Generic technology development - High field magnet R&D

- **Introduction**
- **Examples of Accelerator Magnet R&D with HTS**
- **High Field Magnet Design**

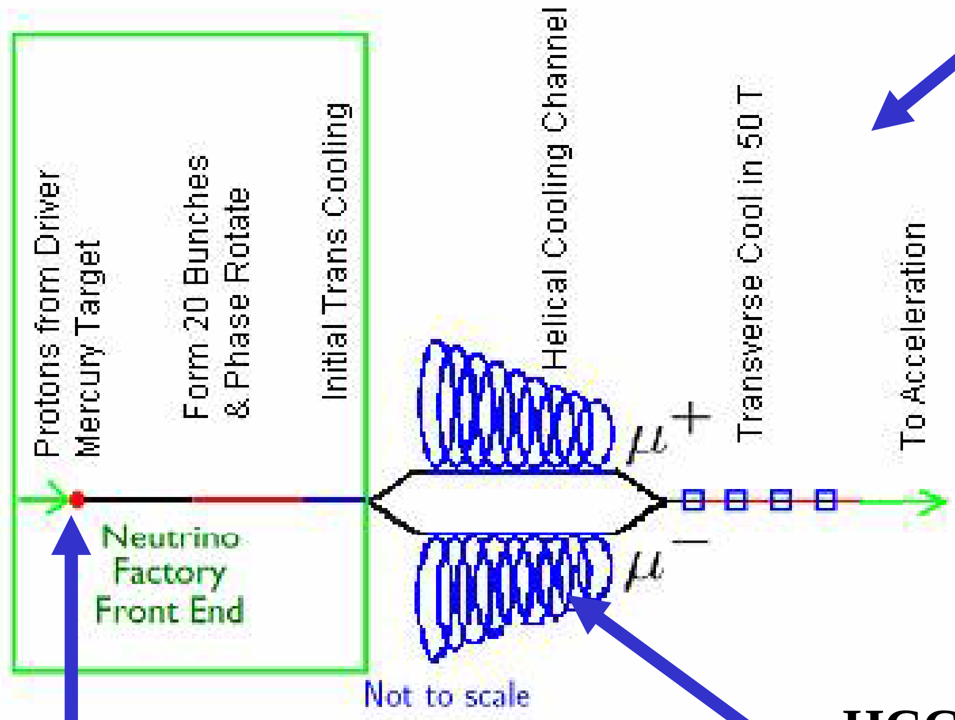
Michael Lamm

With input from several people at the US National Labs

Interesting Magnets in Muon Colliders

One possible scenario…

Very High Field Solenoids



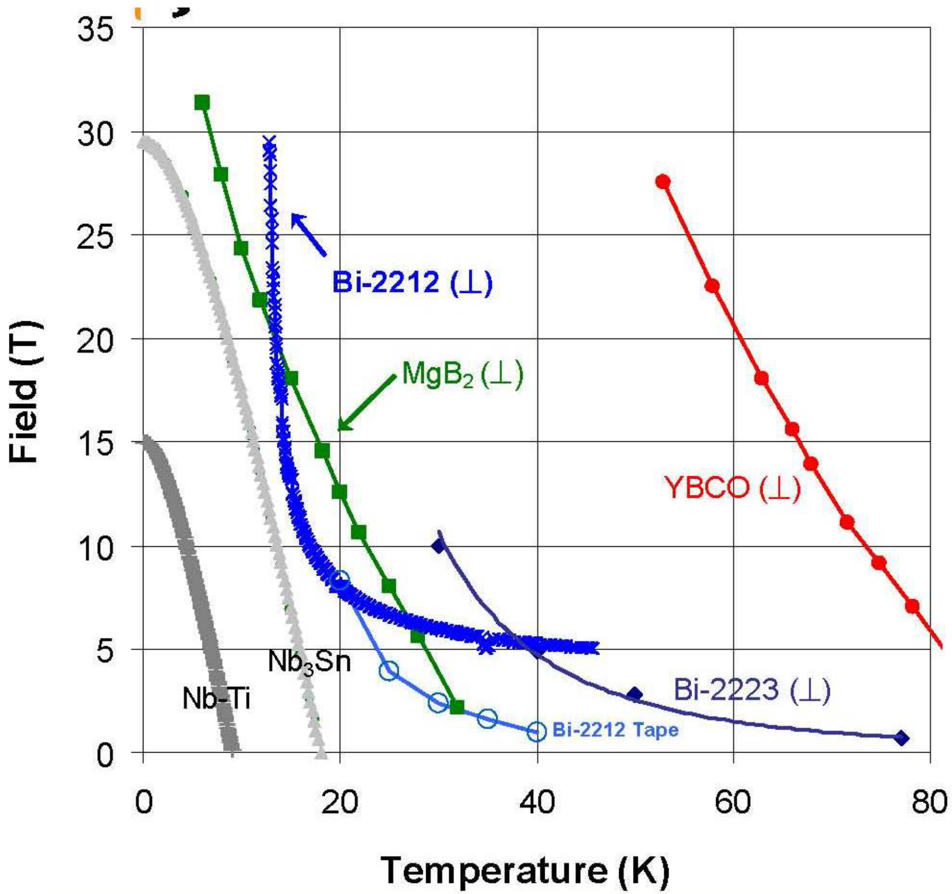
Colliding Ring/IR Magnets ~10 T, wide aperture/open midplane

HCC solenoid rings up to 20 T

Wide(?) aperture pulsed(?) 20 T solenoids

From MCTF End of year report

Why consider HTS? Thermal Margin..



Higher fields require HTS or MgB_2

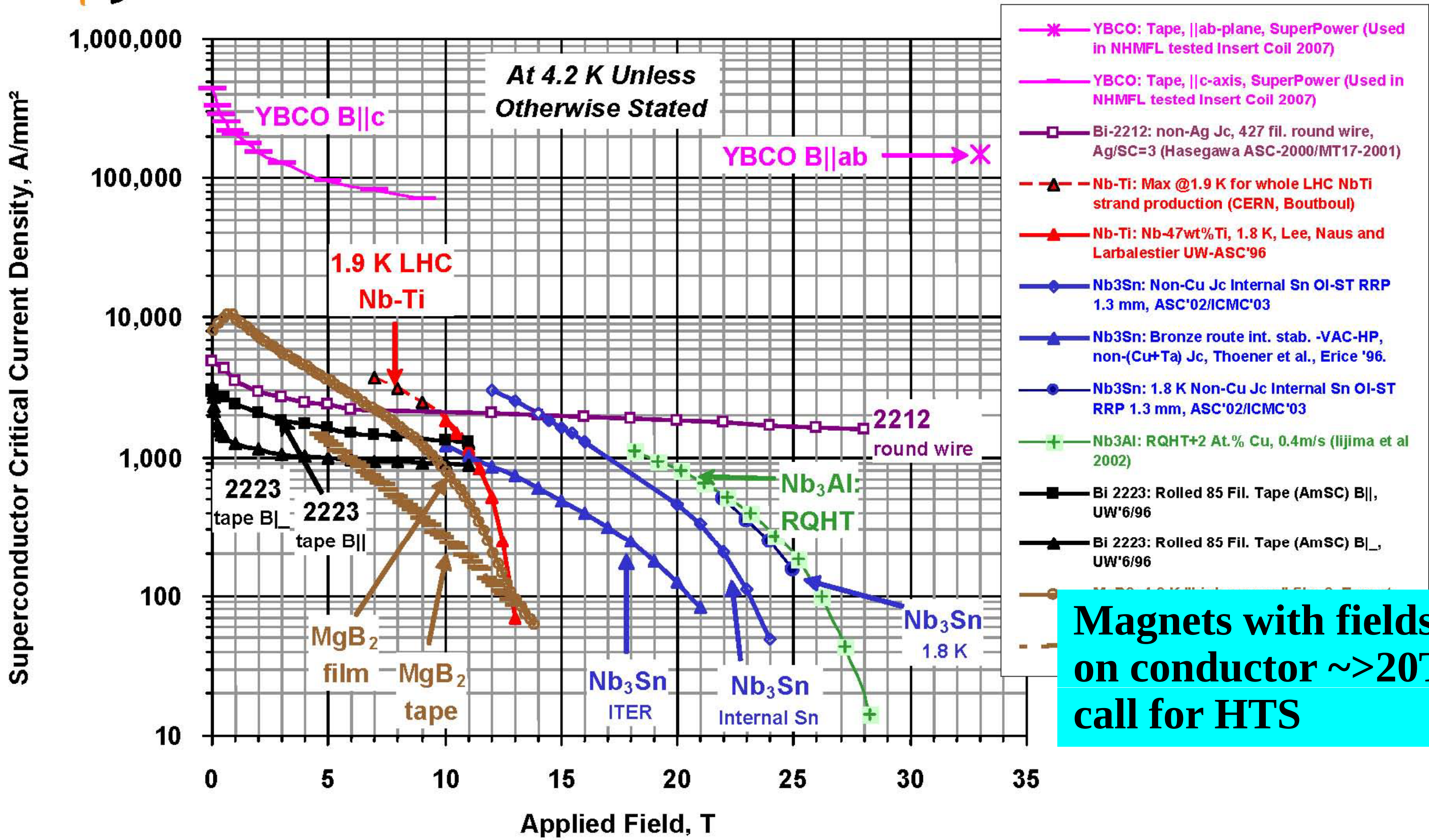
Superconducting state a function of Jc, Field and Temperature

IR and Collider ring and target magnets require high thermal margin at modest fields

>10 T on conductor calls for Nb3Sn or HTS materials

Bi-2212 data Chen, Halperin et al. Nat Phys 2007

Peter Lee's master Jc plot - updated



Magnets with fields on conductor ~>20T call for HTS

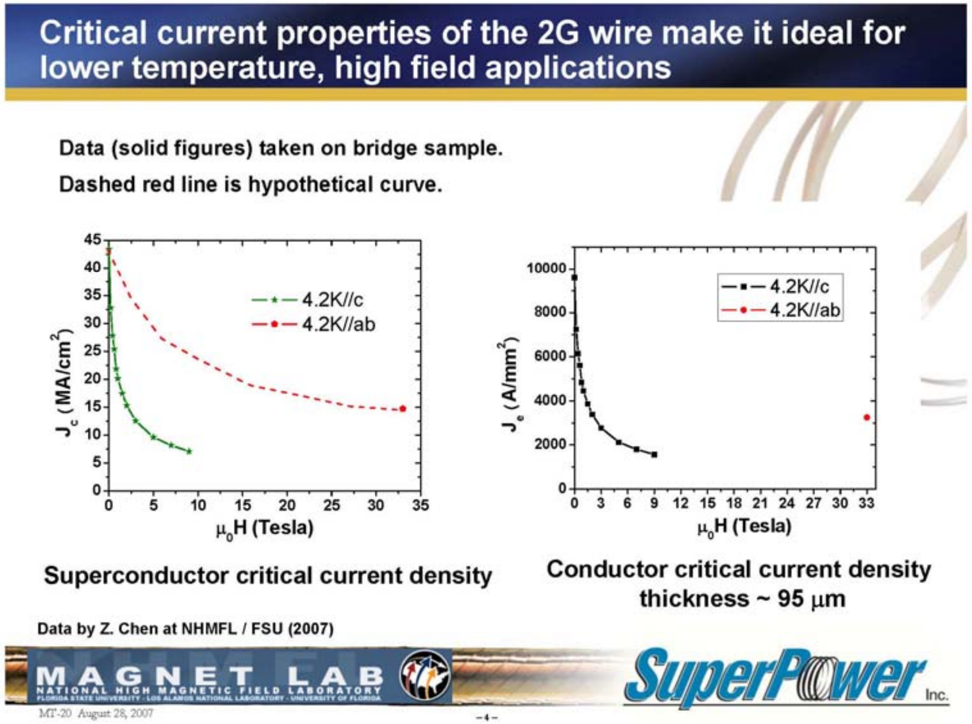
YBCO is in a clear class by itself – fully connected

HTS Materials Used in Magnets

- **Bi 2223 tape**
  - Has been available in long piece lengths from American Superconductor
  - Stainless steel reinforced to improve tensile strength
  - Significant Angular dependence to Jc (field)
- **Bi 2212 Round wire**
  - Available in long piece length from OST
  - No angular dependence
  - Better Je than Bi2223
  - Can be made into a Rutherford cable
  - Wind and react technology….(problems with treatment)

HTS Materials Used in Magnets II

- **2G YBCO Tape**
  - Excellent tensile strain sensitivity
  - Significant improvement in Je over Bi 2223 tape
  - Jc has strong angular dependence with external field.
  - Used in 26T solenoid insert
  - Relatively new…. Still being studied

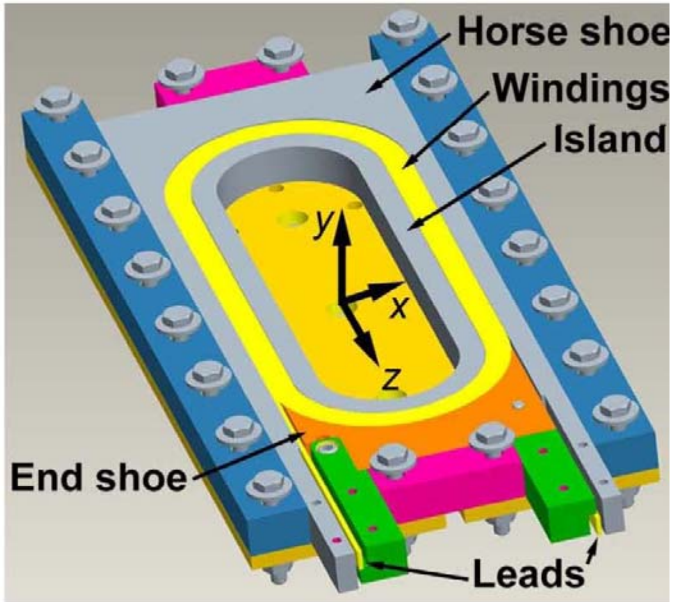


From Drew Hazelton Presentation at MT 20

HTS Accelerator Magnet R&D in the US

- **HEP National Labs study HTS applications in accelerator magnets as part of broader SC magnet R&D Program (Nb3Sn mostly)**
  - BNL
  - LBNL
  - Fermilab
  - Muons Inc has worked with FNAL and BNL several topics
  - Also work at LANL studying HTS materials
- **Studies at the National High Magnetic Field Lab on high field solenoids have applicability to Muon Colliders**

LBNL HTS Program



- **Emphasis on Bi-2212 Wind and React Technology**
- **With SWCC Showa Cable Systems Co. Ltd.**
- **Build HTS subscale racetrack coils from Bi 2212 Rutherford cables. R&D Issues with Bi-2212 W&R**
  - Reaction cycle (precise temperature control +/- 2 degrees at >800K)
  - Insulation to withstand extreme temperatures
  - Bi “leakage” issues
- **Status: 5 coils manufactured, 3 in progress**

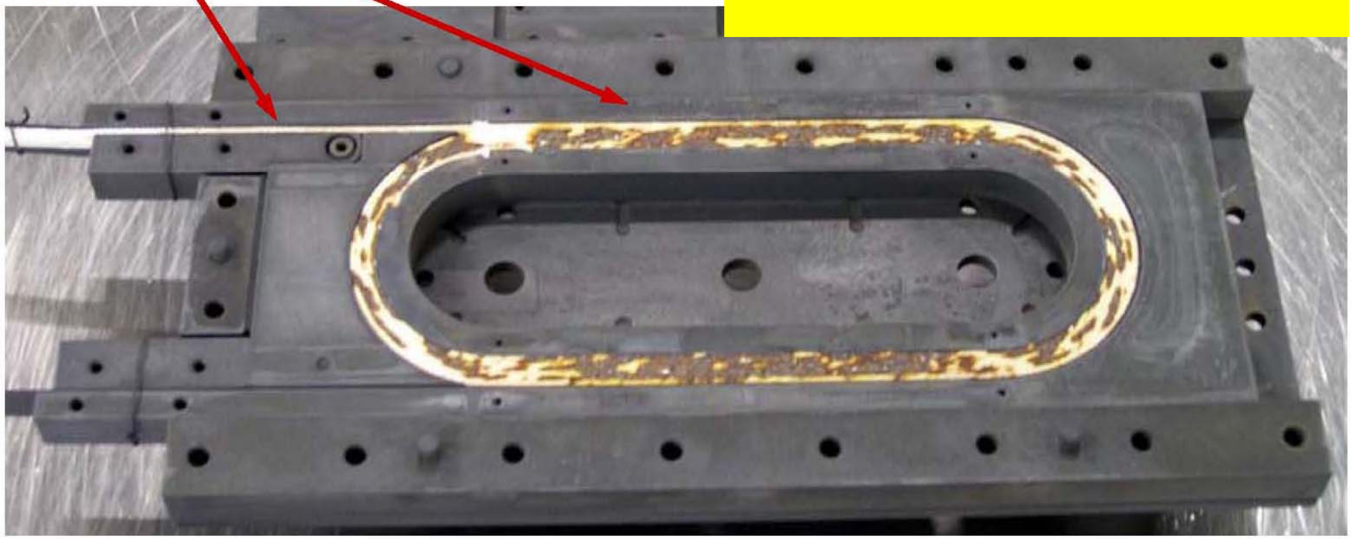
Subscale coil after HT

Leakage occurred

- Not at the leads

Observed at NHMFL as well as HTS vendor: problem not well understood

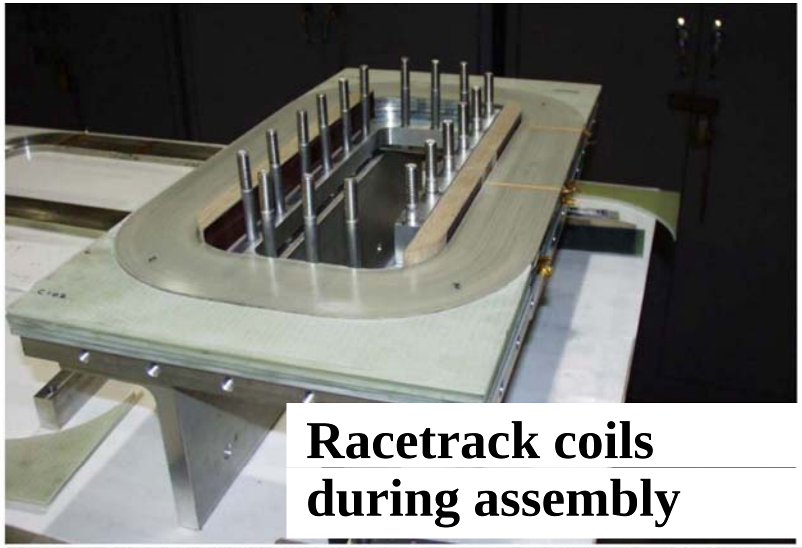
- But inside the package
- More severe at straight sections
  - Better confined



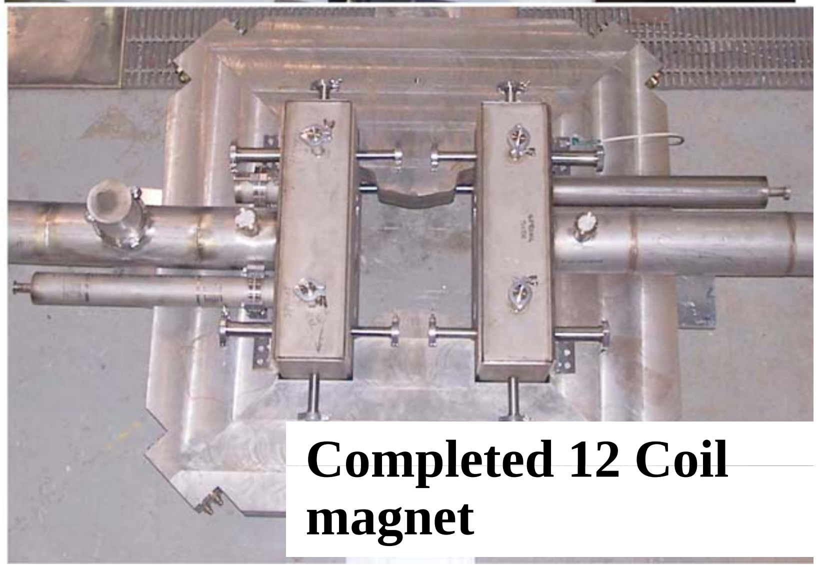
- Leakage is ***absent*** in HT optimizations and insulated “free” wires and cables

BNL Program

- Design/built/test prototype quadrupole for RIA projects
- Expected very high heat deposition (15 kW)
- Magnets built with Bi2223 tape from American Superconductor, with plans to build YBCO magnets

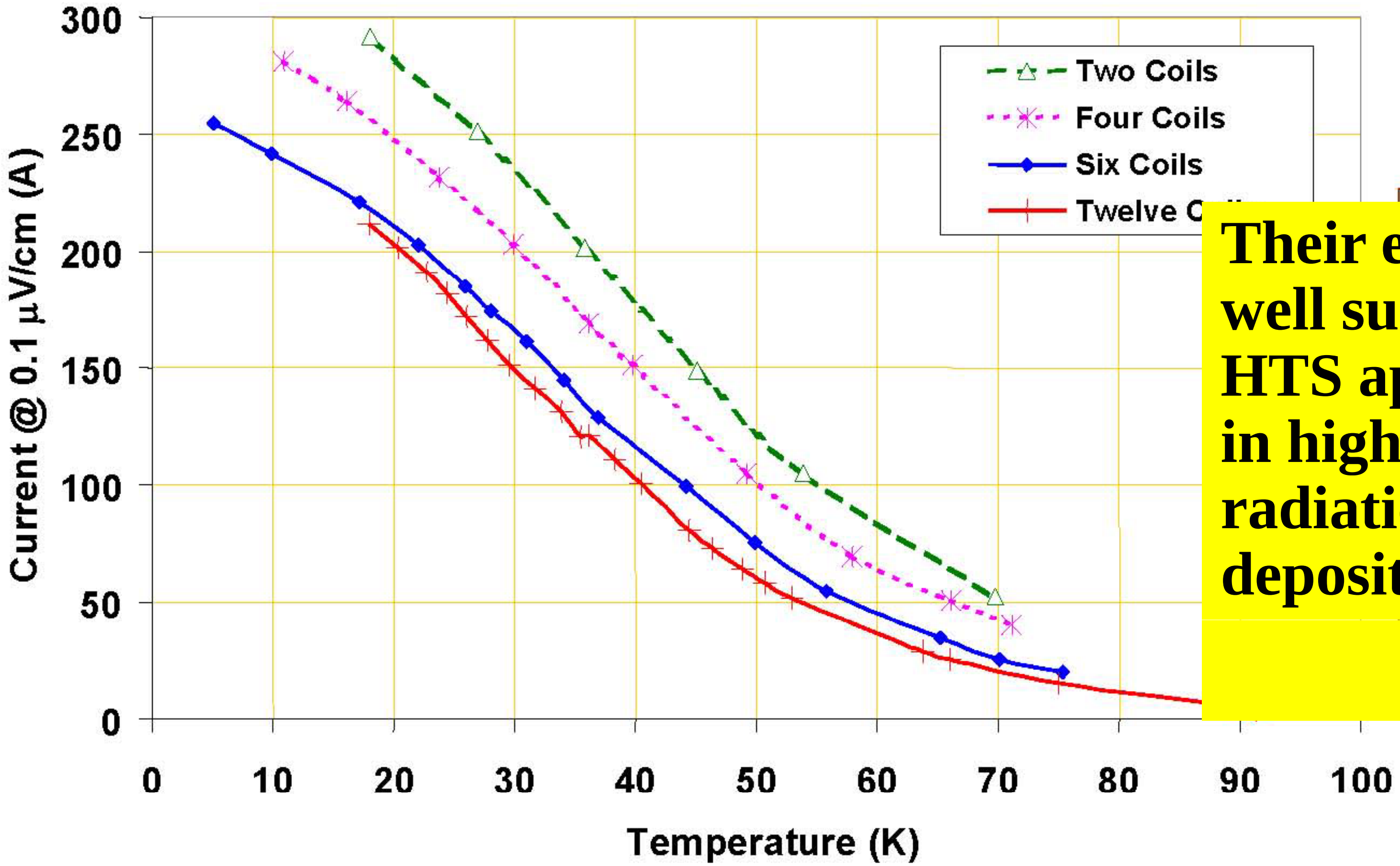


Racetrack coils during assembly



Completed 12 Coil magnet

RIA HTS Mirror Model Test Results
(operation over a large temperature range)



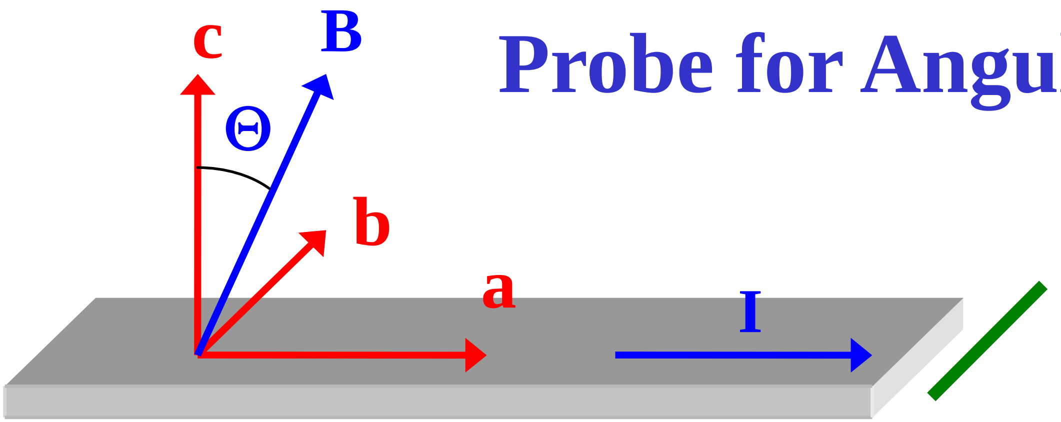
Their experience is well suited toward HTS applications in high radiation/energy deposition

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.

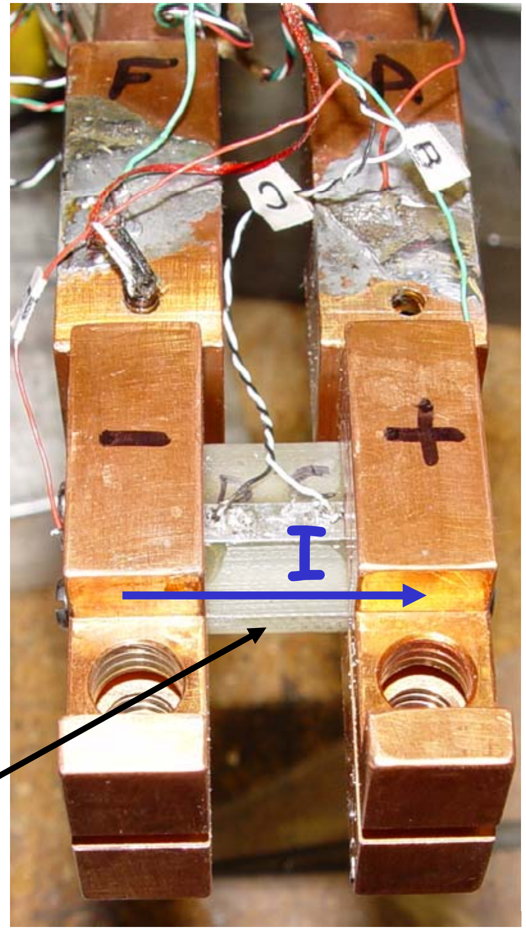
FNAL Program

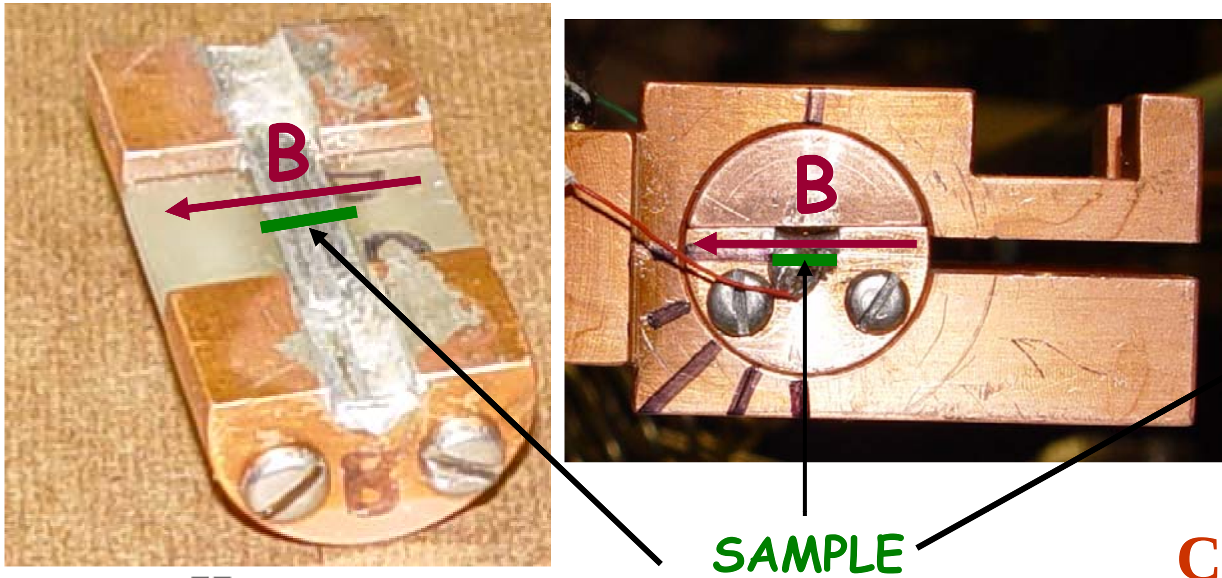
- **Emphasis on HTS cable/strand analysis**
- **Two Oxford Instrument Teslatron, capable of testing up to 17 T solenoid field, from 1.9K to 70K**
- **Cabling machine**
- **Tests performed on Bi 2212 round wire, Bi 2223 tape and YBCO tape**
- **Data used in 50 T solenoid paper studies**
- **Plans in FY08 to wind small solenoids for Teslatron**

Conductor Testing at Fermilab



Probe for Angular Measurements

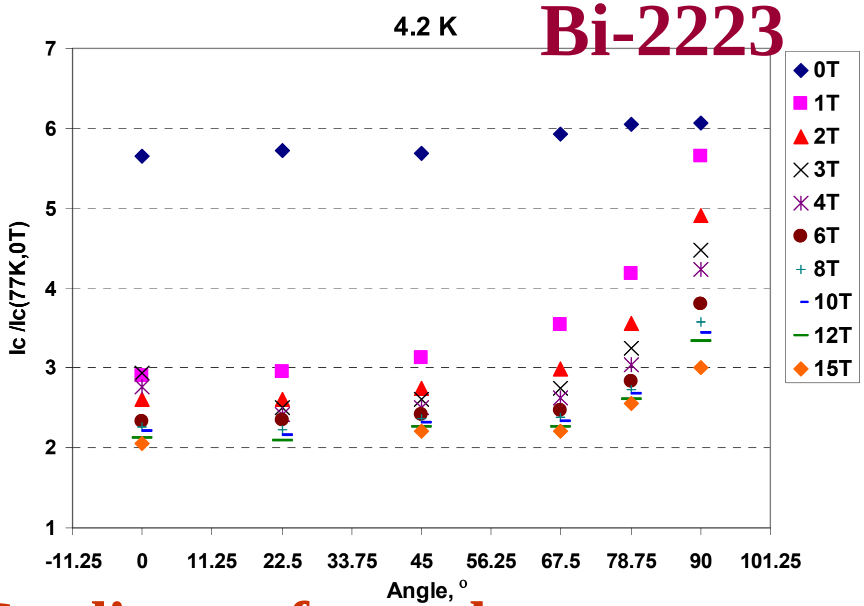


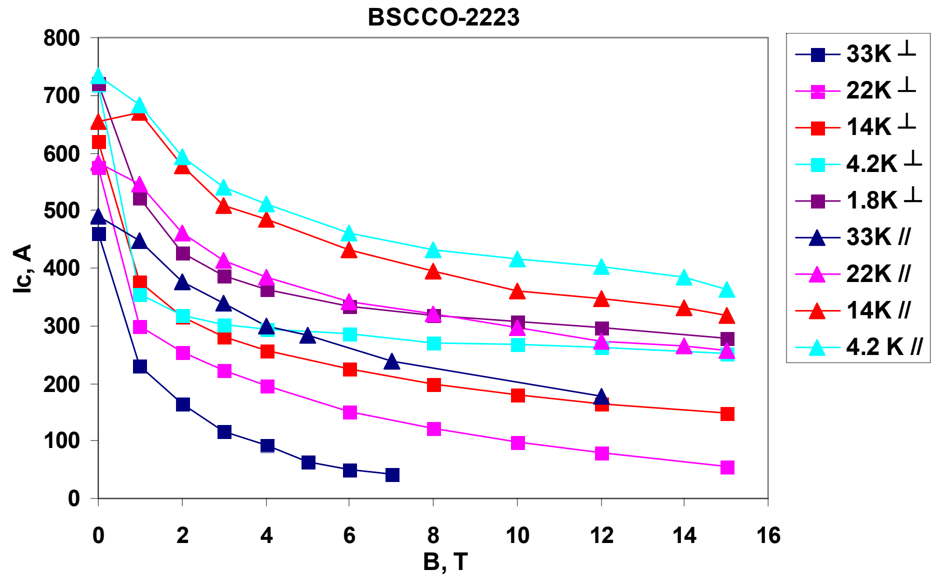


Courtesy of E. Barzi

Example of Measurements Performed

Bi-2223





Studies performed over a wide range of angles, temperatures and fields

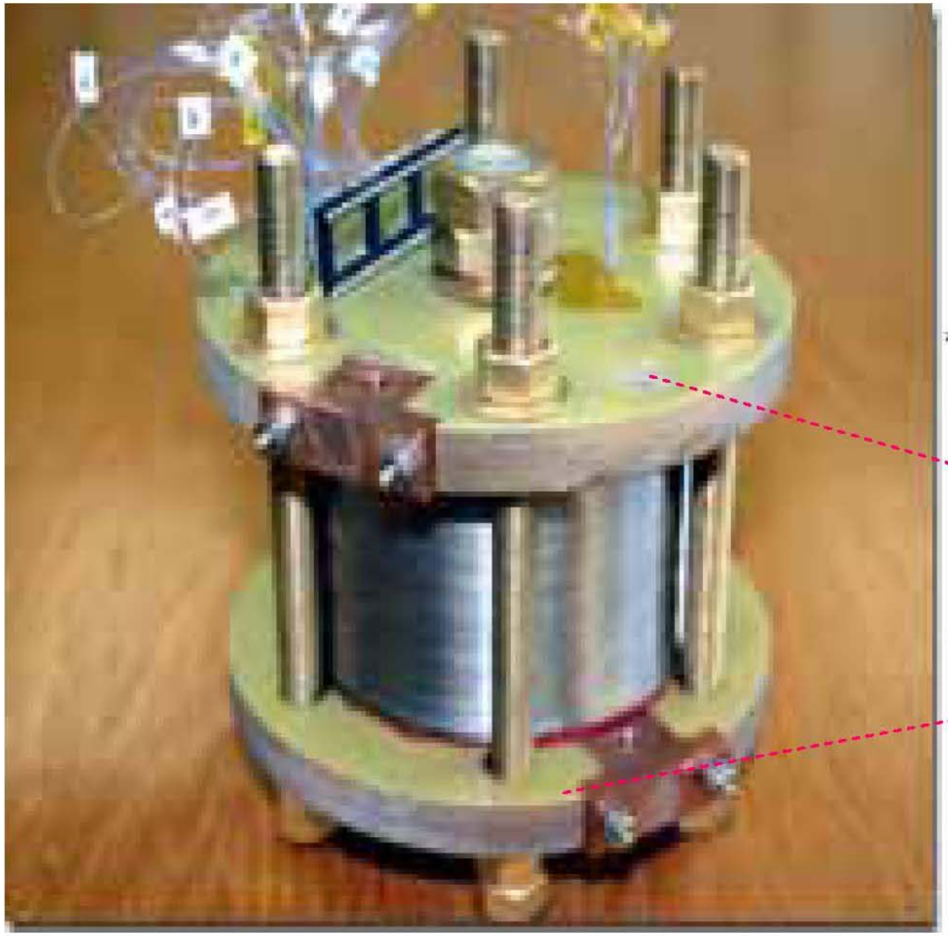
Studies performed on Bi-2223 and YBCO tape (not shown) show Strong angular dependence

E. Barzi, SC R&D Lab

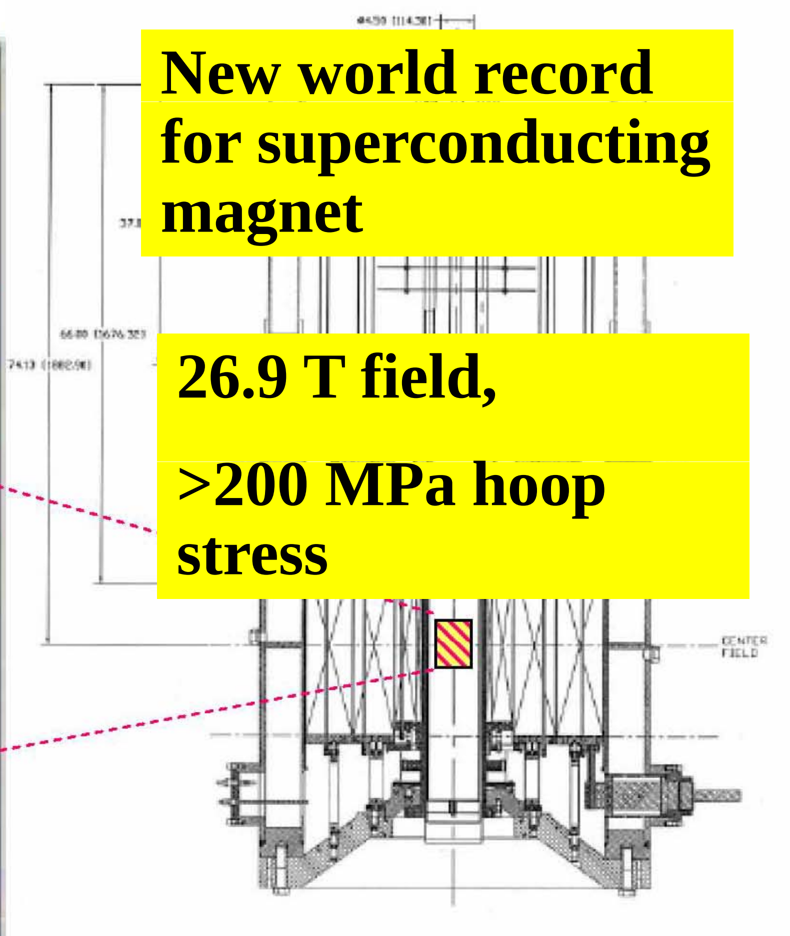
Supported by Muons Inc..

Also extensive temperature and field studies on Bi 2212 wire inc. effect of cabling on Jc (not shown)

2007 Test of 12 pancake SuperPower CC coil in NHMFL 20cm bore, 20 MW, 19T background field



2G HF Insert Coil Showing Terminals, Overbanding and Partial Support Structure. Flange OD is 127 mm.



New world record for superconducting magnet

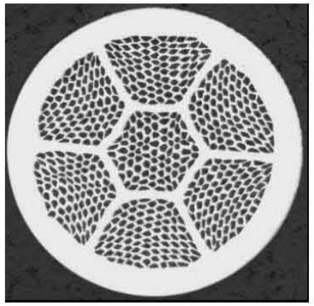
26.9 T field,

>200 MPa hoop stress

Hazelton et al. July 2007

OST-NHMFL Bi-2212 collaborations drove to 25T in 2003

2007 planned – 7T round wire magnet operating in background of 18T 20cm bore Florida Bitter
Springboard for all superconducting 25-30T user magnet



2003- 25 T (5T + 20T)
38 mm bore, 160 mm OD
Reacted before winding
Max stress 120 MPa
$J_{winding}$ = 90 A/mm^2

1997- 18.2 T demonstrated
1.2T in 17T
13mm bore, 50 mm OD
One stack of double pancakes, max. stress 49 MPa
$J_{winding}$ = 85 A/mm^2

Long running program in Justin Schwartz group, amplified now by Hellstrom, Markiewicz and Larbalestier

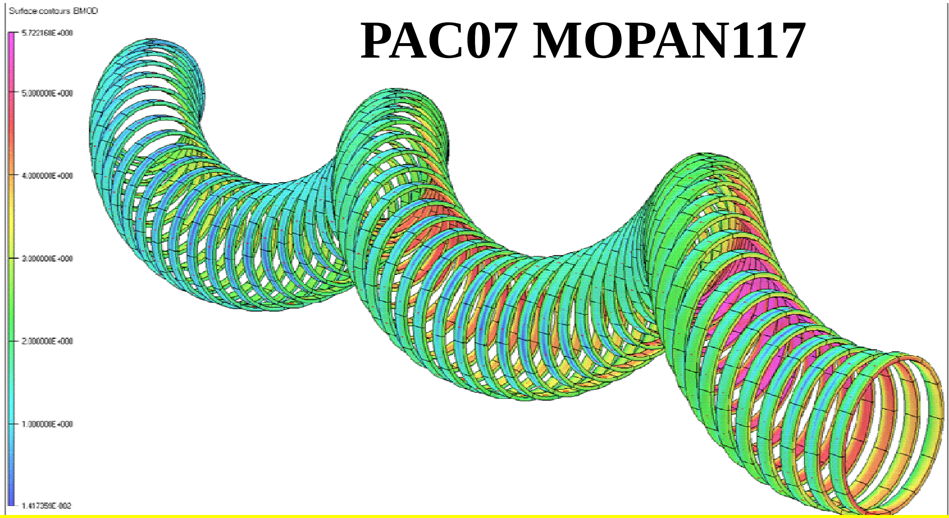
High Field Magnets Under Study

- **Helical Solenoid for Helical Cooling Channel**
  - See talk by Rol Johnson
  - Demonstration Magnet in FY08
    - 0.5 M diameter NbTi 6T on conductor
  - Channel for Real HCC calls for high field solenoid
- **Design Studies for 50 T Solenoids**
  - Paper studies performed by Palmer/Kahn et al. and Kashikhin/Zlobin et al
    - Published at Pac07/MT20

Helical Solenoid

The solenoid consists of a number of ring coils shifted in the transverse plane such that the coil centers follow the helical beam orbit. 1) NbTi 4-coil demo 2) MANX expt. 3) multi stage HCC in Muon accelerator (probably HTS in final stage)

PAC07 MOPAN117



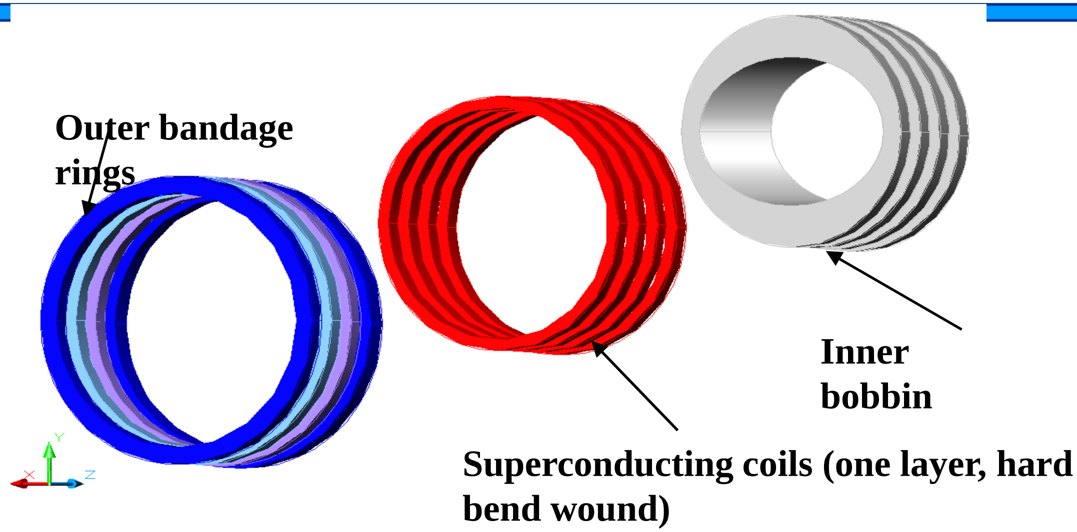
Parameter	Unit	Value
Inner bore diameter	m	0.5
Helical Solenoid length	m	3.2
Helix twist pitch	m	1.6
Radius of beam reference orbit	m	0.255
Initial dipole field, B_τ	T	1.25
Dipole field gradient, $\partial B_\tau/\partial z$	T/m	-0.17
Initial quadrupole field, $\partial B_\tau/\partial r$	T/m	-0.88
Quadrupole field gradient, $\partial^2 B_\tau/\partial r/\partial z$	T/m^2	0.07
Initial field, B_z	T	-3.86
Longitudinal field gradient, $\partial B_z/\partial z$	T/m	0.54
NbTi superconductor peak field	T	5.7
Operational current	kA	10
Operating stored energy	MJ	4.4
Coil section length along Z axis	mm	20
Superconducting cable length	km	3.3

Issues:

- **Mechanical Support**
- **Required field quality (construction tolerances)**
- **Cryostat**
- **Powering and Quench Protection**

Demonstration Magnet in FY08

- **Goals for Demo magnet**
  - Validate Mechanical Structure
  - Develop Field quality measurement
  - Study quench protection issues
- **Features**
  - Use existing SC cable from SSC surplus inventory
  - Test in Vertical Magnet Test Facility
- **Funding**
  - Most Labor costs through Muons Inc. STTR
  - Materials from Fermilab via MCTF/APC



Parameter	Model Nominal	Model Max	MANX
Peak superconductor field	3.3 T	4.84 T	5.7 T
Current	9.6 kA	14 kA	9.6 kA
Number of turns/section	10	10	10
Coil inner diameter	420 mm	420 mm	510 mm
Lorentz force/section, Fx	70 kN	149 kN	160 kN
Lorentz force/section, Fy	12 kN	25 kN	60 kN
Lorentz force/section, Fxy	71 kN	151 kN	171 kN
Lorentz force/section, Fz	157 kN	337 kN	299 kN

High Field Solenoid

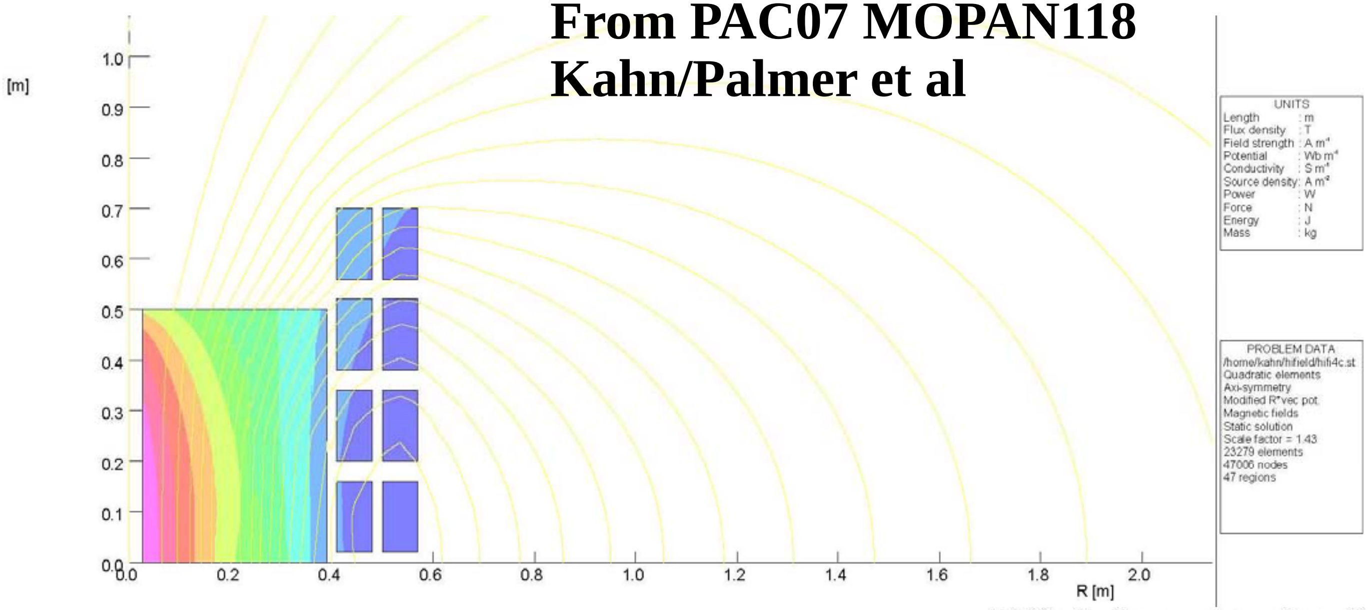
- **Proposed for end of cooling channel for final emittances**
- **30-50 T DC, 30-50 mm aperture, 1 m length**
- **Goals: Highest practical field, accelerator field quality, low manufacturing cost, low operating costs**
- **Superconducting for manageable power reqs**
  - Existing very high field magnets are resistive or resistive/SC hybrids
    ➔ Megawatt Power, one-of-a-kind, expensive to build/operate
  - Engineering current density (Je) of HTS materials measured up to 45 T, have a mild dependence on B… however..
  - Building this solenoid is beyond present capabilities, although 25-30T HTS solenoids are proposed, 25 T solenoid inserts demonstrated

High Field Solenoid Designs

- **Two high field solenoid paper studies related have been performed in the last ~15 months.**
  - Parameters
    - Hybrid magnet with NbTi, Nb3Sn and HTS superconductor
    - Utilize Bi-2223 tapes (steel reinforced, long lengths and reasonable Jc)
      - Extrapolate Je to 45-50T using low field angular dependence
      - Bi-2212 field Je vs. Field
    - Bi-2212 wire is also possible, YBCO not considered (yet)

Design Study #1

From PAC07 MOPAN118
Kahn/Palmer et al



45T Bore Field

- **Inner diameter set by HTS min bend radius**
- **Bi 2223 inner coil, co-wound with SS tape**
- **SS thickness adjusted radial to compensate for hoop stress**

Table 2: Parameters describing the magnet properties

Parameter	Whole Magnet	HTS Magnet	Nb_3Sn Magnet
B_0, Tesla	45.9	30.0	15.9
$\int B \cdot dl$	59.7	32.0	26.7
Stored Energy, Mega-joule	182	57.7	124.6
Axial Force, Mega-newtons	-151	-42	-109
Total Radial Force, Mega-newtons	532	375	157

Design Issues

Demonstrated feasibility of HTS/hybrid approach

Mitigation of hoop stress through SS tape

Need to intercept axial forces

Plan to study new YBCO conductor

Quench Protection Issues explored:

- Internal Heaters unlikely to work
- Need sensitive quench detection circuitry, probably on every layer of coil, with separate extraction circuits for each layer

Fermilab based study

Consider two cases: Minimum Volume/Minimum Cost

TABLE I PARAMETERS OF THE SOLENOID MAGNETS.

Parameter	Units	Minimization parameter	
		Cost	Volume
Coil inner diameter	mm	54	
Clear bore diameter	mm	45	
Cold mass length	m	1014	
Cold mass outer diameter	mm	796	698
Quench field with Bi-2223 at 4.2 K	T	50.35	50.77
Quench field with Bi-2212 at 4.2 K	T	51.42	52.53
Integral $B_z dz$ at 50 T field	T·m	54.40	54.73
Stored energy at 50 T field	MJ	79.3	89.55
Total conductor volume	m^3	0.348	0.223
Total conductor cost	m^3_{NbTi}	2.64	3.24

Va. Kashikhin et al…

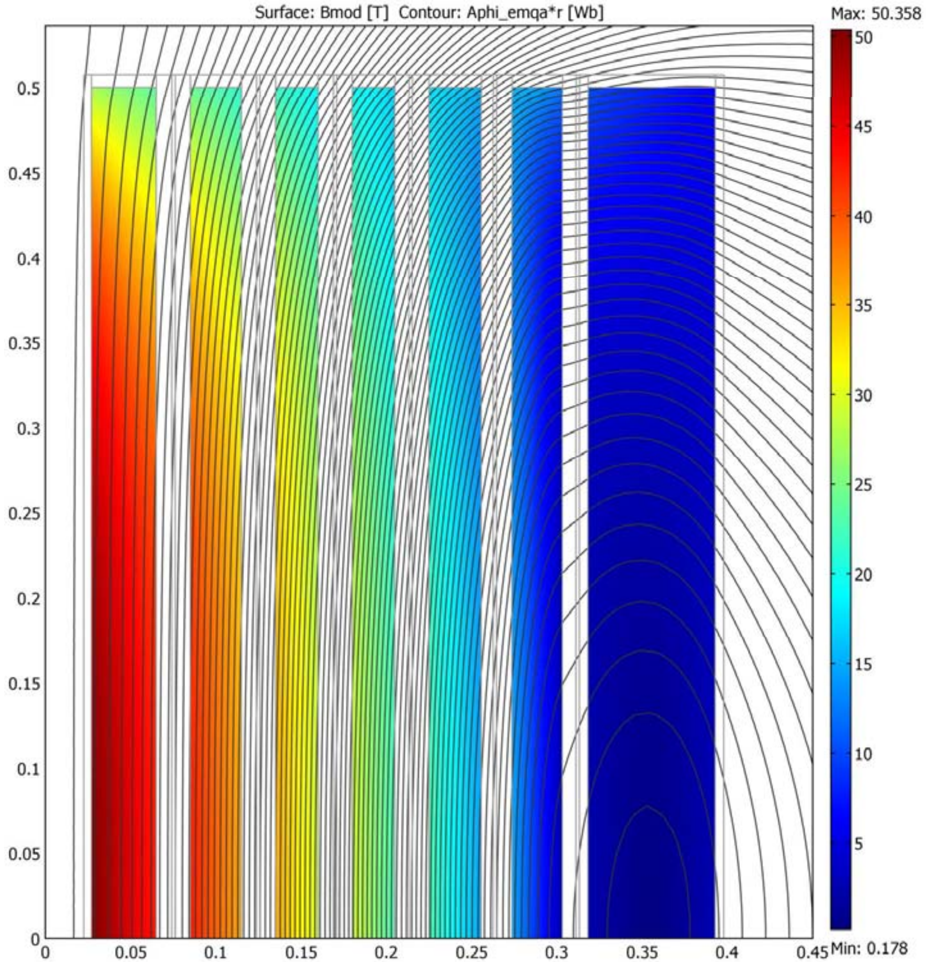
-Several concentric coils independently supported through SS innertube/outersupport structure

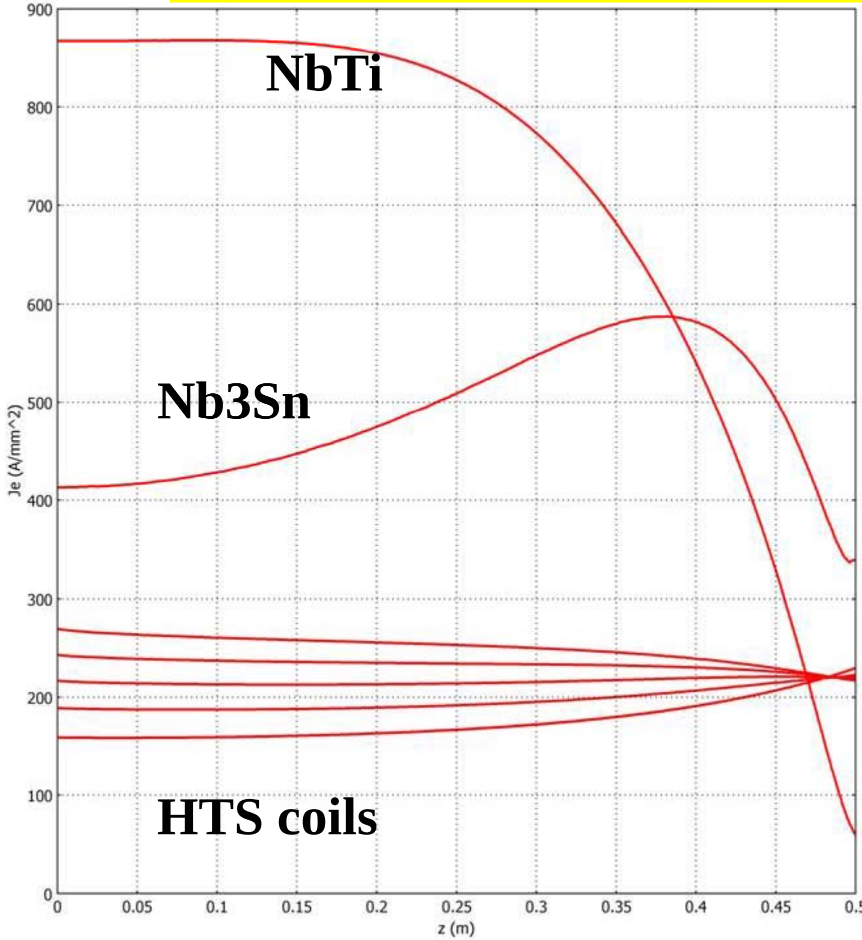
-Coil tension/compression limited to 150 MPa

-Requires bonding/no gaps between inner/outer tubes

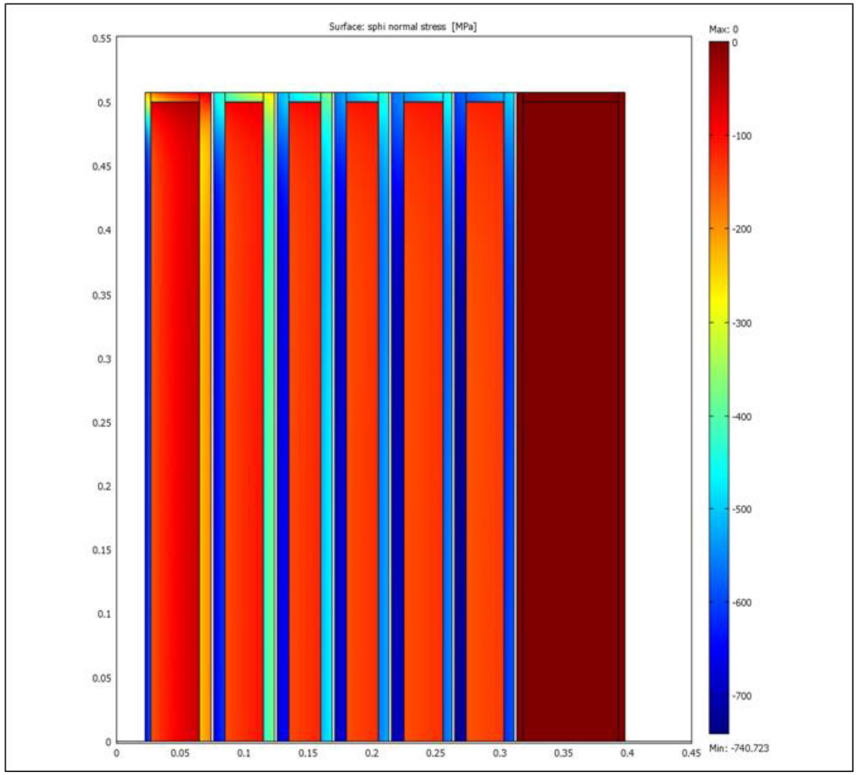
Minimum Cost

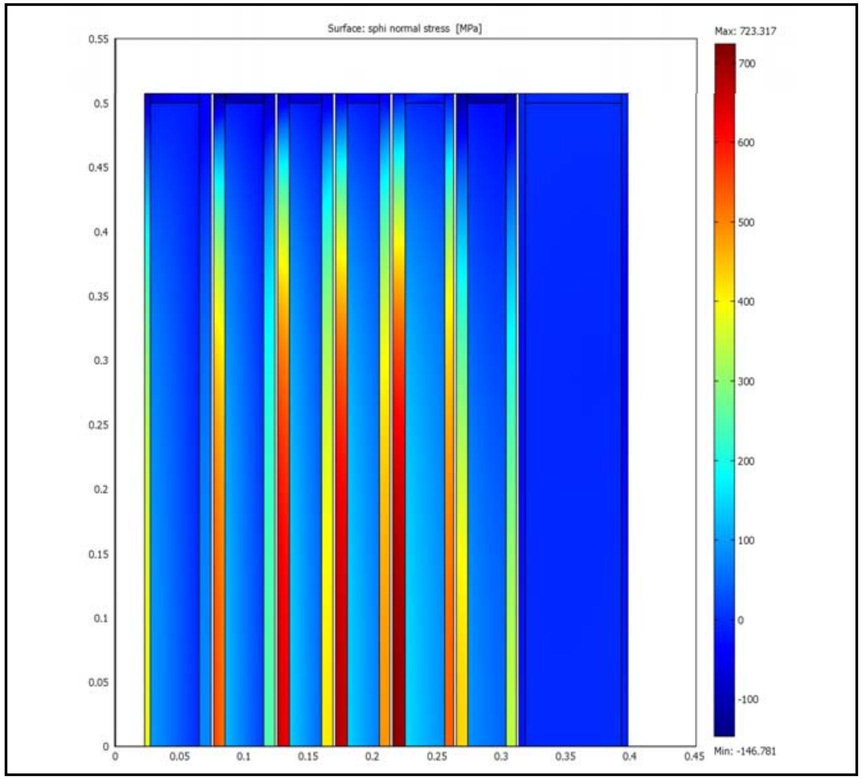
Note: "Minimum Radius eliminates NbTi portion.





Structural Analysis (COMSOL Multiphysics Code)





0 Tesla 150 MPa compression

"Preload"

50 Tesla 150 MPa tension

Compressive force transferred to mechanical structure

Conclusion

- **Several interesting magnet will need to be designed/built at a reasonable cost**
  - Need to start development of magnet list/specification
  - All reasonable options should be considered
- **Active effort on high field magnets in National labs**
  - Plans for a "National HTS Conductor Program" analogous to the existing Nb3Sn program
- **Paper studies show feasibility of HTS for 50T solenoids**
  - Need to consider 2G-YBCO. Need more data on angular dependence with field and strain/stress characteristics