R&D Activities on High Field and HTS Magnets at BNL

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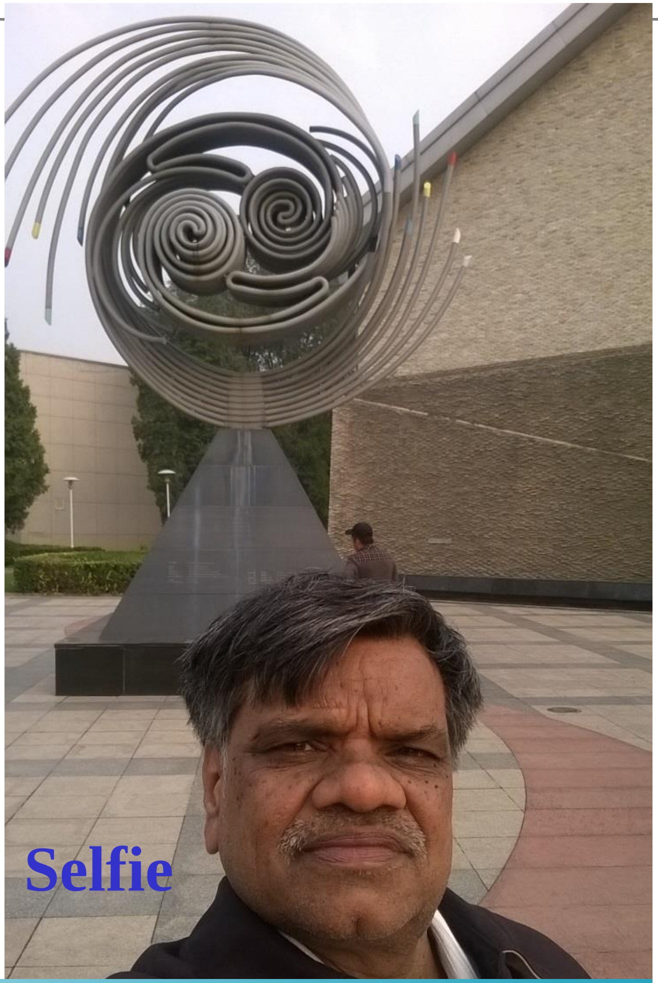
September 21, 2014

First - Personal Thanks

Thank you for inviting me and for asking our participation in CEPC-SppC. I enjoyed my stay here and appreciate your hospitality.



Institute of High Energy Physics, Chinese Academy of Sciences

Contents

- **Alternate Magnet Designs**
  - **Common Coil**
  - **Open Midplane Dipole**
    - ✓ **15 T good field quality magnetic design for both will be presented**
- **Progress in HTS Magnet Technology at BNL**
- **A few thoughts on R&D Plan (separate file)**
- **Summary**

Note: This presentation is limited to the research program at BNL only - mostly in the areas where it has made significant contributions and are relevant to future SppC magnet R&D.

Present Magnet Design and Technology

Tevatron Dipole

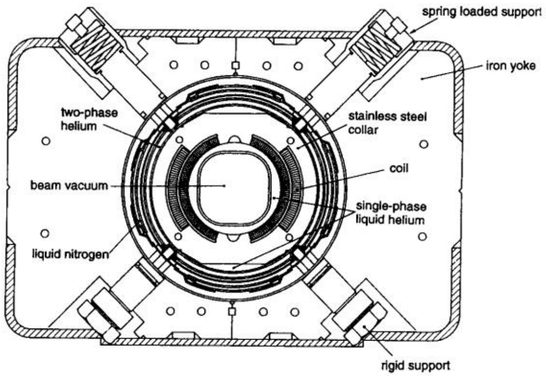
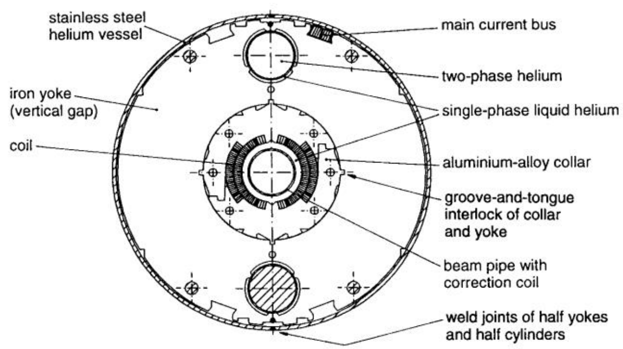
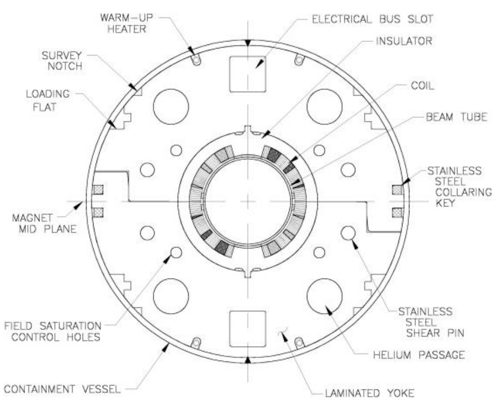


Figure 4.9: The Tevatron 'warm-iron' dipole (Tollestrup 1979).

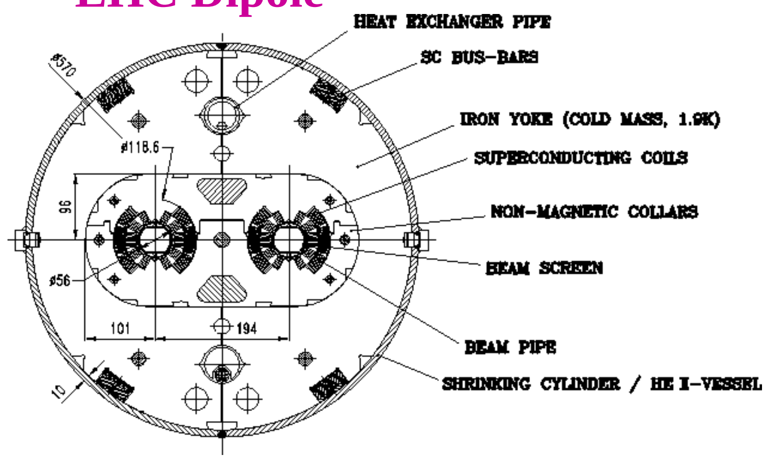
HERA Dipole



RHIC Dipole



LHC Dipole



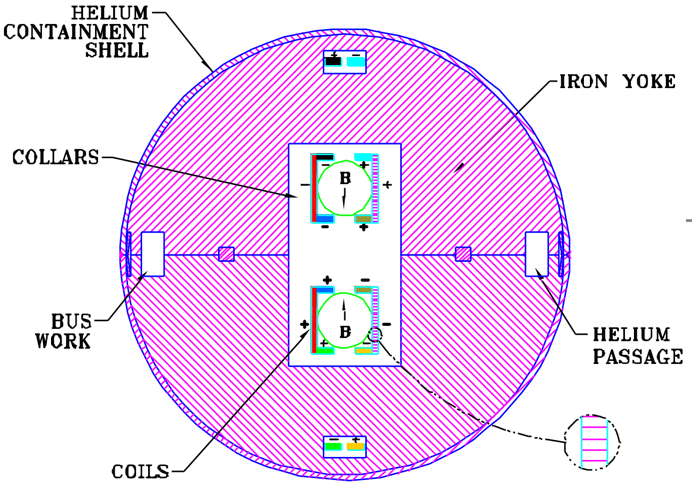
- All magnets use Nb-Ti Superconductor
- All designs use cosine theta coil geometry
- The technology has been in use and mastered for decades
- Significant improvements in performance and/or reduction in cost are unlikely to come now

➢ **From SppC or FCC stated requirements, above are low field magnets.**

Superconductor & Magnet Technologies for a 15 T and 20 T Dipole Design

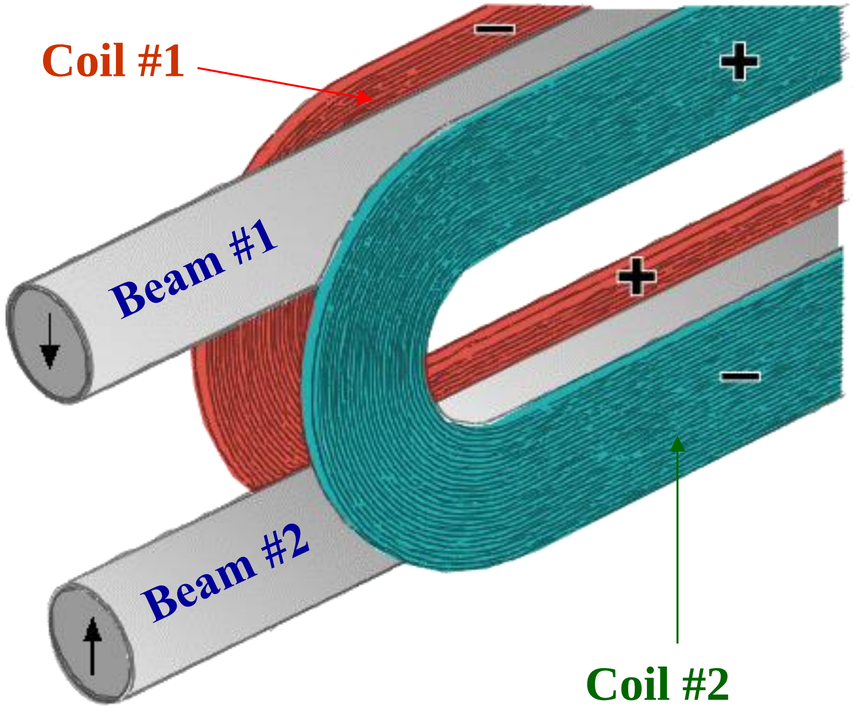
- **A 15 T central field means >16 T peak field on the coil. Similarly, a 20 T central field means ~22 T peak field on the coil.**
- **For machines to reach design energy in a few year after the start (or some time during its lifetime), the magnets should have a reasonable margin. This implies ~19 T peak field on the coil for a 15 T dipole and ~25 T peak field on coil for a 20 T dipole.**
- **Therefore, if the above operating fields are to be taken strongly, a hybrid magnet design with HTS playing some role seem necessary. *"Nb_3Sn only"* is at best marginal for a 15-16 T design.**

Common Coil Design



Common Coil Design
(The Basic Concept)

- **Simple 2-d geometry with large bend radius (no complex 3-d ends)**
- **Conductor friendly (suitable for brittle materials – can do both Wind & React and React & Wind)**
- **Compact (compared to single aperture LBL's D20 magnet, half the yoke size for two apertures)**
- **Block design (for large Lorentz forces at high fields)**
- **Efficient and methodical R&D due to simple & modular design**
- **Minimum requirements on big expensive tooling and labor**
- **Lower cost magnets expected**

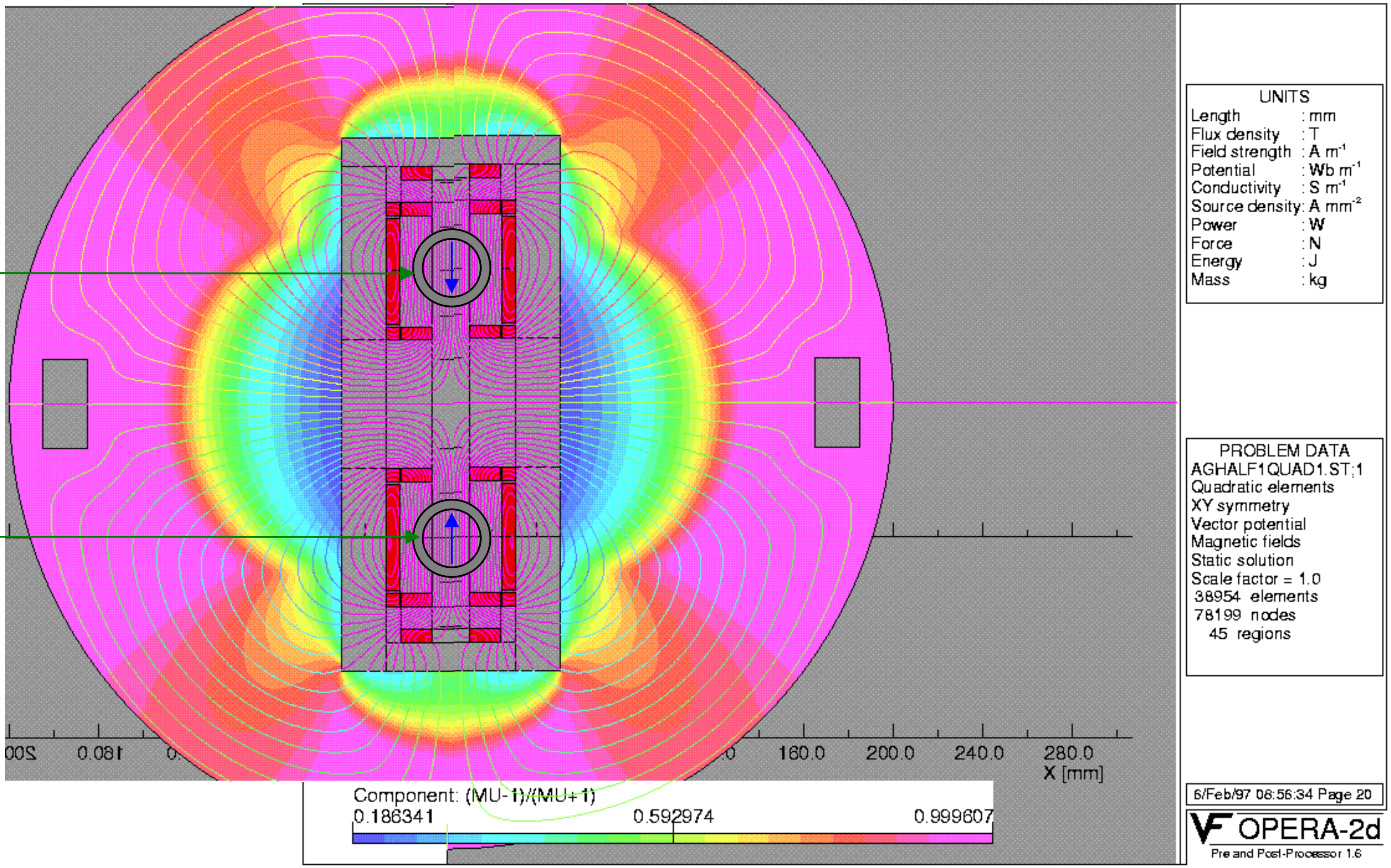


Main Coils of the *Common Coil Design*

Field Lines at 15 T in a Common Coil Magnet Design

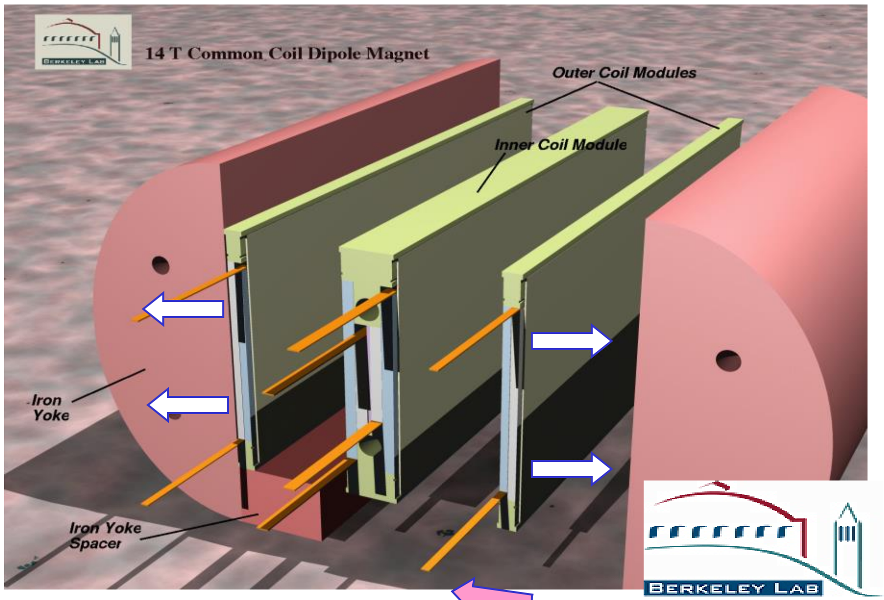
Aperture #1

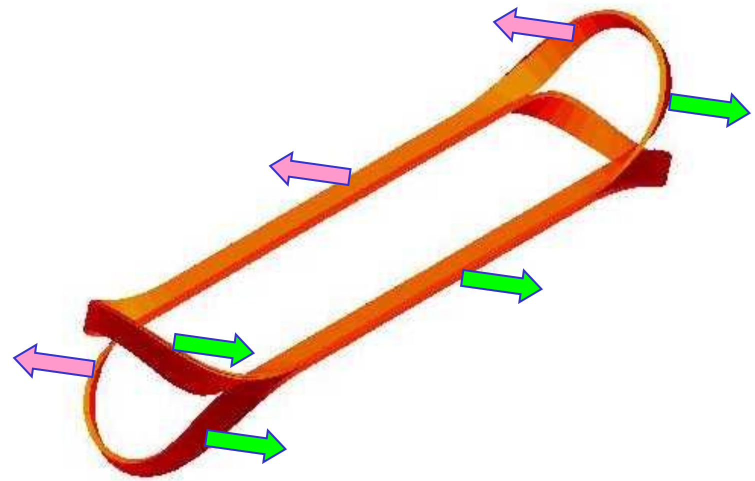
Aperture #2



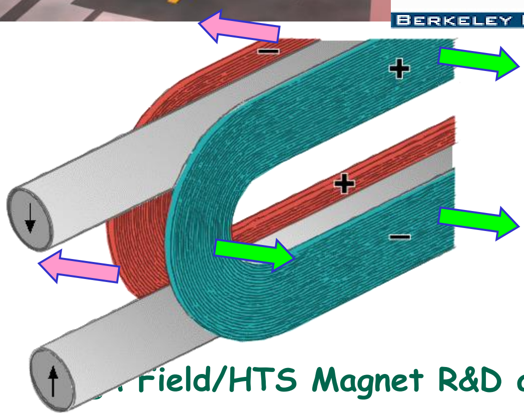
Common Coil Design in Handling Large Lorentz Forces in High Field Magnets

In common coil design, a racetrack coil can move as a block, without straining the conductor in the ends and thus minimize causing quench or damage.





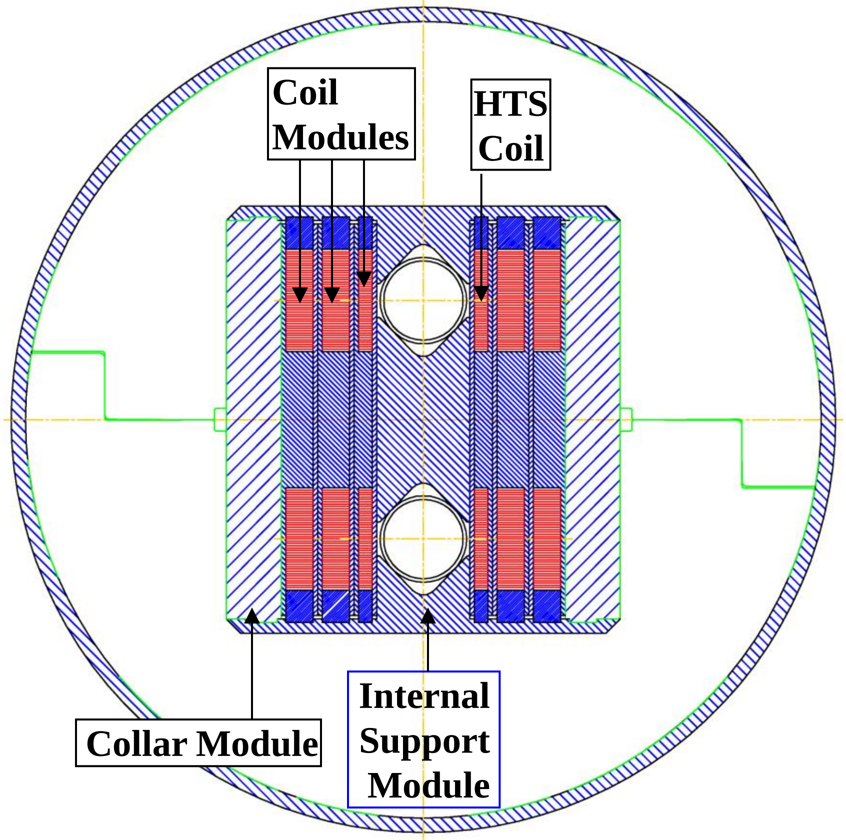
Horizontal forces are larger



In cosine theta or conventional block coil designs, the coil module cannot move as a block. Therefore, Lorentz forces put strain on the conductor at the ends which may cause premature quench.

Possible Layout of Common Coil Designs

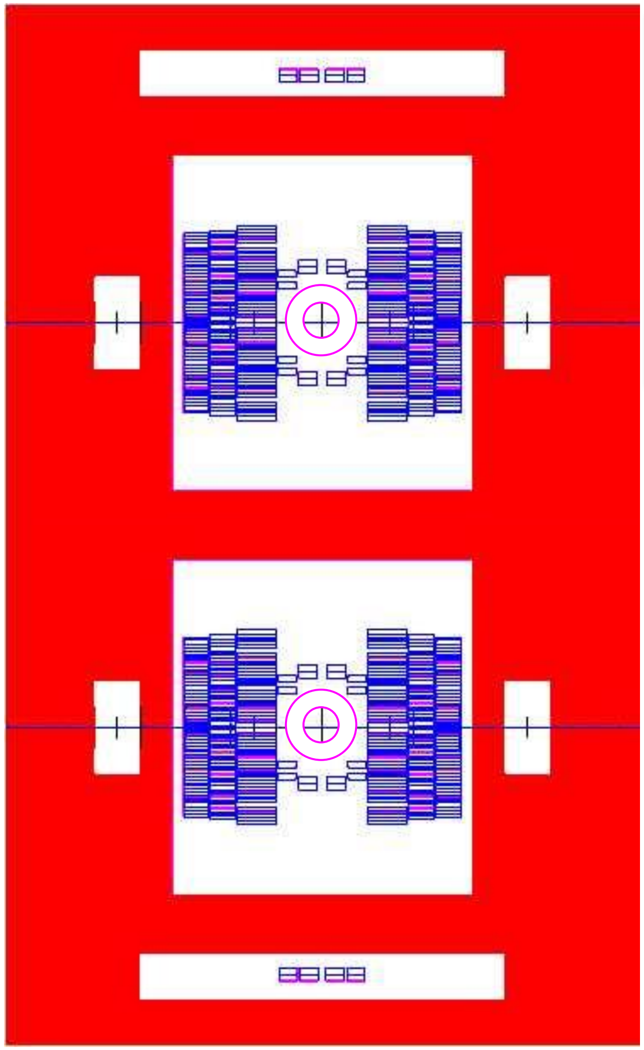
R&D Magnet



Vary aperture after the coils are made

- a unique feature in R&D magnets
- lower separation, higher field

15 T Field Quality Magnet



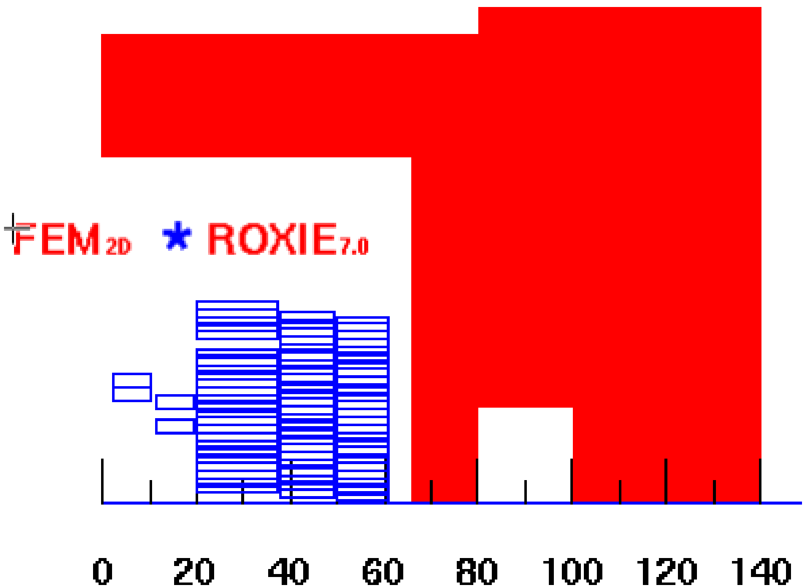
A good field quality magnetic design is demonstrated

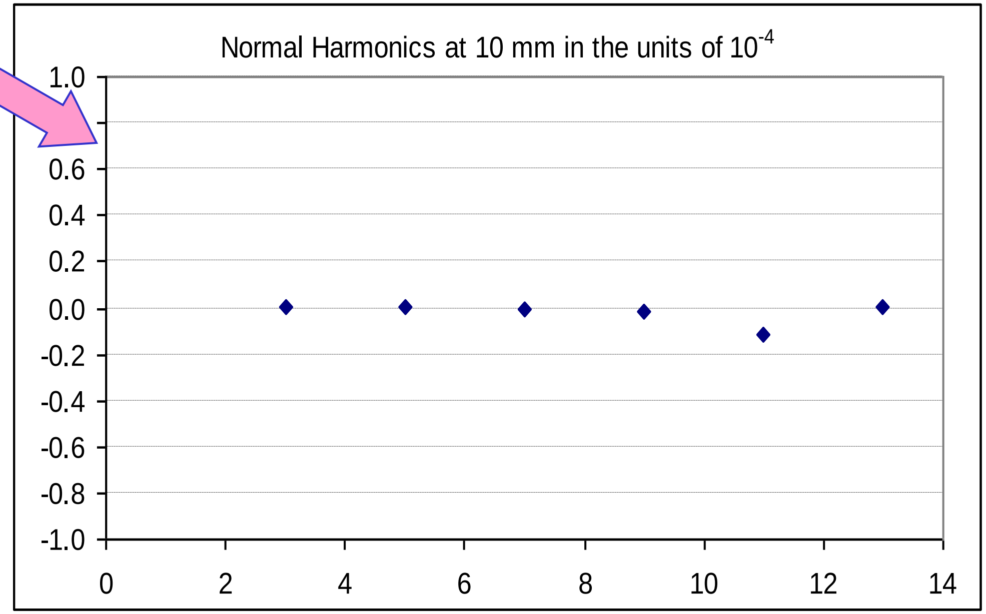
15 T design is based on Nb_3Sn conductor with J_c = 2200 A/mm^2 @(12T, 4.2K)

More horizontal space for structure will need a minor iteration

Demonstration of a Good Field Quality in Geometric Harmonics

Typical Requirements:
~ part in 10^4, we have part in 10^5





Horizontal coil aperture:
40 mm

(from 1/4 model)

MAIN FIELD: -1.86463 (IRON AND AIR):

b 1:	10000.000	b 2:	0.00000	b 3:	0.00308
b 4:	0.00000	b 5:	0.00075	b 6:	0.00000
b 7:	-0.00099	b 8:	0.00000	b 9:	-0.01684
b10:	0.00000	b11:	-0.11428	b12:	0.00000
b13:	0.00932	b14:	0.00000	b15:	0.00140
b16:	0.00000	b17:	-0.00049	b18:	0.00000

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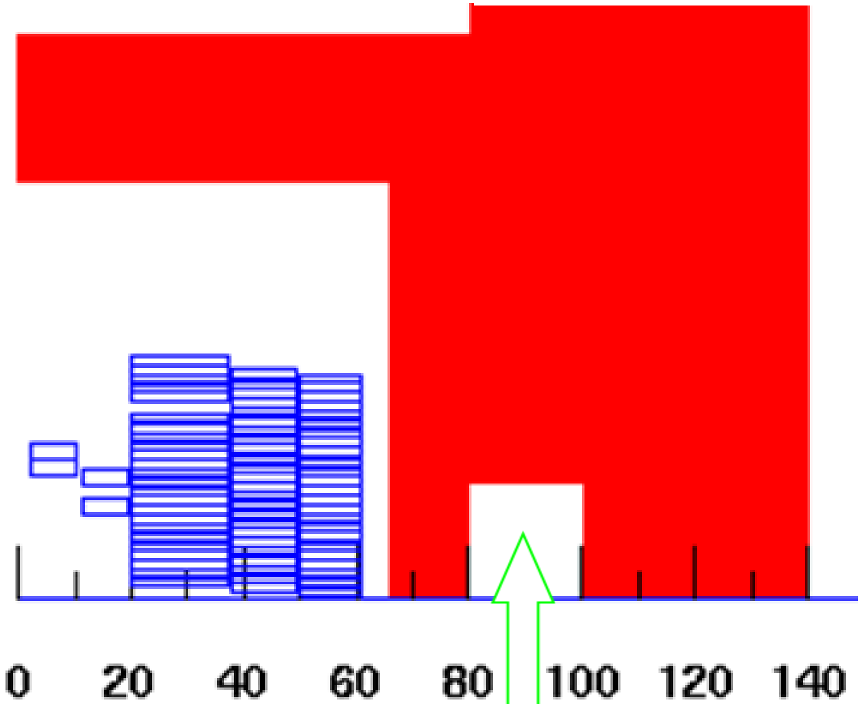
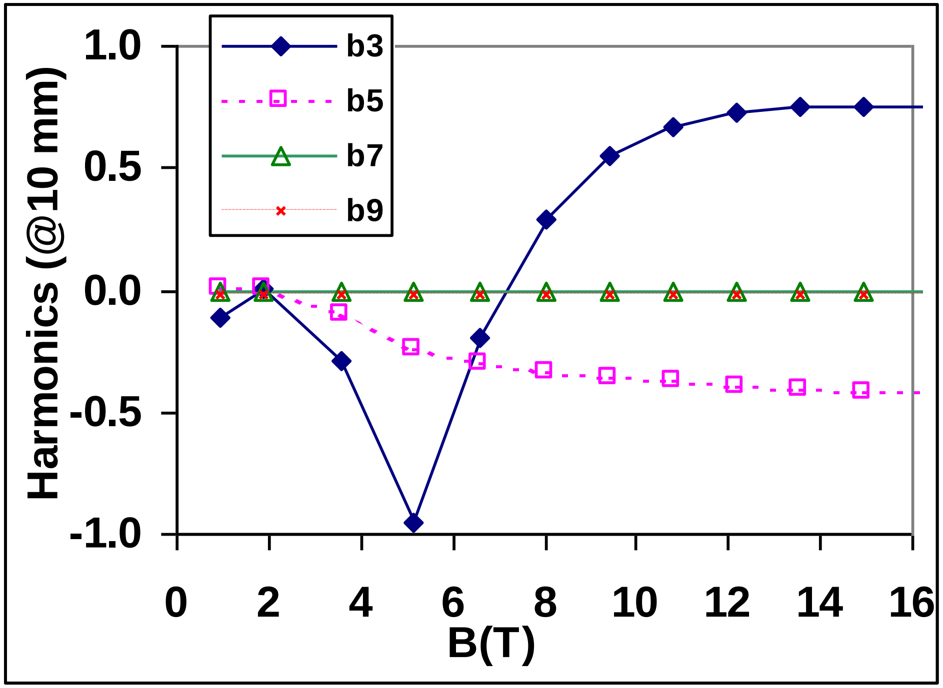
Superconducting Magnet Division

Demonstration of a Good Field Quality in Saturation-induced Harmonics

Maximum change in entire range: ~ part in 10^4 (satisfies general accelerator requirement)





Use cutouts at strategic places in yoke iron to control the saturation

Low saturation-induced harmonics (within 1 unit)

Demonstration of a Good Field Quality in End Harmonics

End harmonics can be made small in a common coil design.

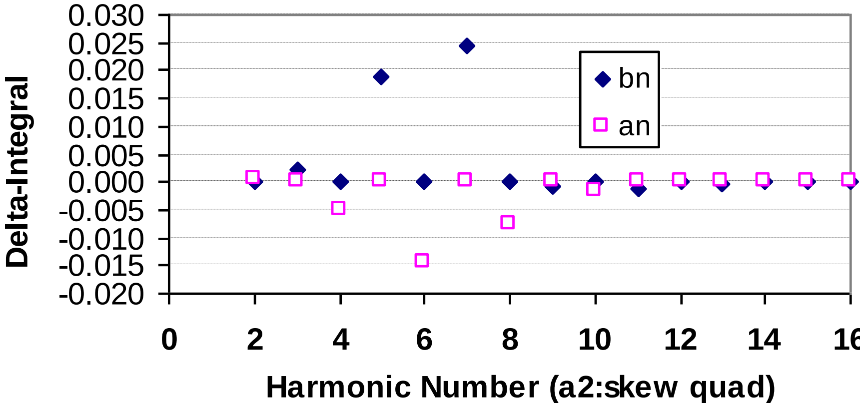
(Very small)

End harmonics in Unit-m

n	Bn	An
2	0.00	0.00
3	0.01	0.00
4	0.00	-0.03
5	0.13	0.00
6	0.00	-0.10
7	0.17	0.00
8	0.00	-0.05
9	0.00	0.00
10	0.00	-0.01
11	-0.01	0.00
12	0.00	0.00
13	0.00	0.00
14	0.00	0.00
15	0.00	0.00
16	0.00	0.00
17	0.00	0.00
18	0.00	0.00

Contribution to integral (a_n,b_n) in a 14 m long dipole (<10^{-6})

n	bn	an
2	0.000	0.001
3	0.002	0.000
4	0.000	-0.005
5	0.019	0.000
6	0.000	-0.014
7	0.025	0.000
8	0.000	-0.008
9	-0.001	0.000
10	0.000	-0.001
11	-0.001	0.000
12	0.000	0.000

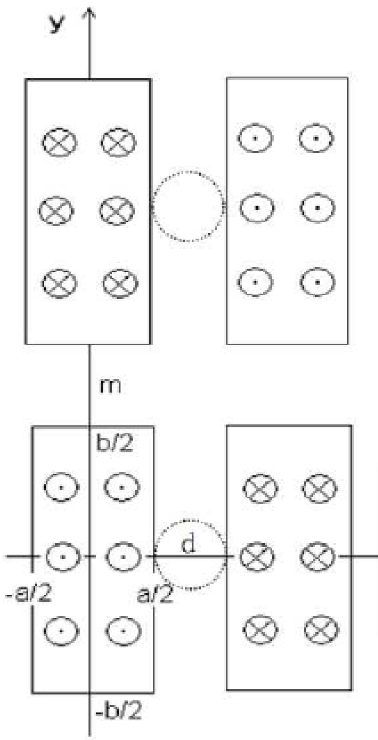


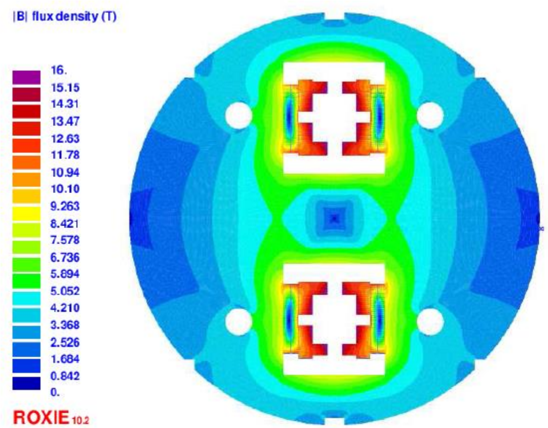
New Analytical Tool for Optimizing Common Coil Design

Magnetic Design Study of the High Field Common Coil Dipole for High Energy Accelerators

Qingjin Xu

ASC2014





50 mm, 15 T Nb_3Sn design for IHEP

Fig. 1 Analytical modeling of the common coil configuration: The four current-carrying blocks represent the two racetrack coils with opposite current directions. The coil width and height are a and b respectively. The bore diameter is d and the bending radius of the coil is $m/2$.

$$B_x = \frac{\mu_0 I}{2\pi}\frac{y-y_0}{(x-x_0)^2+(y-y_0)^2} \quad (1)$$

$$B_y = \frac{\mu_0 I}{2\pi}\frac{x-x_0}{(x-x_0)^2+(y-y_0)^2} \quad (2)$$

By integrating the equation (1) and (2) in the four current-carrying blocks in Fig. 1, the magnetic field in the twin-aperture of the common coil configuration can be derived as

$$B_x = \frac{\mu_0 I}{4\pi}\Bigg[\int_{-\frac{a}{2}}^{\frac{a}{2}} ln\frac{(x-x_0)^2+(y+\frac{b}{2})^2}{(x-x_0)^2+(y-\frac{b}{2})^2}dx_0 - \int_{-\frac{a}{2}}^{\frac{a}{2}} ln\frac{(a+d-x-x_0)^2+(y+\frac{b}{2})^2}{(a+d-x-x_0)^2+(y-\frac{b}{2})^2}dx_0 + \int_{-\frac{a}{2}}^{\frac{a}{2}} ln\frac{(x-x_0)^2+(m+b-y+\frac{b}{2})^2}{(x-x_0)^2+(m+b-y-\frac{b}{2})^2}dx_0 - \int_{-\frac{a}{2}}^{\frac{a}{2}} ln\frac{(a+d-x-x_0)^2+(m+b-y+\frac{b}{2})^2}{(a+d-x-x_0)^2+(m+b-y-\frac{b}{2})^2}dx_0\Bigg] \quad (3)$$

and

$$B_y = \frac{\mu_0 I}{4\pi}\Bigg[\int_{-\frac{b}{2}}^{\frac{b}{2}} ln\frac{(x+\frac{a}{2})^2+(y-y_0)^2}{(x-\frac{a}{2})^2+(y-y_0)^2}dy_0 + \int_{-\frac{b}{2}}^{\frac{b}{2}} ln\frac{(\frac{3a}{2}+d-x)^2+(y-y_0)^2}{(\frac{a}{2}+d-x)^2+(y-y_0)^2}dy_0 - \int_{-\frac{b}{2}}^{\frac{b}{2}} ln\frac{(x+\frac{a}{2})^2+(m+b-y-y_0)^2}{(x-\frac{a}{2})^2+(m+b-y-y_0)^2}dy_0 - \int_{-\frac{b}{2}}^{\frac{b}{2}} ln\frac{(\frac{3a}{2}+d-x)^2+(m+b-y-y_0)^2}{(\frac{a}{2}+d-x)^2+(m+b-y-y_0)^2}dy_0\Bigg] \quad (4)$$

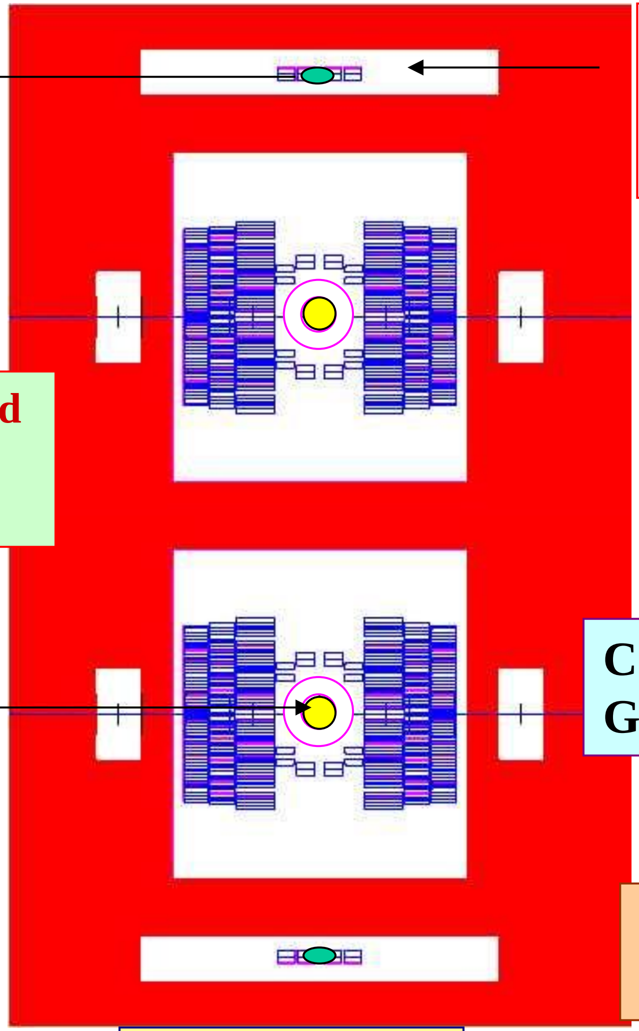
Assume the bending radius of the racetrack coil is large enough that the cross-talk of the magnetic field between the two apertures are negligible, by replacing the x with $(a+d)/2$ and y with 0 in equation (4), we get the main dipole field of the common coil configuration as

$$B_y = \frac{\mu_0 J}{2\pi}\int_{-\frac{b}{2}}^{\frac{b}{2}} ln\Big(\frac{(a+\frac{d}{2})^2+{y_0}^2}{(\frac{d}{2})^2+{y_0}^2} + \frac{\left(\frac{d}{2}\right)^2+(m+b-y_0)^2}{\left(a+\frac{d}{2}\right)^2+(m+b-y_0)^2}\Big)dy_0 \quad (5)$$

A Common Coil Magnet System for SppC

May eliminate the High Energy Booster

A 4-in-1 magnet for a 2-in-1 machine



Inject in the iron dominated aperture at low field and accelerate to medium field

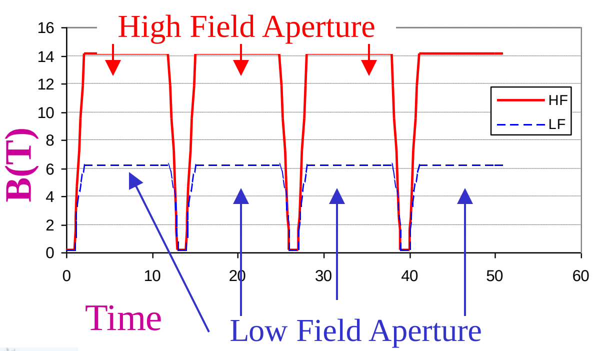
Injection at low field in iron dominated aperture should solve the large persistent current problem associated with Nb3Sn

Transfer to conductor dominated aperture at medium field and then accelerate to high field

Conductor dominated aperture Good at high field (1.5-15T)

Iron dominated aperture Good at low field (0.1-1.5T)

Field profile with time



Compact size

AP issues? Compare with the Low Field Design.

Common Coil Magnet System (Estimated cost savings by eliminating HEB)

SSC: 20+20 TeV;
SppC: 50+50 TeV

Based on 1990 cost in US$

2 TeV HEB Cost in SSC (derived):
$700-800 million

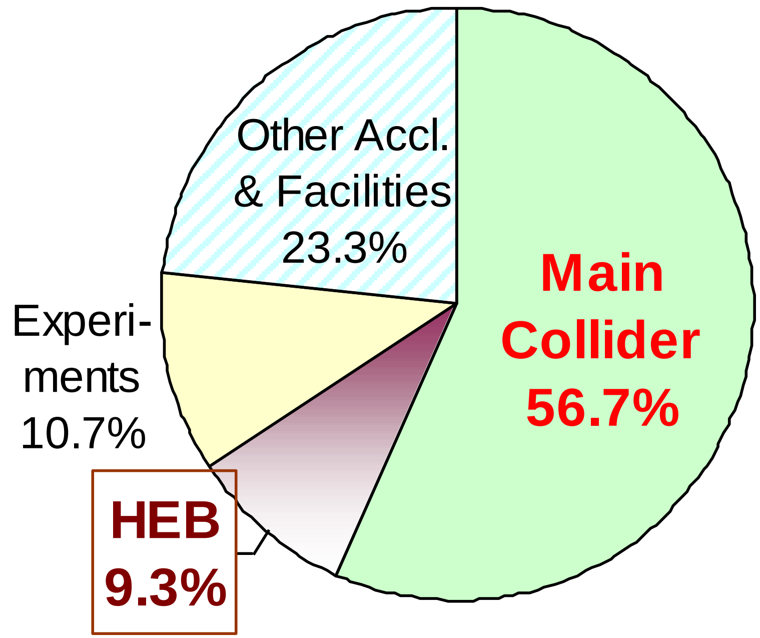
Estimated for 5 TeV (5-50 TeV vlhc):
~$1,500 million (in 1990 US$)

A part of this saving (say ~20-30%) may be used towards two extra apertures, etc. in main tunnel. Estimated savings ~ $1 billion.

Cost savings in equivalent 2040 $?

Cost Distribution of Major Systems

(Reference SSC Cost: 1990 US $7,837 million)

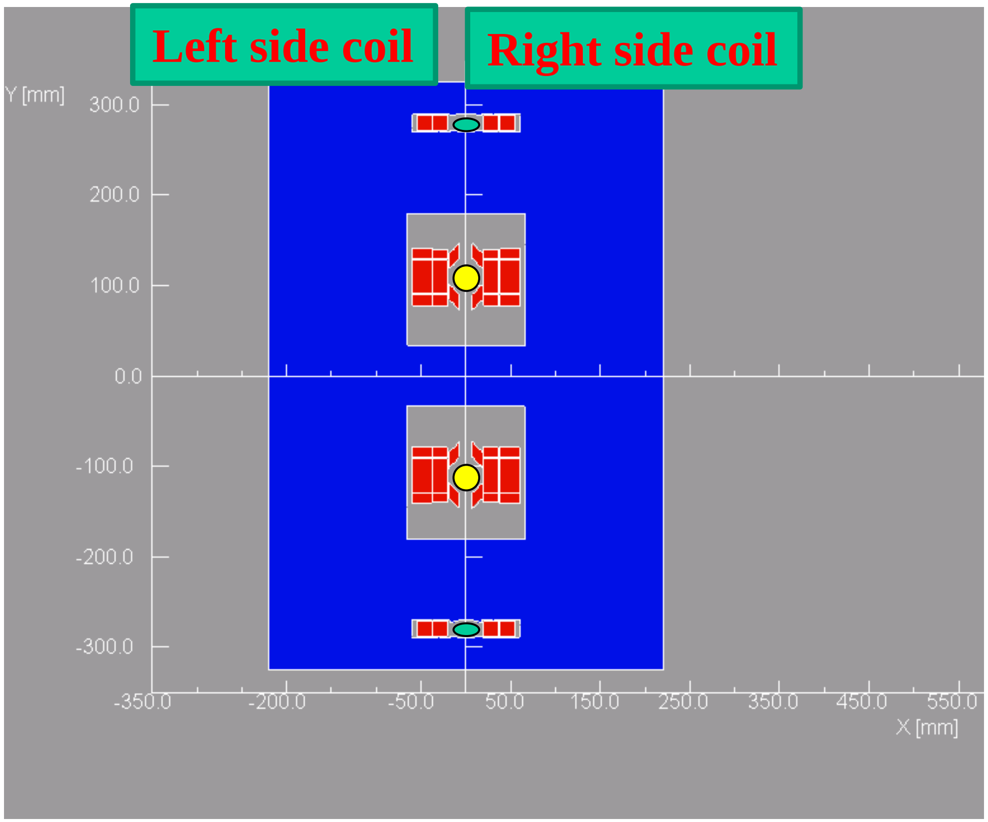


(Derived based on certain assumptions)

Possibility of a Combined Function Common Coil Magnet Design

In a conventional superconducting magnet design, the right side of the coil return on the left side. In a common coil magnet, the coil does not return on the other side, it returns to other aperture.

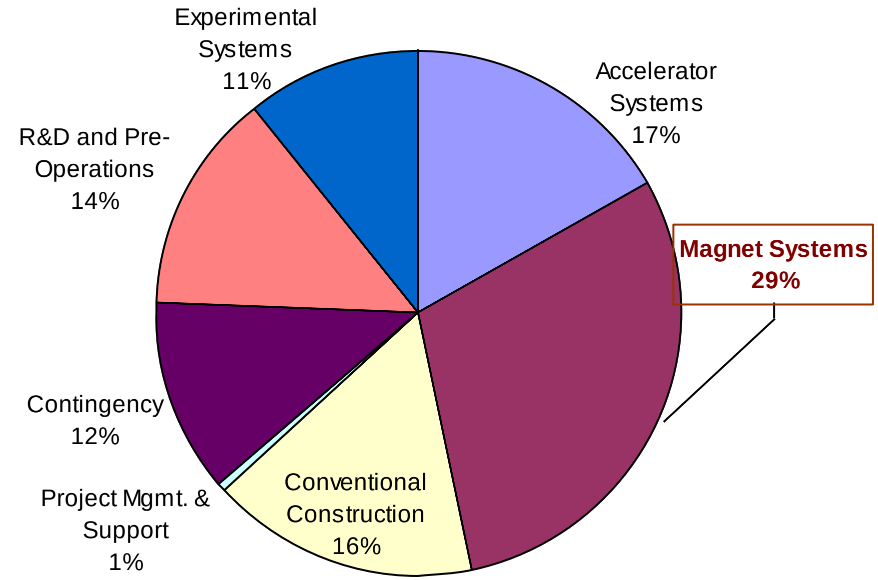
- **Thus in a common coil magnet, the combined function magnet design is simpler as the coils on the right and left sides could be easily different.**



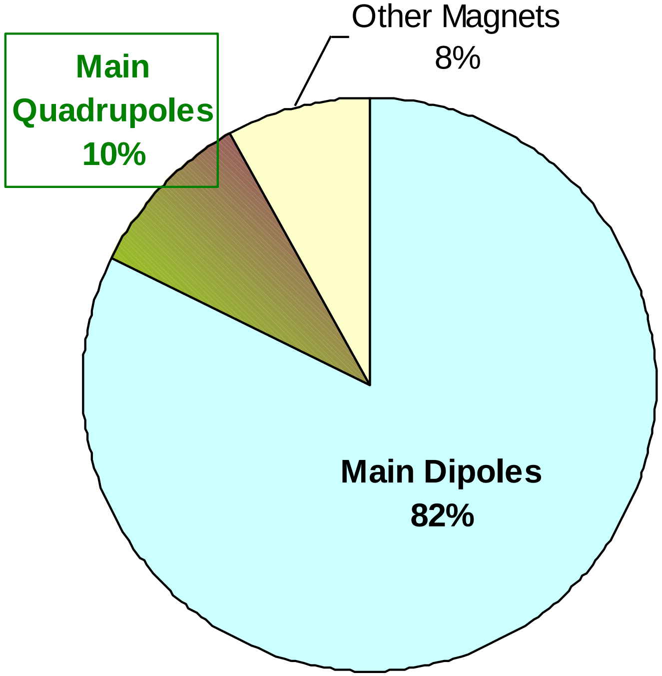
A Combined Function Magnet Option (Estimated cost savings for SppC)

SSC Project Cost Distribution

(Reference SSC Cost: 1990 US $7,837 million)



Collider Ring Magnet Cost Distribution



Total: $2,037 million

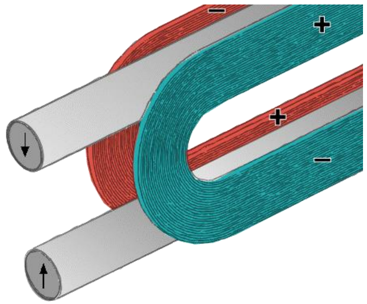
SSC (20 TeV) Main Quads: ~$200 million; SppC (50 TeV) Main Quads: ~$400 million (x2 not 2.5).

Additional savings from tunnel, interconnect, etc.

Estimated potential savings: ~$0.3-0.5 billion (1990 US$).

Cost savings in equivalent 20xx $?

React & Wind Nb_3Sn Common Coil Dipole



R. Gupta, M. Anerella, J. Cozzolino, J. Escallier, G. Ganetis, A. Ghosh, M. Harrison, J. Muratore, W. Sampson and P. Wanderer

Presented by Ramesh Gupta

@ ASC 2006

(also included react & wind Bi2212 HTS)

Special Consideration for Nb_3Sn Magnets

High temperature (~650° C) reaction is required to turn Nb-Sn mixture in to Nb_3Sn A15 phase which becomes superconducting at low temperatures.

Nb_3Sn is brittle after this high temperature reaction. Moreover, during the reaction, Nb-Sn expands and contracts while becoming sensitive to strain.

Two distinct approaches for making Nb_3Sn magnets:

1. Wind & React

   First wind the coil and then react the entire coil package.

   First "good news" then "bad news"!

2. React & Wind

   First react the conductor and then wind the coil.

   First "bad news" then "good news"!

A Few Advantages of React & Wind Approach

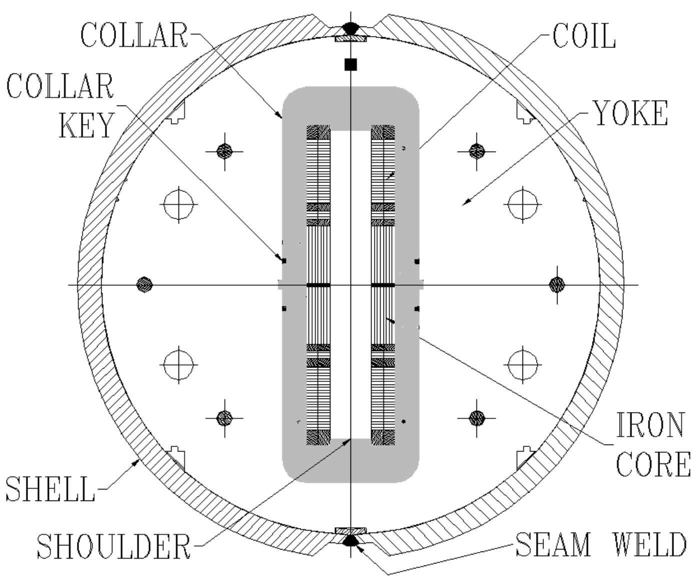
• In the "React & Wind" approach the coil and associated structure is not subjected to the high temperature reaction. This allows one to use a variety of insulation and other materials in coil modules.

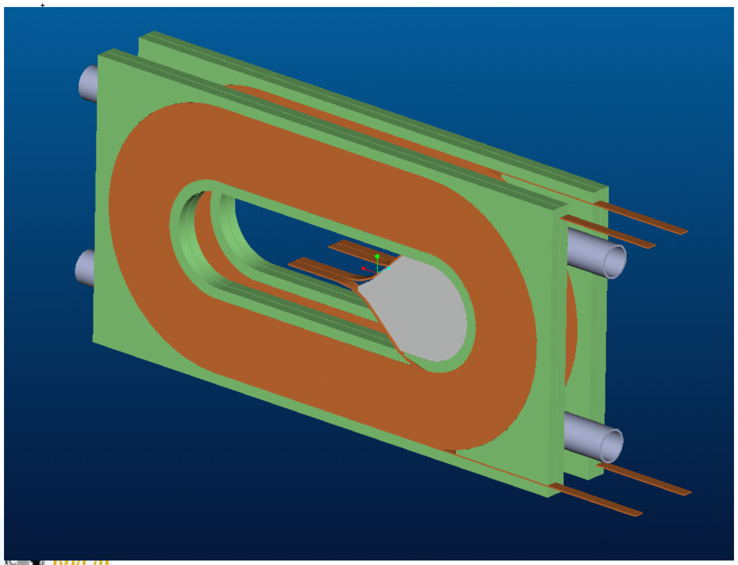
» In "Wind & React", one is limited in choosing insulating material, etc. since the entire coil package goes through reaction.

• The "React & Wind" approach appears to be more adaptable for building production magnets in industry by extending most present techniques. Once the proper tooling is developed and the cable is reacted, most remaining steps in industrial production of magnets remain nearly the same in both Nb-Ti and Nb_3Sn magnets.

• Since no specific component of "React & Wind" approach appears to be length dependent, demonstration of a particular design and/or technique in a short magnet, should be applicable in long production magnet (except for mechanical, quench protection, etc.).

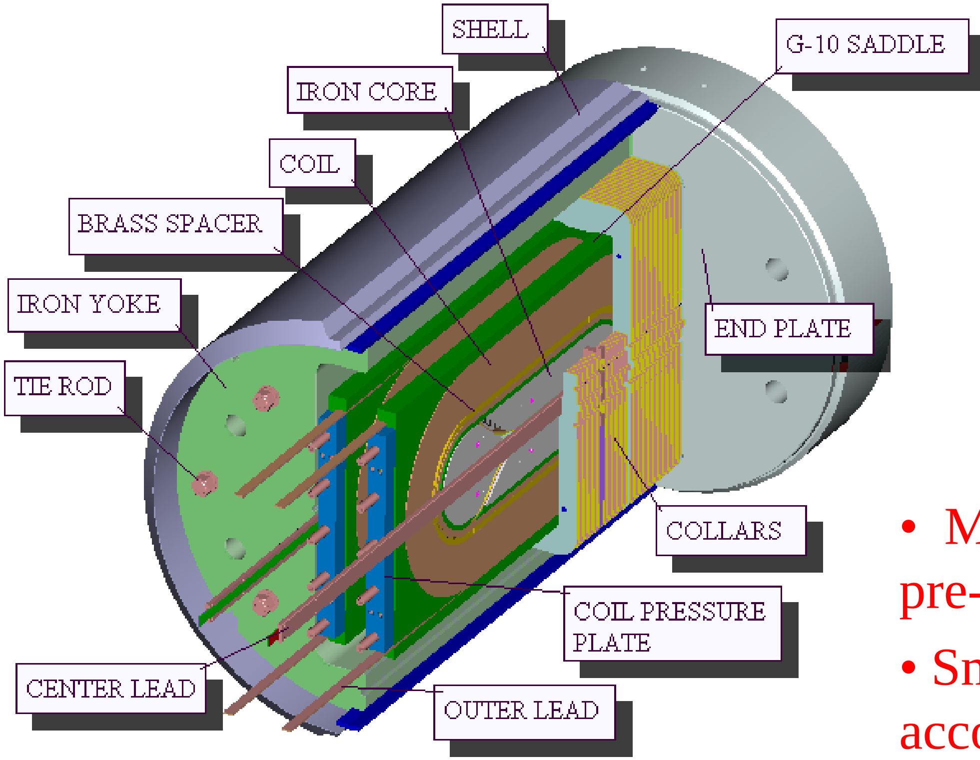
Basic Features of BNL Nb_3Sn 10^+ T React & Wind Common Coil Dipole





- Two layer, 2-in-1 common coil design
- 10.2 T bore field, 10.7 T peak field at 10.8 kA short sample current
- 31 mm horizontal aperture
- Large (338 mm) vertical aperture
  - » A unique feature for coil testing
- Dynamic grading by electrical shunt
- 0.8 mm, 30 strand Rutherford cable
- 70 mm minimum bend radius
- 620 mm overall coil length
- Coil wound on magnetic steel bobbin
- One spacer in body and one in ends
- Iron over ends
- Iron bobbin
- Stored Energy@Quench ~0.2 MJ

Mechanical Design Features



Main components of support structure:

- Stainless steel collar: 13 mm thick
- Rigid yoke: 534 mm o.d.
- Stainless steel shell : 25 mm thick
- End plate: 127 mm thick

The original support structure was designed for 40 mm, 12.5 T dipole.

Choice of conductor, etc. made it 31 mm, 10.2 T dipole.

- Magnet is designed for almost no cold pre-stress (horizontal, vertical or axial)
- Small warm vertical load is applied to account for differential thermal expansion
- Inflatable bladder to keep coil outward
- Keepers (SS) to lock coil to collars
- End plates (SS) were circumferentially welded to shell

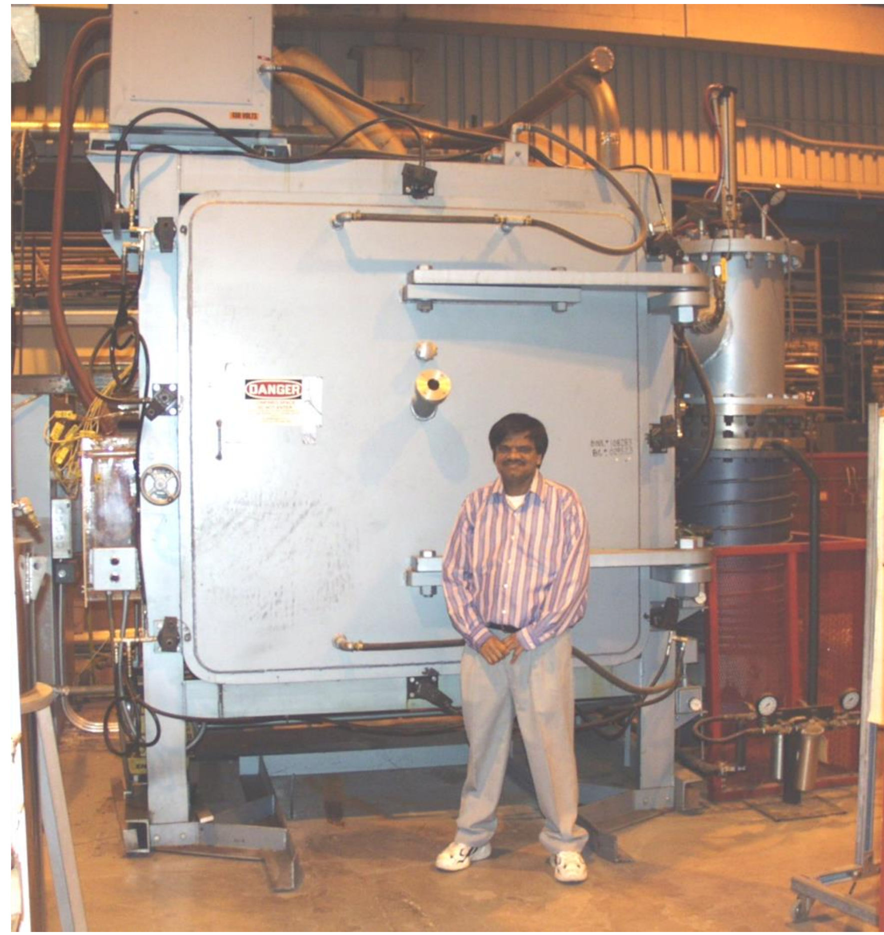
Nb_3Sn High Temperature Reaction

Oil Impregnation Setup

Oil impregnation puts a thin coating on wires of Rutherford cable to avoid sintering during the reaction

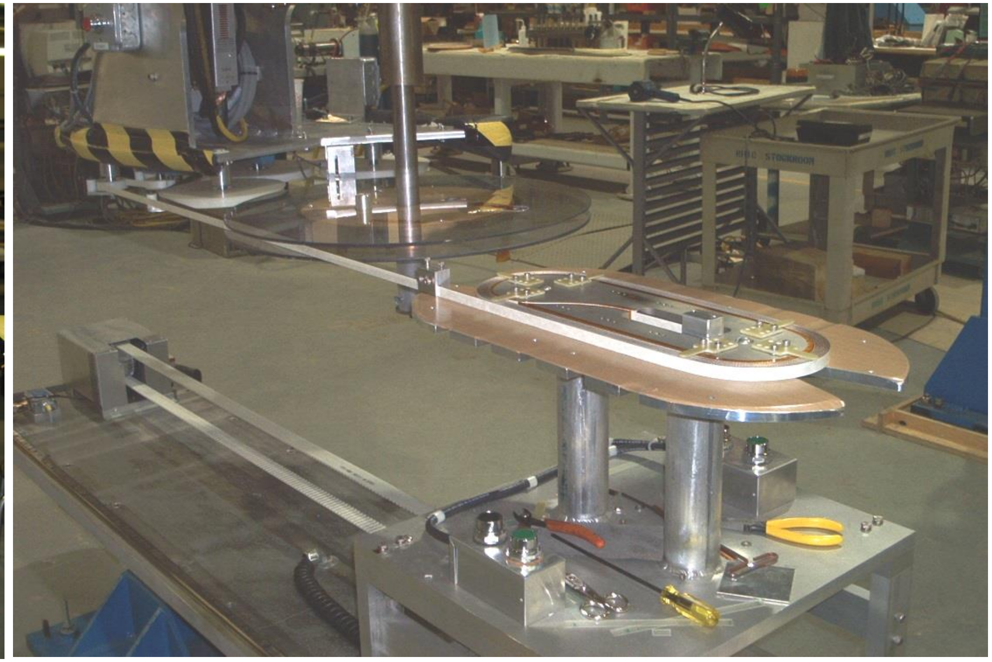
Cable was pre-annealed to take out initial thermal expansion and to avoid possible local strain during high temperature reaction.

Large (1.5 m^3) reaction furnace



Used for reacting long lengths of Nb_3Sn cable

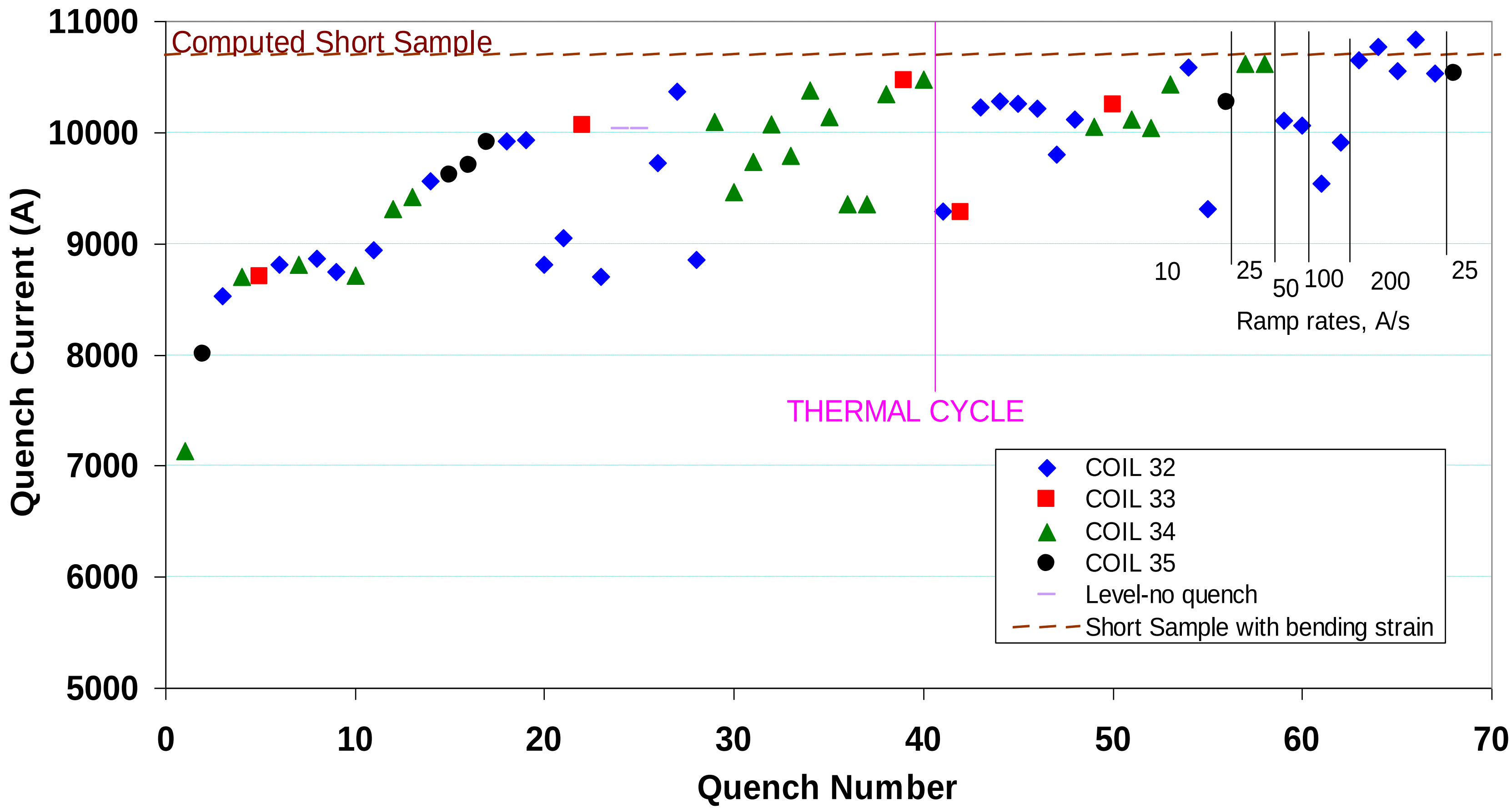
Automatic Coil Winder : A Key Component in Developing "React & Wind" Technology



Each part and step in this new automatic coil winder is carefully designed to minimize the potential of bending degradation to brittle superconductors during the winding process. The machine is fully automated and computer controlled to minimize uncontrolled errors (human handling). All steps are recorded to carefully debug the process, as and if required.

BNL Nb_3Sn React & Wind Common Coil Dipole DCC017 During Final Assembly

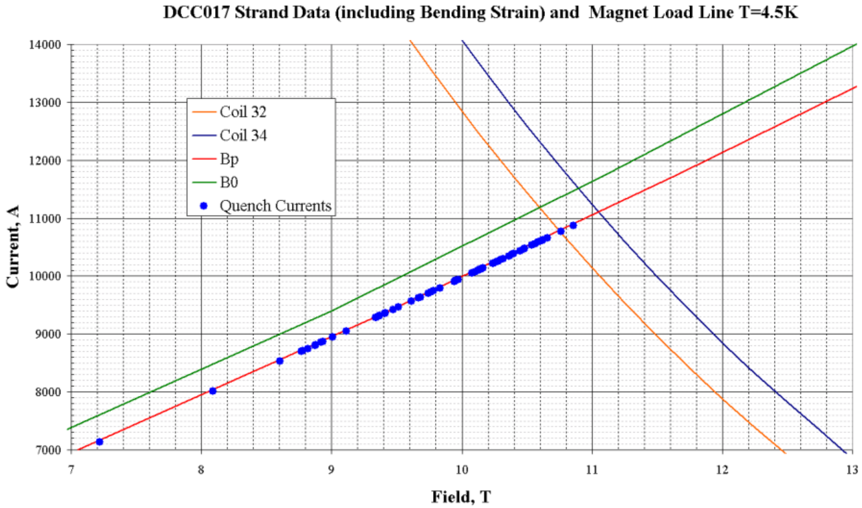
Quench Plot of BNL React & Wind Common Coil Dipole DCC017

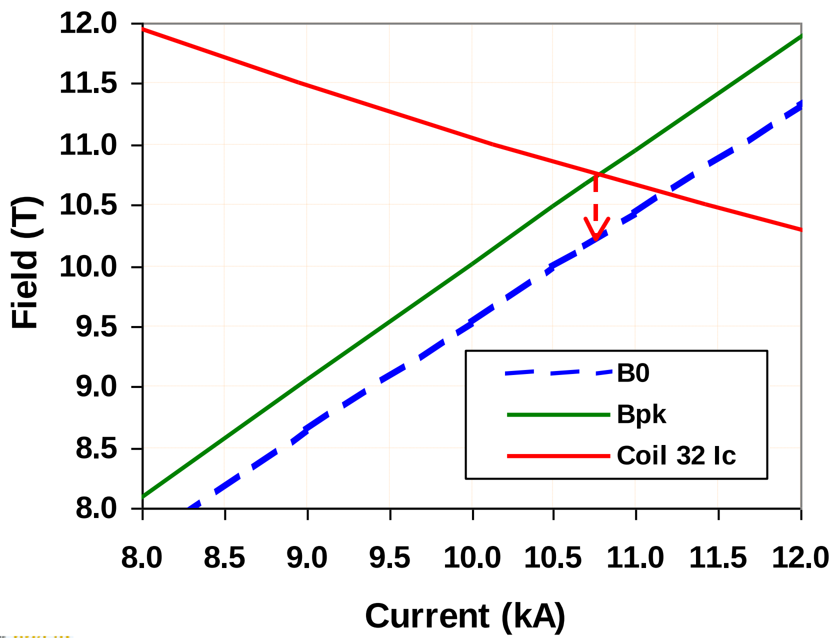


- Magnet reached short sample after a number of quenches
  - √ Reasonable for the first technology magnet
- No significant ramp rate dependence

I_c=10.8 kA
B_{pk}=10.7 T
B_{ss}=10.2 T

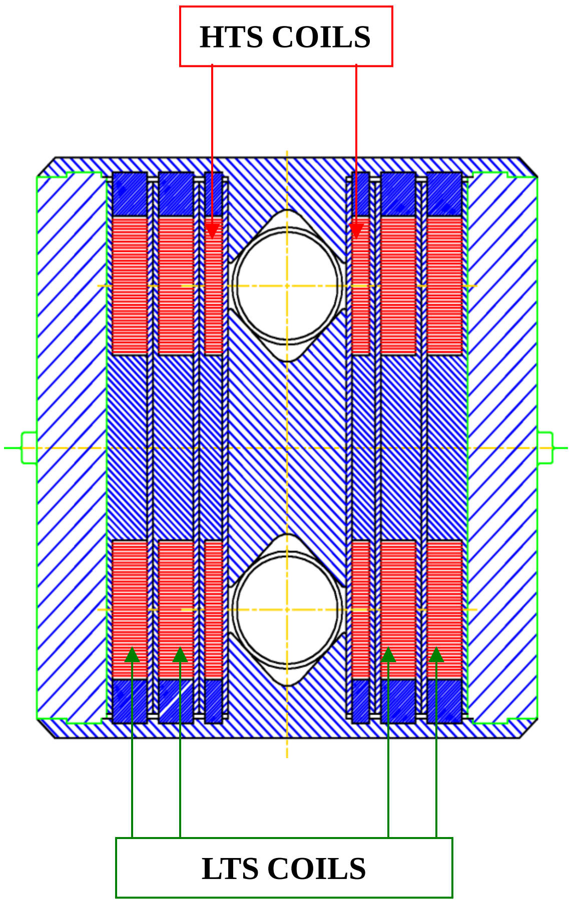
Load-line and Peak Field Line with Extracted Strand Measurements





- Magnet reached short sample based on the measurements of the extracted strand of the two types of cables used in coils.
- Magnet did not have any energy extraction system. There was a concern if there could be strain degradation due to thermo-mechanical effects. No conclusive evidence based on limited information.
- Magnet had practically no pre-stress on the coil (horizontal, vertical or axial). No experiment are planned to determine if pre-stress could improve the performance.
- Relative (internal) deflections of coils could have been ~100 µm. Absolute deflections much higher (~a factor of two).

HTS Magnet R&D in a Common Coil Hybrid Design



- **Perfect for R&D magnets now.**

  HTS is subjected to the similar forces that would be present in an all HTS magnet. Therefore, several technical issues will be addressed.

- **Also a good design for specialty magnets where the performance, not the cost is an issue. Also future possibilities for main dipoles.**

- **Field in outer layers is ~2/3 of that in the 1st layer. Use HTS in the 1st layer (high field region) and LTS in the other layers (low field regions).**

Bi2212 HTS Coils and Magnets @ BNL

TABLE II

COILS AND MAGNETS BUILT AT BNL WITH BSCCO 2212 CABLE. I_c IS THE MEASURED CRITICAL CURRENT AT 4.2 K IN THE SELF-FIELD OF THE COIL. THE MAXIMUM VALUE OF THE SELF-FIELD IS LISTED IN THE LAST COLUMN. ENGINEERING CURRENT DENSITY AT SELF-FIELD AND AT 5 T IS ALSO GIVEN.

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

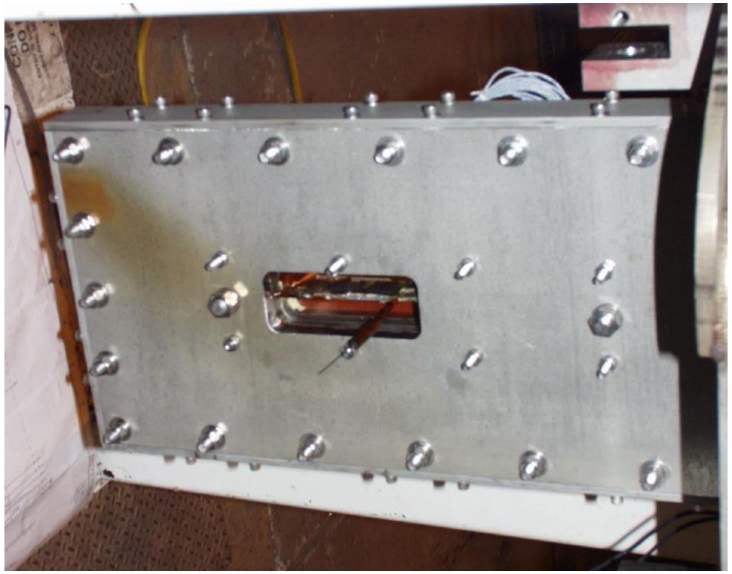
BNL pursued "React & Wind" technology for Bi2212

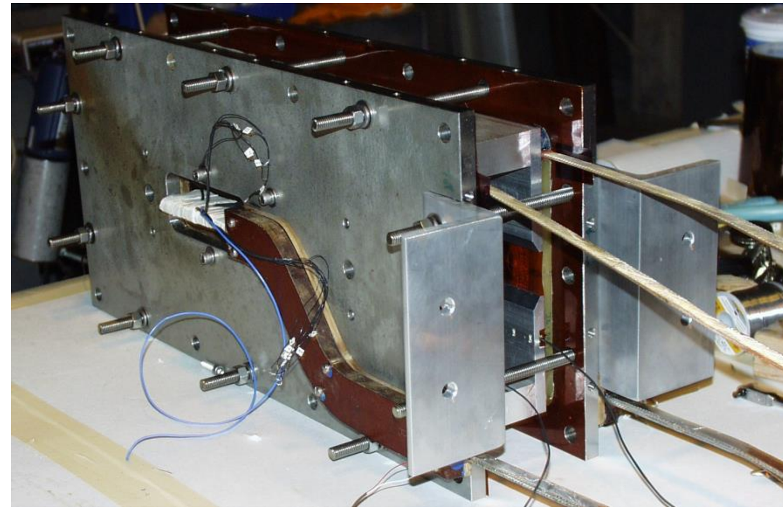
Eight coils and five magnets were built at BNL with Rutherford Bi2212 Cable (Showa/LBNL)

BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

Magnet Structures for Bi-2212

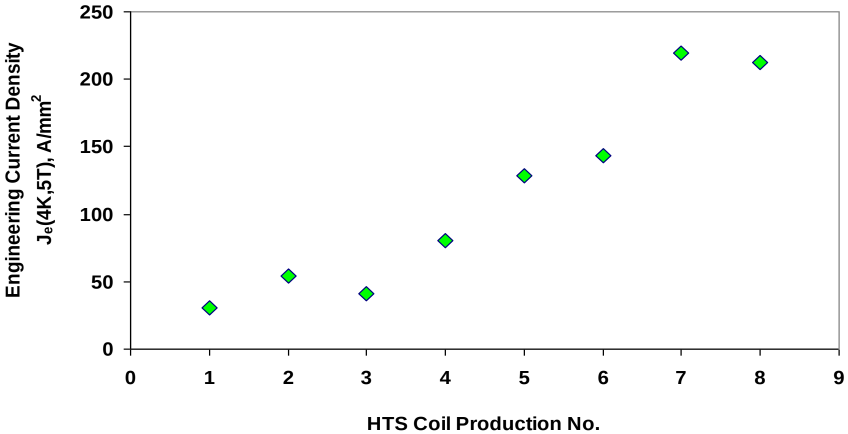




Common Coil Design

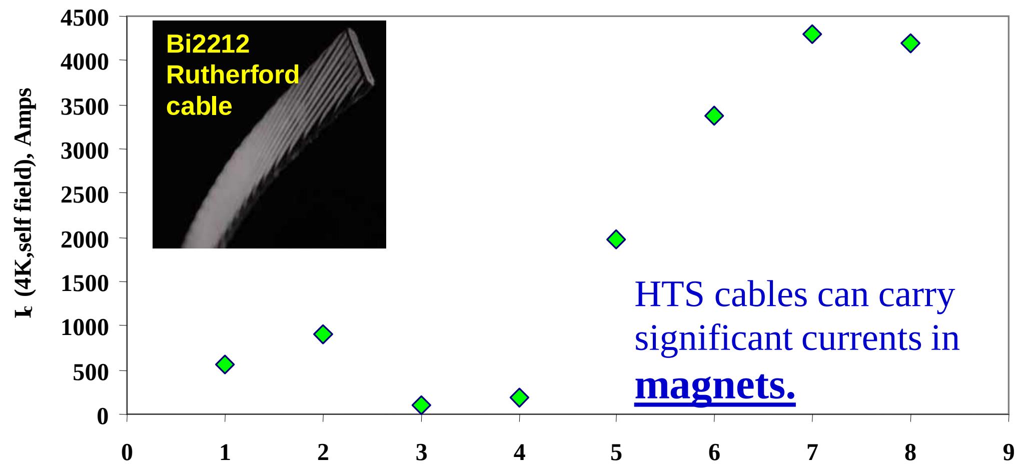
HTS Common Coil Dipole with Bi2212 Rutherford Cable

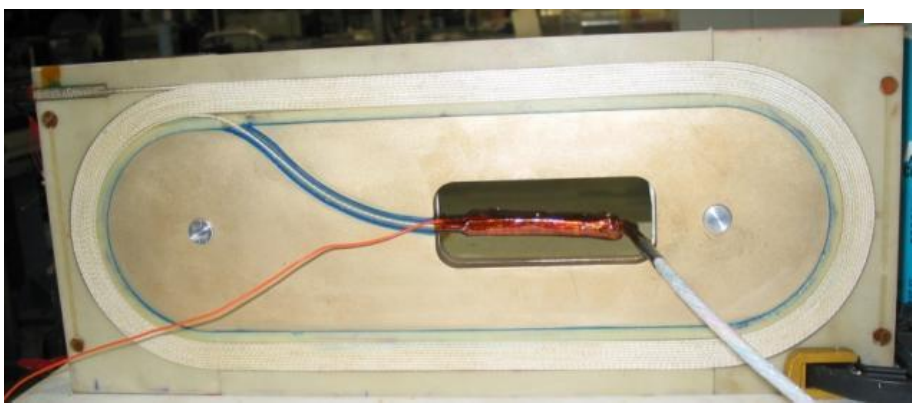
8 Coils and 5 Magnets built with Rutherford Bi2212 Cable



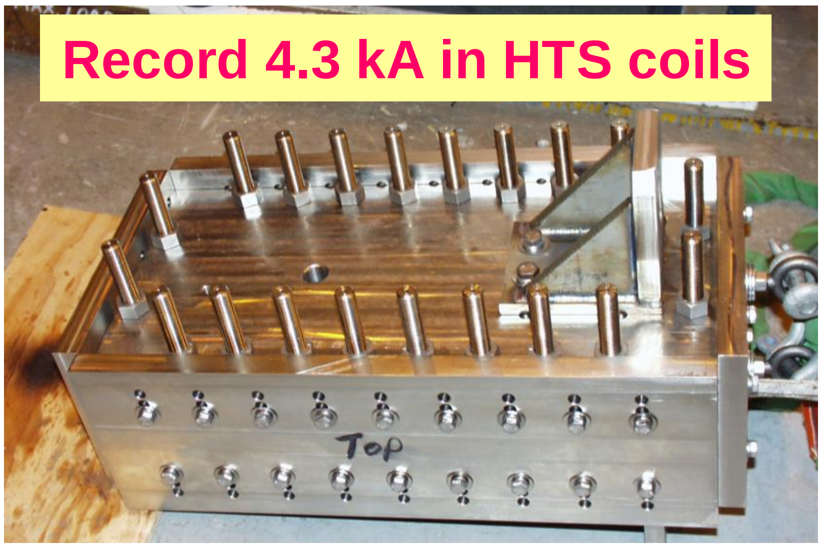
Earlier coils
<1 kA (~2001)

Later coils
4.3 kA (2003)





Racetrack HTS coil with Bi2212



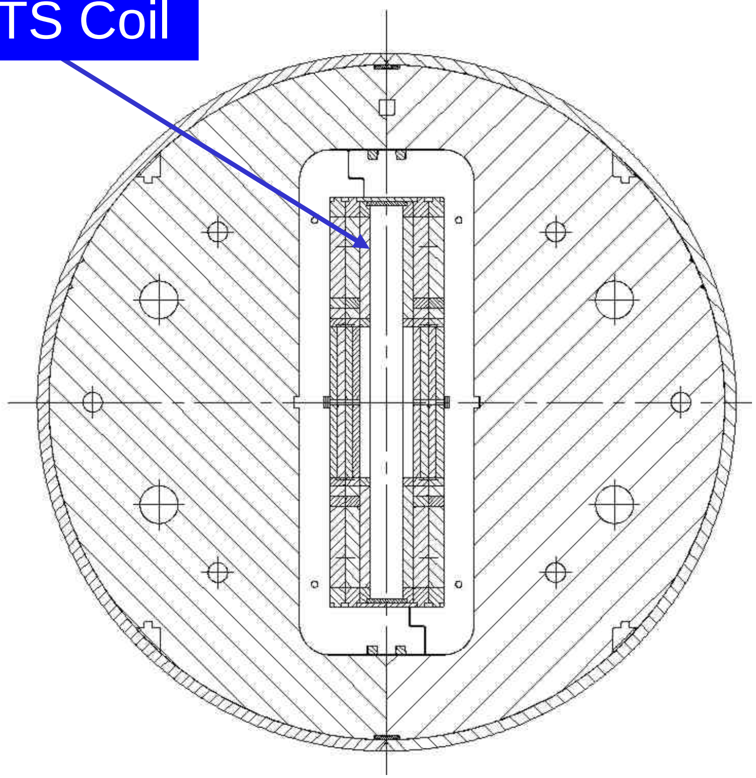
2T

Still a record

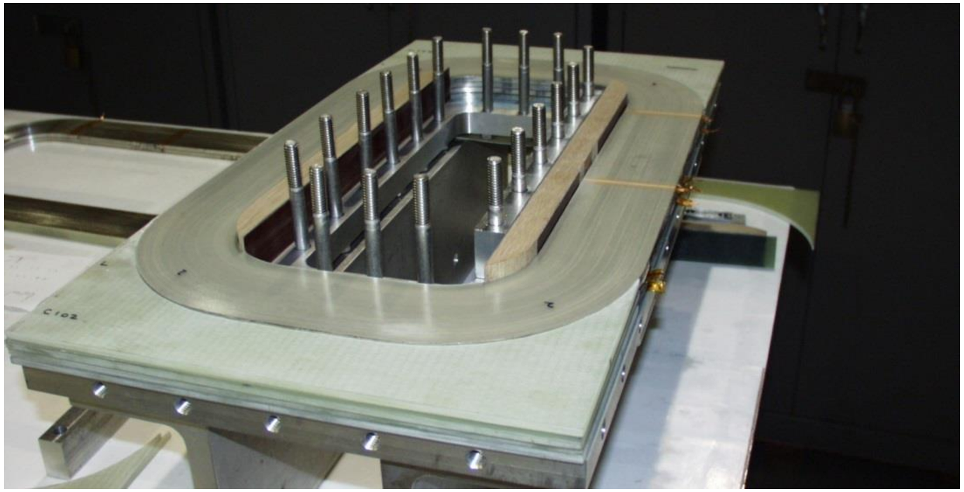
Unique Coil Test Features

A unique feature of this design is a large vertical open space for high field testing of racetrack HTS insert coils without disassembling the magnet.

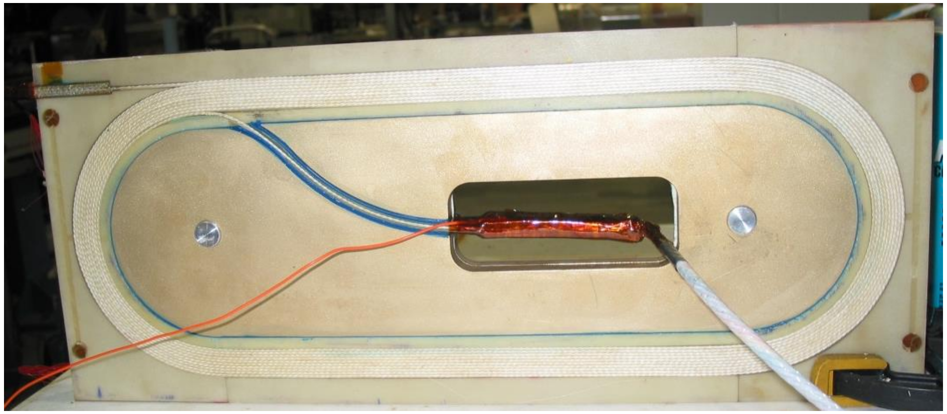
HTS Coil



HTS insert coil test configuration (HTS/Nb_3Sn Hybrid magnet)



HTS coils made with BSCCO tape from ASC



HTS coil made with Rutherford cable from Showa/LBL

Conclusions from BNL Experience of React & Wind Common Coil Dipole

- "React & Wind" is an appealing alternate option for building long length high field Nb_3Sn production magnet.

- Successful construction and test of the BNL common coil magnet proves that, "React & Wind is a viable technology for high field Nb_3Sn accelerator magnets".

- It should be possible to make React & Wind magnets up to ~15 T.

- Due to a unique large open space, this magnet can be used for inexpensive and fast turn around high field HTS insert coil tests

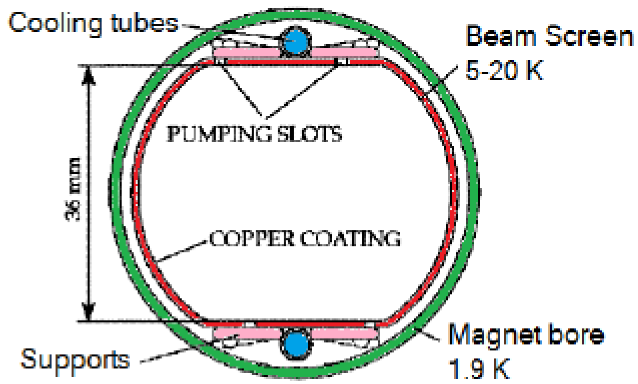
Open Midplane Dipole

Open Midplane Dipole for FCC (as championed by Bob Palmer)

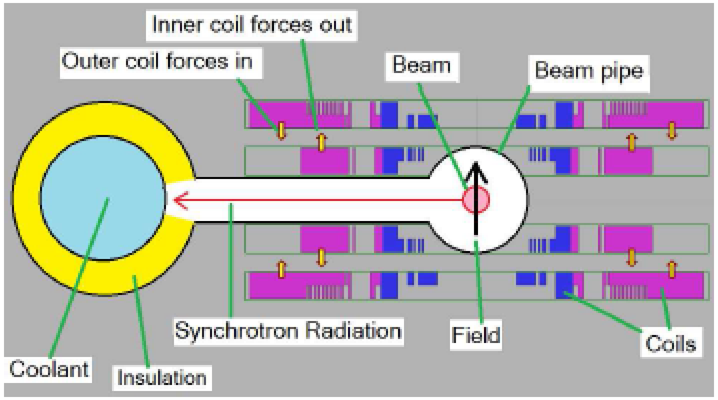
SYNCHROTRON RADIATION

In 100TeV p-p collider (CERN FCC-hh) 0.5 amp 16 T:

- Total SR power = 4.8 MW
- If on magnet bore: wall power to cool is crazy
- Requires beam screen at 50 K
- If screen inside beam pipe: uses valuable space
- If screen in beam tube: Emits electrons → electron cloud
- If deposited away from beam tube, as in e+e- ring colliders, BOTH PROBLEMS SOLVED



CERN Beam Screen

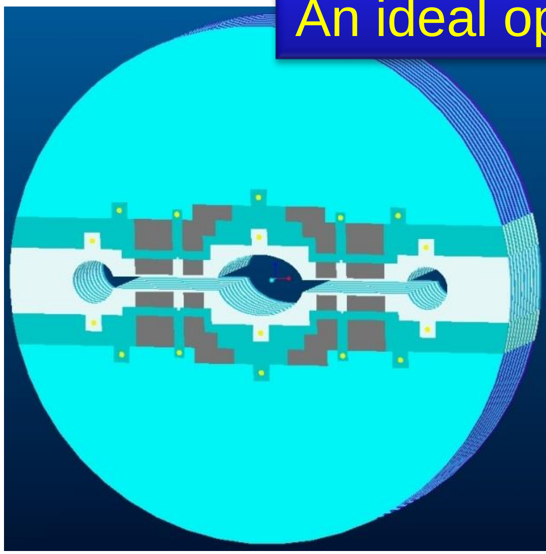


With Open-Plane Magnet

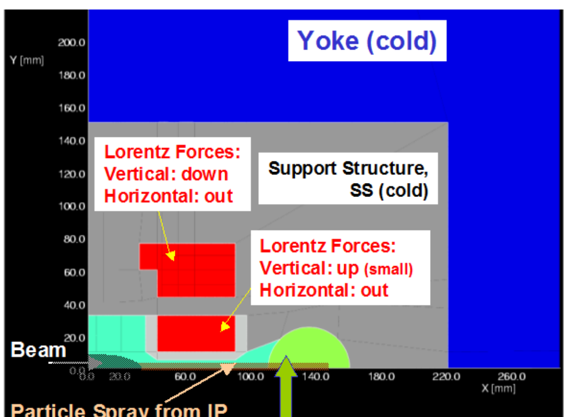
Courtesy: Bob Palmer, BNL

An Ideal Open Midplane Design

An ideal open midplane design will have no structure on the axis

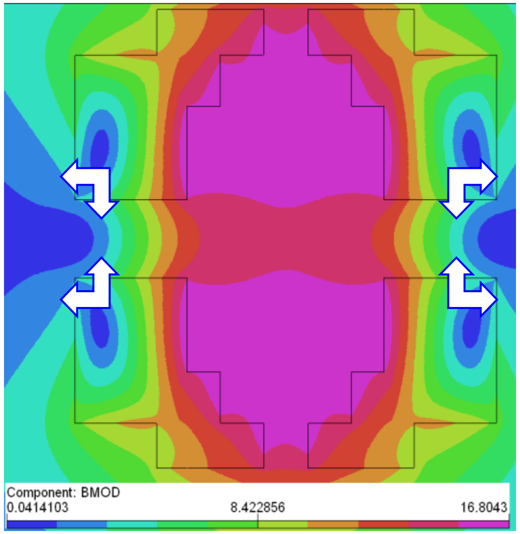


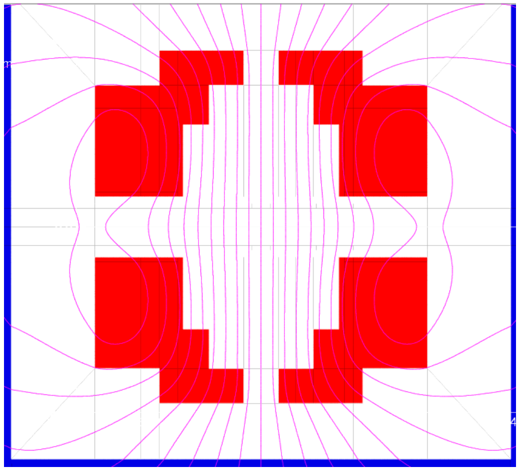
- Decay particles will, therefore, deposit energy in a warm absorber that is sufficiently away from the superconducting coils or support structure.
- In a partial "open midplane design", although there is "no conductor" at the midplane, there could be some "other structure" between the upper and lower halves of the coil to help deal with Lorentz forces.
- Those designs, though significantly reduce energy deposited in coils from direct hit, could still face heat from secondary showers produced by the other structure. In addition, the energy deposition in that cold structure itself could be significant.
- Therefore, an "ideal" or "true" open midplane dipole should be preferred, if a viable design can be proven.



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.

Challenges associated with the "Ideal" or "True" Open Midplane Dipole Design





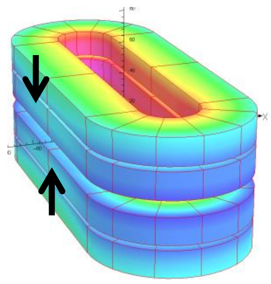
#1 In usual cosine theta or block coil designs, there are large attractive forces between upper and lower coils. How can these coils hang in air with no structure in between?

#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.

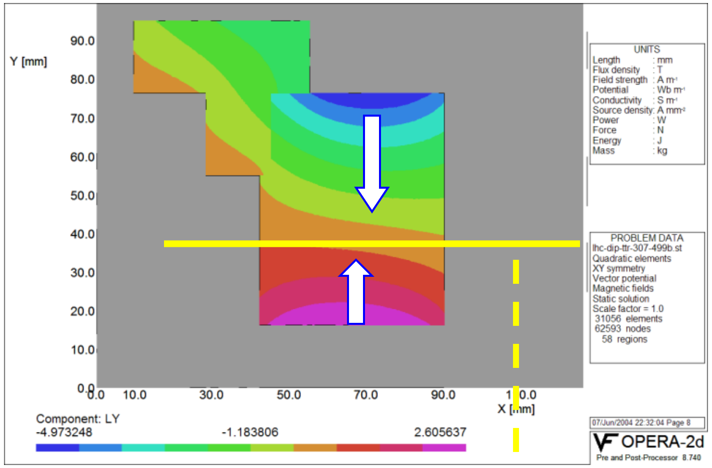
⇨ Several innovative solutions were developed to overcome above challenges (at least theoretically) with a significant funding from LARP. However, the funding was terminated before those solutions could be proven.

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.

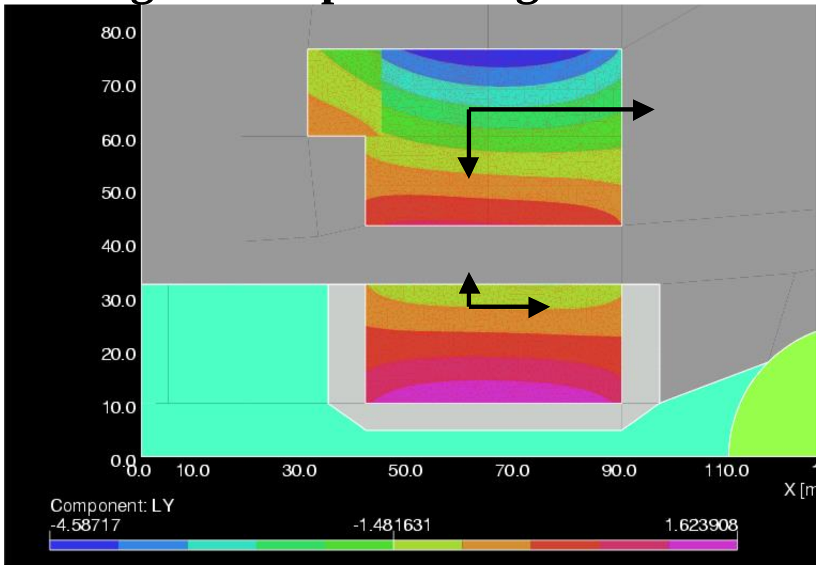
Original Design



Zero vertical force line

Lorentz force density (Vertical)

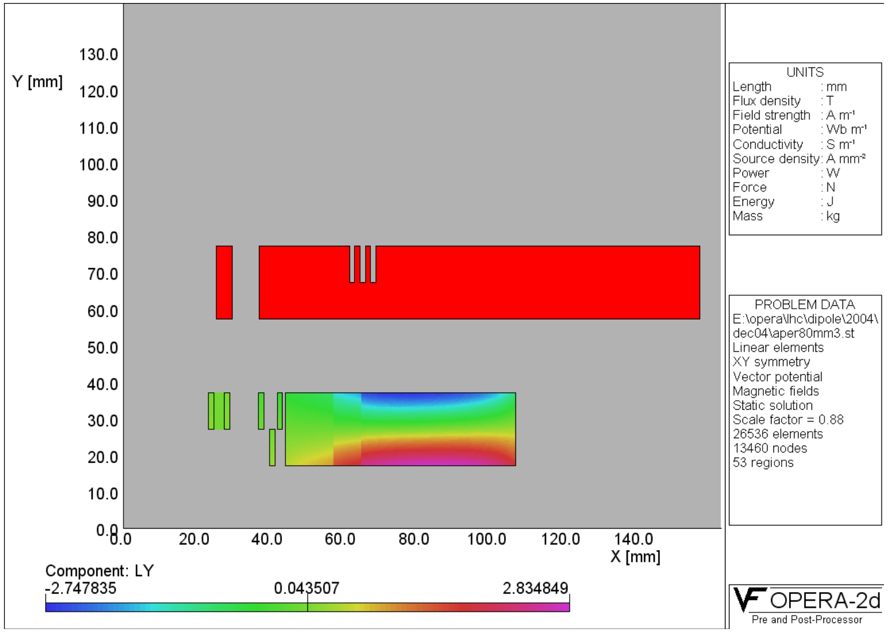
New Design Concept to navigate Lorentz forces



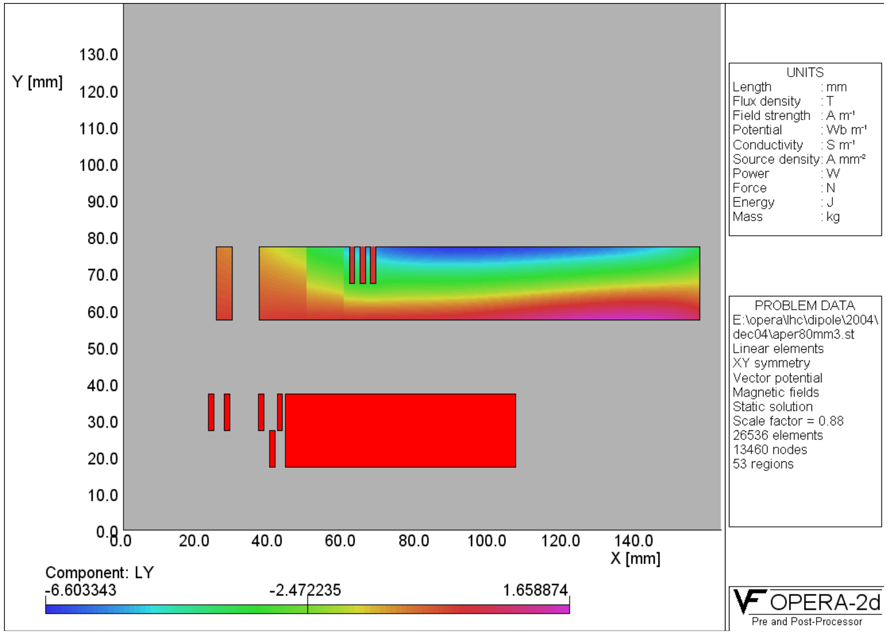
Since there is no downward force on the lower block (there is slight upward force), we do not need much support below if the structure is segmented. The support structure can be designed to deal with the downward force on the upper block using the space between the upper and the lower blocks.

Vertical Forces at 15 T (design optimized to first order)

Net upward vertical force on lower double pancake coil



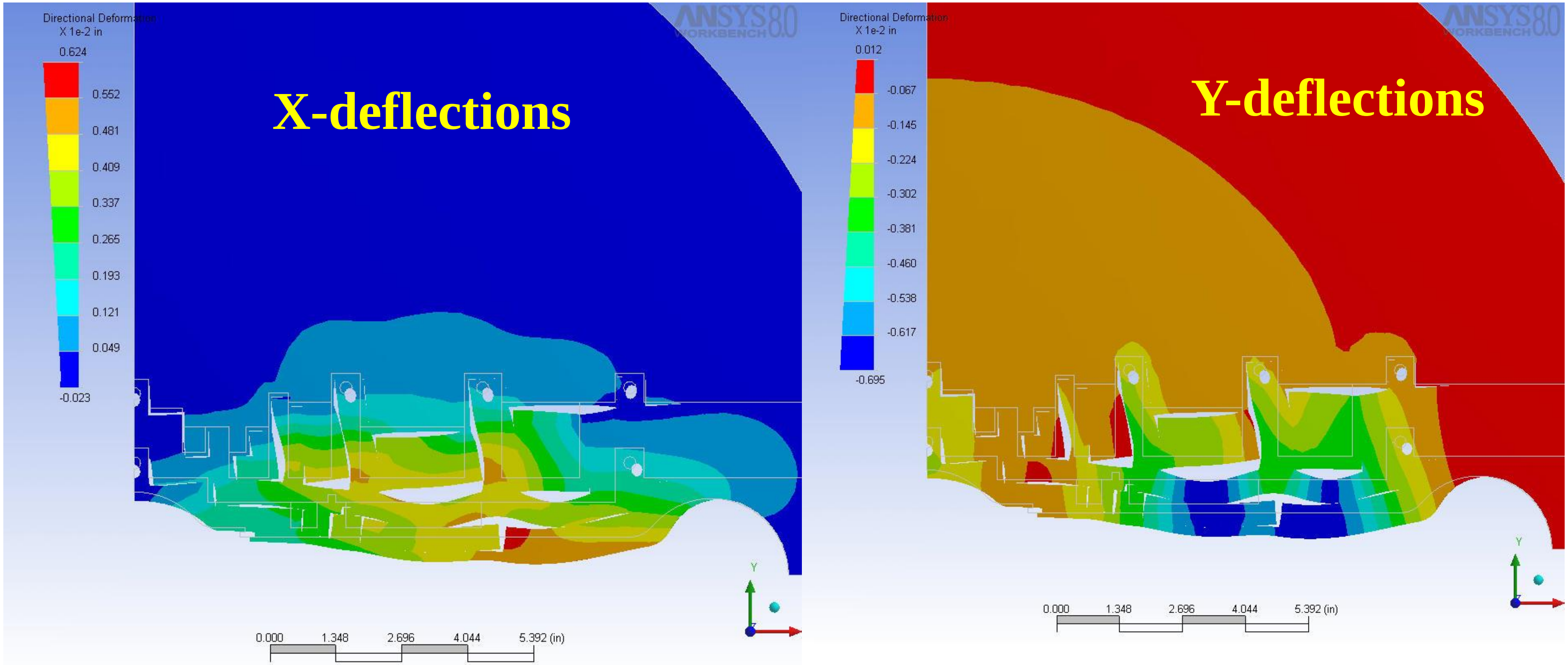
Downward vertical force on upper double pancake coil is taken by the support structure between two double pancake coils



Net Force per quadrant:

Horizontal = 11 MN/m; Vertical –5.4 MN/m

Mechanical Analysis (J. Schmalzle)



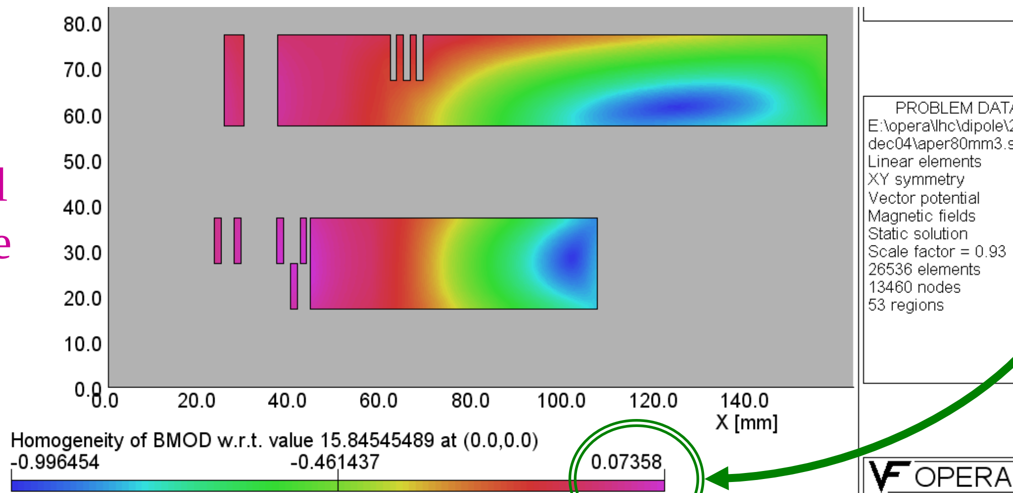
In a more optimized design the relative values of the x and y deflections are 3-4 mil (100 micron) and the maximum value is 6-7 mil (170 micron)

Above deflections are at design field (13.6 T). They are ~1-2 mil higher at 15 T.

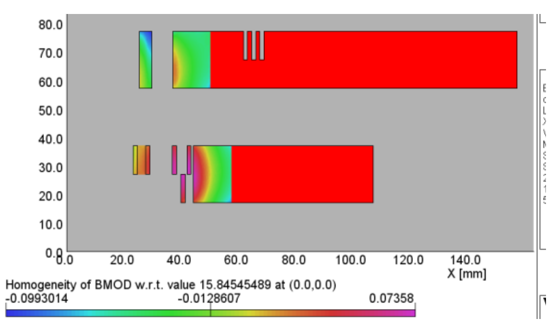
Challenge #2: Peak Field

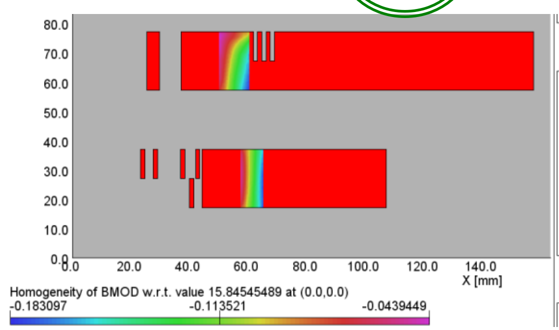
Several designs have been optimized with a small peak enhancement: ~7% over B_o

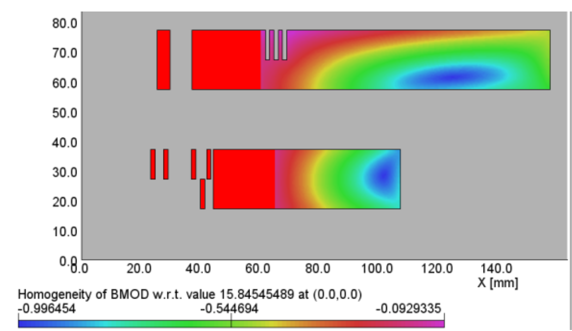
Relative field enhancement in coil (peak field) over the central field



Similar to that in an optimized cosine theta designs







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

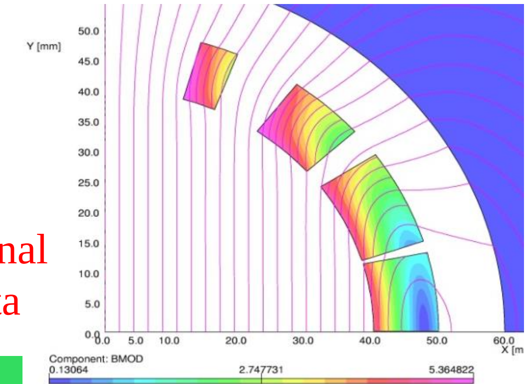
Challenge #3: Field Quality

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

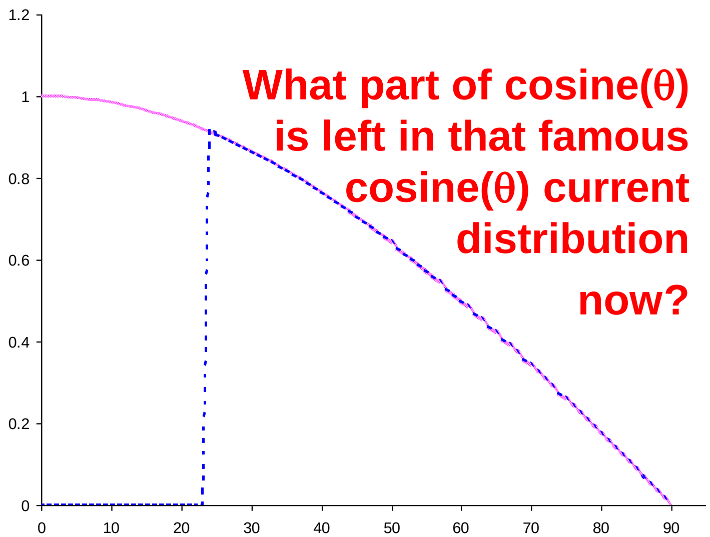
Horizontal aperture = 80 mm

⇒ Vertical gap is > 42% of horizontal aperture

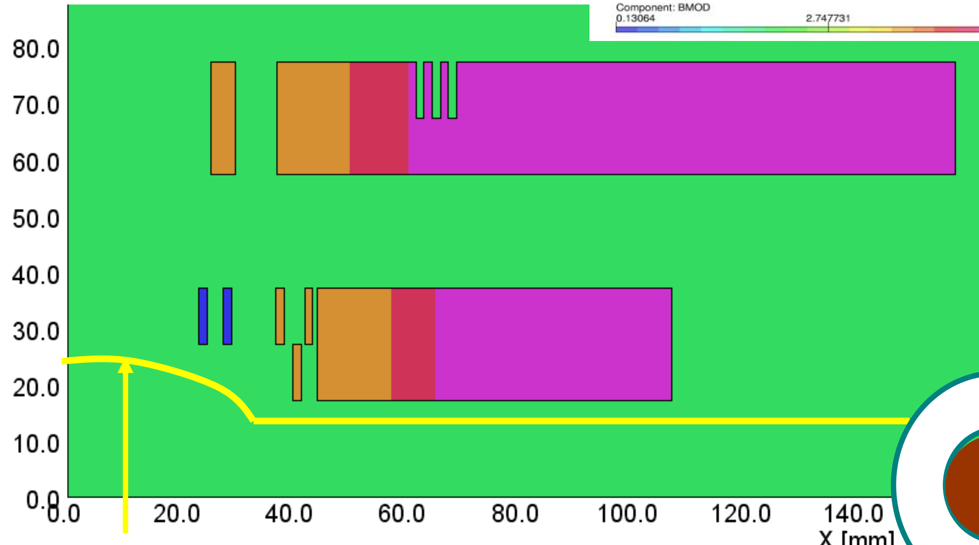
(midplane angle: 23°)

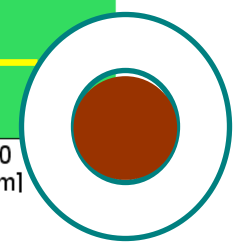


Conventional cosine theta



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 !

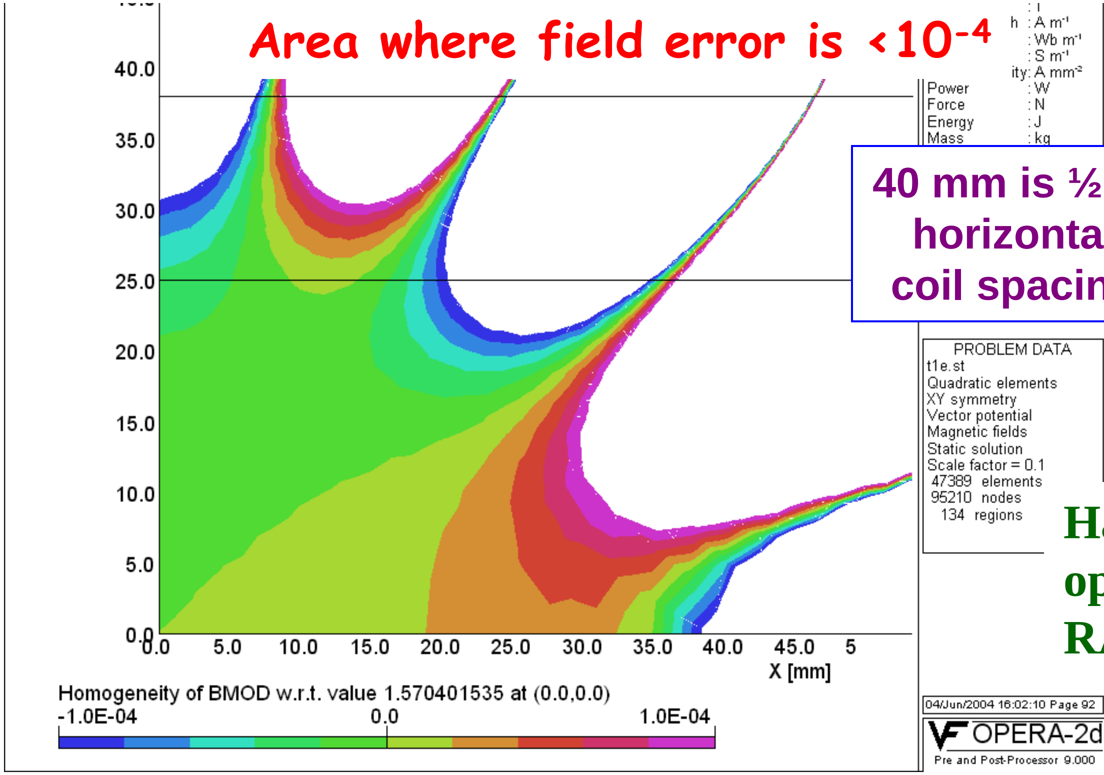
Open midplane design

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)

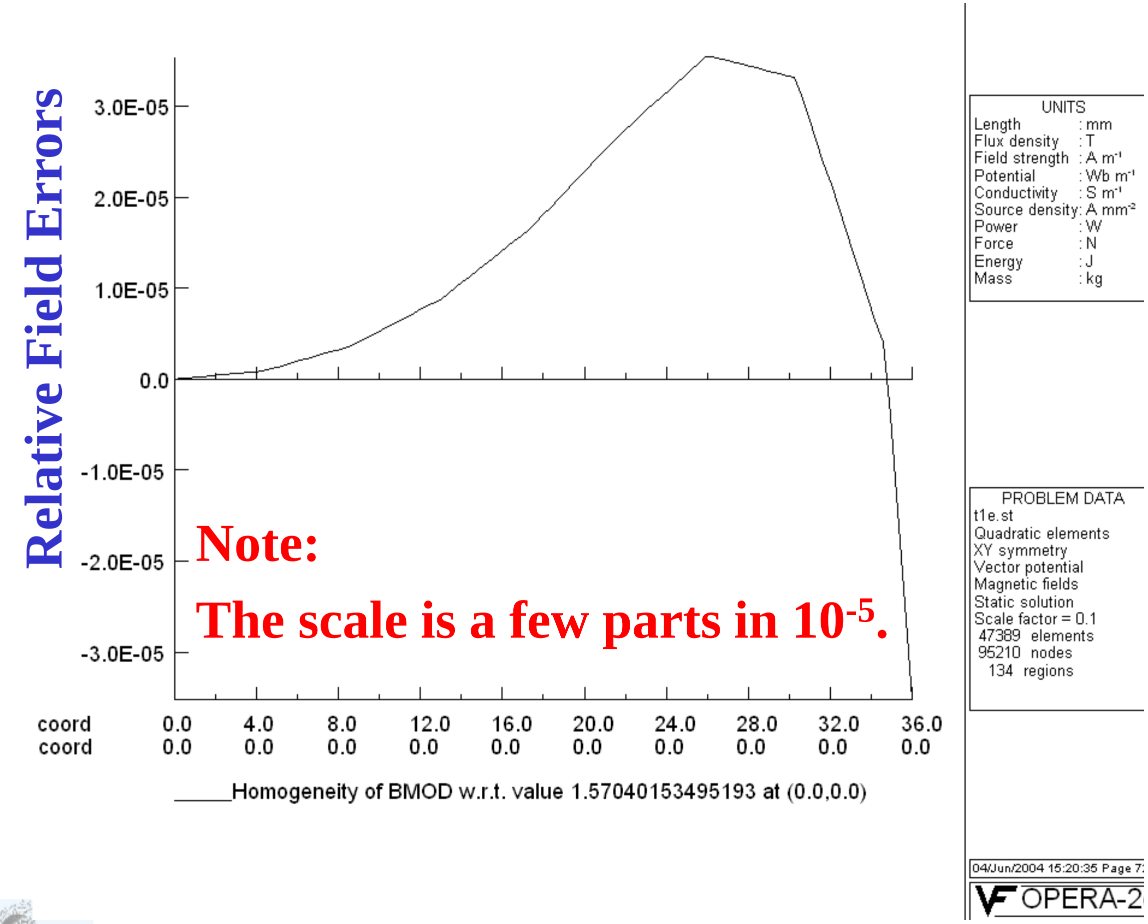
Geometric Field Harmonics:

	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}.

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.; i.e., they are not limited by the design geometry.

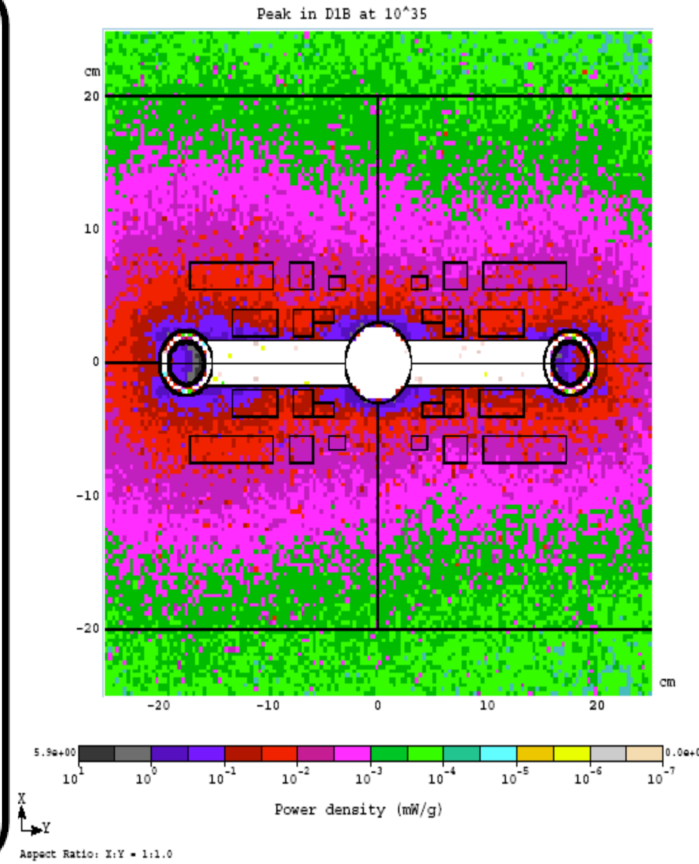
Energy Deposition Summary (Nikolai Mokhov 04/05)

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



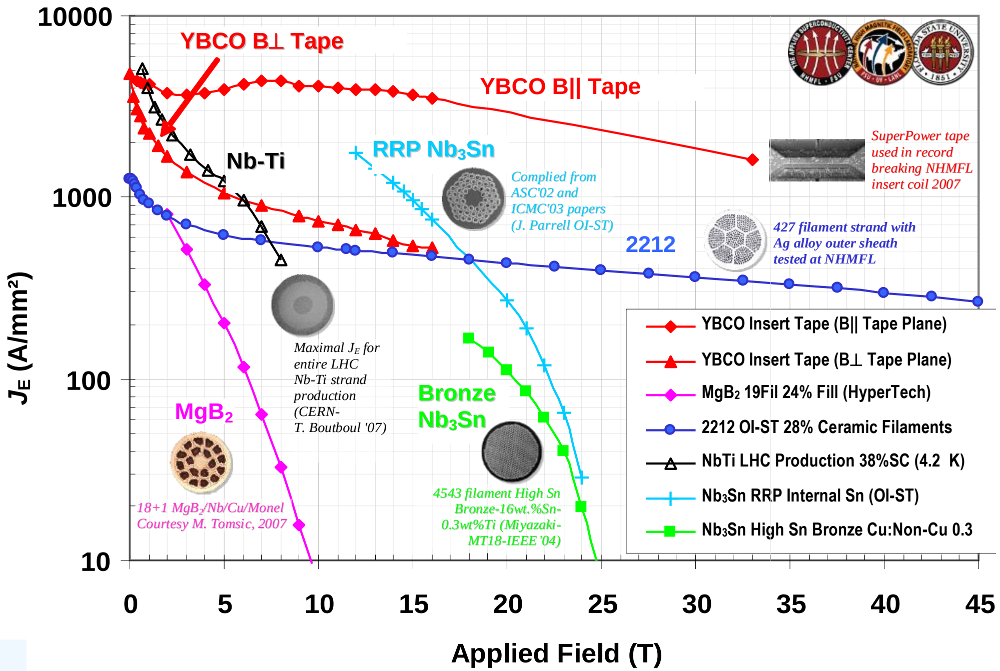
Summary of Optimized Open Midplane Nb_3Sn Dipole Designs for LARP

	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/

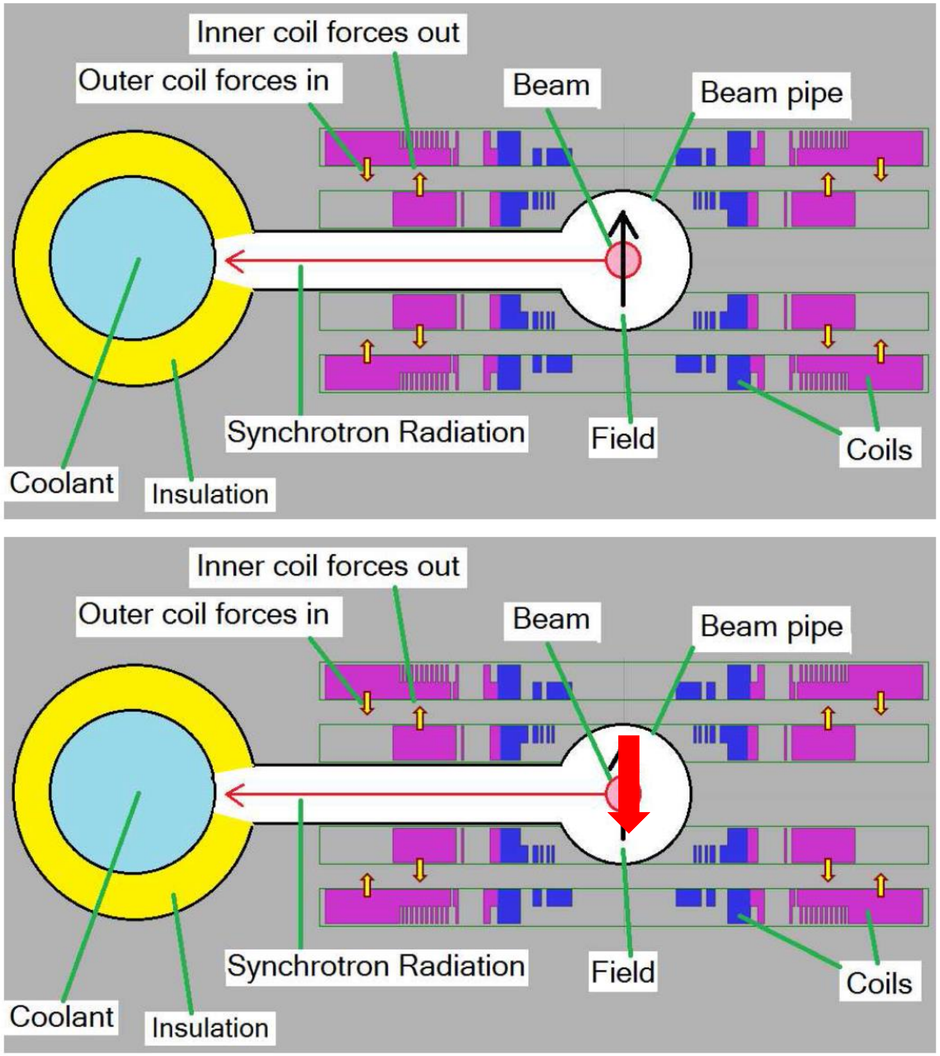
Open Midplane Designs With HTS (High Temperature Superconductors)

- HTS could generate very high fields (say ~20 T)
- HTS can be used in a hybrid designs with Nb_3Sn and NbTi coils
  - Geometry and field distribution is such that it can be done easily
- HTS could tolerate large energy deposition and operate with larger increase in local or global temperature



- Large temperature margin in HTS will tolerate several degrees of temperature rise in HTS coils
- HTS could also remove energy more efficiently at higher temperature, as in FRIB

Common Coil Open Midplane Dipole?



How about common coil open midplane dipole?

Can one tolerate some perturbation in a small region in the ends where turns must go from one aperture to another?

Other HTS Magnet R&D Programs at BNL

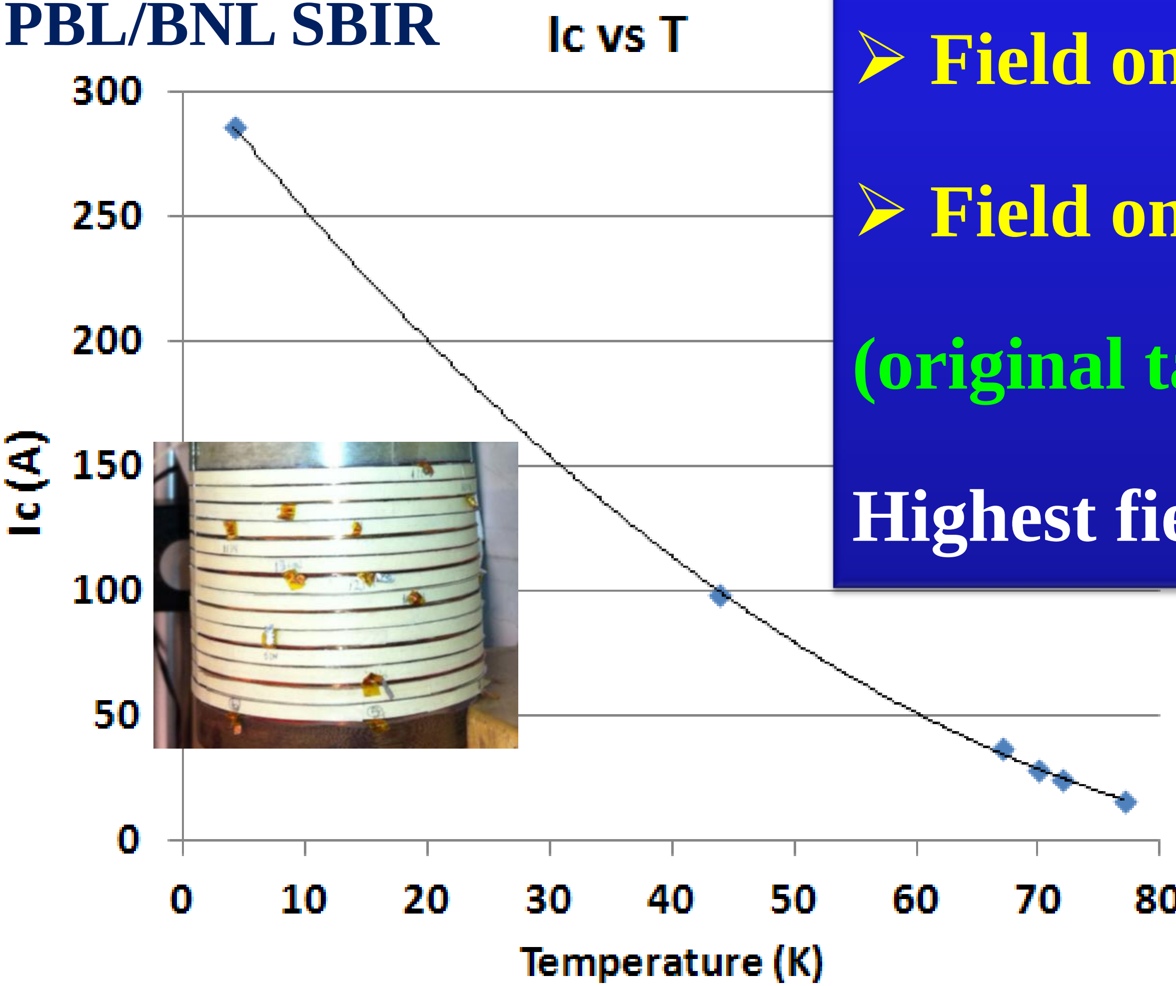
(select cases)

HTS Magnet Program at BNL

- HTS magnet R&D over a wide range:
  - High field, Medium field and low field (high temperature)
  - Many geometries – racetrack, cosine theta, solenoid
- Number of HTS coils/magnets designed built & tested:
  - Well over 100 HTS coils and well over 10 HTS magnets
- Type of HTS used:
  - Bi2223, Bi2212, ReBCO, MgB_2 – wire, cable, tape
- Amount of HTS acquired:
  - ~50 km (4 mm tape equivalent)
- Our recent activities have been largely on magnets with ReBCO
  - (yet one Bi2223 and one MgB_2 magnet is ready for testing)

High Field (16T) Demo of HTS Magnet

PBL/BNL SBIR



- **Field on axis: 15.7 T**
- **Field on coil : 16.2 T**

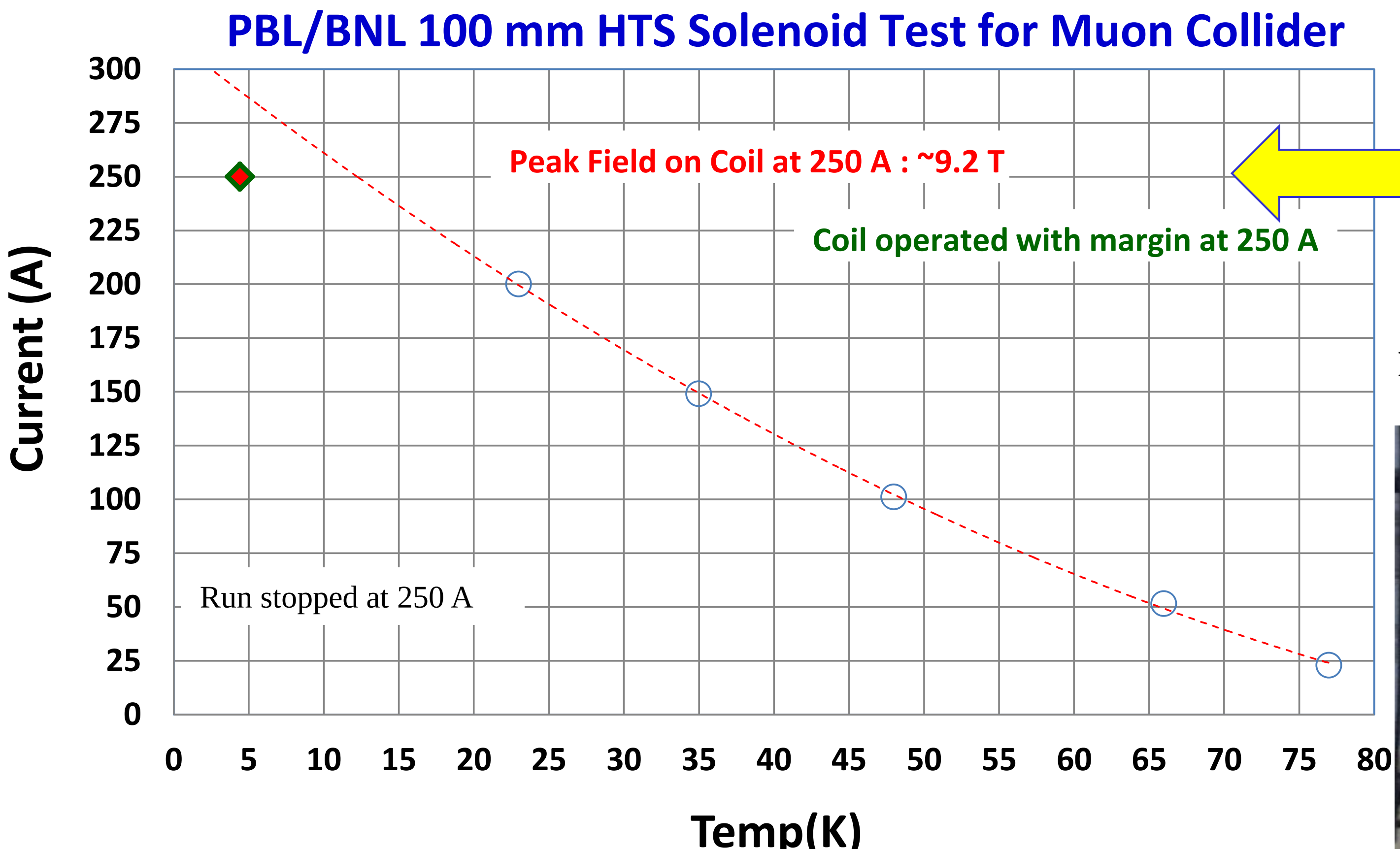
(original target: 10-12T)

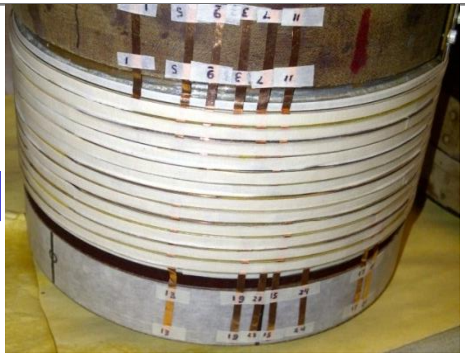
Highest field all HTS solenoid

Overall J_o in coil:
>500 A/mm^2 @16 T

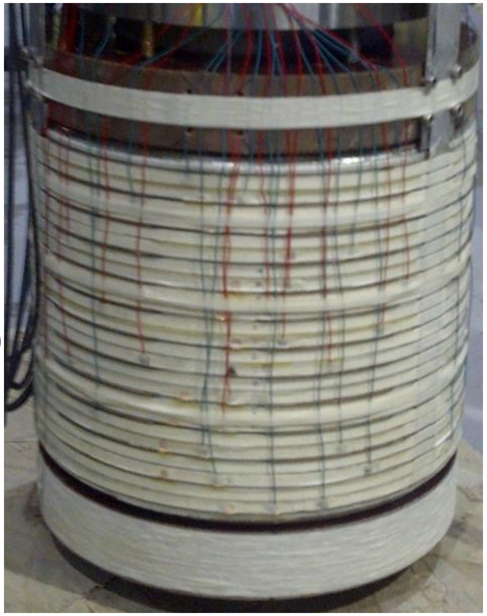
Insert solenoid: 14 pancakes, 25 mm aperture

Large Aperture High Field HTS Magnet





Half midsert (12 pancakes)



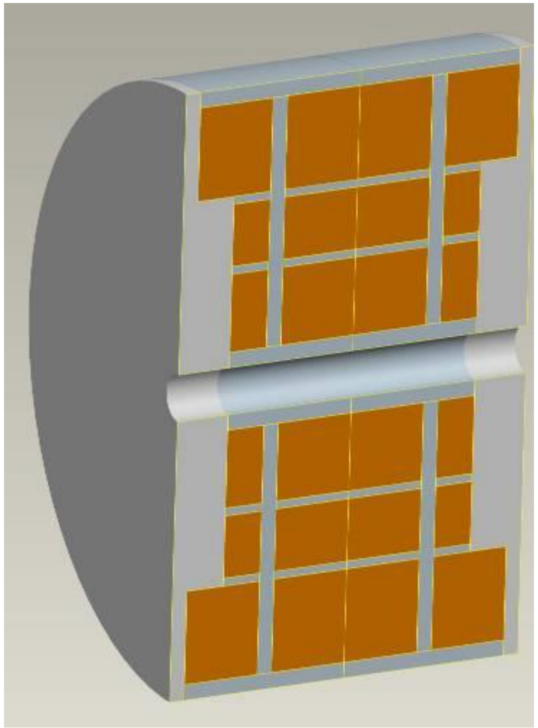
Full midsert (24 pancakes)

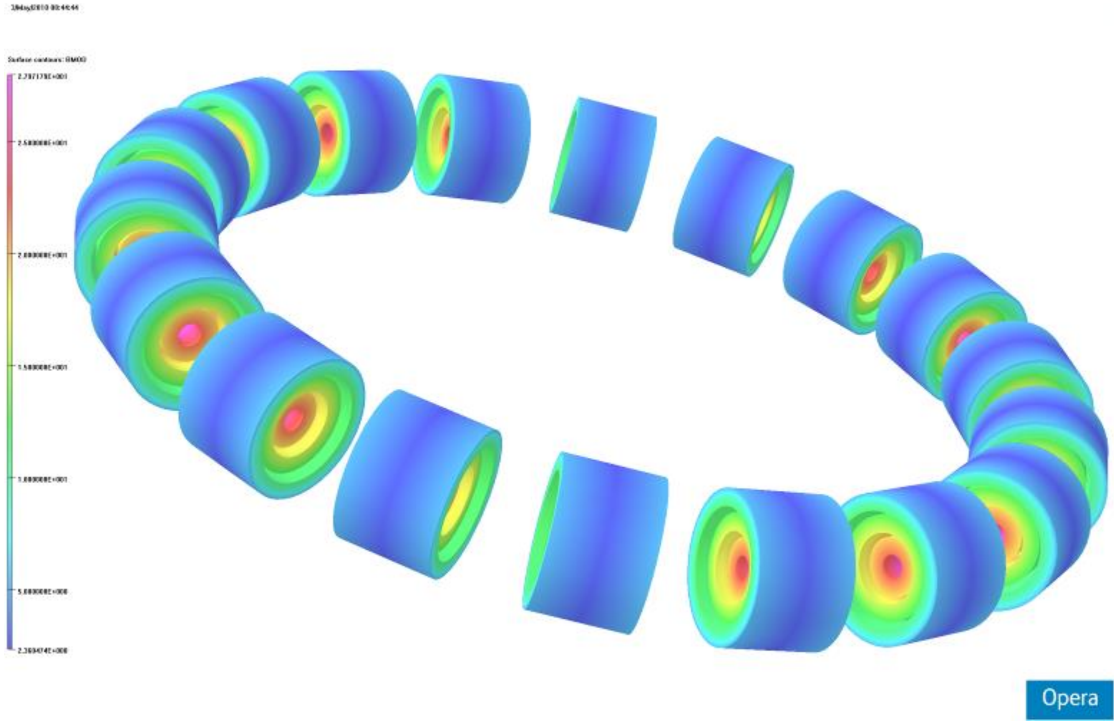
- Half midsert operated at 250 A @4 K
  (6.4 T field on axis, 9.2 T peak field on coil
- Design value for full midsert: 220 A for 10 T

Superconducting Magnetic Energy Storage (SMES)

Key Target Parameters: 25T, 100mm, 1.7MJ, 12mm ReBCO

High field large aperture HTS solenoid with huge stresses

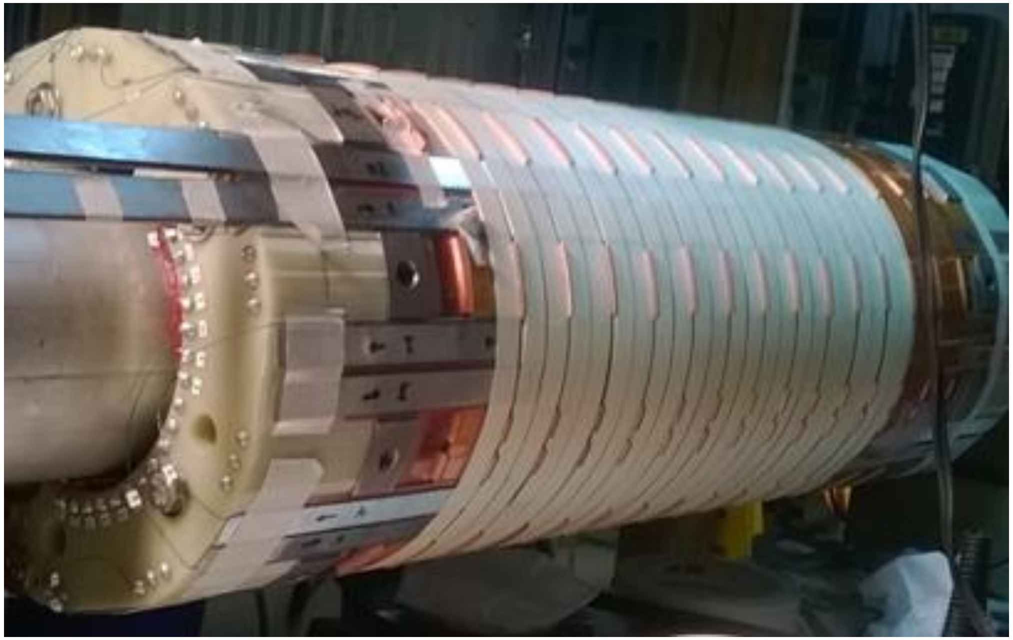


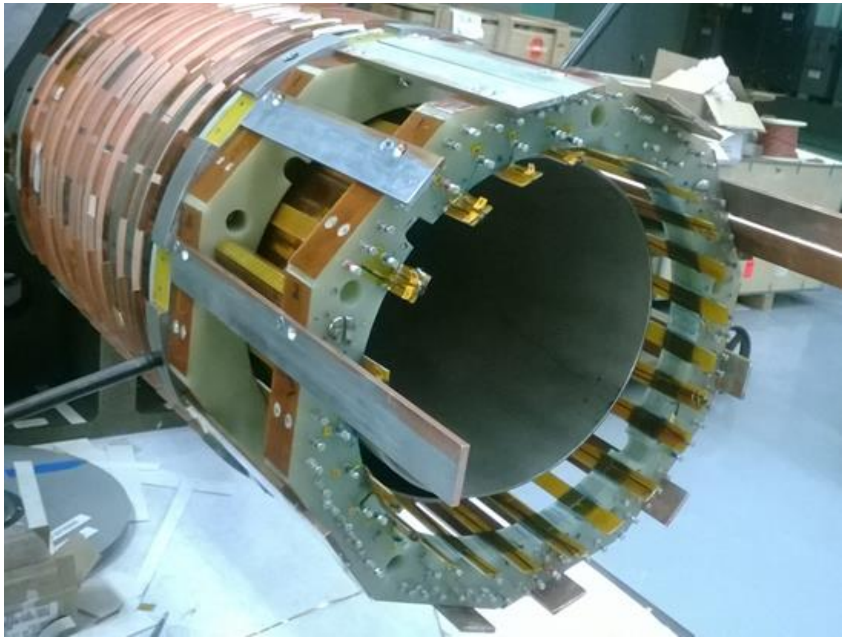


- **Funded by arpa-e as a "high risk, high reward" project**

arpa·e CHANGING WHAT'S POSSIBLE
BROOKHAVEN NATIONAL LABORATORY
ABB
SuperPower Inc.
UNIVERSITY of HOUSTON

SMES Magnet





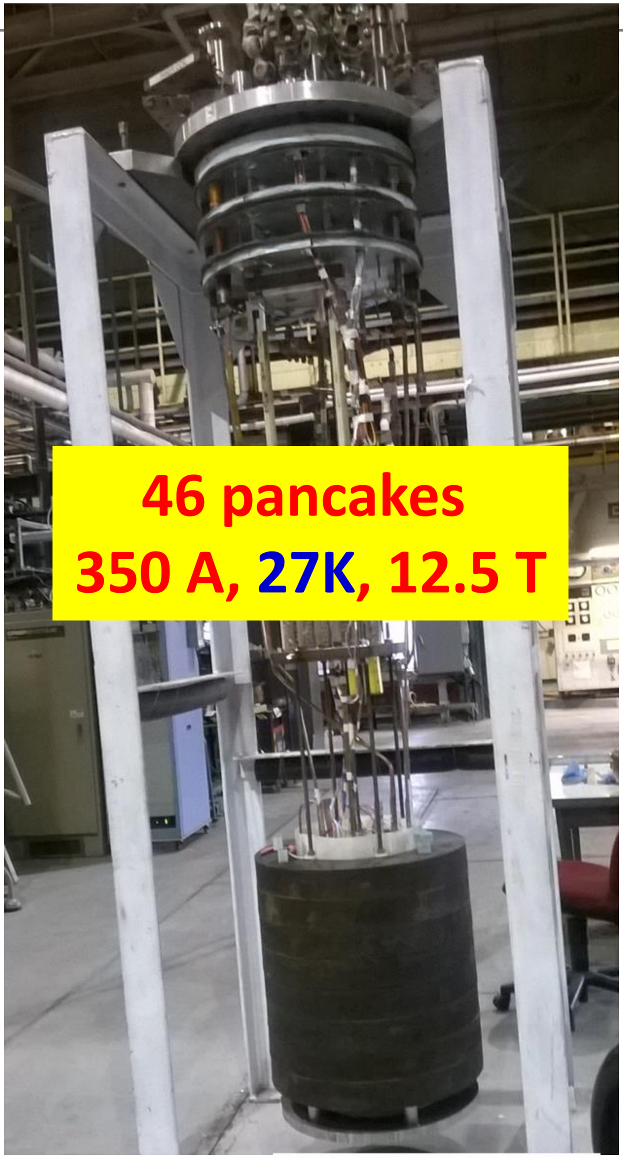
Inner Coil
(28 pancakes)

Outer Coil
(16 pancakes)

HTS SMES Magnet Test Results
100 mm bore ReBCO SMES Coil

2 pancakes
1140 A, 4K

12 pancakes
760 A, 4K, 11.4 T



46 pancakes
350 A, 27K, 12.5 T

Peak fields higher

HTS Quadrupole for FRIB

(now part of baseline design)

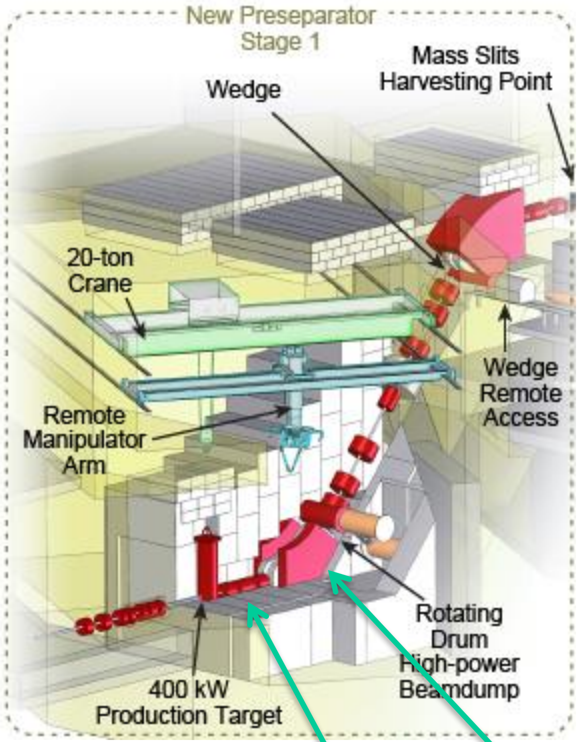
FRIB: Facility for Rare Isotope Beams, now under construction at MSU, USA.

Radiation Tolerant HTS Quad for the Fragment Separator Region of FRIB

To create intense rare isotopes, 400 kW beam hits the production target.

Magnets in the fragment separator region are exposed to unprecedented radiation and heat loads. HTS can efficiently remove that at elevated temperatures.

Courtesy: Al Zeller, FRIB/MSU

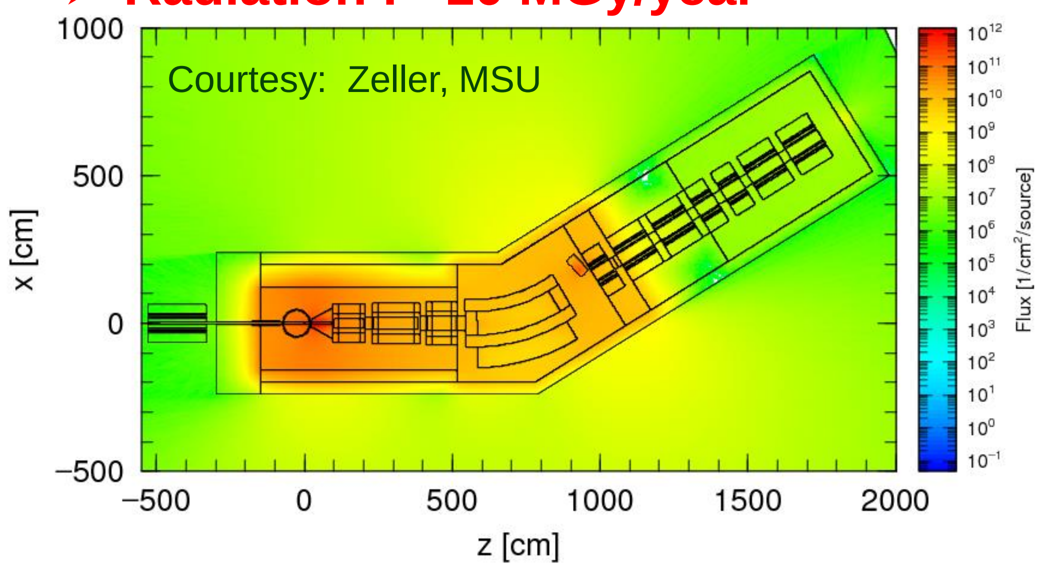


Radiation resistant

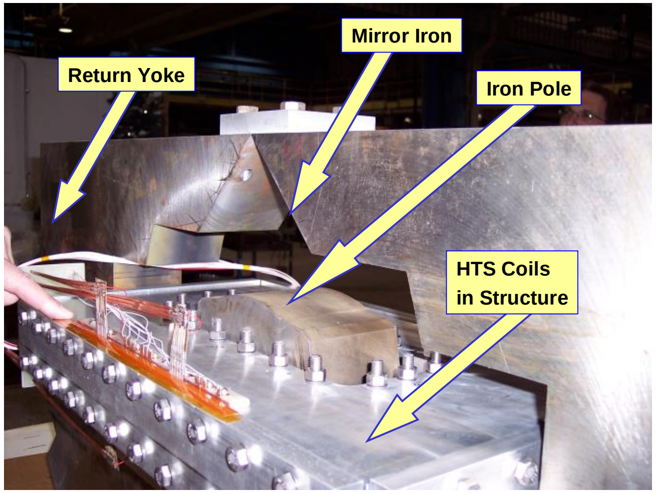
Pre-separator quads and dipole

Exposure in the first magnet itself:

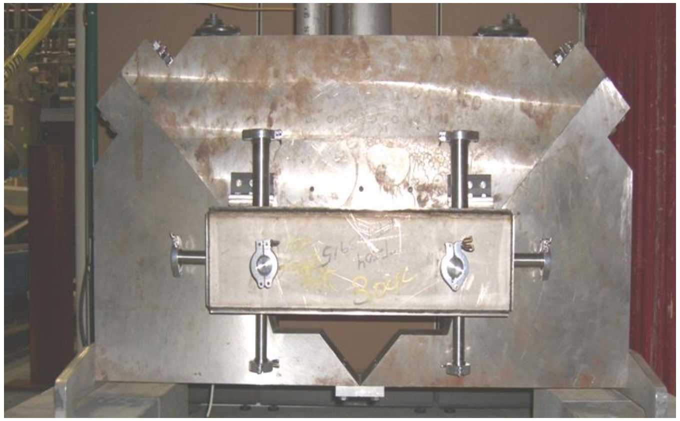
- **Head Load : ~10 kW/m, 15 kW**
- **Fluence : 2.5 x10^{15} n/cm^2 per year**
- **Radiation : ~10 MGy/year**



First Generation HTS Quad for FRIB

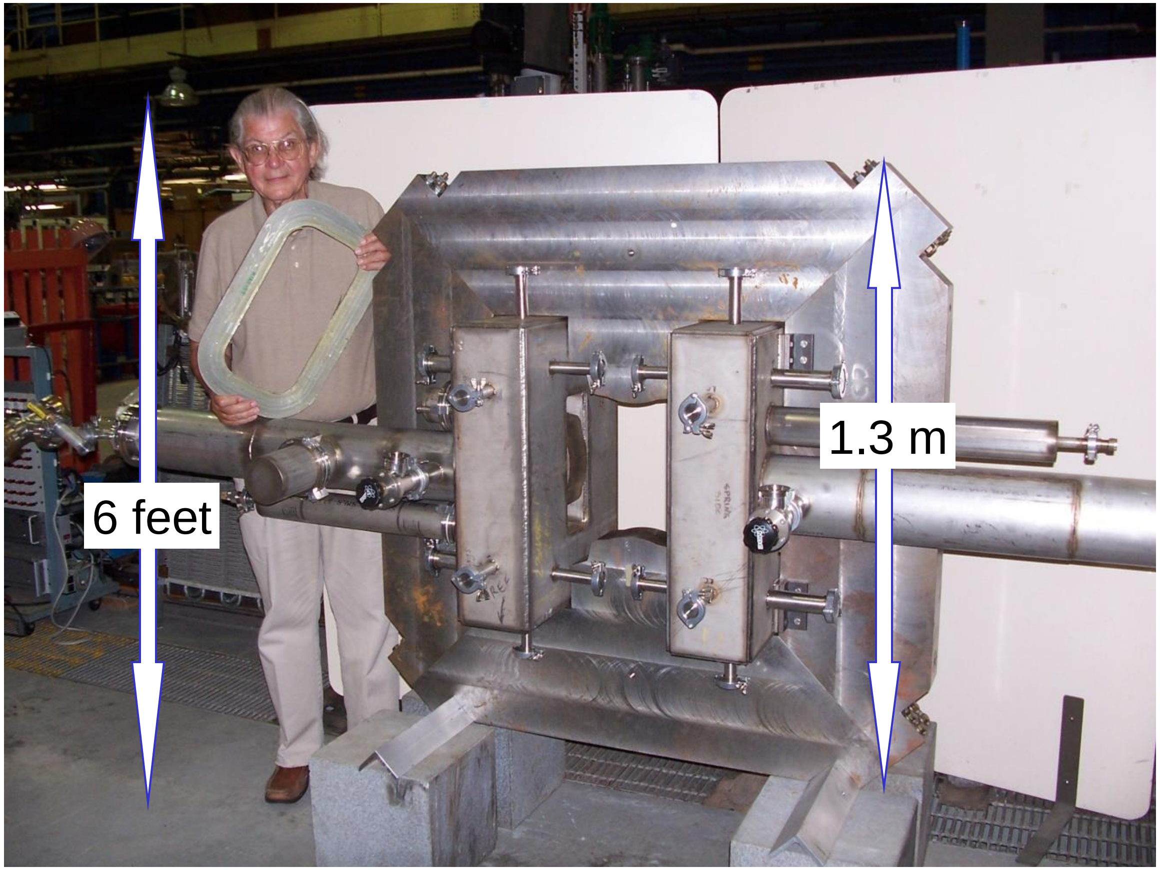


Mirror cold iron

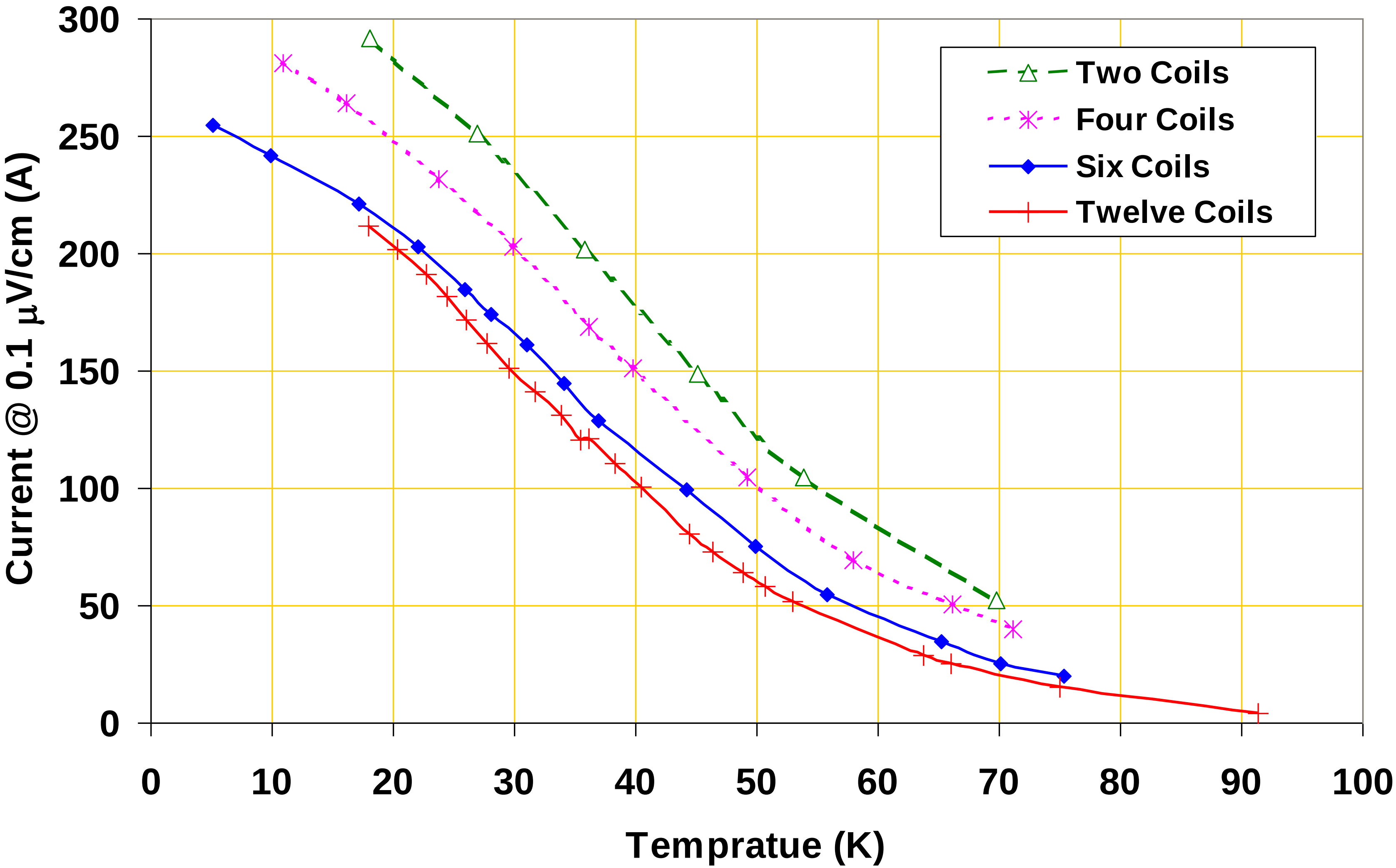


Mirror warm iron

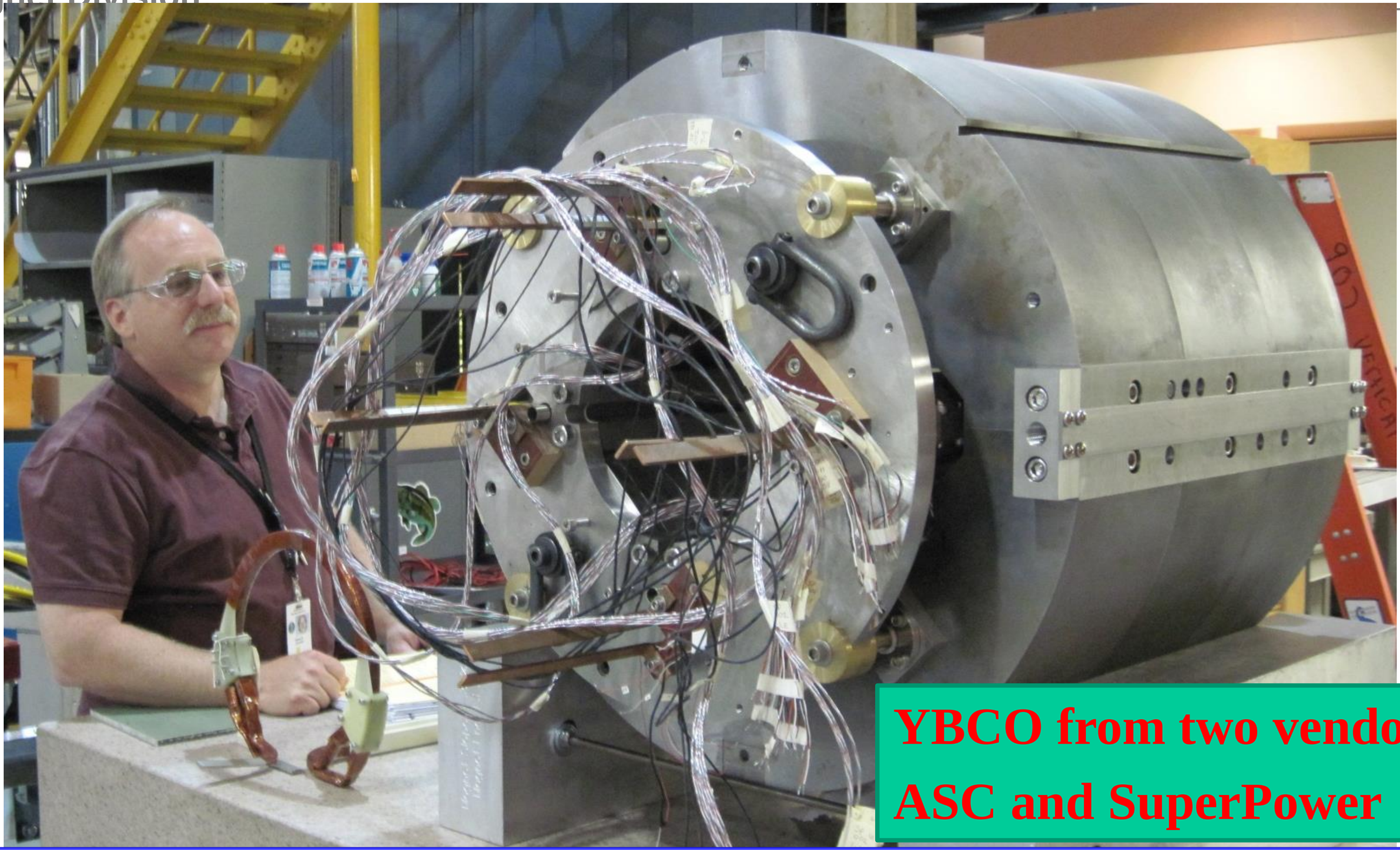
Warm Iron Design with Bi2223 HTS



First Generation HTS Quad Test
(operation over a large temperature range)



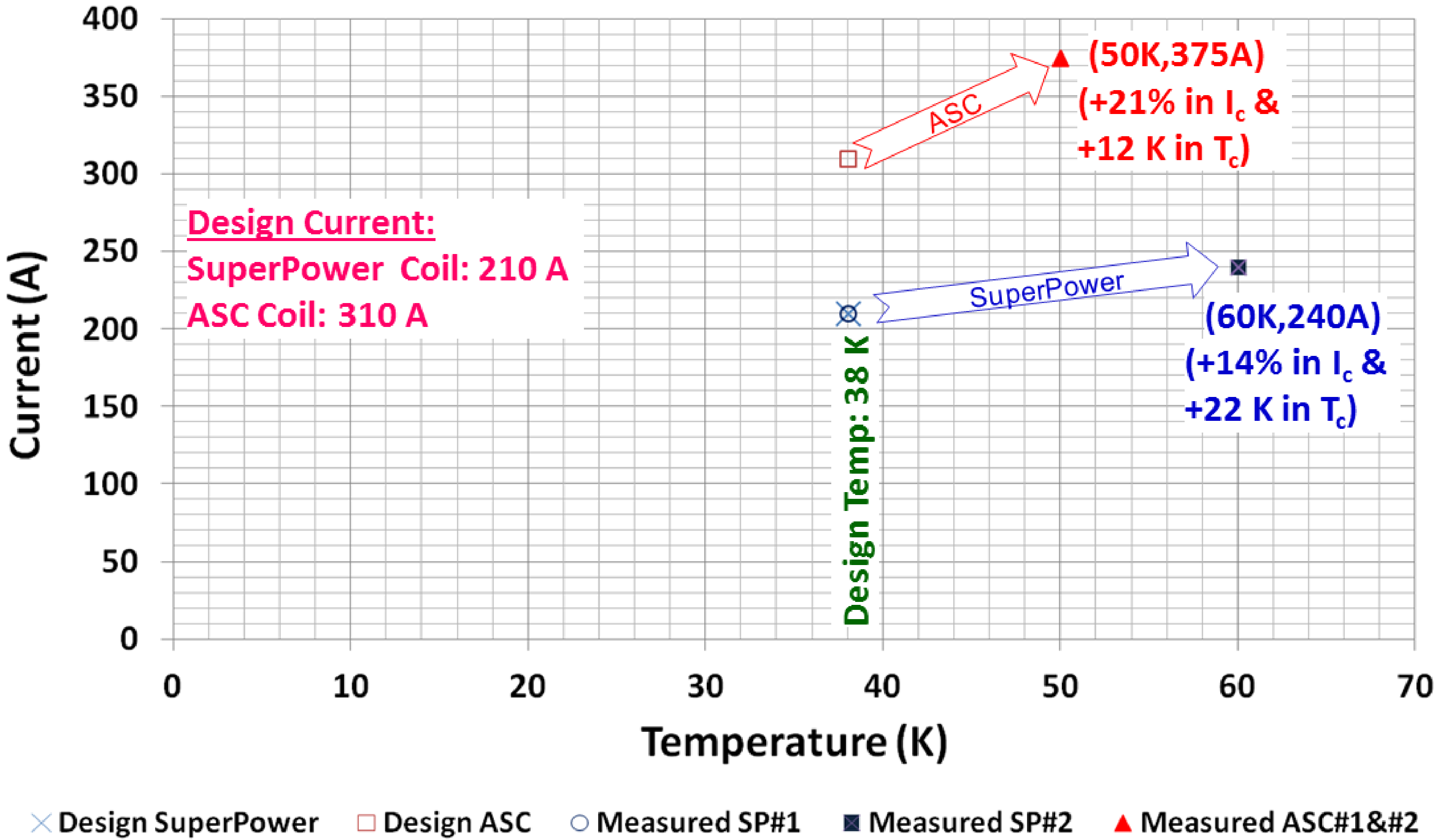
Second Generation HTS Quad for FRIB Fragment Separator Region



YBCO from two vendors
ASC and SuperPower

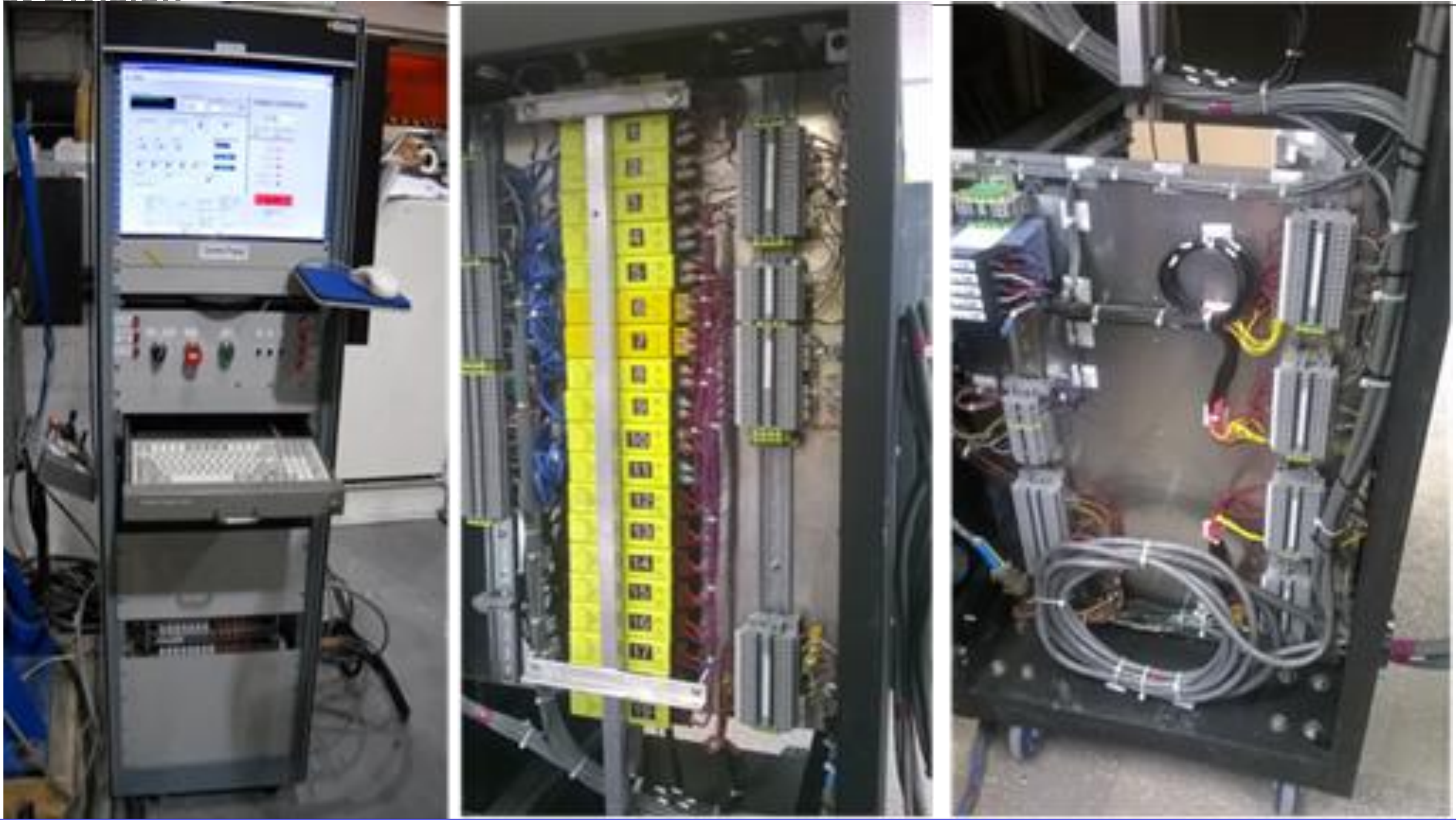
Important: Magnet for a real machine- baseline design of FRIB

Large Temperature Margins (only possible with HTS)



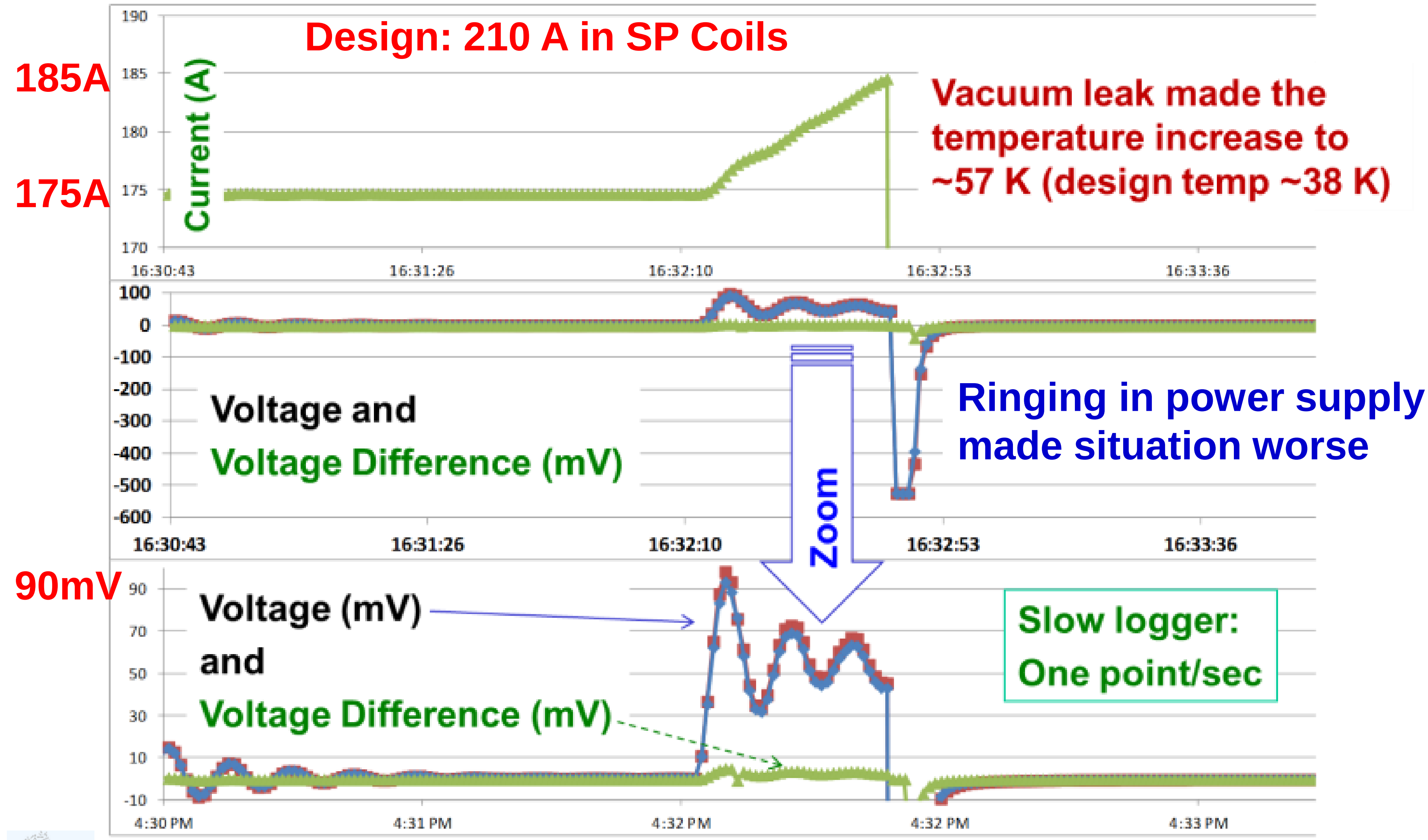
HTS provides robust operation against local and global heat loads

Advanced Quench Protection Electronics

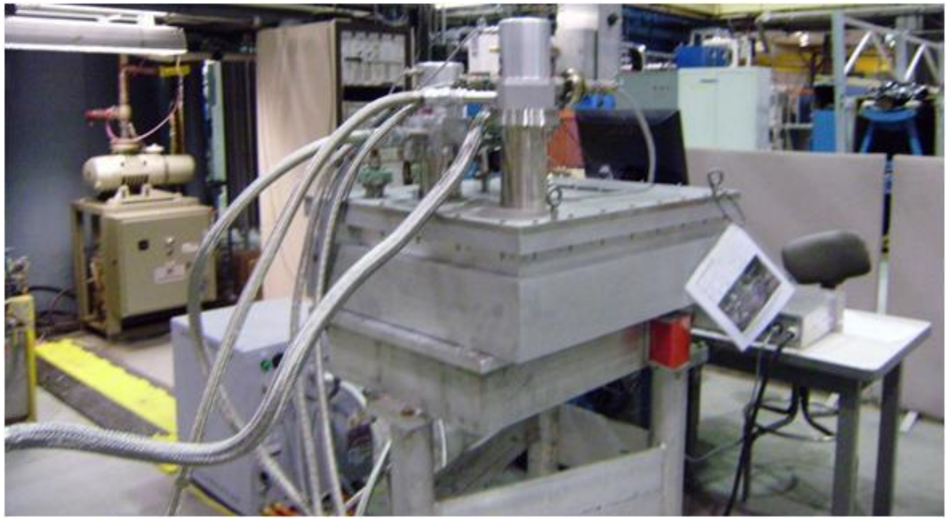


Detects onset of pre-quench voltage at < 1mV and with isolation voltage > 1kV allows fast energy extraction

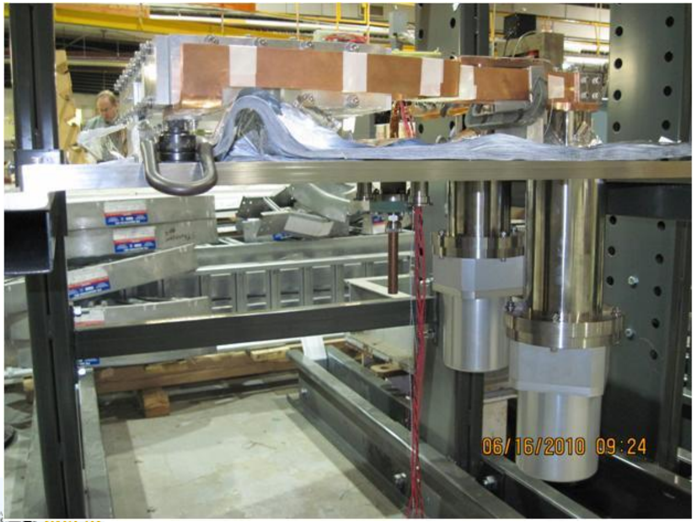
Protection of HTS Magnet During an Operational Accident Near Design Current



A Warm bore Cryo-cooled Magnet with 6 HTS coils



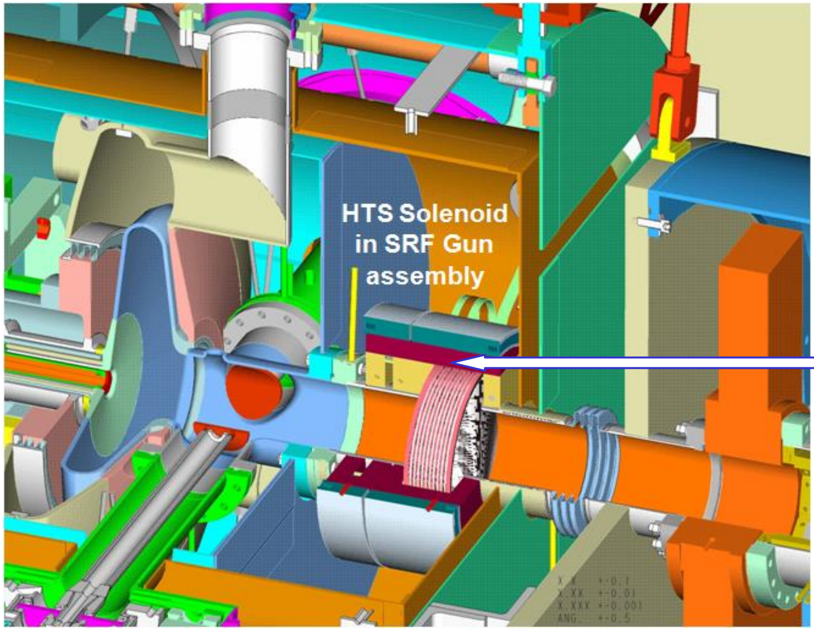
Evening: Switch ON; Morning: COLD

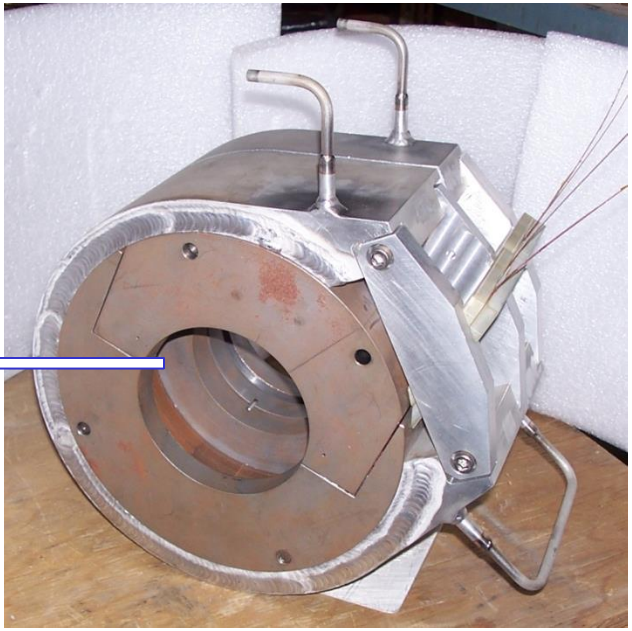


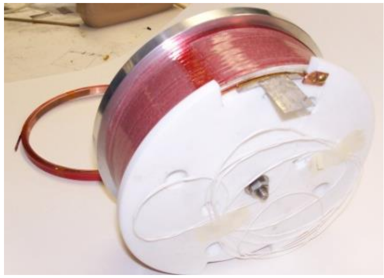
Suitable for various studies

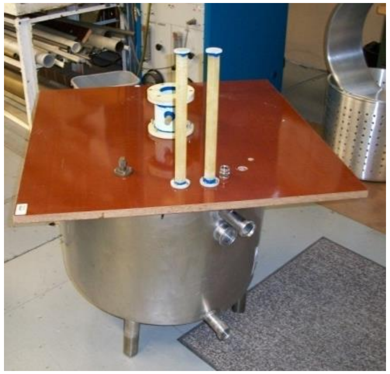
- ❑ **Quench studies**
- ❑ **Measure magnetization induced harmonics**
  - ➢ **as a function of time**
  - ➢ **as a function of temperature**
  - ➢ **as a function of field**

Low Magnetic Field Application
HTS Solenoid with Superconducting Cavity for the Energy Recovery Linac (ERL) at BNL









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

Early focusing provides a unique and better technical solution

HTS Cosine Theta R&D for Hadron Collider

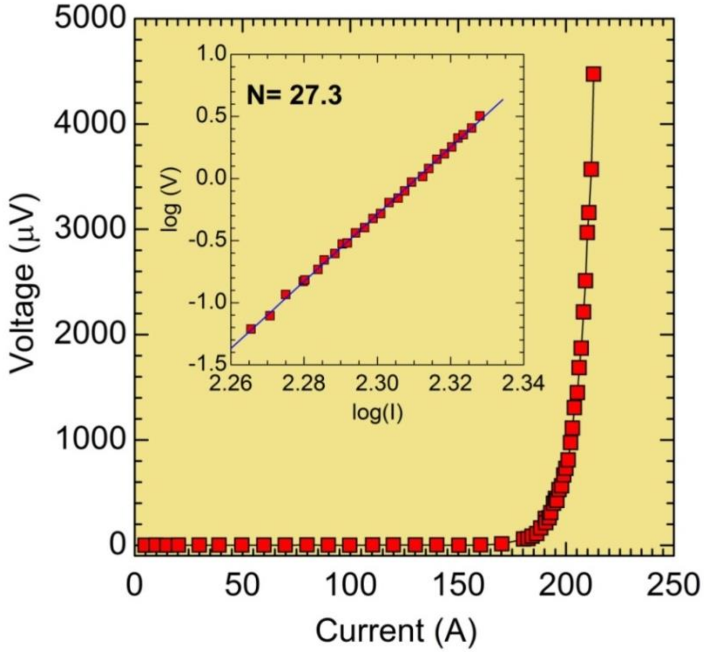
BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

Cos (θ) Coil - PBL/BNL STTR#1 (12 mm, one block, 77 K)

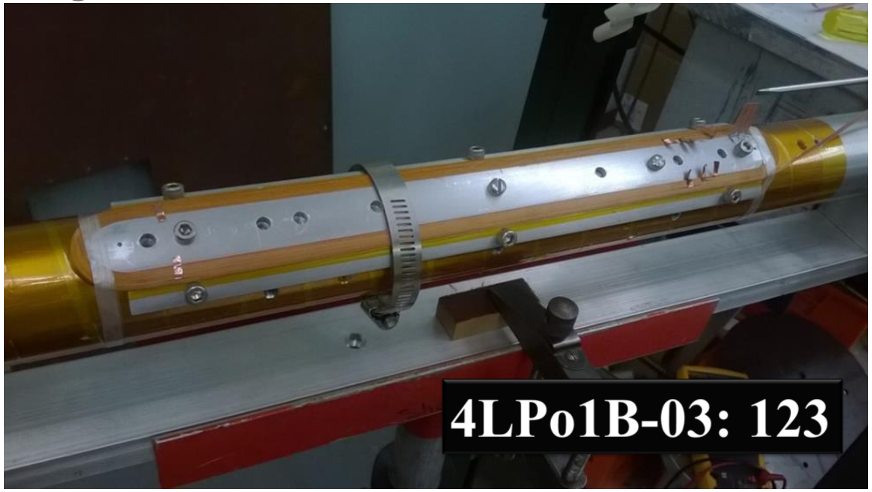
BENEFITS of Kapton-CI:

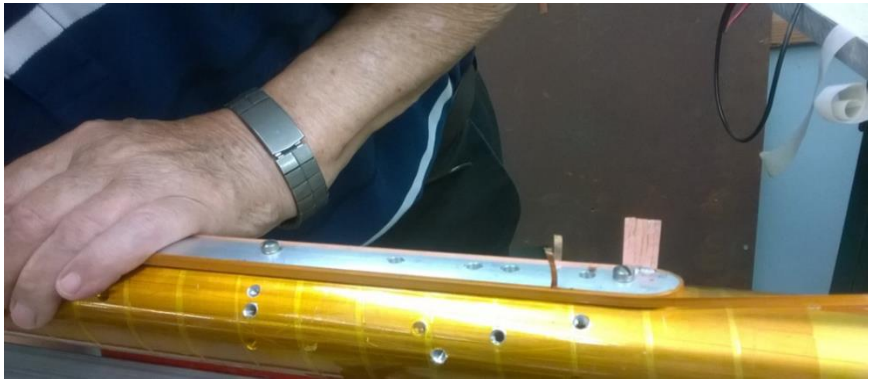
- No epoxy/adhesive to HTS tape (prone to degradation by epoxy)
- Standard insulation in magnets
- Cured coil can be handled easily
- Makes good coil (including ends)

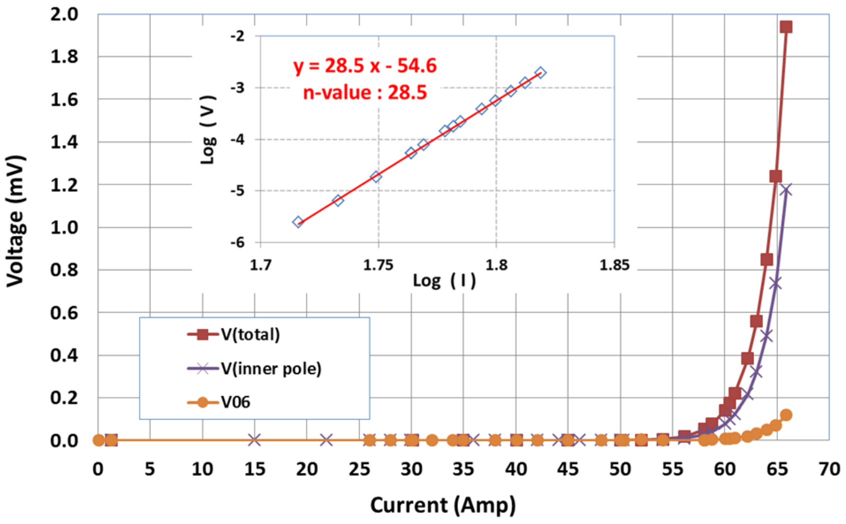


No measurable degradation@77 K

Cos (θ) Coil - PBL/BNL STTR#2 (4 mm, goal: full coil, 4 K test)







No measurable degradation@77 K

Future Plan (Phase I & Phase II)

- Construction and 4 K test of full cos (θ) coil in next few months
- R&D to develop base technology for accelerator magnets in next few years (includes measuring and finding ways to deal with magnetization)
- Use these magnets in an accelerator in next few decades

SUMMARY and CONCLUSIONS

- This presentation summarized research activities at BNL that are directly relevant to future circular colliders such as SppC.
- Common coil and open midplane magnet design are appealing as they offer some unique and attractive technical solutions.
- Use of HTS is essential for magnets with design field of >16 T.
- A significant progress has been made in HTS magnet technology. Given the time frame for building the next high energy collider, HTS magnets should become a mature technology provided a proper investment is made in R&D at this stage.
- There is a significant similarity between the IHEP and BNL on how to carry out future magnet programs. A collaboration between the two would be beneficial for developing technology.