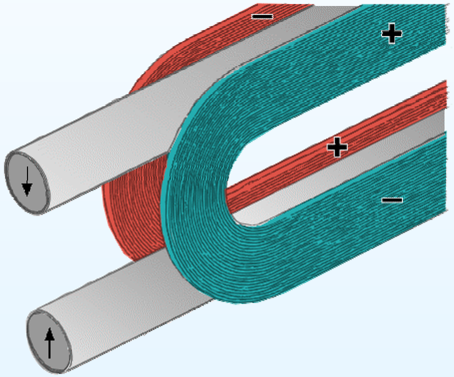

HTS Magnets and Nb_3Sn Quads

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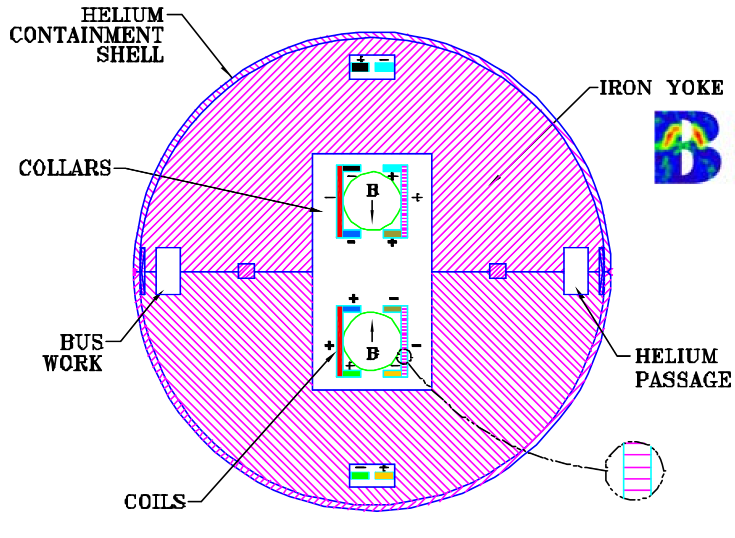
HTS and High Field Magnet R&D Program at BNL

At present "common coil design" with "React & Wind" technology and "rapid turn around approach" remains the work horse of our technology development program.

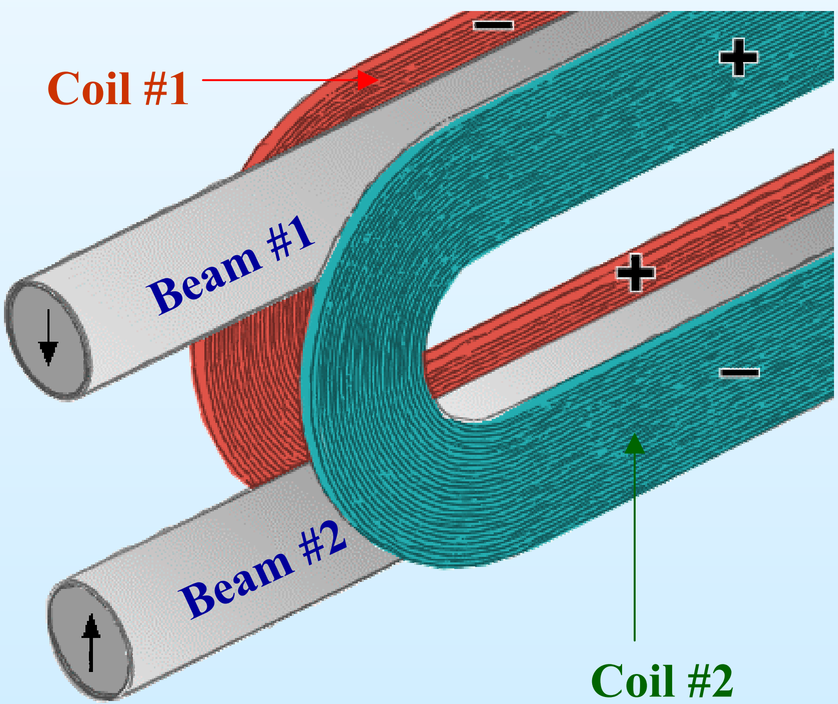
However, responding to more likely needs of next 10 years:

- We are in the process of moving more towards IR quadrupole R&D.
- Though we prefer "React & Wind" approach and see it as a more likely candidate for long magnets, we examine the elements of "Wind & React" approach, as well.

Common Coil Design

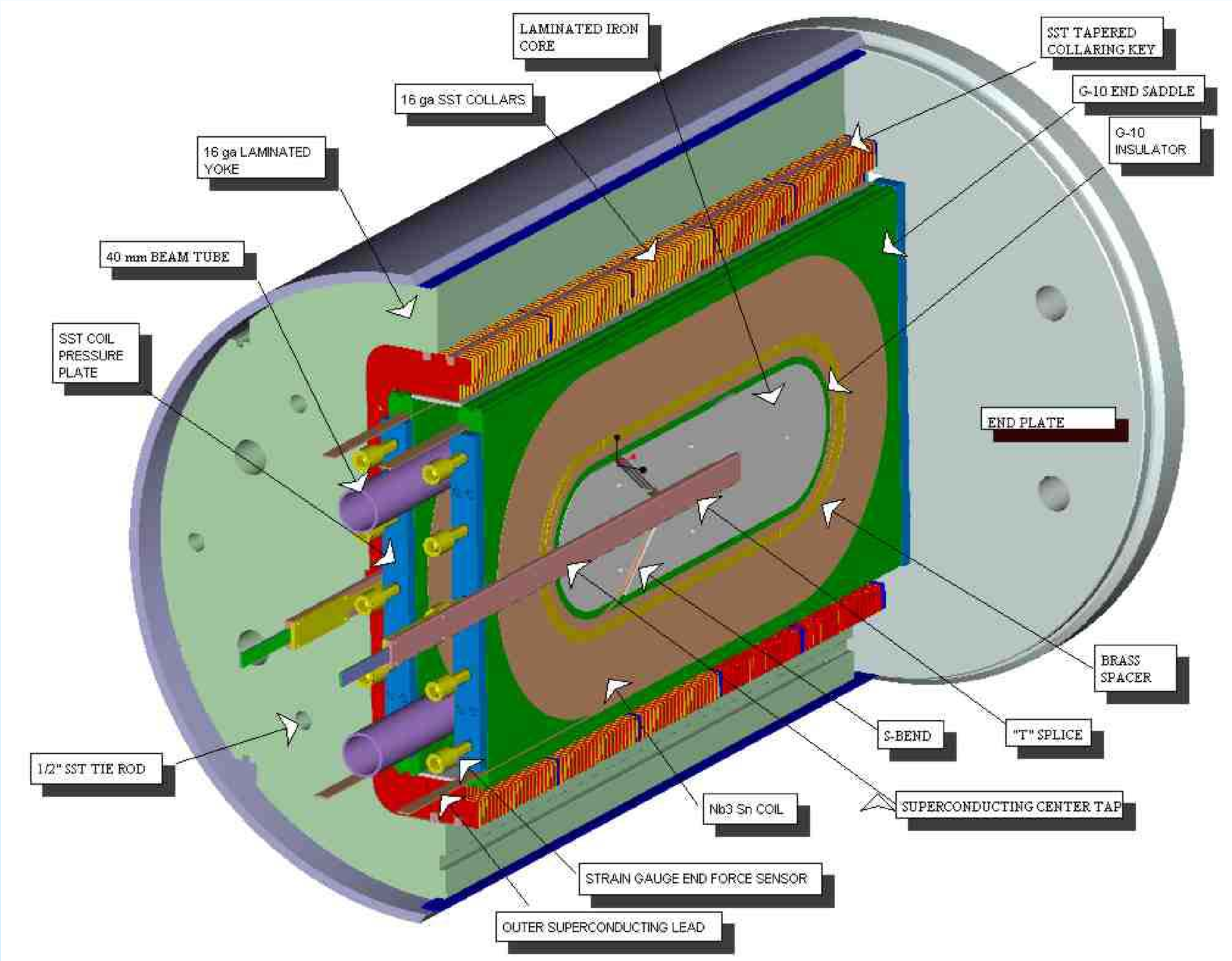


- **Simple 2-d geometry with large bend radius** (determined by spacing between two apertures, rather than aperture itself)
- **Conductor friendly (no complex 3-d ends, suitable for brittle materials such as HTS and Nb_3Sn)**
- **Compact (quadrupole type cross-section, field falls more rapidly)**
- **Block design (for handling large Lorentz forces at high fields)**
- **Combined function magnets possible**
- **Efficient and methodical R&D due to simple & modular design**
- **Minimum requirements on big expensive tooling and labor**
- **Lower cost magnets expected**

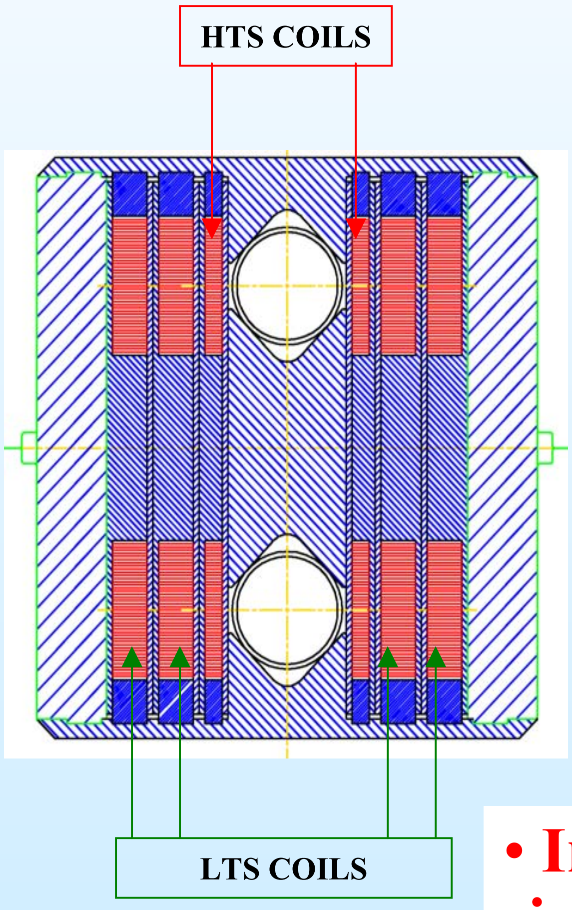


Main Coils of the *Common Coil Design*

Overall Design of BNL 12 T Common Coil Background Field Dipole



12 T Background Field Magnet: The Next Step in HTS R&D Program

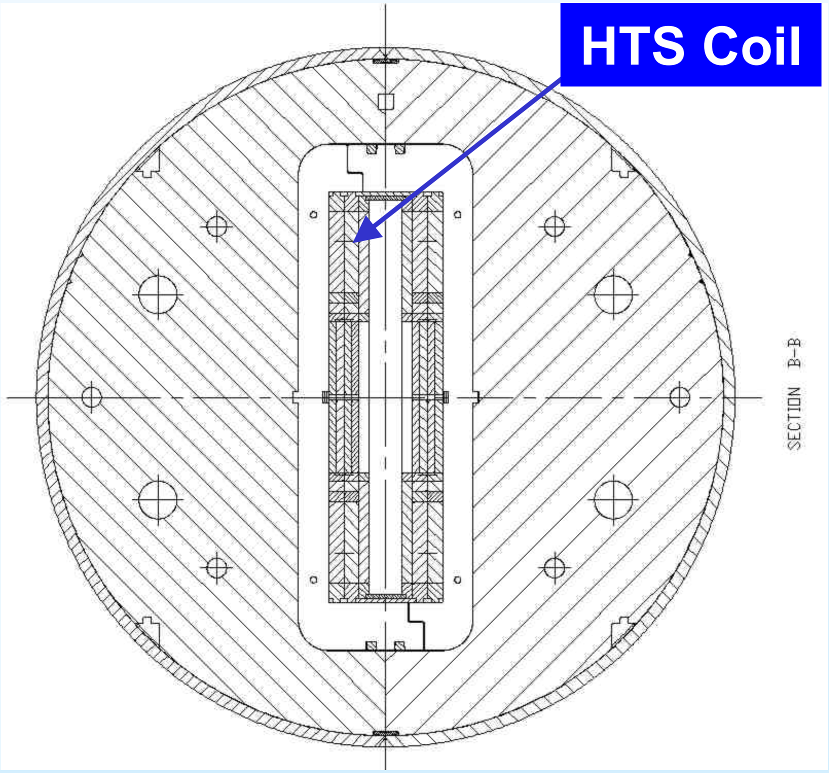


- At present, HTS alone can not generate the fields we are interested in.
- Nb_3Sn coils provides high background fields. The HTS coils will be subjected to high field and high stresses that would be present in an all HTS magnet. Therefore, several technical issues will be addressed.
- Since 12 T Nb_3Sn magnet uses similar technology (building high field magnet with brittle material), it also provides a valuable learning experience in building an all HTS high field magnet.

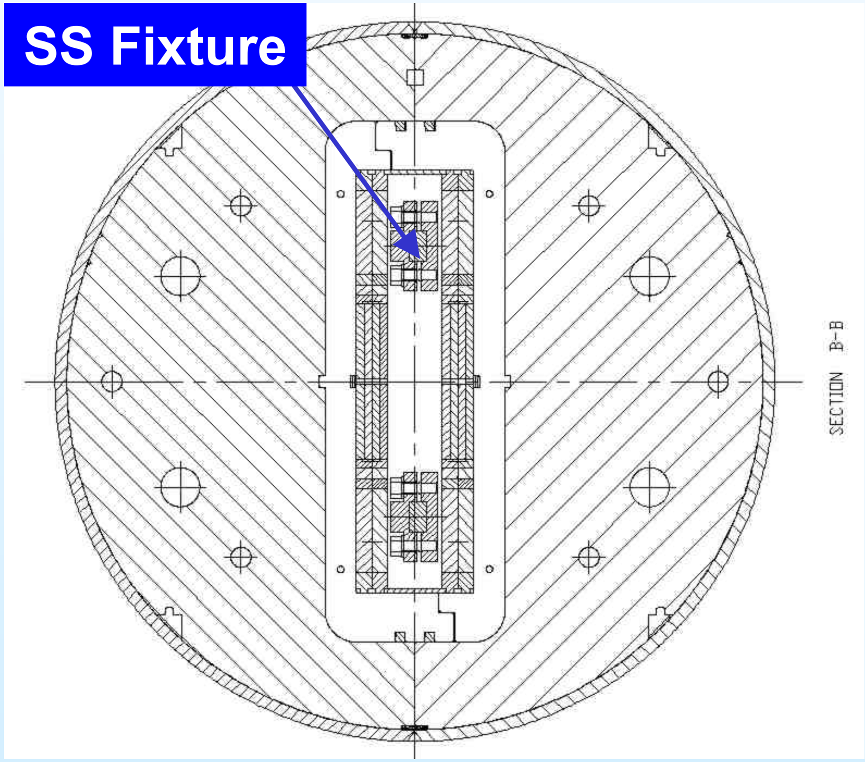
• Important design consideration: Allow a simple mechanism for testing HTS insert coils.

Insert Coil and Sample Test Scenarios

An interesting feature of the design, which will make it a truly facility magnet, is the ability to test short sample and HTS insert coils without disassembling it.



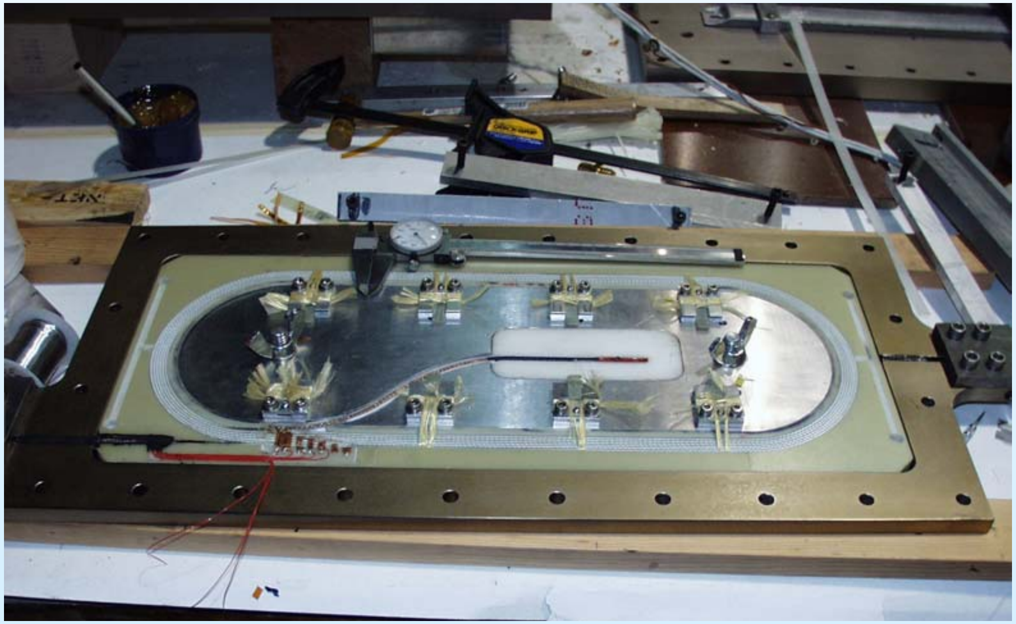
HTS insert coil test configuration



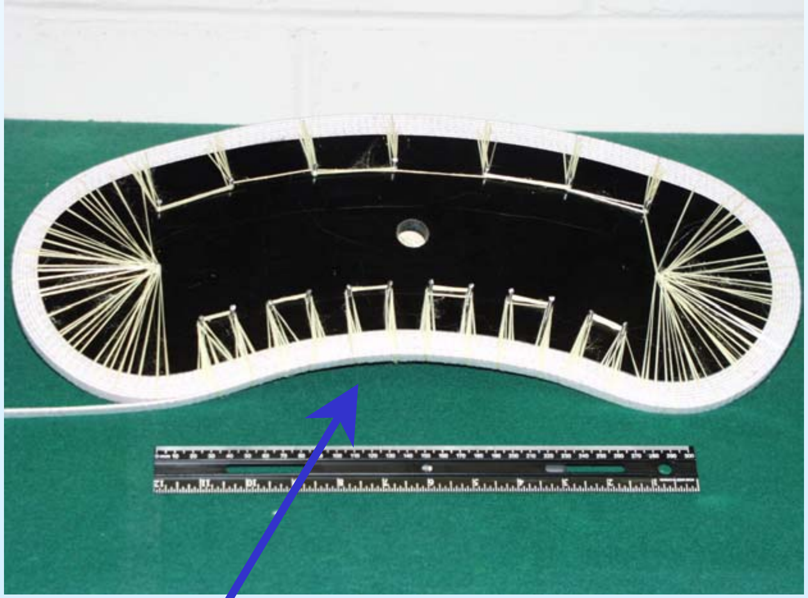
Short sample test configuration

Coil Winding with Kevlar Strings

Kevlar strings make well compressed coils with brittle materials in shapes that were thought to be difficult before

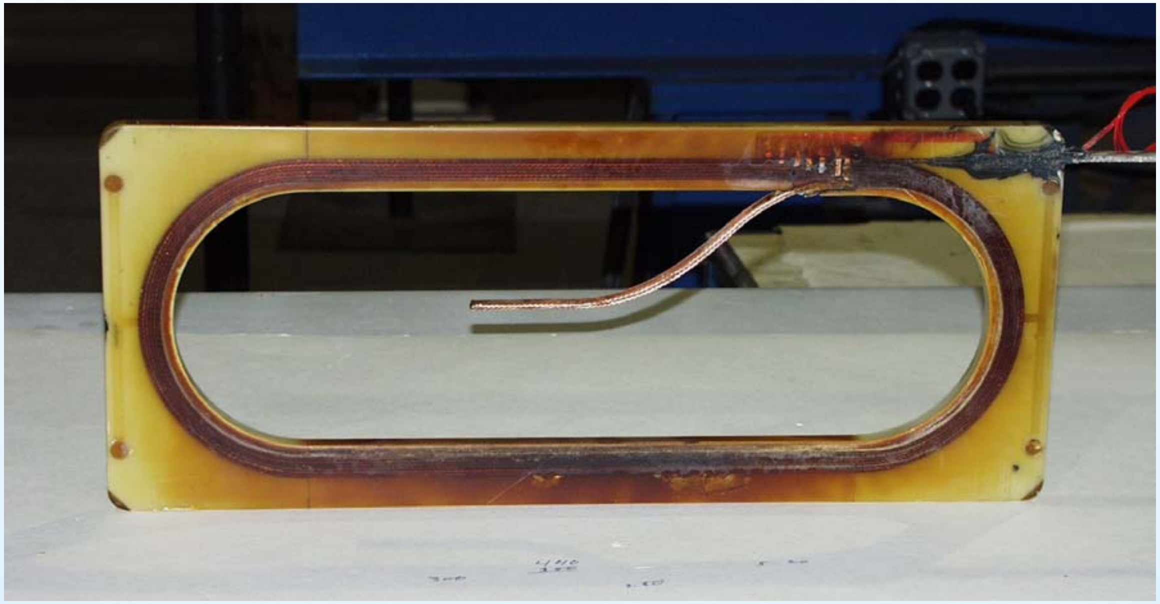


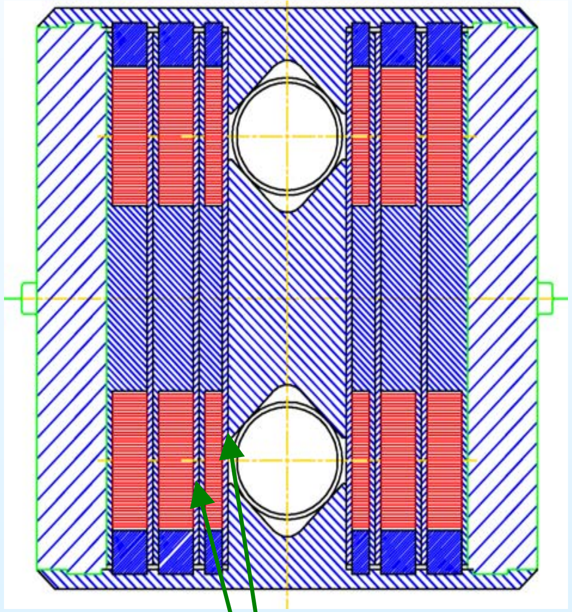
Kevlar clamp setup, coil locked into fixturing



Coils with reverse curvature

Bobbinless Coil With No Additional Structure



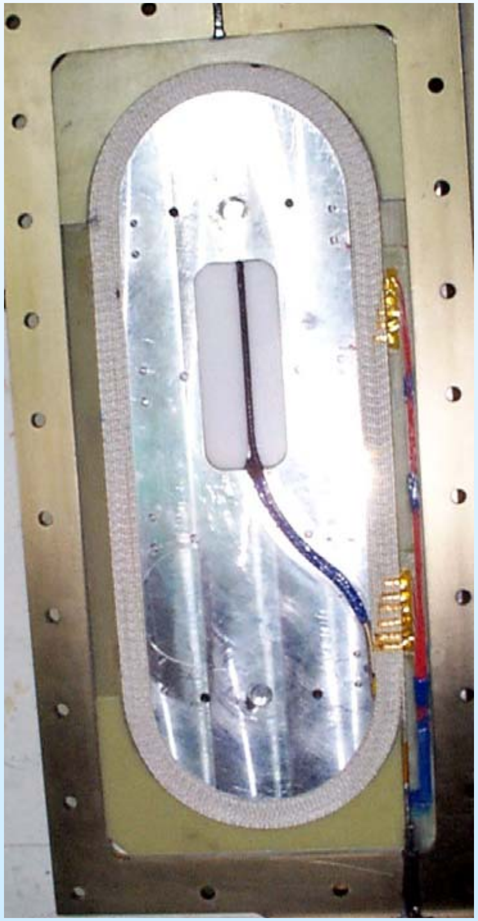


Bobbin (Island) is not suitable for long and accelerator magnet. Here the technology is demonstrated that the bobbin can be removed from the coil. Also please note that there is no additional structure on the two sides of the coil.

Minimizing valuable "Real Estate", minimizes conductor requirements.

10 Turn Coil Rapid Turn Around Program

Experimentally test an item, beginning to end, in ~1-2 month



Rapid turn-around encourages test of new ideas and allows iterations in them.

It scientifically evaluates the validity of old biases and the limit of present technologies.

Such a program is must for HTS magnet R&D program given the state of technology and the cost of conductor.

HTS Test Coils

BNL has made a number of short test coils -- 16 with brittle pre-reacted material and of them five are made with HTS cable (in addition many more are made with HTS tapes). The purpose of this program is to to systematically develop this new and challenging technology in a rapid turn around and cost effective manner.

Coil #	Magnet #	Impreg #	Conductor	Conductor pedigree	Insulation type	Bobbin	Process additions
CC001	None	001	Nb_3Sn	ITER chrome	3 mil glass wrap	Iron	First impreg, single ended
CC002	DCC001&2	002	Nb_3Sn	ITER chrome	2 mil glass wrap	Iron	Double hole impreg
CC003	DCC002	003	Nb_3Sn	ITER chrome	2 mil glass wrap	Iron	Double hole impreg
CC004	DCC003 & 8	005	Nb_3Sn	ITER chrome	2 mil glass wrap	Stainless steel	V taps added
CC005	DCC003 & 8	006	Nb_3Sn	ITER chrome	2 mil glass wrap	Stainless steel	V taps added
CC006	DCC004	004	HTS	Low performance	Tube braided glass	Aluminium	
CC007	DCC004	007	HTS	Low performance	Tube braided glass	Stainless steel	
CC008	DCC005	010	Nb_3Sn	LBL RD3 cable	2 mil glass wrap	Stainless steel	
CC009	DCC005	011	Nb_3Sn	LBL RD3 cable	2 mil glass wrap	Stainless steel	
CC010	DCC006	008	HTS/Ag	2 BSCCO, 16 Ag	2 mil glass wrap	Brass	Teflon tape on mold faces
CC011	DCC006	009	HTS/Ag	2 BSCCO, 16 Ag	2 mil glass wrap	Stainless steel	
CC012	DCC008	012	HTS	High Performance	2 mil glass wrap	Aluminium	New mold plates
CC013	None	013	Nb_3Sn	ITER NEEWC	NEEW braided	Stainless steel	Removable bobbin test
CC014	None	014	Nb_3Sn	ITER NEEWC	2 mil glass wrap	Stainless steel	First vacuum bag impreg
CC015	None	015	Nb_3Sn	ITER NEEWC	2 mil glass wrap	Stainless steel	First kevlar string clamping
CC016	DCC009	016	Nb_3Sn	LBL RD3 cable	2 mil glass wrap	Brass	Kevlar string clamping

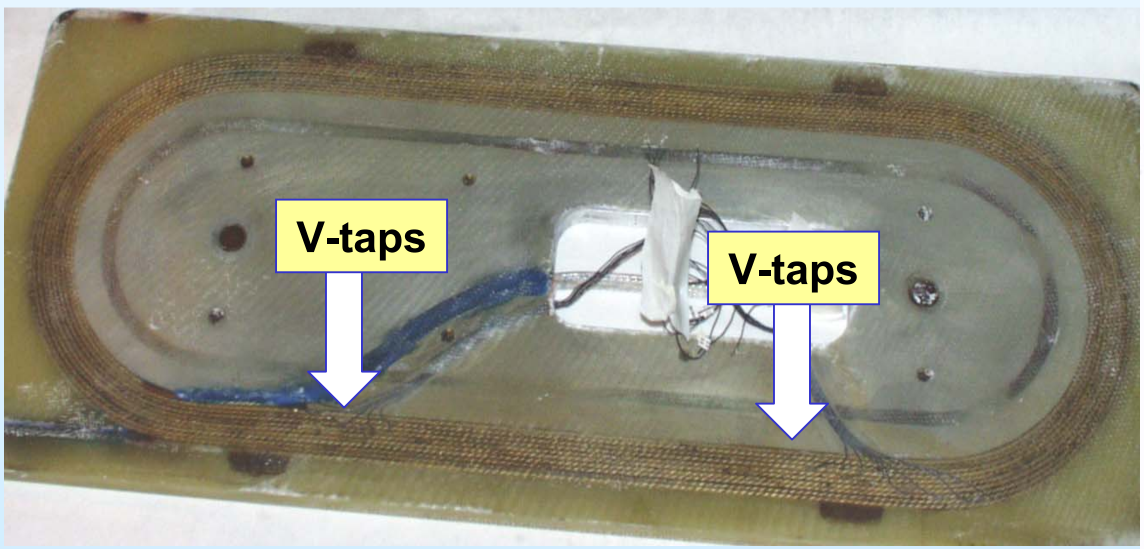
*Not listed here are (a) DCC007, an HTS tape and (b) an earlier NbTi cable common magnet.

Magnet DCC002: 1st HTS Dipole/Quad

Given the aggressive R&D and learning nature of the program, we instrument the magnet, as much as we can.

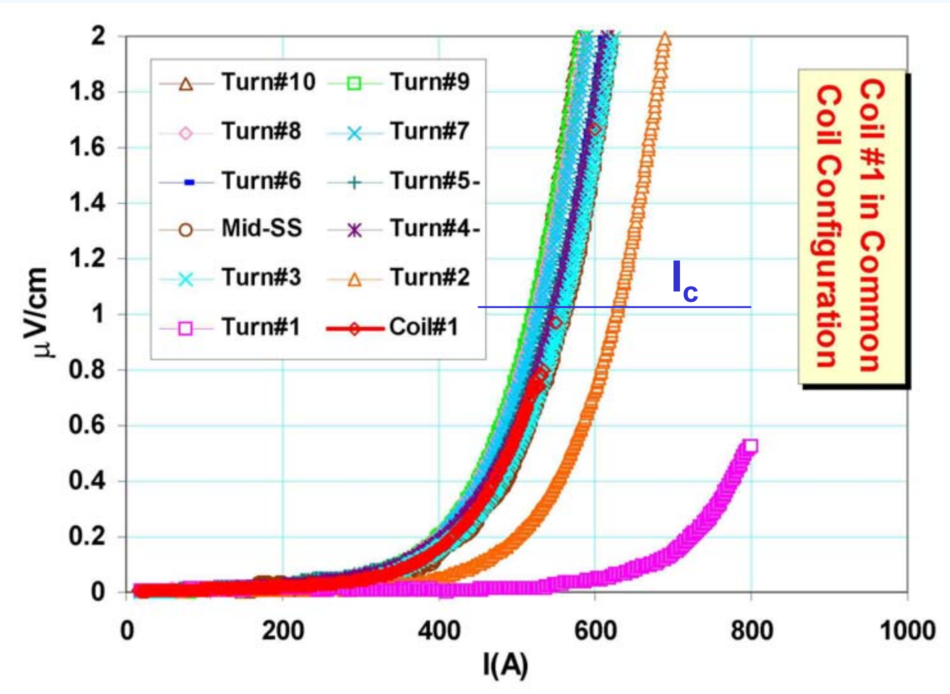
We put at least one voltage tap on each turn

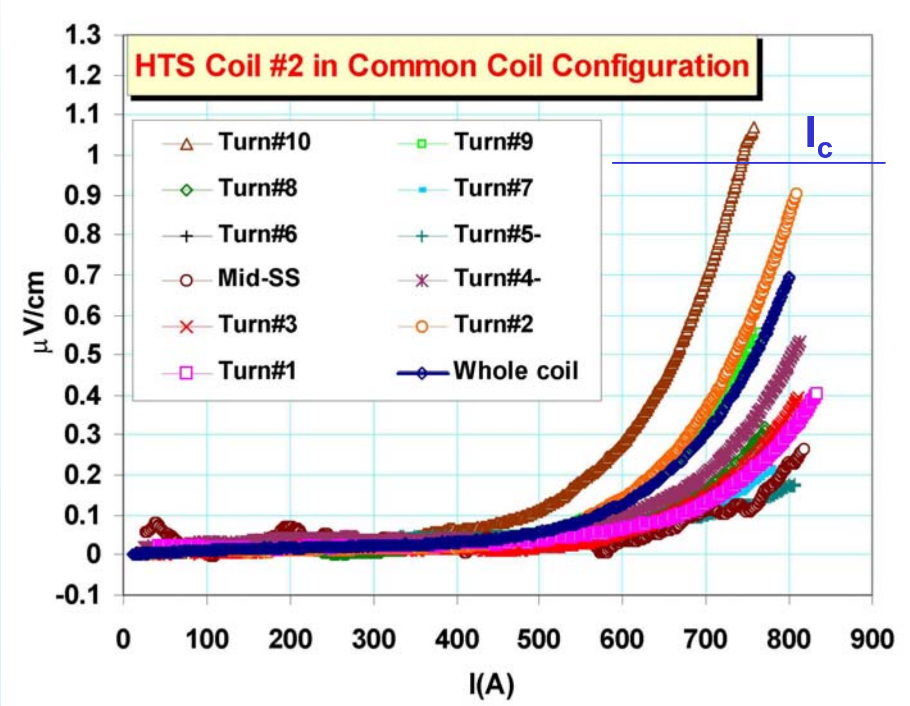
Coils are assembled for a flexible and extensive testing. Four leads are taken out of the cryostat.



Magnet DCC002: 1st HTS Dipole/Quad

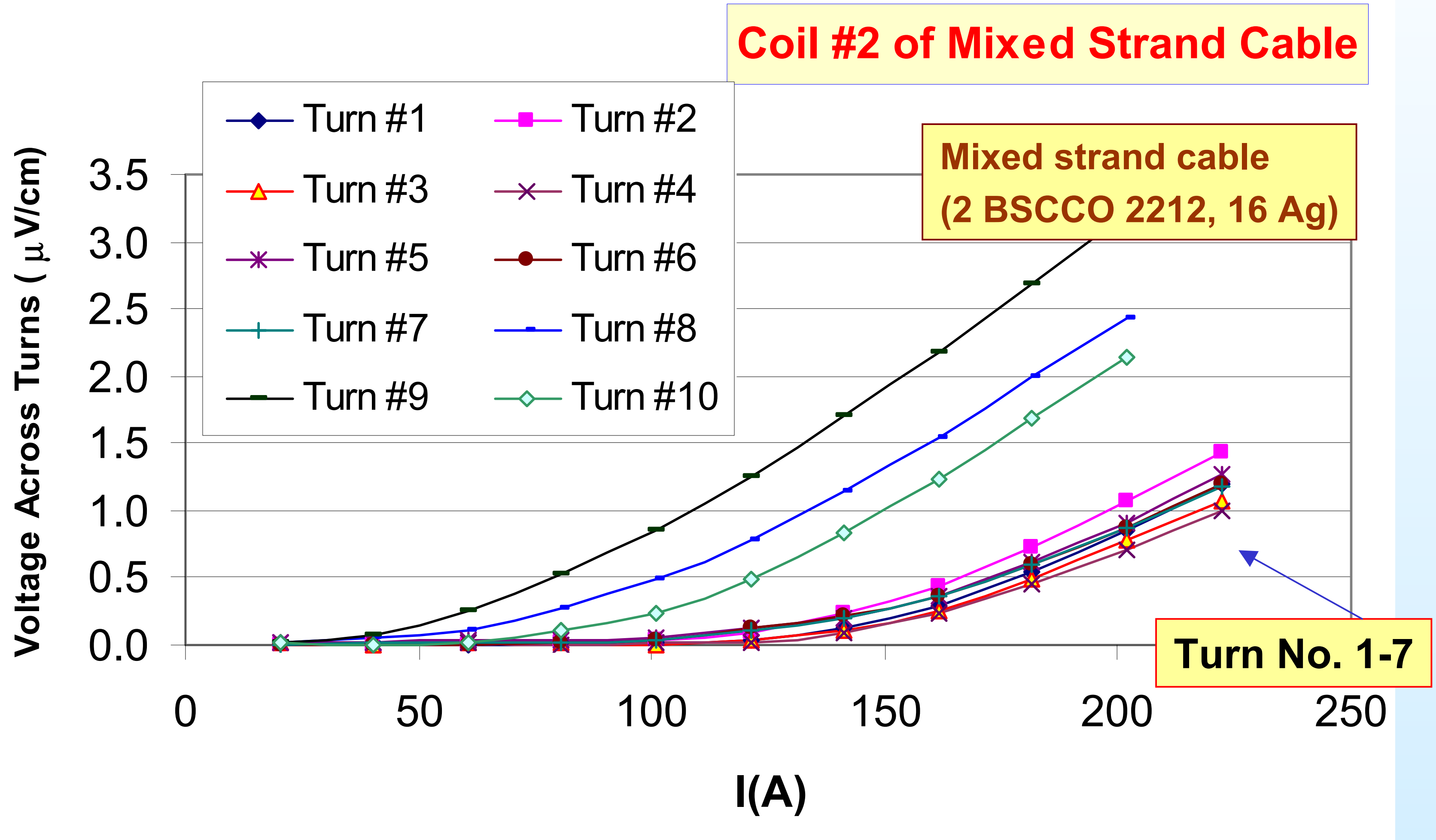
Voltage difference between each consecutive turn and on each coil at 4.2 K





- This test magnet was made with cable from early wire
- The state-of-the-art wire is now about a factor of five better

Measured I_c of Various Turns of Common Coil Magnet DCC006

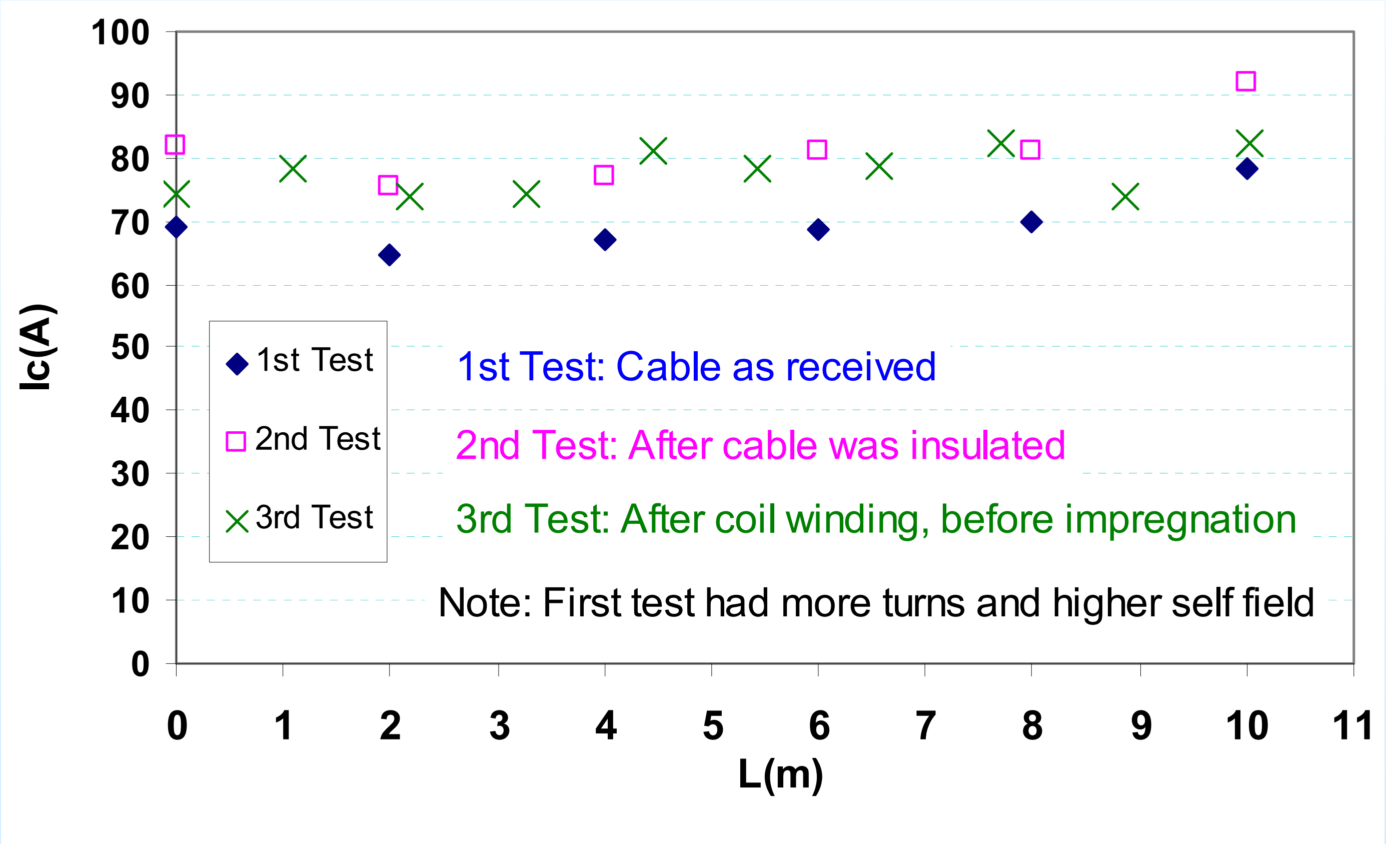


Turns No. 1-7 show an I_c close to the best measured in cable prior to winding.

<u>This suggest a low level of degradation!</u>

Systematic Test during the steps of making High Performance HTS coil for DCC008

The coil CC012 is made with the best HTS delivered to date (best claimed is about a factor of 2 better). We want to study degradation, if any, in each and every step of the process. The following LN_2 measurements track the process.



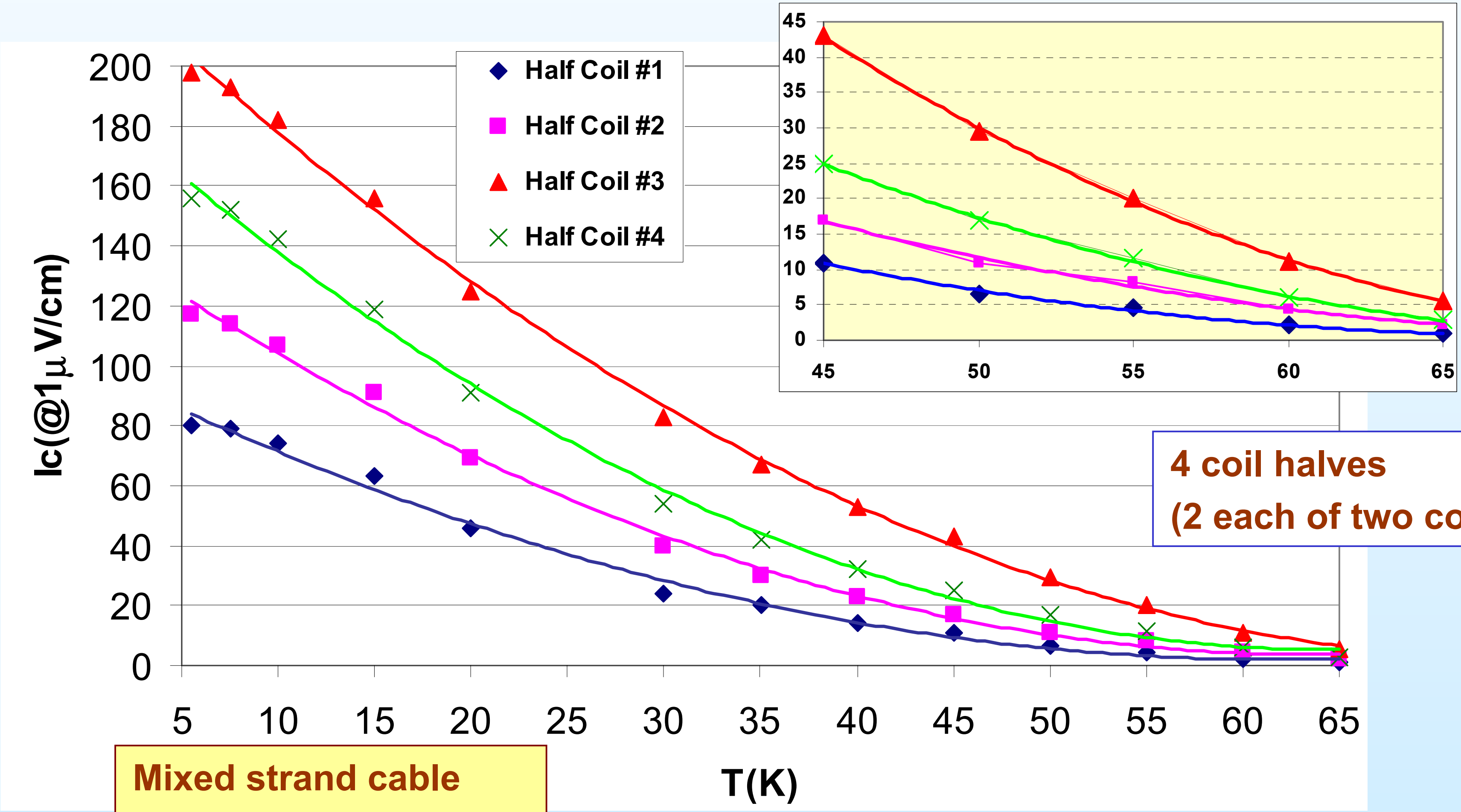
Next Test

Assemble a hybrid magnet to measure the performance of this HTS coil at 4 K in the background field created by Nb_3Sn coils.

Rutherford cable made with 18 strands of BSCCO2212. Strand diameter = 0.8 mm.

Measured Critical Current as a Function of Temperature in DCC006

A few degree change in temperature has a small effect on critical current



4 coil halves
(2 each of two coils)

Mixed strand cable
(2 BSCCO 2212, 16 Ag)

IR Magnet Design Considerations

Differences between the IR magnets and main magnets:

- Only a few IR magnets as compared to a large number of main magnets.
- A few magnets may make a large difference in luminosity performance.
- The cost of material is a fraction of the overall cost of R&D and production.

These contrasts suggest that we should be open to adopting different design strategies for IR magnets as compared to what we do in main magnets.

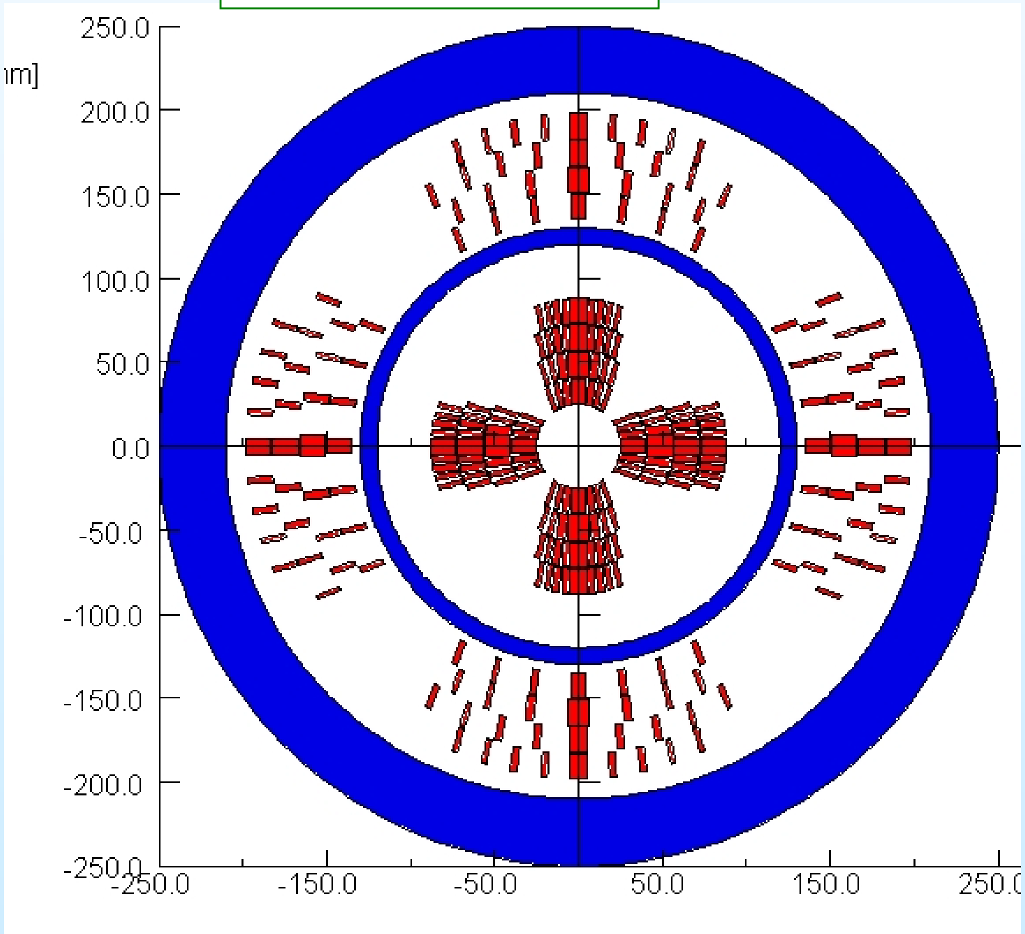
- They can use much more expensive materials.
- They can be more complicated in construction, as we need only a few.

$\Rightarrow$ This makes a good case for HTS in IR magnets.

An Initial Concept for HTS based Q0 Quads LHC IR Upgrade

The following design is made to allow large bend radii

OPERA MODEL

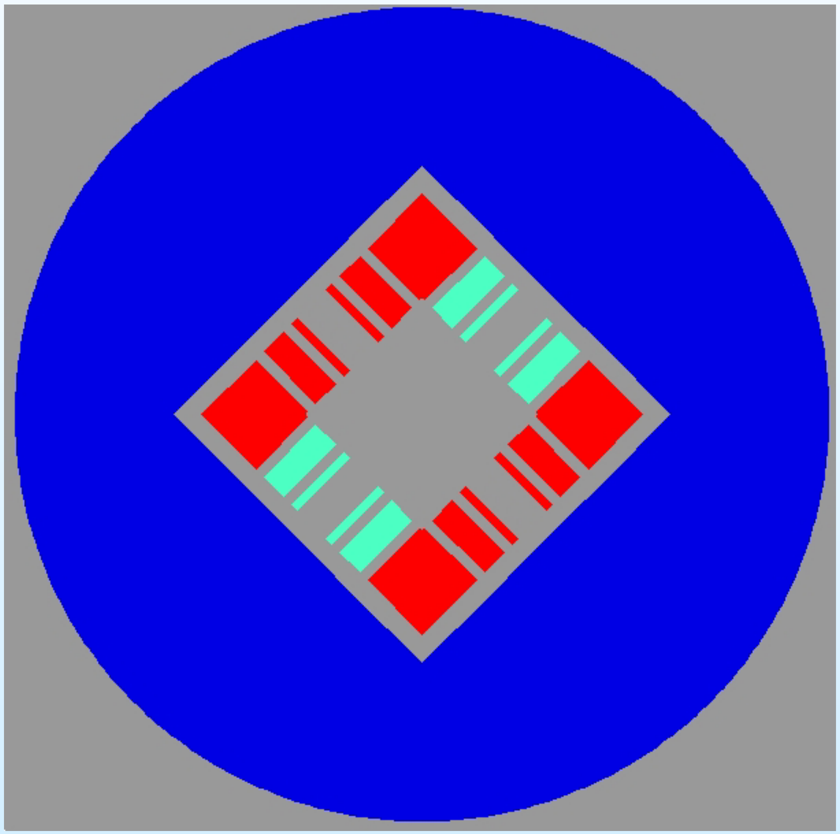


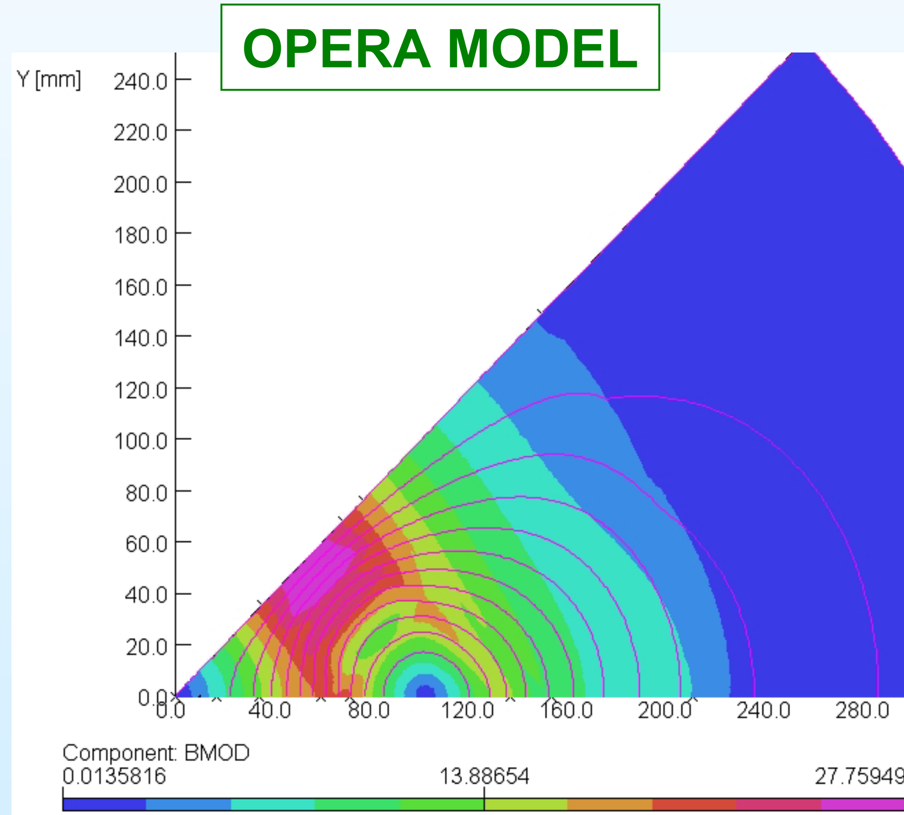
	Q0A	Q0B	
Aperture	50	70	mm
$G_{operating}$	540	320	T/m
B_{peak}	16	13	T
$P_{Luminosity}$>	1000		W

Requires a factor of 2-3 improvement in J_c over the present value.

HTS Quad for LHC IR
(Racetrack Coil Geometry)

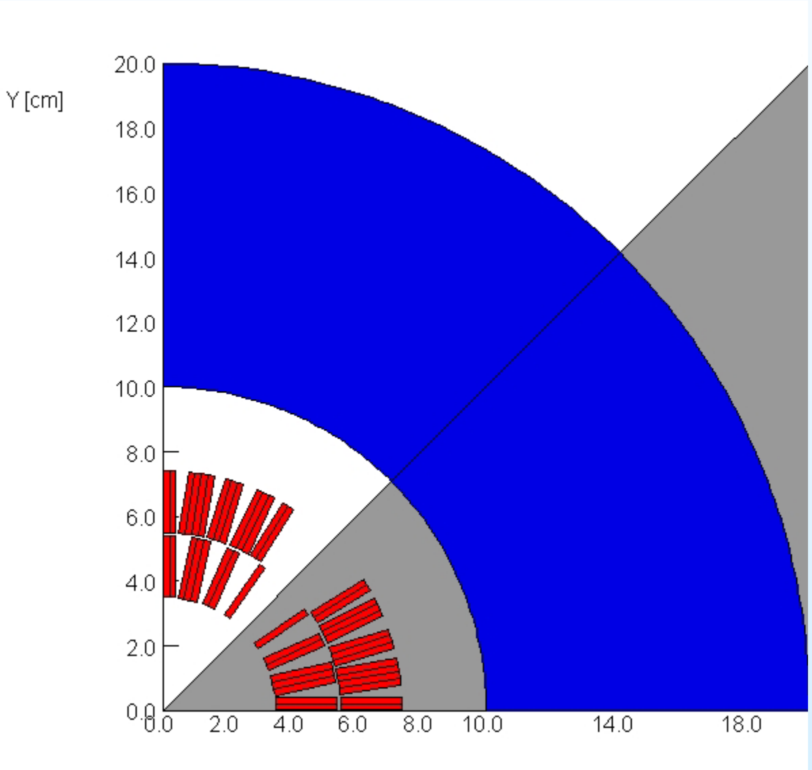
Gradient: 400 T/m; Jo = 1 KA/mm^2, Jc ~ 4-5 kA/mm^2





Note: Peak field is not a major concern in HTS quadrupole designs.

Magnet/ Conductor Technology Options for HTS Quads



OPERA MODEL

- One option is to use "Wind and React" Approach. We are evaluating that.

We prefer "React & Wind" approach over "Wind & React" for reacting long (~5 m) magnets at ~885 C while maintaining ~0.5 C temperature control. Also "React & Wind" approach allows more options for insulation and structure materials.

- One option under consideration under "React & Wind" approach is to evaluate possibilities of very small diameter flexible cable/wire, especially since the magnet need not ramp fast.

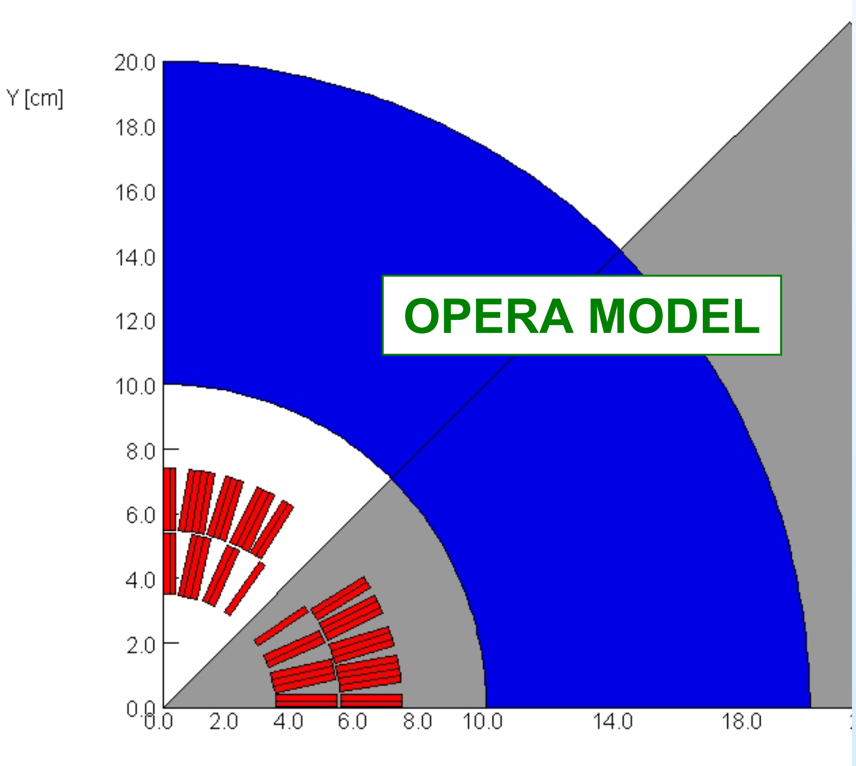
➢ This requires a significant conductor R&D.

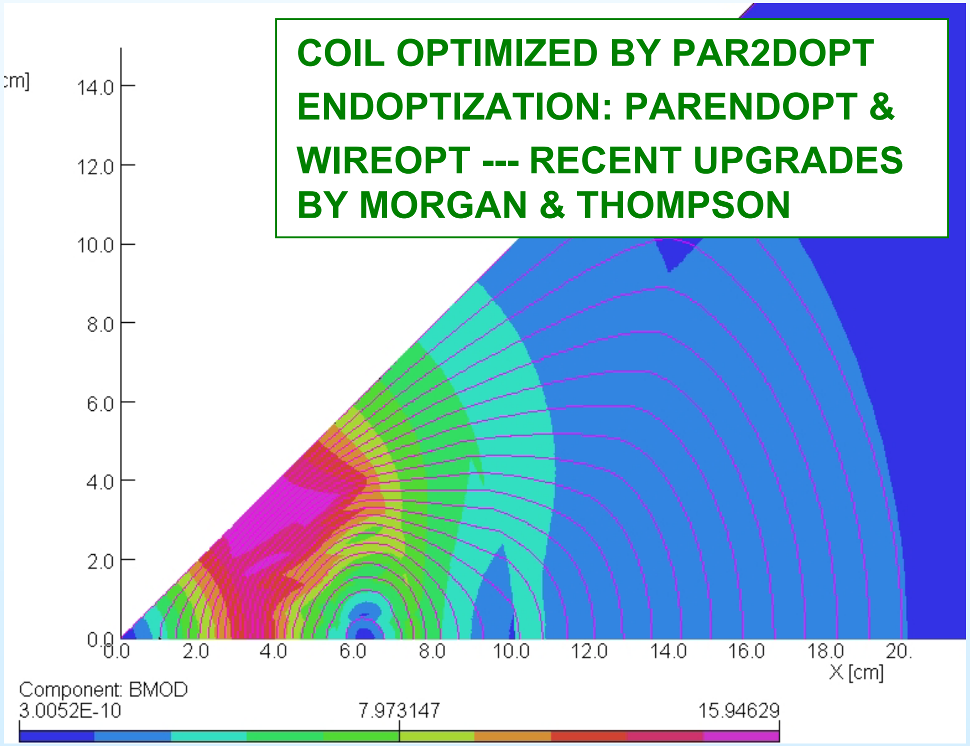
Primary goal of our program is to develop HTS technology. We would use whatever is best.

HTS Quad for LHC IR (70 mm Aperture, 400 T/m Gradient)

2 Layers, 20 mm X 2 mm Cable, 8 turns inner and 14 outer

Jo = 1 KA/mm^2, Jc ~ 4-5 kA/mm^2

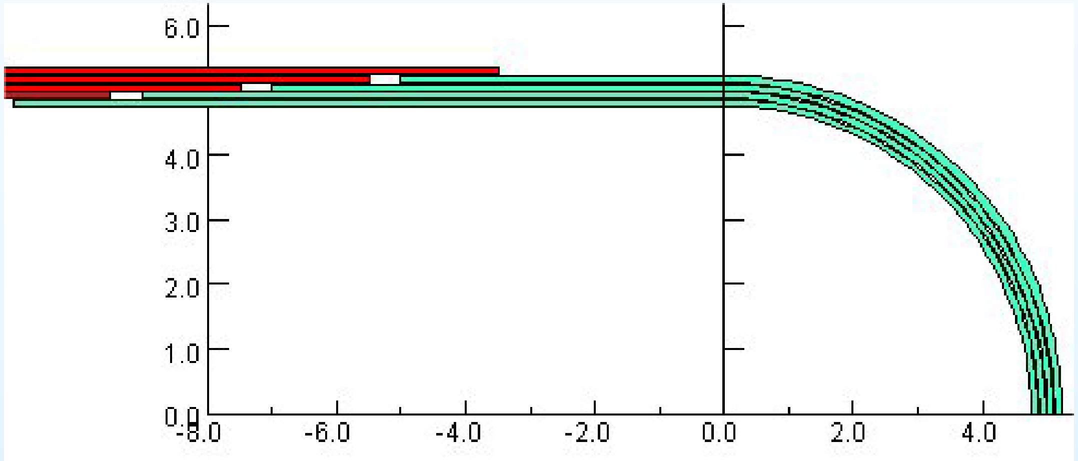




Note: Peak field is not a major concern in HTS quadrupole designs.

A React & Wind HTS Quadrupole Design

Pre-fabricated and pre-reacted ends spliced to straight section turns



The end turns are bent in small diameter before reaction.

- Requires significant R&D on splice joint technology: improve reliability and minimize contact resistance.

Note:

HTS allow much larger temperature rise for a small degradation in critical current.

This labor intensive construction should be acceptable for a few critical magnets.

Each segment could be pre-tested in LN_2.

Near Term HTS R&D Program

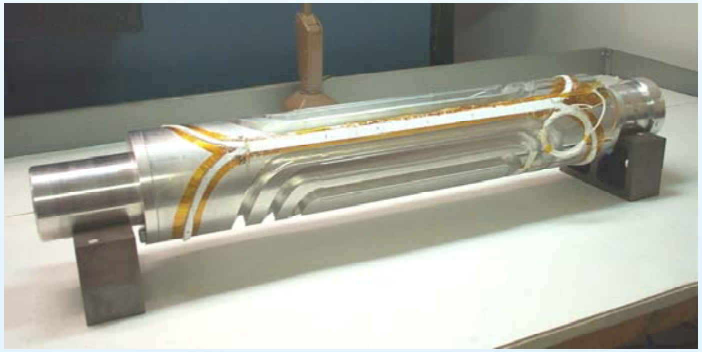
- Continue to build a series of 10 turn coils with better HTS cable.
- Build ~30 turn HTS coil from the material ordered.
- In parallel, build ~12 T magnet with Nb_3Sn to provide background field.
- Assemble hybrid magnet to study issues related to the performance of HTS coils in high field, high stress environment.
- Examine various design options for IR quads. Test small coils following the "low cost, rapid turn around" R&D to test initial feasibility of basic idea.

Present the results of this R&D to accelerator community so it can make a more informed decision about the viability of HTS.

Nb_3Sn Magnet Program with Flexible Pre-reacted Cable

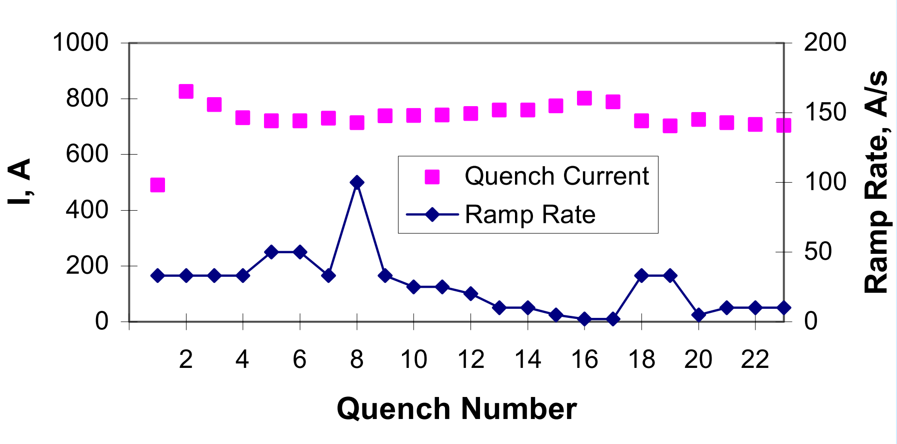
Erich Willen

A dipole coil using small-diameter, pre-reacted Nb_3Sn cable has been built and tested successfully. This proof-of-principal result opens the door to a promising, new approach to building high field magnets.



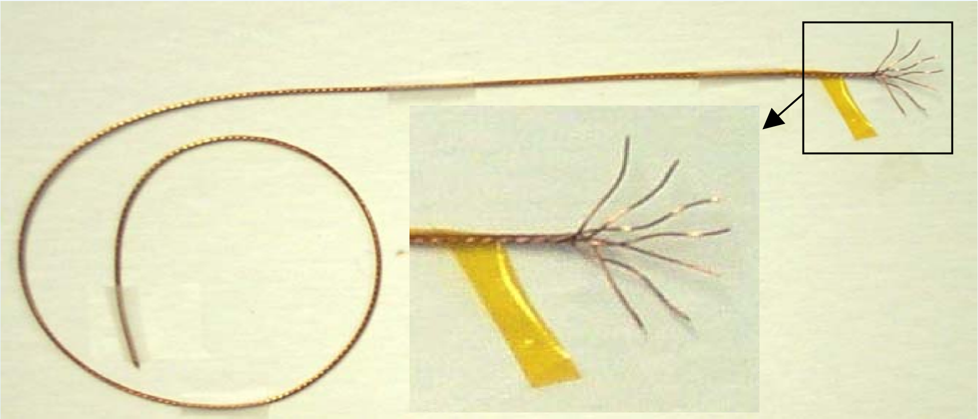
The quench results showed that the coil operated near the short-sample limit of the conductor, 820 A. The field at the winding is ~2.5T. The high current and low field, a difficult combination for stability in a superconductor, would be more favorable in a full scale magnet.

The construction technique subdivides the coil into many sectors, each independently supported, and can therefore control the Lorentz forces in high field magnets. This technique has been used to build many successful helical magnets for RHIC.

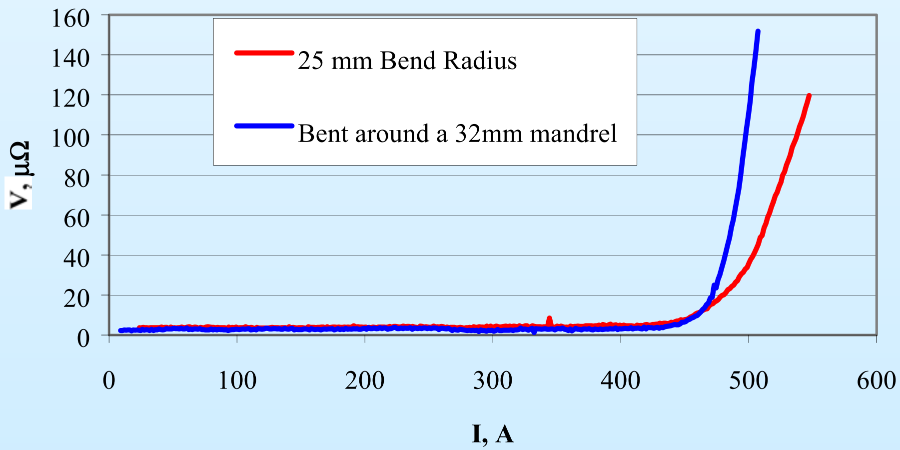


6-around-1 Flexible Nb_3Sn Cable

The cable used for the coil was made of 0.33 mm diameter wires wound into a 6-around-1 cable of 0.99 mm diameter.



Nb3Sn 6x1 cable
NSC-013-RD5

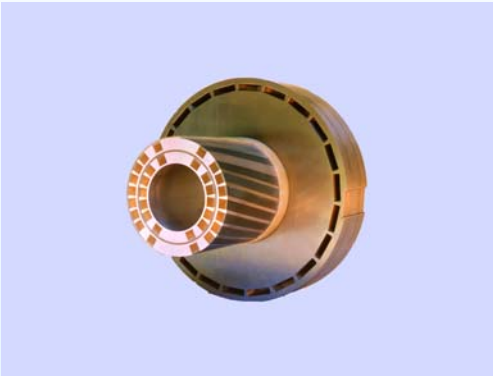


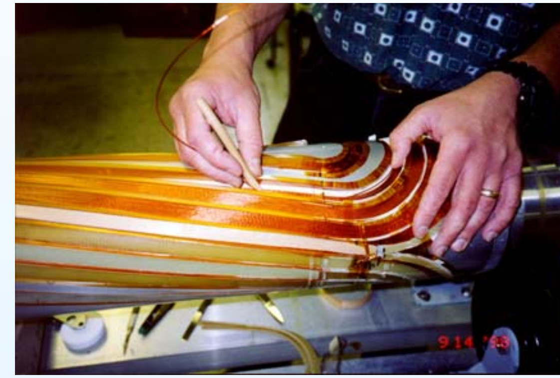
N-value @ 8T ~ 30

When bent around a 32mm diameter mandrel Jc does not change but the n-value drops to ~ 25

Willen & Ghosh, BNL

Slotted Magnets Used Extensively in RHIC Spin Program



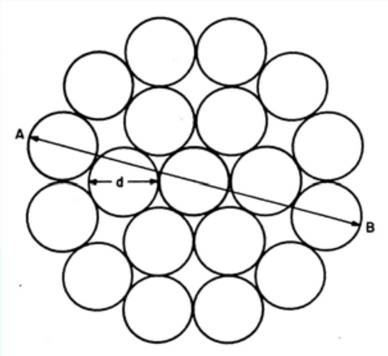


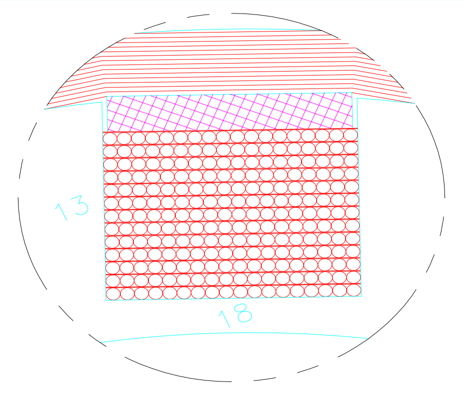
Required R&D in Nb_3Sn Magnet Program

R&D is required in a number of areas to adapt the existing designs for helical magnets to the requirements of Nb_3Sn and high field magnets:

- **Conductor**

This drawing shows a favorable geometry for a 19 wire cable.





- **Coil**
- **Cooling**
- **Forces**
- **Direct Wind Construction Method**

SUMMARY

- Rapid turn around program has been very successful and inspiring in developing technology in a systematic and inspiring fashion at a cost which we can afford.

- No major degradation has been discovered in HTS coils at low field, low stress environment. Background field magnet will determine their performance in high field environment.

- Flexible Nb_3Sn cable offers an attractive option for Nb_3Sn magnets. Initial results are encouraging.