High Field Accelerator Magnets

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High Field Accelerator Magnets

- Introduction: magnetic field and high field magnets
- How to get high fields in accelerator dipole and quadrupole magnets ?
- Superconductors for magnets
- Practical accelerator magnet design
- High field magnets for future accelerators
- Literature on High Field Magnets

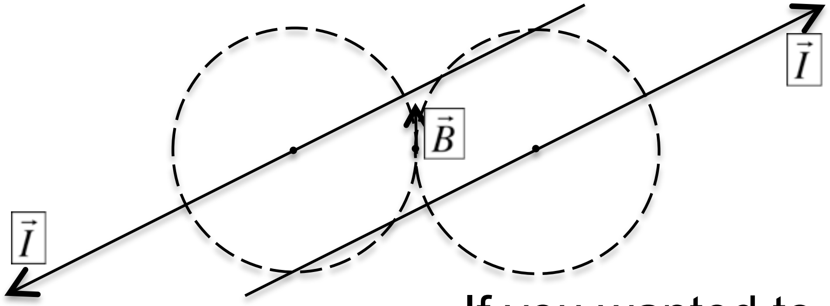
Magnetic fields

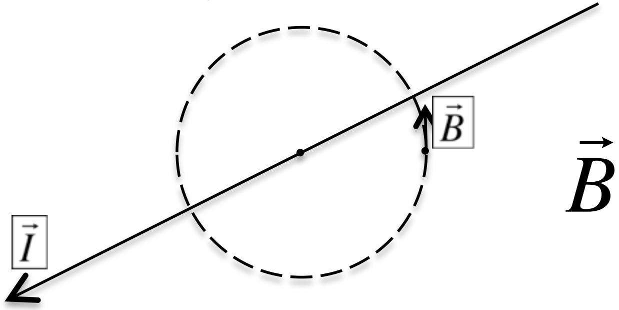
From Ampere's law with no time dependencies

(Integral form)

$$\oint_C \vec{B} \cdot d\vec{l} = \mu_0 I_{encl.}$$

We can derive the law of Biot and Savart



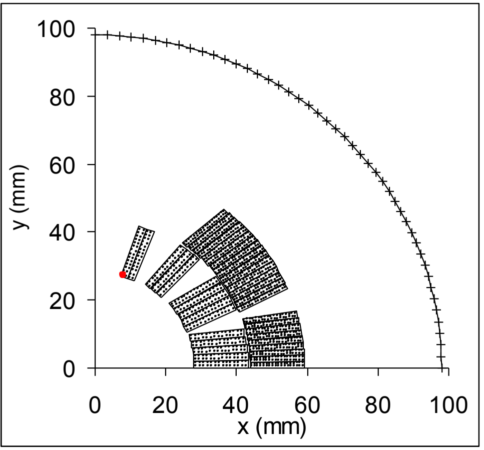


$$\vec{B} = \frac{\mu_0 I}{2\pi r}\hat{\varphi}$$

If you wanted to make a B = 8 T magnet with just two infinitely thin wires placed at 50 mm distance one needs : $I = 5 \bullet 10^5$ A

LHC dipole coil 80 turns of 11850 A at 8.3 T = $9.48 \bullet 10^5$ A)

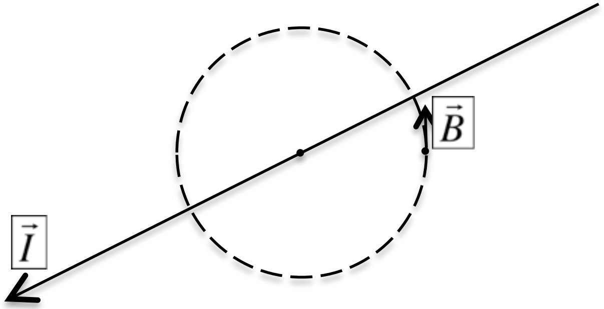
➔ To get high fields (B > 10 T) one needs very large currents in small volumes



Courtesy E. Todesco

For LHC dipole@8.3 T ~1 MA in 3300 mm^2 : ~300 A/mm^2 (overall current density in the coil area)

Iron magnets "resistive" or "classical" magnets



$$\oint_C \vec{H} \cdot d\vec{l} = N \cdot I$$

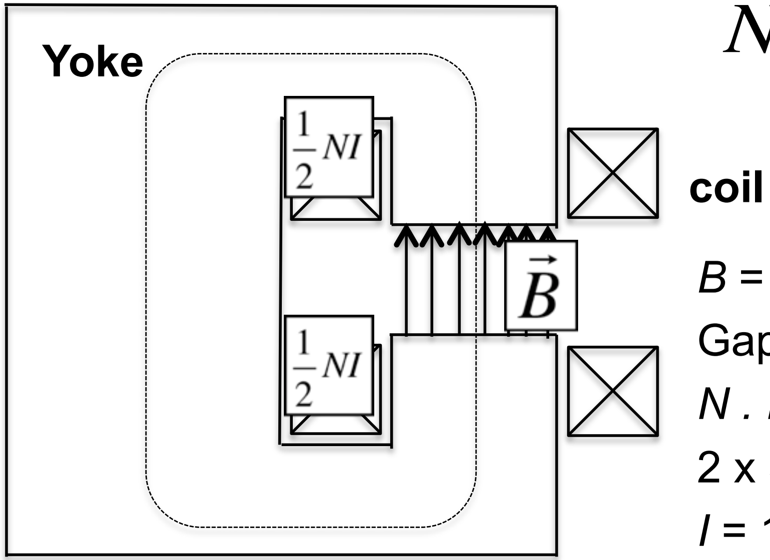
$$N \cdot I = H_{iron} \cdot l_{iron} + H_{airgap} \cdot l_{airgap} \Rightarrow$$

$$N \cdot I = \cancel{\frac{B}{\mu_0 \mu_r} \cdot l_{iron}} + \frac{B}{\mu_0} \cdot l_{airgap} \Rightarrow$$

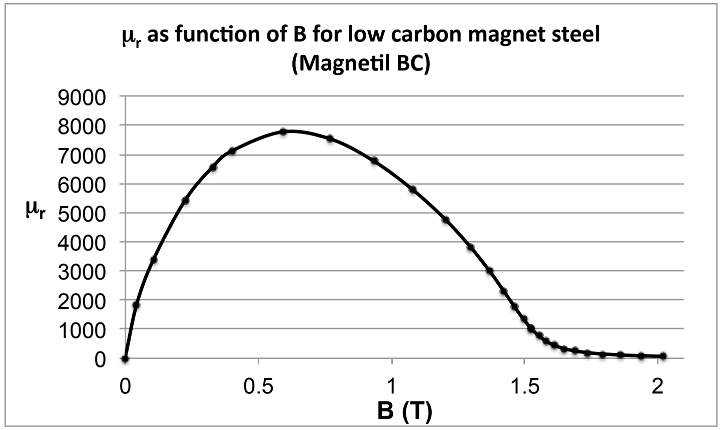
$$N \cdot I = \frac{l_{airgap} \cdot B}{\mu_0}$$

This is valid as $\mu_r >> \mu_0$ in the iron : limited to B < 2 T

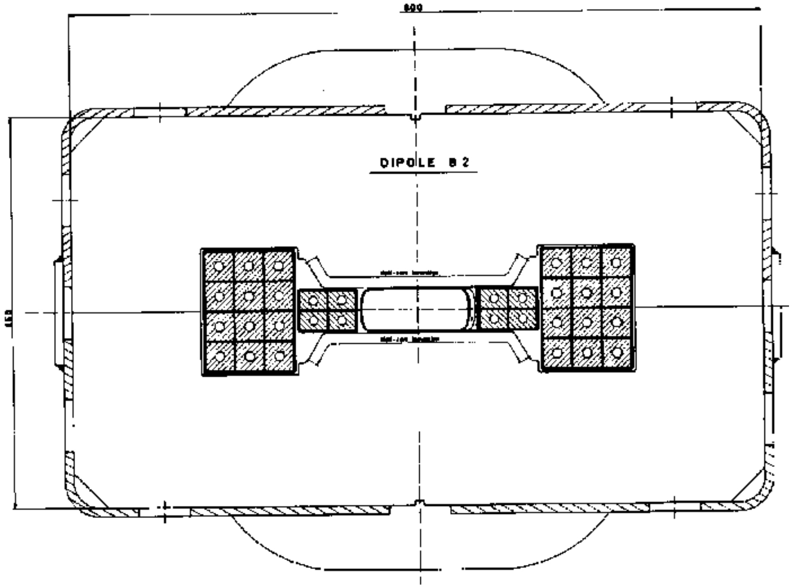
Example: C shaped dipole for accelerators



B = 1.8 T
Gap = 50 mm
N . I = 71619 A
2 x 36 turn coil
I = 1000 A
@5 A/mm^2, 200 mm^2
14 x 14 mm Cu



Resistive accelerator magnet example: SPS dipole



H magnet type MBB

$B = 2.05$ T

Coil : 16 turns

$I_{max} = 4900$ A

Aperture = 52 × 92 mm^2

$L = 6.26$ m

Weight = 17 t

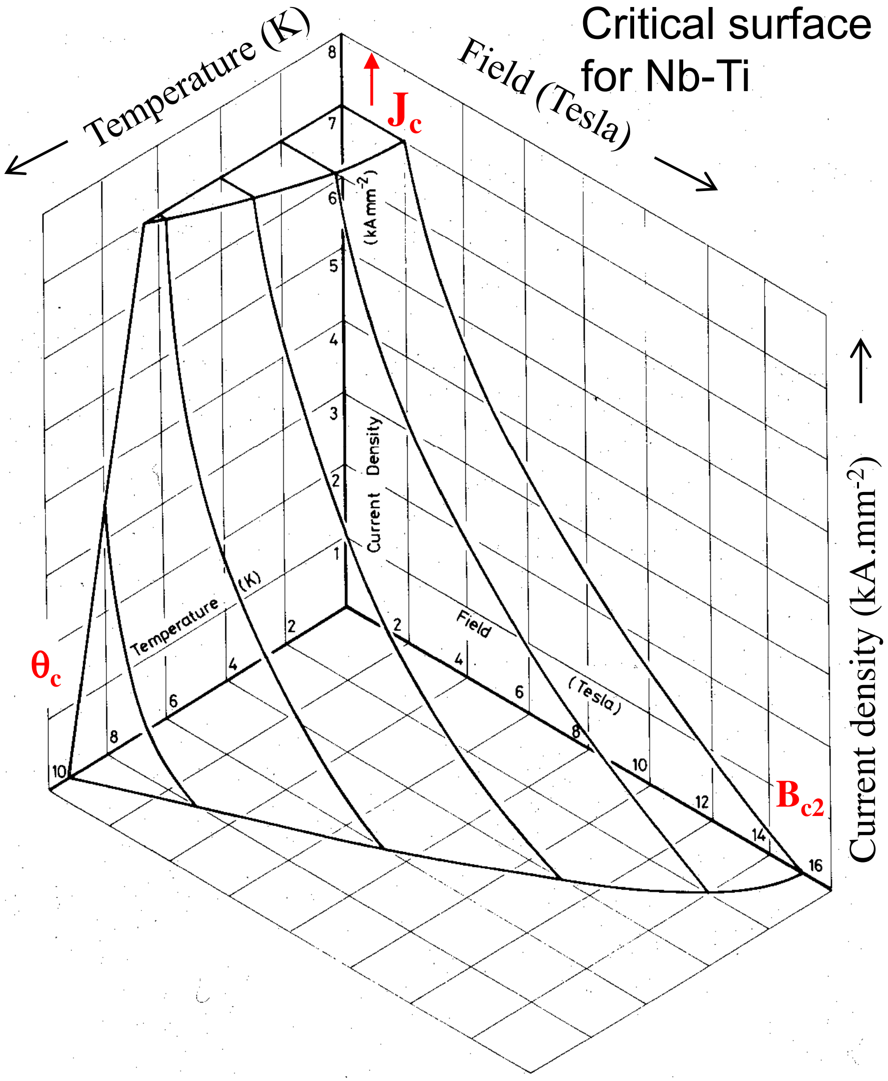
Superconductors

Below a the critical surface the material is "superconducting". Above the surface it is "normal conducting"

- Θ_c Critical Temperature (at zero field and current density)
- B_{c2} Critical Field (at zero temperature and current density)
- J_c Critical Current Density (at zero temperature and field)

The Critical surface depends on the material type Nb-Ti, Nb_3Sn, etc) and the processing

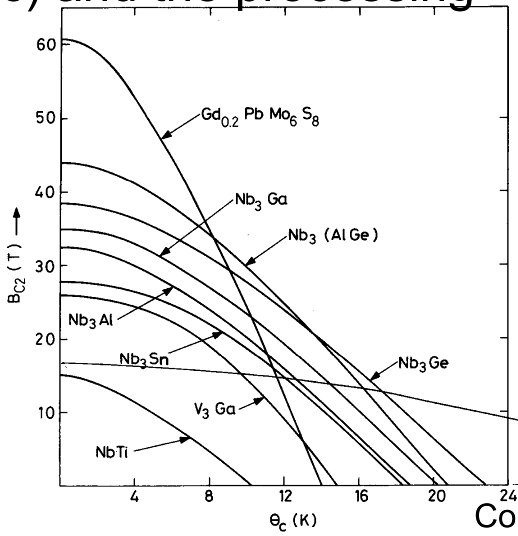
Critical surface for Nb-Ti



Courtesy M. Wilson

Superconducting means: R = 0

J: few x 10^3 A/mm^2 inside the superconductor

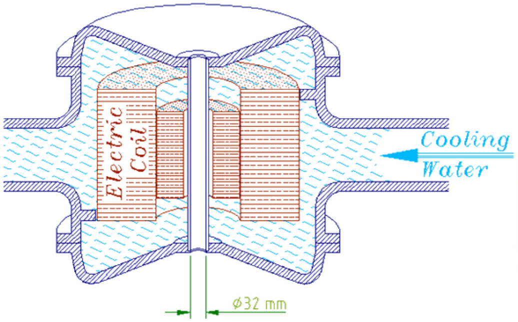


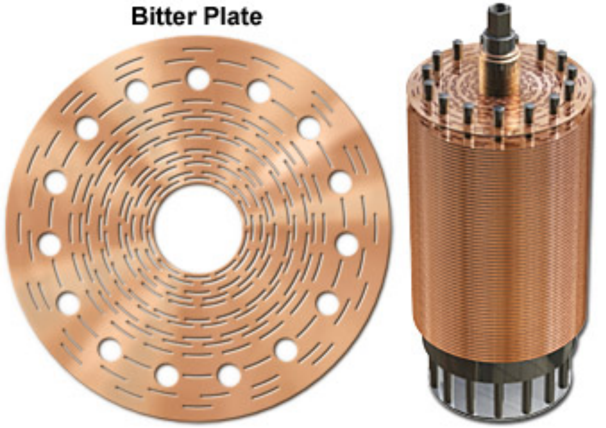
Courtesy L. Rossi

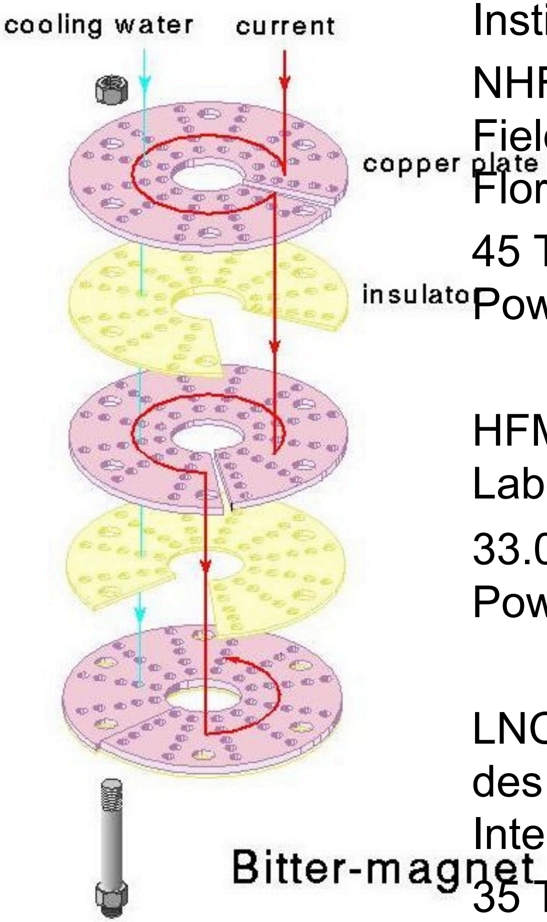
High field magnets example: resistive solenoids

High field resistive solenoids

- **Onion shells of coils**
- **High power consumption**







Institutes:

NHFML, National High Magnetic Field Laboratory, Tallahassee, Florida (US)

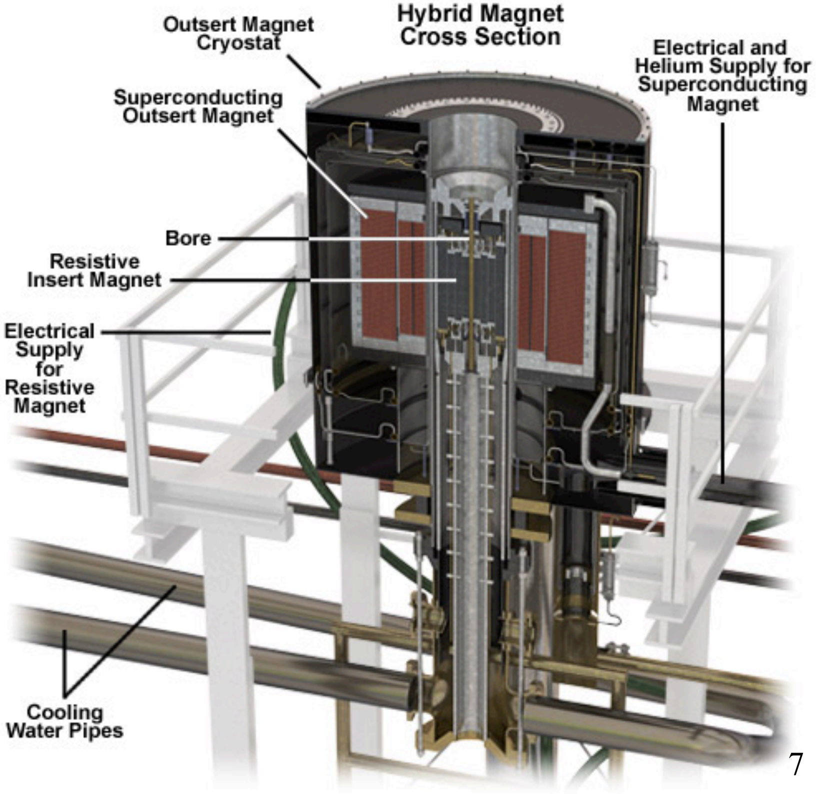
45 T Hybrid magnet, Ø 32mm,
Power: 33 MW

HFML, High Field Magnet Laboratory, Nijmegen (NL)

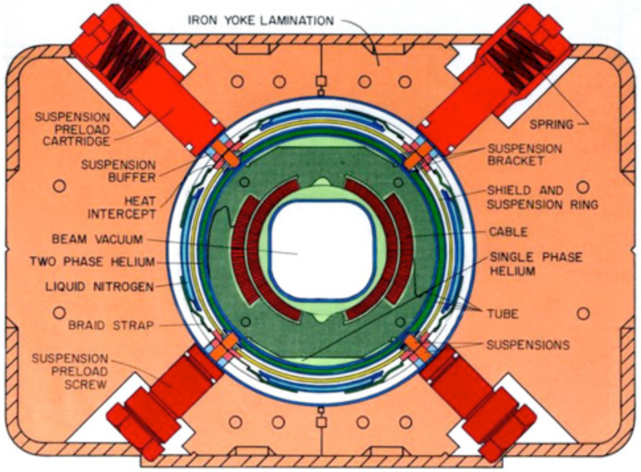
33.0 T Bitter magnet , Ø 32mm
Power: 17 MW

LNCMI, Laboratoire National des Champs Magnétique Intenses, Grenoble (Fr)

35 T Hybrid magnet, Ø 34mm



Superconducting Accelerator dipole magnets (1)



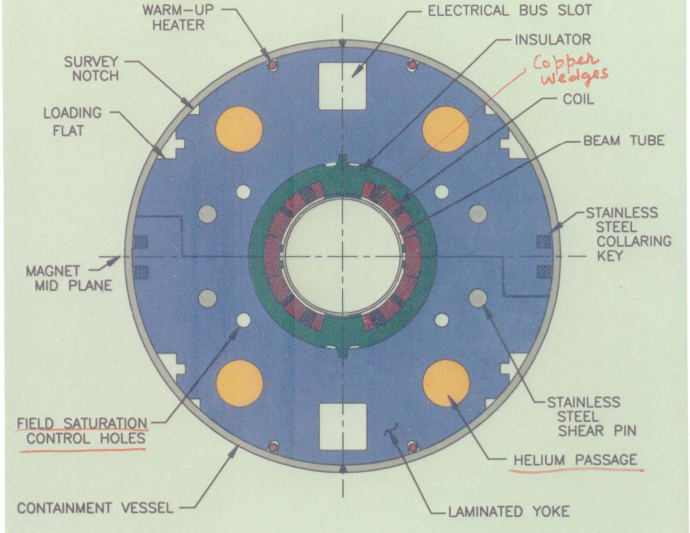
Tevatron: 4.4 T

1983

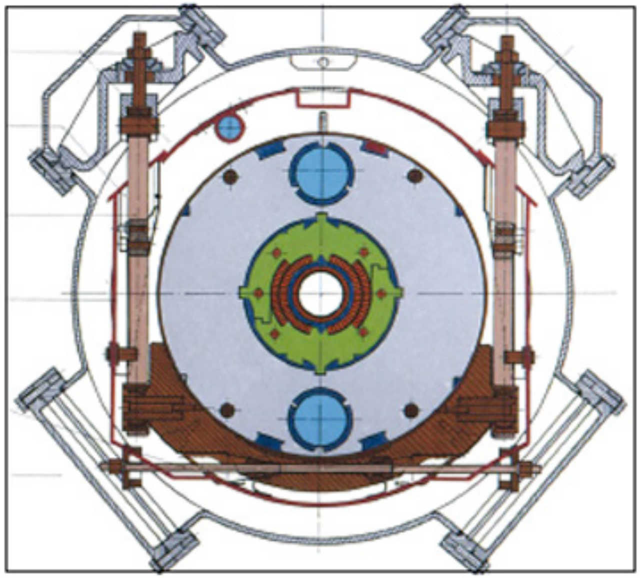
RHIC: 3.5 T

2000

RHIC: Relativistic Heavy Ion Collider



Courtesy R. Gupta

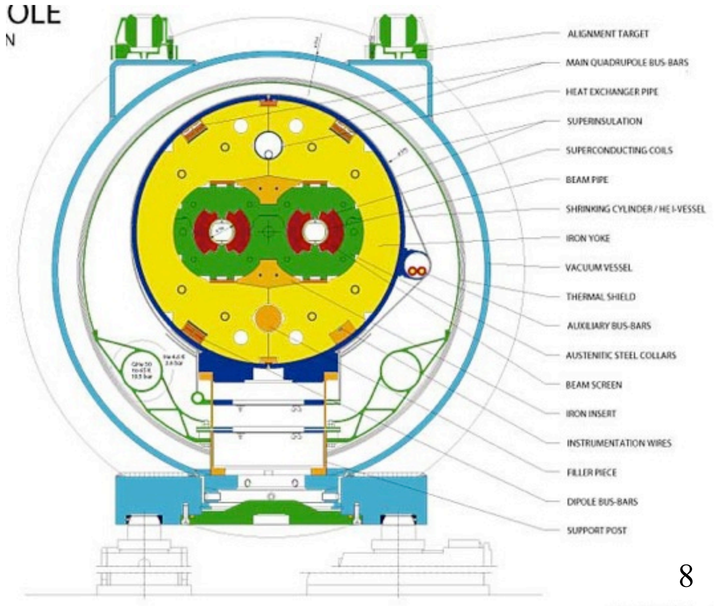


HERA: 5 T

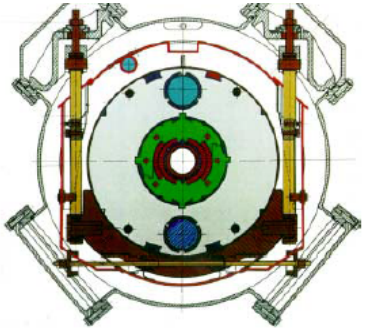
1992

LHC: 8.34 T

2008

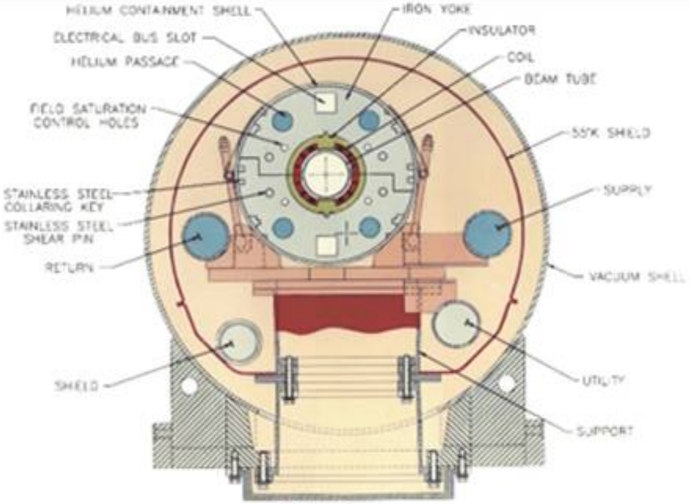


Size overview



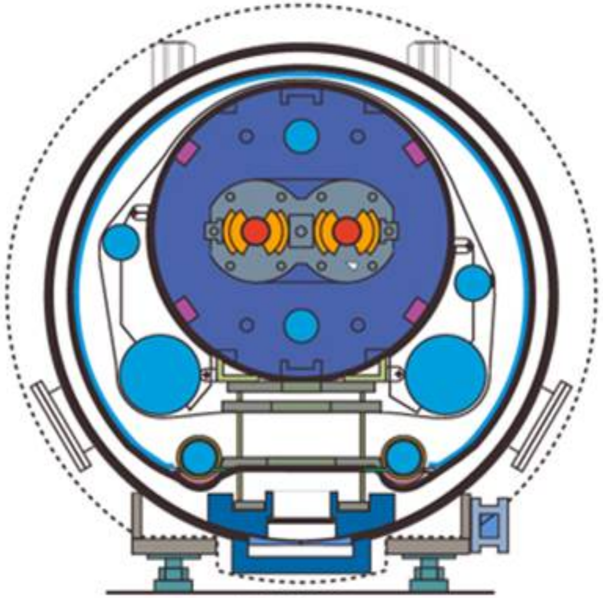
HERA dipole in cryostat

HERA
B = 4.7 T
BORE : 75 mm



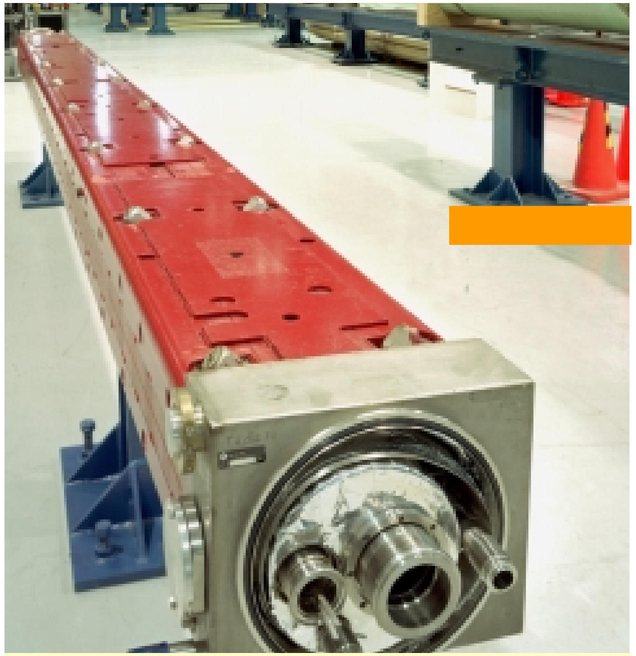
RHIC
B = 3.5 T
Bore : 80 mm

TEVATRON
B = 4.5 T
Bore : 76 mm



LHC
B = 8.3 T
Bore : 56 mm

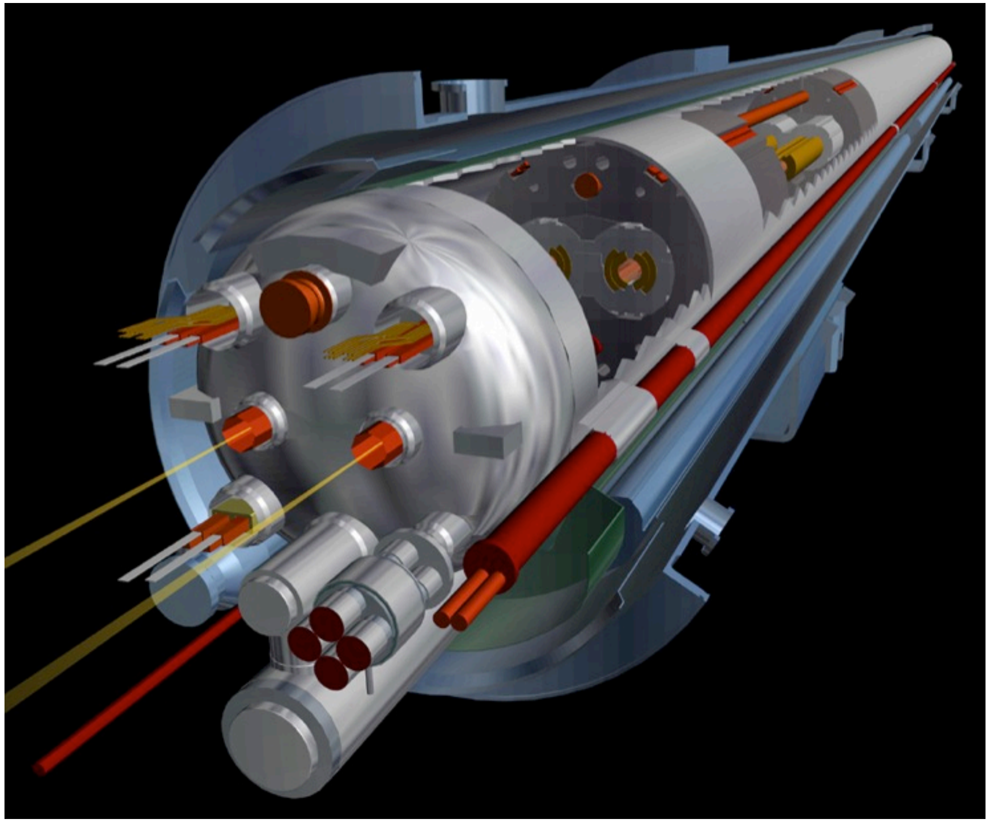
Superconducting Accelerator dipole magnets (2)



Tevatron dipoles: 4.2 T

single aperture, warm yoke

Tevatron



LHC

Superconducting Accelerator dipole magnets (2)

Machine	place	Type	Energy (GeV)	Peak Dipole field (T)	# dipoles	Dipole Length (m)	Ring circ. (km)	Year
Tevatron	FNAL (USA)	p-pbar FT/coll.	1000 x 1000	4.4	774	6.12	6.28	1983/ 1987
HERA	DESY (D)	$e^{-/+}$ - p collider	40x920	5	416	8.82	6.34	1992
RHIC	BNL (USA)	p-p, Au-Au, Cu-Cu, d-Au	100/n	3.5	2x192+12	9.45	3.83	2000
LHC	CERN (Eu)	p-p, Pb-Pb	7000 x 7000	8.34	1232	14.3	26.66	2008

20 years were needed to go from 4 T to 8 T !

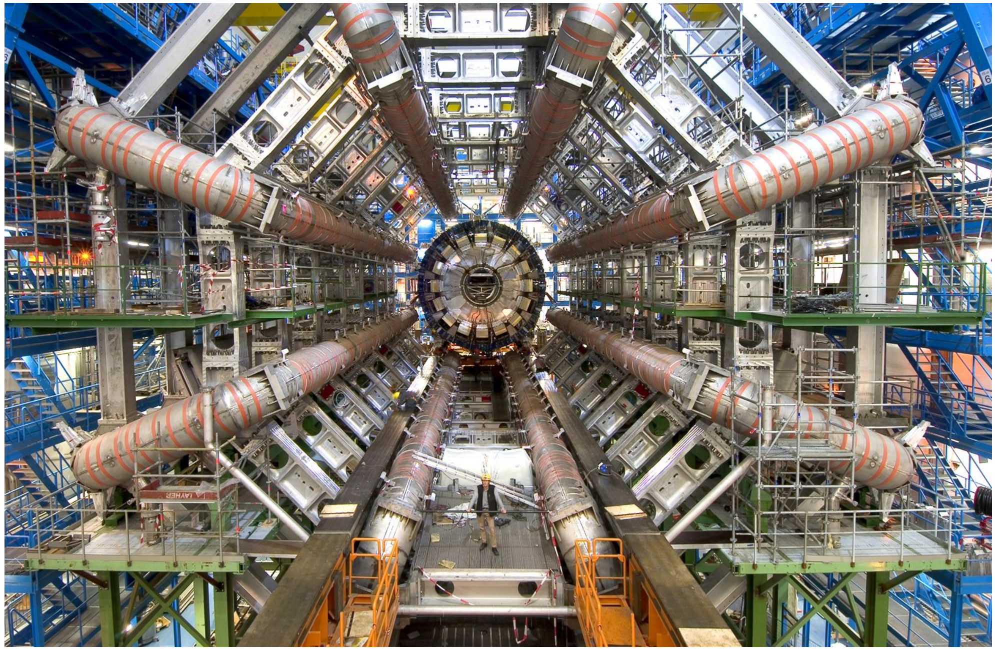
Detector magnets

CMS Solenoid

- Inner Bore 6.3 m
- Length 12.5 m
- Central field 4 T
- Nominal current 19 kA
- Stored Energy 2.65 GJ
- Cold mass 220 t

ATLAS barrel toroid

- Outer diameter 21 m
- Length 26 m
- B_{peak} 4.1 T
- Stored Energy 1500 MJ



NMR and research magnets

Solenoids up to 21 T and with a bore of 50 mm (max 89 mm) are available off the shelf of many firms: Bruker, Agilent, Oxford, Cryogenic, Varian, etc

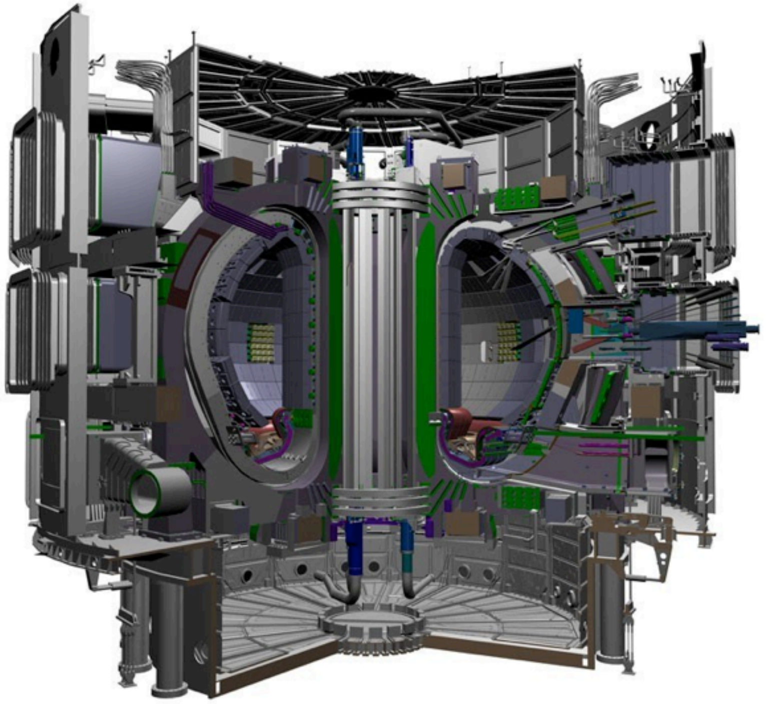
As an example from Cryogenic:

solenoid 20 T, 2.2 K, 52 mm Ø bore, l = 285 mm, Ø 500 mm

Fusion Tokamak: ITER

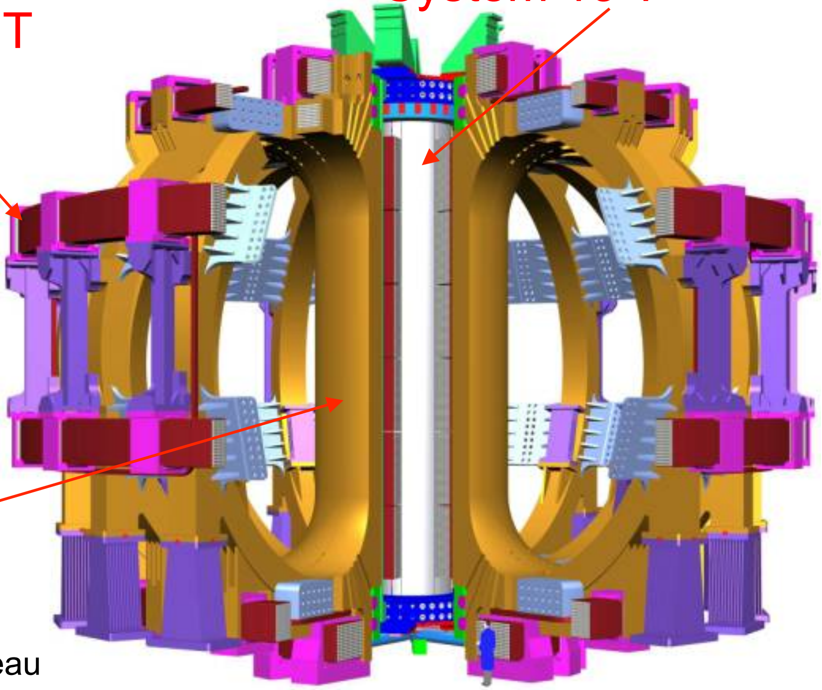
The Tokamak has several magnet systems to confine

- the plasma (TF),
- control it (PF and correction coils),
- and heat it up (CS)



Large amounts of conductor are needed:

- TF system: 376 tonnes Nb_3Sn
- CS system : 132 tonnes Nb_3Sn
- PF system : 244 tonnes Nb-Ti



Central Solenoid System 13 T

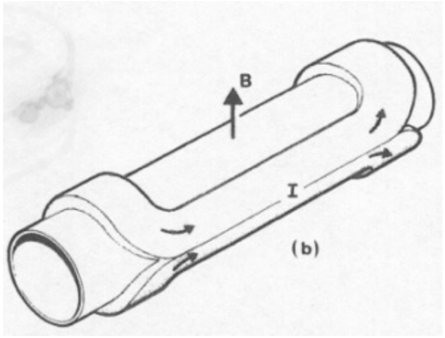
Poloidal Field System 6 T

Toroidal Field System 11.8 T

Courtesy J-L. Duchateau

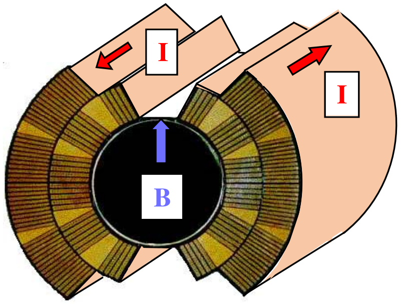
What is specific about accelerator magnets ?

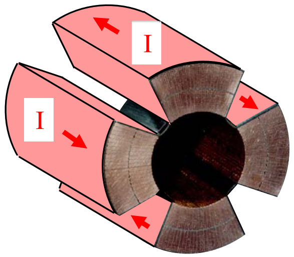
- Cylindrical volume with perpendicular field

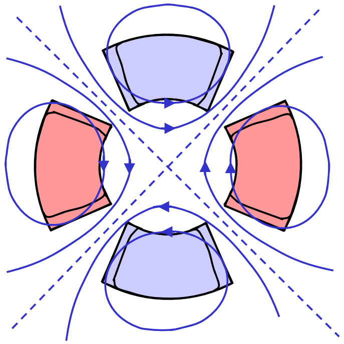


Artist view of a dipole, from M. N. Wilson « Superconducting Magnets »

- Dipoles, quadrupoles, etc

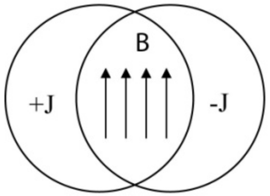






- Field quality: $$\frac{\Delta B_z}{|B|} \leq few \cdot 10^{-4}$$

CosΘ coil : $J = J_0 \cos\Theta$



- Field quality formulated and measured in a multipole expansion,

$$B_y + iB_x = 10^{-4} B_1 \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{R_{ref}} \right)^{n-1}$$

$$b_n, a_n \leq few \cdot units$$

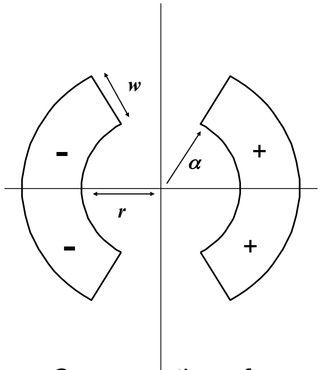
- Long magnets: dipoles from 6 m (Tevatron) to 15 m (LHC)

- Often magnets are bend (9.14 mm sagitta for the LHC dipoles)

How to get high fields in accelerator dipole and quadrupole magnets ?

From Ampere’s law one can derive the field resulting from the current in a line conductor and integrate this over the surface of a coil

- Dipole 60º sector coil [see ref 10, 14]
  - The field is *proportional to the current density j*
  - The field is *proportional to coil width*
  - The field is *independent of aperture*

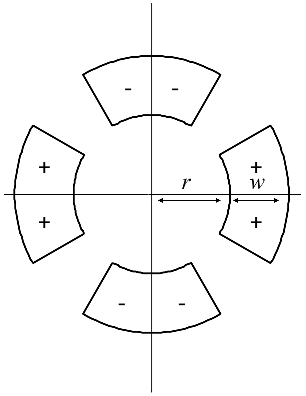


Cross-section of a dipole based on 60º sector coils

$$B_1 = -4\frac{j\mu_0}{2\pi}\int_0^{\pi/3}\int_r^{r+w}\frac{\cos\theta}{\rho}\rho\,d\rho\,d\theta = -\frac{\sqrt{3}\mu_0}{\pi}jw$$

with: r : inner radius coil
w : coil width
ρ : radial coordinate
J : current density

- Quadrupole 30º sector coil [see ref 11, 14]
  - The gradient is *proportional to the current density j*
  - The gradient depends on *w/r*



Cross-section of a quadrupole based on 30º sector coils

$$G = -8\frac{j\mu_0}{2\pi}\int_0^{\pi/6}\int_r^{r+w}\frac{\cos\theta}{\rho}\rho\,d\rho\,d\theta = -\frac{\sqrt{3}\mu_0}{\pi}j\ln\left(1+\frac{w}{r}\right)$$

➔ by having very high current density close to the beam pipe

See: E. Todesco et al. ref[10] and indirectly : N. Wilson ref[1], K-H Mess et al. ref[2]
For a in depth study of magnetic field calculations: S. Russenschuck ref[4]

The forces with high field dipole and quadrupole magnets

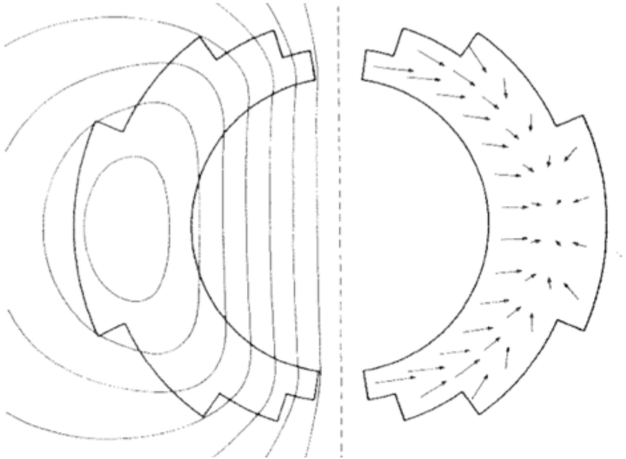
One can derive the maximum stress in the midplane for a sector dipole coil

- Dipole 60º sector coil [see ref 1, 12]

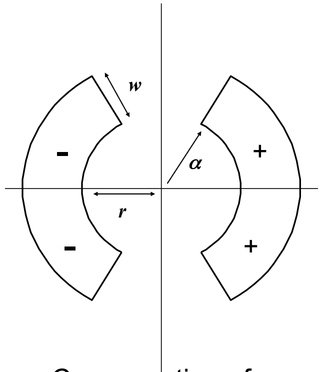
$$\sigma \approx j^2 \frac{\mu_0 \sqrt{3}}{6\pi} Max_{\rho\varepsilon[r,r+w]}\left[2\rho^2+\frac{r^3}{\rho}-3\rho\left(r+w\right)\right]$$

(Typically: for 8T : 40 MPa , for 13 T 130 MPa)

with: r : inner radius coil
ρ : radial coordinate
w : coil width
J : current density



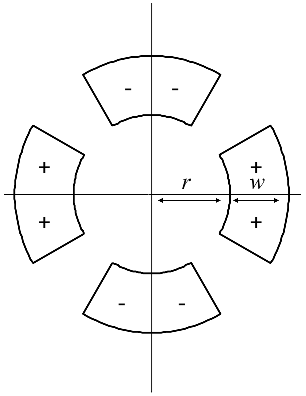
Courtesy M. Wilson



Cross-section of a
dipole
based on 60º sector coils

- Quadrupole 30º sector coil [see ref 1, 13]

$$\sigma \approx j^2 \frac{\mu_0 \sqrt{3}}{16\pi} Max_{\rho\varepsilon[r,r+w]}\left[2\rho^2+\frac{r^4}{\rho^2}+4\rho^2 \ln\left(\frac{r+w}{\rho}\right)\right]$$

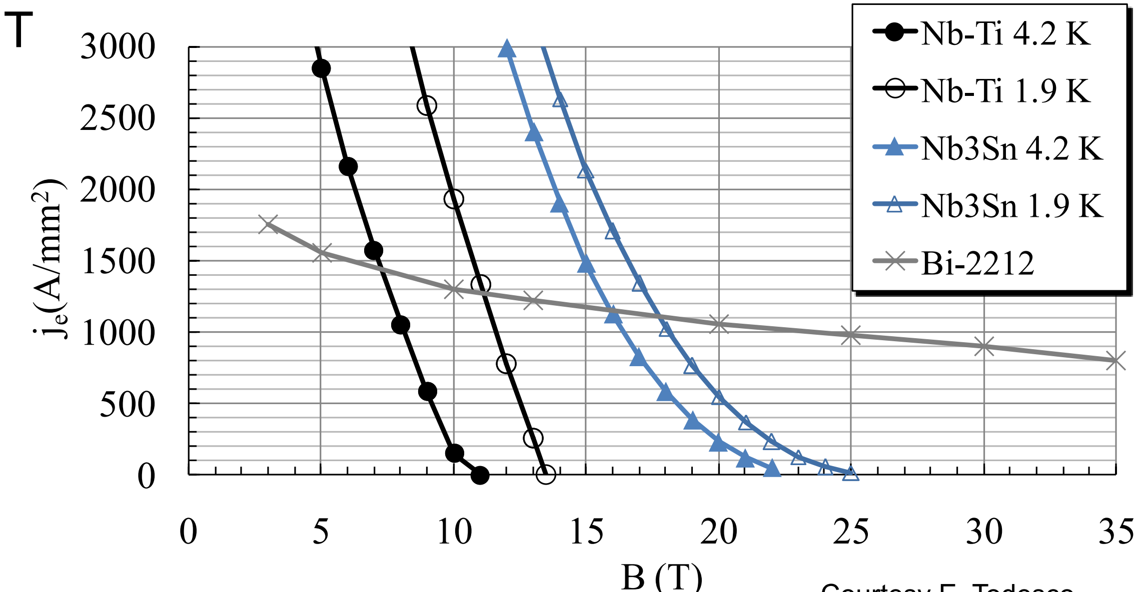


Cross-section of a
quadrupole
based on 30º sector coils

Superconductors

Nb-Ti is the workhorse for 4 to 10 T

- Up to ~2500 A/mm^2 at 6 T and 4.2 K or at 9 T and 1.9 K
- Well known industrial process, good mechanical properties
- Thousands of accelerator magnets have been built
- 10 T field in the coil is the practical limit at 1.9 K



Courtesy E. Todesco

Nb_3Sn: towards 20 T

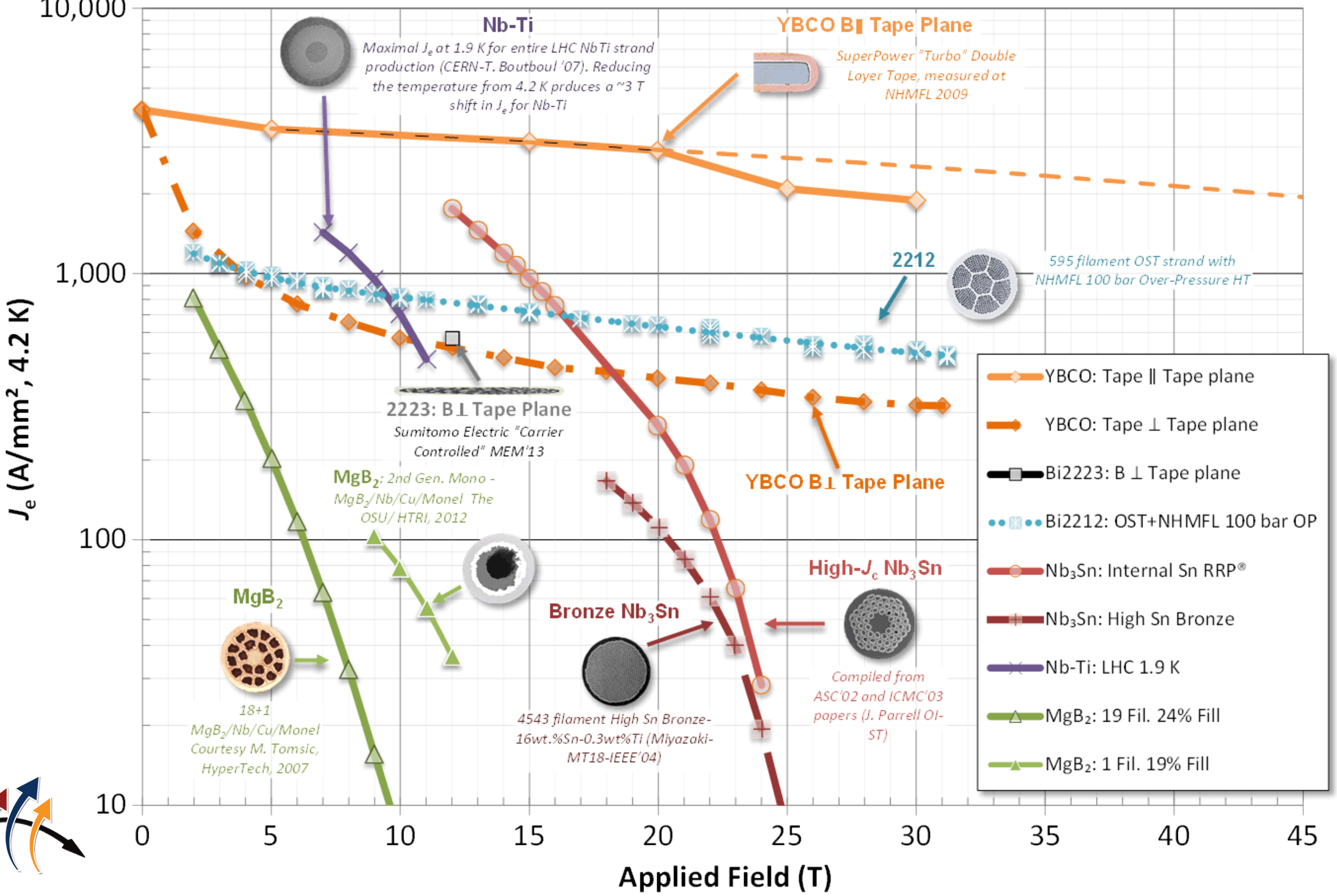
- Can reach up to ~3000 A/mm^2 at 12 T and 4.2 K
- Complex industrial process, higher cost, brittle and strain sensitive
- ~25 short models for accelerator magnets have been built
- ~20 T field in the coil is the practical limit at 1.9 K

HTS materials: dreaming 40 T (Bi-2212, YBCO)

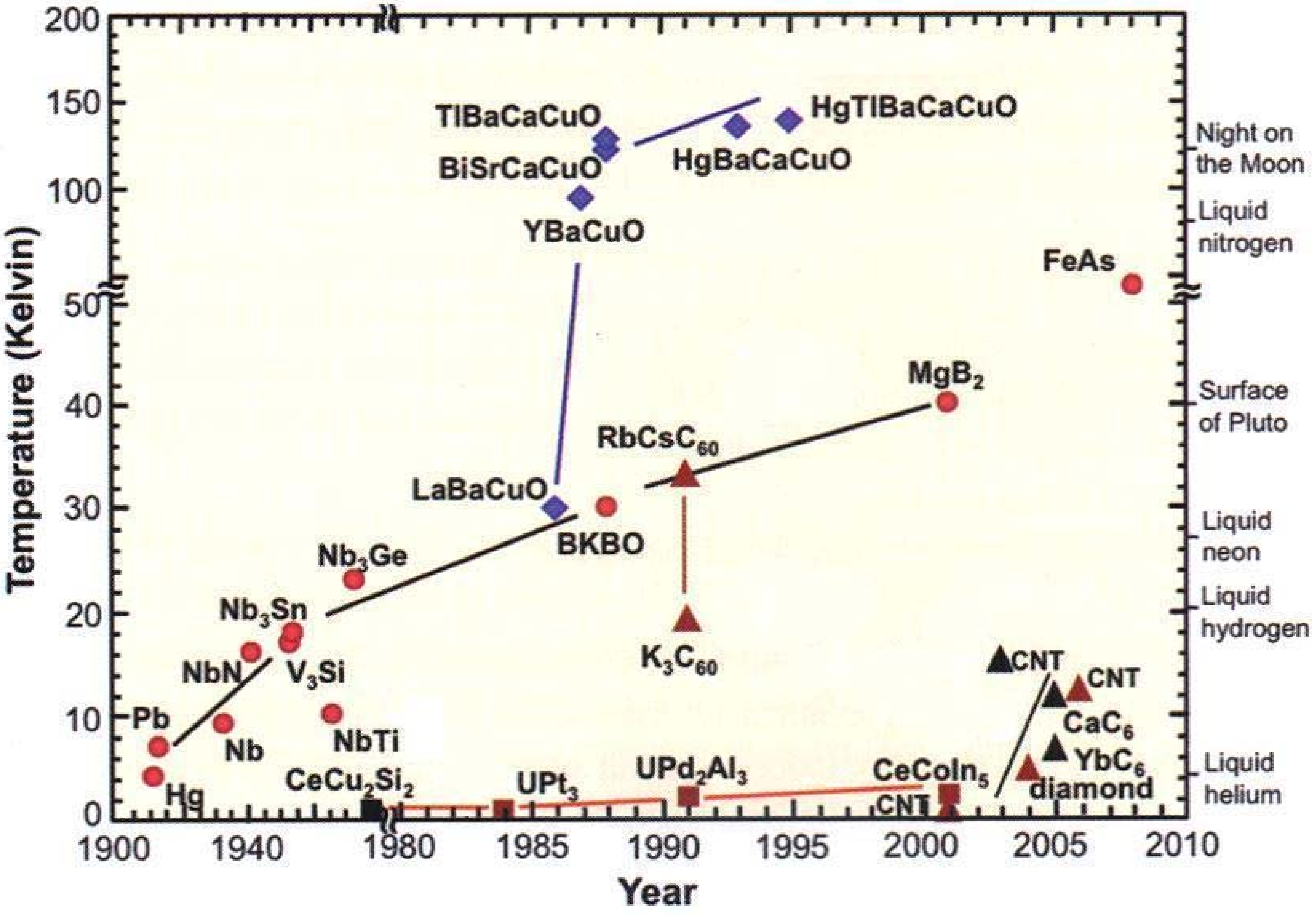
- –Current density is low, but very little dependence on the magnetic field
- –Used in solenoids, used in power lines – no accelerator magnets (only 1 model) have been built – small racetracks have been built

Superconductors

Compilation of engineering current densities (See ref 15, NHMFL)

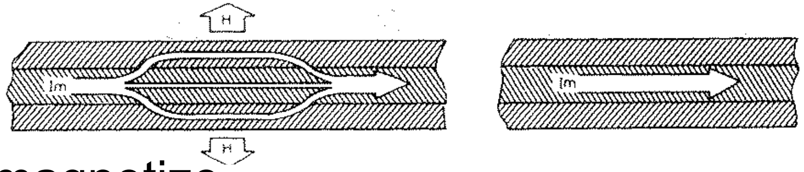


High temperature superconductor zoo

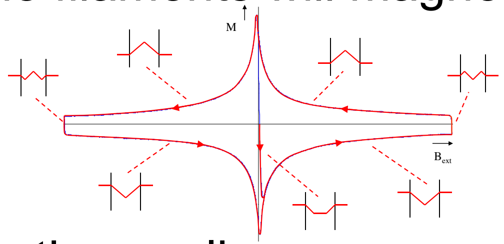


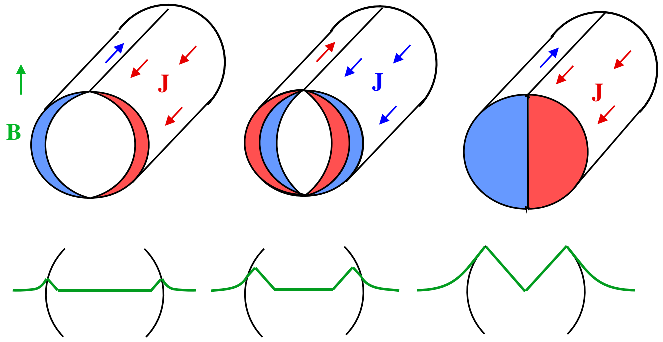
Conductor stability and AC behaviour

- Pure massive superconductor is not stable as they (Nb-Ti, Nb_3Sn) are poor normal conductors
- To ‘cryogenically stabilize’ the conductor one surrounds it in Cu:
  - good electrical conductivity
  - good heat transfer to the He

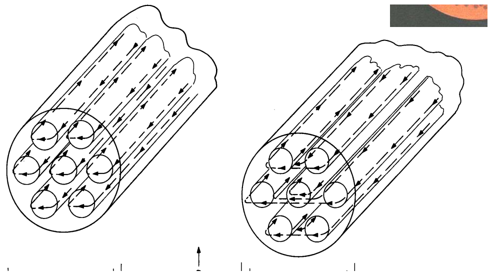


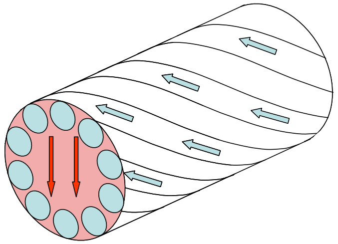
- During current ramping the filaments will magnetize
  ➔ make them thinner



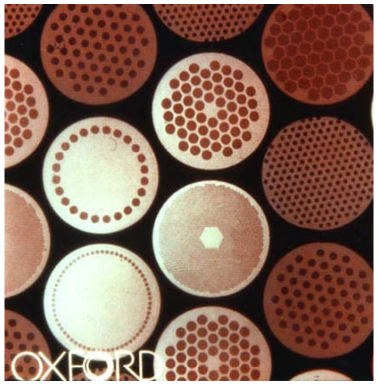


- Filaments will have magnetic coupling
  ➔ twist the strand





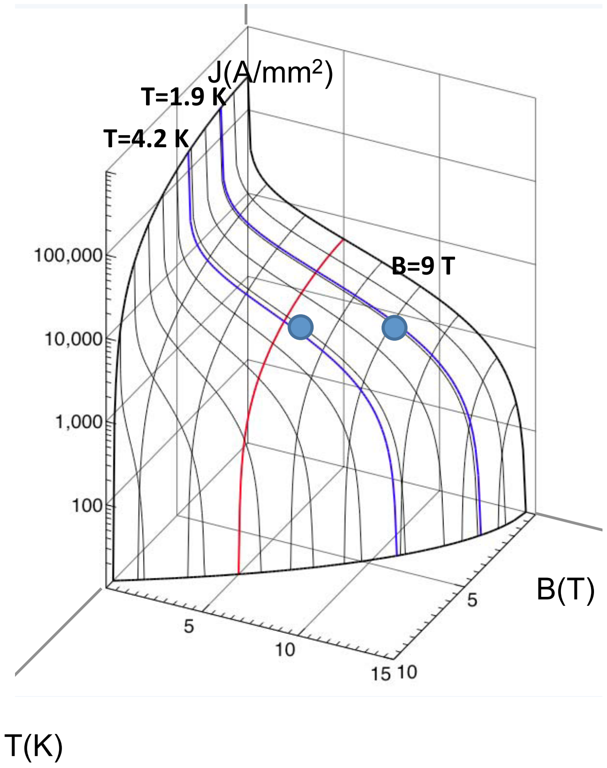
Courtesy M. Wilson



- Practical low temperature superconductors are made as thin (5 μm – 100 μm) superconducting filaments in a Cu matrix , which is twisted

Superconducting strands: Nb-Ti

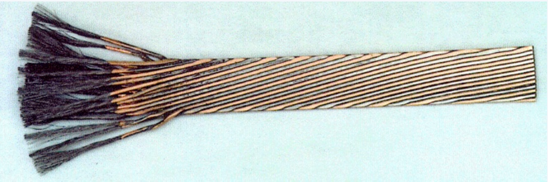
- Nb-Ti is the workhorse for present accelerators, medical magnets, cyclotrons, etc

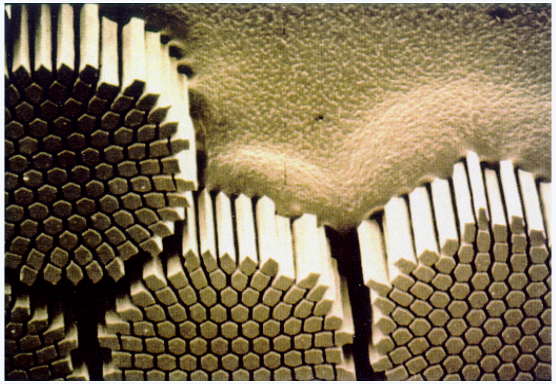


Strands and Cables for LHC Dipole Magnets

Performance specification

STRAND	Type 01	Type 02
Diameter (mm)	1.065	0.825
Cu/NbTi ratio	1.6-1.7 ± 0.03	1.9-2.0 ± 0.03
Filament diameter (μm)	7	6
Number of filaments	8800	6425
Jc (A/mm^2) @1.9 K	1530 @ 10 T	2100 @ 7 T
μ_0M (mT) @1.9 K, 0.5 T	30 ±4.5	23 ±4.5
CABLE	**Type 01**	**Type 02**
Number of strands	28	36
Width (mm)	15.1	15.1
Mid-thickness (mm)	1.900 ±0.006	1.480 ±0.006
Keystone angle (degrees)	1.25 ±0.05	0.90 ±0.05
Cable Ic (A) @ 1.9 K	13750 @ 10T	12960 @ 7T
Interstrand resistance (μΩ)	10-50	20-80



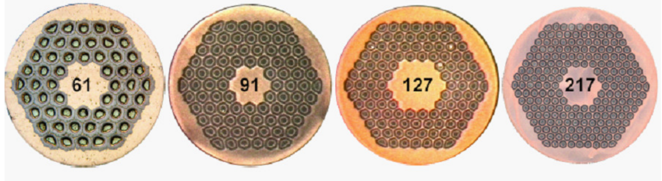


Cable compaction ~ 91 %

Superconducting strands: Nb$_3$Sn

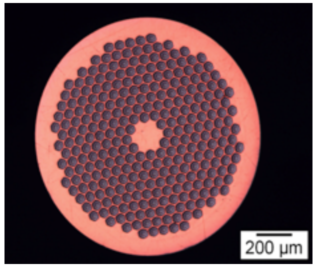
Nb$_3$Sn for High Field Magnets examples

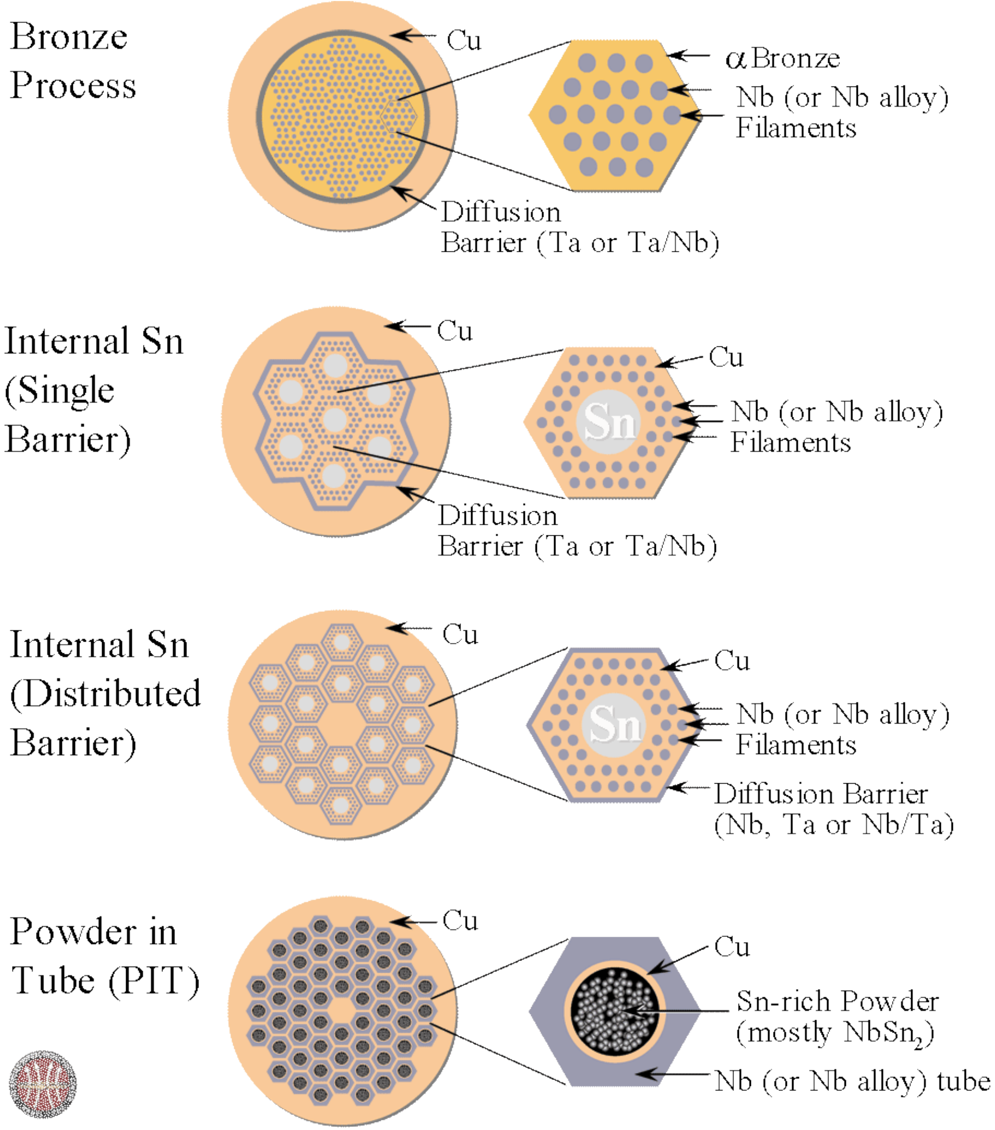
- OST (US)
  - –Restacked Rod Process (RRP) for High Energy Physics (r= 0.7 mm or 0.8 mm, J_c up to 3000 A/mm^2@12T, 4.2 K, filaments~50 µm, Cu-nonCu=0.9)



- EAS-Bruker (De)
  - –Powder in Tube (PIT) for HEP and others (r=1 mm, J_c up to 2400 A/mm^2@12T , 4.2 K, filaments ~50 µm, Cu-nonCu=1.25)

To be reacted at 650°C for ~120 hr

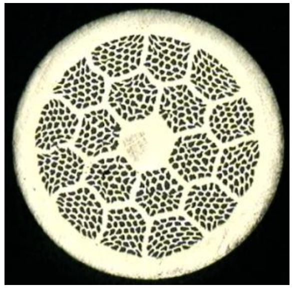




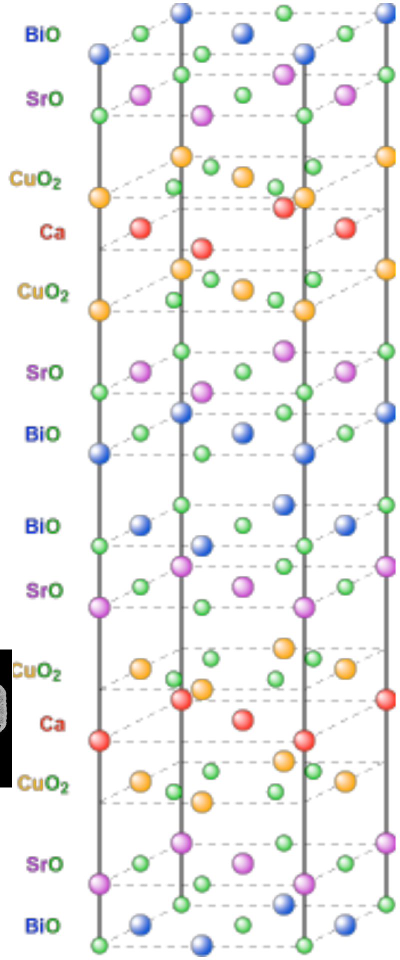
Superconducting strands and tapes: BSCO

BSCO: Bismuth strontium calcium copper oxide

- Available in strands (OST)
- Can reach 400 A/mm^2 (overall)
- Is fragile under stress and strain
- Powder in a silver tube
- Has to be reacted at 850°C with a temperature precision of 1°C in an oxygen atmosphere
- Can be cabled in high current Rutherford cables



OST wire 0.8 mm using Nexans precursor

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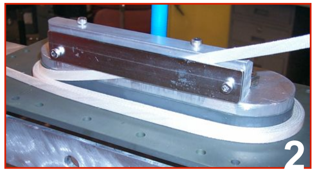
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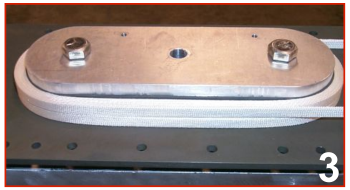
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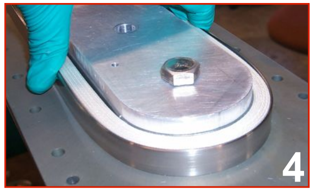
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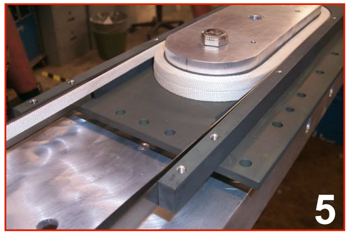
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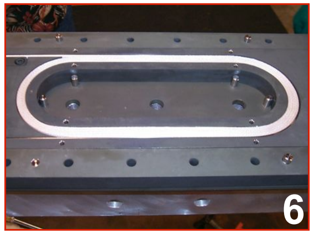
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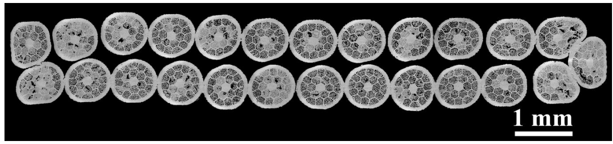
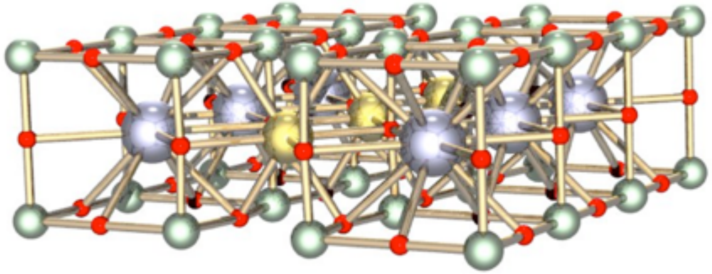


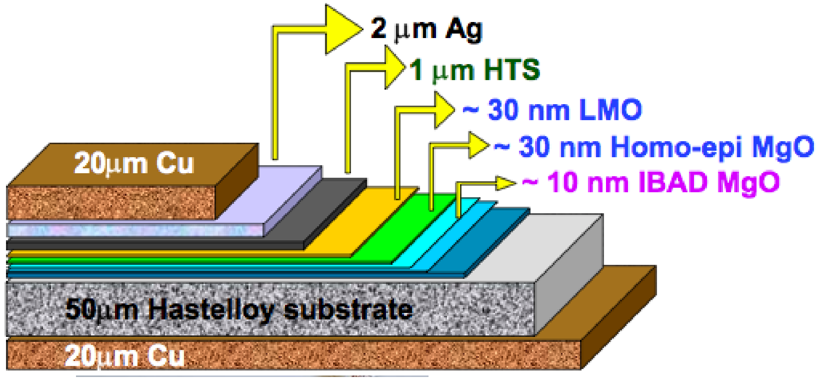
Difficult technology but could be promising for high field magnets in >20 T region

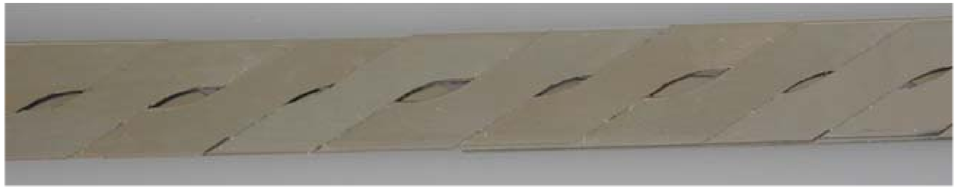
Superconducting tapes: YBCO



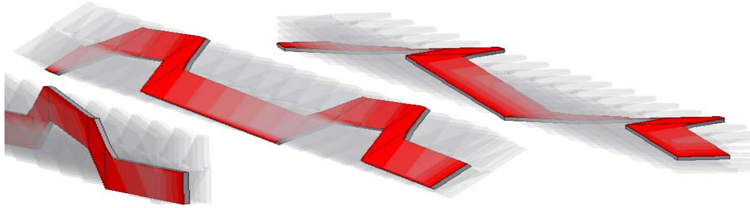
YBCO: Yttrium barium copper oxide

- Available in tapes : YBCO deposited on a substrate to impose the texture (1-2 μm)
- Can reach > 600 A/mm^2 (overall)
- Is strong under axial stress and strain
- Limited cabling possibilities:

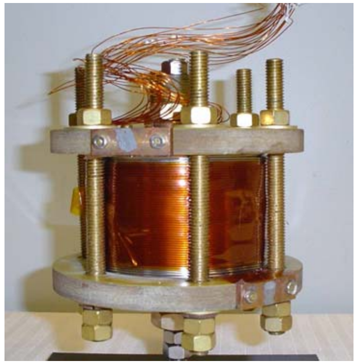




- Difficult technology but could be promising for high field magnets in >20 T region.



Potted racetrack coils



YBCO
SUPERPOWER
Record field (25 T),
adding 3 T
NHMFL - Florida

Superconducting cables for magnets

We need multi-strand cables

- Superconducting accelerators are ramped up in time spans 100 s to 1000 s
- Coils are designed for voltages to ground of around 1000 V
- With the number of turns and the current the inductance is to be limited to keep the voltage below 1000 V
- Dipoles and Current:
  - Tevatron B = 4.4 T ; I ~ 4000 A
  - Hera B = 5 T ; I ~ 6000 A
  - LHC B = 8.3 T ; I ~ 12000 A
- For magnets 10 T < B < 15 T the current has to be 10kA < I < 15 kA
- For stability reasons strands are 0.6 mm < strand diameter < 1 mm
- With a Cu-nonCu ratio (stability) around 1 and a Jc ~ 1000 A/mm^2

  ➔ a 1 mm diameter strand can carry ~400 A

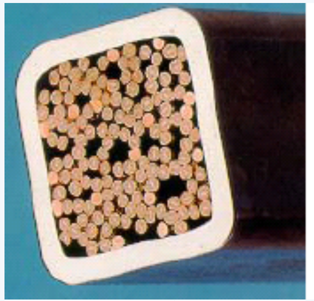
  ➔ need a 30 strand cable to get up to 12 kA

$$V = -L\frac{dI}{dt}$$

$$L \approx N^2$$

Cable types

CIC



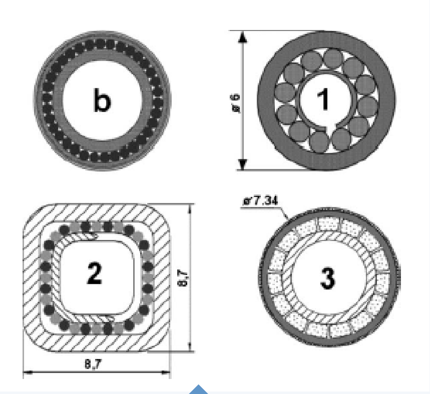
ITER magnets

Rutherford

Accelerator magnets

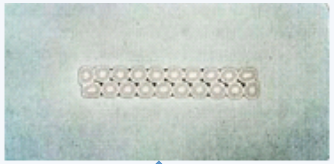
Tevatron, HERA
RHIC and LHC

Indirectly cooled

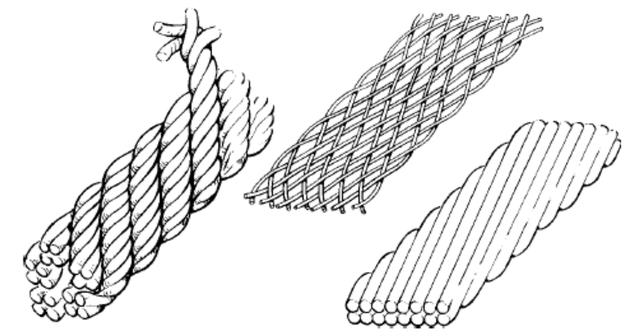


Nuclotron Type (b)
Pulsed SIS 100 magnets

Rutherford



Detector magnets

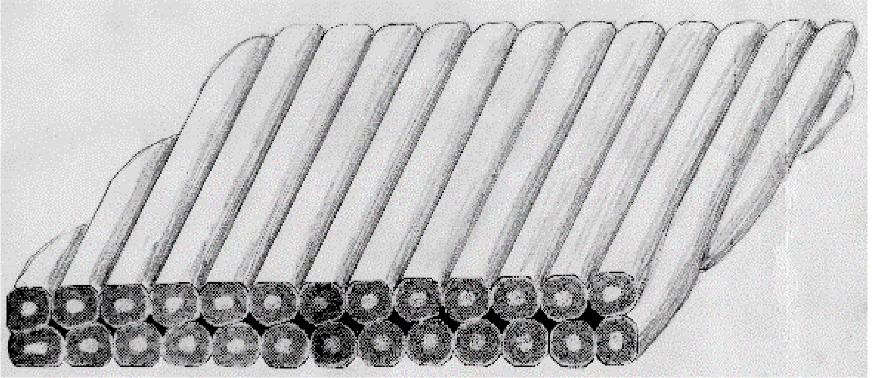


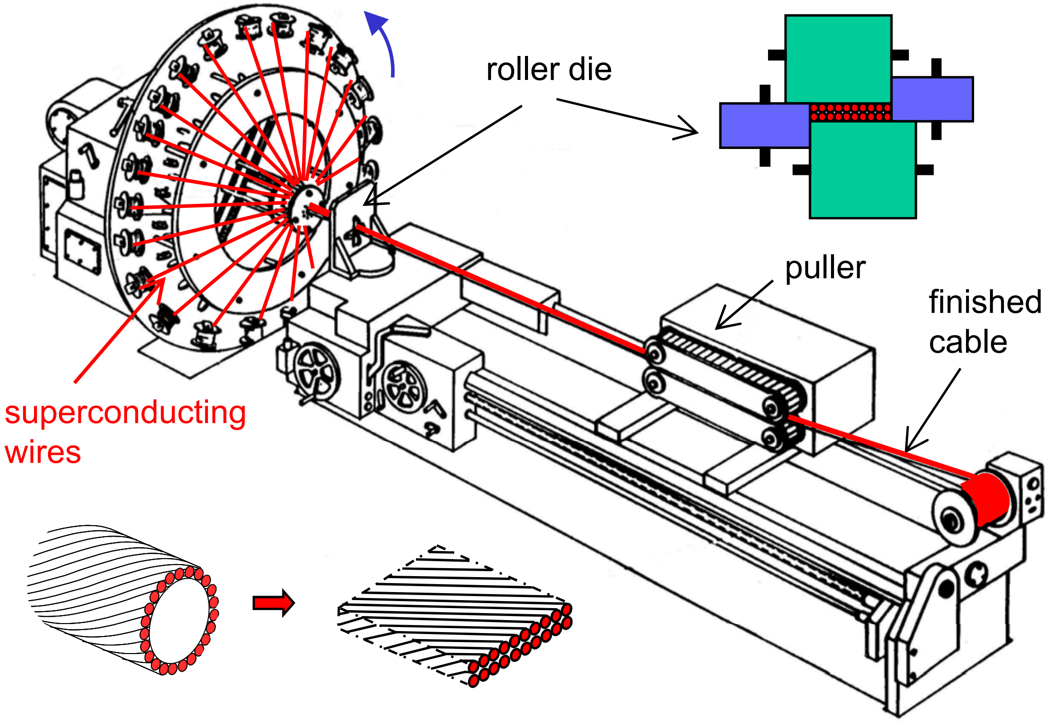
Rope, Braid and Rutherford cables

Courtesy A. Balarino

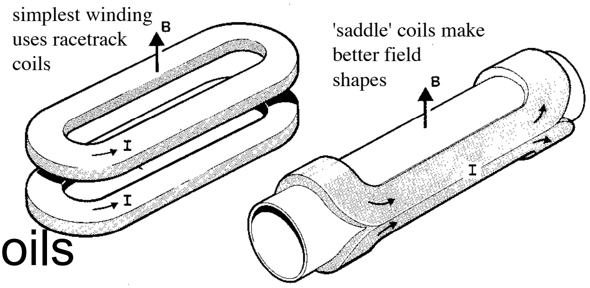
Rutherford cables

- Compact cables giving high over current density
- Can be wound relatively easy
- Easy rectangular geometry





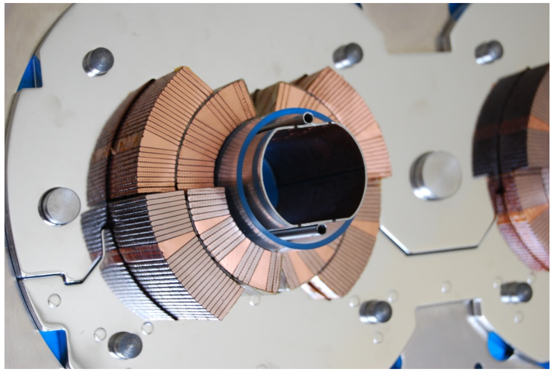
Practical accelerator magnet design: Dipoles

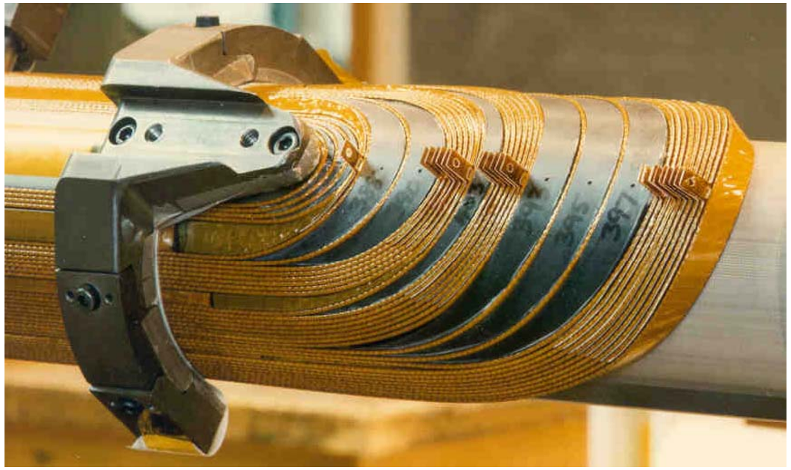


Two types of coils are in use for high field magnets:

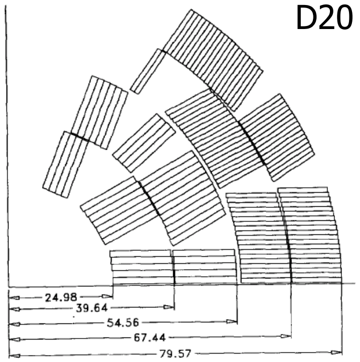
Cos(Θ) coil and *Block coil*

- Cos(Θ) coil
  - Allows a very good field quality ($b_n < 1 \cdot 10^{-4}$) in thin coils
    - all (but one) existing accelerators use this type of coil
  - Is very efficient wrt the quantity of superconductor used
  - The EM forces cause a stress buildup at the midplane where also high fields are located
  - Wedges are needed in the straight part (‘Keystoned’ cable)
  - The ends are short, special geometry for which there is a large experience but not it is easy





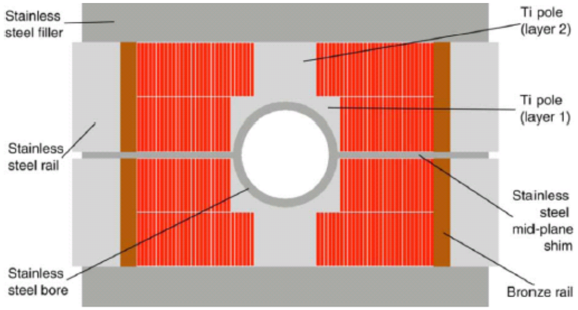
Courtesy M. Wilson

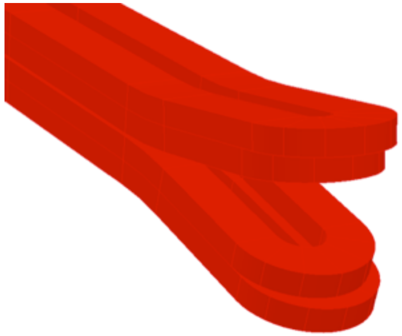


Courtesy LBNL

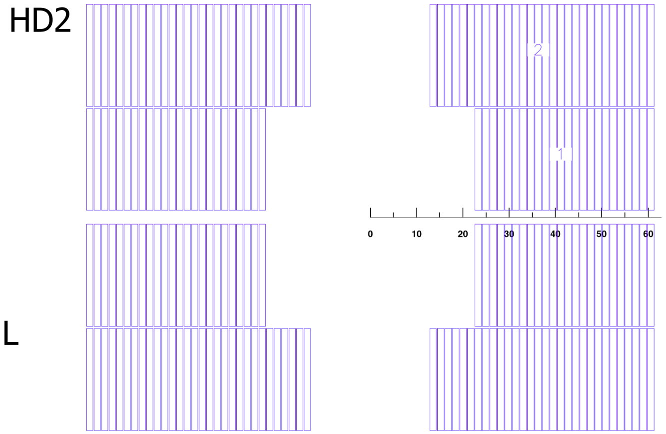
Practical accelerator magnet design: Dipoles

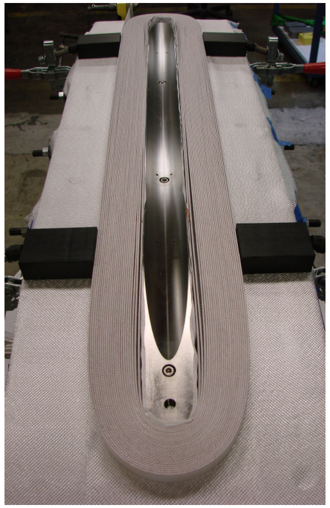
- Block coil
  - Used with thick coils the field quality is good
    - Not yet used in accelerators
  - Is less efficient (~10%) wrt to cos(Θ) for quantity of superconductor used
  - The EM forces cause a stress buildup at the outside edge of the coil where the fields are lower
  - The straight part is very easy : rectangular cable and wedges (field quality)
  - ‘flared ends’ look easy but there is little experience exists to make them





Courtesy LBNL

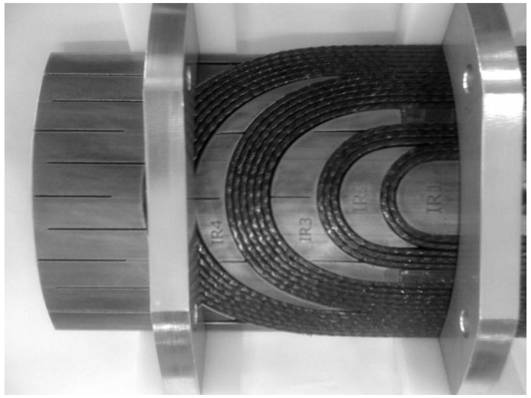


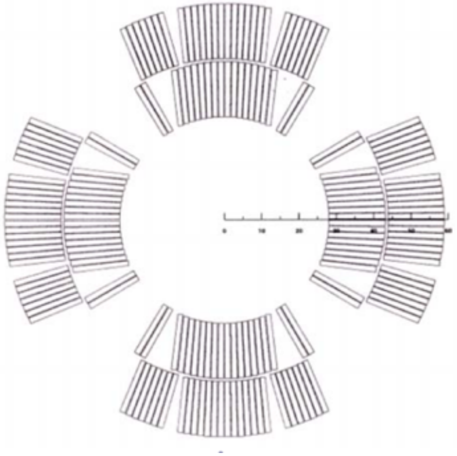


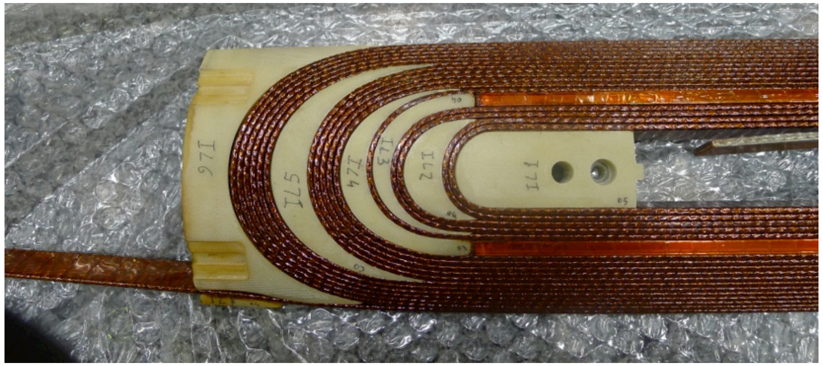
Quadrupole coil geometries

- Cos(Θ) coil
  - Allows a very good field quality ($b_n < 1 \cdot 10^{-4}$)
    - all (but one) existing accelerators use this type of coil
  - Is very efficient wrt the quantity of superconductor used
  - The EM forces cause a stress buildup at the midplane where also high fields are located, (but are limited)
  - Wedges are needed in the straight part (‘Keystoned’ cable)
  - The ends are short, special geometry for which there is a large experience but not it is easy

Courtesy M. Wilson



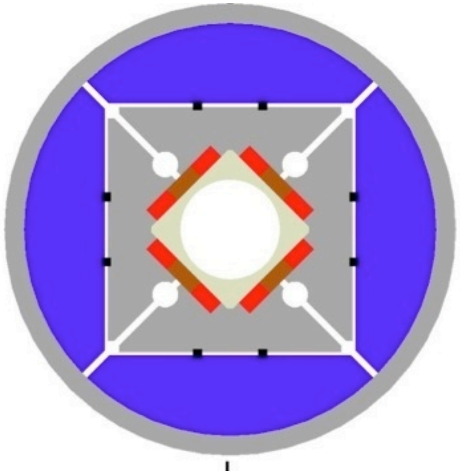




Quadrupole coil geometries

- Block coil
  - Used with thick coils the field quality is good
    - Not yet used in accelerators
  - Is less efficient (~10%) wrt to cos(Θ) for quantity of superconductor used
  - The EM forces cause a stress buildup at the outside edge of the coil where the fields are lower
  - The straight part is very easy : rectangular cable and wedges (field quality)
  - Model with racetrack coils were built but is not pursued

Subscale Quadrupole
SQ
0.3 m long
110 mm bore



Prestress

- Why prestress ?
  - Field quality is determined by the cable positions (be precise to ~0.02 mm)
  - Under the MN forces the coils will move

    ➔Apply prestress to fix the positioning
  - Very small amounts of heat can quench the coil: limit the movement (avoid stick-slip effects on ~10 μm movements)

    ➔Apply prestress to fix the positioning
- How to put prestress ?

  Three methods:

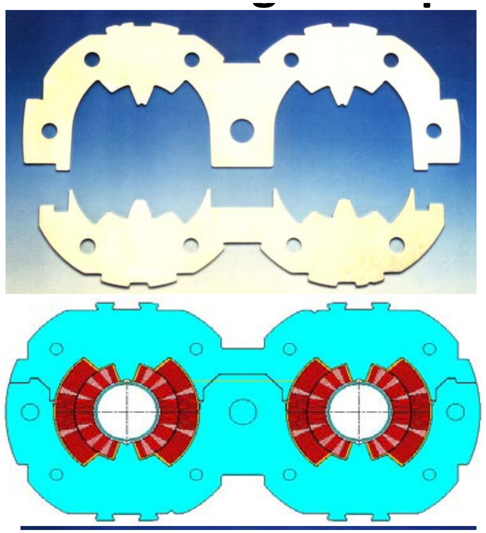
  1. Compress at room temperature: collar system
  2. Use room temperature prestress plus differential shrinkage at cooldown: Al or stainless steel shrinking cylinder and/or a (shrinking) key
  3. Compress a bit at room temperature and use differential shrinkage at cooldown: Al shrinking cylinder + bladder and key system
- Order of magnitudes: LHC 8.34 T: 70 MPa warm, 30 MPa cold

  Fresca2 13 T: 60 MPa warm, 130 MPa cold

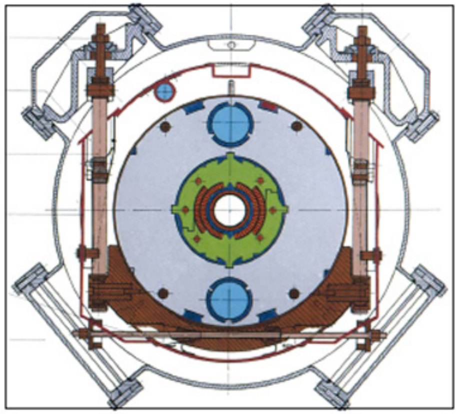
Prestress: collars

"The classical solution"

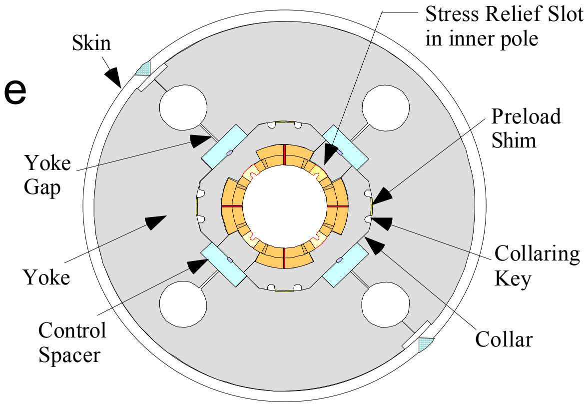
- Thin collars put around the coil
- The coil is well contained in a fixed cavity
- Pressed together and locked with pins or keys
- At 300K apply a prestress 2-3 times of what is needed as part of the stress is lost during cooldown: for very high field tends to be too high (LHC:70 MPa at 300 K and 40 MPa at cold)
- Field quality is in good part determined by collar shape
- If the coils size is not so well controlled, the stress can be too high or too low
- Nb_3Sn is stress sensitive and this could be a problem



LHC dipole
CERN



Hera dipole
DESY

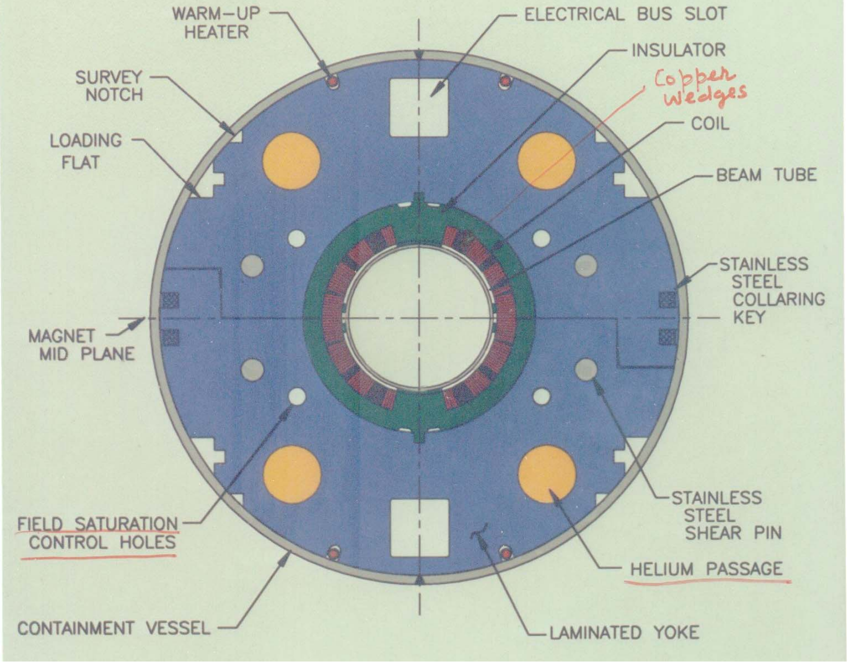


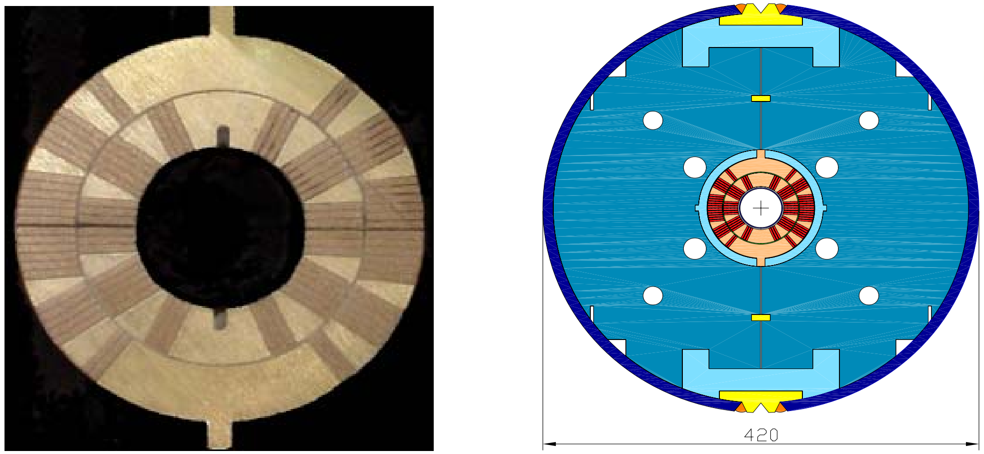
TQC quadrupole
LARP-FNAL

Prestress: shrinking cylinder and/or prestress key

- The differential shrinking and room temperature prestress between a (thick) shell or key and the Fe (split) yoke provides prestress
- Pre-stress completely depends on dimensioning of the components and the materials

Relativistic Heavy Ion Collider





HFDA
FNAL

Figure 1: HFDA coil and magnet cross-sections.

Courtesy A. Zlobin

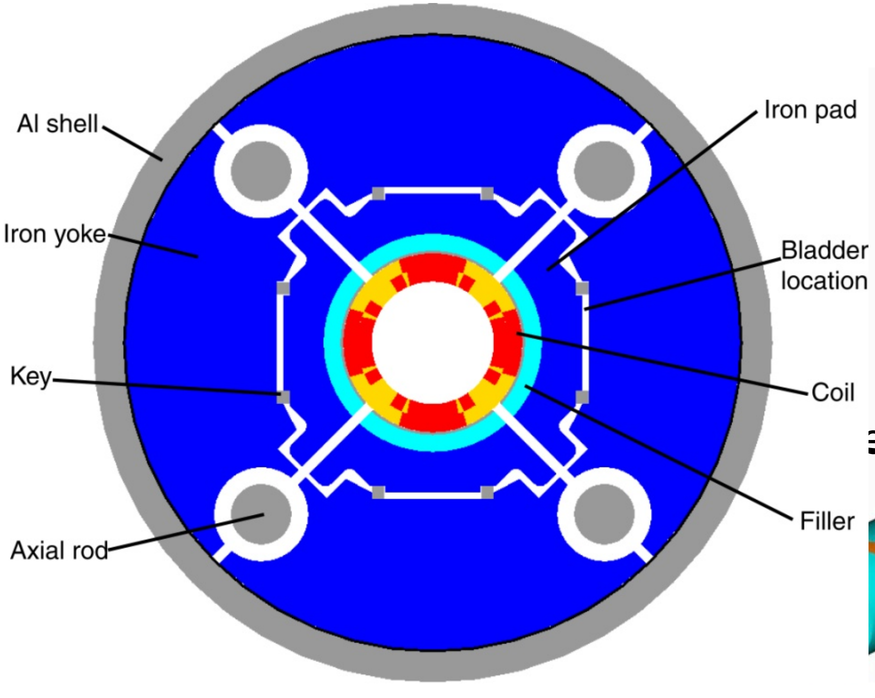
Prestress: Al shrinking cylinder + bladder and keys

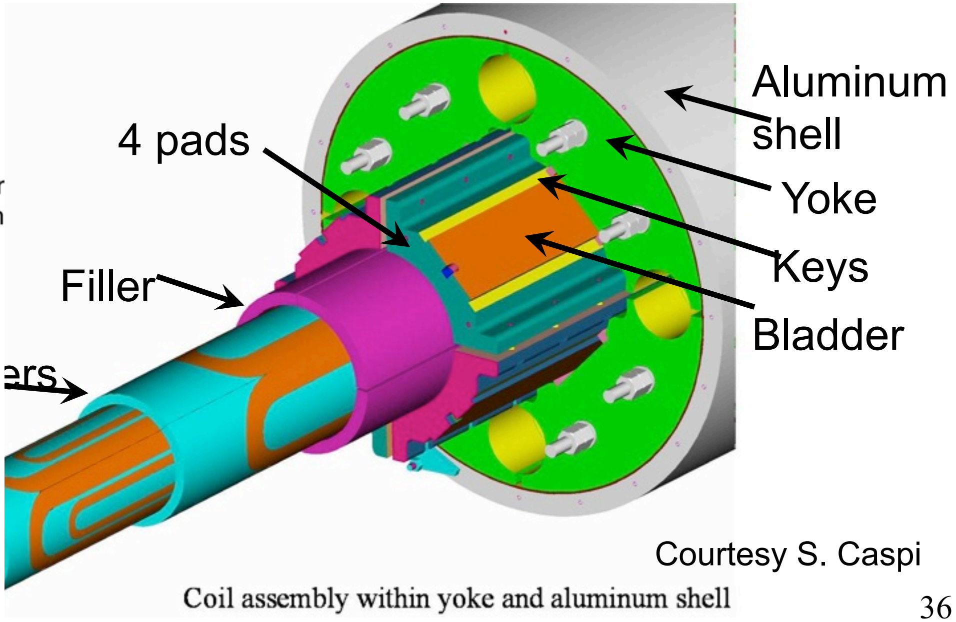
Developed at LBNL, example: TQS a LARP model quadrupole

300K: Bladders pressurized with water (<600 bar) , then insert keys ➔ load between 10 MPa and 80 MPa

Cooldown: differntial shrinkage between AL shell and Fe yoke load another ~100 MPa

Needs careful mechanical FE modeling before and strain measurements during bladder operations and cooldown



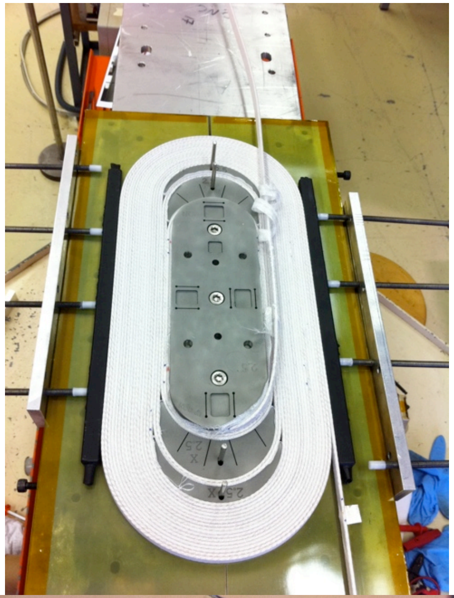


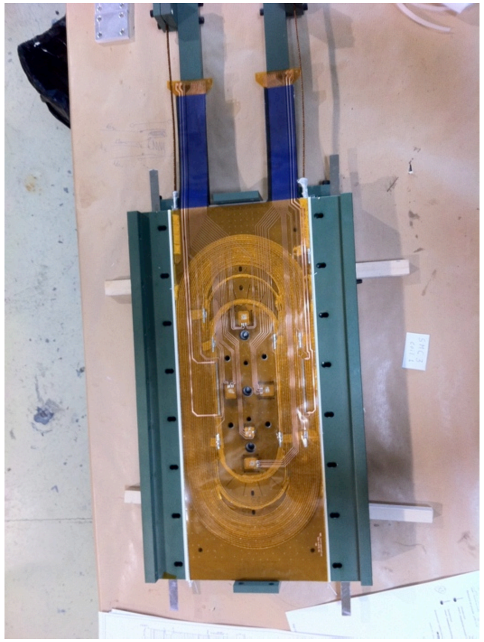
Courtesy S. Caspi

Coil assembly within yoke and aluminum shell

Manufacturing of Nb_3Sn Magnets

- Nb_3Sn has to be reacted after winding for ~120 hr at 650°C (react and wind)
- Cables have to be insulated with a non-organic woven insulation: glass fibre or ceramic
- After reaction the coils has to be impregnated to prevent any movements and to take care that stresses are distributed, instrumentation connections are moulded in
- Reacted Nb_3Sn is brittle and stress sensitive



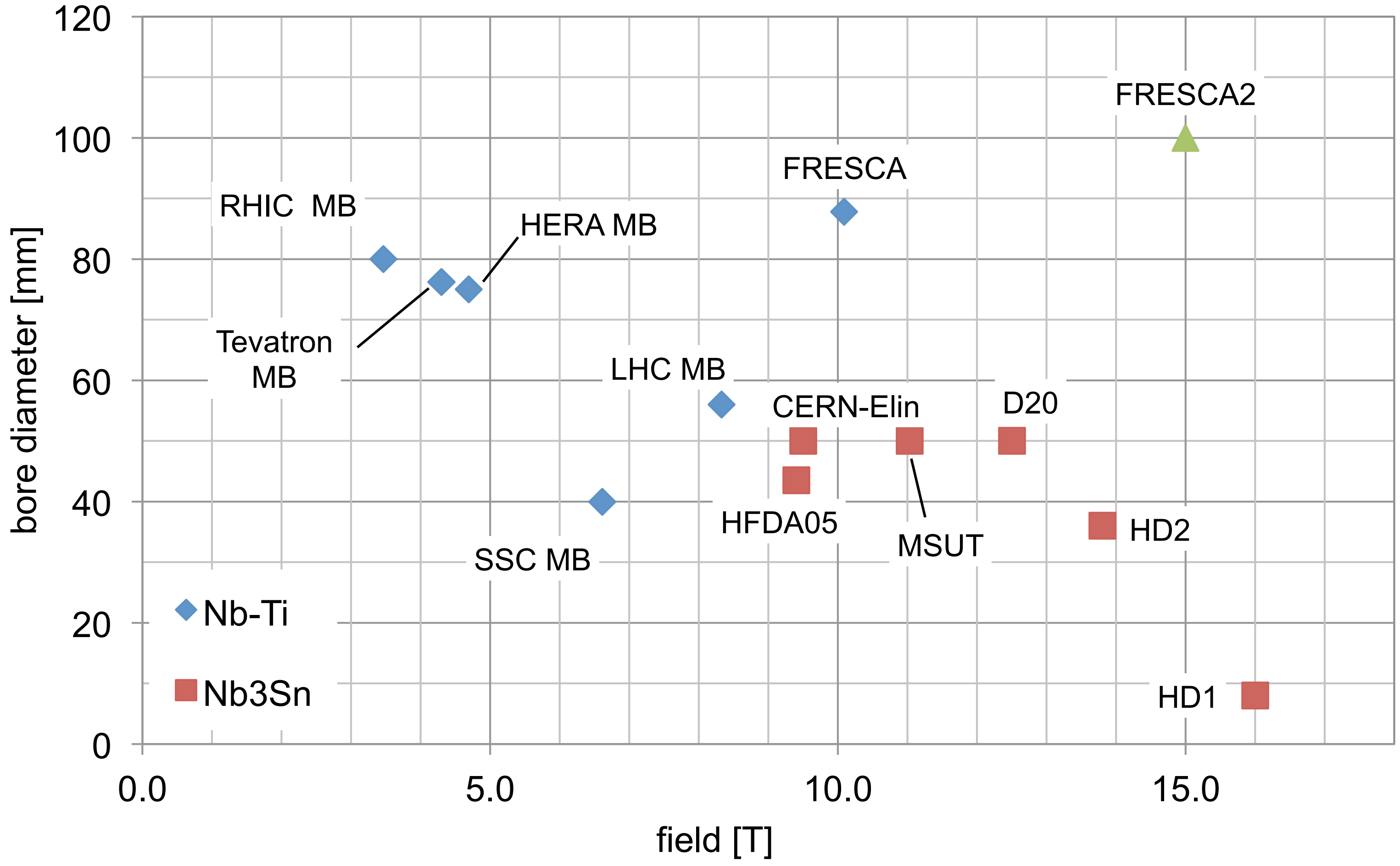


Comparison of magnets

Nb-Ti : blue diamonds, nominal field

Nb_3Sn: red squares, maximum field

As a rule magnets are used with ~20% margin (nominal = 0.8 x maximum)



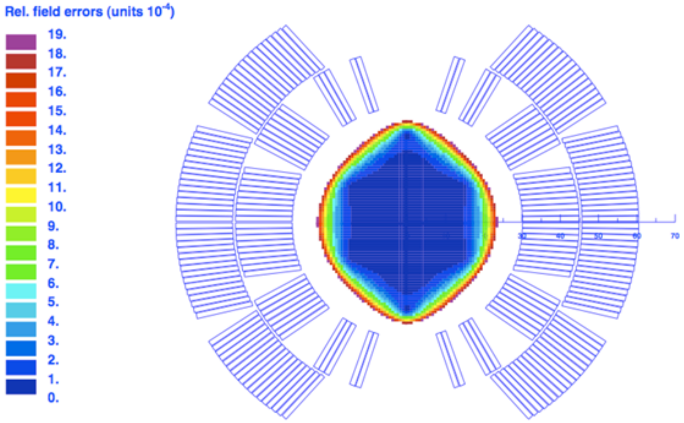
High Field dipole designs: 11T Dispersion Suppressor

Developed at FNAL and CERN for the LHC luminosity upgrade.

two 5.5 m 11 T dipoles should replace one 15 m 8.3 T main dipole

Has to operate in series with the main bend dipole chain: 11 T @ 11850 A

Potentially the first Nb_3Sn magnet to be used in an accelerator (2017)



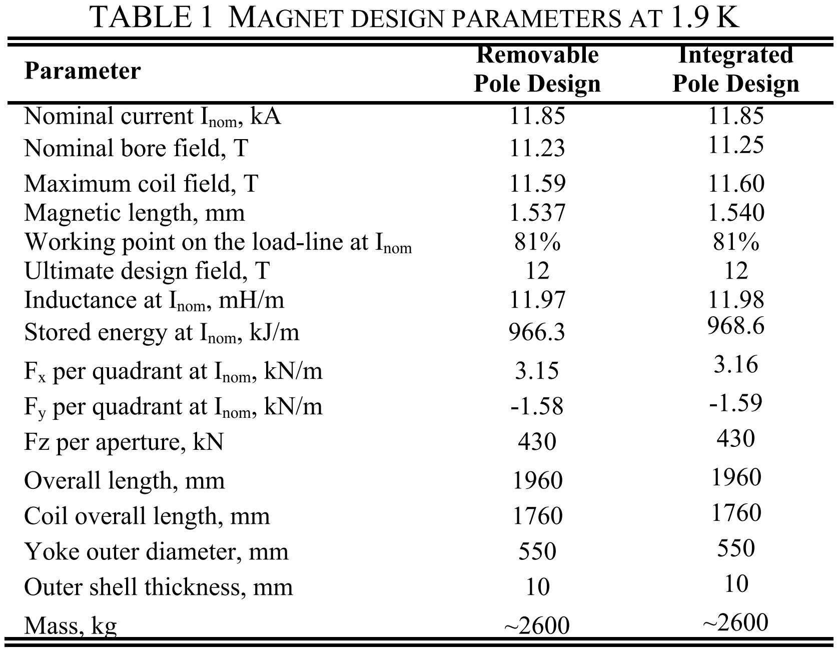
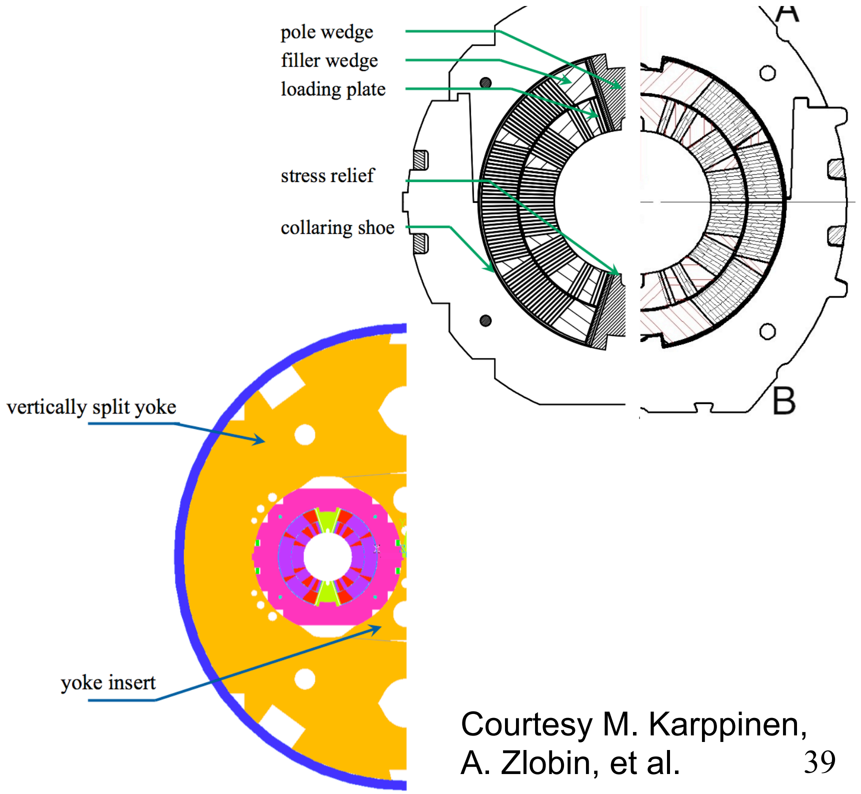


TABLE 1 MAGNET DESIGN PARAMETERS AT 1.9 K

Parameter	Removable Pole Design	Integrated Pole Design
Nominal current I_{nom}, kA	11.85	11.85
Nominal bore field, T	11.23	11.25
Maximum coil field, T	11.59	11.60
Magnetic length, mm	1.537	1.540
Working point on the load-line at I_{nom}	81%	81%
Ultimate design field, T	12	12
Inductance at I_{nom}, mH/m	11.97	11.98
Stored energy at I_{nom}, kJ/m	966.3	968.6
F_x per quadrant at I_{nom}, kN/m	3.15	3.16
F_y per quadrant at I_{nom}, kN/m	-1.58	-1.59
Fz per aperture, kN	430	430
Overall length, mm	1960	1960
Coil overall length, mm	1760	1760
Yoke outer diameter, mm	550	550
Outer shell thickness, mm	10	10
Mass, kg	~2600	~2600



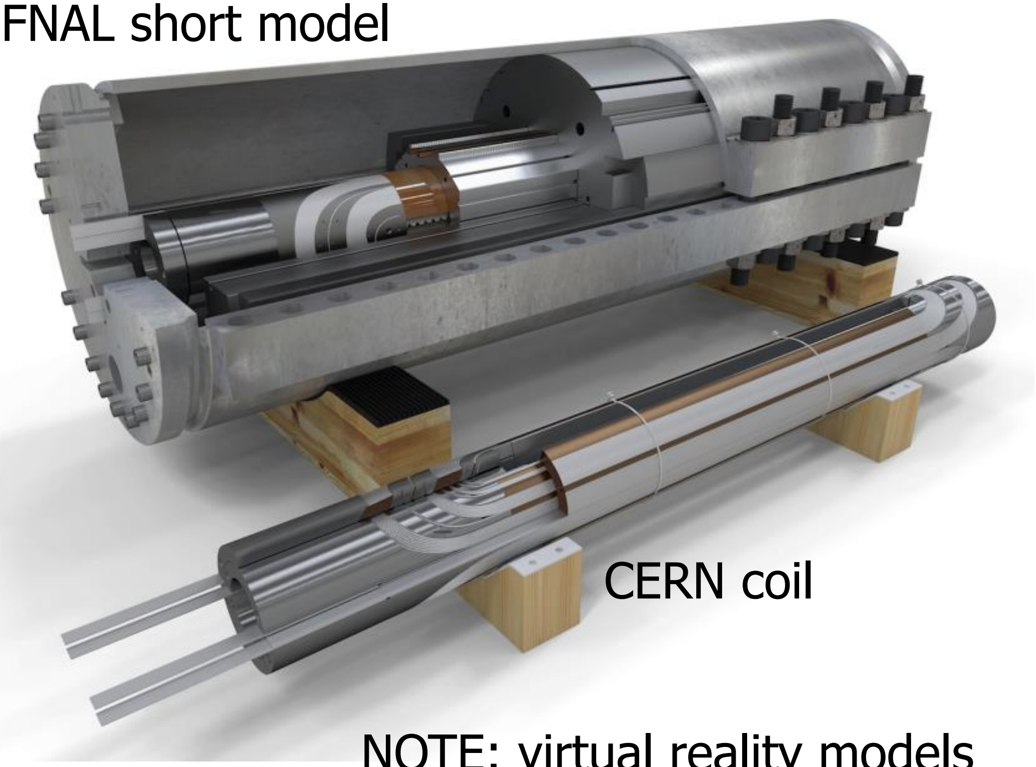
Courtesy M. Karppinen, A. Zlobin, et al.

11 T model program

- Demonstrate the required performance (11.25 T at 11850 A)
- Achieve accelerator field quality
- Study in depth mechanics and manufacturing
- Address specific issues such as quench protection

Next 2 years !

FNAL short model



CERN coil

NOTE: virtual reality models

FNAL MBHSP02 ready for test

CERN 54/61 *practice* coil

By courtesy of D. Mitchell, F. Nobrega (FNAL) and M. Karppinen (CERN)

High Field dipole designs: HD2

- HD2 : LBNL, working model
- Maximum field 13.8 T (87% x Jc)

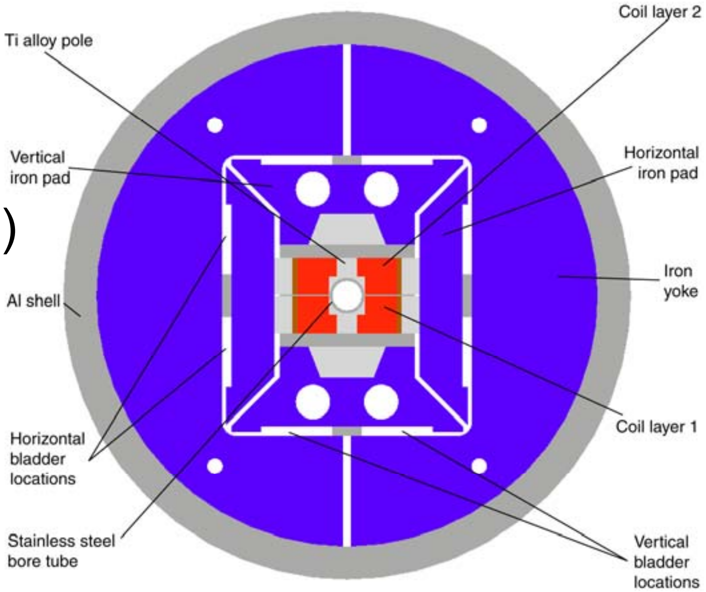


Fig. 2. HD2 cross-section.

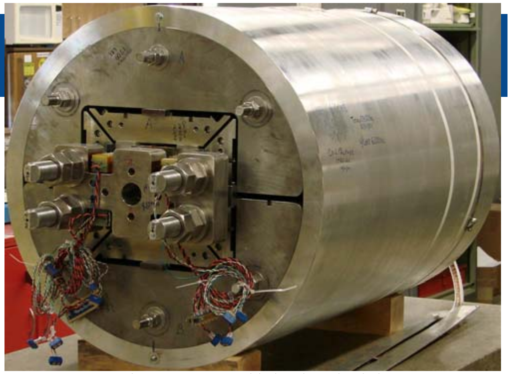


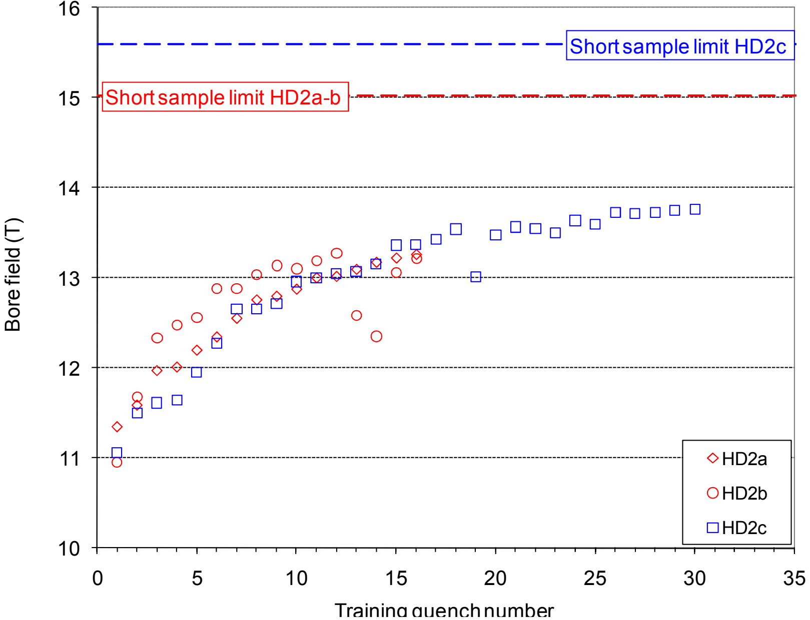
Fig. 1. HD2 assembled and pre-loaded.

TABLE I Cable Parameters

Parameter	Unit	Coil 1	Coil 2-3
Strand diameter (before reaction)	mm	0.802	0.801
Process		Restacked Rod Process	
Stack		54/61	
Non Cu %		51	54
RRR		16	287
Twist pitch	mm	13	14
No. strands		51	
Cable width (bare)	mm	22.008	21.999
Cable thickness (bare)	mm	1.401	1.406
Insulation thickness	mm	0.095	

TABLE II Magnet Parameters

Parameter	Unit	HD2a-b	HD2c
Clear aperture	mm	36	
Magnet outer diameter	mm	705	
No. turns in layer 1 (quadrant)		24	
No. turns in layer 2 (quadrant)		30	
Short sample current I_{ss} at 4.3/1.9 K	kA	17.3/19.2	18.1/20.0
Bore field at 4.3/1.9 K I_{ss}	T	15.0/16.5	15.6/17.1
Coil peak field at 4.3/1.9 K I_{ss}	T	15.9/17.4	16.5/18.1
Fx/Fy layer 1 (quadrant) at 17.3 kA	MN/m	+2.3/-0.4	
Fz layer 1 (quadrant)at 17.3 kA	kN	90	
Fx /Fy layer 2 (quadrant) at 17.3 kA	MN/m	+3.3/-2.2	
Fz layer 2 (quadrant) at 17.3 kA	kN	126	
Stored energy at 17.3 kA	MJ/m	0.84	
Inductance	mH/m	5.6	



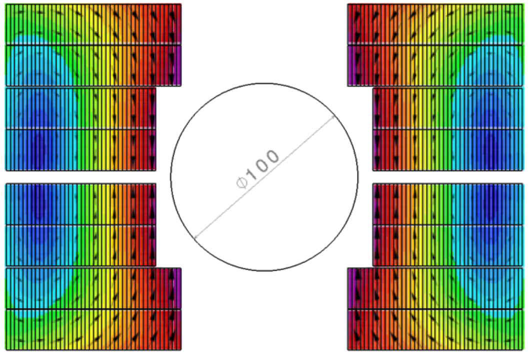
Courtesy P. Ferracin

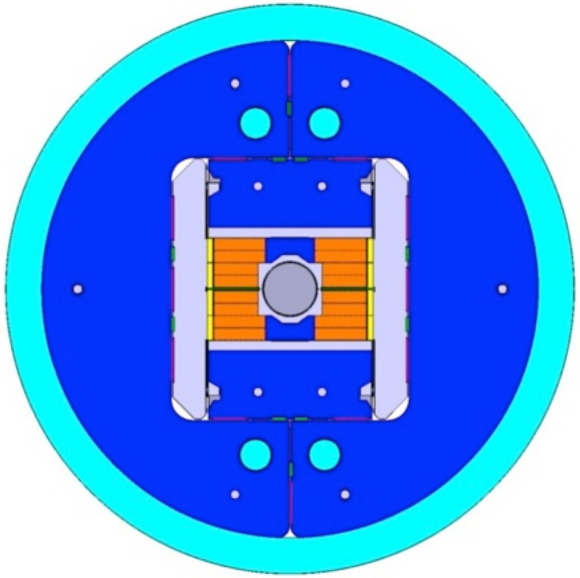
EuCARD high field dipole (Fresca2)

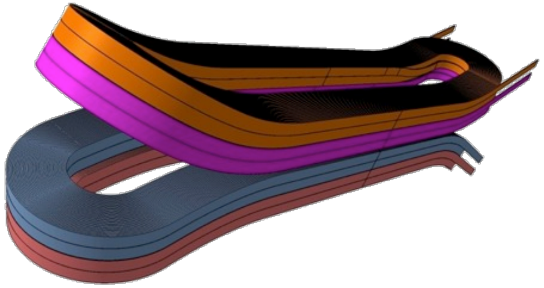
- Fresca2 : CERN, CEA construction phase
- First tests 2014

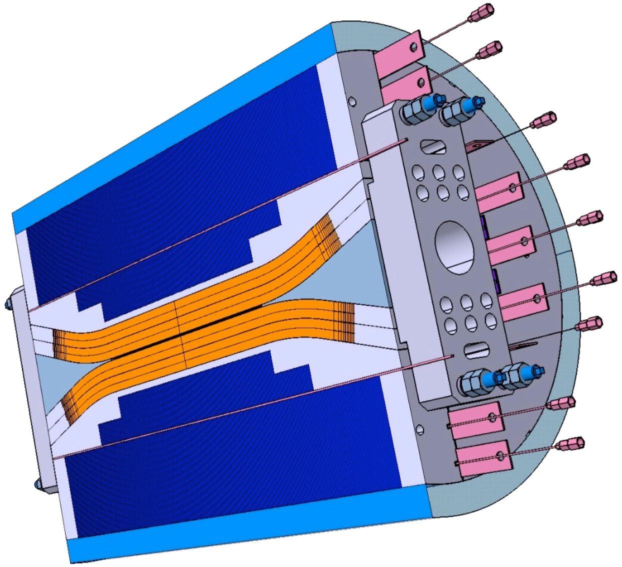
- 156 turns per pole
- Iron post
- B_{center} = 13.0 T
- I_{13T} = 10.7 kA
- B_{peak} = 13.2 T
- E_{mag} = 3.6 MJ/m
- L = 47mH/m

- Diameter Aperture = 100 mm
- L coils = 1.5 m
- L straight section = 700 mm
- L yoke = 1.6 m
- Diameter magnet = 1.03 m







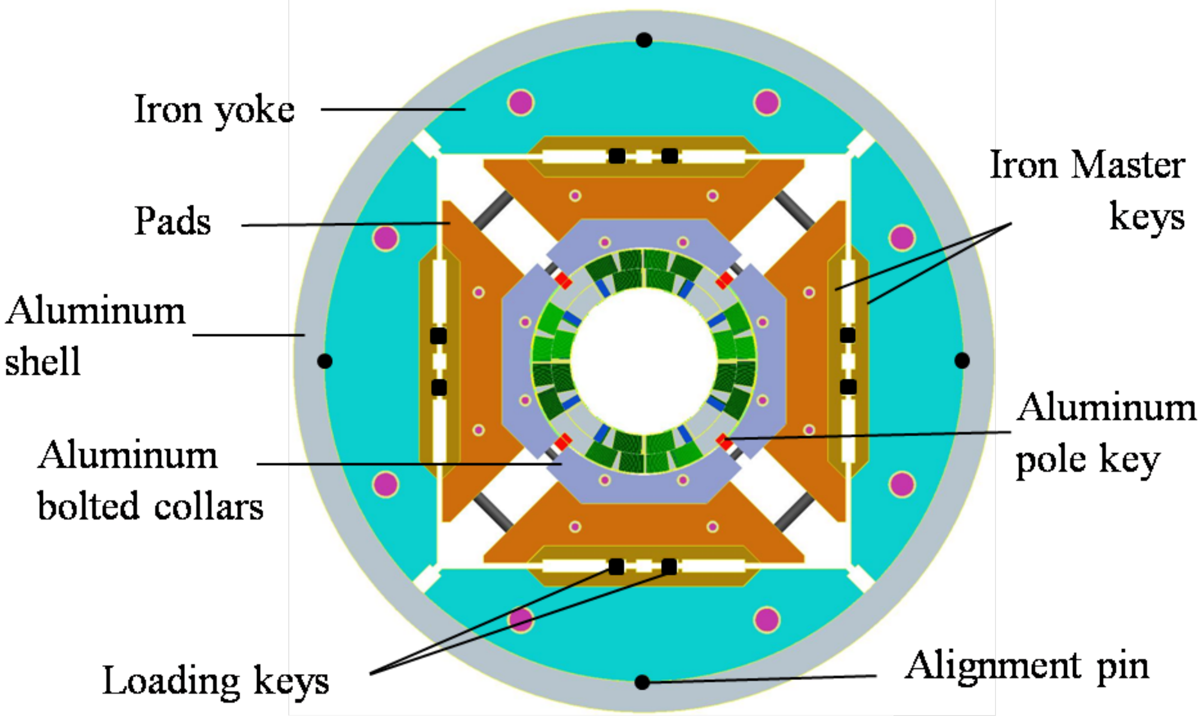


Courtesy Attilio Milanese, Pierre Manil

High Field quadrupole designs: HQ

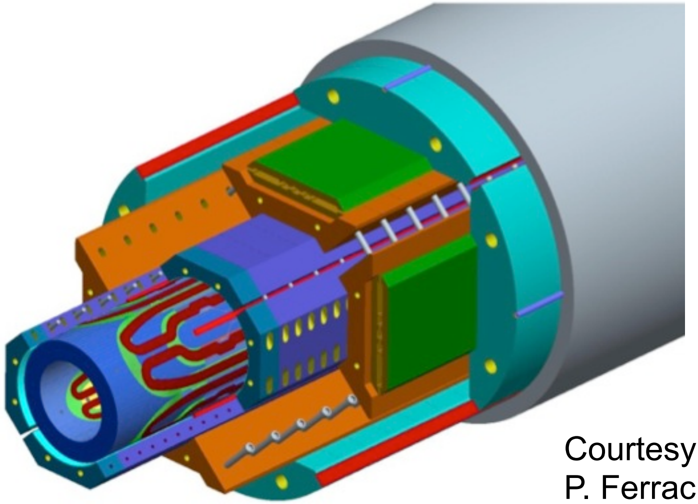
HQ: model quadrupole for LHC insertion upgrade,

Developed by LARP: LBNL, FNAL and BNL



- 0.8 mm strand
- 15 mm wide cable
- 120 mm bore

4.4 K/1.9 K -195/214 T/m
4.4 K/1.9 K – 13.7/14.9 T



Courtesy S.Caspi, H. Felice, P. Ferracin

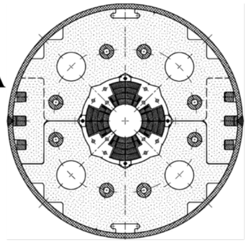
High field magnets for future accelerators: HL-LHC

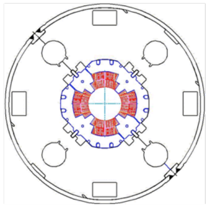
For the Luminosity upgrade of the LHC (High Luminosity LHC) several scenarios are under study which mainly involve the following high field magnets:

1. Make space for a collimator in the Dispersion Suppressor regions: replace a 15 m long 8.34 T dipole (MB) with two 5.5 m long 11 T dipoles with a collimator in between (11 T DS magnets, FNAL-CERN project)
2. Replace the low-β insertion quadrupoles (MQXA/B, 6.4/5.5 m, 70 mm, 215 T/m), with new wide aperture quadrupoles: MQXD, 8 m, 120-140 mm, 195 T/m (HQ, LARP project)
3. Replace the warm single aperture D1 separation dipoles (6 x 3.4 m, 1.28 T) with a single 8 T 150 mm dipole (D1, KEK project)
4. Replace the SC D2 double aperture separation dipoles with new larger aperture magnets (7 m, 100 mm, 5 T)
5. Replace the Q4 double aperture quadrupole with large aperture ones (4.2 m, 90 mm, 120 T/m)
6. + various corrector magnets

LHC IP Quadrupole design and technology evolution

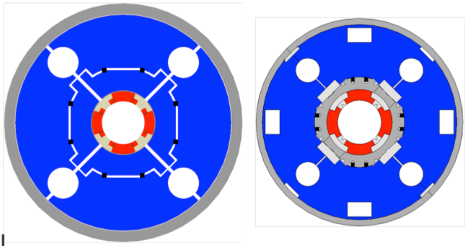
KEK MQXA
Nb-Ti, 6.6 m
70 mm apert.
205 T/m

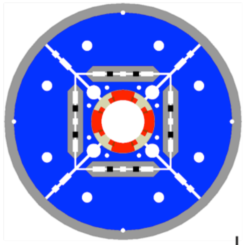




FNAL MQXB
Nb-Ti, 5.7 m
70 mm apert.
205 T/m

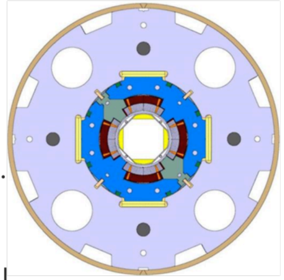
LARP TQS-TQC
Nb_3Sn, 1 m
90 mm apert.
200 T/m

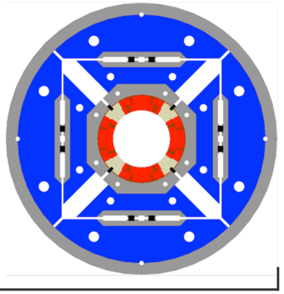




LARP LQS
Nb_3Sn, 3.7 m
90 mm apert.
200 T/m

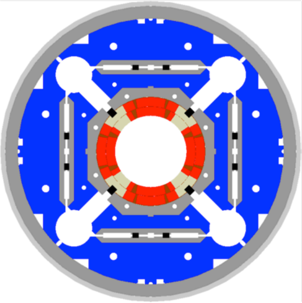
CERN-CEA MQXC
Nb-Ti, 2 m
120 mm apert.
118 T/m





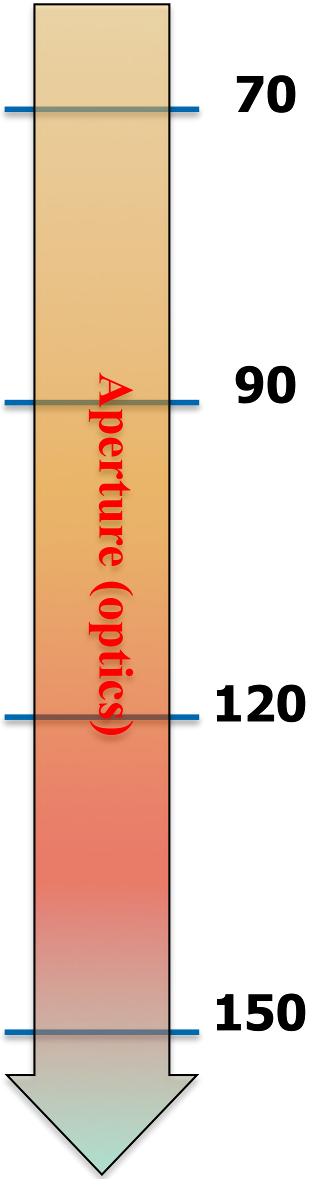
LARP HQ
Nb_3Sn, 1 m
120 mm apert.
170 T/m

LARP-CERN QXF
Nb_3Sn, 1.5 m
150 mm apert.
140 T/m



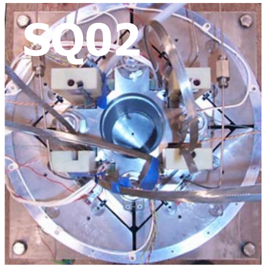
Courtesy L. Bottura

US LHC Accelerator Research Program
brookhaven - fermilab - berkeley



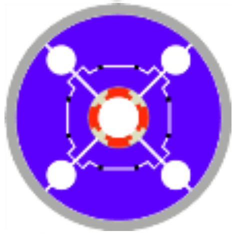
Ten years of intense R&D

Subscale Quadrupole
SQ
0.3 m long
110 mm bore
2004-2006

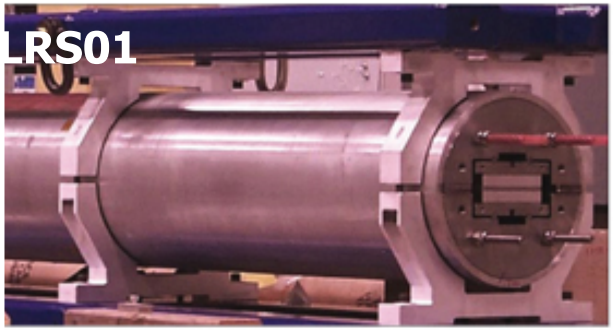


U.S. DEPARTMENT OF ENERGY
Office of Science
BROOKHAVEN NATIONAL LABORATORY
BERKELEY LAB

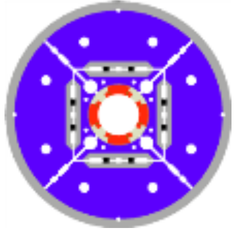
Technology Quadrupole
TQS - TQC
1 m long
90 mm bore
2006-2010



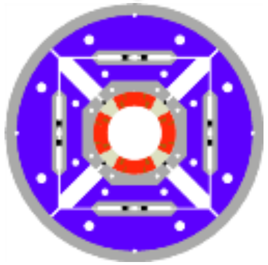
Long Racetrack
LRS
3.6 m long
No bore
2006-2008

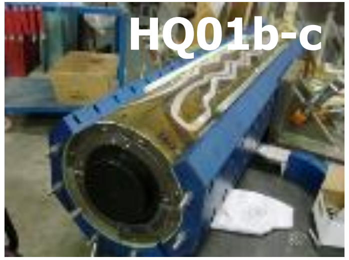


Long Quadrupole LQS
3.7 m long
90 mm bore
2007-2012



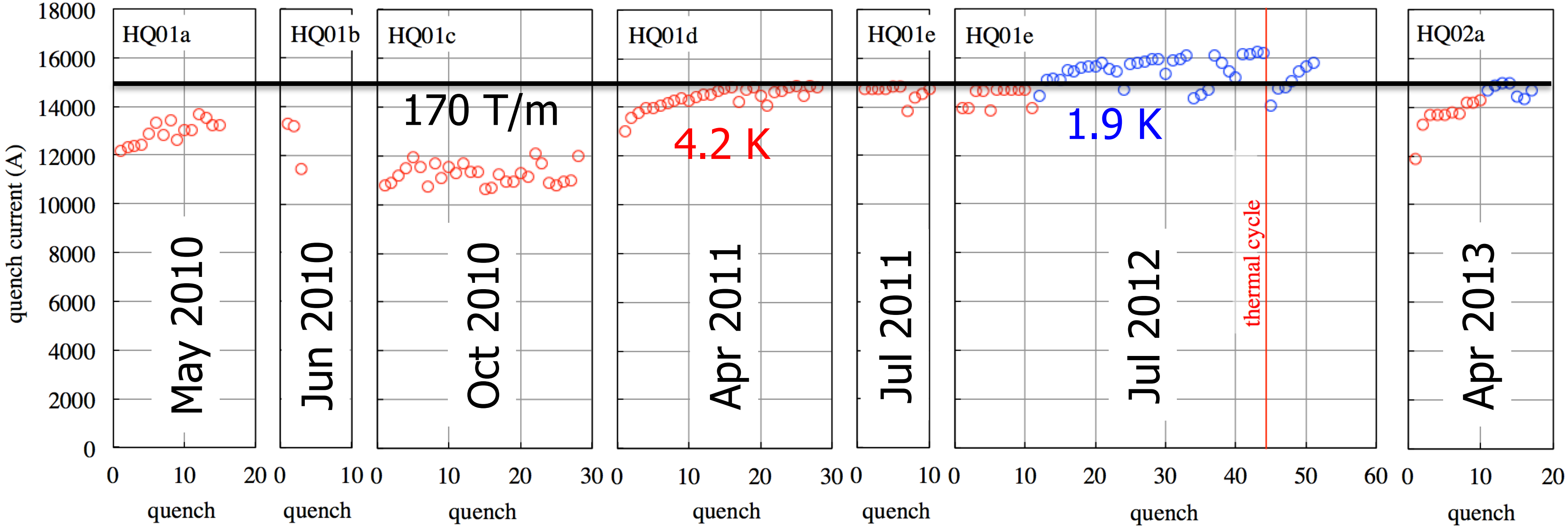
High Field Quadrupole HQ
1 m long
120 mm bore
2008-2014

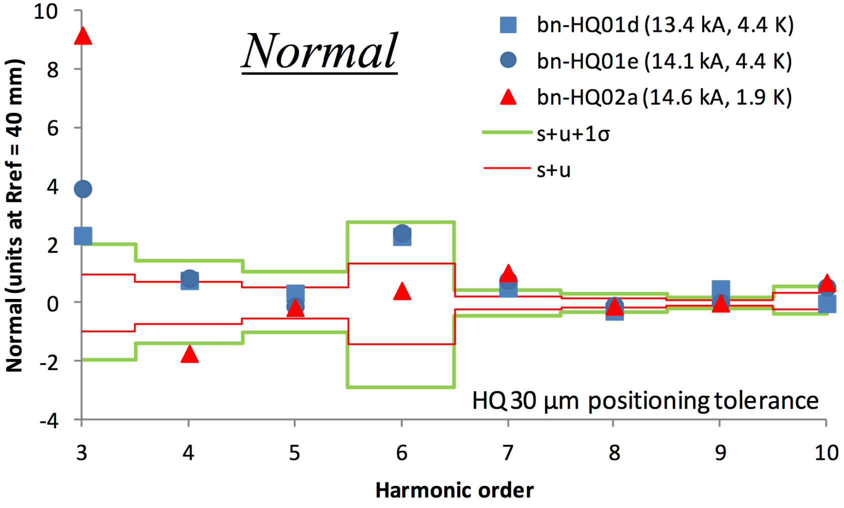


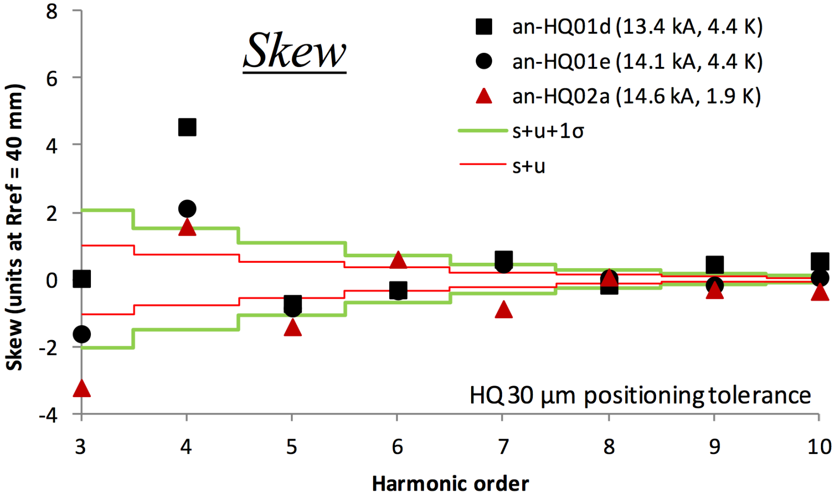


Courtesy G. Sabbi & H. Felice

HQ performance (120 mm, 170 T/m)



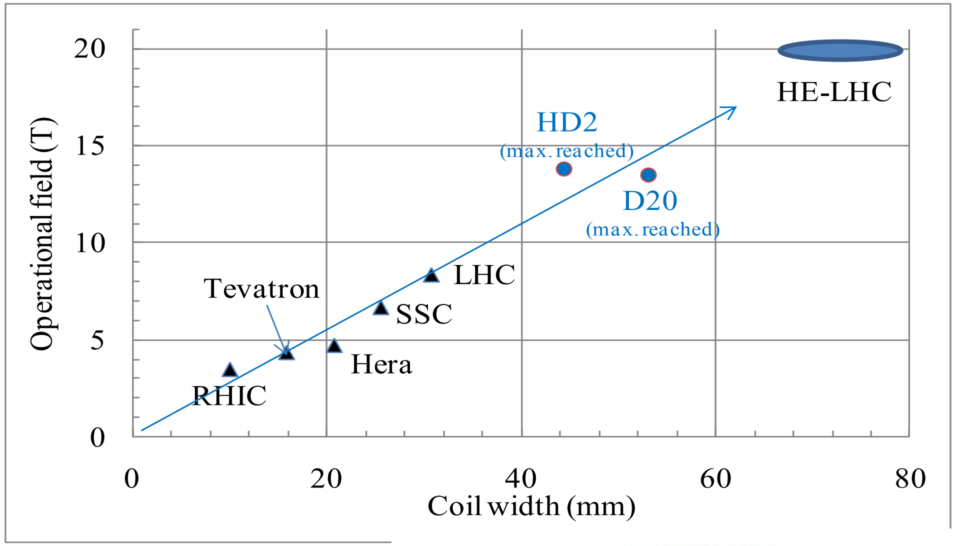


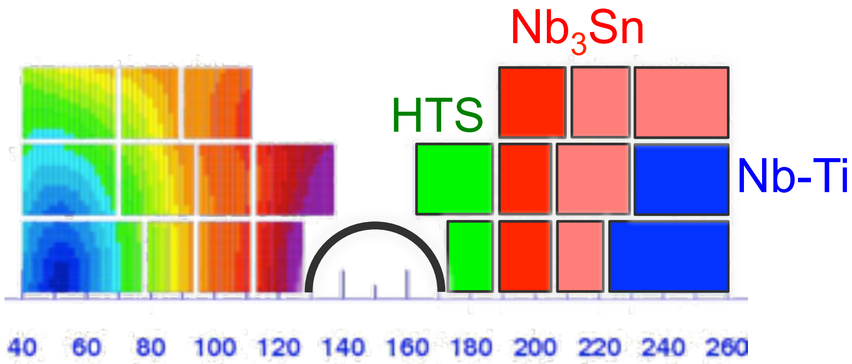


CourtesyG. Chlachidze, J. Di Marco (FNAL), X. Wang (LBNL)

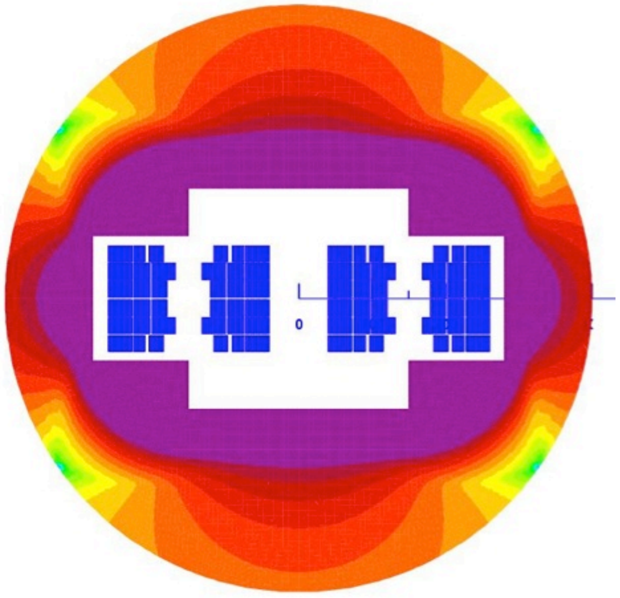
Magnets for HE-LHC

- For a 17 + 17 TeV collider
  - Need 20 T dipoles
- study to start soon
  - HTS-Nb_3Sn-Nb-Ti nested coil
- EuCARD2 HFM proposal being discussed
  - 20 T conductor development
  - Construct demonstrator
- CERN + others 20 T design study



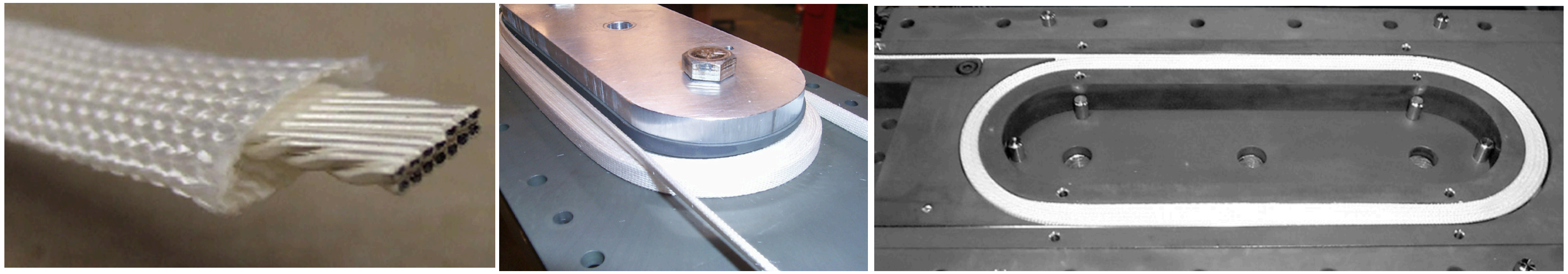


Material	N. turns	Coil fraction	Peak field	$J_{overall}$ (A/mm^2)
Nb-Ti	41	27%	8	380
Nb3Sn (high Jc)	55	37%	13	380
Nb3Sn (Low Jc)	30	20%	15	190
HTS	24	16%	20.5	380



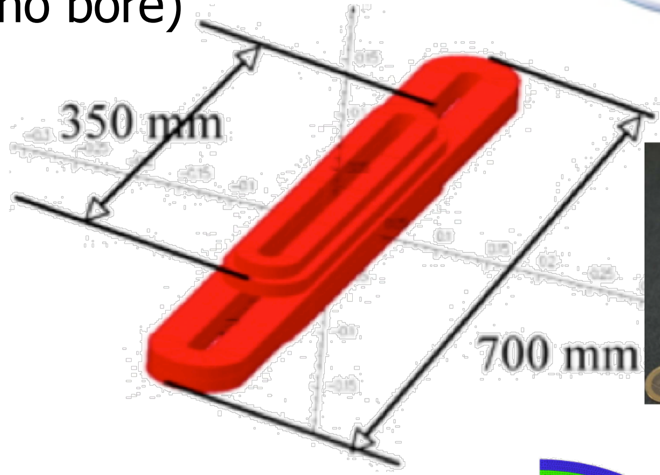
Courtesy: E. Todesco

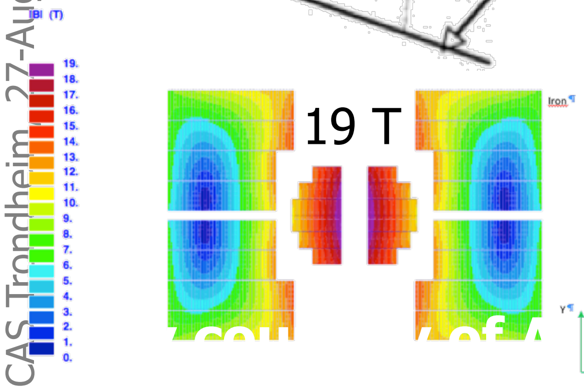
Inserts for a 20 T dipole – present…

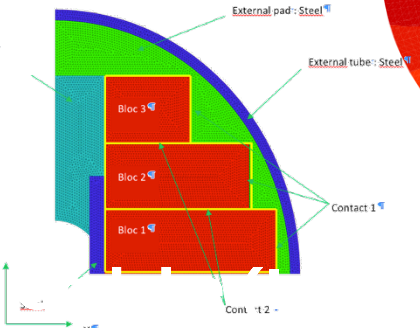


BSCCO-2212 sub-scale coil program

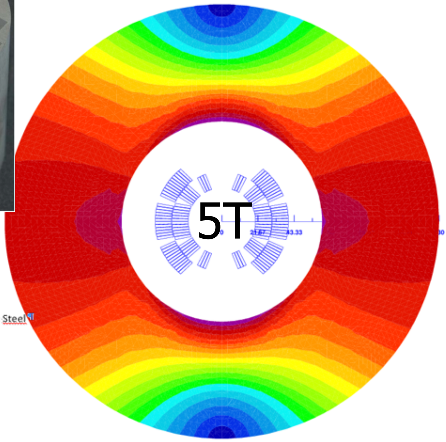
6 T HTS (YBCO) insert for test in FReSCa2 (no bore)



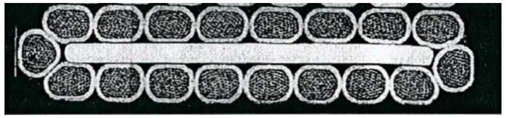




5 T HTS magnet with accelerator features (40 mm bore)



Roebel cable (YBCO)



Rutherford (BSCCO-2212)

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2) K-H. Mess, P. Schmüser, S. Wolff, Superconducting Accelerator Magnets, Singapore, World Scientific, 1996. - 218 p.
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