MAP Magnet R&D Program

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Fermilab

Outline

- **Overview**
- **HCC – Helical Cooling Channel**
- **HTS – High Field Final Cooling Solenoid & SBIR – BNL/PBL R&D HTS Solenoid**
- **Collider Ring Magnet Design**
- **Summary**

MAP Magnet R&D

- Very High Fields Required
  - Conductor dominated
    - High J_c at high fields (>25 T)
    - Must support high stresses
  - HTS materials
    - Bi2212 – round strand ⇒ cables
    - YBCO – flat tape (⇒ Roebel cables…)
    - Different technologies - both present challenges…
- Challenging geometries
  - Helical solenoids
  - Collider ring magnets
- Challenging environments
  - Target solenoid
  - Collider ring
    - Muon decay $e^{\pm}$

•Overall effort is largely design / calculation / modeling based

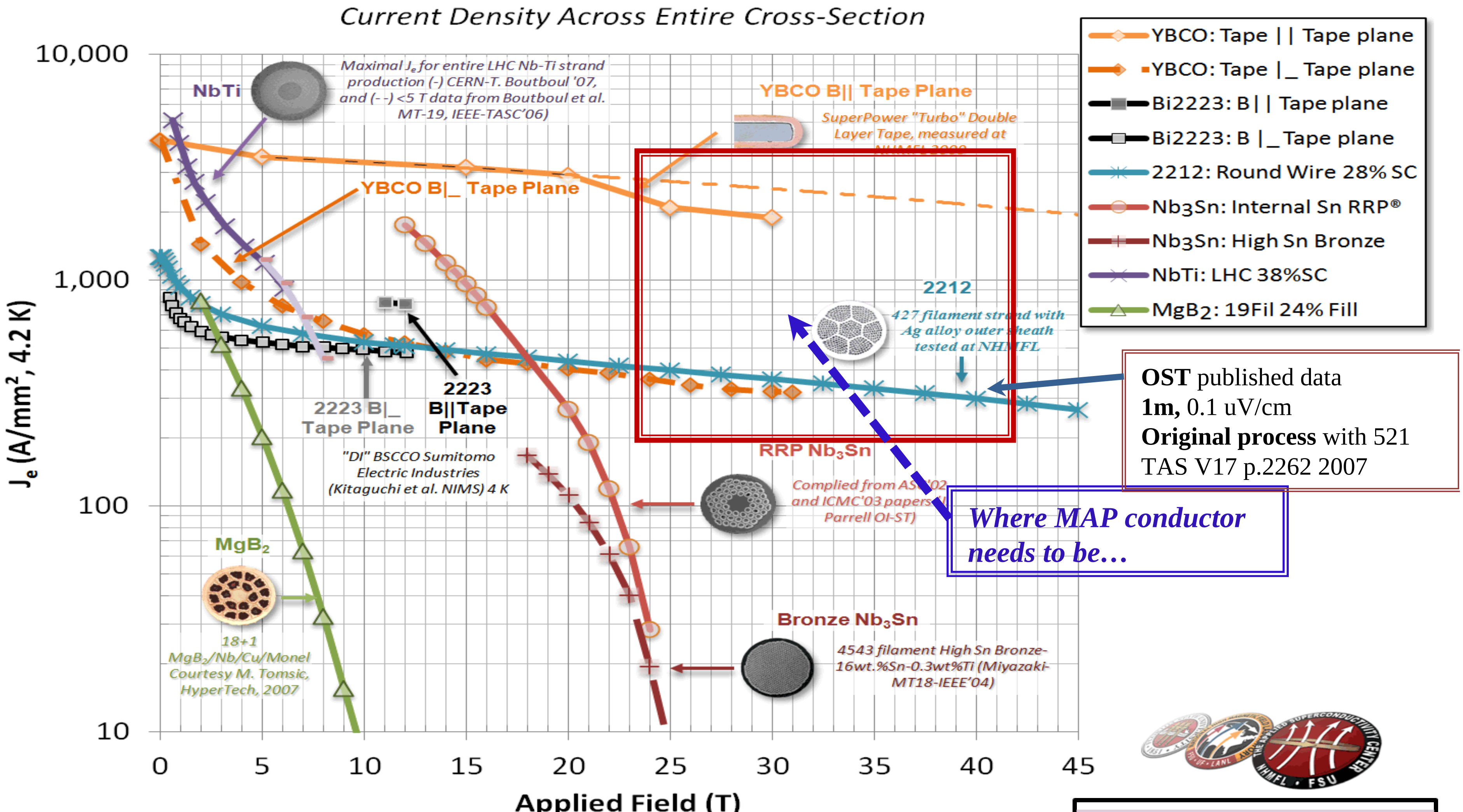
Overview, cont.

- SBIR funding plays an important role
  - Muons, Inc.
  - BNL / PLB 40 T R&D HTS solenoid
  - Support of lab & industry HTS development
- 'Leverage' from other high field programs - mainly LARP
  - Large aperture quadrupoles
  - Experience with less forgiving materials…
    - Wind & react
    - High temp heat treatments
    - Brittle materials
- Ongoing programmatic interest/support at DOE labs in HTS materials for very high field magnets
  - LBNL, BNL, FNAL R&D programs
  - VHFSMC (DOE/ARRA funding) - includes the above, plus FSU-NHFML/ASC, LANL, NIST, & TAMU

Overview, cont.

- DOE/ARRA funding through VHFSMC - $4M total
    - Direct support of HTS R&D for HEP applications
    - Funding now in 2nd / final year
    - Focus on Bi2212
        - Suitability for cabling ⇨ potential for range of HEP magnet requirements (dipoles, quads, etc.)
    - Support of further conductor development – *TBD*
- HTS is the ‘enabling technology’ for a Muon Collider: an ongoing conductor development program must continue beyond VHFSMC
    - A conductor development program similar to that for Nb_3Sn?

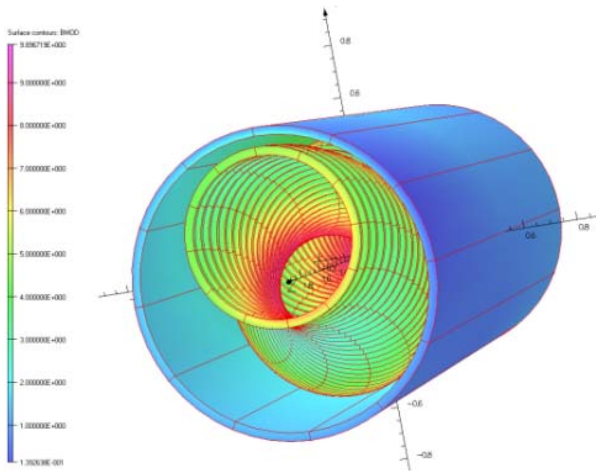
FSU-NHMFL/ASC Superconductors - "the best" plot



Peter Lee, FSU-NHMFL

Helical Cooling Channel

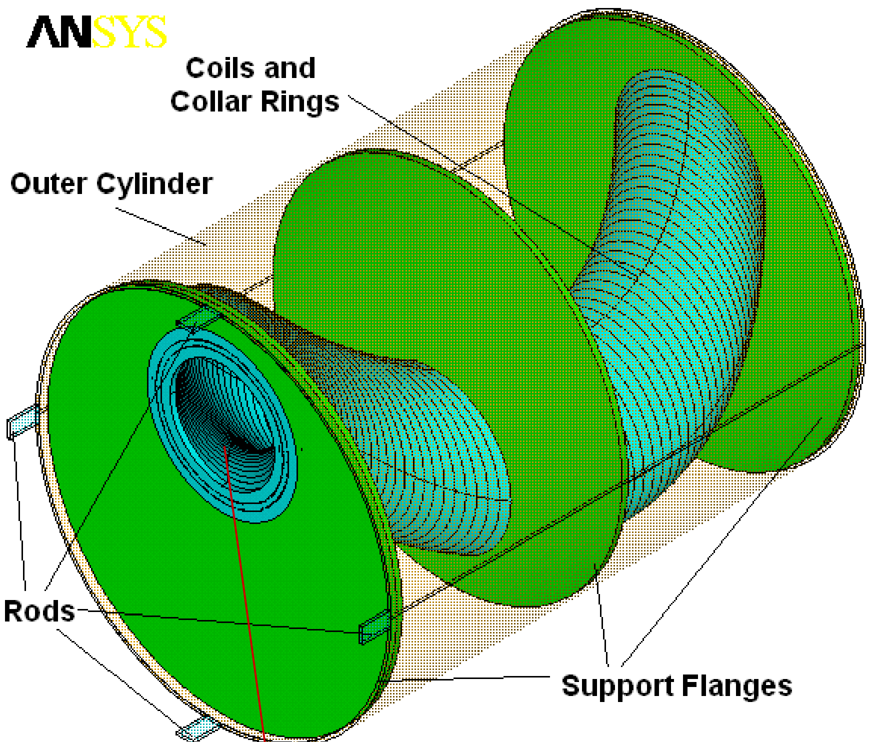
- **The helical solenoid (HS) concept concept (FNAL/Muons Inc.) :**
  - **Coils follow the helical beam orbit generating solenoidal, helical dipole and helical quadrupole fields**
  - **Multi-section HCC**
- **Would require 160 meters of magnets**
- **Wide range of fields, helical periods, apertures**
- **Room for RF system**
- **Field tuning is more complicated at high fields**
- **NbTi, Nb_3Sn/Nb_3Al and HTS in final stage**

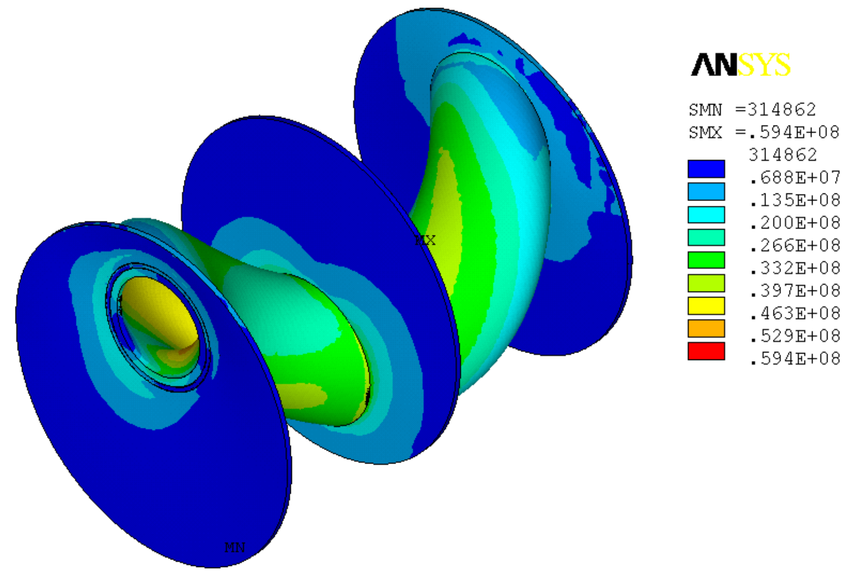


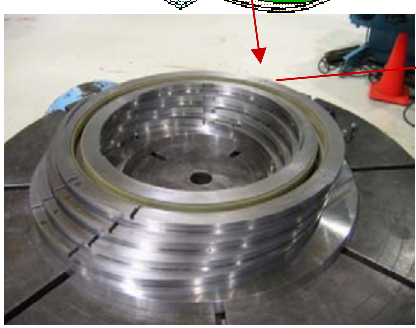
Early Specs, ca. 2006-K. Yonehara, S. Kahn, R. Johnson et al.

Parameter			Section			
			1st	2nd	3rd	4th
Total length		m	50	40	30	40
Period		mm	1000	800	600	400
Orbit radius		mm	159	127	95	64
Solenoidal field	B_z	T	-6.95	-8.69	-11.6	-17.3
Helical dipole	B_t	T	1.62	2.03	2.71	4.06
Helical gradient	G	T/m	-0.7	-1.1	-2	-4.5

HS Mechanical Concept
(FNAL)







The first model built and successfully tested

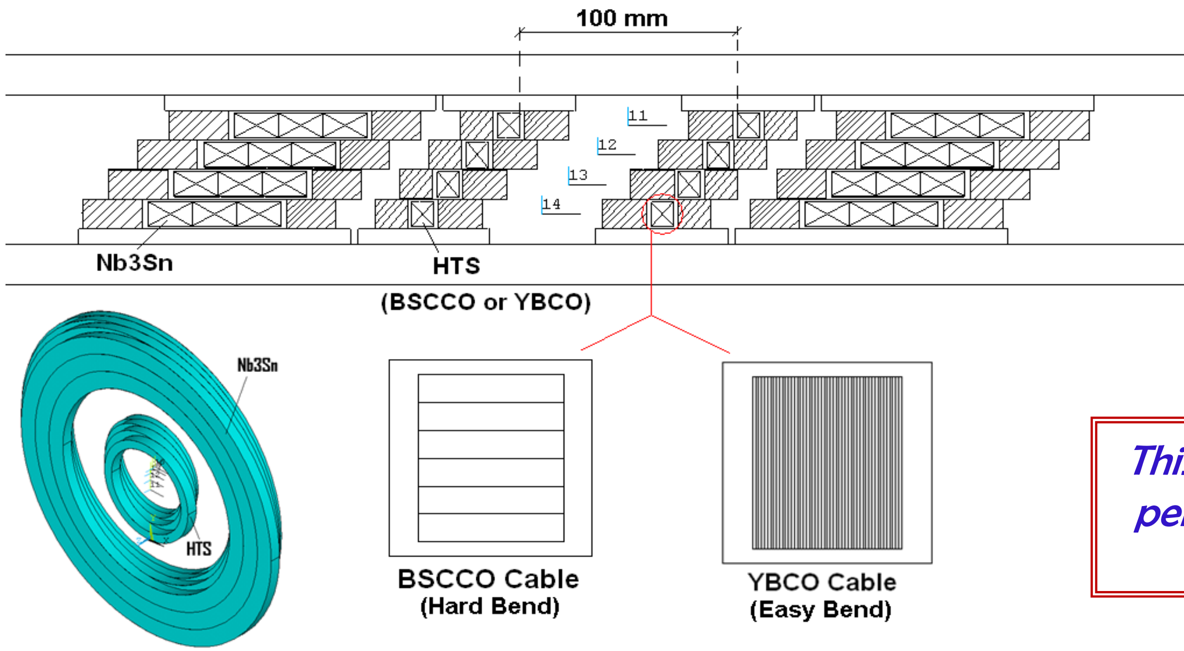
- Hoop Lorentz forces intercepted by stainless steel rings around the coils
- Transverse Lorentz forces intercepted by support flanges
- Outer LHe vessel shell provide mechanical rigidity to the structure
- The peak stress is ~60 MPa

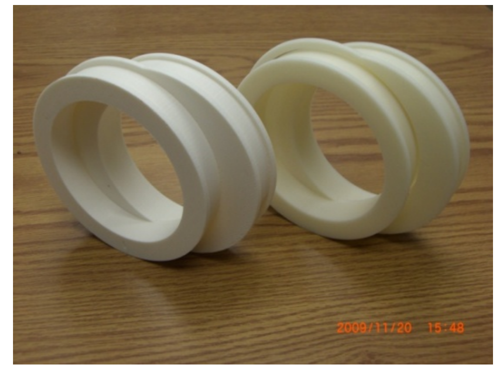
4-Coil NbTi Model Fabrication 2010

A second model HSM02 has been built to improve the solenoid manufacturing technology and performance.

- **HSM02 baseline magnetic and mechanical design is the same as for HSM01**
- **Improved:**
  - **mechanical structure and insulation**
  - **cable geometry and insulation**
  - **coil winding and impregnation procedures**
- **SSC cable re-sized (flattened):**
  - **Cable test => no degradation**
- **HSM02 status:**
  - **Test at Fermilab MTF later this year (Sept/Oct…)**

HCC - Hybrid HS Model





This work is partially funded and performed in collaboration with Muons Inc. (SBIR funded)

- **Conceptual design study shows that a Hybrid HS may be needed for HCC**
- **The goal - develop mechanical design and technology for HTS section based on G2 tape/cable and its assembly with RF and Nb_3Sn section**
- **Support structure was designed and prototyped**
- **12-mm YBCO tape procurement has been initiated by Muons Inc.**

HCC – MAP Program

Model magnet program to support HCC Development

1)4 coil magnet NbTi

- Rebuild of first model to fix programs (*year1= now*)
  - Rebuild complete – awaiting test
- Assuming full period, do quench protection study to determine amount of stabilizer required
- Design magnet with proper amount of stabilizer

2)4 coil magnet with Nb_3Sn

- design tooling, build magnet with Nb_3Sn (*Year 2*) Needed for higher field sections
- incorporate magnet with indirect cool (as are going be needed for these magnets) (*year 3*)

3)HTS magnets

- design tooling, build magnet with Nb_3Sn (*year 2*)
- build 2 coil model using YBBCO tape. Test in self field (*year 1*)
- build several more models (*year 2*)
- successful 4 coil HTS (*year2*)

4)Hybrid

- Build using 4 coil NbTi or HTS AND HTS hybrid. Test combined model (*year 3*)

High Field Solenoid Conceptual Design

Activities

Conceptual Design
Conductor development
Cable R&D
Insert coil studies

Approach - graded design

- Outer coils – lower field region – NbTi
- Intermediate layers – up to ~20T – Nb_3Sn
- Highest field regions – HTS materials
  - YBCO
  - Bi2212

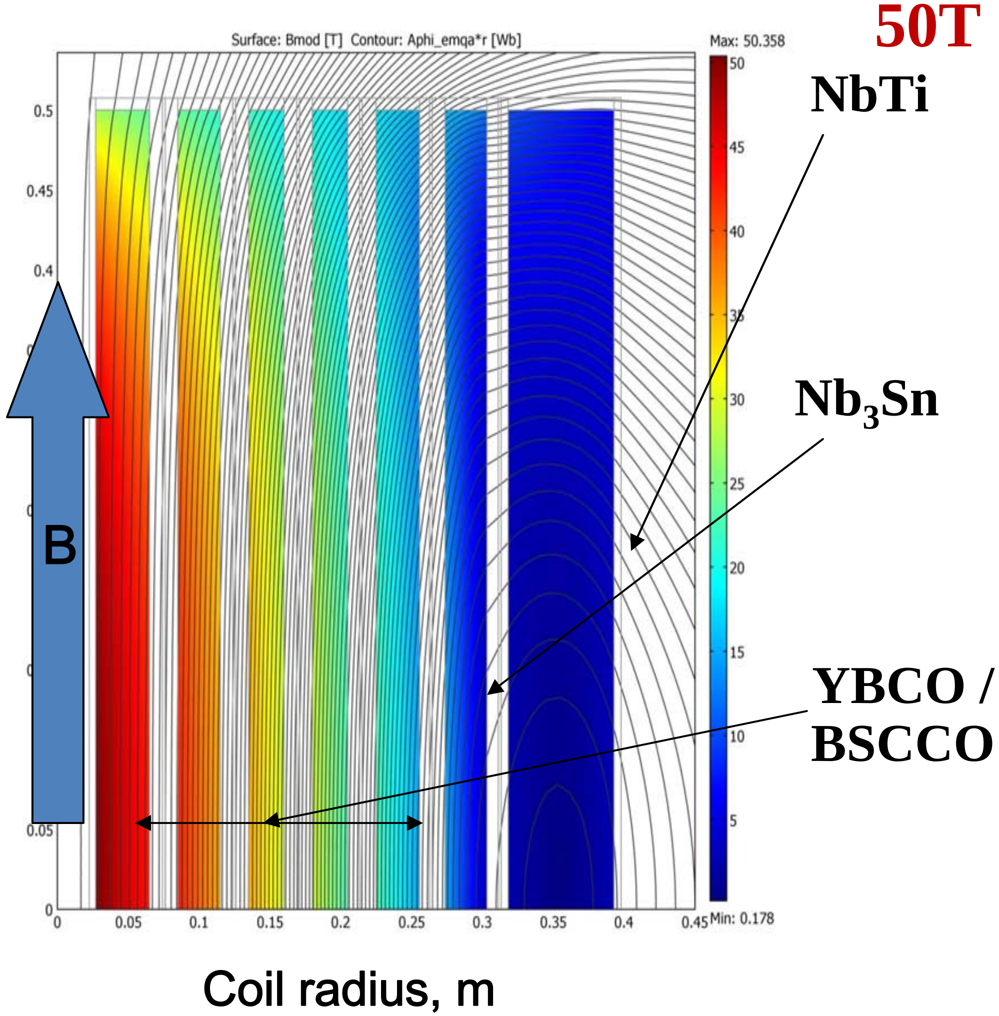
Key design issues

- Superconductor (HTS)
- J_c, effect of field direction (in case of HTS tapes)
- stress management
- quench protection
- cost

Conceptual design

- Hybrid coil design
- Coil sections

50T Solenoid Conceptual Design



Basic Parameters

- Inner bore diameter 50 mm
- Length 1 meter
- Fields 30 T or higher ➔ HTS materials

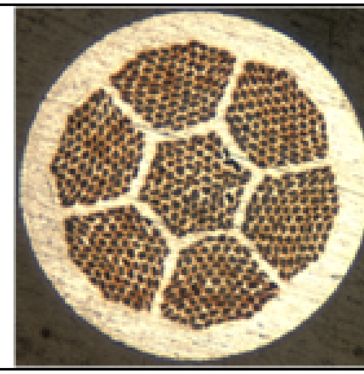
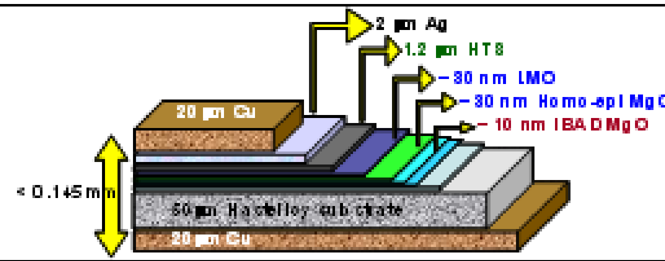
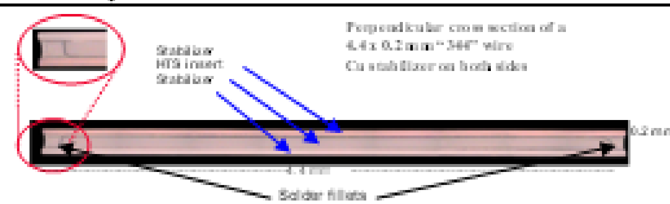
Key design issues:

- superconductor type
- J_c, effect of field direction (in the case of HTS tapes)
- stress management
- quench protection
- cost

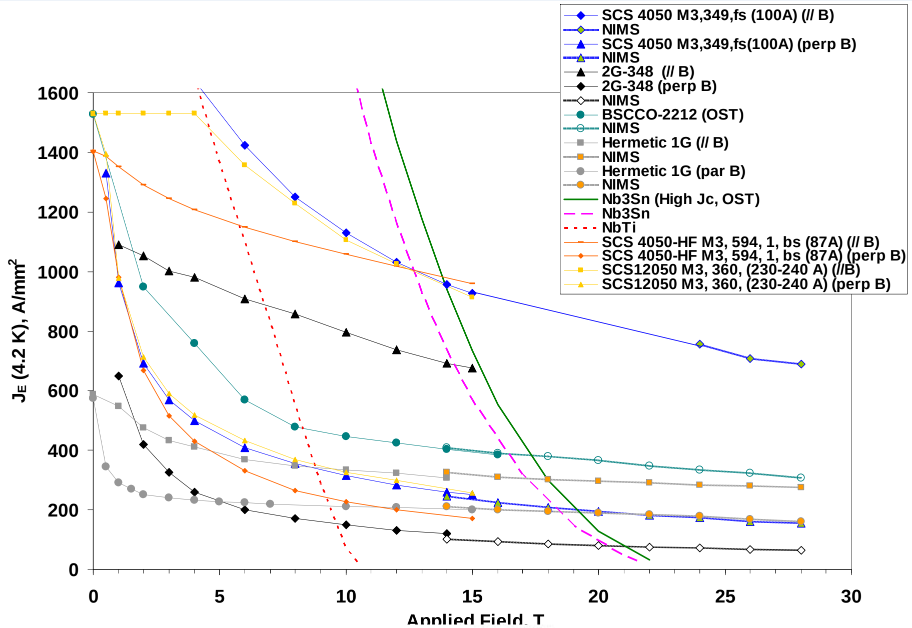
Conceptual design:

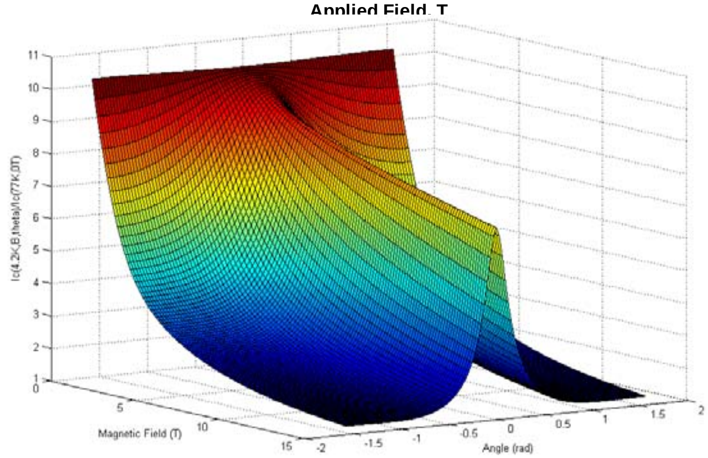
- hybrid coil design
- coil sections

Strand and Tape Examples

Superconductor	Conductor Type	Company	
BSCCO-2212	Round strand	Oxford SC Technologies	
BSCCO-2223	Hermetic tape	American Superconductor	
YBCO-123	SCS4050 tape	Super Power	
YBCO-123	2G-348 tape	American Superconductor	

HTS/HFS Conductor R&D



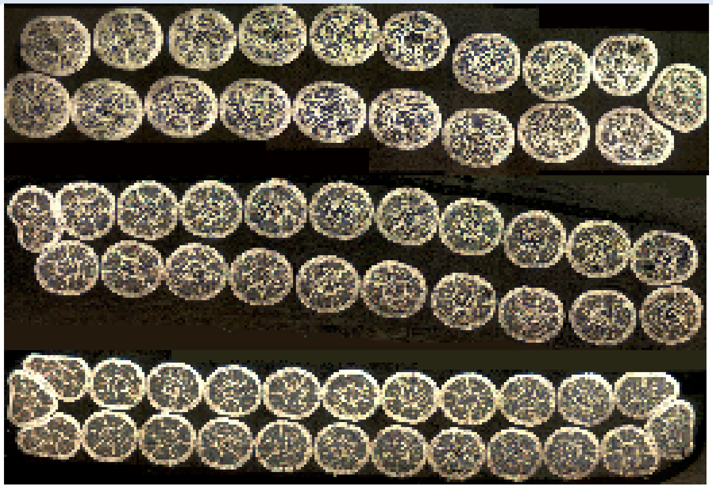


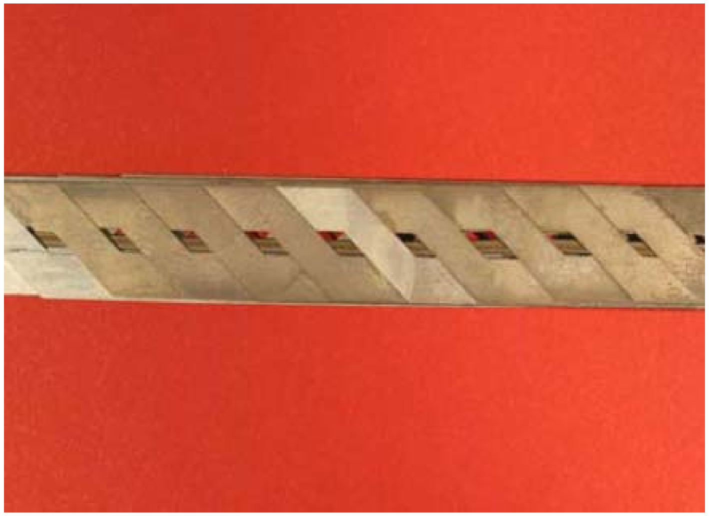
Monitoring industry progress to provide input to magnet design.

This includes studies of the engineering current density (J_e) as a function of:

- **magnetic field => up to 28 T (FNAL-NIMS)**
- **temperature => from superfluid He to LN**
- **field orientation (for tapes)**
- **bending strain**
- **longitudinal**
- **transverse pressure**

HTS cable R&D





G1 cable:

• In FY07-08 fabricated and tested several Rutherford cable designs based on Bi-2212 strand (OST)

cabling technology

effect of cable packing factor

• Starting from FY2009 continue this work as part of National HTS program

G2 cable:

•In FY09 started G2 Roebel cable studies

Insert Coil R&D

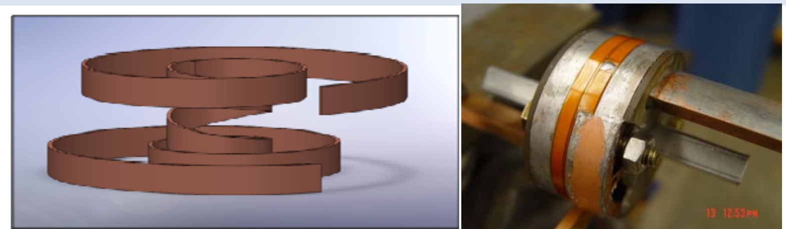
Present focus on single and double-layer pancake coils based on HTS tapes.

~20 single and double-layer pancake coils (YBCO and Bi-2223) were built and tested in self-field and external solenoid

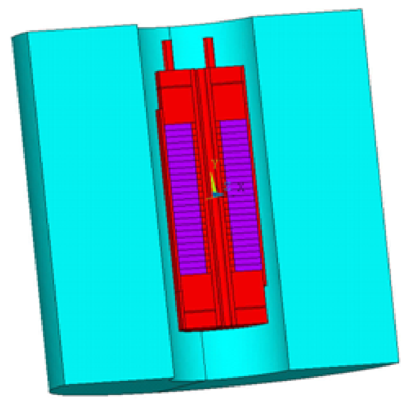
- ⇒ Study tape splicing techniques, effect of coil impregnation, coil preload

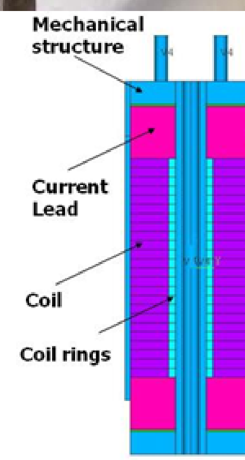
A modular HTS Insert Test Facility to test up to 14 double-layer pancake coils inside the 14 T/16 T solenoid (B>20 T)

For the second phase of the coil program, larger multi-section HTS coils will be designed, fabricated and tested to achieve higher magnetic field and force levels.



Final Design





Fermilab Test Facility for Conductor and Inserts

	Oxford Teslatron #1	Oxford Teslatron #2	Oxford Teslatron #3	Oxford Teslatron #4
Bz_max	15 T (4.2K) 17 T (2.2K)	14 T (4.2K) 16 T (2.2K)	Not equipped with solenoid for external field generation.	8.5 T (4.2K) 10 T (2.2K)
External Nb3Sn/NbTi Fully SC Magnet Geometry	Cold Bore: **68 mm** OD: 192 mm Height: 167 mm	Cold Bore: **77 mm** OD: 218 mm Height: 180 mm	Max Magnet OD: **253 mm** (accommodates <u>up to 4 DP helical units</u>)	Cold Bore: **147 mm** OD: 224 mm Height: 240 mm

2 kA power supply (5 kA on order), data acquisition for quench monitoring and cryogenic monitoring

SBIR R&D – BNL & PBL

- **YBCO HTS Solenoid at ~40 T - BNL, PBL (Particle Beam Lasers)**

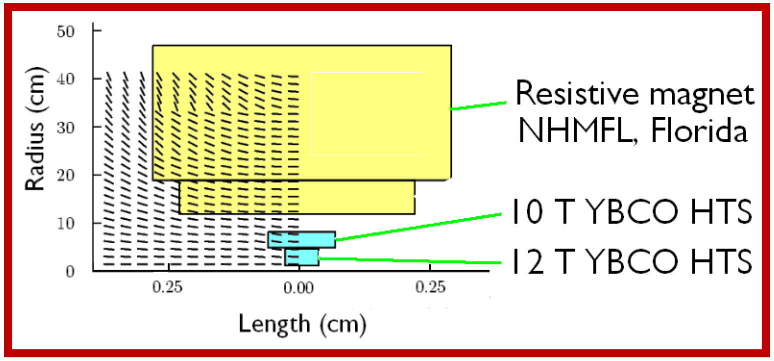
  [Information from talks by Bob Palmer (7/2010) at FNAL & Ramesh Gupta at ASC2010 (8/2010)]

- **Requirements for final cooling (from Bob Palmer talk)**

Number of magnets	≈20	More if field is lower
Lengths	≈1 m at start	≈10 cm at end
Beam sigmas	4 mm at start	0.7 mm at end
Min. magnet bore	2 cm at start	1 cm at end
Field Quality	very loose	very loose

The program

- **First Phase 2 SBIR**
  - **Build 10 T Solenoid 10 cm diameter bore**
  - **Chose to use YBCO to explore very high current densities – compact**
- **Second Phase 2 SBIR**
  - **Build 12 T YBCO Solenoid 2.5 cm diameter bore that fits inside #1**
  - **Test both solenoids in 19 T magnet at NHMFL**



SBIR R&D – BNL & PBL, cont.

- **They are winding, assembling, and testing coils**
  - **2G tape from SuperPower**
    - **Outer Solenoid**
      - **100 mm dia. Coils ("pancakes")**
      - **240 turns**
    - **Inner Solenoid**
      - **25 mm**
      - **260 turns**
- **Issues**
  - **At present, one splice per coil is allowed => cost/yield reasons**
  - **2G tape has excellent strain tolerance in transverse direction**
  - **Axial strain tolerance is less well known, and perhaps an order of magnitude worse**
  - **Other material properties need further investigation (thermal shock, low temp/high current performance, fatigue)**

SBIR R&D – BNL & PBL, cont.

- YBCO COILS AT BNL

Each coil has ~240 turns and uses 100 meter tape (maximum one splice)

Interaction between the SBIR HTS Solenoid and the MAP Program

No direct support of PBL/BNL 40 T Solenoid Program has been included in the proposed MAP budget. The PBL/BNL effort's narrow focus on a 40 T demonstration solenoid is complementary to the broader based approach taken by the MAP program. Technology developments in MAP will be available to, and could play a significant role in the PBL/BNL effort. A strong interchange of information, ideas, and expertise is expected, including topics such as quench detection and protection, studies of structural and conductor materials, and magnetic design.

40-50T Solenoid MAP Program

1) Conductor R&D (emphasis on FY10-FY13)

- Procure state of the art conductor (first 3 years)
  - YBCO (R&D topics)
    - high strength, improved J_c, doping to reduce angular dependence
  - Bi 2212 wire (R&D topics)
    - improve J_c, reaction cycle studies, improved strain tolerance
  - Nb_3Sn, Nb_3Al
    - As needed for outsert studies
- Test Program (first 4 years)
  - Jc function of external field, field orientation and temperature
  - Virgin strand
  - Cable/extracted strand (Rutherford and Roebel)

2) Coil Technology/Inserts

- **Conductor Choice**
  - **YBCO studies – conductor engineering/angular dependence (end effects in solenoids)**
  - **YBCO Roebel cable**
  - **BSSCO single wire & cable studies (use in end regions)**
- **Coil Studies**
  - **Test axial compression on insert coil**
  - **Develop ways to cause a local quench**
  - **Develop ways to observe these quenches**
  - **Test cyclical tension on tape**
  - **Test radial compression**

These tests need to be performed by FY13 to support the conceptual design

3) Demonstration Magnet (a FY 13 magnet milestone)

- Develop magnet insert to demonstrate state-of-the-art conductor and magnet fabrication technology. Target:
  - Maximum self field coil to fit into Fermilab 147 mm aperture 8T Teslatron
    - Estimated self field 20 T
  - Conductor parameters will be complementary to PBL insert
  - Possible design consideration
    - Graded coils with YBCO, Bi2212 to accommodate end field effects
    - Cable vs. strand to minimize inductance

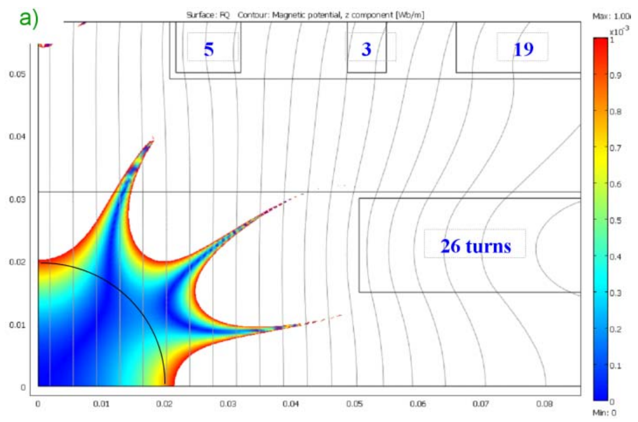
Strand, cable and insert program will continue through "high field solenoid" conceptual design phase which begins in FY13

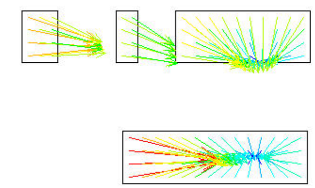
Collider Ring Magnets

- **The Collider Ring - in keeping with all other parts of μ collider - presents a challenge to the magnets (and detectors as well)**
  - **$\mu \rightarrow e\nu\bar{\nu}$ decays create a serious $e^{\pm}$ background**
- **Dipole requirements and operating conditions call for either an open mid-plane design approach with absorber placed outside the coil, or a large aperture design with absorber within the aperture**
  - **Nb_3Sn has the most appropriate combination of the critical parameters J_c, T_c, B_{c2} for this application**
- **Conceptual designs developed to evaluate different options to deal with competing requirements**
  - **Open midplane - both cosθ-like and 'block coil' designs considered**
  - **Cosθ design large aperture w/ absorber within aperture**
    - **LARP-like design**

Open Midplane Designs

- Good field region
- 2 double-pancake coils, a vertical split yoke, with a thick stainless steel outer skin with two alignment keys and two control spacers

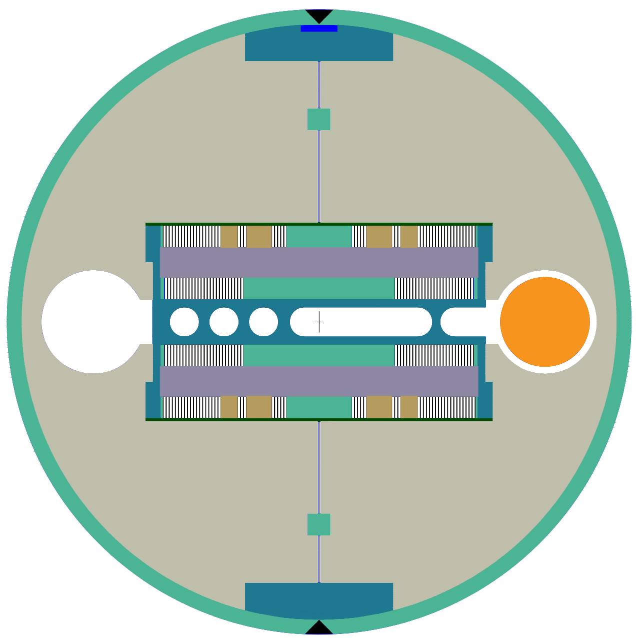




Fx=3796 kN/m

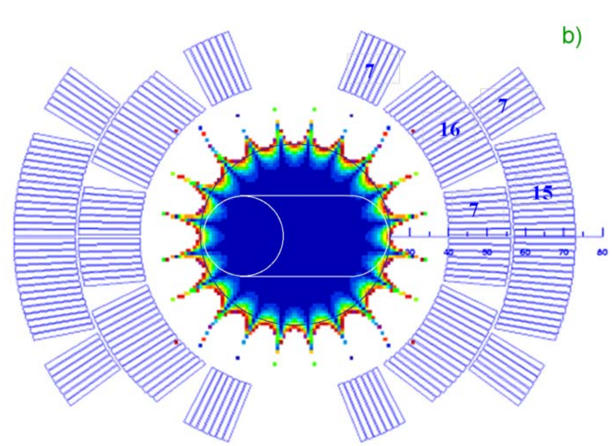
Fy=-1694 kN/m

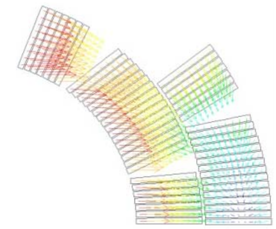
Similar work is being carried out at BNL



Large Aperture Shell-type Structure Dipole

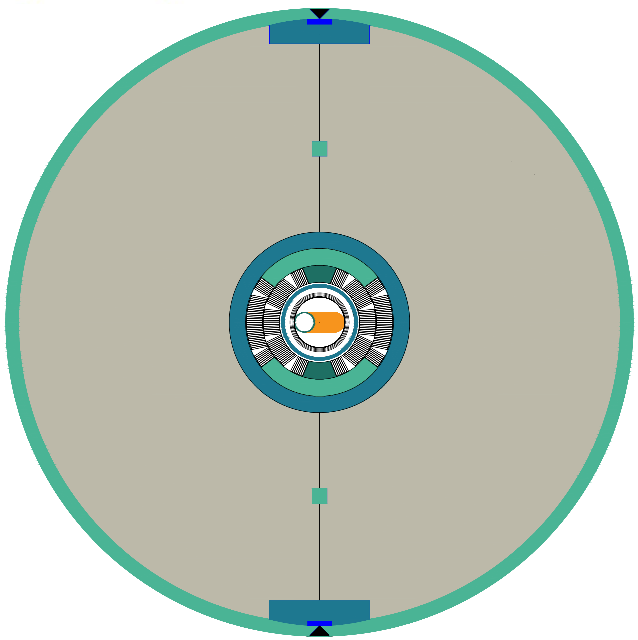
- Note beam shifted pipe and internal absorber is in the uniform field area
- The collars are thin stainless steel
- Support structure similar to that used in Fermilab’s high field 90 mm Nb_3Sn quadrupole models





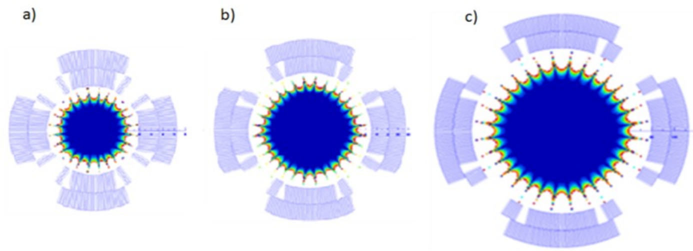
Fx=3033kN/m

Fy=-1498kN/m

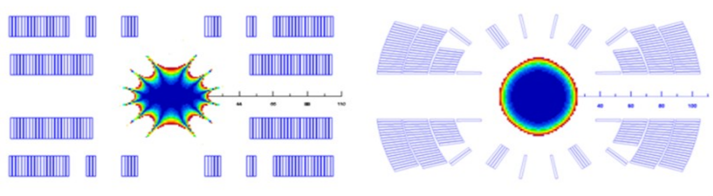


From paper 5LPM03 – ASC2010, A. Zlobin, FNAL

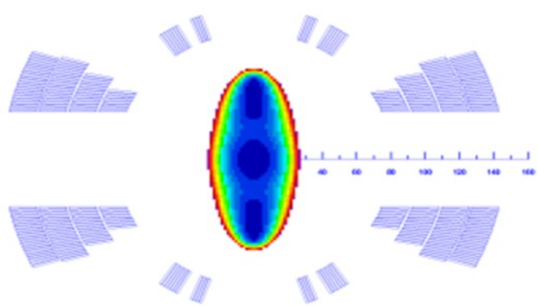
Collider Ring Dipoles & Quadrupoles



Q1 (a), Q2 (b), Q3-Q5 (c) cross-sections.



MC Storage Ring dipole based on 4-layer block-type coil (left) or 4-layer shell-type coil (right).



IR dipole cross-section.

Table 6: IR Quadrupole Parameters.

Parameter	Q1	Q2	Q3-Q5
Aperture (mm)	80	110	160
B_{max} coil at 4.5 K (T)	12.76	13.19	13.49
G_{max} apert at 4.5 K (T/m)	281.5	209.0	146.0
G_{op} (T/m)	250	187	130
Inductance at G_{op} (mH/m)	3.57	6.58	12.88
Stored energy at G_{op} (kJ/m)	493.0	771.3	1391.8
F_x at G_{op} (kN/m)	1790	2225	2790
F_y at G_{op} (kN/m)	-2180	-2713	-3380

Table 4: Storage Ring Dipole Parameters.

Parameter	Block design	Shell design
B_{max} coil at 4.5K (T)	13.37	13.13
B_{max} at 4.5 K (T)	11.24	11.24
B_{op} (T)	10.0	10.0
Inductance at B_{op} (mH/m)	6.72	9.52
Stored energy at B_{op} (kJ/m)	1280	1100
F_x at B_{op} (kN/m)	4084	3990
F_y at B_{op} (kN/m)	-2216	-1870

Table 8: IR Dipole Parameters.

Parameter	Value
Aperture (mm)	160
B_{max} in coil at 4.5 K (T)	13.03
B_{max} in aperture at 4.5 K (T)	9.82
B_{op} (T)	8.0
Inductance at B_{op} (mH/m)	15.89
Stored energy at B_{op} (kJ/m)	1558
F_x at B_{op} (kN/m)	3960
F_y at B_{op} (kN/m)	-1650

MOPEB053 Proceedings of IPAC’10, Kyoto, Japan

Collider Ring Magnets Design Status

- **Several design options studied for Collider Ring magnets to avoid mid-plane electron flux**
  - **Block design with open mid-plane**
  - **Shell (cosθ related) design with open mid-plane**
- **Open mid-plane designs present structural as well as field quality ‘challenges’**
- **A large aperture, cos(θ) approach, with a support structure similar to Fermilab’s 90 mm Nb_3Sn quadrupole models, allows**
  - **Acceptable good field region for beam pipe off-center in the aperture**
  - **Room for internal absorber**
  - **Management of forces on the coil structure**

Collider Ring Magnets MAP Program

- **Ongoing design studies for Collider Ring magnets in close collaboration with Collider Ring design group**
  - **Magnets will be based on Nb_3Sn conductor – (ongoing)**
    - **Significant investment in conductor development – DOE CDP and LARP**
  - **Magnet R&D is beneficially coupled to the LARP magnet program – (ongoing)**
    - **Similar apertures and field gradients**
    - **Thermal studies**
  - **More realistic magnet designs as Collider parameters mature (years 3-4)**

Summary

- **Critical path for the Muon Collider is through magnets**
- **Conceptual solutions exist 'on paper' for magnets varieties in HTS and Nb_3Sn**
  - **Aggressive designs**
  - **Based on advanced HTS conductors**
  - **Some are quite advanced**
- **R&D has begun on several key magnet designs**
  - **Early HCC prototype work**
  - **YBCO coil fabrication for final cooling section solenoid study**
  - **All appear plausible at this time**
- **Magnet R&D depends on Conductor R&D**
  - **Dependent on HTS materials**
    - **Fundamental properties – J_c (H,T)**
    - **Strain sensitivity**
    - **Uniformity**
  - **Piece length, $, etc.**
- **R&D still at an early stage for high field magnets**
  - **Coils, model magnets, R&D (pre-)prototypes, … needed**

Acknowledgements

The ongoing design effort for Muon Collider magnets has a large list of contributors. I had help from many people - they include:

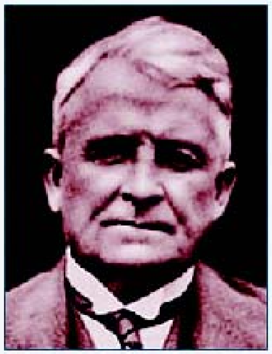
Emanuela Barzi	Arup Ghosh	Arno Godeke
Ramesh Gupta	Rolland Johnson	Steve Kahn
Vadim Kashikhin	Vladimir Kashikhin	Mike Lamm
David Larbalestier	Mau Lopes	Ken Marken
Igor Novitski	Bob Palmer	Alvin Tollestrup
Miao Yu	Sasha Zlobin	

the members of VHFSMC, and many others…

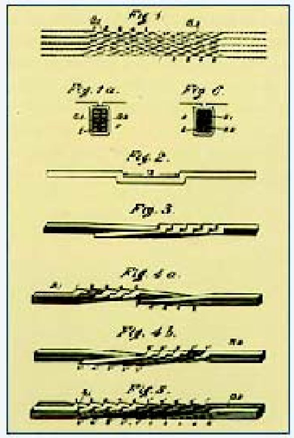
Origin of Roebel Cable

The ROEBEL bar concept for cabling

Karlsruhe Institute of Technology



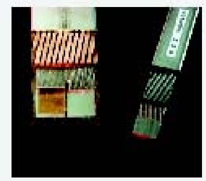
Ludwig Roebel, born at Kusel May 6th, 1878.

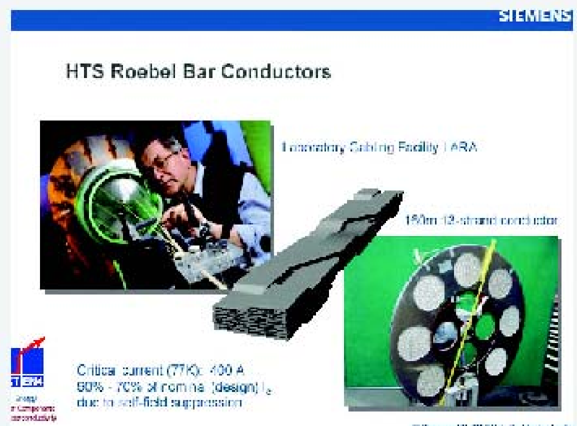


The ROEBEL bar, an assembling method for low AC loss cables

Patent (1912) of Ludwig Roebel BBC (STOTZ) Mannheim for low loss generator Cu-Cables in power generators

Invented for generator Cu-cables, already applied for NbTi-LCT coils, NET, BSCCO-cable (SIEMENS)





12 23.06.2010 Dr. Sonja Schlachter – "HTS Roebel and Rutherford Cables for High-Current Applications" 5. Braunschweiger Supraleiterseminar, 23.-24. Juni 2010 Institute for Technical Physics