Superconducting Magnets

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CAS

Vysoke-Tatry, Slovakia
12th September 2019

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:

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

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

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

Magnetostatics

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

Gauss law of magnetism	(1)	$\operatorname{div} \vec{B} = 0$	always holds
Ampere's law with no time dependencies	(2)	$\operatorname{rot} \vec{H} = \vec{J}$	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 $multipole$ $component,$

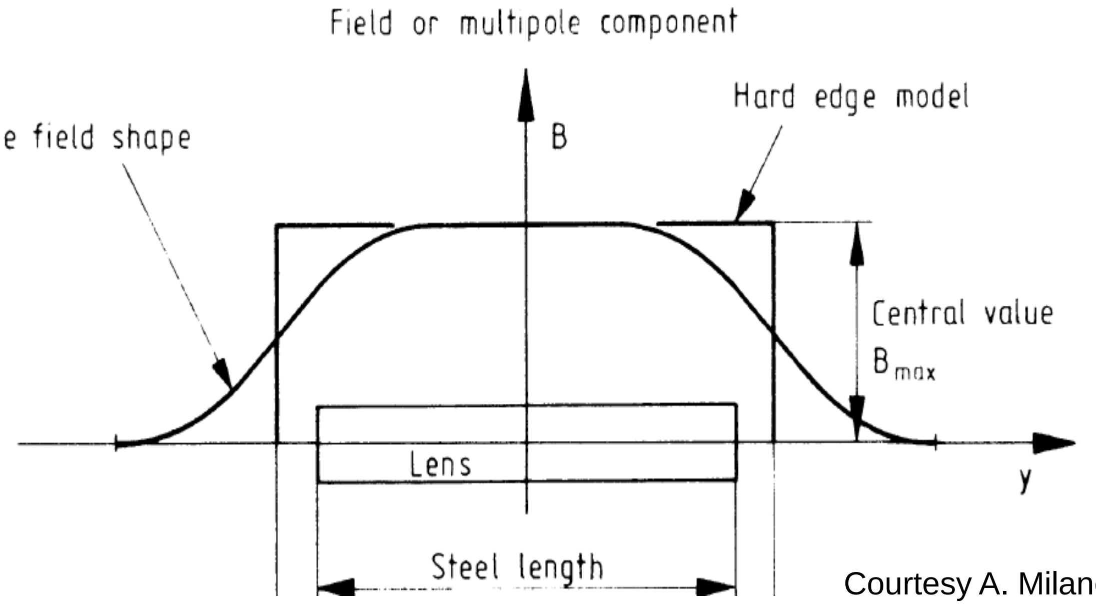
a_n the $skew$ nth $multipole$ $component$.

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

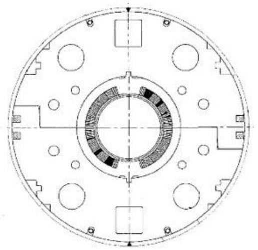
In 3D, the longitudinal dimension of the magnet is described by a magnetic length



Courtesy A. Milanese, CERN

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

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



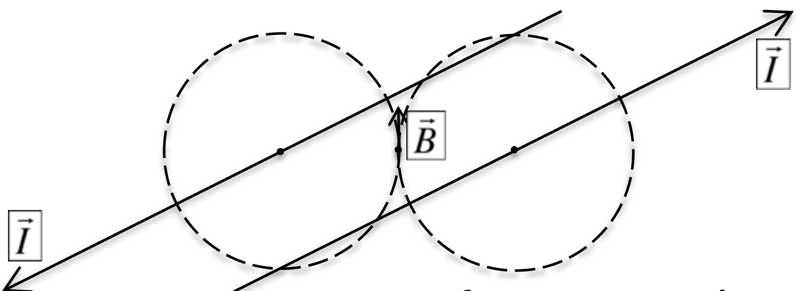
The magnetic length L_{mag} for SC magnets is adjustable by varying the length of the yoke: often the coils stick outside the end of the yoke: no easy rule of thumb for L_{mag}

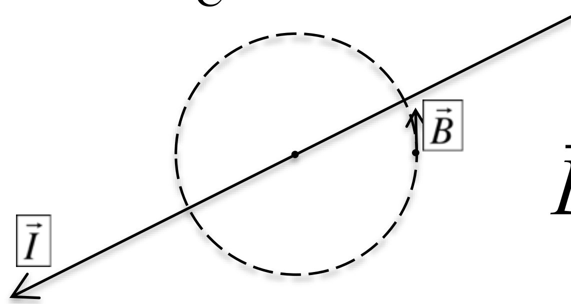
Magnetic fields

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

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

We can derive the law of Biot and Savart



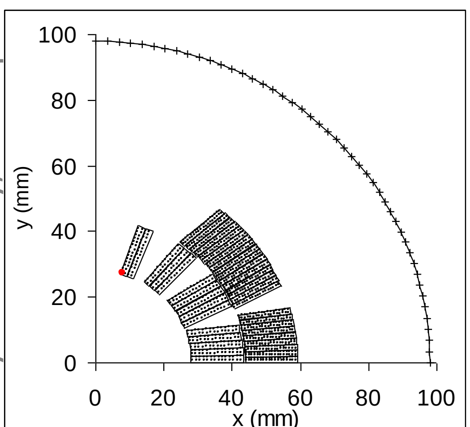


$$\vec{B} = \frac{\mu_0 I}{2\pi r}\hat{\jmath}$$

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

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

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



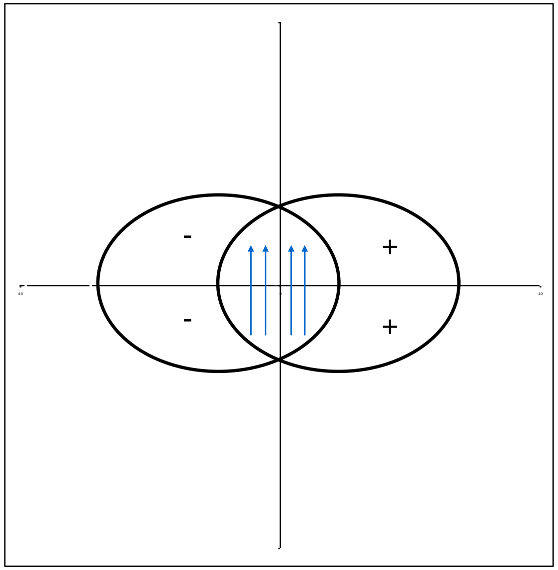
Courtesy E. Todesco

For LHC dipole@8.3 T ~1 MA in 3300 mm^2 : ~300 A/mm^2

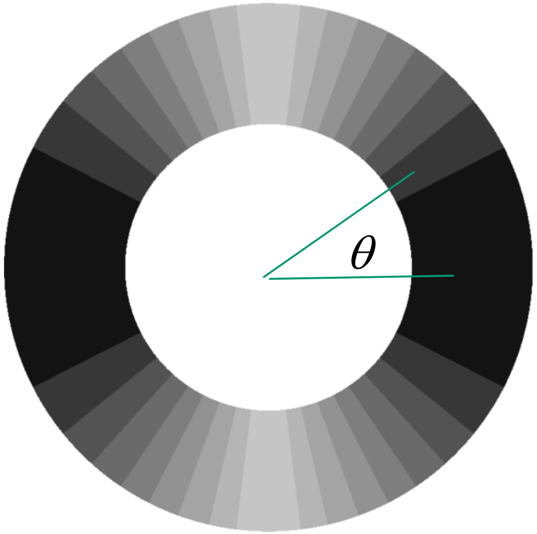
(overall current density in the coil area)

Coils for generating the Perfect Dipole Field

- 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

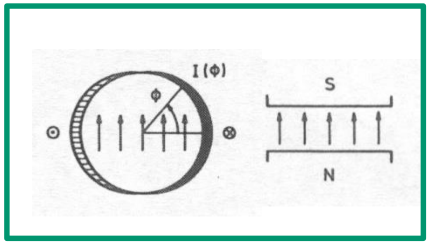
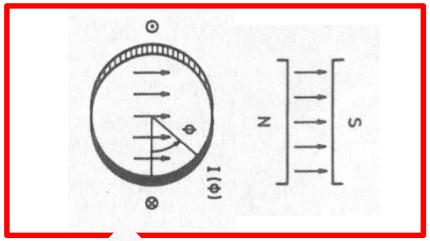
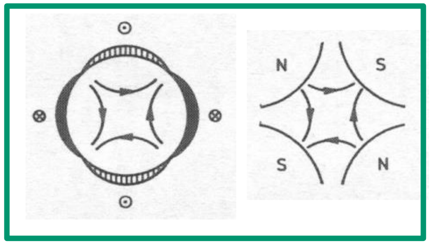
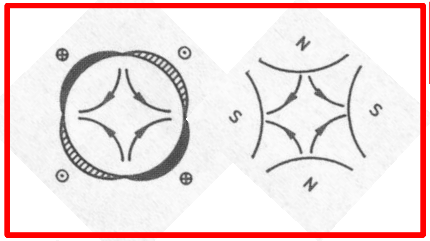
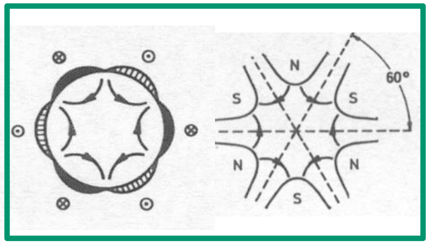
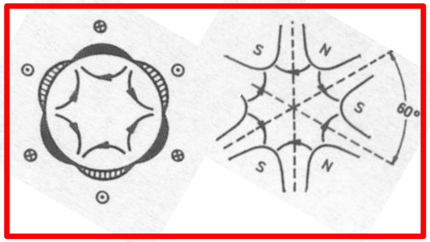


- Thick conductor shell with a $cos\theta$ current distribution $J = J_0 \cos\Theta$
  - Pure dipolar field
  - Easier to reproduce with a flat rectangular cable



Magnet types and higher orders

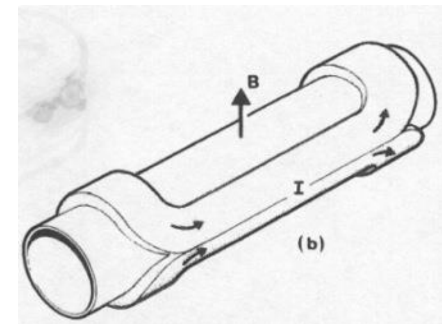
a “pure” multipolar field can be generated by a specific coil geometry

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

Courtesy P. Ferracin, CERN

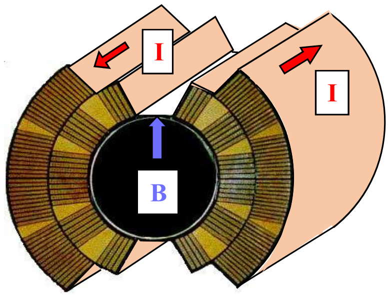
What is specific about accelerator magnets ?

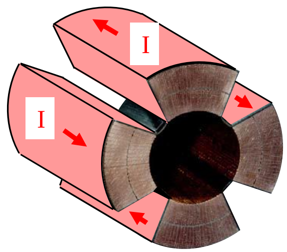
- Cylindrical volume with perpendicular field

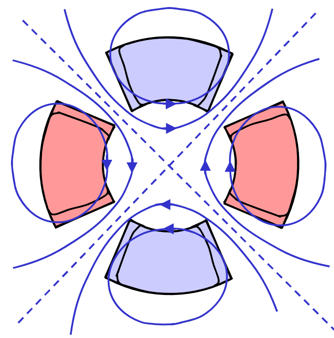


Artist view of a dipole, from M. N. Wilson « Superconducting Magnets »

- Dipoles, quadrupoles, etc

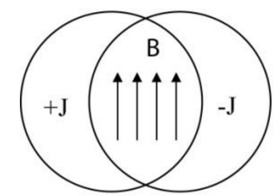






- Field quality: $\dfrac{\Delta B_z}{|B|} \le few \cdot 10^{-4}$

CosΘ coil : $J = J_0 \cos\Theta$



- Field quality formulated and measured in a multipole expansion,

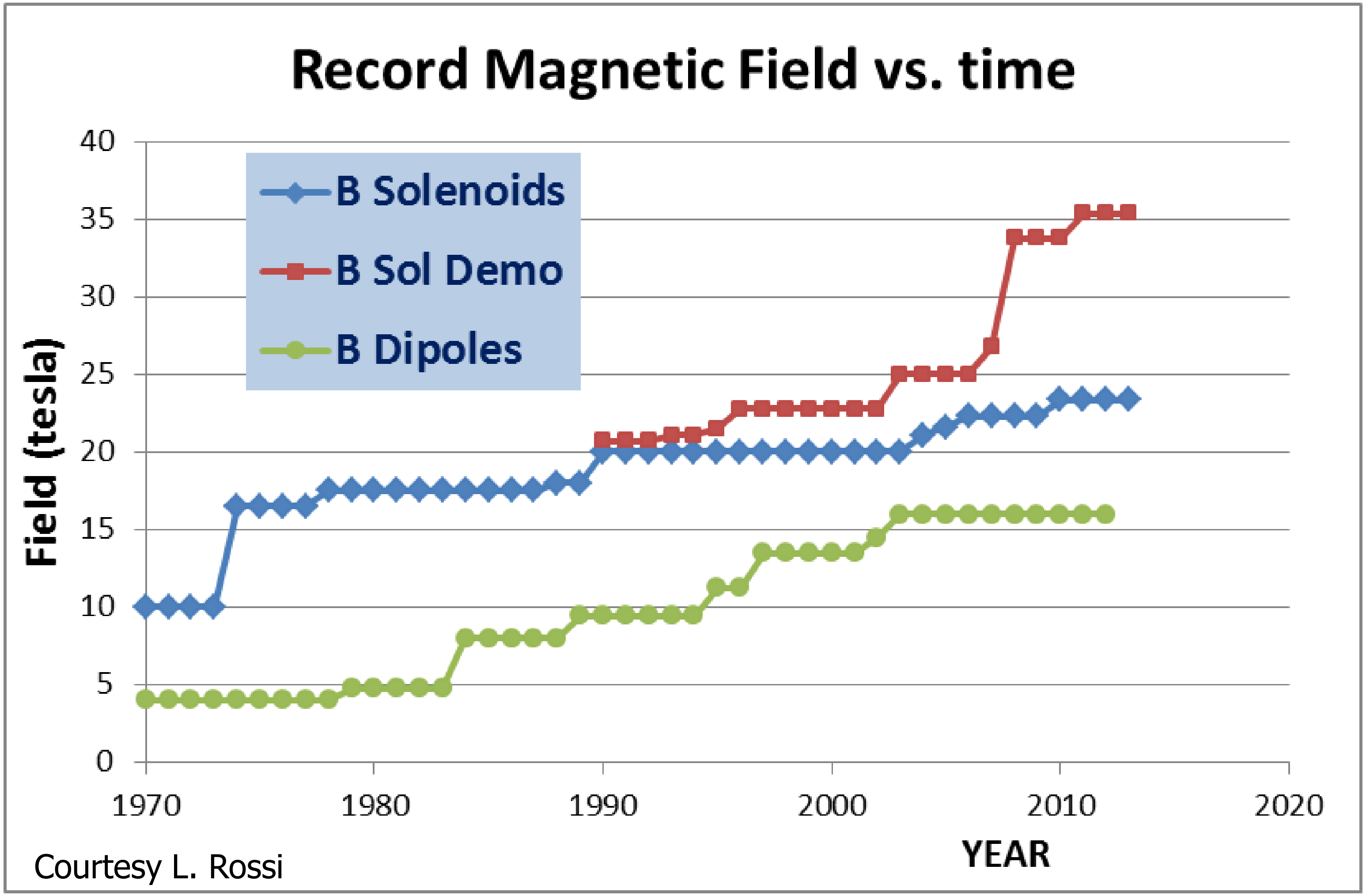
$$B_y + iB_x = 10^{-4} B_1 \sum_{n=1}^{\infty} (b_n + i a_n) \left(\frac{x + iy}{R_{ref}} \right)^{n-1} \qquad b_n, a_n \le few \cdot units$$

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

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

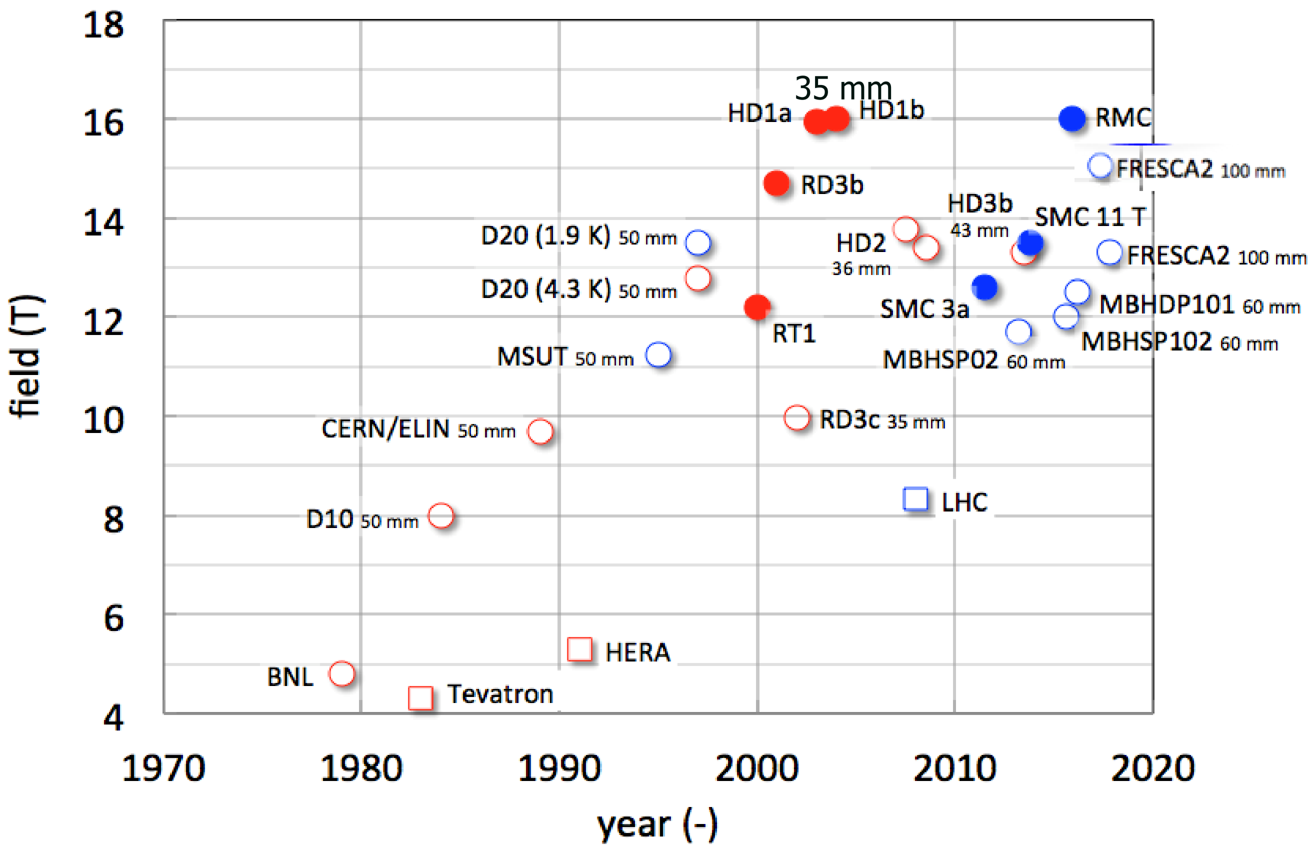
The state of the art: Comparison between dipoles and solenoids

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



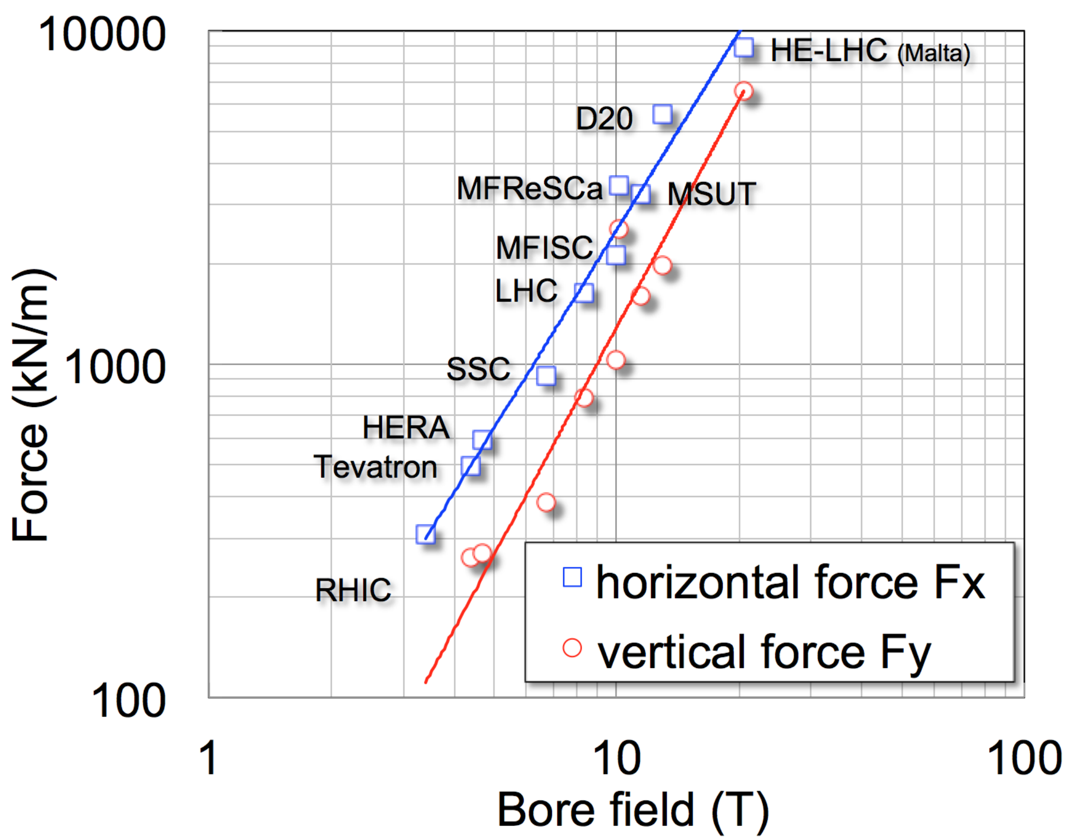
Superconducting accelerators magnets; the state of the art

- 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



Forces

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

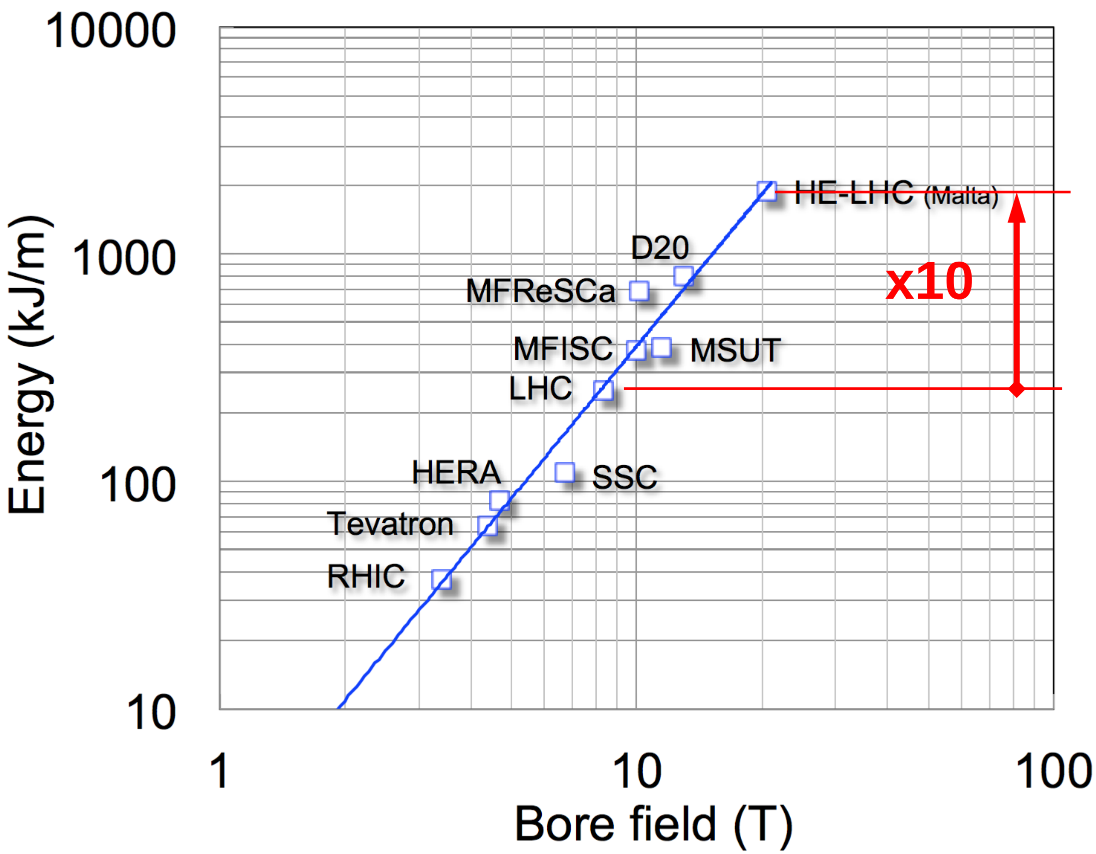


The electromagnetic loads in a 20 T dipole would be a factor 5 to 8 larger than in the LHC dipoles

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

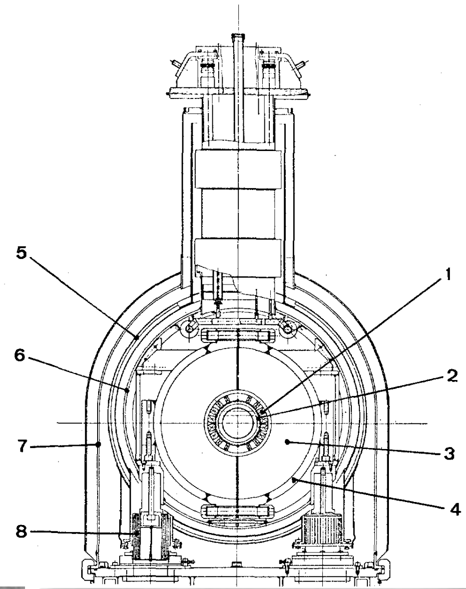
Early SC magnets for accelerators: Beam Transfer line magnets: Castor and Cesar @CERN

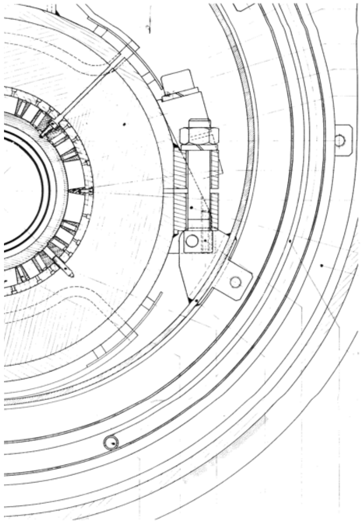
1977: Very first SC magnets at CERN in an SPS beam line

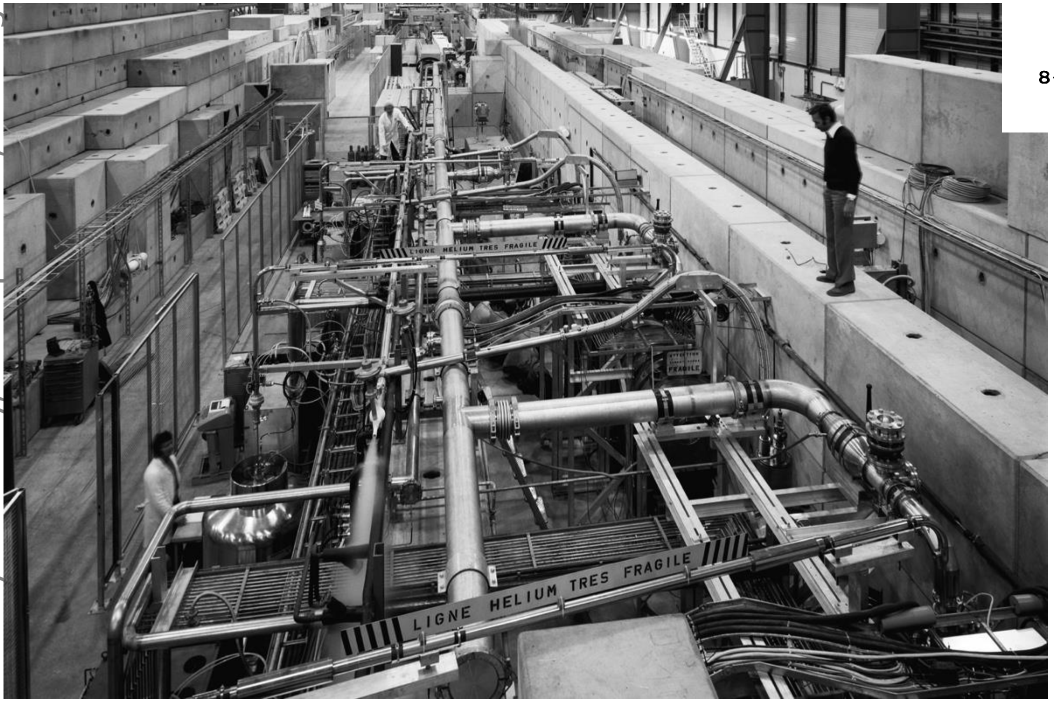
- CESAR dipole: aperture 150 mm, B=4.5 T l = 2 m
- CASTOR quadrupole

Both use a monolithic conductor would into a cosΘ coil

D.F. Leroy**

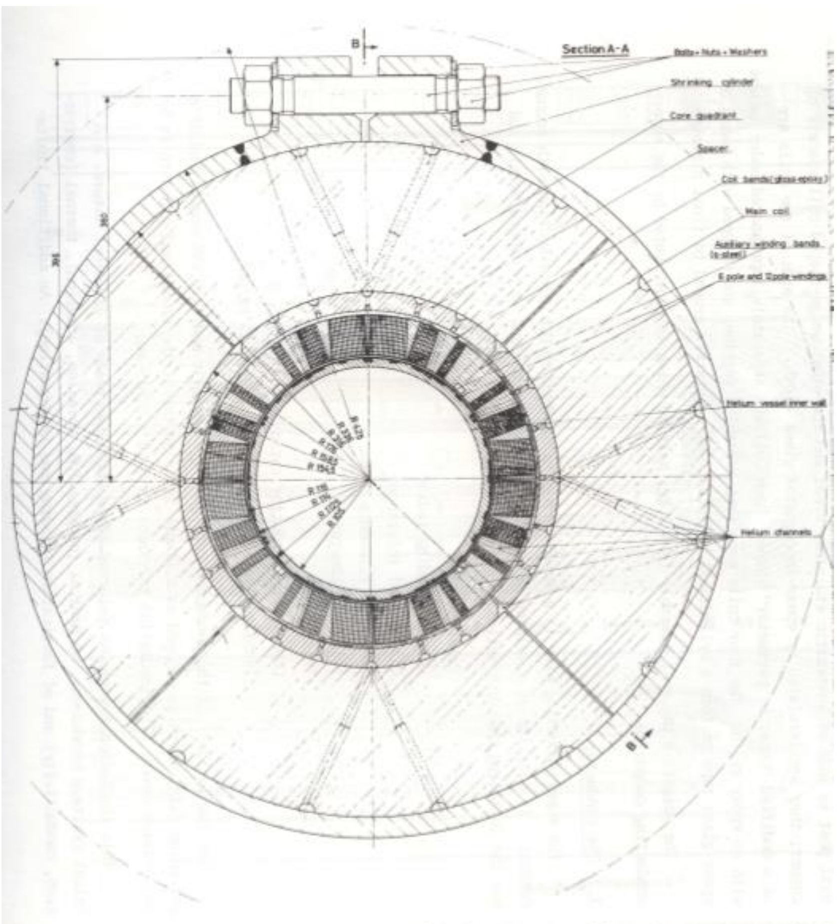


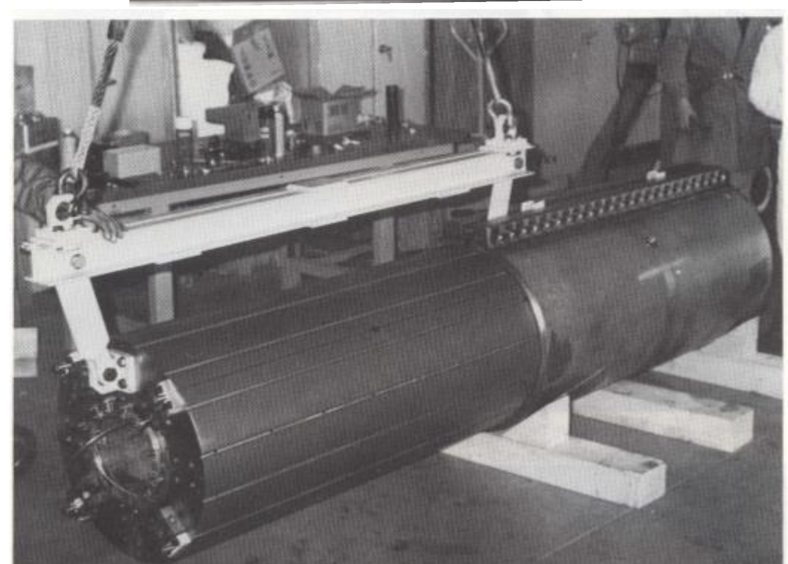




Early SC magnets for accelerators: ISR Insertion quadrupole (end 1970-ies)

- Nb-Ti monolitic conductor
- fully impregnated coil
- Prestress from yoke + shell





Existing Superconducting Accelerator dipole magnets (1)

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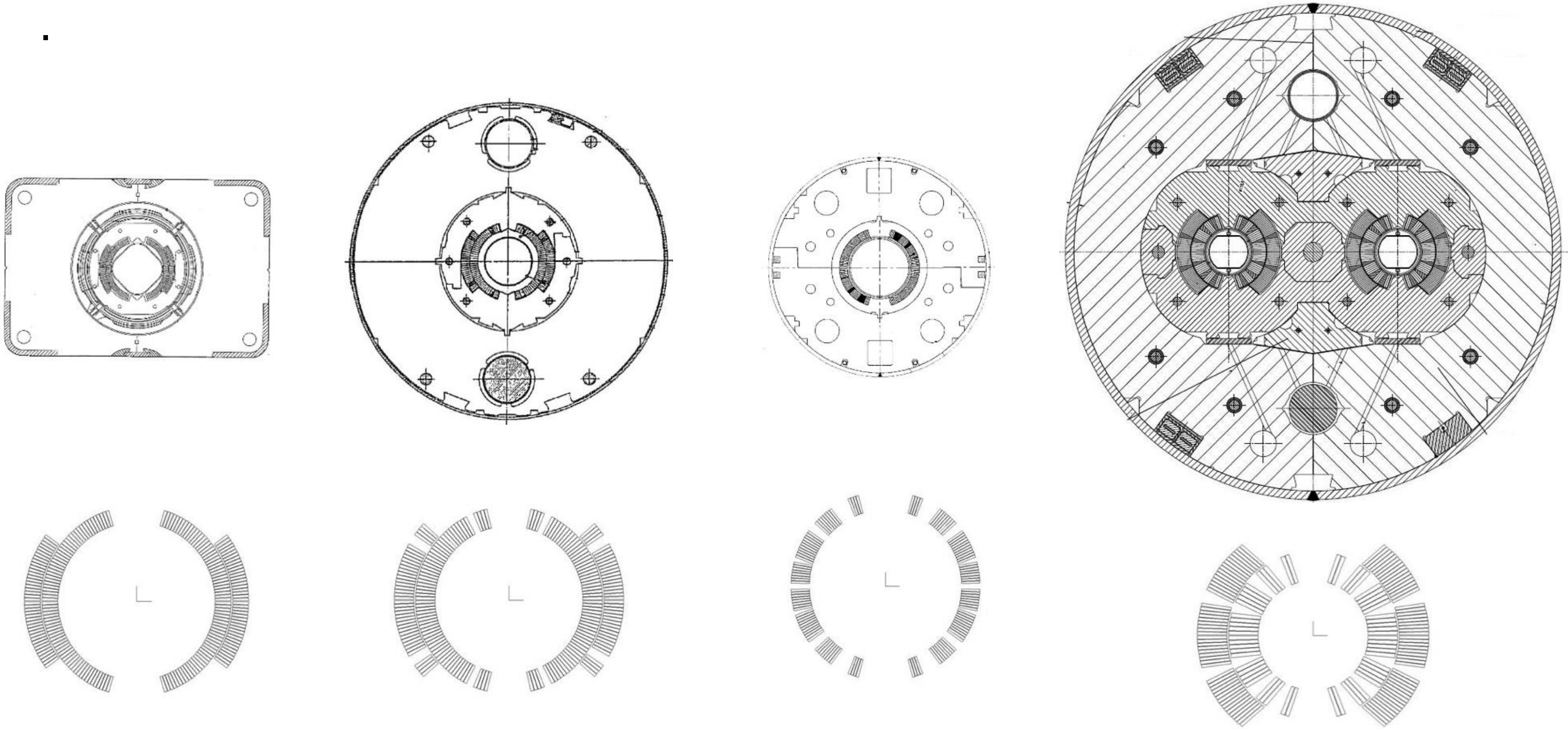


Tevatron
76 mm bore
B = 4.4 T
T = 4.2 K
first beam 1983

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

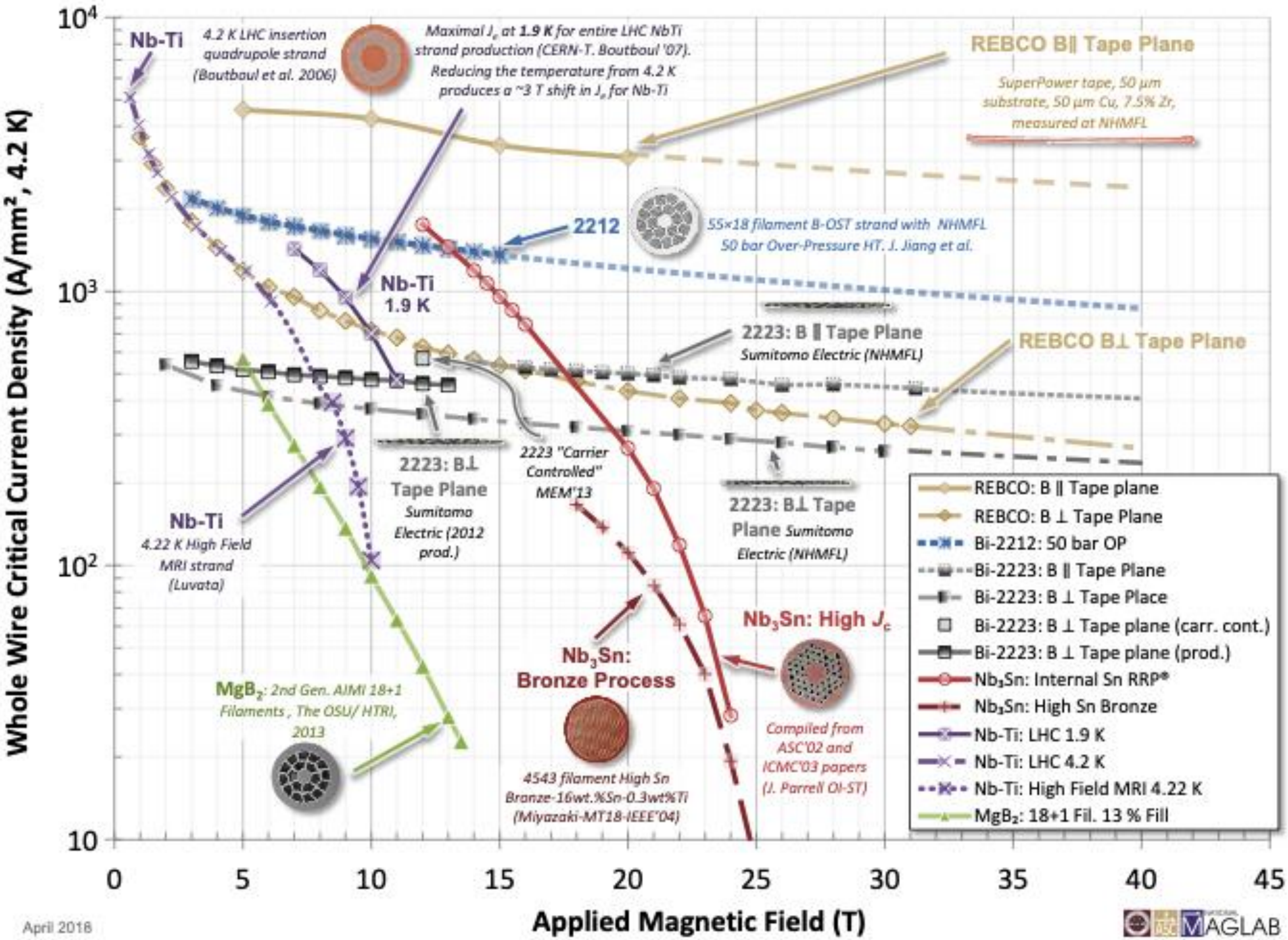
Courtesy P. Ferracin, CERN

Existing Superconducting Accelerator dipole magnets (3)

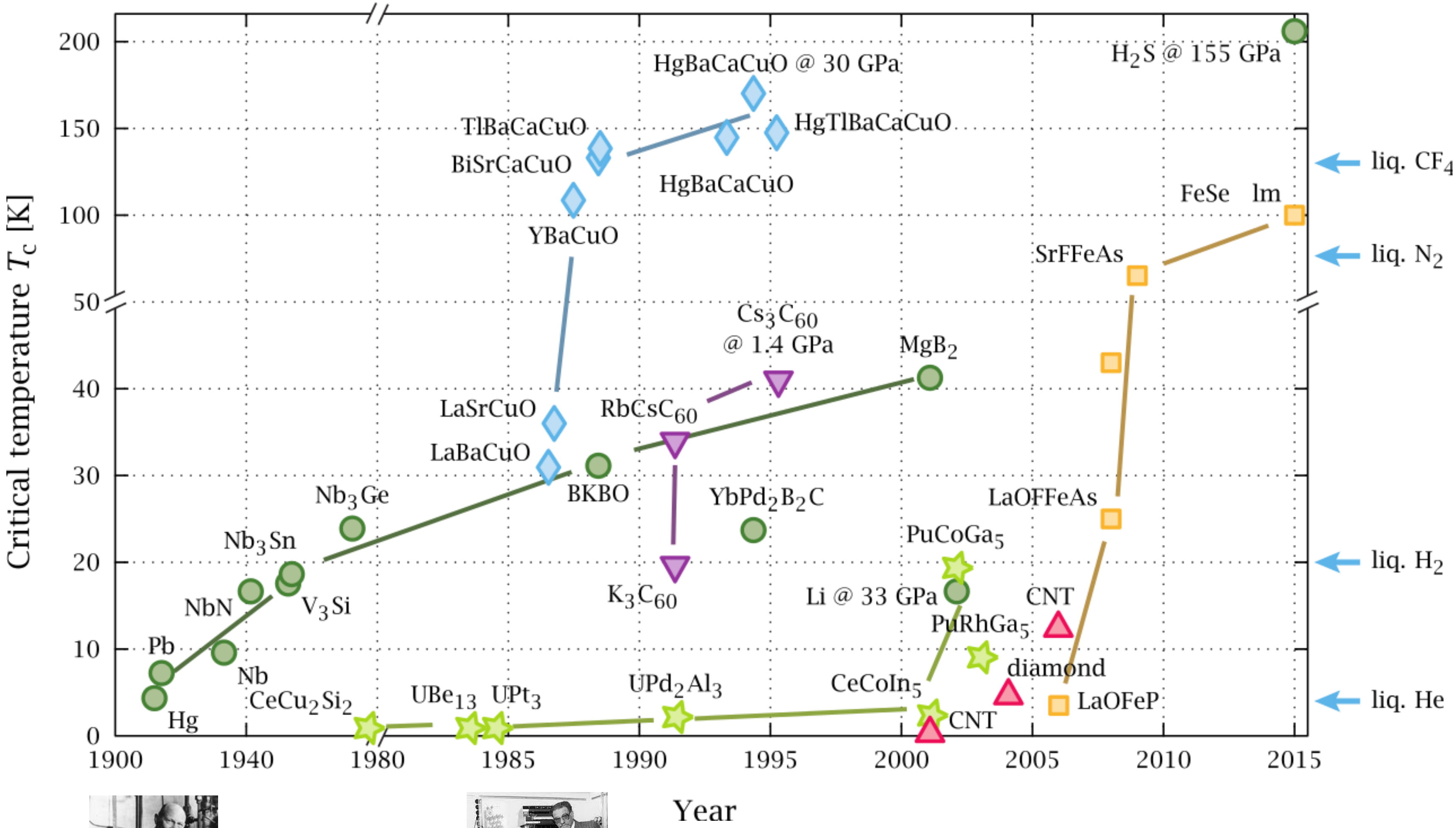
Machine	place	Type	Energy (GeV)	Peak Dipole field (T)	# dipoles	Dipole Length (m)	Ring circ. (km)	Year
Tevatron	FNAL (USA)	p-pbar FT/coll.	1000 x 1000	4.4	774	6.12	6.28	1983/ 1987
HERA	DESY (D)	$e^{-/+}$ - p collider	40x920	5	416	8.82	6.34	1992
RHIC	BNL (USA)	p-p, Au-Au, Cu-Cu, d-Au	100/n	3.5	2x192+12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

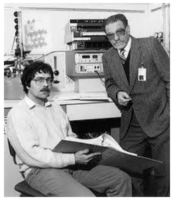
20 years were needed to go from 4 T to 8 T !

Available Superconductors



Superconductor discovery timeline





CAS Vysoke-Tatry, 12-Sept-2019, SC magnets, GdR

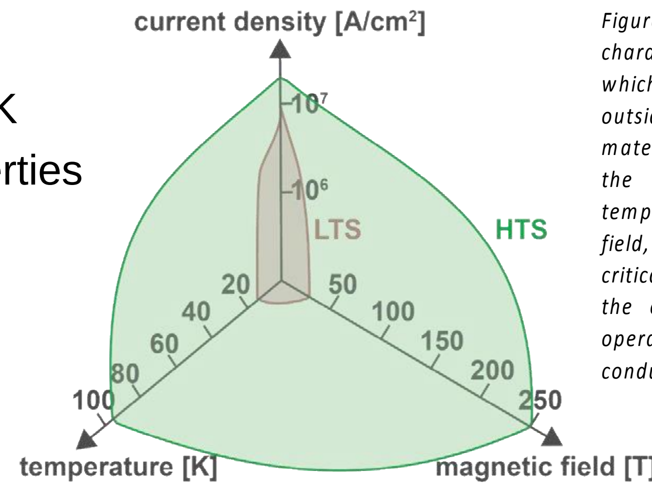
Available Superconductors

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

- Up to ~2500 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



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LTS; Nb_3Sn: towards 20 T

- Up to ~3000 A/mm^2 at 12 T and 4.2 K
- Complex industrial process, higher cost, brittle and strain sensitive
- 25+ short models for accelerator magnets have been built
- ~20 T field in the coil is the practical limit at 1.9 K, but above 16 T coils will get very large

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

- Current density is low, but very little dependence on the magnetic field
- Used in solenoids (20T range), used in power lines – no accelerator magnets have been built (only 1 model) – small racetracks coils have been built

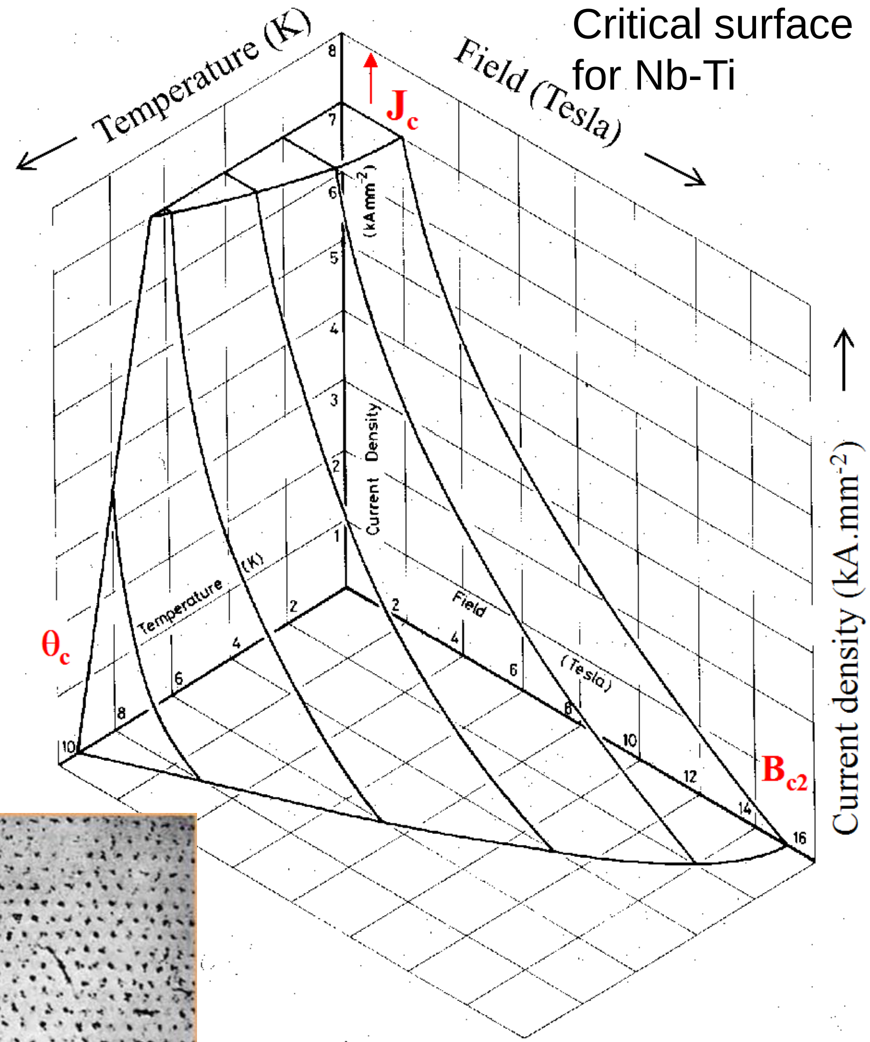
LTS: Type II Superconductors

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, Nb_3Sn, etc) and the processing

Critical surface for Nb-Ti

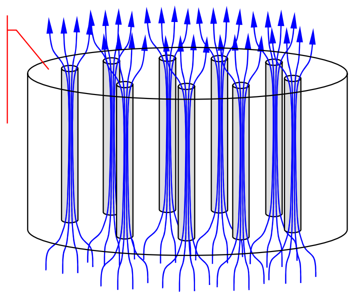


Courtesy M. Wilson

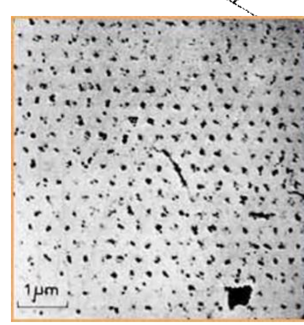
Superconducting means: R = 0

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

Type II



Courtesy L. Bottura

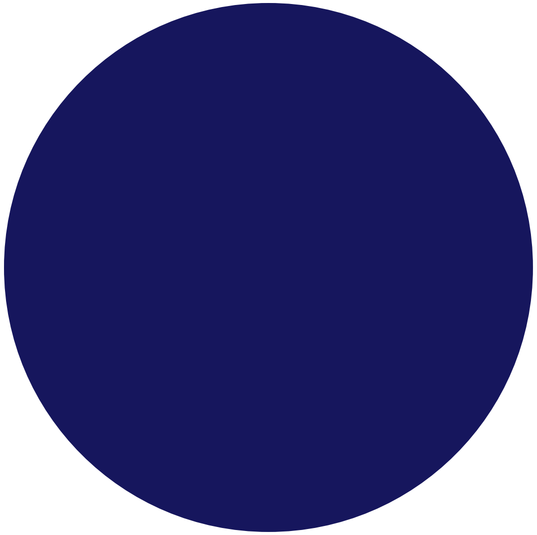


Quantized fluxoids in a superconductor

Comparing wires, LTS Superconductors vs Copper

Typical operational conditions (0.85 mm diameter strand)

Cu

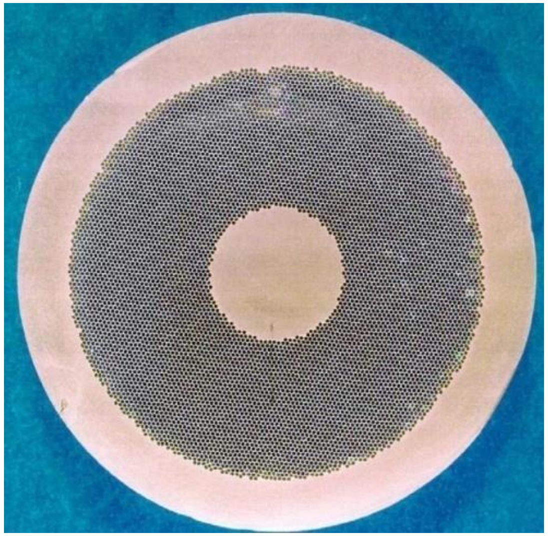


$J \sim 5$ A/mm^2

$I \sim 3$ A

$B = 2$ T

Nb-Ti

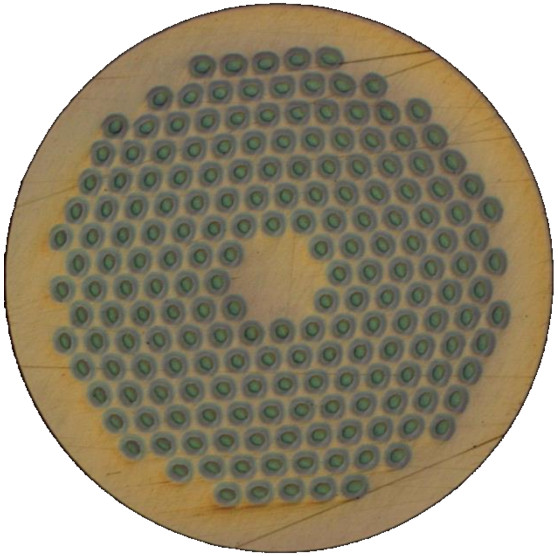


$J \sim 1500\text{-}2000$ A/mm^2

$I \sim 400$ A

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

Nb_3Sn



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

$I \sim 400$ A

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

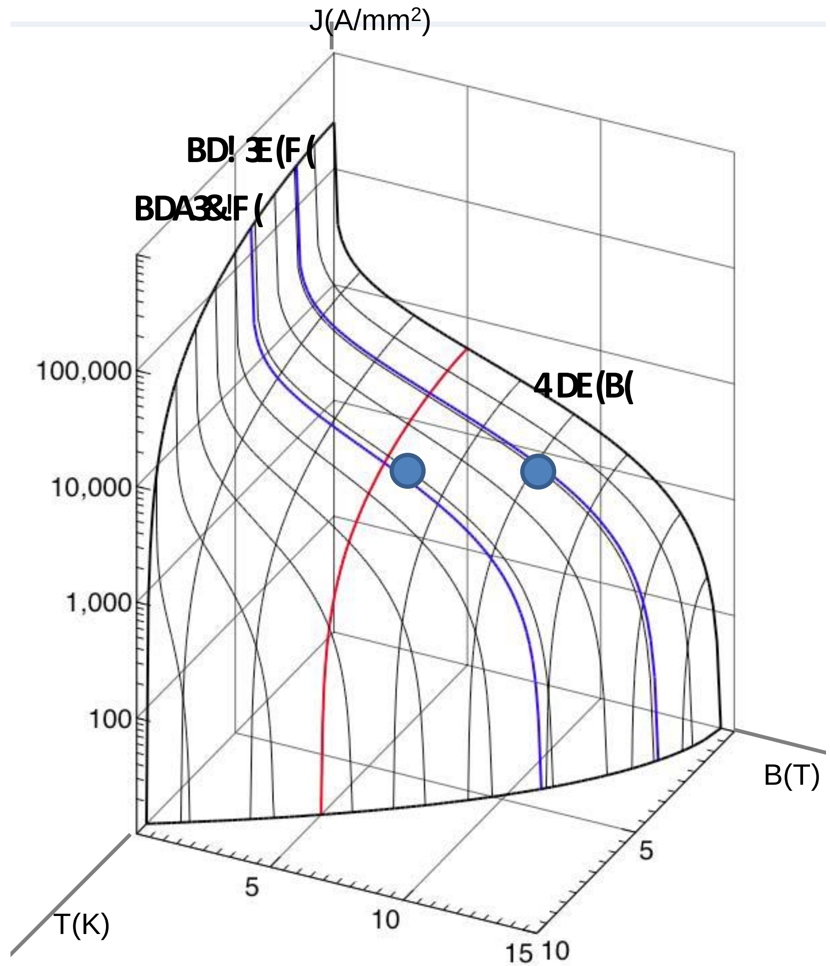
Courtesy P. Ferracin, CERN

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.

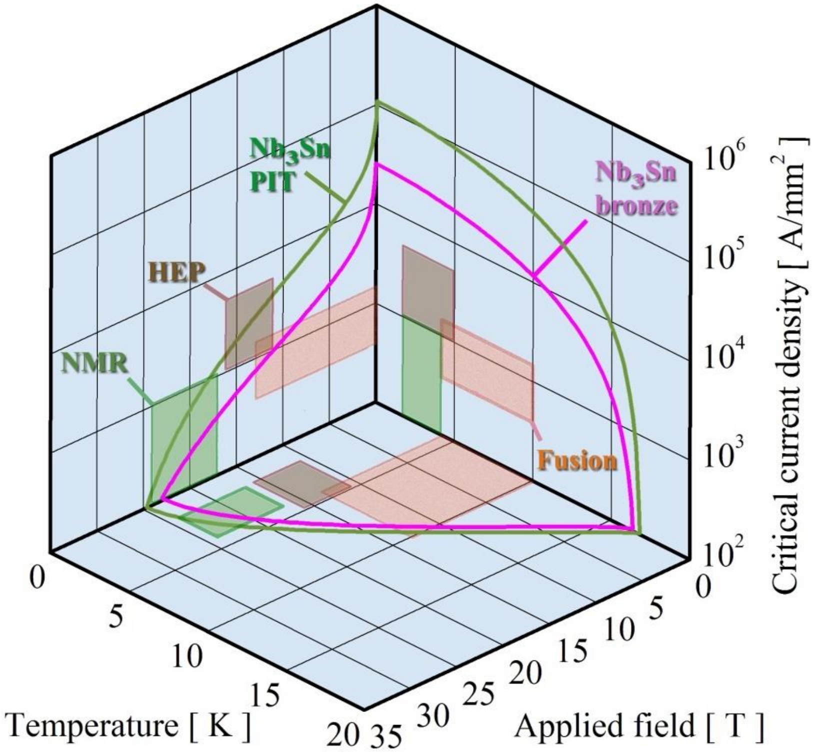


Superconducting materials: Nb_3Sn

- 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.

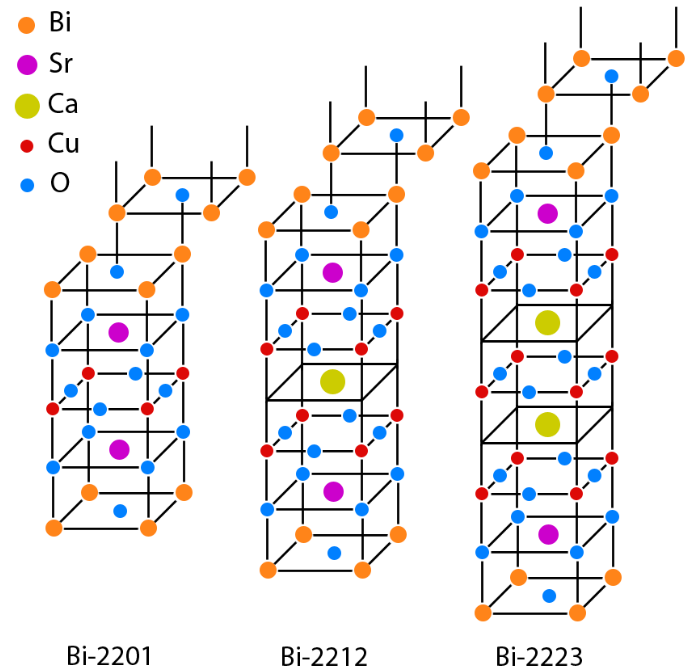


Courtesy: A. Godeke

Superconducting strands and tapes: BSCCO

BSCCO: Bismuth strontium calcium copper oxide

- Available in strands (OST)
- Can reach 400 A/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



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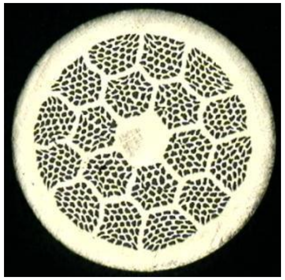
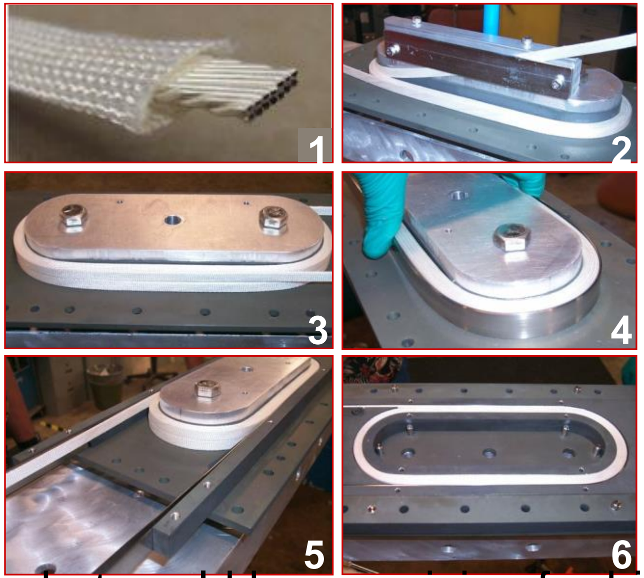
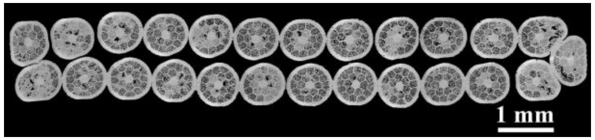


OST wire 0.8 mm using Nexans precursor



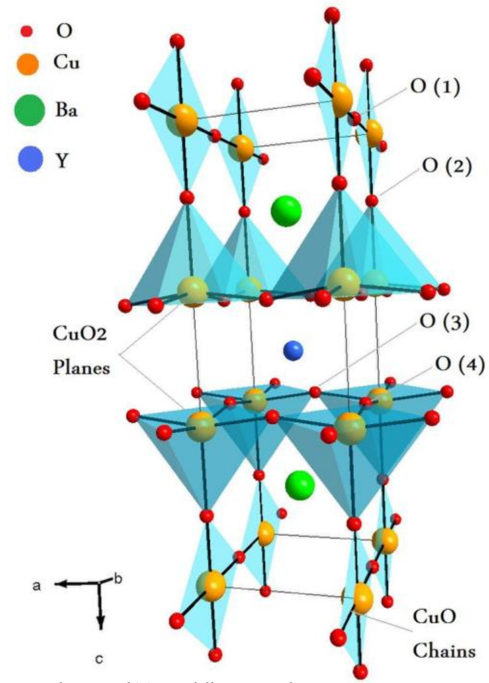


Difficult technology but could be promising for high field magnets in >20 T region

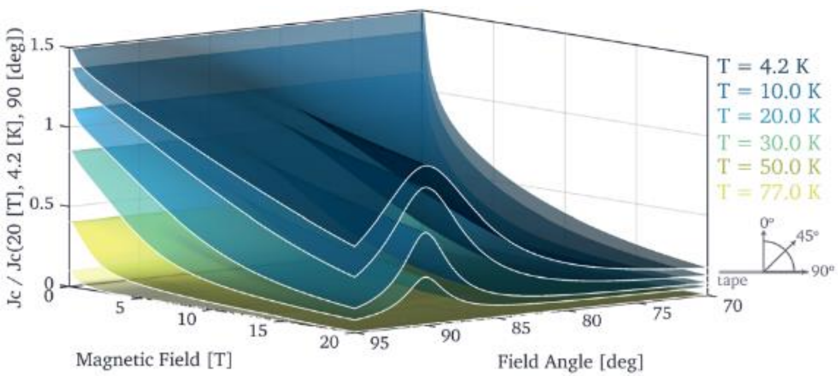
Superconducting tapes: YBCO (or REBCO)

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

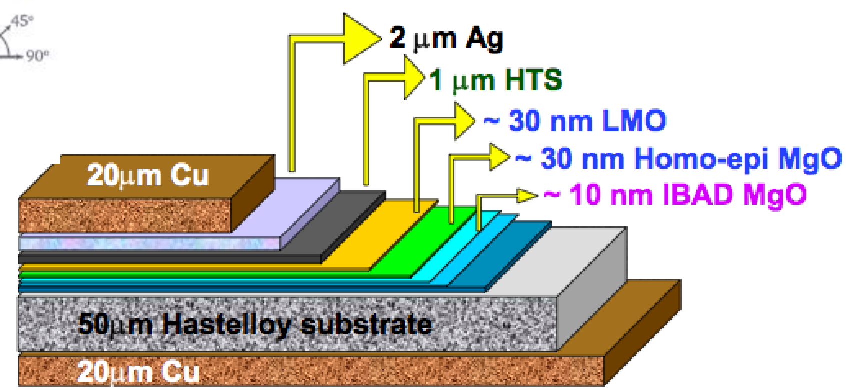
- Available in tapes : YBCO deposited on a substrate to impose the texture (1-2 μm)
- Can reach > 600 A/mm² (overall)
- Is strong under axial stress and strain
- Limited cabling possibilities:
- Difficult technology but could be promising for high field magnets in >20 T region.



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

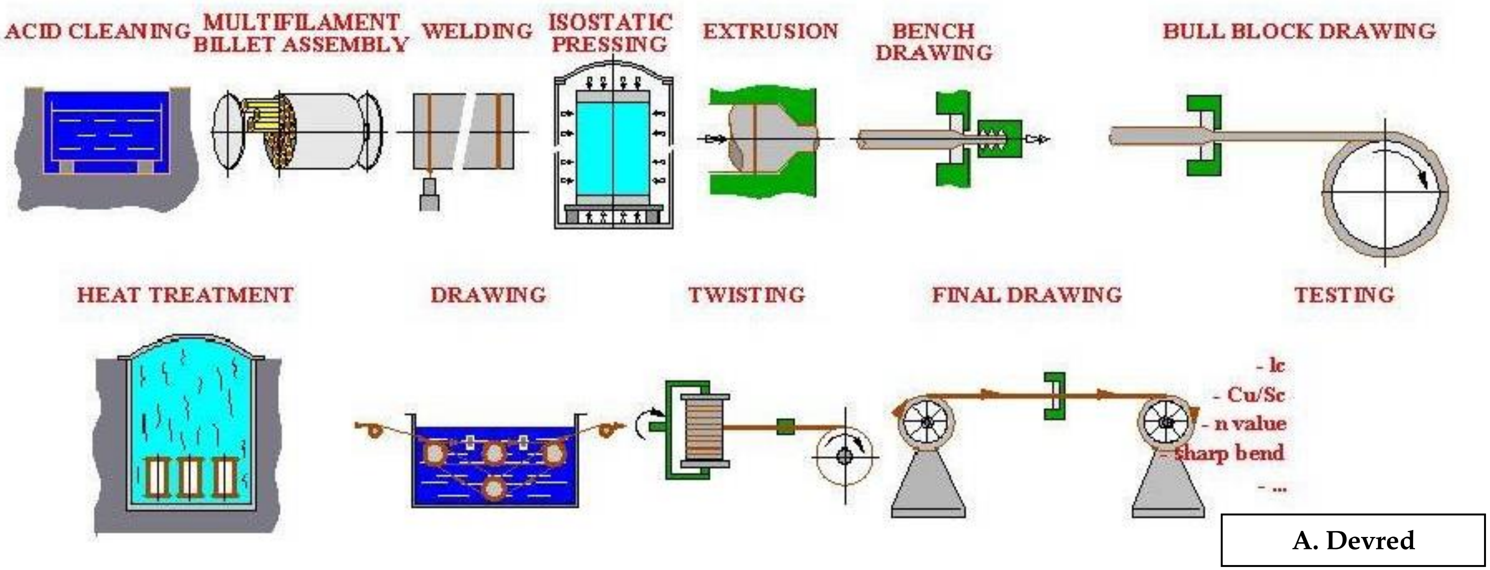


Critical current depends on the angle between the face of the tape and the B field



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).



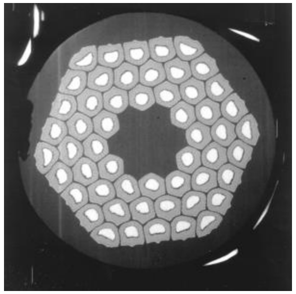
Courtesy A. Devred, ITER; P. Ferracin, CERN

Multifilament wires
Fabrication of Nb_3Sn multifilament wires

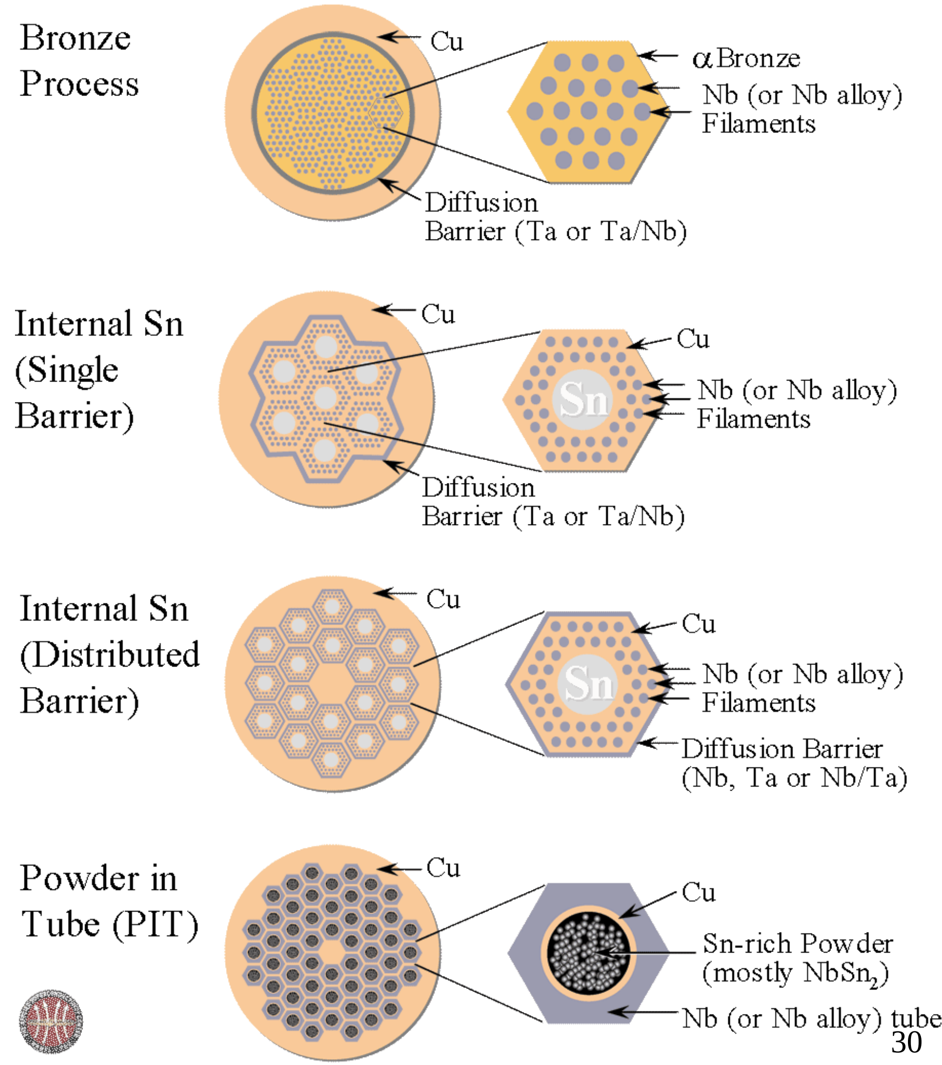
Since Nb_3Sn is brittle, it cannot be extruded and drawn like Nb-Ti.

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



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

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

$$L \approx N^2$$

- Dipoles and Current:
  - Tevatron B = 4.4 T ; I ~ 4000 A
  - Hera B = 5 T ; I ~ 6000 A
  - LHC B = 8.3 T ; I ~ 12000 A
- For magnets 10 T < B < 15 T the current has to be 10kA < I < 15 kA
- For stability reasons strands are 0.6 mm < strand diameter < 1 mm
- With a Cu-nonCu ratio (stability) around 1 and a Jc ~ 1000 A/mm^2

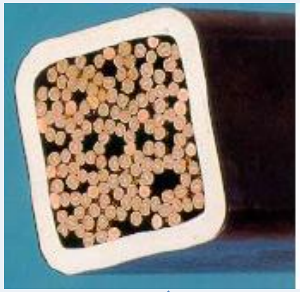
  ➔ a 1 mm diameter strand can carry ~400 A

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

LTS Cable types

.

CIC



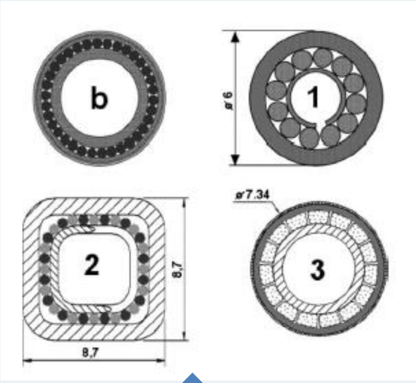
ITER magnets

Rutherford

Accelerator magnets

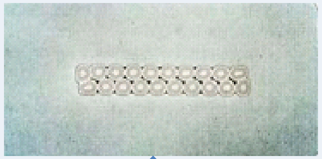
Tevatron, HERA
RHIC and LHC

Indirectly cooled

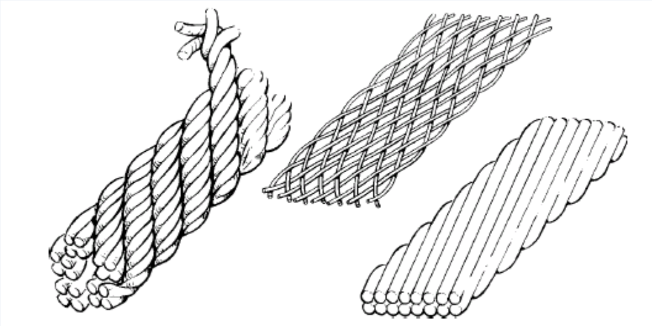


Nuclotron Type (b)
Pulsed SIS 100 magnets

Rutherford



Detector magnets

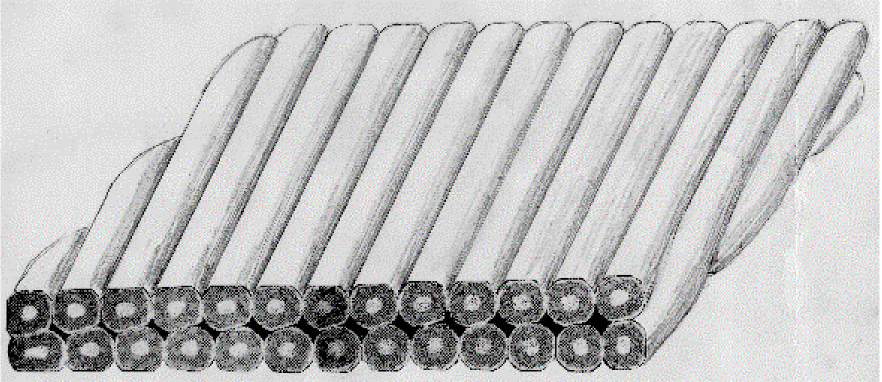


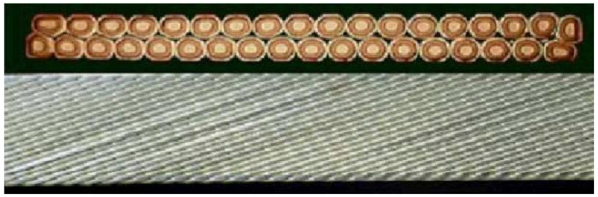
Rope, Braid and Rutherford cables

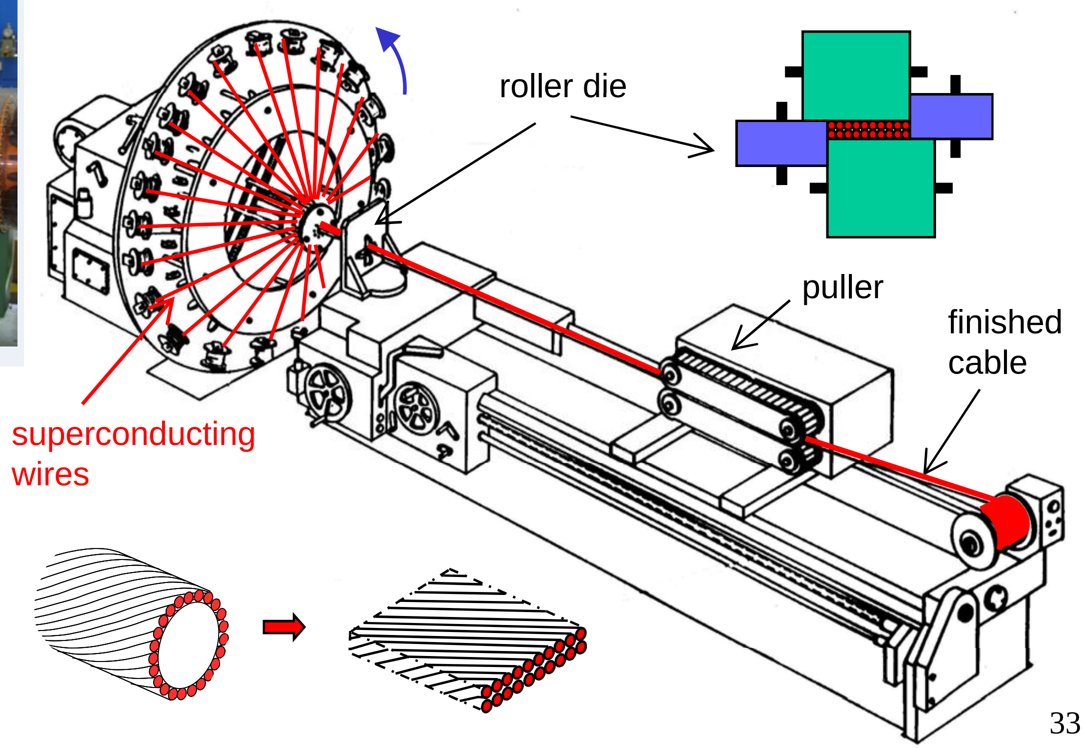
Courtesy A. Balarino

Rutherford cables

- Compact cables giving high overall current density
- Easy rectangular geometry for convenient winding







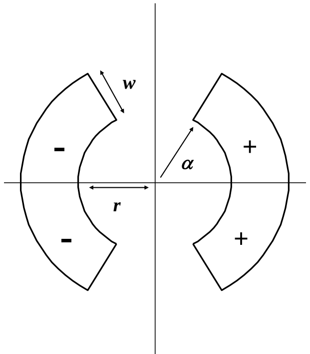
How to get high fields in accelerator dipole and quadrupole magnets ?

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

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

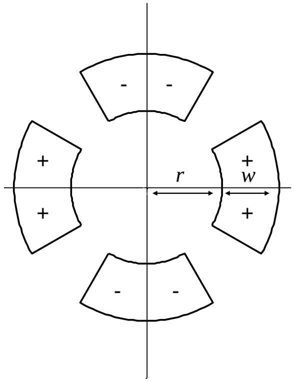
with: r : inner radius coil
w : coil width
ρ : radial coordinate
J : current density



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

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

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



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

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

See: E. Todesco et al. ref[10] and indirectly : N. Wilson ref[1], K-H Mess et al. ref[2]

For a in depth study of magnetic field calculations: S. Russenschuck ref[4]

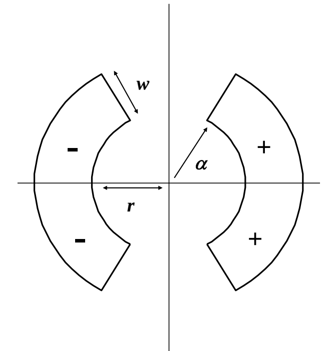
The forces with high field dipole and quadrupole magnets

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

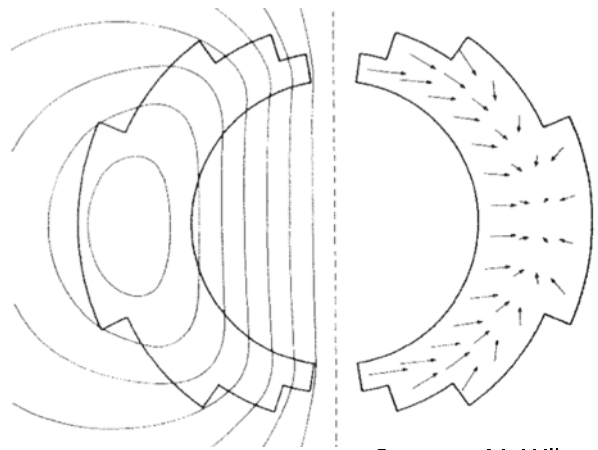
- Dipole 60º sector coil [see ref 1, 12]

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

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



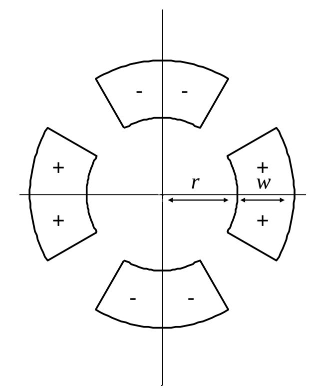
Cross-section of a dipole based on 60º sector coils


Courtesy M. Wilson

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

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

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



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

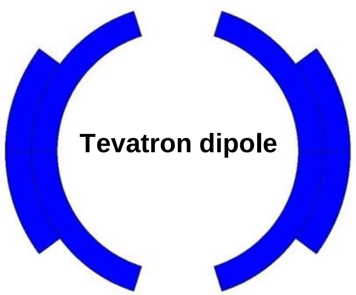
Electromagnetic forces

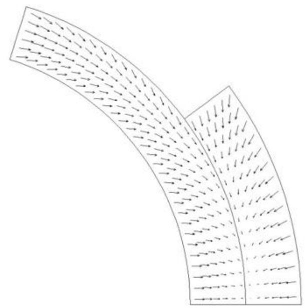
The e.m. forces in a dipole magnet tend to push the coil

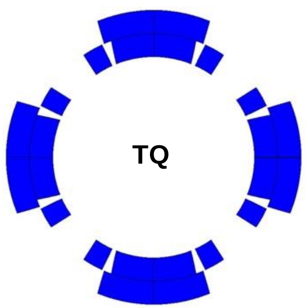
- Towards the mid plane in the vertical-azimuthal direction (F_y, $F_\theta < 0$)
- Outwards in the radial-horizontal direction (F_x, $F_r > 0$)

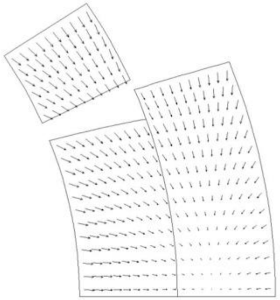
The e.m. forces in a quadrupole magnet tend to push the coil

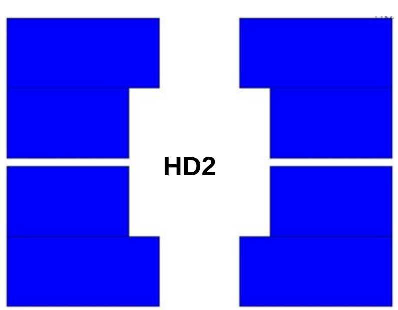
- Towards the mid plane in the vertical-azimuthal direction (F_y, $F_\theta < 0$)
- Outwards in the radial-horizontal direction (F_x, $F_r > 0$)

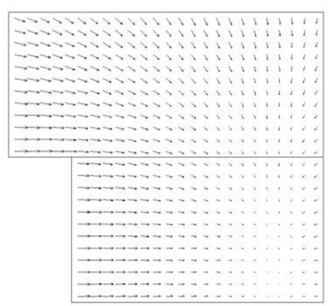


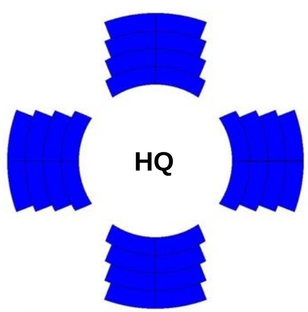


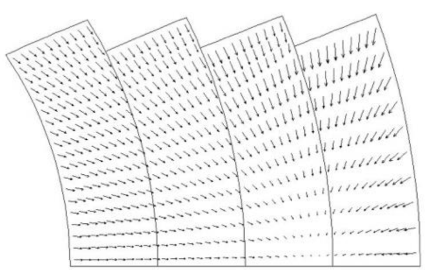








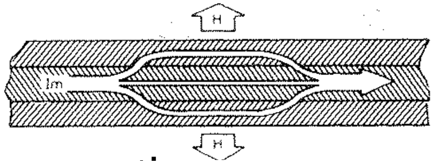


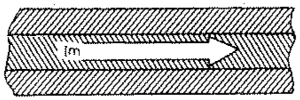


Courtesy P. Ferracin, CERN

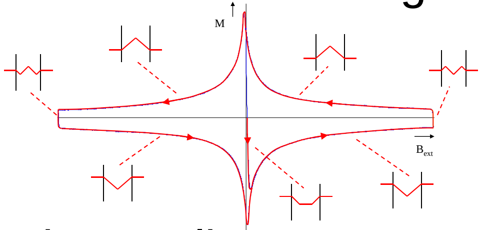
Conductor stability and AC behaviour

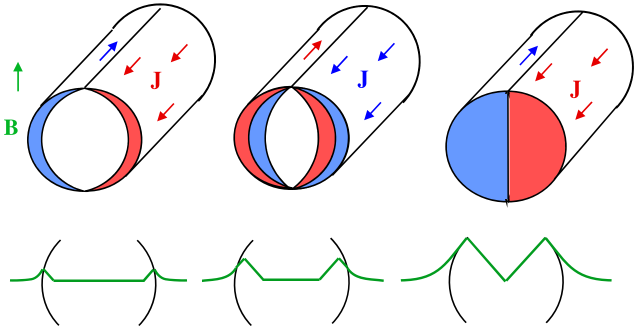
- Pure massive superconductor is not stable as they (Nb-Ti, Nb_3Sn) are poor normal conductors
- To 'cryogenically stabilize' the conductor one surrounds it in Cu:
  - good electrical conductivity
  - good heat transfer to the He



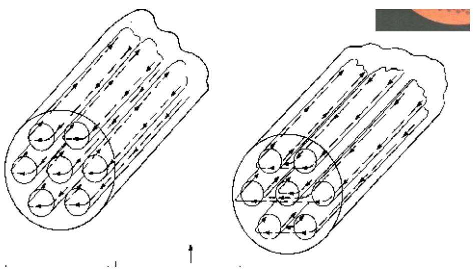


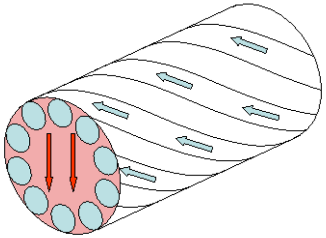
- During current ramping the filaments will magnetize
  ➔ make them thinner



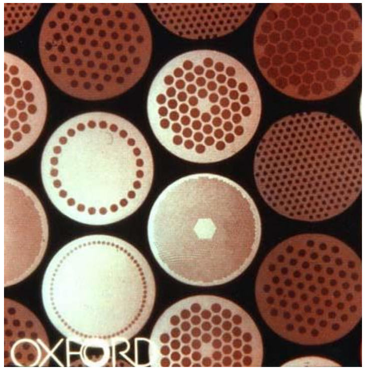


- Filaments will have magnetic coupling
  ➔ twist the strand





Courtesy M. Wilson

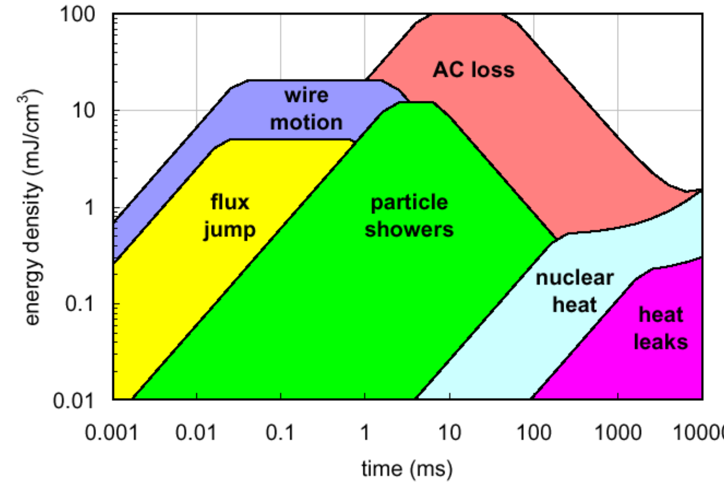


- Practical low temperature superconductors are made as thin (5 μm – 100 μm) superconducting filaments in a Cu matrix , which is twisted

Quench: a thermal runaway effect

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

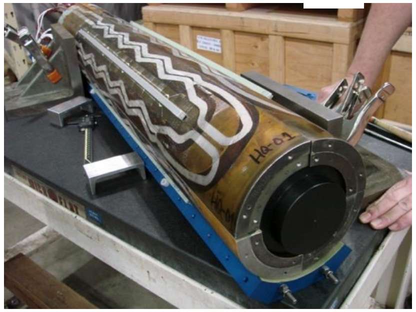
A thermal runaway can then occur, called a **Quench**



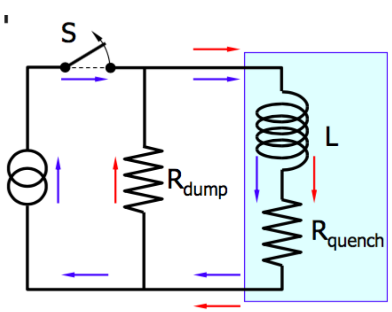
With stored energies > MJ the coils can overheat if nothing is done (T = 3000K is possible !)

What to do ?

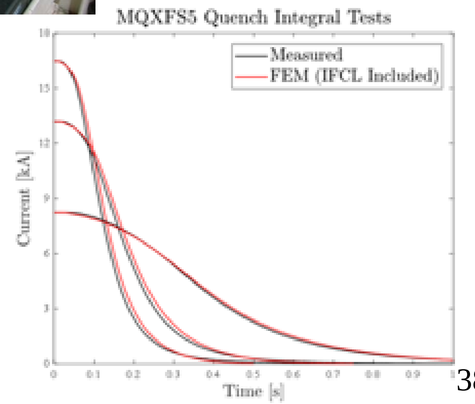
- Detect the quench : SC: R=0 → V=0, quench V>0 (typically 100mV threshold)
- Switch power convertor off
- Heat up the whole coil with quench heaters
- Dump energy of the circuit into a dump resistor



MQXFS coils



When something went wrong



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

ρ(T) the resistivity of the non superconducting part of the cable

γ the density

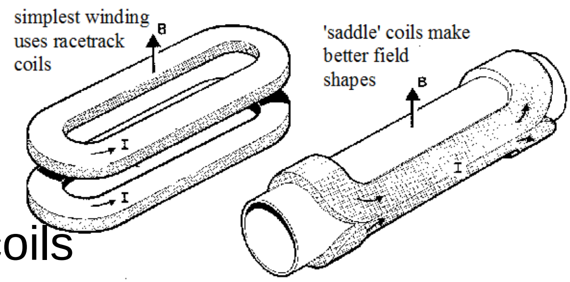
C(T) the heat capacity

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.

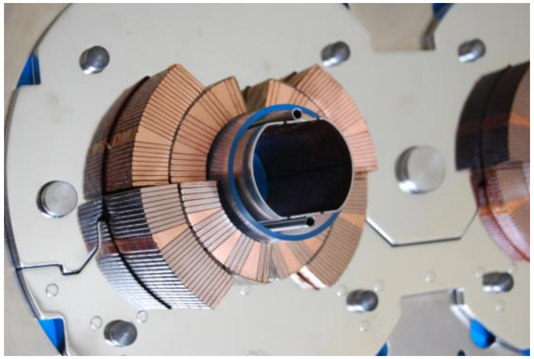
Practical accelerator magnet design: Dipoles



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

Cos(Θ) coil and *Block coil*

- Cos(Θ) 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

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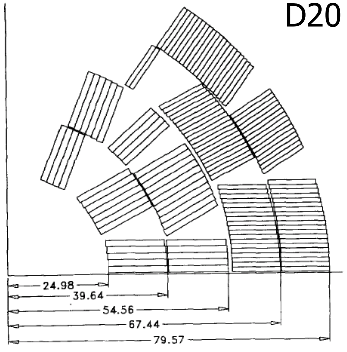
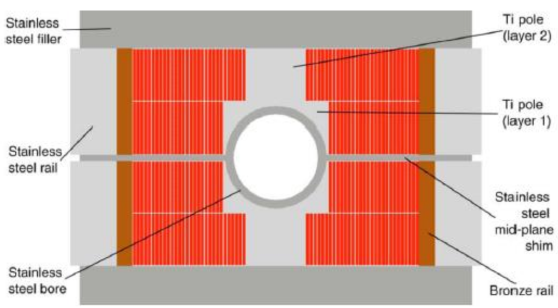


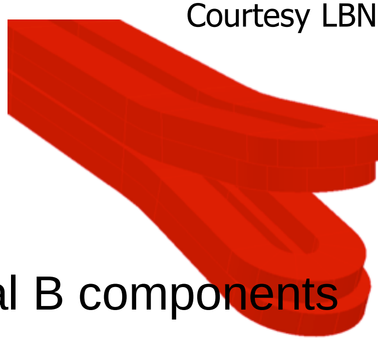
Courtesy LBNL

Practical accelerator magnet design: Dipoles

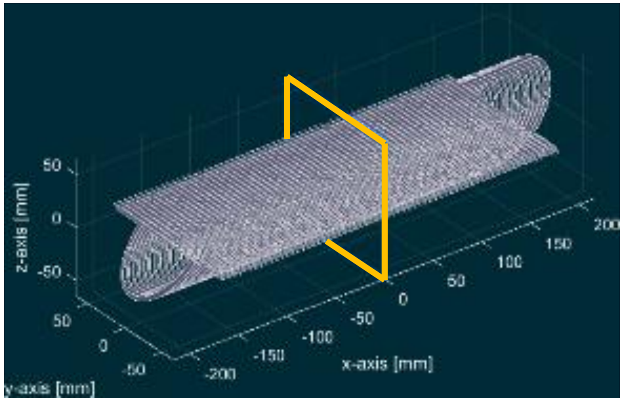
- Block coil (used on development magnets)
  - With thick coils the field quality is good
  - Less efficient (~10%) wrt to (thin) cos(Θ) for quantity of superconductor used
  - The EM forces cause a stress buildup at the outside edge of the coil where the fields are lower
  - The straight part is very easy
  - ‘flared ends’ look easy but we need more experience

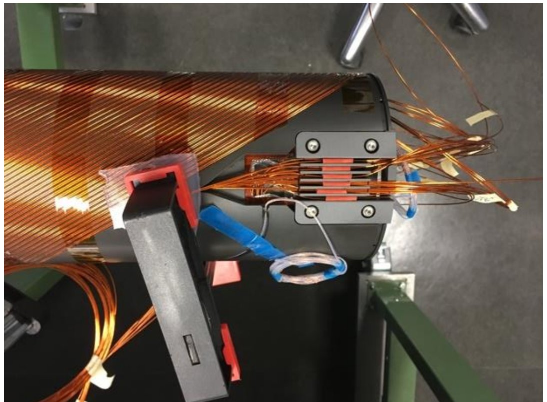


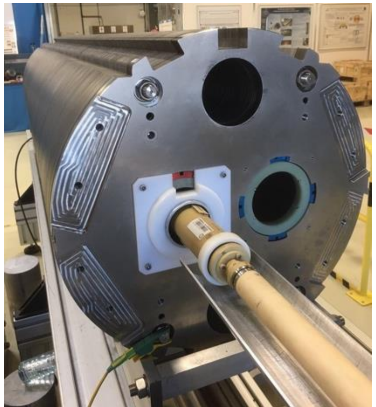
HD2 Courtesy LBNL



- 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



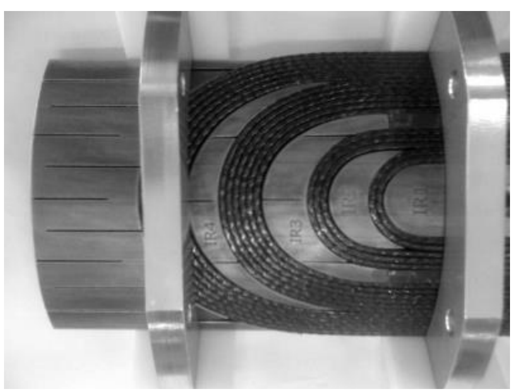


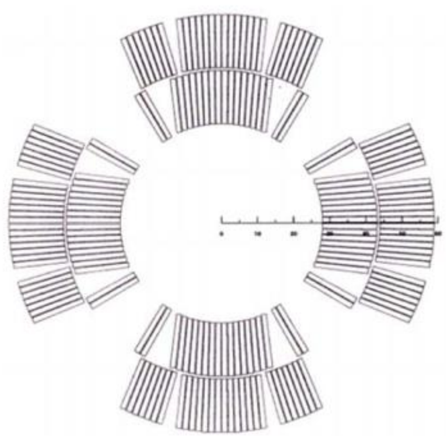


Quadrupole coil geometries

- 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





Pre-stress

- 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 ?

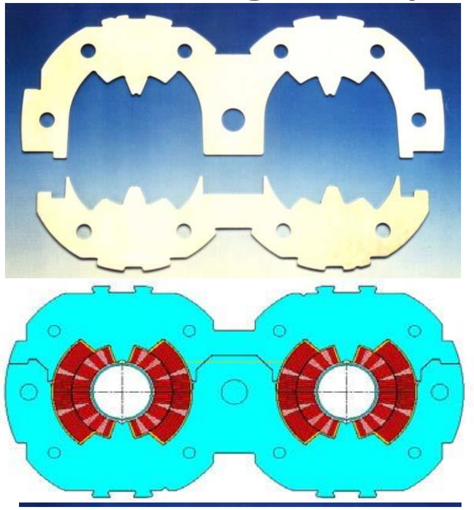
  Three methods:
  1. Compress at room temperature: collar system
  2. Use room temperature pre-stress plus differential shrinkage at cooldown: Al or stainless steel shrinking cylinder and/or a (shrinking) key
  3. Compress a bit at room temperature and use differential shrinkage at cool-down: Al shrinking 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

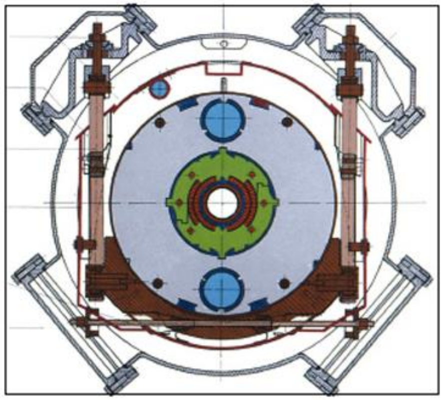
Pre-stress: collars

"The classical solution"

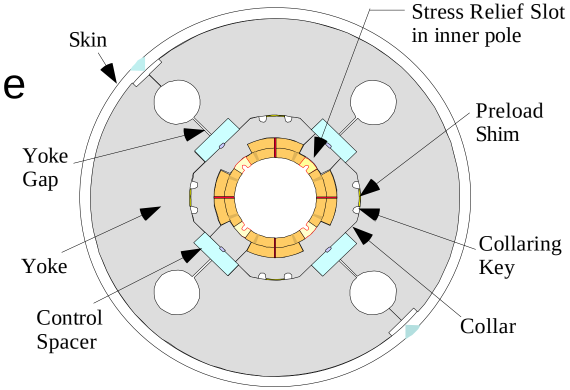
- Thin collars put around the coil
- The coil is well contained in a fixed cavity
- Pressed together and locked with pins or keys
- At 300K apply a pre-stress 2-3 times of what is needed as part of the stress is lost during cooldown: for very high field tends to be too high (LHC:70 MPa at 300 K and 40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



LHC dipole
CERN



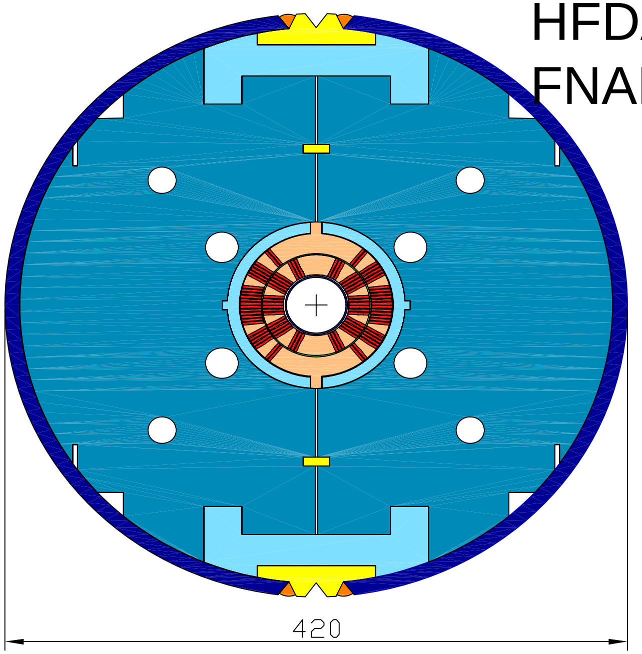
Hera dipole
DESY



TQC quadrupole
LARP-FNAL

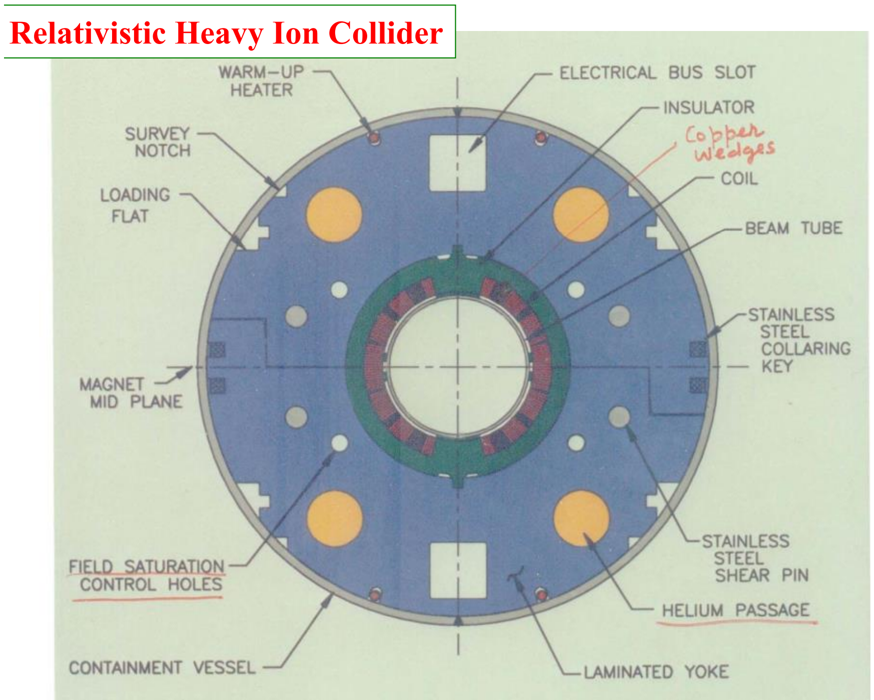
Pre-stress: shrinking cylinder and/or pre-stress key

- 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



HFDA
FNAL

Courtesy A. Zlobin



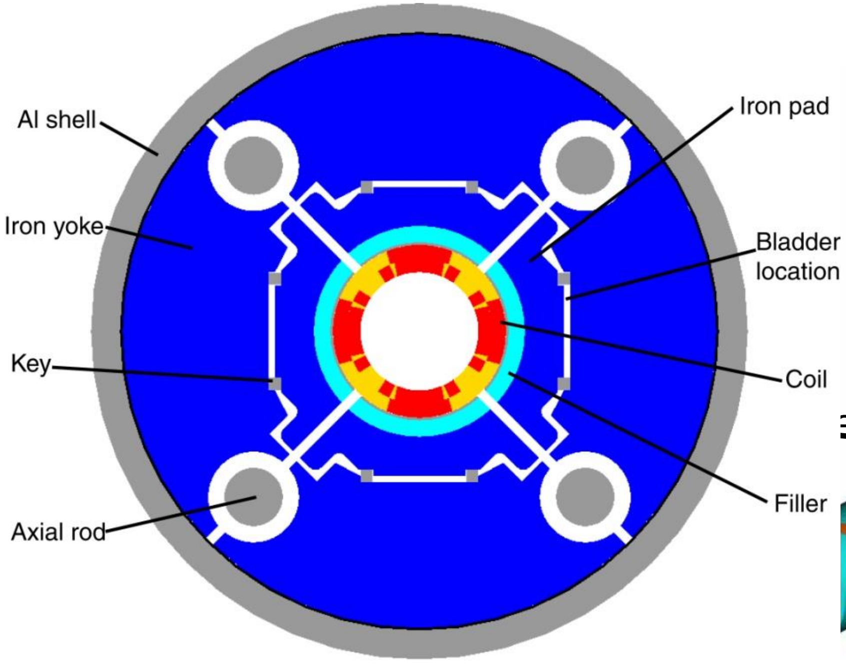
Pre-stress: Al shrinking cylinder + bladder and keys

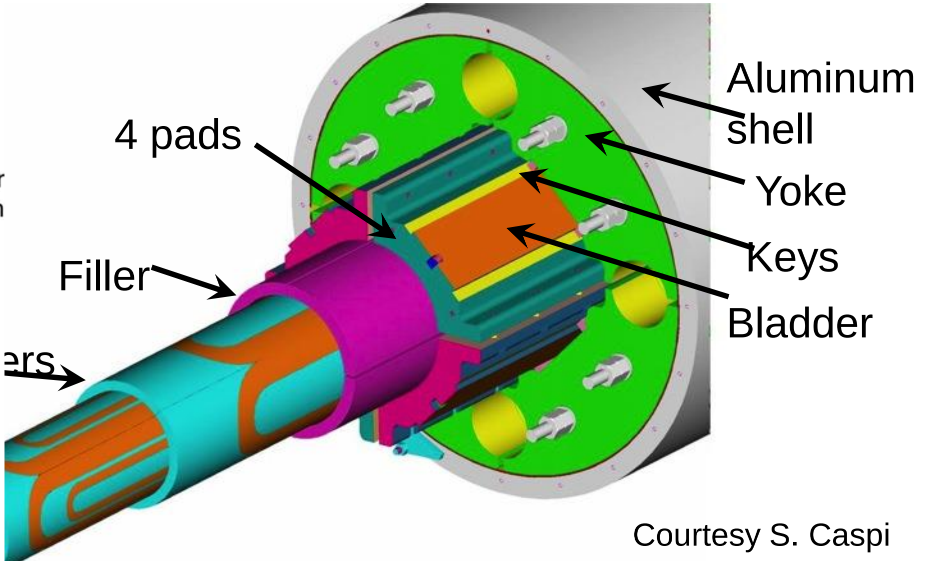
Developed at LBNL, example: TQS a LARP model quadrupole

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





Courtesy S. Caspi

Coil assembly within yoke and aluminum shell

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 Nb_3Sn triplet quadrupoles (12T class)
   - improve collimation: use a few 11T dipoles to make space
2. Go to higher energies
   - 16 T Nb_3Sn dipoles in the LHC ring for E_{com}=26 TeV : HE-LHC
   - 16 T Nb_3Sn 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

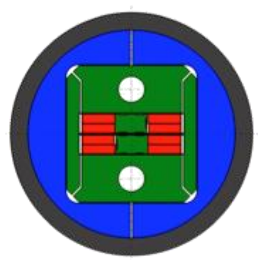
A similar completely new project is being studied in China: SPPC (C=100 km, 12-20 T)

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

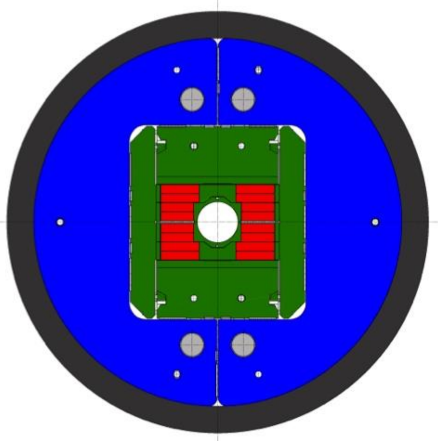
CERN-European development evolution

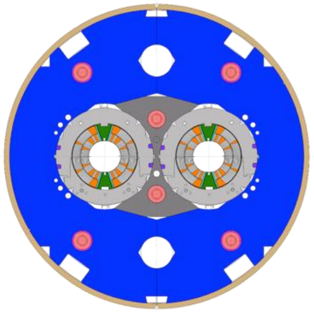
Short Model Coil

Race-track Model Coil



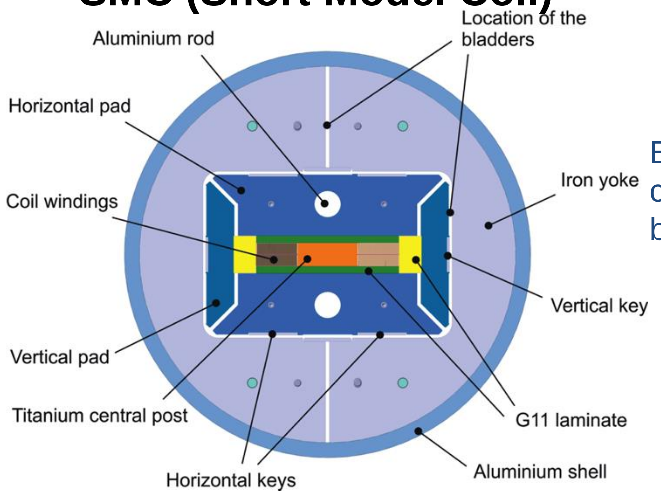
FReSCa2 13T Nb_3Sn Dipole



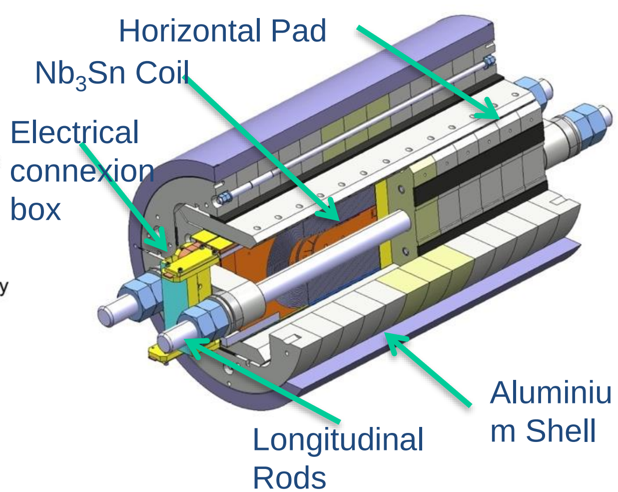


11 T dipole (CERN)

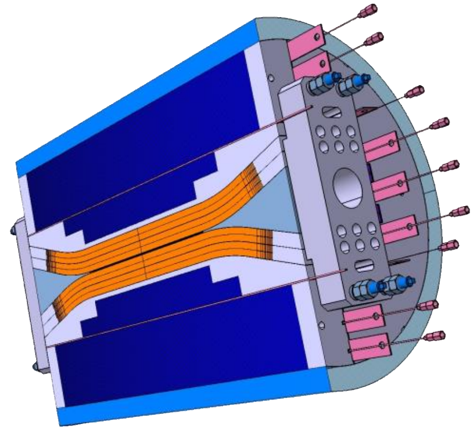
SMC (Short Model Coil)



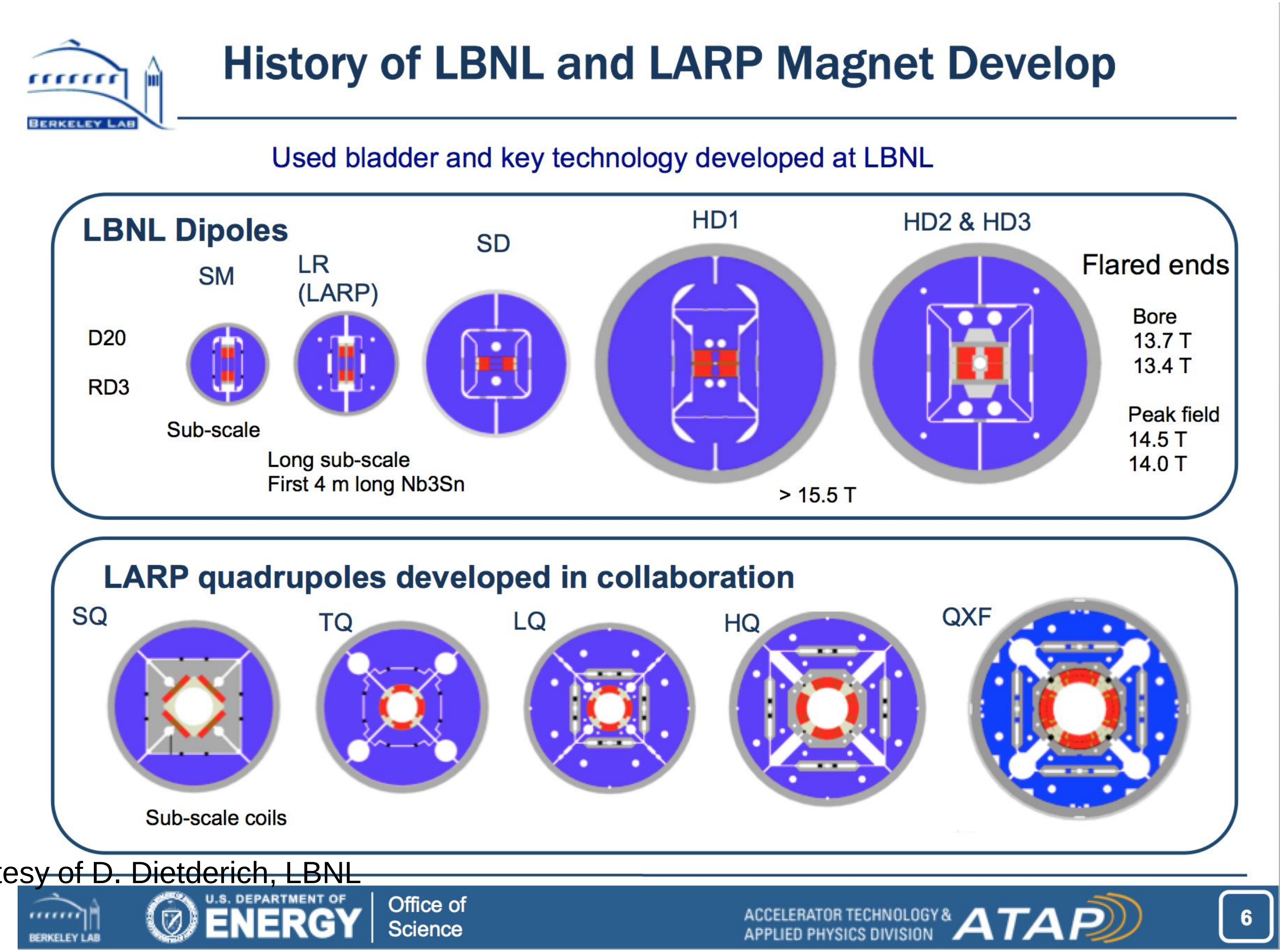
RMC (Racetrack Model Coil)



FReSCa2



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



By courtesy of D. Dietderich, LBNL

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, cosΘ 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

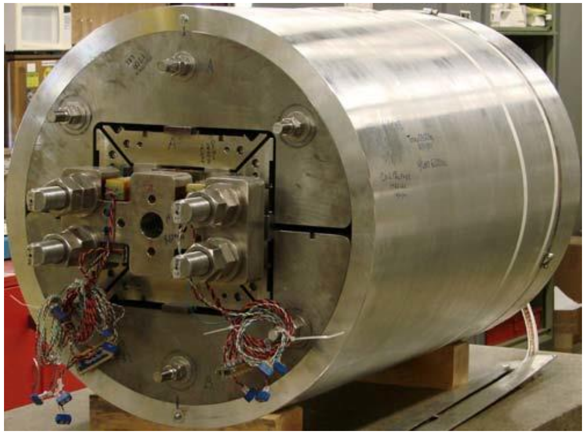


Fig. 1. HD2 assembled and pre-loaded.

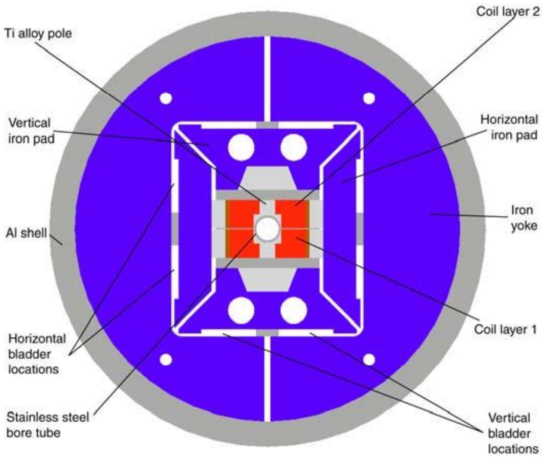
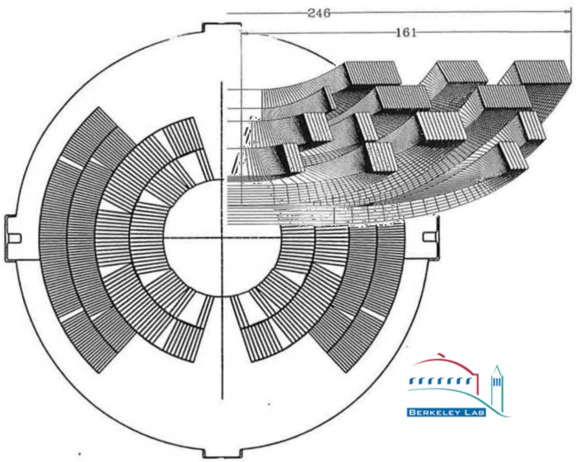


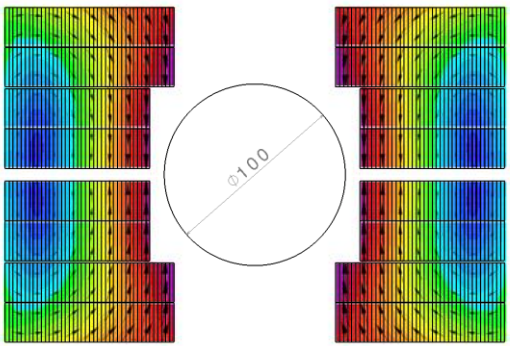
Fig. 2. HD2 cross-section.

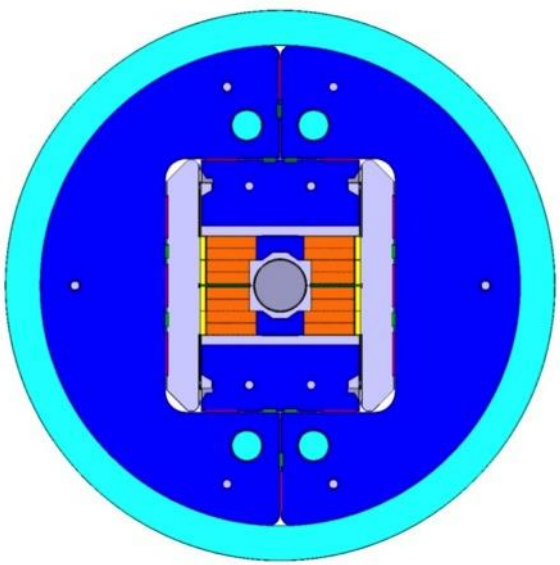


A.D. McInturff, et al., Proc. of PAC 1997, 3212

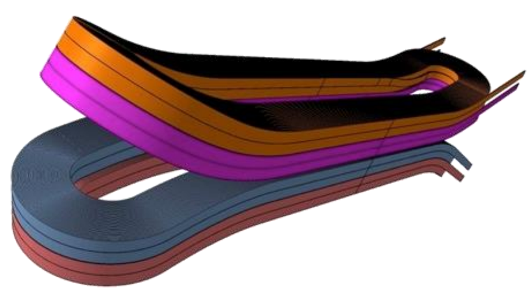
Basic HFM development : EuCARD high field dipole (Fresca2):

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

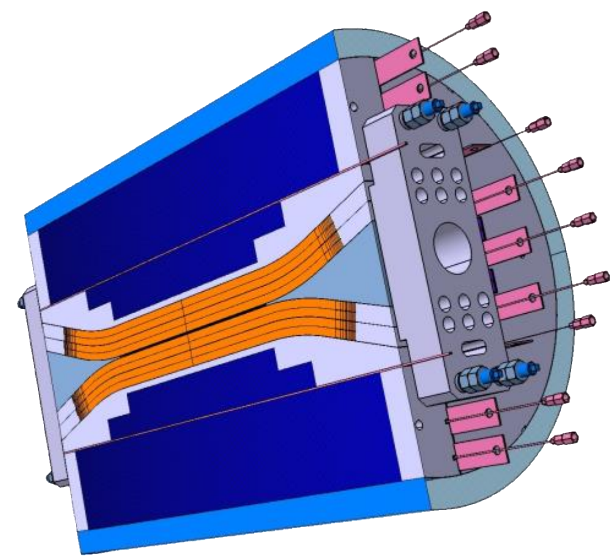




- 156 turns per pole
- Iron post
- B_{center} = 13.0 T
- I_{13T} = 10.7 kA
- B_{peak} = 13.2 T
- E_{mag} = 3.6 MJ/m
- L = 47mH/m



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

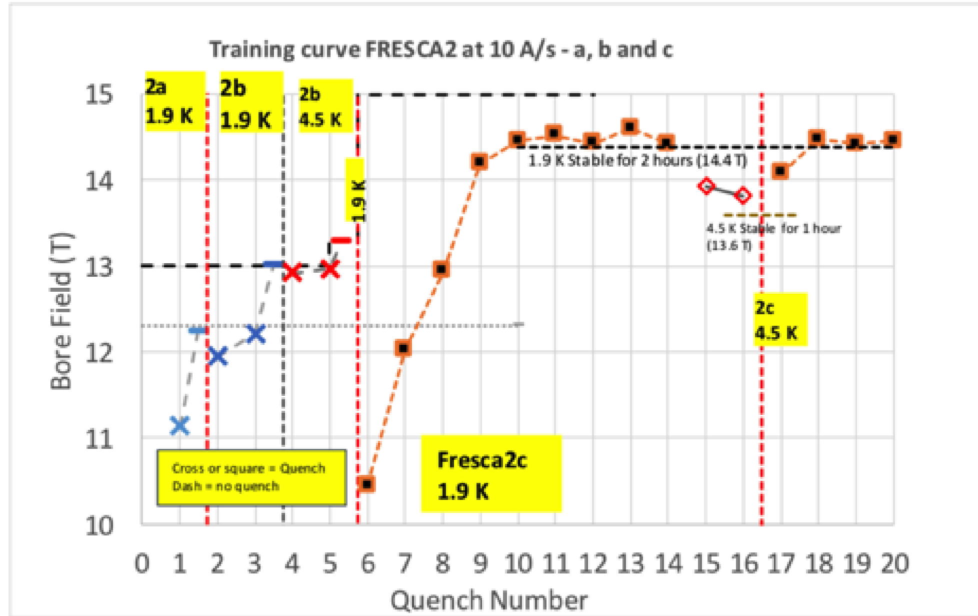


Courtesy Attilio Milanese, Pierre Manil

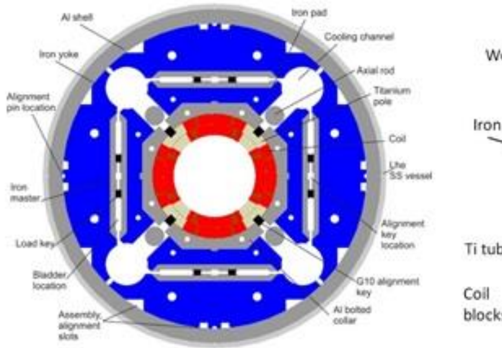
Fabrication of Fresca2 coils

Straightforward technology to wind block coils with flared ends:

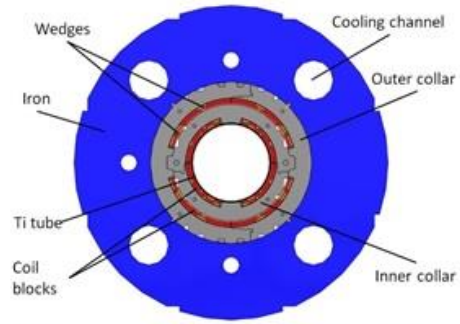
This is a lesson for FCC magnets !



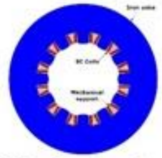
HL-LHC Inner Triplet magnet zoo

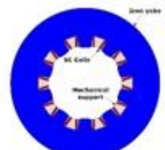


Triplet [G. Ambrosio, P. Ferracin et al.]

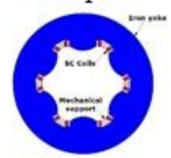


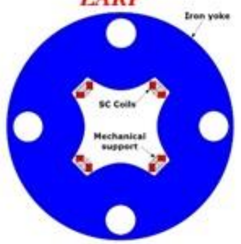
MCBXFB [F. Toral, et al.]


Dodecapole


Decapole

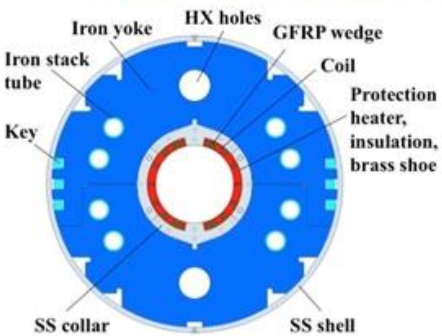

Octupole



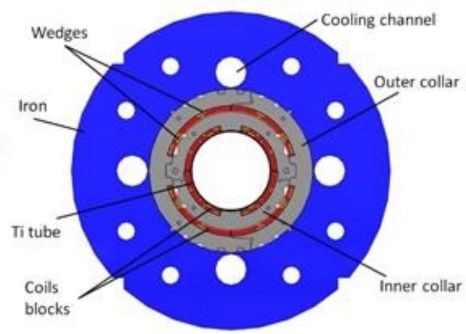


Skew quad

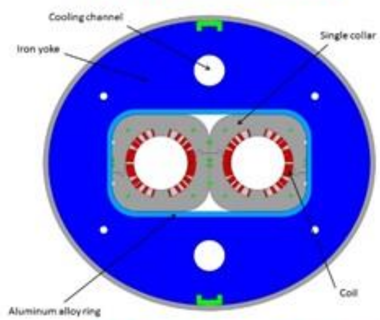
[G. Volpini, et al.]



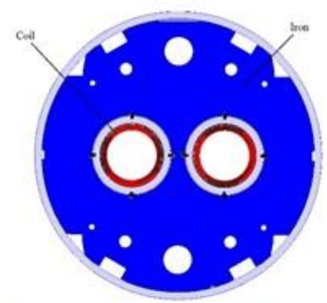
D1 [T. Nakamoto et al.]



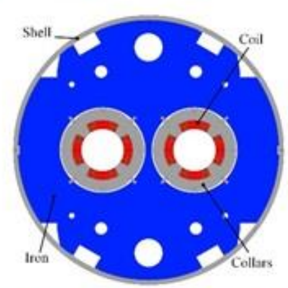
MCBXFA [F. Toral, et al.]



D2 [P. Fabbricatore, S. Farinon]



D2 Q4 correctors [G. Kirby]



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

Courtesy E. Todesco

HL-LHC: MQXF low beta Nb_3Sn quadrupole

Model have good performance, long prototypes are being fabricated

A CERN LARP collaboration.

Nominal Gradient 132.6 T/m

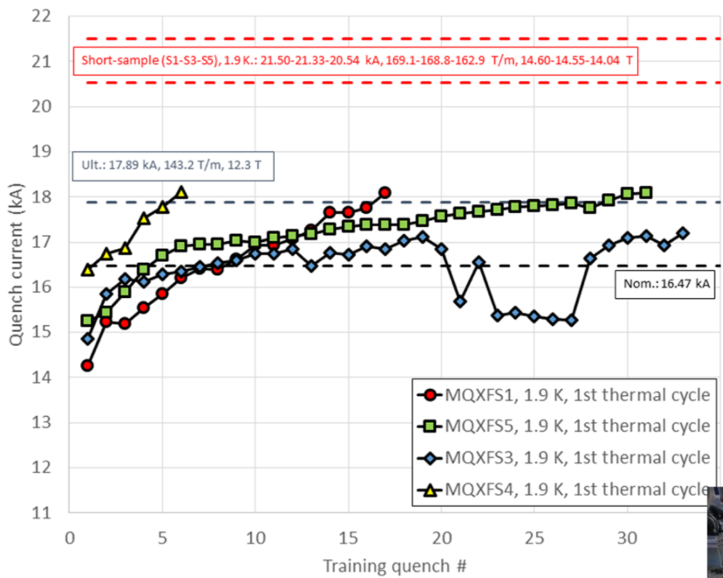
Aperture diameter 150 mm

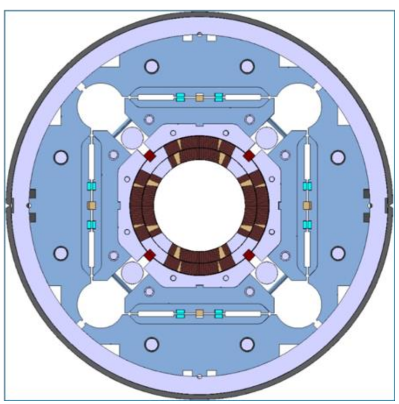
Peak Field 12.1 T

Current 17.5 A

Load-line Margin 20% @ 1.9 K

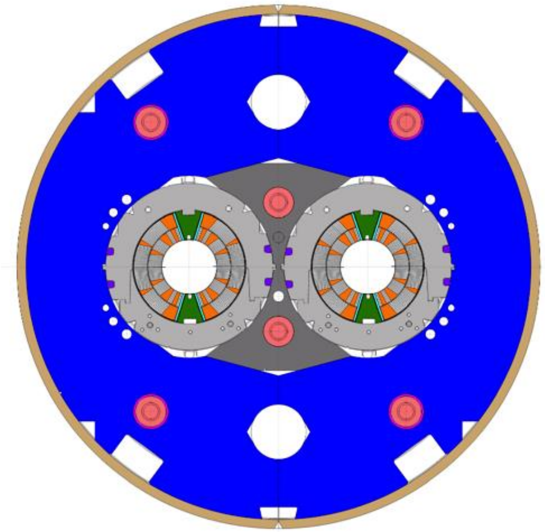
Stored Energy 1.32 MJ/m





Courtesy P. Ferracin

HL-LHC: 11 T Dispersion suppressor magnet



- 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

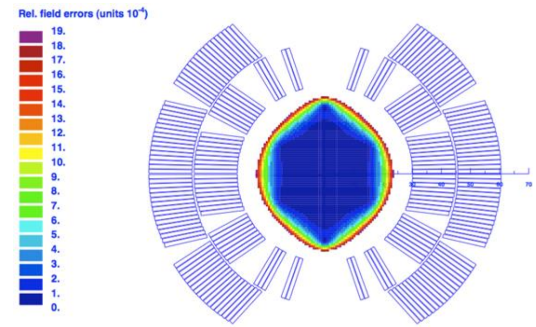
Aperture diameter 60 mm

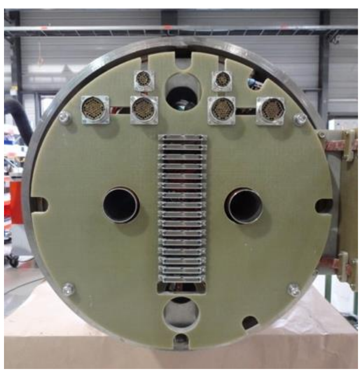
Peak Field 11.35 T

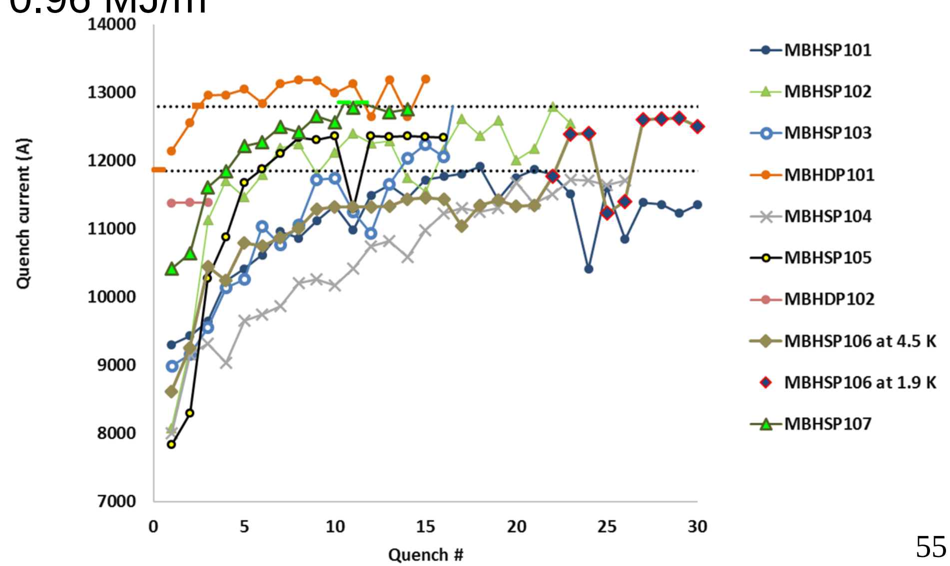
Current 11.85 kA

Loadline Margin 19.7% @ 1.9 K

Stored Energy 0.96 MJ/m

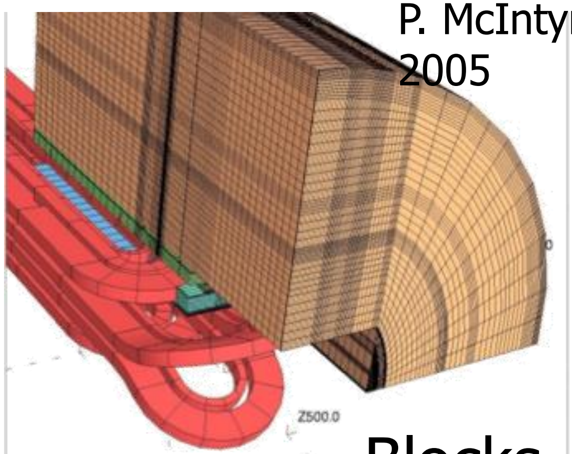






Magnet design for >12 T dipoles, LTS Nb_3Sn

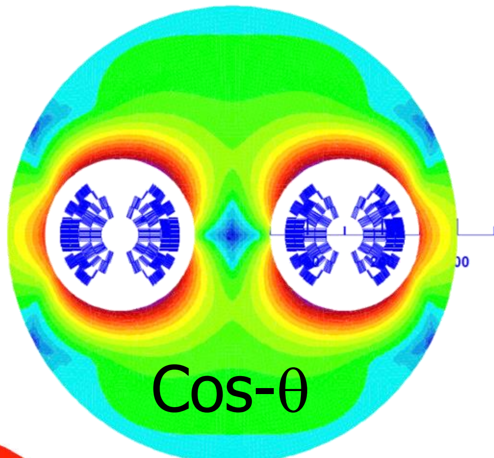
Many studies & proposals since the mid 1990-ies



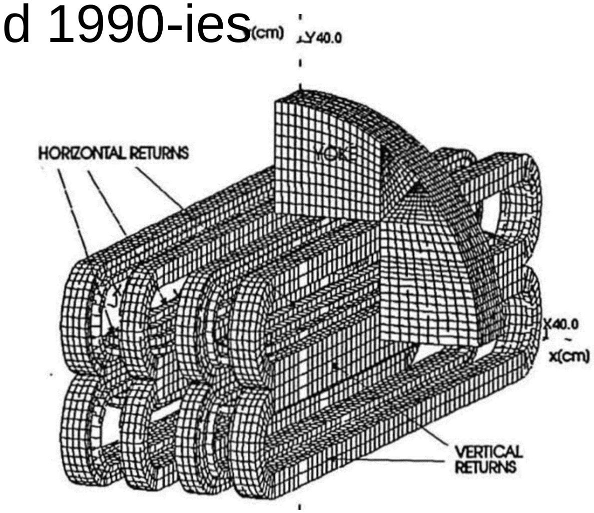
P. McIntyre, 2005

Blocks

E. Todesco 2013
D. Schoerling 2015

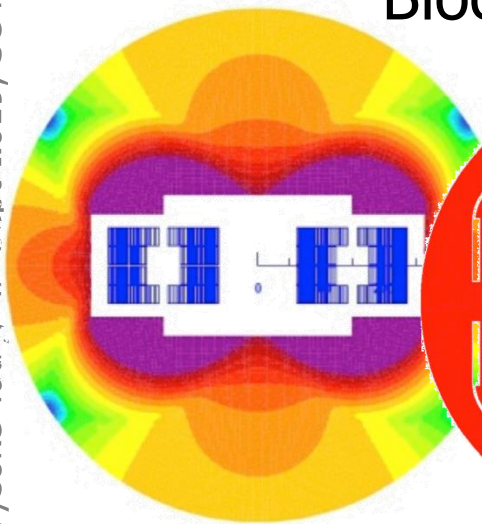


Cos-θ

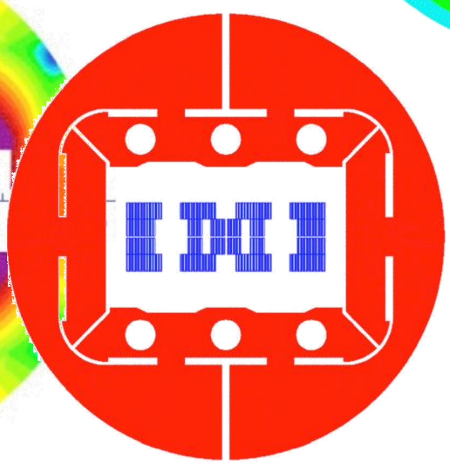


J.M. Van Oort, R. Scanlan, 1994

Common coils

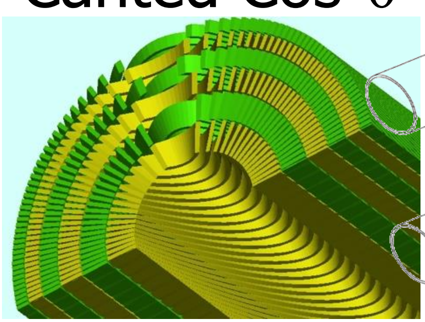


E. Todesco, 2013

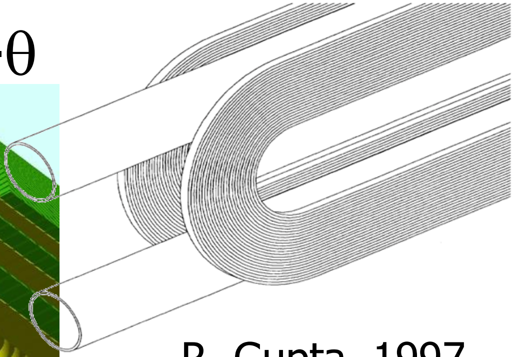


GL. Sabbi, 2014

Canted Cos-θ



S. Caspi, 2014



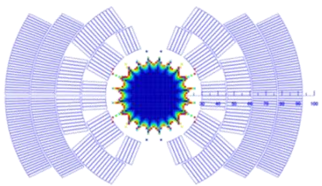
R. Gupta, 1997

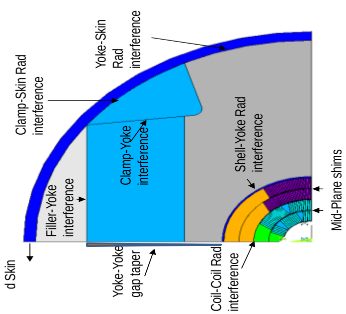
US program lines

U.S. DEPARTMENT OF ENERGY | Office of Science

cos-θ

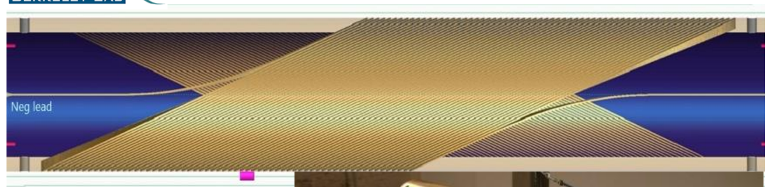
2017-2019



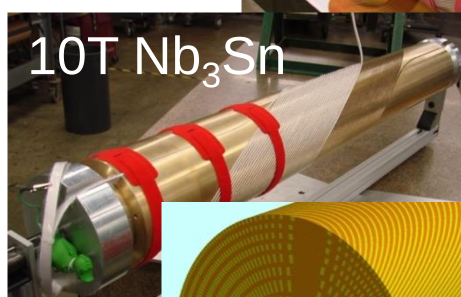


reached 14.1T in spring 2019

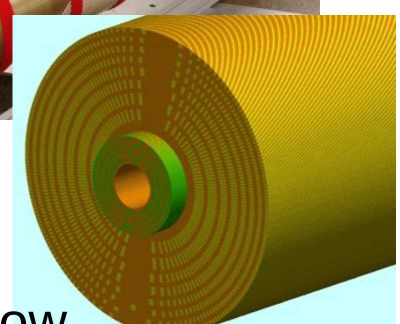
canted-cos-θ



2014-2015



2015-2016

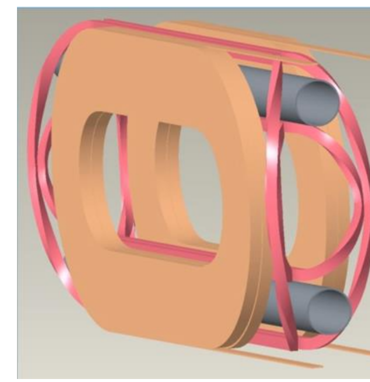


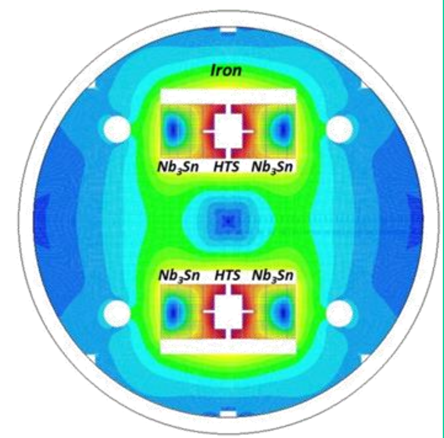
2016-now

BROOKHAVEN NATIONAL LABORATORY

common coils

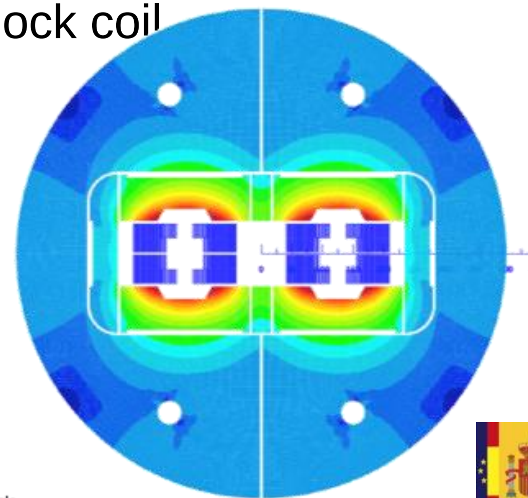
2017





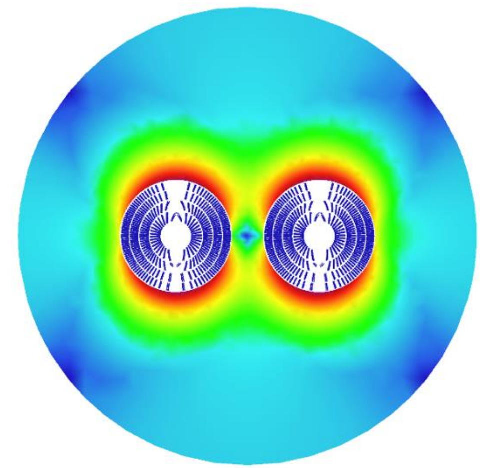
FCC: 16T dipole options

Block coil



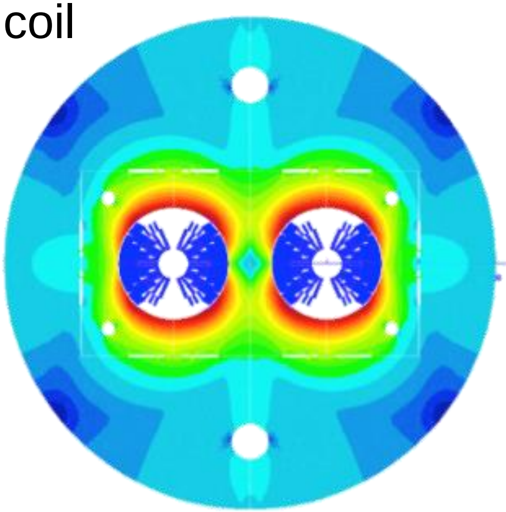
C. Lorin, M. Durante (CEA)

Canted Cos-theta



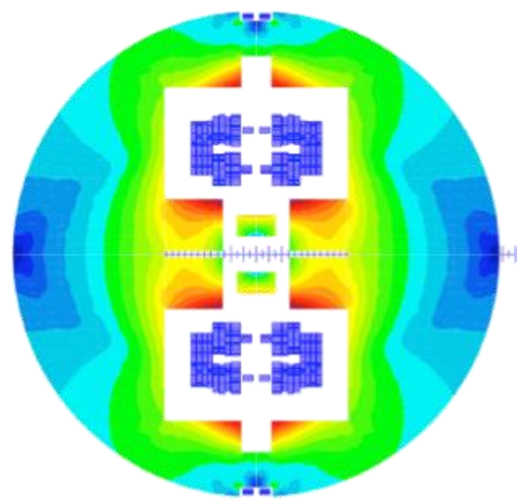
B. Auchmann (CERN/PSI)

Cos-theta coil



S. Farinon, P. Fabbricatore (INFN)

Common coils



F. Toral (CIEMAT)

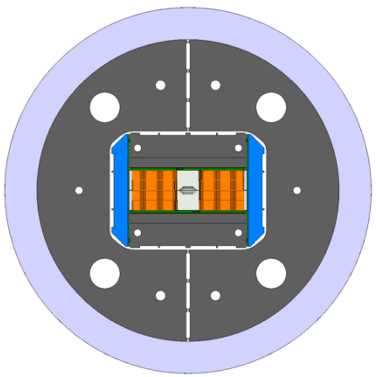
16 T , CERN approach , go in steps

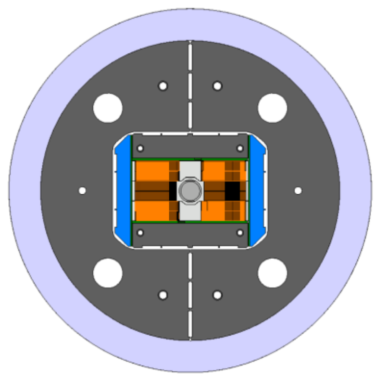
1 Extended Racetrack Model Coil , ERMC

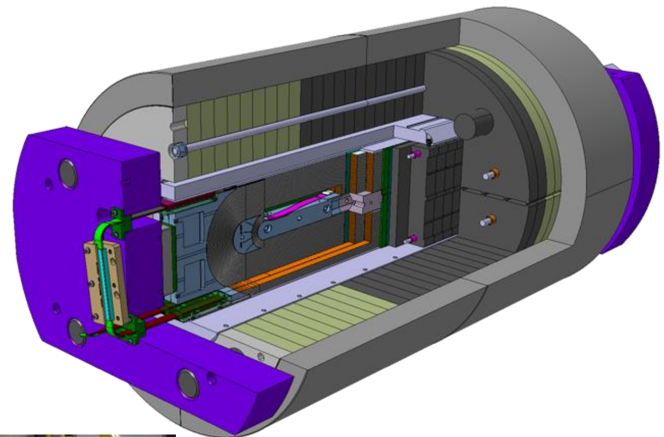
2 Racetrack Model Magnet, RMM

3 Demonstrator, DEMO

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

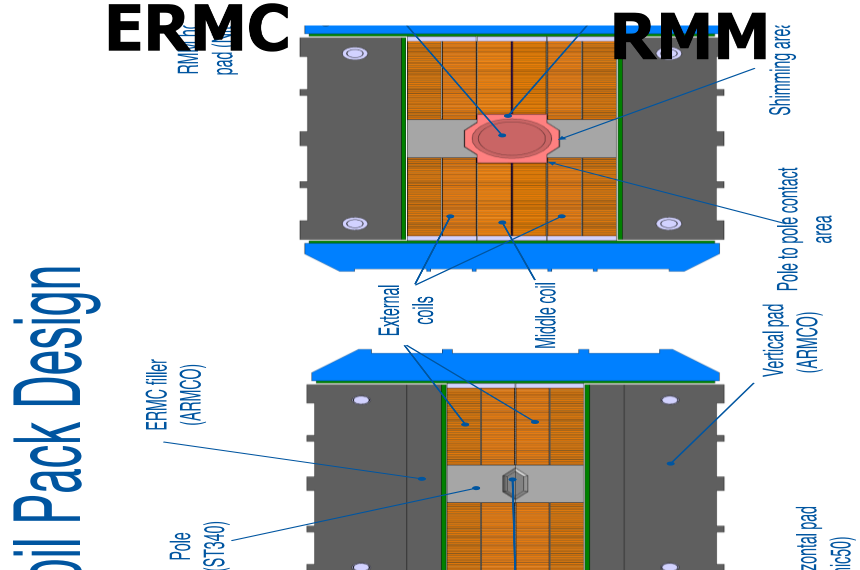




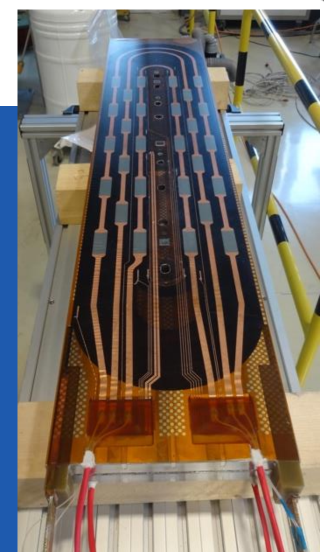


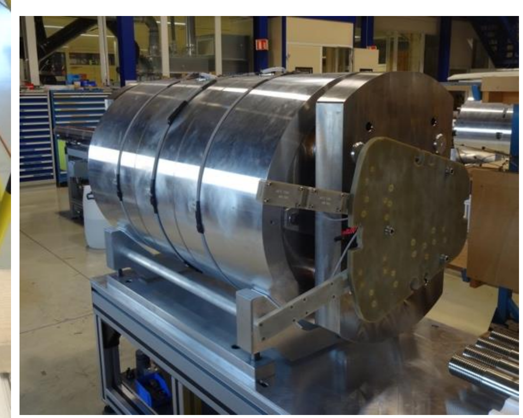
ERMC

RMM



, SC magnets, GdR

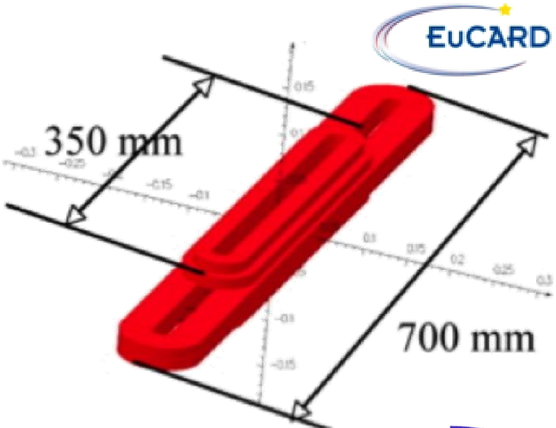


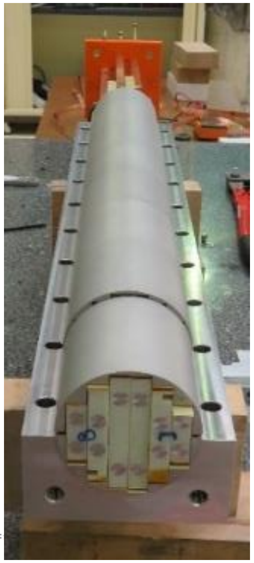


First test ERMC Jan 2020

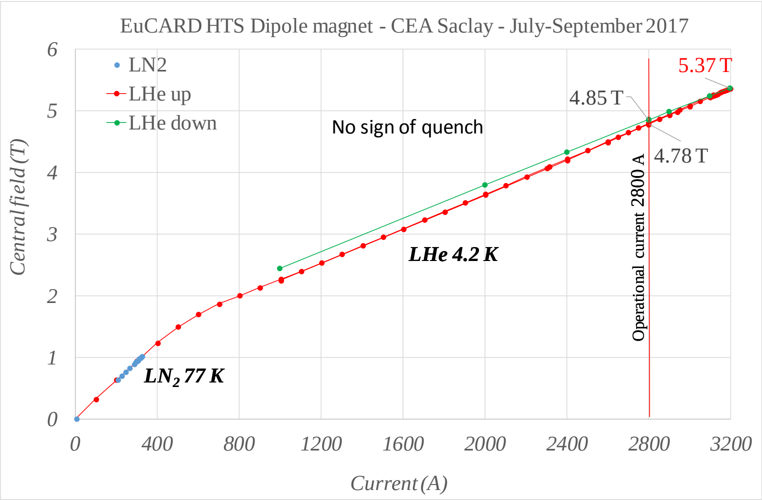
HTS: First attempt towards 20 T

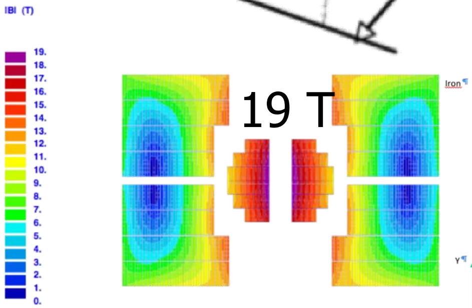
6 T HTS (YBCO) insert for test in Fresca2 , to get to 19 T
But without bore

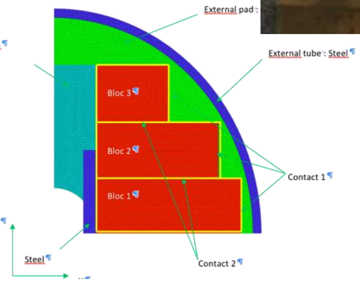


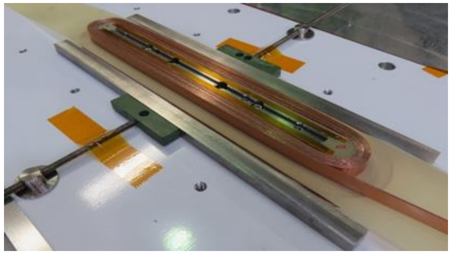


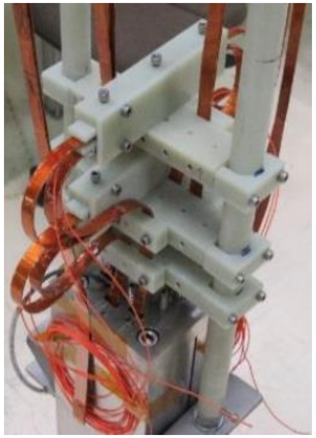
Stand alone tested Sept 2017:
Reached 5.37 T @ 4.2K (I=3200A)
Next test mid 2019 inside Fresca2









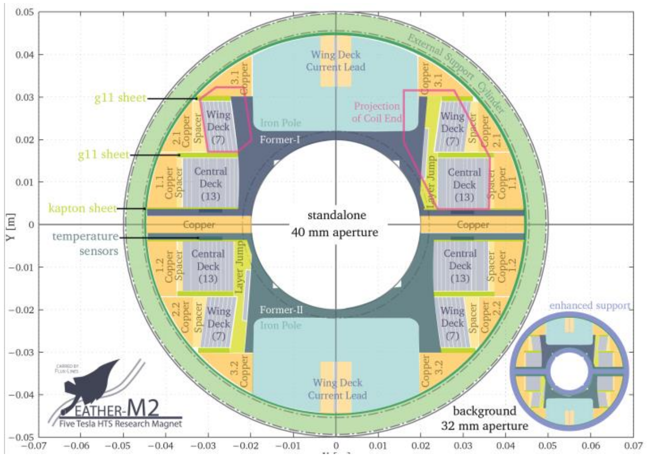


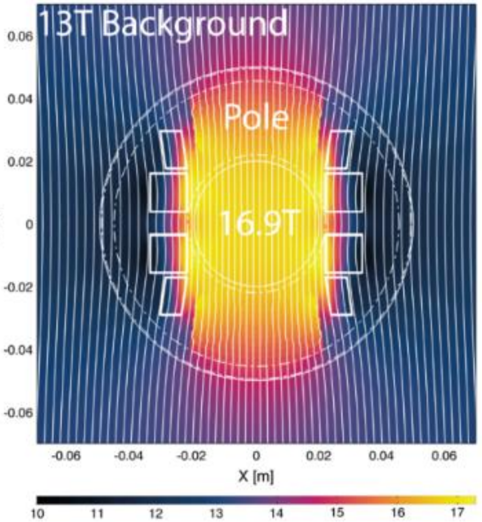
a CEA + CRNS Grenoble project

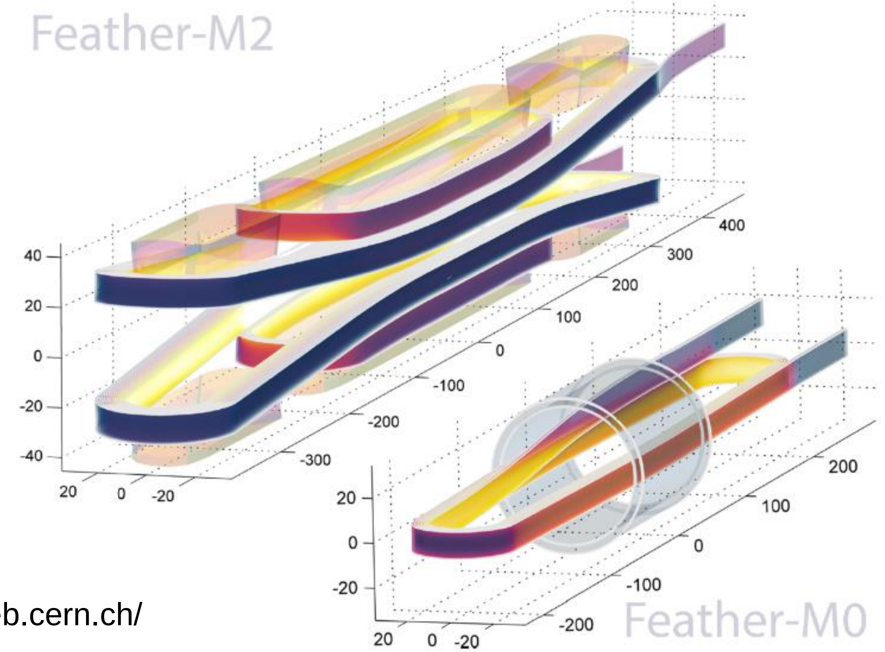
J.M. Rey, F. Borgnolutti, M. Durante, CEA-Saclay

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



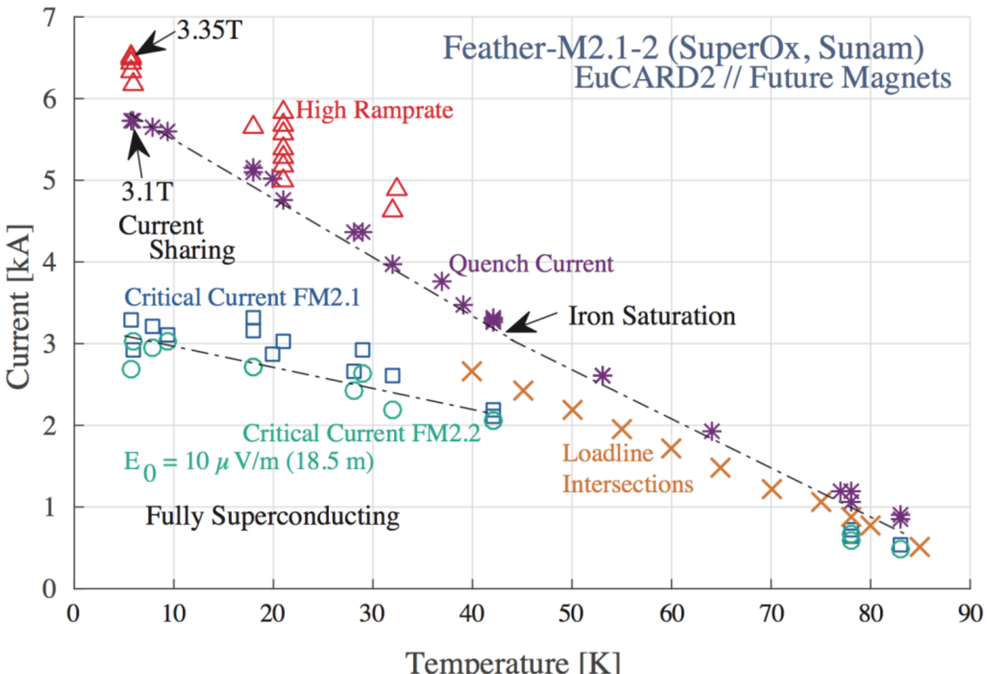


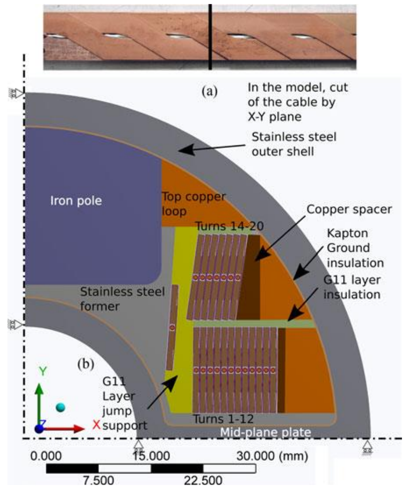


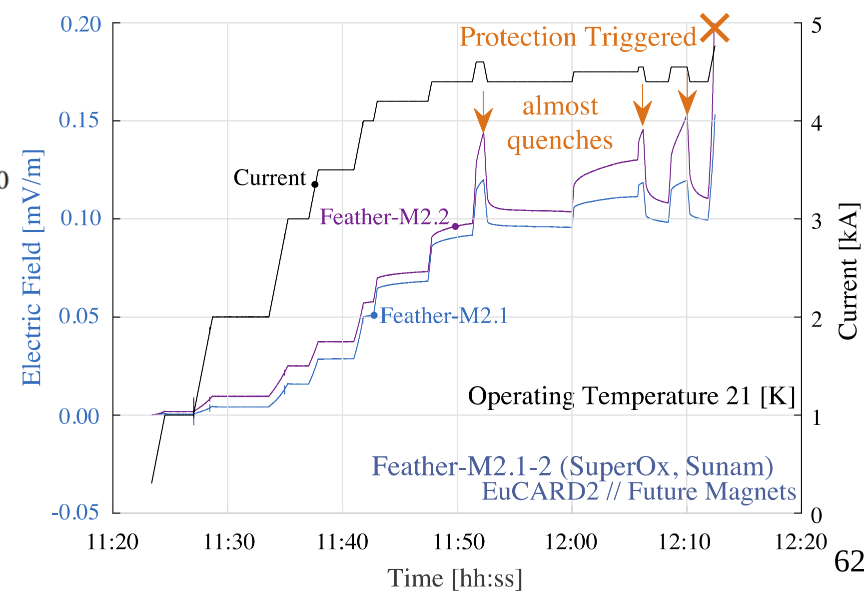
http://eucard2.web.cern.ch/

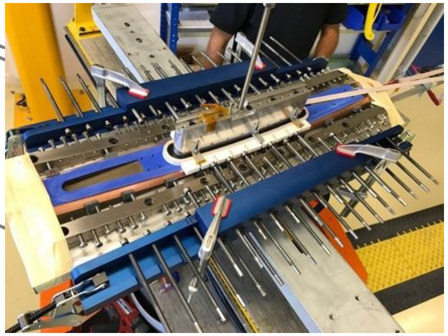
Feather-M2.0 test results

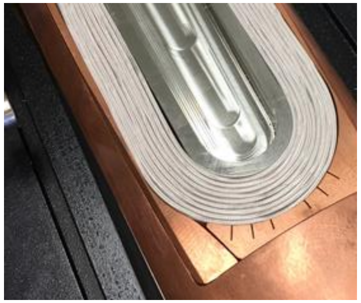
HTS magnets work differently than LTS magnets due to a larger enthalpy margin



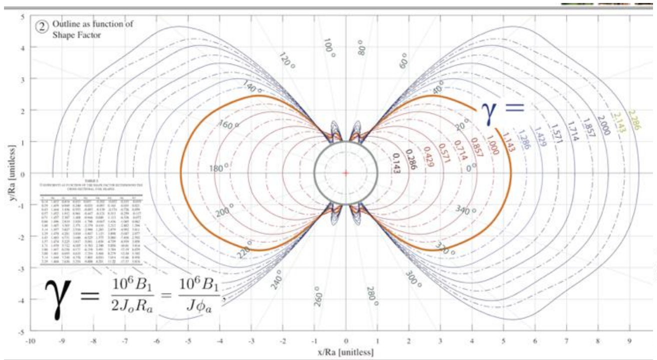


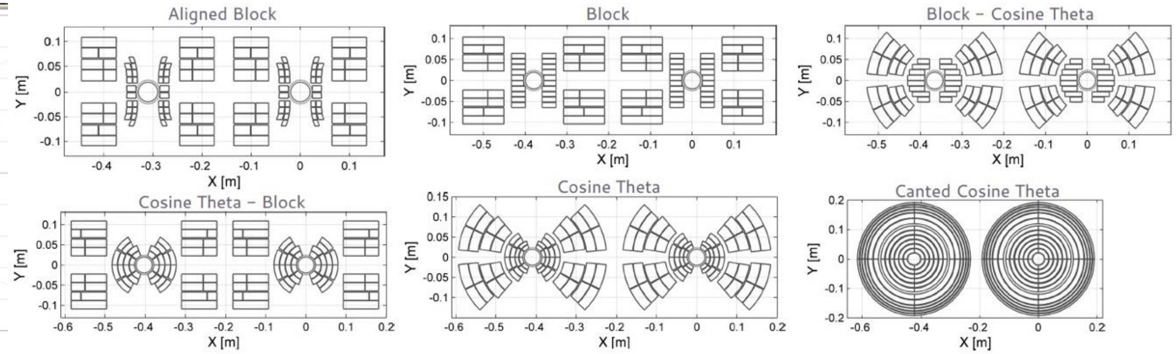






20T design activity @CERN





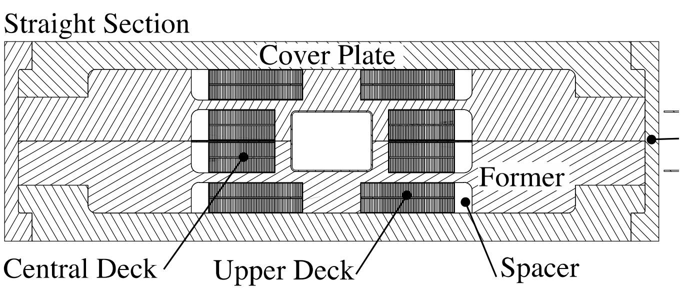


Fig. 8. Conceptual cross-sectional mechanical desi

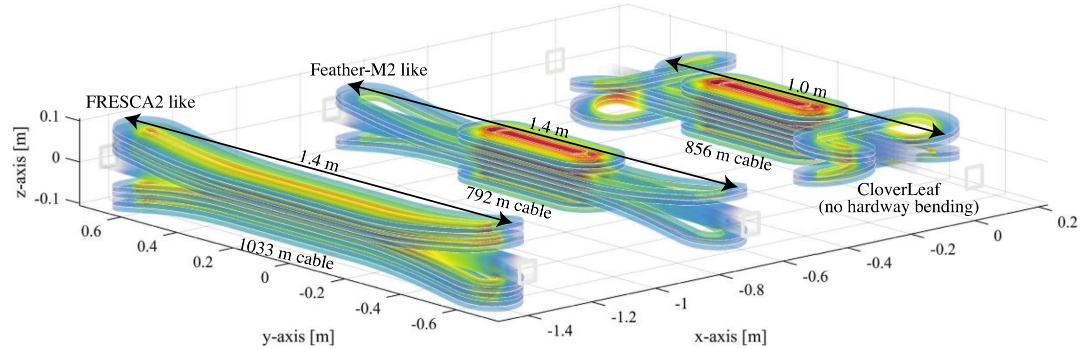
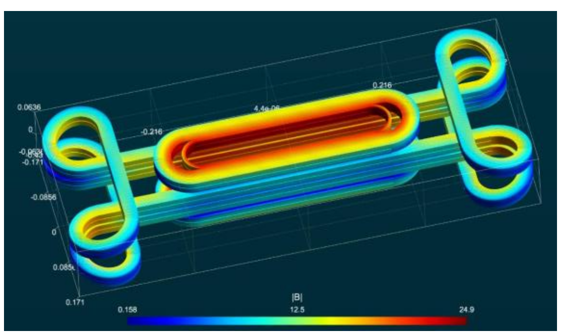


Fig. 10. Illustration showing the three-dimensional coil layouts with the three different coil-end types that are considered. The cross-section of these coils correspond exactly to coil layout 5 in Table I.



Courtesy J. van Nugteren, G. Kirby

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 Nb_3Sn 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 !

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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

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6) 21st International Conference on Magnet Technology, Hefei, China, 18 - 23 Oct 2009, IEEE Trans. Appl. Supercond. 20 (2010)
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11) E. Todesco, L. Rossi, AN ESTIMATE OF THE MAXIMUM GRADIENTS IN SUPERCONDUCTING QUADRUPOLES, CERN/AT 2007-11(MCS),
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Acknowledgements

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