BNL Magnet Program Related to Muon Collider

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Areas of Interest

1. **High Field Solenoids**
   - **Collaborative work with PBL - funded under a series of SBIR**
   - **Target field 35-40 T in an all superconducting solenoid (HTS+LTS)**
2. **Open Midplane Dipole**
   - **Significant progress was made in the design under LARP funding**
   - **Intellectual and design experienced is directly useful to *Muon Collider***
3. **Radiation Damage and Energy Deposition Studies**
   - **Crucial to HTS Quad for FRIB (Facility for Rare Isotope Beams)**
   - **Ongoing R&D with significant results (work performed under DOE-NP)**

High Field Solenoid with PBL

A few key players:

- **PBL: Bob Weggel, Ron Scanlan, Jim Kolonko, David Cline, Al Garren, …**
- **BNL: Bob Palmer, Harold Kirk and staff of Superconducting Magnet Division**

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

Collaboration:

- A useful collaborative program between PBL & BNL to develop high field superconducting solenoid technology for muon collider.
- PBL brings ideas and funding through SBIR.
- BNL contributes its staff, ideas, facilities and past experience with HTS.

Overall program philosophy and strategy:

- There is not enough funding in one SBIR to build 35-40 T solenoid.
- However, this could be done with a series of SBIR with each attractive in its own right.
- This approach also provides a natural segmentation which is anyway needed to reduce accumulation of stress/strain on the conductor due to Lorentz forces.
- It also allows lessons learnt from one SBIR (year) to apply to the next.

Components of 35-40 T Solenoid

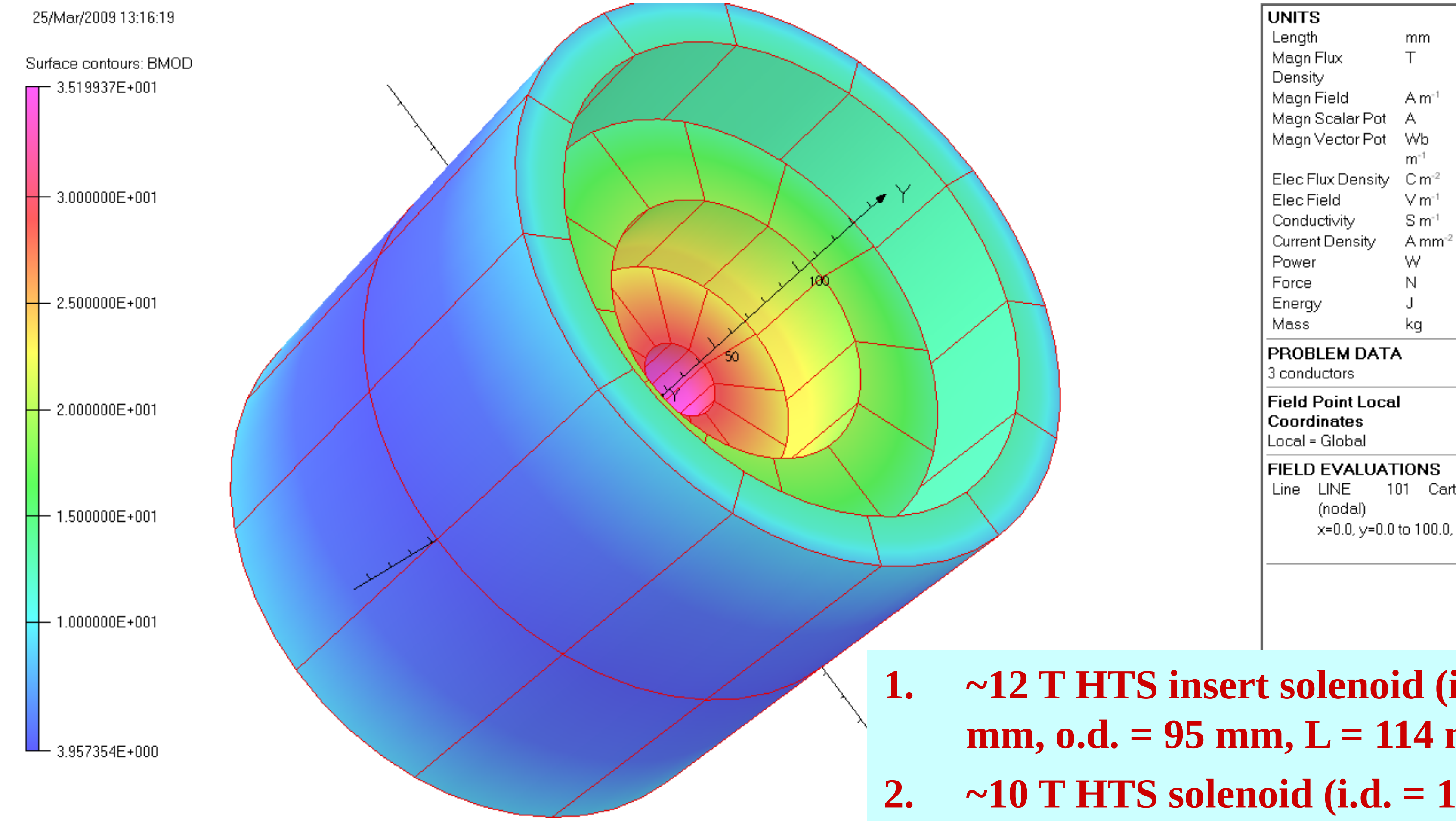
SBIR proposals from PBL:

1. Phase II #1, 08-10 (funded): ~10 T HTS solenoid (i.d.=100 mm, o.d.=165 mm, L ~128 mm)
2. Phase II #2, 09-11 (funded): ~12 T HTS insert (i.d. = 25 mm, o.d. = 95 mm, L ~64 mm)
3. Phase 1, 10-11 (proposed): 12-15 T Nb_3Sn outsert (i.d.=180 mm,o.d.=210$^+$ mm,L = 200$^+$mm)

Overall programmatic features:

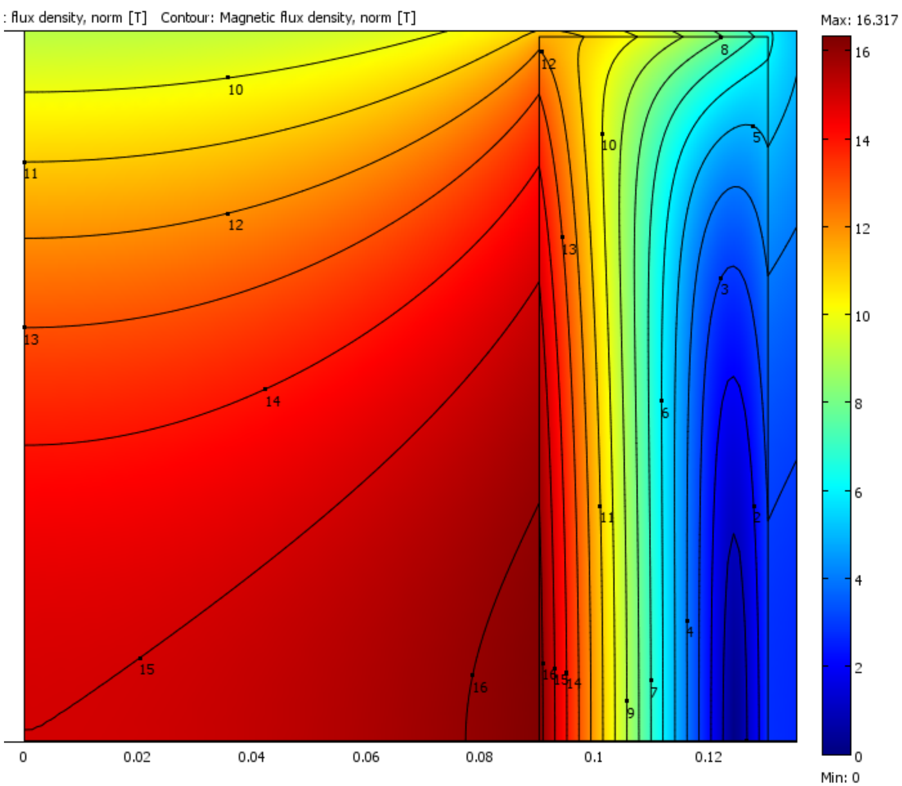
- The dimensions of all solenoids have been carefully chosen so that one fits inside the other and the two HTS solenoid (generating 20+ T) fit inside the NHFML ~19 T resistive solenoid.
- As a part of the Phase II SBIR #2, we will test the above ~20+ T HTS solenoid in the background field of NHFML ~19 T resistive magnet to reach fields approaching 40 T.
- Then, as a part of the third SBIR (currently a Phase I proposal), we would build a Nb_3Sn solenoid made with Rutherford cable and incorporate above 20+T HTS inside.
- Thus above will make a 35-40 T all superconducting solenoid to demonstrate the technology.

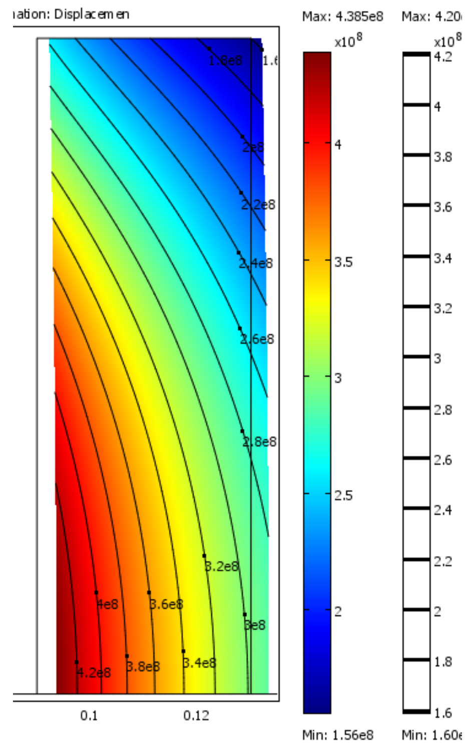
Preliminary Design with 12 T Nb_3Sn outsert



1. ~12 T HTS insert solenoid (i.d. = 25 mm, o.d. = 95 mm, L = 114 mm)
2. ~10 T HTS solenoid (i.d. = 100 mm, o.d. = 165 mm, L = 128 mm)
3. ~12 T Nb_3Sn outsert (i.d. = 180 mm, o.d. = 215 mm, L = 200 mm)

15 T Nb_3Sn Preliminary Design





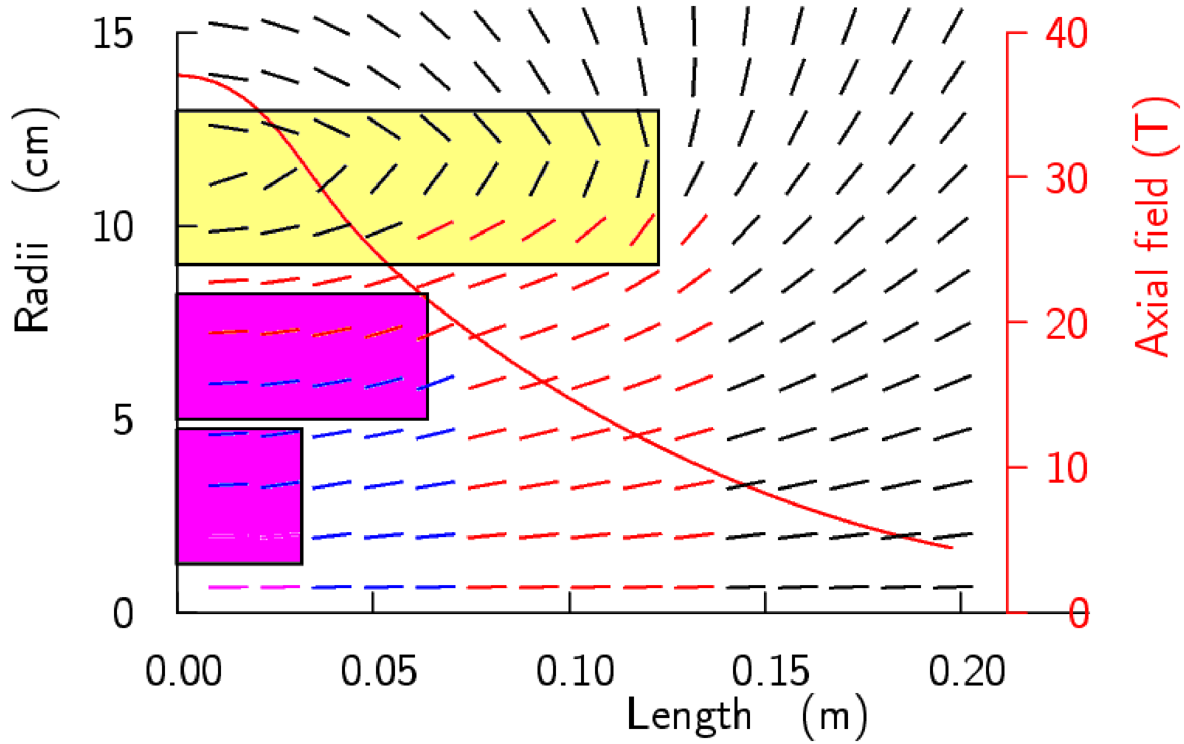
(from Phase 1 SBIR Proposal)

Courtesy Bob Weggel

15 T Nb_3Sn example; Left: Field $|B| \equiv (B_r^2+B_z^2)^{½}$ of solenoid of I.D. = 180 mm, O.D. = 260 mm; Length = 246 mm; Overall current density = 400 A/mm²; Central field = 15.00 T; Maximum field = 16.32 T; Energy = 914 kJ. Right: Stresses and deformation. Von Mises stress, $\sigma_{vM} \equiv ½\,[(\sigma_r-\sigma_\varphi)^2 + (\sigma_r-\sigma_z)^2 + (\sigma_\varphi-\sigma_z)^2]^{½}$, ranges from 156 MPa (= 23 ksi) to 438 MPa (= 64 ksi). Total deformation, $\Delta R \equiv (\Delta r^2 + \Delta z^2)^{½}$, with Young's modulus of 100 GPa (= 14.5x10^6 psi), ranges from 0.262 mm to 0.363 mm.

Layout of Three Solenoids

Courtesy
Bob Palmer

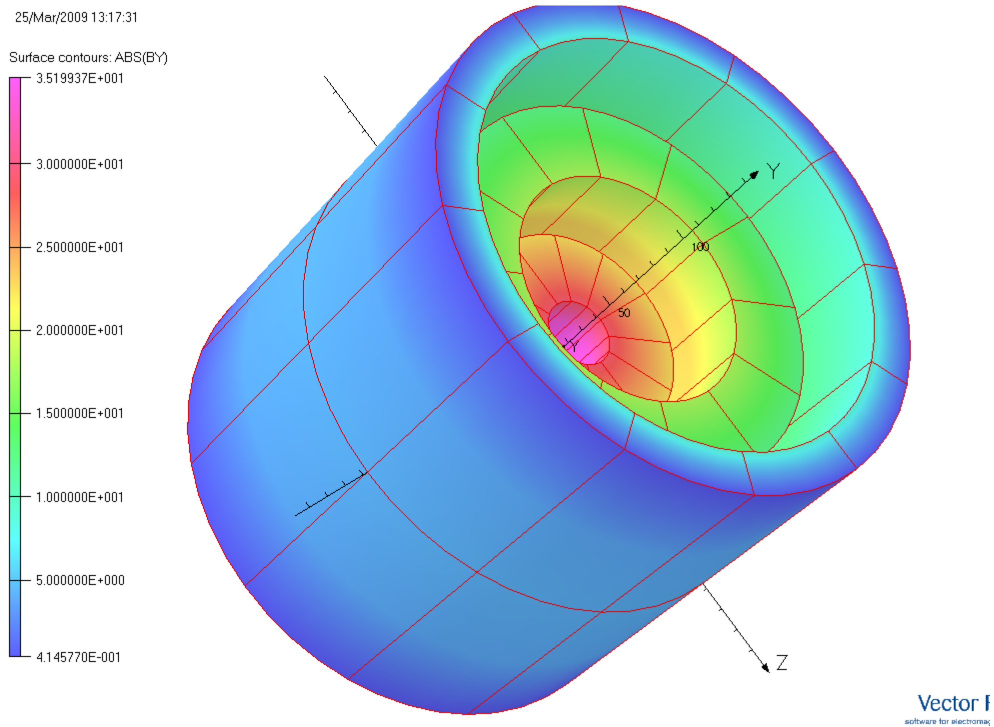


Field directions and axial fields for the combined magnet using the Nb_3Sn coil (yellow) and the two YBCO coils (magenta)

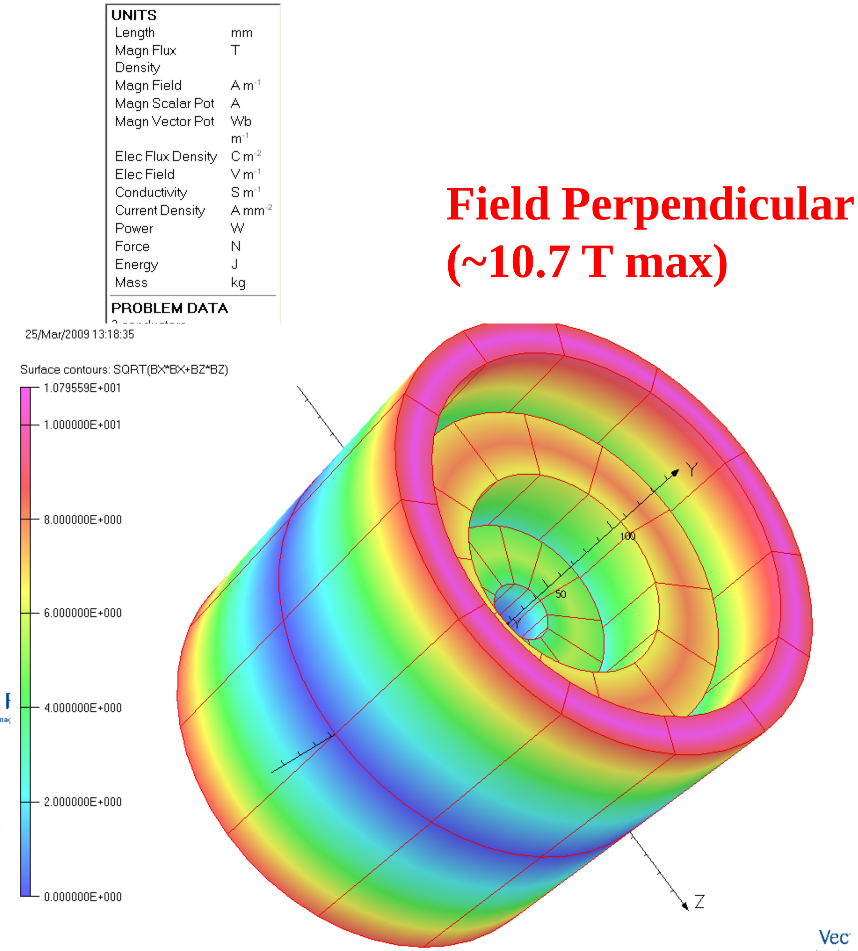
Angular Field Dependence of Ic is in Helpful Direction

Field Parallel (~35.2 T, max)

Inner two are HTS coils and outermost is Nb3Sn



Field Perpendicular (~10.7 T max)



2G HTS carry significantly more current in field parallel direction than in field perpendicular

Bi2212 HTS Insert Solenoid

- Bi2212 round wire is isotropic. It carries the same current density in the field parallel direction as in field perpendicular direction (or in any other direction).
- The original SBIR proposal included a Bi2212 insert solenoid as well.
- However, that was dropped because of the reduced funding allocation.
- Moreover, Bi2212 is being pursued as a part of the national program.
- There is a proposal to replace YBCO insert by Bi2212 insert (built elsewhere).
- It is possible that a combination of Bi2212 and YBCO HTS, along with an outer Nb_3Sn coil, might provide an overall attractive solution.

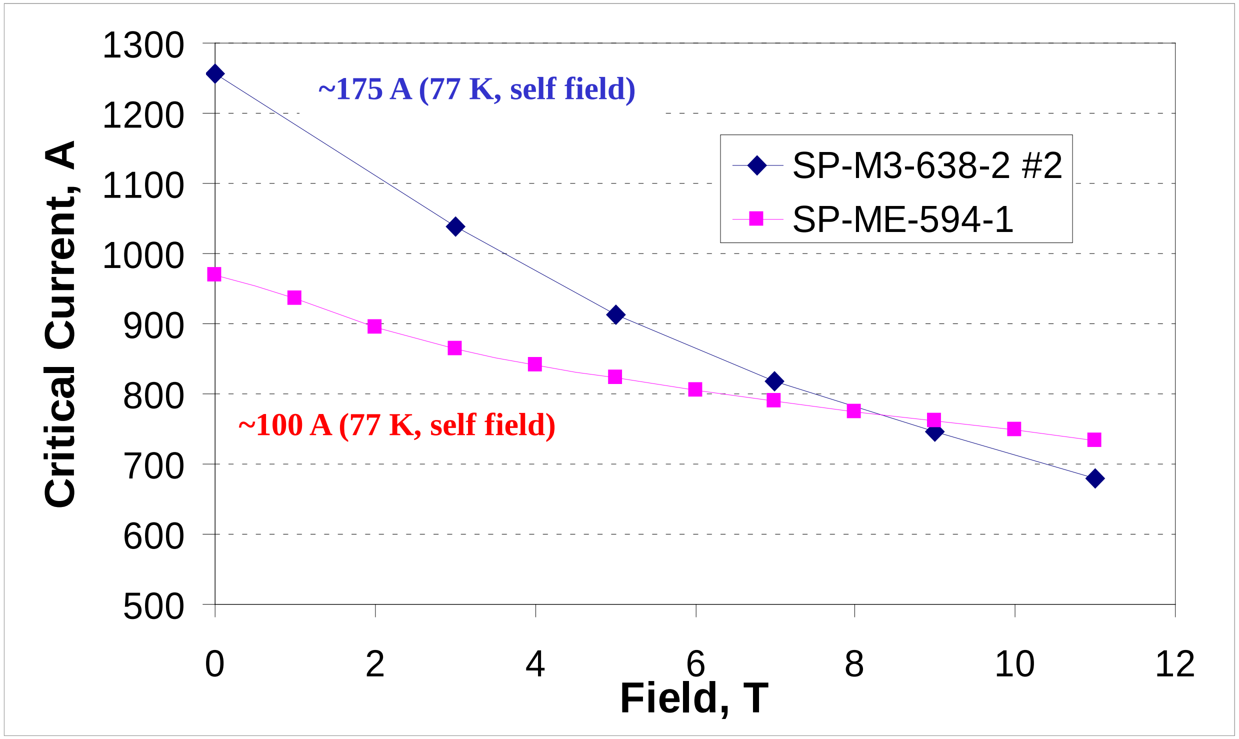
Status of HTS Solenoid

- High Ic conductor (~165 A, 77 K self-field, on average – spec was 100 A) and high field (advanced pinning) conductor purchased from SuperPower in the first year. Over 1 km has been delivered and the rest is coming soon (making it 1.6 km).
- Test results from the conductors (next slide).
- FRIB/RIA coils and MgB2 solenoid have already been built and tested for several key construction features (including the measurement of performance as a function of current).
- Solenoid winding with pancake coils is starting soon.
- More conductor order (1. 4 km) has been placed for the second year.
- Above order is being increased by another 1 km for the second Phase 2 SBIR.

- Total conductor purchased: ~4 km.

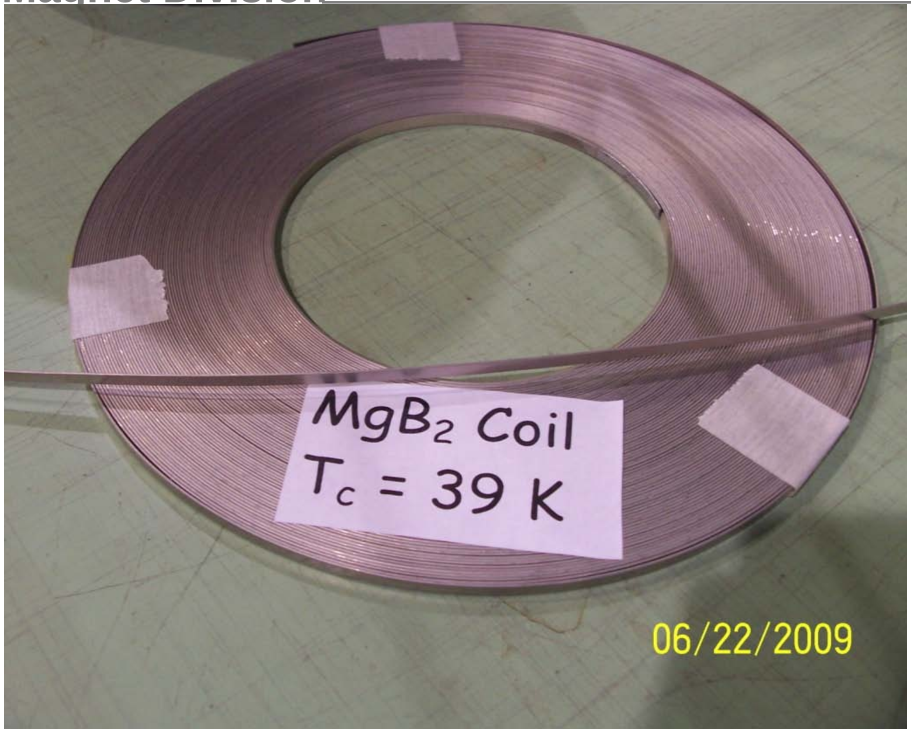
Critical Current Measurements at 4K as a Function of B// in SuperPower Wire

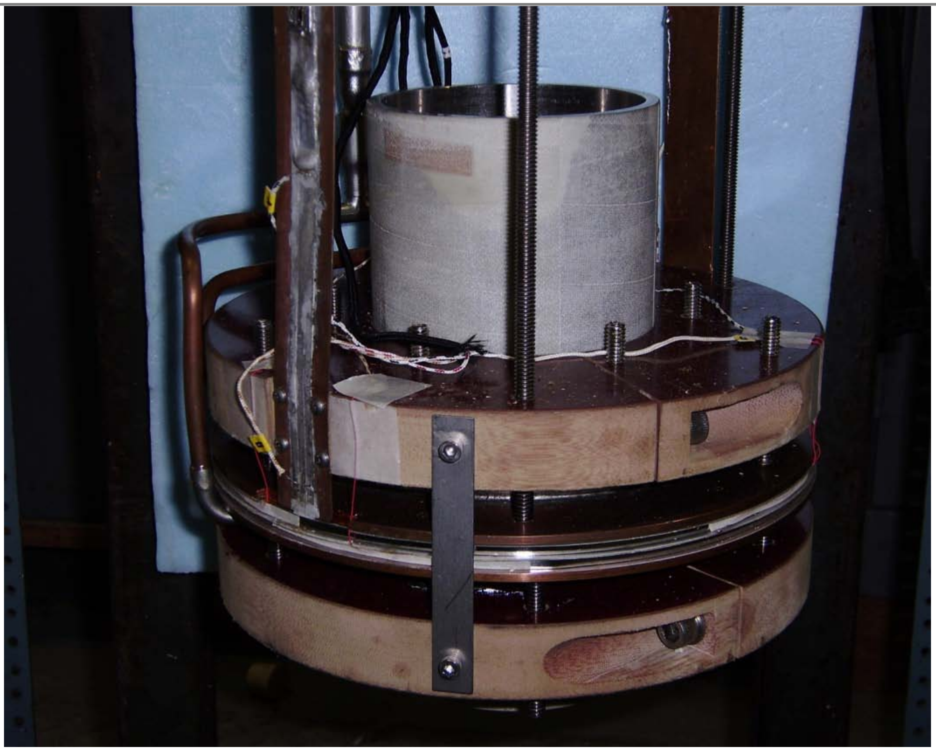
Two 2G wires from different production



- **Wire chemistry influences the field dependence.**
- **But what happens to the angular dependence?**

MgB_2 Solenoid made with Conductor from COLUMBUS SUPERCONDUCTORS SpA

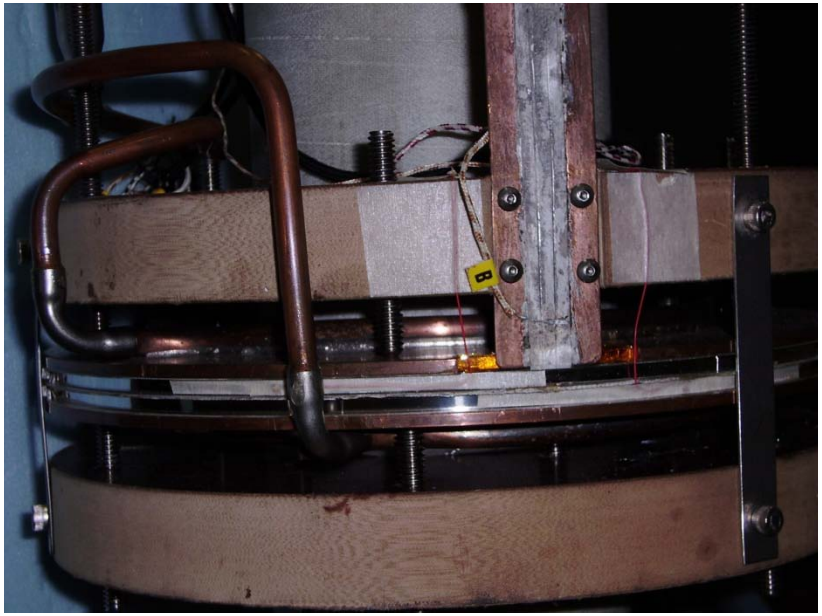


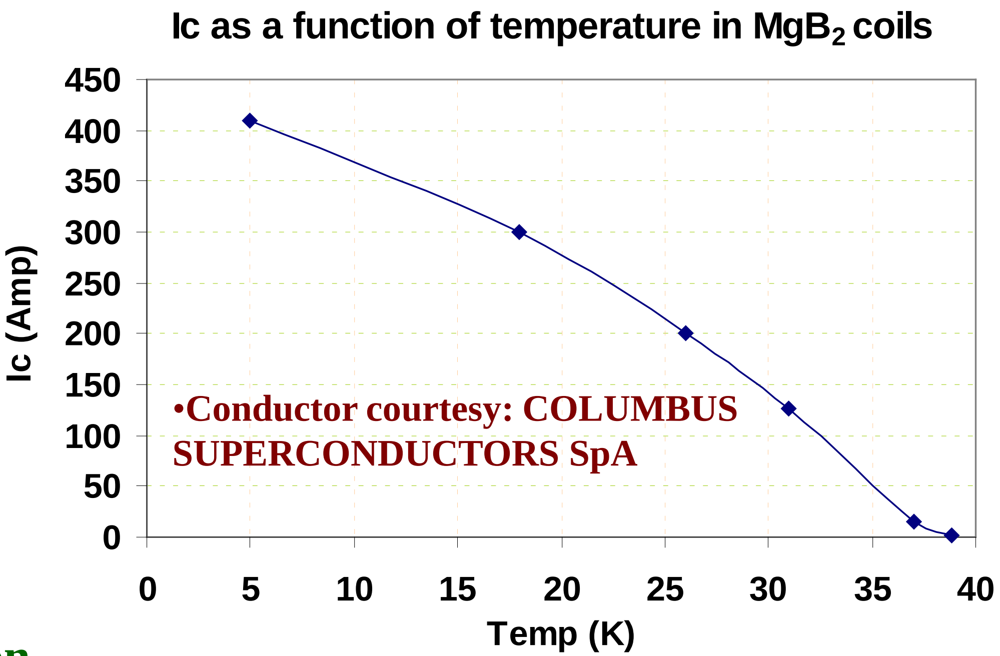


- Coil i.d. = 100 mm
- Coil o.d. = 200 mm
- Numbers of turns = 80

- MgB_2 Solenoid with a double pancake coils.
- Same i.d. as in the HTS solenoid.
- Several aspects of the design and technology tested.

MgB_2 Solenoid
Critical Current as a Function of Temperature





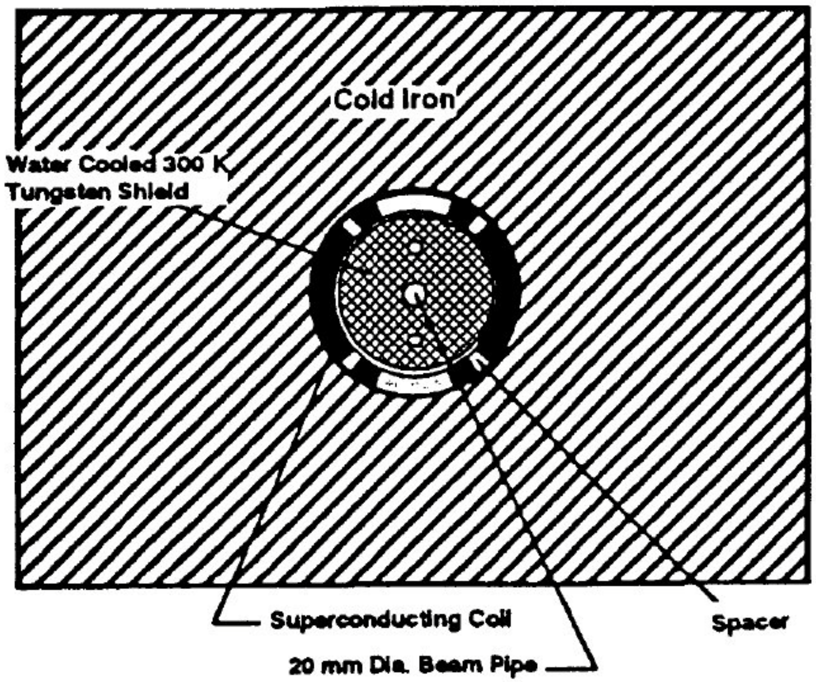
- Top and bottom plates are conduction cooled with the helium gas.
- Helium flow is adjusted to vary the temperature.
- Similar studies (Field vs. temperature) are planned in the HTS solenoid.

- ~1.3 T peak field
- 100 A => ~0.31 T

Progress in Open Midplane Dipole Design

(work performed under the auspices of LARP)

Motivation for Open Midplane Dipole Design

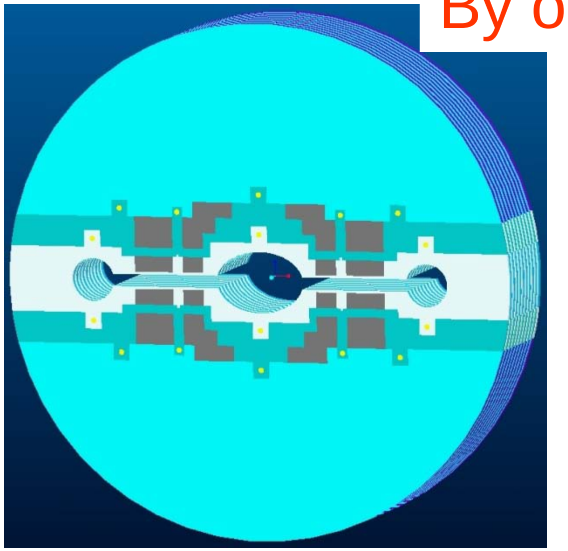


Conventional cosine theta design with Tungesten Liner

- **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 previous open midplane dipole designs were trapped in non-superconducting material at the midplane. Different versions of this design have been examined earlier by M. Green and P. McIntyre, etc.**

In the proposed open midplane design, there will be no structure at the midplane.

Why a True Open Midplane Design?



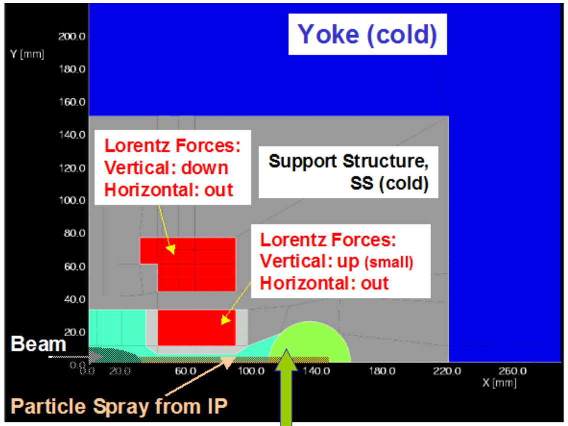
By open midplane, we mean truly open midplane:

- 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.

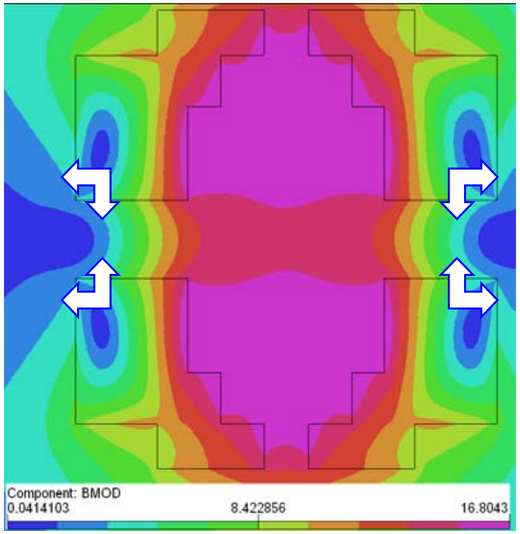
- Those designs, though avoided a direct hit from primary shower, created secondary showers in that other structure. The secondary shower then deposited a significant amount of energy in the superconducting coils.

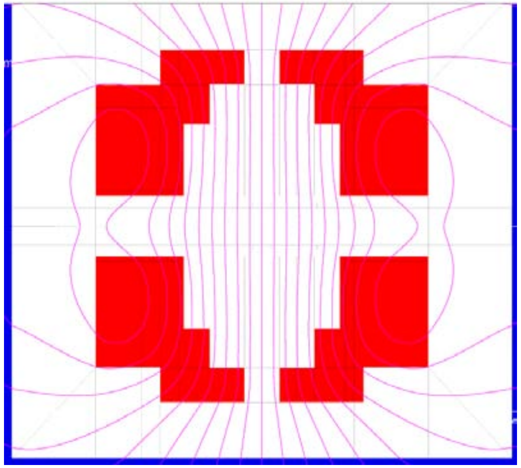
- Earlier designs, therefore, did not work as well in protecting coils against large energy deposition.



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 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?

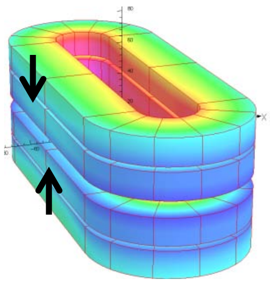
#2 The ratio of peak field in the coil to the design field appears to become large for large midplane gaps.

#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.**

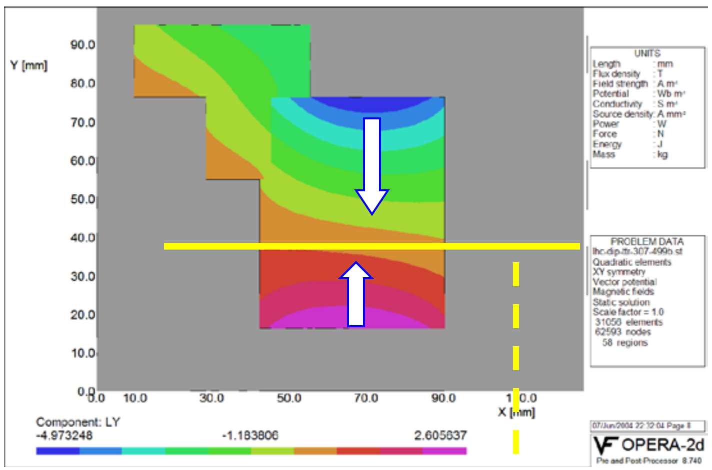
Challenge #1: Lorentz Forces between coils

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.

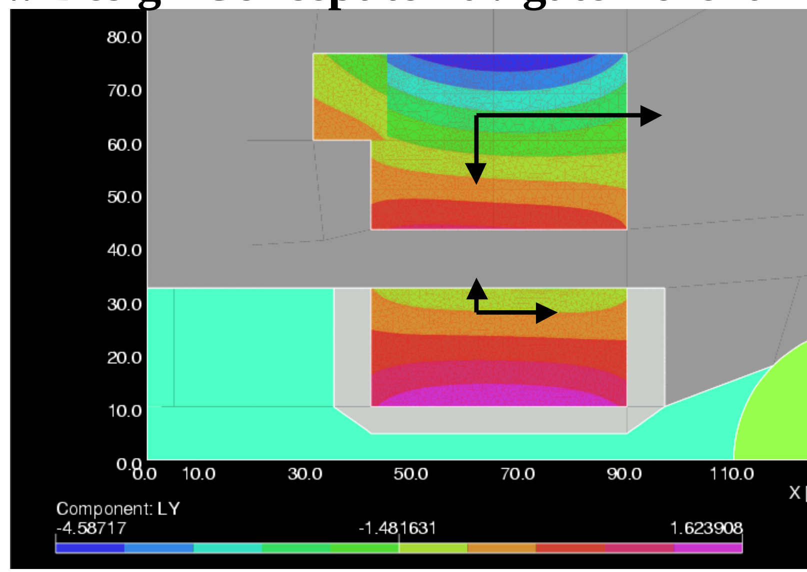
Original Design



Zero vertical force line

Lorentz force density (Vertical)

New Design Concept to navigate Lorentz forces

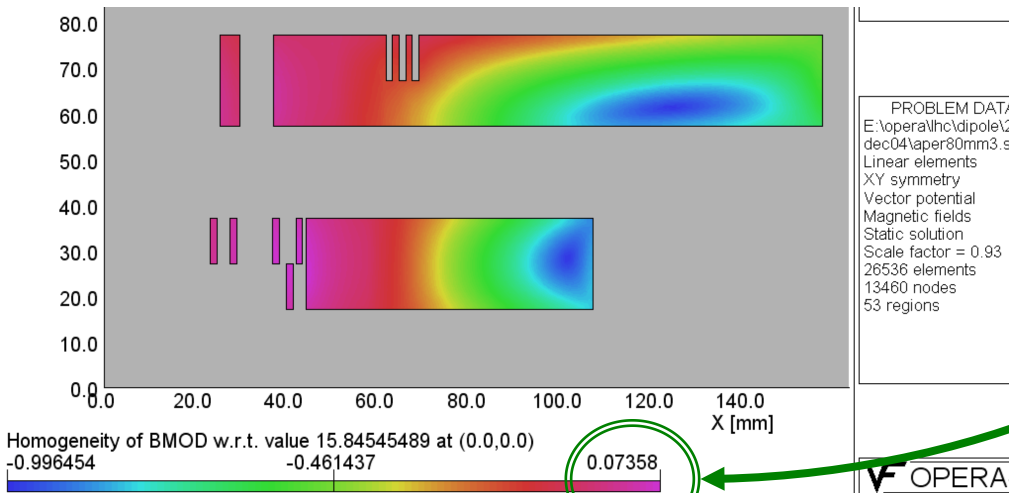


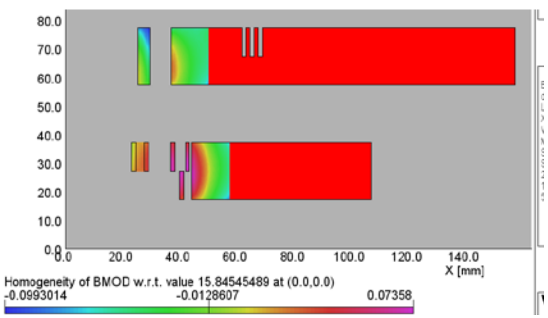
Since there is no downward force on the lower block (there is slight upward force), we do not need much support below if the structure is segmented. The support structure can be designed to deal with the downward force on the upper block using the space between the upper and the lower blocks.

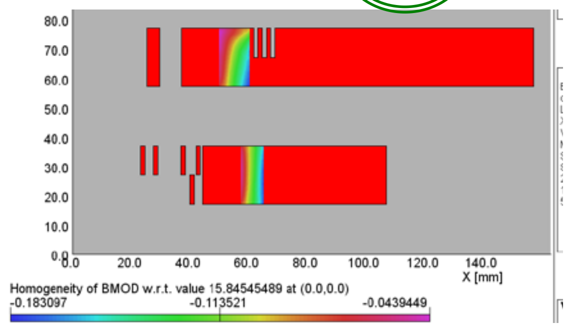
Challenge #2: Peak Field

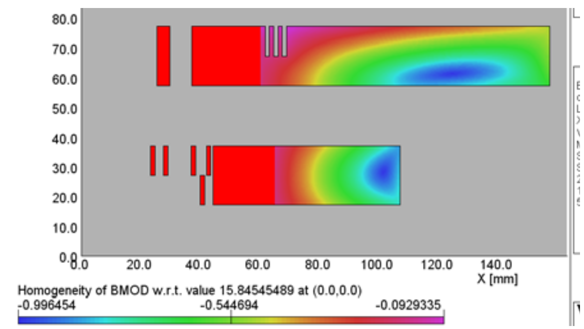
Several designs have been optimized with a small peak enhancement: ~7% over B_o

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

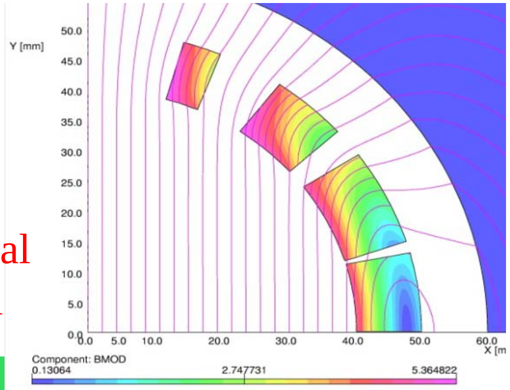
Challenge #3: Field Quality

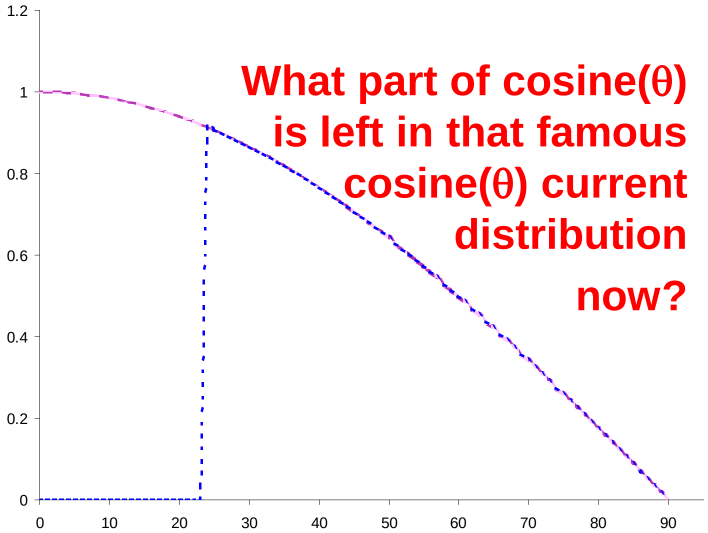
Coil-to-coil gap in this design = 34 mm (17 mm half gap)

Horizontal aperture = 80 mm

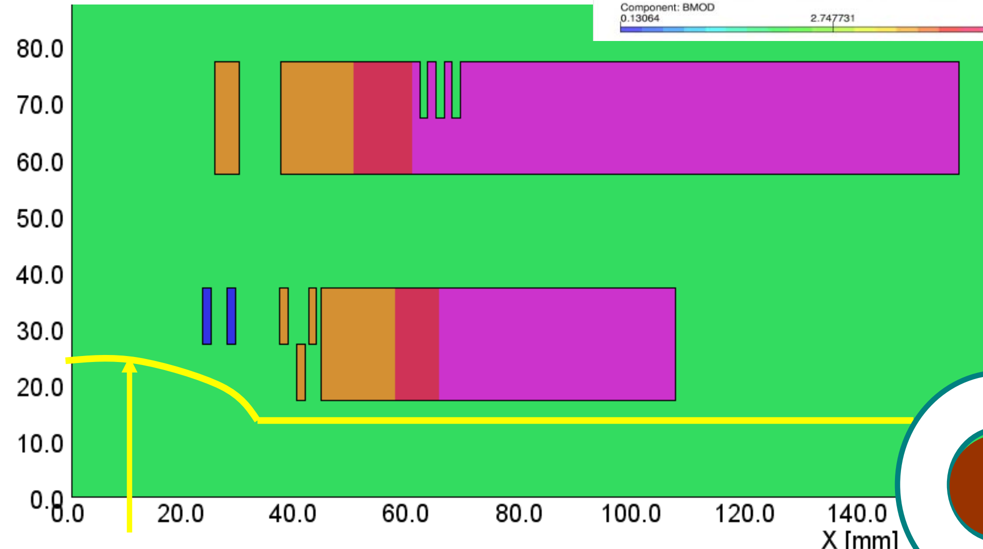
⇒ Vertical gap is > 42% of horizontal aperture (midplane angle: 23°)

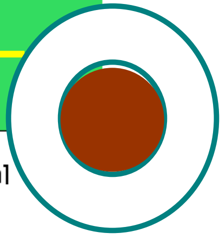
Conventional cosine theta





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





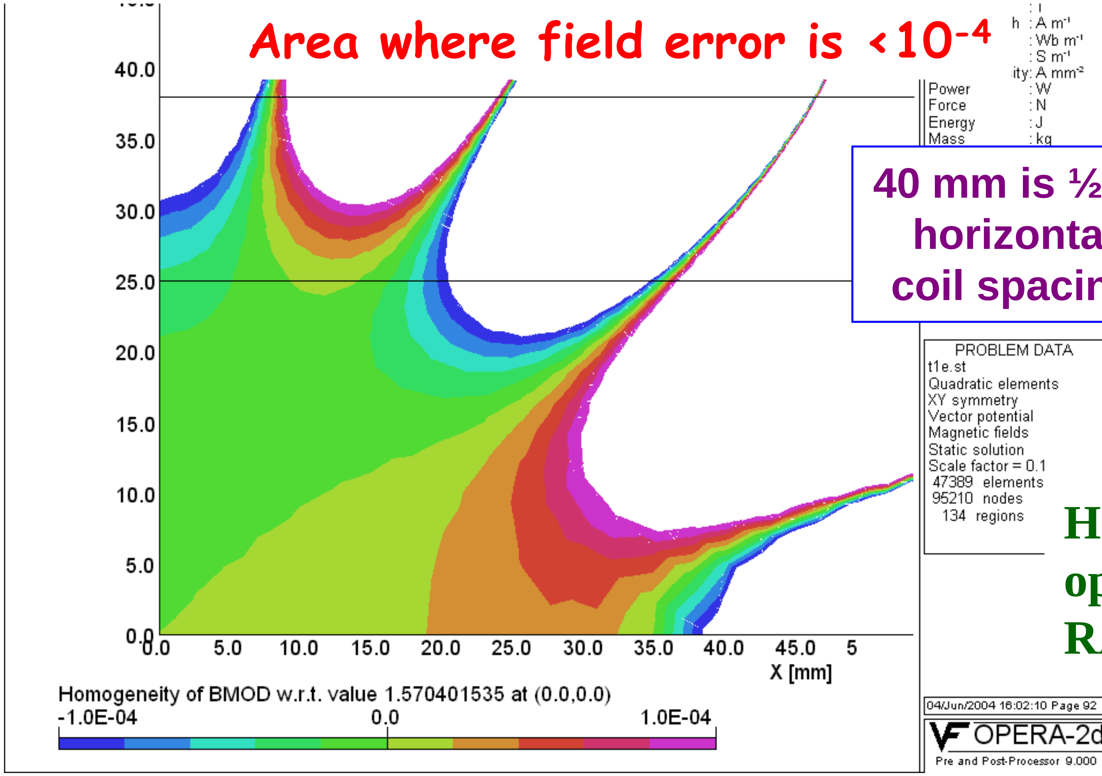
This makes obtaining high field and high field quality a challenging task !

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:



Harmonics optimized by RACE2dOPT

(Beam @ x=+/- 36 mm at far end)
(Max. radial beam size: 23 mm)

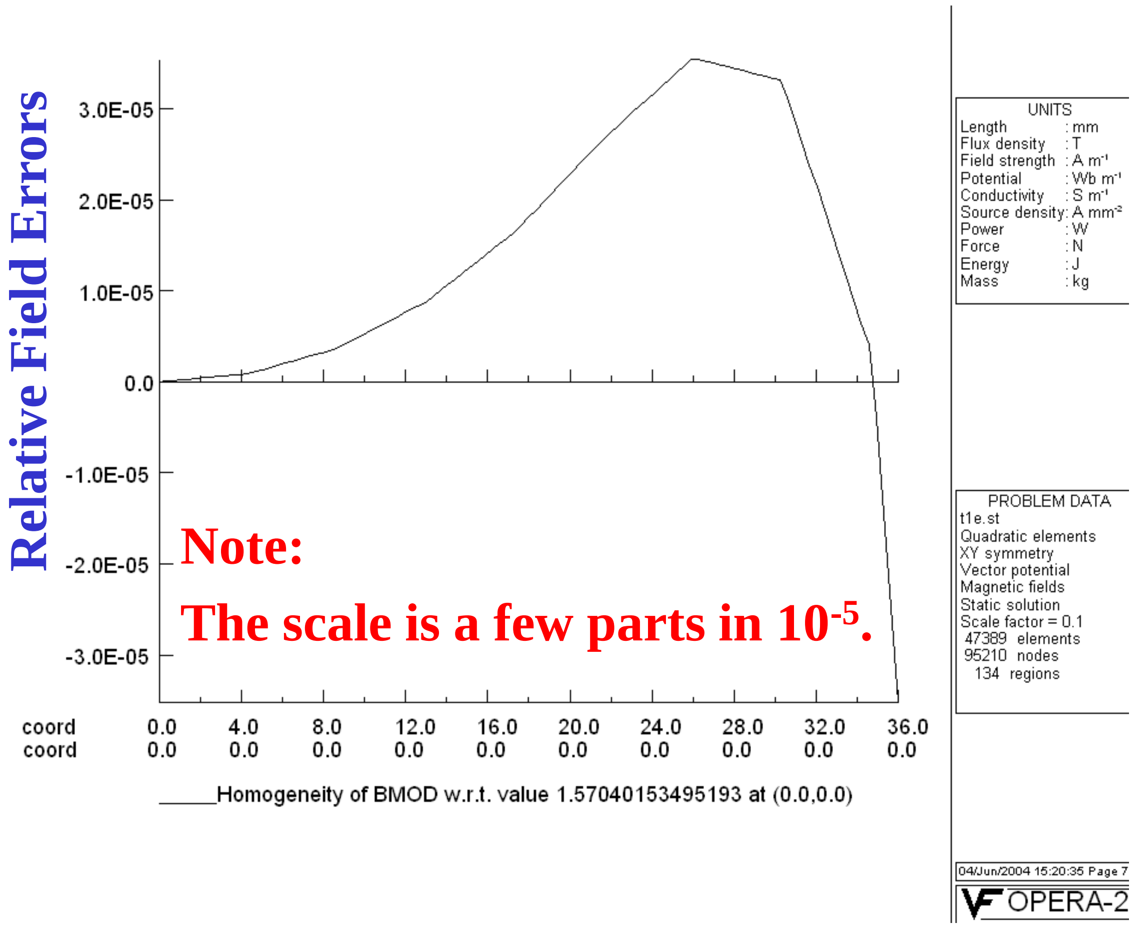
Geometric Field Harmonics:

	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

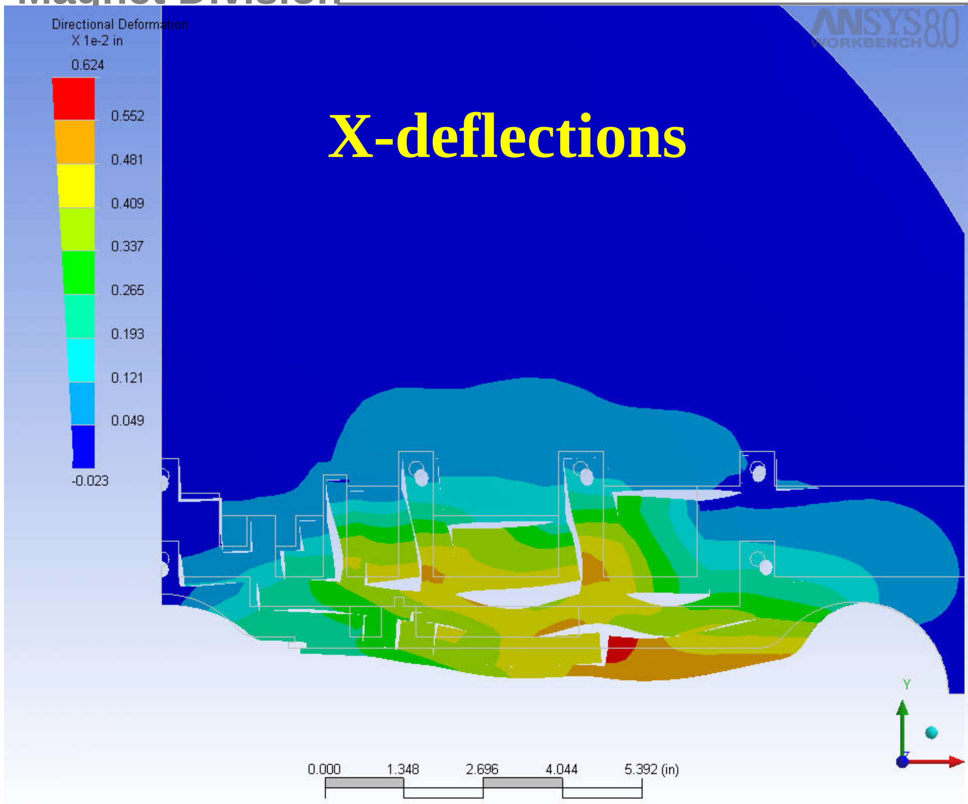
Proof that good field quality can be obtained in such a wide open midplane dipole design:

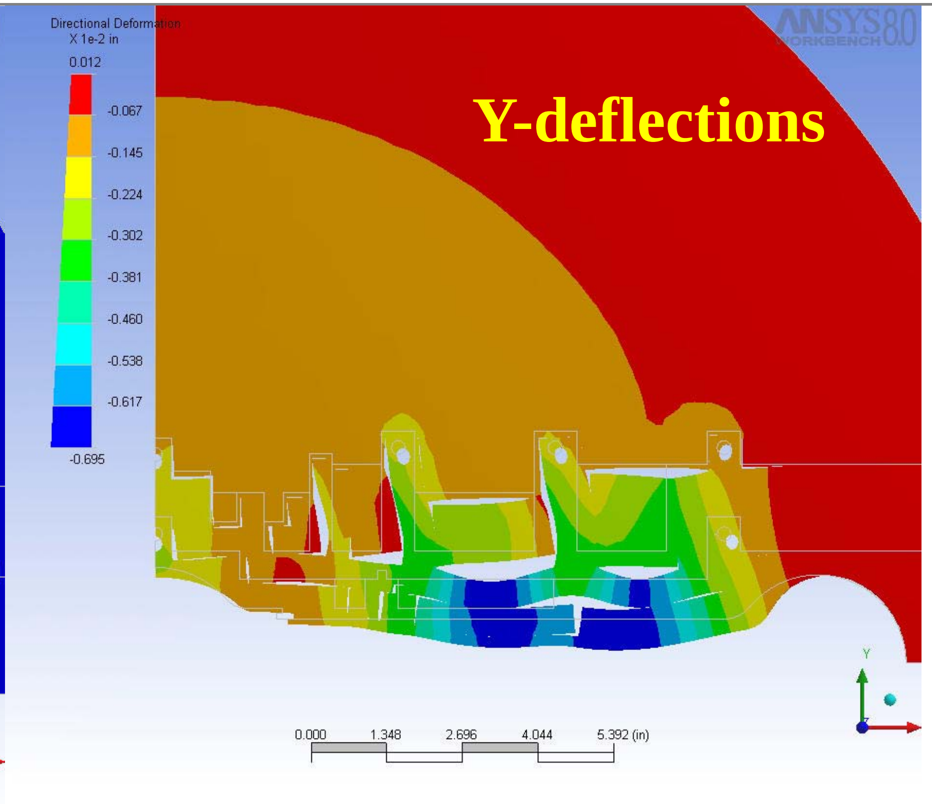


The maximum horizontal displacement of the beam at the far end of IP is +/- 36 mm.

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

Mechanical Analysis

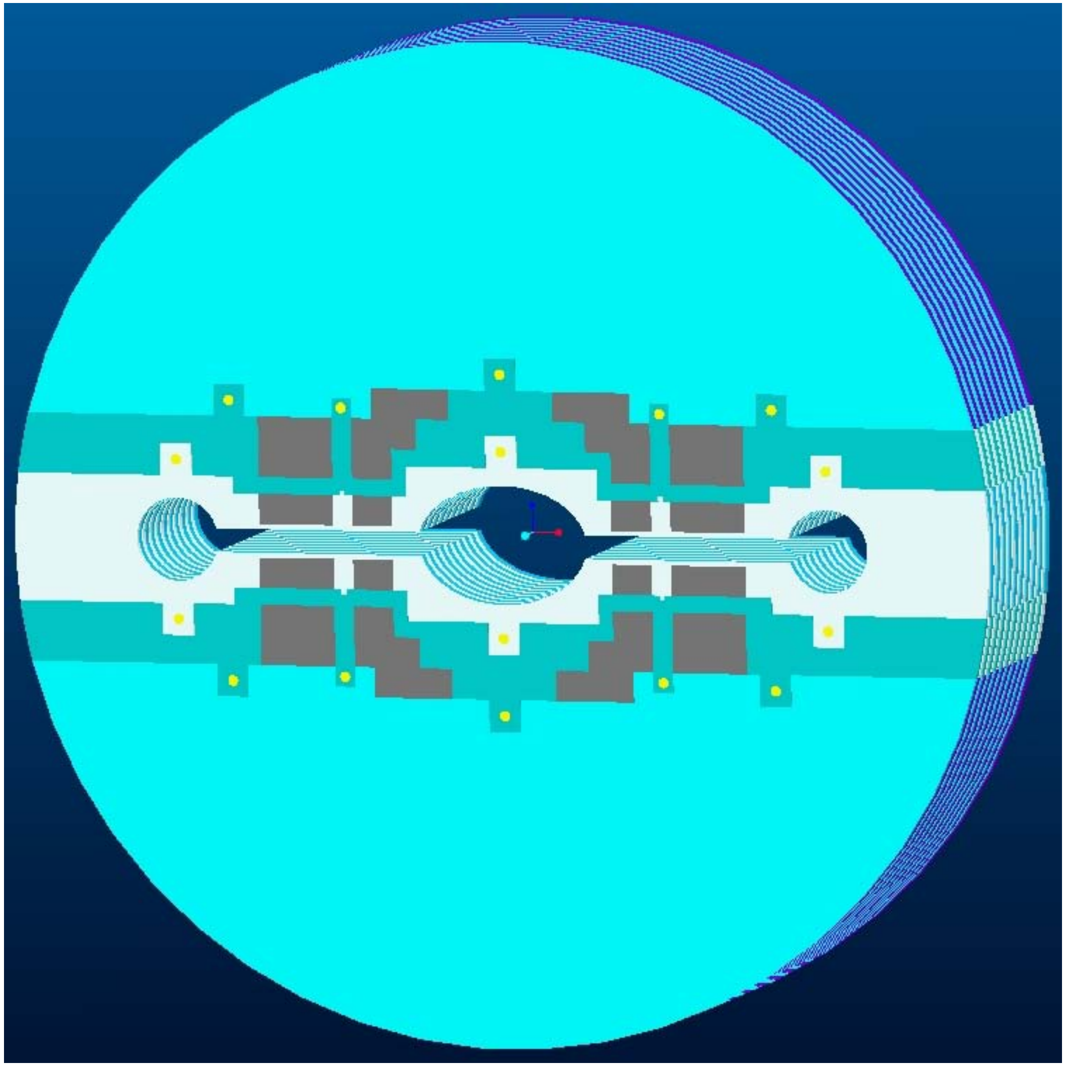




In the present design the relative values of the x and y deflections are 3-4 mil (100 micron) and the maximum value is 6-7 mil (170 micron).

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

Mechanical Assembly



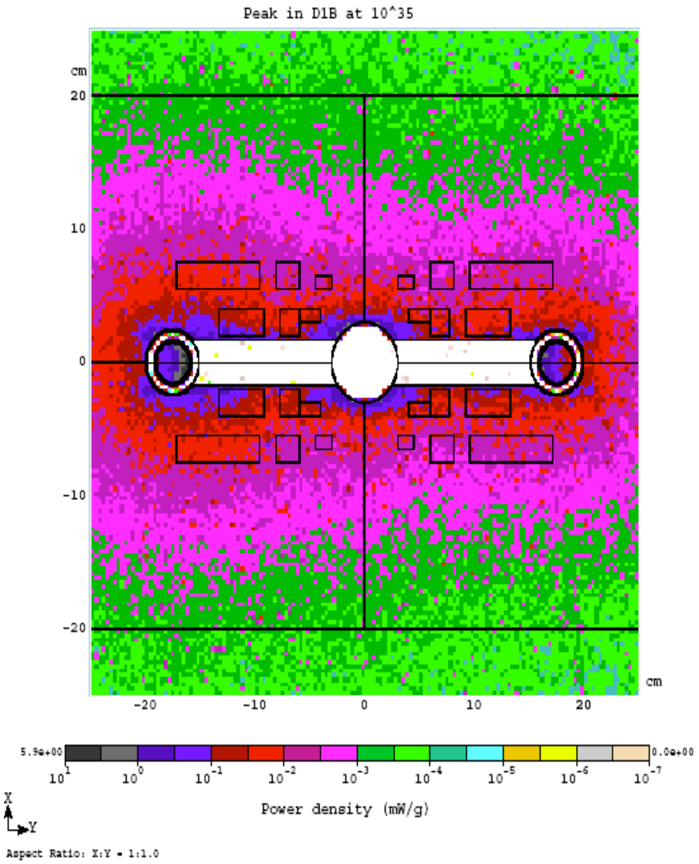
- Several possible assembly concepts for the open midplane dipole design were examined.

- 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

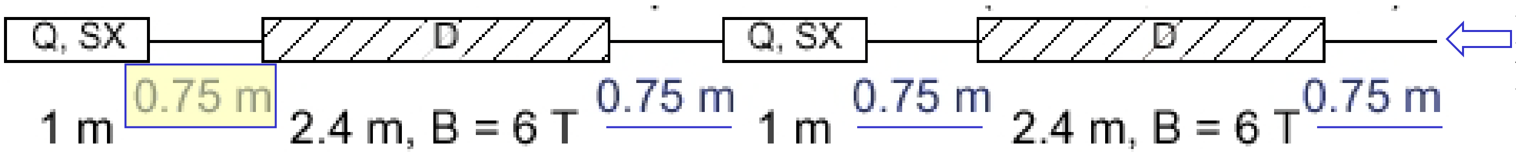
For more information (publications + talks): http://www.bnl.gov/magnets/Staff/Gupta/

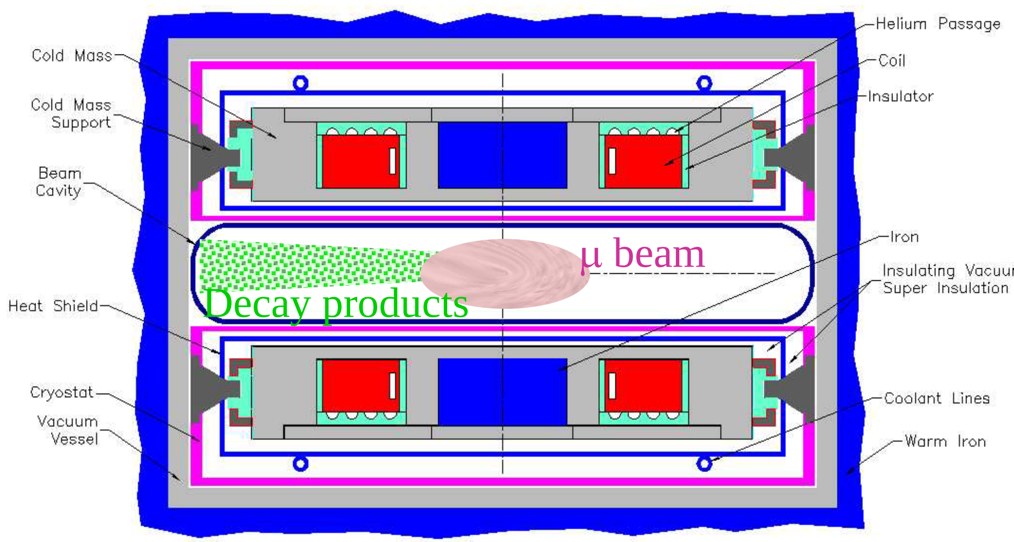
Combined Function Open Midplane Design with Skew Quadrupole Lattice

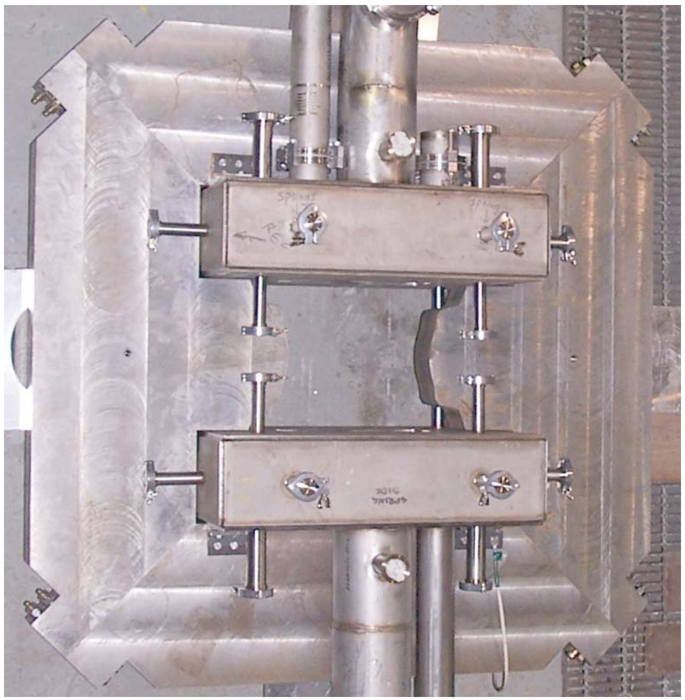
(developed under BNL LDRD)

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



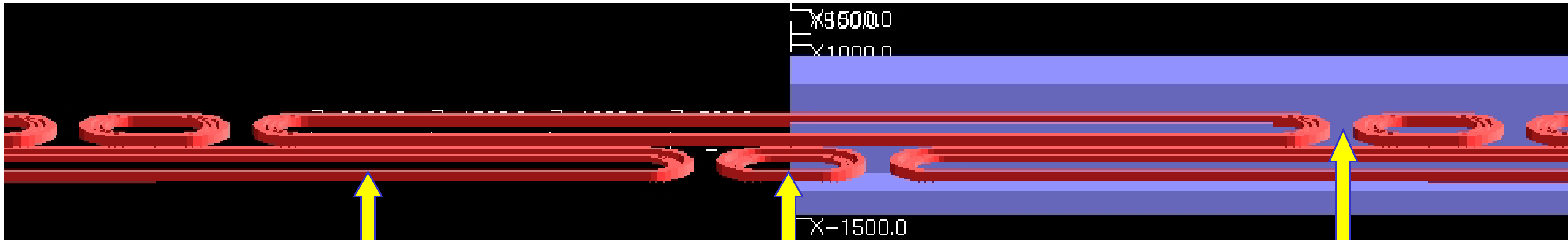




To first order, dipole becomes a skew quad, if the relative polarity of coils is changed.

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

Coil Layout for Obtaining A Variety of Magnet Configurations



Normal Coils
Dipole

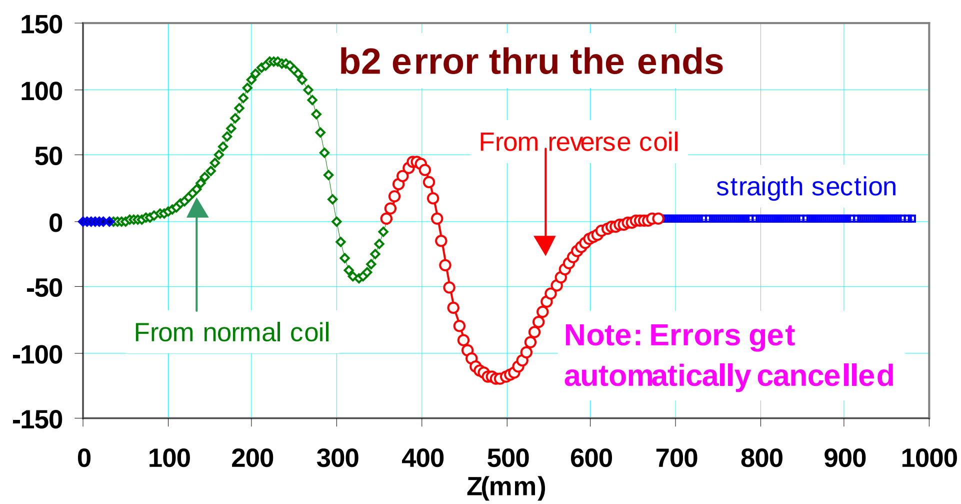
Reverse Coils
Skew Quad

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



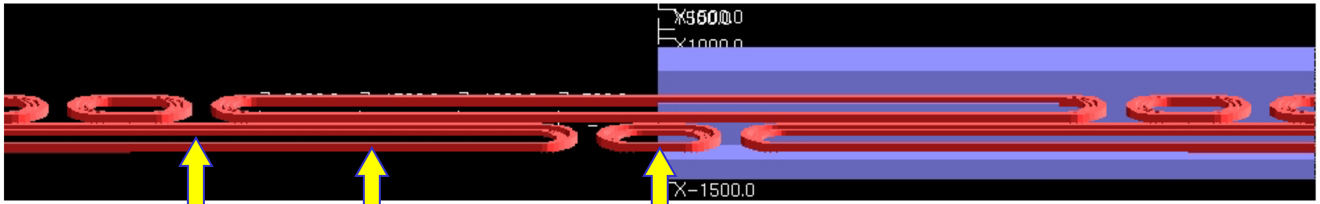
BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

A Possible Magnet Test Setup

Structure to test magnet performance in various configuration:

Magnet system layout in the proposed ν factory storage ring:

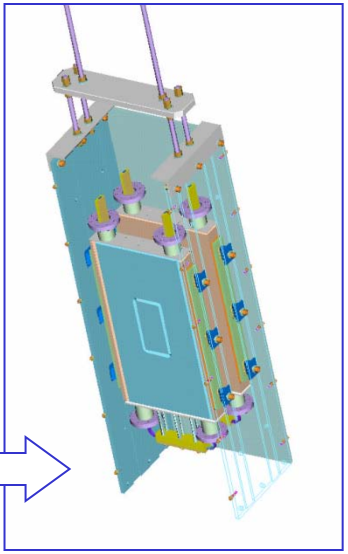


One Coil D/2 & Q/2

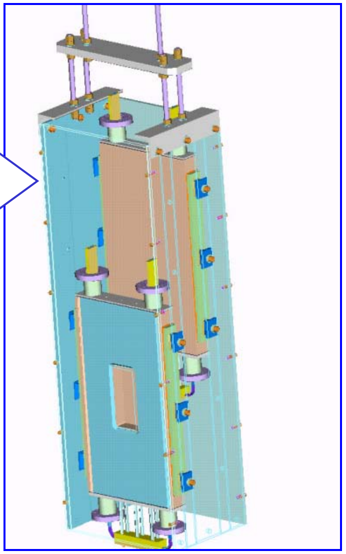
Normal Coils Dipole (D)

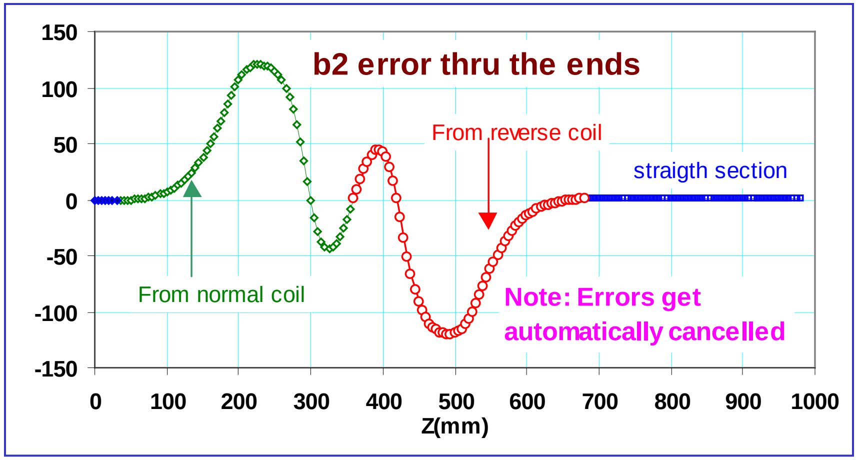
Reverse Coils Skew Quad (Q)

Dipole/Quad test setup (switch relative current direction)



Staggered coil setup

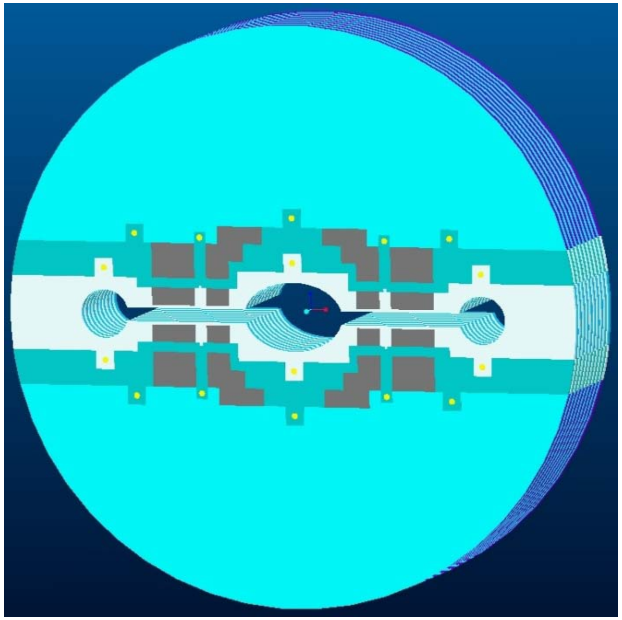




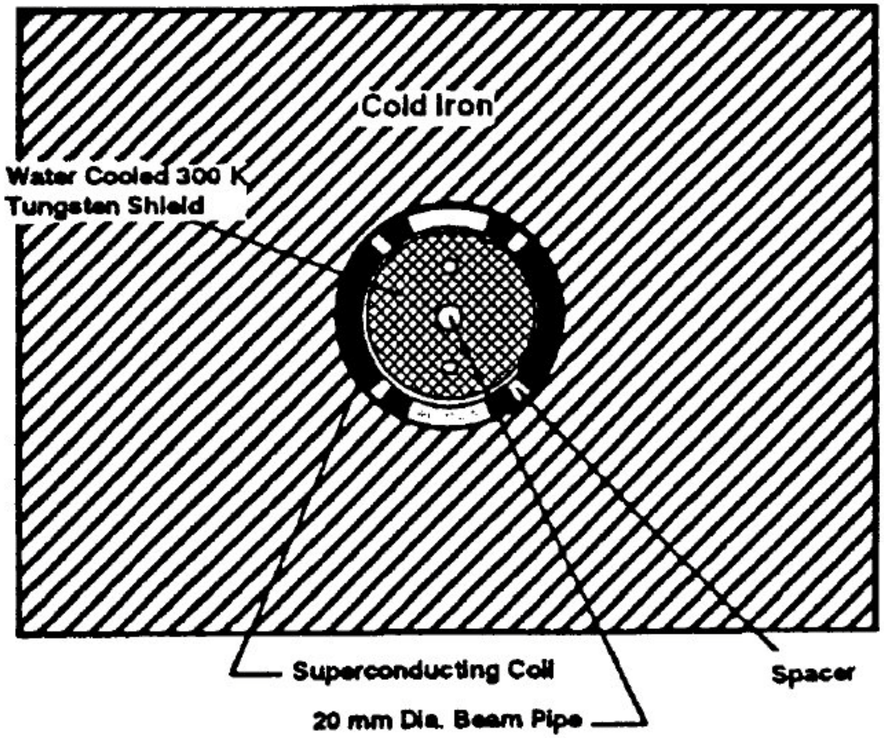
Work carried out under a BNL LDRD

Open Midplane Dipole Design Recap

Open Midplane dipole



Cosine theta design with tungeston liner



Pros of Open Midplane Dipole:

- Does not need thick tungeston liner
- Aperture could be significantly smaller
- Has positive influence on the machine detector interface (FNAL workshop 11/09)

Cons of Open Midplane Dipole:

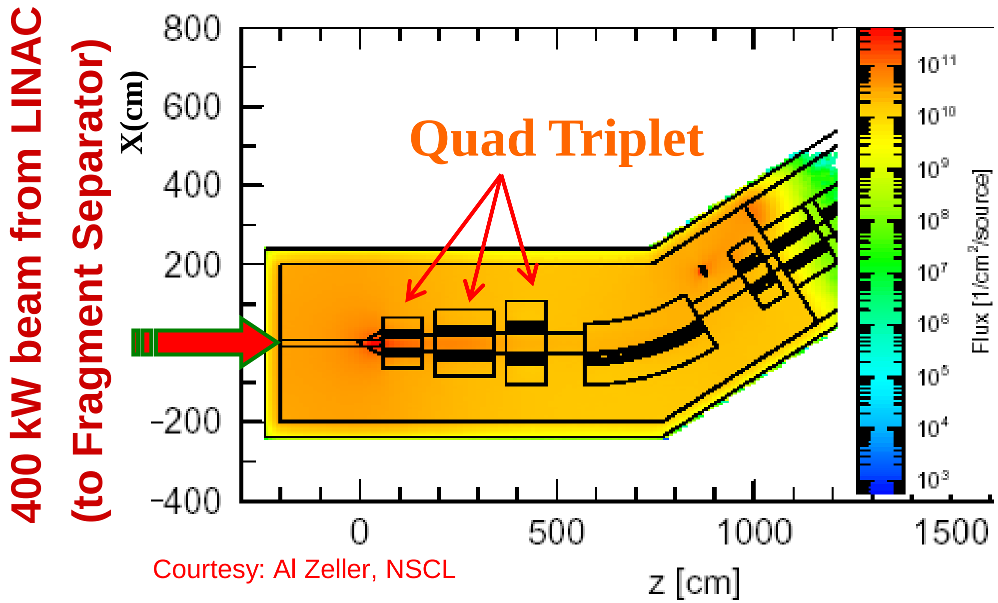
- New design
- More complex structure

Need a reasonable R&D program to make a good cost and technical decision.

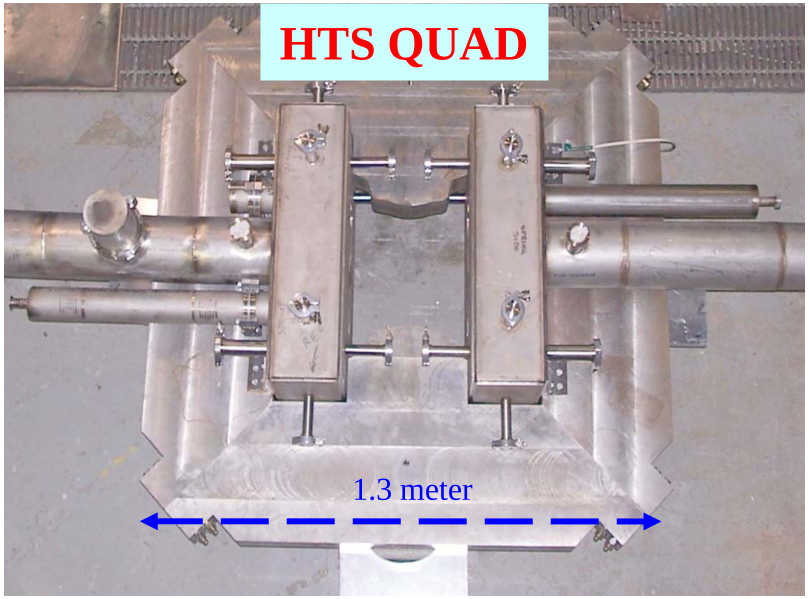
Radiation Damage and Energy Deposition Studies

(work performed under the auspices of DOE-NP for FRIB)

Motivation for Recent Radiation Damage Studies on HTS

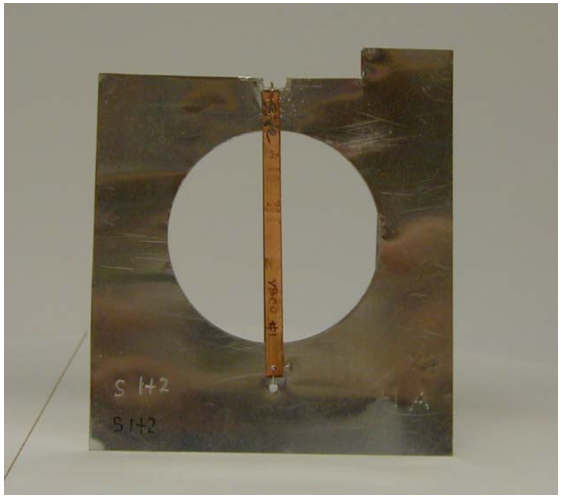


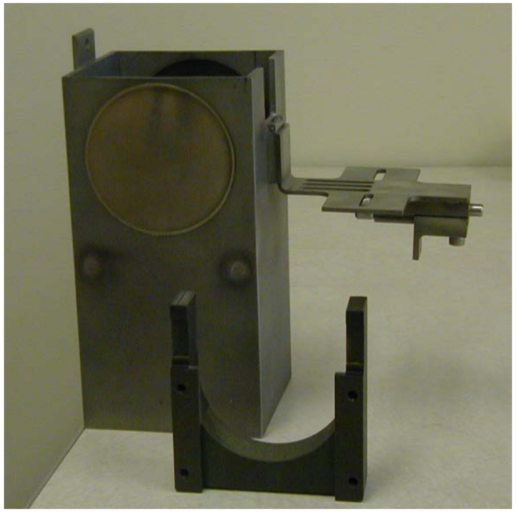
Courtesy: Al Zeller, NSCL

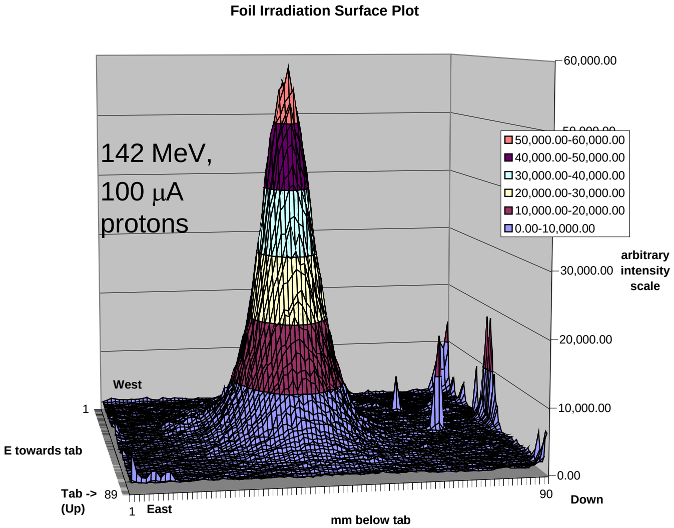


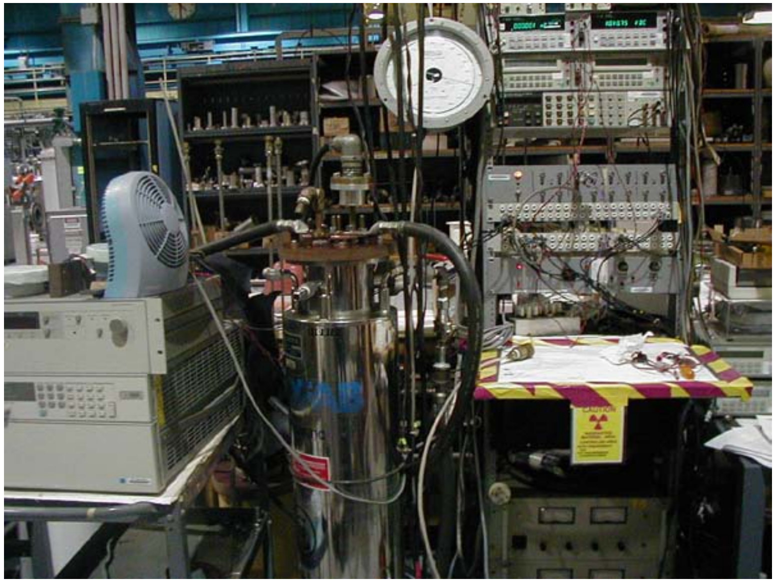
- Radiation damaged studies are being carried for the proposed Facility for Rare Isotope Beams (FRIB) for magnets in the Fragment Separator region. Use of HTS offers several advantages.
- Critical quadrupoles are exposed to unprecedented level of radiation (~20 MGy/year) and very large heat loads (~10 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 many other future programs, such as muon collider.

Key Steps of Radiation Damage Experiment









Radiation Damage Studies at BLIP

Figure 2. The BLIP facility.

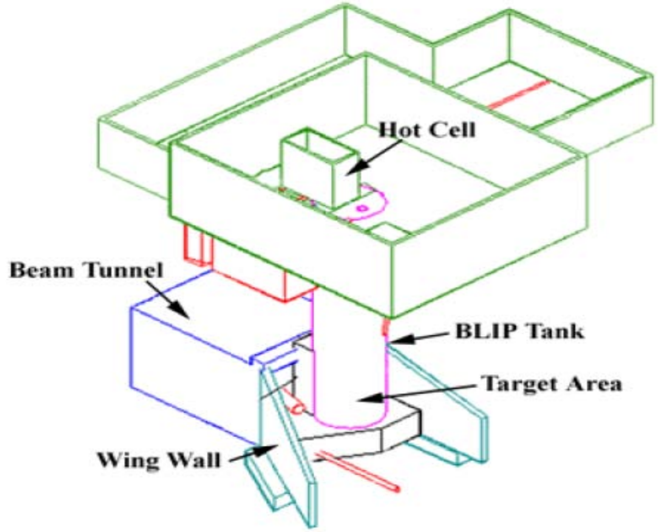
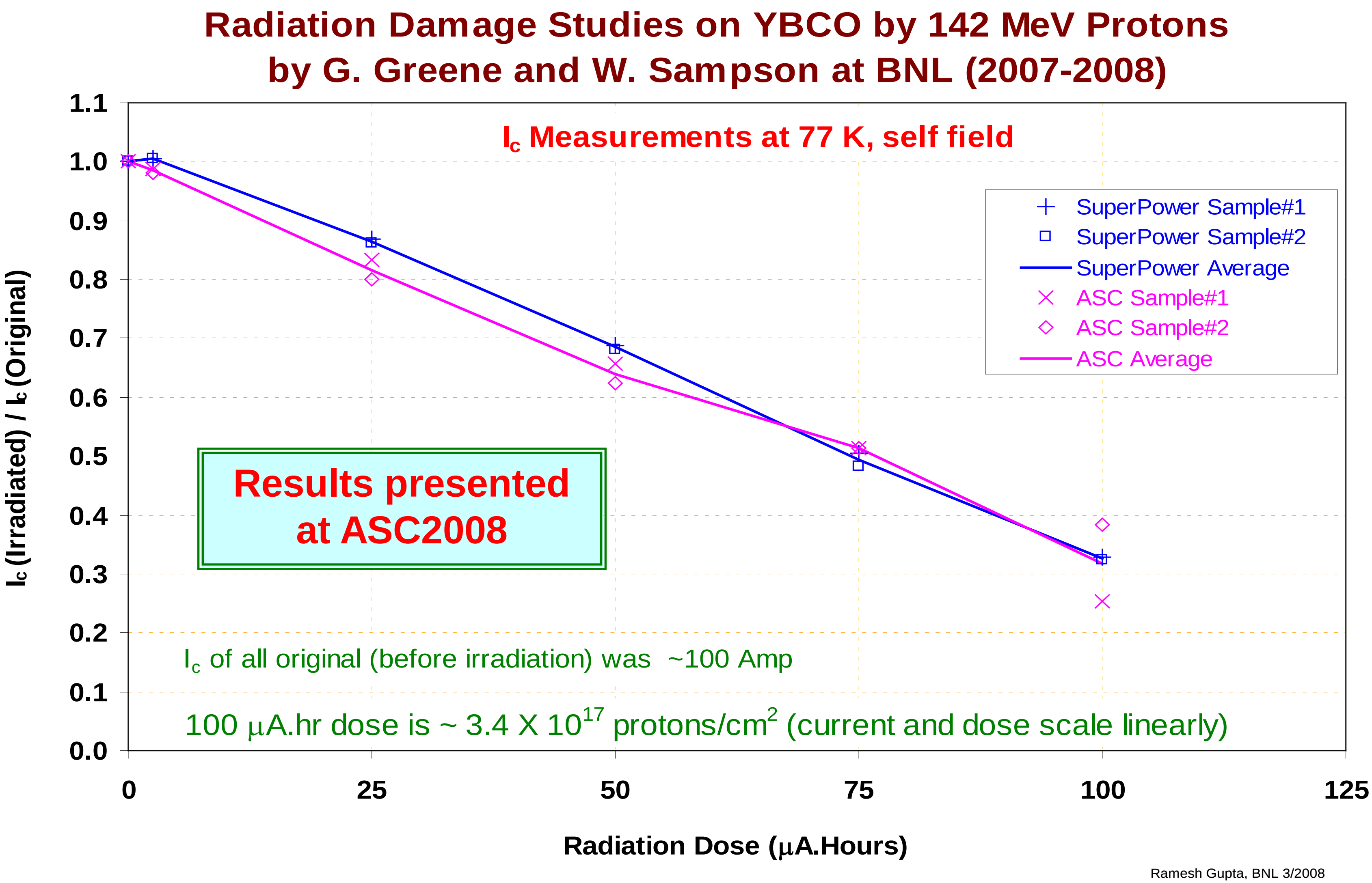


Figure 3. BLIP Beam Tunnel and Target Schematic

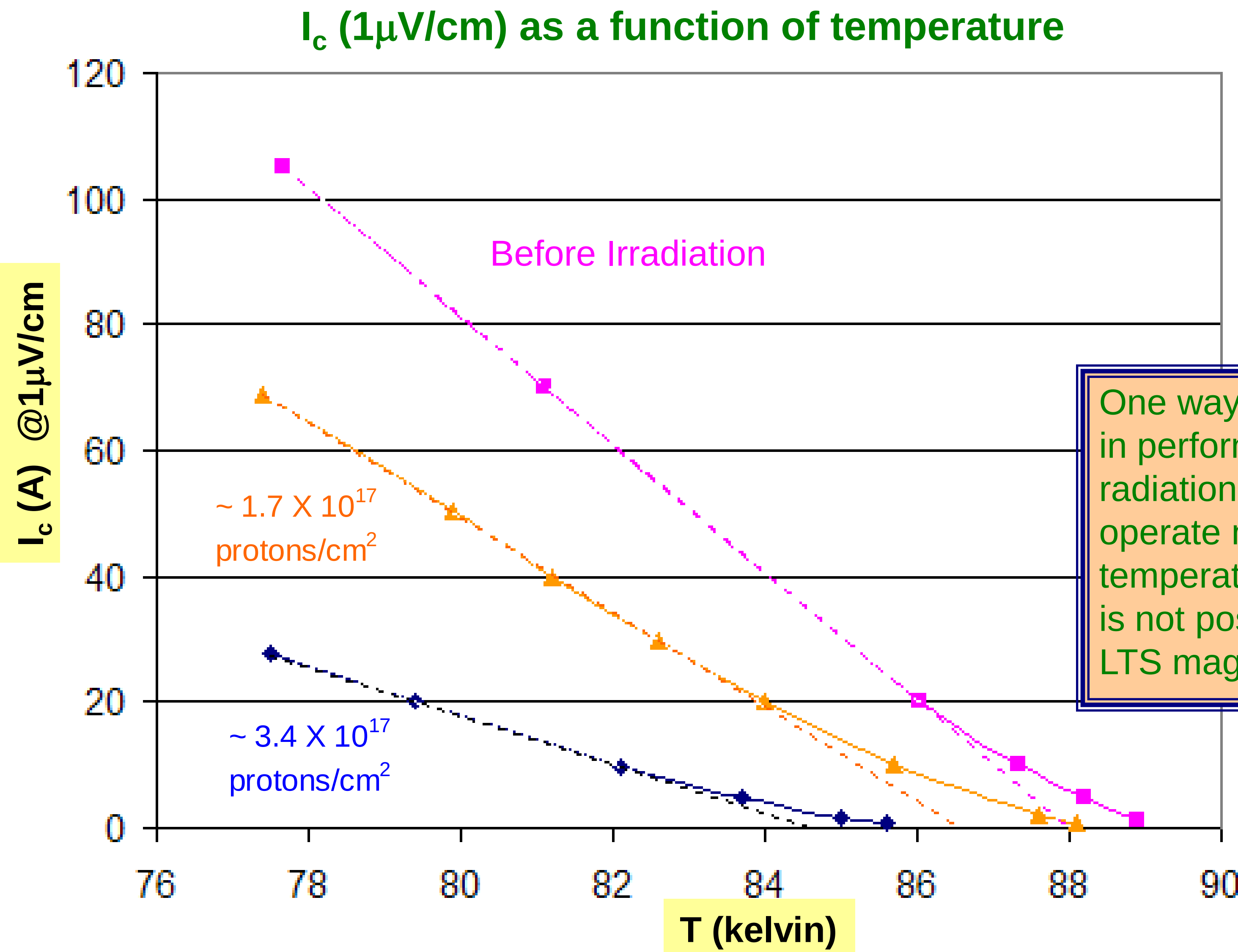
From a BNL Report (11/14/01)

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 nuclear and high energy physics programs.

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



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.

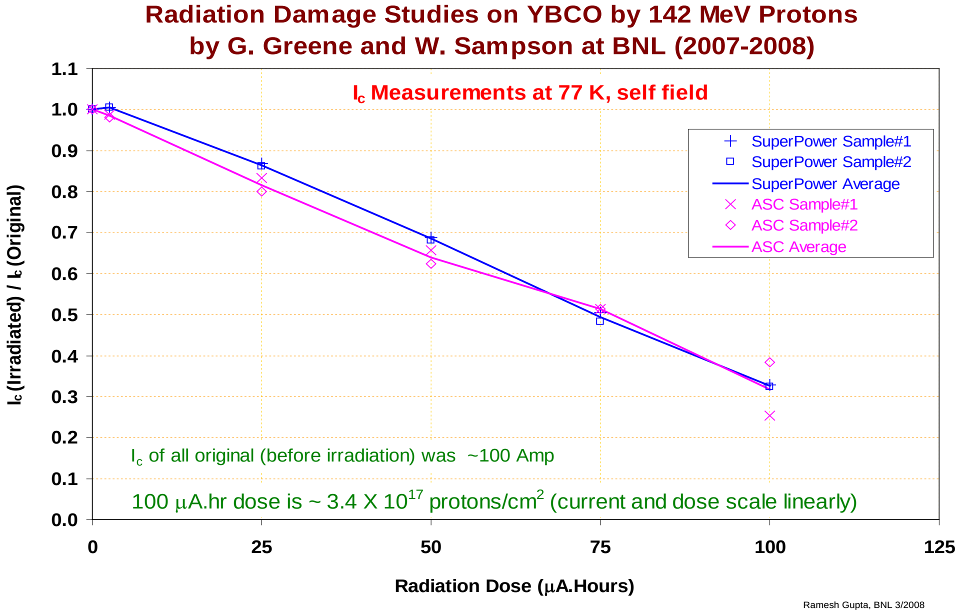
One way to recover the loss in performance due to radiation damage is to operate magnet at a lower temperature – something that is not possible in conventional LTS magnets.

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.

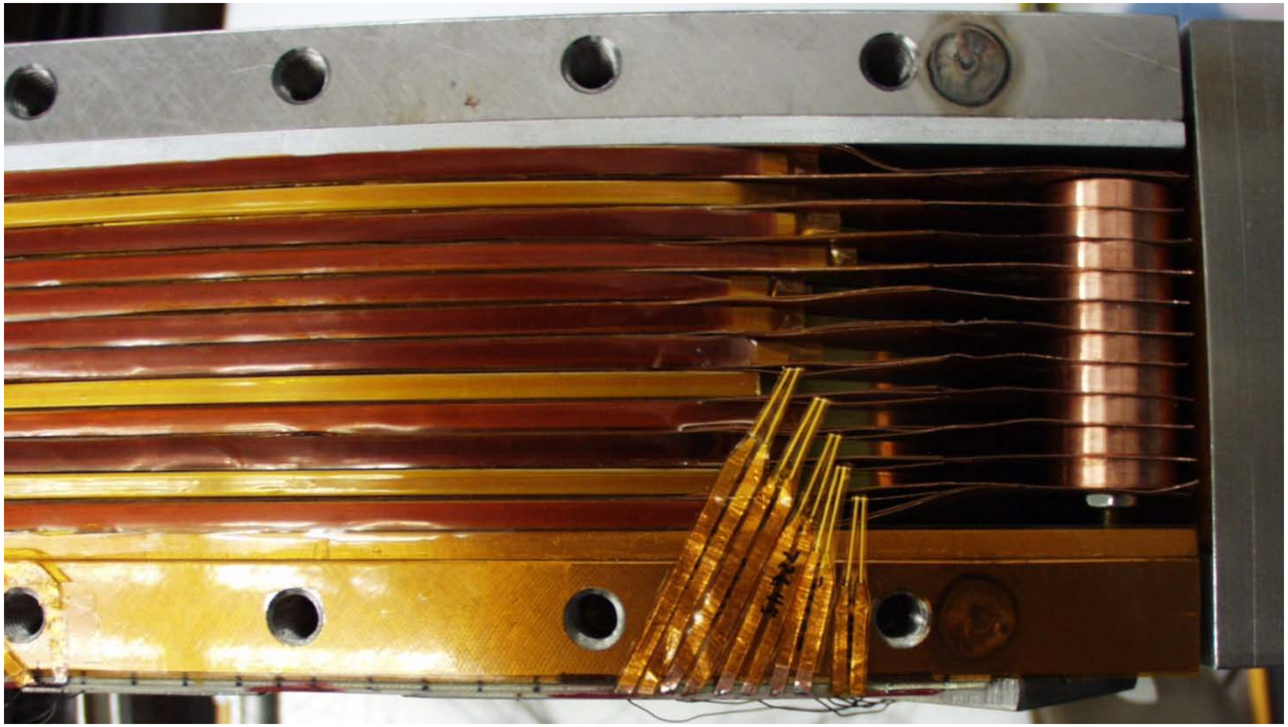
To be completely sure, we are making measurements at lower temperature and in the presence of field.

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

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.

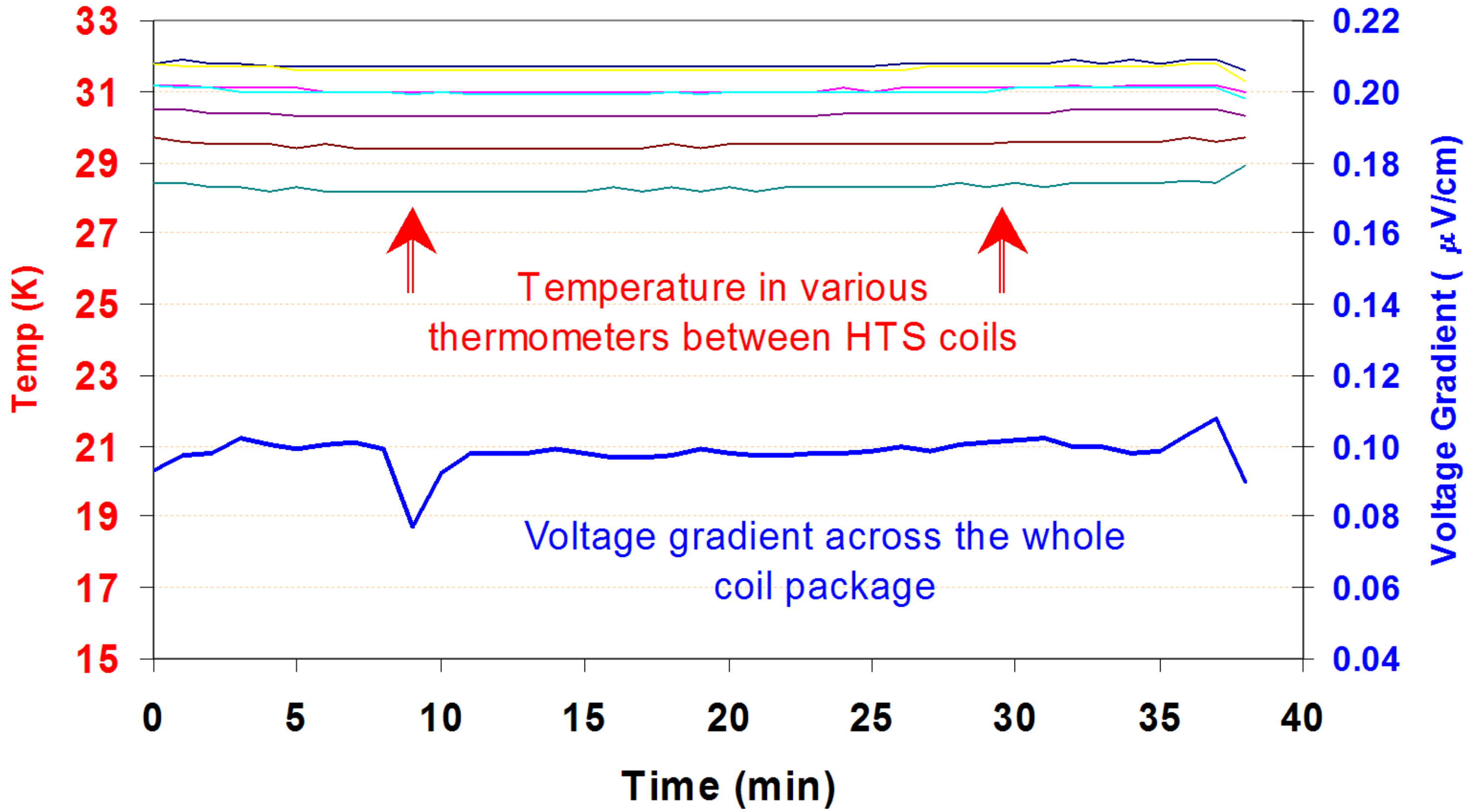
Stainless steel tape heaters for energy deposition experiments



- 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

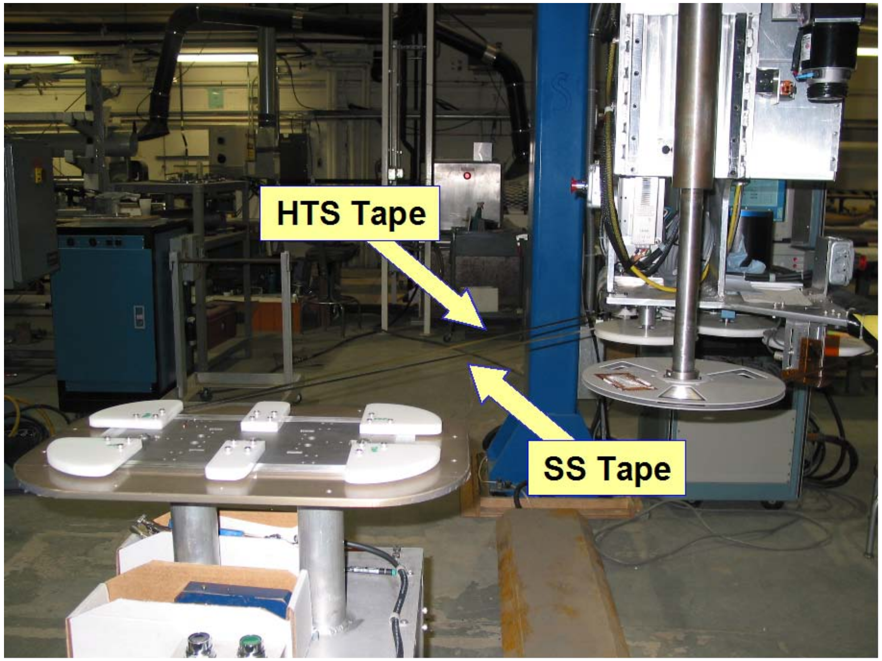
Voltage spikes are related to the noise

FRIB/RIA HTS QUAD Program

- **Providing a significant experience with the construction and test of HTS magnets in high radiation environment**
- **Both use HTS Pancake coils**

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

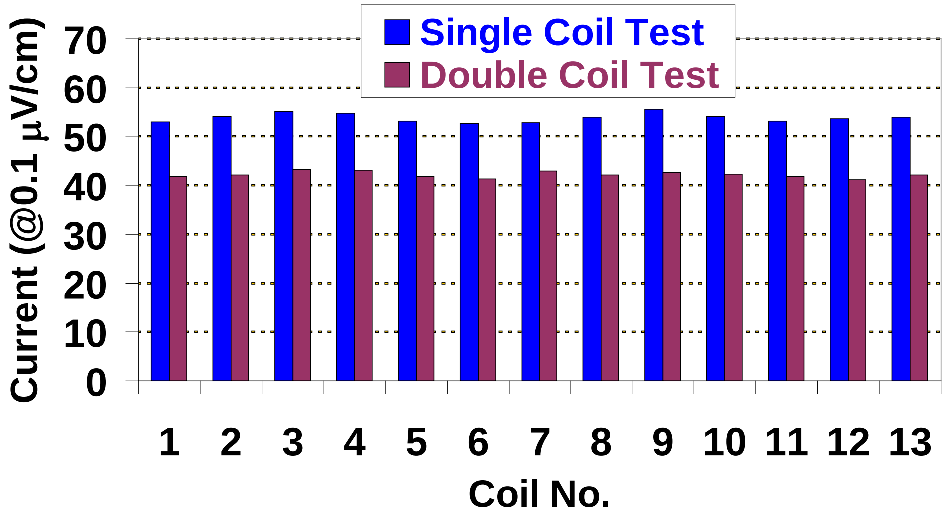
FRIB: Facility for Rare Isotope Beams

BROOKHAVEN NATIONAL LABORATORY

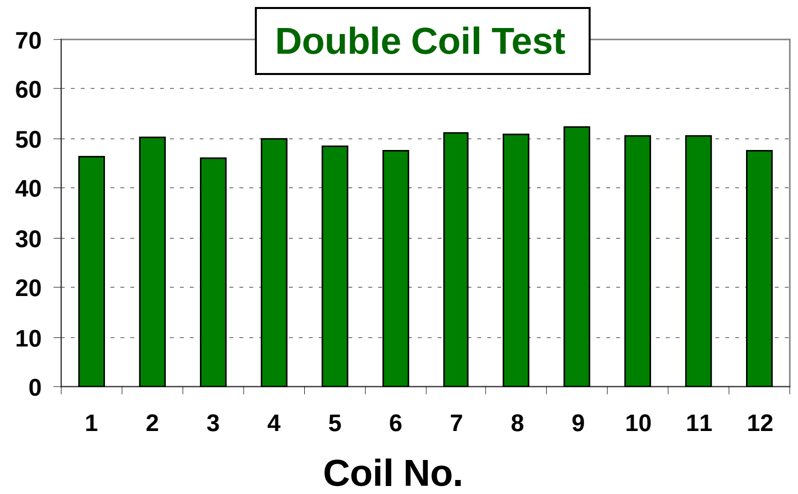
Superconducting Magnet Division

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.

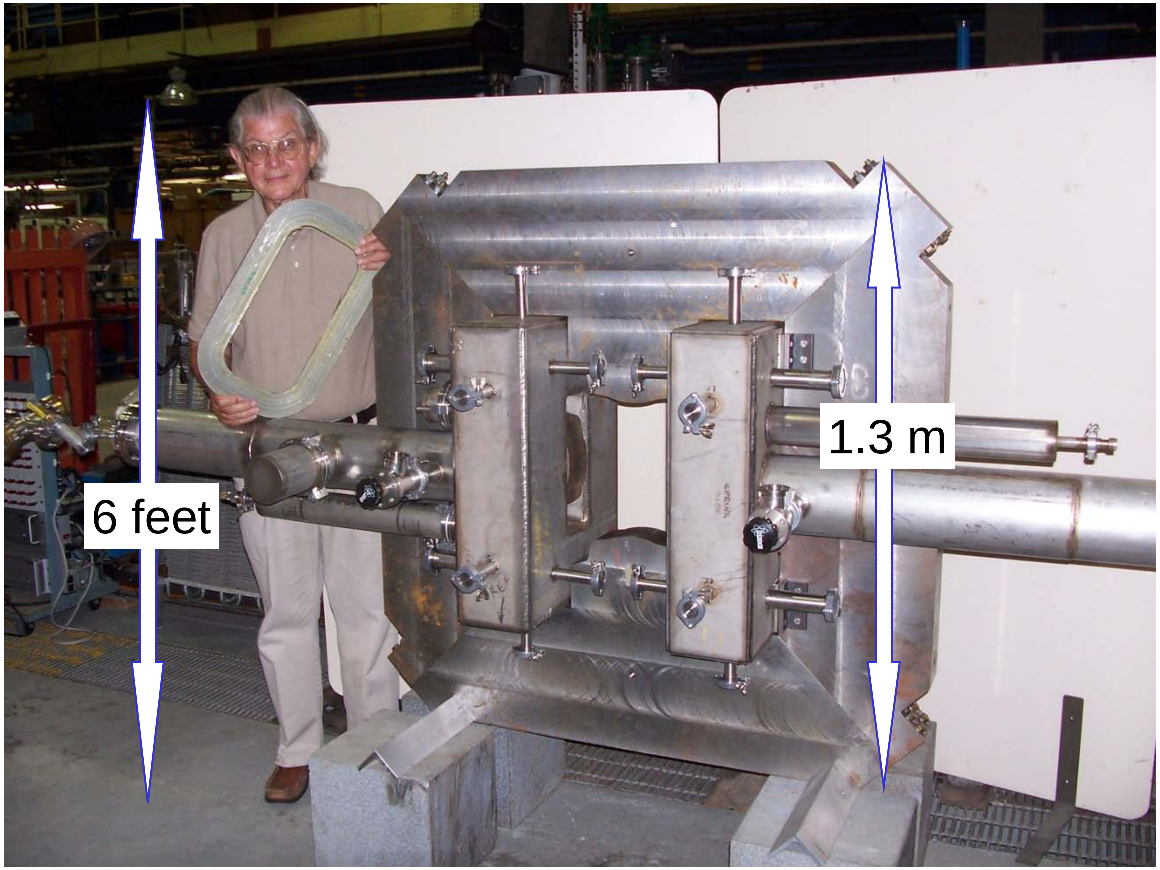
Note: A uniformity in performance of a large number of HTS coils.

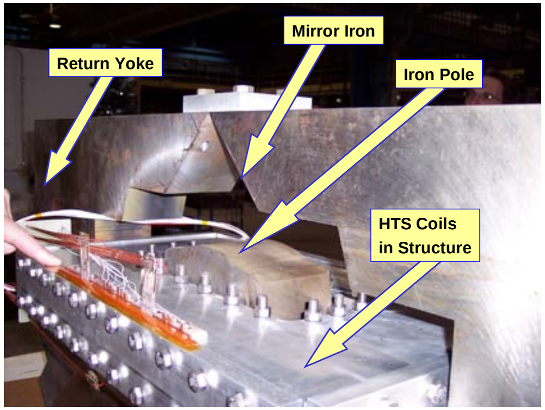
It shows that the HTS coil technology is now maturing !

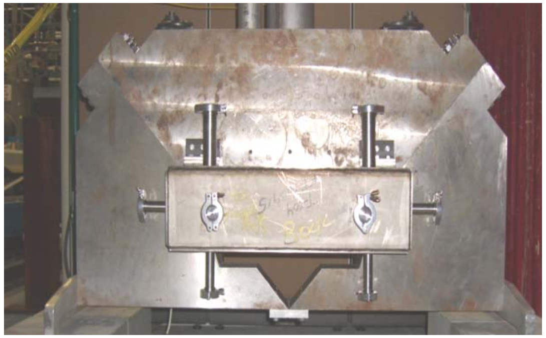
Various Magnet Structures of RIA Quad (a part of step by step R&D program)

Unique Features of RIA HTS Quad :

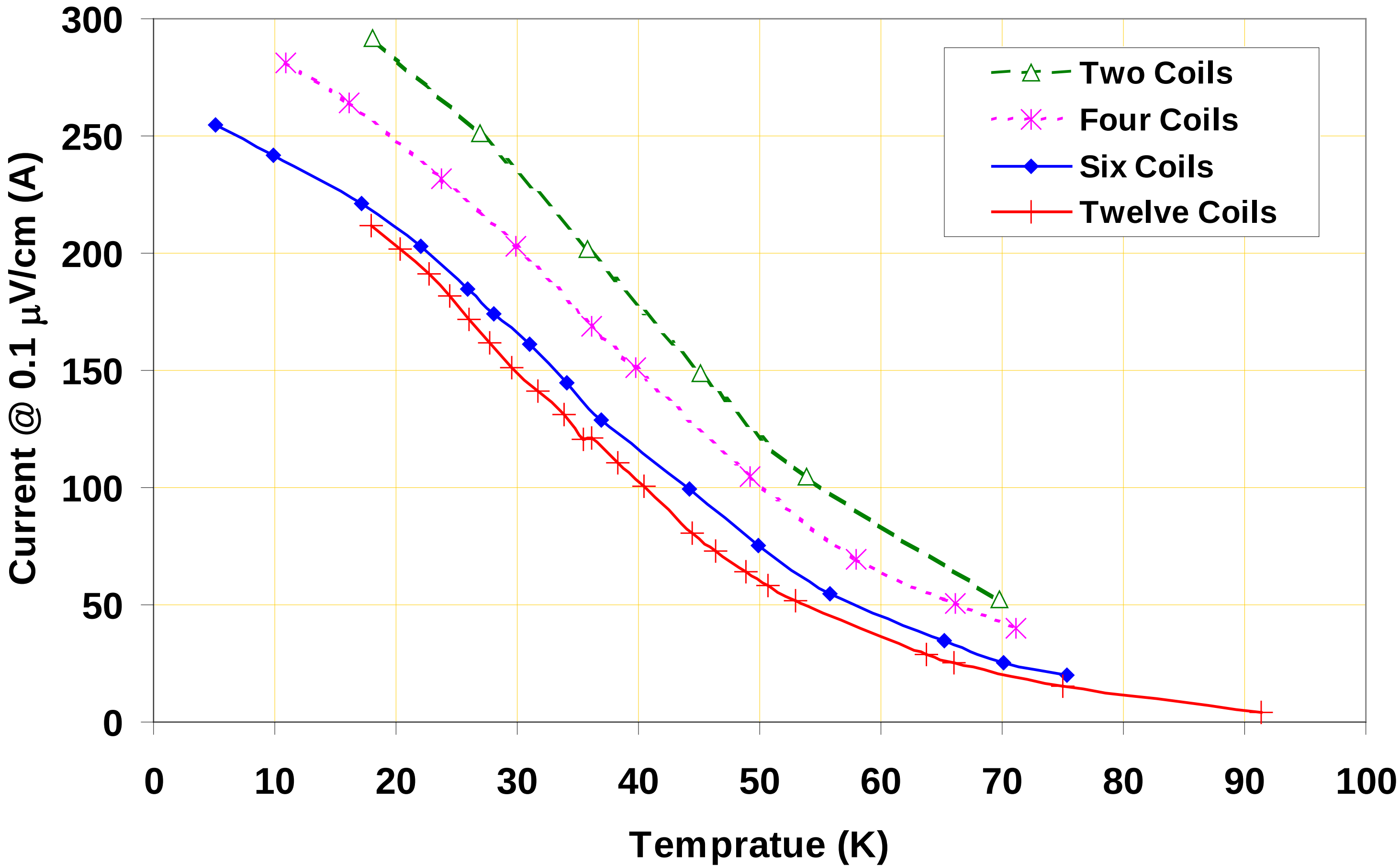
- Large Aperture, Radiation Resistant







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.

Summary

• PBL & BNL have undertaken a program to develop YBCO (2G) based high field solenoid by building a short 35-40 T all superconducting solenoid.

• 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.

• We would be glad to carry it forward for a muon collider open midplane dipole.

• Initial test results under FRIB program show that HTS is robust against the radiation damage and can tolerate large heat loads.

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