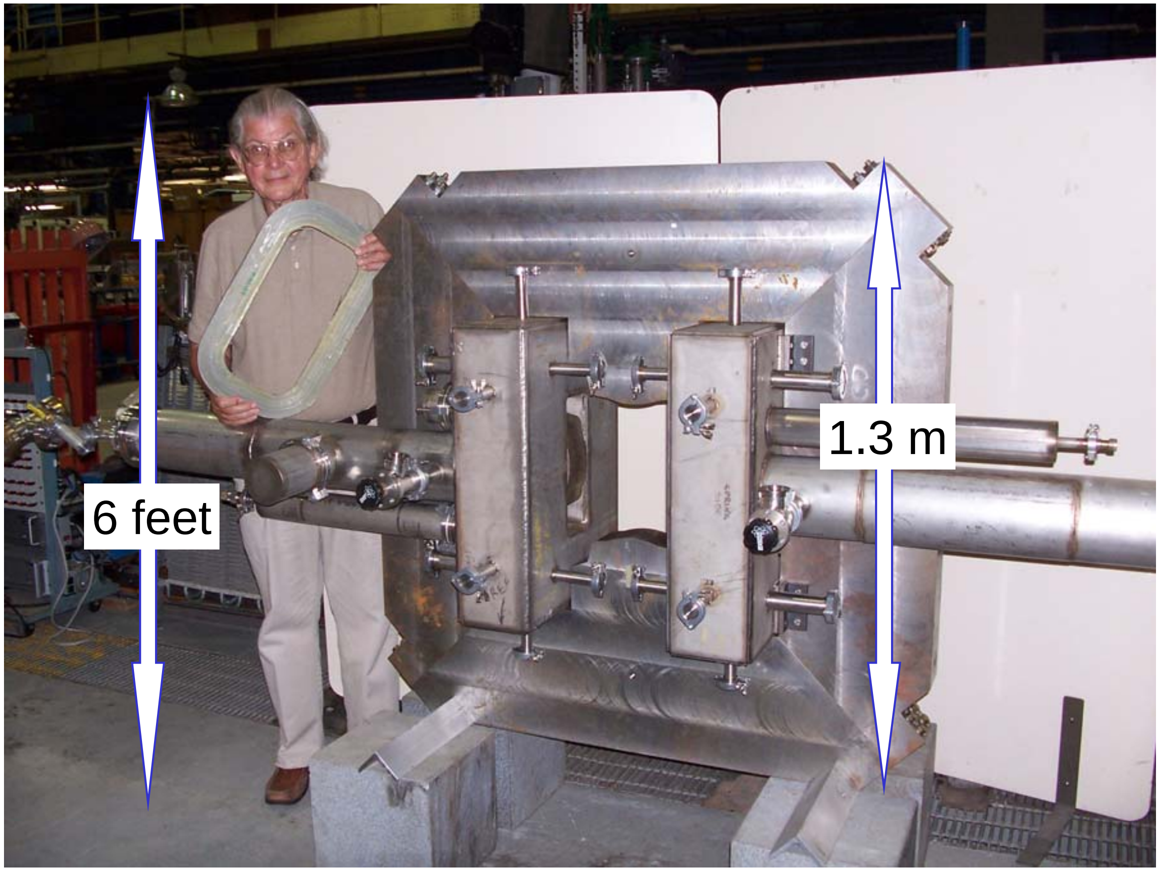
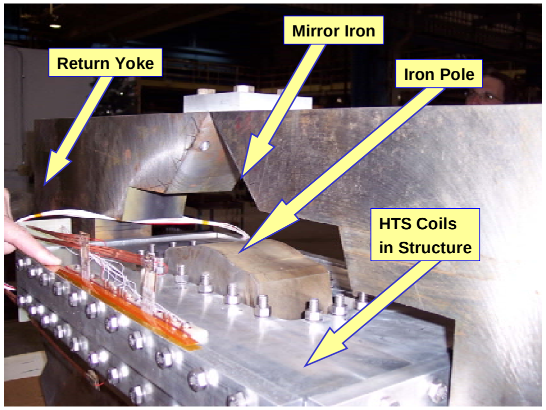
Various Magnet Structures of RIA Quad (a part of step by step R&D program)

Unique Features of RIA HTS Quad :

- Large Aperture, Radiation Resistant





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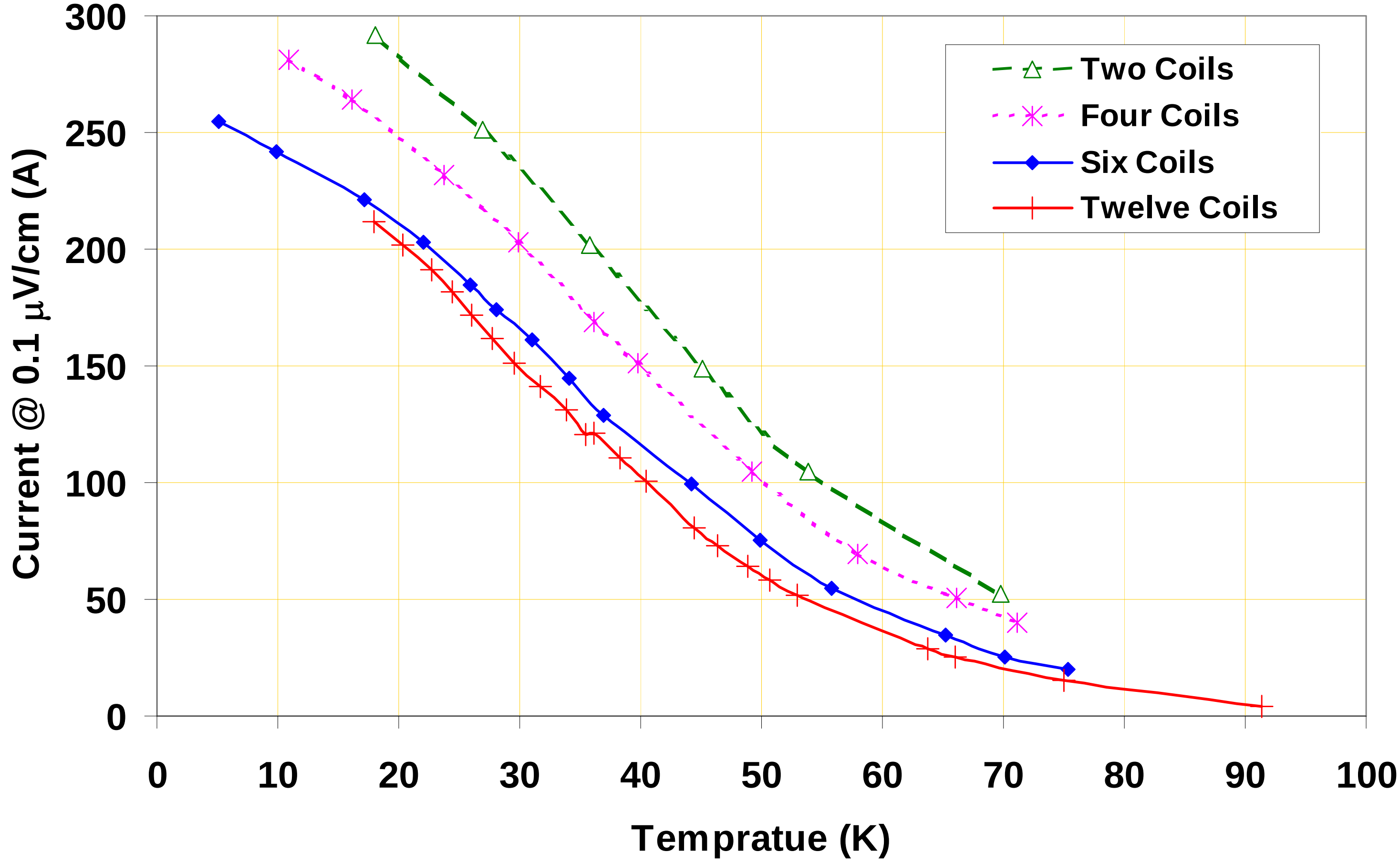
Superconducting Magnet Division

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

Courtesy/Contributions Sampson

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.

High field solenoid

High Field Muon Collider Solenoid
SBIR with PBL (Particle Beam Lasers)

- A forward looking collaborative SBIR program between PBL & BNL.
- PBL brings ideas with highly respected individuals (most working part time)
  - Some of them are: Bob Weggel, Bob Palmer, Ron Scanlan (in magnets) and Al Garren, David Cline, Jim Kolonko (in accelerators)
- BNL contributes its staff, ideas, facilities and past experience with HTS and AP.
- There is not enough funding in one SBIR to build 35-40 T solenoid. So why not attempt to build it with several serial SBIRs. It provides a natural segmentation for Lorentz force purpose and allows lessons learnt from one to transfer to other.
- Currently there are two funded Phase 2 SBIR : (1) ~100-165 mm, ~10 T solenoid and (2) 25-95 mm ~12 T insert solenoid.
- There is also one important upcoming Phase 1 proposal for Nb_3Sn > 165 mm outsert solenoid with hope that with Phase 1 this year and Phase 2 funding next year, all three will attempt to make a short 35-40 T superconducting solenoid.

Unique Features of Phase 1 Nb_3Sn Solenoid Proposal

- High field Nb_3Sn solenoid have been primarily built with CICC technology.
- CICC is proven technology. However, it offers a relatively lower J_w as compared to the Rutherford cables, used in accelerator magnets.
- Higher J_w offers many advantages. However, industry is more likely to use this technology after it is proven in solenoids.
- One purpose of this SBIR is to do just that - that will be a significant contribution to high field solenoid technology in itself.
- Another purpose of this SBIR is to build the outsert to build 35-40 T solenoid with other two segments coming from previous two SBIR.

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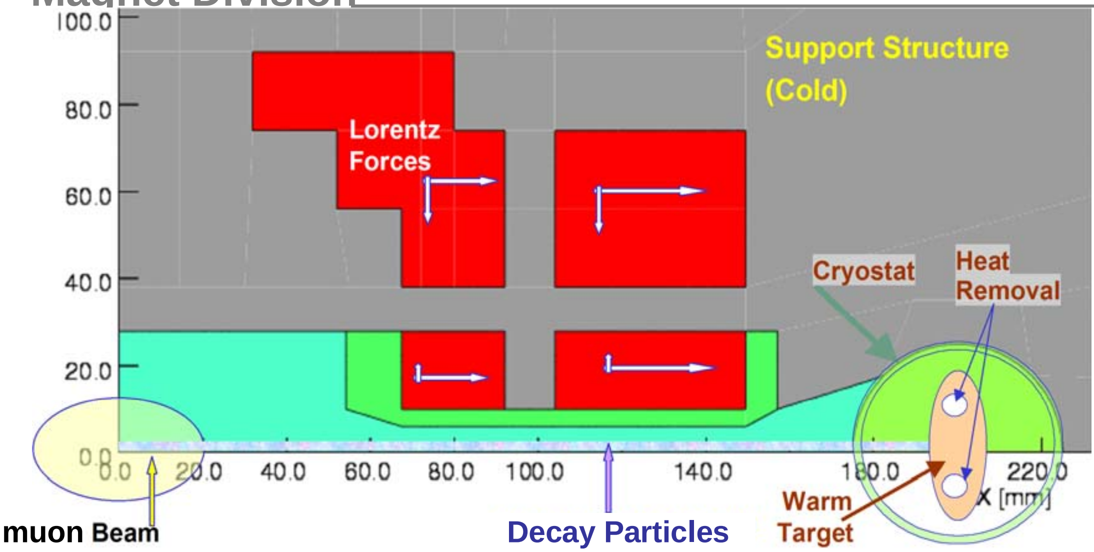
Superconducting Magnet Division

HTS Open Midplane Dipole SBIR (Another BNL/PBL collaboration)



- An ideal open midplane design will have no structure on the midplane.
- Use of HTS (a) will allow very high magnetic fields (20 T or above) and (b) can tolerate high heat loads).
- Higher field will allow higher energy and/or higher luminosity.

- Significant progress was made during LARP funding
- A conceptual engineering design was developed which showed how to deal with Lorentz forces, assemble coils and magnet, remove large heat loads and obtain good field quality.
- This has been recognized as a topic of interest by muon collider collaboration and has been placed in DOE SBIR solicitation list.
- Phase 1 is to study this for muon collider and Phase 2 to test key issues.

Summary

- The development of open midplane design is important to $\mu^+\mu^-$ colliders, as large number of decay particles at the midplane may limit the performance of superconducting coils and/or increase the operating cost of the machine.
- The design concept has been significantly developed under LARP funding. Now, we can have a truly "Open Midplane" design with a way to deal with Lorentz forces and obtain a good field quality, as well.
- HTS plays an important role in high field open midplane design. HTS can generate very high fields and can tolerate and remove large heat loads.
- It has been shown that HTS magnets can be designed, built and operated in presence of a large radiation and heat load environment.
- Combined function magnet design with skew quadrupole offers an interesting possibility. Such magnets and lattice has been designed.

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