Superconducting Accelerator Magnets - a key to high-energy high-luminosity colliding beams

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Fermilab

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Outline

- Electromagnet in accelerators
- Why superconducting magnets?
- SC magnet possibilities and limitations
- Why do we need higher fields in accelerators and how to generate high fields?
- SC material options for HF magnets
- Nb-Ti magnets
- Nb_3Sn magnets
- Example of HFM design, fabrication and test
  - 11 T dipole for LHC upgrade or VLHC
- HTS/LTS hybrid magnets
- Summary

Magnetic fields in accelerators

- **Magnetic field is the most efficient way to affect charged particle beam in accelerators**
- **The force acting on a charged particle**

$$\vec{F} = q[\vec{v} \times \vec{B}]$$

- **Important field configurations**
  - **Dipole – B=const – beam bending**
  - **Quadrupole – B~r – beam focusing**
  - **Sextupole – B~r² – cromaticity correction**
  - **…**
  - **Solenoids**

Accelerator Electromagnets

- Magnetic fields are generated by electrical currents (Bio-Savart law)

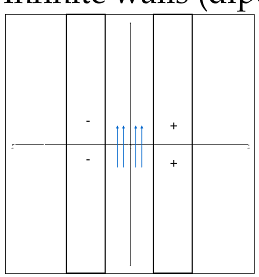
$$B(z) = \frac{I\mu_0}{2\pi(z - z_0)}.$$

- Magnetic field could be represented as combination of multipoles

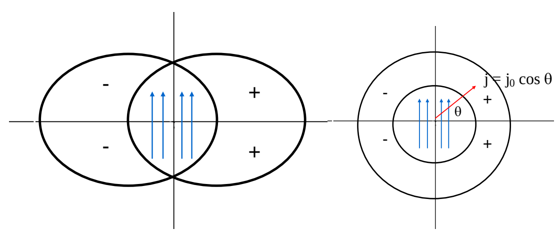
$$B(z) = \sum_{n=1}^{\infty} C_n \left(\frac{z}{R_{ref}}\right)^{n-1} = \sum_{n=1}^{\infty} (B_n + iA_n)\left(\frac{z}{R_{ref}}\right)^{n-1}$$

- Good field quality ~10^{-4} in aperture is achieved by block size and position optimization

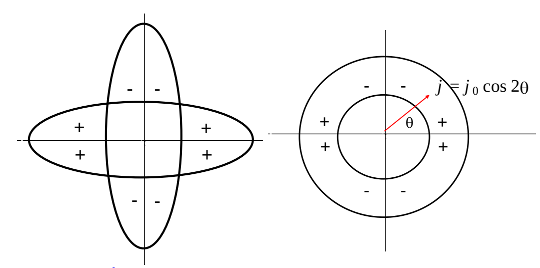
Infinite walls (dipole)



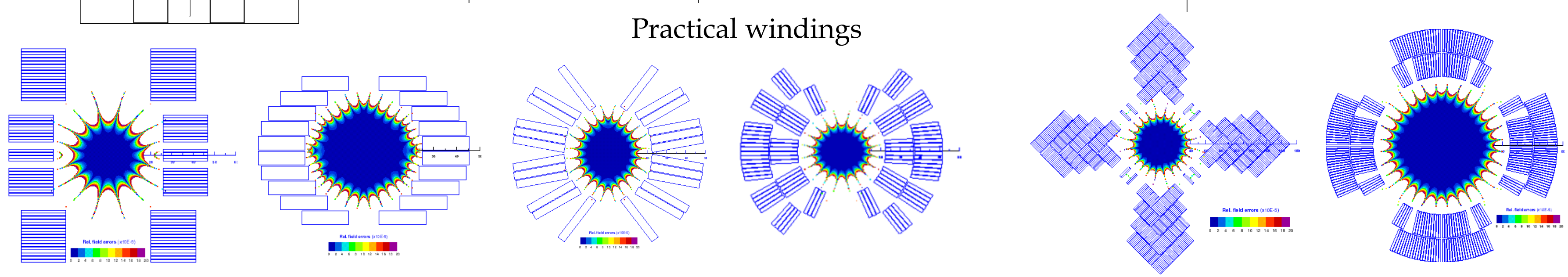
Intersecting ellipses and cos (dipole)



Intersecting ellipses and Cos2θ (quadrupole)



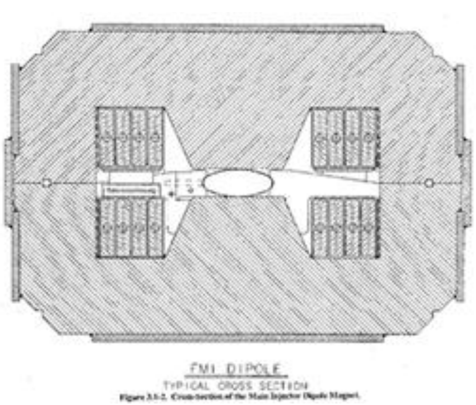
Practical windings



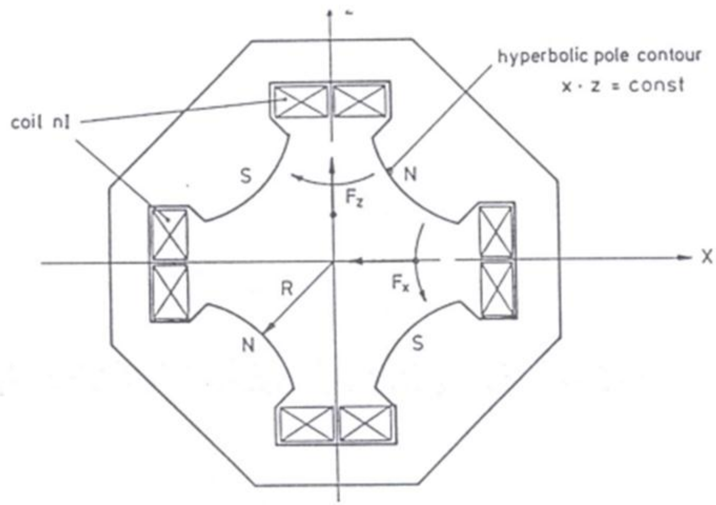
Iron dominated electromagnets

- **Magnetic field produced by current**
- **Field quality formed by iron pole shape**
- **Field quality limit B_{max} ~ 2 T (iron saturation)**
- **Joule heating => coil cooling**

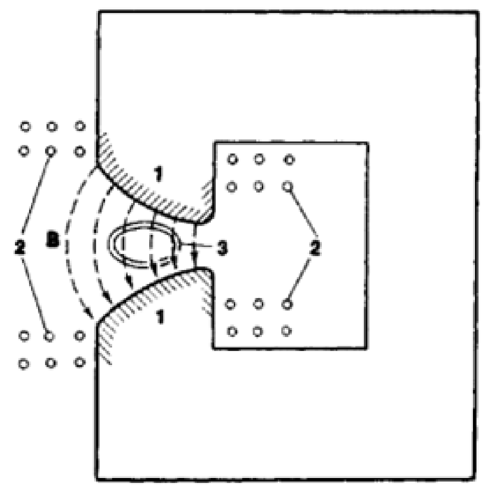
Dipole



Quadrupole



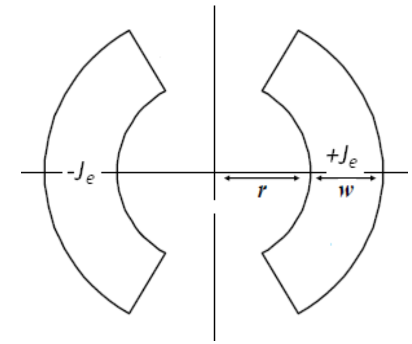
Combined function (D+Q)



Accelerator dipoles and quadrupoles

❖ Dipole configuration (60° coil)

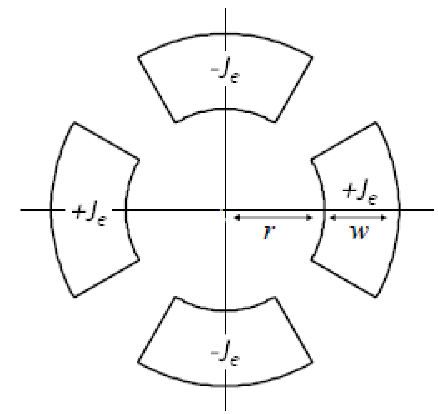
$$B_D = -\frac{\sqrt{3}\mu_0}{\pi} J_e w \qquad B_3 = 0, B_{2k} \circ 0, k = 1, 2, \ldots$$



❖ Quadrupole configuration (30° coil)

$$G_Q = -\frac{\sqrt{3}\mu_0}{\pi} J_e \ln(1 + \frac{w}{r}) \qquad B_6 = 0, B_{2k+1} \circ 0, k = 0, 1, 2, \ldots$$

$$G_Q \approx -\frac{\sqrt{3}\mu_0}{\pi} J_e w/r \;\; for \;\; w/r \ll 1$$

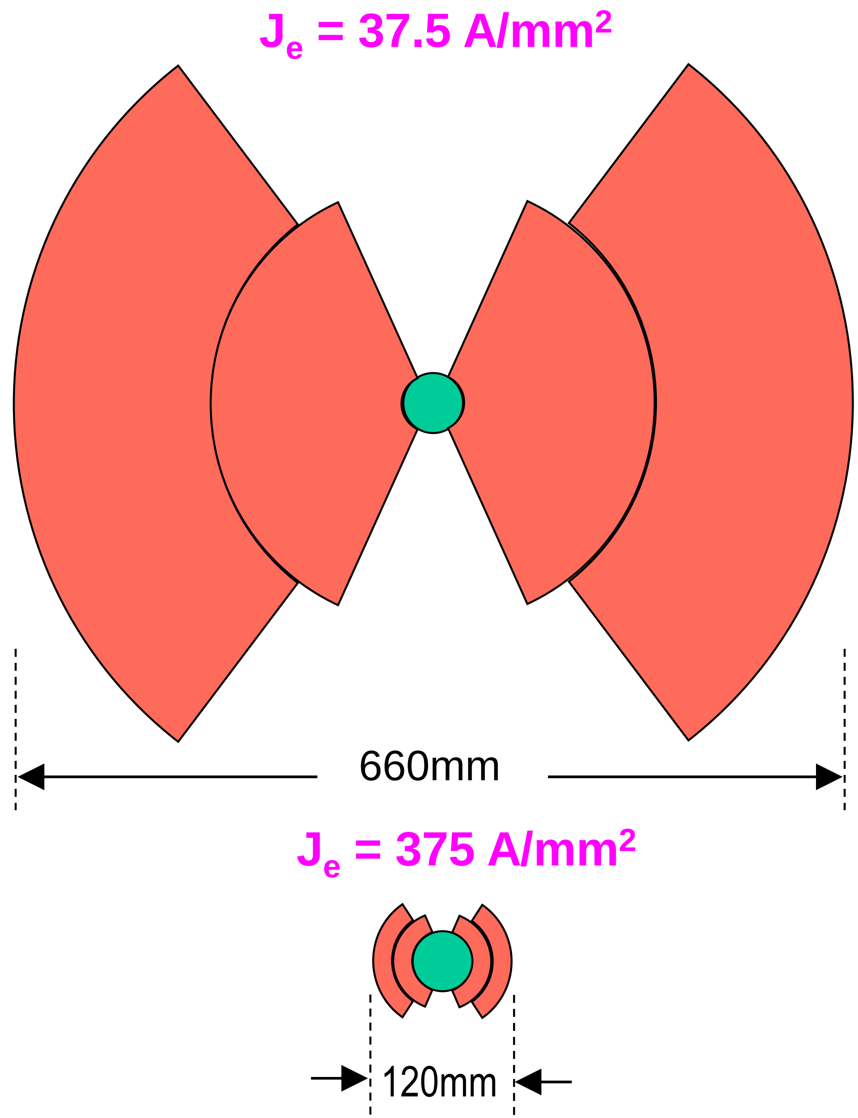


B_D and G_Q are proportional to coil width w and current density J_e

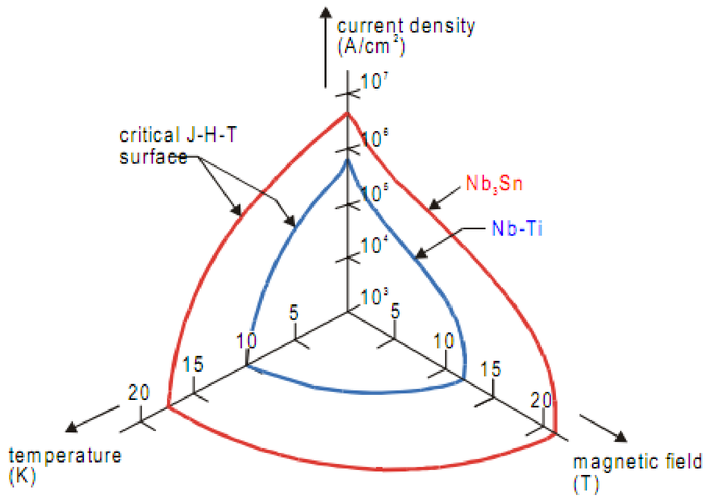
Importance of current density Je

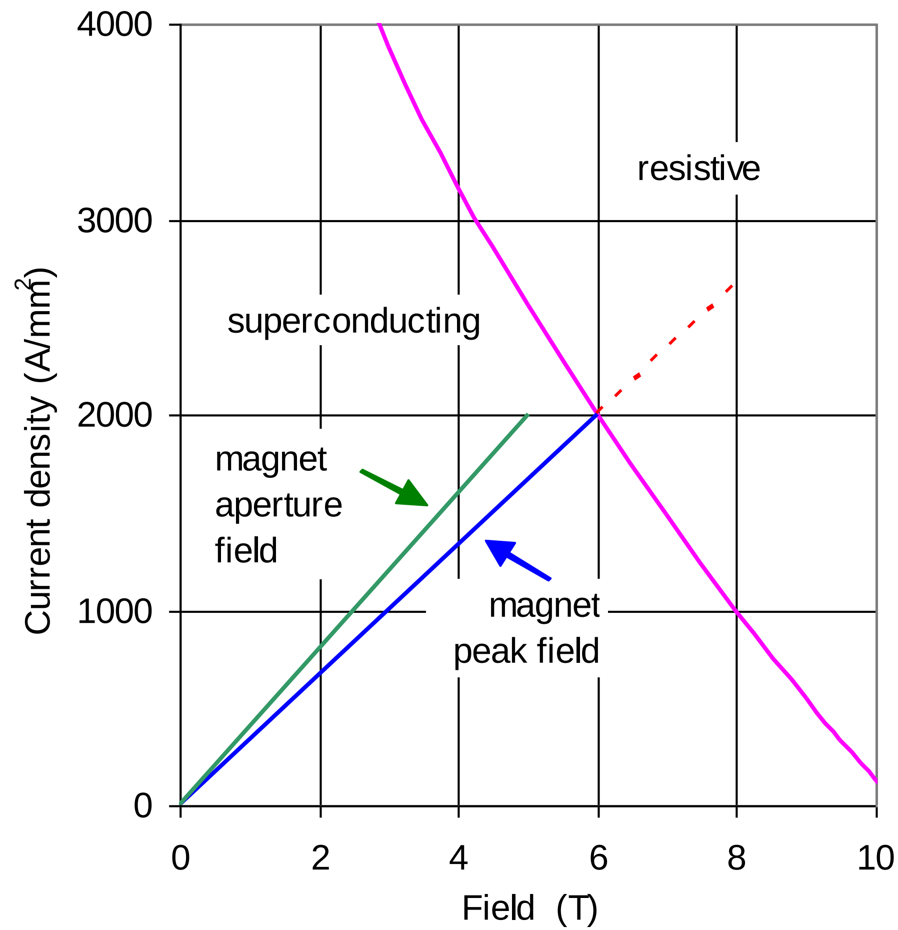
$$B_D = -\frac{\sqrt{3}\mu_0}{\pi} J_e w$$

- **Coil J_e is a key parameter.**
- **Resistive magnets with water cooled Cu or Al cable**
  - **J_e ~5-50 A/mm^2**
- **Superconducting magnets**
  - **J_e ~500-1000 A/mm^2**
- **SC magnets are more compact and have lower operational costs (only power consumption is to keep them cold)**
- **The highest fields in accelerator magnets was achieved using SC magnets.**



J_e and B limit for SC magnets





- **Superconductivity exists inside the critical surface in (J,B,T) space.**
- **Critical surface depend on superconductor chemical composition**
- **J_e (and B) in SC magnets is limited by the J_c(B) in superconductor at given operation temperature.**

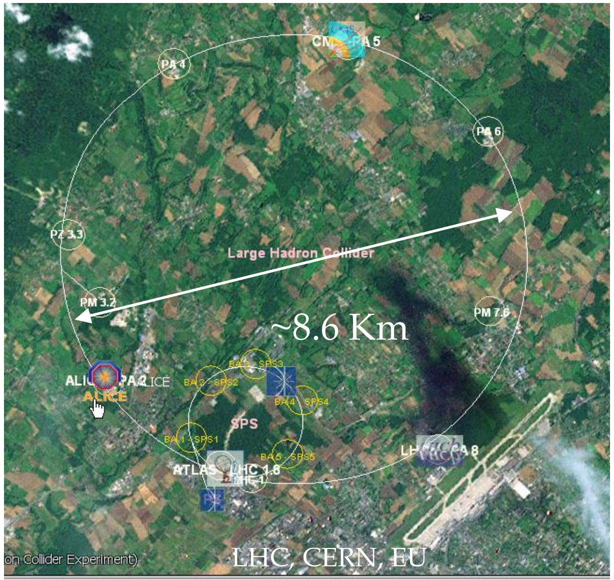
Why do we need higher field magnets?

- **For a fixed size of a circular collider, its energy is limited by the strength of bending dipole magnets.**

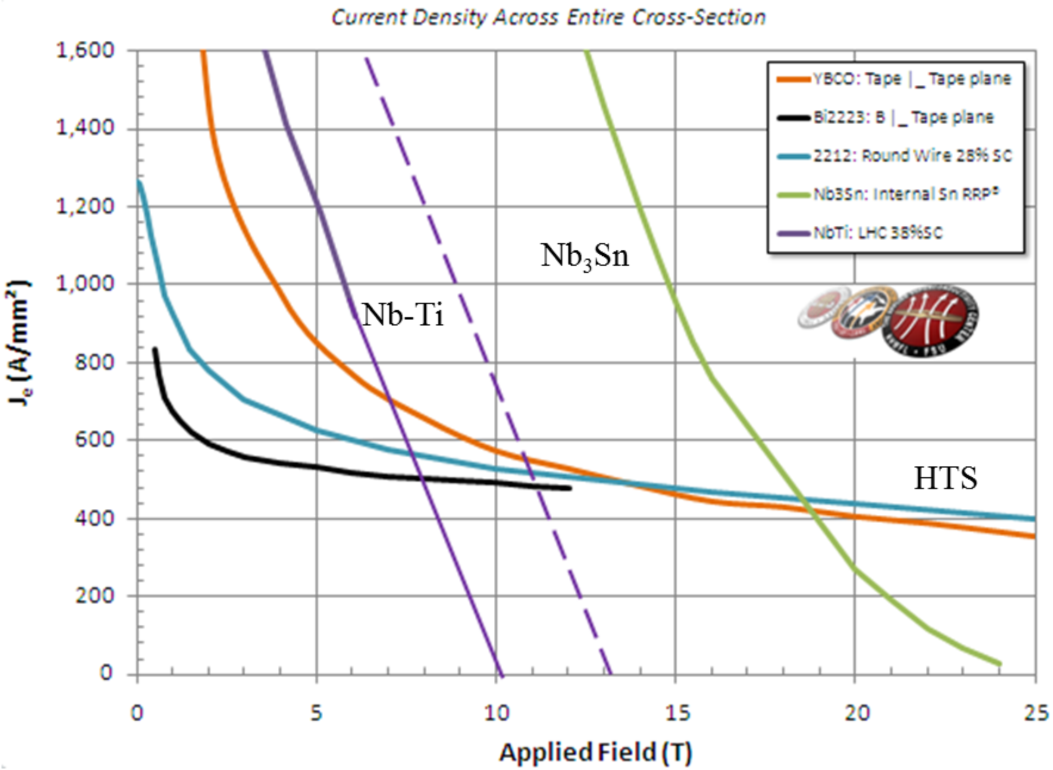
$$E[GeV] = 0.3RB\ [m \cdot T]$$

  - **Tevatron: E~1 TeV, B~4 T, D~2 km**
  - **LHC: E~7 TeV, B~8 T, D~9 km**

- **For both linear and circular machines, their maximum luminosity is determined (among other factors) by the strength of quadrupole magnets used for the final beam focusing.**



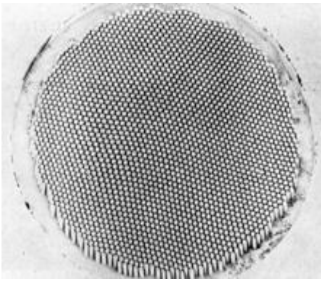
What SC materials are available?

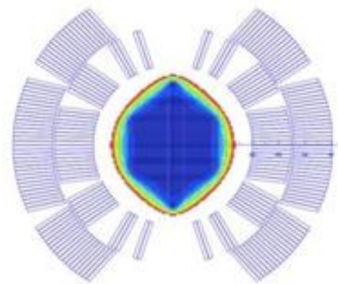


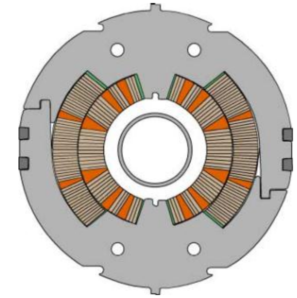
Courtesy P. Lee,

- **There are many superconductors (>100), not all of them are practical**
- **Practical superconductors**
  - **Nb-Ti – $B_{c2}(0)$~14 T, $T_c(0)$~9 K => 10 T magnets**
  - **Nb_3Sn – $B_{c2}(0)$~27 T, $T_c(0)$~18 K => 16-17 T magnets**
  - **BSCCO/YBCO – $B_{c2}(4.2\ K)$>50 T, $T_c(0)$~110/90 K => 15+ T magnets**
- **These materials are produced by industry in long length (~1 km)**

Nb-Ti Accelerator Magnet R&D







Key design elements

- Multifilament Cu-stabilized strand => high-Jc, stable, low magnetization
- Rutherford cable => high packing factor (~95%), low degradation (<5%)
- Cos-theta coils => accelerator field quality
- Collar-based mechanical structure => precision geometry, coil prestress and support
- Internal quench protection heaters => quench temperature and voltage limit

Magnet performance (R&D models in 1960-70's)

- Quench performance => operation margins
- Field quality => operation field range
- Reproducibility

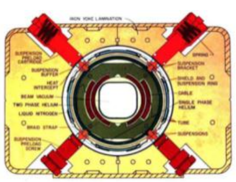
Technology scale up to 6+ m long units in 1970-80's

All that in less than 15 years!!!

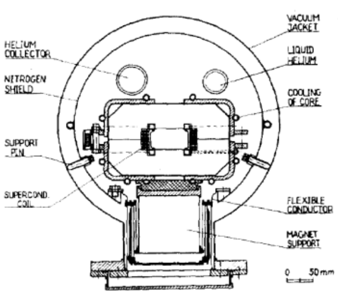
Nb-Ti Magnets in Accelerators

- **SC magnets need cryostat to keep them cold**
- **Large production experience**
  - o **Laboratory production (Tevatron, Nuklotron)**
  - o **Industrial production (HERA, RHIC, LHC)**
- **Reliable long-term operation in real machines**

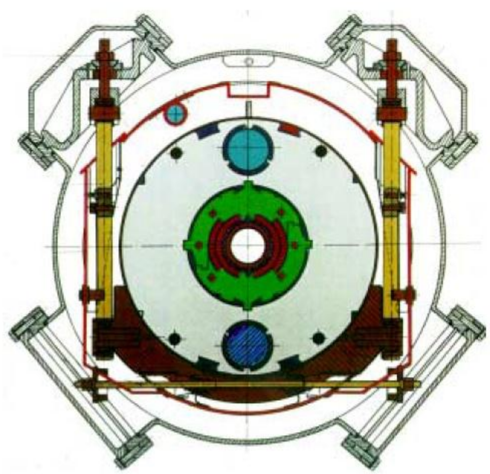
Tevatron,
B=4.5 T
6 m, 76 mm



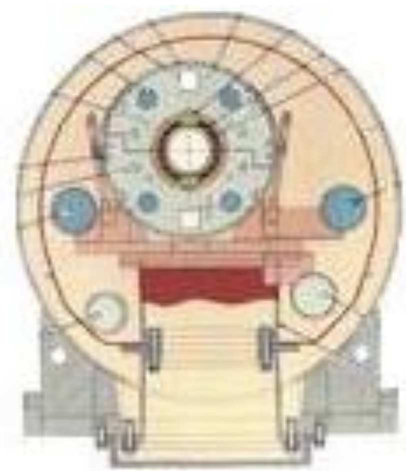
Nuklotron,
B=2 T
1.5 m, 90x42 mm^2



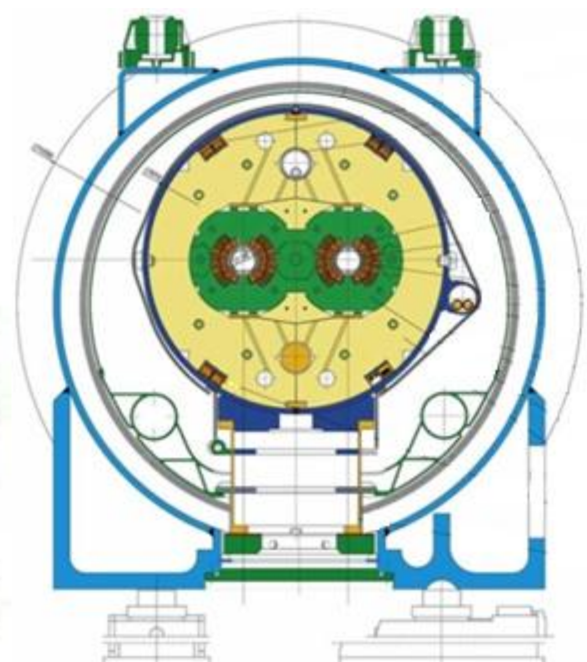
HERA,
B=4.7 T
9 m, 75 mm



RHIC,
B=3.5 T
9 m, 80 mm

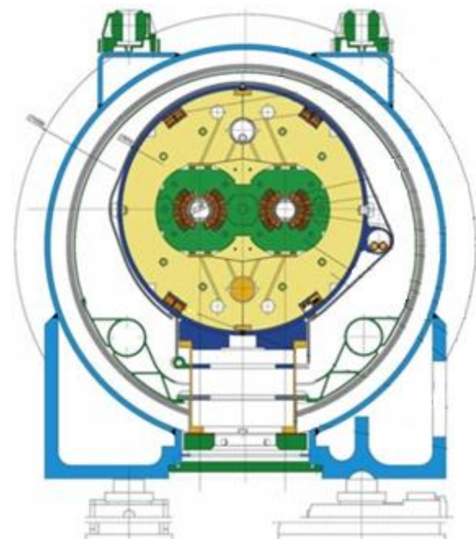


LHC,
B=8.3 T
15 m, 56 mm

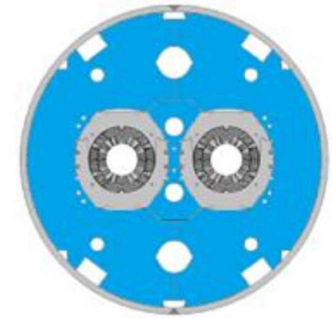


High field magnet R&D

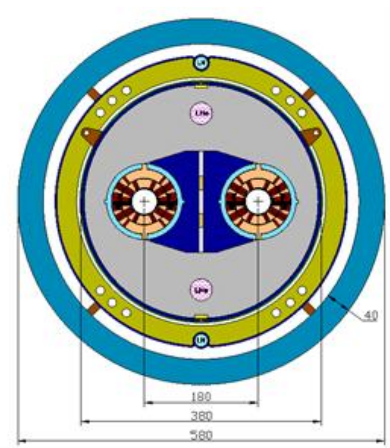
- LHC has pushed Nb-Ti to its limits
  - Nb-Ti magnet record field B_{max}=10.5 T at 1.9 K
- R&D directions
  - Improve performance
  - Reduce cross-section
  - Increase magnet length



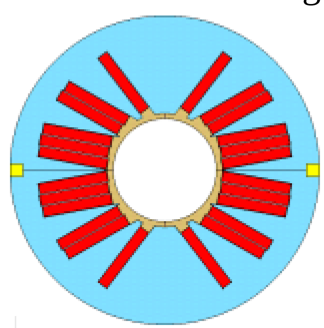
Higher field and operation temperature



Warm yoke design

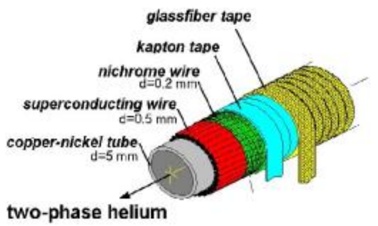


Low inductance design



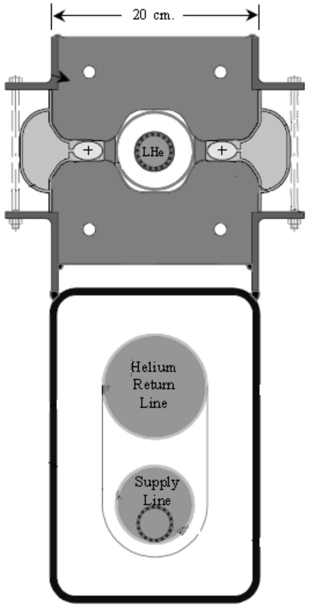
Low field SC magnet R&D

Superferric magnet based on hollow superconductor

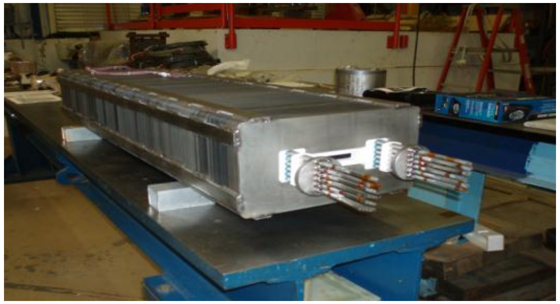


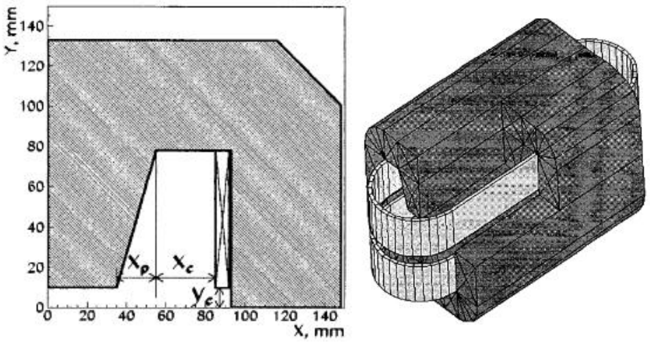
- ❖ **Field level and quality provided by iron yoke**
- ❖ **R&D directions**
  - o **Reduce size, cost and increase length**
  - o **Increase operation temperature, reduce cost**
  - o **Rapid cycling magnets**

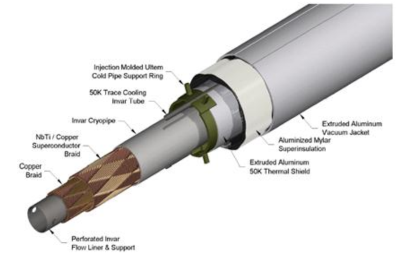
Transmission line combined function magnet based on SC transmission line cable



Superferric magnets based on HTS superconductor



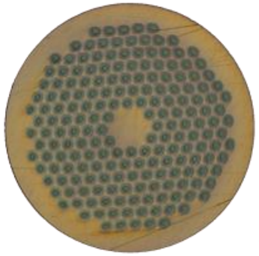


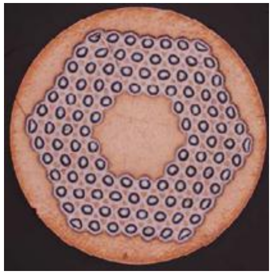


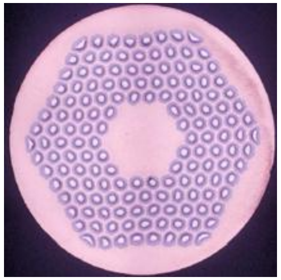
Nb_3Sn Magnet R&D

- Nb_3Sn magnet R&D started simultaneously with Nb-Ti magnets (1960s) adopting the key design solutions, used in Nb-Ti magnets, to specifics of Nb_3Sn superconductor and higher field level:
  - High-J_c Cu-stabilized round strand (several technologies)
    - complicate Heat Treatment to form the Nb_3Sn phase and obtain optimal microstructure for high J_c
    - brittle, strain sensitive after reaction
    - Large d_{eff}, flux jump instabilities, large magnetization
  - Rutherford-type cable fabrication before reaction
    - Low packing factor (85-87%) to avoid strand damage
    - Sensitive to transverse pressure σ_{max}<150-200 MPa
  - Coil with small bending radii
    - Wind-&-react approach
    - Component compatibility with high-T heat treatment
    - Coil expansion during reaction
    - Brittle coil delicate handling
  - Large Lorentz forces – mechanics
  - Large stored energy - protection

Powder-in-tube

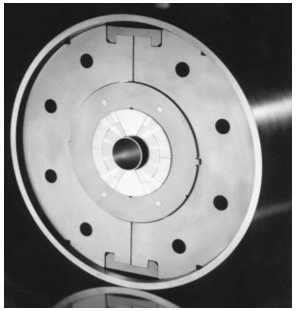




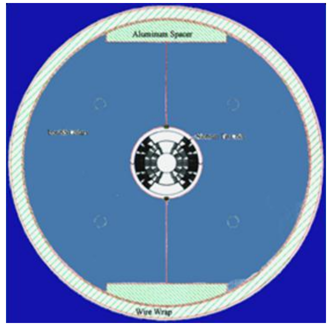


Internal-Tin

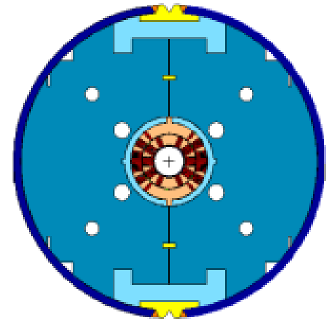
Nb_3Sn Dipole Short Models



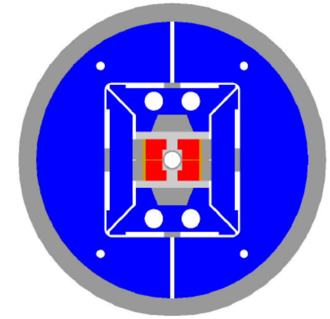
MSUT (UT), 1995
50-mm, W&R
B_{max}=11.5 T @4.3 K



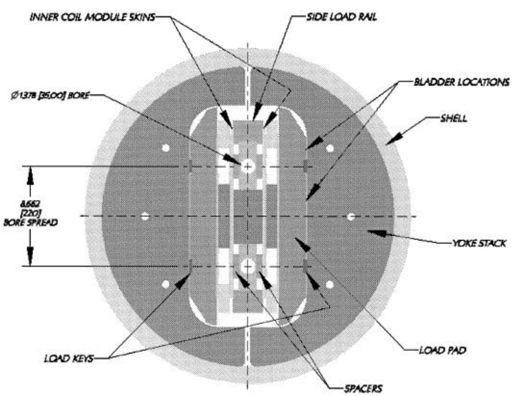
D20 (LBNL), 1997
50-mm, W&R
B_{max}=13.35 T @1.9 K



HFDA05-07 (FNAL), 2004-2006
43-mm, W&R
B_{max}=10.2 T @1.9 K

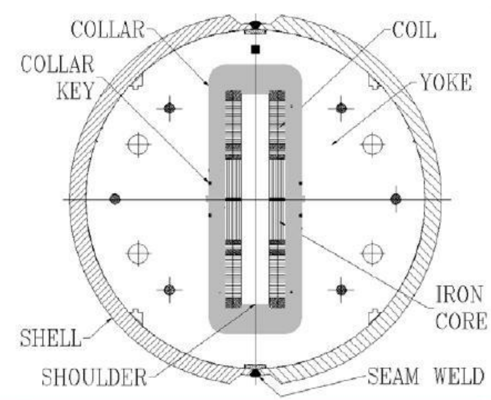


HD2 (LBNL), 2008
36-mm, W&R
B_{max}=13.8 T @4.3 K



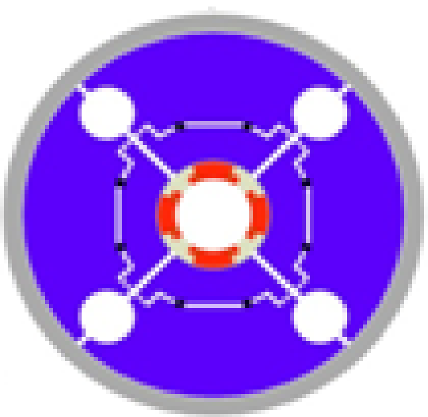
RD3c (LBNL), 2003
35-mm, W&R
B_{max}=10.0 T @4.3 K

- W&R and R&W approach
- Different mechanical structures
- 1967-1995 to reach B>10 T
- Record field 13.8 T (HD2)
- Good quench performance
- Accelerator field quality
- Reliable quench protection
- Reproducibility

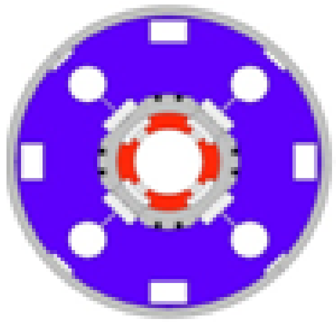


DCC017 (BNL), 2006
31-mm, R&W
B_{max}=10.2 T @4.3 K

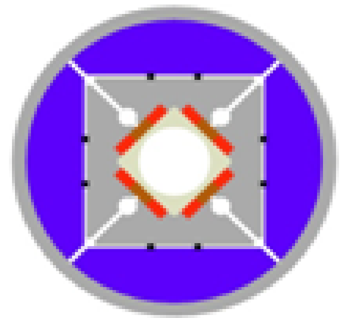
Nb3Sn quadrupole models



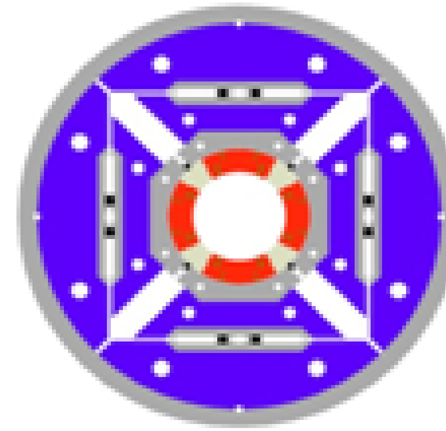
TQS, 90-mm



TQC, 90-mm



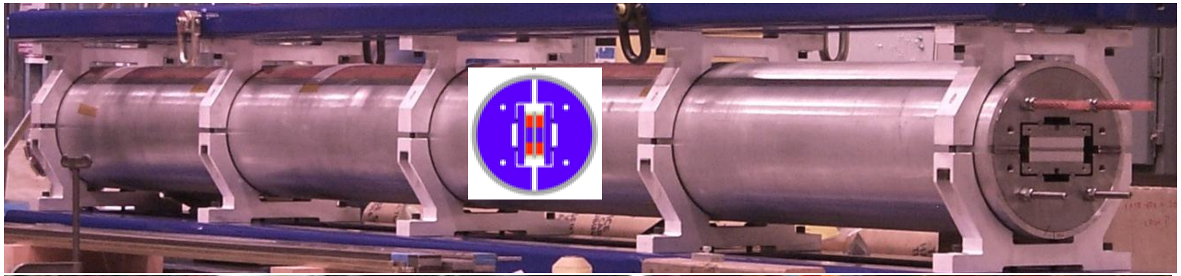
SQ, 110-mm



HQ, 120-mm

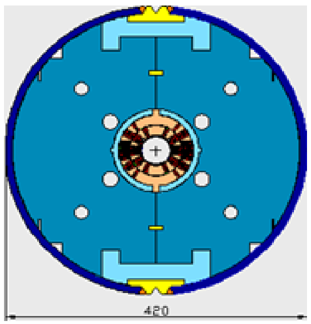
- **US-LARP Quadrupole models - 2005-2013**
- **W&R approach**
- **Large aperture – 90-120 mm**
- **B_{max}~11-13 T**
- **Two mechanical structures**
  - **Collar-SS skin**
  - **Aluminum shell**

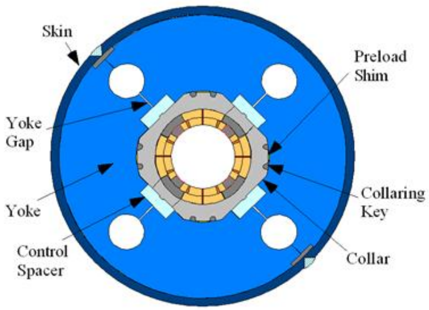
Nb_3Sn Technology Scale Up

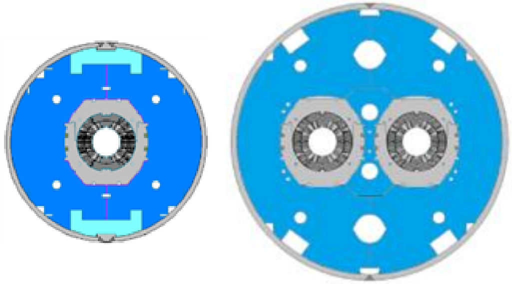


4-m long Racetrack, D and Q mirror configurations; 90-mm quadrupoles

FNAL Experience in Nb_3Sn Magnet R&D







❖ 2002-2006 – VLHC

- 6 43-mm dipoles and 6 dipole mirrors
- first in the world series of nearly identical 10 T Nb_3Sn magnets
- first data on quench performance and field quality reproducibility

❖ 2007-2010 – LHC upgrade

- 7 90-mm quadrupoles and 6 quadrupole mirrors
- collar based mechanical structure
- G_{nom}=200 T/m, accelerator quality

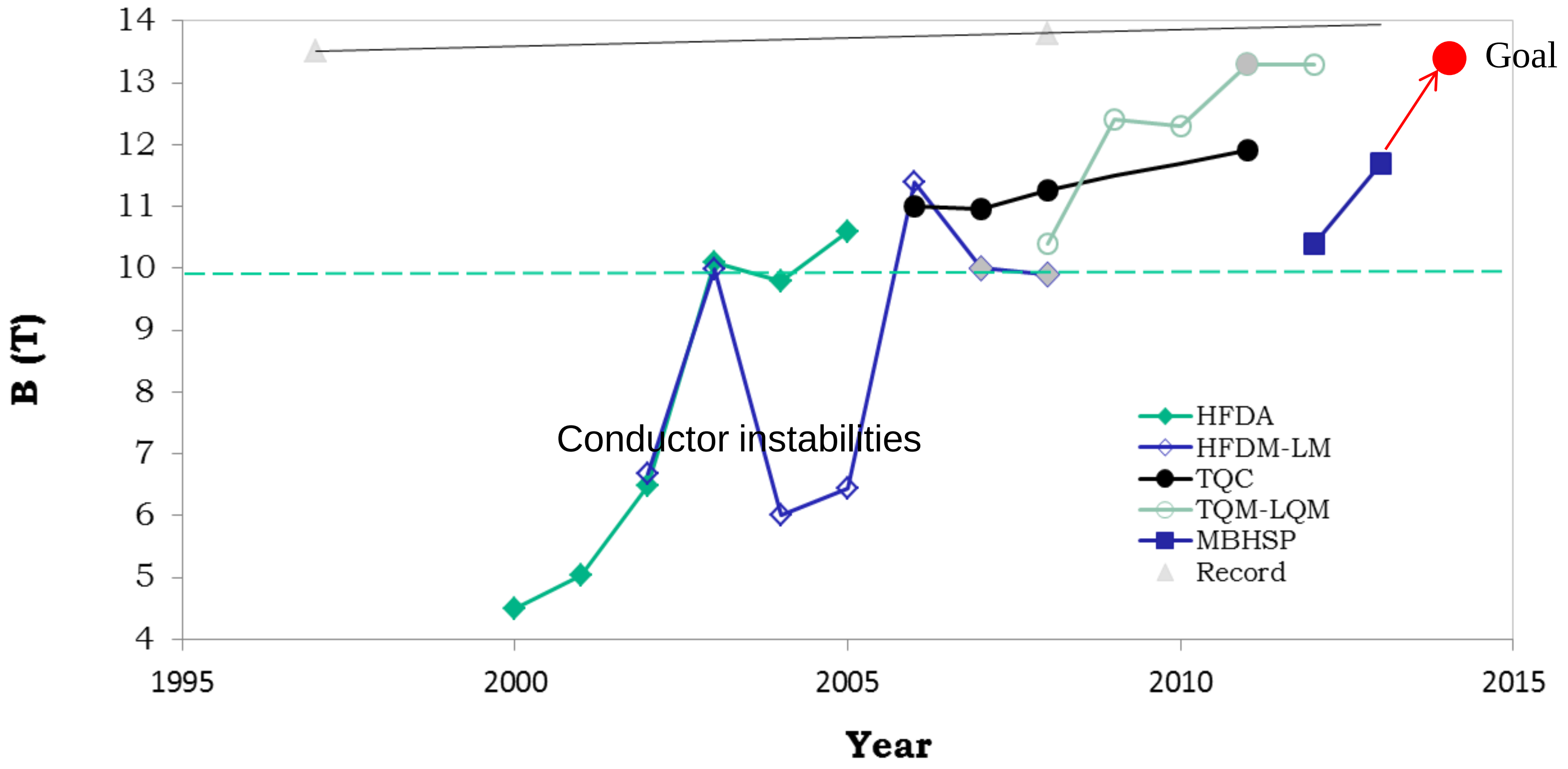
❖ 2007-2011 – technology scale up using mirror structure

- 2 and 4 m long dipole coils
- 4-m long quadrupole coil - the first Nb_3Sn long coil reached SSL

❖ 2011-2015 – 11 T dipole

- first 2-in-1 Nb_3Sn design compatible with LHC
- B_{max}=11.7 T (2013)

B_{max} Progress at Fermilab

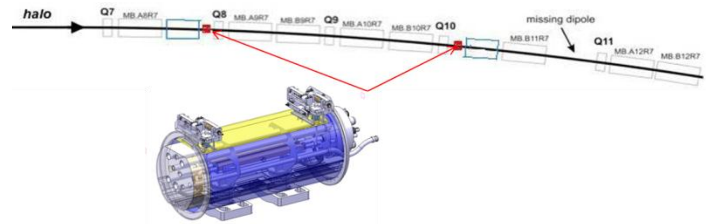


- **Although the main focus of HFM program at Fermilab was on the accelerator-quality magnets the field level is close to the record fields reached in special models.**
- **Conductor is a key component of HFM R&D.**

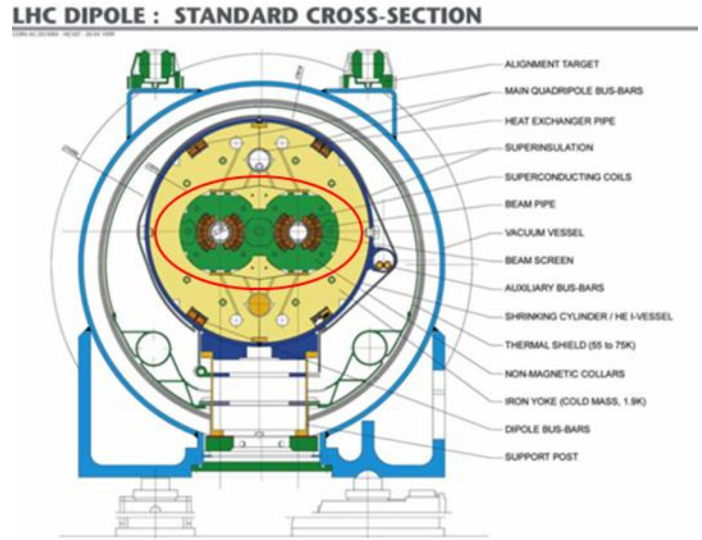
Nb_3Sn Magnet Applications

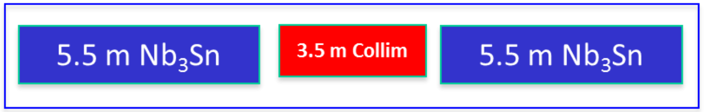
- **Nb_3Sn accelerator magnet technology is almost ready to provide B_{op} up to 10-12 T**
  - **more R&D is needed to increase B_{op} to 15 T**
- **Possible applications**
  - **LHC upgrades**
    - **11T twin-aperture dipoles for LHC collimation system upgrade - 2016-2018**
    - **150 mm aperture high-gradient quadrupoles for LHC high-luminosity IRs upgrade (ATLAS, CMS) – 2020-2021**
    - **15 T arc dipoles and quadrupoles for the LHC energy upgrade – 2030+?**
  - **Muon Collider Storage Ring (MCSR) – 2030+**
    - **10 T arc dipole and quadrupole**
    - **8 T large-aperture large-margin IR dipoles**
    - **Large-aperture high-gradient IR quadrupoles**

11 T dipole program

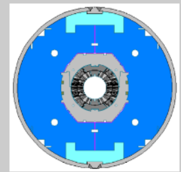
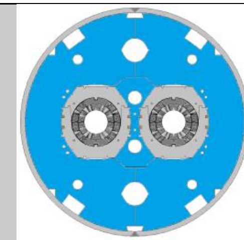


- **In 2010 CERN has started planning to upgrade the LHC collimation system**
- **The ~3.5 m space can be provided by stronger (11 T) and shorter (11 m) dipoles**
  - **Nb_3Sn technology**
- **FNAL and CERN have started joint R&D program to demonstrate feasibility and build a twin-aperture 11 T, 5.5 m long Nb_3Sn dipole prototype by 2015**
- **The 11 T magnet must be compatible with the LHC lattice and main systems**





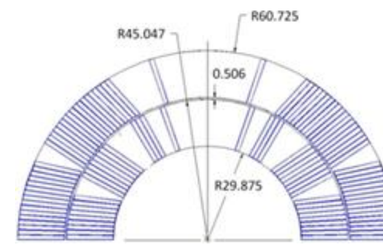
Magnet Design and Parameters (FNAL)

Parameter	 Single-aperture	 Twin-aperture
Aperture	60 mm	
Yoke outer diameter	400 mm	550 mm
Nominal bore field at I_{nom}	10.88 T	11.23 T
Short sample field B_{SSL} at T_{op}	13.4 T	13.9 T
Margin B_{nom}/B_{SSL} at T_{op}	0.81	0.83
Stored energy at I_{nom}	424 kJ/m	969 kJ/m
F_x/quadrant at I_{nom}	2.89 MN/m	3.16 MN/m
F_y/quadrant at I_{nom}	-1.58 MN/m	-1.59 MN/m

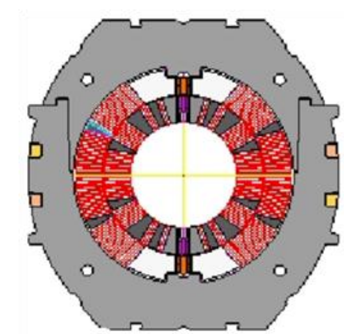
Jc(12T, 4.2K)=2750 A/mm^2, cable degradation 10%


0.7 mm Nb_3Sn strand


40-strand cable



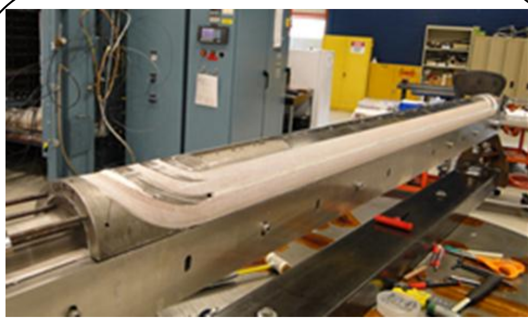
60-mm 2-layer 6-block coil


Stainless steel collar

- **Challenges: large field, forces, stored energy!**

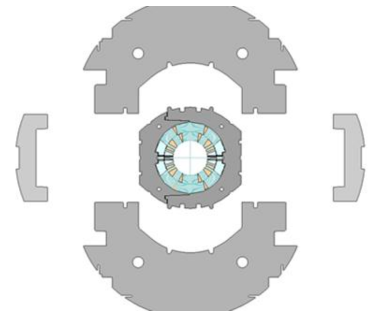
Magnet Fabrication

40-strand cable fabricated using FNAL cabling machine



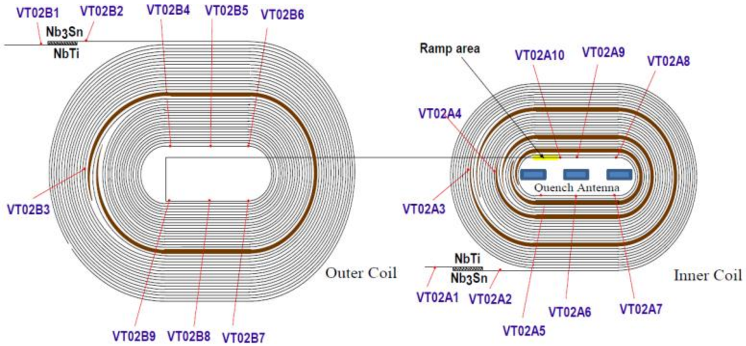
Coil fabrication

Collared coil assembly

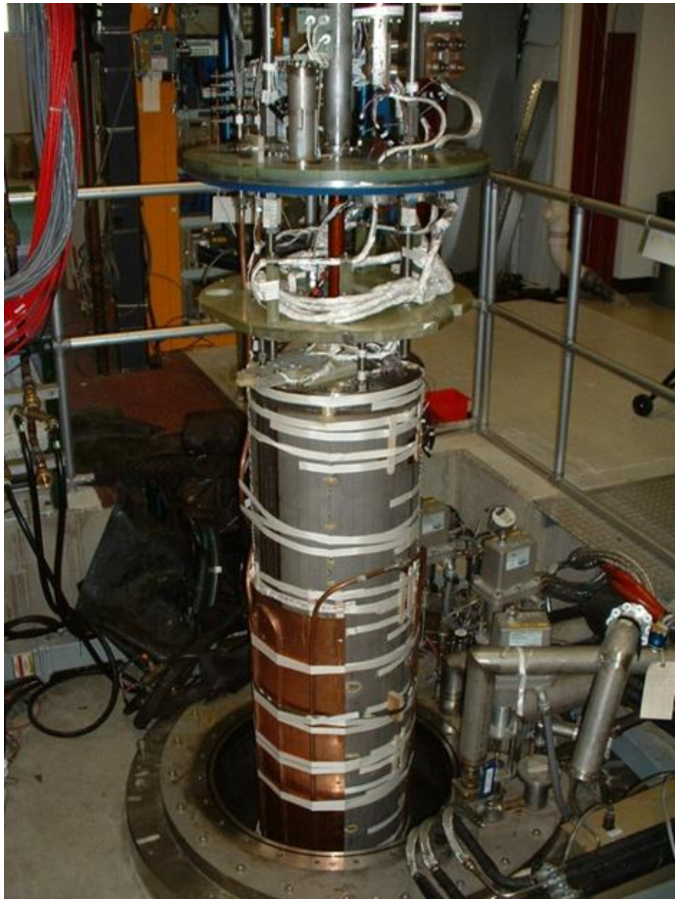


Cold mass assembly

Magnet Instrumentation and Test



Installation in vertical dewar (VMTF)



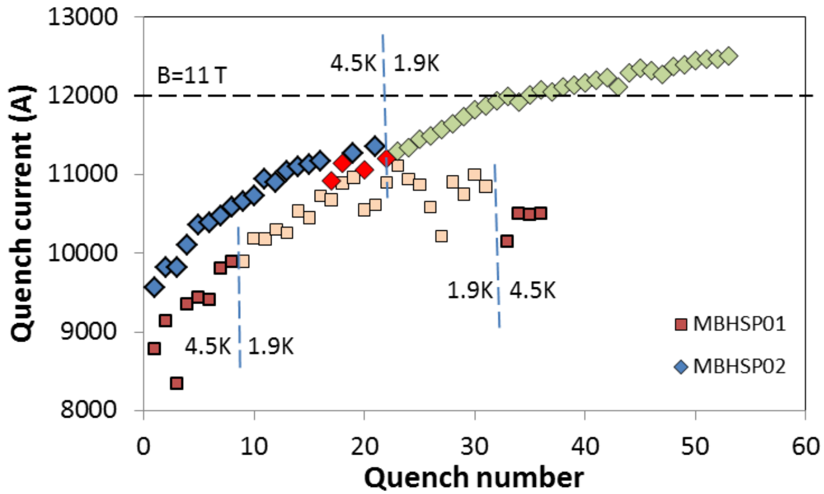
Instrumentation

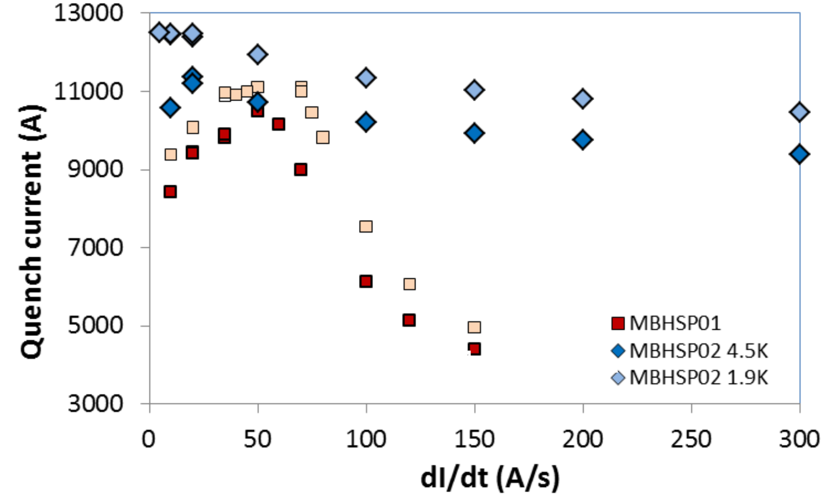
- Voltage taps
- Strain gauges
- Temperature sensors
- Quench antenna
- Rotating probes

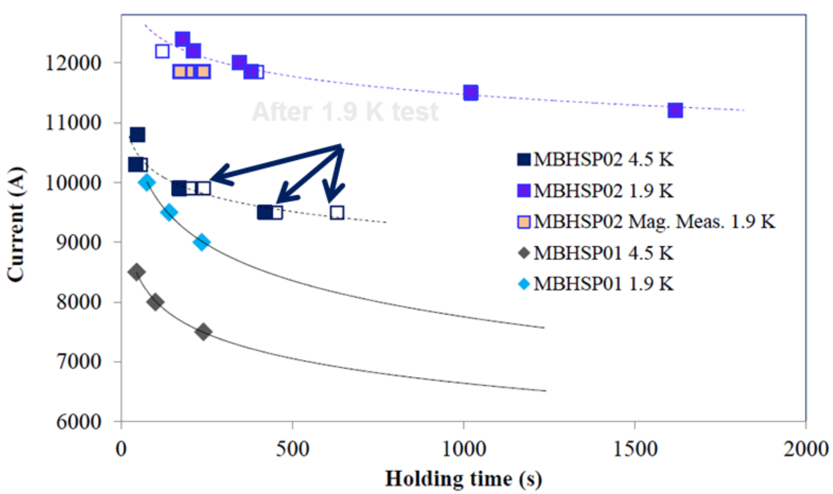
Vertical Magnet Test Facility (FNAL)

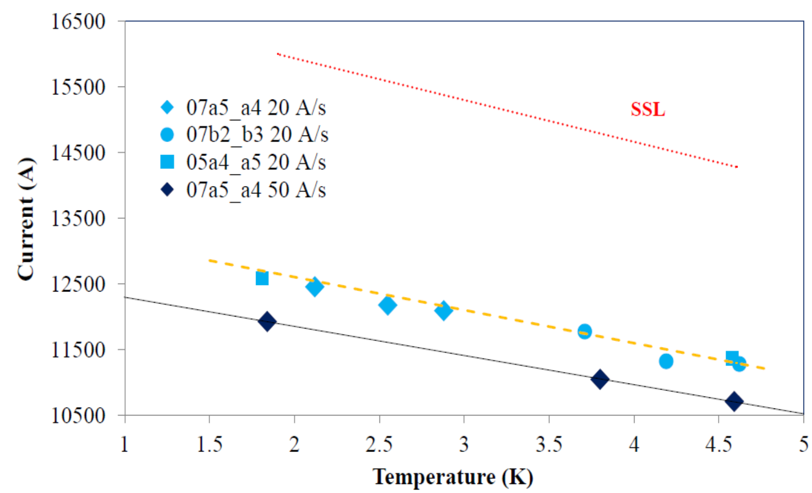
- Temperature range 1.9-4.6 K
- Quench performance
- Magnetic measurements
- Heater study
- Splice resistance, coil RRR

Quench Performance





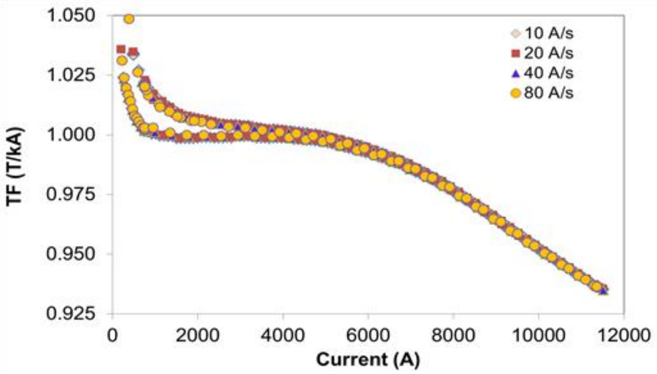


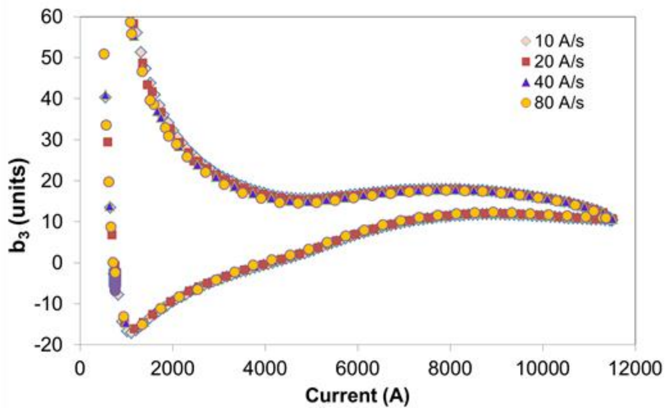


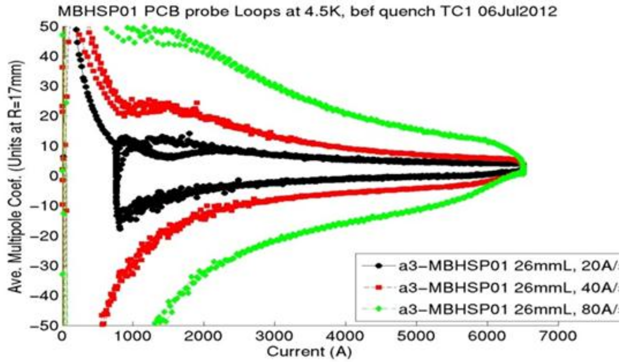
Magnetic Measurements

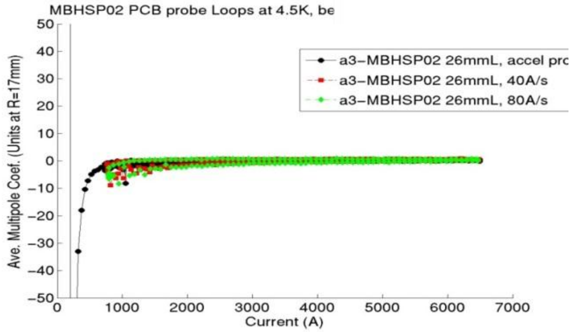
Geometrical harmonics

b_n a_n	Design	MBHSP01	MBHSP02
b_2	0.00	-0.50±0.05	-4.93
b_3	0.21	6.38±0.18	8.44
b_4	0.00	0.02±0.16	-0.17
b_5	0.88	-0.73±0.02	1.02
b_6	0.00	2.46±1.40	-0.23
b_7			0.03
b_8			0.18
b_9			0.9
a_2	0.00	-1.43±1.18	0.14
a_3	0.00	4.67±0.05	-1.44
a_4	0.00	-2.50±0.24	0.24
a_5	0.00	1.46±0.37	0.15
a_6	0.00	-2.32±0.03	0.00
a_7			-0.05
a_8			012
a_9			0.3

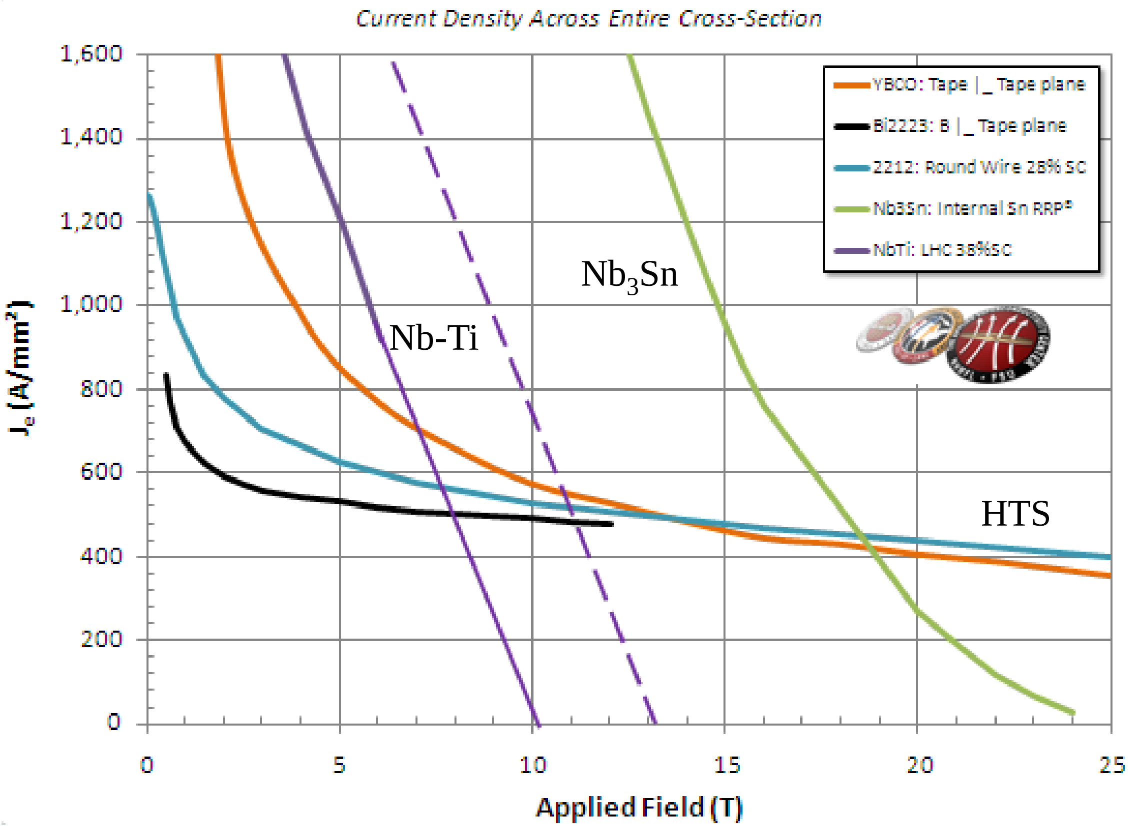








HTS Accelerator Magnets



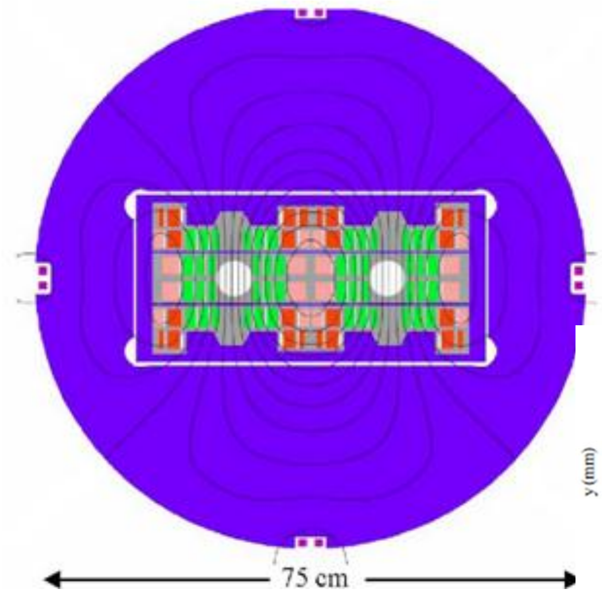
Courtesy P. Lee,

- **High-field high-temperature superconductors open the possibility of accelerator magnets with B_{nom}>15 T (B_{des}>18 T assuming typical 20% margin).**
- **Due to the lower J_c @ B<18 T (and higher cost) for HTS, a hybrid approach with Nb_3Sn coils in fields <15 T is an attractive option.**

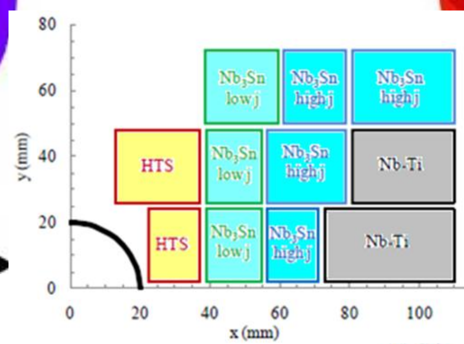
24 T Dipoles for LHC Energy Upgrade

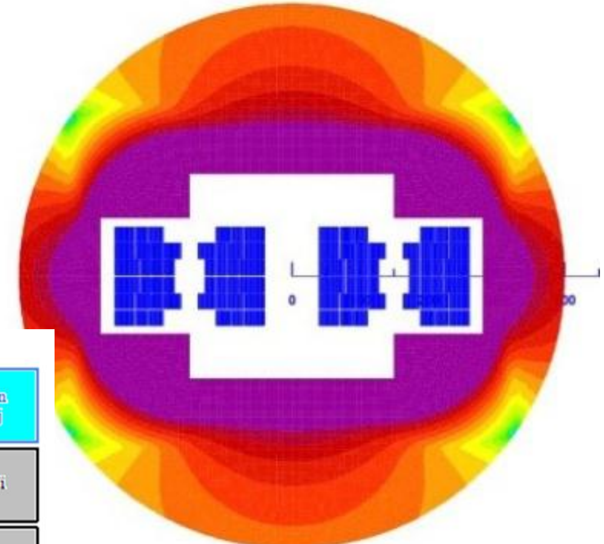
P. McIntyre et al.(TAMU), PAC’2005

L. Rossi, E. Todesco (CERN), HE-LHC’2010



Bi2212 + Nb_3Sn





Bi-2212+Nb_3Sn+NbTi

Table 1. Main parameters of the 24 T hybrid dipole.

Dipole dimensions:		
length	30	m
cold mass diameter	80	cm
Beam tube diameter	40	mm
Operating temperature	4.5	K
Coil current	33	KA
Maximum stress in windings	150	MPa
Stored energy/bore	5	MJ/m
Total horizontal Lorentz force/bore	40	MN/m

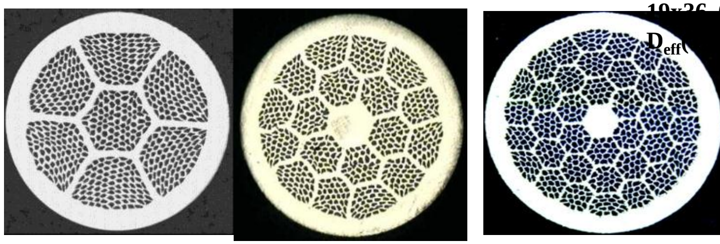
Table : Main parameters of the HE-LHC and LHC dipole

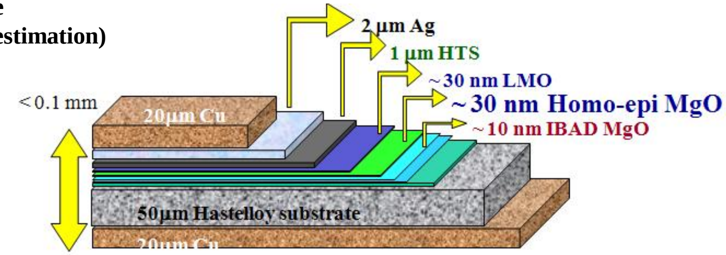
		HE-LHC	LHC
Operational field	(T)	20.0	8.3
Operational current	(kA)	13.8/6.9	11.8
Operational margin	(%)	20	14
Magnetic lenght	(m)	14.3	14.3
Total stored energy	(MJ)	100	7.0
Distance between beams	(mm)	300	194
Maximum coil thickness	(mm)	97.3	31
Cold mass diameter	(mm)	800	570

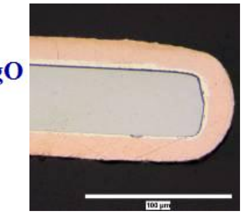
Practical HTS Strands

Filament diameter=25 µm
37x18, D_{eff}(12 T)=116.8 µm.

305 m, PMM130411
10x36, 0.8 mm wire
D_{eff}(? T)=80 µm (estimation)







- $Bi_2Sr_2CaCu_2O_x$ => Bi-2212
- Multifilament round 0.7-1.0 mm wire with Ag matrix
- SC fraction ~25-30%
- Traditional PIT process (OST)
  - Unit length >1 km
- Complex high-temperature final heat treatment in O_2
- Brittle after heat treatment, sensitive to longitudinal and transverse load
- Isotropic properties

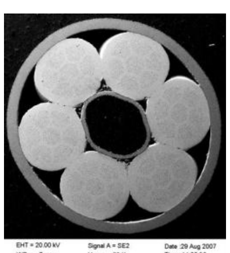
- $YBa_2Cu_3O_y$ => YBCO-123
- 4-12 mm wide tape, 50% is high strength superalloy (Hastelloy) and ~40% is Cu coating
- YBCO fraction ~1%
- Complex multilayer deposition process and final Cu electroplating (SP)
  - Unit length ~500-1000 m
- No final heat treatment
- Brittle but withstand substantial load
- Large Ic variation along the tape
  - limit unit length to 50-200 m
- Highly anisotropic

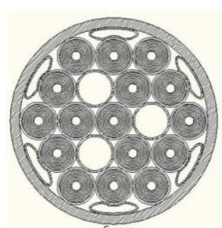
Present J_e(24T) is ~400A/mm^2 for both materials. It needs to be increased by a factor of 2-3 for 20 T accelerator magnets.

HTS cables

E. Barzi et al., Fermilab

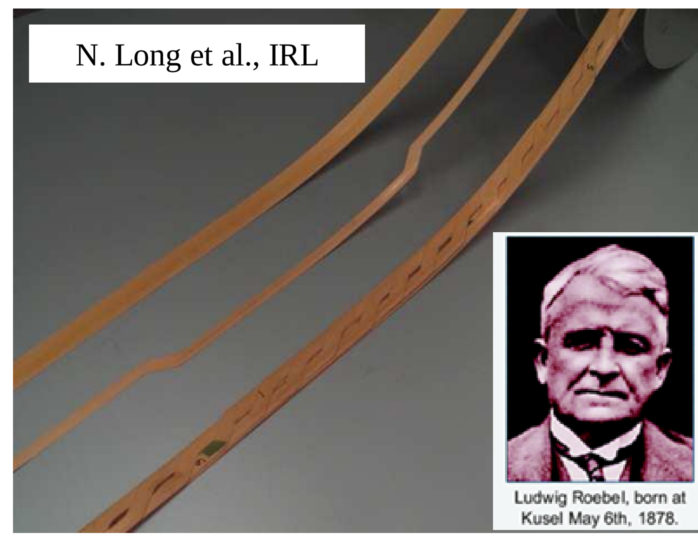
- **Rutherford cable works well for round Bi-2212 wire**
  - o **High packing factor ~85%**
  - o **I_c degradation after cabling <20%**
  - o **Sensitive to transverse pressure**
  - o **R&D at Fermilab and LBNL**
- **Alternative option**
  - o **Round cable inside metal tube to reduce transverse and axial load on Bi-2212 strands**
  - o **Low packing factor**





P. McIntyre et al., TAMU

- **YBCO tape can be cabled using the Roebel method**
  - o **Large packing factor**
  - o **I_c degradation and sensitivity to transverse pressure are being studied**
  - o **Under development by Karlsruhe (Germany) and General Cable and Industrial Research,Ltd (NZ)**
    - **15/5 YBCO Roebel cable self-field I_c>10 kA**



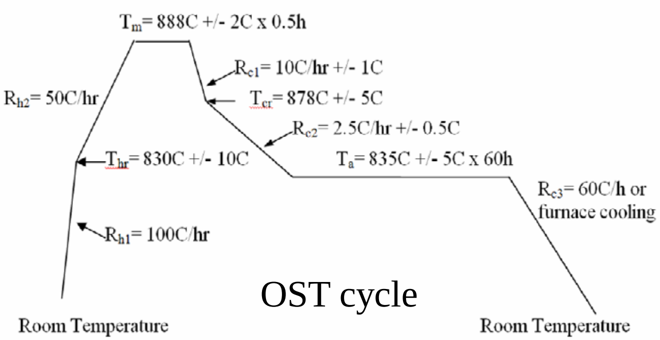
N. Long et al., IRL

10-kA HTS cable R&D is critical for 20 T accelerator magnets.

HTS Coil technology

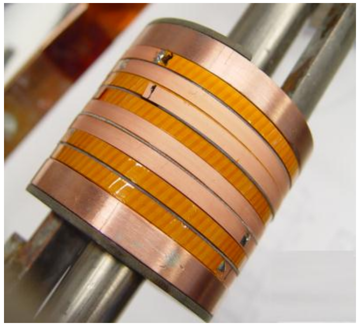
Bi-2212 coils:

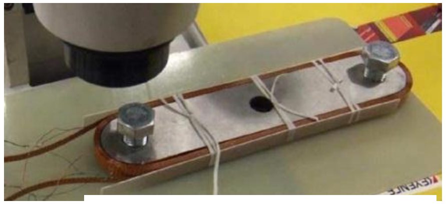
- Cos-theta and block-type coil geometry possible
  - R&D using solenoids and small racetrack coils made of single strand and Rutherford cables
- W&R approach
- Complicate multi-step HT cycle
  - Temperature variations ±1-2 C
- Liquid BSCCO can leak through the Ag matrix during reaction
  - Coil performance is ~50-70% of short sample limit
- Insulation/structure/conductor chemical compatibility



YBCO coils:

- Block-type coil geometry with relatively small bending radii
  - R&D using solenoids and small racetrack coils based on single tapes so far
- R&W approach
- Coil performance is ~80-90% of short sample limit
  - Tape splicing may degrade the coil performance





A. Godeke et al., LBNL

V. Lombardo et al., Fermilab

The key step is HTS Coil technology R&D based on high-current HTS cables and realistic mechanical structures.

Summary

- **NbTi magnets are baseline technology for present circular machines**
  - **Bop up to 9 T**
- **Nb_3Sn magnet technology will provide next step for higher energy higher luminosity machines**
  - **Bop=9-15 T**
- **Accelerator magnets based on HTS materials look feasible thanks to recent progress with HTS materials**
  - **Present focus on HTS cables and coil technologies**
  - **NbTi/Nb_3Sn coils will generate ~70% of the total field and play an important role in magnet quench protection and cost**