Magnets

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CAS - Basics of Accelerator Physics and Technology

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Contents

- Introduction
  - magnetic field and magnet principles for resistive and superconducting magnets
  - Field description and magnet types

- Resistive magnets

- Superconducting magnets

- Literature on Magnets

The 2 Maxwell equations relevant for magnets

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:
"A magnetic field is produced by an electrical current or a time varying electrical field"

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

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

Gauss's law for magnetism:
The magnetic field is divergence free: the flux lines are closed

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

With: $\vec{B} = \mu \vec{H} = \mu_0 \mu_{\mathbf{r}} \vec{H}$

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 $the\ skew\ nth\ multipole\ component.$

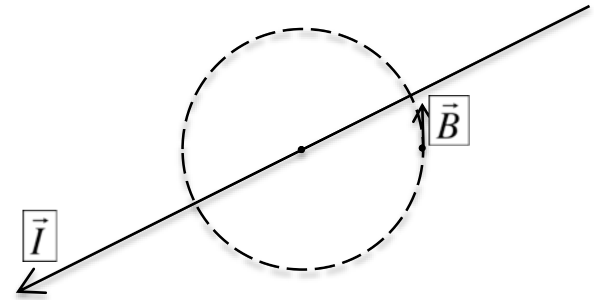
In a ring shaped accelerator, where the beam does multiple passes, one typically demands :

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

Magnetic fields

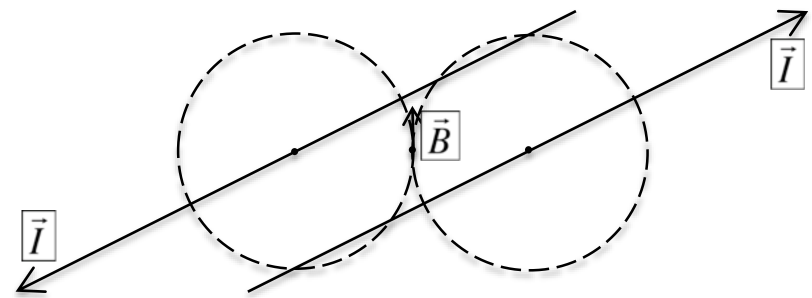
From Ampere's law with no time dependencies , We can derive the law of Biot and Savart

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



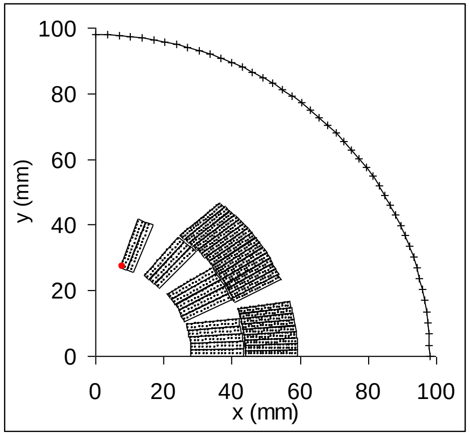
If you wanted to make a *B* = 1.5 T magnet with just two infinitely thin wires placed at 100 mm distance in air one needs : *I* = 187500 A

- To get reasonable fields (*B* > 1 T) one needs large currents
- Moreover, the field homogeneity will be poor



And If you wanted to make a *B* = 8 T one needs : *I* = 5•10^5 A
(LHC dipole coil 80 turns of 11850 A at 8.3 T = 9.48•10^5 A)

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



Courtesy E. Todesco

Iron dominated magnets (aka: Classical, Resistive)

With the help of an iron yoke we can get fields with less current

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

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

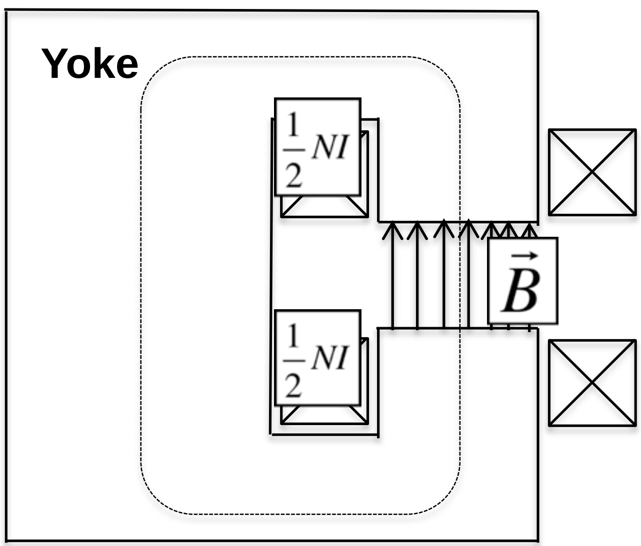
$$N \cdot I = \frac{B}{\mu_0 \mu_r} \cdot l_{iron} + \frac{B}{\mu_0} \cdot l_{airgap} \Rightarrow$$

(the iron term $\frac{B}{\mu_0 \mu_r} \cdot l_{iron}$ is struck through)

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

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

Example: C shaped dipole for accelerators



coil

B = 1.5 T

Gap = 50 mm

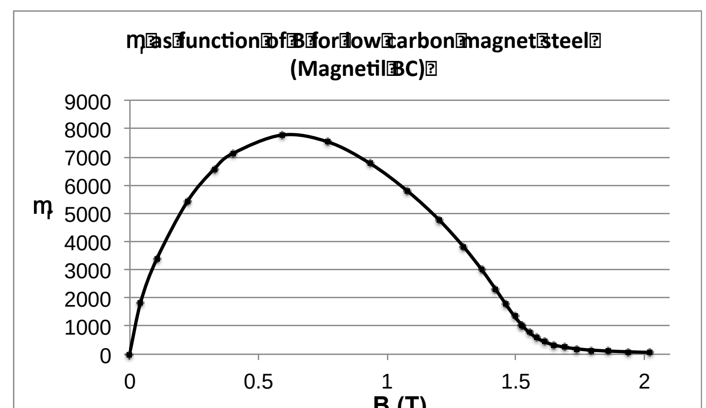
N . I = 59683 A

2 x 30 turn coil

I = 994 A

@5 A/mm^2, 200 mm^2

14 x 14 mm Cu

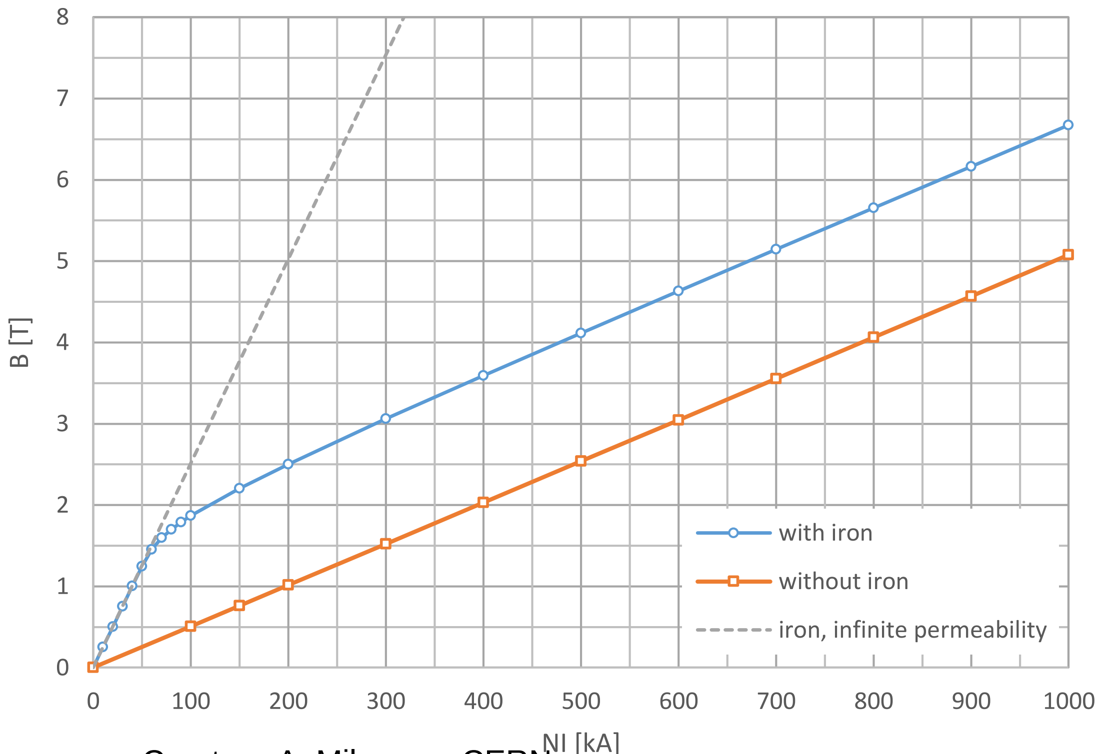


Comparison : iron magnet and air coil

Imagine a magnet with a 50 mm vertical gap (horizontal width ~100 mm)
Iron magnet wrt to an air coil:

- Up to 1.5 T we get ~6 times the field
- Between 1.5 T and 2 T the gain flattens of : the iron saturates
- Above 2 T the slope is like for an air-coil: currents become too large to use resistive coils

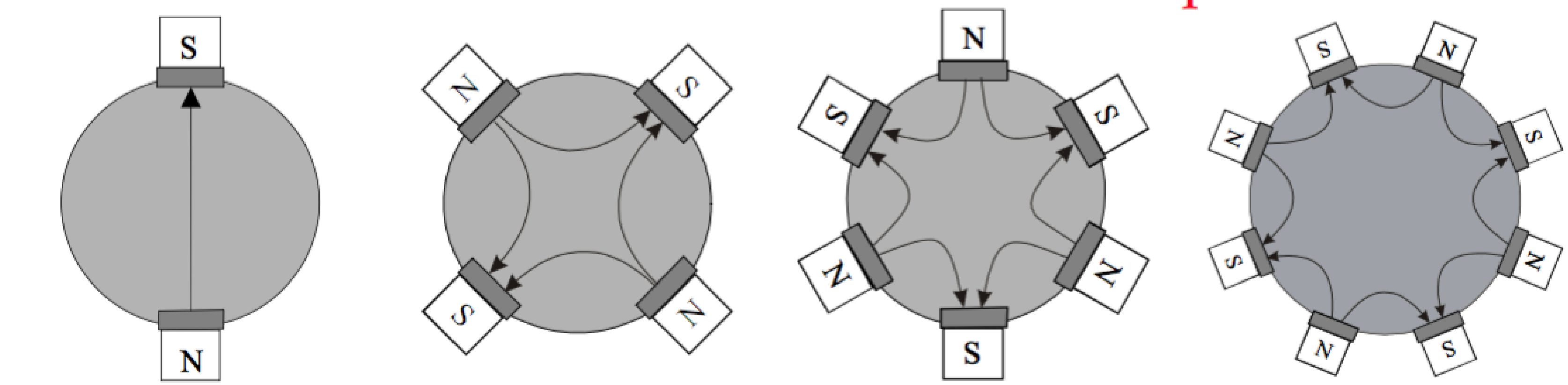
These two curves are the transfer functions – B field vs. current – for the two cases



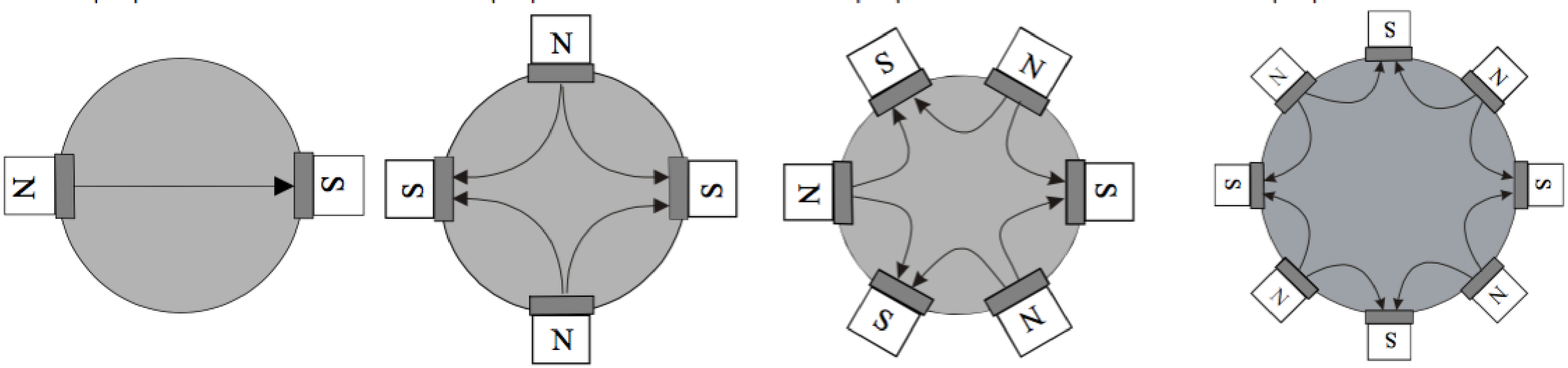
Courtesy A. Milanese, CERN

Types of magnet fields for accelerators

NORMAL : vertical field on mid-plane



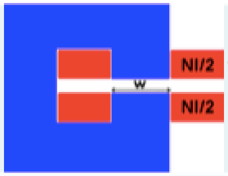
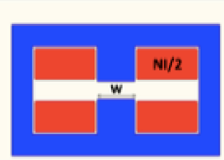
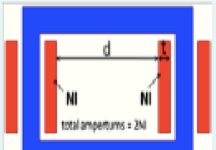
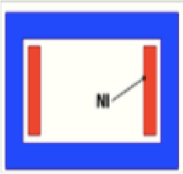
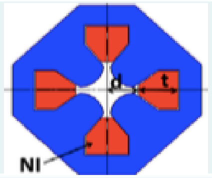
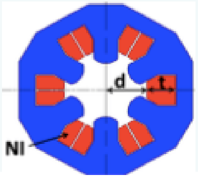
Dipole	Quadrupole	Sextupole	Octupole
$\|B\|=const$	$\|B\|=G\cdot r$	$\|B\|=1/2\cdot B''\cdot r^2$	$\|B\|=1/6\cdot B'''\cdot r^3$



Courtesy D. Tommasini, CERN

SKEW : horizontal field on mid-plane

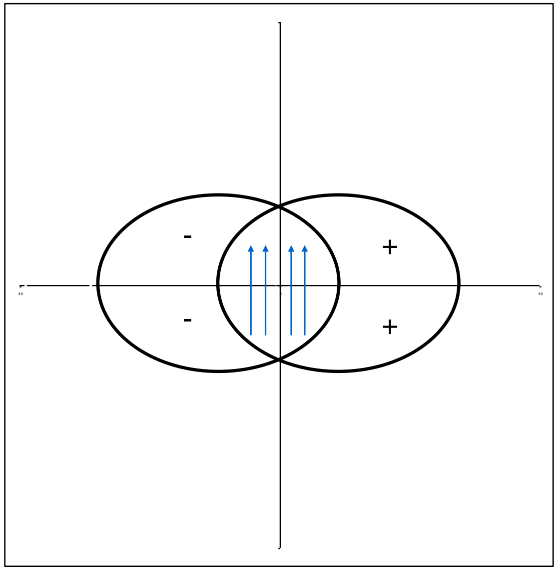
Basic resistive magnet types

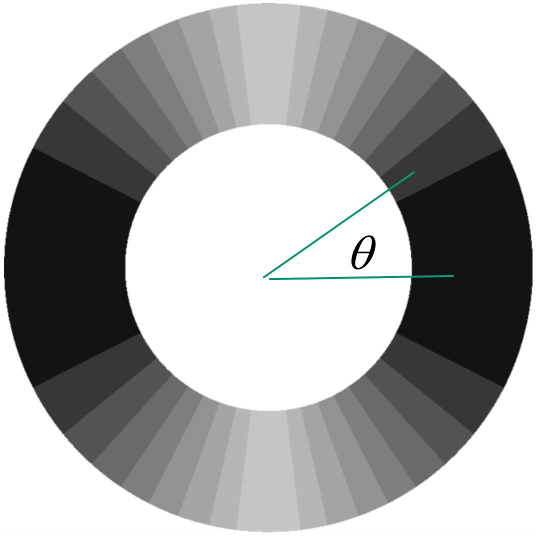
Magnet		Pole shape	Transfer function
	w : pole width g : vertical gap	parallel	$B=\mu_0 NI/g$
	w : pole width g : vertical gap	parallel	$B=\mu_0 NI/g$
	w : pole width g : pole gap t : coil width	parallel	$B=\mu_0 NI/g$
	w : pole width g : pole gap t : coil width	parallel	$B=\mu_0 NI/g$
	R : aperture radius d : coil distance t : coil width	$2xy=R^2$	$B(r)=G\cdot r$ $G=2\mu_0 NI/R^2$
	R : aperture radius d : coil distance t : coil width	$3x^2y-y^3=R^3$	$B(r)=S\cdot r^2=\frac{1}{2}B''\cdot r^2$ $S=3\mu_0 NI/R^3$

Courtesy D. Tommasini, CERN

"Free" Coils for generating the Perfect Dipole Field

- Used for magnets where the field is fully determined by the coil only (not by the poles), mostly the case for superconducting magnets
- 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*θ current distribution $J = J_0 \cos\Theta$
  - Pure dipolar field
  - Easier to reproduce with a flat rectangular cable





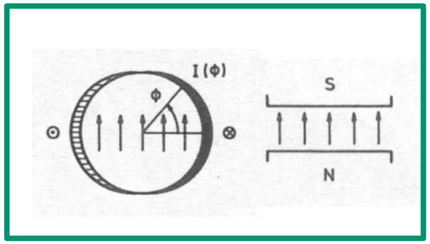
Magnet types and higher orders

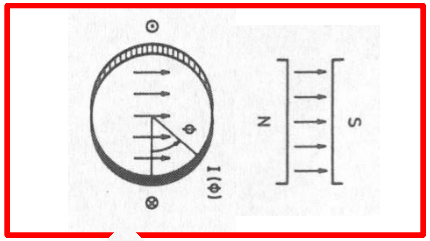
a “pure” multipolar field can be generated by a specific coil geometry

normal | skew

dipole n=1

B_1

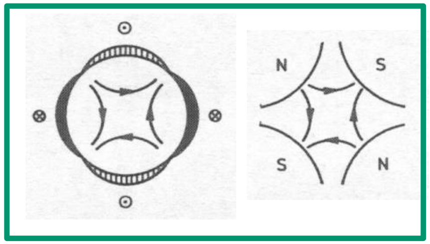


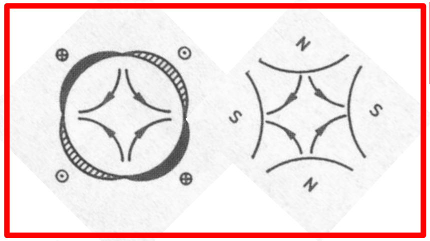


A_1

quadrupole n=2

B_2

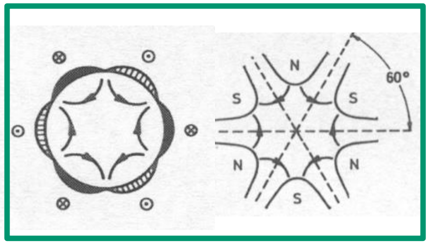


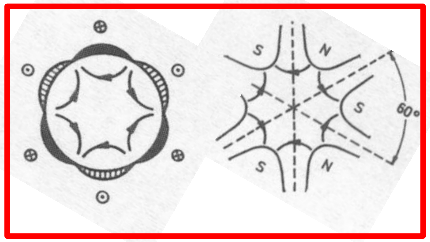


A_2

sextupole n=3

B_3



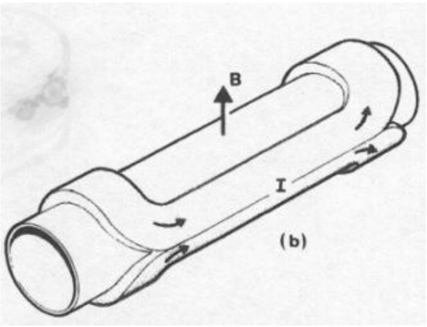


A_3

Courtesy P. Ferracin, CERN

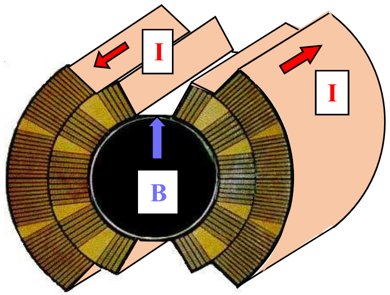
What is specific about sc accelerator magnets ?

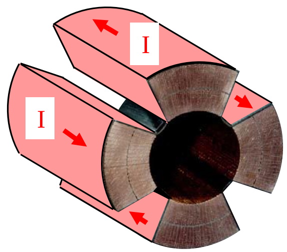
- Cylindrical volume with perpendicular field

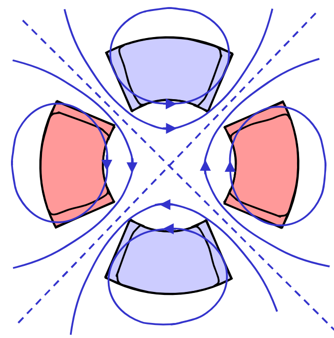


Artist view of a dipole, from M. N. Wilson « Superconducting Magnets »

- Dipoles, quadrupoles, etc

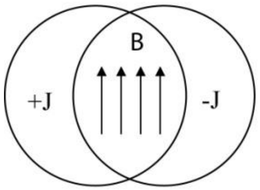






- Field quality: $\frac{\Delta B_z}{|B|} \leq few \cdot 10^{-4}$

CosΘ coil : $J = J_0 \cos\Theta$



- Field quality formulated and measured in a multipole expansion,

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

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

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

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

Resistive magnets

Also called: Classical magnets, Iron dominated magnets

Practical resistive magnet design & manufacturing

Steps in the process:

1. Specification
2. Conceptual design
3. Raw materials choice
4. Detailed design
    1. Coil cross-section geometry: cooling
    2. Yoke shape, pole shape: FE model optimization
    3. Yoke ends, coil ends design
5. Yoke manufacturing, tolerances, alignment, structure
6. Coil manufacturing, insulation, impregnation type
7. Magnetic field measurements

Specification

Before you start designing you need to get from the accelerator designers:

- B(T) or G (T/m) (higher orders: G_3(T/m^2), etc)
- Magnet type: C-type, H-type, DC (slow ramp) or AC (fast ramp)
- Aperture:
  - Dipole : "good field region" → airgap height and width
  - quads and higher order: "good field region" → aperture inscribed circle
- Magnetic length and estimated real length
- Current range of the power convertor (and the voltage range: watch out for the cables)
- Field quality:

$$dipole: \frac{\Delta B}{B} (ref\ volume), \qquad quadrupole: \frac{\Delta G}{G} (reference\ circle)$$

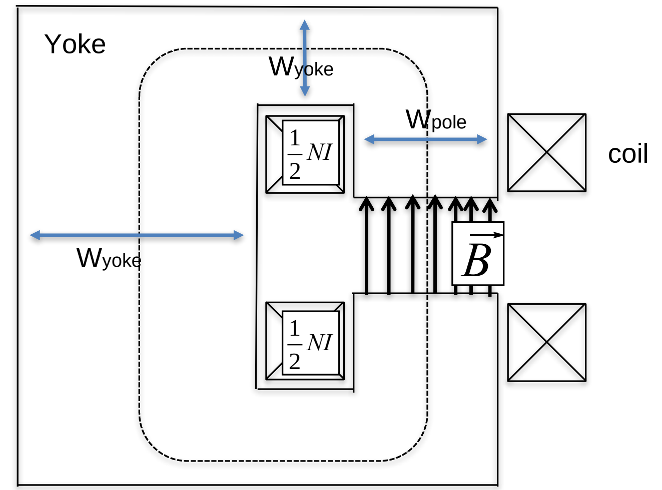
$$or \qquad b_n, a_n \quad for\ n = 1,2,3,4,5, \ldots$$

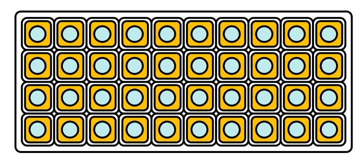
- Cooling type: air, water (P_{max} , Δp_{max} and Q_{max} (l/min)
- Jacks and Alignment features
- Vacuum chamber to be used → fixations, bake-out specifics

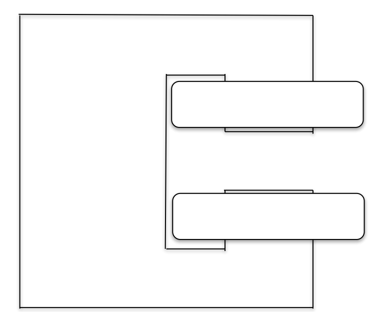
These need careful negotiation and often iteration after conceptual (and detailed) design

Conceptual design

- From B and l you get NI (A) $$NI = \frac{l_{airgap} B}{\mu_0}$$
- *From NI* (A) and the power convertor I_{max} you get N
- Then you decide on a coil X-section using:
$$j_{coil} = 5 \; {}^{A}/_{mm^2} \; for\ water\ cooled$$
$$or\ j_{coil} = 1 \; {}^{A}/_{mm^2} \; for\ air\ cooled$$
- This defines the coil cavity in the yoke (you add 0.5 mm insulation around each conductor and 1 mm ground insulation around the coil) and select the best fitting rectangular
- You can the draw the draft X-section using:
$$W_{yoke} = W_{pole} \frac{B}{B_{sat}} \quad with \quad 1.5\,T < B_{sat} < 2\,T$$
- Decide on the coil ends: racetrack, bedstead
- You now have the rough magnet cross section and envelope







Power and cooling

Power generated by coil

- DC: from the length of the conductor $N \cdot L_{turn}$, the cross section σ and the specific resistivity ρ of the material one gets the spent Power in the coil

$$P/l[W/m] = \frac{\rho}{S} I^2 \quad with: \quad \rho_{Cu} = 1.72\big(1 + 0.0039(T - 20)\big)10^{-8}\Omega m \quad \rho_{Al} = 2.65\big(1 + 0.0039(T - 20)\big)10^{-8}\Omega m$$

- For pulsed magnets: take the average I^2 for the duty cycle

Coil Cooling

- ΔT (entrance-exit of the coil) is usually chosen as 20ºC or 30ºC depending on the $T_{cooling\ water}$)
- The cooling water needs to be in moderately turbulent regime (with laminar flow the flow speed is zero on the wall !) (*Reynolds* > 2000)
- In general a few bars (eg. 4 bar) pressure drop is chosen

Courtesy D. Tommasini, CERN

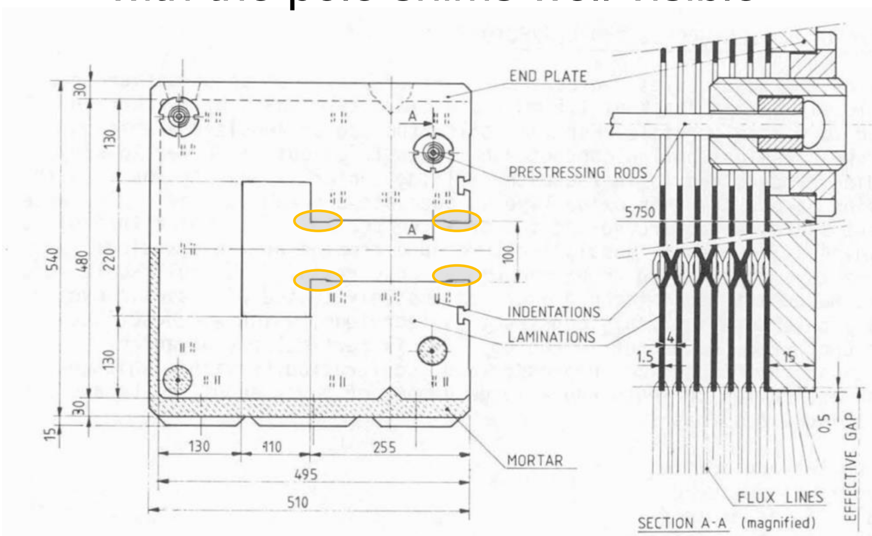
Theoretical pole shapes

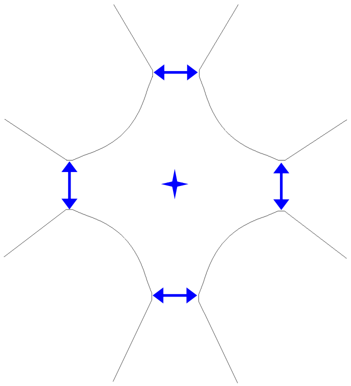
The ideal poles for dipole, quadrupole, sextupole, etc. are lines of constant scalar potential

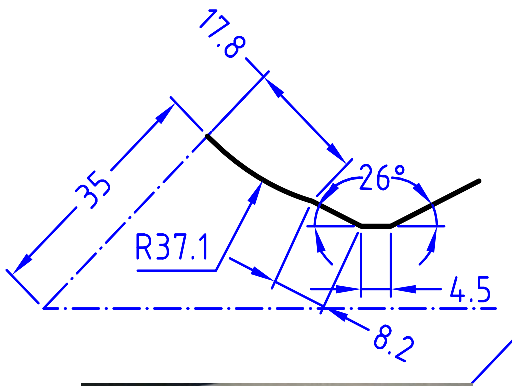
Dipole	$y = \pm h/2$	straight line
quadrupole	$2xy = \pm r^2$	hyperbola
sextupole	$3x^2y - y^3 = \pm r^3$	

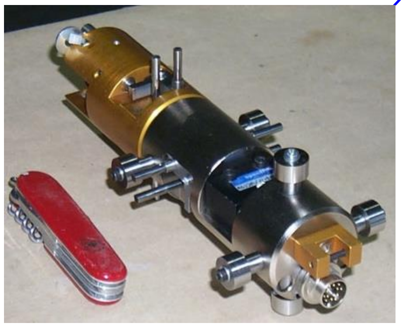
Practical pole shapes: shims and alignment features

- Dipole example: below a lamination of the LEP main bending magnets, with the pole shims well visible

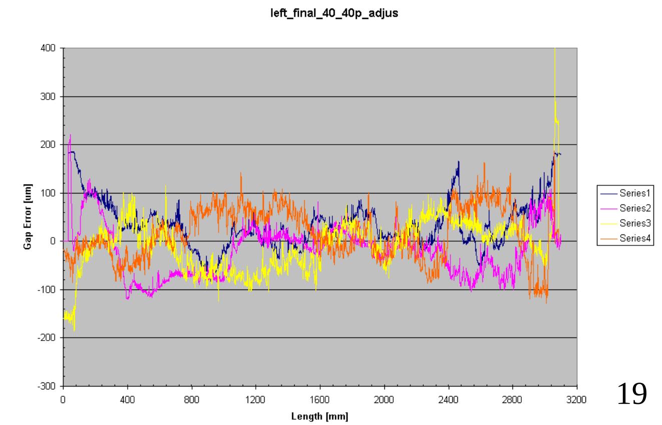








- Quadrupoles: at the edge of the pole one can put a combination a shim and alignment feature (examples: LHC-MQW, SESAME quads, etc)
- This then also allows to measure the pole distances : special instrumentation can be made for this



Finite Element electromagnetic models

- Aim of the electromagnetic FE models:
  - The exact shape of the yoke needs to be designed
    - Optimize field quality: adjust pole shape, minimize high saturation zones
    - Minimize the total steel amount (magnet weight, raw material cost)
  - Calculate the field: needed for the optics and dynamic aperture modelling
    - transfer function $B_{xsection}(I)$, $\int B dl$, magnetic length
    - multipoles (in the centre of the magnet and integrated) b_n and a_n

- Some Electromagnetic FE software packages that are often used:
  - Opera from Cobham: 2D and 3D commercial software see: http://operafea.com/
  - "Good old" Poisson, 2D: now distributed by LANL-LAACG see: http://laacg.lanl.gov/laacg/services/download_sf.phtml
  - ROXIE (CERN) 2D and 3D, specialized for accelerator magnets; single fee license for labs & universities see: ttps://espace.cern.ch/roxie/default.aspx
  - ANSYS Maxwell: 2D and 3D commercial software see: http://www.ansys.com/Products/Electronics/ANSYS-Maxwell

Yoke shape, pole shape: FE model optimization

Use symmetry and the thus appropriate boundary conditions to model only ¼th (dipoles, quadrupoles) or even 1/6th sextupoles.

Meshing needs attention in the detailed areas like poles, slits, etc

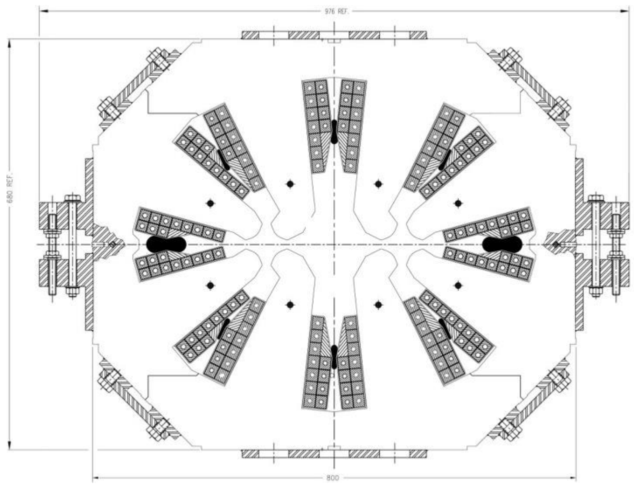
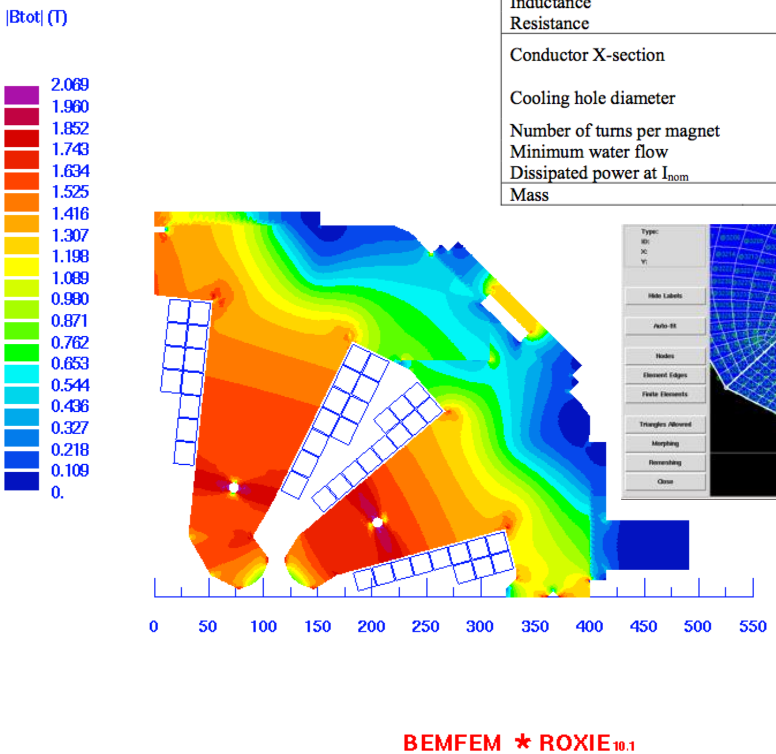
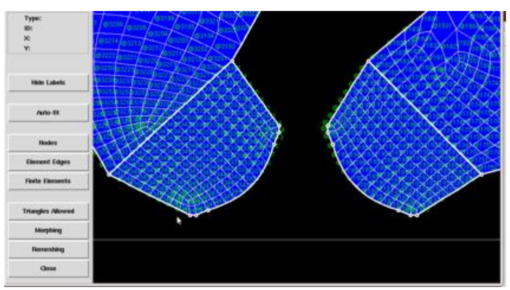
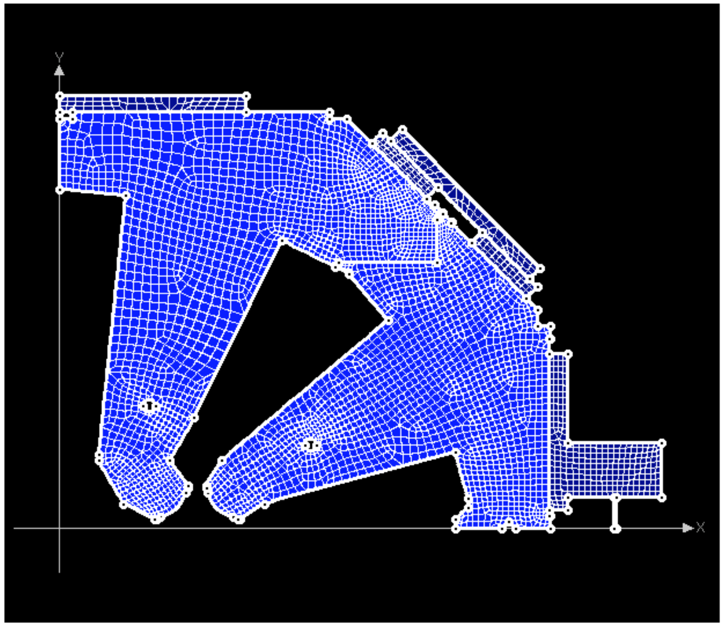


Table 8.6: Main parameters of the MQW normal conducting quadrupole magn

Magnet type	MQWA	MQWB
Magnetic length	3.1 m	
Beam separation	224 mm	
Aperture diameter	46 mm	
Operating temperature	< 65° C	
Nominal gradient	35 T/m	30 T/m
Nominal current	710 A	600 A
Inductance	28 mH	
Resistance	37 mΩ	
Conductor X-section	20.5 x 18.0 mm² inner poles 17.0 x 17.0 mm² outer poles	
Cooling hole diameter	7 mm inner poles, 8 mm outer poles	
Number of turns per magnet	8 x 11	
Minimum water flow	28 l/min	
Dissipated power at I_{nom}	19 kW	14 kW
Mass	11700 kg	







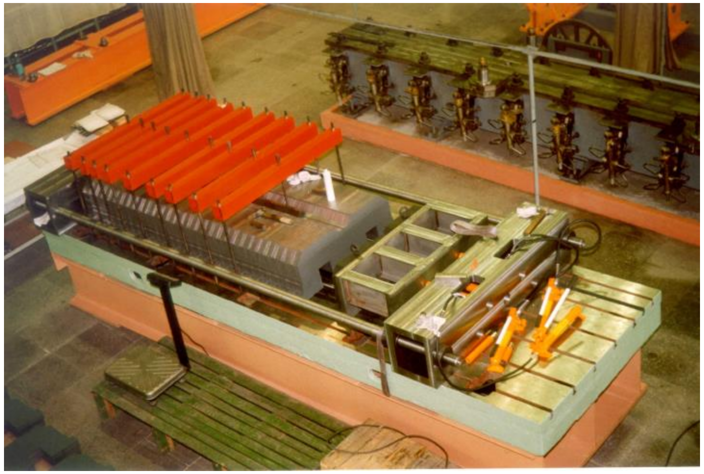
Yoke manufacturing

- Yokes are nearly always laminated to reduce eddy currents during ramping
- Laminations can be coated with an inorganic (oxidation, phosphating, Carlite) or organic (epoxy) layer to increase the resistance
- Magnetic properties: depend on chemical composition + temperature and mechanical history
- Important parameters: coercive field H_c and the saturation induction.
  - H_c has an impact on the remnant field at low current
    - H_c < 80 A/m typical or H_c < 20 A/m for magnets at low field (B < 0.05 T)
- low carbon steel (C content < 0.006%) is best for higher fields B > 1 T
- Yokes are either :
  - Glued , using epoxy coated laminations
  - Welded, full length plates are welded on the outside
  - Compressed by tie rods in holes

  or a combination of all these
- To be able to keep the yoke (or yoke stack) stable you probably need end plates (can range from ± 1 cm to 5 cm depending on the size)
- The end plates have pole chamfers and often carry end shims

Yoke manufacturing

Stacking an MBW dipole yoke stack



Double aperture LHC quad. MQW
Stacking on a precision table

Welding the structural plates

Half magnet handling

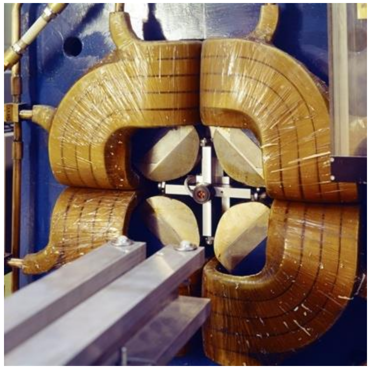
Glued yoke (MCIA LHC TL)

Coil manufacturing, insulation, impregnation type

- Winding Cu conductors is an well established technique
- When the Cu conductor is thick it is best to use “dead soft” Cu (T treatment)
- Insulation of the coil
  - Glass fibre – epoxy impregnated
    - Individual conductor 0.5 mm glass fibre, 0.25 mm tape wound half lapped
    - Impregnated with radiation resistant epoxy, total glass volume ratio >50%
  - For thin conductors: Cu emanel coated, possibly epoxy impregnated afterwards

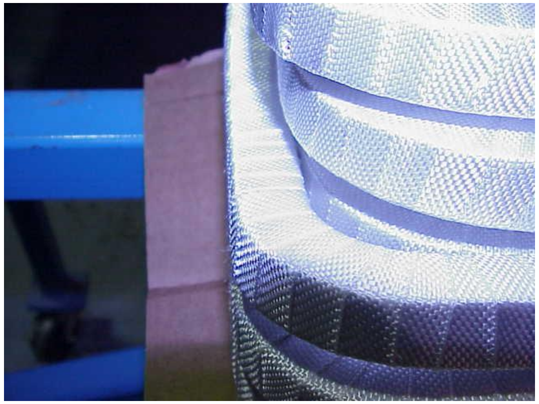
For dipoles some main types are racetrack or bedstead

Quadrupoles



Coil manufacturing

MQW Glass fibre tape wrapping.



Winding the hollow Cu conductor

coil electrical test (under water !)

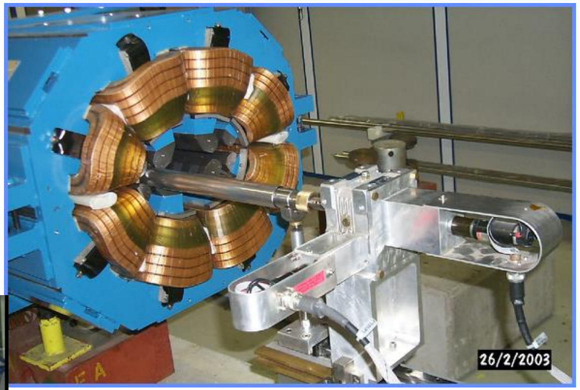
Finished MBXW coil

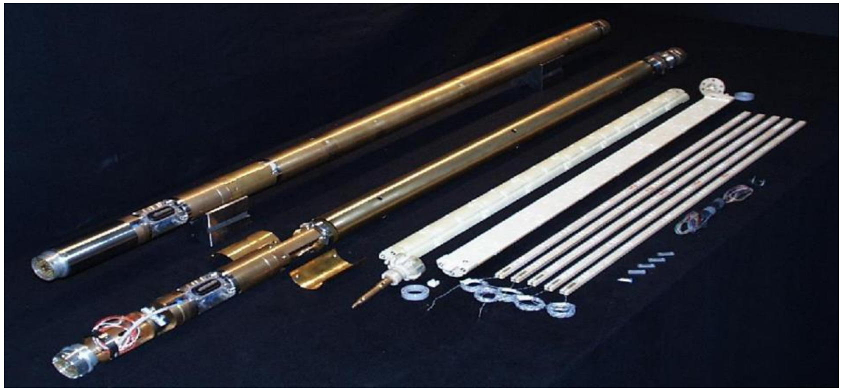
Magnetic field measurements

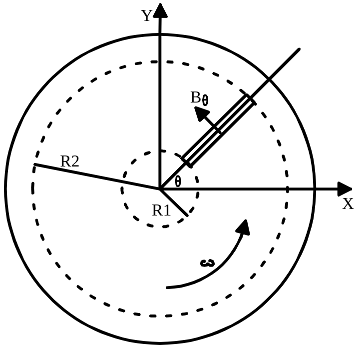
Several Magnetic Measurements techniques can be applied, e.g.:

- Rotating coils: multipoles and integrated field or gradient in all magnets
- Stretched wire: magnetic centre and integrated gradient for *n* > 1 magnets
- Hall probes: field map
- Pickup coils: field on a current ramp

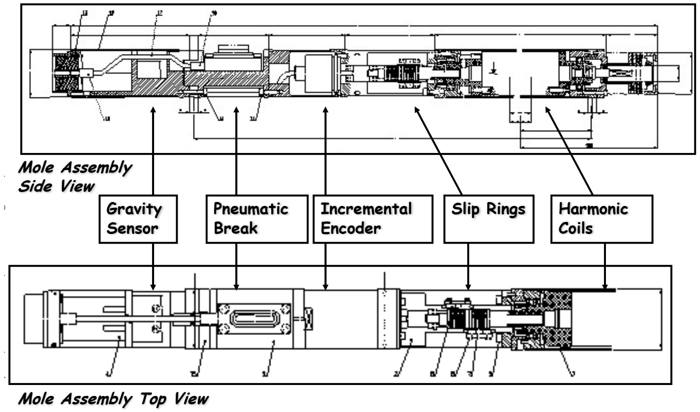
- Example below : MQW : double aperture quadrupole for the LHC.





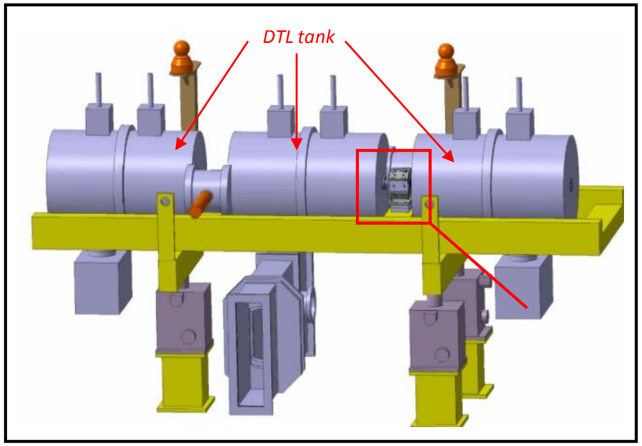


Rotating radial coil

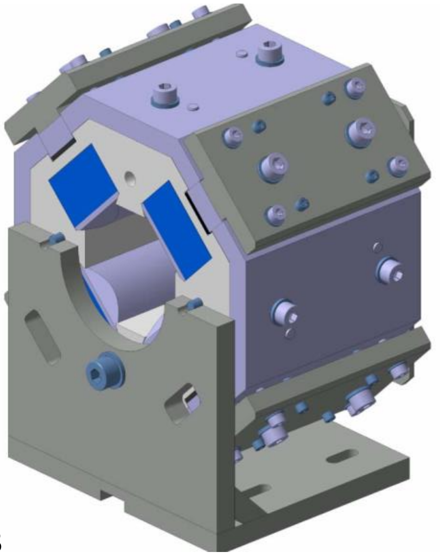


Permanent magnets

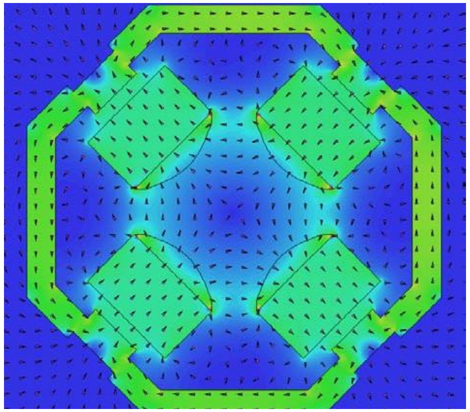
Linac4 @ CERN permanent magnets , quadrupoles



Pictured : Cell-Coupled Drift Tube Linac module.



- **Permanent magnet because of space between DTL tanks**
- **Sm_2Co_{17} permanent magnets**
- **Integrated gradient of 1.3 to 1.6 Tesla**
- **15 magnets**
- **Magnet length 0.100 m**
- **Field quality/amplitude tuning blocks**



Courtesy D. Tommasini, CERN

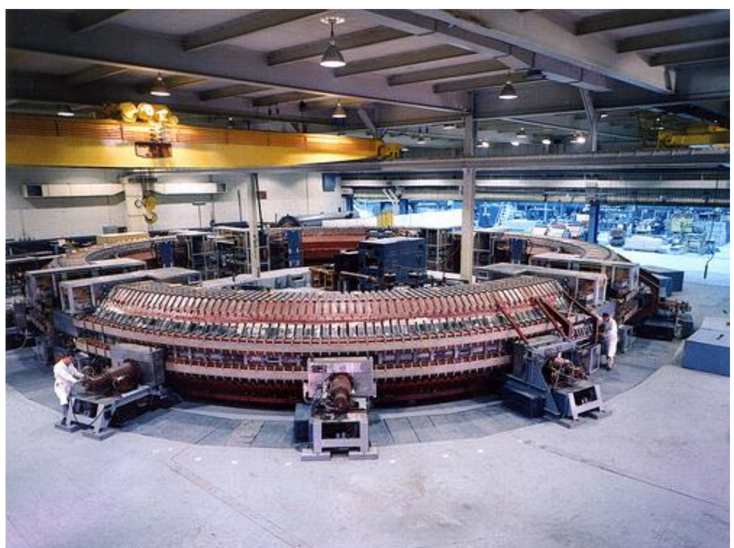
Examples of resistive magnets;

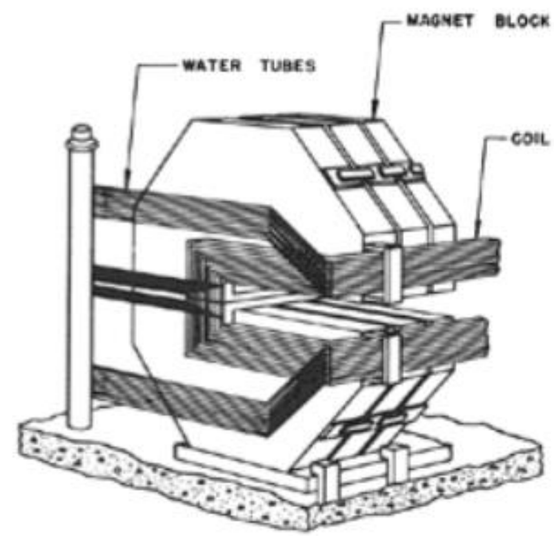
Some history, some modern regular magnets and some special cases

Some early magnets (early 1950-ies)

Bevatron
(Berkeley)
1954, 6.2 GeV

Cosmotron
(Brookhaven)
1953, 3.3 GeV
Aperture:
20 cm x 60 cm



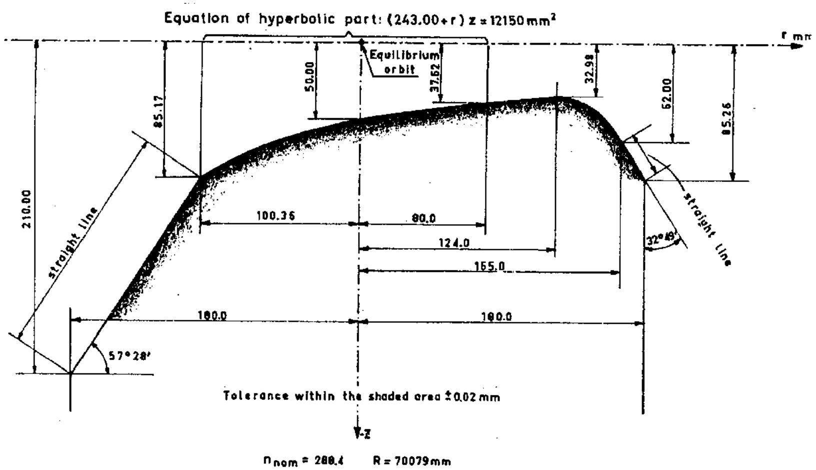


PS combined function dipole

Magnetic field:

at injection	147 G
for 24.3 GeV	1.2 T
maximum	1.4 T
Weight of one magnet unit	38 t

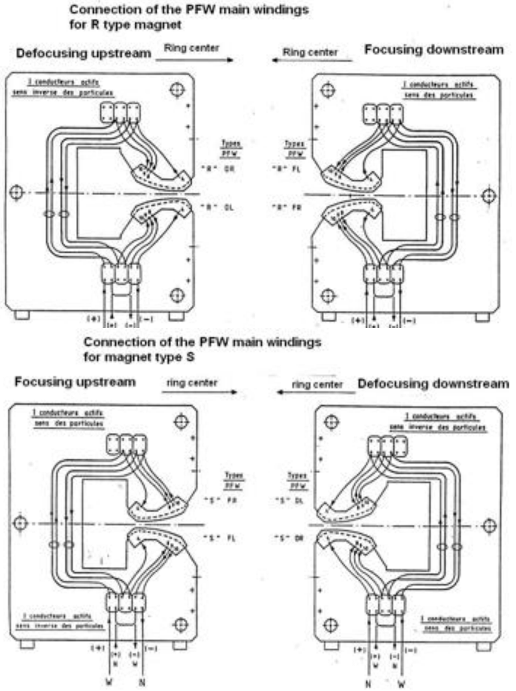
Gradient @1.2 T : 5 T/m



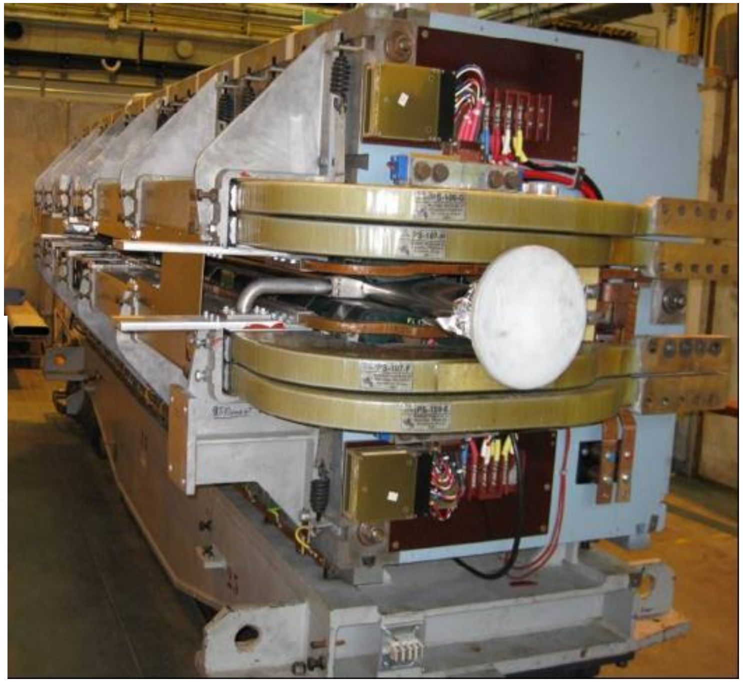
FINAL POLE PROFILE.

Fig. 9: Final pole profile.

Equipped with pole-face windings for higher order corrections



Water cooled Al race-track coils



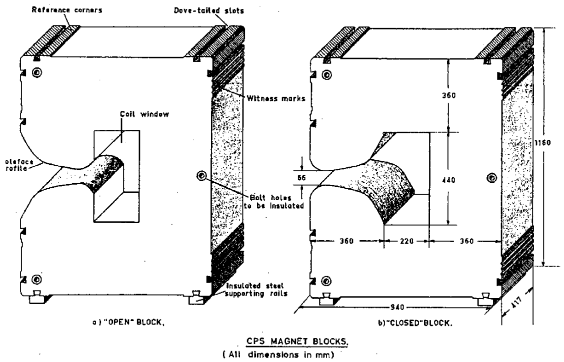


Fig. 12: Final form of the magnet blocks.

Courtesy D. Tommasini, CERN

dipole magnet : SPS dipole

H magnet   type MBB

B = 2.05 T

Coil : 16 turns

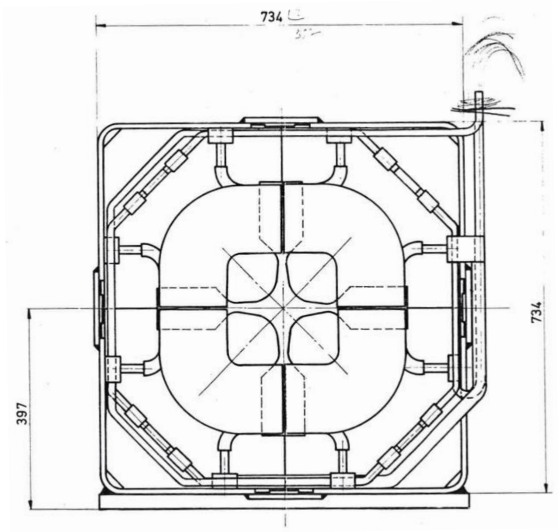
I_{max} = 4900 A

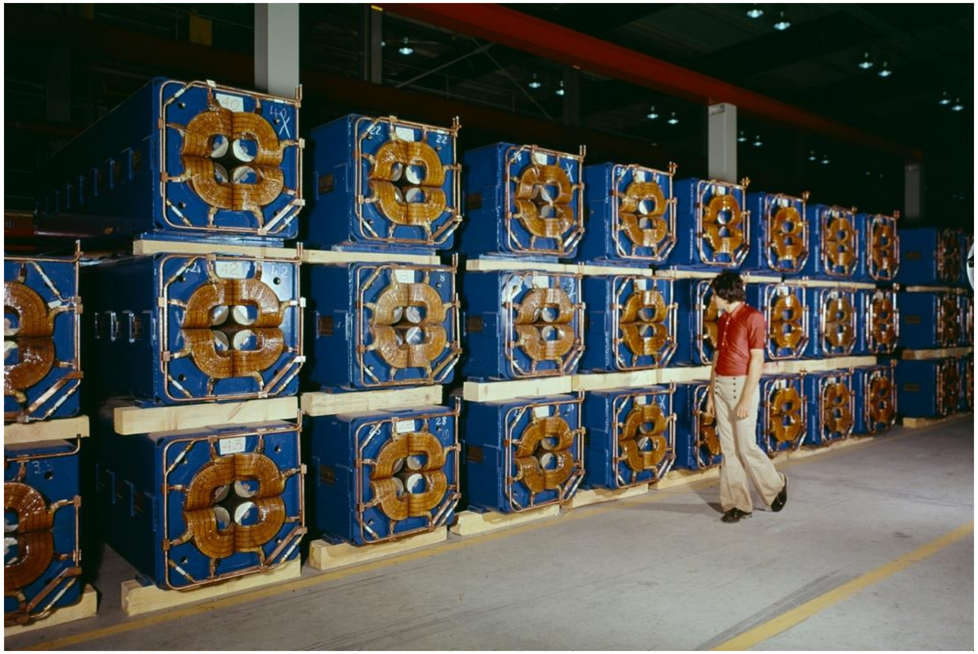
Aperture = 52 × 92 mm^2

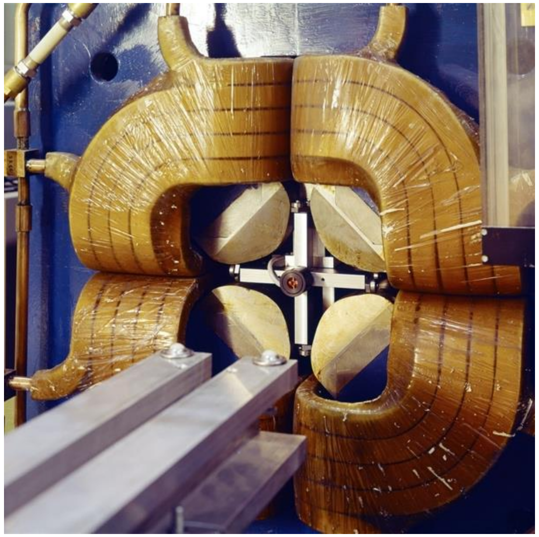
L = 6.26 m

Weight = 17 t

Quadrupole magnet : SPS quadrupole







type MQ

G = 20.7 T/m

Coil : 16 turns

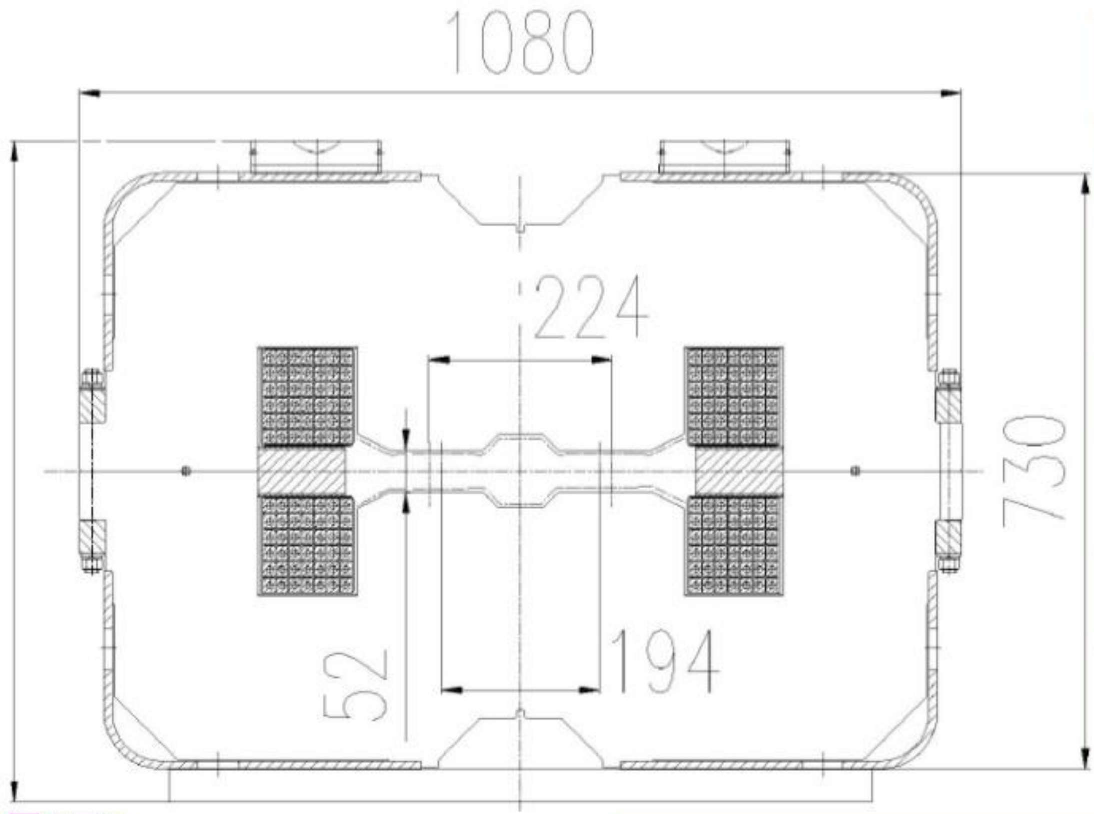
I_{max} = 1938 A

Aperture inscribed radius = 44 mm

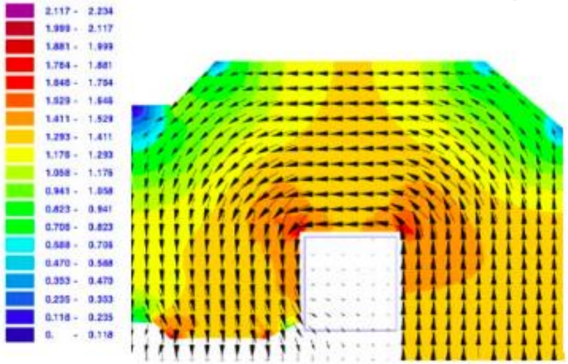
L_{coil} = 3.2 m

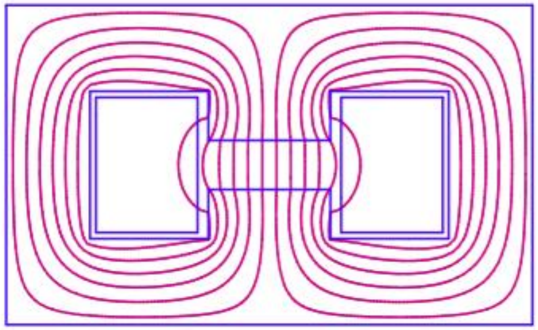
Weight = 8.4 t

MBW LHC warm separation dipole (1)

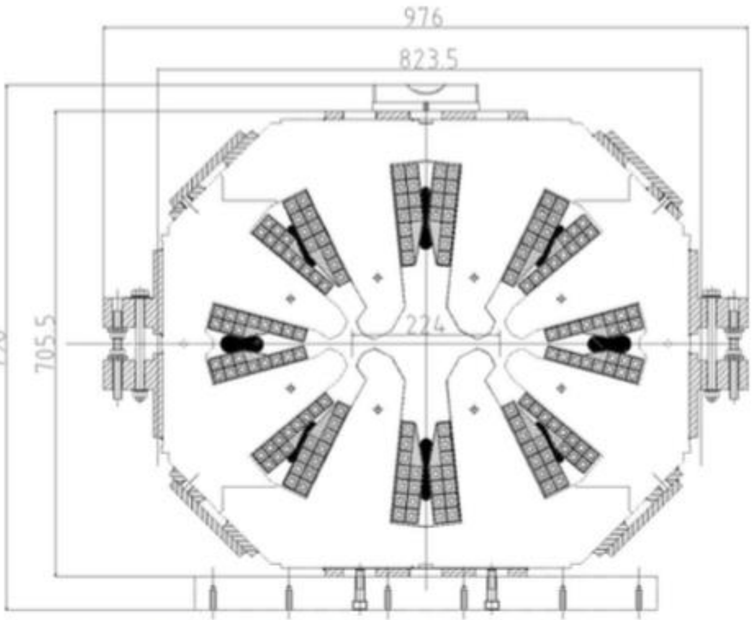


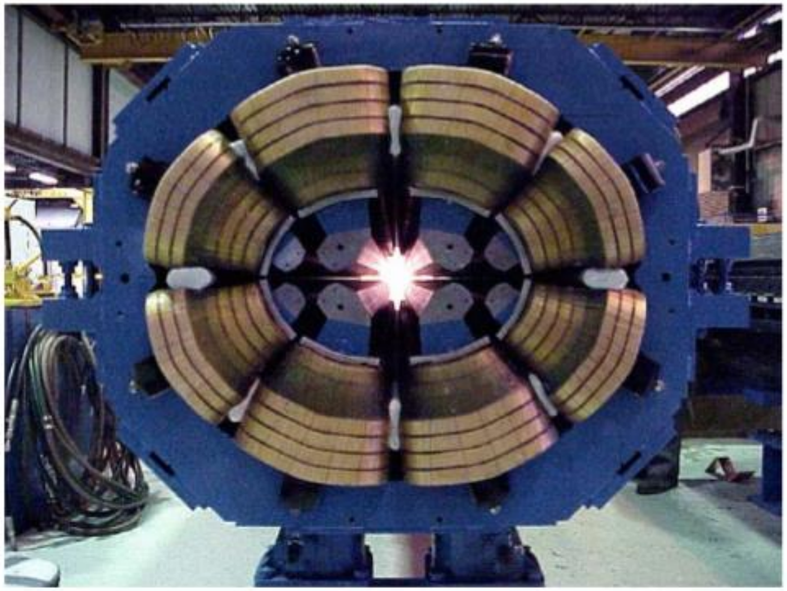
Parameter	Value
Aperture	52 mm
Nominal field	1.42 T
Magnetic length	3.4 m
Weight	18 t
Water flow	19 l/min
Power	29 kW





MQW: LHC warm double aperture quadrupole

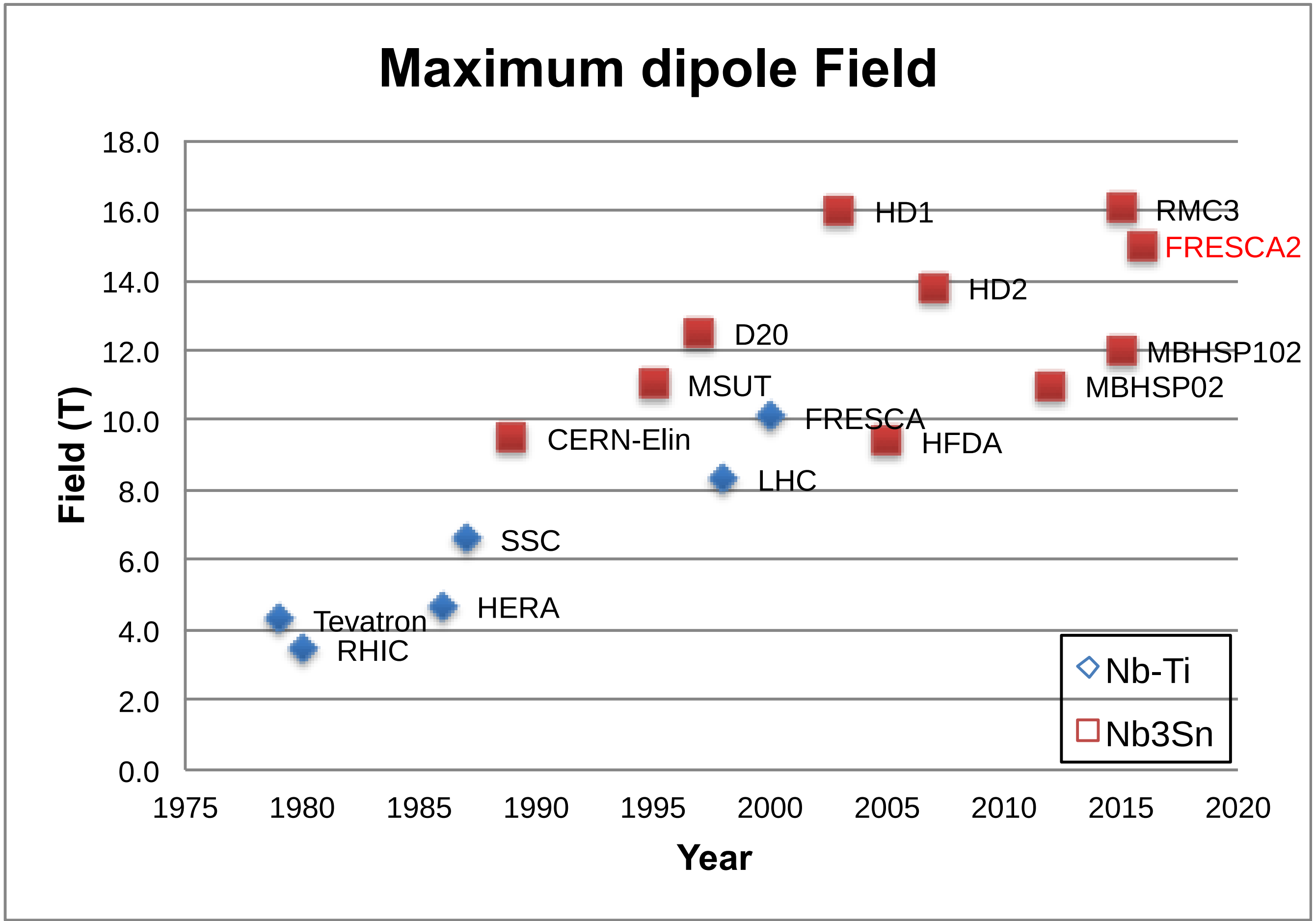




Superconducting magnets

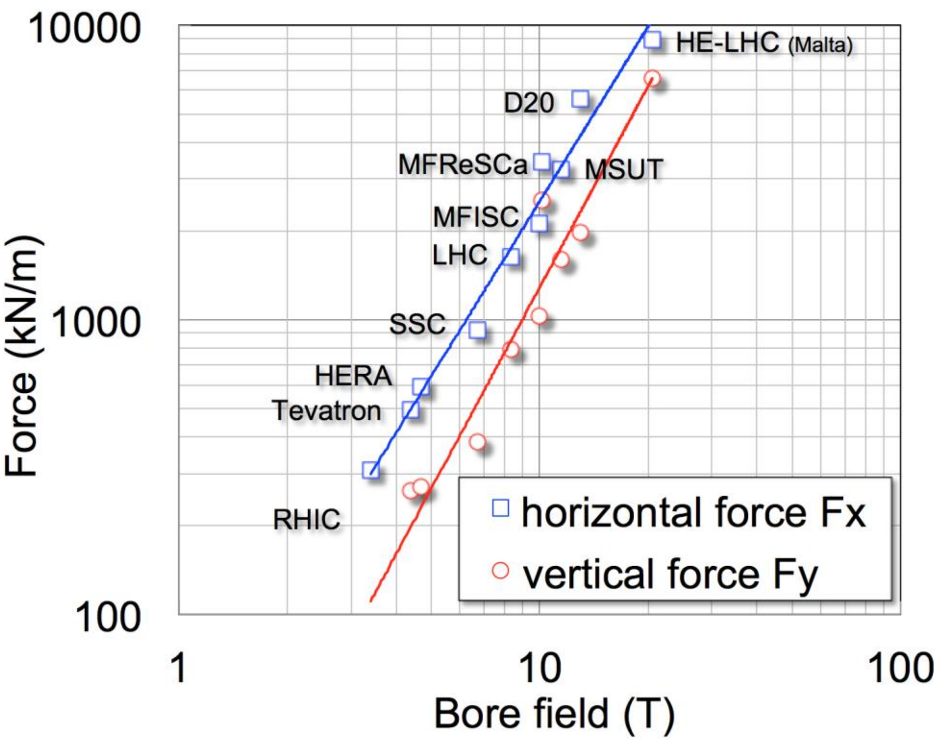
Superconducting accelerators magnets; the state of the art

- 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

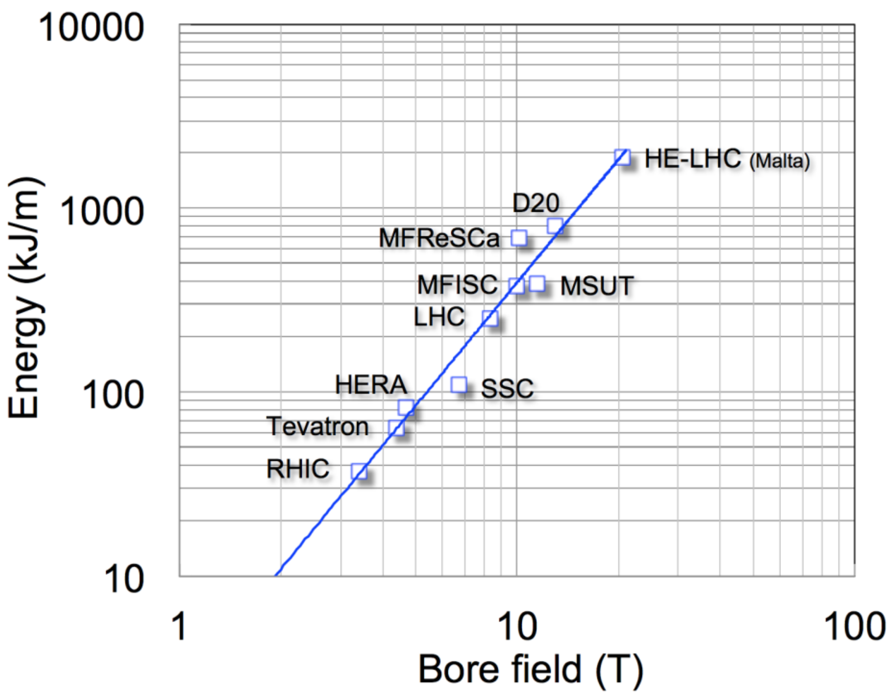


Forces and Stored Energy

Scaling of **forces** on coil quadrant vs. Field, for recent production and R&D dipoles



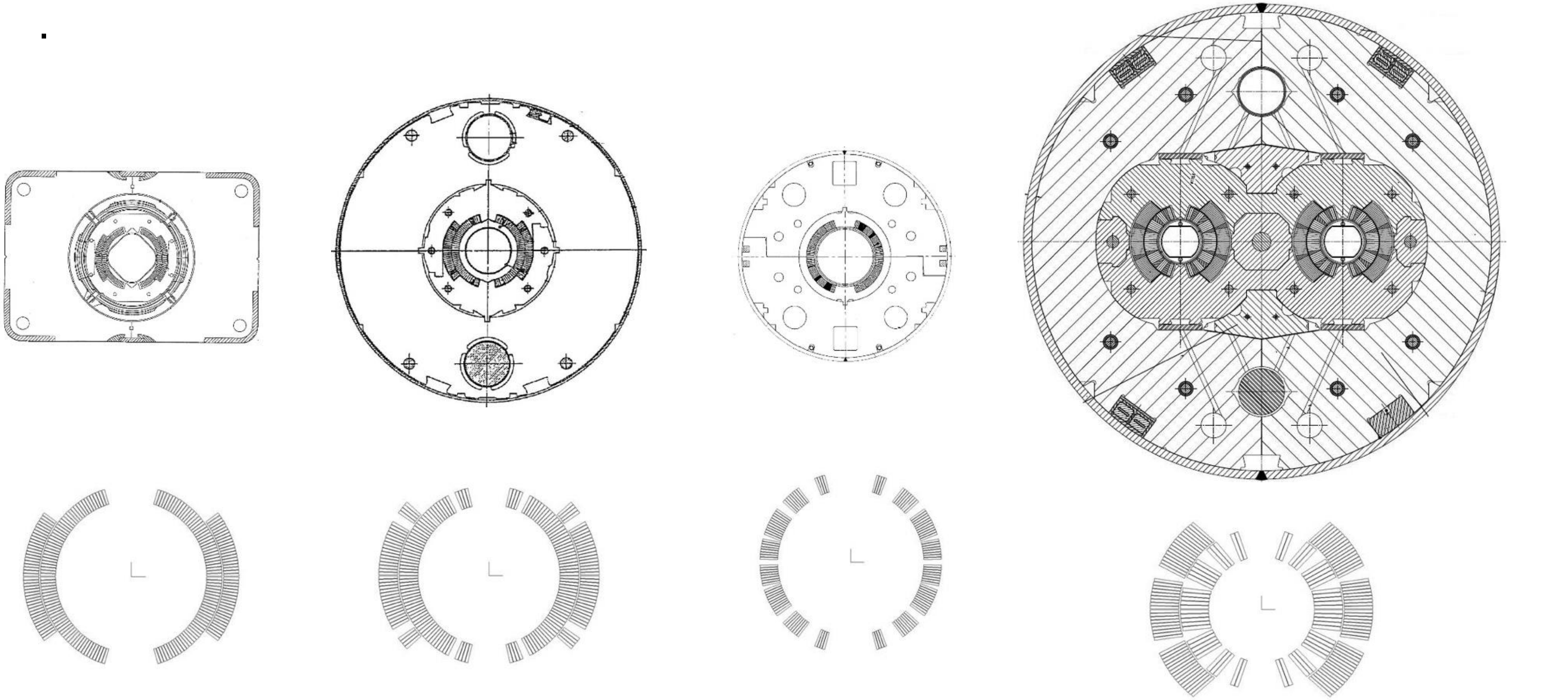
Scaling of the **stored energy** per unit length of magnet vs. Field, for recent production and R&D dipoles



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

Existing Superconducting Accelerator dipole magnets (1)

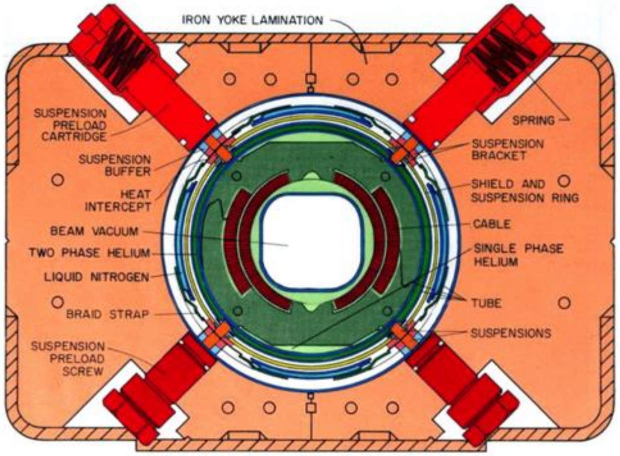
- .



Tevatron	HERA	RHIC	LHC
76 mm bore	75 mm bore	80 mm bore	56 mm bore
B = 4.4 T	B = 5.0 T	B = 3.5 T	B = 8.34 T
T = 4.2 K	T = 4.5 K	T = 4.3-4.6 K	T = 1.9 K
first beam 1983	first beam 1991	first beam 2000	first beam 2008

Courtesy P. Ferracin, CERN

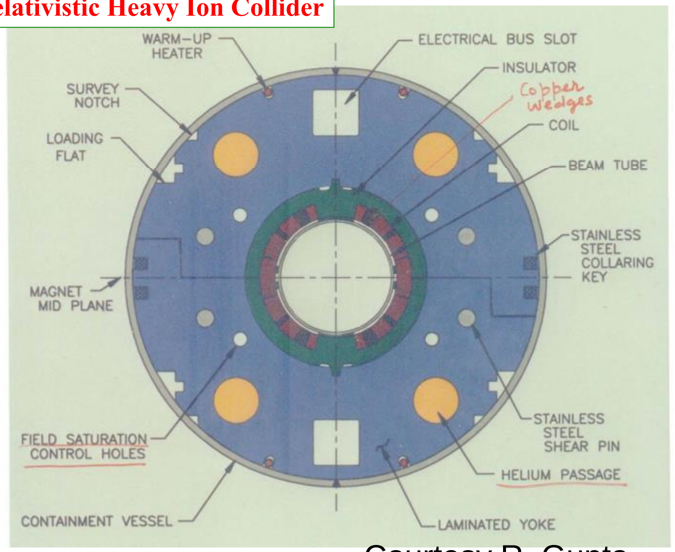
Existing Superconducting Accelerator dipole magnets (2)



Tevatron: 4.4 T

1983

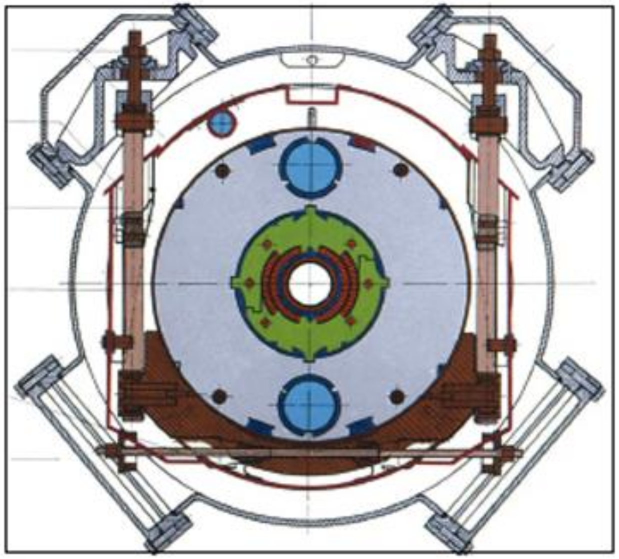
RHIC: Relativistic Heavy Ion Collider



RHIC: 3.5 T

2000

Courtesy R. Gupta

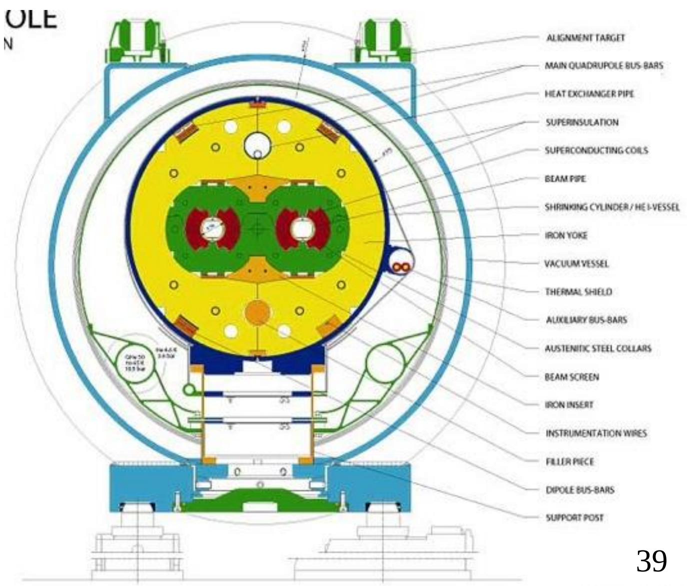


HERA: 5 T

1992

LHC: 8.34 T

2008



CAS Basics, Chavannee-de-Bogis, 7-Febr-2017, Magnets, GdR

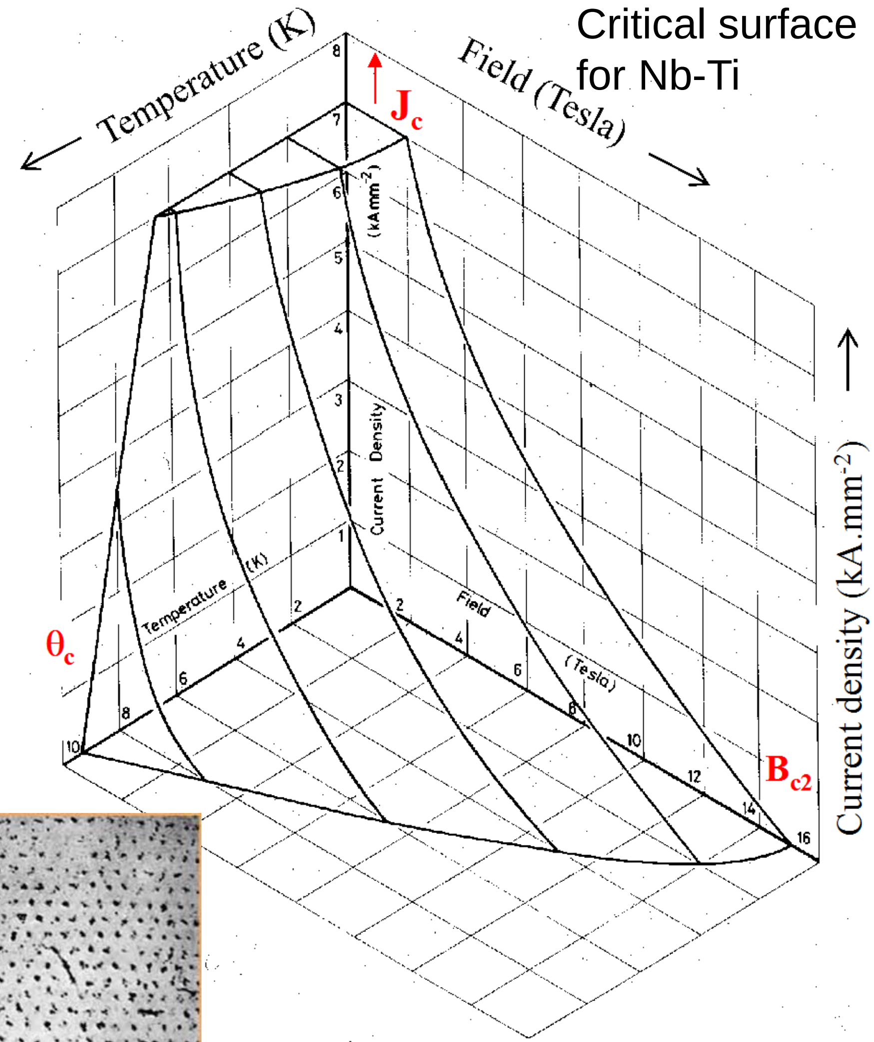
Type II Superconductors

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

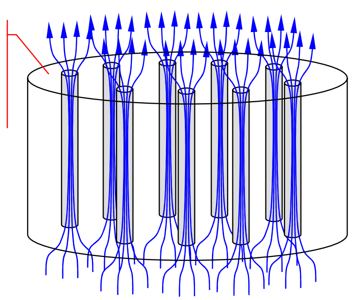


Courtesy M. Wilson

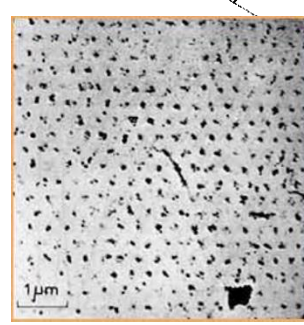
Superconducting means: R = 0

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

Type II



Courtesy L. Bottura

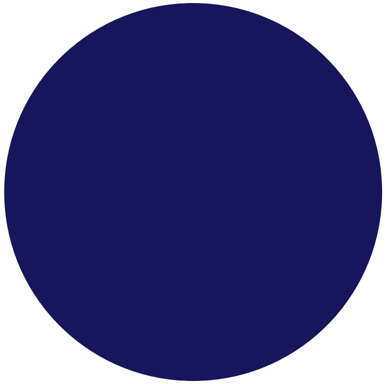


Quantized fluxoids in a superconductor

Superconductivity

Typical operational conditions (0.85 mm diameter strand)

Cu

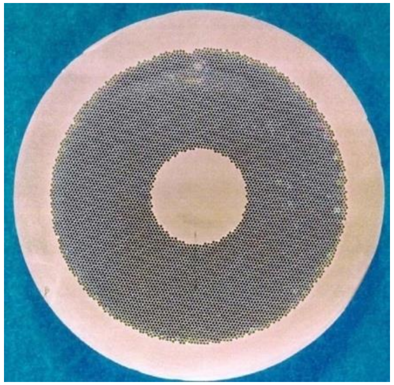


J ~ 5 A/mm^2

I ~ 3 A

B = 2 T

Nb-Ti



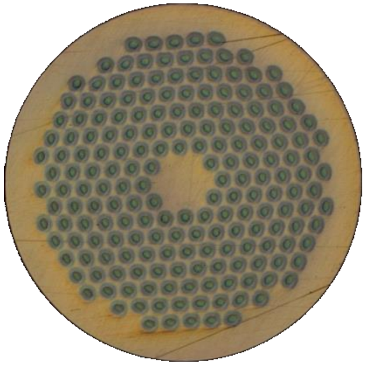
J ~ 1500-2000 A/mm^2

I ~ 400 A

B = 8-9 T

- Nb-Ti: ductile alloy: easy to process by extrusion and drawing
- T < 9 K it becomes a type II superconductor.
  - T_C ~9.2 K @ 0 T ; B_{C2} ~14.5 T @ 0K
- Cost: appr. 100-150 US$/kg of wire

Nb_3Sn



J ~ 1500-2000 A/mm^2

I ~ 400 A

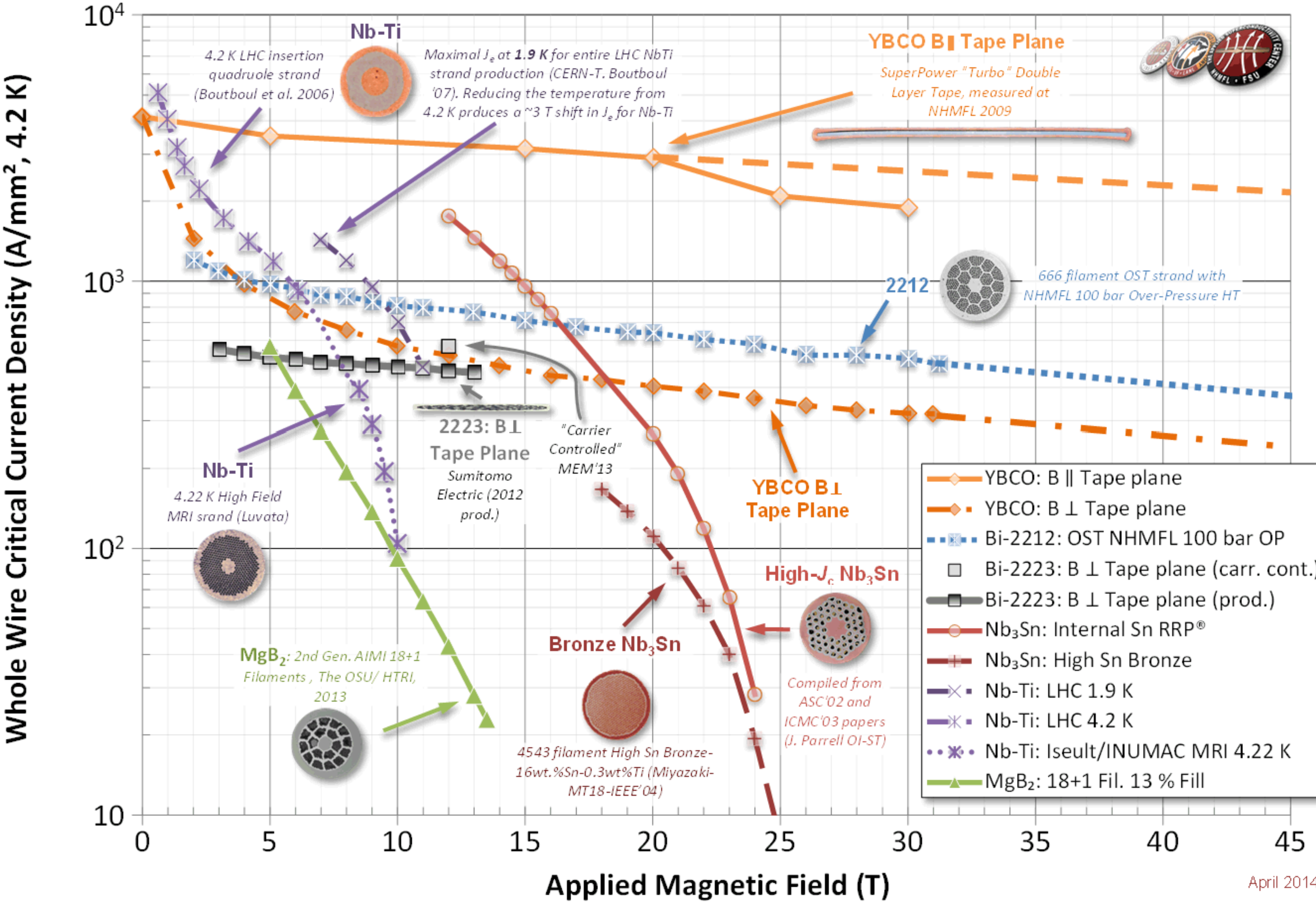
B = 12-13-16 T

- Nb_3Sn: Brittle and strain sensitive
- T < 18 K it becomes a type II superconductor.
  - T_C ~18 K @ 0 T; B_{C2}~28 T @ 0K

  Cost: appr. 700-1500 US$/kg of wire

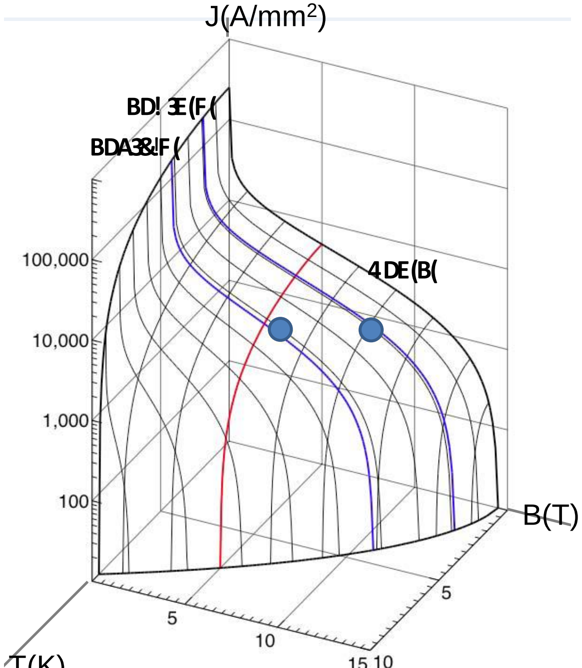
Courtesy P. Ferracin, CERN

Available Superconductors



Superconducting strands: Nb-Ti

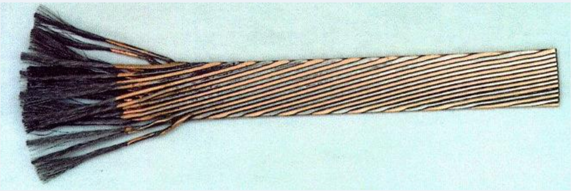
- Nb-Ti is the workhorse for present accelerators, medical magnets, cyclotrons, etc

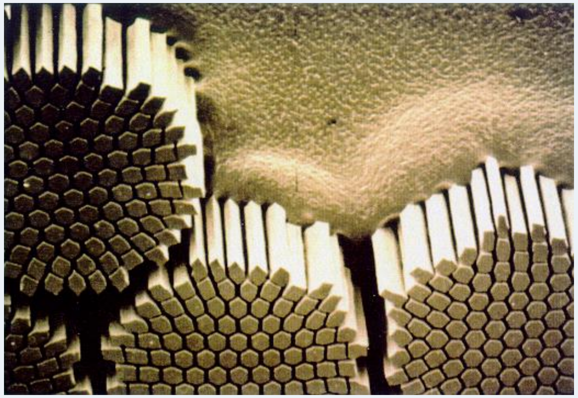


Strands and Cables for LHC Dipole Magnets

Performance specification

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

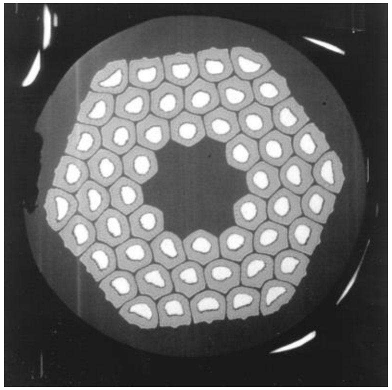




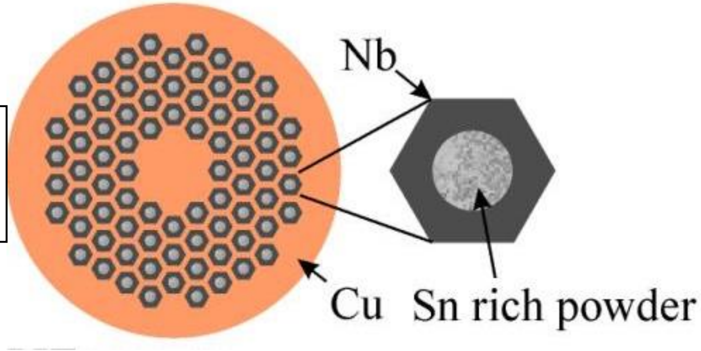
Cable compaction ~ 91 %

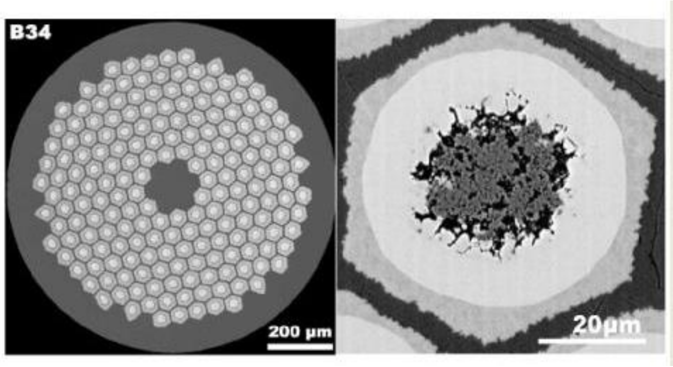
Multifilament wires
Fabrication of Nb_3Sn multifilament wires

- 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: Nb and Sn
  - 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



Powder in tube (PIT) process



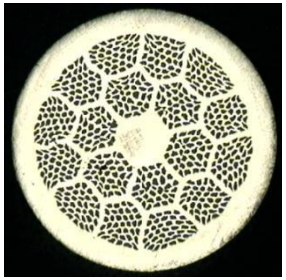


Courtesy P. Ferracin, CERN

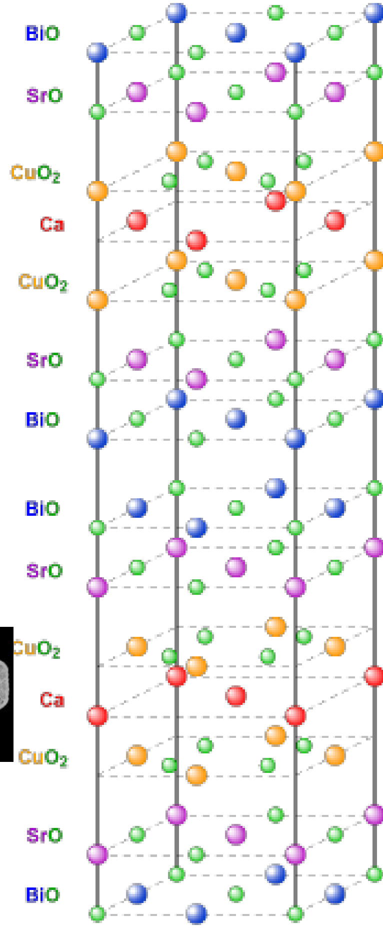
Superconducting strands and tapes: BSCO

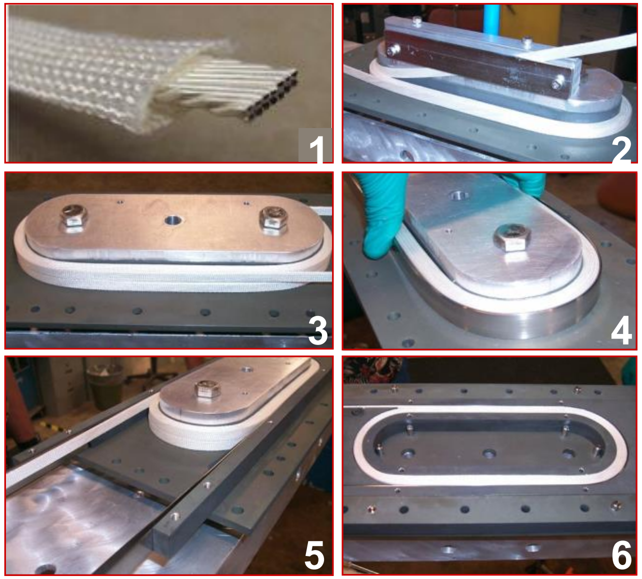
BSCO: Bismuth strontium calcium copper oxide

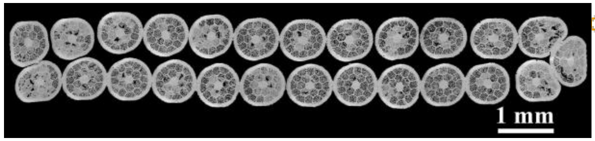
- Available in strands (OST)
- Can reach 400 A/mm^2 (overall)
- Is fragile under stress and strain
- Powder in a silver tube
- Has to be reacted at 850° C with a temperature precision of 1° C in an oxygen atmosphere
- Can be cabled in high current Rutherford cables



OST wire 0.8 mm using Nexans precursor





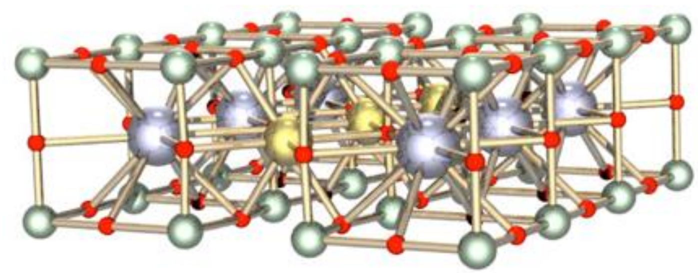


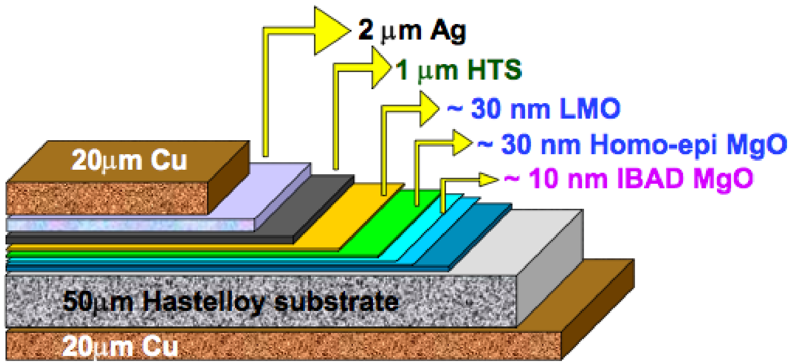
Difficult technology but could be promising for high field magnets in >20 T region

Superconducting tapes: YBCO

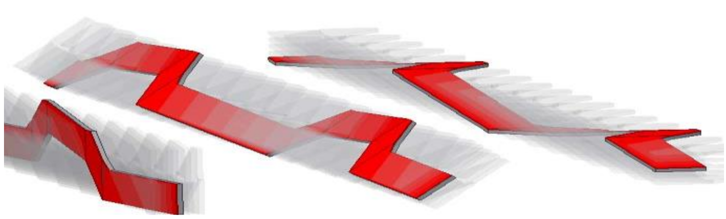
YBCO: Yttrium barium copper oxide

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





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



Potted racetrack coils

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

Superconducting cables for magnets

We need multi-strand cables

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

  ➔ a 1 mm diameter strand can carry ~400 A

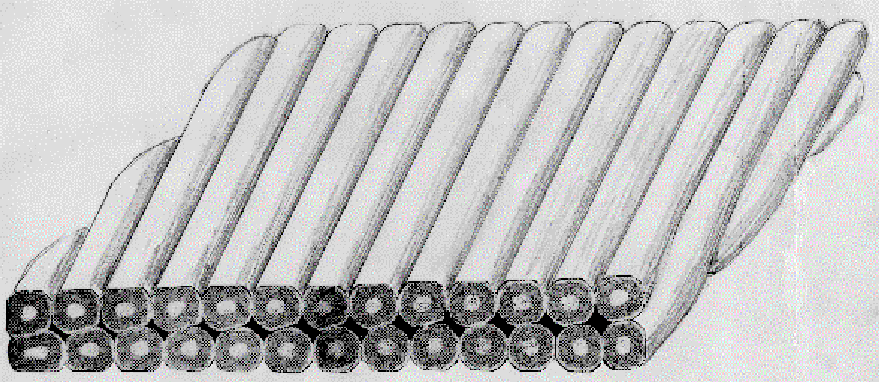
  ➔ so we need a 30 strand cable to get up to 12 kA

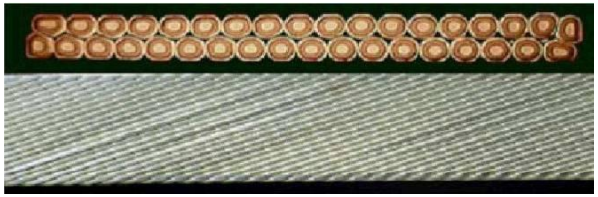
$$V = -L\frac{dI}{dt}$$

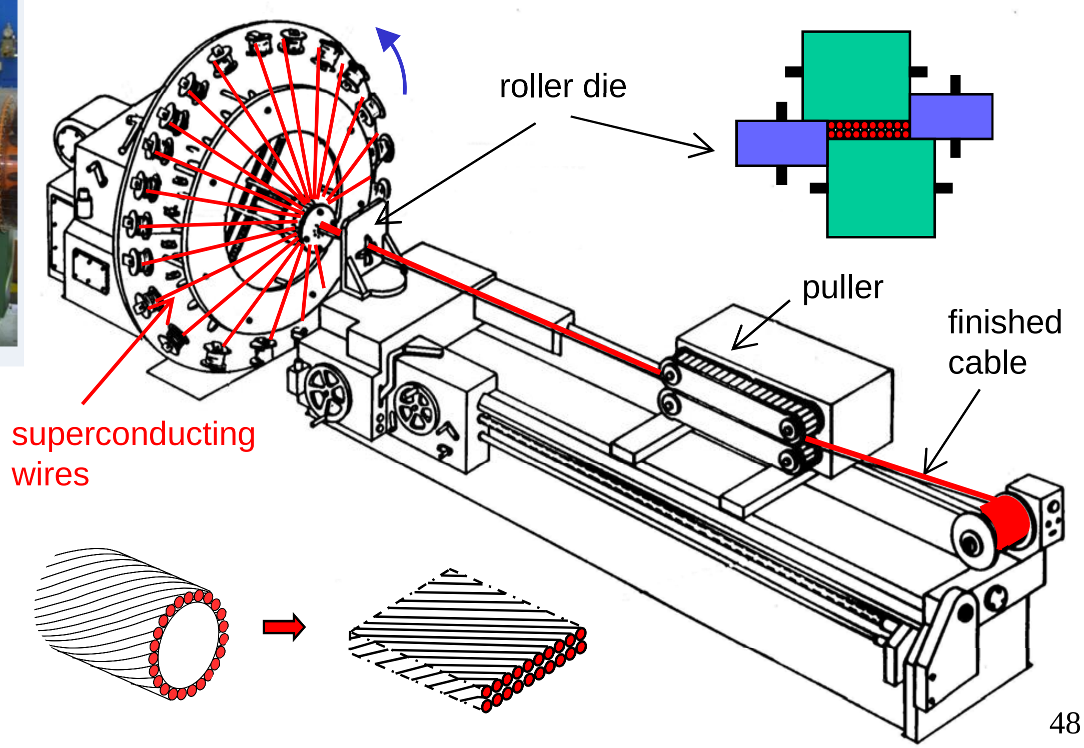
$$L \gg N^2$$

Rutherford cables

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







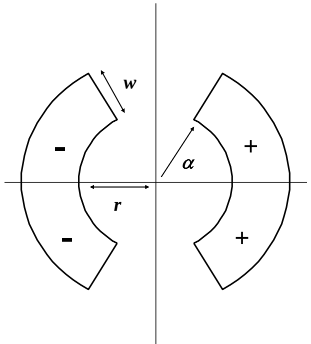
How to get high fields in accelerator dipole and quadrupole magnets ?

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***

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

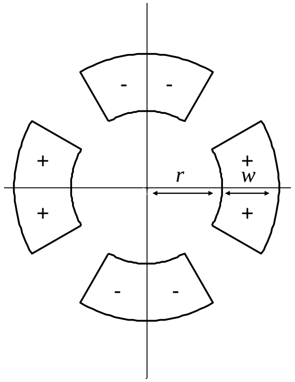
with: r : inner radius coil
w : coil width
ρ : radial coordinate
J : current density



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]

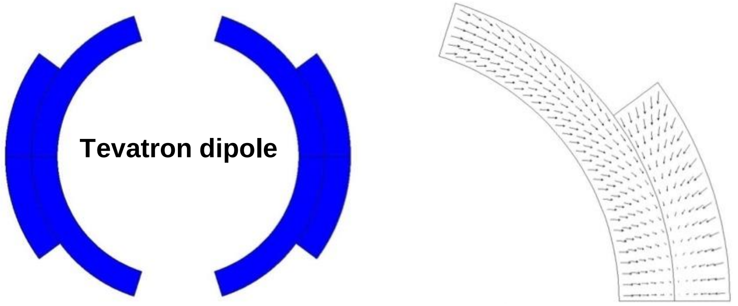
Electro-magnetic forces

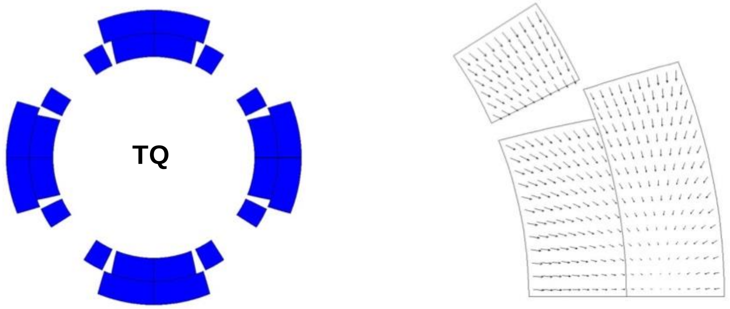
The e.m. forces in a dipole magnet tend to push the coil

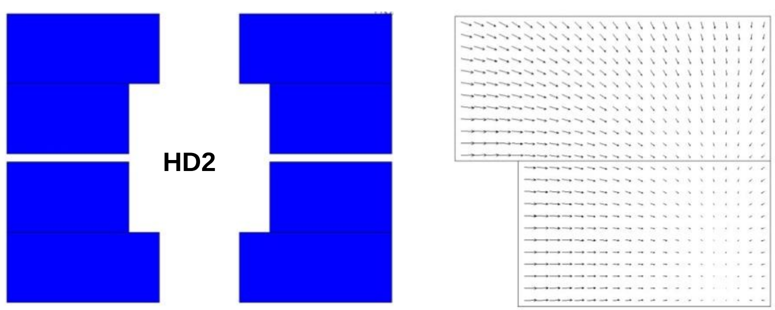
- Towards the mid plane in the vertical-azimuthal direction (F_y, $F_\theta < 0$)
- Outwards in the radial-horizontal direction (F_x, $F_r > 0$)

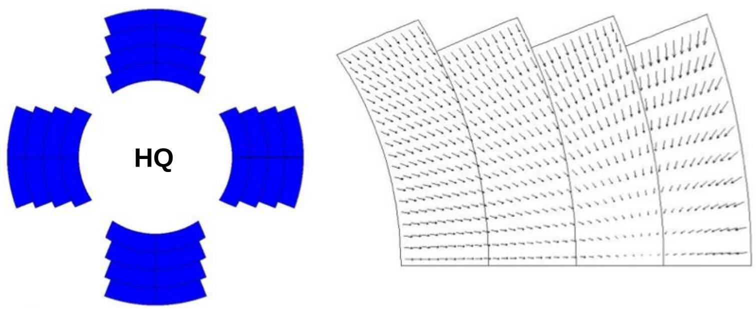
The e.m. forces in a quadrupole magnet tend to push the coil

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





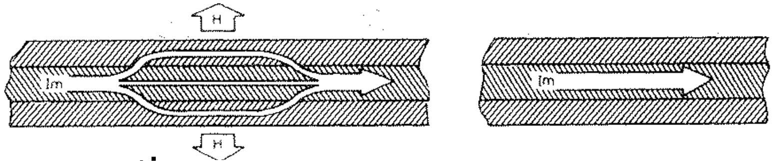




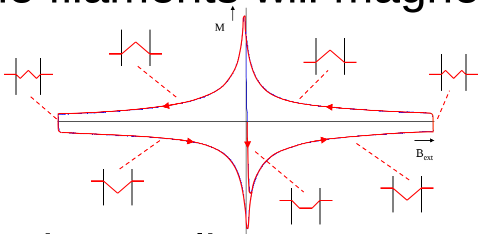
Courtesy P. Ferracin, CERN

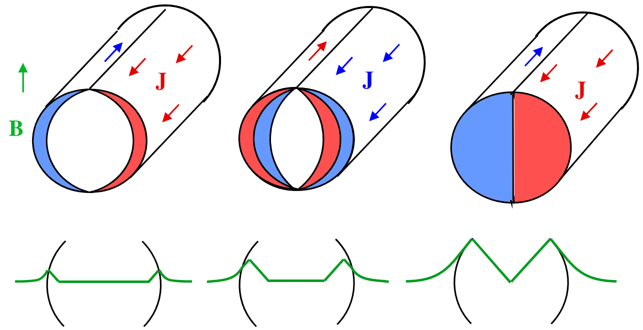
Conductor stability and AC behaviour

- 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

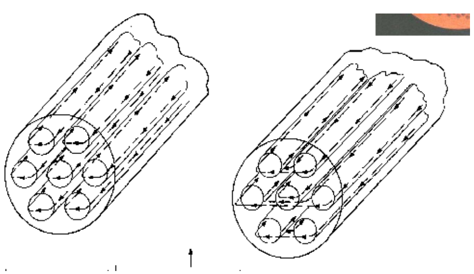


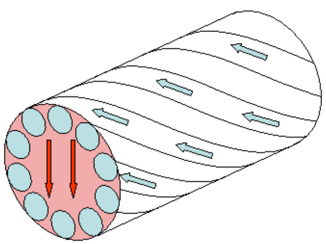
- During current ramping the filaments will magnetize
  ➔ make them thinner



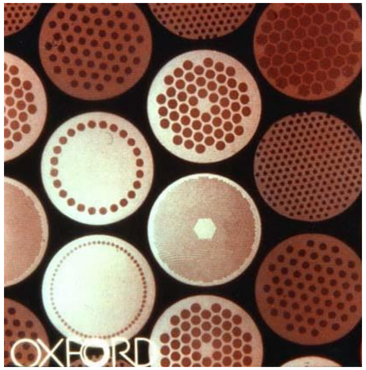


- Filaments will have magnetic coupling
  ➔ twist the strand





Courtesy M. Wilson

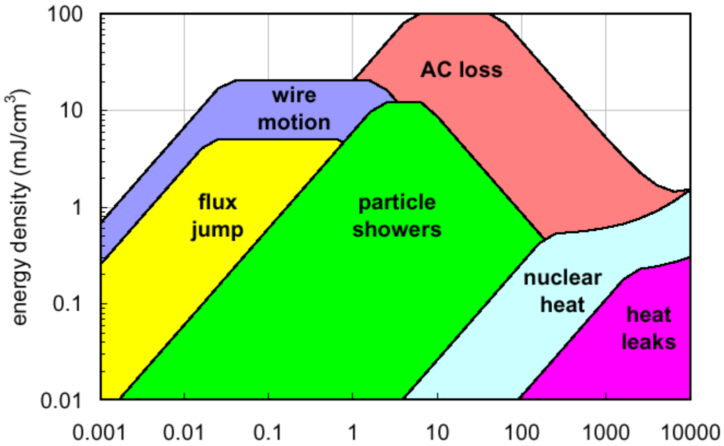


- Practical low temperature superconductors are made as thin (5 μm – 100 μm) superconducting filaments in a Cu matrix , which is twisted

Quench: a thermal runaway effect

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

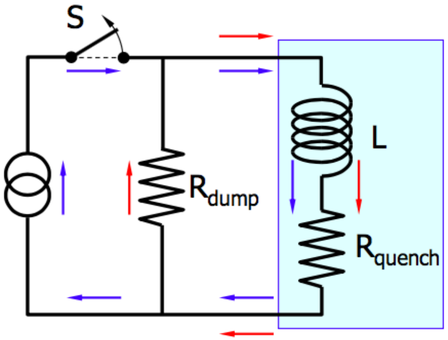
A thermal runaway can then occur, called a **Quench**

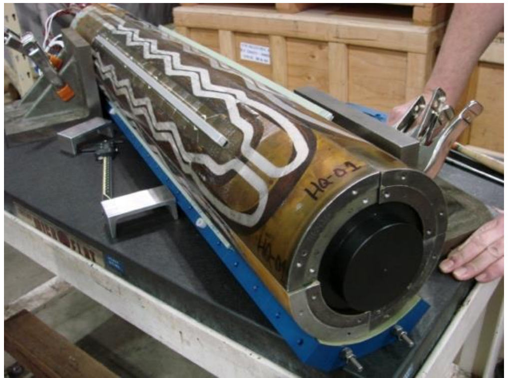


With stored energies > MJ the coils can overheat if nothing is done (T = 3000K is possible !)

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

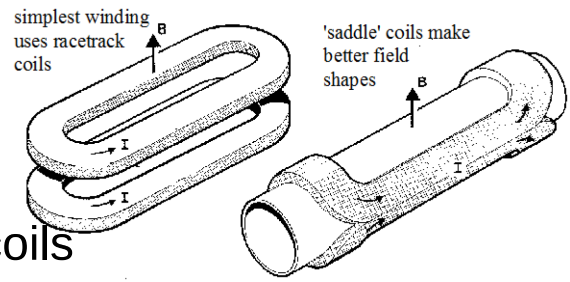




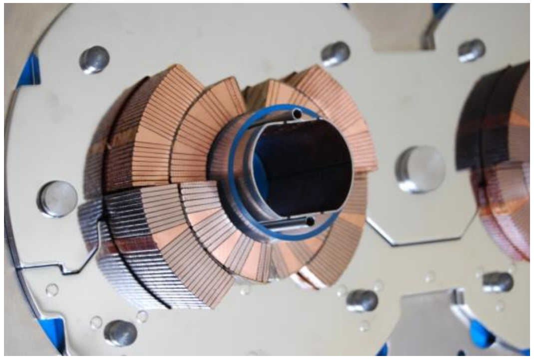
Practical accelerator magnet design: Dipoles

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

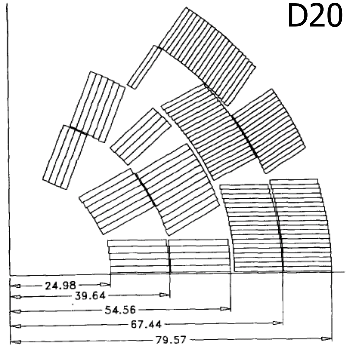
Cos(Θ) coil and *Block coil*



- 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



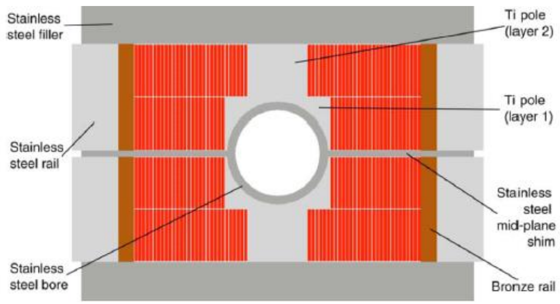
Courtesy M. Wilson



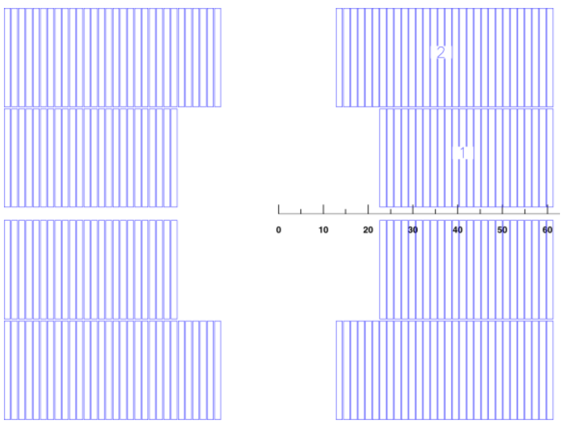
Courtesy LBNL

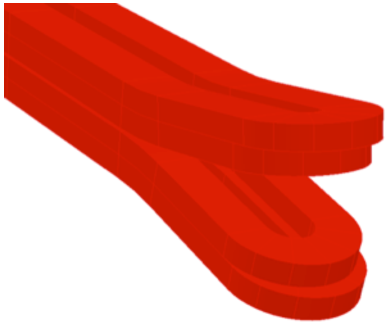
Practical accelerator magnet design: Dipoles

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



HD2





Courtesy LBNL

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:

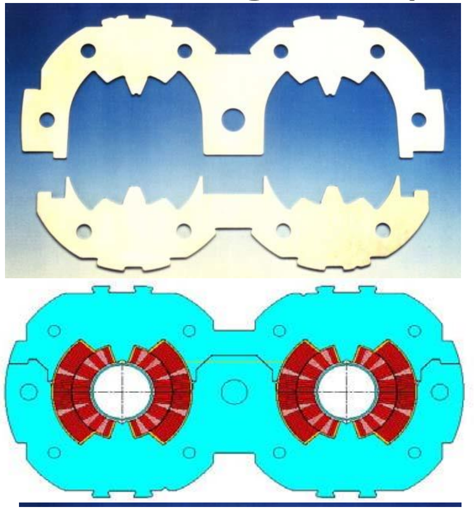
  1. Compress at room temperature: collar system
  2. Use room temperature pre-stress plus differential shrinkage at cool-down: Al or stainless steel shrinking cylinder and/or a (shrinking) key
  3. Compress a bit at room temperature and use differential shrinkage at cool-down: Al shrinking cylinder +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

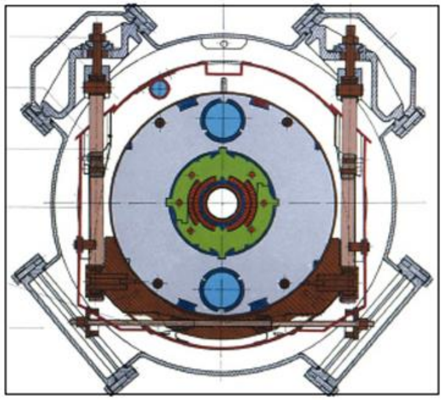
Prestress: collars

"The classical solution"

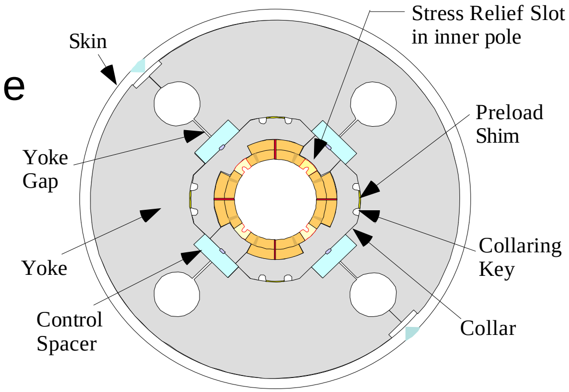
- Thin collars put around the coil
- The coil is well contained in a fixed cavity
- Pressed together and locked with pins or keys
- At 300K apply a prestress 2-3 times of what is needed as part of the stress is lost during cooldown: for very high field tends to be too high (LHC:70 MPa at 300 K and 40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



LHC dipole
CERN



Hera dipole
DESY



TQC quadrupole
LARP-FNAL

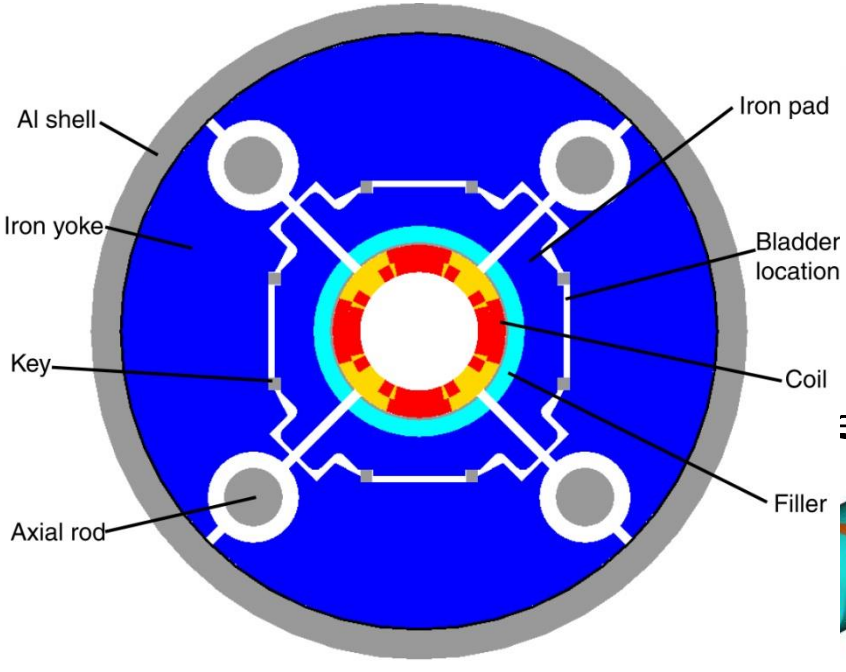
Prestress: Al shrinking cylinder + bladder and keys

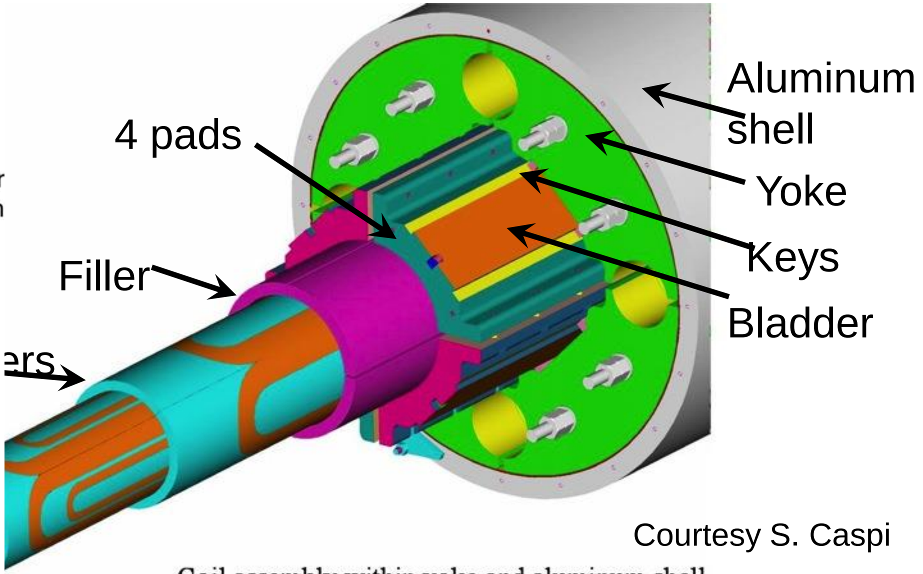
Developed at LBNL, example: TQS a LARP model quadrupole

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 cooldown





Coil assembly within yoke and aluminum shell

Courtesy S. Caspi

CAS Basics, Chavannee-de-Bogis, 7-Febr-2017, Magnets, GdR

Looking in the kitchen of future SC magnet development

What is happening after the 8T magnets for LHC ?

At CERN

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

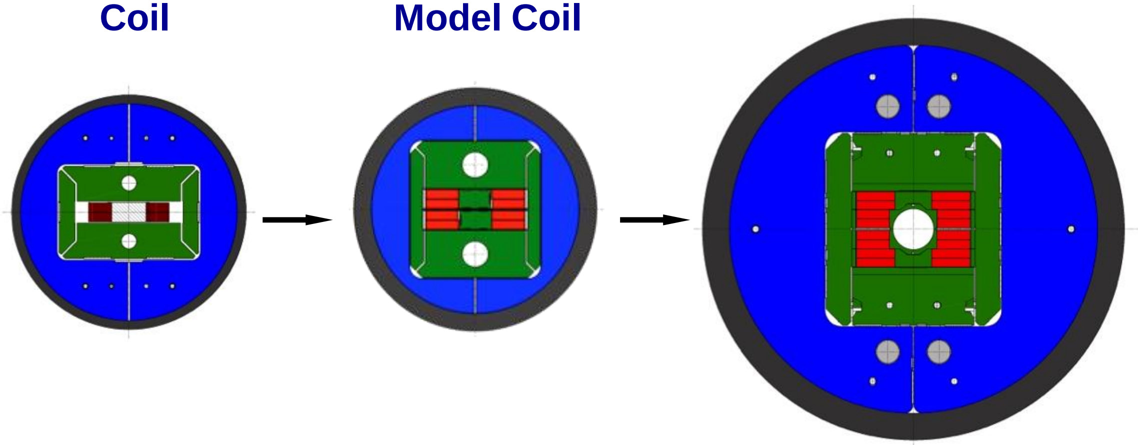
In China

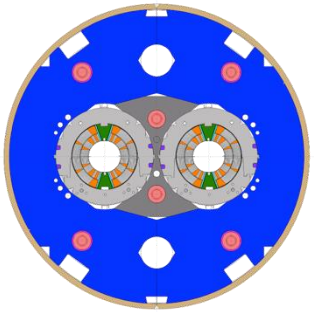
A similar completely new project is being studied in China: SPPC (C=54 km, B=20 T, E_{com}=71 TeV)

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

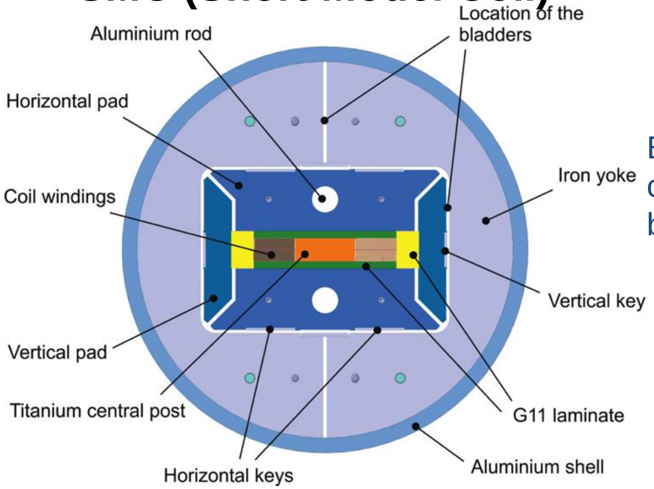
Short Model Coil | **Race-track Model Coil** | **FReSCa2 13T Nb_3Sn Dipole**



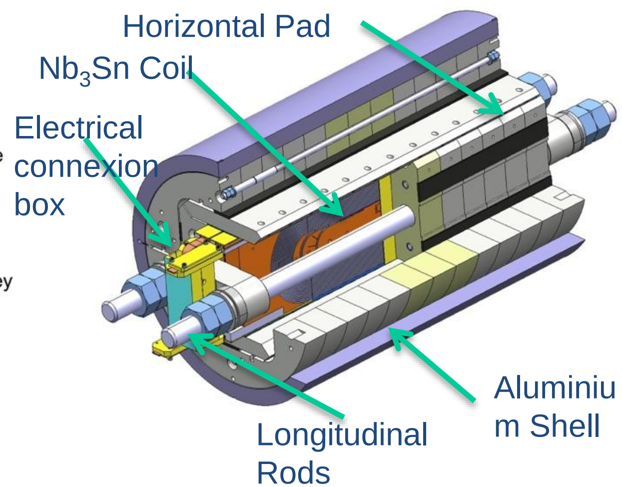


11 T dipole (CERN)

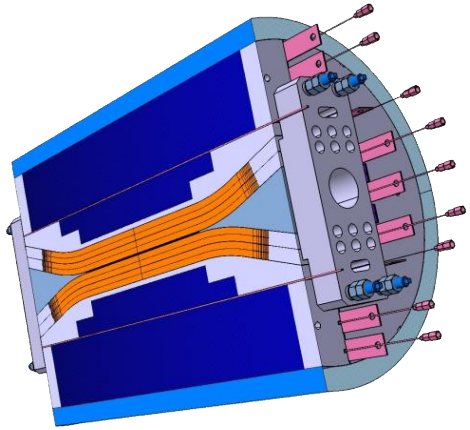
SMC (Short Model Coil)



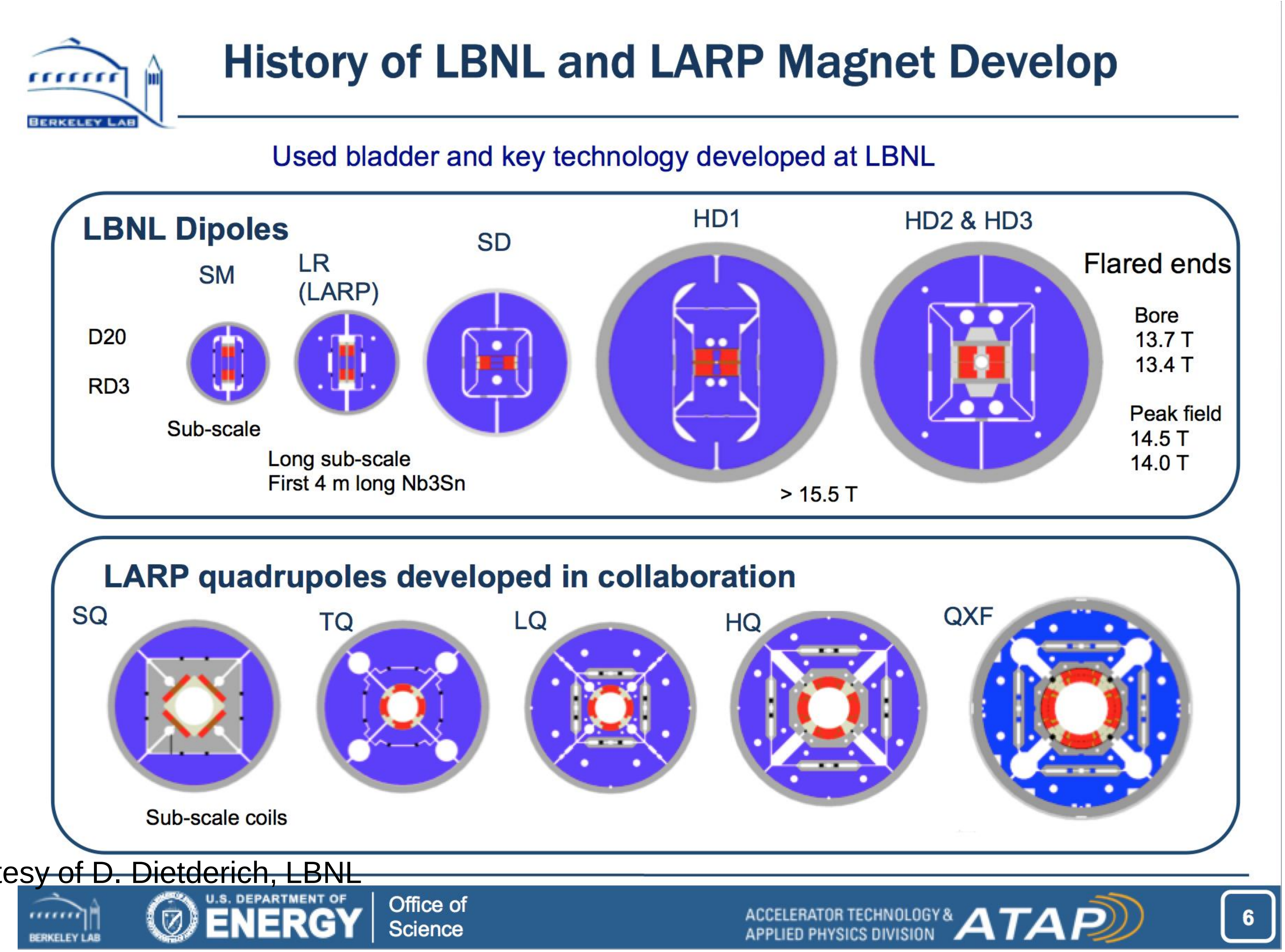
RMC (Racetrack Model Coil)



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, cosQ 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

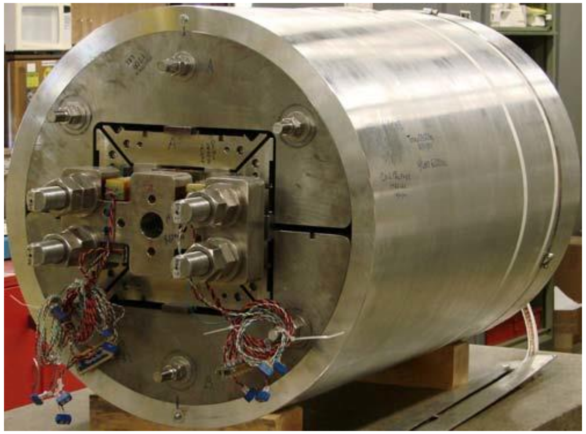


Fig. 1. HD2 assembled and pre-loaded.

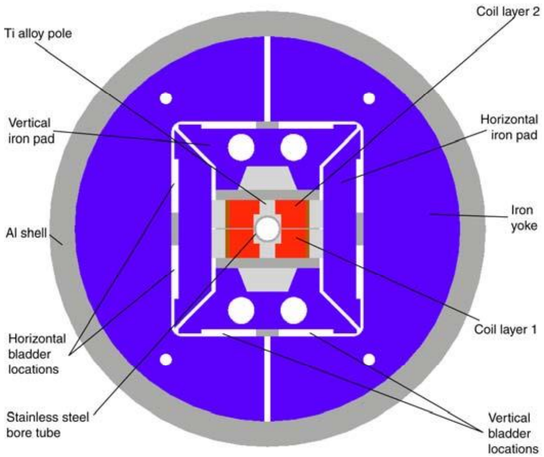
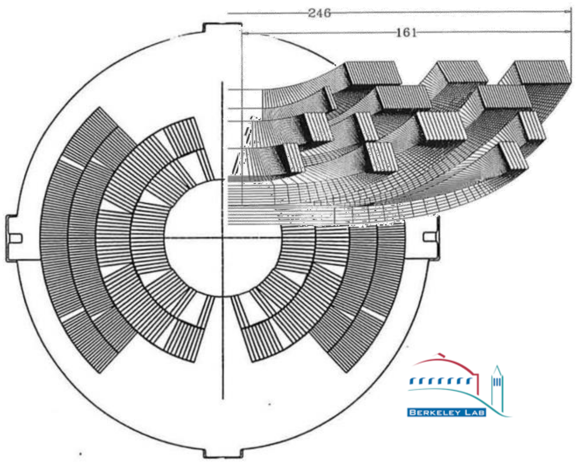


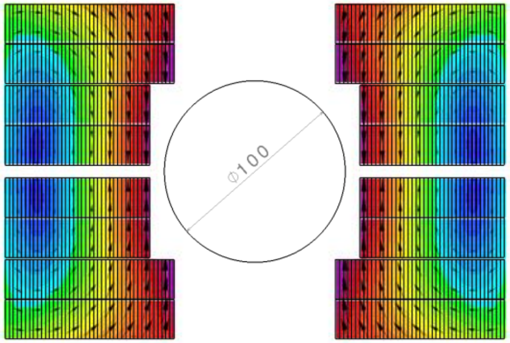
Fig. 2. HD2 cross-section.

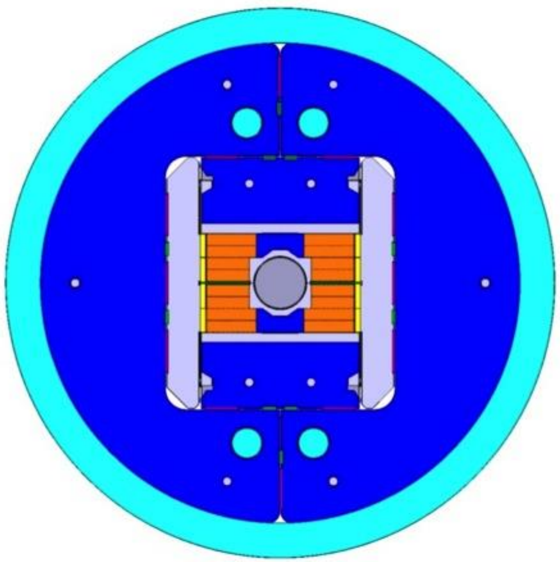


A.D. McInturff, et al., Proc. of PAC 1997, 3212

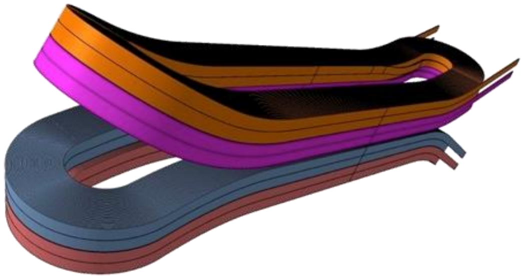
Basic HFM development : EuCARD high field dipole (Fresca2):

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

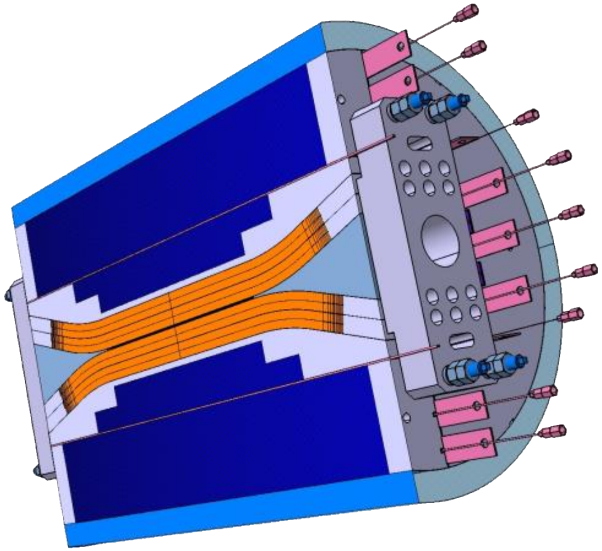




- 156 turns per pole
- Iron post
- B_{center} = 13.0 T
- I_{13T} = 10.7 kA
- B_{peak} = 13.2 T
- E_{mag} = 3.6 MJ/m
- L = 47mH/m



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

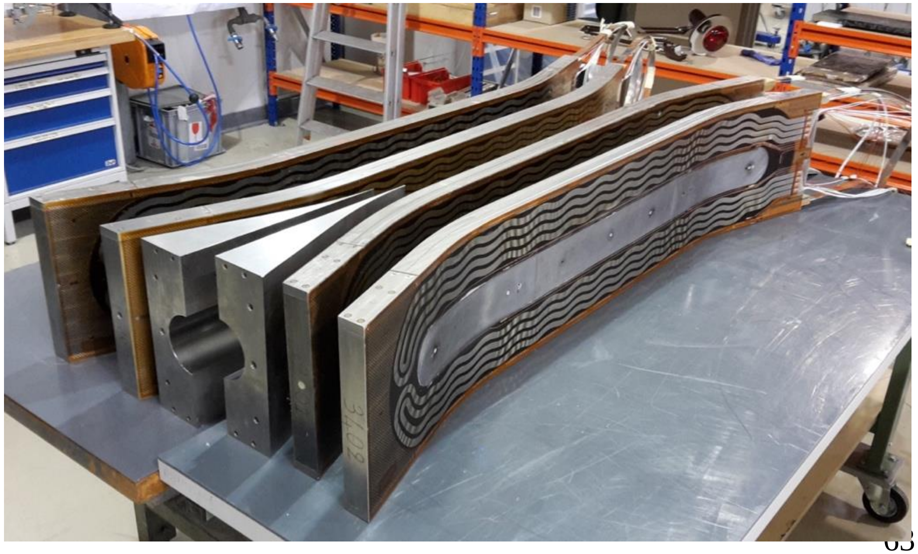


Courtesy Attilio Milanese, Pierre Manil

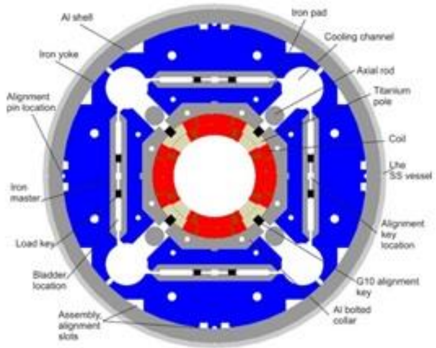
Fabrication of Fresca2 coils

Straightforward technology to wind block coils with flared ends:

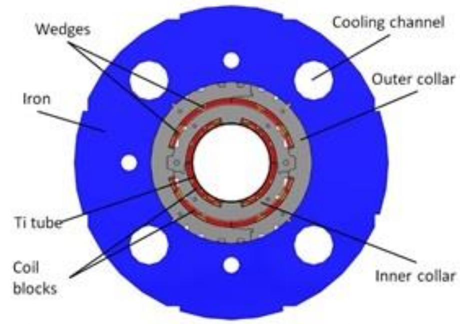
This is a lesson for FCC magnets !



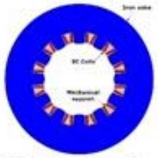
HILUMI IT magnet zoo



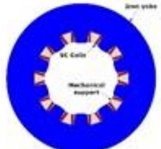
Triplet [G. Ambrosio, P. Ferracin et al.]



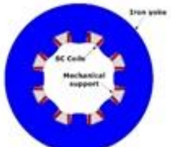
MCBXFB [F. Toral, et al.]



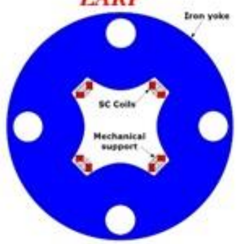
Dodecapole



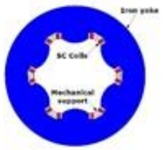
Decapole



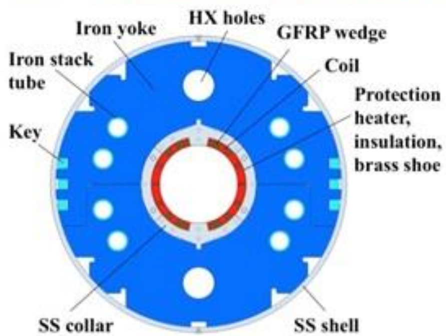
Octupole



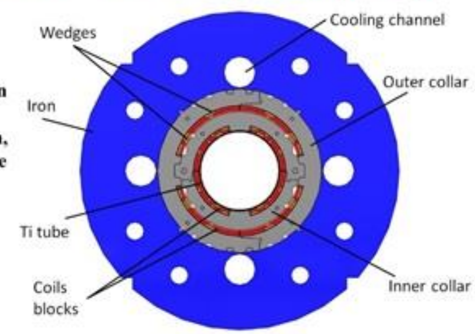
Skew quad



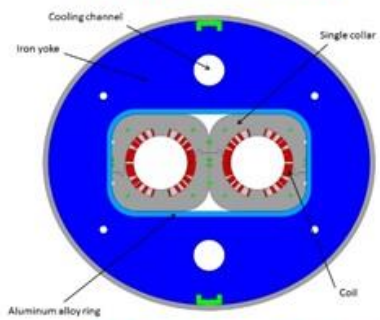
[G. Volpini, et al.]



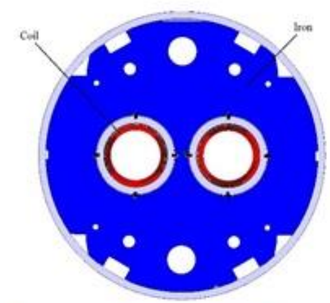
D1 [T. Nakamoto et al.]



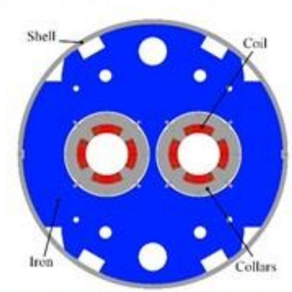
MCBXFA [F. Toral, et al.]



D2 [P. Fabbricatore, S. Farinon]



D2 Q4 correctors [G. Kirby]



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

HL-LHC: MQXF low beta Nb_3Sn quadrupole

Spring 2016 the first model achieved the nominal and ultimate field at FNAL !

A CERN LARP collaboration.

Nominal Gradient 132.6 T/m

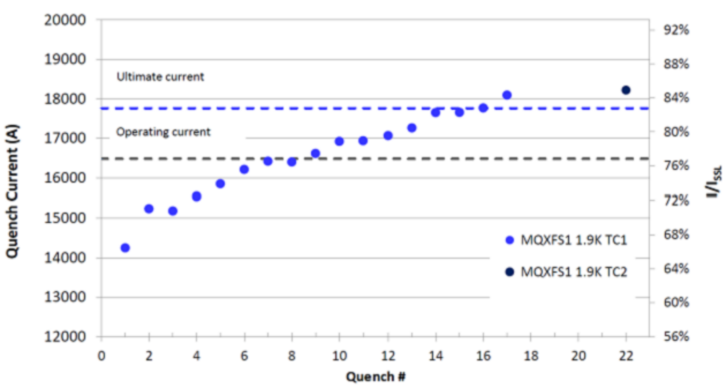
Aperture diameter 150 mm

Peak Field 12.1 T

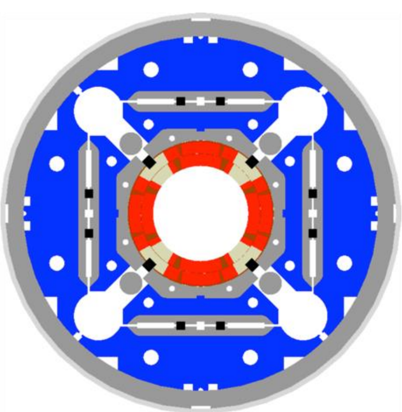
Current 17.5 A

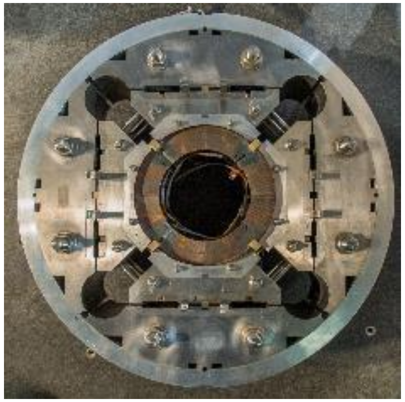
Loadline Margin 20% @ 1.9 K

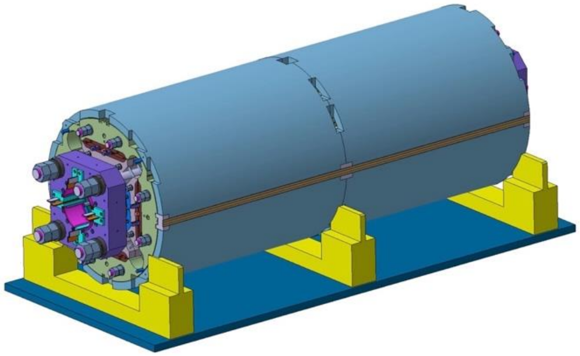
Stored Energy 1.32 MJ/m



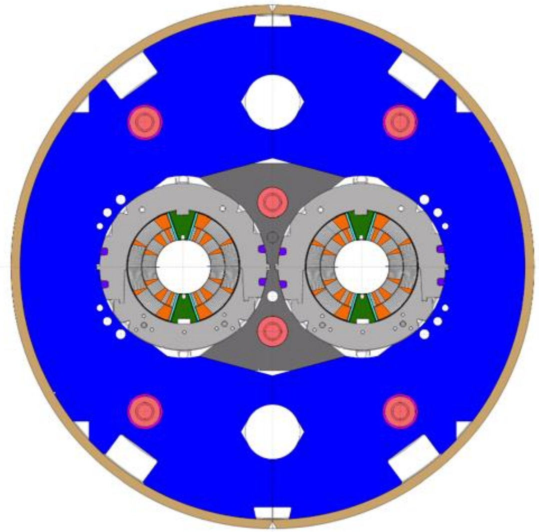
By courtesy of G. Ambrosio (FNAL), P. Ferracin (CERN et al)







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

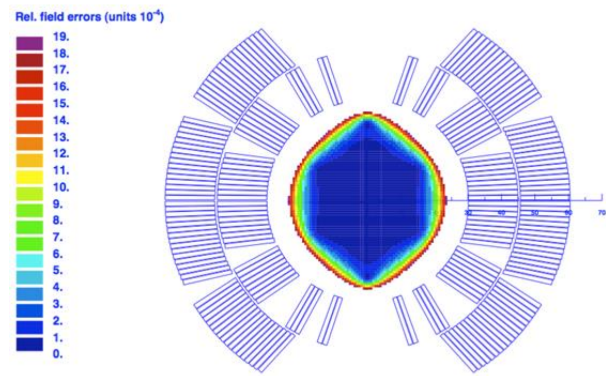
Aperture diameter 60 mm

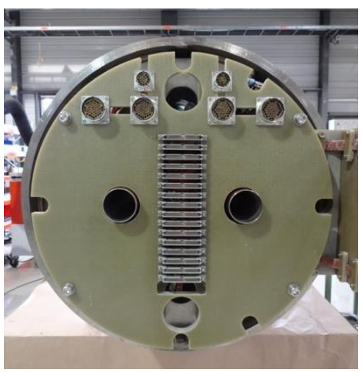
Peak Field 11.35 T

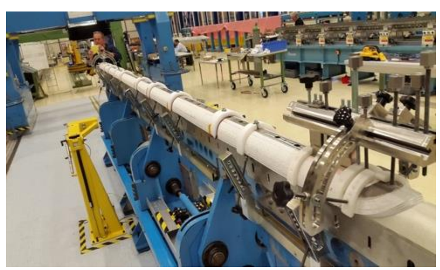
Current 11.85 kA

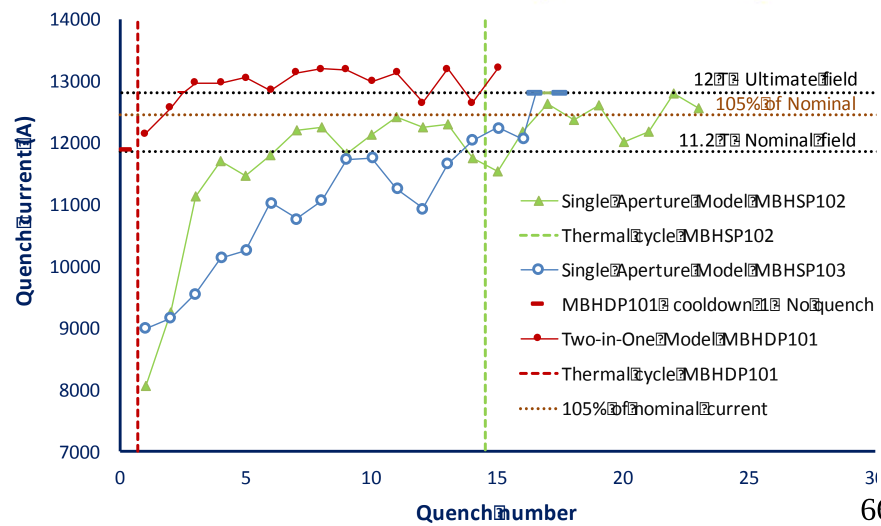
Loadline Margin 19.7% @ 1.9 K

Stored Energy 0.96 MJ/m

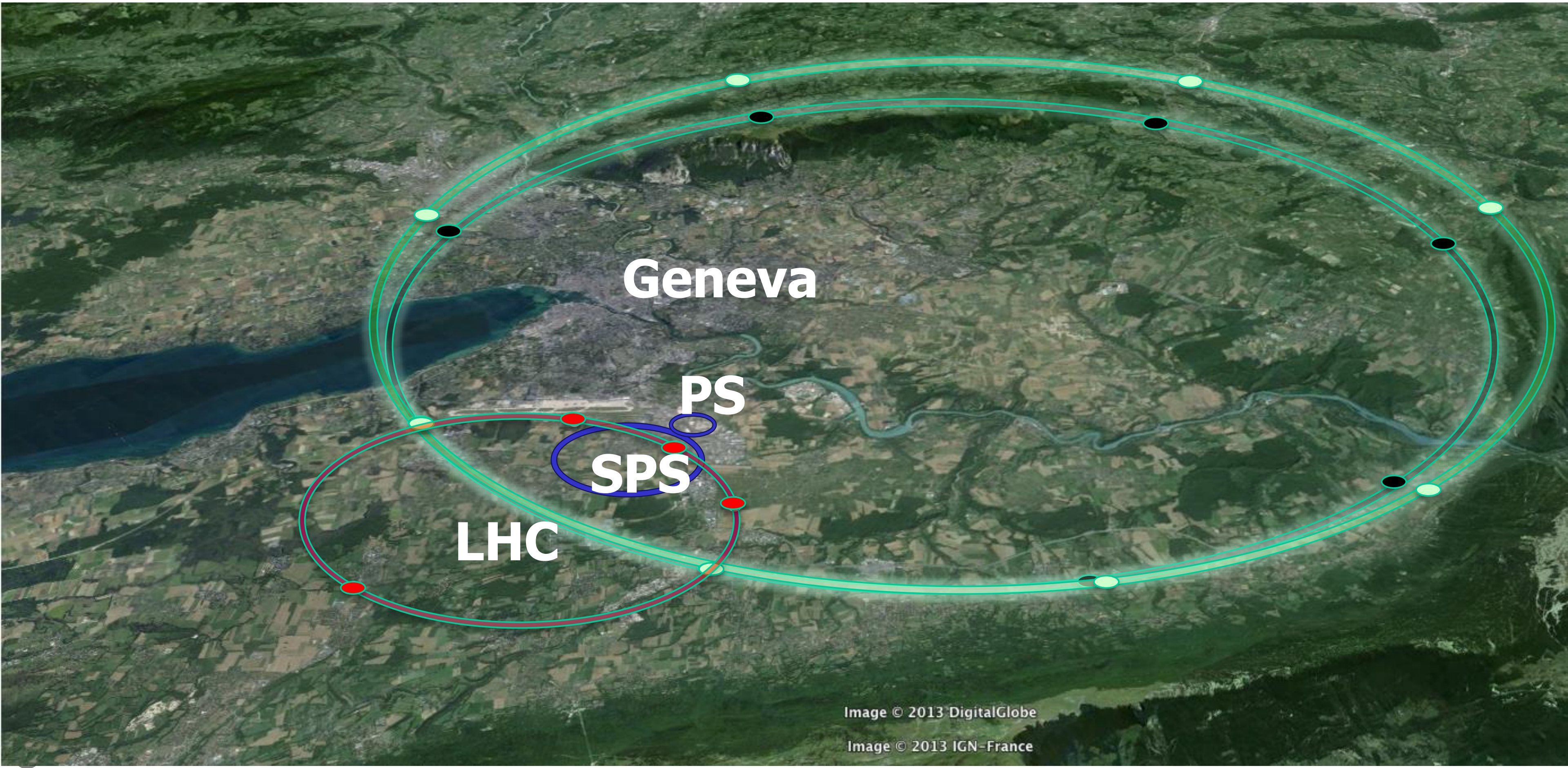








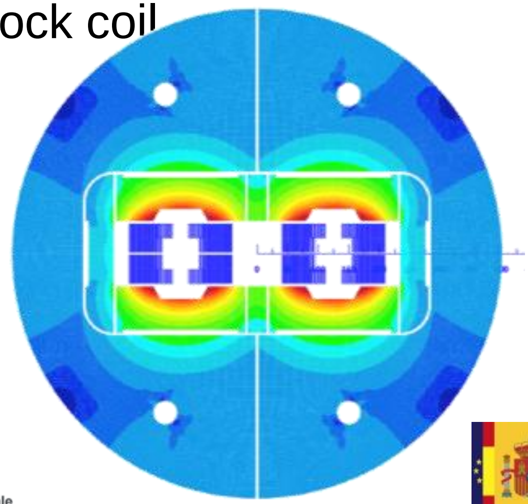
FCC development (2014 - ...)



LHC	HE-LHC	FCC-hh	FCC-hh
27 km, 8.33 T	27 km, 20 T	80 km, 20 T	100 km, 16 T
14 TeV (c.o.m.)	33 TeV (c.o.m.)	100 TeV (c.o.m.)	100 TeV (c.o.m.)

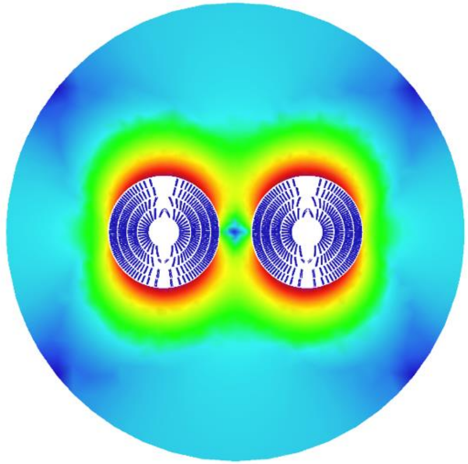
FCC: 16T dipole options

Block coil



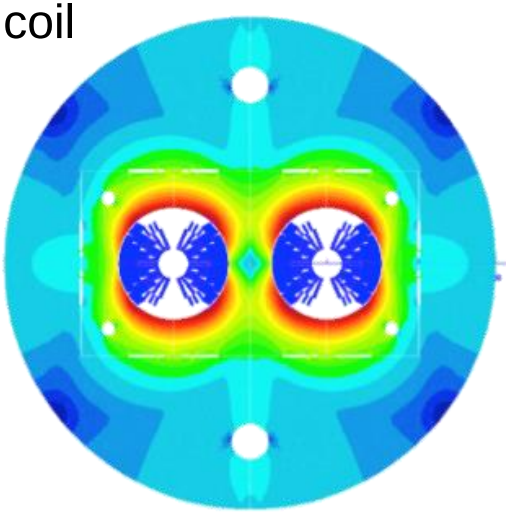
C. Lorin, M. Durante (CEA)

Canted Cos-theta



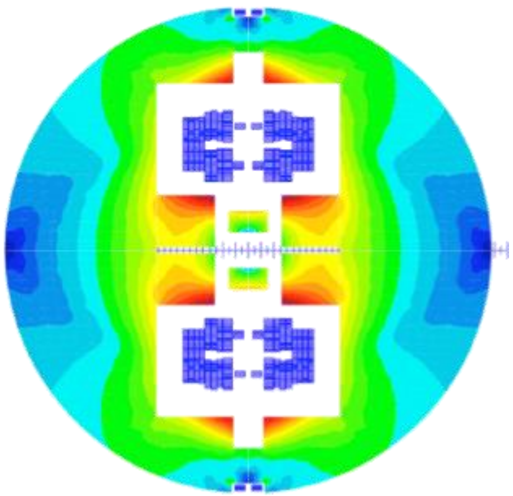
B. Auchmann (CERN/PSI)

Cos-theta coil



S. Farinon, P. Fabbricatore (INFN)

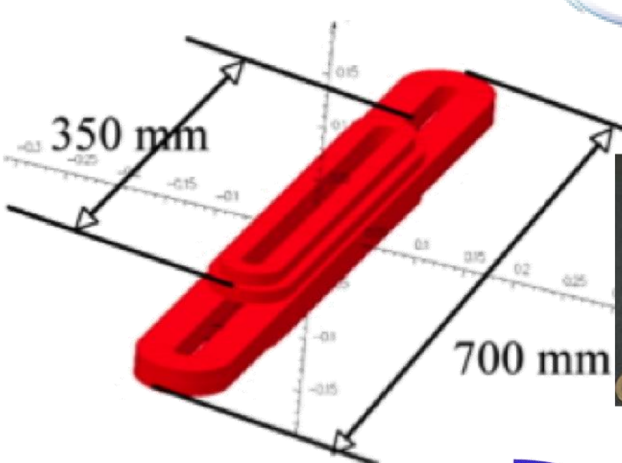
Common coils

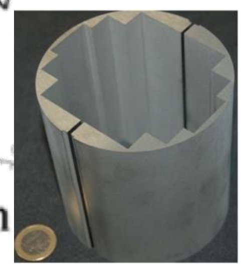


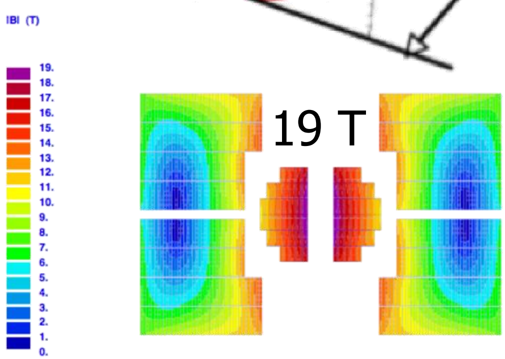
F. Toral (CIEMAT)

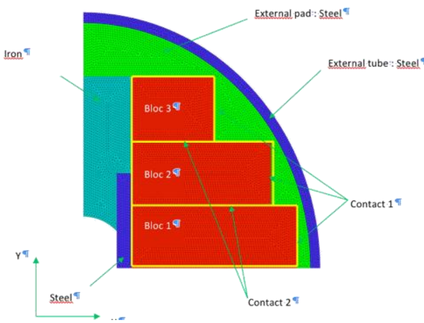
HTS: First attempt towards 20 T

6 T HTS (YBCO) insert for test in FReSCa2
To get to 19 T
But without bore

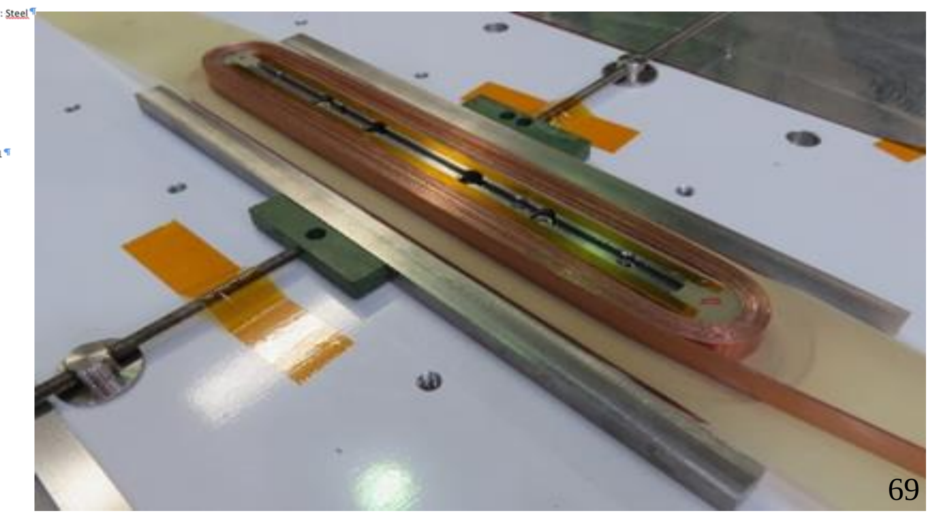








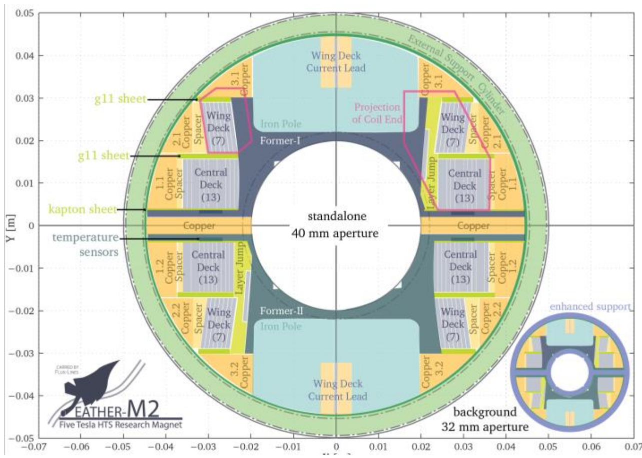
CEA + CRNS Grenoble

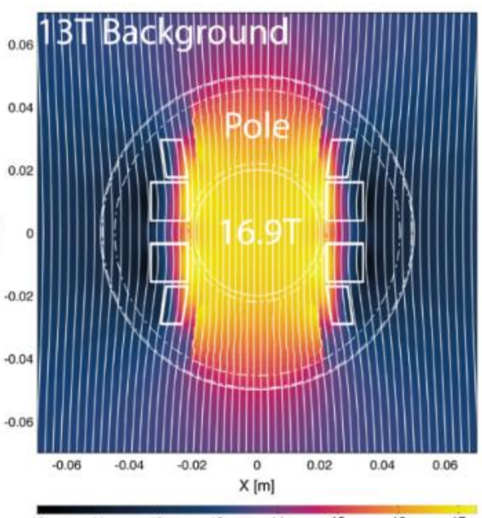


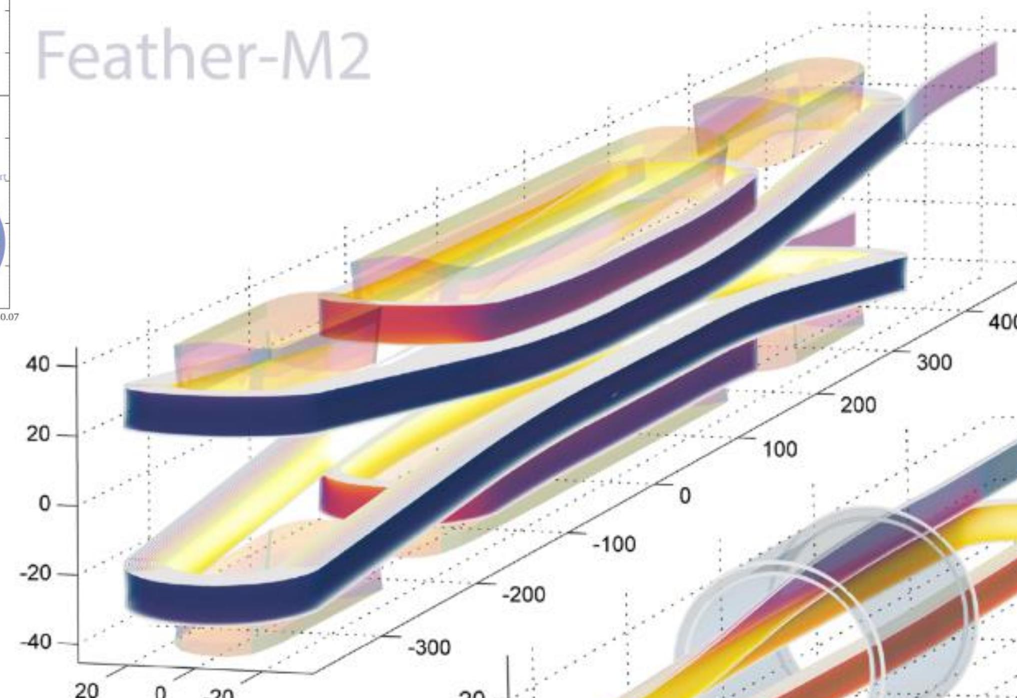
J.M. Rey, F. Borgnolutti, CEA-Saclay

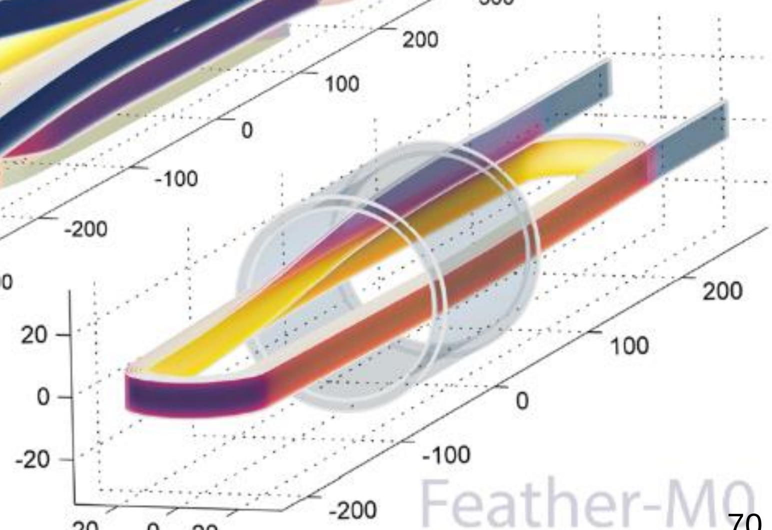
EuCARD2 5T accelerator quality ReBCO magnet

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





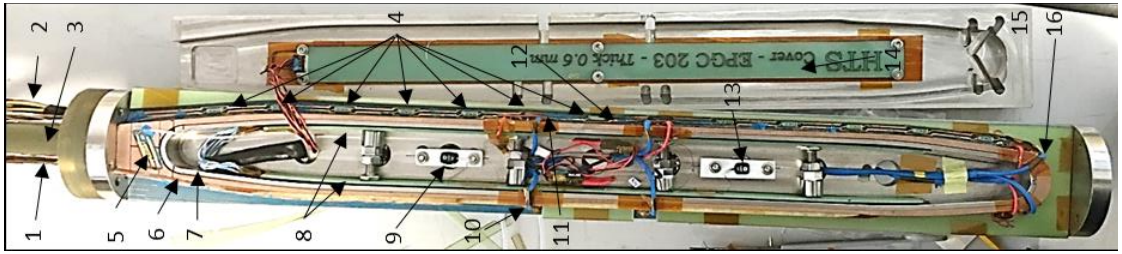


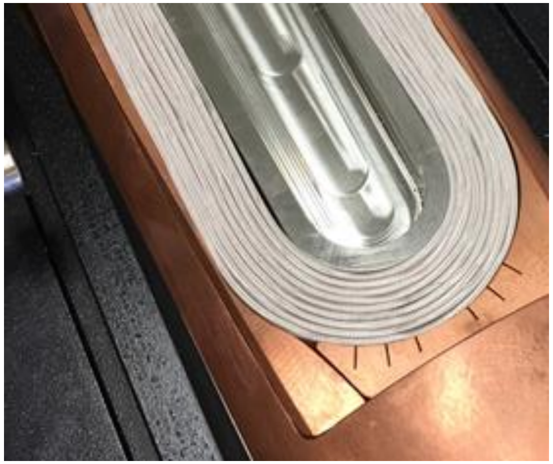


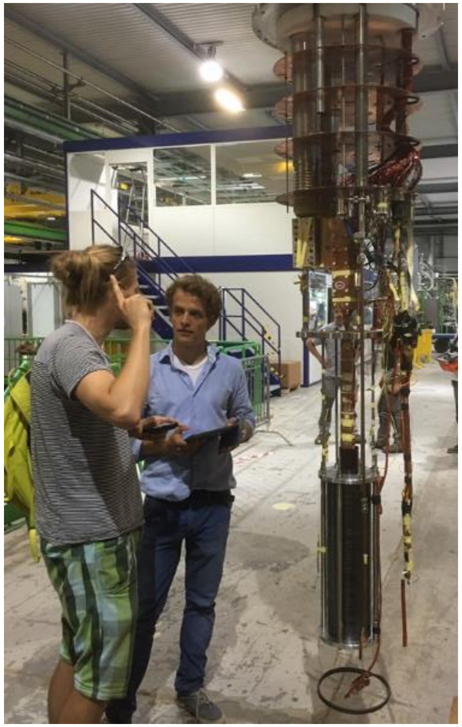
http://eucard2.web.cern.ch/

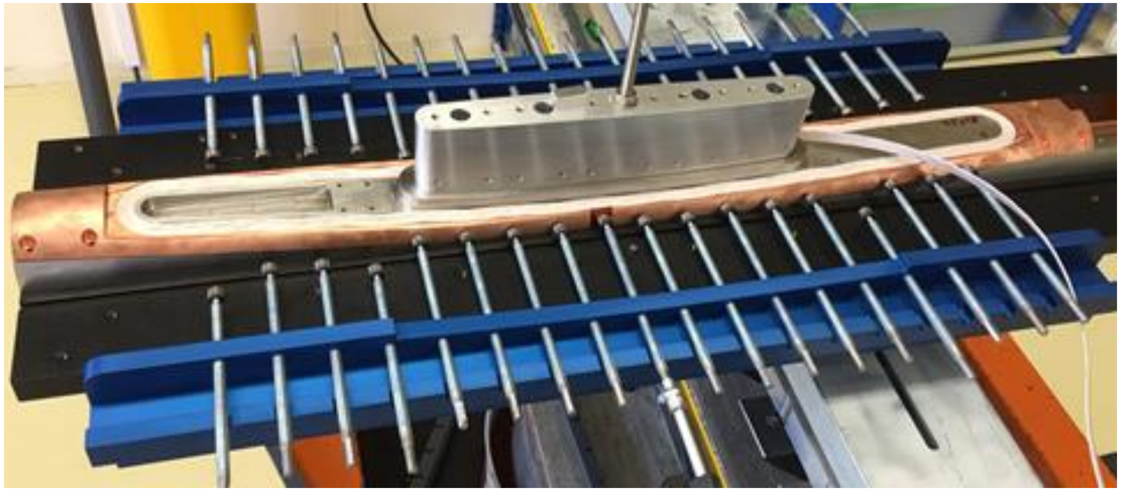
EuCARD2 5T : Feather0 - Feather-M2.0

- Feather0: First coil in the test station
- Feather2: winding of first coil with dummy cable in progress









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  - J. Tanabe, “Iron Dominated Electromagnets”, World Scientific, ISBN 978-981-256-381-1, May 2005
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  - S. Russenschuck, Field computation for accelerator magnets : analytical and numerical methods for electromagnetic design and optimization / Weinheim : Wiley, 2010. - 757 p.

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  - CAS Bruges, 2009, specialized course on magnets, 2009, CERN-2010-004
  - CAS Frascati 2008, Magnets (Warm) by D. Einfeld
  - CAS Varna 2010, Magnets (Warm) by D. Tommasini

- Papers and reports
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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

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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)

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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
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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

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

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And to the people who taught me, years ago, all the fine details about magnets !