



# Warm Magnets

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# 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



# Maxwell equations

Integral 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

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

Faraday's equation

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

Gauss's law for magnetism

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

Gauss's law

Differential form

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

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

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

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

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

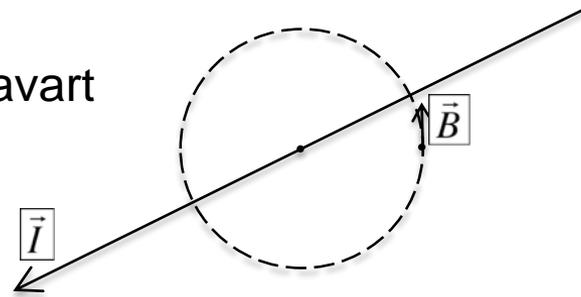
$$\vec{D} = \varepsilon \vec{E} = \varepsilon_0 (\vec{E} + \vec{P})$$

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

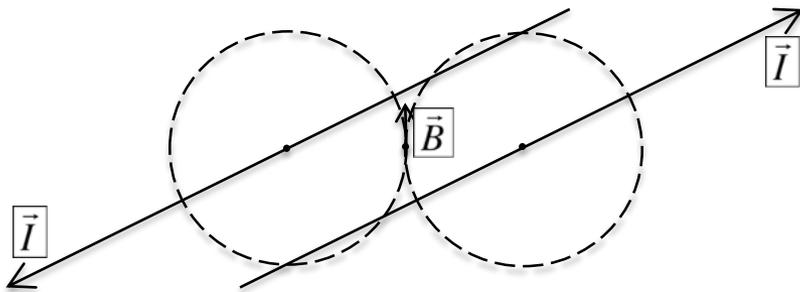
From Ampere's law with no time dependencies

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

We can derive the law of Biot and Savart



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



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

$$I = 187500 \text{ A}$$

- 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

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

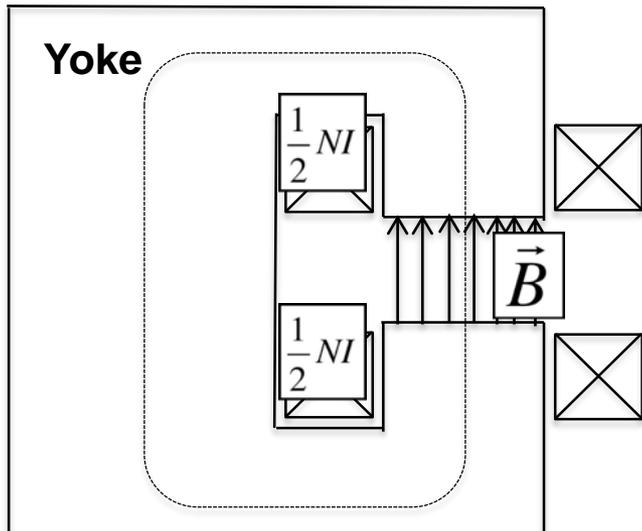
$$N \times I = H_{iron} \times l_{iron} + H_{airgap} \times l_{airgap} \quad \text{D}$$

$$N \times I = \frac{B}{\mu_0 \mu_r} \times l_{iron} + \frac{B}{\mu_0} \times l_{airgap} \quad \text{D}$$

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

This is valid as  $\mu_r \gg \mu_0$  in the iron : limited to  $B < 2 \text{ T}$

Example: C shaped dipole for accelerators



coil

$B = 1.5 \text{ T}$

Gap = 50 mm

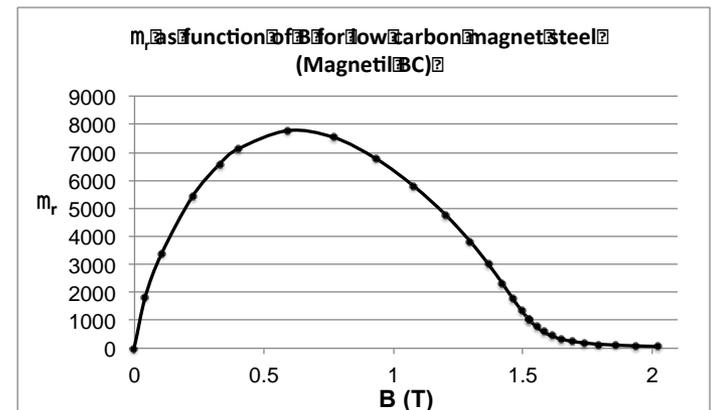
$N \cdot I = 59683 \text{ A}$

2 x 30 turn coil

$I = 994 \text{ A}$

@5 A/mm<sup>2</sup>, 200 mm<sup>2</sup>

14 x 14 mm Cu





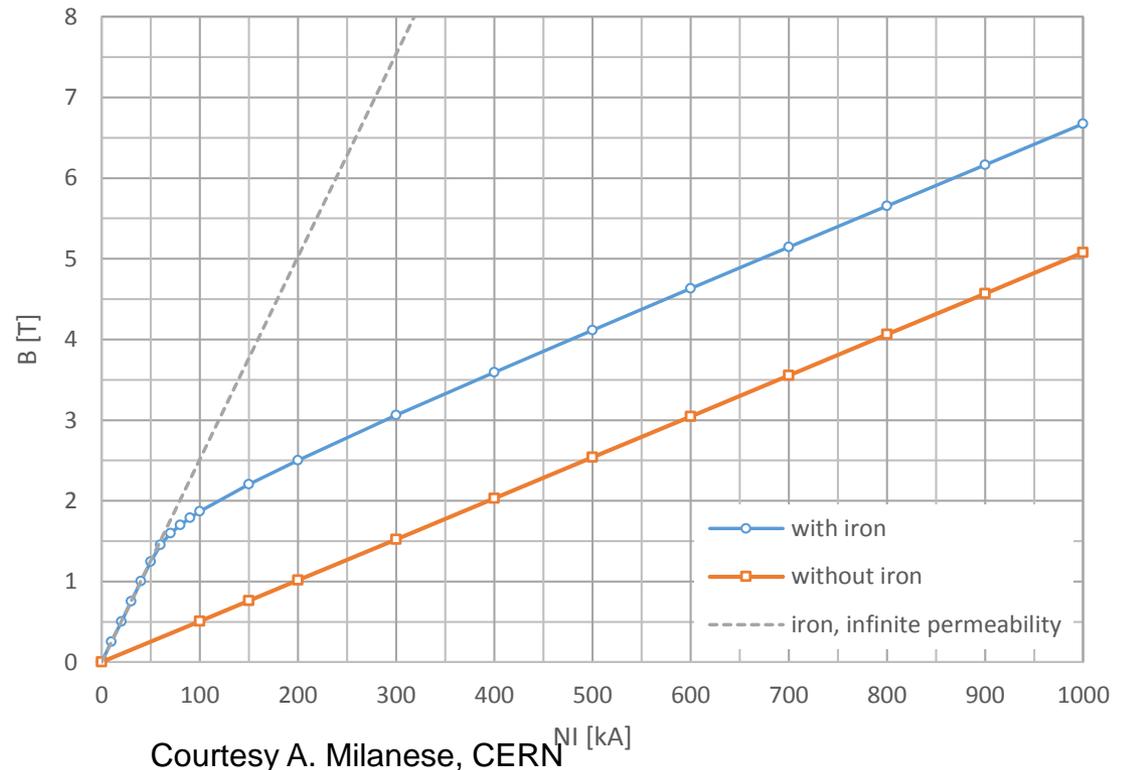
# Comparison : iron magnet and air coil

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





# 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,

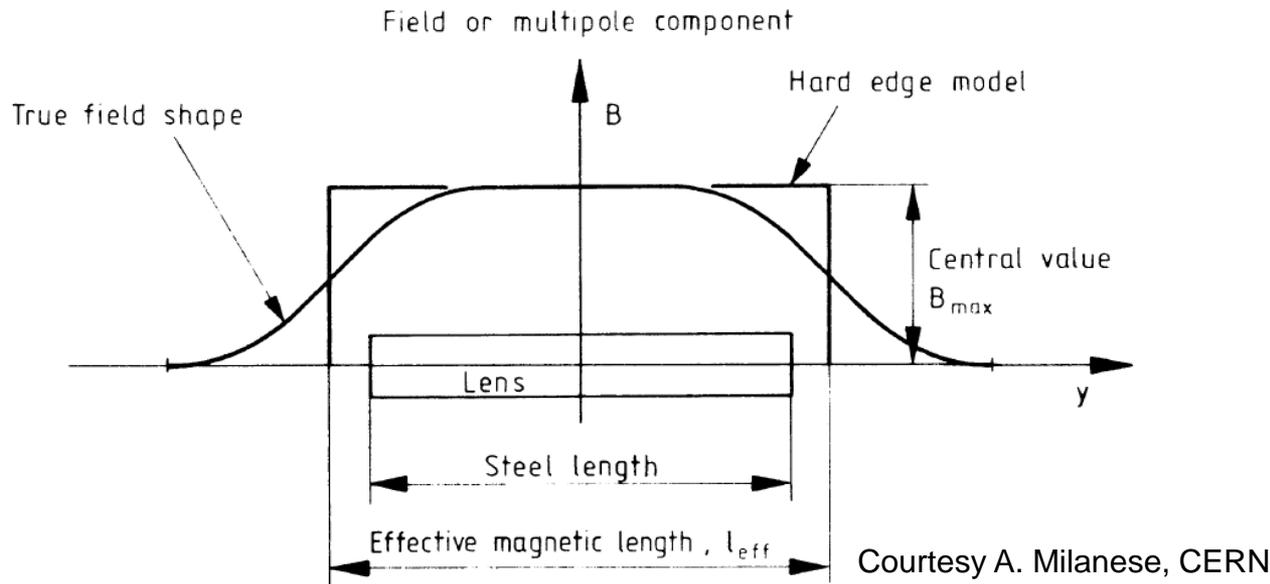
$b_n$  the normal  $n$ th multipole component,

$a_n$  the skew  $n$ th multipole component.

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

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

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



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

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

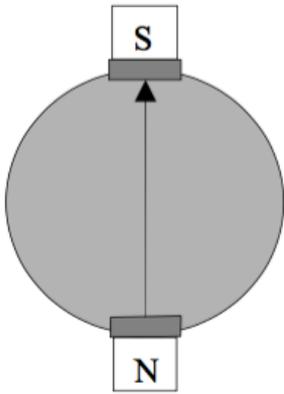
- For dipoles  $L_{mag} = L_{yoke} + d$
- For quadrupoles:  $L_{mag} = L_{yoke} + r$

$d$  = pole distance

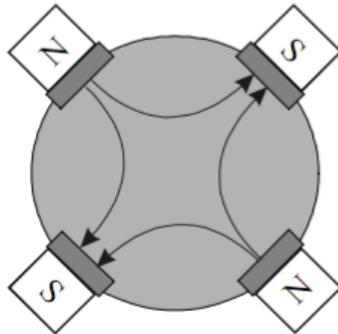
$r$  = radius of the inscribed circle between the 4 poles

# Types of magnet fields for accelerators

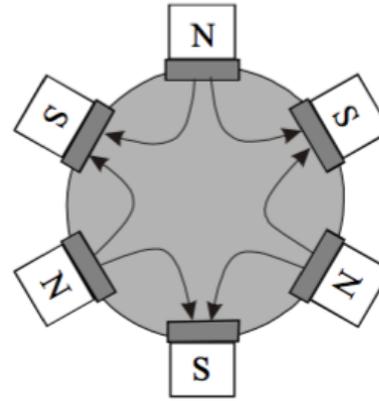
**NORMAL : vertical field on mid-plane**



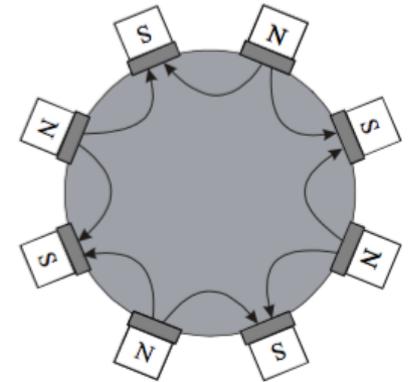
**Dipole**  
 $|B|=const$



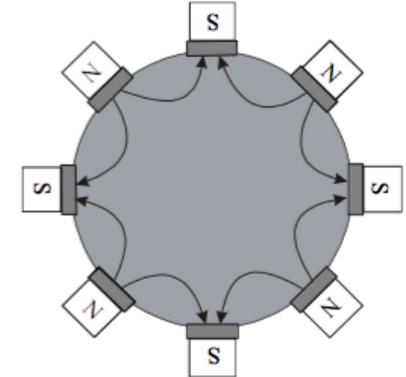
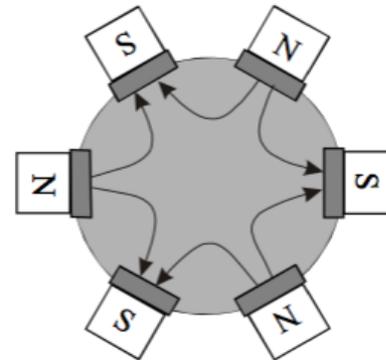
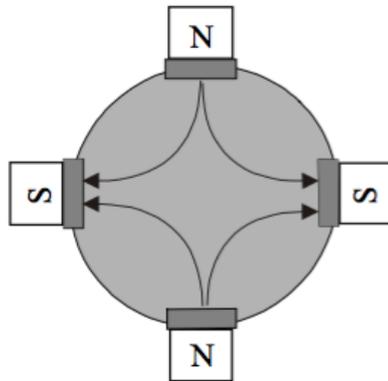
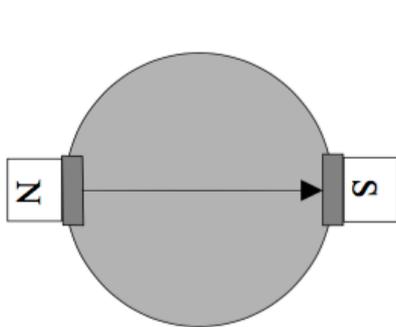
**Quadrupole**  
 $|B|=G \cdot r$



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



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



**SKEW : horizontal field on mid-plane**



# Symmetry and allowed harmonics

In a fully symmetric magnet certain field harmonics are natural.

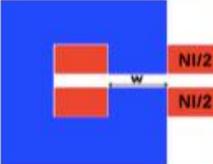
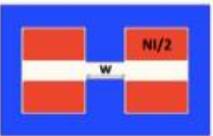
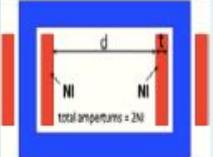
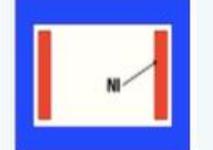
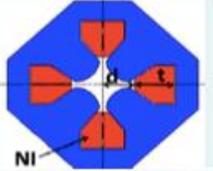
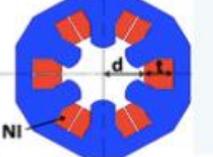
Magnet type	Allowed harmonics $b_n$
n=1 Dipole	n=3,5,7,...
n=2 Quadrupole	n=6,10,14
n=3 Sextupole	n=9,15,21
n=4 Octupole	n=12,20,28

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

Courtesy D. Tommasini, CERN

CAS Budapest, 7-Oct-2016, warm magnets, GdR



# 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

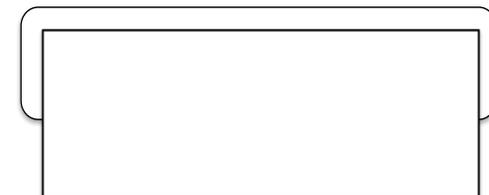
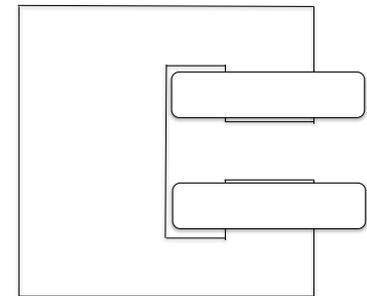
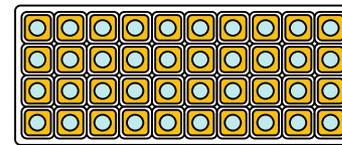
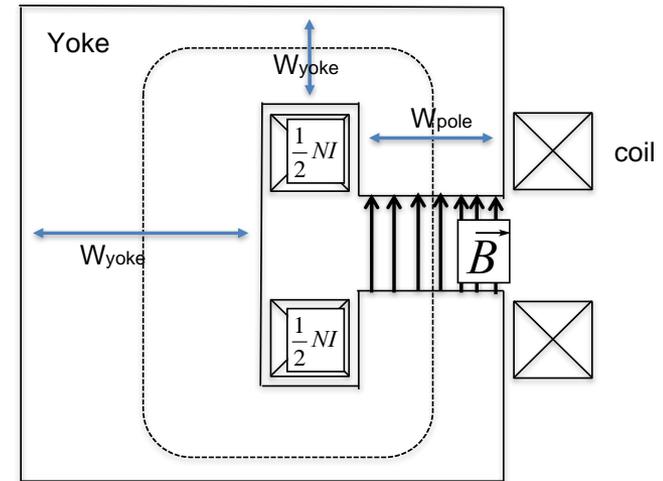
Before you start designing you need to get from the accelerator designers:

- B(T) or G (T/m) (higher orders:  $G_3$ (T/m<sup>2</sup>), 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:  
$$\text{dipole: } \frac{\Delta B}{B} \text{ (ref volume),} \quad \text{quadrupole: } \frac{\Delta G}{G} \text{ (reference circle)}$$
  
$$\text{or } b_n, a_n \text{ for } n = 1, 2, 3, 4, 5, \dots$$
- 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:
  - $j_{coil} = 5 \text{ A/mm}^2$  for water cooled
  - or  $j_{coil} = 1 \text{ A/mm}^2$  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:
 
$$W_{yoke} = W_{pole} \frac{B}{B_{sat}} \quad \text{with} \quad 1.5 T < B_{sat} < 2 T$$
- 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

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

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)

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

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



# Cooling circuit parameters

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

- Choose a desired  $\Delta T$  (20°C or 30°C depending on the  $T_{cooling\ water}$ )
- with the heat capacity of water (4.186 kJ/kg°C) 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 !):  $Reynolds > 2000$

$$Re = \frac{dv}{\nu} \sim 140d[mm]v[m/s] \text{ for } T_{water} \sim 40^\circ C$$

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

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



# Theoretical pole shapes

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

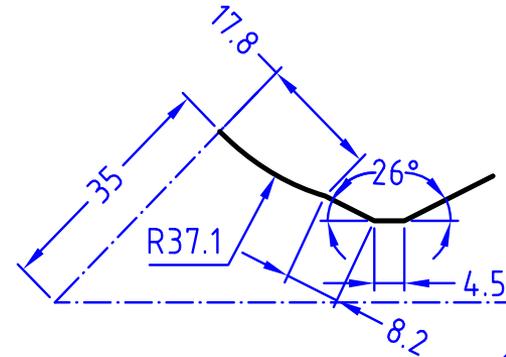
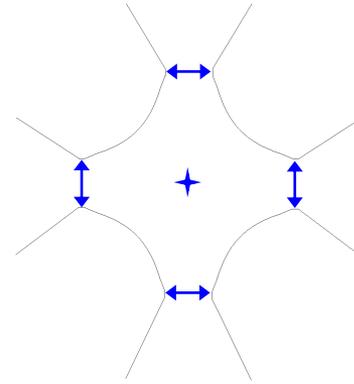
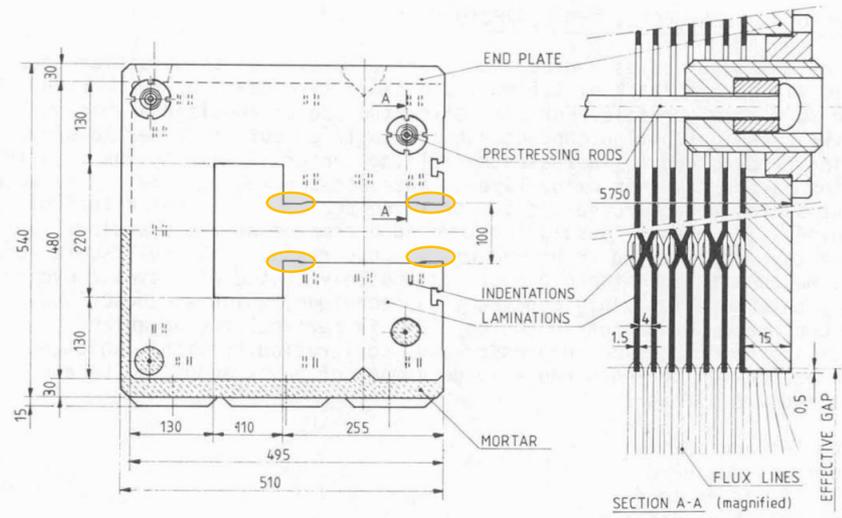
Dipole       $y = \pm h/2$       straight line

quadrupole       $2xy = \pm r^2$       hyperbola

sextupole       $3x^2y - y^3 = \pm r^3$

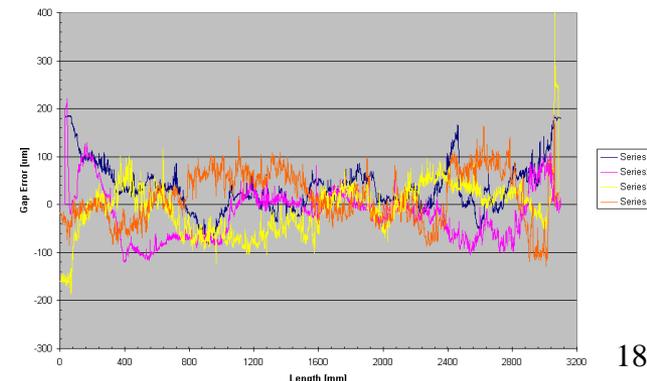
# Practical pole shapes: shims and alignment features

- 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

left\_final\_40\_40p\_adjus





# 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  $B_{xsection}(l)$  ,  $\int B dl$  , 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](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: <https://espace.cern.ch/roxie/default.aspx>
  - **ANSYS Maxwell**: 2D and 3D commercial software see: <http://www.ansys.com/Products/Electronics/ANSYS-Maxwell>



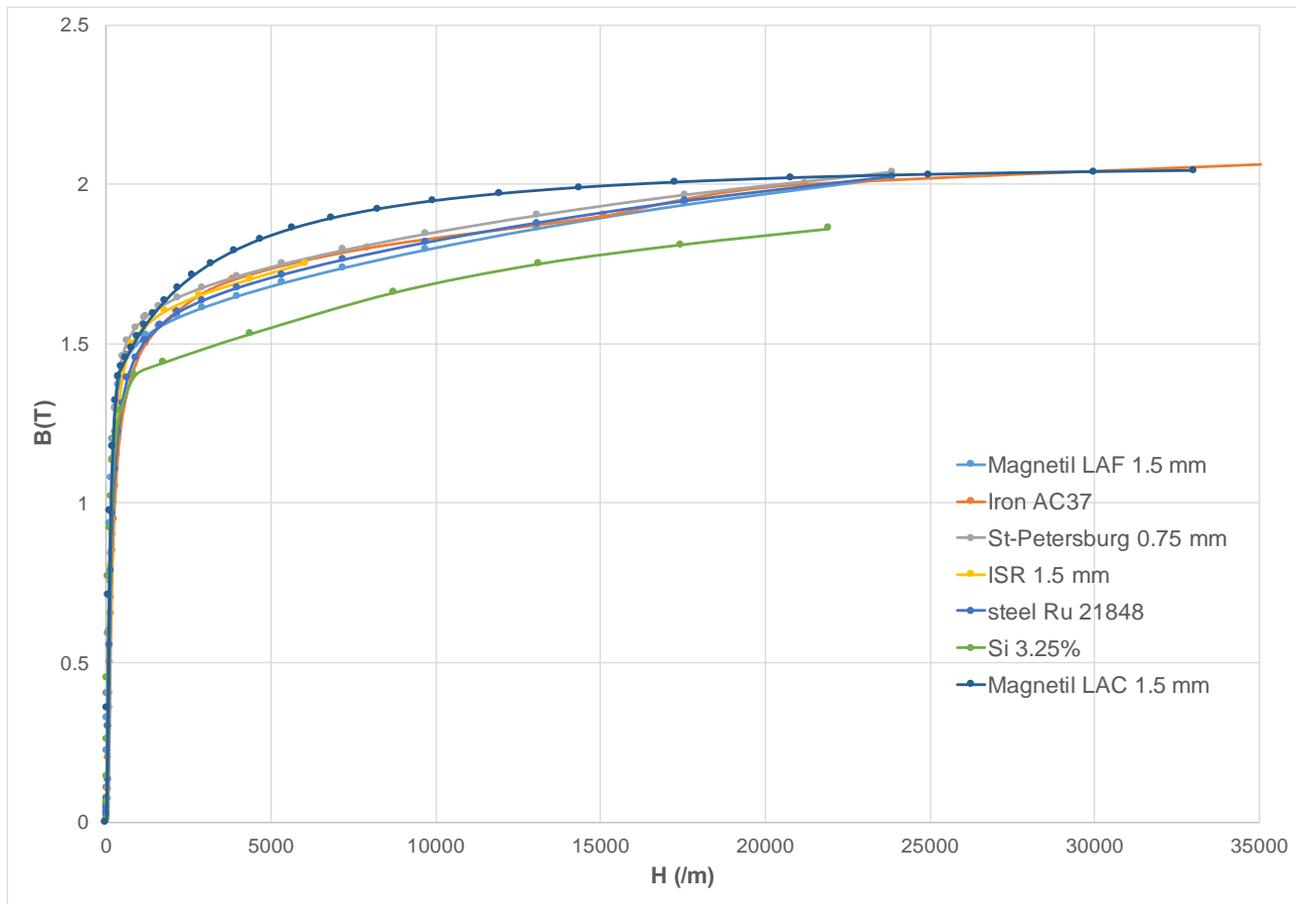
# FE models: steel curves

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

$$B_{xsection}(l), \quad \int B dl, \quad b_n \text{ and } a_n$$

As illustration the curves for several types of steel:





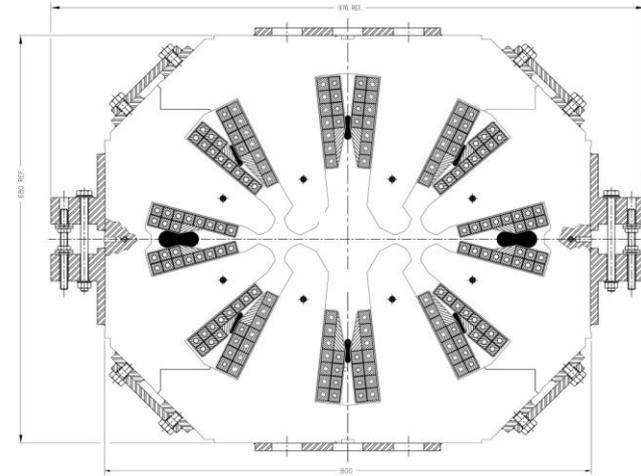
# Yoke shape, pole shape: FE model optimization

Use symmetry and the thus appropriate boundary conditions to model only  $\frac{1}{4}$ <sup>th</sup> (dipoles, quadrupoles) or even  $\frac{1}{6}$ <sup>th</sup> sextupoles.

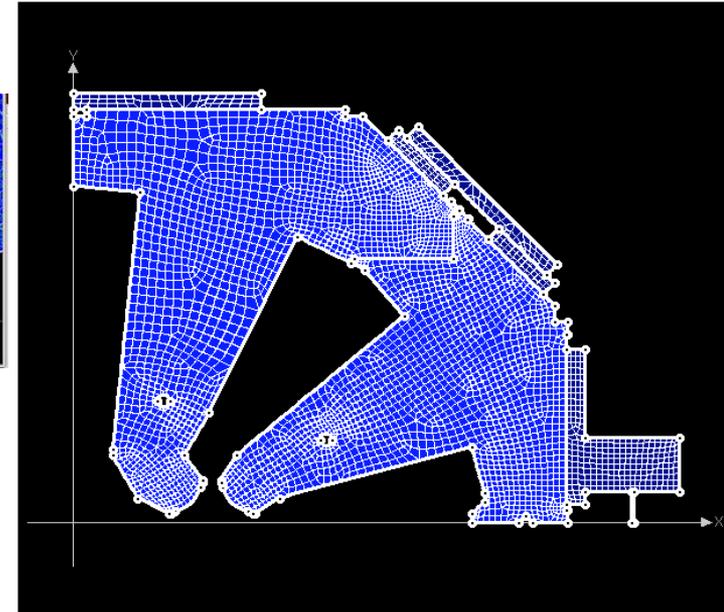
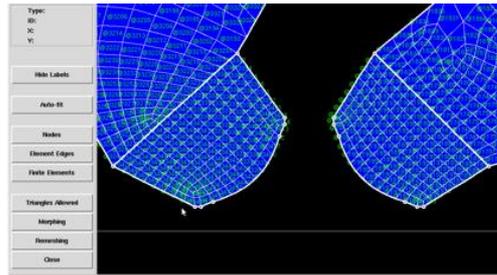
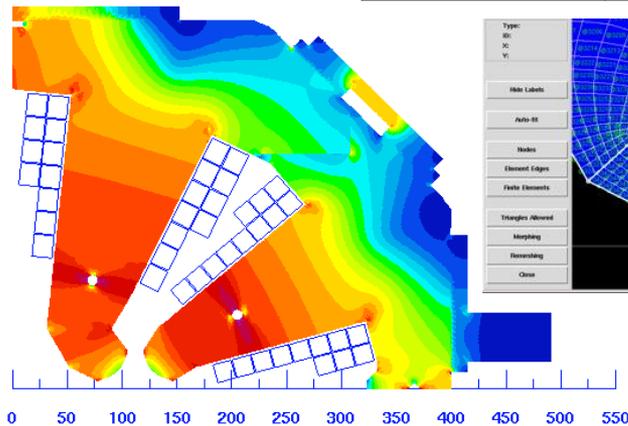
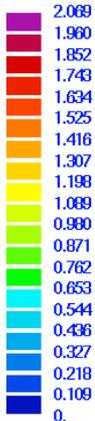
Meshing needs attention in the detailed areas like poles, slits, etc

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

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 <sup>2</sup> inner poles 17.0 x 17.0 mm <sup>2</sup> 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 <sub>nom</sub>	19 kW	14 kW
Mass	11700 kg	



|Btot| (T)





# 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

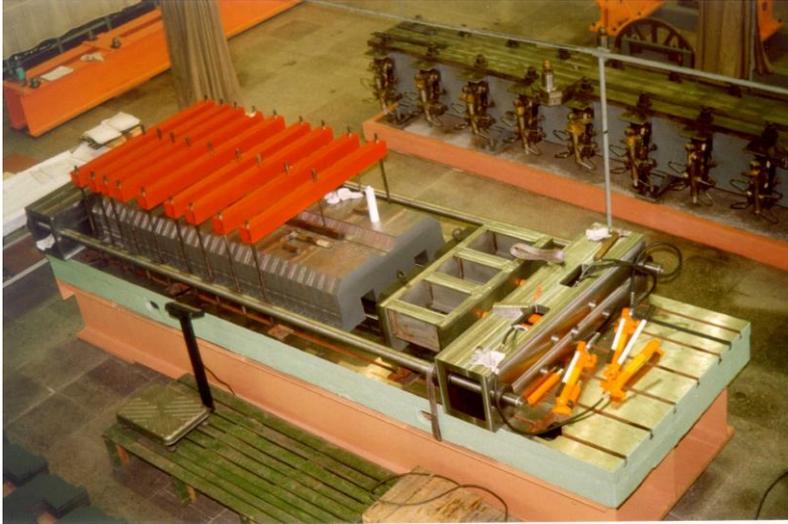
Field Strength H [A/m]	Minimum Induction B [T]
100	0.07
300	1.05
500	1.35
1000	1.50
2500	1.62
5000	1.72
10000	1.82

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

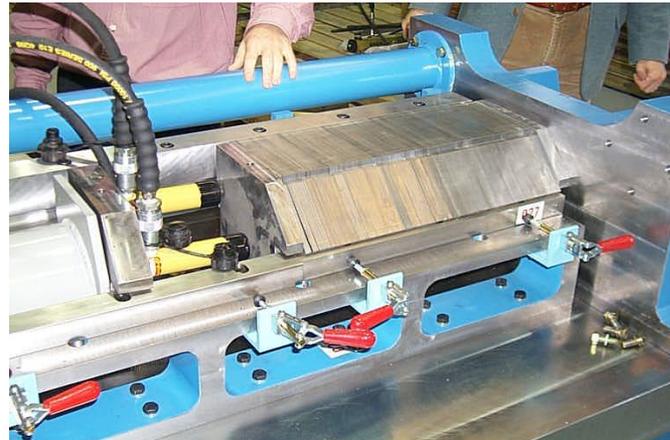




# Yoke stack manufacturing

Double aperture LHC quadrupole MQW

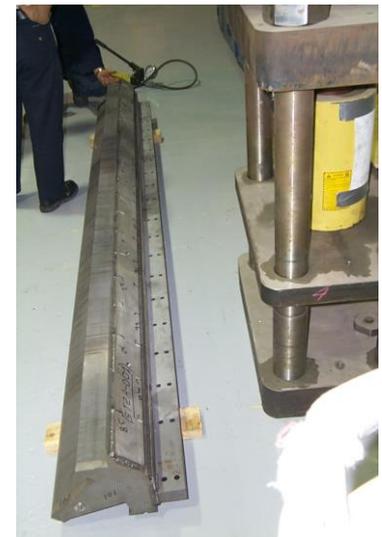
Stacking on a precision table



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  $\pm 1$  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 enamel coated, possibly epoxy impregnated afterwards



# Coil ends

For dipoles some main types are racetrack of bedstead



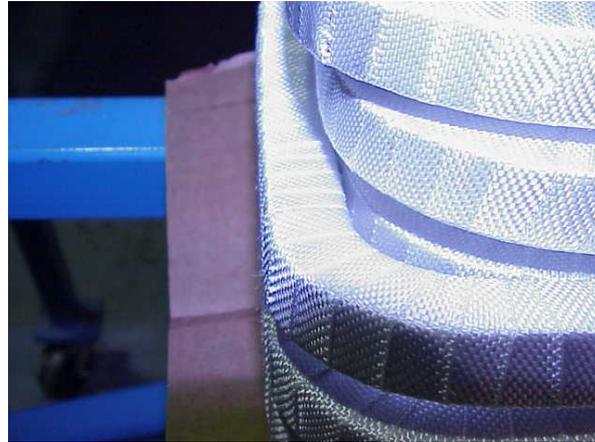
## Quadrupoles





# 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

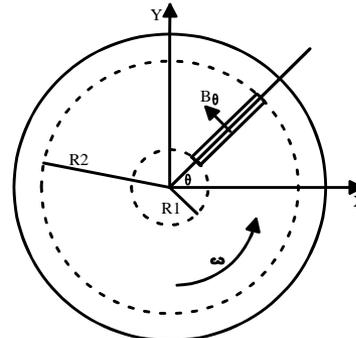
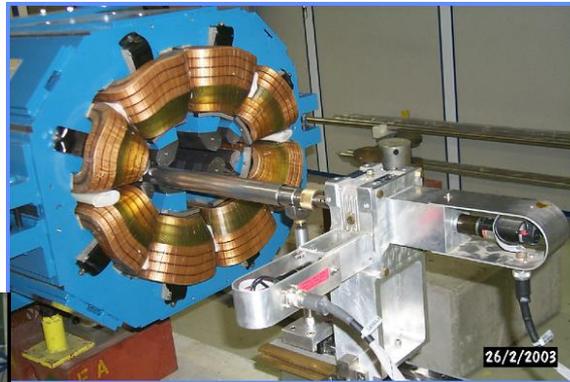
Finished MBXW coil



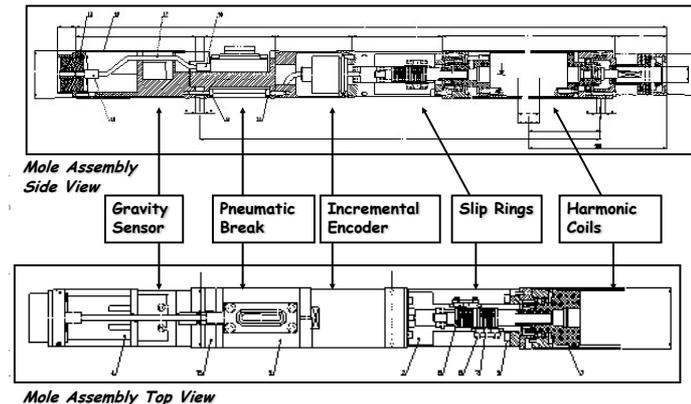
# Magnetic field measurements

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.

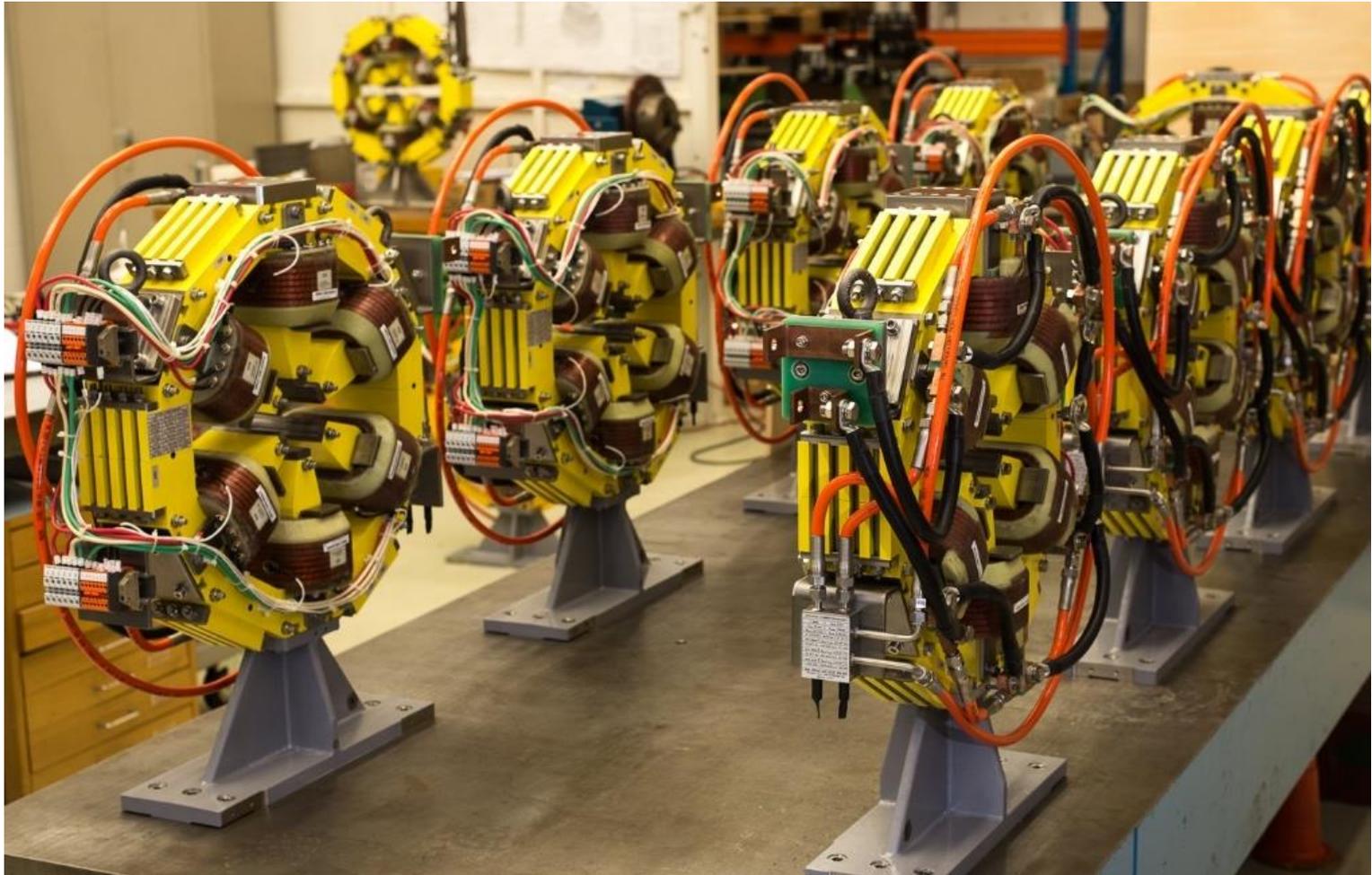


Rotating radial coil



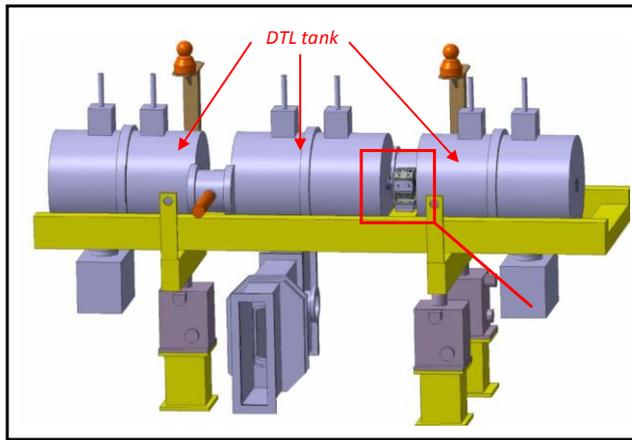
# Sextupoles

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

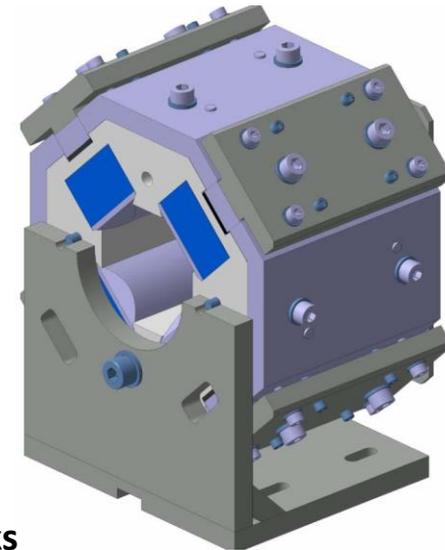


# Permanent magnets

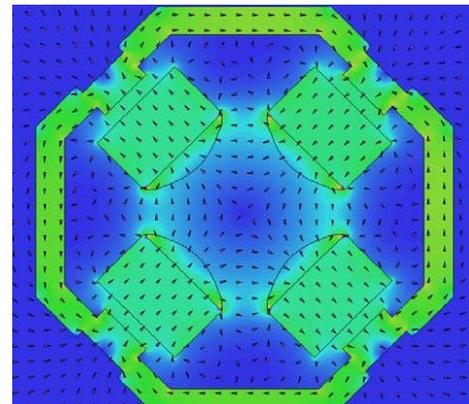
Linac4 @ CERN permanent magnets , quadrupoles



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



- Permanent magnet because of space between DTL tanks
- $\text{Sm}_2\text{Co}_{17}$  permanent magnets
- Integrated gradient of 1.3 to 1.6 Tesla
- 15 magnets
- Magnet length 0.100 m
- Field quality/amplitude tuning blocks



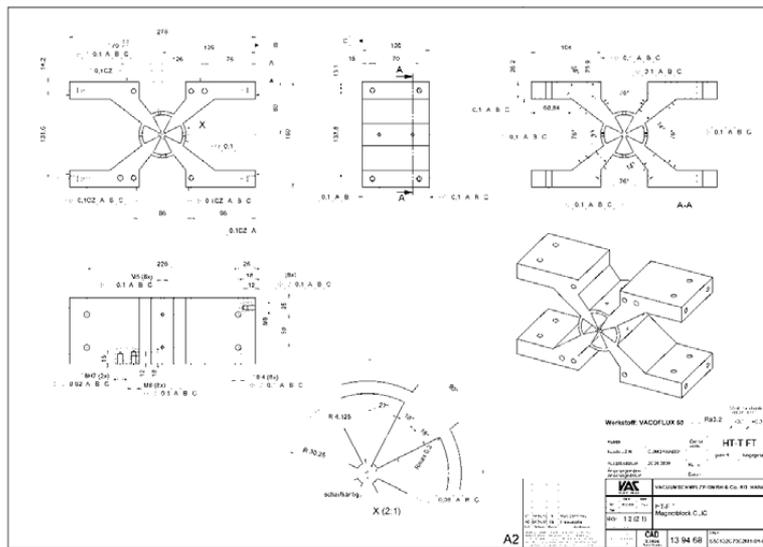
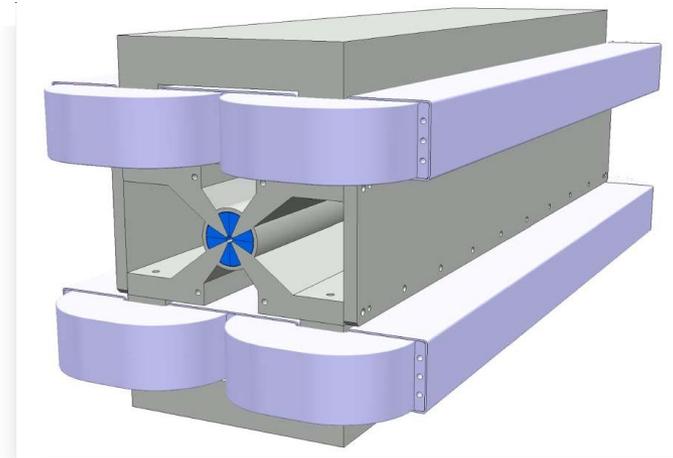
Courtesy D. Tommasini, CERN



# Hybrid magnets

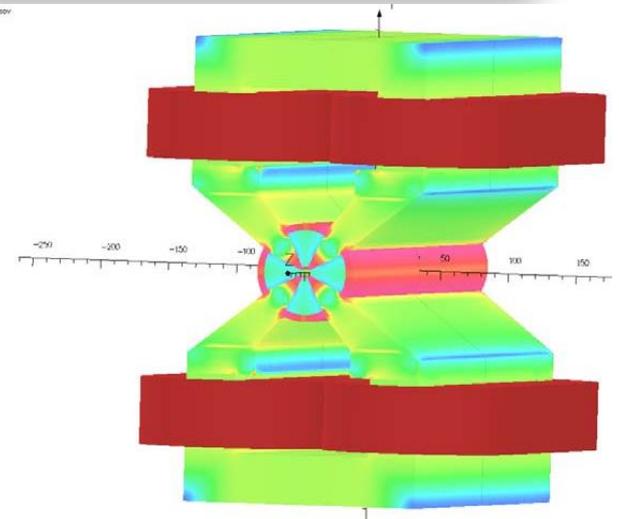
CLIC final focus,

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



13/04/2009 14:36:03, CLIC 000, Aleksey Vlasov/ev

Surface contours: ENOD  
3.127579E+000  
3.000000E+000  
2.500000E+000  
2.000000E+000  
1.500000E+000  
1.000000E+000  
5.000000E-001  
2.577225E-002

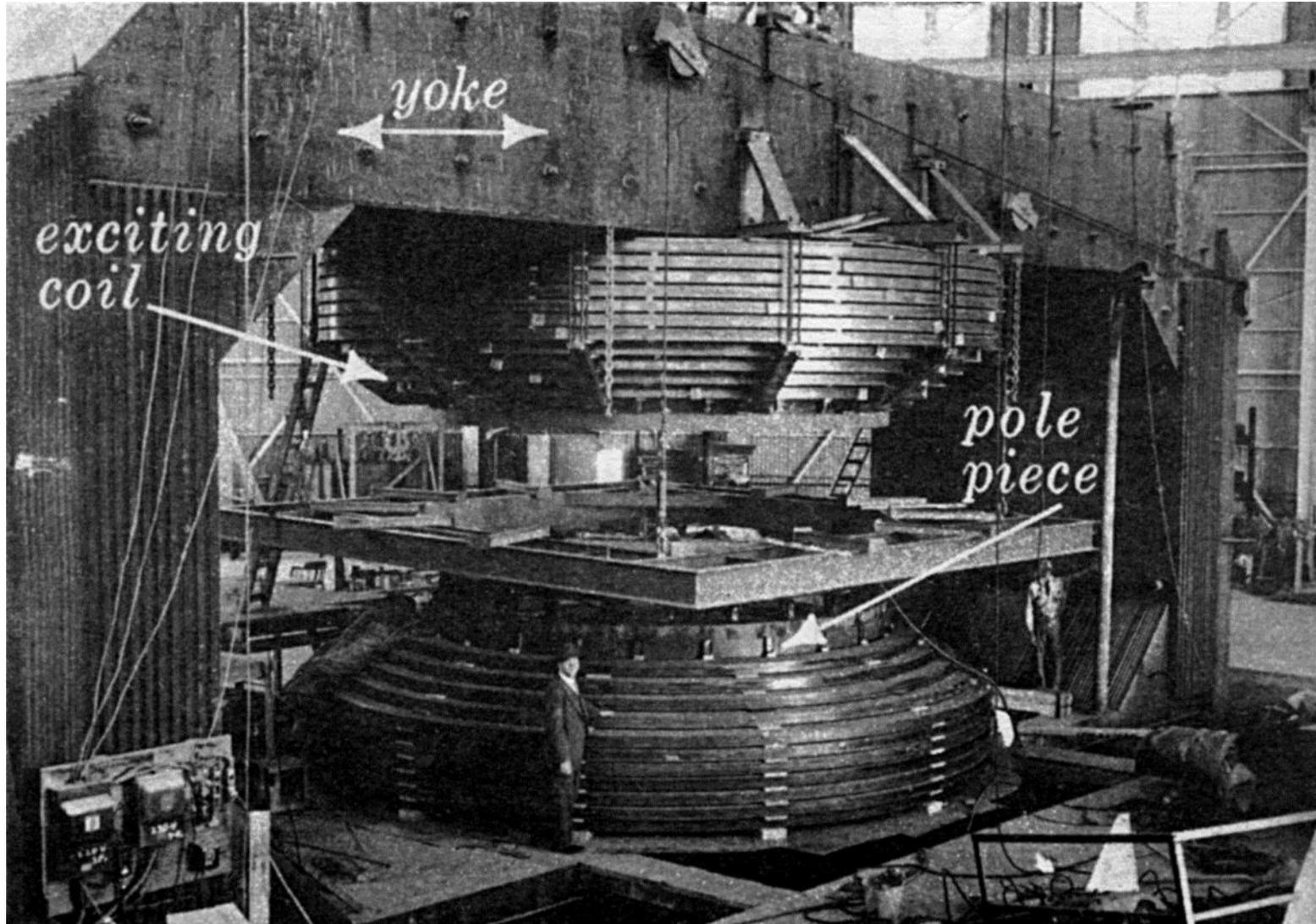


Courtesy D. Tommasini, CERN

## Examples;

Some history, some modern regular magnets and some special cases

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

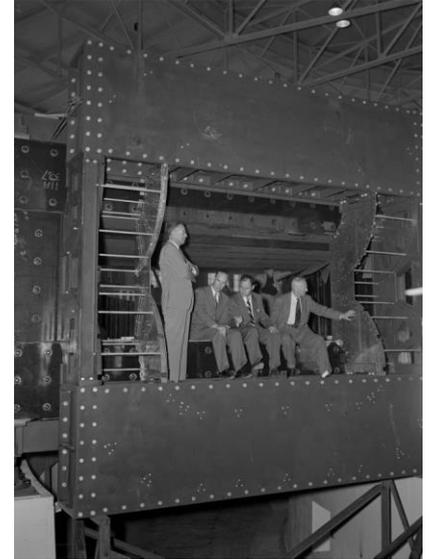


Courtesy A. Milanese, CERN

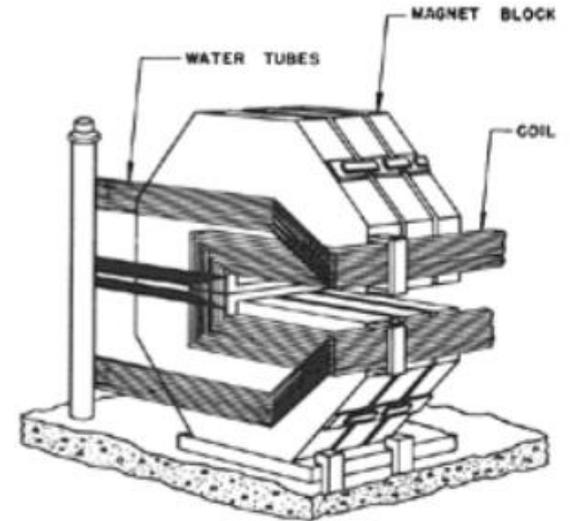
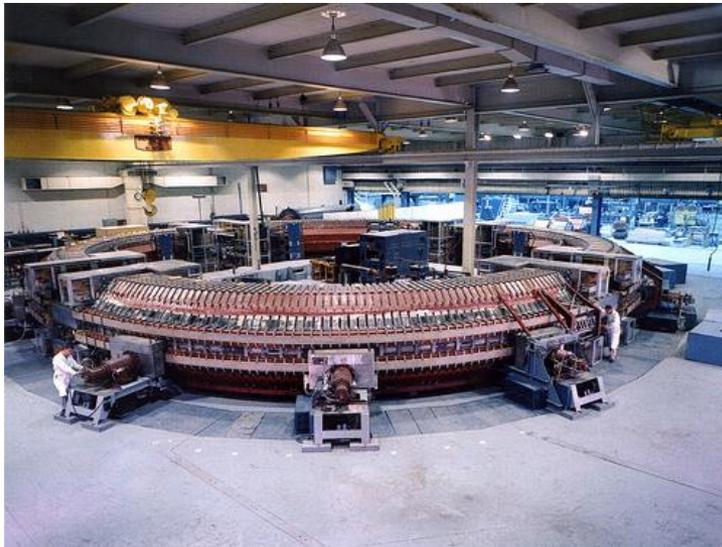


# Some early magnets (early 1950-ies)

Bevatron  
(Berkeley)  
1954, 6.2 GeV



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



CAS Budapest, 7-Oct-2016, warm magnets, GdR

# PS combined function dipole

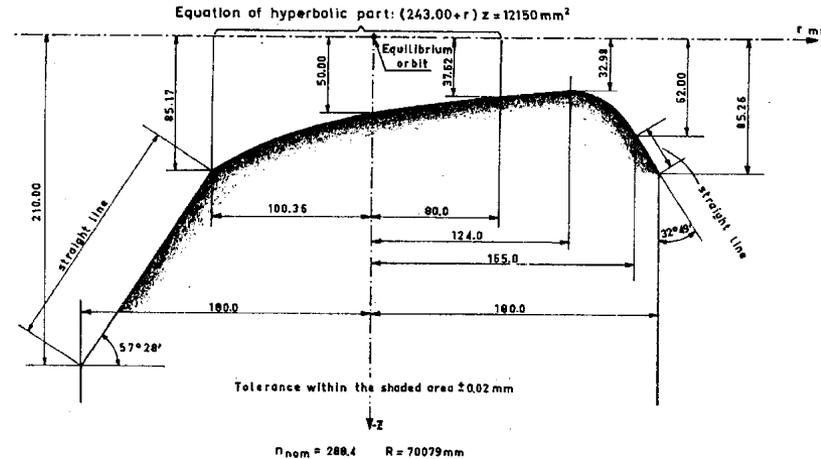
*Magnetic field:*

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.

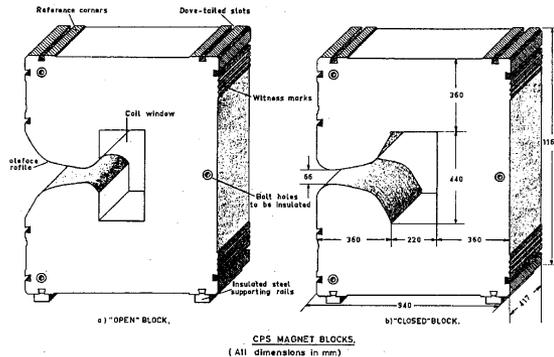
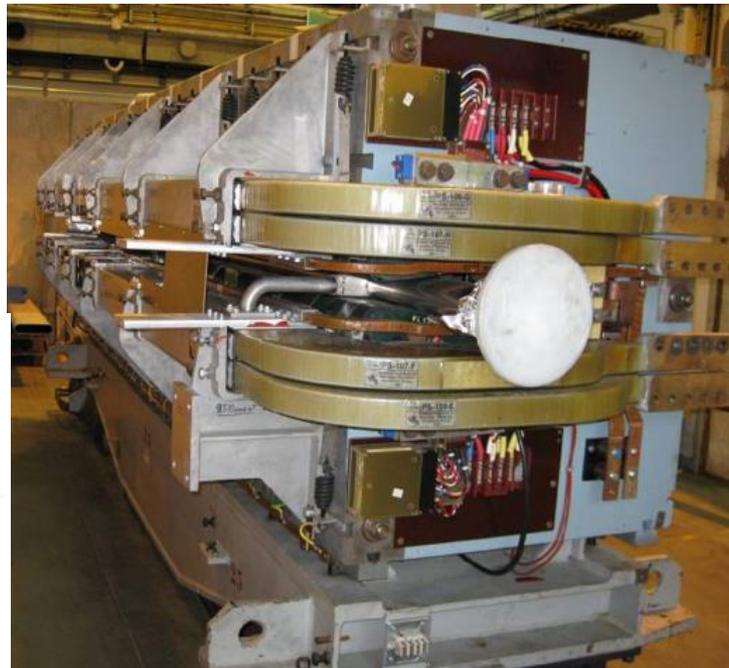
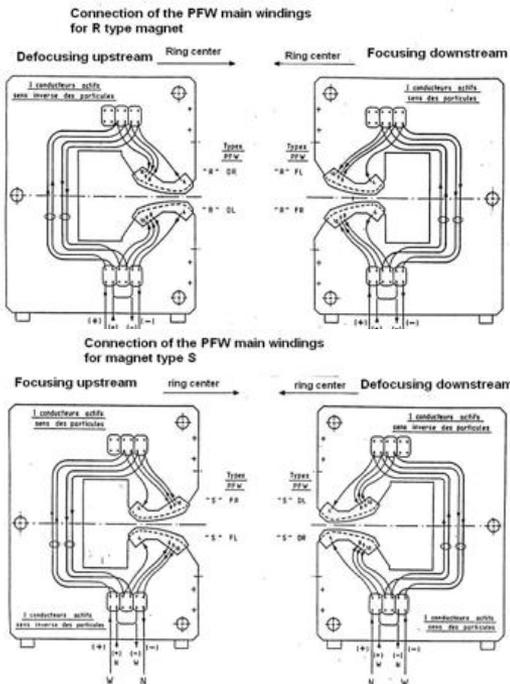


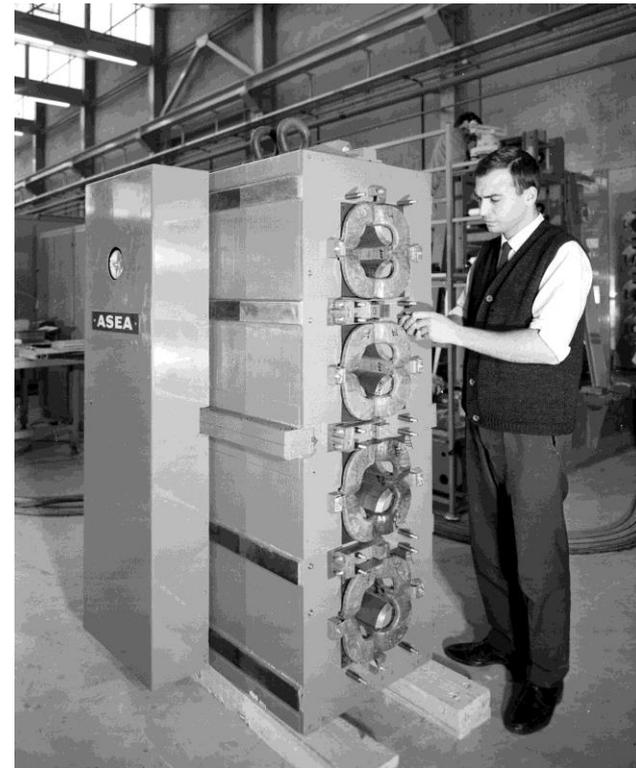
Fig. 12: Final form of the magnet blocks.



# CPS booster

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

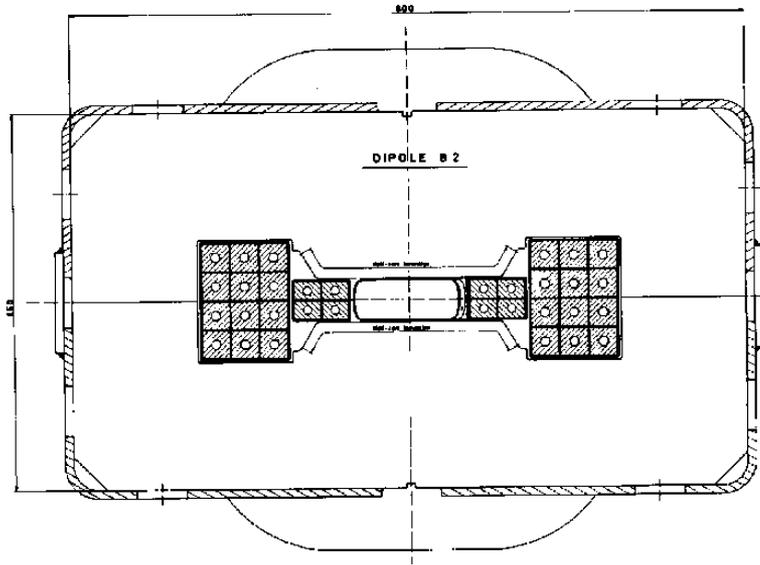
Was originally designed for 0.8 GeV !



Courtesy D. Tommasini, CERN



# dipole magnet : SPS dipole



H magnet type MBB

$B = 2.05 \text{ T}$

Coil : 16 turns

$I_{max} = 4900 \text{ A}$

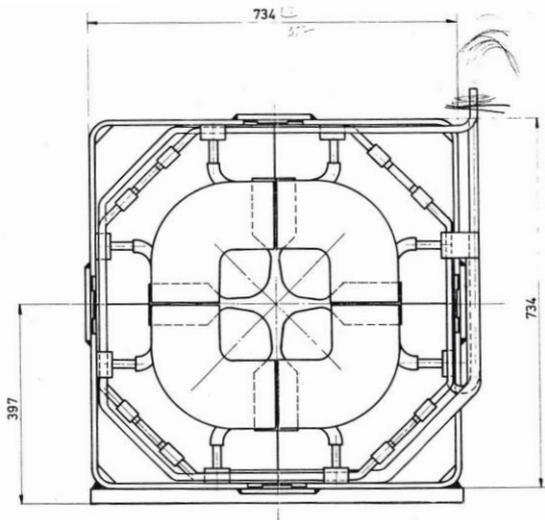
Aperture =  $52 \times 92 \text{ mm}^2$

$L = 6.26 \text{ m}$

Weight = 17 t



# Quadrupole magnet : SPS quadrupole



type MQ

$G = 20.7 \text{ T/m}$

Coil : 16 turns

$I_{max} = 1938 \text{ A}$

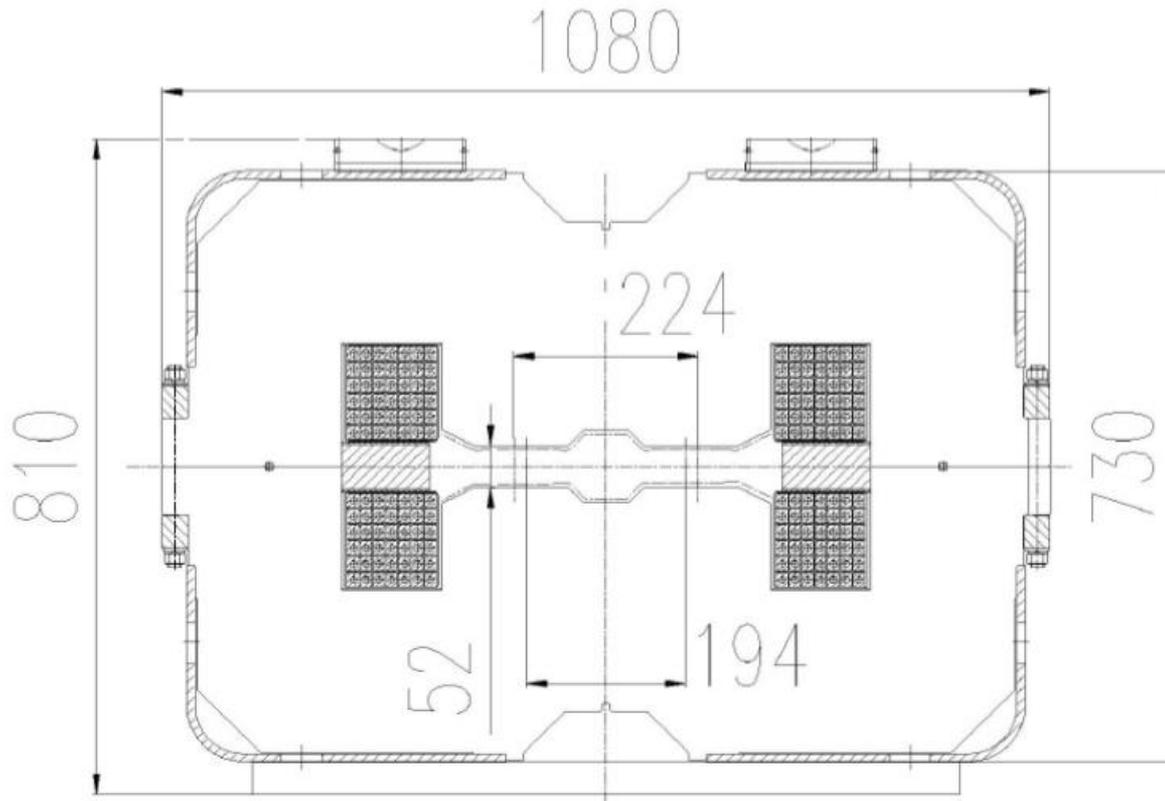
Aperture inscribed radius = 44 mm

$L_{coil} = 3.2 \text{ m}$

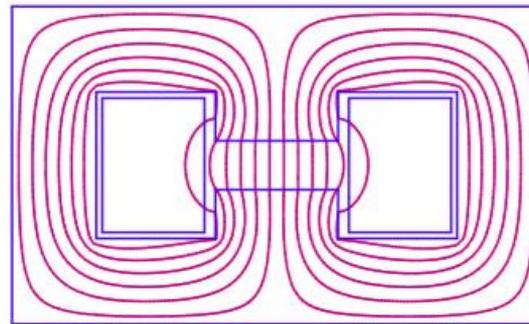
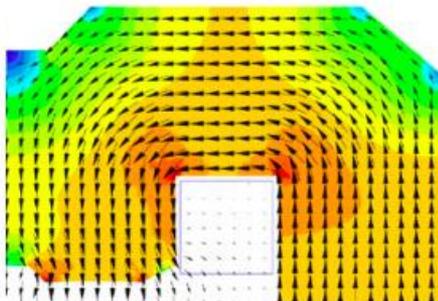
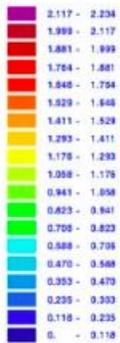
Weight = 8.4 t



# MBW LHC warm separation dipole (1)

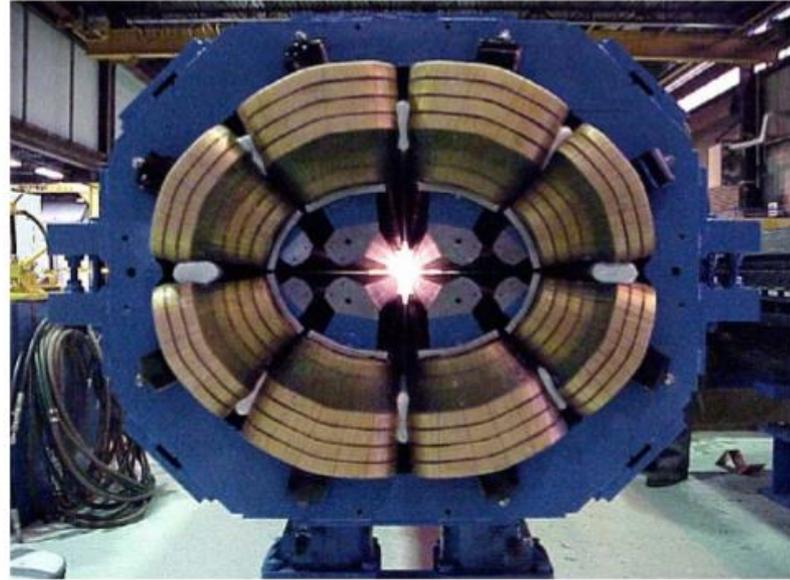
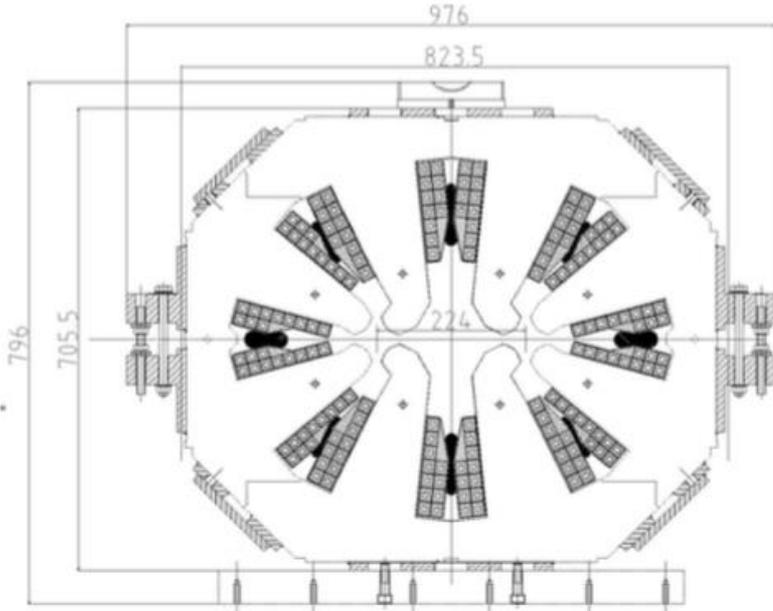


Parameter	Value
Aperture	52 mm
Nominal field	1.42 T
Magnetic length	3.4 m
Weight	18 t
Water flow	19 l/min
Power	29 kW





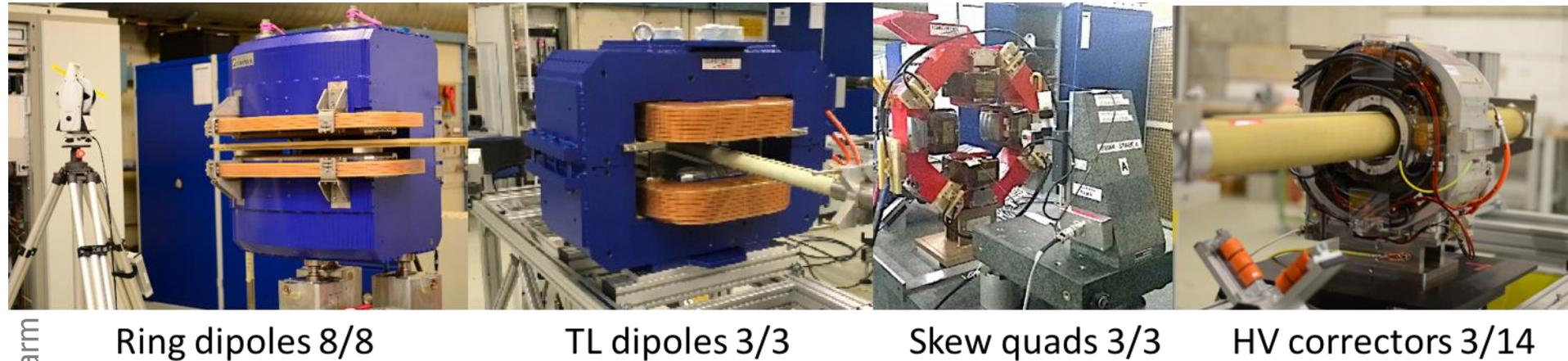
# MQW: LHC warm double aperture quadrupole





# Elena, anti proton decelerator

- 



Ring dipoles 8/8

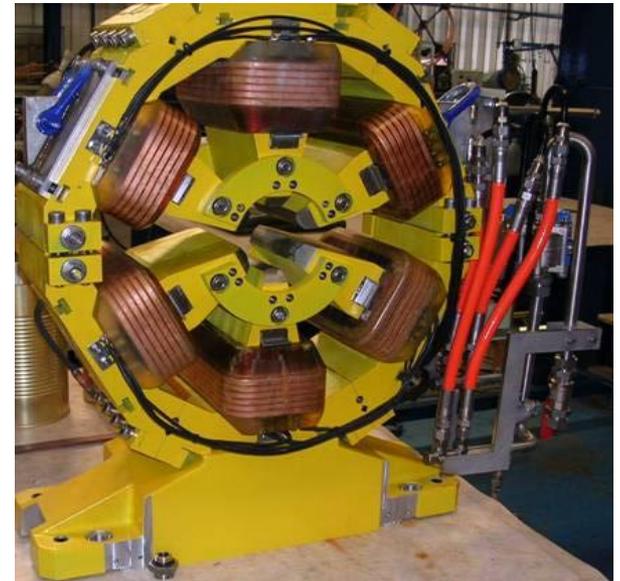
TL dipoles 3/3

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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Thomas Zickler

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



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