



Superconducting Magnets

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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

$$\text{rot} \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}$$

$$\oint \vec{E} d\vec{s} = -\frac{\partial}{\partial t} \int_A \vec{B} d\vec{A}$$

Faraday's equation

$$\text{rot} \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\int_A \vec{B} d\vec{A} = 0$$

Gauss's law for magnetism

$$\text{div} \vec{B} = 0$$

$$\int_A \vec{D} d\vec{A} = \int_V \rho dV$$

Gauss's law

$$\text{div} \vec{D} = \rho$$

With: $\vec{B} = \mu \vec{H} = \mu_0 \mu_r \vec{H} = \mu_0 (\vec{H} + \vec{M})$

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

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



Magnetostatics

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

Gauss law of magnetism

$$(1) \quad \operatorname{div} \vec{B} = 0 \quad \text{always holds}$$

Ampere's law with no time dependencies

$$(2) \quad \operatorname{rot} \vec{H} = \vec{j} \quad \text{holds for magnetostatics}$$

Relation between \vec{H} field and the flux density \vec{B}

$$(3) \quad \vec{B} = \mu_0 \mu_r \vec{H} \quad \text{holds for linear materials}$$



Magnetic field quality: multipole description

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

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 n th multipole component,

a_n the skew n th multipole component.

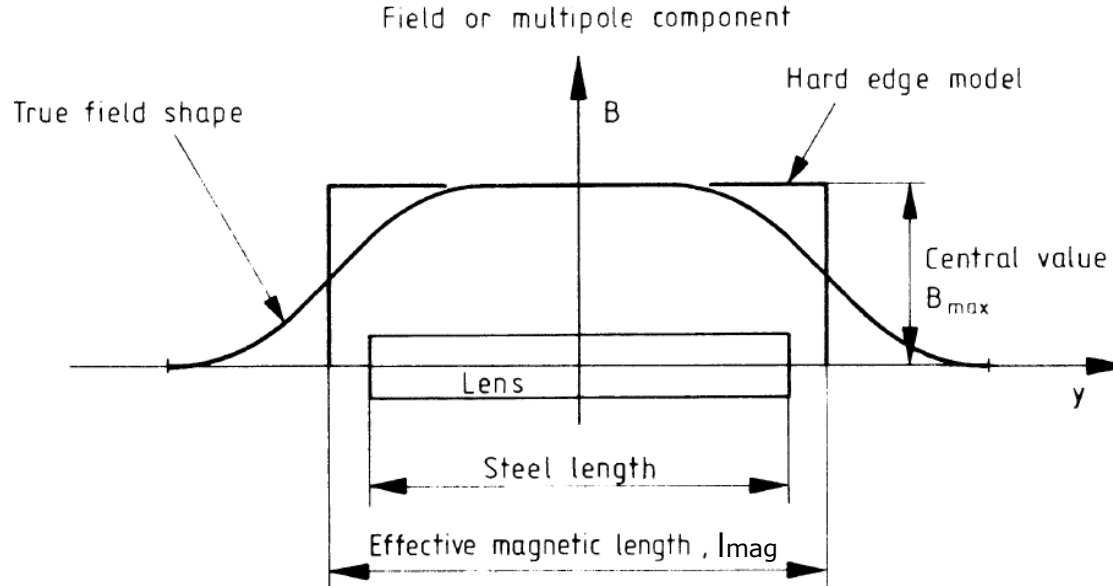
The “wanted” b_n or a_n is equal to 1

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

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

Magnetic Length

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

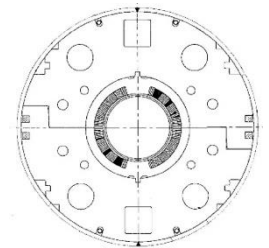


$$L_{mag} B_0 = \int_{-\infty}^{\infty} B(z) dz$$

Courtesy A. Milanese, CERN

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

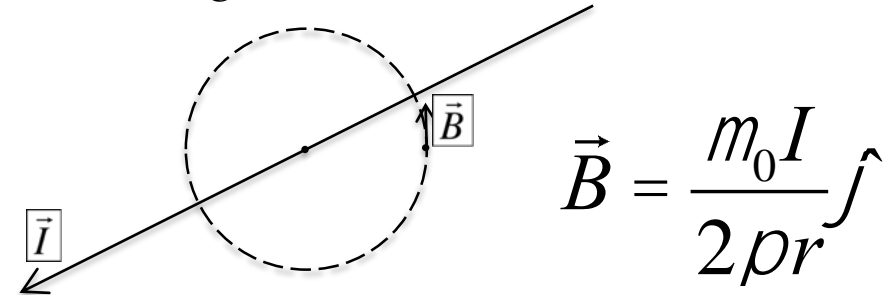
The magnetic length L_{mag} for SC magnets is adjustable by varying the length of the yoke: often the coils stick outside the end of the yoke: no easy rule of thumb for L_{mag}



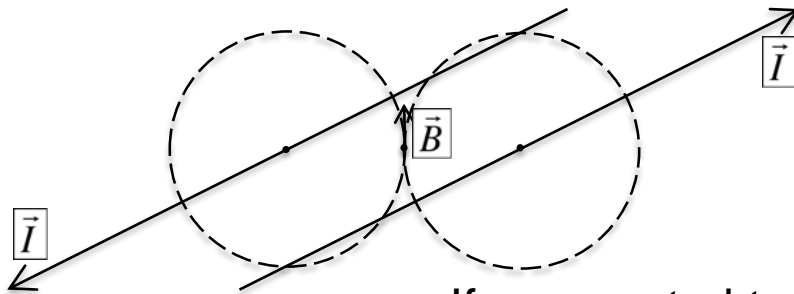
From Ampere's law with no time dependencies
(Integral form)

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

We can derive the law of Biot and Savart



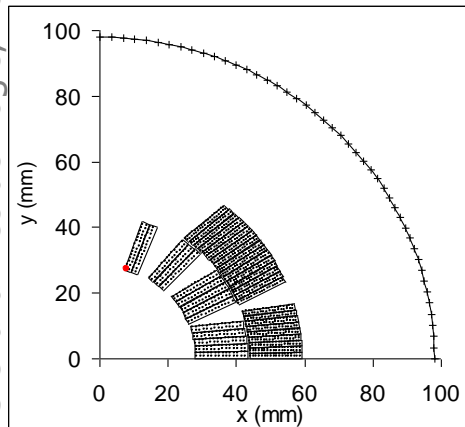
$$\vec{B} = \frac{\mu_0 I}{2\pi r} \hat{j}$$



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

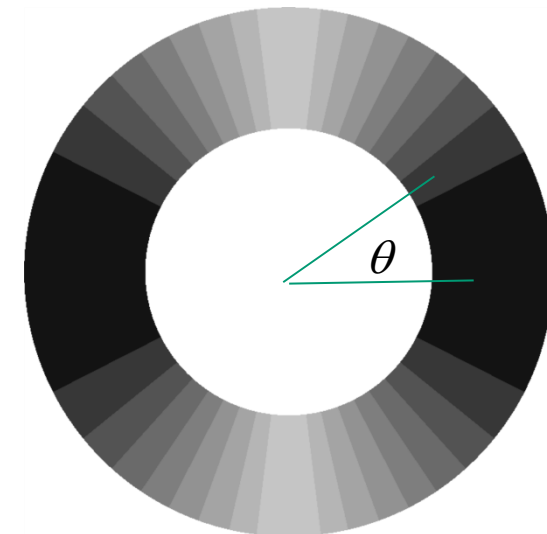
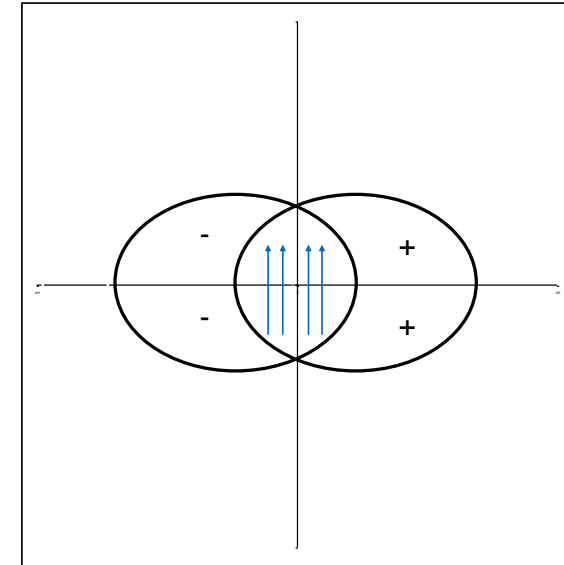
For LHC dipole @ 8.3 T ~1 MA in 3300 mm² : ~300 A/mm²
(overall current density in the coil area)



Courtesy E. Todesco

Coils for generating the Perfect Dipole Field

- Conductors 2 solid Intercepting ellipses (or circles)
 - A uniform, opposite polarity, current density in the area of two intersecting ellipses produces a pure dipolar field, but:
 - The aperture is not circular
 - Not easy to simulate with a flat cable
- Thick conductor shell with a $\cos\theta$ current distribution $J = J_0 \cos\theta$
 - Pure dipolar field
 - Easier to reproduce with a flat rectangular (or slightly key-stoned) cable



Magnet types and higher orders

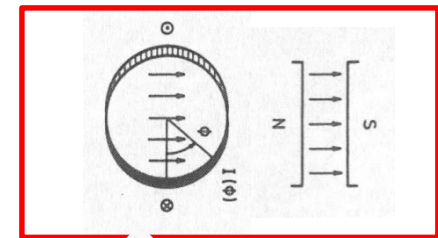
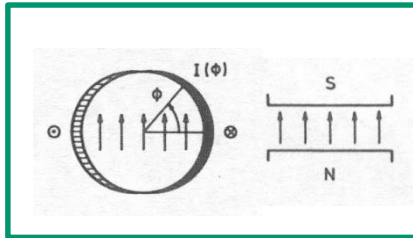
a “pure” multipolar field can be generated by a specific coil geometry

normal

skew

dipole $n=1$

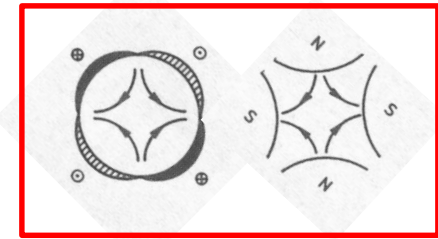
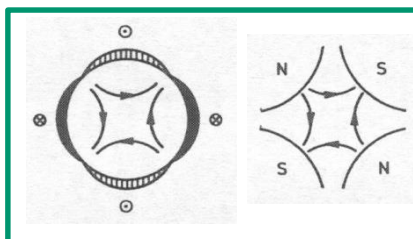
B_1



A_1

quadrupole $n=2$

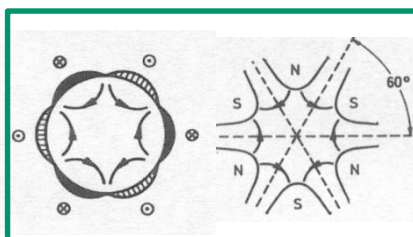
B_2



A_2

sextupole $n=3$

B_3

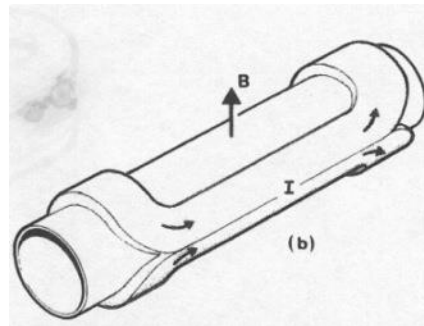
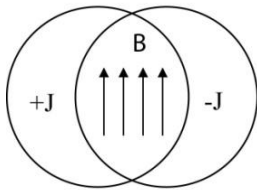


A_3

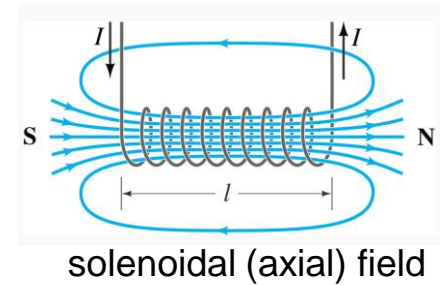
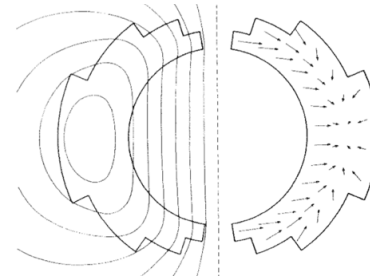
What is specific about accelerator magnets ?

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

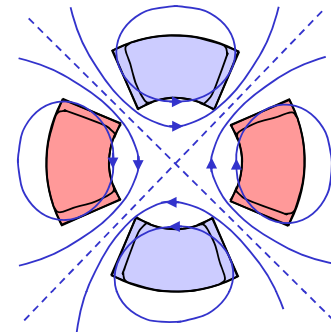
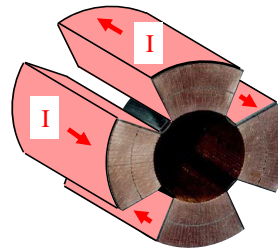
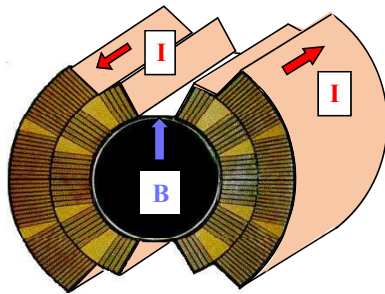
Cos Θ coil : $J = J_0 \cos\Theta$



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



- Dipoles, quadrupoles, etc



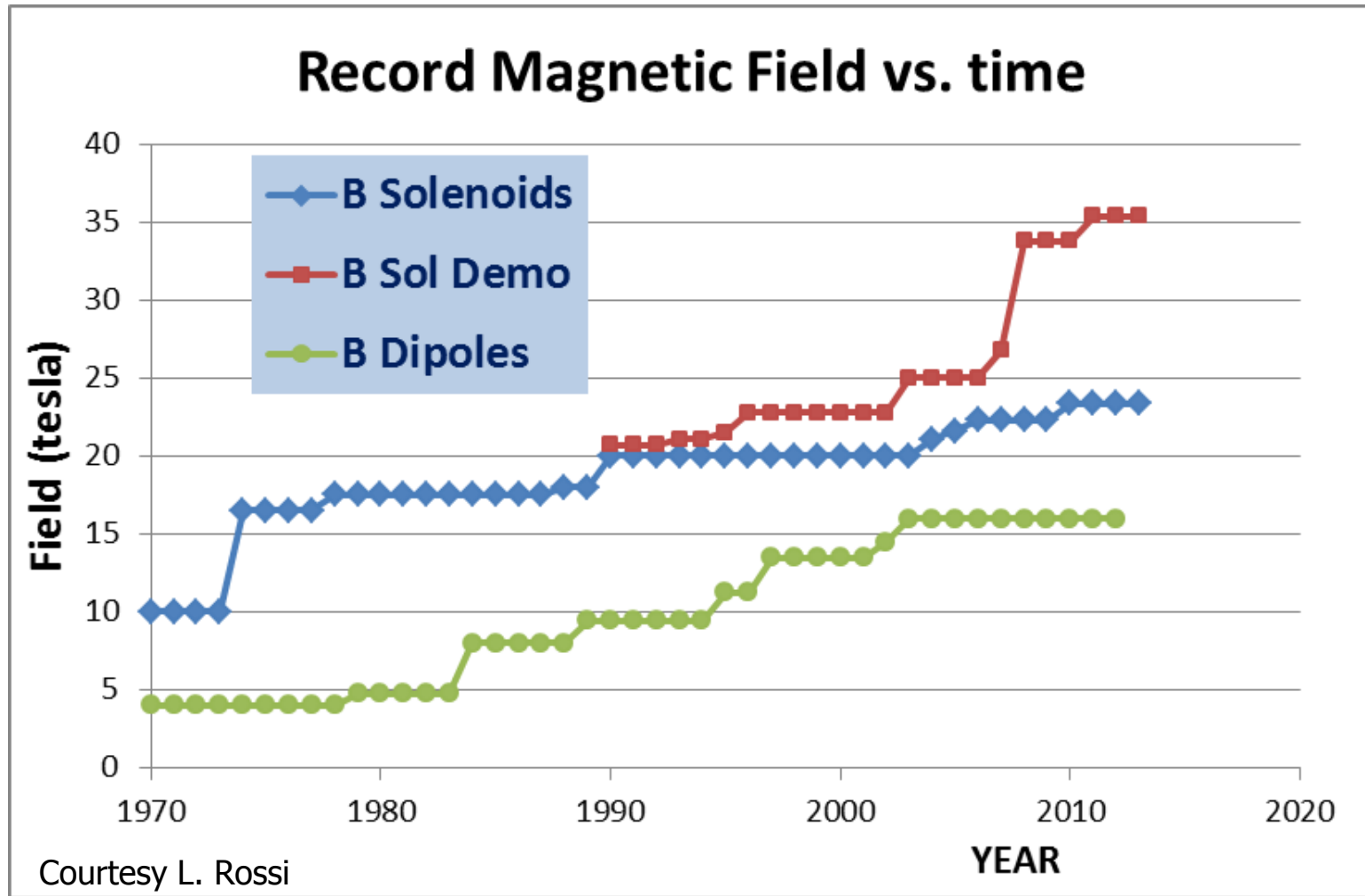
- Long magnets: dipoles from 6 m (Tevatron) to 15 m (LHC)
- Often magnets are bend (9.14 mm sagitta for the LHC dipoles)



The state of the art:

Comparison between dipoles and solenoids

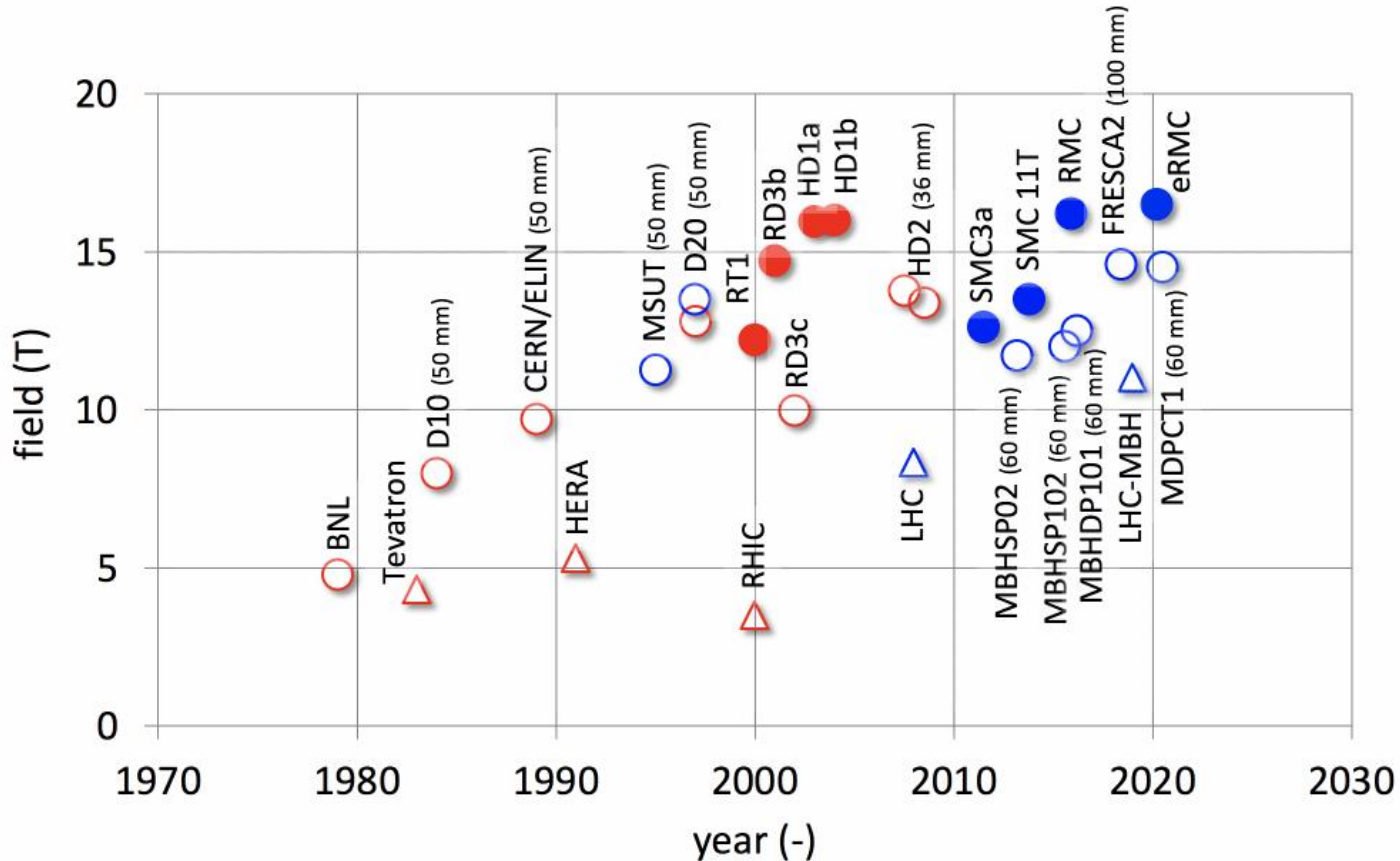
We can see roughly a factor 2 due to Coil «efficiency» and to force-stress management



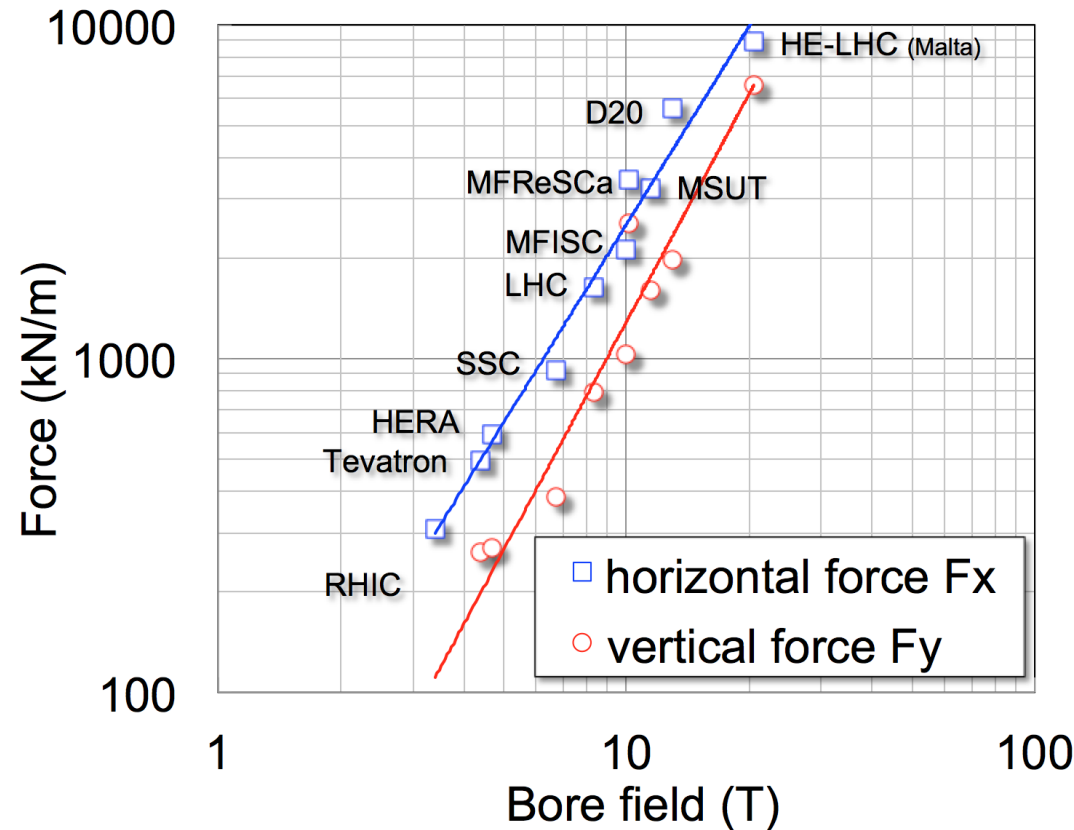


Superconducting accelerators magnets; the state of the art

- 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



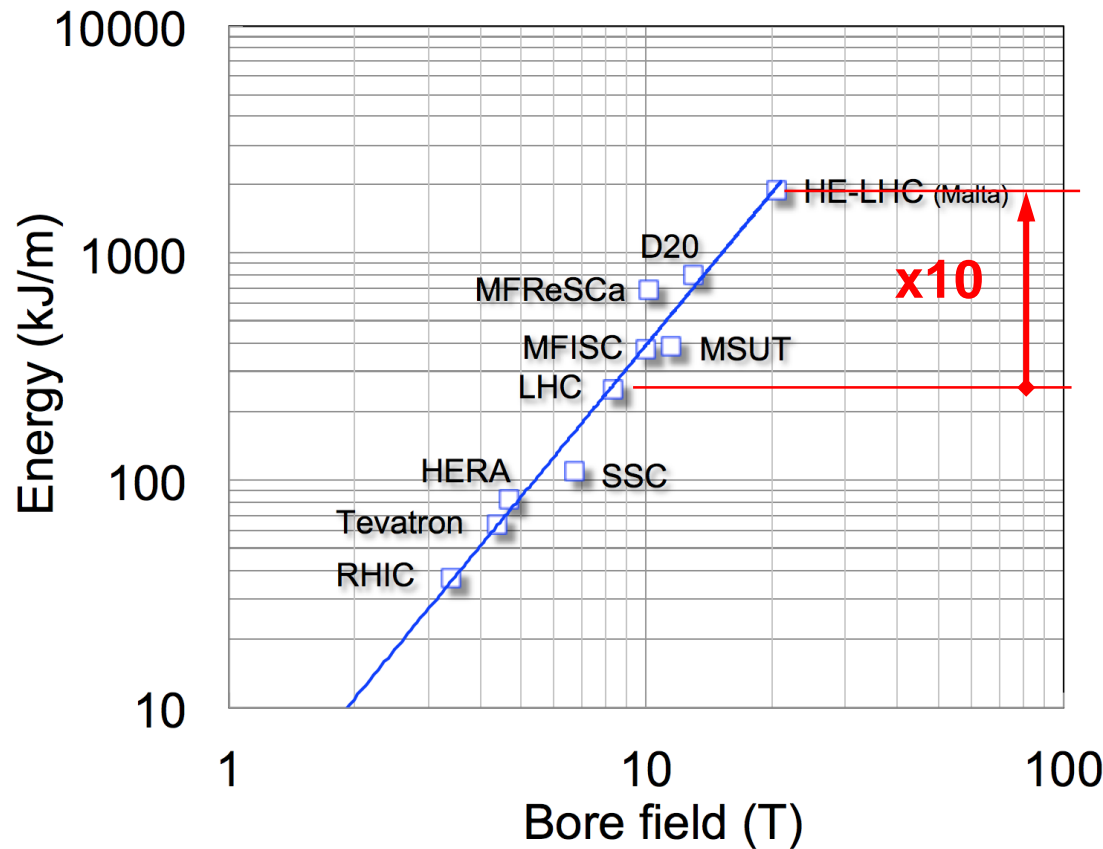
Scaling of force on coil quadrant vs. Field Plot for recent production and R&D dipoles



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

Stored Energy

Scaling of the energy per unit length of magnet vs. Field
Plot for recent production and R&D dipoles



Scaling of the energy per unit length of magnet in recent production vs. R&D dipoles



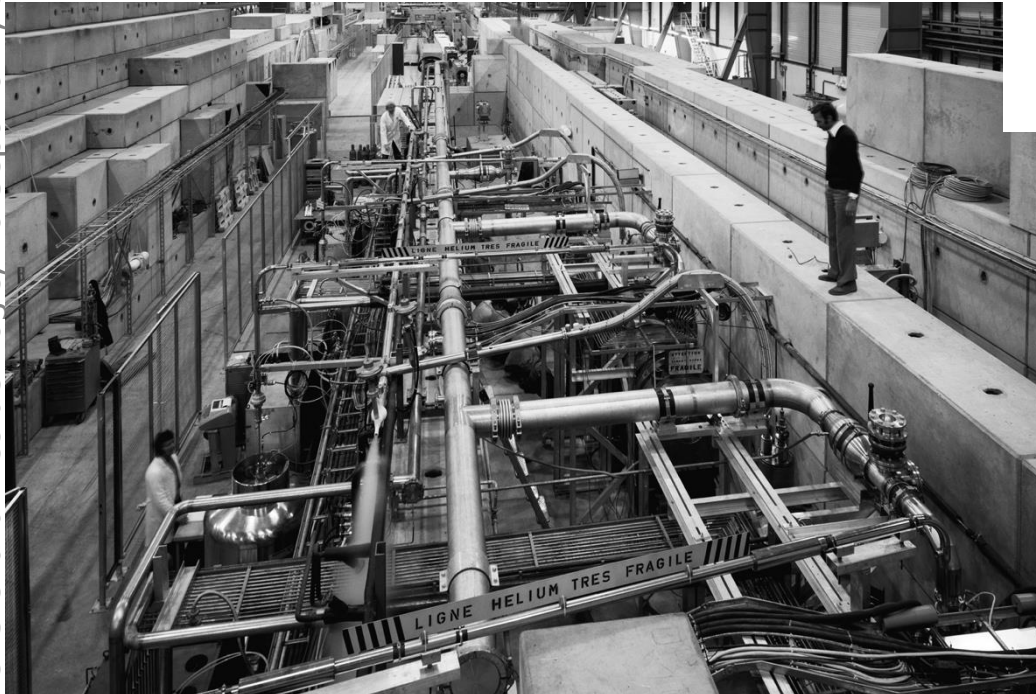
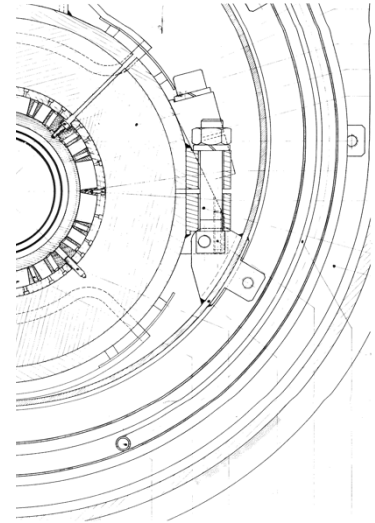
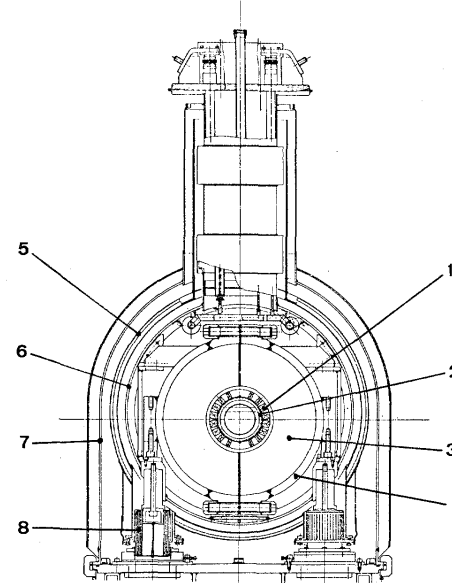
Early SC magnets for accelerators: Beam Transfer line magnets: Castor and Cesar @CERN

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

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

Both use a monolithic conductor wound into a $\cos\theta$ coil

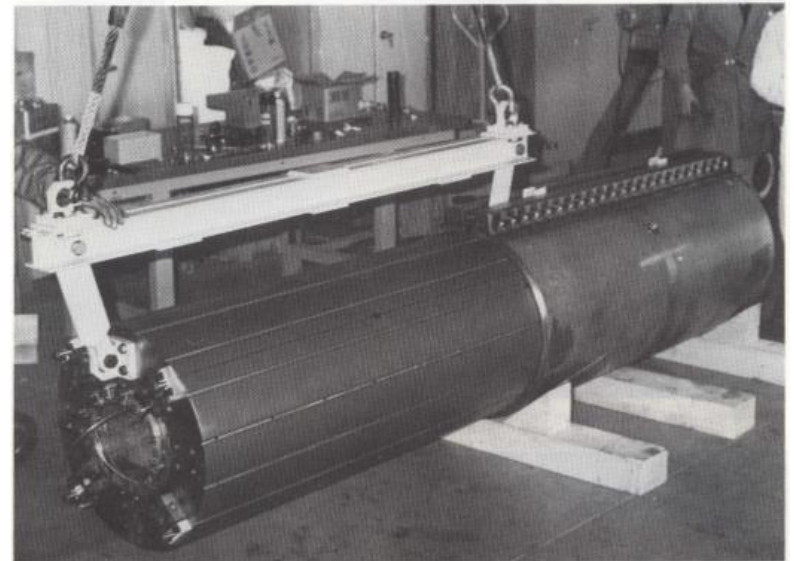
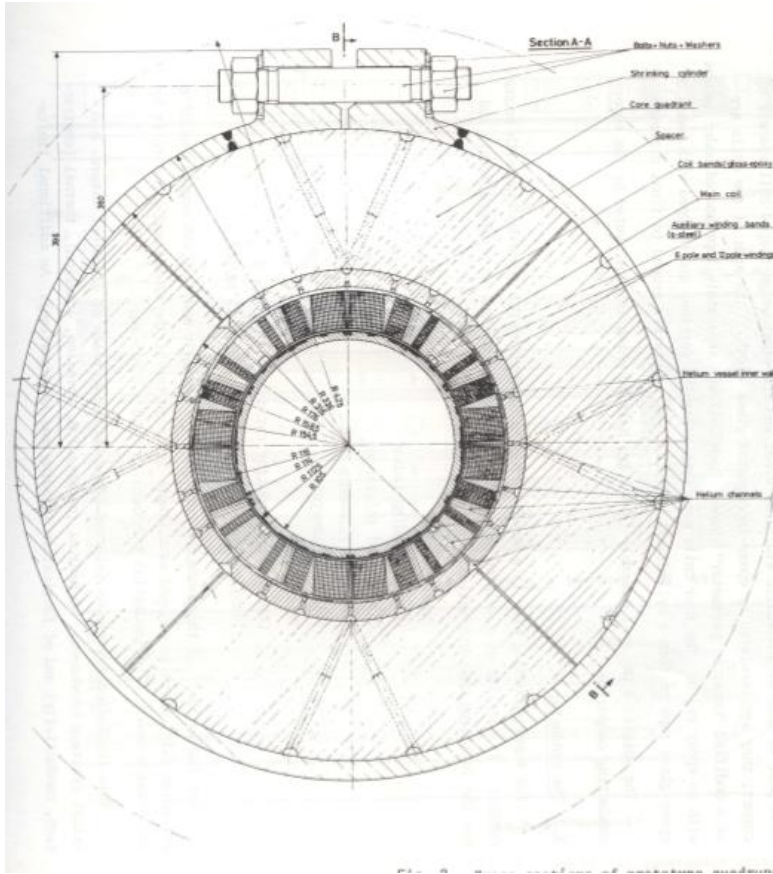
D.F. Leroy**





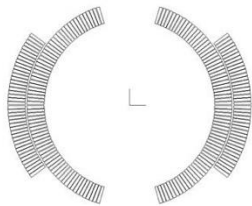
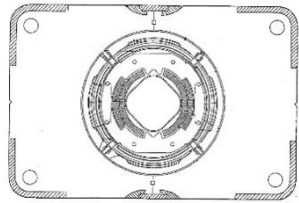
Early SC magnets for accelerators: ISR Insertion quadrupole (end 1970-ies)

- $G=40$ T/m in 73 mm diameter aperture
- Nb-Ti monolithic conductor
- fully impregnated coil
- Prestress from yoke + shell



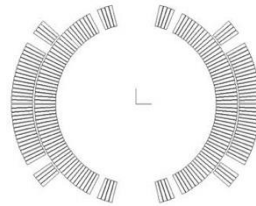
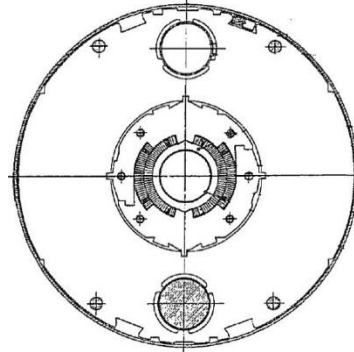


Existing Superconducting Accelerator dipole magnets (1)



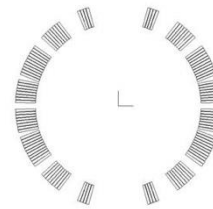
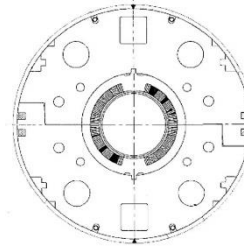
Tevatron

76 mm bore
 $B = 4.4 \text{ T}$
 $T = 4.2 \text{ K}$
first beam 1983



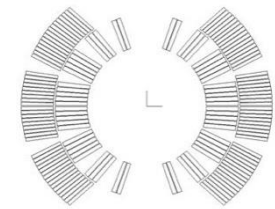
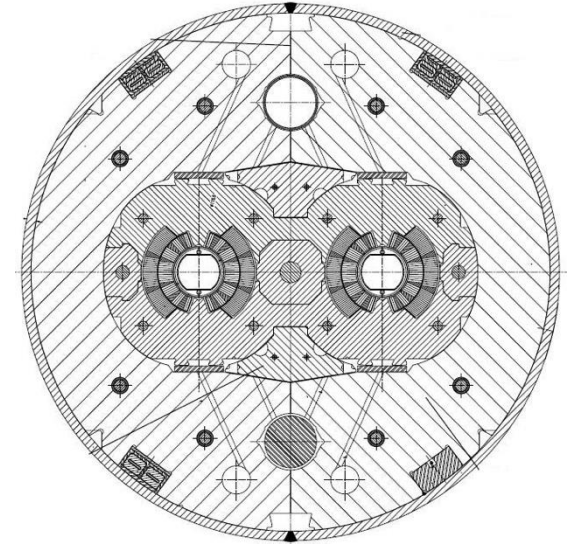
HERA

75 mm bore
 $B = 5.0 \text{ T}$
 $T = 4.5 \text{ K}$
first beam 1991



RHIC

80 mm bore
 $B = 3.5 \text{ T}$
 $T = 4.3\text{-}4.6 \text{ K}$
first beam 2000



LHC

56 mm bore
 $B = 8.34 \text{ T}$
 $T = 1.9 \text{ K}$
first beam 2008

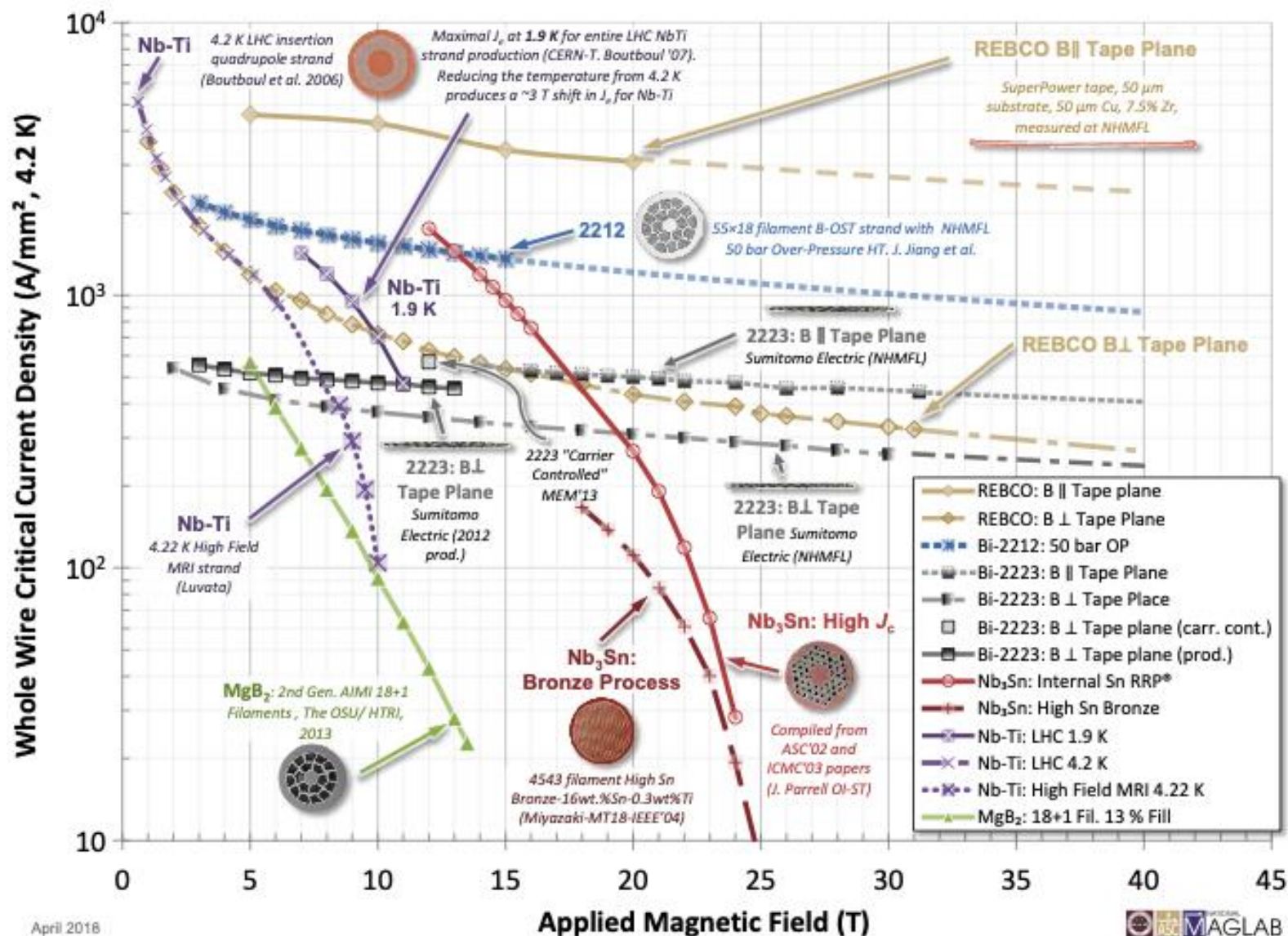


Existing Superconducting Accelerator dipole magnets (3)

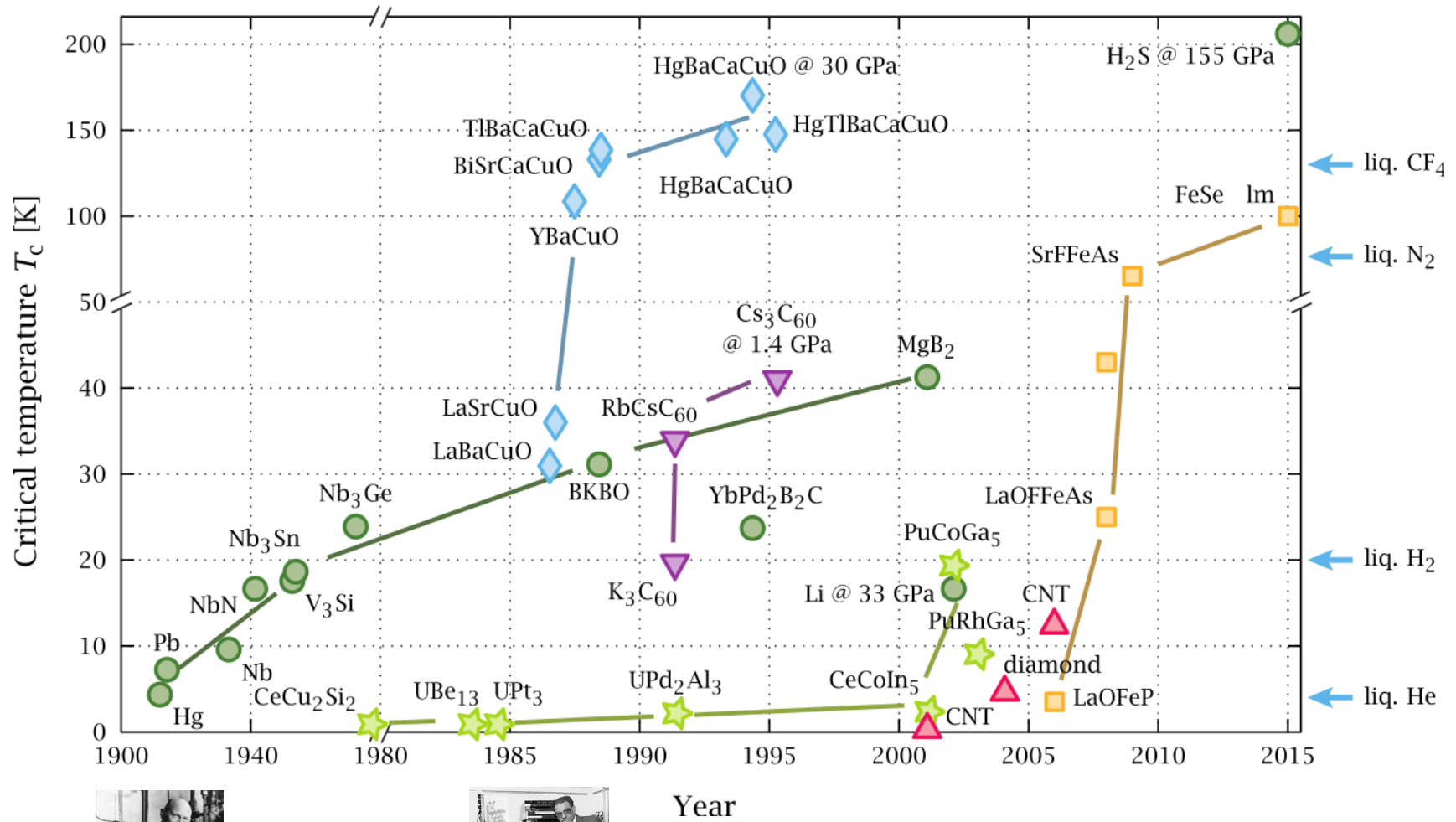
Machine	place	Type	Energy (GeV)	Peak Dipole field (T)	# dipoles	Dipole Length (m)	Ring circ. (km)	Year
Tevatron	FNAL (USA)	p-pbar FT/coll.	1000 x 1000	4.4	774	6.12	6.28	1983/1987
HERA	DESY (D)	e ^{-/+} - p collider	40x920	5	416	8.82	6.34	1992
RHIC	BNL (USA)	p-p, Au-Au, Cu-Cu, d-Au	100/n	3.5	2x192+12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

Available Superconductors



Superconductor discovery timeline



2 families:

- LTS, Low Temperature Superconductor: $T = 4.5$ or lower \rightarrow Liquid He
- HTS, High Temperature Superconductor: $T < 80\text{K} \rightarrow$ LHe, LN2, He gas, etc.

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

- Up to $\sim 2500\text{ A/mm}^2$ at 6 T and 4.2K 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

LTS; Nb₃Sn: towards 20 T

- Up to $\sim 3000\text{ A/mm}^2$ 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
- $\sim 20\text{ T}$ field in the coil is the practical limit at 1.9 K, but 16 T is the real limit for dipoles as above 16 T the coils will become too large for accelerator magnets

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

- Current density is low, but very little dependence on the magnetic field
- 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 racetracks coils have been built

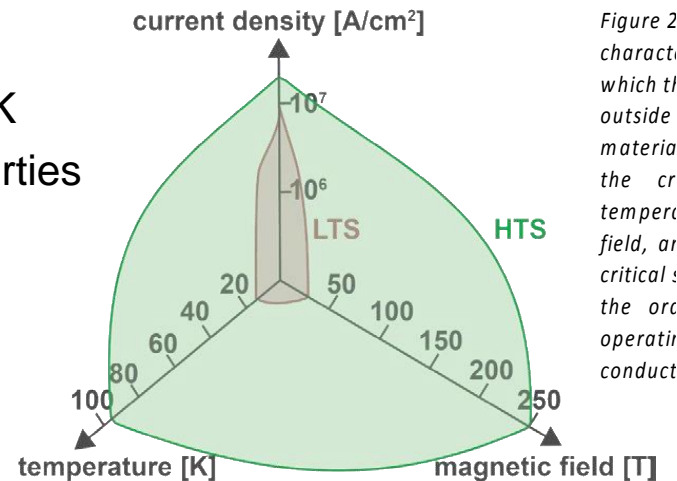


Figure 2 characterizes the operating region for superconductors, showing the relationship between current density, temperature, and magnetic field.

LTS: Type II Superconductors

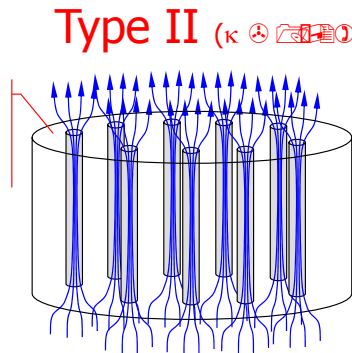
Below a the critical surface the material is “superconducting”. Above the surface it is “normal conducting”

- 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)

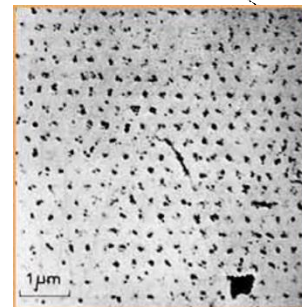
The Critical surface depends on the material type Nb-Ti, Nb₃Sn, etc) and the processing

Superconducting means: $R = 0$

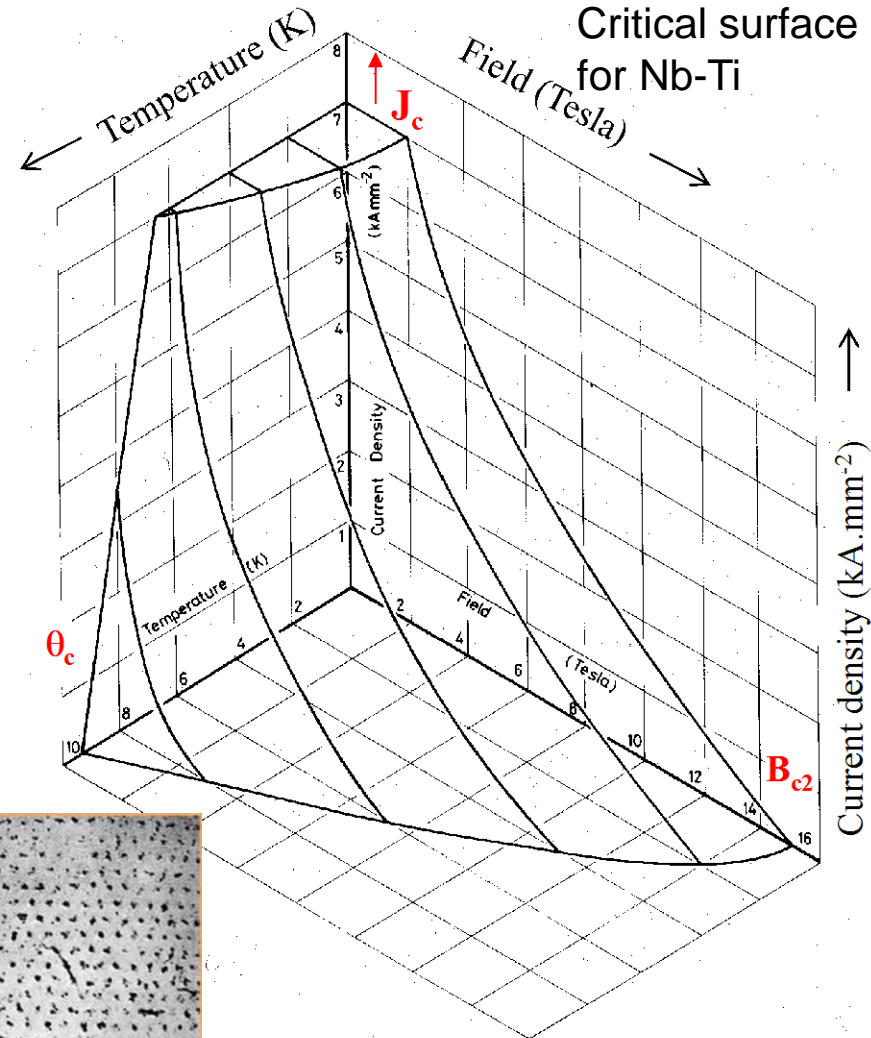
J : few $\times 10^3$ A/mm² inside the superconductor



Courtesy L. Bottura



Quantized fluxoids in a superconductor



Courtesy M. Wilson

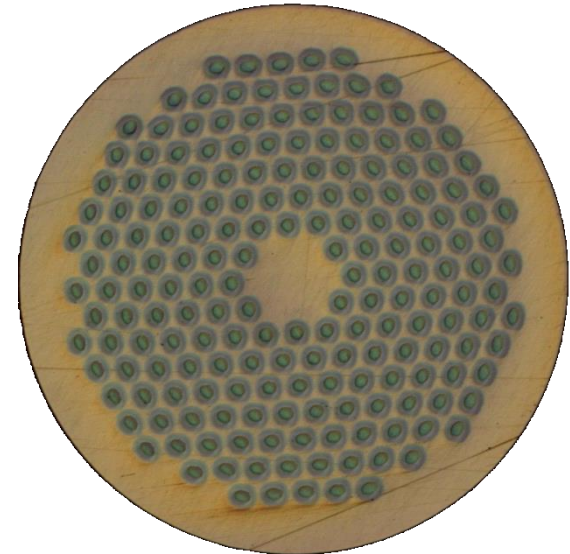
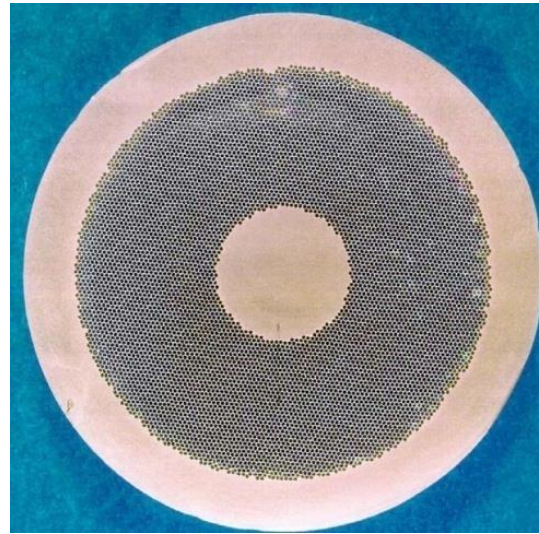
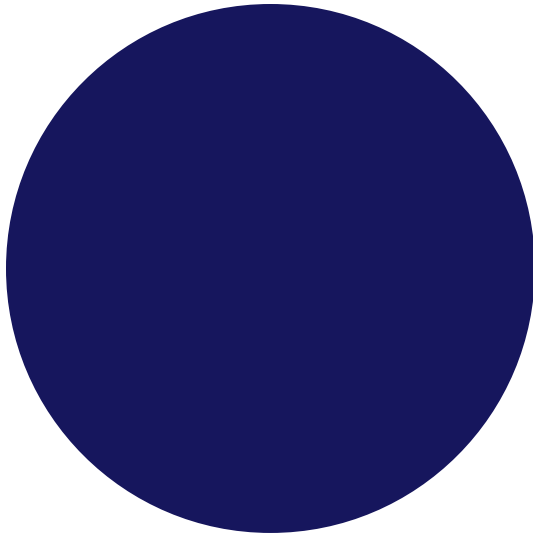
Comparing wires, LTS Superconductors vs Copper

Typical operational conditions (0.85 mm diameter strand)

Cu

Nb-Ti

Nb₃Sn



$J \sim 5 \text{ A/mm}^2$

$I \sim 3 \text{ A}$

$B = 2 \text{ T}$

$J \sim 1500\text{-}2000 \text{ A/mm}^2$

$I \sim 400 \text{ A}$

$B = 8\text{-}9 \text{ T}$

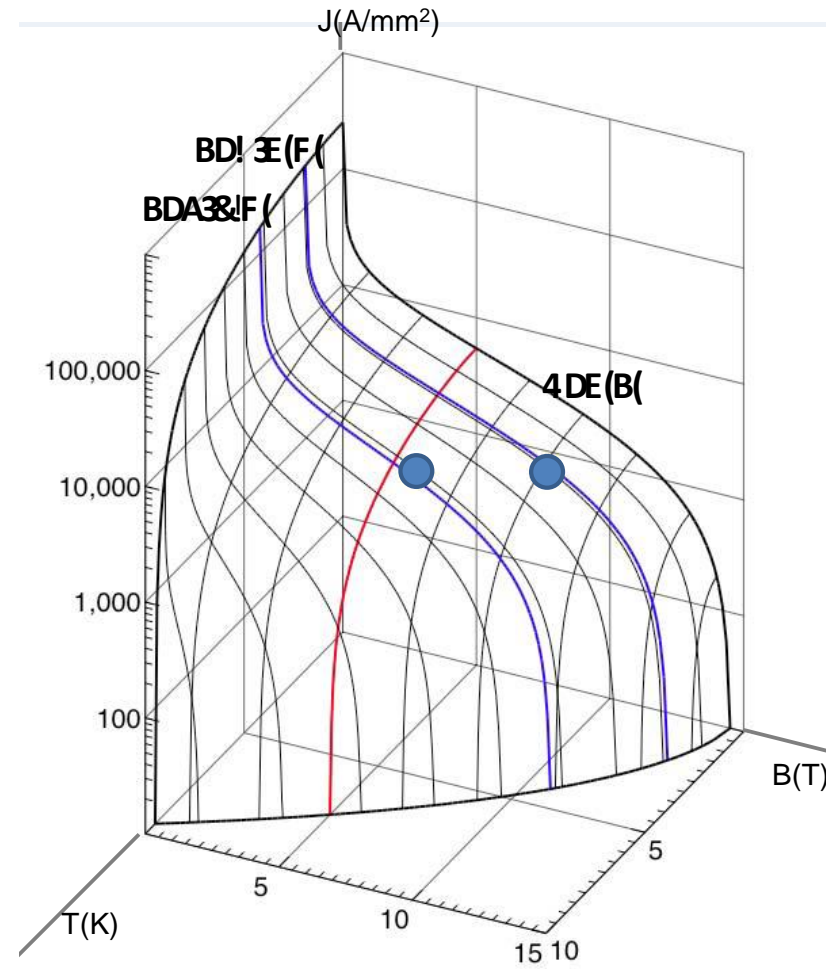
$J \sim 1500\text{-}2000 \text{ A/mm}^2$

$I \sim 400 \text{ A}$

$B = 12\text{-}13\text{-}16 \text{ T}$

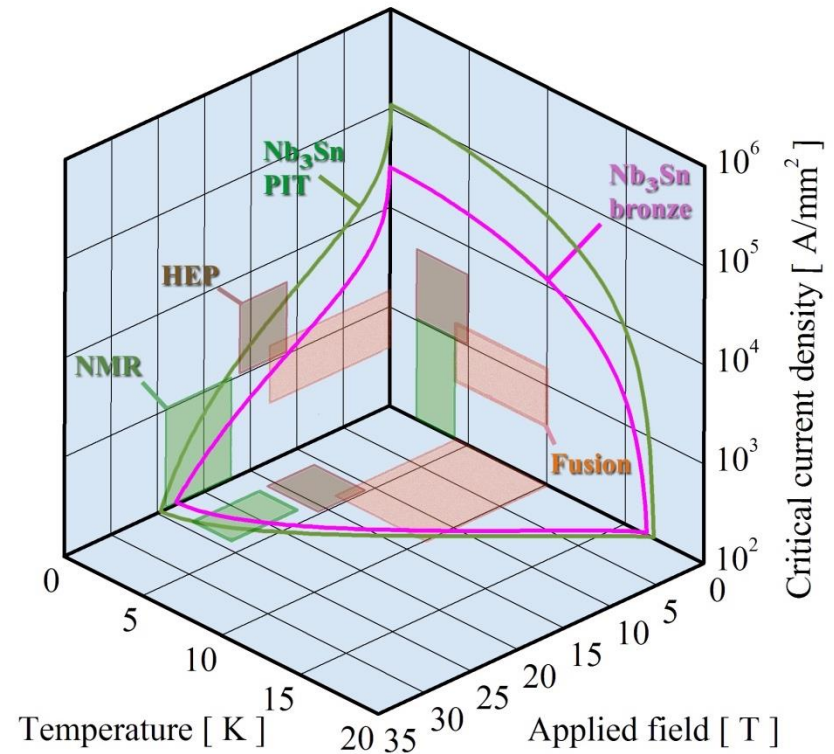
Superconducting materials: Nb-Ti

- Niobium and titanium combine in a ductile alloy
 - It is easy to process by extrusion and drawing techniques.
- 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.
- The cost is approximately 100-150 US\$ per kg of wire.



Superconducting materials: Nb_3Sn

- Niobium and tin form Nb_3Sn
 - Brittle and strain sensitive
- 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.
- The cost is approximately 700-1500 US\$ per kg of wire.

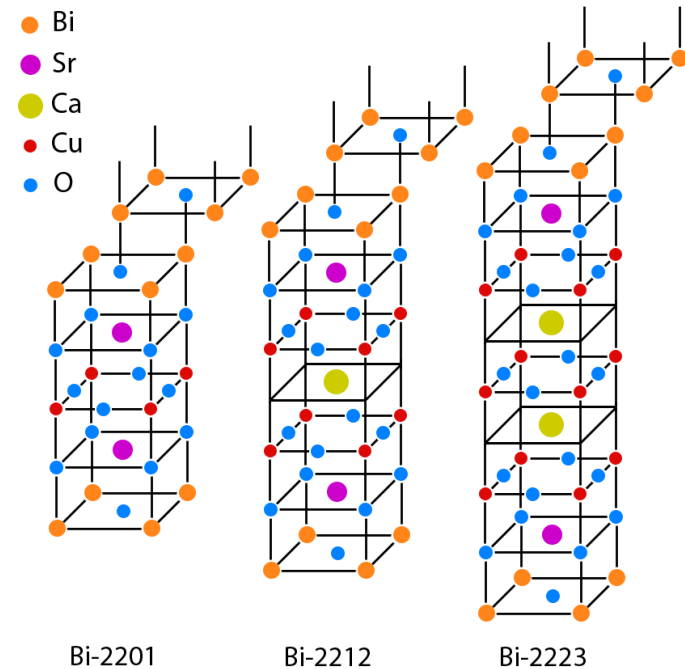


Courtesy: A. Godeke

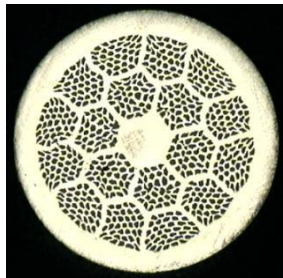
Superconducting strands and tapes: BSCCO

BSCCO: Bismuth strontium calcium copper oxide

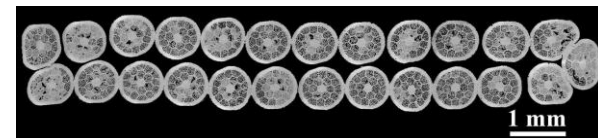
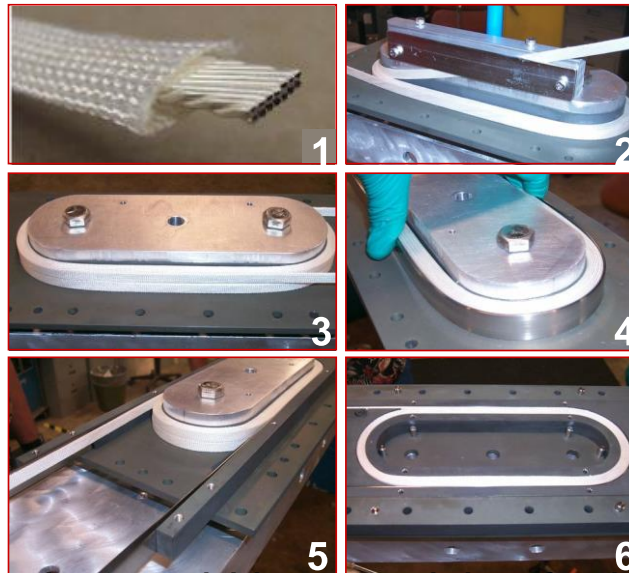
- Available in strands (OST)
- Can reach 400 A/mm² (overall)
- Is fragile under stress and strain
- Powder in a silver tube
- Has to be reacted at 850° C with a temperature precision of 1° C in an oxygen atmosphere
- Can be cabled in high current Rutherford cables



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

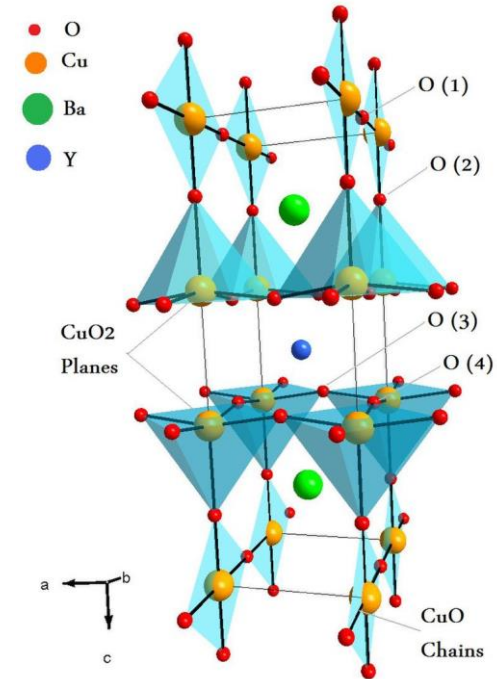


Difficult technology but could be promising for high field magnets in >20 T region

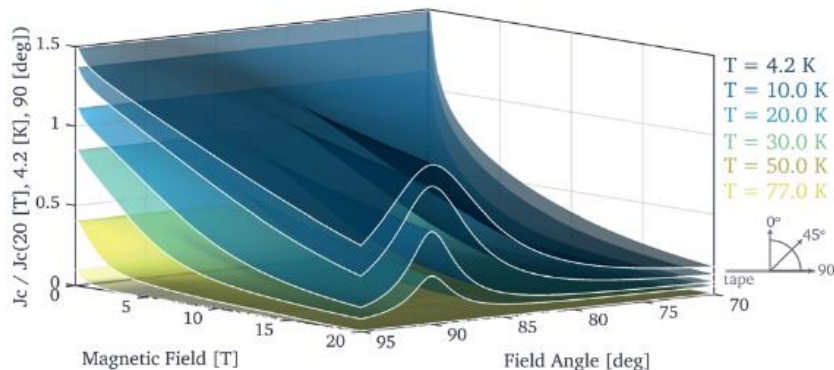
Superconducting tapes: YBCO (or REBCO)

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

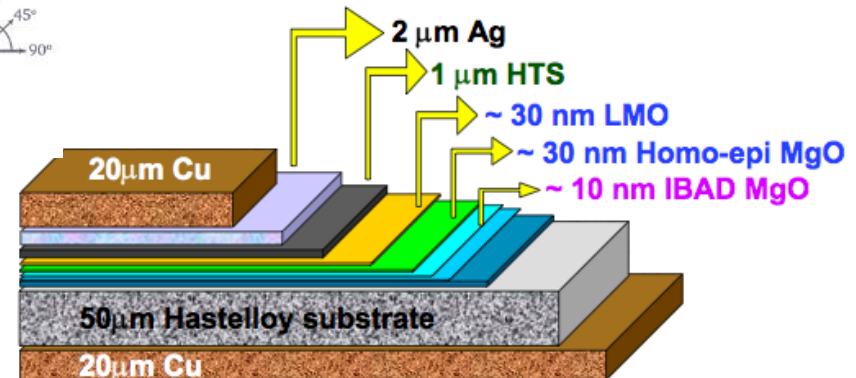
- Available in tapes : YBCO deposited on a substrate to impose the texture (1-2 μm)
- Can reach $> 600 \text{ A/mm}^2$ (overall)
- Is strong under axial stress and strain (300 MPa)
- Limited cabling possibilities:
- Difficult technology but could be promising for high field magnets in $>20 \text{ T}$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



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



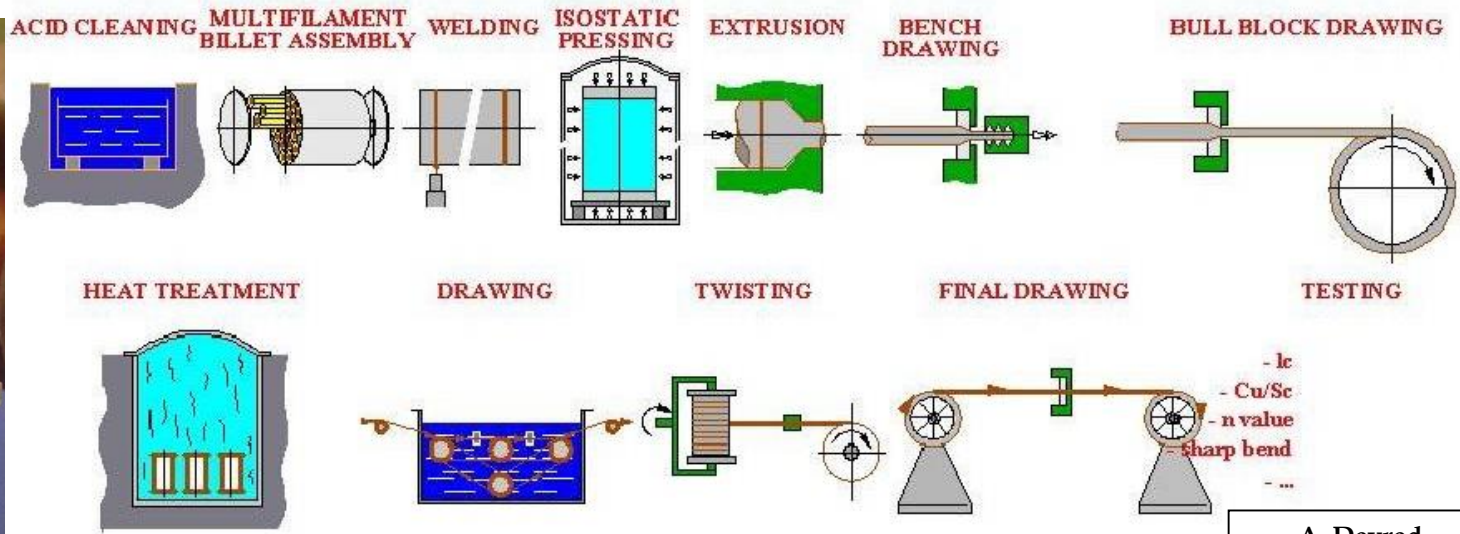
Critical current depends on the angle between the face of the tape and the B field



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).



A. Devred

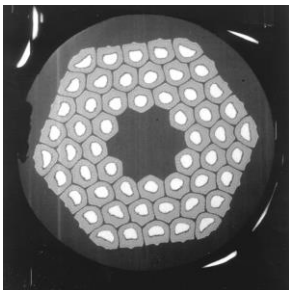
Multifilament wires

Fabrication of Nb_3Sn multifilament wires

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

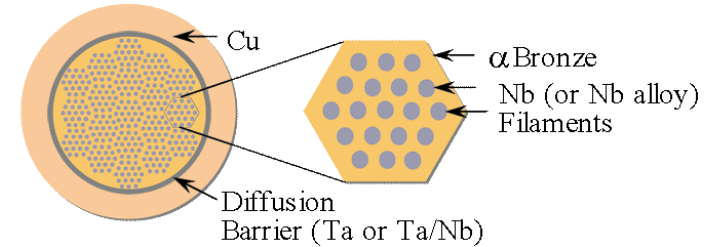
The process requires several steps:

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

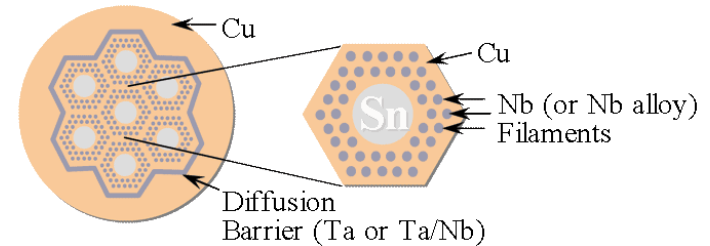


Nb_3Sn strand types

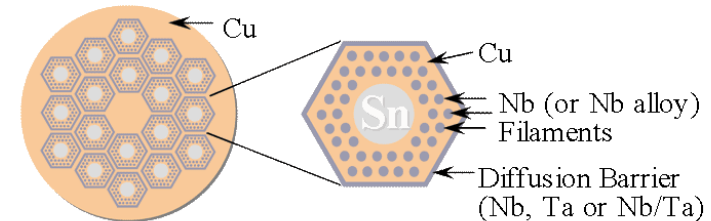
Bronze Process



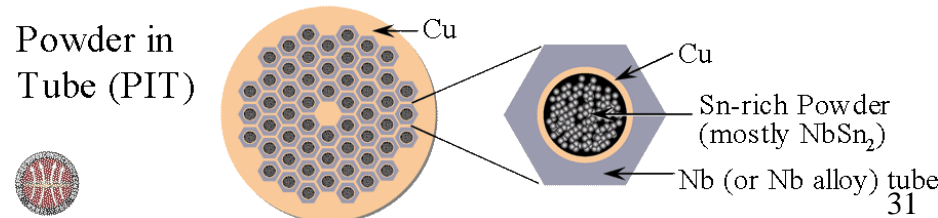
Internal Sn (Single Barrier)



Internal Sn (Distributed Barrier)



Powder in Tube (PIT)





Superconducting cables for magnets

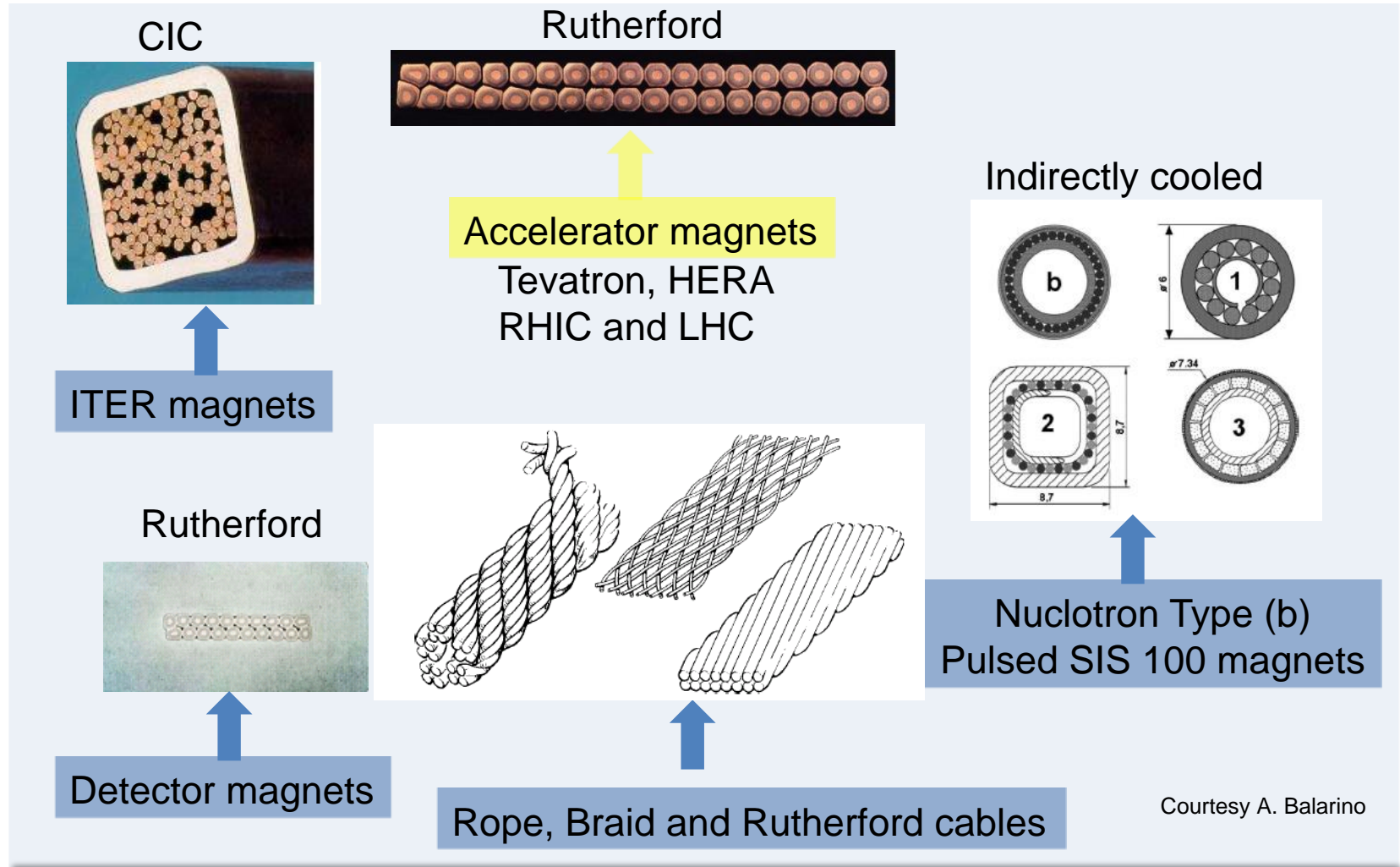
We need multi-strand cables

- 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 $B = 4.4 \text{ T} ; I \sim 4000 \text{ A}$
 - Hera $B = 5 \text{ T} ; I \sim 6000 \text{ A}$
 - LHC $B = 8.3 \text{ T} ; I \sim 12000 \text{ A}$
- For magnets $10 \text{ T} < B < 15 \text{ T}$ the current has to be $10 \text{ kA} < I < 15 \text{ kA}$
- For stability reasons strands are $0.6 \text{ mm} < \text{strand diameter} < 1 \text{ mm}$
- With a Cu-nonCu ratio (for stability reasons) around 1 and a $J_c \sim 1000 \text{ A/mm}^2$
 - ➔ a 1 mm diameter strand can carry $\sim 400 \text{ A}$
 - ➔ so we need a 30 strand cable to get up to 12 kA

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

$$L \gg N^2$$

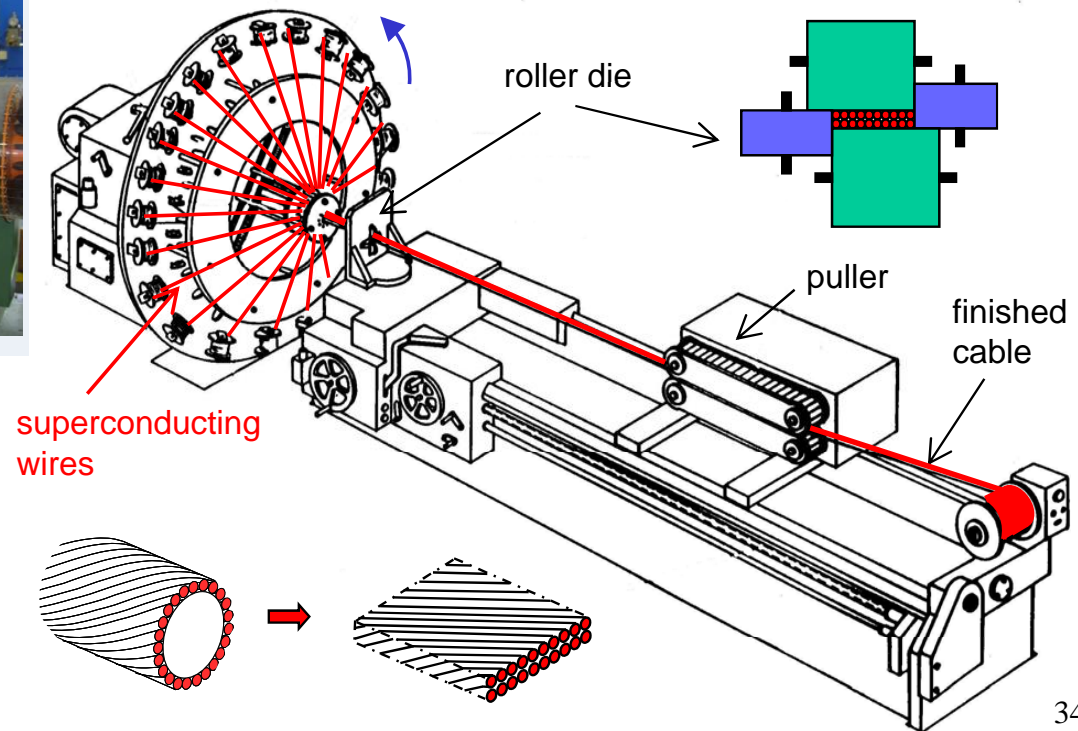
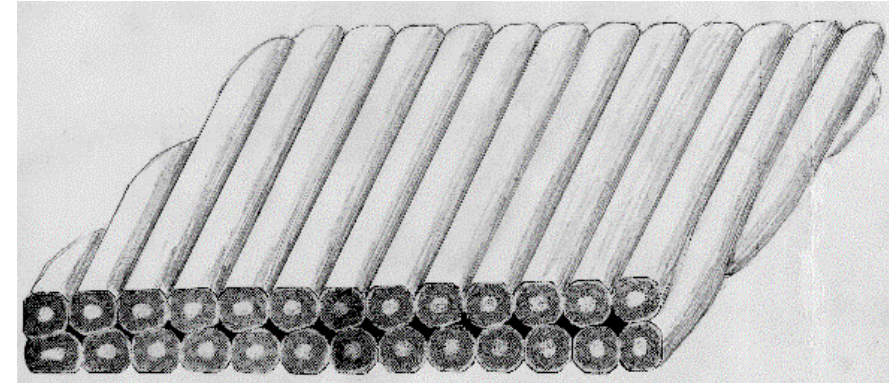
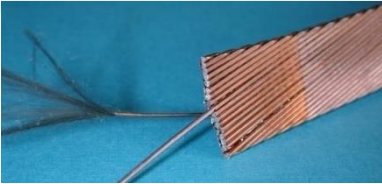
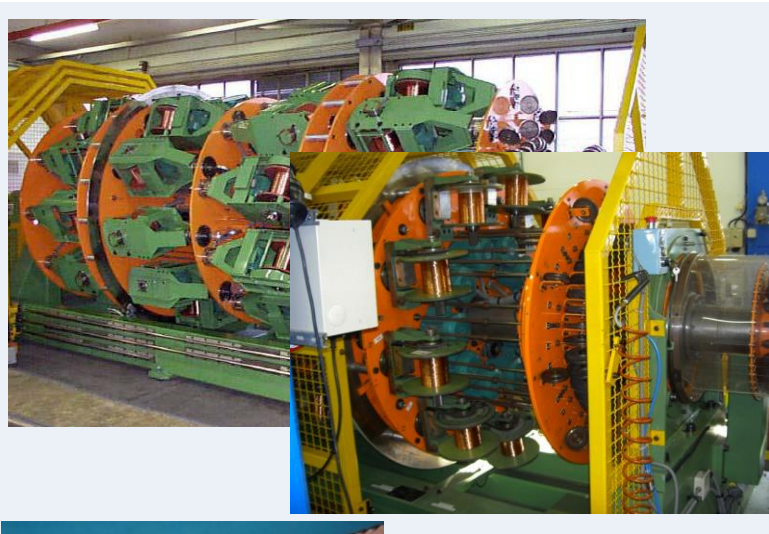
LTS Cable types



Courtesy A. Balarino

Rutherford cables

- Compact cables giving high overall current density
- 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

- Dipole 60° 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*

$$B_1 = -4 \frac{j m_0}{2\rho} \int_0^{\rho/3} \int_r^{\rho/3+r+w} \frac{\cos q}{r} r dr dq = -\frac{\sqrt{3} m_0}{\rho} j w$$

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

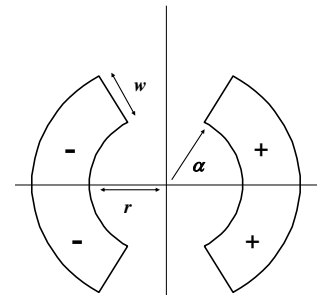
- Quadrupole 30° sector coil [see ref 11, 14]
 - The gradient is *proportional to the current density j*
 - The gradient depends on w/r

$$G = -8 \frac{j m_0}{2\rho} \int_0^{\rho/6} \int_r^{\rho/6+r+w} \frac{\cos q}{r} r dr dq = -\frac{\sqrt{3} m_0}{\rho} j \ln \frac{\rho}{\rho/6} + \frac{w}{r} \frac{\partial}{\partial r}$$

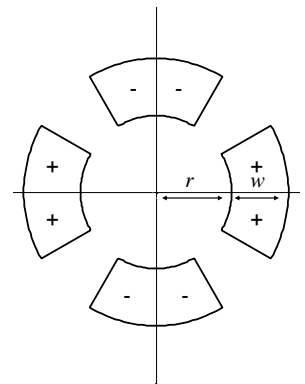
➔ by having very high current density close to the beam pipe

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]



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



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

The forces with high field dipole and quadrupole magnets

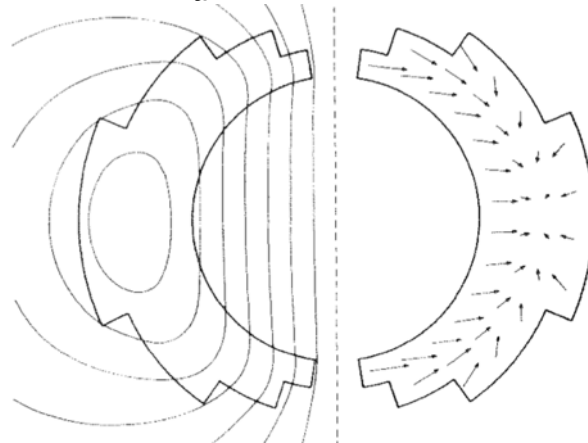
One can derive the maximum stress in the mid-plane for a sector dipole coil

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

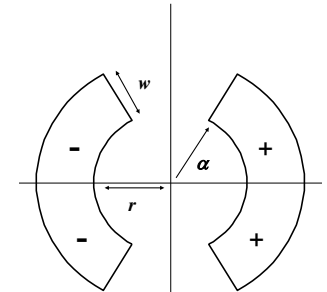
$$S \gg j^2 \frac{m_0 \sqrt{3}}{6\rho} \text{Max}_{re[r, r+w]} \left(2r^2 + \frac{r^3}{r} - 3r(r+w) \right)$$

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

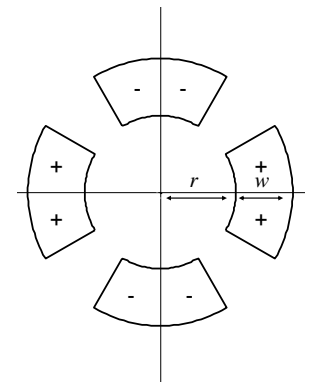
with: r : inner radius coil
 ρ : radial coordinate
 w : coil width
 J : current density



Courtesy M. Wilson



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



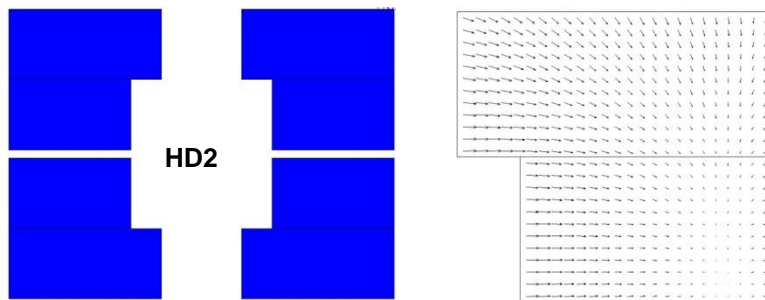
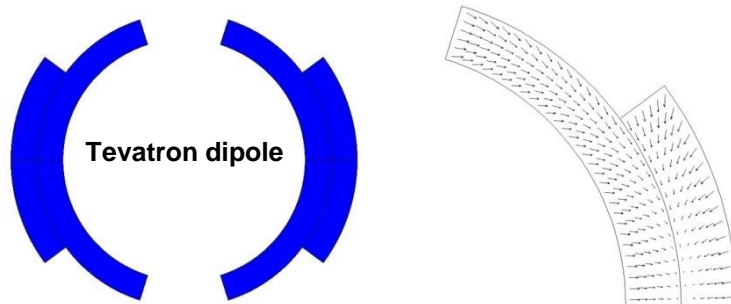
Cross-section of a quadrupole based on 30° sector coils

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

$$S \gg j^2 \frac{m_0 \sqrt{3}}{16\rho} \text{Max}_{re[r, r+w]} \left(2r^2 + \frac{r^4}{r^2} + 4r^2 \ln \frac{r+w}{r} \right)$$

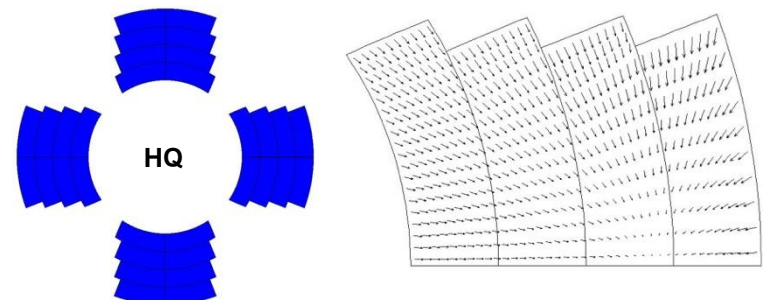
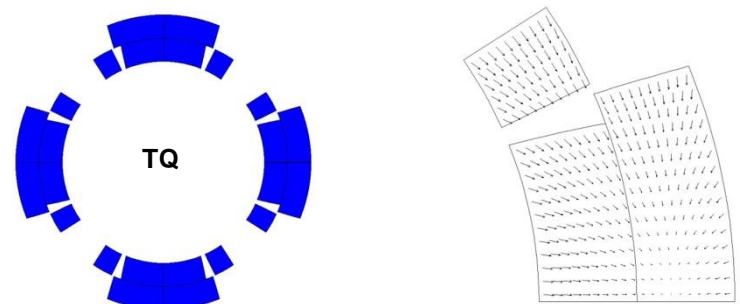
The e.m. forces in a dipole magnet tend to push the coil

- 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 ($F_x, F_r > 0$)

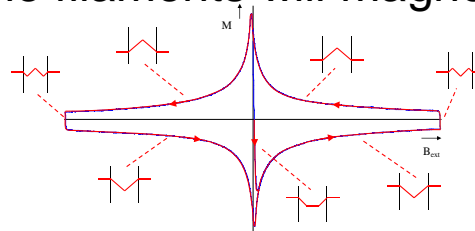


Conductor stability and AC behaviour

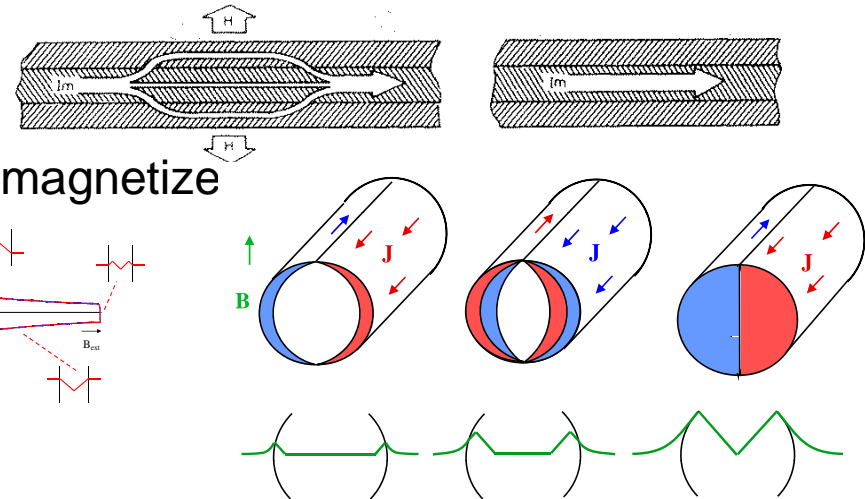
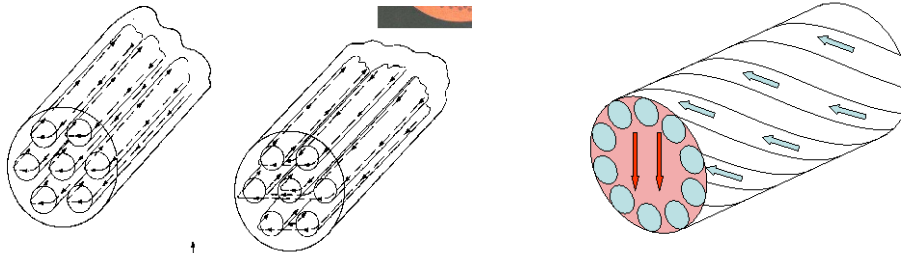
- Pure massive superconductor is not stable as they (Nb-Ti, Nb₃Sn) are poor normal conductors
- To 'cryogenically stabilize' the conductor one surrounds it in Cu:

- good electrical conductivity
- good heat transfer to the He

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

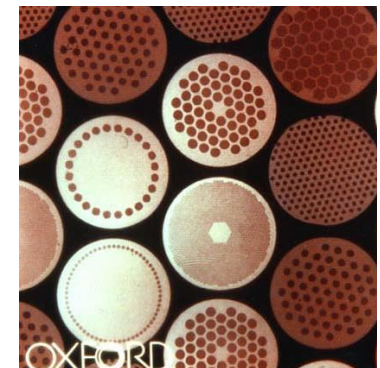


- Filaments will have magnetic coupling
→ twist the strand



Courtesy M. Wilson

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



Quench: a thermal runaway effect

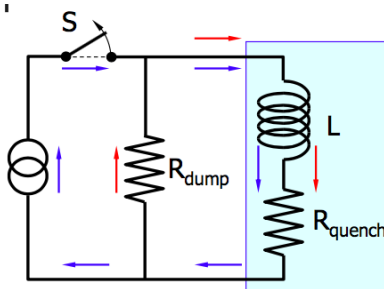
Due to perturbations locally the conductor can get $T > T_c(J_l, B_l)$

A thermal runaway can then occur, called a **Quench**

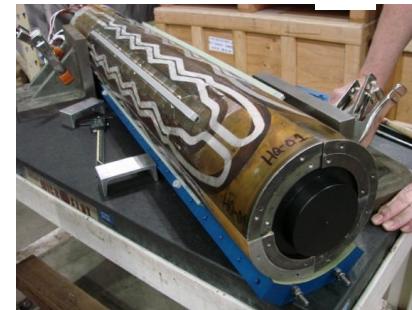
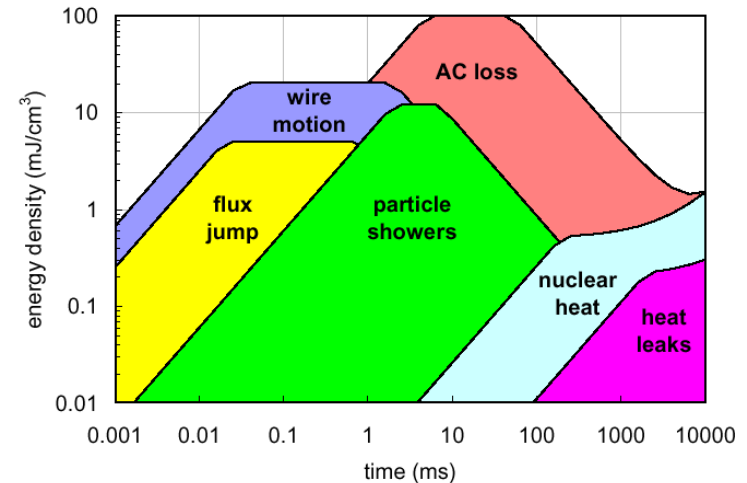
With stored energies > MJ the coils can overheat if nothing is done ($T = 3000K$ is possible !)

What to do ?

- Detect the quench : SC: $R=0 \rightarrow V=0$, 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

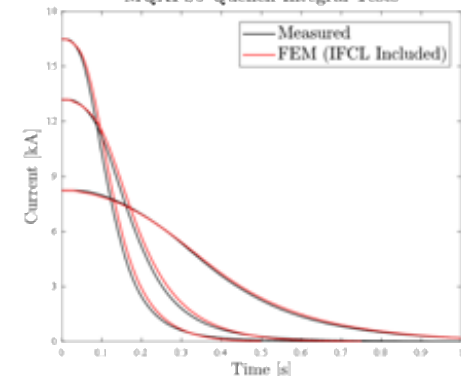


When something went wrong



MQXFS coils

MQXFS5 Quench Integral Tests



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).

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

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

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

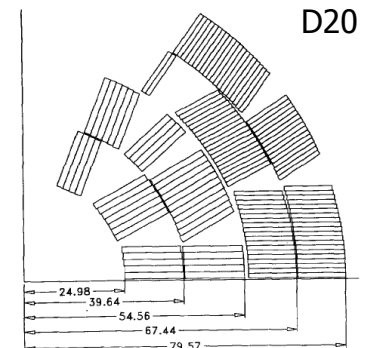
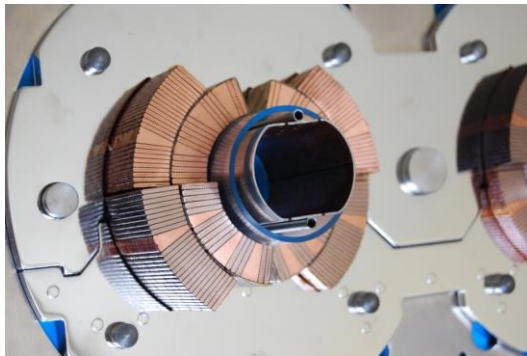
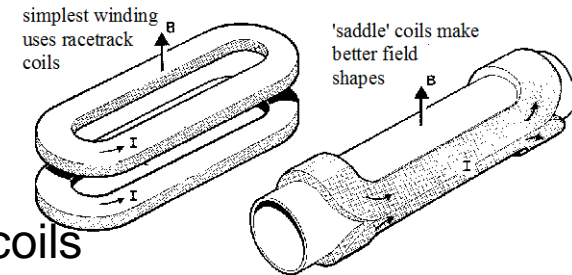
With this one can get a conservative estimate of the maximum temperature in the coil at the end of the quench.

Practical accelerator magnet design: Dipoles (1)

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

$\cos(\theta)$ coil , Block coil , Canted $\cos(\theta)$ coil

- $\cos(\theta)$ coil (the traditional solution)
 - 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

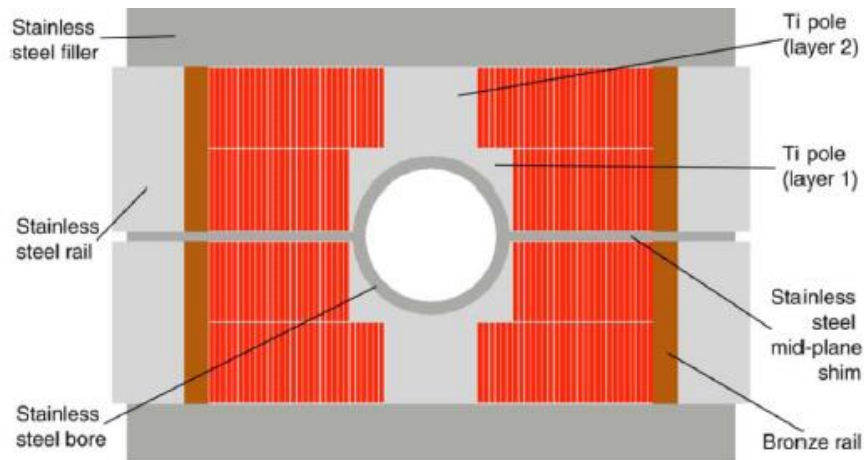


Courtesy M. Wilson

Courtesy LBNL

Practical accelerator magnet design: Dipoles (2)

- Block coil (used on development and test-station magnets)
 - With thick coils the field quality is good
 - Less efficient ($\sim 10\%$) wrt to (thin) $\cos(\Theta)$ 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



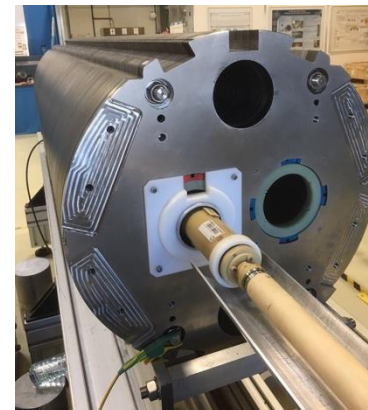
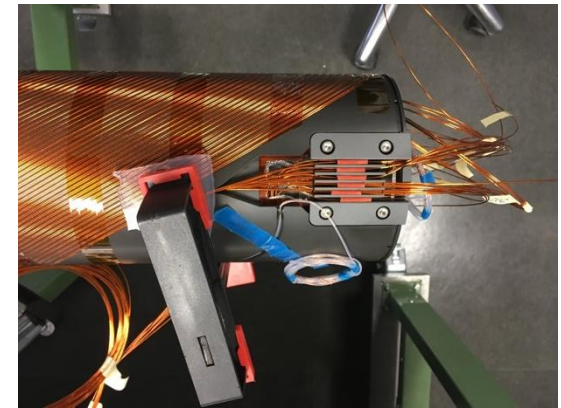
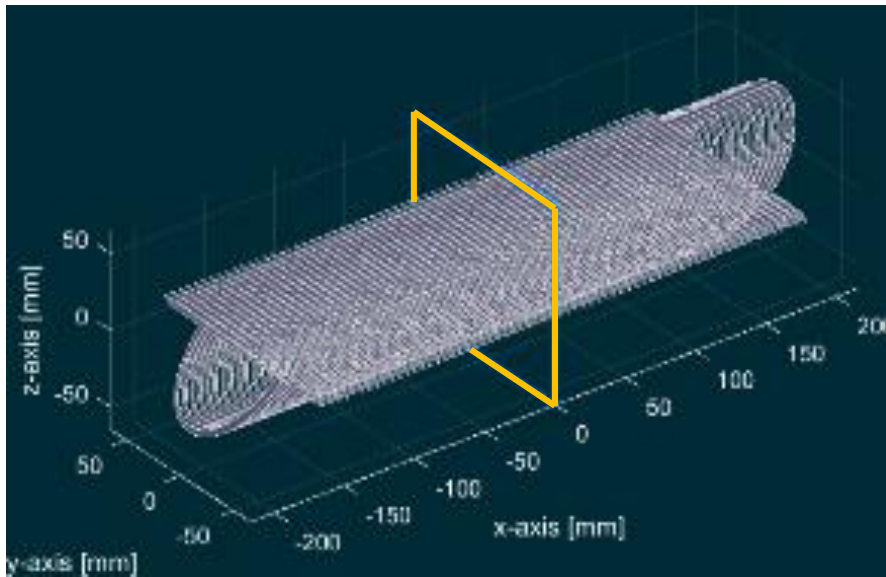
HD2



Courtesy LBNL

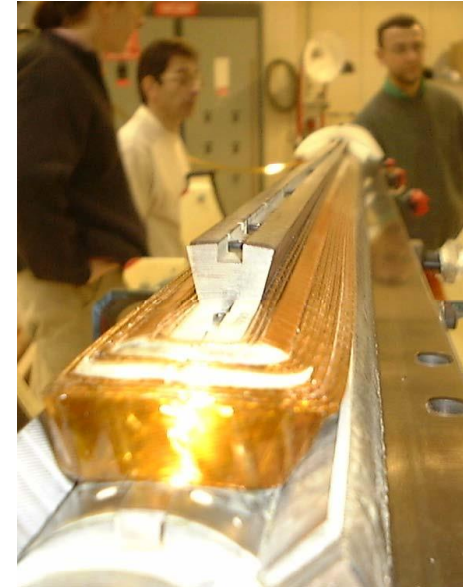
Practical accelerator magnet design: Dipoles (3)

- Canted Cos(Θ) : CCT
 - 2 layers of inclined solenoids: powered such that the axial B components compensate and the transvers B components add up.
 - First 3.5 T corrector dipole CCT (in a circular machine) is for HL-LHC
 - First proposed 40 years ago, recently further developed for accelerators: HL-LHC, HIE-Isolde, gantry magnets, ...

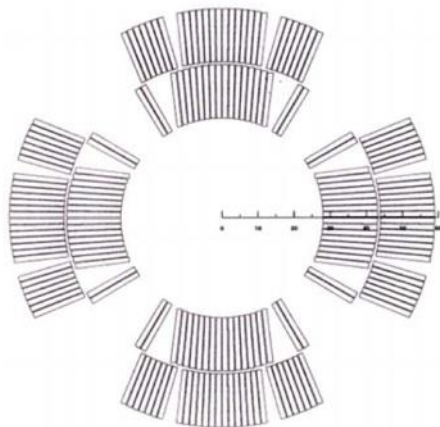
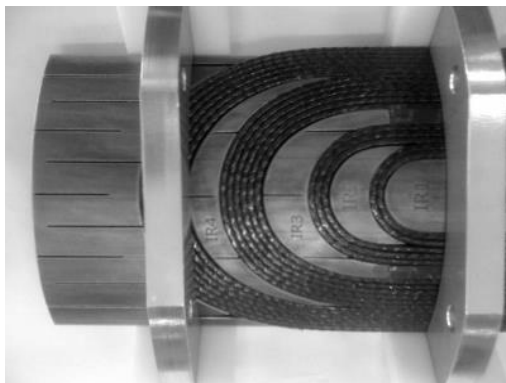


Quadrupole coil geometries

- 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



- Why pre-stress ?
 - Field quality is determined by the cable positioning (be precise to ~ 0.02 mm)
 - Under the MN forces the coils will move
 - ➔ Apply pre-stress 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 pre-stress to fix the positioning
- How to put pre-stress ?

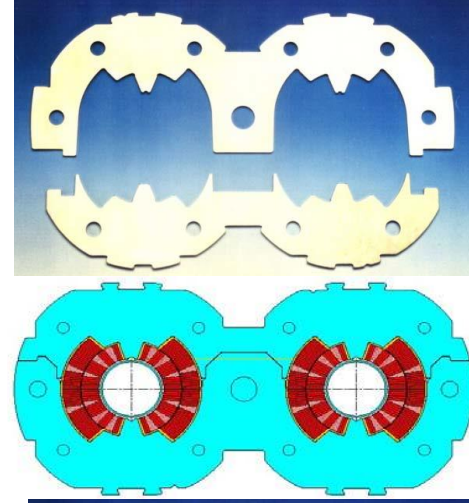
Three methods:

 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
- Order of magnitudes: LHC @ 8.34 T: 70 MPa warm, 30 MPa cold
Fresca2 @ 13 T: 60 MPa warm, 130 MPa cold

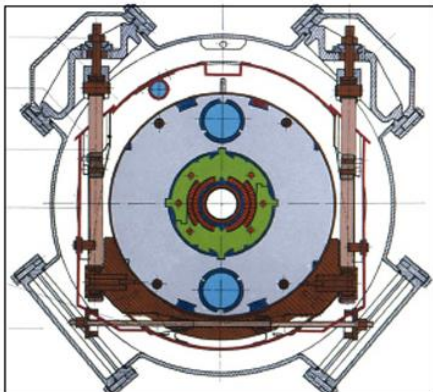
Pre-stress: collars

“The classical solution”

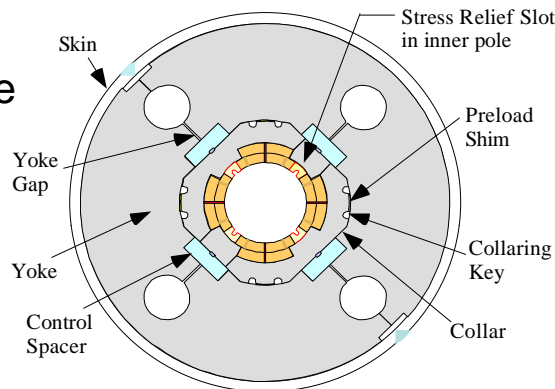
- Thin collars put around the coil
- The coil is well contained in a fixed cavity
- Pressed together and locked with pins or keys
- At 300K apply a pre-stress 2-3 times of what is needed as part of the stress is lost during cooldown: for very high field tends to be too high (LHC:70 MPa at 300 K and 40 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 (is) a problem



LHC dipole
CERN



Hera dipole
DESY

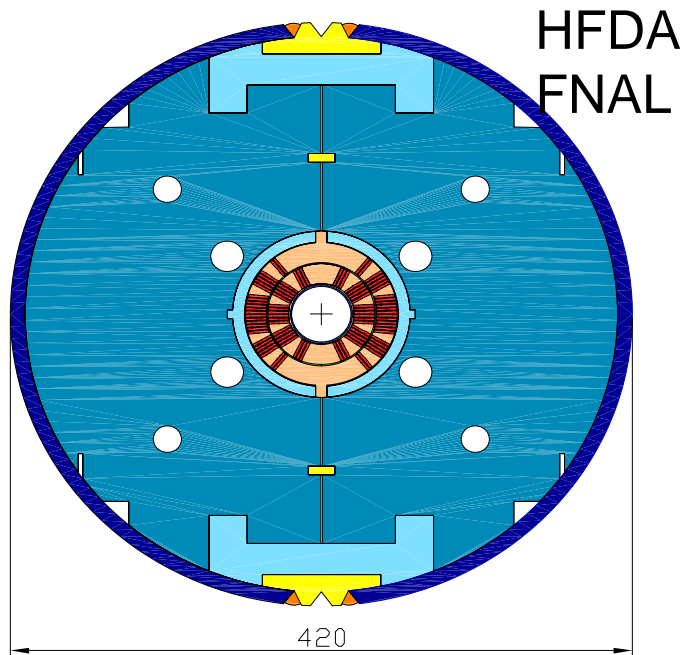


TQC quadrupole
LARP-FNAL



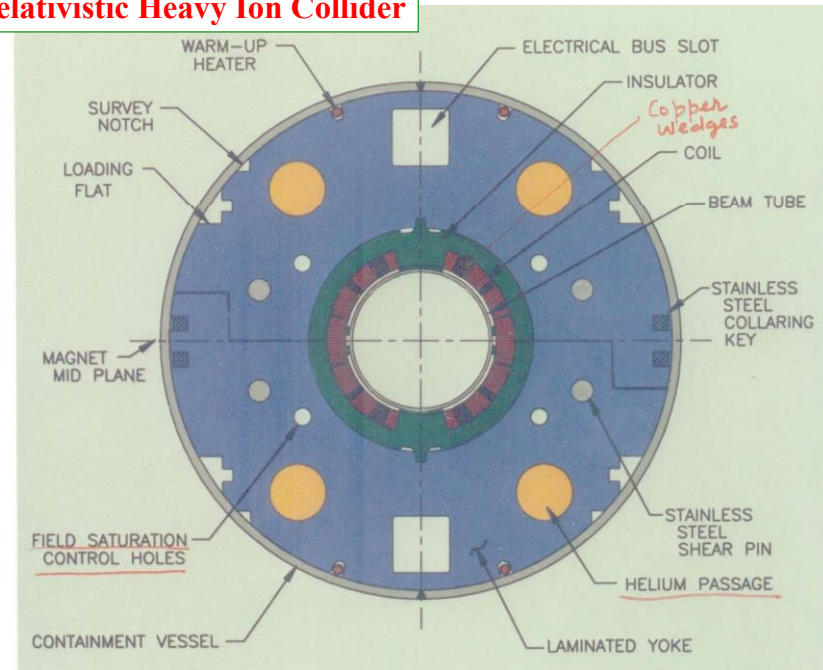
Pre-stress: shrinking cylinder and/or pre-stress key

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



Courtesy A. Zlobin

Relativistic Heavy Ion Collider



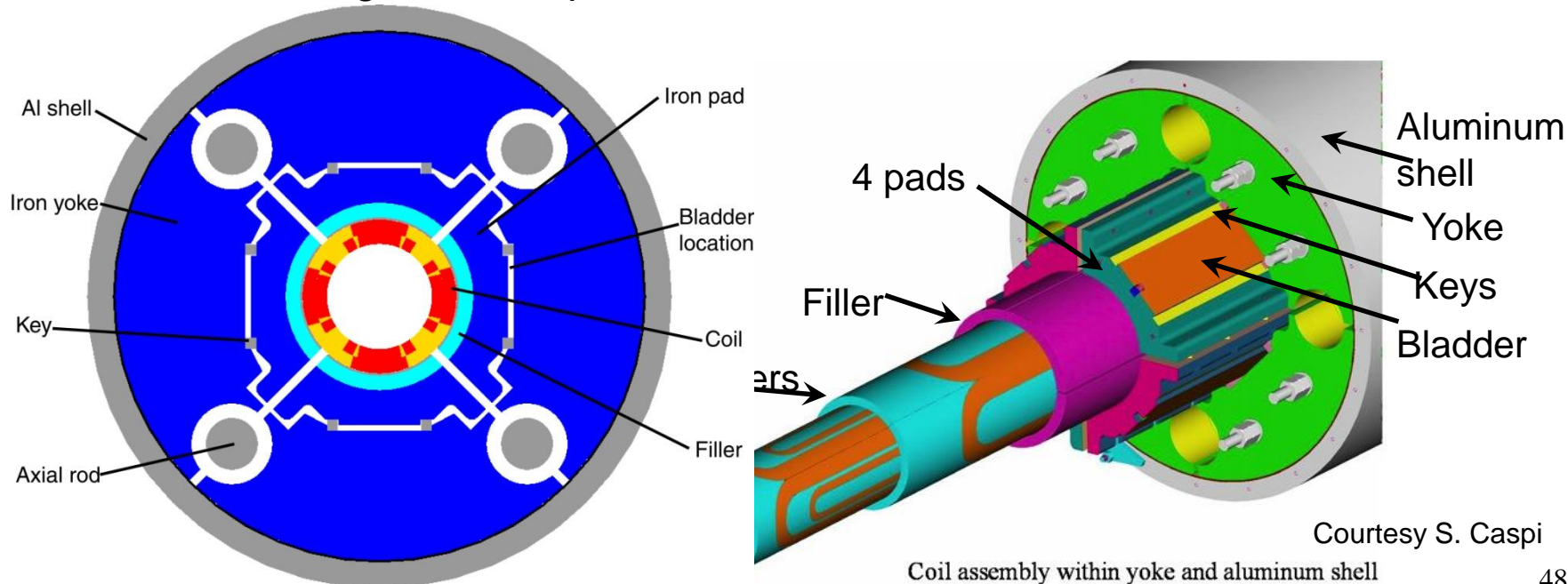
Pre-stress: Al shrinking cylinder + bladder and keys

Developed at LBNL, example: TQS a LARP model quadrupole

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

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





Operating SC magnets in Accelerators

- In synchrotrons with many, or with the majority superconducting magnets special care must be taken to cope with the specific properties of these magnets:
 - ramp rate,
 - excitation curves and calibration,
 - persistent current decay and snapback,
 - machine parameter tuning and hysteresis effects,
 - cryogenic system operation,
 - continuous cryostats.
- For keeping dynamic field effects under control, we need thin filaments in the wires
- 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.
- The relatively slow ramp-up and ramp-down of superconducting accelerators imply that it is not evident to do quick trials 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.



Looking in the kitchen of future magnet development

What is happening after the 8T magnets for LHC ?

At CERN and in the US

1) Upgrade the LHC luminosity: HL-LHC (HILUMI)

- use large aperture Nb₃Sn triplet quadrupoles (12T class)
- improve collimation: use a few 11T dipoles to make space

2. Go to higher energies

- 16 T Nb₃Sn dipoles in the LHC ring for $E_{com}=26$ TeV : HE-LHC
- 16 T Nb₃Sn dipoles in a 100 km new ring for $E_{com}=100$ TeV : FCC (Future Circular Collider)

But even !

- 20 T HTS hybrid dipoles in the LHC ring: for $E_{com}=33$ TeV : HE-LHC
- 20 T HTS hybrid dipoles in a 80 km new ring for $E_{com}=100$ TeV : FCC

In China

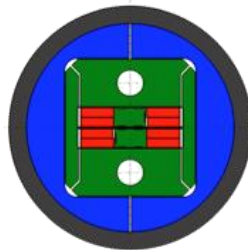
A similar completely new project is being studied in China: SPPC (C=100 km, 12-20 T)

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

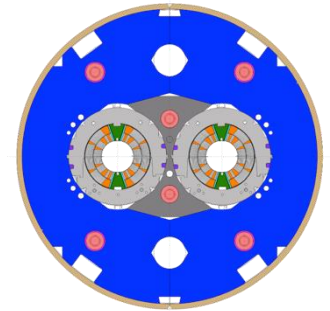
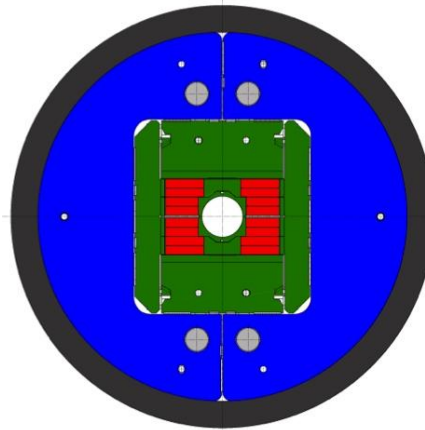
**Short Model
Coil**



**Race-track
Model Coil**

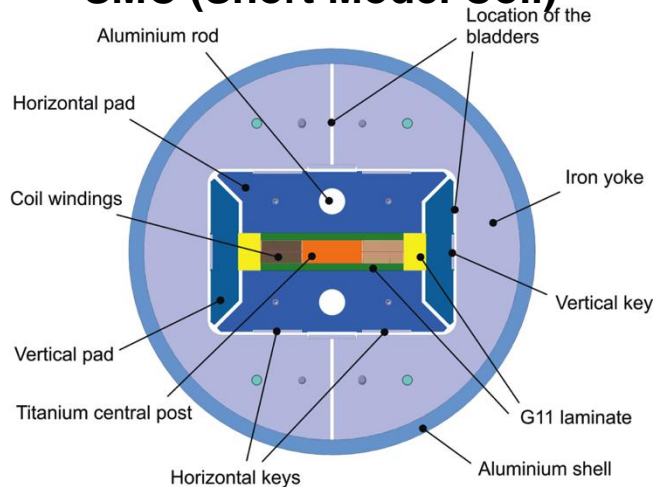


**FReSCa2 13T
Nb₃Sn Dipole**

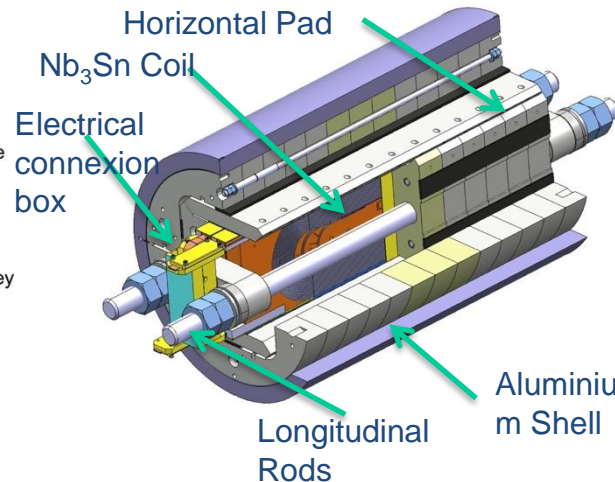


**11 T dipole
(CERN)**

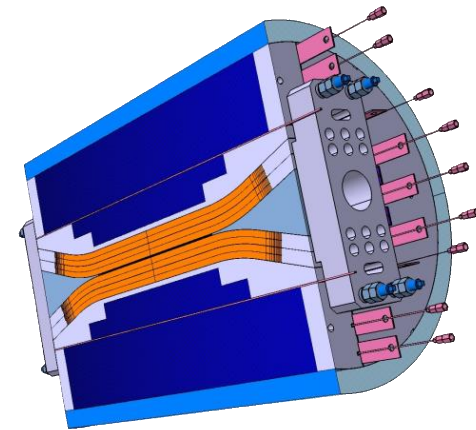
SMC (Short Model Coil)



RMC (Racetrack Model Coil)



FReSCa2



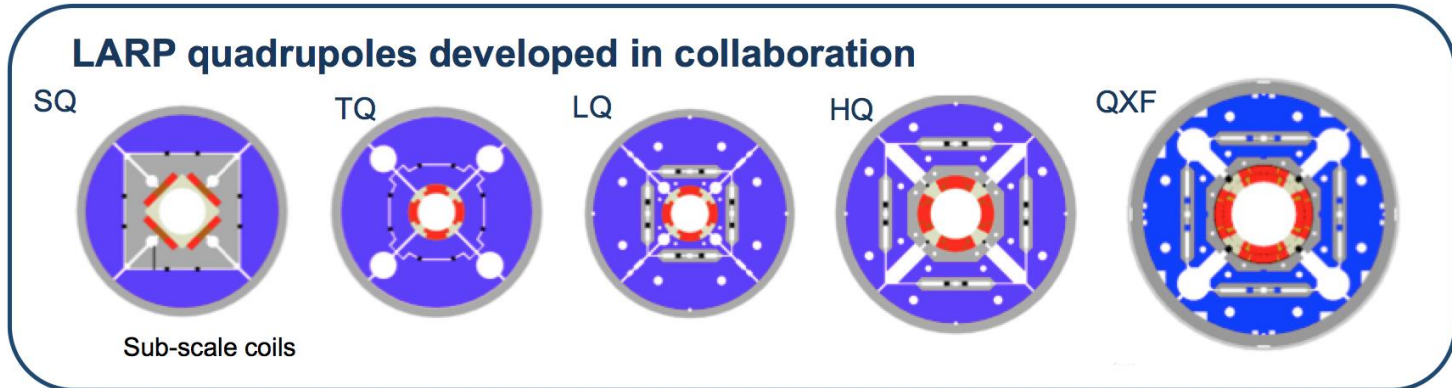
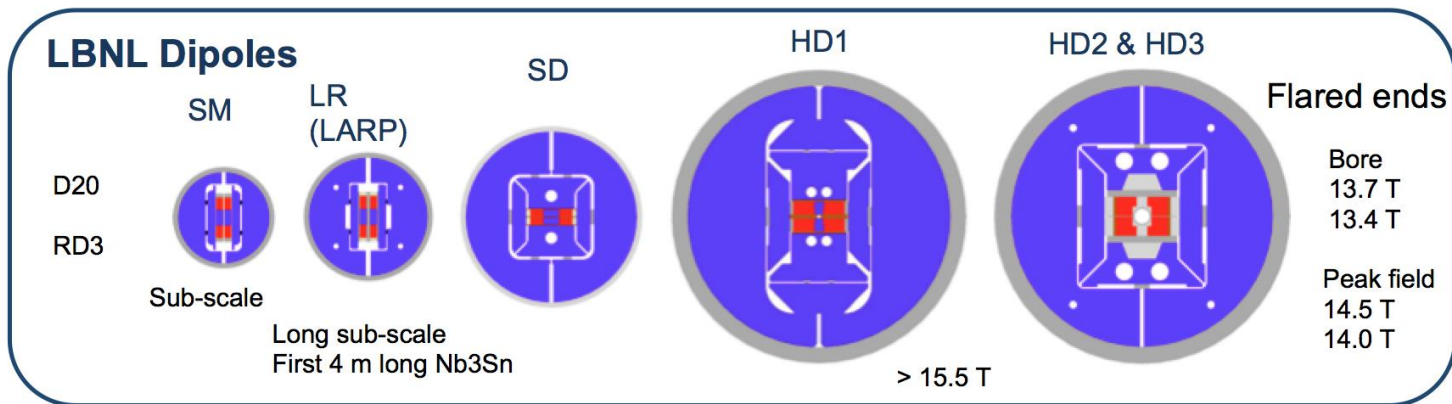


Basic magnet technology development for HILUMI and beyond (2004-2013) ; US development evolution



History of LBNL and LARP Magnet Develop

Used bladder and key technology developed at LBNL



By courtesy of D. Dietderich, LBNL



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ACCELERATOR TECHNOLOGY &
APPLIED PHYSICS DIVISION



6

Basic HFM development :

Some achievements at LBNL (1995-2004)

Since 20 years LBNL is running a high field dipole development program

Some achievements:

- D20, 50 mm aperture, $\cos\Theta$ 4 layer dipole, reached 13.5 T@1.9K
- HD1, flat block coil, 8 mm aperture, reached 16 T
- HD2, flared end block coil, 36 mm aperture, reached 13.8 T

These pose a clear breakthrough above 10 T with a new coil layout (block coil) and a mechanical structure aimed (shell-bladder and keys) at high fields

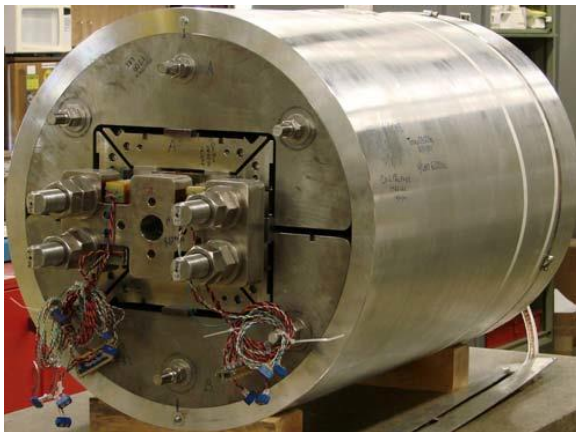


Fig. 1. HD2 assembled and pre-loaded.

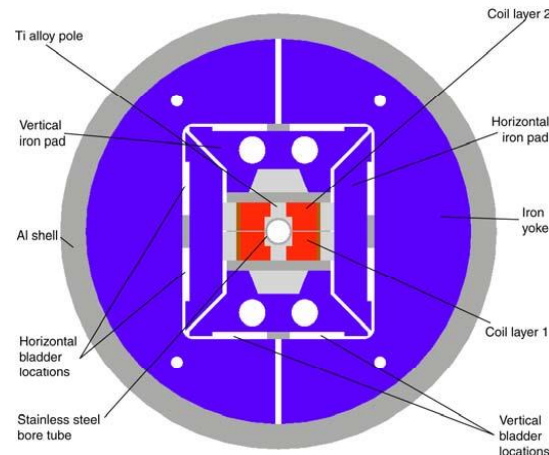
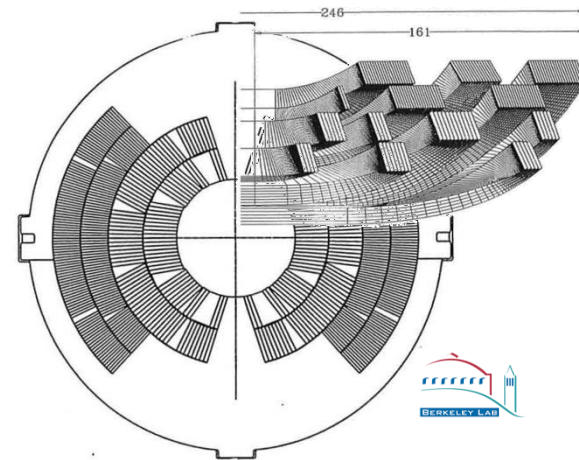


Fig. 2. HD2 cross-section.

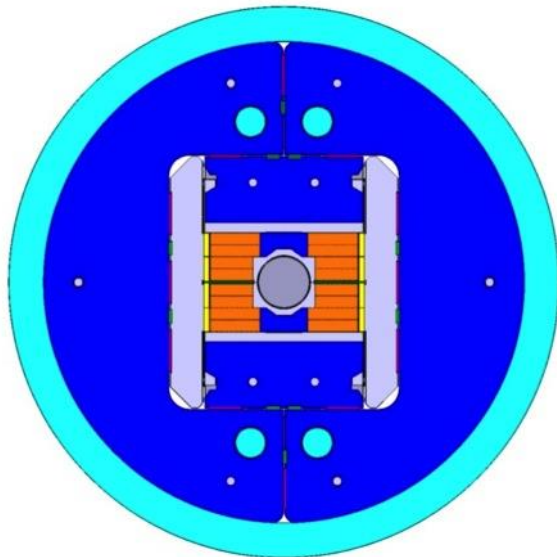
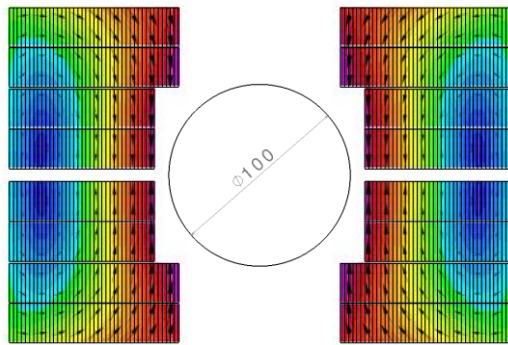


A.D. McInturff, et al., Proc. of PAC 1997, 3212

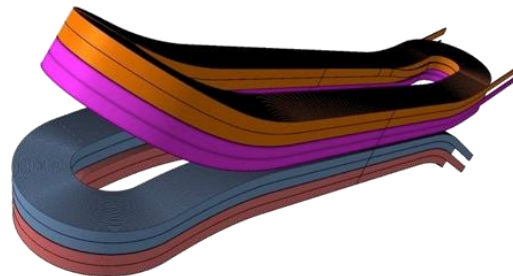


Basic HFM development : EuCARD high field dipole (Fresca2):

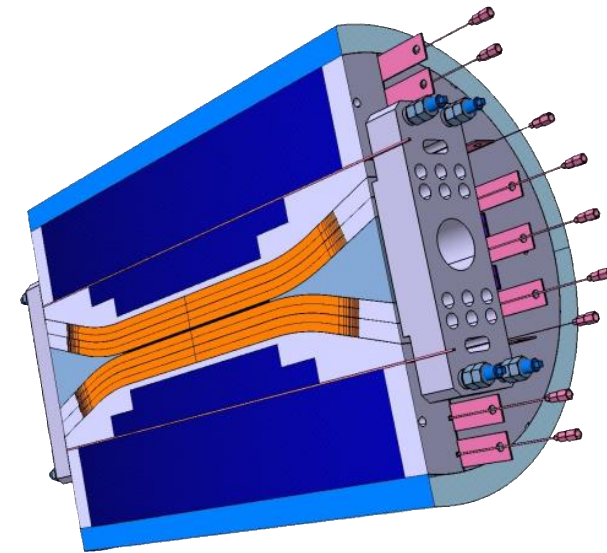
- Fresca2 : CERN, CEA construction phase
- First tests 2014



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



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

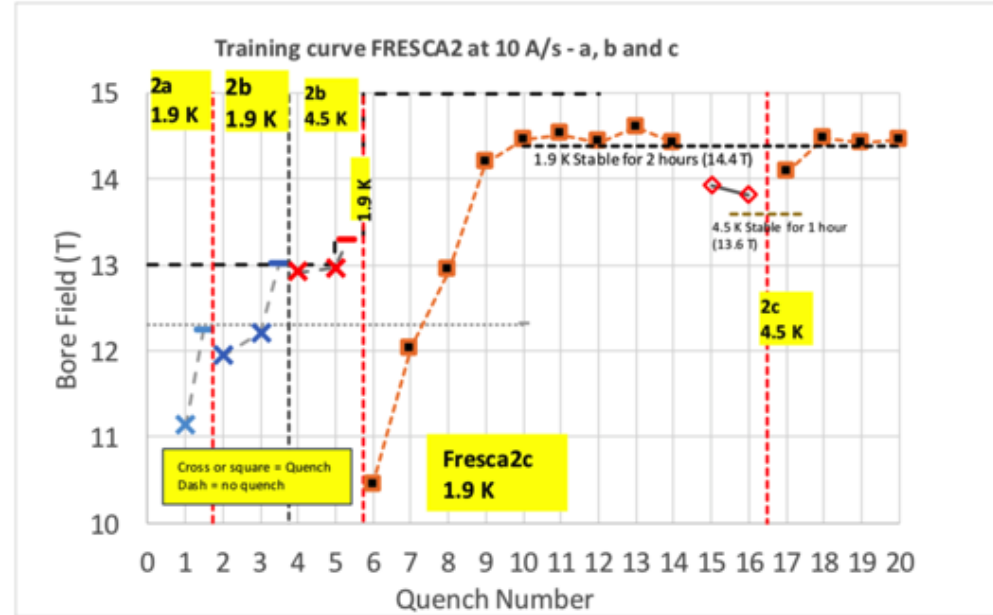
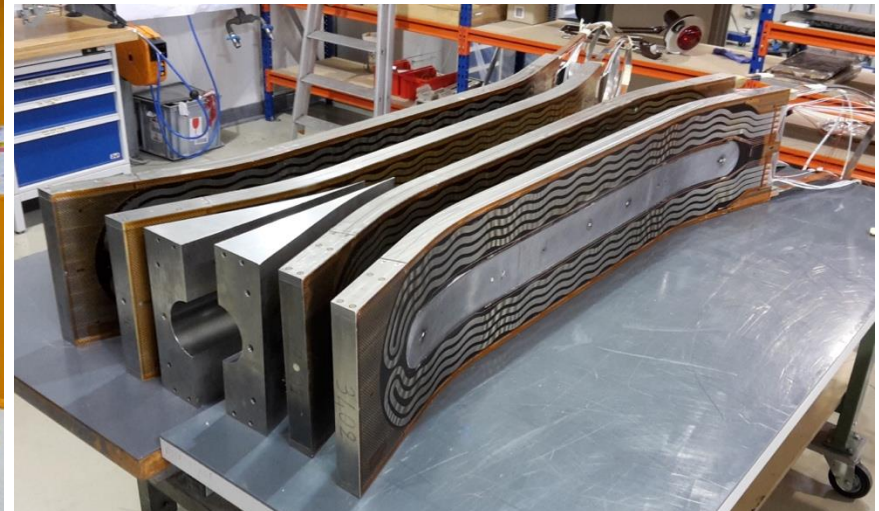


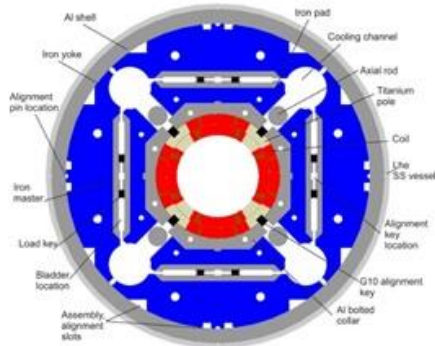
Courtesy Attilio Milanese,
Pierre Manil

Fabrication of Fresca2 coils, test results

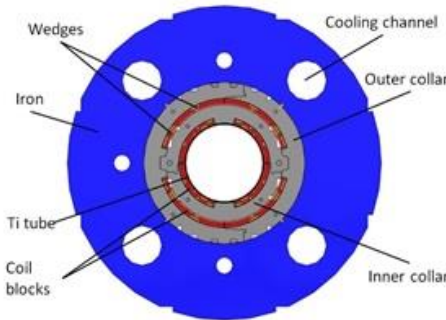
Straightforward technology to wind block coils with flared ends:

This is a lesson for FCC magnets !

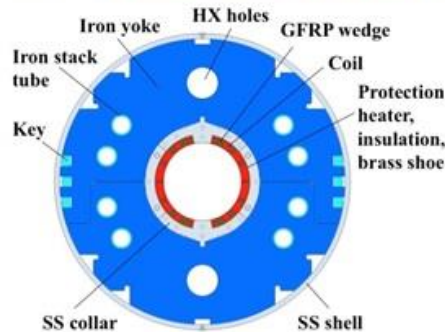




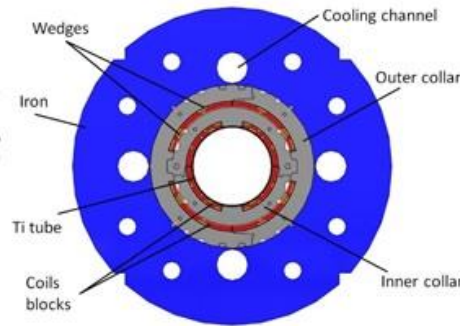
Triplet [G. Ambrosio, P. Ferracin et al.]



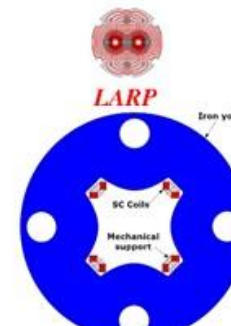
MCBXFB [F. Toral, et al.]



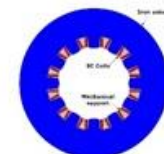
D1 [T. Nakamoto et al.]



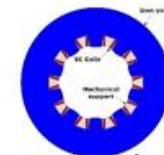
MCBXFA [F. Toral, et al.]



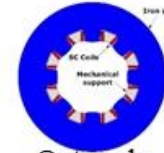
Skew quad [G. Volpini, et al.]



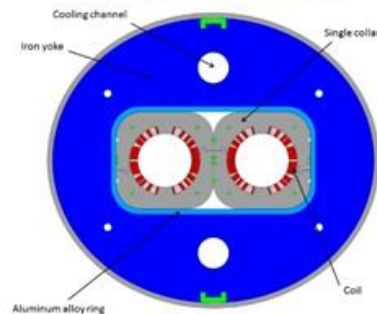
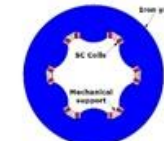
Dodecapole



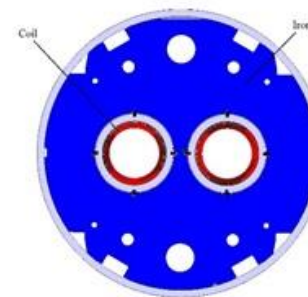
Decapole



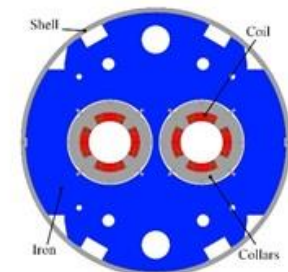
Octupole



D2 [P. Fabbriatore, S. Farinon]



D2 Q4 correctors [G. Kirby]



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

Model have good performance, long prototypes are being fabricated

A CERN LARP collaboration.

Nominal Gradient 132.6 T/m

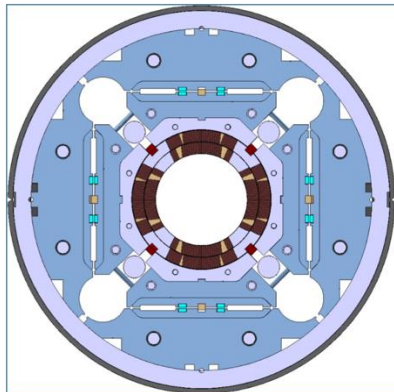
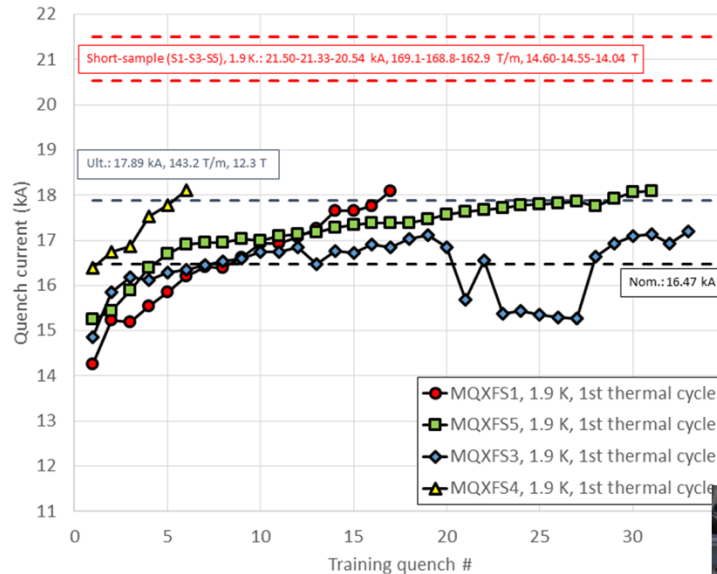
Aperture diameter 150 mm

Peak Field 12.1 T

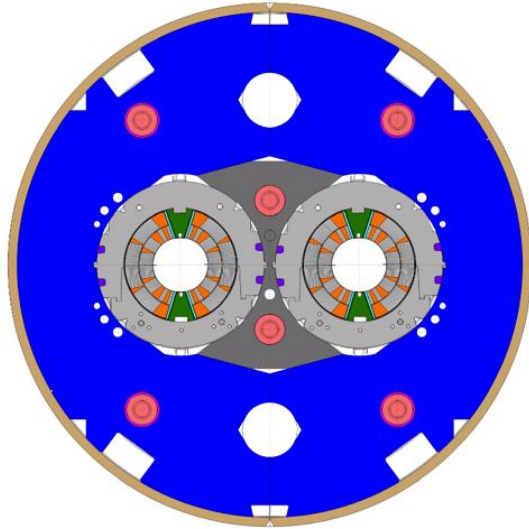
Current 17.5 A

Load-line Margin 20% @ 1.9 K

Stored Energy 1.32 MJ/m



Courtesy P. Ferracin



- First Nb3Sn magnet to go into an accelerator (2019) !
- Present model program (CERN and FNAL)
 - demonstrated the required performance (11.25 T at 11850 A) and Achieved accelerator field quality

Nominal Field 11 T

Aperture diameter 60 mm

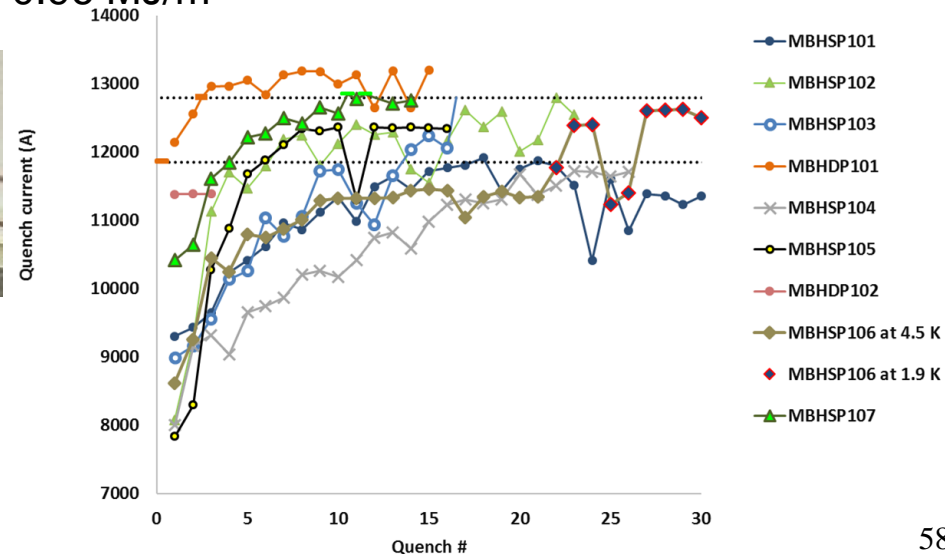
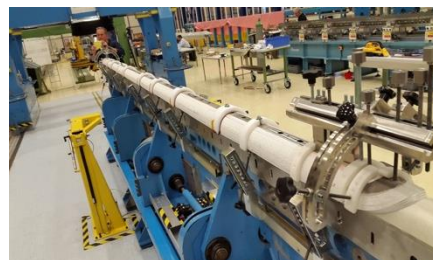
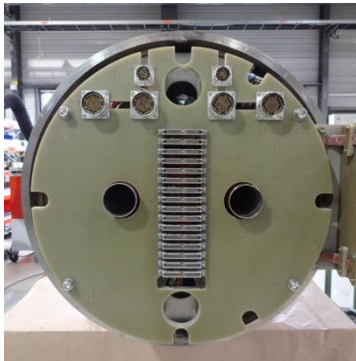
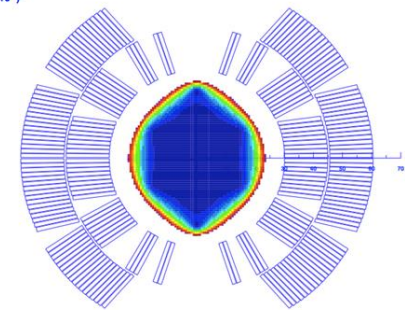
Peak Field 11.35 T

Current 11.85 kA

Loadline Margin 19.7% @ 1.9 K

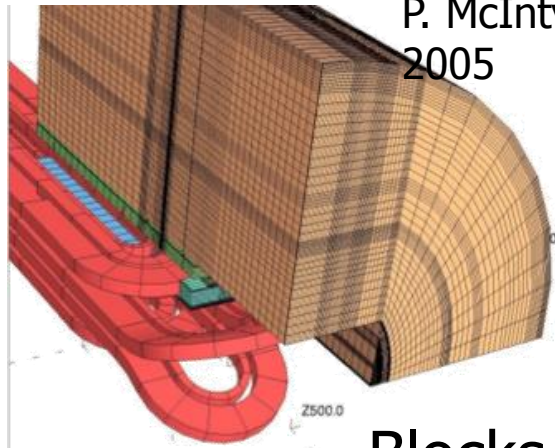
Stored Energy 0.96 MJ/m

Rel. field errors (units 10^{-5})



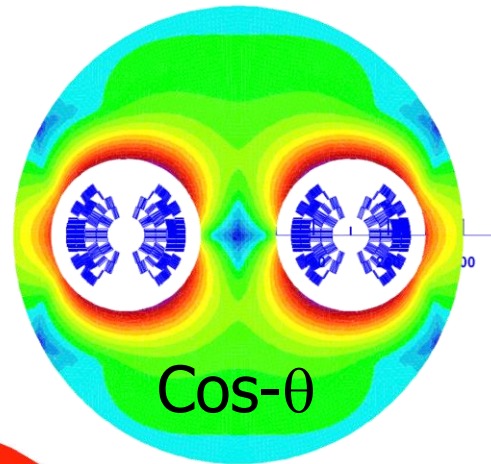
Magnet design for >12 T dipoles, LTS Nb₃Sn

Many studies & proposals since the mid 1990-ies



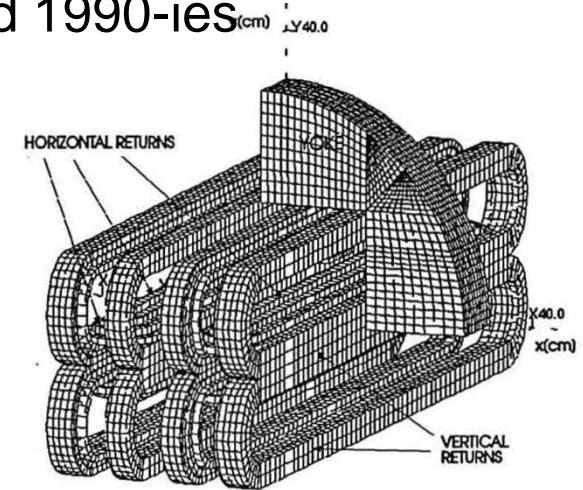
P. McIntyre,
2005

Blocks



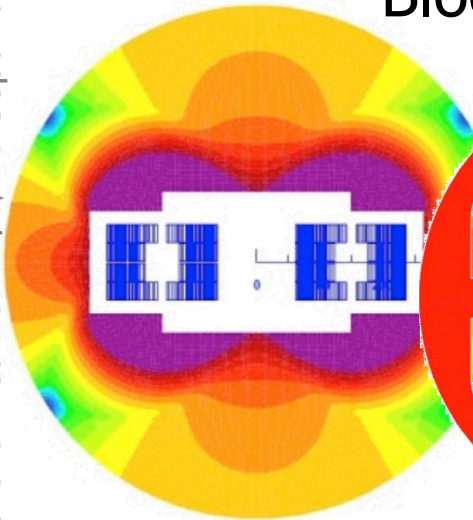
E. Todesco 2013
D. Schoerling 2015

Cos-θ

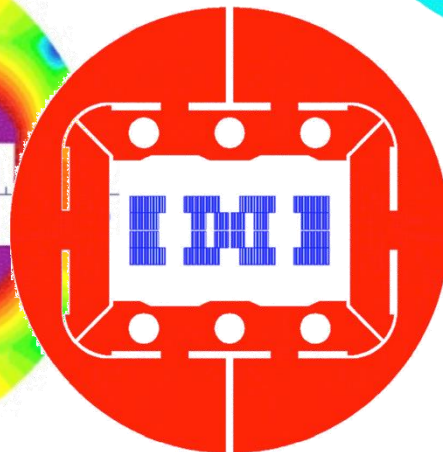


J.M. Van Oort, R. Scanlan,
1994

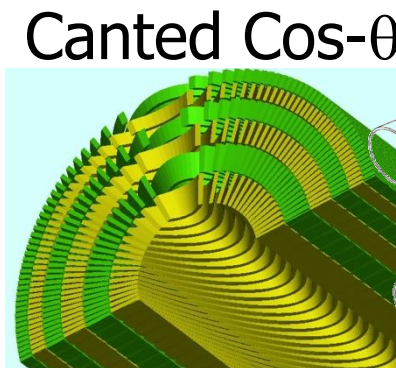
Common coils



E. Todesco, 2013

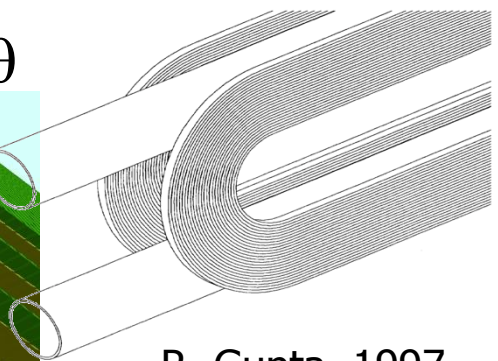


GL. Sabbi, 2014



Canted Cos-θ

S. Caspi, 2014



R. Gupta, 1997



US program lines



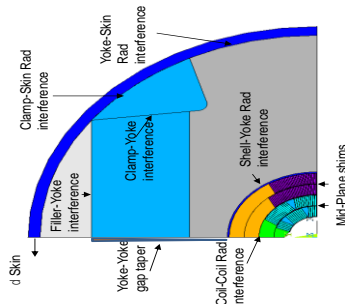
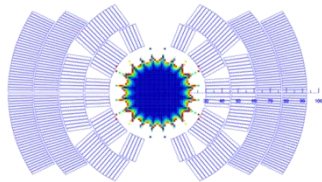
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Science



cos- θ

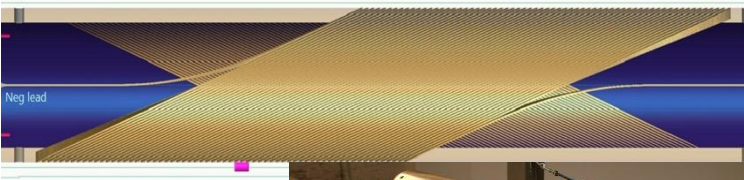
2017-2019



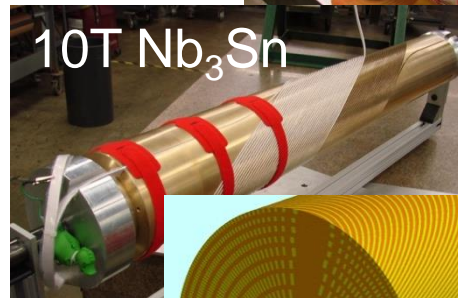
reached 14.1T in
spring 2019



canted-cos- θ

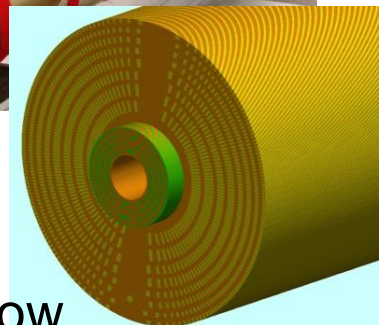


2014-2015



10T Nb₃Sn

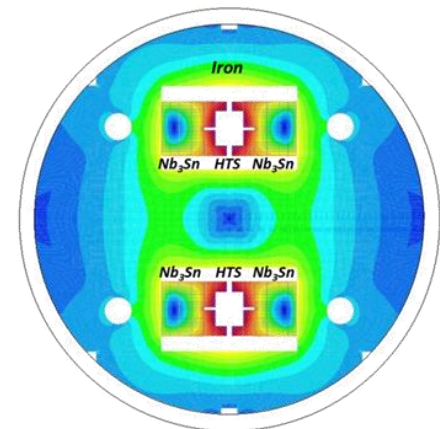
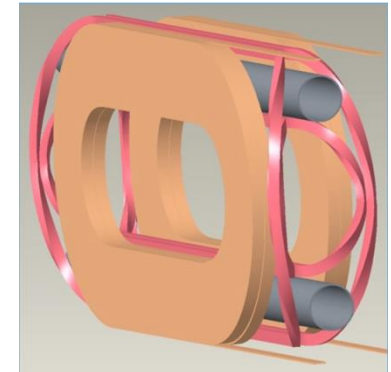
2015-2016



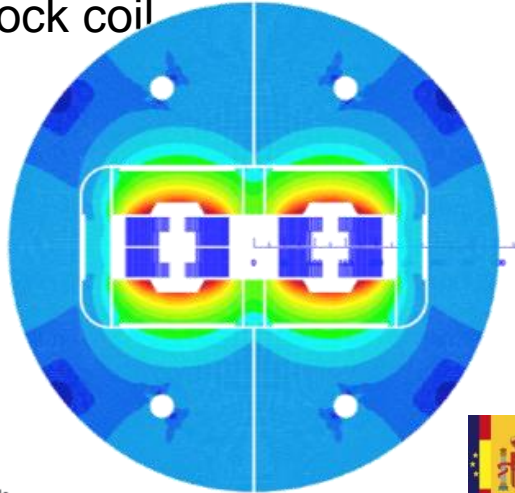
2016-now

BROOKHAVEN
NATIONAL LABORATORY

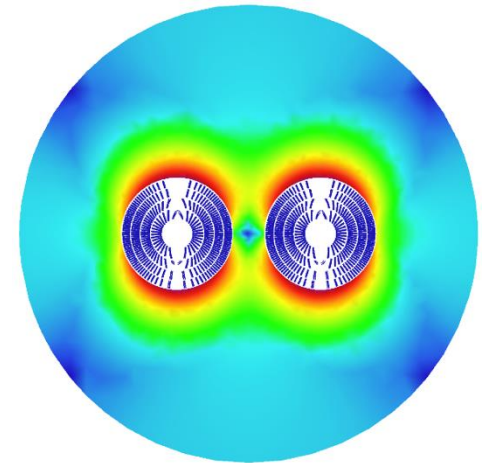
common coils
2017



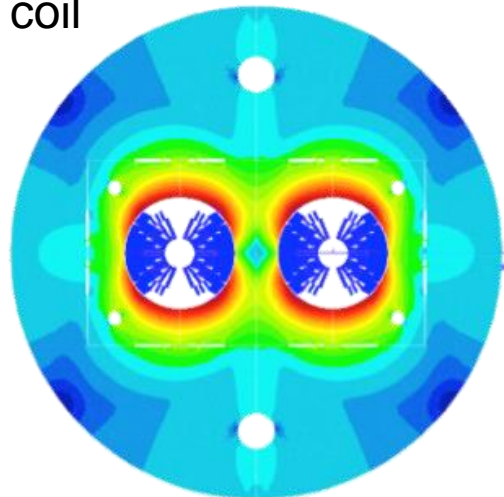
Block coil



Canted Cos-theta



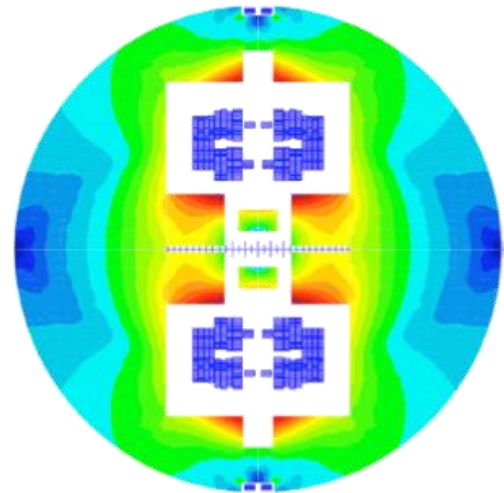
Cos-theta coil



C. Lorin, M. Durante (CEA)



Common coils



B. Auchmann (CERN/PSI)



S. Farinon, P. Fabbriatore (INFN)

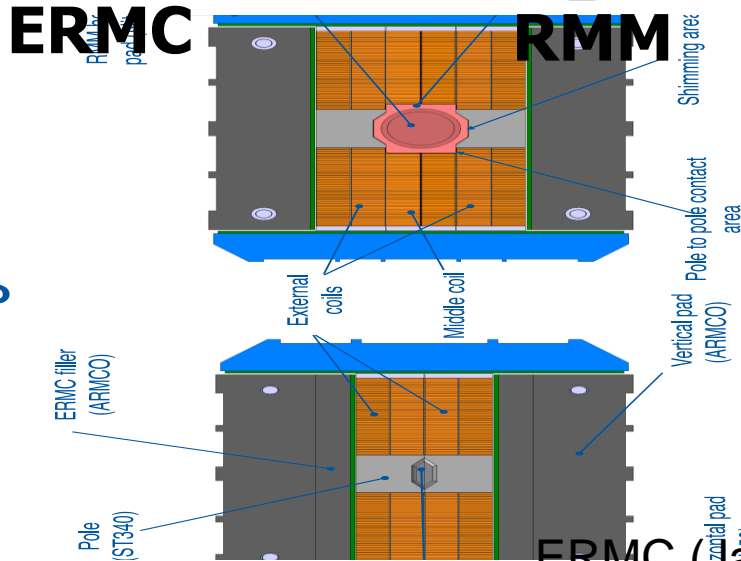
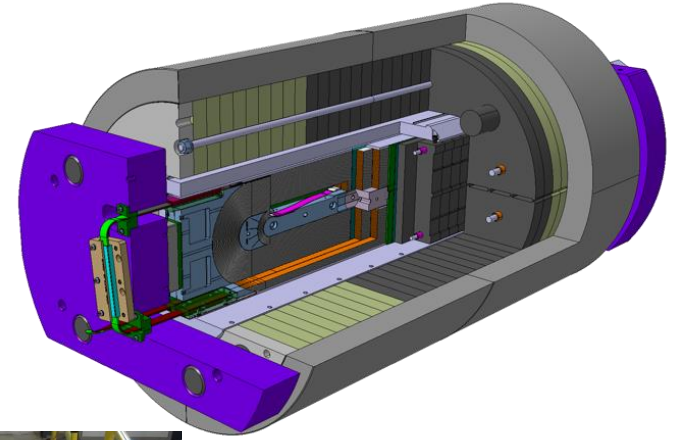
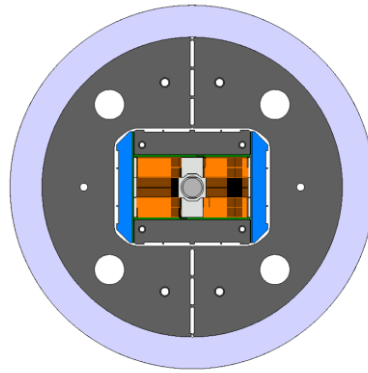
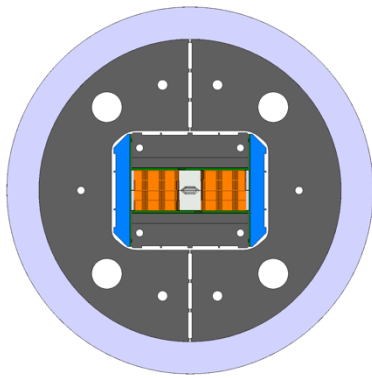
F. Toral (CIEMAT)



16 T , CERN approach , go in steps

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

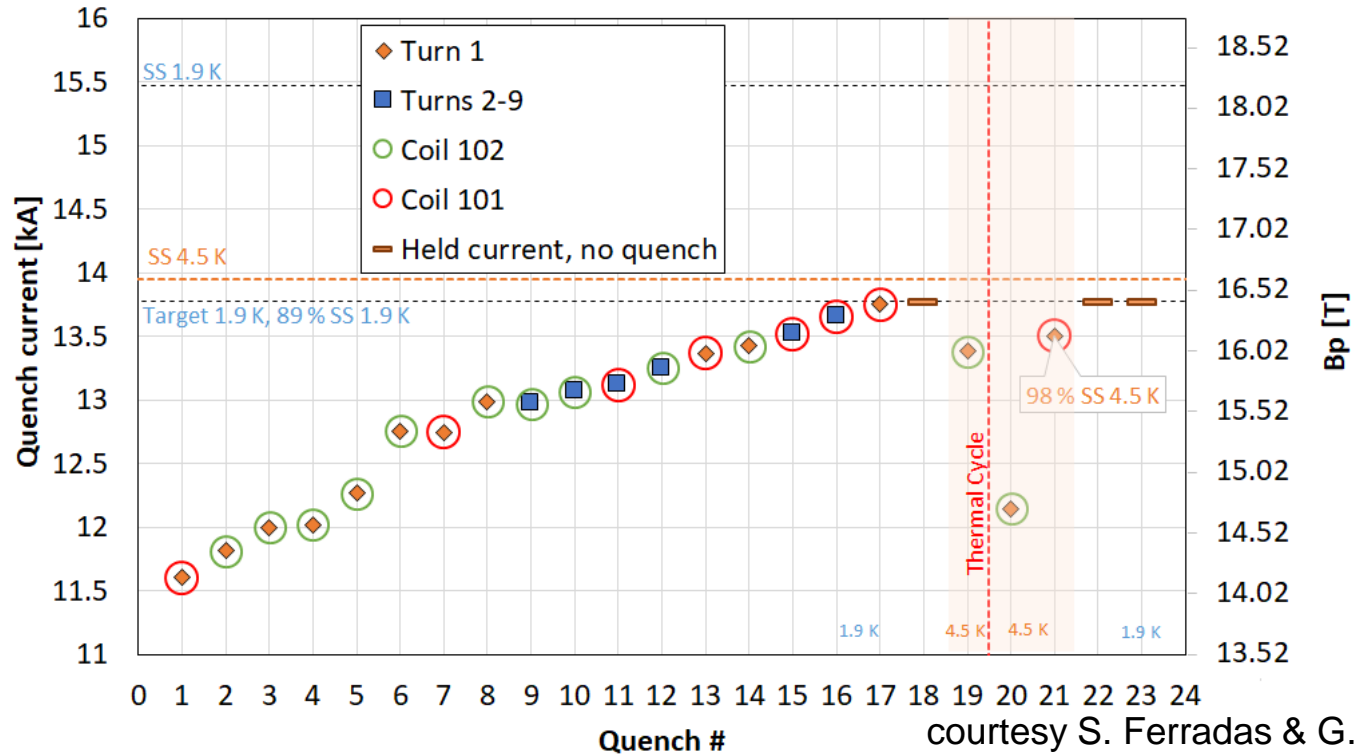
First with one conductor , then with 2 different ones to optimise the coil: Grading



ERMCo (Jan 2020): reached 16.5 T on the coil @1.9K 62

ERMC test results

Training of eRMC 1a



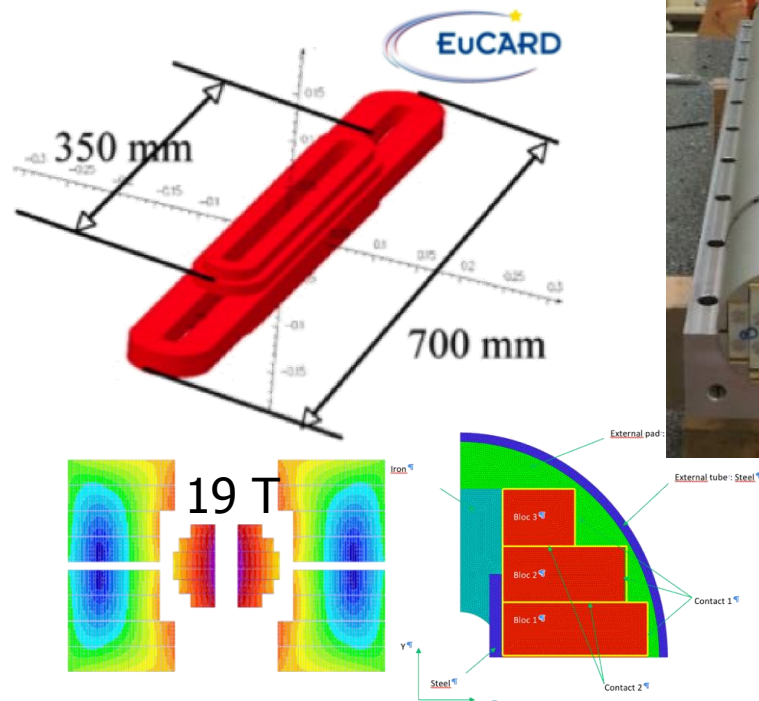
courtesy S. Ferradas & G. Willering

- The training dl/dt was reduced after quench 17. Then, it reached 13.77 kA (Bp 16.5 T)
- The magnet reached 98% of SS at 4.5 K
- Good memory after the thermal cycle: Only one training quench

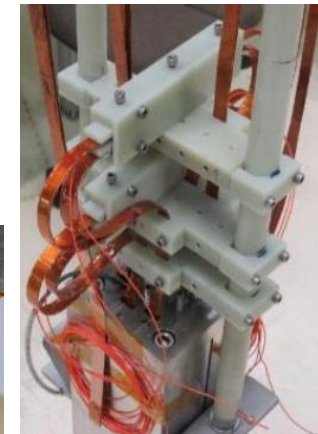
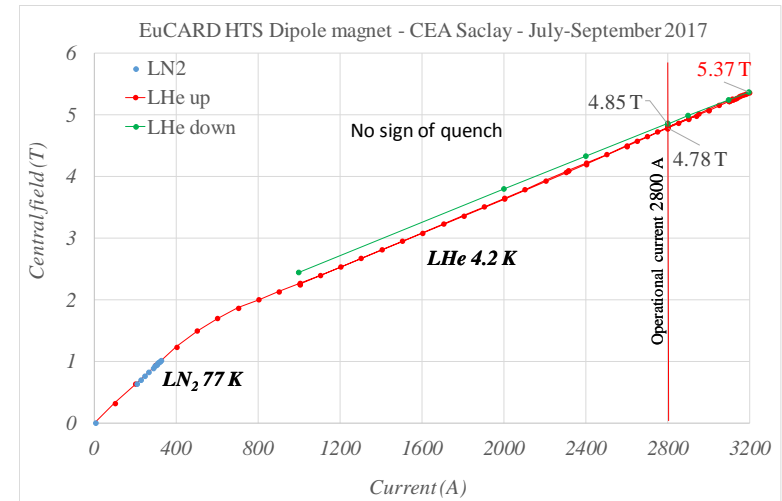


HTS: First attempt towards 20 T

6 T HTS (YBCO) insert for test in Fresca2 , to get to 19 T
But without bore

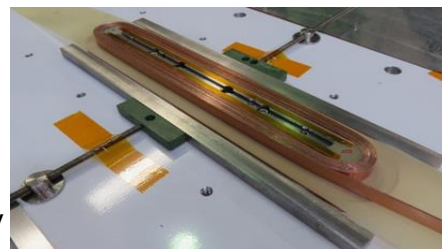


Stand alone tested Sept 2017:
Reached 5.37 T @ 4.2 K ($I=3200A$)
Next test mid 2019 inside Fresca2



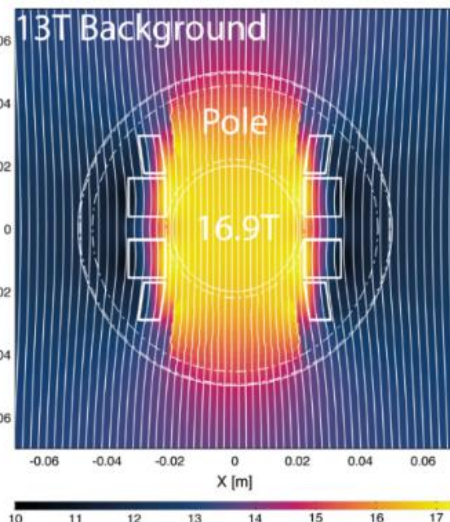
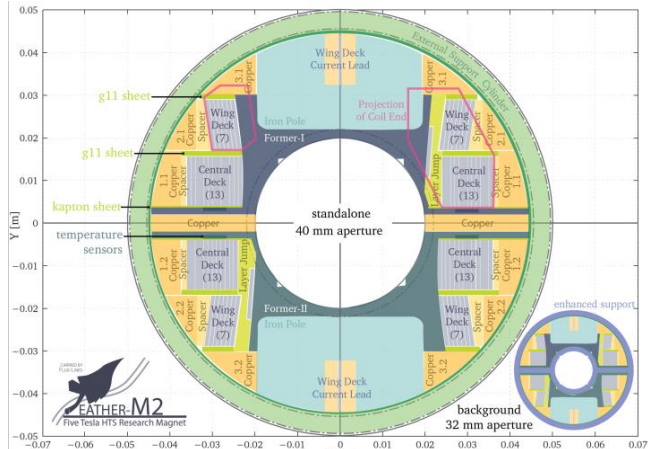
a CEA + CRNS Grenoble project

J.M. Rey, F. Borgnolutti, M. Durante, CEA-Saclay

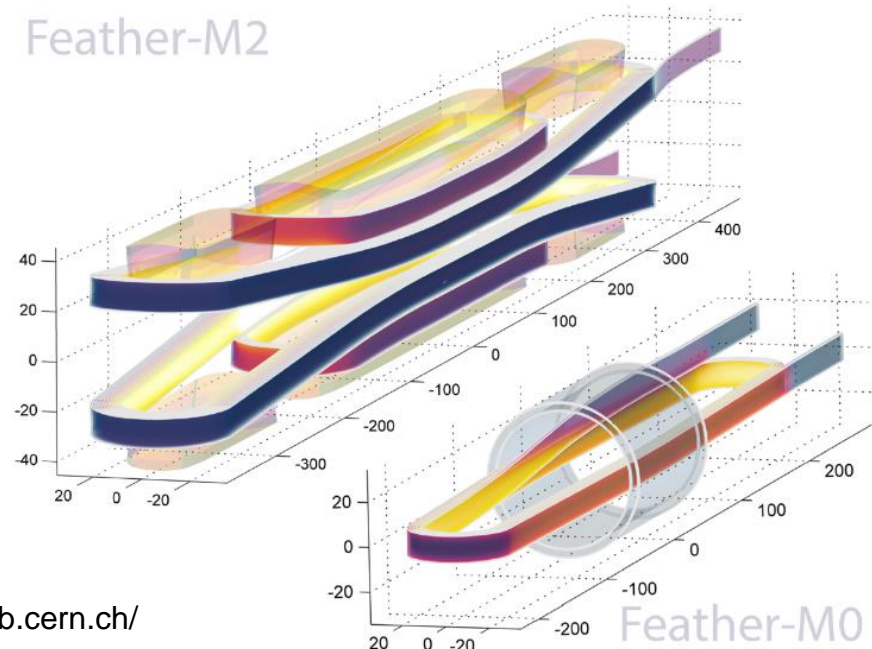


EuCARD2 5T accelerator quality ReBCO magnet

5 Tesla stand alone, (18 T in 13 T background), @ 4.5K,
40 mm aperture, 10 kA class Roebel cable, Accelerator Field
quality

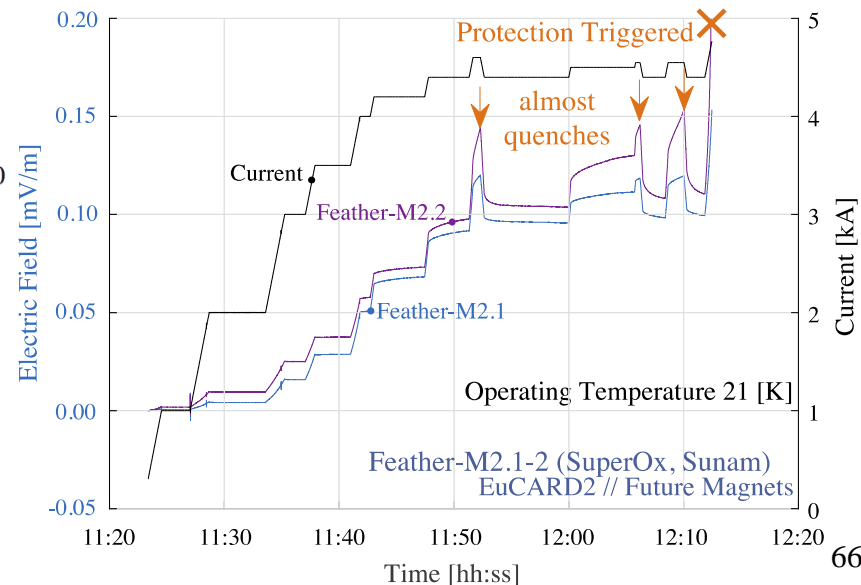
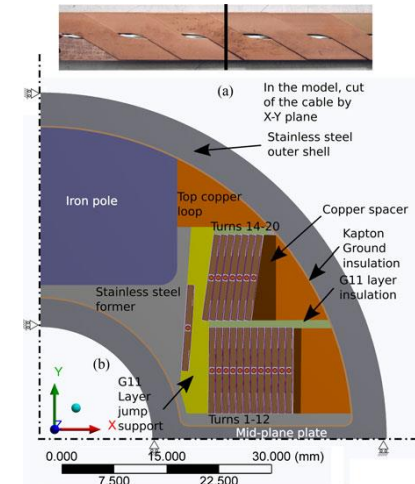
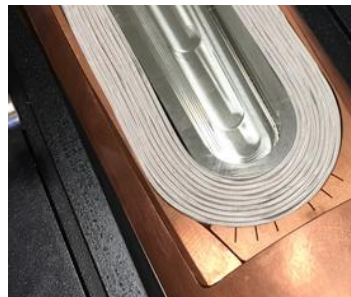
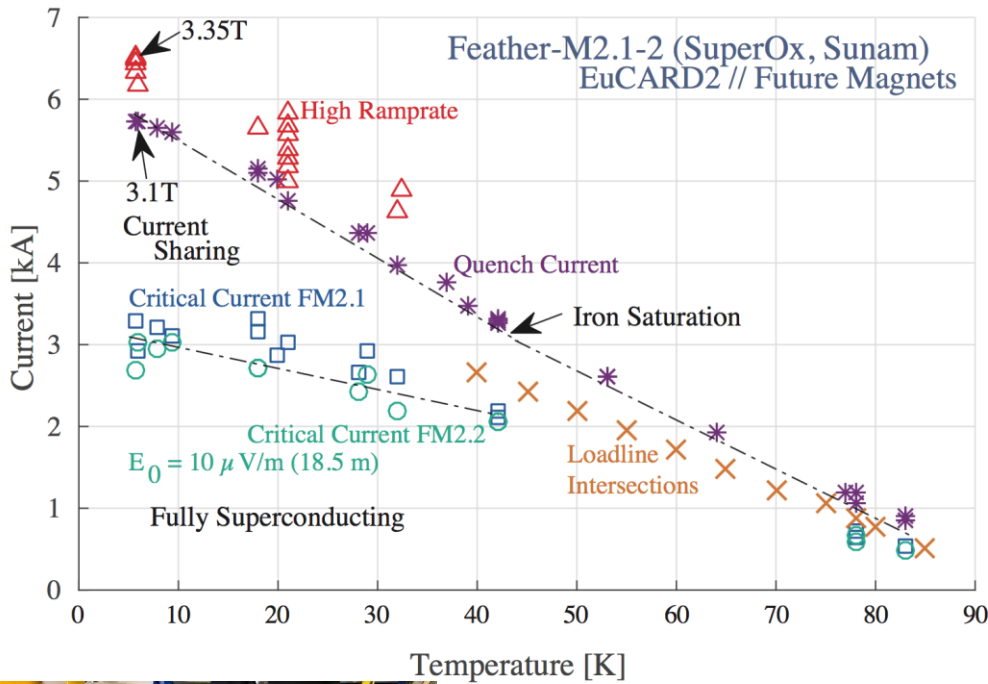


Feather-M2



Feather-M0

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





20T design activity @CERN

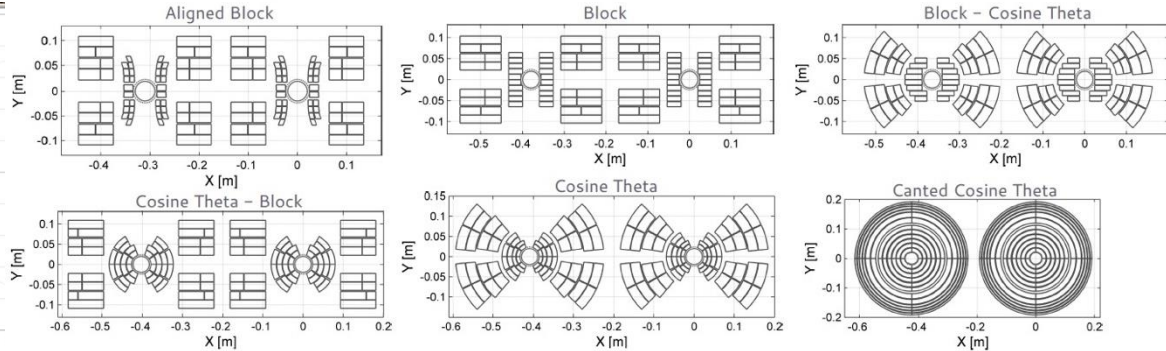
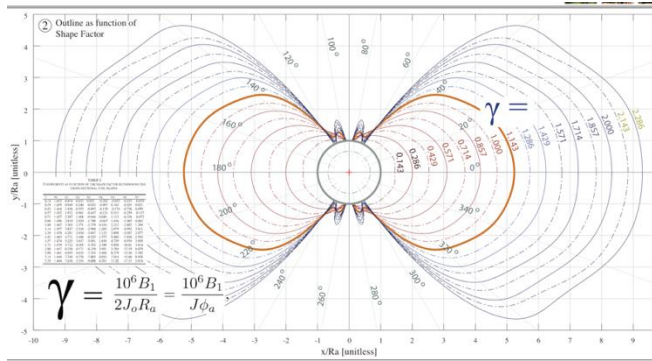


Fig. 8. Conceptual cross-sectional mechanical design

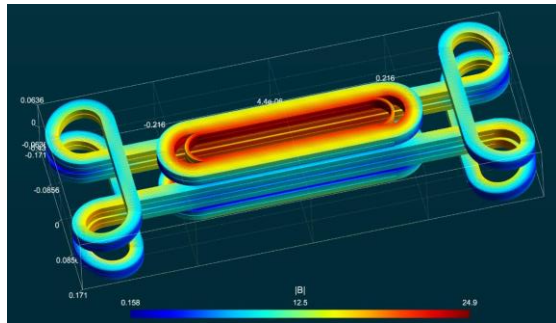


Fig. 10. Illustration showing the three-dimensional coil layouts with the three different coil-end types that are considered. The cross-section of these coils correspond exactly to coil layout 5 in Table I.

Cable options

Twisted stack

CORC

Roebel

“DOCO”





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 Nb₃Sn are in the prototyping phase for HILUMI, and the 11T dipole is ready for installation

Development models have been shown to work up to 16 T

For future colliders 12 -16 T magnets are being designed

Development for HTS magnets for the 20 T range has started

Lots of fun ahead !



Literature on High Field Magnets

- **Books**

- 1) M. Wilson, Superconducting magnets / Oxford : Clarendon Press, 1983 (Repr. 2002). - 335 p
- 2) K-H. Mess, P. Schmüser, S. Wolff, Superconducting Accelerator Magnets, Singapore, World Scientific, 1996. - 218 p.
- 3) Y. Iwasa, Case studies in superconducting magnets : design and operational issues . - 2nd ed. Berlin : Springer, 2009. - 682 p.
- 4) S. Russenschuck, Field computation for accelerator magnets : analytical and numerical methods for electromagnetic design and optimization / Weinheim : Wiley, 2010. - 757 p.
- 5) CERN Accelerator school, Magnets, Bruges, Belgium 16 – 25 June 2009, Editor: D. Brandt, CERN–2010–004

- **Conference proceedings and reports**

- 6) 21st International Conference on Magnet Technology, Hefei, China, 18 - 23 Oct 2009, IEEE Trans. Appl. Supercond. 20 (2010)
- 7) The 2010 Applied Superconductivity Conference, Washington DC, US, 1-6 Aug 2010, , IEEE Trans. Appl. Supercond. 21 (2011)



Literature on High Field Magnets (2)

- Papers and reports

- 8) S. Caspi, P. Ferracin, "Limits of Nb₃Sn accelerator magnets", *Particle Accelerator Conference* (2005) 107-11.
- 9) S. Caspi, P. Ferracin, S. Gourlay, "Graded high field Nb₃Sn dipole magnets", *19th Magnet Technology Conference, IEEE Trans. Appl. Supercond.*, (2006) in press.
- 10) E. Todesco, L. Rossi, "Electromagnetic Design of Superconducting Dipoles Based on Sector Coils", *Phys. Rev. Spec. Top. Accel. Beams* 10 (2007) 112401
- 11) E. Todesco, L. Rossi, AN ESTIMATE OF THE MAXIMUM GRADIENTS IN SUPERCONDUCTING QUADRUPOLES, CERN/AT 2007-11(MCS),
- 12) P. Fessia, et al., Parametric analysis of forces and stresses in superconducting dipoles, *IEEE, trans. Appl, Supercond.* Vol 19, no3, June 2009.
- 13) P. Fessia, et al., Parametric analysis of forces and stresses in superconducting quadrupole sector windings, sLHC Project Report 0003

- Websites

- 15) <http://www.magnet.fsu.edu/magnettechnology/research/asc/plots.html>



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For this lecture I used material from lectures, seminars, reports, etc. from the many colleagues. Special thanks goes to:

Giorgio Ambrosio (FNAL), Luca Bottura (CERN), Shlomo Caspi (LBNL), Arnaud Devred (ITER), Paolo Ferracin (LBNL), Attilio Milanese (CERN), Jeroen van Nugteren, Juan-Carlos Perez (CERN), Lucio Rossi (CERN), Stephan Russenschuck (CERN), Ezio Todesco (CERN), Davide Tommasini (CERN), Martin Wilson



www.cern.ch