Warm Magnets

Gijs de Rijk
CERN

CAS

Vysoke-Tatry, Slovakia
11th September 2019

Contents

- Introduction: magnetic field and warm magnet principles
- Field description and magnet types
- Practical magnet design & manufacturing
- Permanent magnets
- Examples of accelerator magnets from the early times until the present
- Literature on warm Magnets

Magnet types, technological view

We can also classify magnets based on their technology

electromagnet

permanent magnet

iron dominated

coil dominated

normal conducting (resistive)

superconducting

static

cycled / ramped slow pulsed

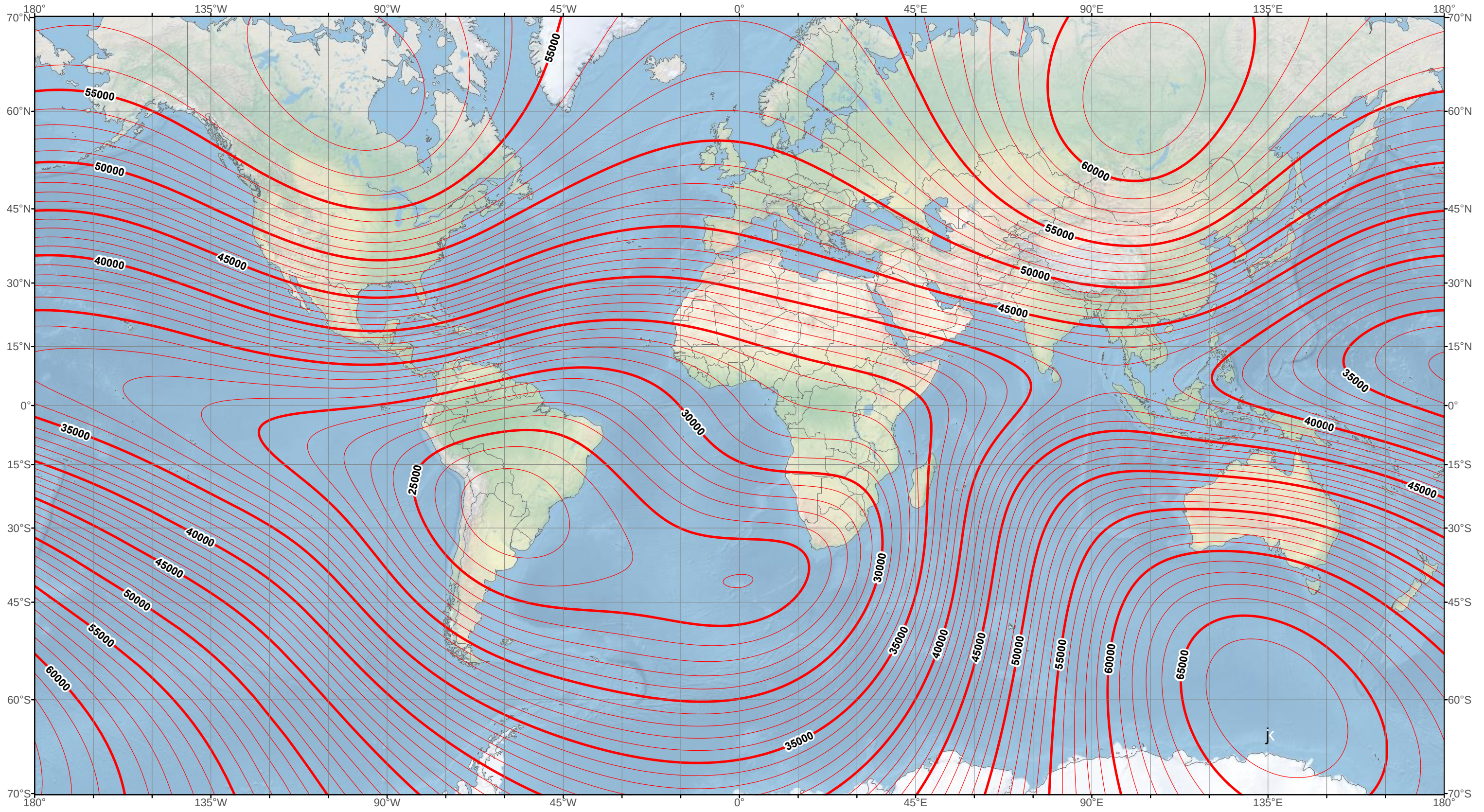
fast pulsed

Earth magnetic field

In Geneva, on 15/08/2019, the (estimated) magnetic field (flux density) is

$|B| = 40054\ \text{nT} = 0.040054\ \text{mT} = 4.0054 \cdot 10^{-5}\ \text{T} \approx 0.5\ \text{Gauss}.$ $B_{\text{horizontal}} = 19045\ \text{nT}$

US/UK World Magnetic Model - 2019.0
Main Field Total Intensity (F)



Main Field Total Intensity (F)
Contour interval: 1000 nT.
Mercator projection.

Map developed by NOAA/NCEI and CIRES
https://ngdc.noaa.gov/geomag/WMM
Published February 2019

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:

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

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

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

Magnetostatics

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

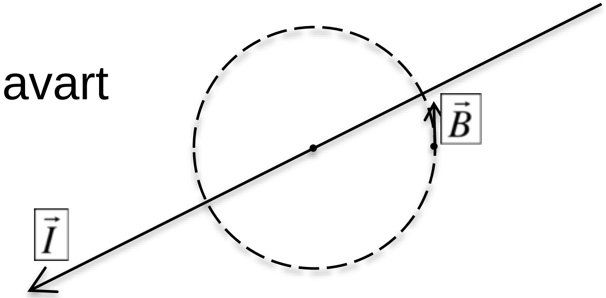
Gauss law of magnetism	(1)	$\operatorname{div}\vec{B} = 0$	always holds
Ampere’s law with no time dependencies	(2)	$\operatorname{rot}\vec{H} = \vec{J}$	holds for magnetostatics
Relation between $\vec{H}$ field and the flux density $\vec{B}$	(3)	$\vec{B} = \mu_0\mu_r\vec{H}$	holds for linear materials

Magnetic fields

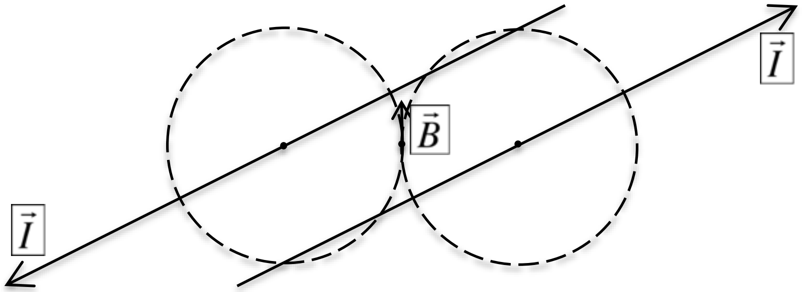
From Ampere’s law with no time dependencies

(Integral form) $$\oint_C \vec{B} \cdot d\vec{l} = \mu_0 I_{encl.}$$

We can derive the law of Biot and Savart



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



If you wanted to make a *B* = 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

Iron dominated magnets

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

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

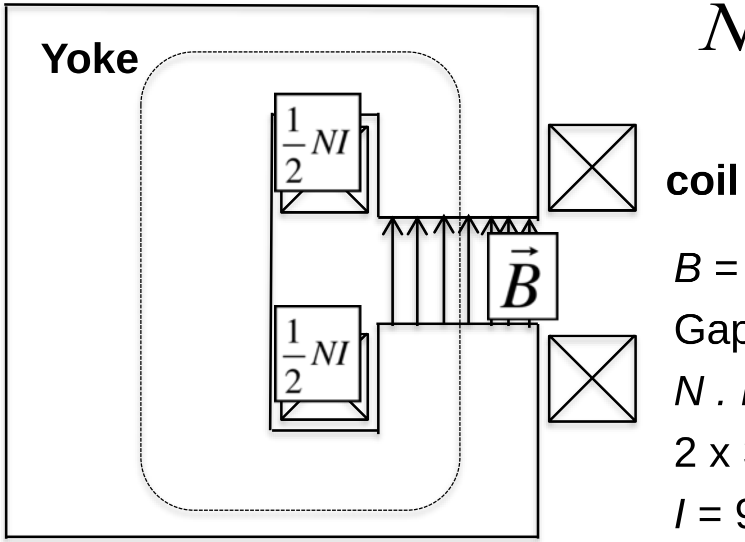
$$N\cdot I = H_{iron}\cdot l_{iron} + H_{airgap}\cdot l_{airgap} \Rightarrow$$

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

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

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

Example: C shaped dipole for accelerators



B = 1.5 T

Gap = 50 mm

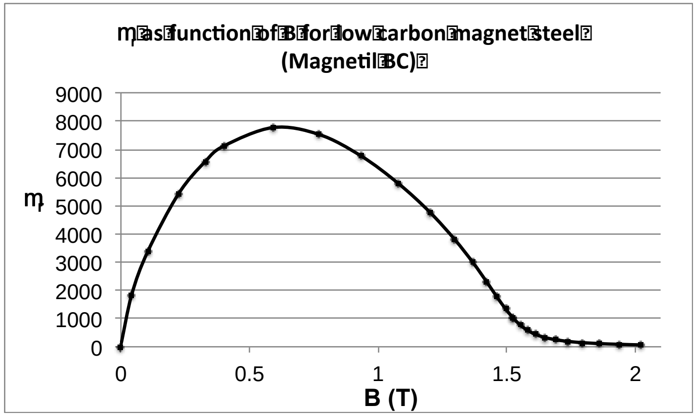
N . I = 59683 A

2 x 30 turn coil

I = 994 A

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

14 x 14 mm Cu

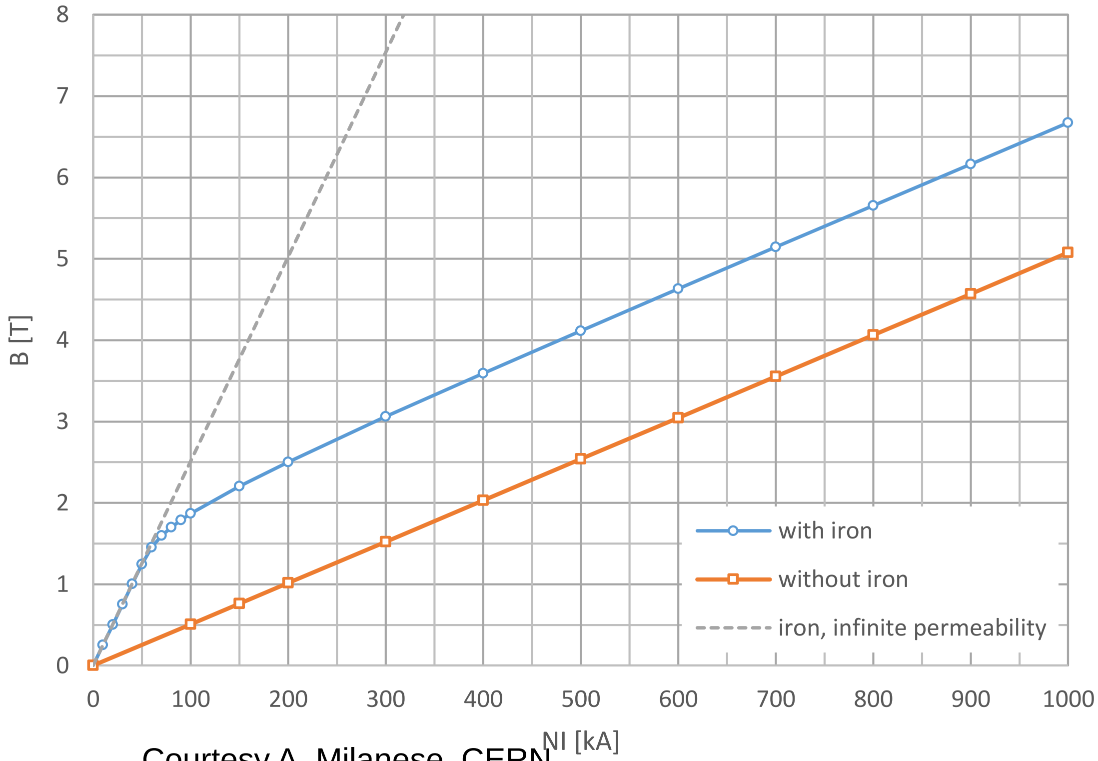


Comparison : iron magnet and air coil

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

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 $the\ normal\ nth\ multipole\ component,$

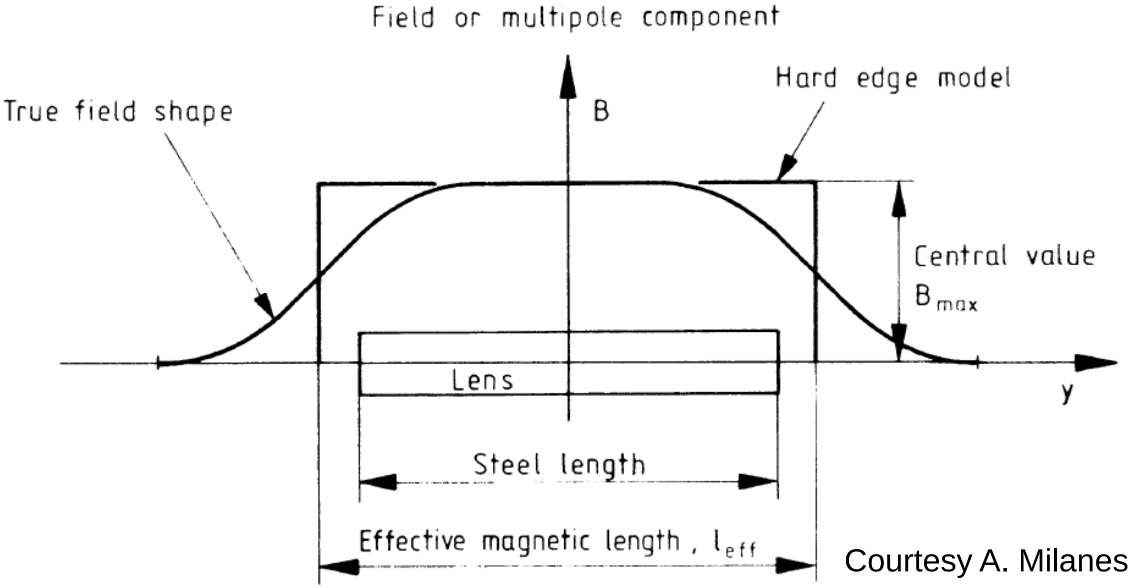
a_n $the\ skew\ nth\ multipole\ component.$

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



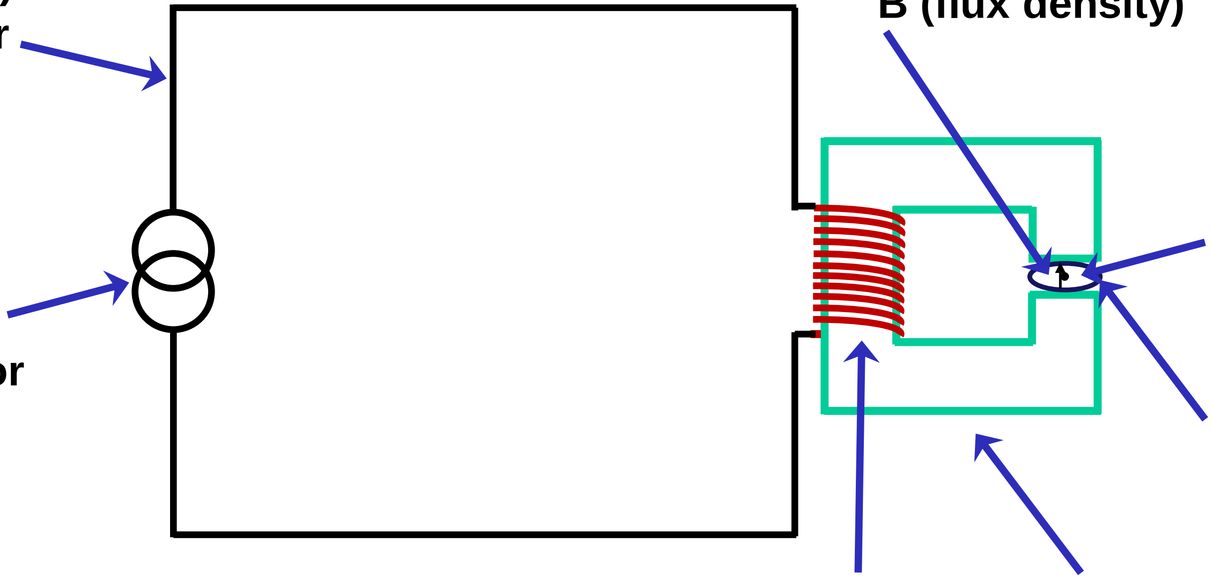
Courtesy A. Milanese, CERN

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

magnetic length L_{mag} as a first approximation:

- For dipoles $L_{mag} = L_{yoke} + d$ d = pole distance
- For quadrupoles: $L_{mag} = L_{yoke} + r$ r = radius of the inscribed circle between the 4 poles

Magnets in an accelerator: power convertor and circuit



Cu (or Al) cables or busbars

power Convertor (current source)

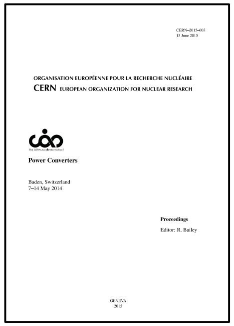
B (flux density)

beam

Vacuum chamber

Cu or Al coil

Steel yoke



CERN–2015–003
15 June 2015

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

The CERN Accelerator School

Power Converters

Baden, Switzerland
7–14 May 2014

Proceedings

Editor: R. Bailey

GENEVA
2015

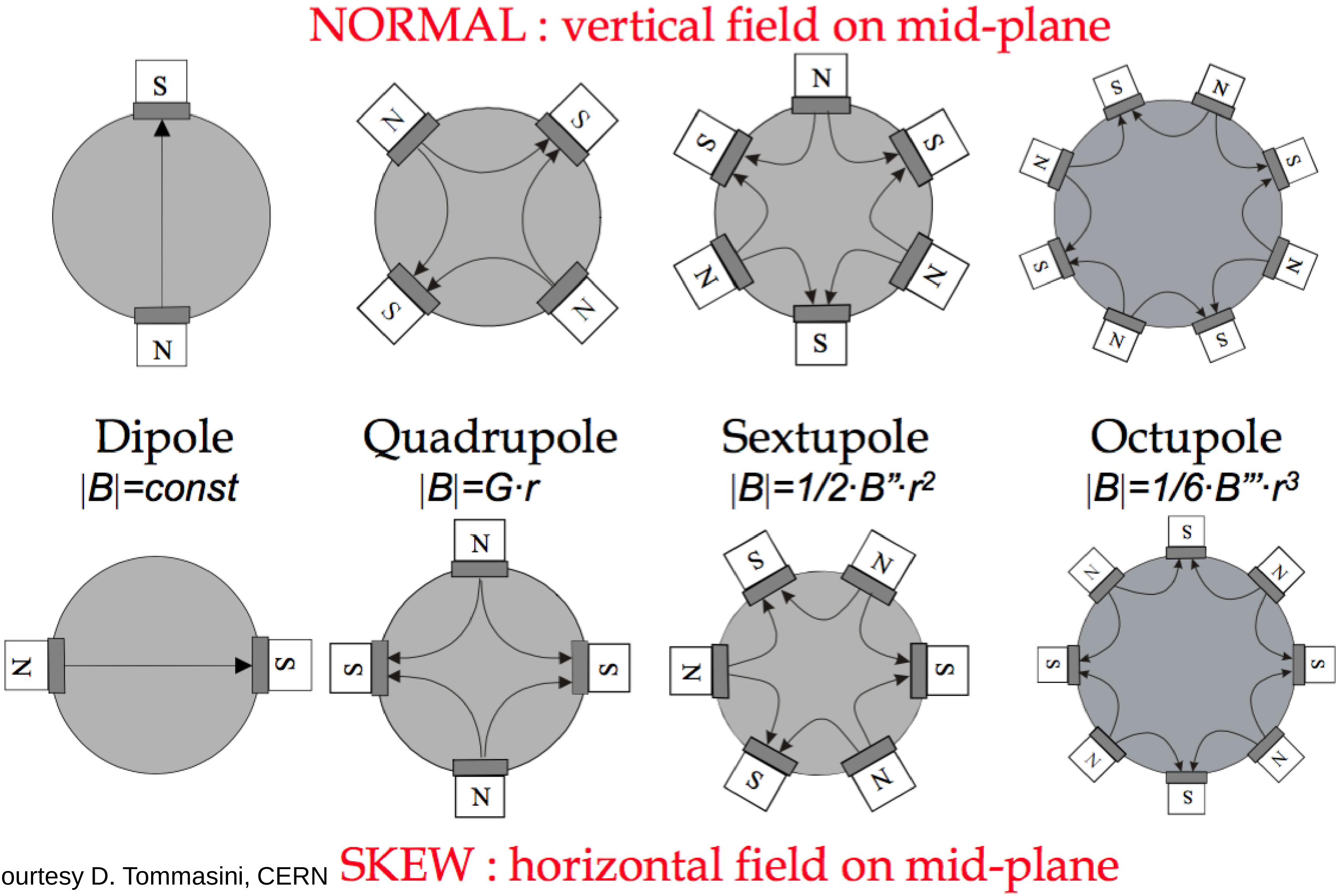
- B field stability in time: ~10^{-5} - 10^{-6}
- Typical R of a magnet ~20mΩ - 60mΩ
- Typical L of a magnet ~20mH – 200mH
- Powering cable (for 500A): Cu 250 mm^2 (Cu: 17 nΩ.m) R = 70 μΩ/m, for 200m: R= 13mΩ
- Take a typical rise time 1s

Then the Power Convertor has to Supply : 0-500 A with a stability of a few ppm.

Voltage up to 40 V (resitive)

And 100 V (inductive)

Types of magnet fields for accelerators



NORMAL : vertical field on mid-plane

Dipole
$|B| = \text{const}$

Quadrupole
$|B| = G \cdot r$

Sextupole
$|B| = 1/2 \cdot B'' \cdot r^2$

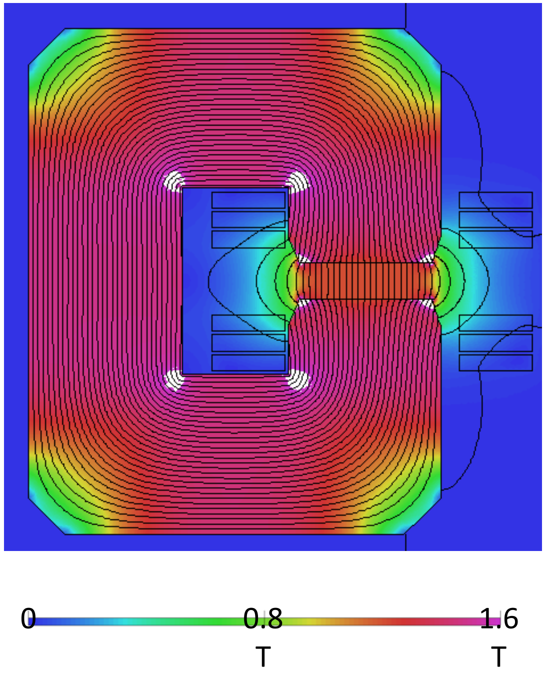
Octupole
$|B| = 1/6 \cdot B''' \cdot r^3$

SKEW : horizontal field on mid-plane

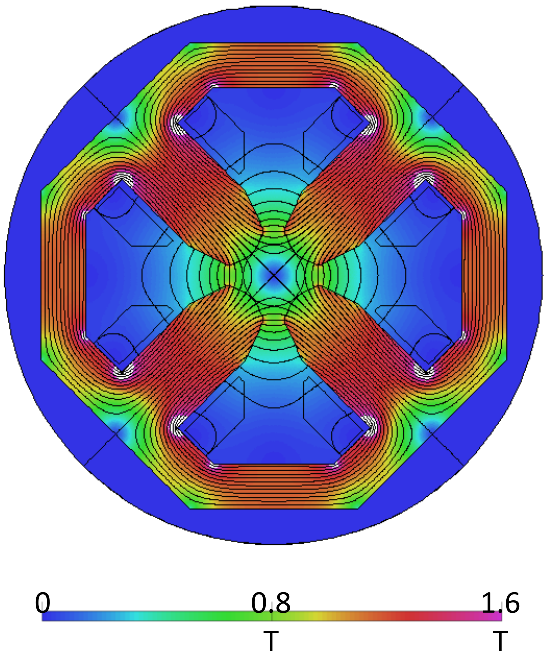
Courtesy D. Tommasini, CERN

fluxlines in magnets

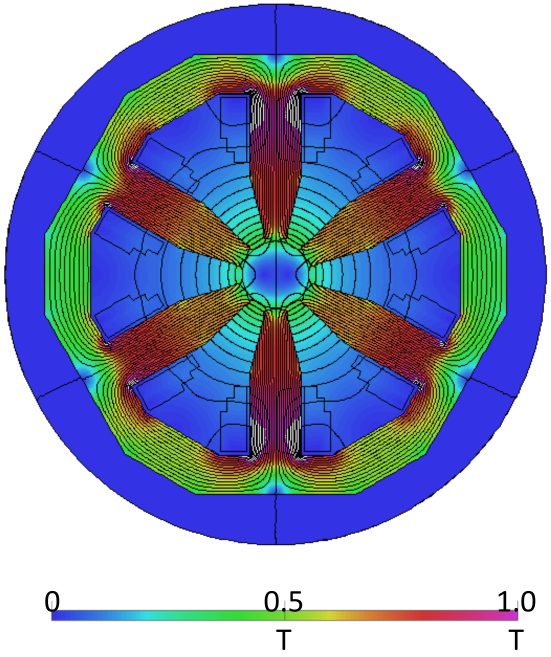
Dipole



Quadrupole



sextupole



Symmetry and allowed harmonics

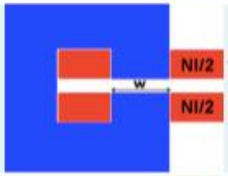
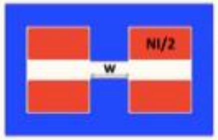
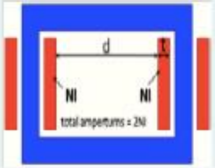
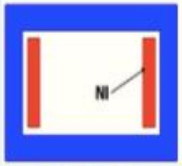
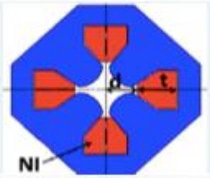
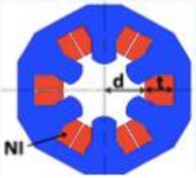
In a fully symmetric magnet certain field harmonics are natural.

Magnet type	**Allowed harmonics b_n**
n=1 Dipole	n=3,5,7,...
n=2 Quadrupole	n=6,10,14
n=3 Sextupole	n=9,15,21
n=4 Octupole	n=12,20,28

Non-symmetric designs and fabrication errors give rise to non allowed harmonics: b_n with n other than listed above and a_n with any n

NB: For “skew” magnets this logic is inverted !

Basic magnet types

Magnet	Pole shape	Transfer function	Inductance (H)
 w : pole width g : vertical gap	parallel	$B=\mu_0 NI/g$	$L=\mu_0 N^2 A/g$ $A \approx (w+1.2\cdot g)\cdot(l+g)$
 w : pole width g : vertical gap	parallel	$B=\mu_0 NI/g$	$L=\mu_0 N^2 A/g$ $A \approx (w+1.2\cdot g)\cdot(l+g)$
 w : pole width g : pole gap t : coil width	parallel	$B=\mu_0 NI/g$	$L=2\mu_0 N^2 A/g$ $A \approx (d+2/3t)\cdot(l+g)$
 w : pole width g : pole gap t : coil width	parallel	$B=\mu_0 NI/g$	$L=\mu_0 N^2 A/g$ $A \approx (d+2/3t)\cdot(l+g)$
 R : aperture radius d : coil distance t : coil width	$2xy=R^2$	$B(r)=G\cdot r$ $G=2\mu_0 NI/R^2$	$L=8\mu_0 N^2 A/R$ $A \approx (d+1/3t)\cdot(l+2/3R)$
 R : aperture radius d : coil distance t : coil width	$3x^2y-y^3=R^3$	$B(r)=S\cdot r^2=\frac{1}{2}B''\cdot r^2$ $S=3\mu_0 NI/R^3$	$L=20\mu_0 N^2 A/R$ $A \approx (d+1/3t)\cdot(l+1/2R)$

Courtesy D. Tommasini, CERN

Practical 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:

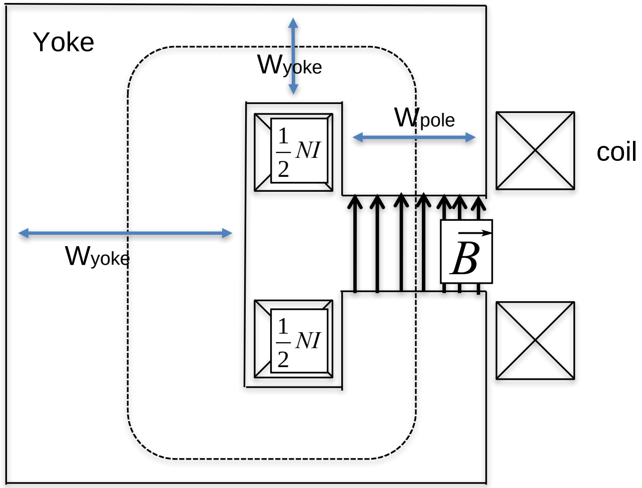
$$j_{coil} = 5\ {}^{A}\!/_{mm^2}\ \ for\ water\ cooled$$

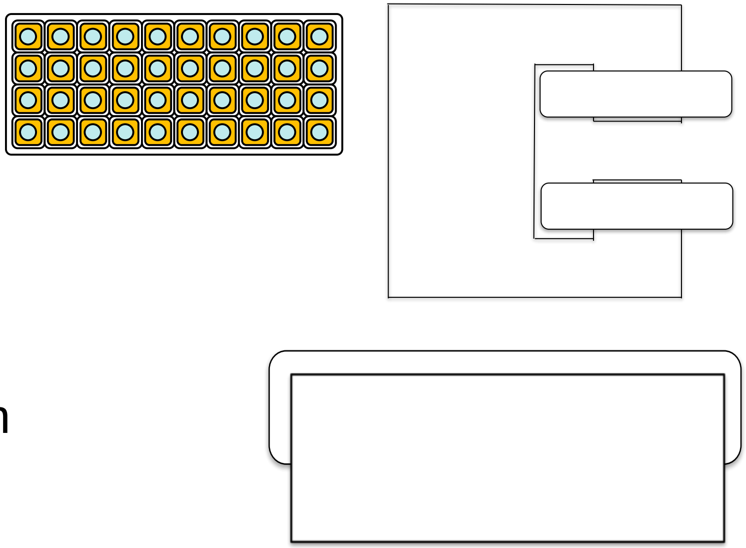
$$or\ j_{coil} = 1\ {}^{A}\!/_{mm^2}\ \ for\ air\ cooled$$

- 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 generated

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

$$P/l[W/m] = \frac{\rho}{S} I^2 \quad with:$$

$$\rho_{Cu} = 1.72\big(1 + 0.0039(T - 20)\big)10^{-8}\Omega m$$
$$\rho_{Al} = 2.65\big(1 + 0.0039(T - 20)\big)10^{-8}\Omega m$$

For AC: take the average I^2 for the duty cycle

Power losses due to hysteresis in the yoke: (Steinmetz law up to 1.5 T)

$$P[W/kg] = \eta f B^{1.6}\ with\ \eta = 0.01\ to\ 0.1,\ \eta_{Si\ steel} \approx 0.02$$

Power losses due to eddy currents in the yoke

$$P[W/kg] = 0.05\left(d_{lam}\frac{f}{10}B_{av}\right)^2$$

$$with\ d_{lam} the\ lamination\ thickness\ in\ mm, B_{av} the\ average\ flux\ density$$

Courtesy D. Tommasini, CERN

Cooling circuit parameters

Aim: to design $d_{cooling}$, $P_{water}[bar]$, $\Delta P[bar]$, $Q[l/min]$

- Choose a desired ΔT (20ºC or 30ºC depending on the $T_{cooling\ water}$)
- with the heat capacity of water (4.186 kJ/kgºC) we now know the required water flow rate: Q(l/min)
- The cooling water needs to be in moderately turbulent regime (with laminar flow the flow speed is zero on the wall !): *Reynolds* > 2000

$$R_e = \frac{dv}{\nu} \sim 140 d[mm] v[m/s] \ \ for\ T_{water} \sim 40°C$$

- A good approximation for the pressure drop in smooth pipes can be derived from the Blasius law, giving:

$$\Delta P[bar] = 60 L[m] \frac{Q[l/min]^{1.75}}{d[mm]^{4.75}}$$

Courtesy D. Tommasini, CERN

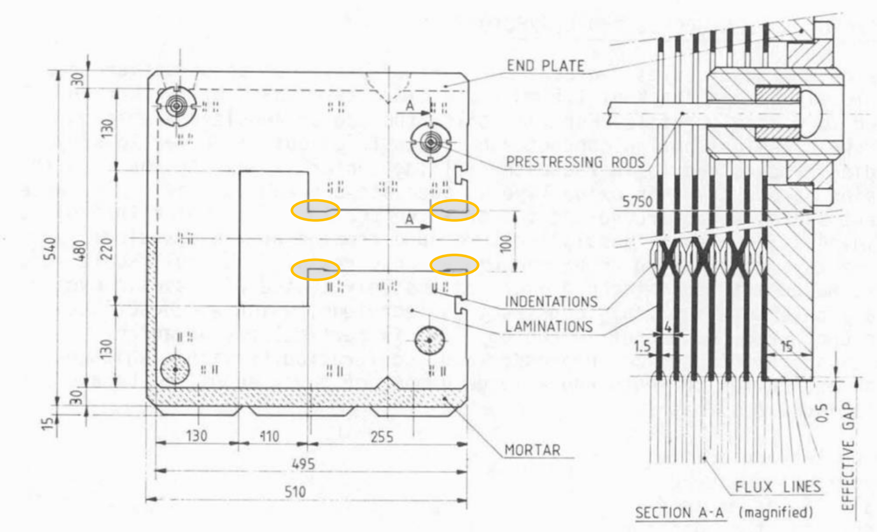
Theoretical pole shapes

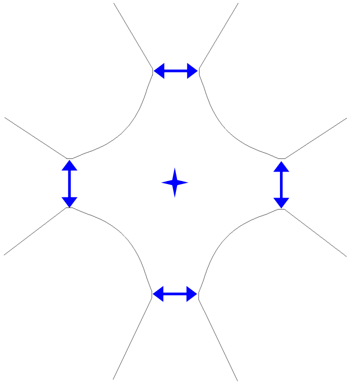
The ideal poles for dipole, quadrupole, sextupole, etc. are lines of constant scalar potential

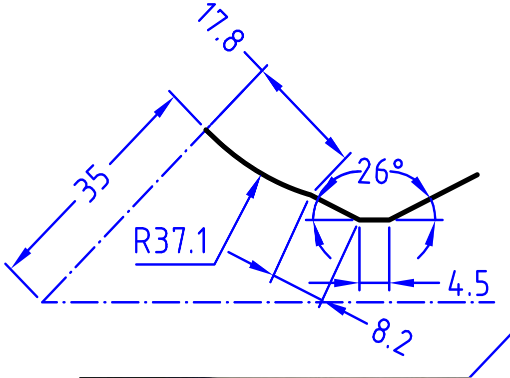
Dipole	$y = \pm h/2$	straight line
quadrupole	$2xy = \pm r^2$	hyperbola
sextupole	$3x^2y - y^3 = \pm r^3$	

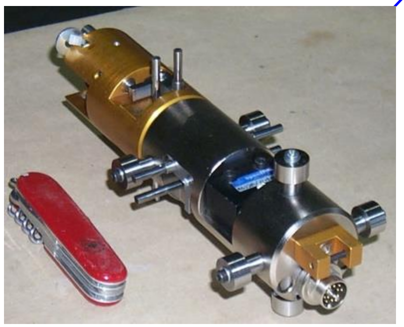
Practical pole shapes: shims and alignment features

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

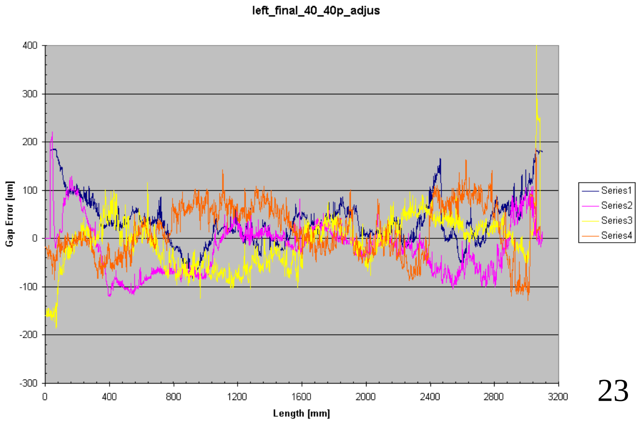








- Quadrupoles: at the edge of the pole one can put a combination a shim and alignment feature (examples: LHC-MQW, SESAME quads, etc)
- This then also allows to measure the pole distances : special instrumentation can be made for this



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 $B_{xsection}(I)$, $\int Bdl$, magnetic length
    - multipoles (in the centre of the magnet and integrated) b_n and a_n

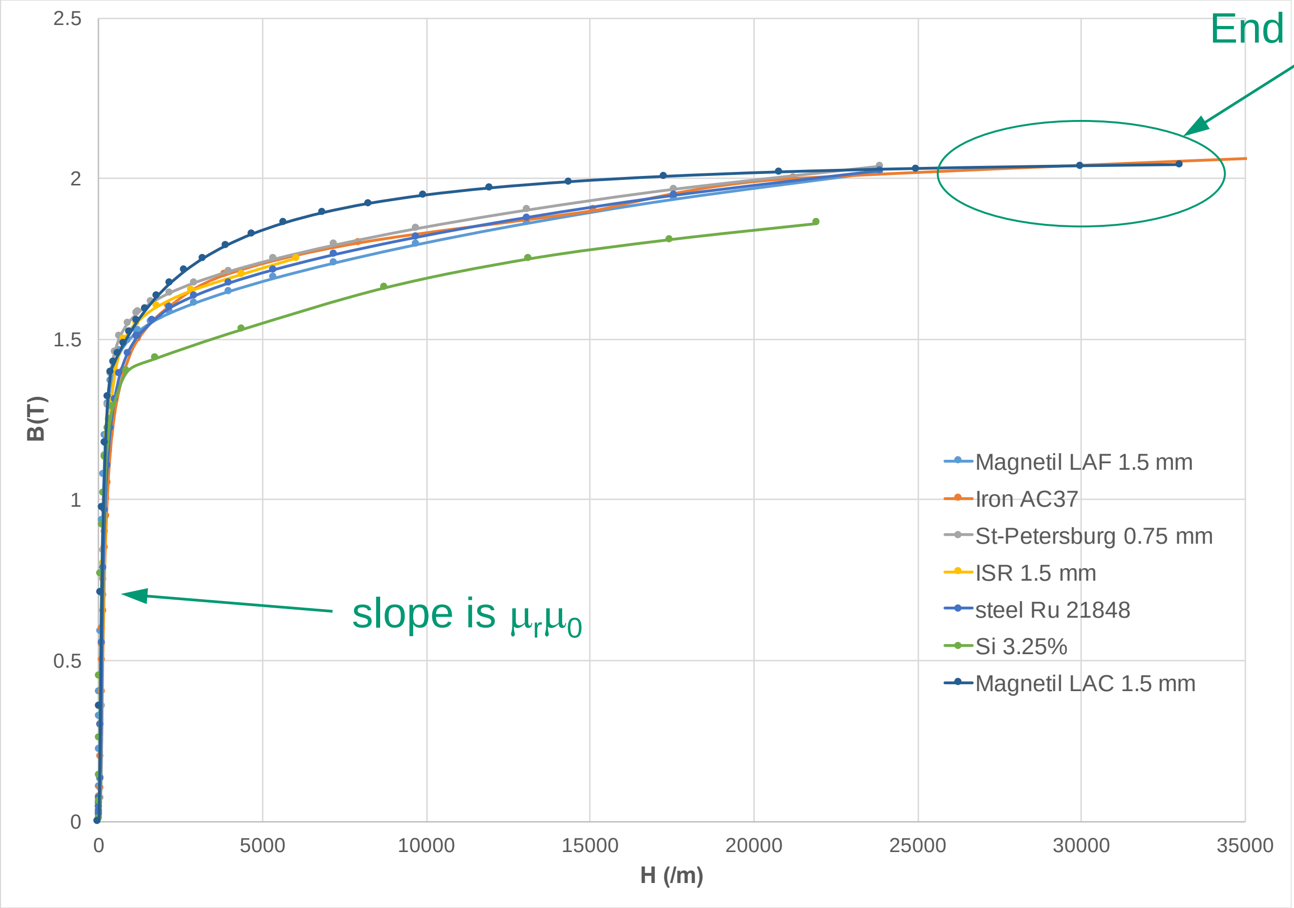
- Some Electromagnetic FE software packages that are often used:
  - Opera from Cobham: 2D and 3D commercial software see: http://operafea.com/
  - “Good old” Poisson, 2D: now distributed by LANL-LAACG see: http://laacg.lanl.gov/laacg/services/download_sf.phtml
  - ROXIE (CERN) 2D and 3D, specialized 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

FE models: steel curves

You can use a close ‘generic’ B(H) curve for a first cut design

You HAVE to use a measured, and smoothed, curve to properly calculate $B_{xsection}(I)$, $\int Bdl$, b_n and a_n

As illustration the curves for several types of steel:



End slope is μ_0

slope is $\mu_r\mu_0$

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

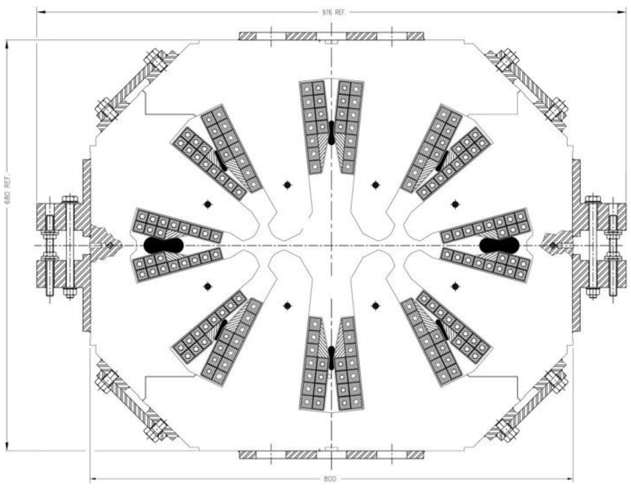
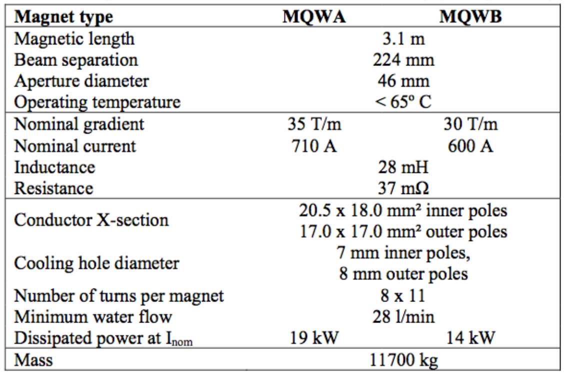
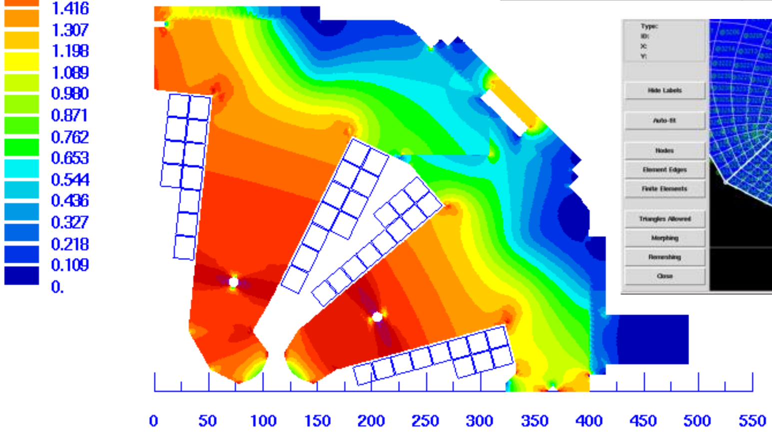
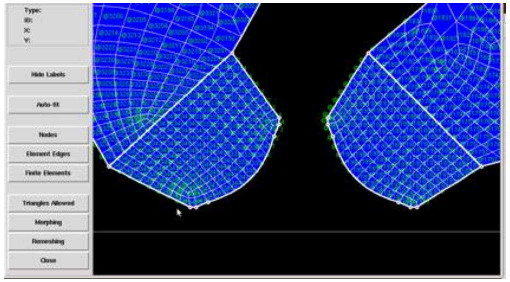


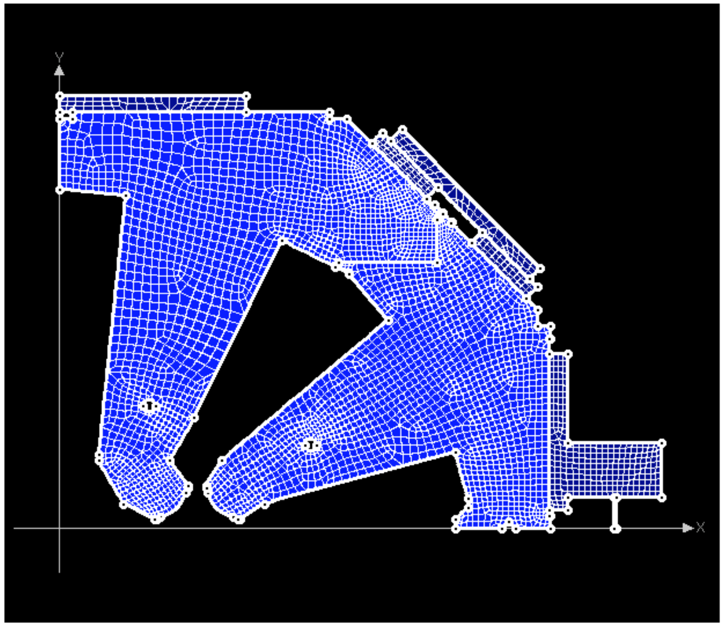
Table 8.6: Main parameters of the MQW normal conducting quadrupole magn



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 mm^2 inner poles 17.0 x 17.0 mm^2 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	







BEMFEM ★ ROXIE 10.1

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
    - H_c < 20 A/m for magnets ranging down also to low field B < 0.05 T
  - low carbon steel (C content < 0.006%) is best for higher fields B > 1 T

Field Strength [A/m]	**Minimum Induction [T]**
40	0.20
60	0.50
120	0.95
500	1.4
1 200	1.5
2 500	1.62
5 000	1.71
10 000	1.81
24 000	2.00

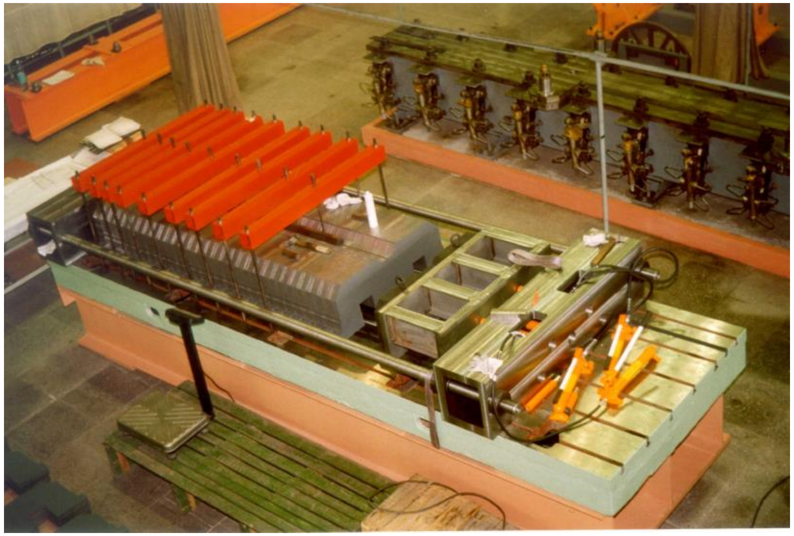
Example specification for 1.5 mm epoxy thick oxide steel for the LHC warm separation magnets, B_{max}= 1.53 T

Field Strength H [A/m]	**Minimum Induction B [T]**
100	0.07
300	1.05
500	1.35
1000	1.50
2500	1.62
5000	1.72
10000	1.82

Example specification for 0.5 mm thick epoxy coated steel for LHC transfer line corrector magnet B_{max}=0.3 T

Yoke manufacturing

Stacking an MBW dipole yoke stack



Stacking an MQW quadrupole yoke stack

MQW yoke assembly

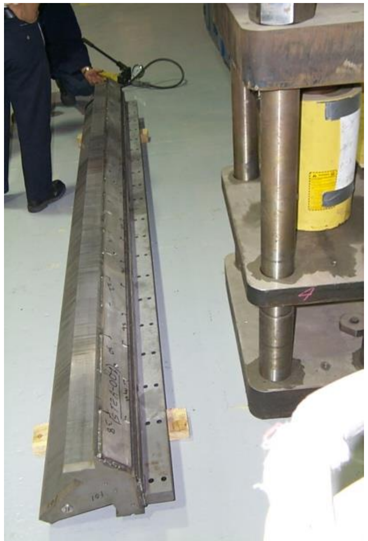
Yoke stack manufacturing

Double aperture LHC quadrupole MQW

Stacking on a precision table

Welding the structural plates

Finished stack



Yokes: holding a laminated stack together

- 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

Glued yoke (MCIA LHC TL)

Welded stack

Tie rod

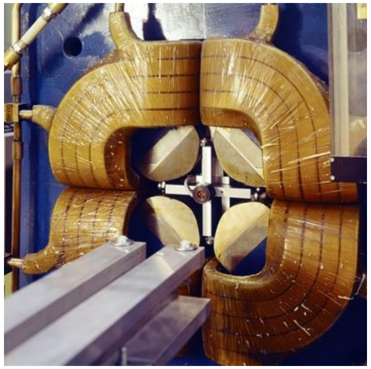
Coil manufacturing, insulation, impregnation type

- 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

Coil ends

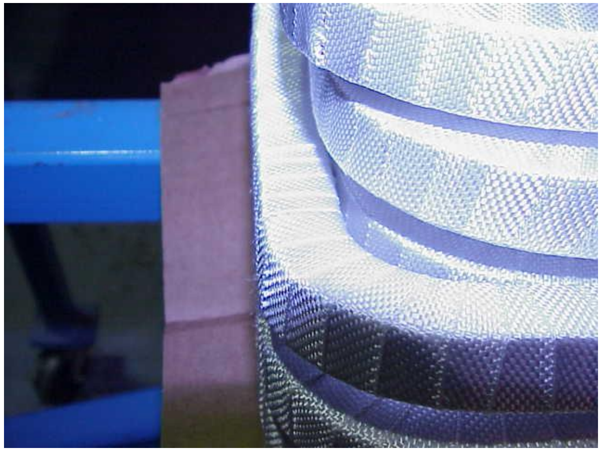
For dipoles some main types are racetrack of bedstead

Quadrupoles



Coil manufacturing

MQW Glass fibre tape wrapping.



Glass fiber tape winding

Winding the hollow Cu conductor

winding

Coil manufacturing

Mounted coil

coil electrical test (under water !)

Dipoles racetrack coil

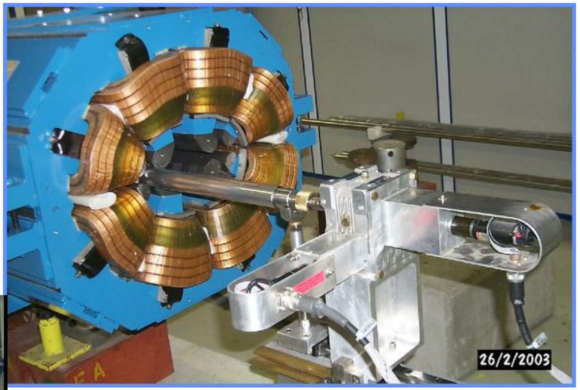
MBXW Coil winding

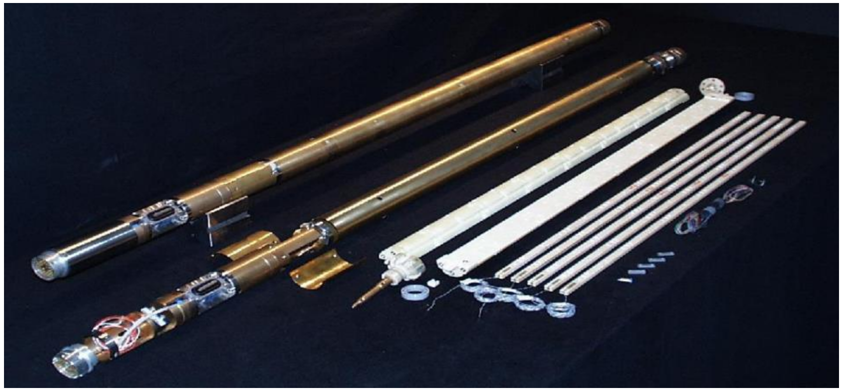
Finished MBXW coil

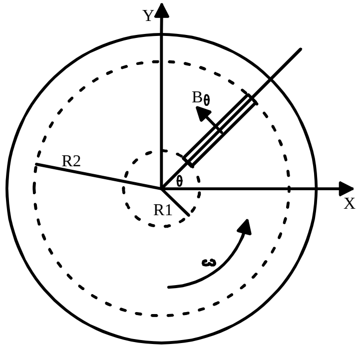
Magnetic field measurements

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

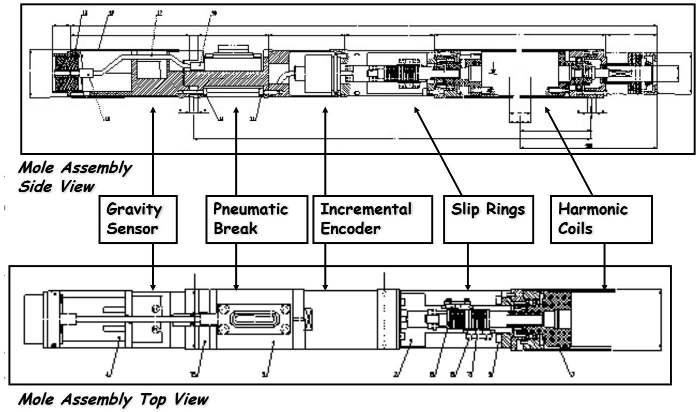
  - Rotating coils: multipoles and integrated field or gradient in all magnets
  - Stretched wire: magnetic centre and integrated gradient for *n* > 1 magnets
  - Hall probes: field map
  - Pickup coils: field on a current ramp
- Example below : MQW : double aperture quadrupole for the LHC.





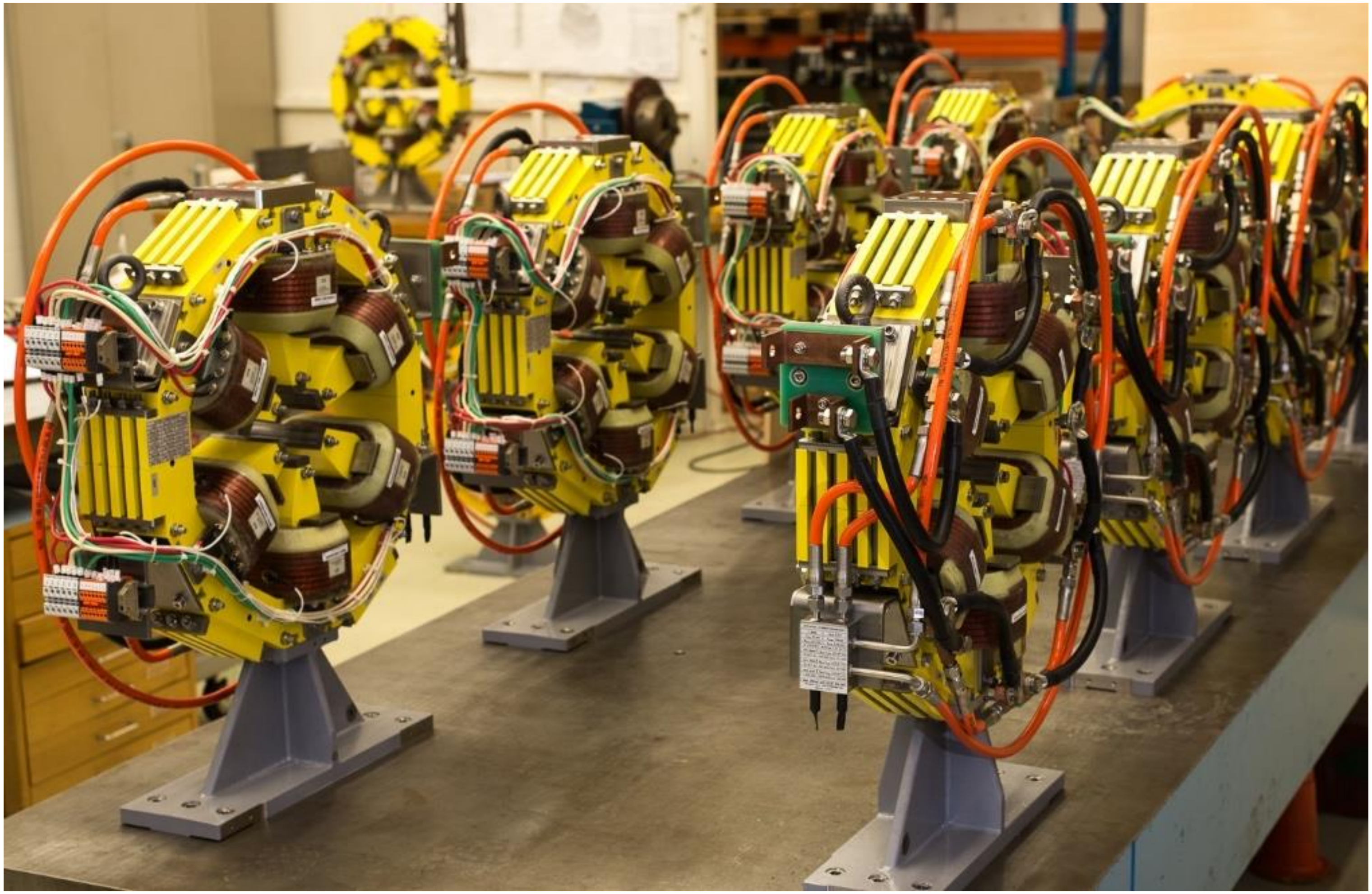


Rotating radial coil



Sextupoles

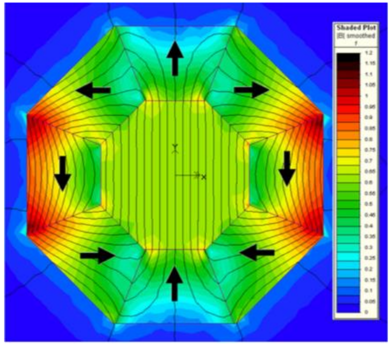
- These are sextupoles (with embedded correctors) of the main ring of the SESAME light source

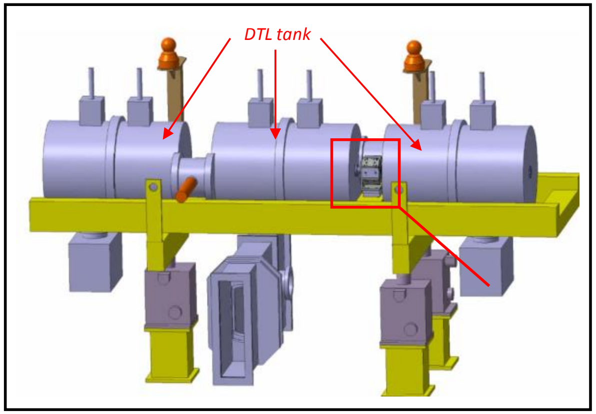


Courtesy A. Milanese, CERN

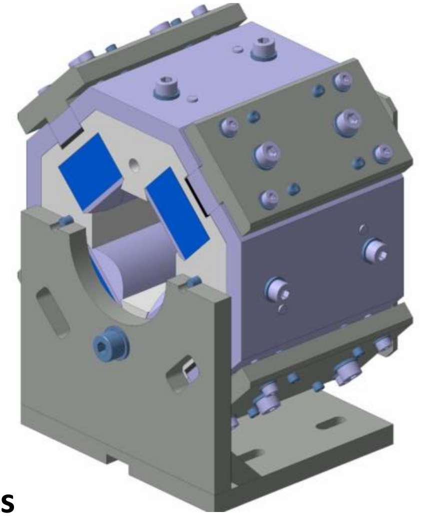
Permanent magnets

Linac4 @ CERN permanent magnets , quadrupoles





Pictured : Cell-Coupled Drift Tube Linac module.



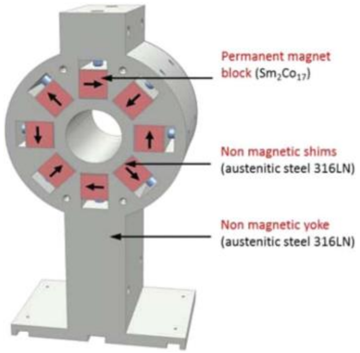
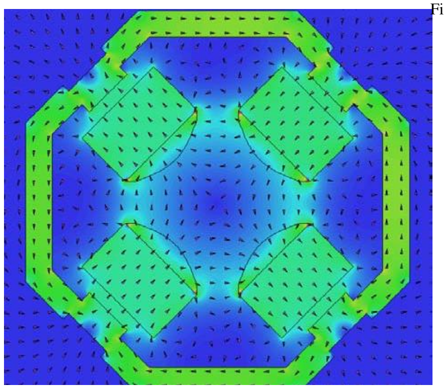
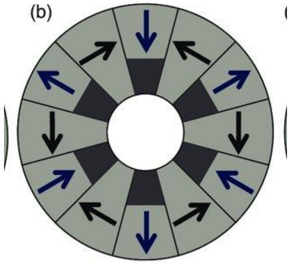


Fig. 1. Schematic layout of the Linac4 permanent-magnet quadrupole.

- **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



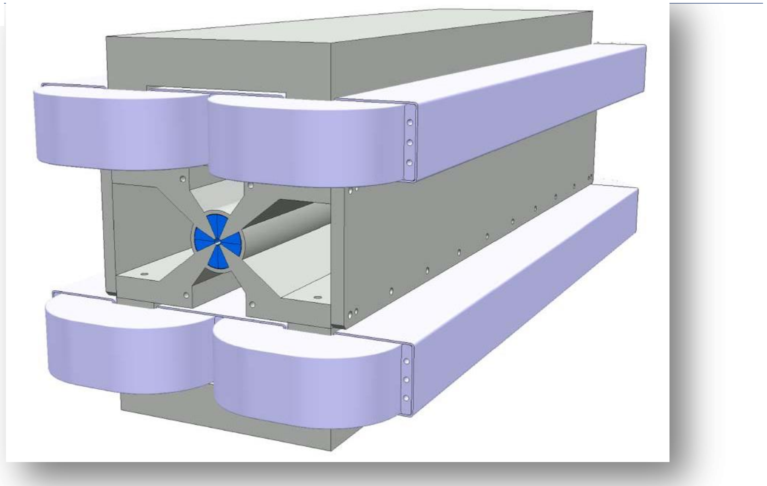


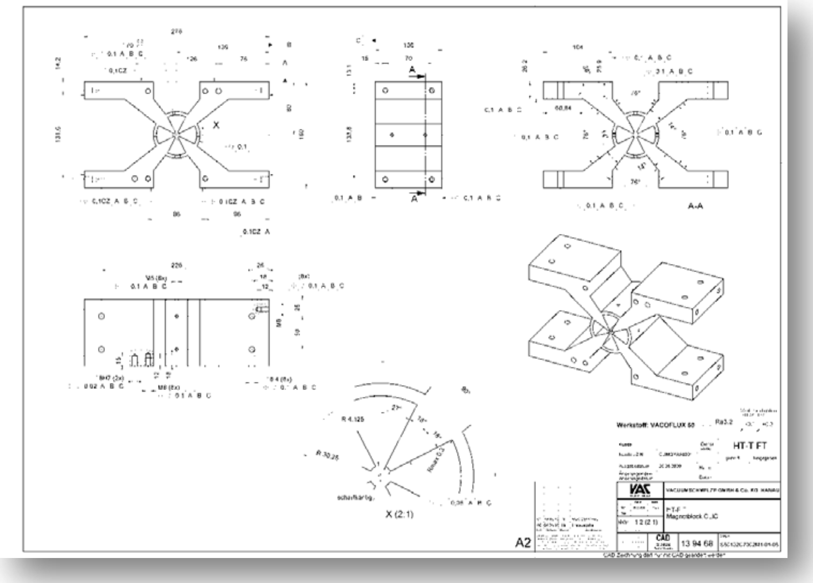
Sextupole Hallback Array

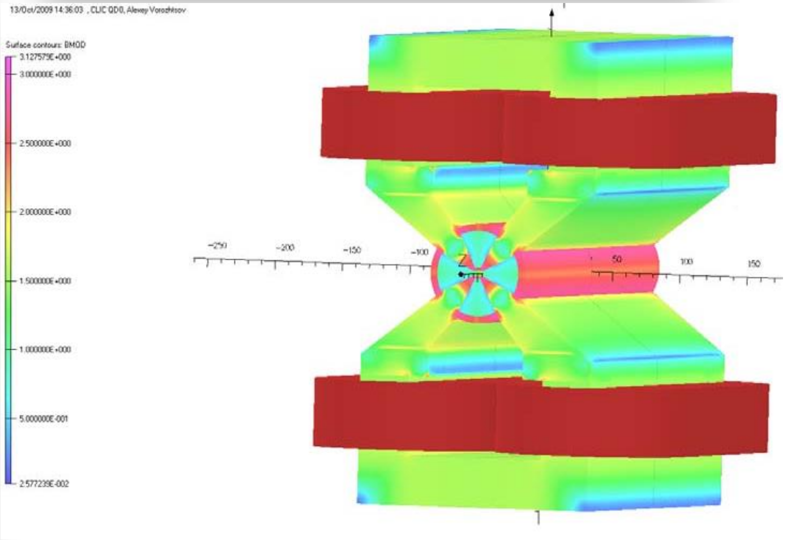
Hybrid magnets

CLIC final focus,

Gradient: > *530 T/m*
Aperture Ø: *8.25 mm*
Tunability: *10-100%*





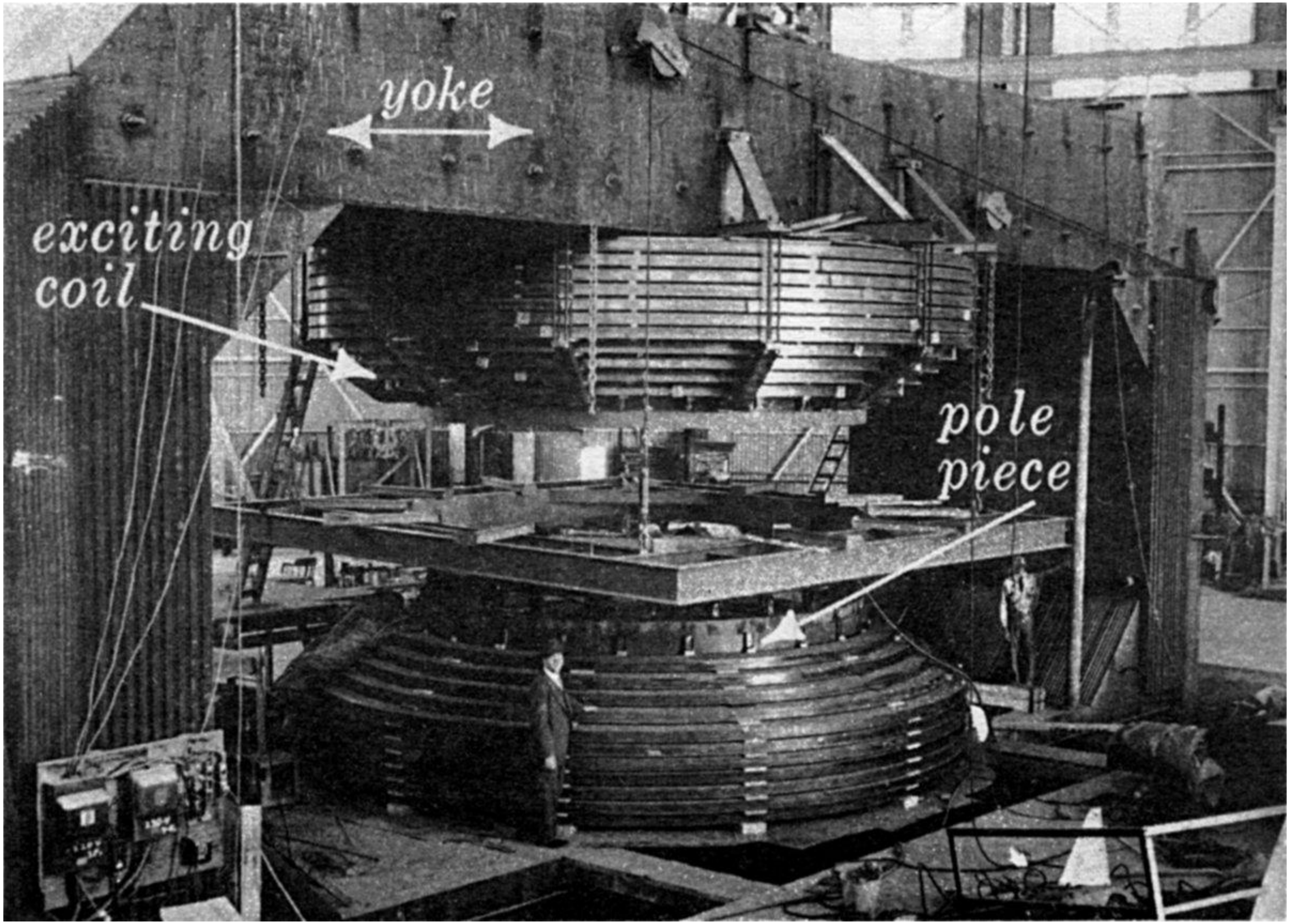


Courtesy D. Tommasini, CERN

Examples;

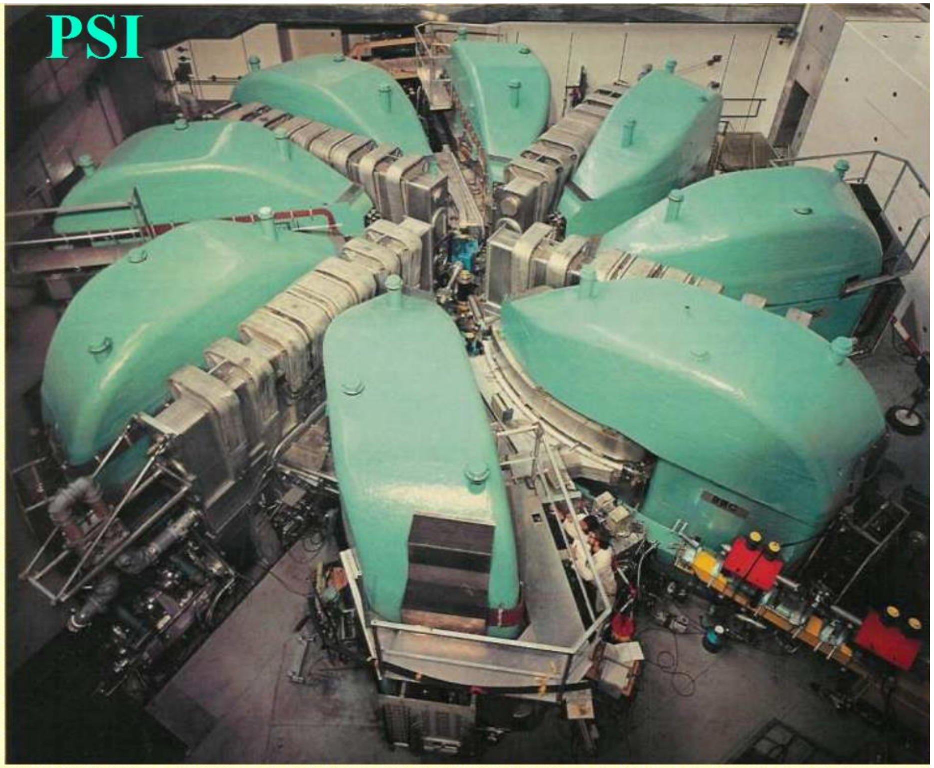
Some history, some modern regular magnets and some special cases

The 184’’ (4.7 m) cyclotron at Berkeley (1942)

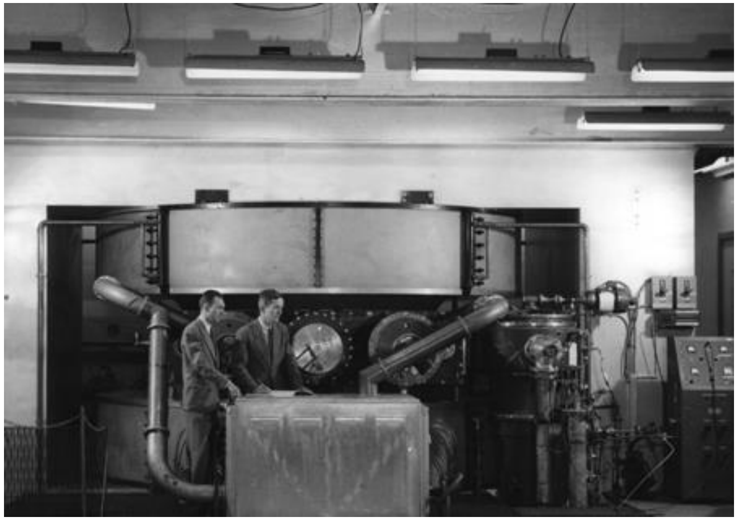


Courtesy A. Milanese, CERN

Cyclotrons



PSI= 590 MeV proton 1974

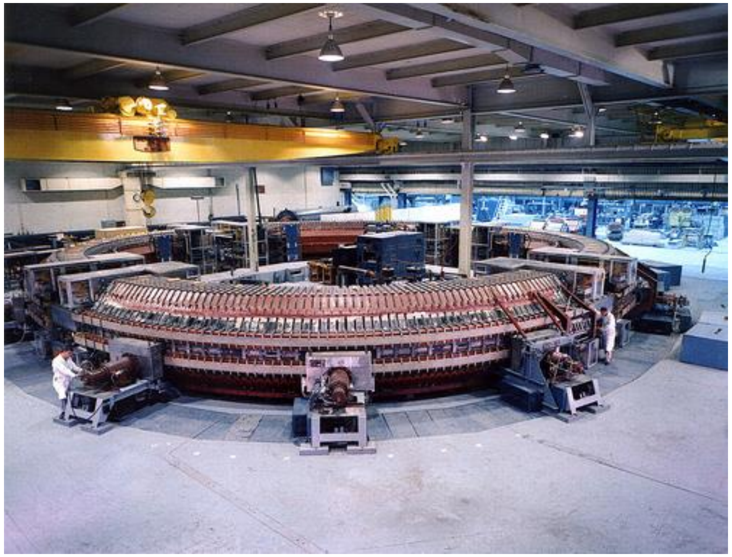


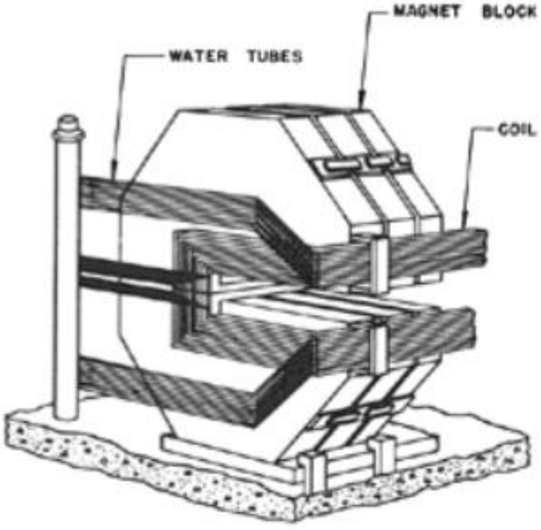
Harvard 1948

Some early magnets (early 1950-ies)

Bevatron
(Berkeley)
1954, 6.2 GeV

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





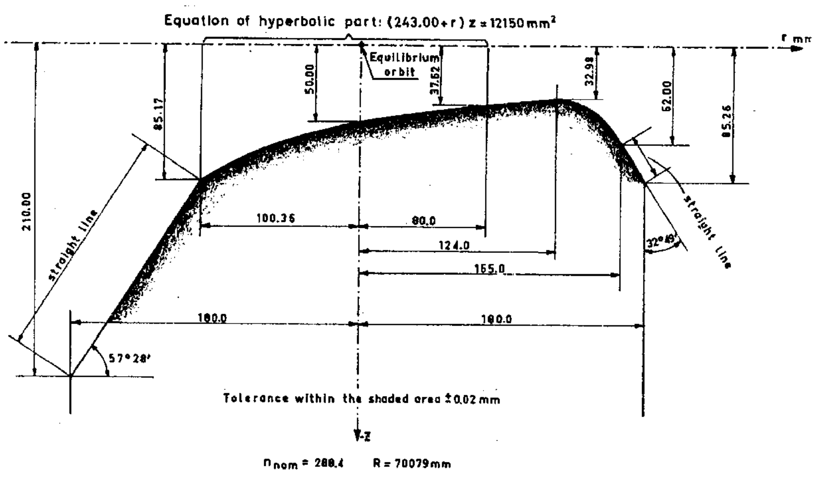
PS combined function dipole

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

Equipped with pole-face windings for higher order corrections

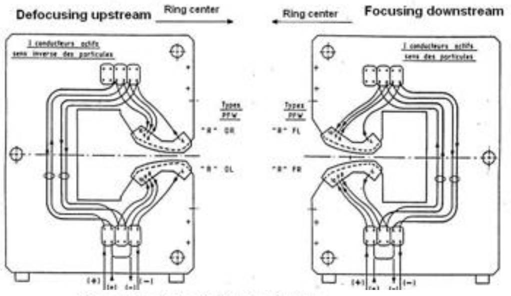
Water cooled Al race-track coils



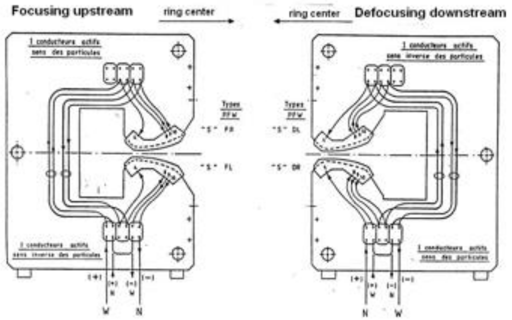
FINAL POLE PROFILE.

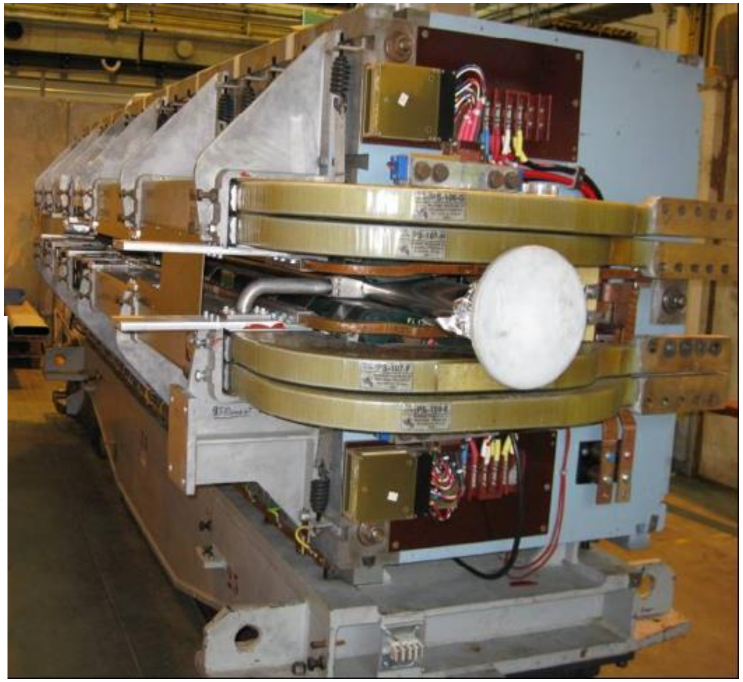
Fig. 9: Final pole profile.

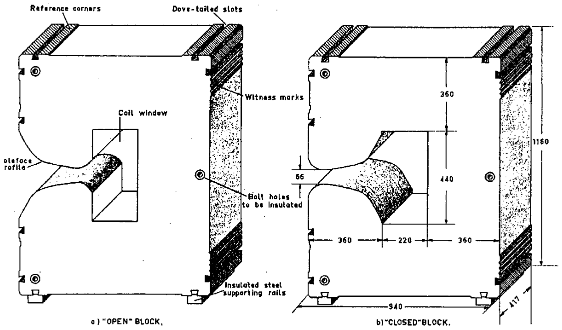
Connection of the PFW main windings for R type magnet



Connection of the PFW main windings for magnet type S







CPS MAGNET BLOCKS.
(All dimensions in mm)

Fig. 12: Final form of the magnet blocks.

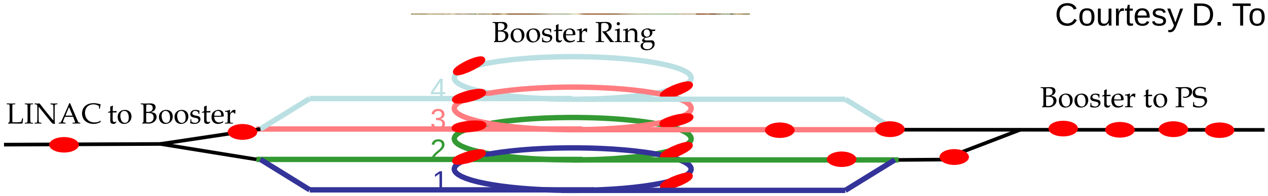
Courtesy D. Tommasini, CERN

CPS booster

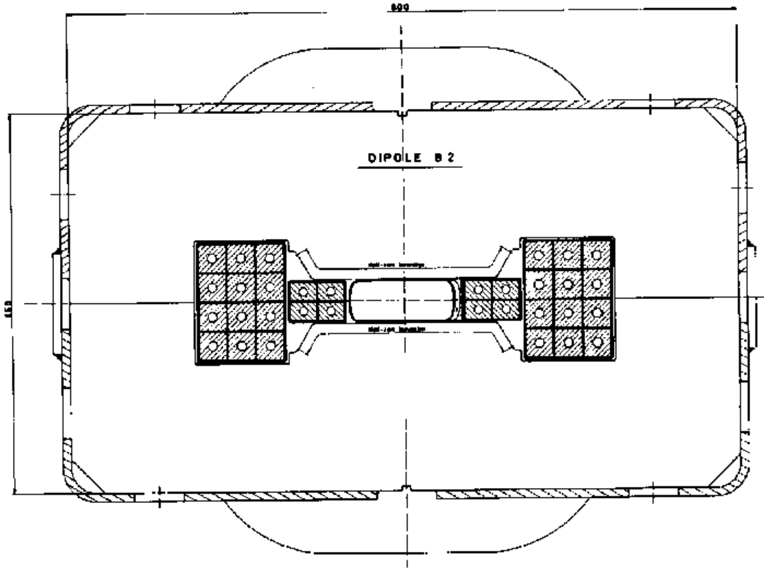
4 accelerator rings in a common yoke. (increase total beam intensity by 4 in presence of space charge limitation at low energy): B=1.48 T @ 2 GeV

Was originaly designed for 0.8 GeV !

Courtesy D. Tommasini, CERN



dipole magnet : SPS dipole



H magnet   type MBB

B = 2.05 T

Coil : 16 turns

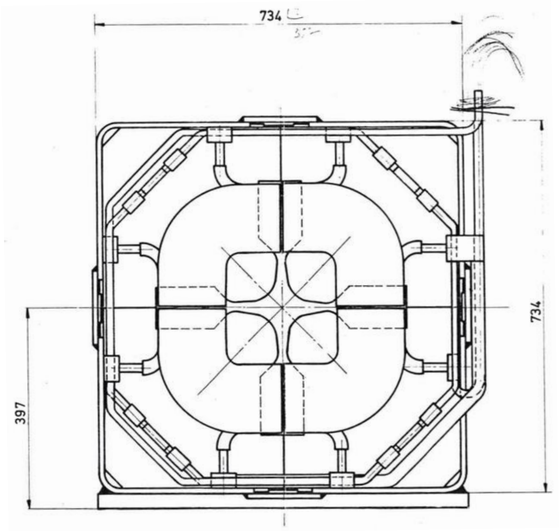
I_{max} = 4900 A

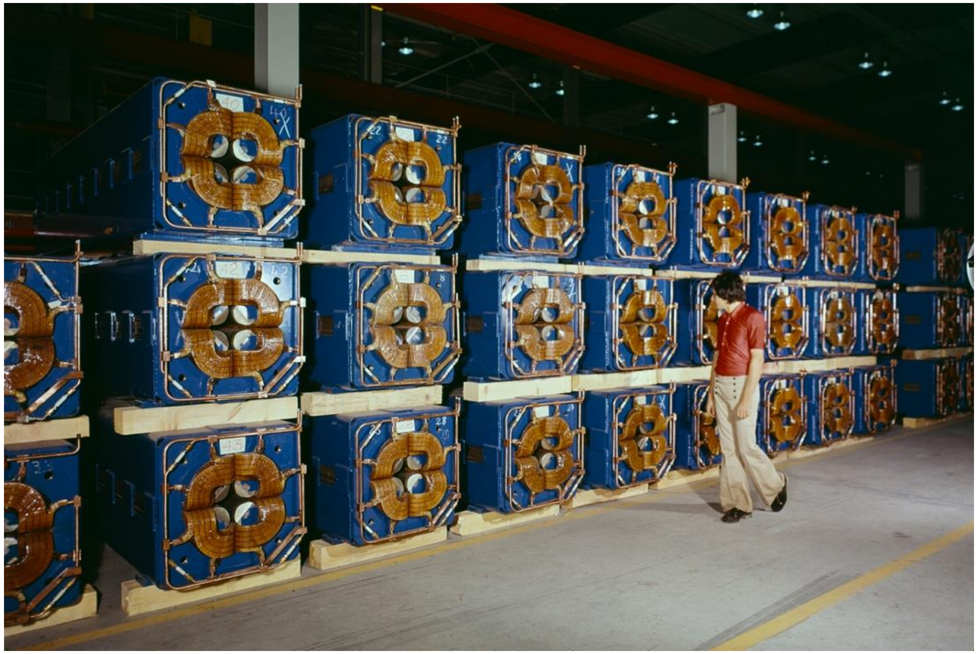
Aperture = 52 × 92 mm^2

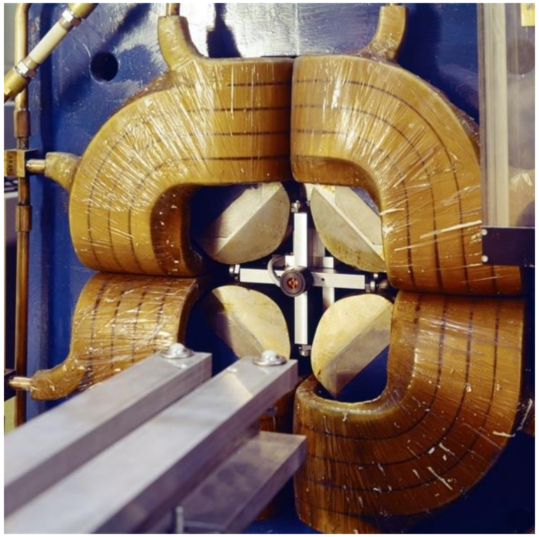
L = 6.26 m

Weight = 17 t

Quadrupole magnet : SPS quadrupole







type MQ

$G = 20.7$ T/m

Coil : 16 turns

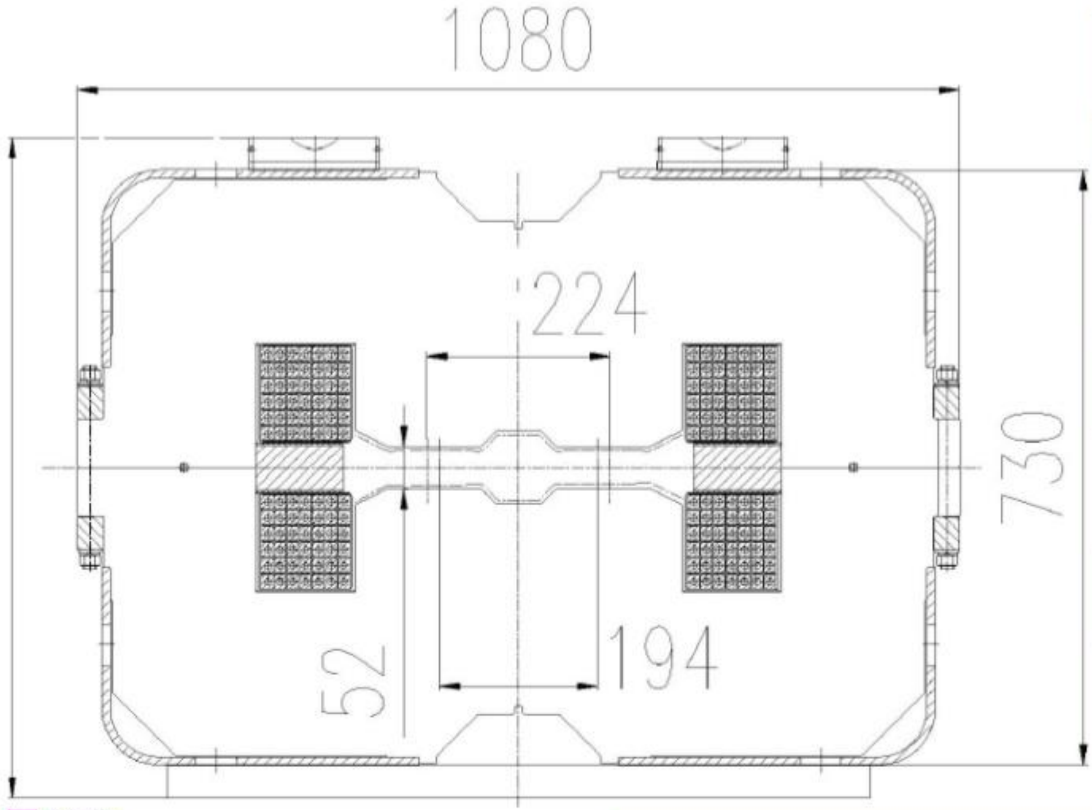
$I_{max} = 1938$ A

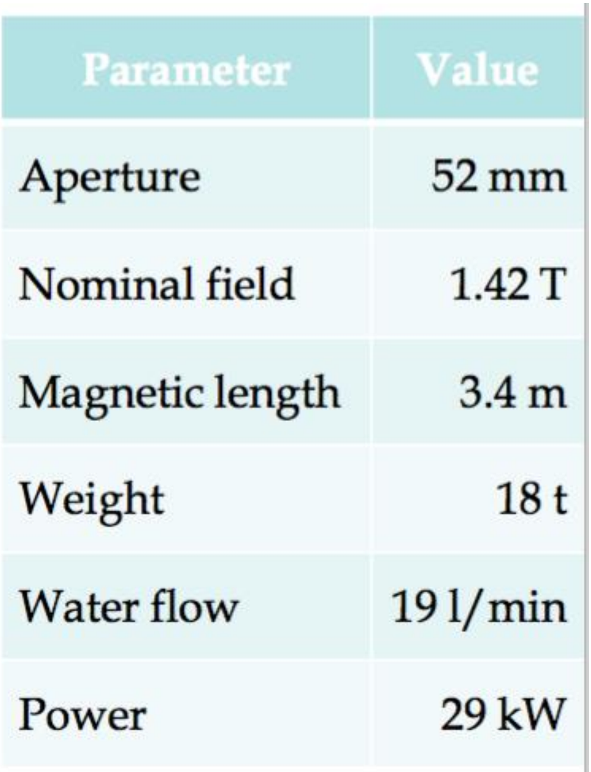
Aperture inscribed radius = 44 mm

$L_{coil} = 3.2$ m

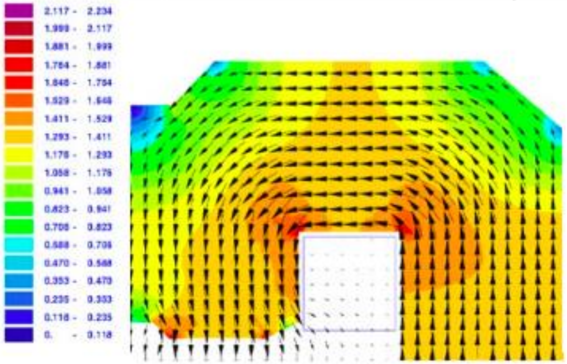
Weight = 8.4 t

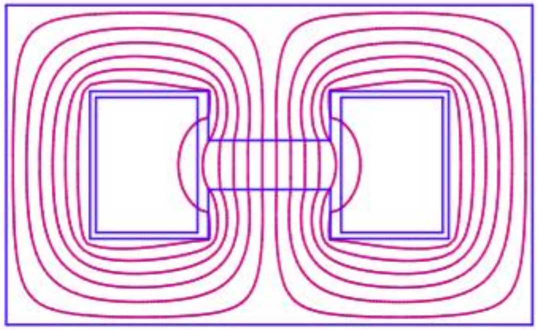
MBW LHC warm separation dipole (1)



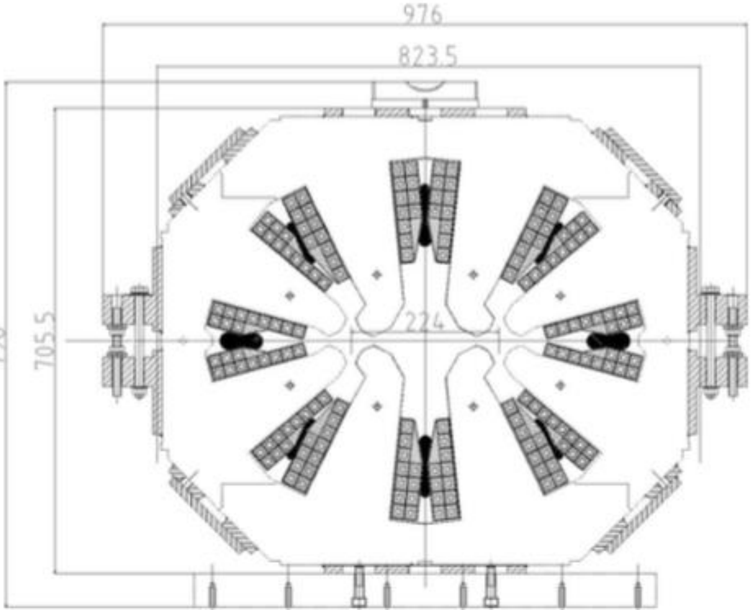


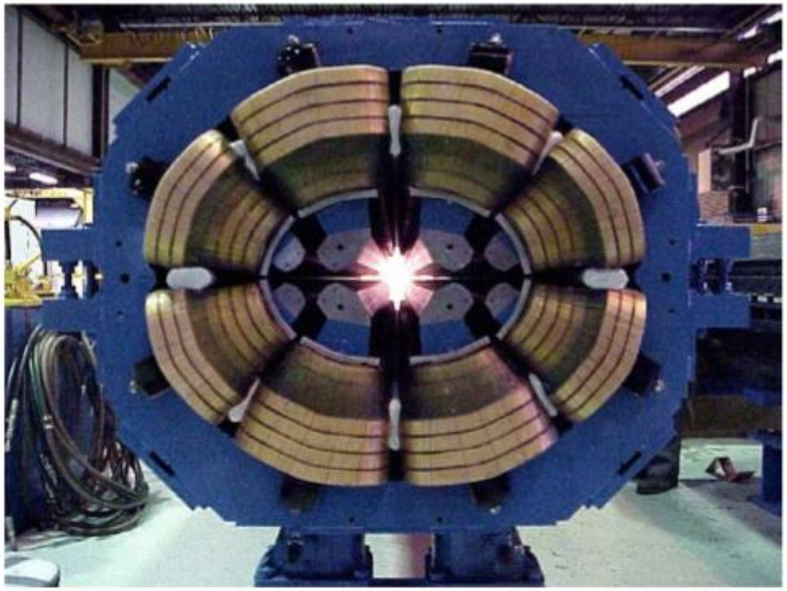
Parameter	Value
Aperture	52 mm
Nominal field	1.42 T
Magnetic length	3.4 m
Weight	18 t
Water flow	19 l/min
Power	29 kW





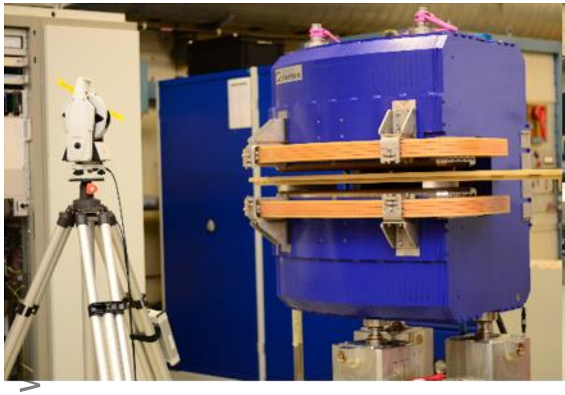
MQW: LHC warm double aperture quadrupole



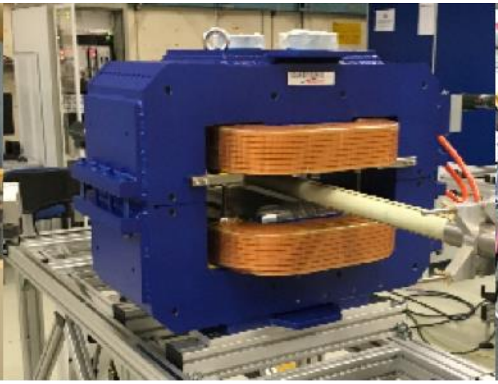


Elena, anti proton decelerator

- .

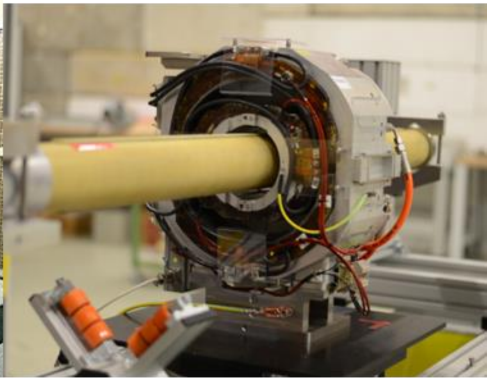


Ring dipoles 8/8



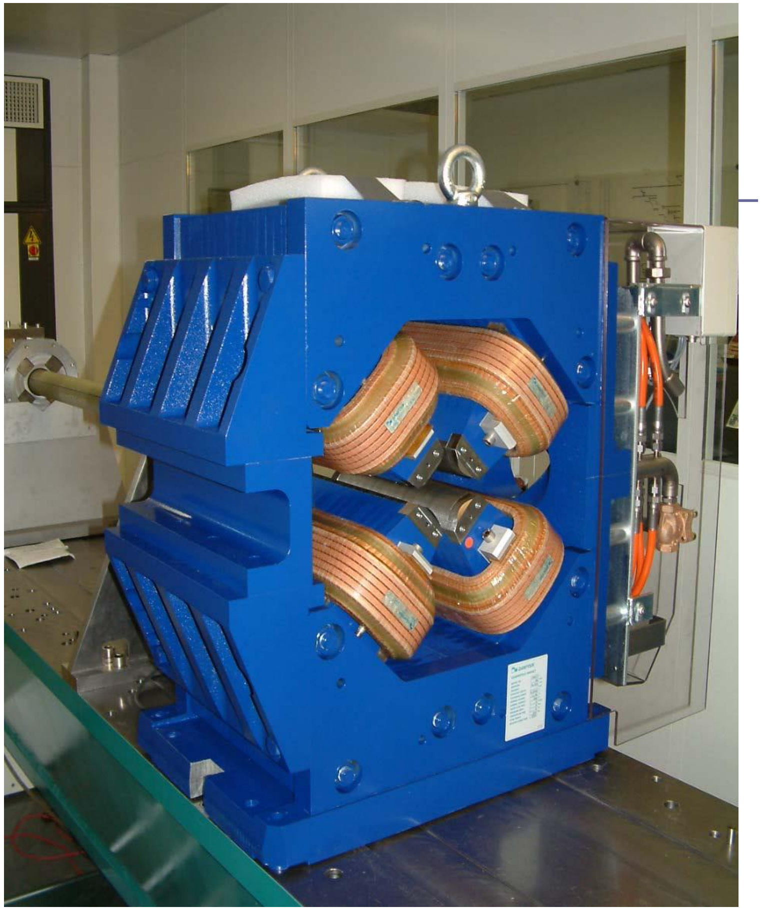
TL dipoles 3/3

Skew quads 3/3



HV correctors 3/14

Soleil, synchrotron light-source



Courtesy A. Dael, CEA

Literature on warm accelerator magnets

- Books
  - G.E.Fisher, “Iron Dominated Magnets” AIP Conf. Proc., 1987 -- Volume 153, pp. 1120-1227
  - J. Tanabe, “Iron Dominated Electromagnets”, World Scientific, ISBN 978-981-256-381-1, May 2005
  - P. Campbell, Permanent Magnet Materials and their Application, ISBN-13: 978-0521566889
  - S. Russenschuck, Field computation for accelerator magnets : analytical and numerical methods for electromagnetic design and optimization / Weinheim : Wiley, 2010. - 757 p.

- Schools
  - 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
  - D. Tommasini, “Practical definitions and formulae for magnets,” CERN,Tech. Rep. EDMS 1162401, 2011

Acknowledgements

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

Davide Tommasini, Attilio Milanese, Antoine Dael, Stephan Russenschuck, Thomas Zickler

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

www.cern.ch