Superconducting Magnets

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The CERN Accelerator School

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High Field Accelerator Magnets

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

Magnet types, technological view

We can classify magnets based on their technology

electromagnet	permanent magnet
iron dominated	coil dominated
normal conducting (resistive)	superconducting

static	cycled / ramped slow pulsed	fast pulsed

Maxwell equations

Integral form		Differential form
$\oint \vec{H} d\vec{s} = \int_A \left(\vec{J} + \frac{\partial \vec{D}}{\partial t} \right) d\vec{A}$	Ampere's law	$rot\,\vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}$
$\oint \vec{E} d\vec{s} = -\frac{\partial}{\partial t} \int_A \vec{B} d\vec{A}$	Faraday's equation	$rot\,\vec{E} = -\frac{\partial \vec{\boldsymbol{B}}}{\partial t}$
$\int_A \vec{B} d\vec{A} = 0$	Gauss's law for magnetism	$div\,\vec{B} = 0$
$\int_A \vec{D} d\vec{A} = \int_V \rho dV$	Gauss's law	$div\,\vec{D} = \rho$

With:

$$\vec{B} = \mu \vec{H} = \mu_0 \mu_r \vec{H} = \mu_0 \left(\vec{H} + \vec{M} \right)$$

$$\vec{D} = \varepsilon \vec{E} = \varepsilon_0 \left(\vec{E} + \vec{P} \right)$$

$$\vec{J} = \kappa \vec{E} + J_{imp.}$$

Magnetostatics

Let's have a closer look at the 3 equations that describe magnetostatics

Gauss law of magnetism	(1)	$\text{div}\ \vec{B} = 0$	always holds
Ampere's law with no time dependencies	(2)	$\text{rot}\ \vec{H} = \vec{J}$	holds for magnetostatics
Relation between $\vec{H}$ field and the flux density $\vec{B}$	(3)	$\vec{B} = \mu_0 \mu_r \vec{H}$	holds for linear materials

Magnetic field quality: multipole description

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

with:

$z = x + iy,$

B_x *and* B_y *the flux density components in the x and y direction,*

R_{ref} *the radius of the reference circle,*

B_1 *the dipole field component at the reference circle,*

b_n *the normal nth multipole component,*

a_n *the skew nth multipole component .*

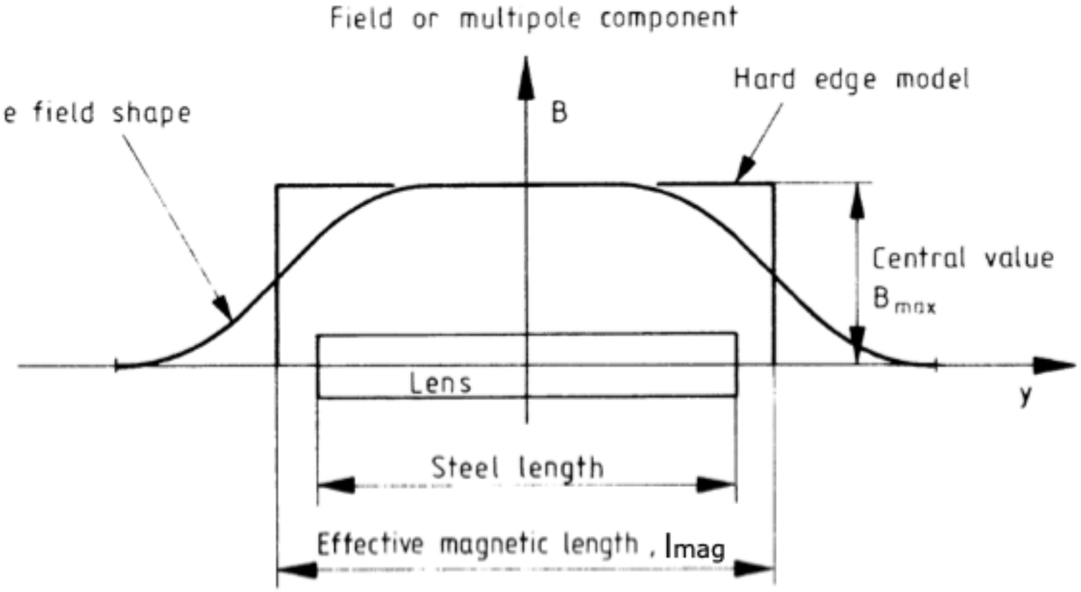
The "wanted" b_n or a_n is equal to 1

In a ring-shaped accelerator, where the beam does multiple passes, one typically demands :

$$a_n,\ b_n \leq 1\ unit\ 10^{-4}$$

Magnetic Length

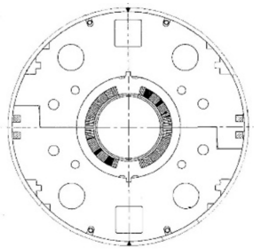
In 3D, the longitudinal dimension of the magnet is described by a magnetic length



$$L_{mag} B_0 = \int_{-\infty}^{\infty} B(z)dz$$

Courtesy A. Milanese, CERN

A circular yoke around the coil can give a 10-15% field increase



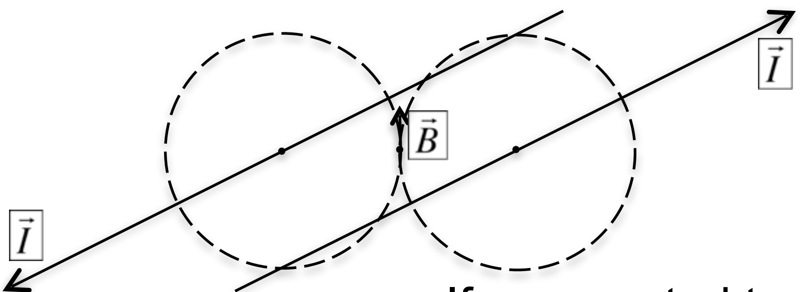
The magnetic length L_{mag} for SC magnets is adjustable by varying the length of the yoke: often the coils stick outside the end of the yoke: no easy rule of thumb for L_{mag}

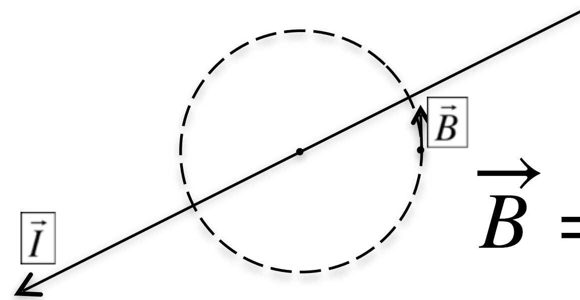
Magnetic fields

From Ampere's law with no time dependencies (Integral form)

$$\oint_c \overrightarrow{B}\,\overrightarrow{\mathrm{d}l} = \mu_0 I_{encl}$$

We can derive the law of Biot and Savart



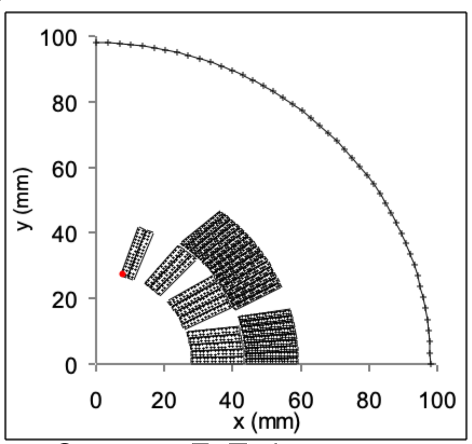


$$\overrightarrow{B} = \frac{\mu_0 I}{2\pi r} \cdot \hat{\varphi}$$

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

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

➔ To get high fields one needs very large currents in small volumes

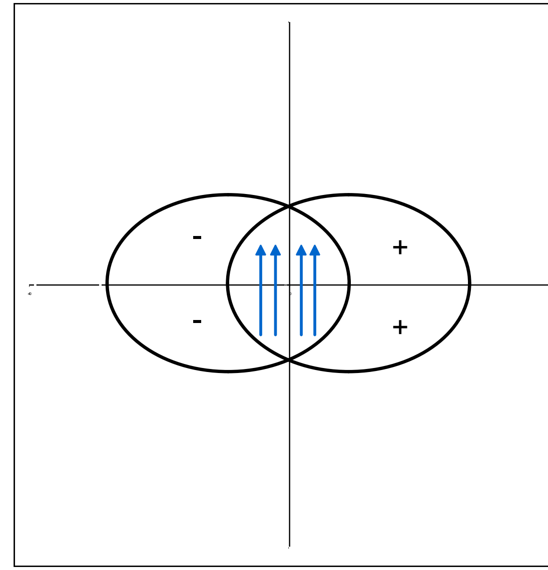


Courtesy E. Todesco

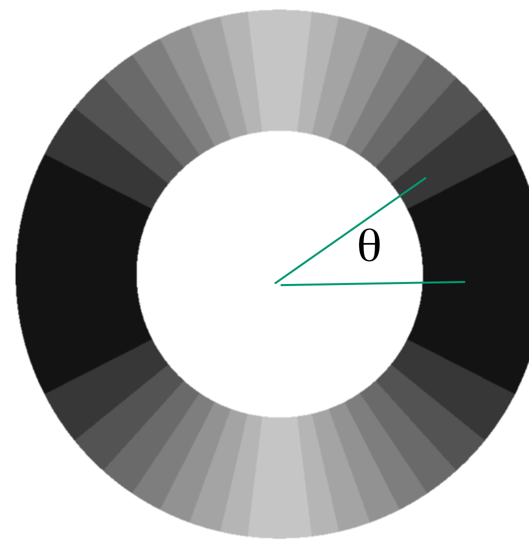
For LHC dipole@8.3 T ~1 MA in 3300 mm^2 : ~300 A/mm^2 (overall current density in the coil area)

Coils for generating the Perfect Dipole Field

1) Conductors: 2 solid Intercepting ellipses (or circles)
    1) A uniform, opposite polarity, current density in the area of two intersecting ellipses produces a pure dipolar field *, but:
        1) The aperture is not circular
        2) Not easy to realise with a flat or round cable



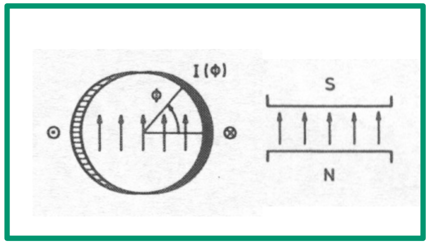
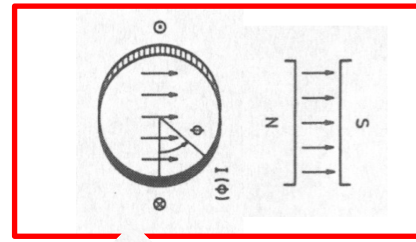
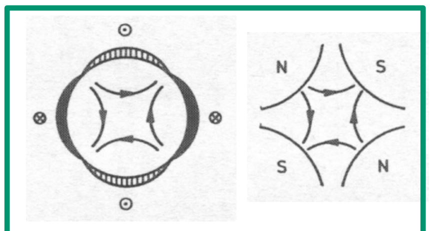
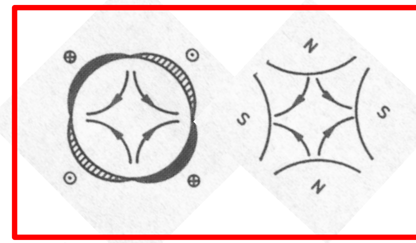
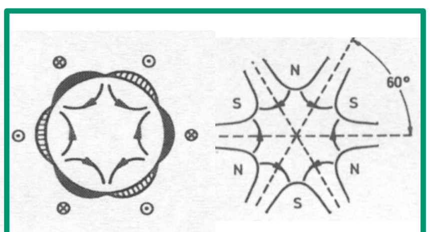
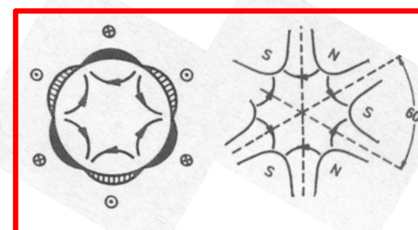
4) Thick conductor shell with a *cos*θ current distribution $J = J_0 \cos\Theta$
    1) Pure dipolar field
    2) Easier to reproduce with a flat rectangular (or slightly key-stone) cable



* This very easy and elegant calculation can be found in Ref[9], slides 49-50

Magnet types and higher orders

A “pure” multipolar field can be generated by a specific coil geometry

	normal		skew	
dipole n=1	B_1			A_1
quadrupole n=2	B_2			A_2
sextupole n=3	B_3			A_3

Courtesy P. Ferracin, CERN

Coils for generating the Perfect multipole Field

For the generation of multipolar fields similar arguments apply

e.g. for quadrupolar field: $J = J_0 \cos 2\Theta$

This is only one way to look at possible coil layout for coil dominated magnets.

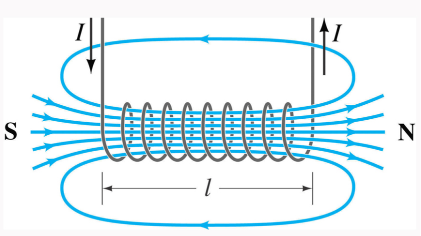
Developments are still ongoing for alternative coil layouts.

eg. see:

Uni-layer magnets: a new concept for LTS and HTS based superconducting magnets, J-L. Rudeiros Fernández and P. Ferracin
Lawrence Berkeley National Laboratory, 2023 Supercond. Sci. Technol. 36 055003

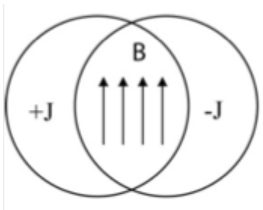
What is specific about accelerator magnets ?

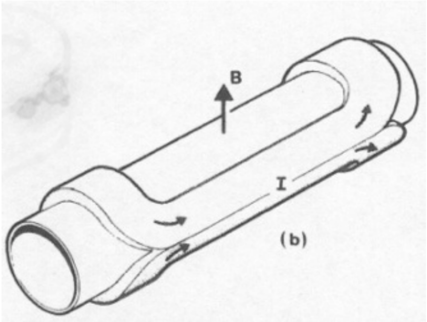
1) Cylindrical volume with perpendicular field → Less efficient coil with more difficult forces compared to a solenoid

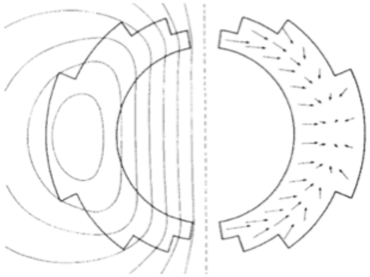


solenoidal (axial) field

CosΘ coil : $J = J_0 \cos\Theta$

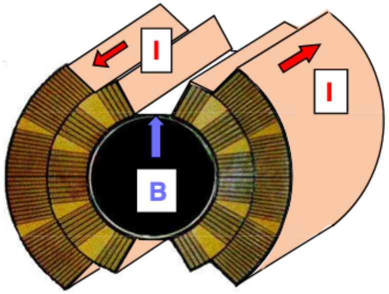


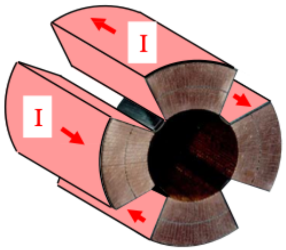


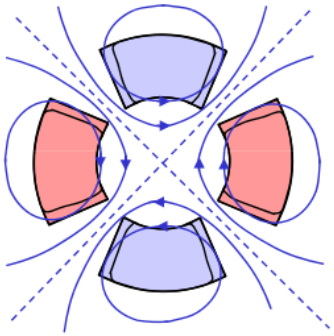


Artist view of a dipole, from M. N. Wilson « Superconducting Magnets »

9) Dipoles, quadrupoles, etc







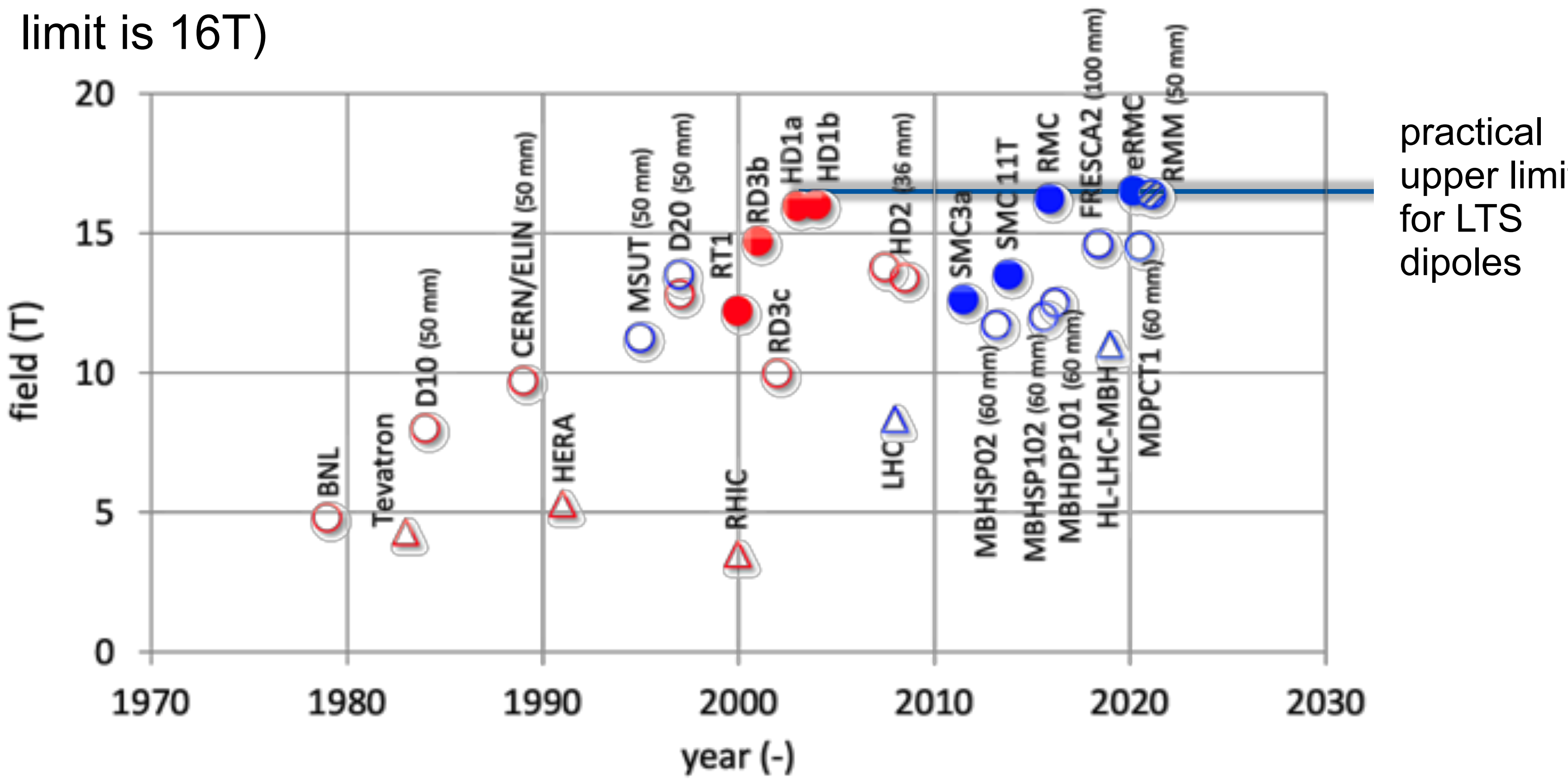
13) Long magnets: dipoles from 6 m (Tevatron) to 15 m (LHC)

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

CAS Santa Susanna, 27-Sept-2023, SC magnets, GdR

Superconducting accelerators magnets; the state of the art

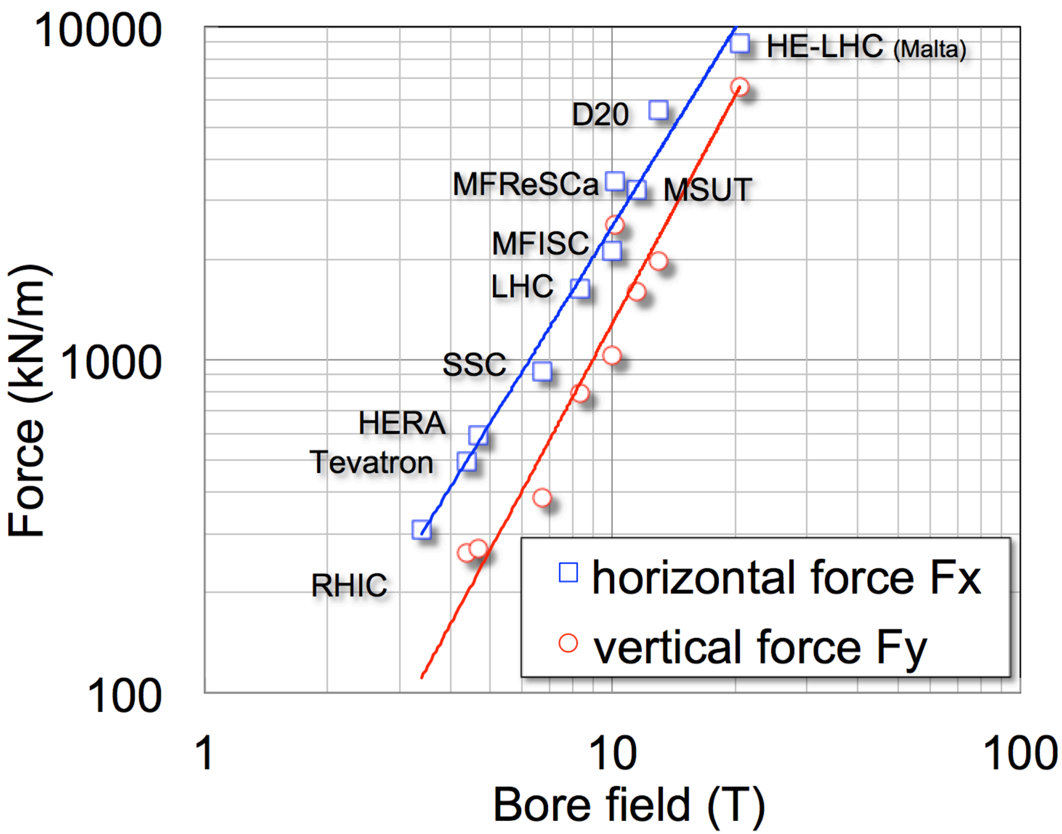
- Maximum attainable field slowly approaches 16 T
  - 20% margin needed (80% on the load line):
    for a 16 T nominal field we need to design for 20 T (or B_n=14.5T if the limit is 16T)



Courtesy L. Bottura

Electromagnetic Forces

Scaling of electromagnetic force on a coil quadrant vs. B Field
Plot for recent production and R&D dipoles



The electromagnetic loads in a 20 T dipole would be a factor 5 to 8 larger than in the LHC dipoles

Electromagnetic Stored Energy

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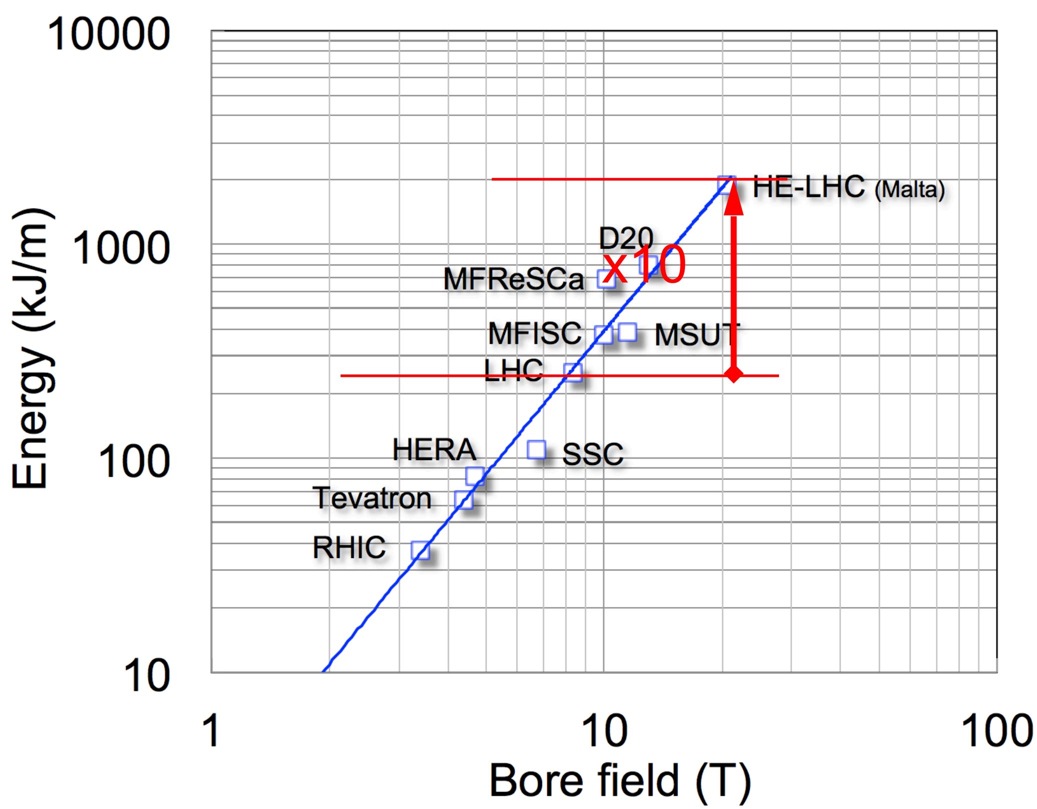
Scaling of the electromagnetic stored energy per unit length of magnet vs. B Field

Plot for recent production and R&D dipoles



The electromagnetic stored energy in a 20 T dipole would be close to a factor 10 larger than in the LHC dipoles

Early SC magnets for accelerators: Transfer line magnets: Castor and Cesar @CERN

1977: Very first SC magnets at CERN in an SPS beam transfer line

1) CESAR dipole: aperture 150 mm, B=4.5 T , l = 2 m
2) CASTOR quadrupole

Both use a monolithic conductor would into a cosΘ coil

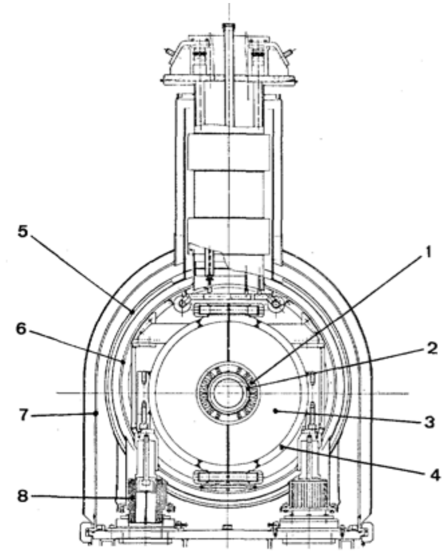
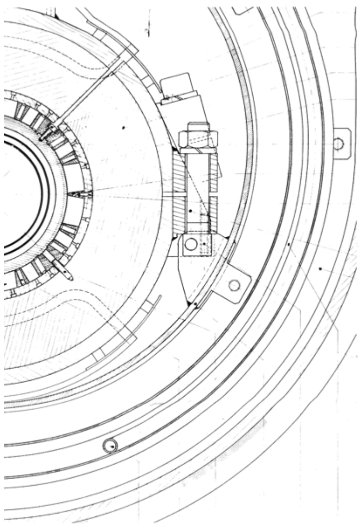
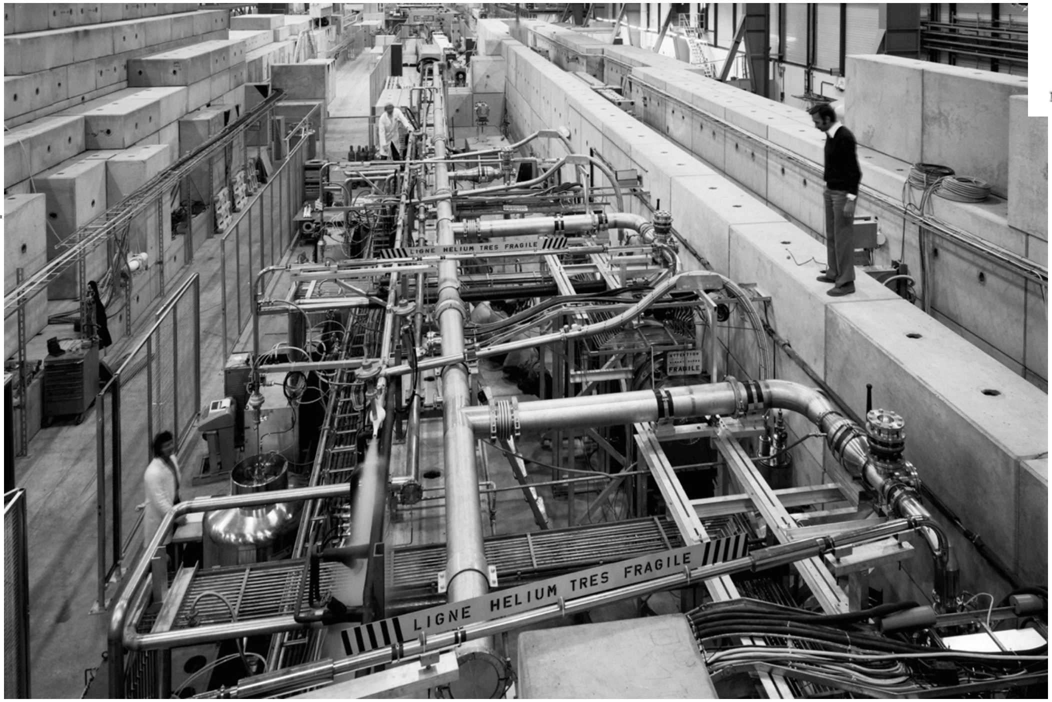


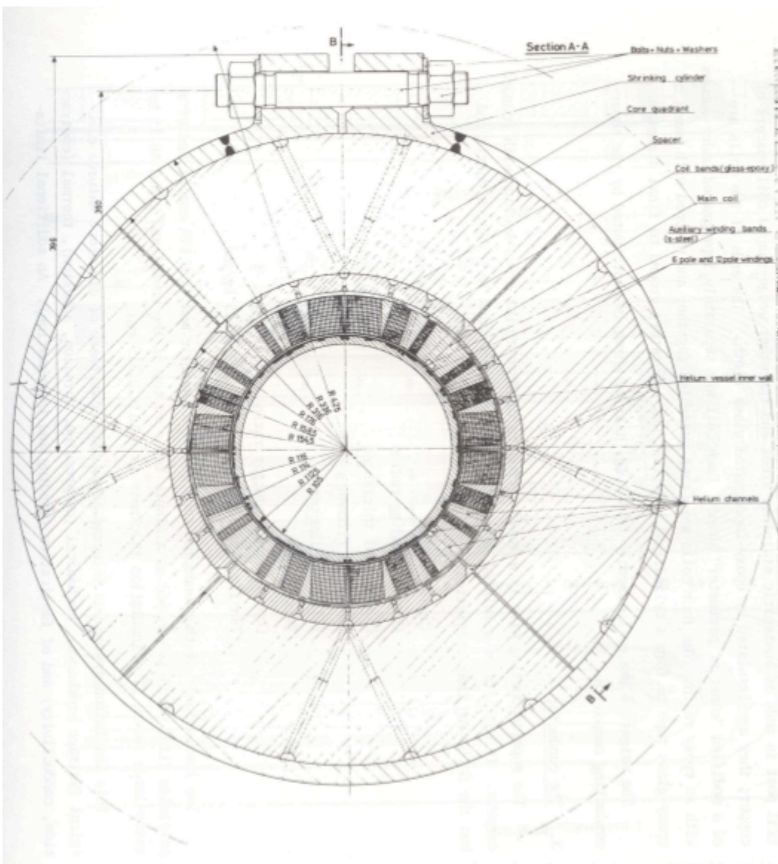
Fig.1. Magnet cross section.

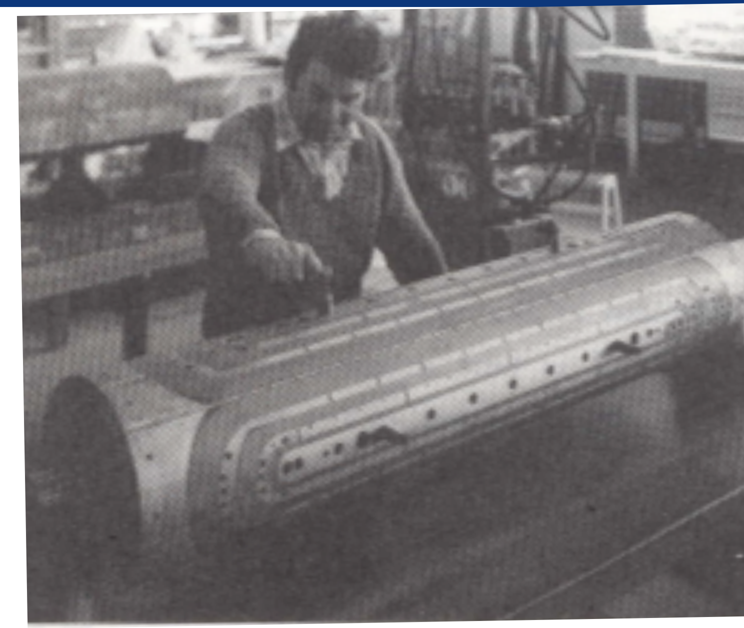


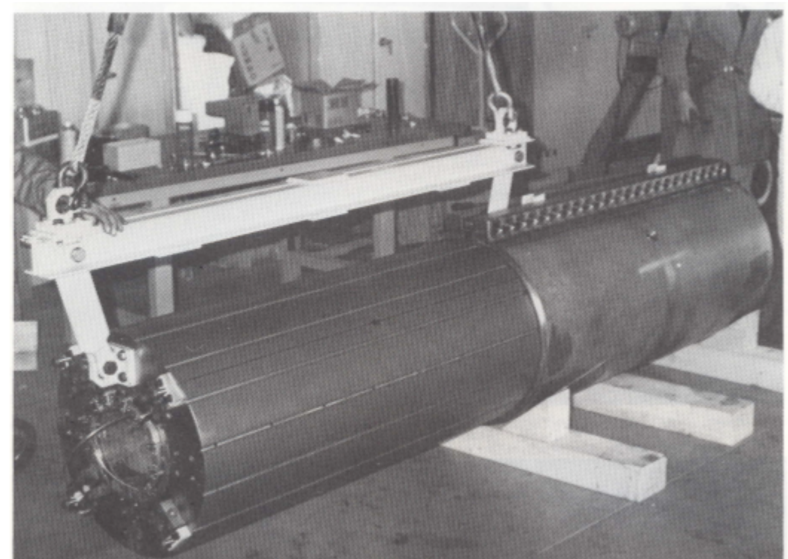


Early SC magnets for accelerators: ISR Insertion quadrupole (end 1970-ies)

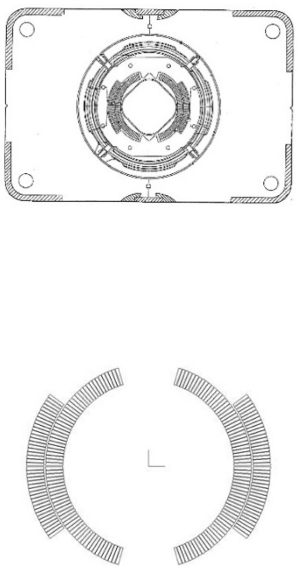
1) G=40 T/m in 73 mm diameter aperture
2) Nb-Ti monolitic conductor
3) fully impregnated coil
4) Prestress from yoke + shell





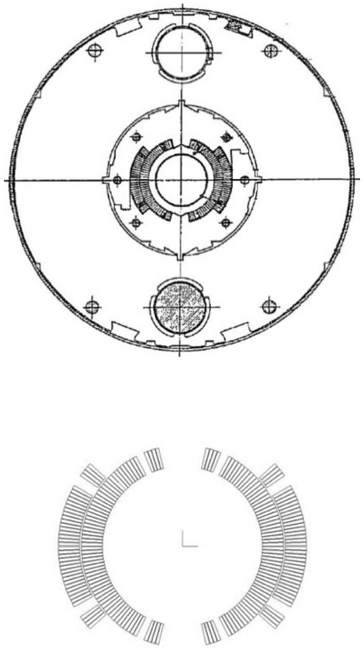


Existing Superconducting Accelerator dipole magnets (1)



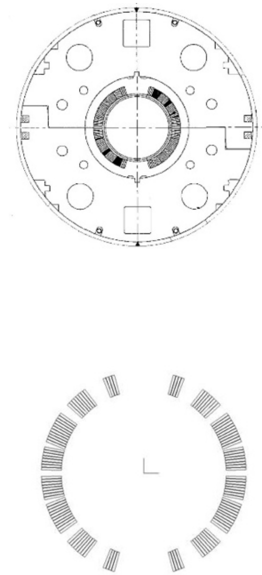
Tevatron

76 mm bore
B = 4.4 T
T = 4.2 K
first beam 1983



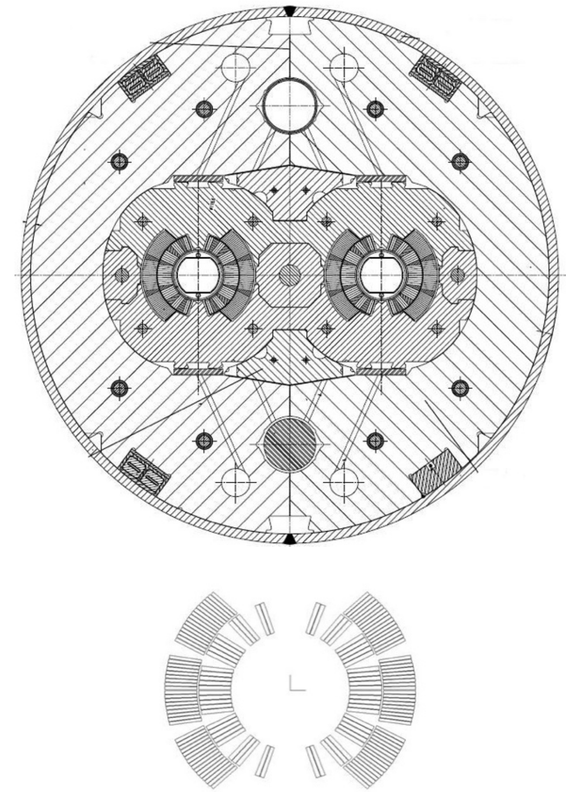
HERA

75 mm bore
B = 5.0 T
T = 4.5 K
first beam 1991



RHIC

80 mm bore
B = 3.5 T
T = 4.3-4.6 K
first beam 2000

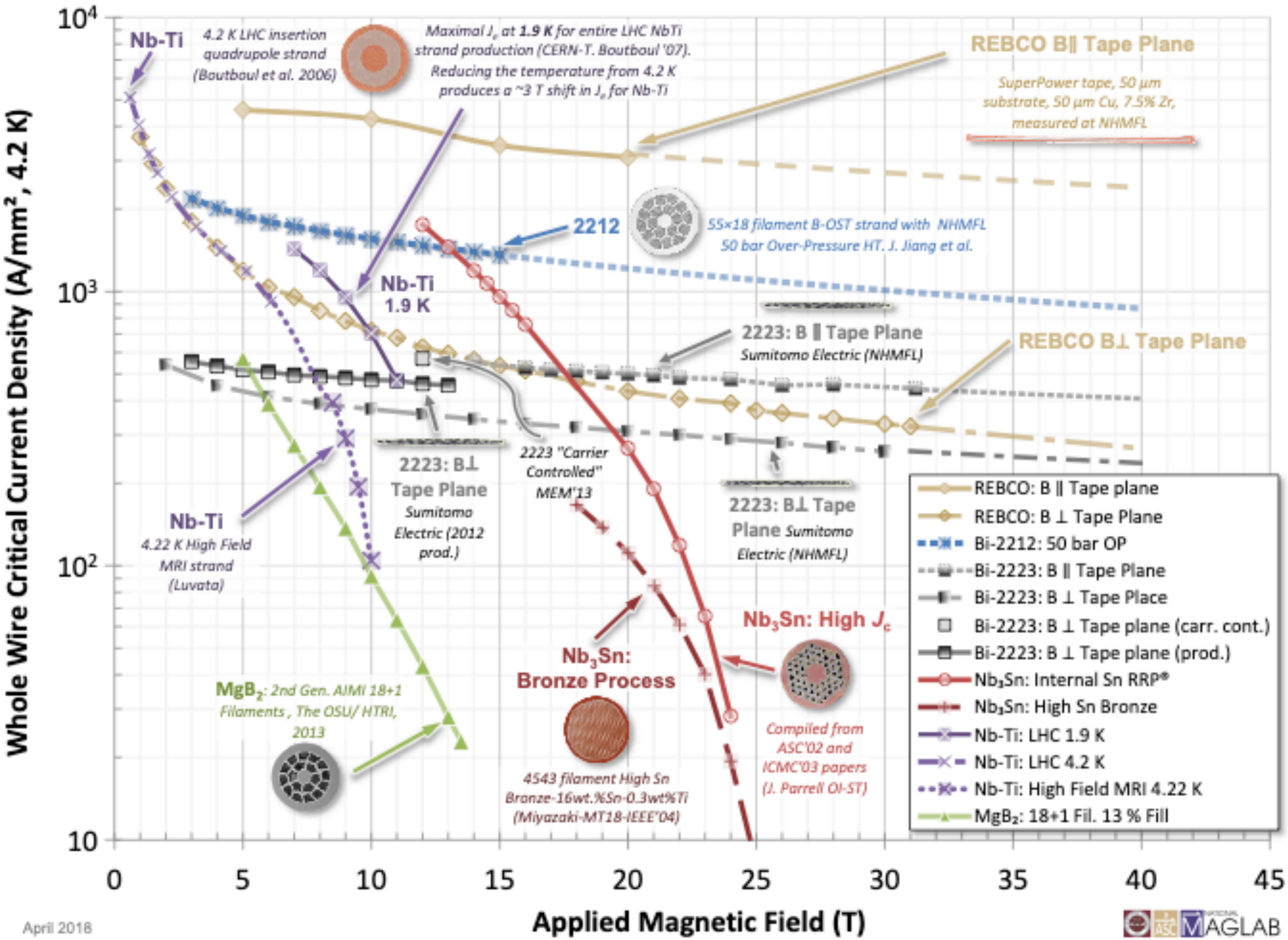


LHC

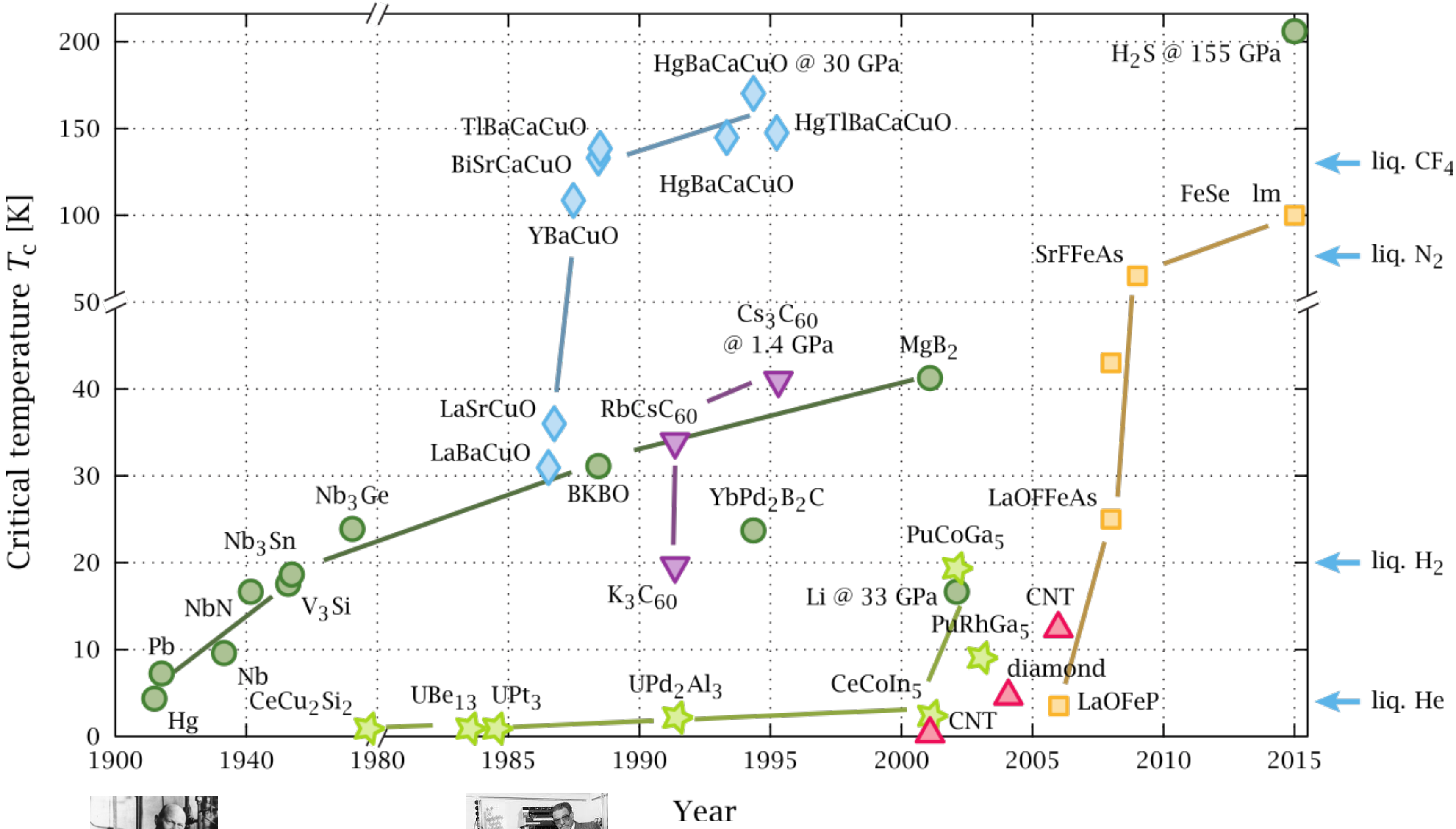
56 mm bore
B = 8.34 T
T = 1.9 K
first beam 2008

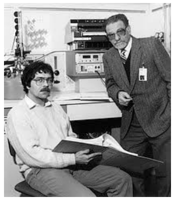
Courtesy P. Ferracin, CERN

Available Superconductors



Superconductor discovery timeline





Available Superconductors

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2 families:

- LTS, Low Temperature Superconductor: T = 4.5 or lower → Liquid He
- HTS, High Temperature Superconductor: T < 80K → LHe, LN2, He gas, etc.

- LTS; Nb-Ti: the workhorse for 4 to 10 T

  Well known industrial process, good mechanical properties

  Thousands of accelerator magnets have been built

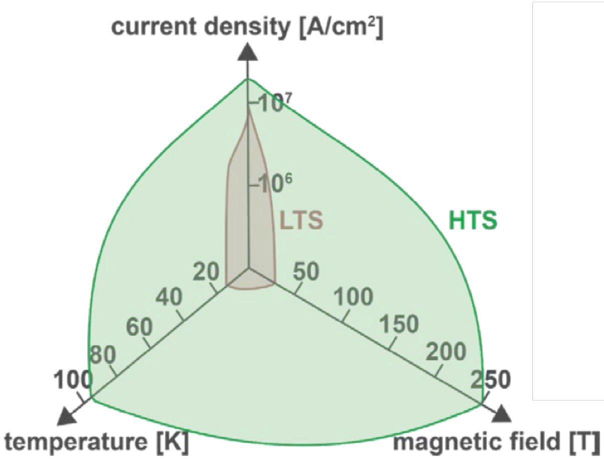
- LTS; Nb_3Sn: towards 20 T

  Complex industrial process, higher cost, brittle and strain sensitive

  First usage in HL-LHC, several long magnet built and ready for installation, 25+ short development models have been built

- HTS materials: getting to 20 T and shooting to 40 T (Bi-2212, REBCO)

  Used in solenoids (20-30 T range), used in power lines – no real accelerator magnets have been built yet (only a few models) – several small model magnets have been built



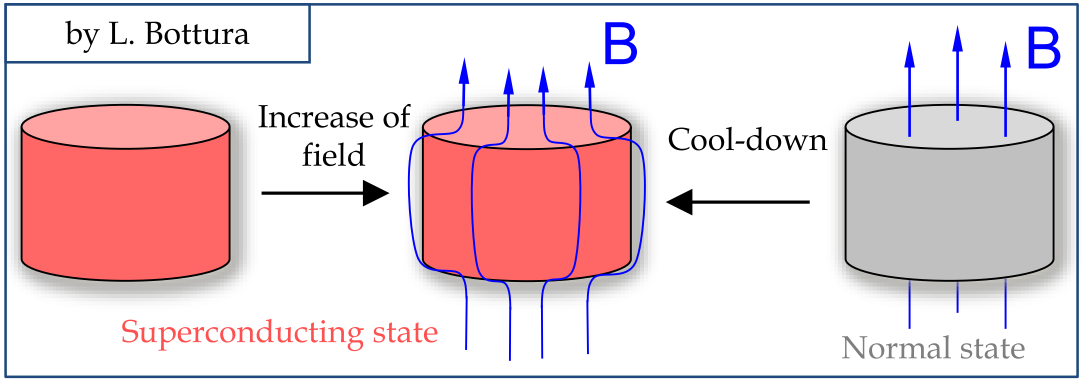
LTS Superconductors

Superconducting means: $R \equiv 0$

Type I

B_c<<1T

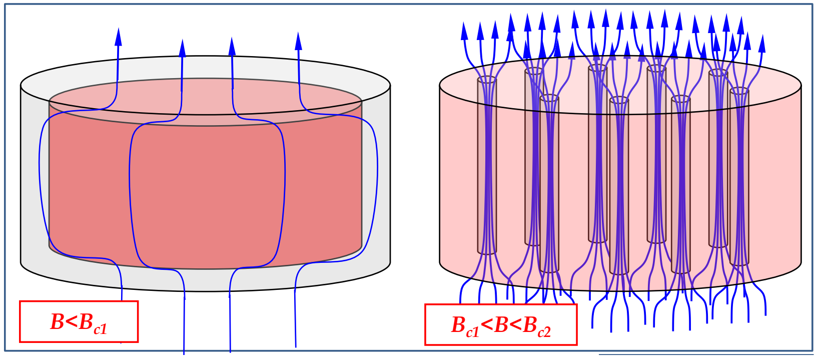
Meissner effect

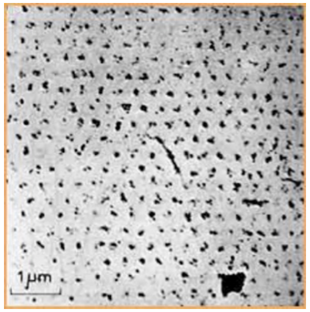


Type II

B_{c2}>1T

Quantized fluxoids



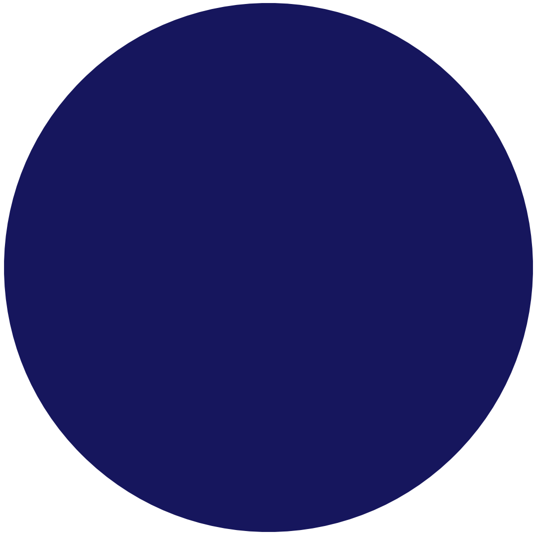
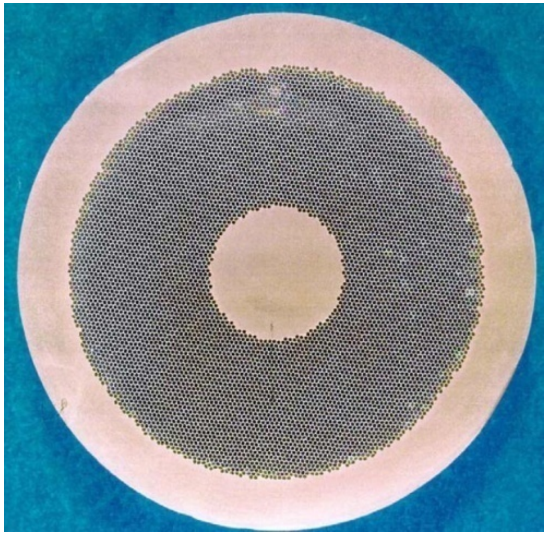
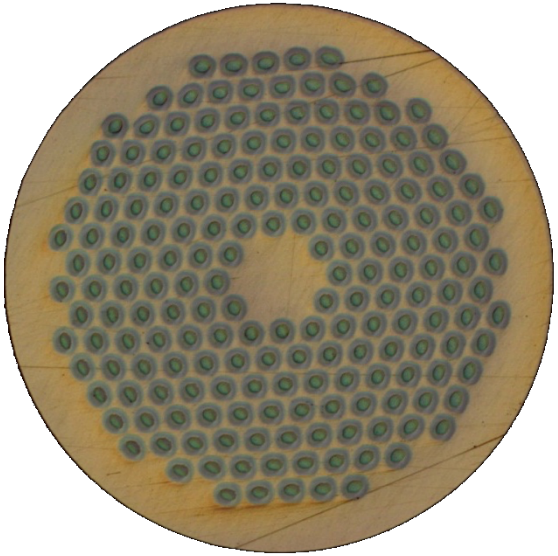


Quantized fluxoids in a superconductor

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

Comparing wires, LTS Superconductors vs Copper

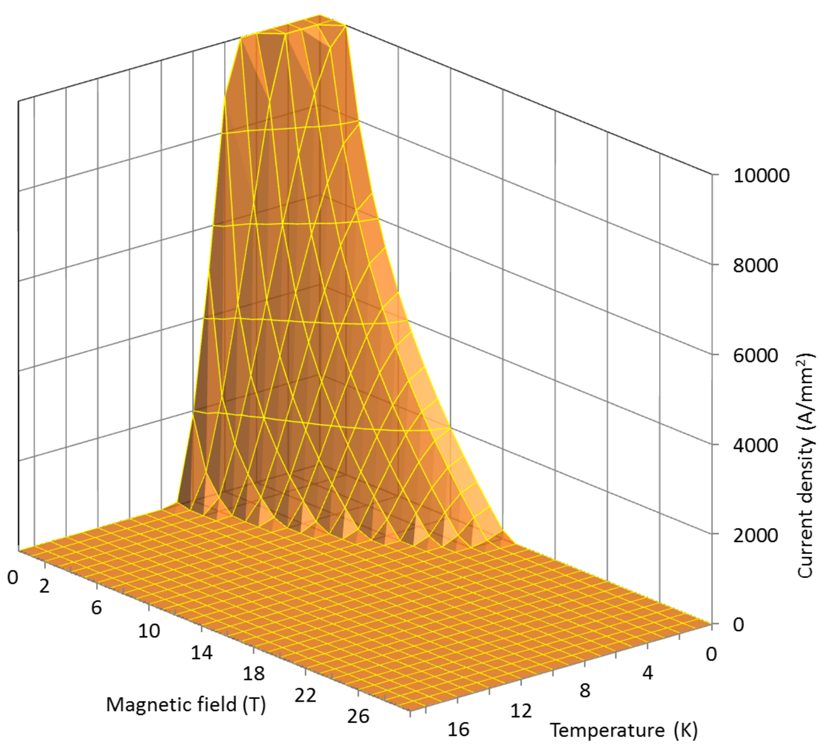
Typical operational conditions (0.85 mm diameter strand)

Cu	Nb-Ti	Nb_3Sn
		
$J \sim 5$ A/mm^2	$J \sim 1500$-2000 A/mm^2	$J \sim 1500$-2000 A/mm^2
I ~ 3 A	I ~ 400 A	I ~ 400 A
B = 2 T	B = 8-9 T	B = 12-13-16 T

Courtesy P. Ferracin, CERN-LBNL

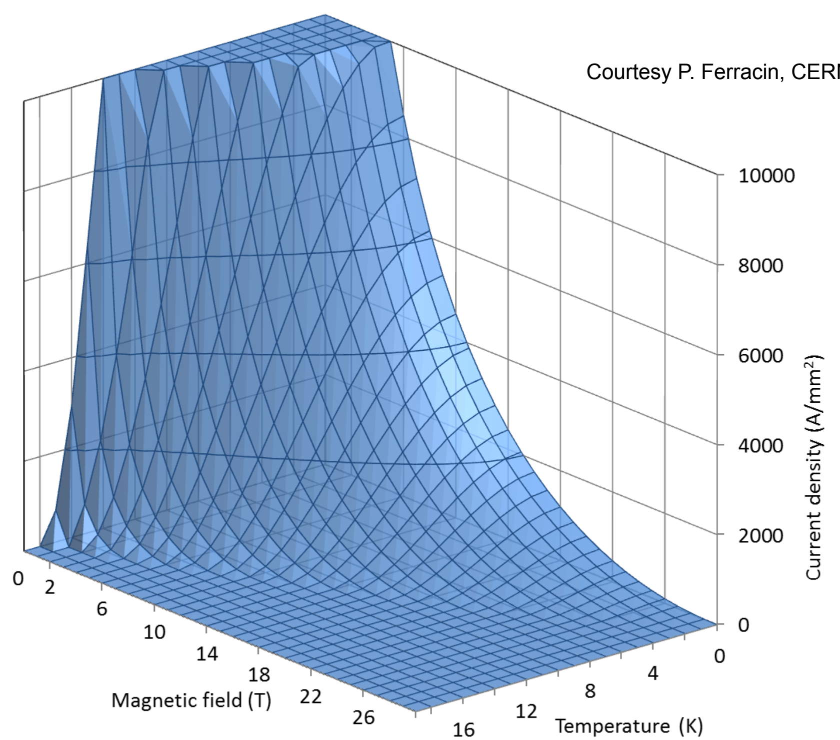
comparison critical surface Nb-Ti vs Nb_3Sn

Nb-Ti



Nb_3Sn

Courtesy P. Ferracin, CERN-LBNL



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

- T_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

Superconducting materials: Nb-Ti

1) Niobium and titanium combine in a ductile alloy
   - It is easy to process by extrusion and drawing techniques.

3) When cooled down to about 9 K it becomes a type II superconductor.
   - T_c is ~9.2 K at 0 T.
   - B_{C2} is ~14.5 T at 0 K.

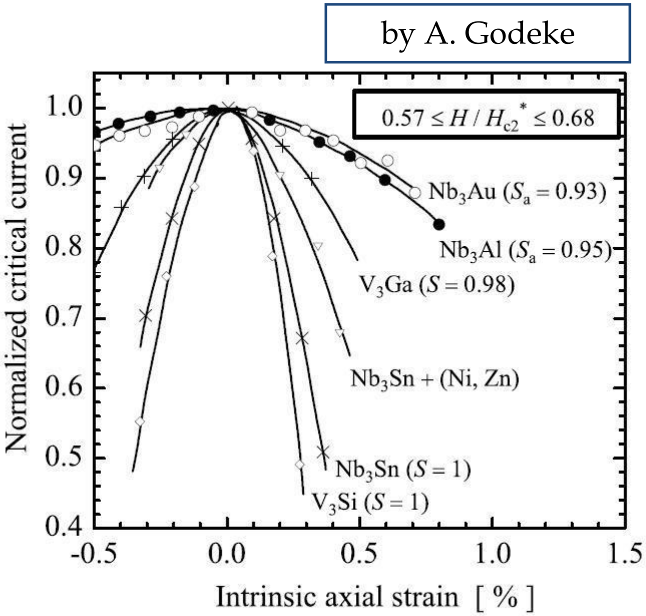
5) The cost is approximately 100-150 US$ per kg of wire.

Superconducting materials: Nb_3Sn

1) Niobium and tin form Nb_3Sn
   - Brittle and strain sensitive

2) When cooled down to about 18 K it becomes a type II superconductor.
   - T_{C0m} is ~18 K at 0 T and 0 strain.
   - B_{C20m} is ~28 T at 0 K and 0 strain.

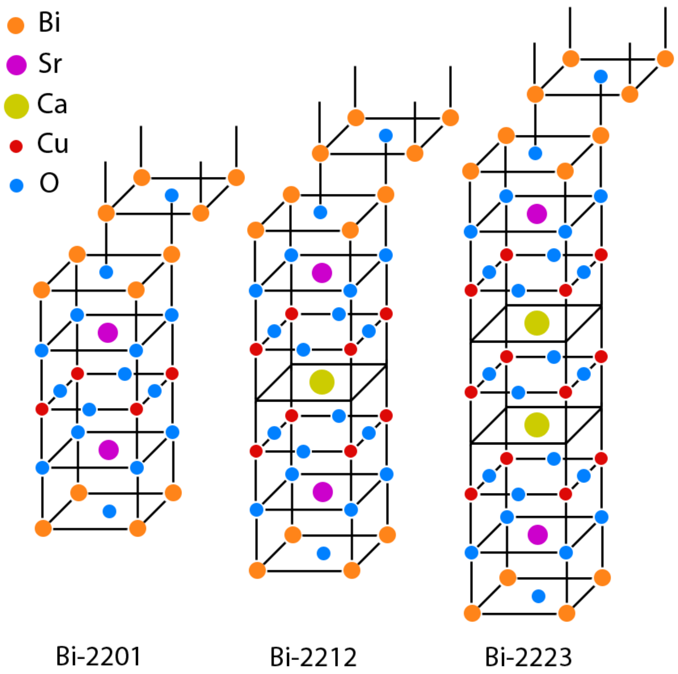
3) The cost is approximately 700-1500 US$ per kg of wire.



Superconducting strands and tapes: BSCCO

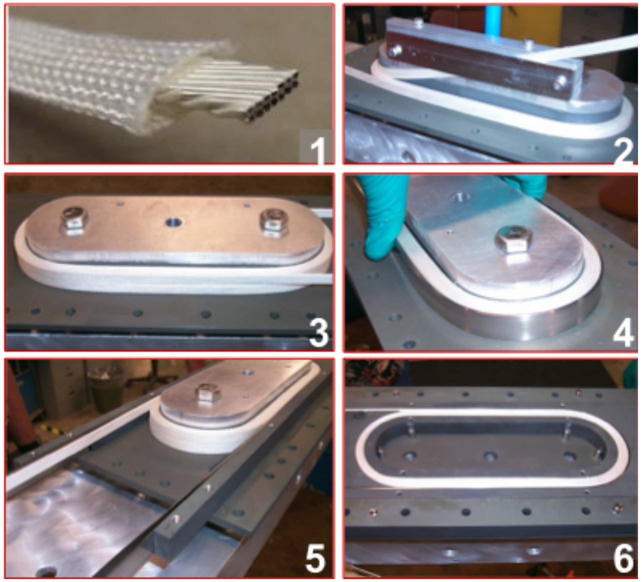
BSCCO: Bismuth strontium calcium copper oxide

- 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

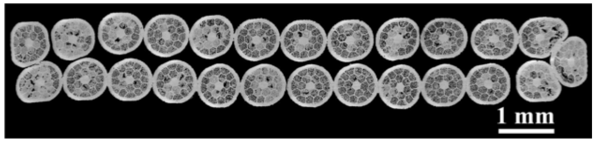


By Nazargulov - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=80940329

OST wire 0.8 mm using Nexans precursor



Photos: courtesy LBNL

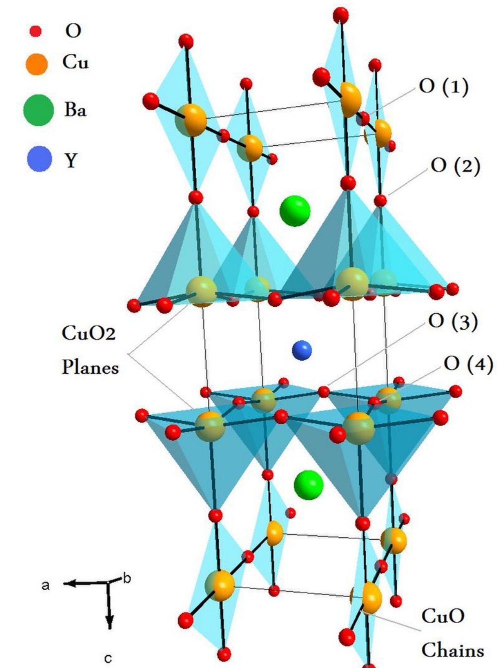


Difficult technology but could be promising for high field magnets in >20 T region

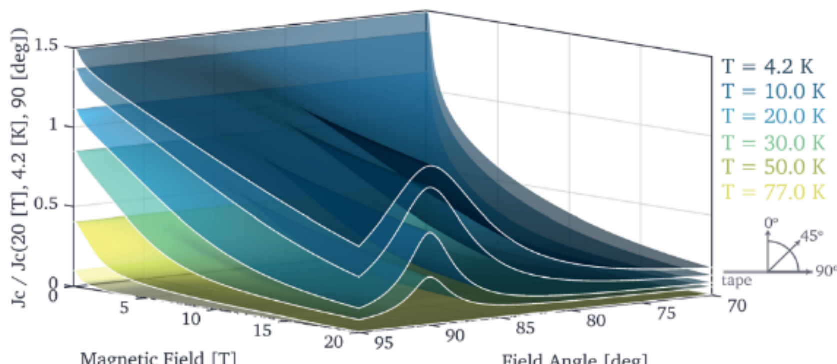
Superconducting tapes: YBCO (or REBCO)

YBCO: Yttrium barium copper oxide. (RE=Rare-Earth)

- Available in tapes : YBCO deposited on a substrate to impose the texture (1-2 μm)
- Can reach > 600 A/mm² (overall)
- Is strong under axial stress and strain (300 MPa)
- Limited cabling possibilities:
- Difficult technology but could be promising for high field magnets in >20 T region.

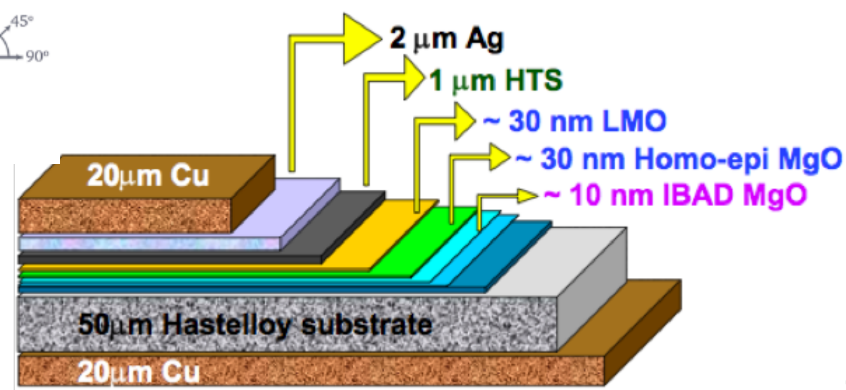


By Haj33 - Template:Haj33, Public Domain, https://commons.wikimedia.org/w/index.php?curid=8777295



PhD thesis J. van Nugteren

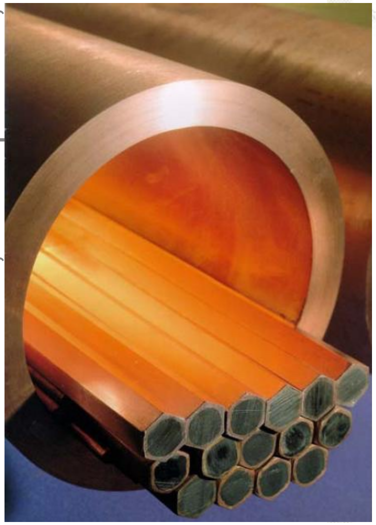
Critical current depends on the angle between the face of the tape and the B field

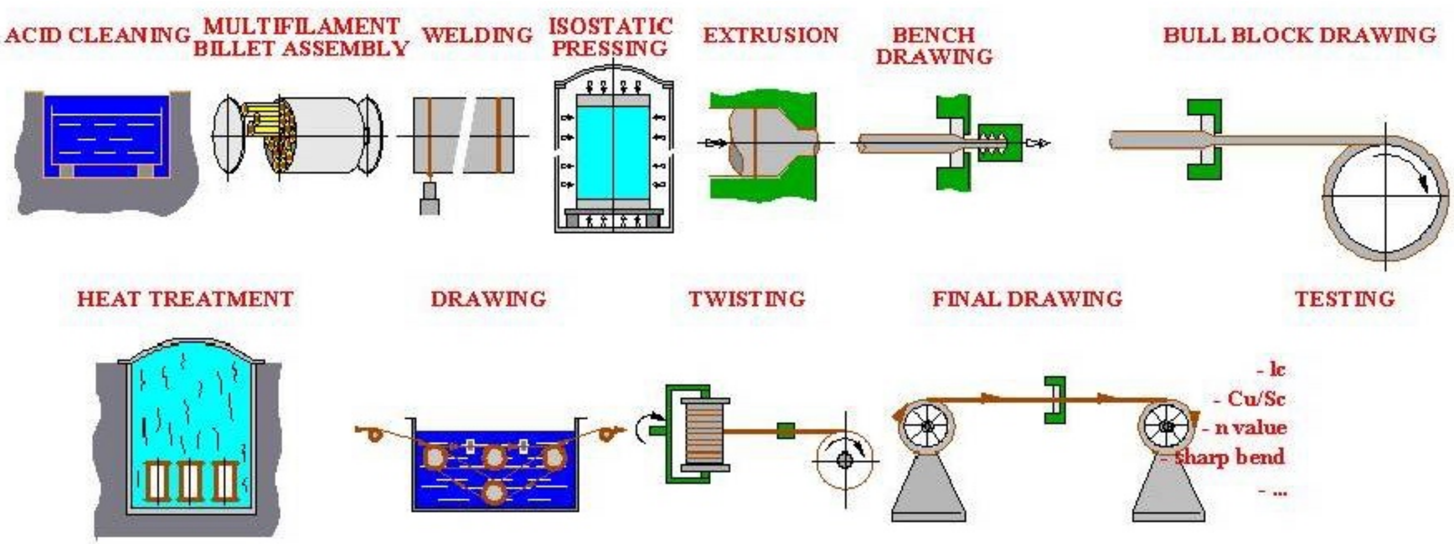


Multifilament wires, Fabrication of Nb-Ti multifilament wires

- Monofilament rods are stacked to form a multifilament billet, which is then extruded and drawn down.

- When the number of filaments is very large, multifilament rods can be re-stacked (double stacking process).





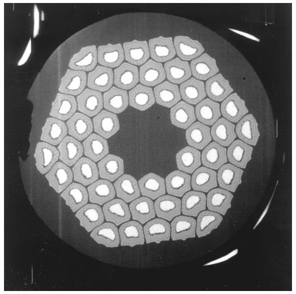
Courtesy A. Devred, ITER; P. Ferracin, CERN

Multifilament wires
Fabrication of Nb_3Sn multifilament wire

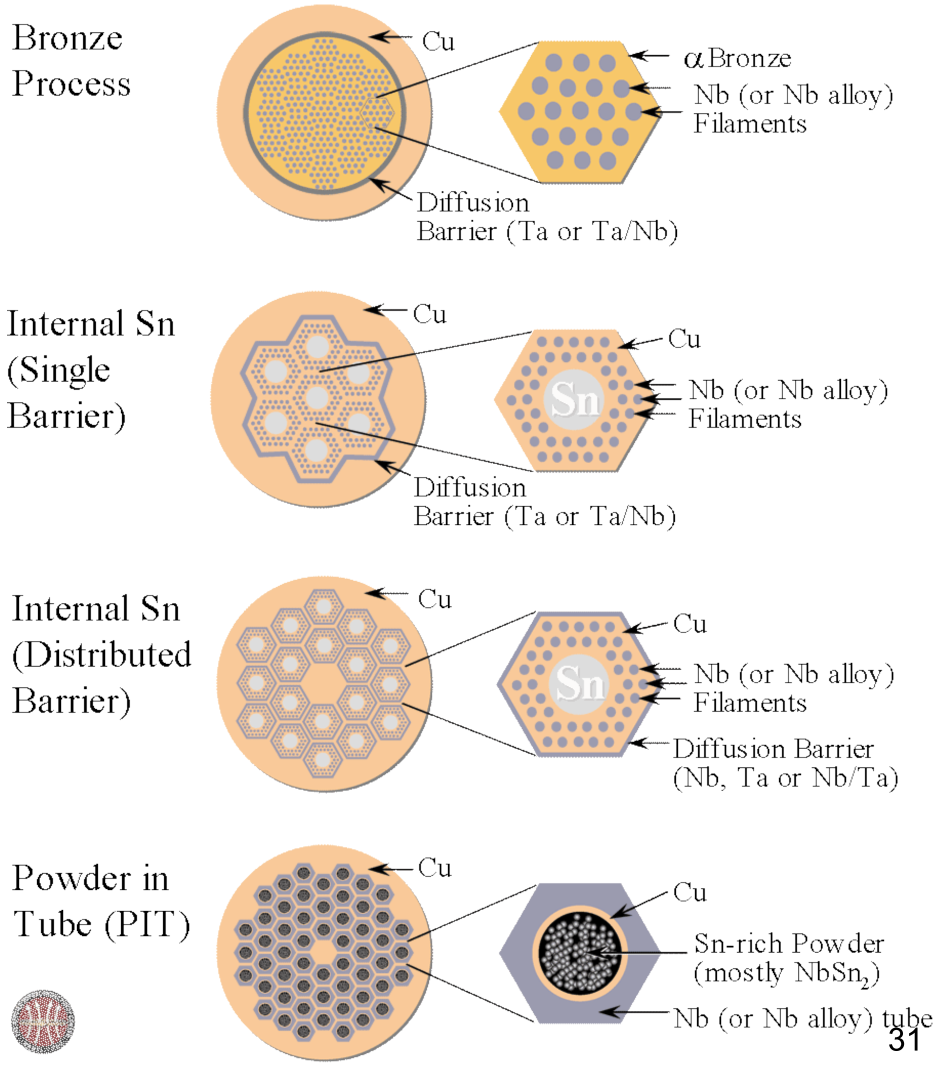
Since Nb_3Sn is brittle, it cannot be extruded and drawn like Nb-Ti.

The process requires several steps:

1) Assembly multifilament billets from Nb_3Sn precursor
2) Fabrication of the wire through extrusion-drawing
3) Fabrication of the cable
4) Fabrication of the coil
5) “reaction”: the Cu, Sn and Nb are heated to 600-700 C and the Sn diffuses in Nb and reacts to form Nb_3Sn



Nb_3Sn strand types



Superconducting cables for magnets

We need multi-strand cables

1) Superconducting accelerators are ramped up in time spans 100 s to 1000 s
2) Coils are designed for voltages to ground of around 1000 V
3) With the number of turns and the current the inductance is to be limited to keep the voltage below 1000 V

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

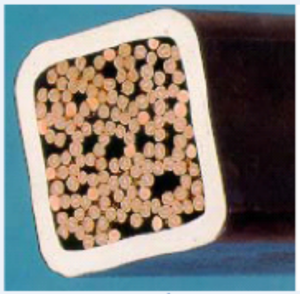
$$L \sim N^2$$

4) Dipoles and Current:
    1) Tevatron B = 4.4 T ; I ~ 4000 A
    2) Hera B = 5 T ; I ~ 6000 A
    3) LHC B = 8.3 T ; I ~ 12000 A
5) For magnets 10 T < B < 15 T the current has to be 10kA < I < 15 kA
6) For stability reasons strands are 0.6 mm < strand diameter < 1 mm
7) With a Cu-nonCu ratio (for stability reasons) around 1 and a Jc ~ 1000 A/mm^2
    ➔ a 1 mm diameter strand can carry ~400 A
    ➔ so we need a 30 strand cable to get up to 12 kA

LTS Cable types

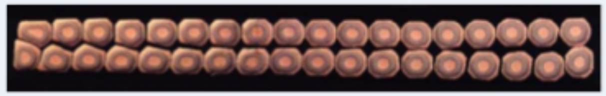
.

CIC



ITER magnets

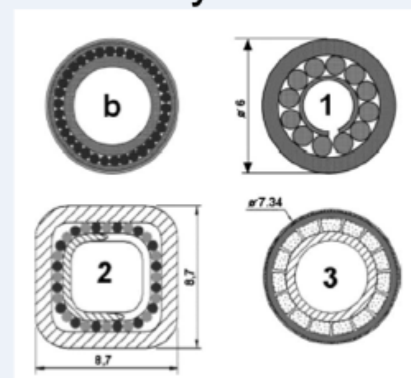
Rutherford



Accelerator magnets

Tevatron, HERA
RHIC and LHC

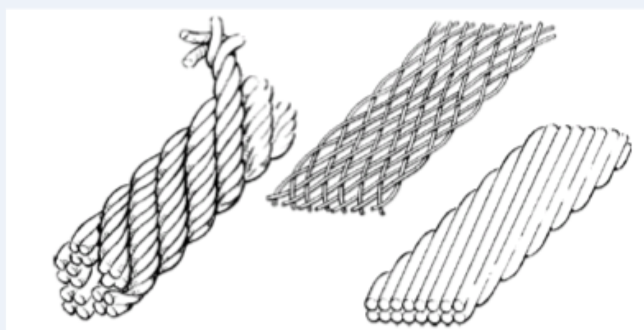
Indirectly cooled



Nuclotron Type (b)
Pulsed SIS 100 magnets

Rutherford

Detector magnets

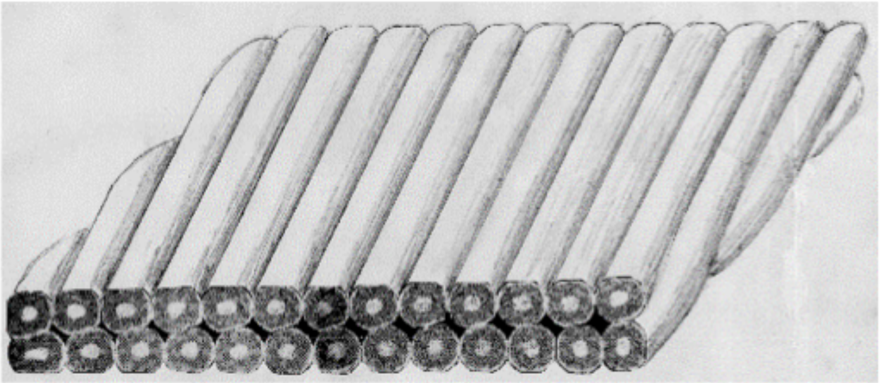


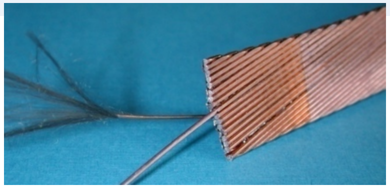
Rope, Braid and Rutherford cables

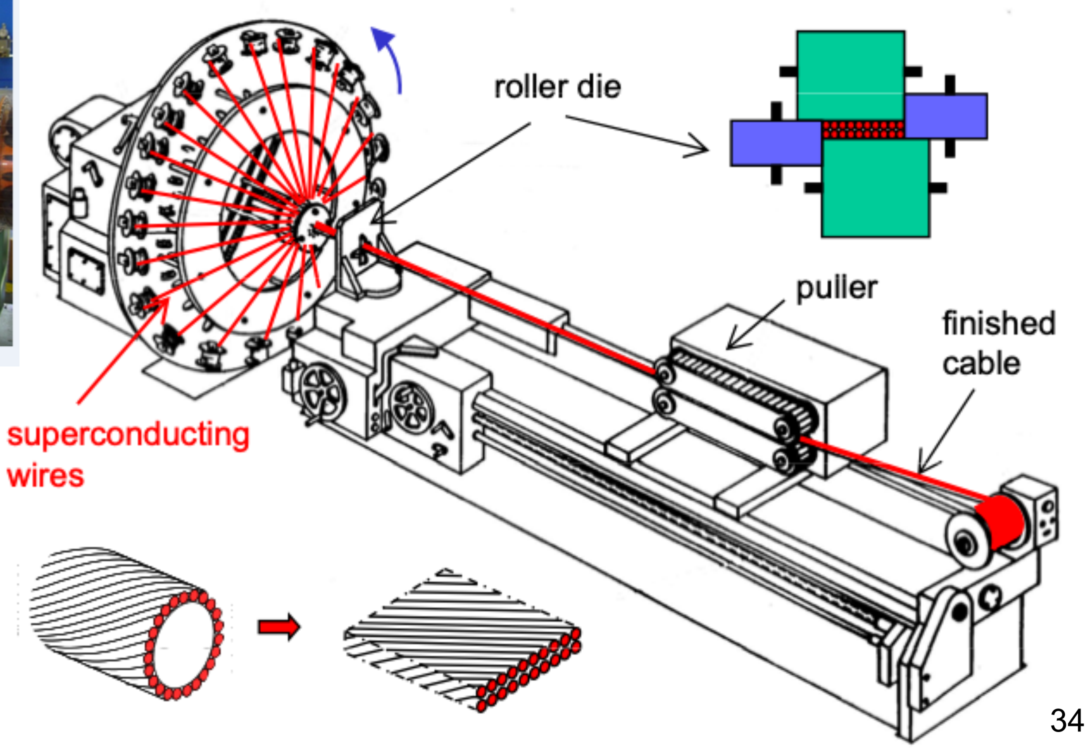
Courtesy A. Balarino

Rutherford cables

1) Compact cables giving high overall current density
2) Easy rectangular geometry for convenient winding



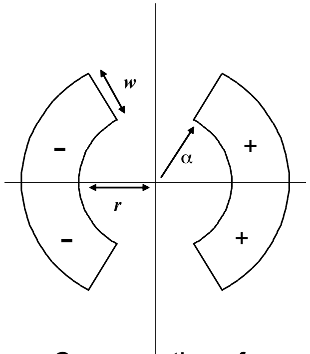




How to get high fields in accelerator dipole and quadrupole magnets ?

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

1) Dipole 60º sector coil [see ref 13]
   1) The field is *proportional to the current density j*
   2) The field is *proportional to coil width*
   3) The field is *independent of aperture*

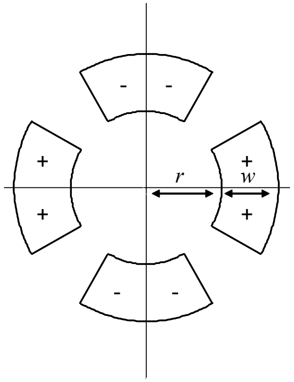


Cross-section of a dipole based on 60º sector coils

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

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

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



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

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

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

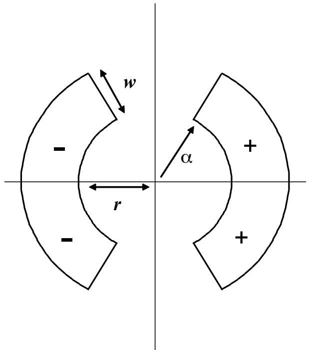
See: E. Todesco et al. ref[11] and ref[14] and indirectly : N. Wilson ref[1], K-H Mess et al. ref[2],
For a in depth study of magnetic field calculations: S. Russenschuck ref[4]

The forces with high field dipole and quadrupole magnets

One can derive the maximum stress in the mid-plane for a sector dipole coil

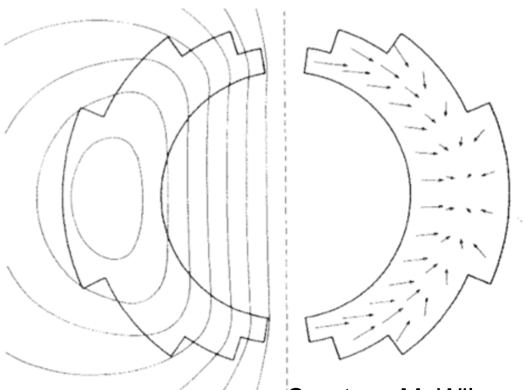
1) Dipole 60° sector coil [see ref 1, 15]

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



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

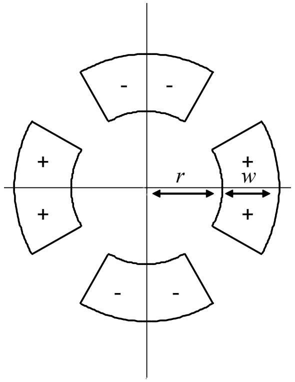
(Typically: for 8T : 40 MPa , for 13 T 130 MPa)



Courtesy M. Wilson

with:

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



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

5) Quadrupole 30° sector coil [see ref 1, 16]

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

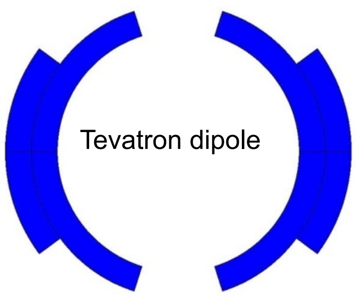
Electromagnetic forces

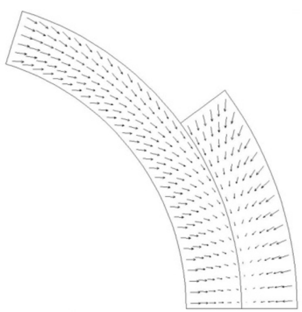
The e.m. forces in a dipole magnet tend to push the coil

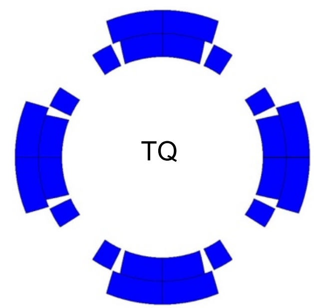
- Towards the mid plane in the vertical-azimuthal direction (F_y, $F_\theta < 0$)
- Outwards in the radial-horizontal direction (F_x, $F_r > 0$)

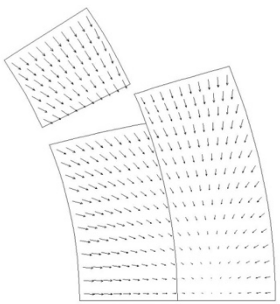
The e.m. forces in a quadrupole magnet tend to push the coil

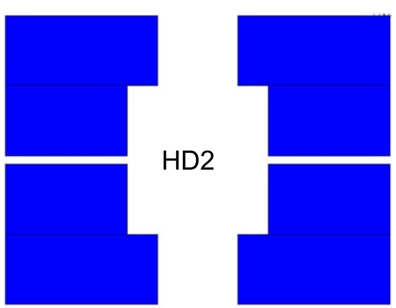
- Towards the mid plane in the vertical-azimuthal direction (F_y, $F_\theta < 0$)
- Outwards in the radial-horizontal direction (F_x, $F_r > 0$)

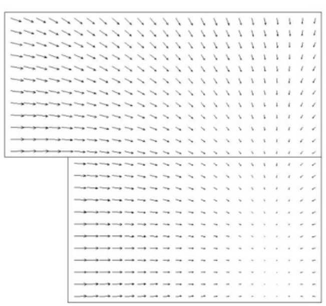


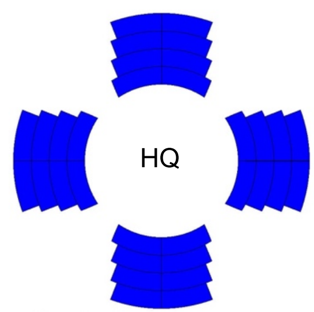


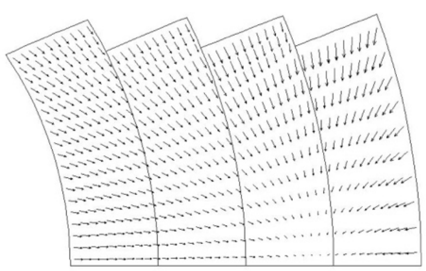










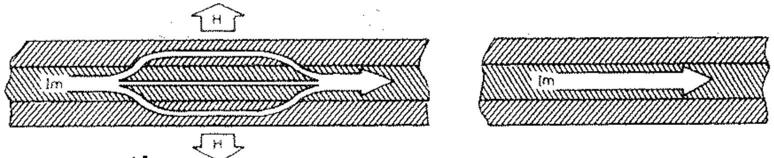


Courtesy P. Ferracin, CERN

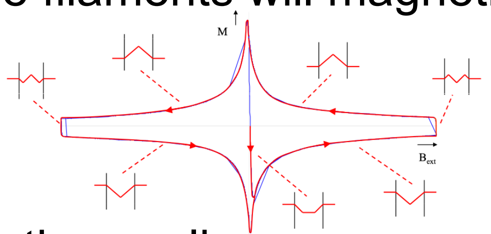
Conductor stability and AC behaviour

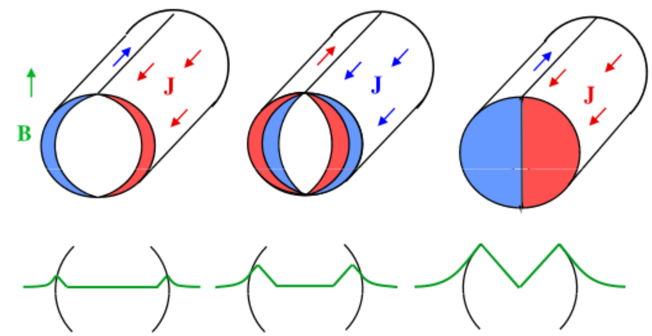
1) Pure massive superconductor is not stable as they (Nb-Ti, Nb_3Sn) are poor normal conductors

2) To ‘cryogenically stabilize’ the conductor one surrounds it in Cu:
   1) good electrical conductivity
   2) good heat transfer to the He

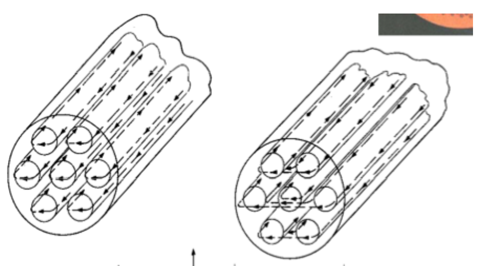


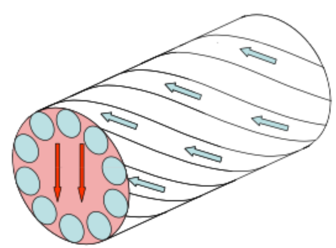
3) During current ramping the filaments will magnetize
   ➔ make them thinner





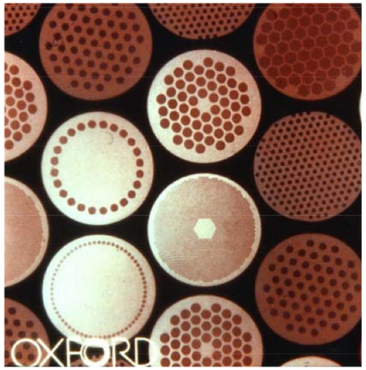
5) Filaments will have magnetic coupling
   ➔ twist the strand





Courtesy M. Wilson

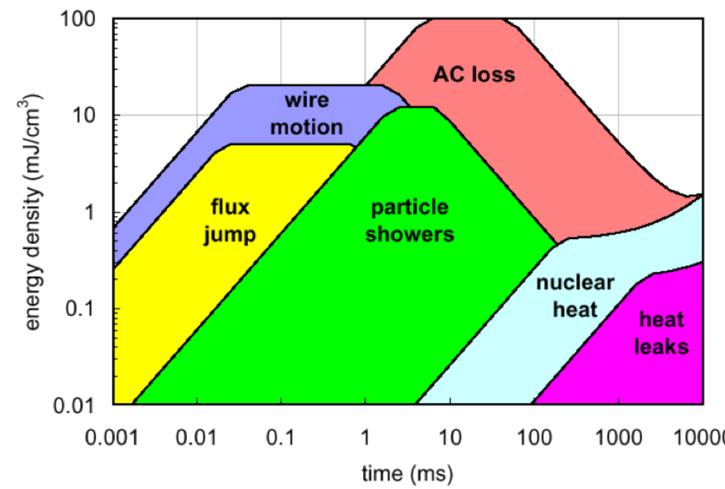
9) Practical low temperature superconductors are made as thin (5 μm – 100 μm) superconducting filaments in a Cu matrix , which is twisted



Quench: a thermal runaway effect

Due to perturbations locally the conductor can get $T > T_c\,(J_l,B_l)$

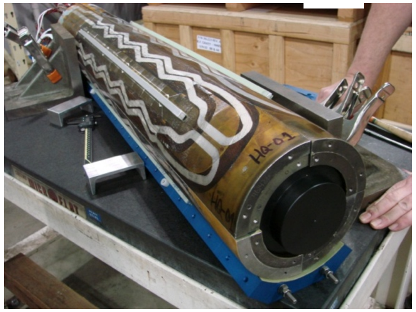
A thermal runaway can then occur, called a **Quench** (see also ref[17])



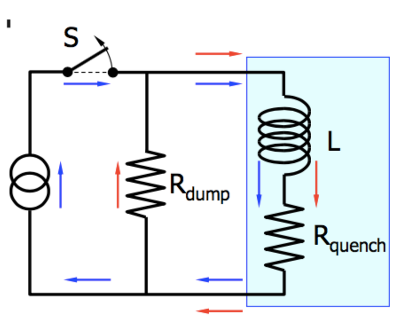
With stored energies > MJ the coils can overheat if nothing is done (T = 3000K is possible !)

What to do ?

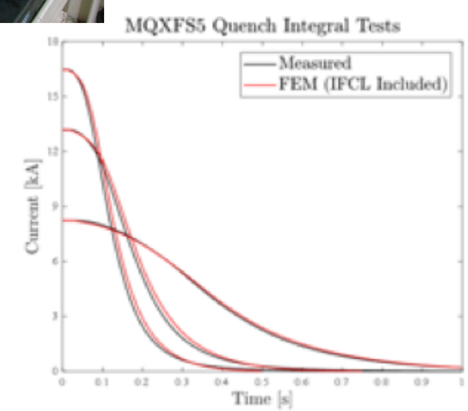
- Detect the quench : SC: R=0 → V=0, quench V>0 (typically 100mV threshold)
- Switch power convertor off
- Heat up the whole coil with quench heaters
- Dump energy of the circuit into a dump resistor



MQXFS coils



When something went wrong in an LHC dipole



Quench hot spot

In a simple approach:

assume that on the <1s time scale a volume element of the coil is not able to evacuate the heat (adiabatic case).

The heat balance of a unit volume of coil is: $J^2(t)\rho(T)dt = \gamma C(T)dT$

With:
- t time
- T temperature
- $J(t)$ the current density
- $\rho(T)$ the resistivity of the non superconducting part of the cable
- γ the density
- C(T) the heat capacity

rearrange: $$J^2(t)dt = \frac{\gamma C(T)}{\rho(T)}dT$$

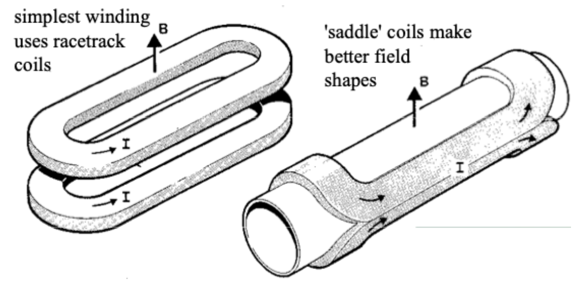
Integrate: $$\int_0^\infty J^2(t)dt = \int_{T_0}^{T_{max}} \frac{\gamma C(T)}{\rho(T)}dT$$

With this one can get a conservative estimate of the maximum temperature in the coil at the end of the quench.

Practical accelerator magnet design: Dipoles (1)

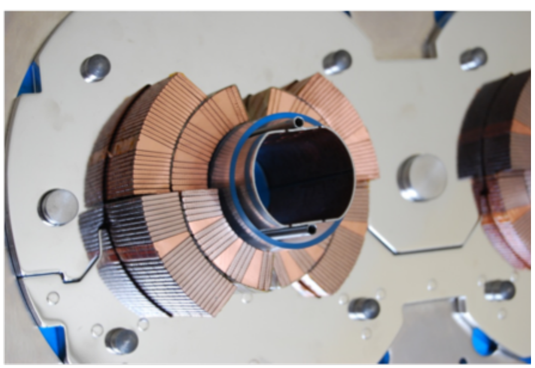
Three types of coils are in use for high field magnets:

Cos(Θ) coil , Block coil , Canted Cos(Θ) coil



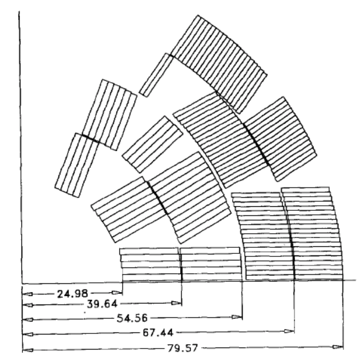
1) Cos(Θ) coil (all, but one, existing accelerators use this type of coil)

- Allows a very good field quality ($b_n < 1{\cdot}10^{-4}$) in thin coils
- Is very efficient wrt the quantity of superconductor used
- The EM forces cause a stress buildup at the mid-plane where also high fields are located
- Wedges are needed in the straight part ('Keystone' cable)
- The ends are short, special geometry for which there is a large experience but not it is easy



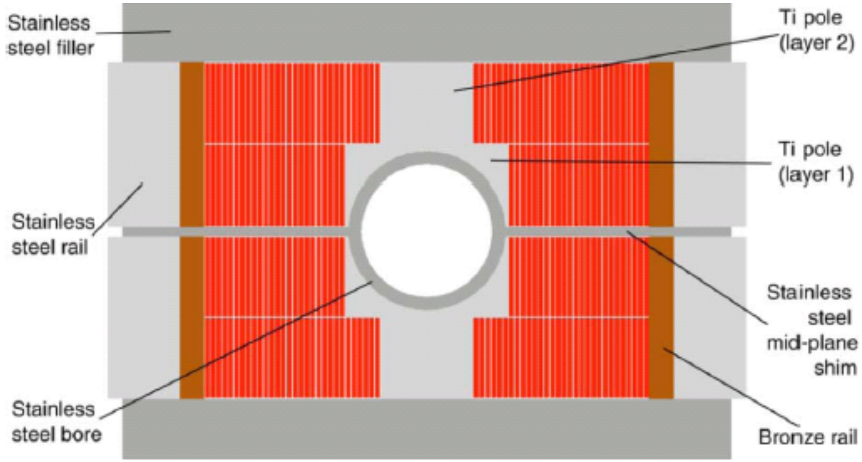
Courtesy M. Wilson

D20

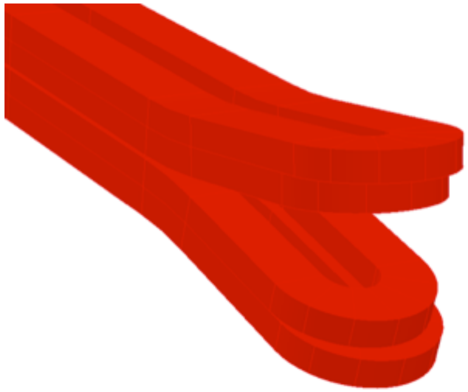


Courtesy LBNL

2) Block coil (used on development and test-station magnets)
- With thick coils the field quality is good
- Less efficient (~10%) wrt to (thin) cos(Θ) for the 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
- ‘flared ends’ look easy but we need more experience



HD2

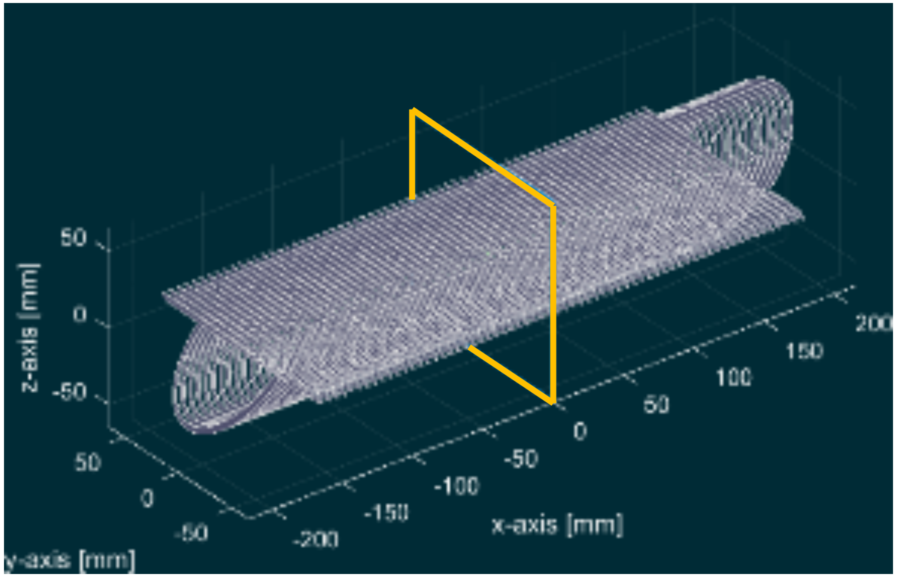


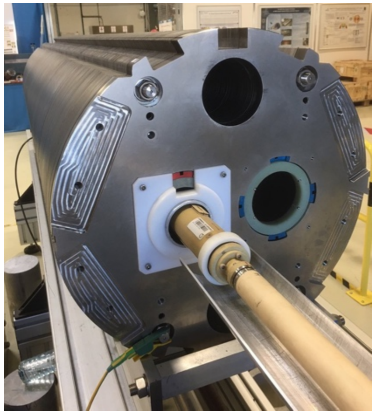
courtesy P. Ferracin, S. Caspi, LBNL

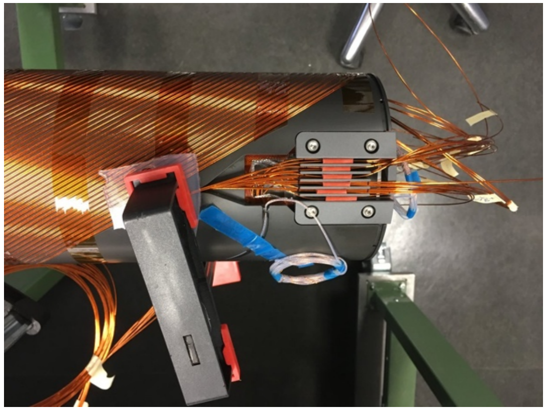
Practical accelerator magnet design: Dipoles (3)

3) Canted Cos(Θ) : CCT (recent usage in accelerators)

- 2 layers of inclined solenoids: powered such that the axial B components compensate and the transverse B components add up.
- First proposed 40 years ago, recently further developed for accelerators: HL-LHC, HIE-Isolde, medical beam-lines, gantry magnets, …
- First in a circular machine is a 3.5 T corrector dipole MCBRD for HL-LHC
- Being designed for an ISOLDE beam line at CERN (curved, combined function magnet)
- Proposed for medical beam lines with bend dipoles and combined function magnets (H2020-HITRIplus)





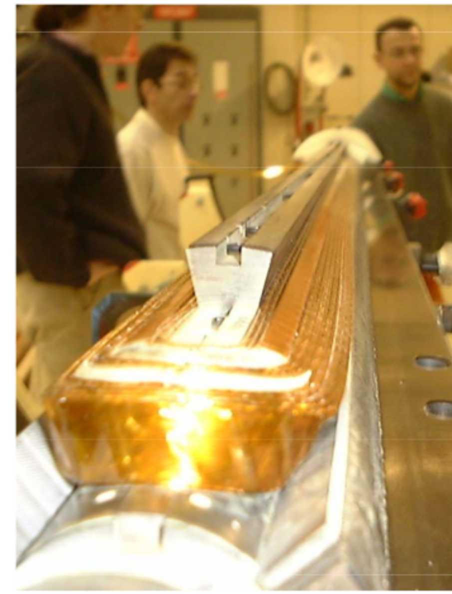


Courtesy G. Kirby, CERN

Quadrupole coil geometries

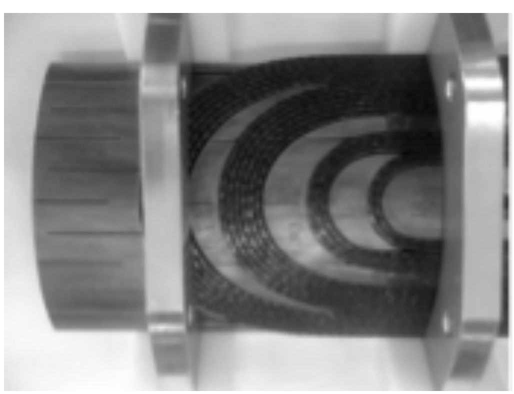
1) Cos(Θ) coil

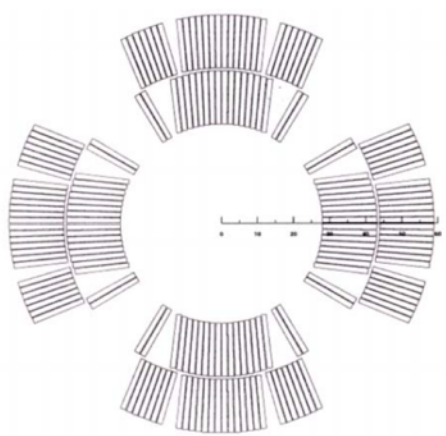
- Allows a very good field quality ($b_n < 1 \cdot 10^{-4}$)
  - all (but one) existing accelerators use this type of coil
- Is very efficient wrt the quantity of superconductor used
- The EM forces cause a stress buildup at the mid-plane where also high fields are located, (but are limited)
- Wedges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

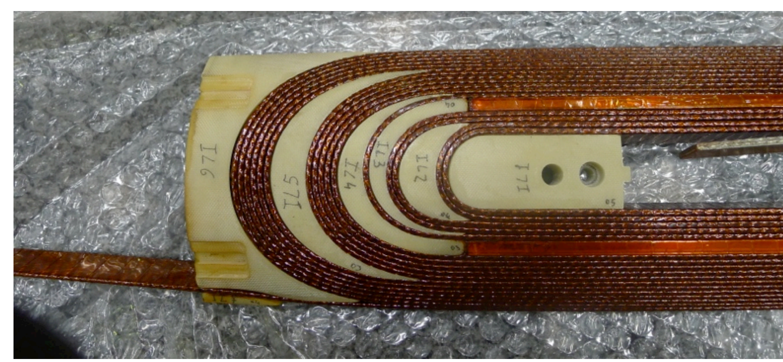


Courtesy M. Wilson

3) Canted Cos(Θ) : CCT



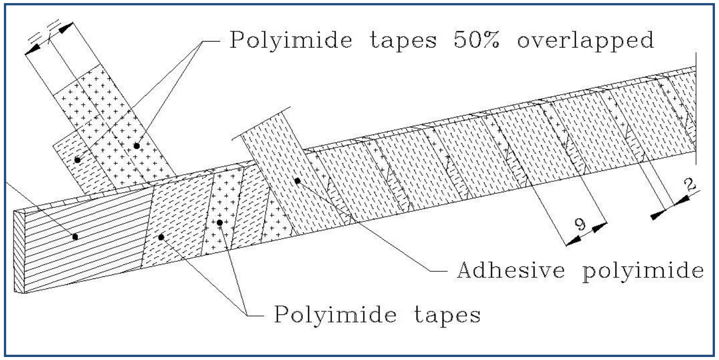


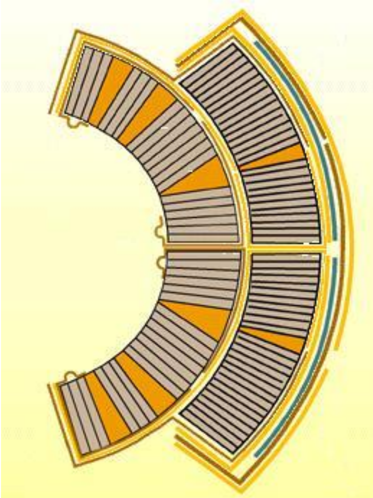


Courtesy CEA

Insulation

- Cable insulation
  - requirements:
    - Good electrical properties to withstand turn-to-turn voltage after a quench
    - Good mechanical properties to withstand high pressure conditions
    - Porosity to allow penetration of helium (or epoxy)
    - Radiation hardness
  - Nb-Ti magnets: overlapped layers of polyimide (e.g. Kapton™)
  - In Nb3Sn magnets: fibre-glass braided or as tape/sleeve.
  - Typically the insulation thickness: 100 and 200 μm.





- Coil insulation: typically several layers (4-6) of polyimide between the coil and the structure.

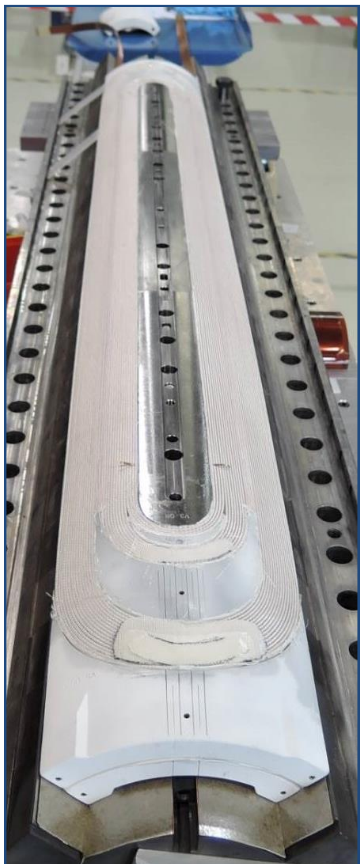
Nb$_3$Sn coil fabrication

The three manufacturing steps of Nb$_3$Sn coils:

1) winding, 2) reaction at 650degC, 3) impregnation with epoxy

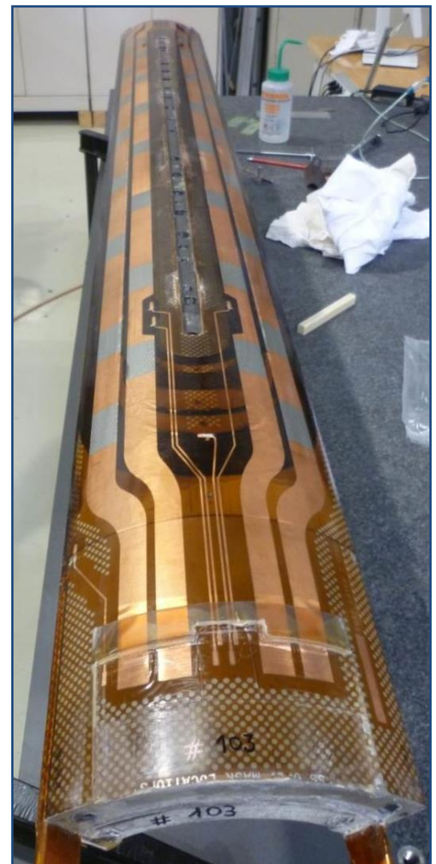
Radiation hardness of the epoxy can be a strong requirement

after winding



after reaction

after epoxy impregnation



Pre-stress

1) Why pre-stress ?
   1) Field quality is determined by the cable positioning (be precise to ~0.02 mm)
   2) Under the MN forces the coils will move

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

      → Apply pre-stress to fix the positioning
2) How to put pre-stress ?

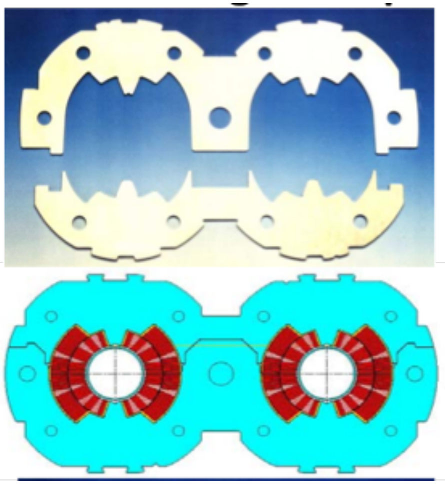
   Three methods:
   1. Compress at room temperature: collar system
   2. Use room temperature pre-stress plus differential shrinkage at cooldown: Al or stainless steel shrinking cylinder and/or a (shrinking) key
   3. Compress a bit at room temperature and use differential shrinkage at cool-down: Al shrinking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

   Fresca2 @ 13 T: 60 MPa warm, 130 MPa cold

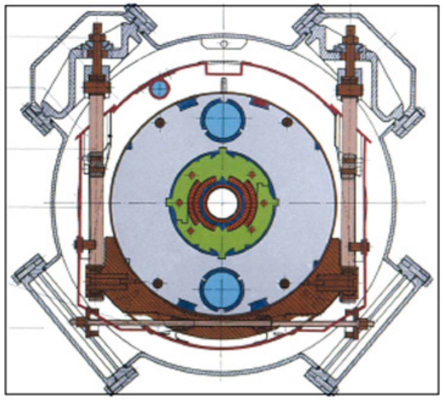
Pre-stress: collars

"The classical solution"

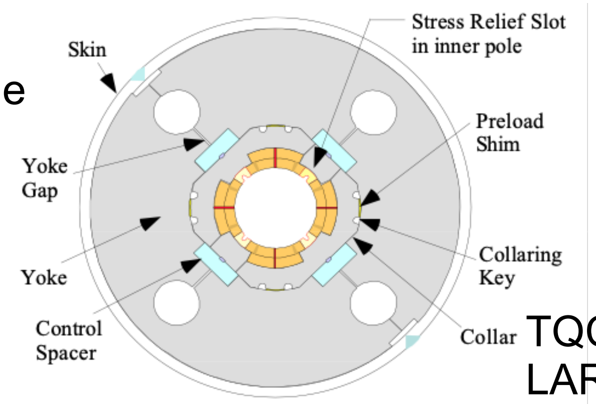
1) Thin collars put around the coil
2) The coil is well contained in a fixed cavity
3) Pressed together and locked with pins or keys
4) At 300K apply a pre-stress 2-3 times of what is needed as part of the stress is lost during cooldown: for very high fields this tends to be too high (LHC:70 MPa at 300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



LHC dipole
CERN



Hera dipole
DESY



TQC quadrupole
LARP-FNAL

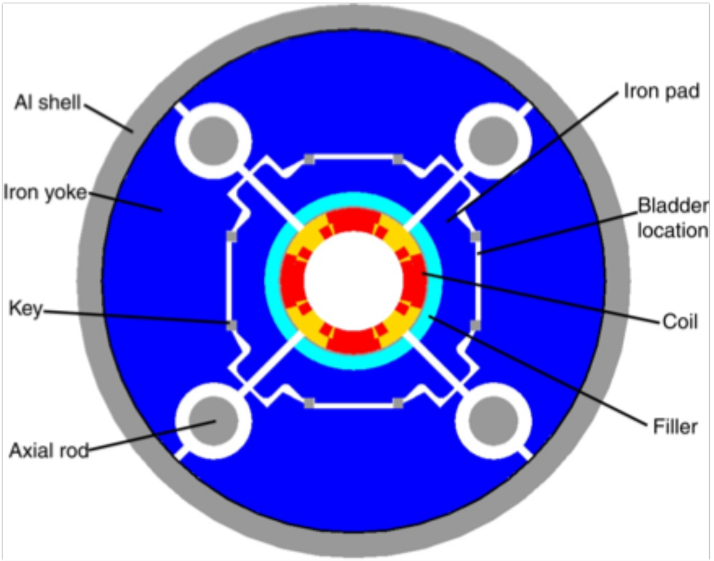
Pre-stress: Al shrinking cylinder + bladder and keys

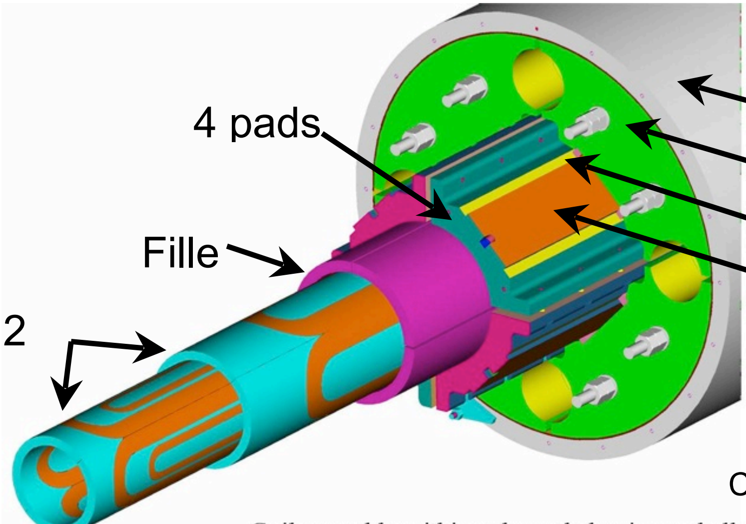
Developed at LBNL, example: TQS,   HL-LHC quadrupole MQXF

1) 300 K: Bladders pressurized with water (<600 bar) , then insert keys → load between 10 MPa and 80 MPa

2) Cooldown: differential shrinkage between AL shell and Fe yoke load another ~100 MPa

Needs careful mechanical FE modeling before and strain measurements during bladder operations and cool-down





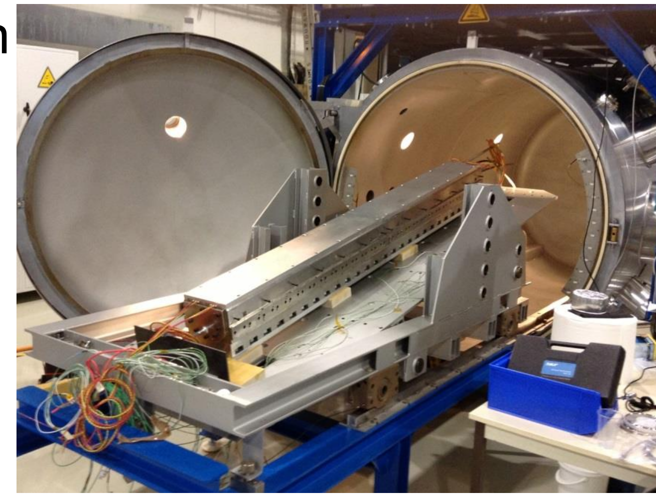
Coil assembly within yoke and aluminum shell

Courtesy S. Caspi

tooling for magnet fabrication

winding

impregnation



reaction

collaring

Operating SC magnets in Accelerators

1) In synchrotrons with many, or with the majority superconducting magnets special care must be taken to cope with the specific properties of these magnets:
   1) ramp rate,
   2) excitation curves and calibration,
   3) persistent current decay and snapback,
   4) machine parameter tuning and hysteresis effects,
   5) cryogenic system operation,
   6) continuous cryostats.
2) For keeping dynamic field effects under control, we need thin filaments in the wires
3) Magnet strings that are situated inside long cryostats with long warm-up and cool-down times, which render any repair very tedious: the entire system must be engineered to very high reliability standards.
4) The relatively slow ramp-up and ramp-down of superconducting accelerators imply that it is not evident to do quick trails with the beam settings. To get to a good efficiency, careful preparation with appropriate computer simulations are needed before trying new setting parameters out on the beam.

The CERN Accelerator School

What is happening after the 8T magnets for LHC ?

At CERN and in the US:

1) Upgrade the LHC luminosity: HL-LHC (HILUMI)
   1) Use large aperture Nb_3Sn triplet quadrupoles MQXF (12T class)
2. Go to higher energies
   1) 16 T Nb_3Sn dipoles in the LHC ring for E_{com}=26 TeV : HE-LHC
   2) 16 T Nb_3Sn dipoles in a 100 km new ring for E_{com}=100 TeV: FCC Future Circular Collider

   But even !

   3) 20 T HTS dipoles in the LHC ring: for E_{com}=33 TeV : HE-LHC
   4) 20 T HTS dipoles in a 80 km new ring for E_{com}=100 TeV : FCC
3. Muon collider (@CERN or elsewhere)

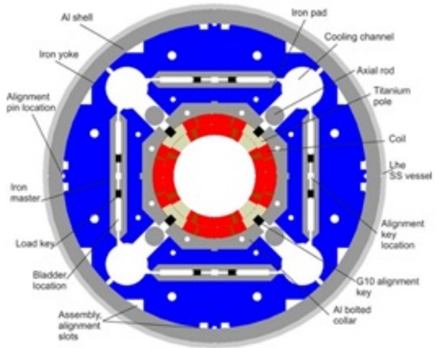
For the CERN High Field Magnet program see: https://indico.cern.ch/event/1279349/

In China:

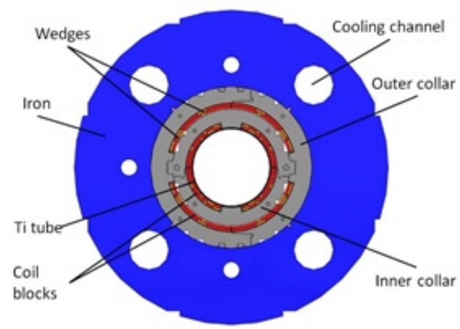
A similar completely project is being studied in China: SPPC (C=100 km, 12-20 T)

For these, basic High Field Magnet development programs are since many years running in the US and Europe and recently in China

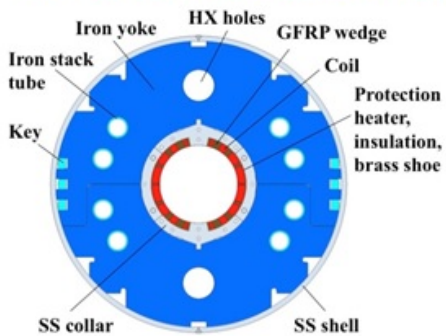
HL-LHC Inner Triplet magnet zoo



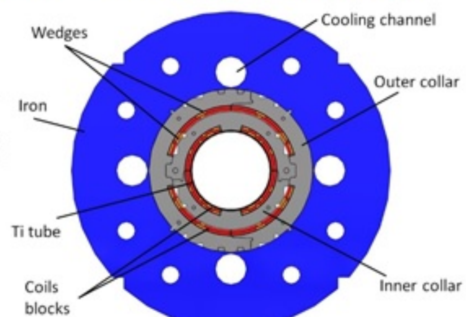
Triplet [G. Ambrosio, P. Ferracin et al.]



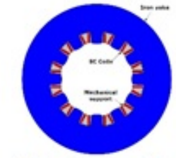
MCBXFB [F. Toral, et al.]



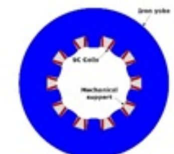
D1 [T. Nakamoto et al.]



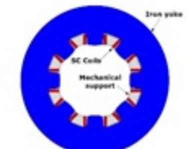
MCBXFA [F. Toral, et al.]



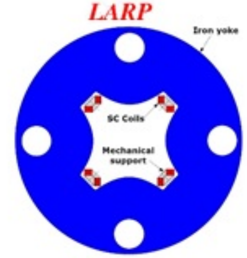
Dodecapole



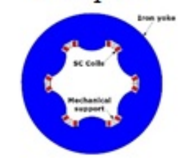
Decapole



Octupole

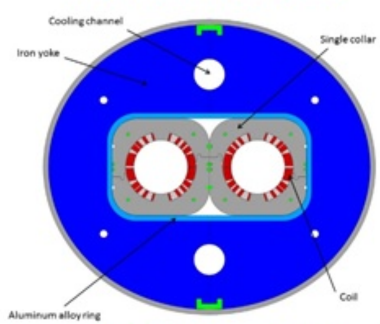


Skew quad

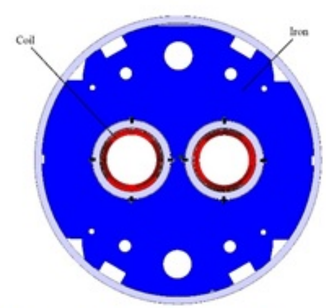


[G. Volpini, et al.]

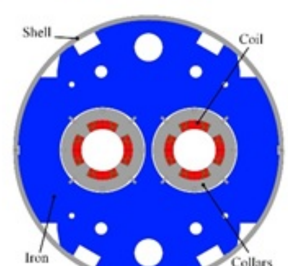
LARP



D2 [P. Fabbricatore, S. Farinon]



D2 Q4 correctors [G. Kirby]



Q4 [J. M. Rifflet, M. Segreti, et al.]

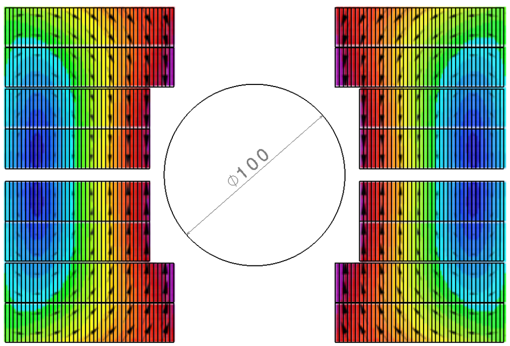
Courtesy E. Todesco

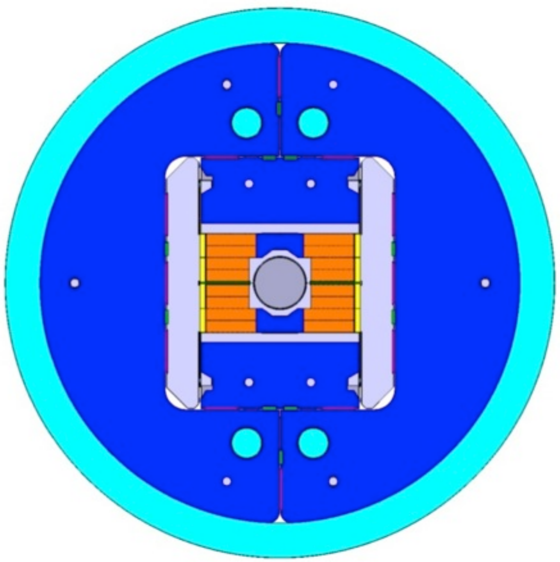
Basic HFM development (HL-LHC technology): EuCARD high field dipole (Fresca2):

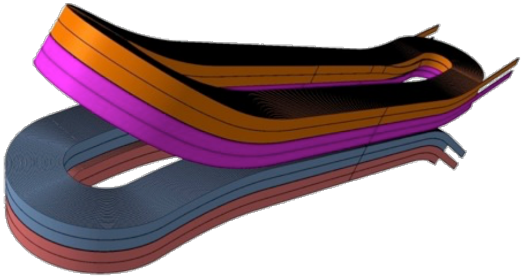
- Fresca2 : CERN, CEA construction phase
- First tests 2014

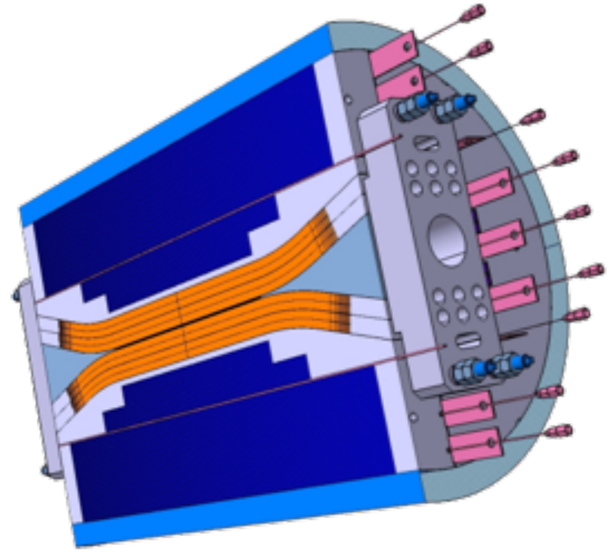
- 156 turns per pole
- Iron post
- B_{center} = 13.0 T
- I_{13T} = 10.7 kA
- B_{peak} = 13.2 T
- E_{mag} = 3.6 MJ/m
- L = 47mH/m

1) Diameter Aperture = 100 mm
2) L coils = 1.5 m
3) L straight section = 700 mm
4) L yoke = 1.6 m
5) Diameter magnet = 1.03 m







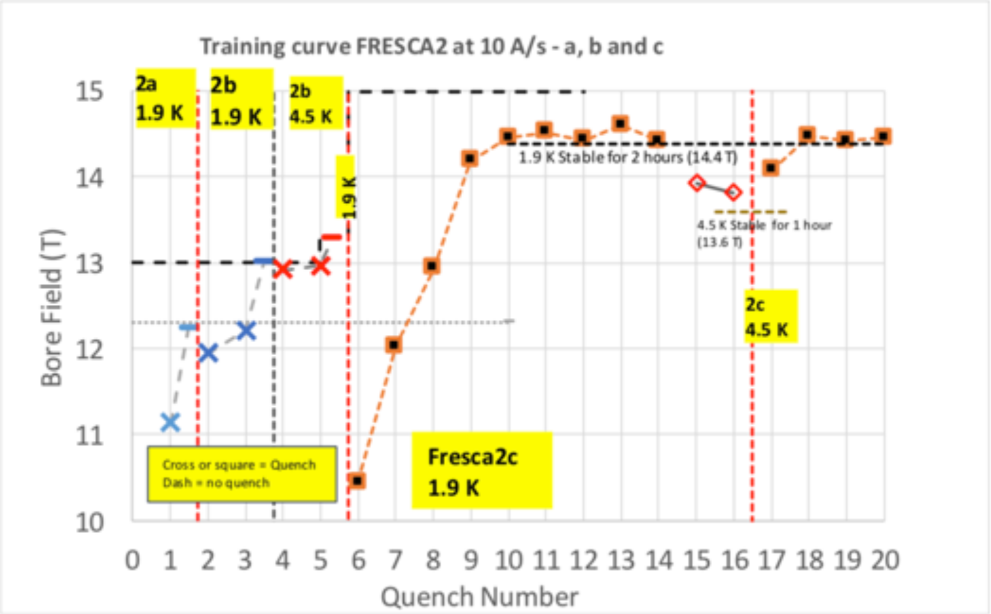


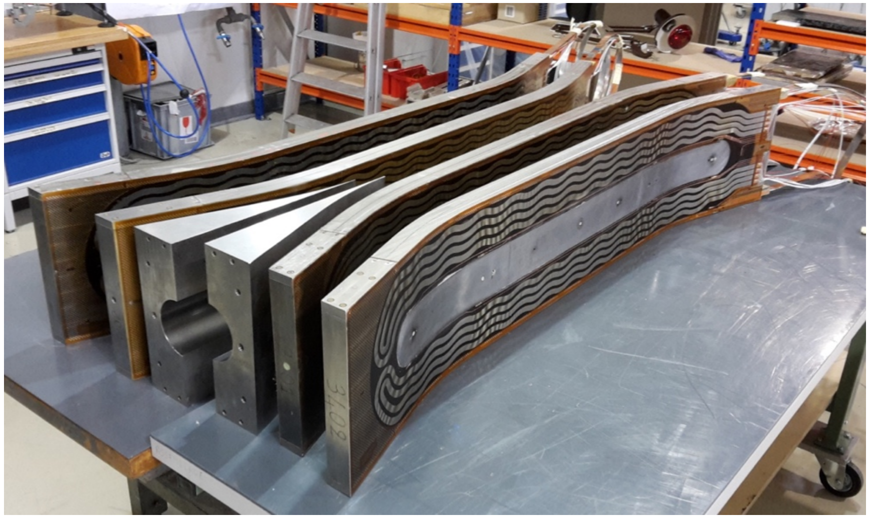
Courtesy Attilio Milanese, Pierre Manil

Fabrication of Fresca2 coils, test results

Straightforward technology to wind blo coils with flared ends:

This is a lesson for FCC magnets !





HL-LHC: MQXF low beta Nb_3Sn quadrupole

Models had good performance, long prototypes are being fabricated in the US and at CERN

A CERN LARP collaboration.

Nominal Gradient 132.6 T/m

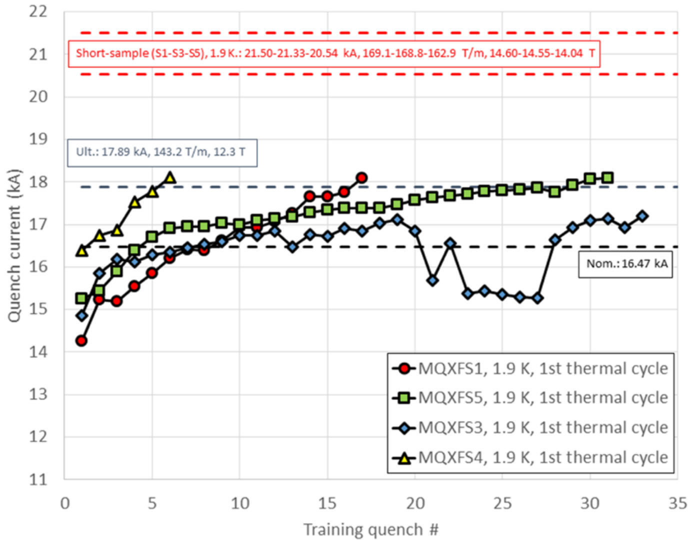
Aperture diameter 150 mm

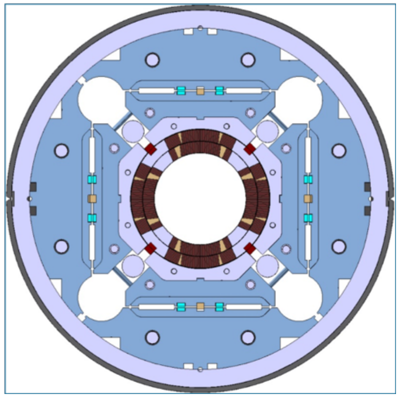
Peak Field 12.1 T

Current 17.5 A

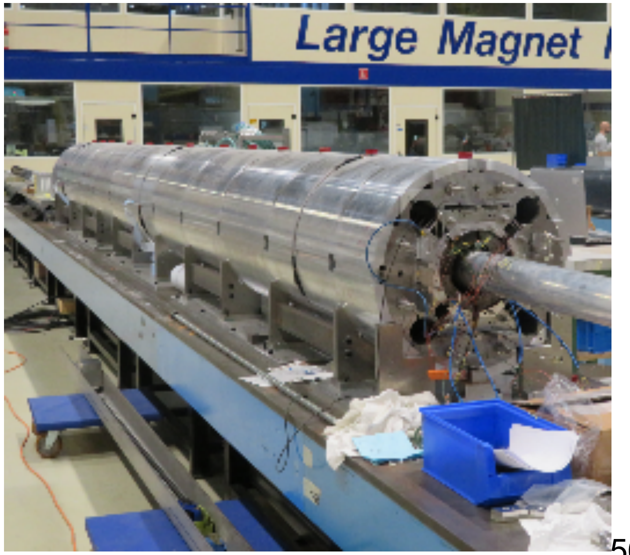
Load-line Margin 20% @ 1.9 K

Stored Energy 1.32 MJ/m



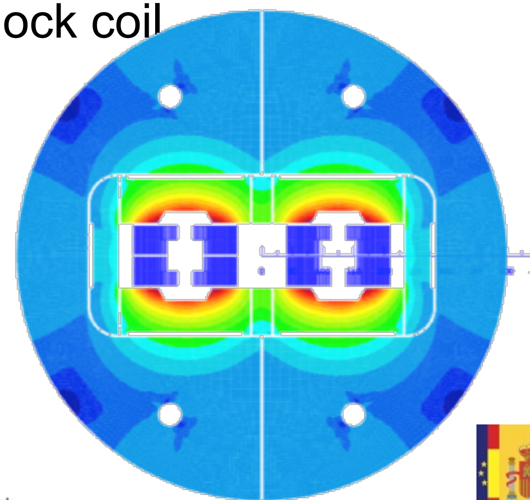


Courtesy P. Ferracin, S. Izquierdo



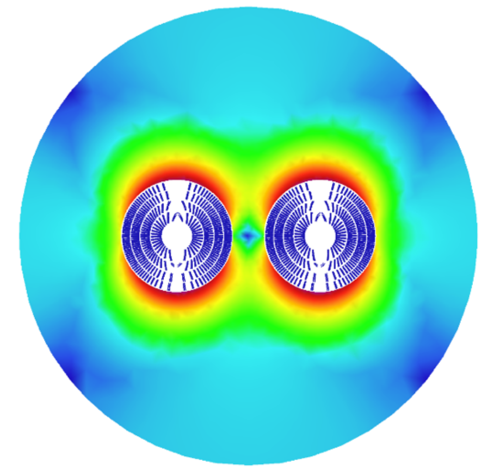
FCC: 16T dipole options

Block coil



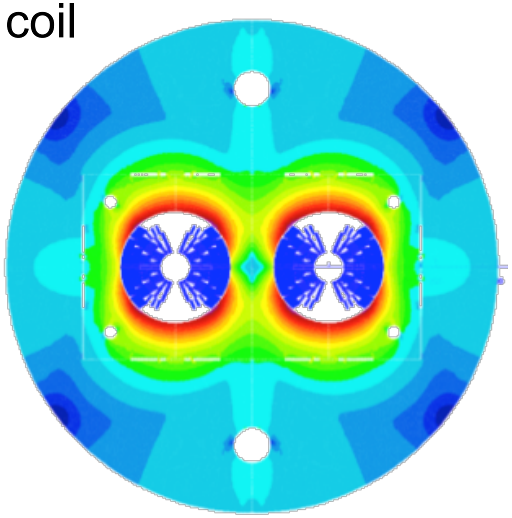
C. Lorin, M. Durante (CEA)

Canted Cos-theta



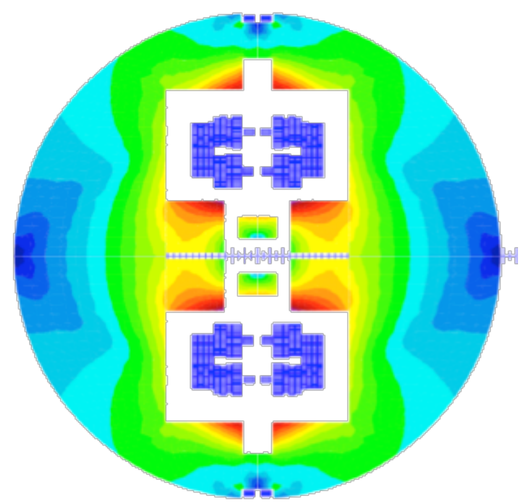
B. Auchmann (CERN/PSI)

Cos-theta coil



S. Farinon, P. Fabbricatore (INFN)

Common coils

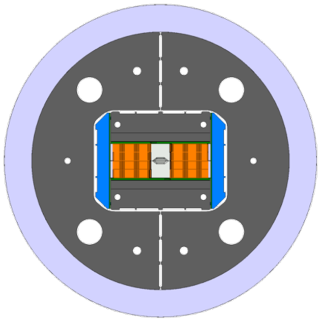


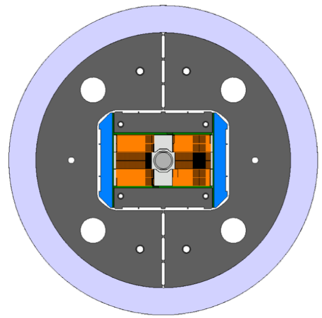
F. Toral (CIEMAT)

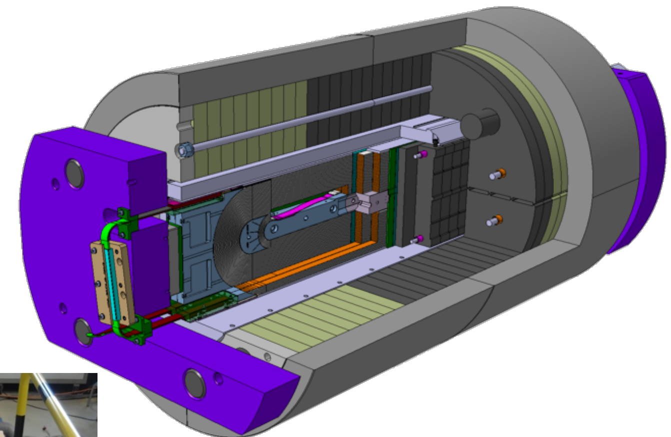
16 T, CERN approach, go in steps

1 Extended Racetrack Model Coil , ERMC
2 Racetrack Model Magnet, RMM
3 Demonstrator, DEMO

First with one conductor , then with 2 different ones to optimise the coil: Grading

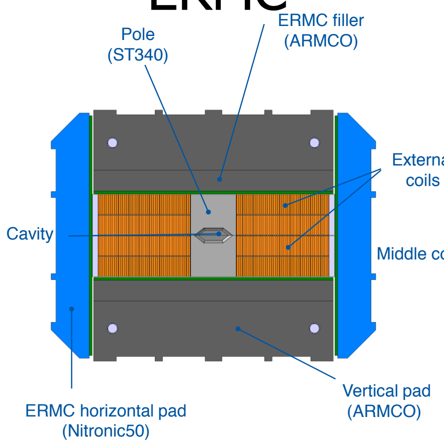




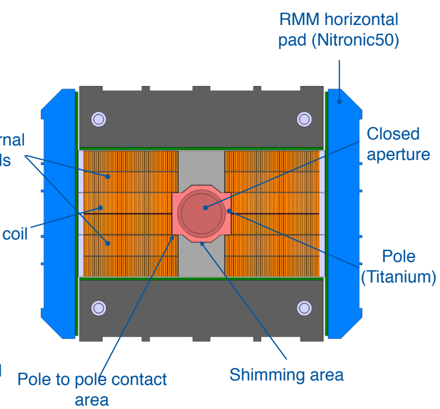


ERMC

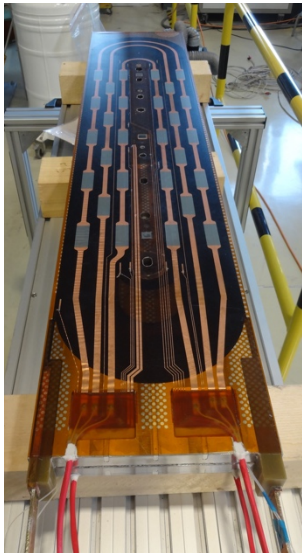
RMM

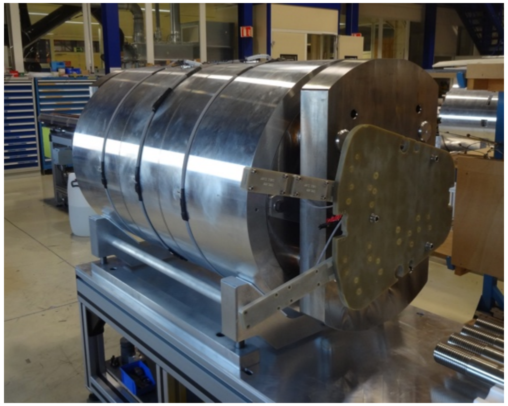


coil: 2 x 45 t/l



middle coil: 2 x 42 t/l





courtesy: S. Izquierdo, J-C. Perez

RMM test Sept 2022: reached conductor peak field Bp of 16.7T and 16.5 T in aperture cavity

Muon collider development

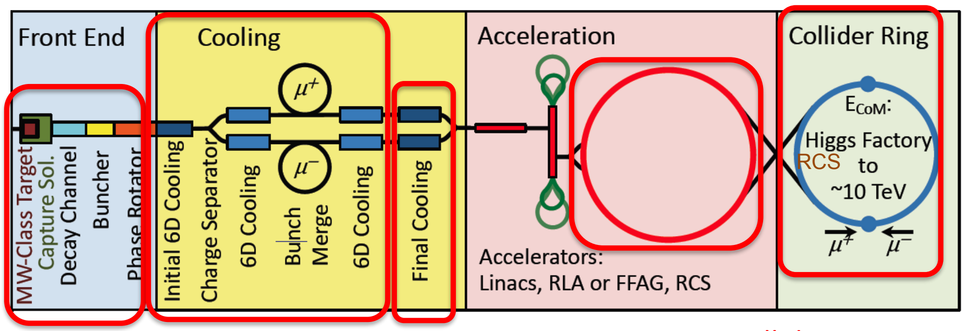
Extensive magnet development is needed for a muon collider.
This development has started in the institutes of the muon collaboration

Muon Collider magnet "specs"

Target solenoids
Field: 20 T… 2T
Bore: 1200 mm
Length: 18 m
Radiation heat: ≈ 4.1 kW
Radiation dose: 80 MGy

6D Cooling solenoids
Field: 4 T … 19 T
Bore: 90 mm … 600 mm
Length: 500 mm (x 17)
Radiation heat: TBD
Radiation dose: TBD

Accelerator magnets
Field: ±1.8 T (NC), < 10 T (SC)
Rate: 400 Hz (NC), SS (SC)
Bore: 100 mm(H) x 30 mm(V)
Length: 3 m … 5 m (x 1500)
Radiation heat: ≈ 3 W/m
Radiation dose: TBD



Final Cooling solenoids
Field: > 40 T (ideally 60 T)
Bore: 50 mm
Length: ≈ 1 km (x 2)
Radiation heat: TBD
Radiation dose: TBD

Collider ring magnets
Field: 16 T peak (IR 20 T)
Bore: 150 mm
Length: 10 m … 15 m (x 700)
Radiation heat load: ≈ 5 W/m
Radiation dose: ≈ 20…40 MGy

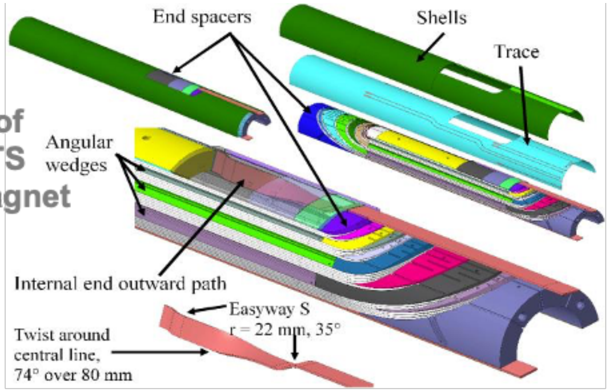
see: https://muoncollider.web.cern.ch/

HTS magnet development

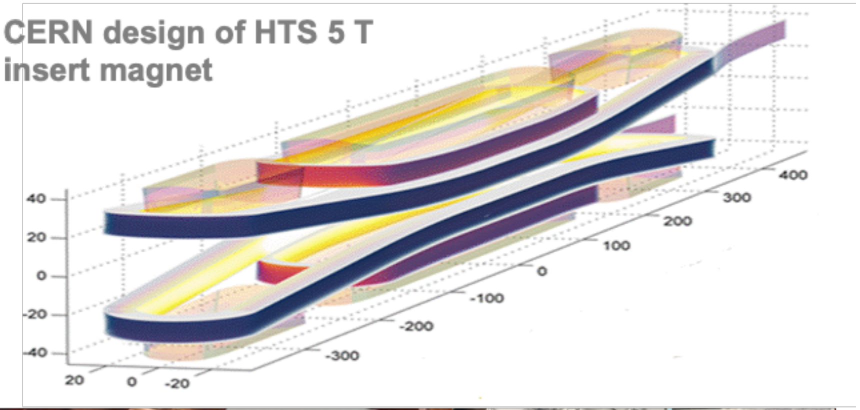
HTS is the only path beyond 16 Tesla

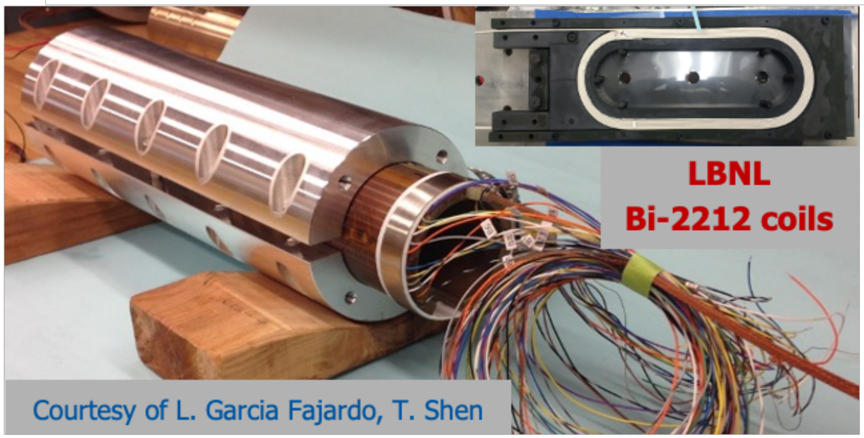
- So far, many small experimental solenoid magnets have been built, but only a few coils for accelerator dipole magnets made either of ReBCO tapes or Bi-2212 cables, and only the first HTS inserts for hybrid dipole demonstrators, such as 5 T inserts at CERN and CEA and 3 T at BNL
- **In practice, all insert coils built for hybrid LTS/HTS magnets had significant performance limitations**

CEA design of Cos-theta HTS 5 T insert magnet



CERN design of HTS 5 T insert magnet

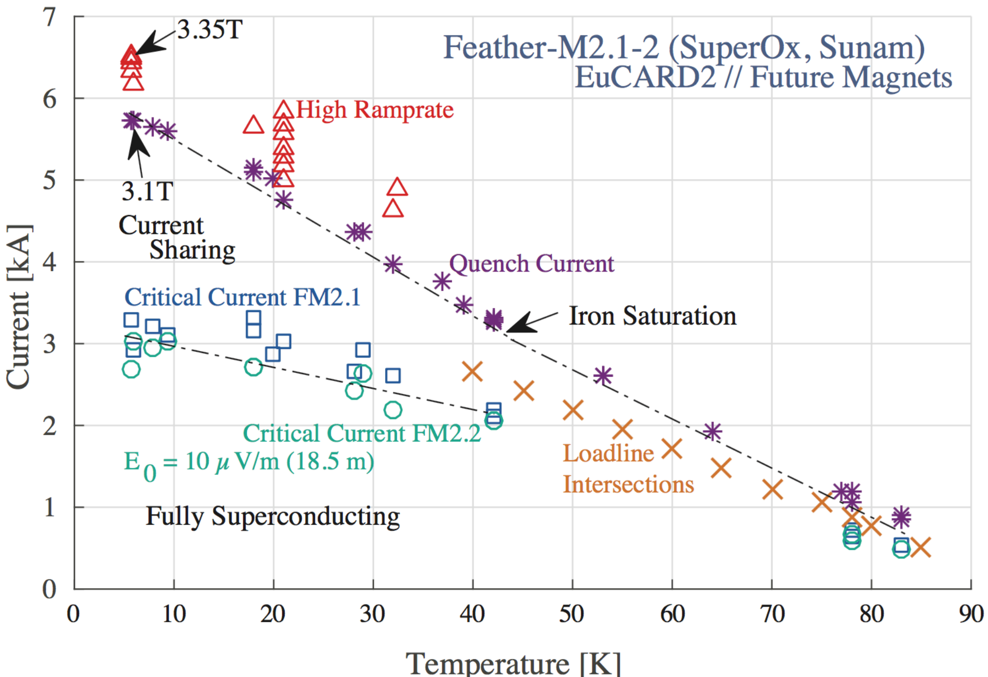


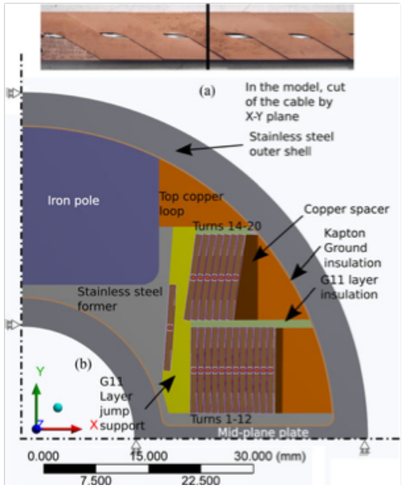


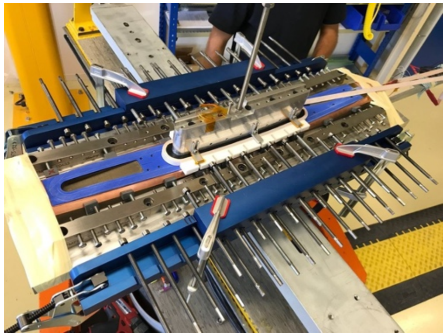
courtesy: A. Siemko

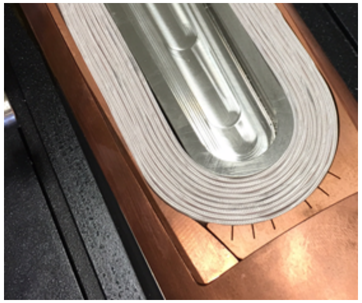
Feather-M2.0: HTS has special dynamics

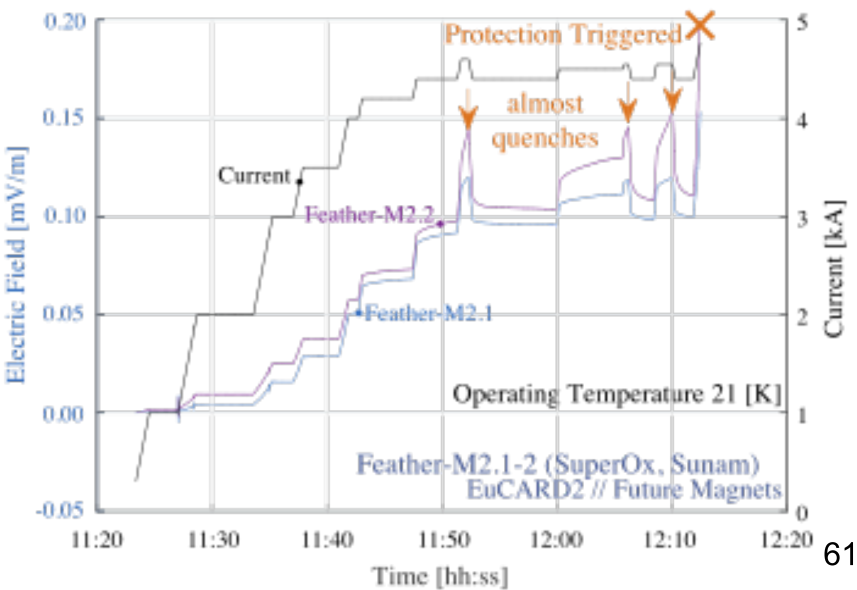
HTS magnets work differently than LTS magnets due to a larger enthalpy margin











HTS possibilities, an example at PSI

PSI built and tested a stack of 4 ReBCO flat non-insulated disk coils .

The disks were powered in series.

The coils were produced under a license- and collaboration agreement with Tokamak Energy Ltd

Cooling: two cryo-coolers

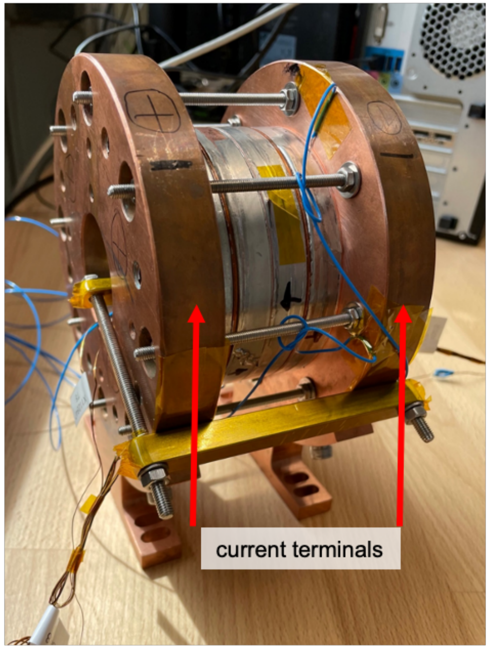
Current: 2 kA (maximum of power supply)

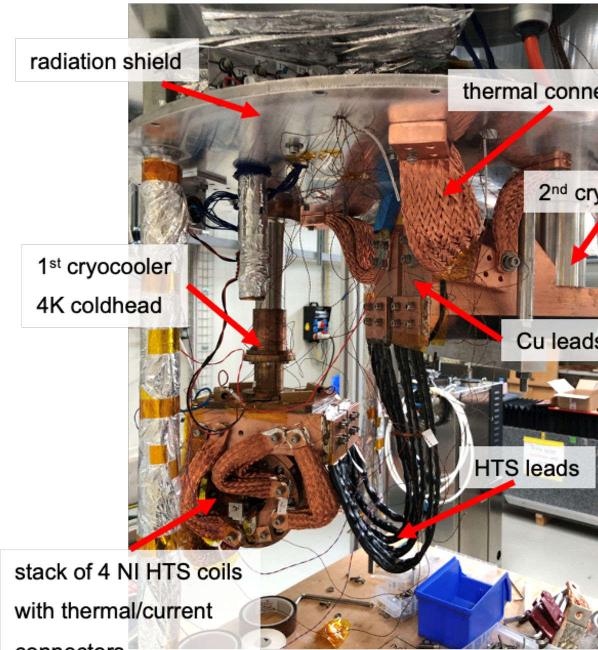
Coil temperature: 12 K on plateau (higher during ramp)

Resistive-lead bottom temperature: 72 K

Central field: 18.2 T (measured)

Coil field: 20.3 T (simulated)





Courtesy B. Auchmann, PSI

Final remarks

Superconducting accelerator magnets in the 4 T – 8 T range are “state of the art” using Nb-Ti conductor

Magnets in the 12 T range using Nb_3Sn are in the production phase for HL-LHC.

Development models have been shown to work up to 16 T

For future collider 12 -16 T magnets are being designed

Development for HTS magnets for the 20 T range has started

Magnet development for the muon collider has recently started in the very high field range

Lots of fun ahead !

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