# Warm Magnets

**Gijs de Rijk**
CERN

**CAS**

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- 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

# 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:

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

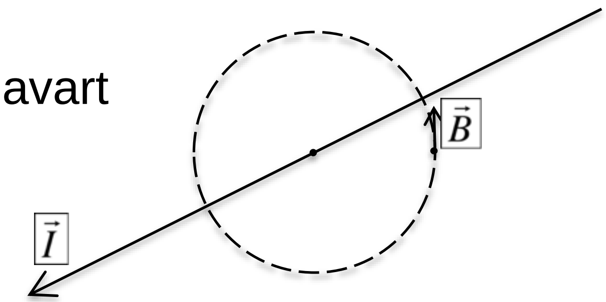
$$\vec{D} = \varepsilon\vec{E} = \varepsilon_0\left(\vec{E} + \vec{P}\right)$$

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

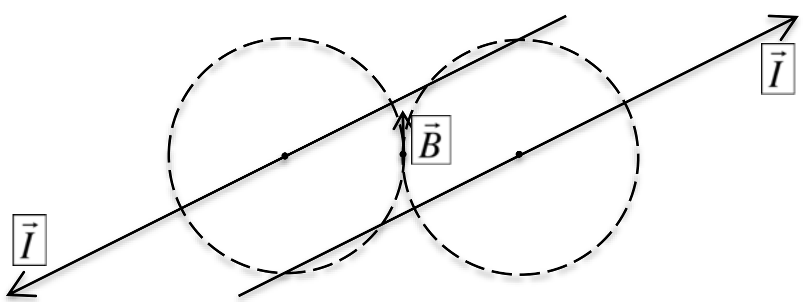
# Magnetic fields

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

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

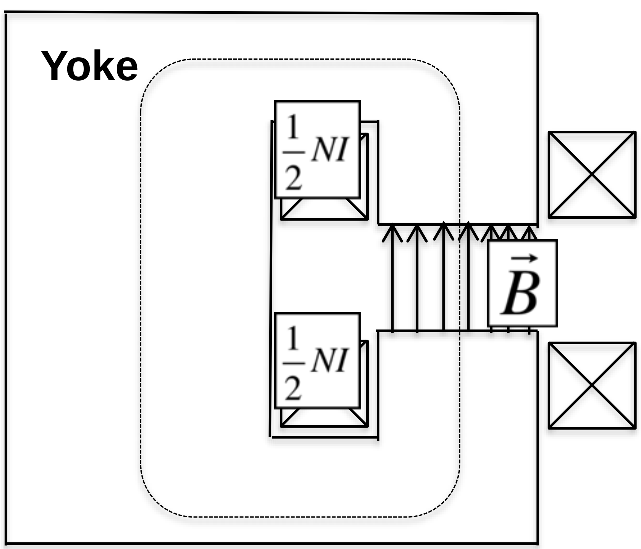
$$N\cdot I = H_{iron}\cdot l_{iron} + H_{airgap}\cdot l_{airgap} \Rightarrow$$

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

Example: C shaped dipole for accelerators

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

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




**coil**

$B$ = 1.5 T

Gap = 50 mm

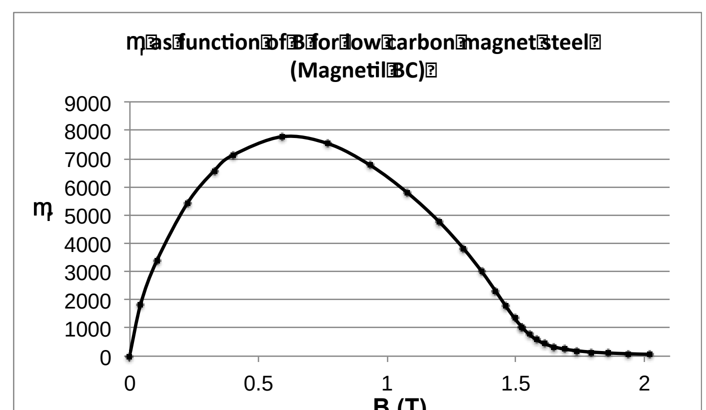
$N$ . $I$ = 59683 A

2 x 30 turn coil

$I$ = 994 A

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

14 x 14 mm Cu

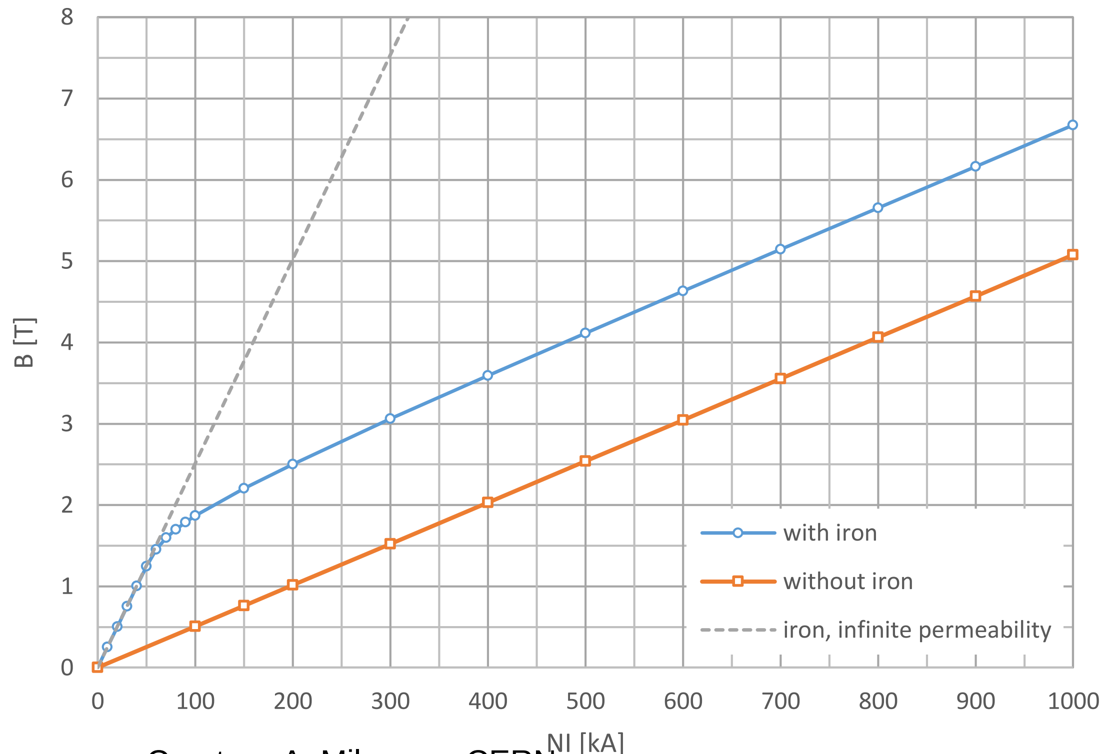


# Comparison : iron magnet and air coil

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

# Magnetic field quality: multipole description

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

$with$:

$z = x + iy,$

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

$R_{ref}$ $the\ radius\ of\ the\ reference\ circle,$

$B_1$ $the\ dipole\ field\ component\ at\ the\ reference\ circle,$

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

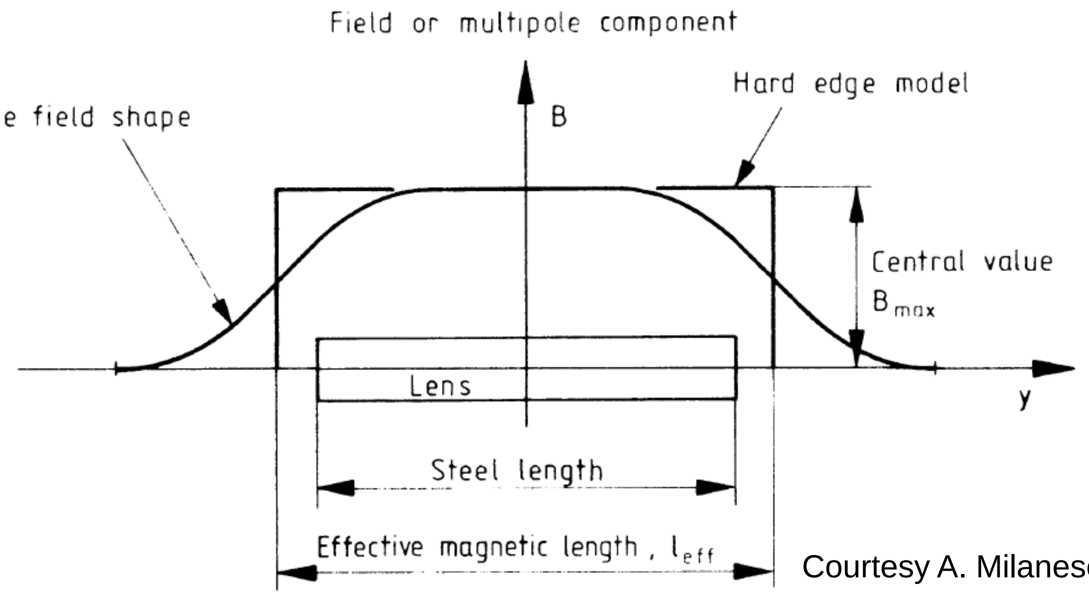
$a_n$ $the\ skew\ nth\ multipole\ component.$

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

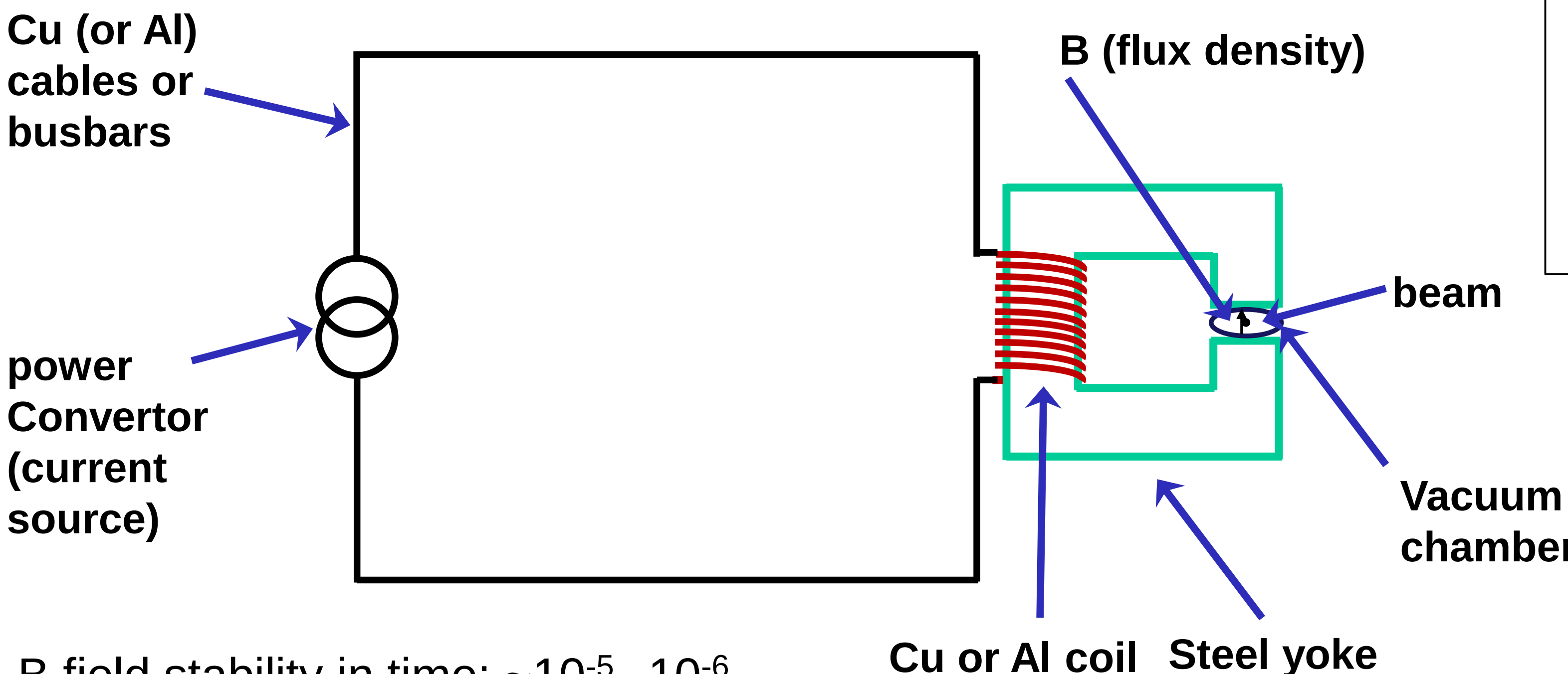
$$l_m B_0 = \int_{-\infty}^{\infty} B(z)dz$$

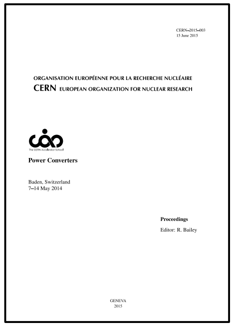
magnetic length $L_{mag}$ as a first approximation:

- 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

CAS Constanta, 22-Sept-2018, warm magnets, GdR

# Magnets in an accelerator: power convertor and circuit





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

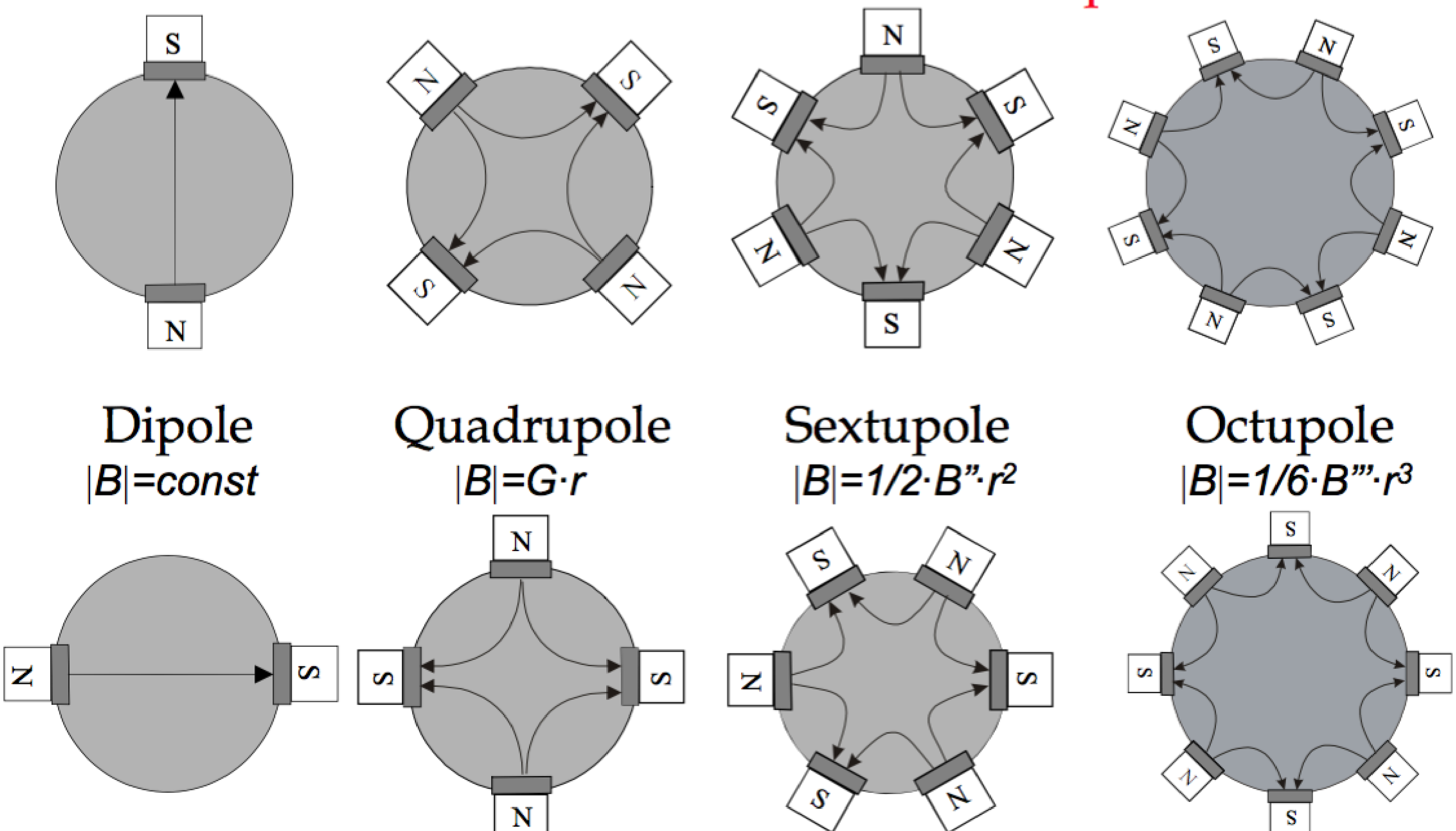
Then the Power Convertor has to Supply : 0-500 A with a stability of a few ppm.

Voltage up to 40 V (resitive)

And 100 V (inductive)

# Types of magnet fields for accelerators

NORMAL : vertical field on mid-plane




SKEW : horizontal field on mid-plane

Courtesy D. Tommasini, CERN

# Symmetry and allowed harmonics

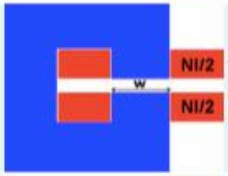
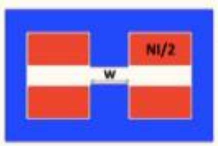
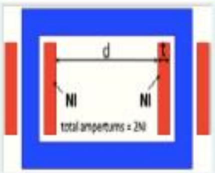
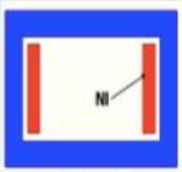
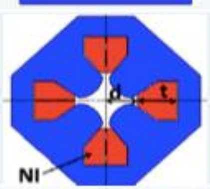
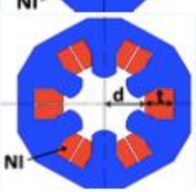
In a fully symmetric magnet certain field harmonics are natural.

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

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 ($P_{max}$ , $\Delta p_{max}$ 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

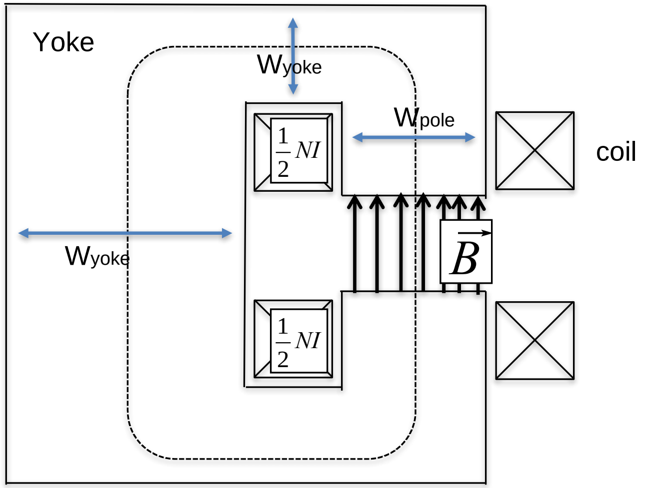
- From *B* and *l* you get *NI* (A) $$NI = \frac{l_{airgap} B}{\mu_0}$$
- *From NI* (A) and the power convertor $I_{max}$ you get *N*
- Then you decide on a coil X-section using:

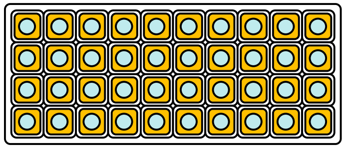
$$j_{coil} = 5\ {}^{A}/_{mm^2}\ for\ water\ cooled$$
$$or\ j_{coil} = 1\ {}^{A}/_{mm^2}\ for\ air\ cooled$$

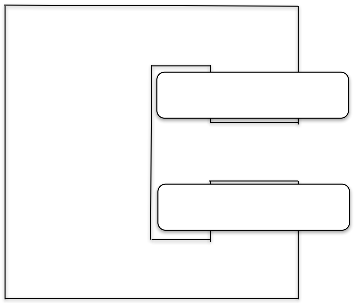
- This defines the coil cavity in the yoke (you add 0.5 mm insulation around each conductor and 1 mm ground insulation around the coil) and select the best fitting rectangular
- You can the draw the draft X-section using:

$$W_{yoke} = W_{pole} \frac{B}{B_{sat}} \quad with \quad 1.5\,T < B_{sat} < 2\,T$$

- 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 $\sigma$ and the specific resistivity $\rho$ of the material one gets the spent Power in the coil

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

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 $\Delta T$ (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

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

- 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

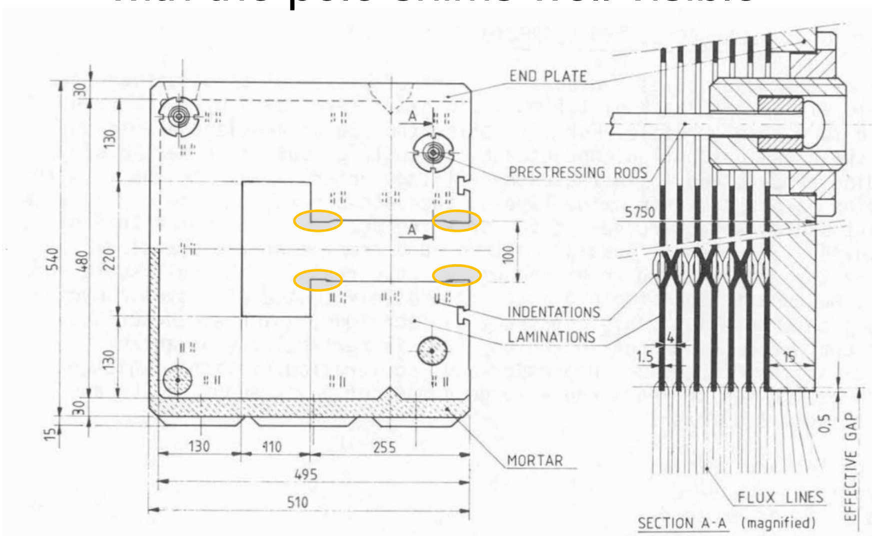
# Theoretical pole shapes

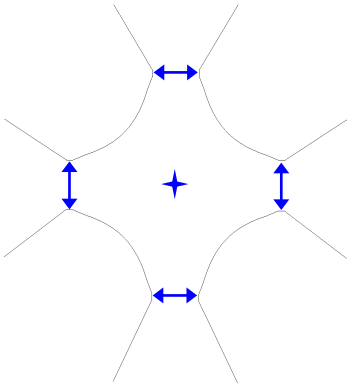
The ideal poles for dipole, quadrupole, sextupole, etc. are lines of constant scalar potential

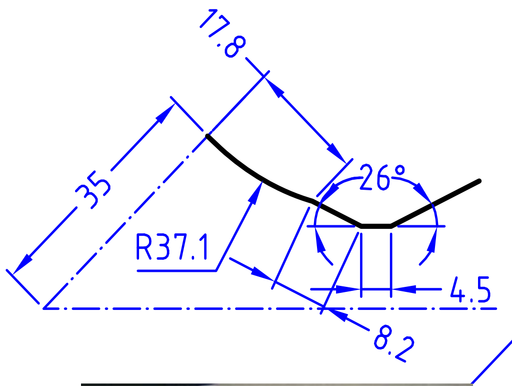
| | | |
|---|---|---|
| Dipole | $y = \pm h/2$ | straight line |
| quadrupole | $2xy = \pm r^2$ | hyperbola |
| sextupole | $3x^2y - y^3 = \pm r^3$ | |

# Practical pole shapes: shims and alignment features

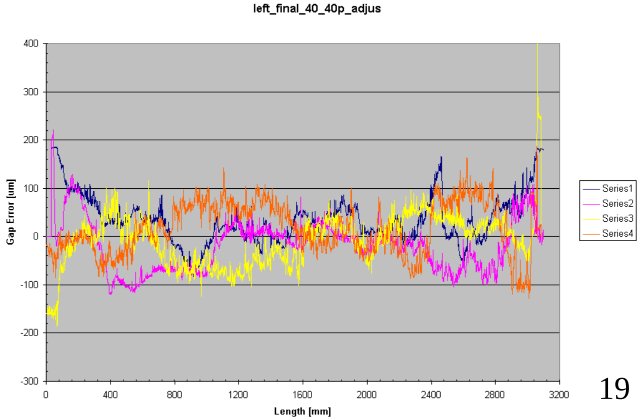
- Dipole example: below a lamination of the LEP main bending magnets, with the pole shims well visible






- 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 $a_n$

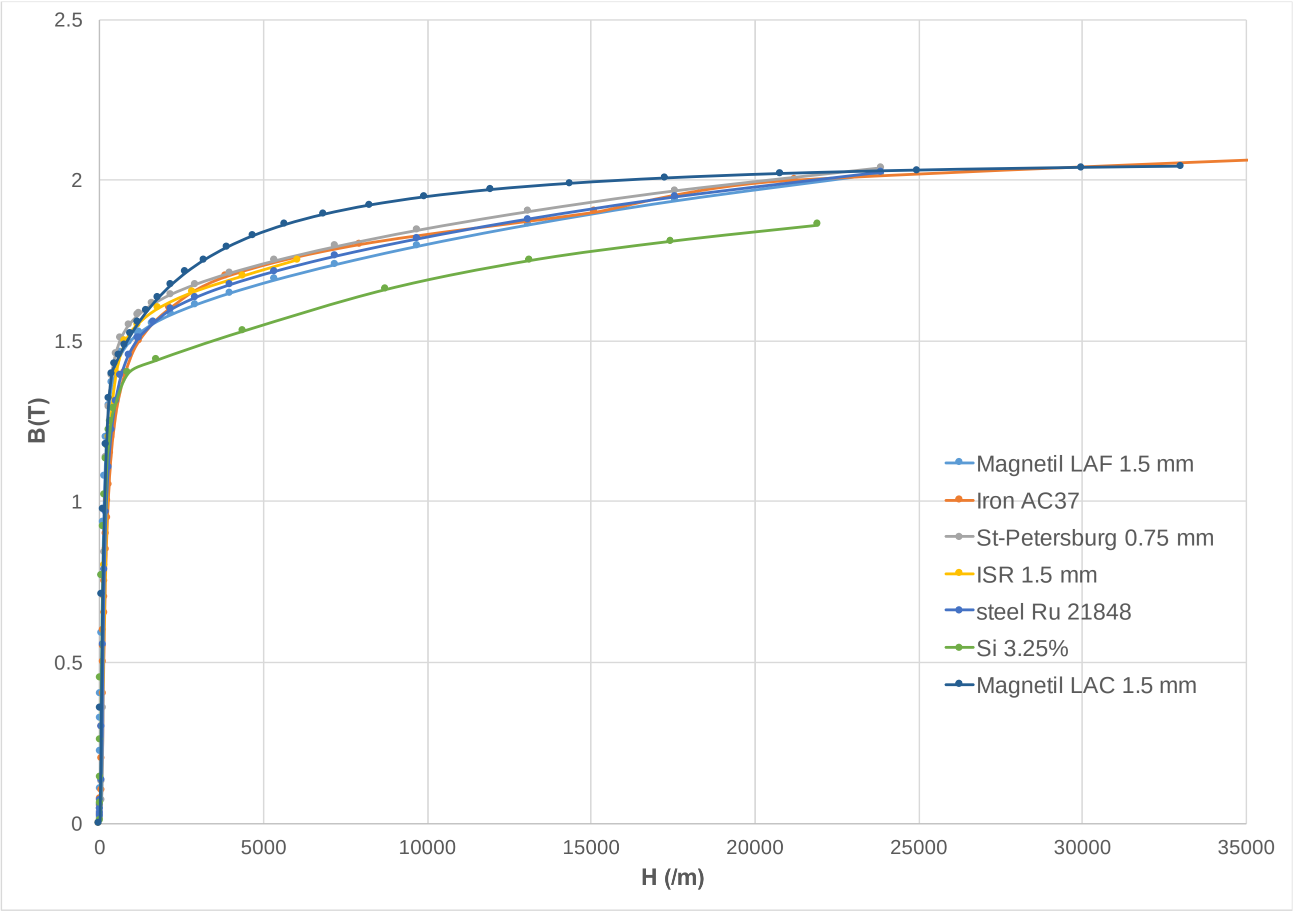
- Some Electromagnetic FE software packages that are often used:
  - Opera from Cobham: 2D and 3D commercial software see: http://operafea.com/
  - "Good old" Poisson, 2D: now distributed by LANL-LAACG see: http://laacg.lanl.gov/laacg/services/download_sf.phtml
  - ROXIE (CERN) 2D and 3D, specialized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



# Yoke shape, pole shape: FE model optimization

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

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

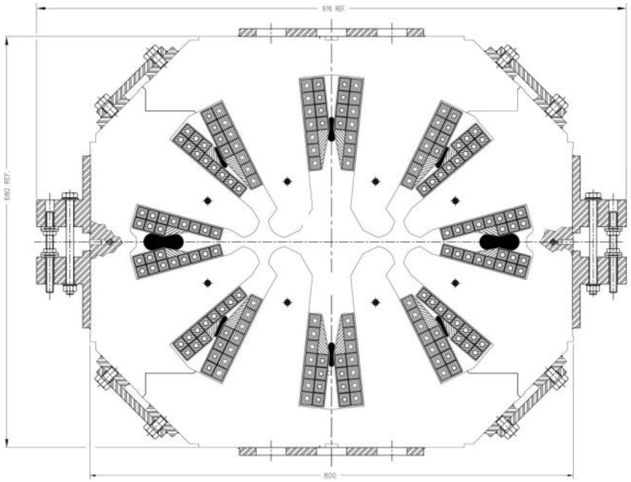
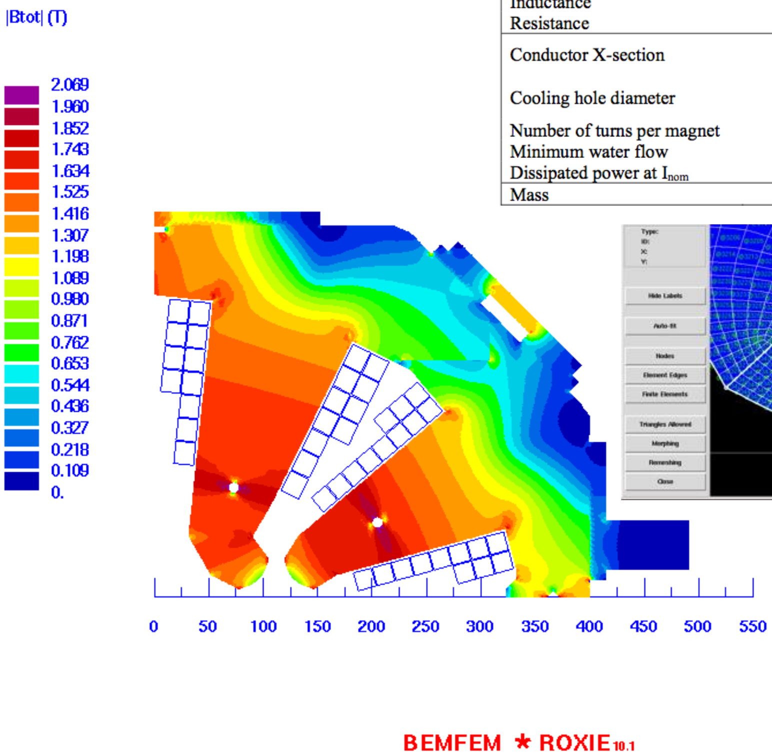
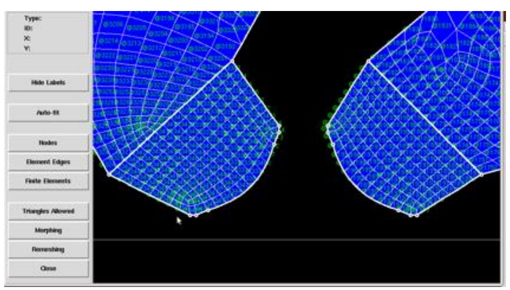
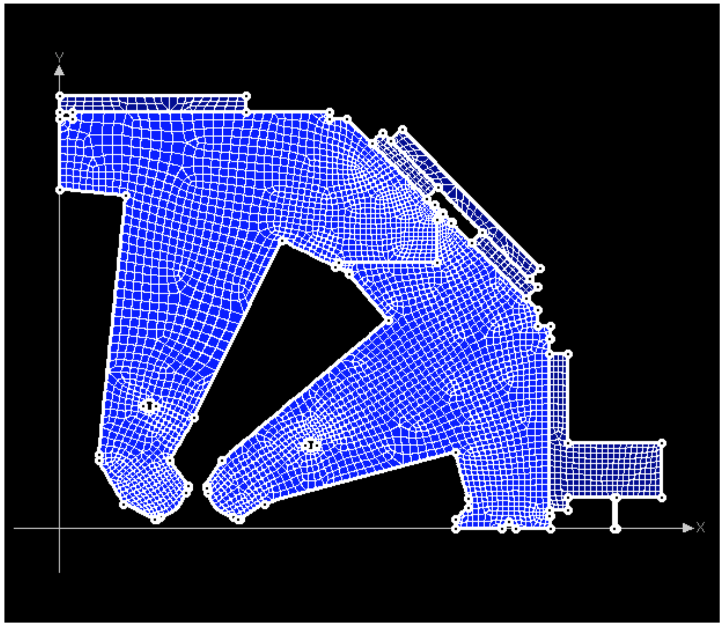


Table 8.6: Main parameters of the MQW normal conducting quadrupole magn

| 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<br>17.0 x 17.0 mm² outer poles | |
| Cooling hole diameter | 7 mm inner poles,<br>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
    - $H_c$ < 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 |

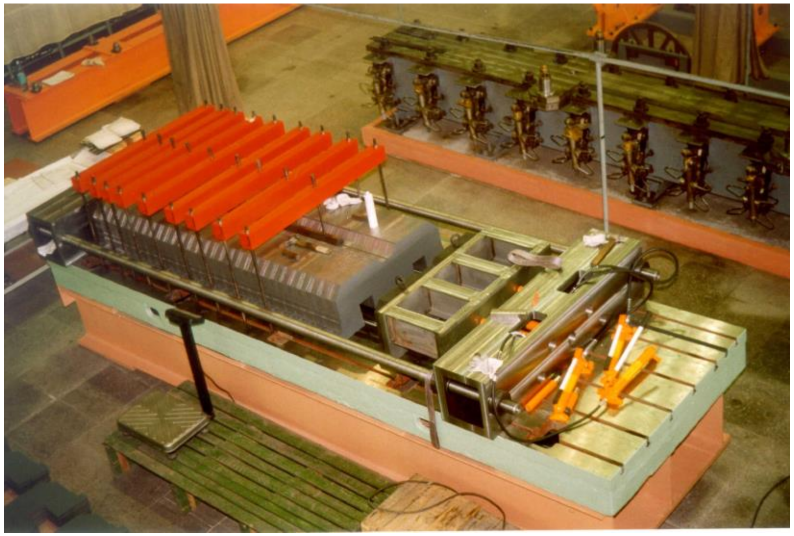
Example specification for 1.5 mm epoxy thick oxide steel for the LHC warm separation magnets, $B_{max}$= 1.53 T

| 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

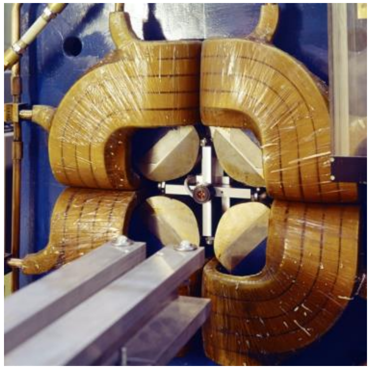
# Coil manufacturing, insulation, impregnation type

- 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

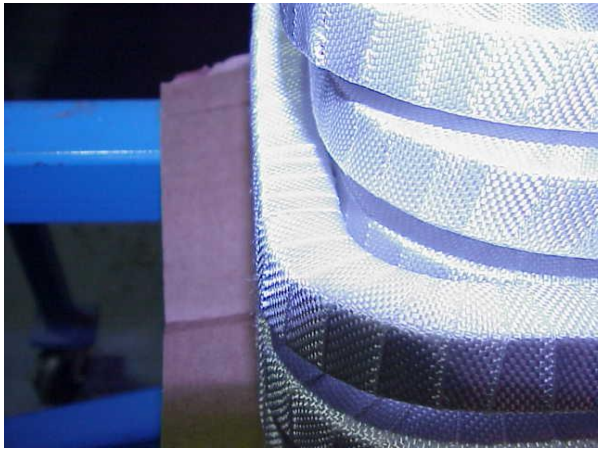
For dipoles some main types are racetrack of bedstead


Quadrupoles



# Coil manufacturing

MQW Glass fibre tape wrapping.



Glass fiber tape winding

Winding the hollow Cu conductor


# Coil manufacturing

Mounted coil

coil electrical test (under water !)

Dipoles racetrack coil

MBXW Coil winding

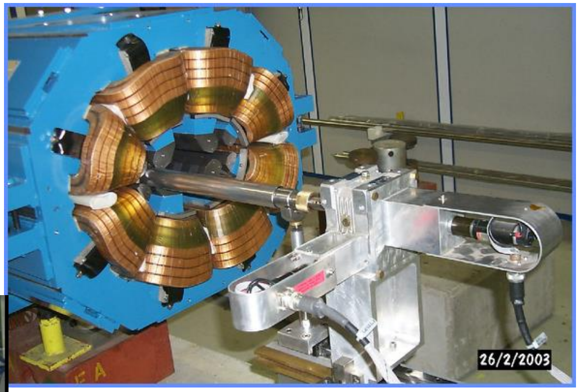
Finished MBXW coil

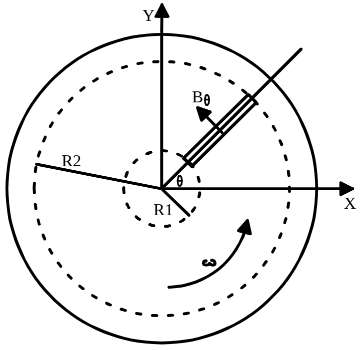
# Magnetic field measurements

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

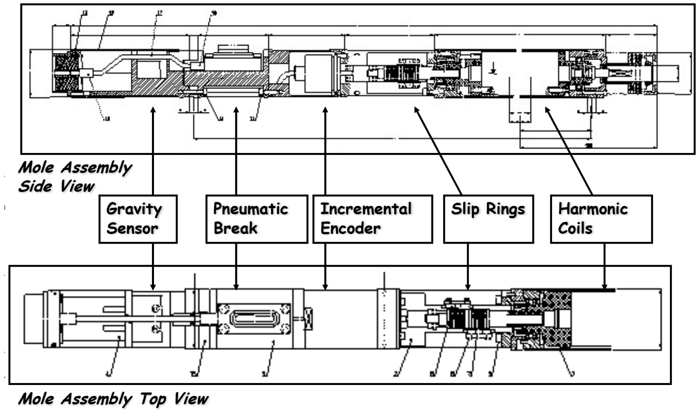
- Rotating coils: multipoles and integrated field or gradient in all magnets
- Stretched wire: magnetic centre and integrated gradient for *n* > 1 magnets
- Hall probes: field map
- Pickup coils: field on a current ramp

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



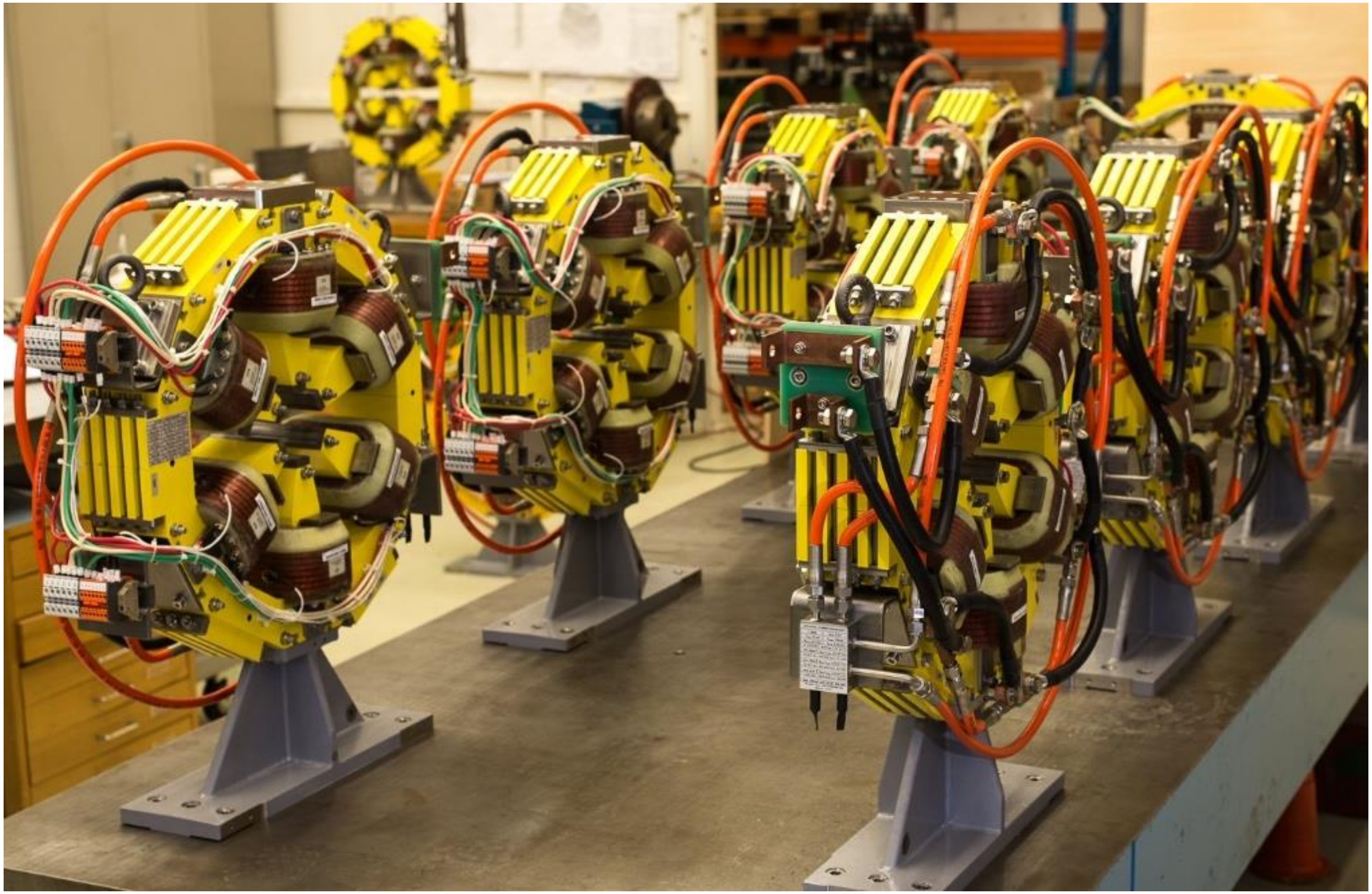




Rotating radial coil



# Sextupoles

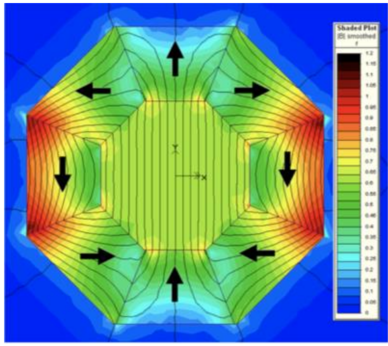
- These are sextupoles (with embedded correctors) of the main ring of the SESAME light source

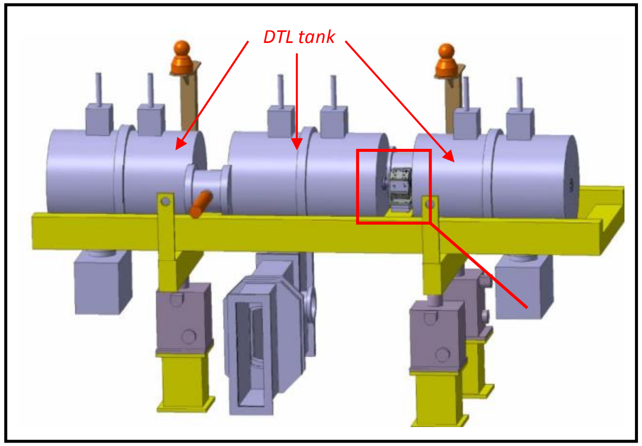


Courtesy A. Milanese, CERN

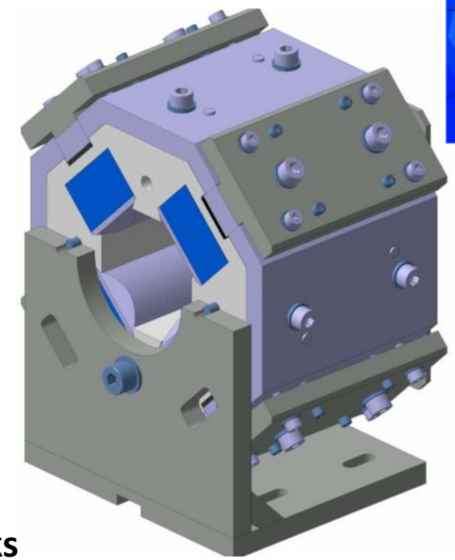
# Permanent magnets

Linac4 @ CERN permanent magnets , quadrupoles

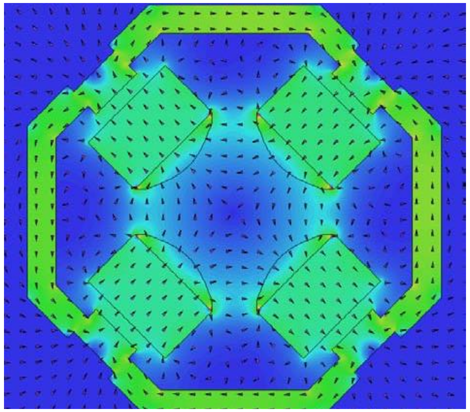





*Pictured : Cell-Coupled Drift Tube Linac module.*



- **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**

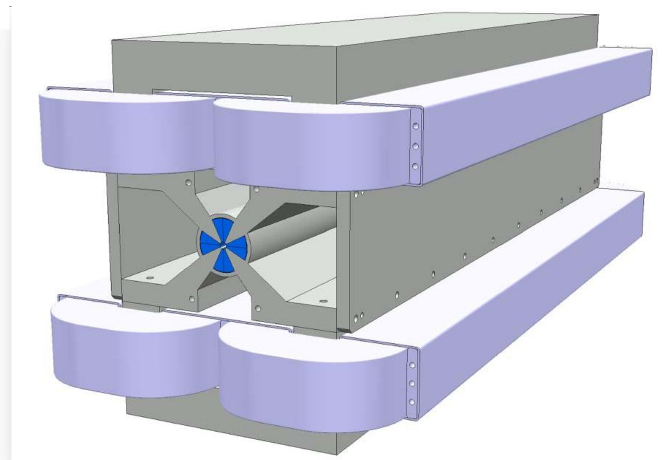


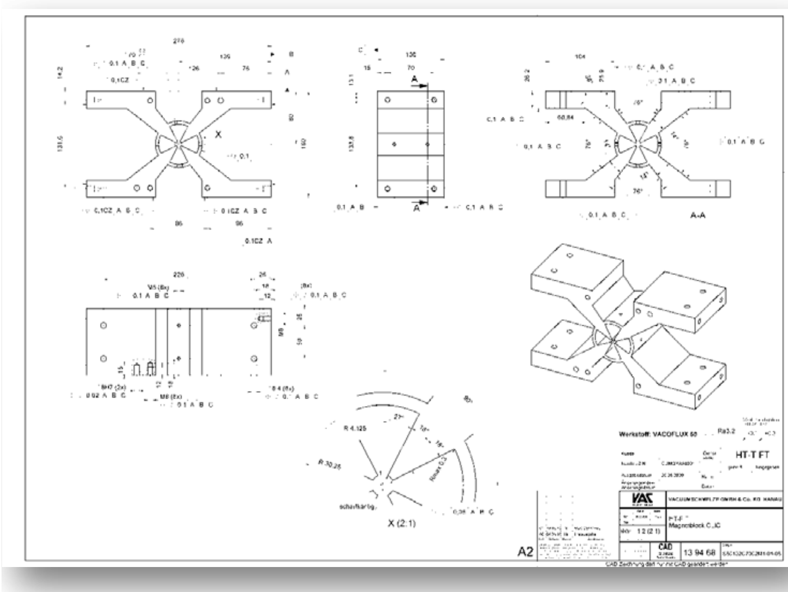
Courtesy D. Tommasini, CERN

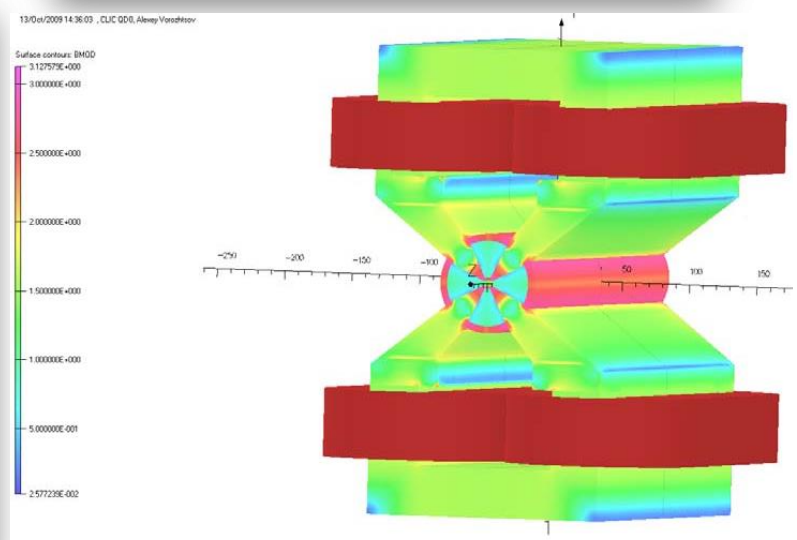
# Hybrid magnets

CLIC final focus,

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





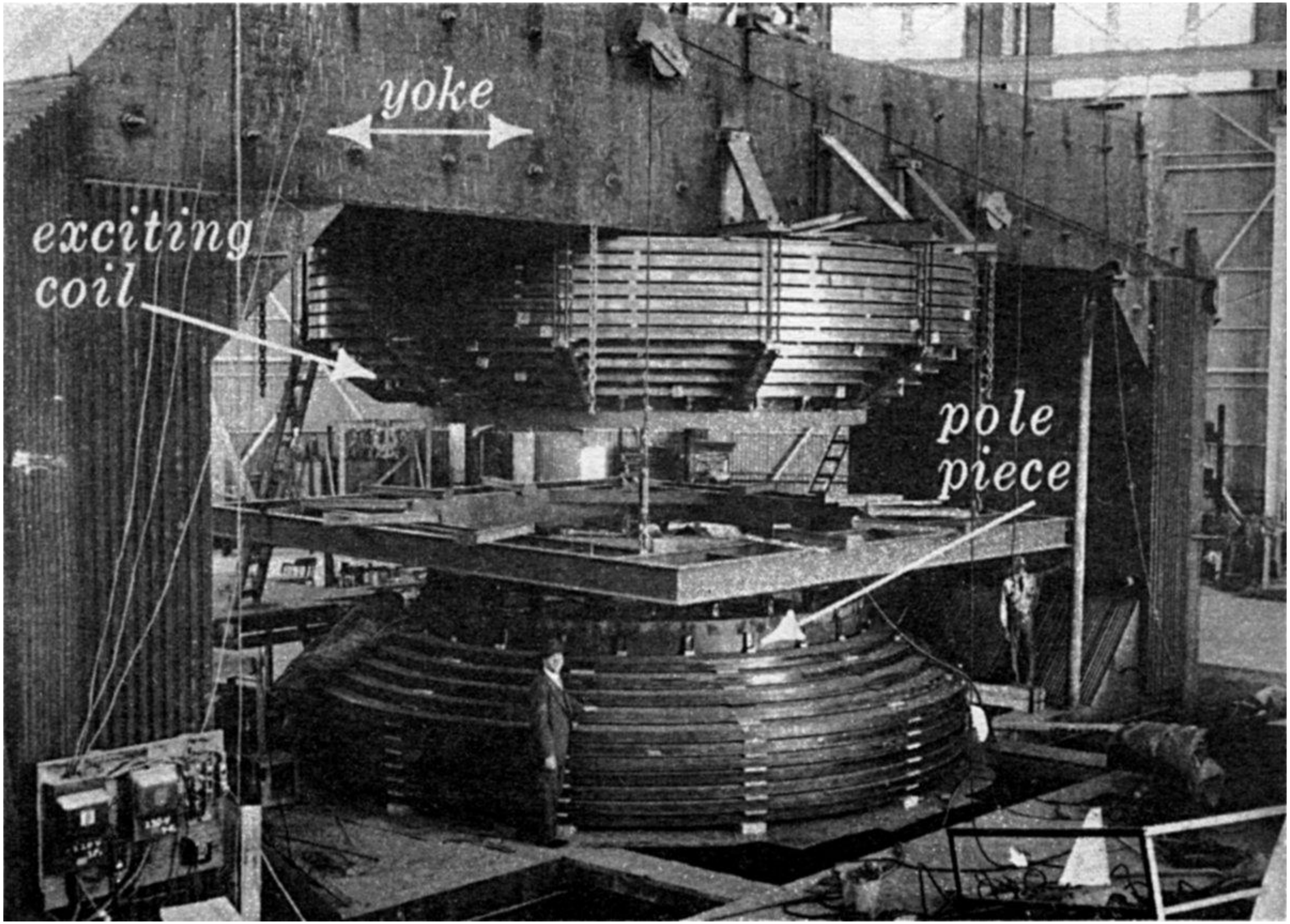


Courtesy D. Tommasini, CERN

Examples;

Some history, some modern regular magnets and some special cases

# The 184'' (4.7 m) cyclotron at Berkeley (1942)

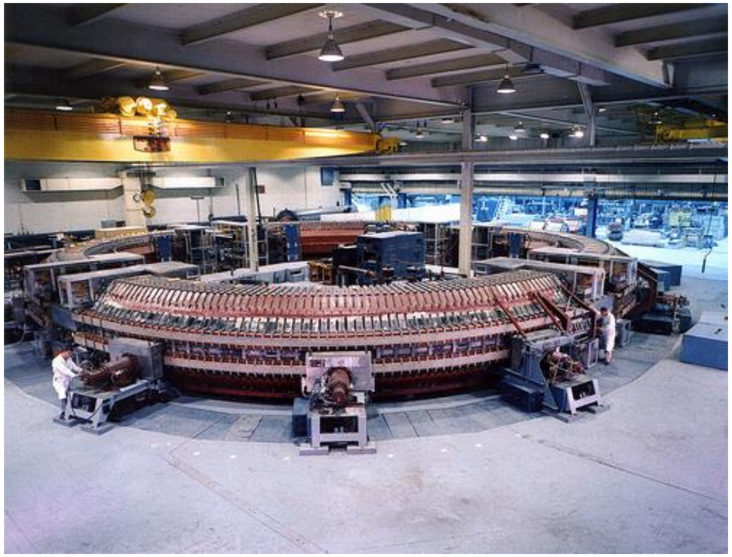


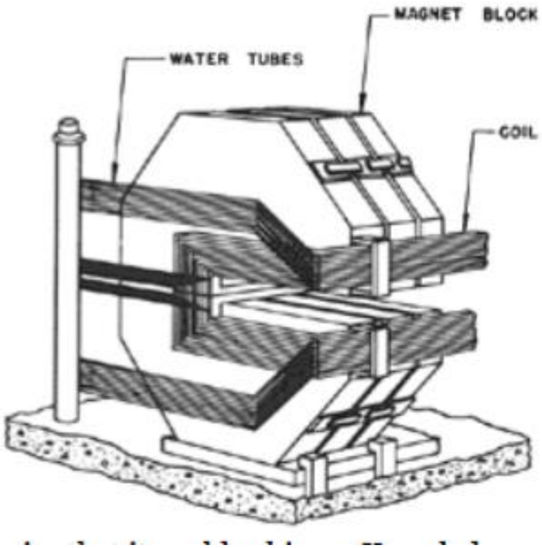

Courtesy A. Milanese, CERN

# 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

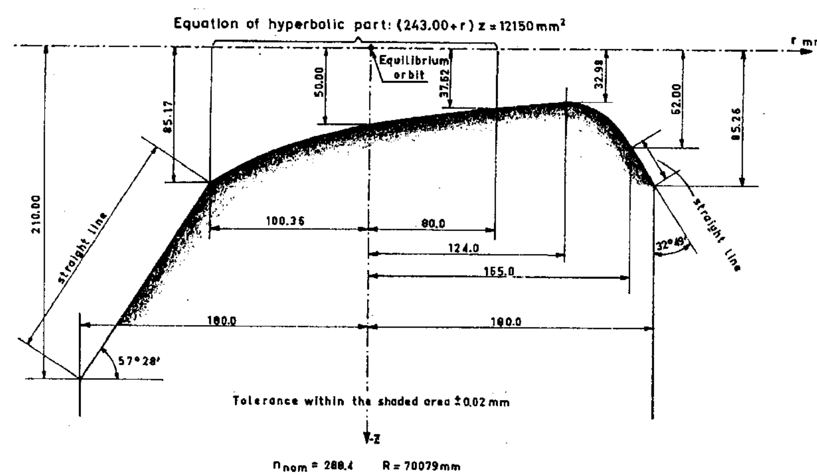
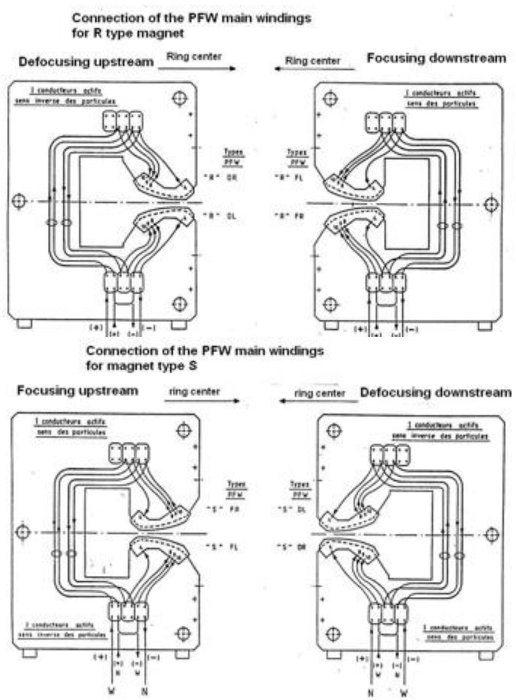



Fig. 9: Final pole profile.

Equipped with pole-face windings for higher order corrections




Water cooled Al race-track coils

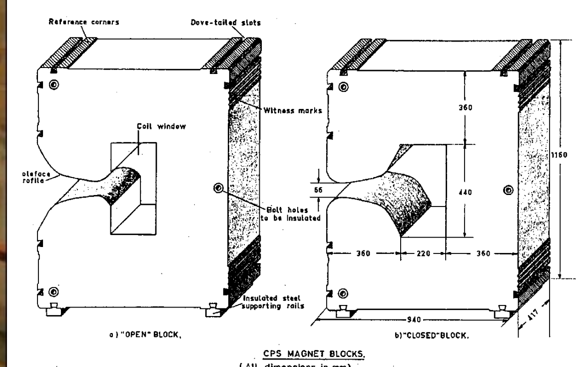



Fig. 12: Final form of the magnet blocks.

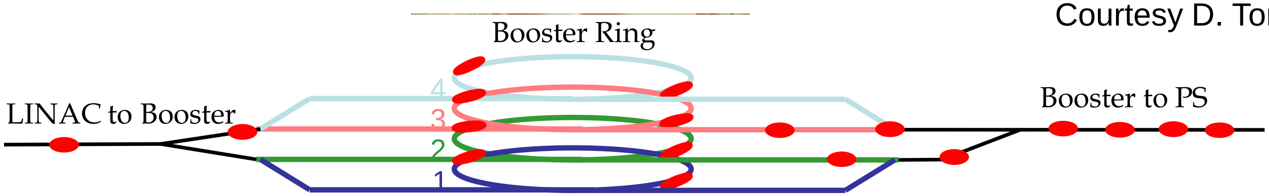
Courtesy D. Tommasini, CERN

# CPS booster

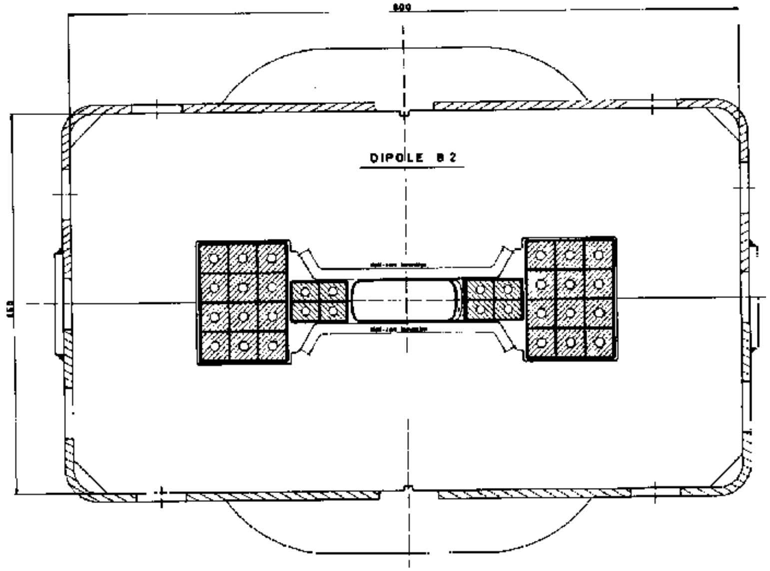
4 accelerator rings in a common yoke. (increase total beam intensity by 4 in presence of space charge limitation at low energy): B=1.48 T @ 2 GeV

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

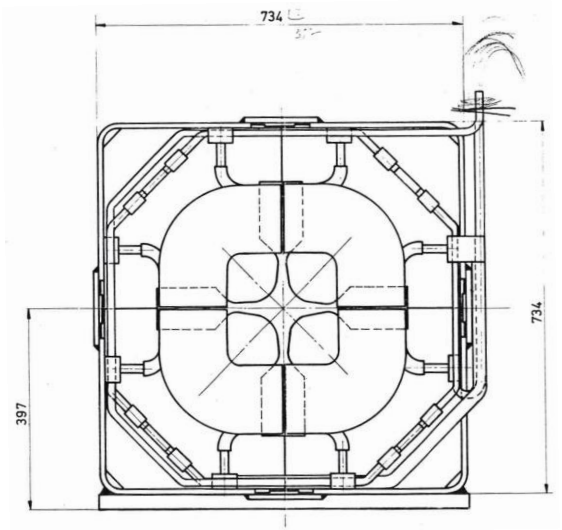
$I_{max}$ = 4900 A

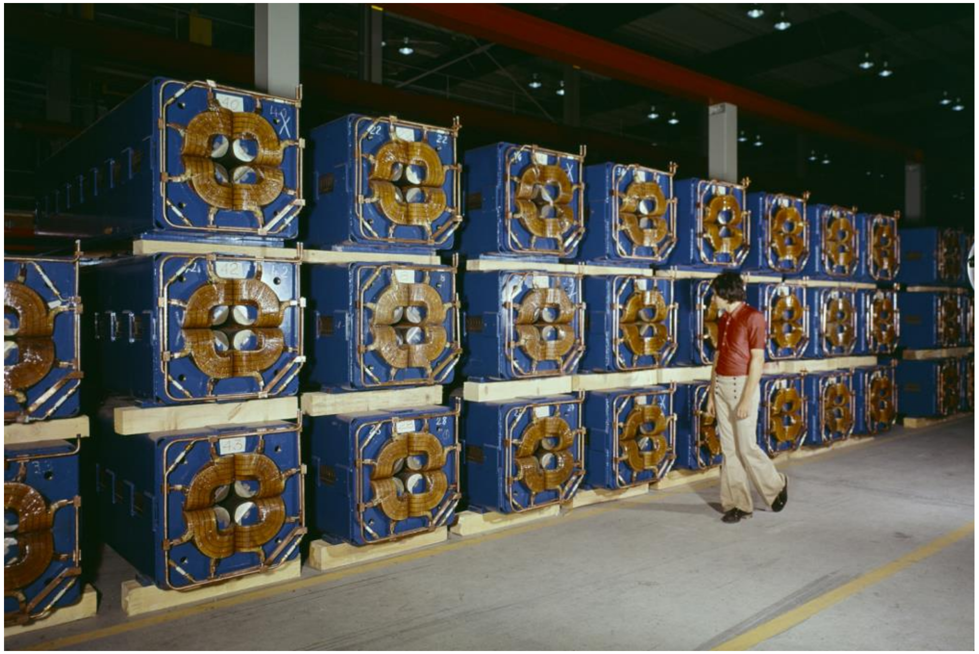
Aperture = 52 × 92 mm$^2$

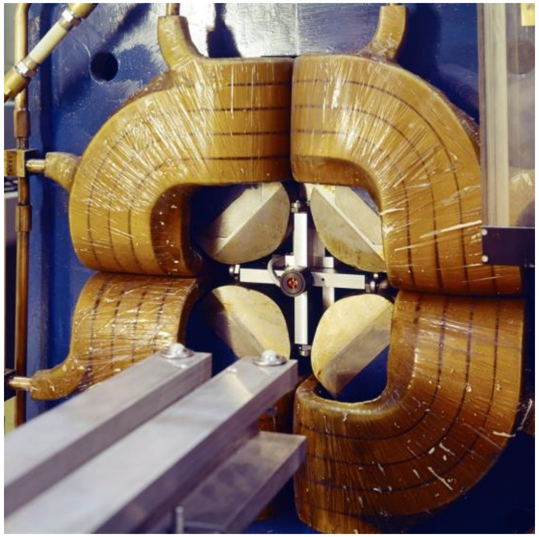
$L$ = 6.26 m

Weight = 17 t

# Quadrupole magnet : SPS quadrupole





type MQ

$G$ = 20.7 T/m

Coil : 16 turns

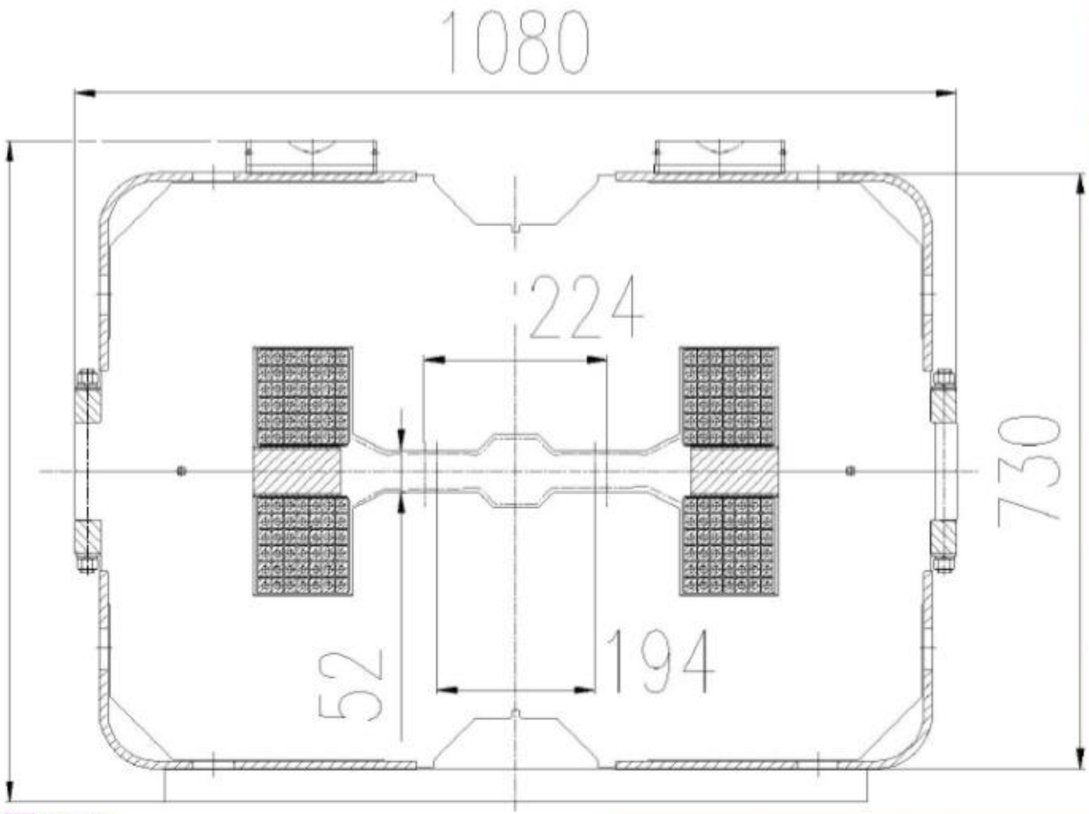
$I_{max}$ = 1938 A

Aperture inscribed radius = 44 mm

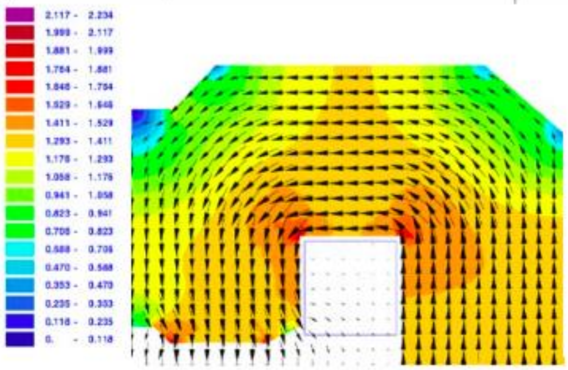
$L_{coil}$ = 3.2 m

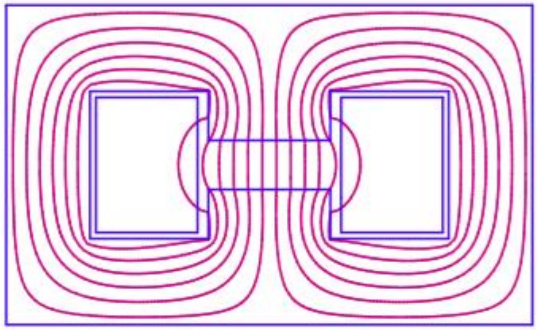
Weight = 8.4 t

# MBW LHC warm separation dipole (1)

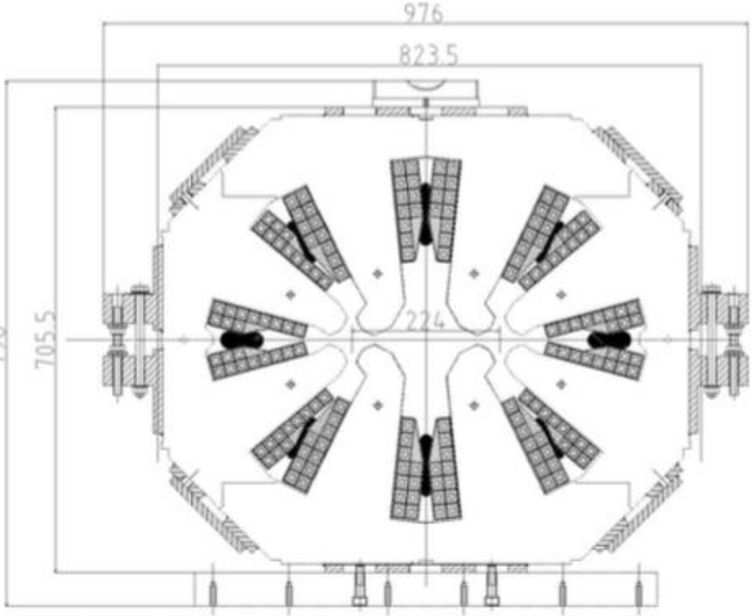


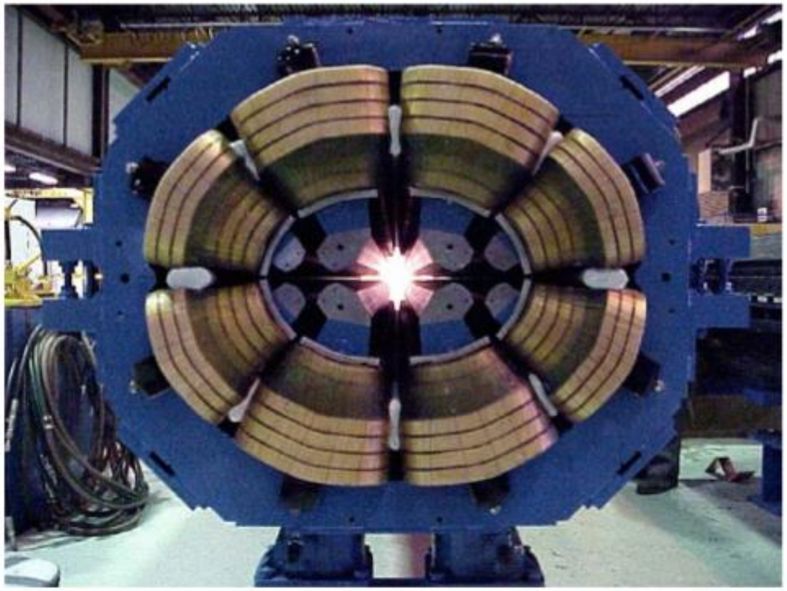

| Parameter | Value |
|---|---|
| Aperture | 52 mm |
| Nominal field | 1.42 T |
| Magnetic length | 3.4 m |
| Weight | 18 t |
| Water flow | 19 l/min |
| Power | 29 kW |





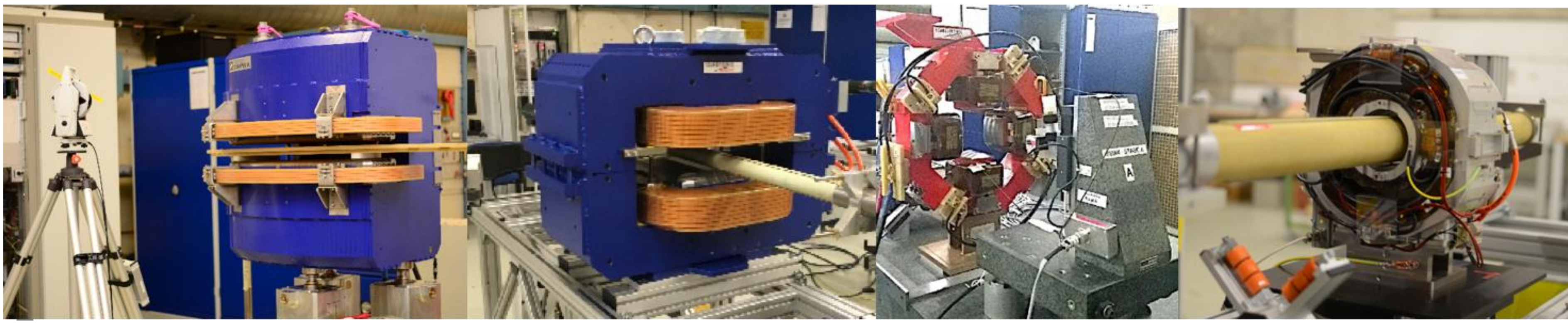
# MQW: LHC warm double aperture quadrupole



# 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

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

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