Magnets (warm)

Davide Tommasini
CERN

- Recommended reading
- Basic principles
- Requirements
- Design
- Manufacture
- Examples

Recommended reading

N. Marks

http://cas.web.cern.ch/cas/UK-2007/Lectures/PDF/Marks/Marks-Magnets.pdf

http://www.cockroft.ac.uk/education/Construction.ppt

D. Einfeld

http://cas.web.cern.ch/cas/Italy%202008/Lectures/PDFs/Einfeld.pdf

CAS Bruges (case study + T. Zickler + A.Dael + S. Sgobba)

http://cas.web.cern.ch/cas/Belgium-2009/Lectures/Bruges-lectures.htm

G.E.Fisher

"Iron Dominated Magnets" AIP Conf. Proc., 1987 -- Volume 153, pp. 1120-1227

1120

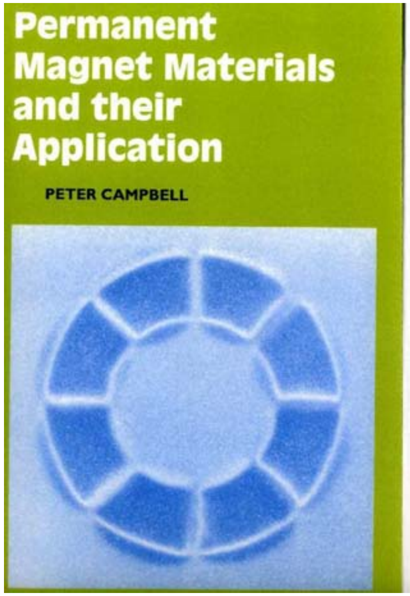
IRON DOMINATED MAGNETS

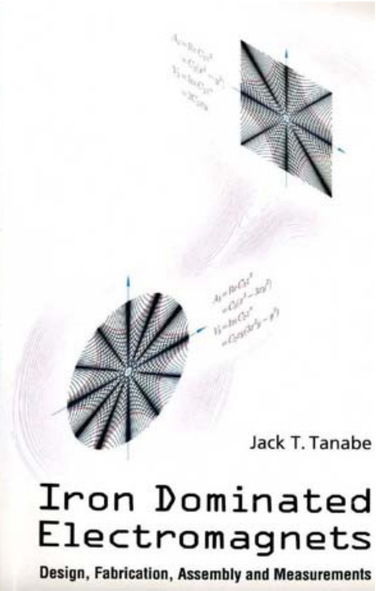
G. E. Fischer

Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94305

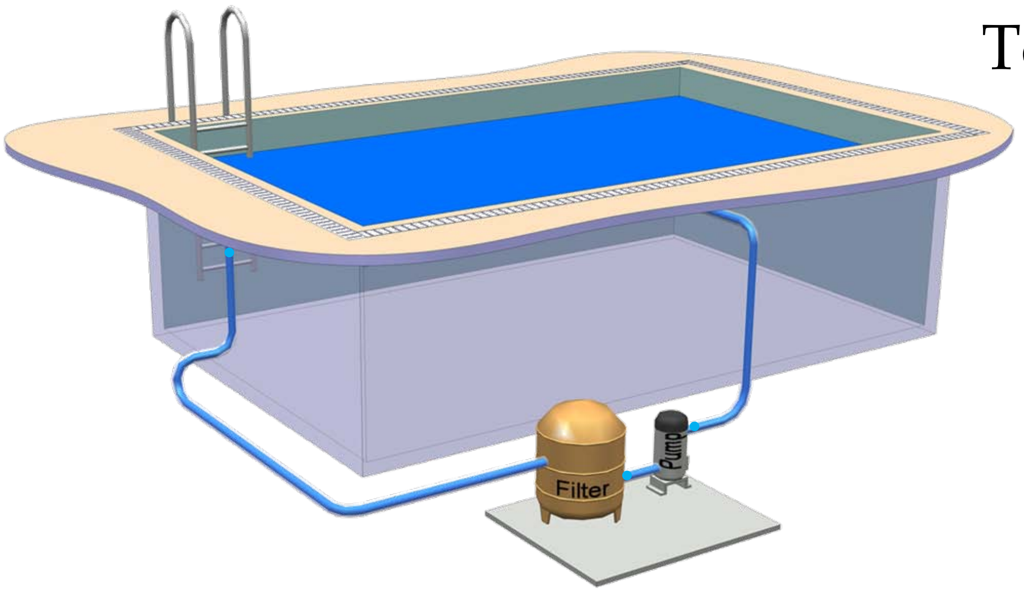
TABLE OF CONTENTS

1121





Basic principles : hydraulic circuit



To make a fluid circulating you need a pump

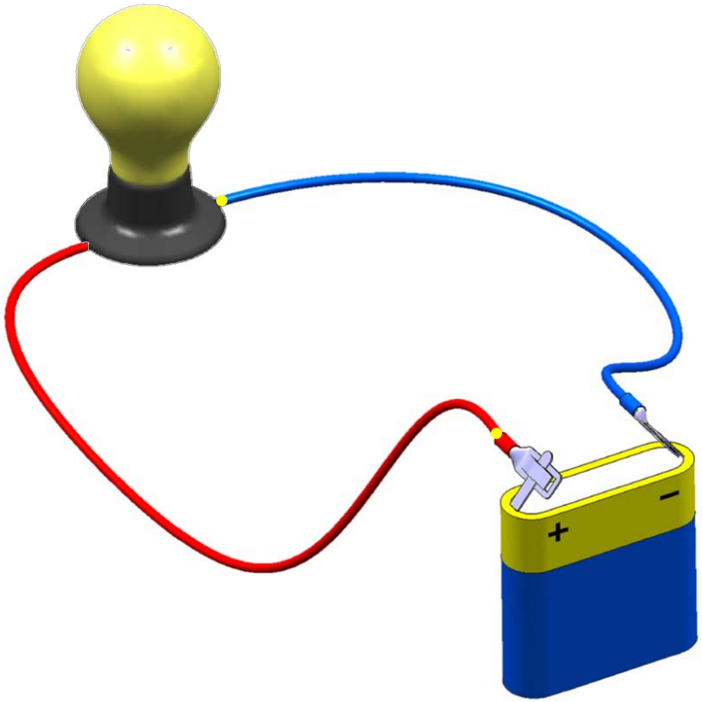
A difference of pressure creates a flow

The flow density is:
v=Q/A

$$\Delta P = R \times Q$$

Little **pressure drop** across the hoses
Hoses are the highways of water

Basic principles : electric circuit

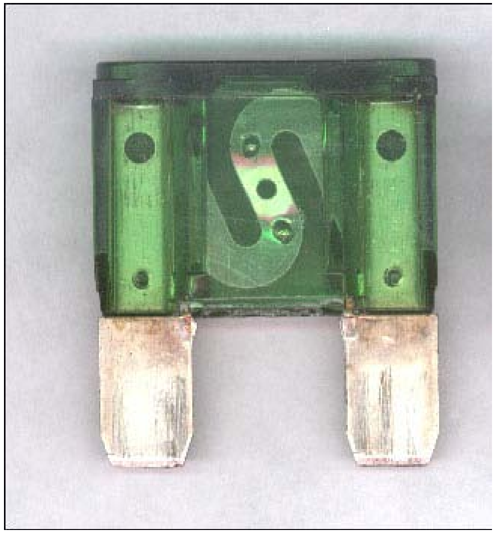


To produce electrical current you need a generator

A difference of voltage creates a current flow I

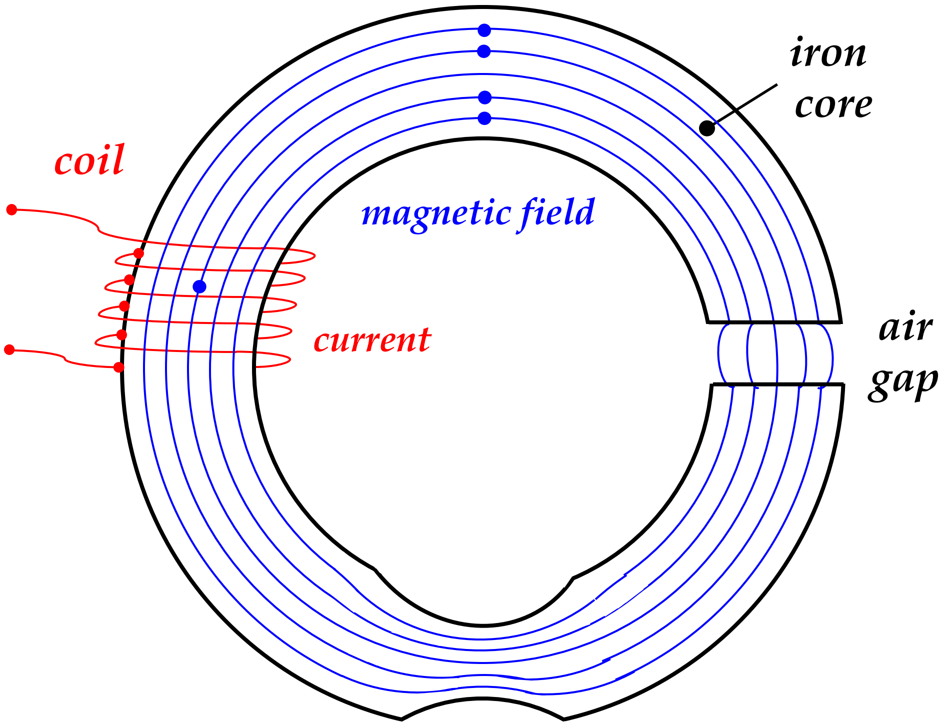
The current density is:
$J = I / A$

$$\Delta V = R \times I$$



Little **voltage drop** across the wires
Wires are the highways of electricity

Basic principles : magnetic circuit



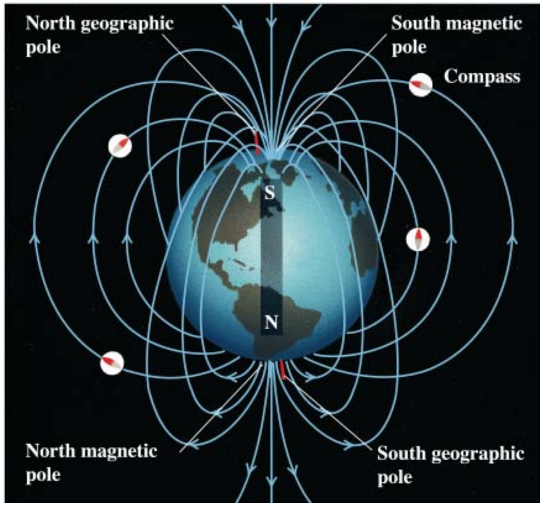
To produce a magnetic field you need a coil

A magnetomotive force creates a magnetic flux Φ

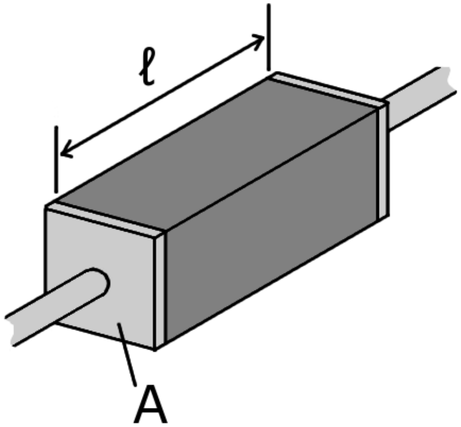
The flux density is:
$B=\Phi / A$

$$NI = \mathcal{R} \times \Phi$$

Little **magnetomotive force** in the iron
Iron is the highway of magnetic field



Basic principles : constitutive equations



R = length /(electrical conductivity x section)
$\mathcal{R}$ = length/ (magnetic permeability x section)

$$R = \frac{1}{\sigma \cdot A} \qquad \mathcal{R} = \frac{1}{\mu \cdot A}$$

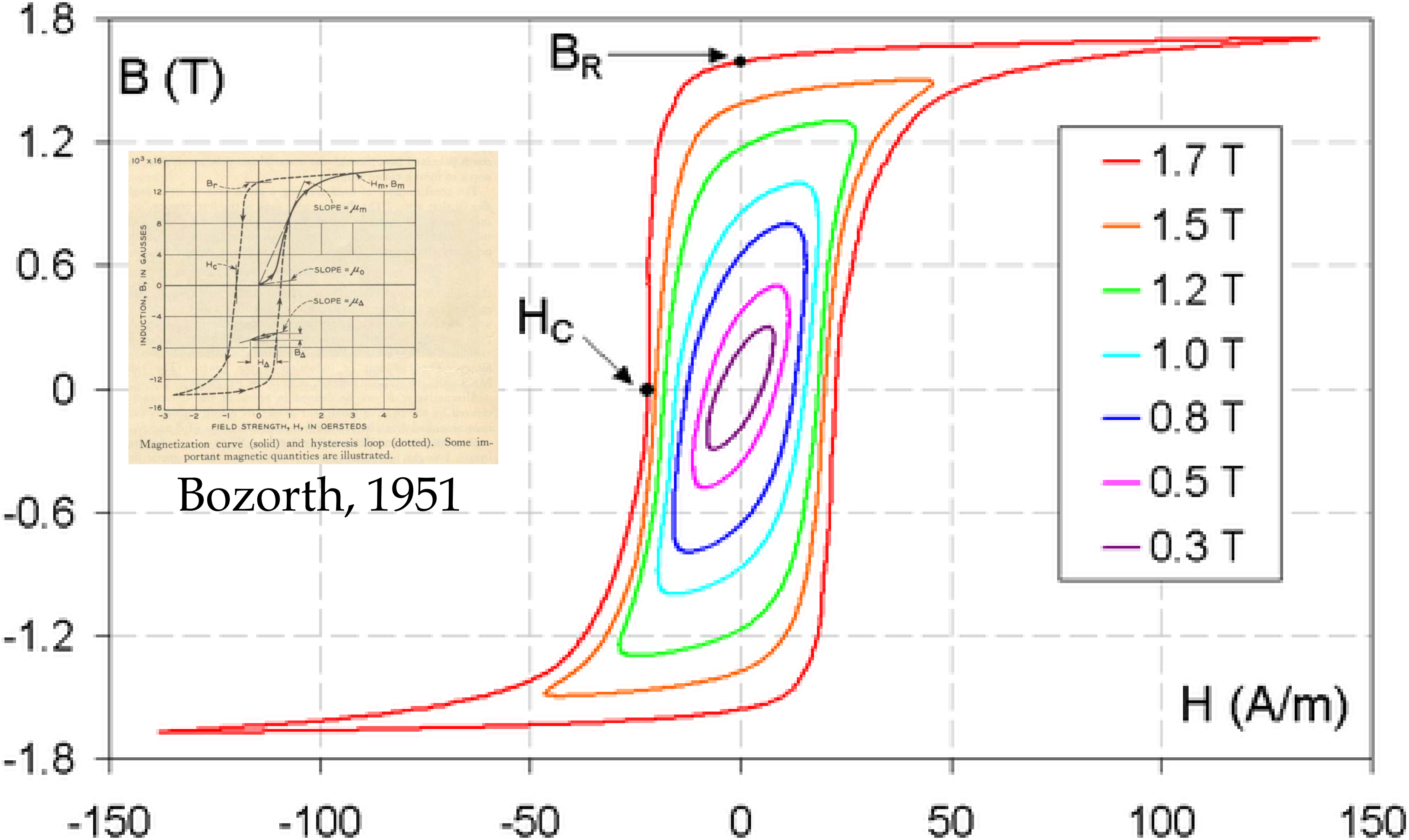
magnetomotive force =
- **$\oint$ H·dl (Ampère's law)**
- **$\mathcal{R}$ x Φ (Hopkinson's law)**

H can be interpreted as "magnetizing pressure"
In ferromagnetic materials you can create high **B "using"** little **H**dl

$$B = \mu \cdot H = \mu_0 \cdot \mu_r \cdot H$$

$\mu_0 = 4\pi \cdot 10^{-7}\ Tm/A$

Basic principles : constitutive equations

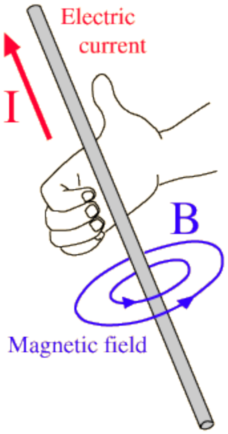


For iron, above 1.5-2 T any increase of magnetic field costs a lot of magnetomotive force

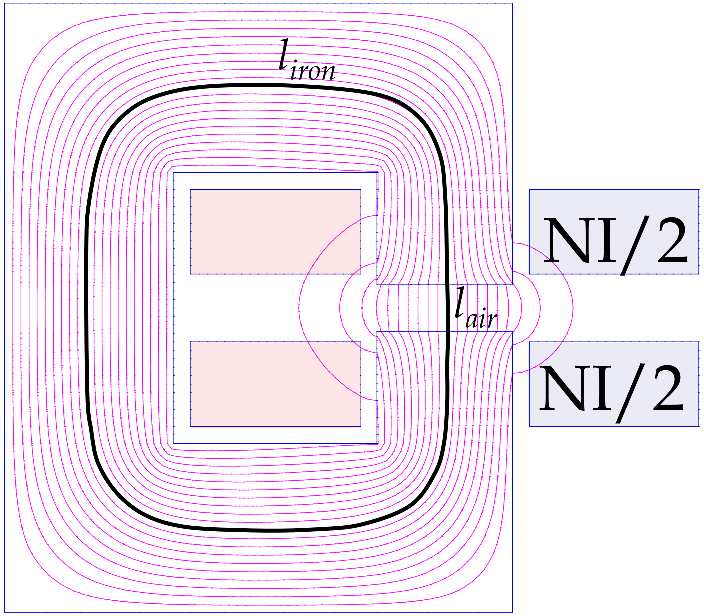
Basic principles : magnetic field generation

CURRENTS (coils) **NI**

PERMANENT MAGNETS $H_m l_m$



$$NI = \oint \vec{H} \cdot \vec{dl} = \frac{B}{\mu_0} 2\pi r$$



$$NI = H_{iron} \cdot l_{iron} + H_{air} \cdot l_{air}$$

$$NI = \frac{B}{\mu_0 \cdot \mu_r} \cdot l_{iron} + \frac{B}{\mu_0} \cdot l_{air}$$

Basic principles : energy

Over an elementary length dl of elementary section ds the magnetizing pressure H·dl produces a field B

The associated energy is:

$$E = \frac{1}{2} H \cdot dl \cdot B \cdot ds$$

In a magnet little magnetizing pressure is used in the iron, most of energy is stored in air.

Basic principles : inductance

The inductance is the equivalent of the inertia.

A large inertia (***I***)/inductance (***L***) means you need:

- a large force to suddenly increase the speed
- a large voltage to suddenly increase the current/field

✓ you can store energy in a wheel rotating at speed $\boldsymbol{\omega}$

✓ you can store energy in a coil supplied by a current $\boldsymbol{i}$

$$E = \frac{1}{2} I \cdot \omega^2 = \frac{1}{2} L \cdot i^2$$

When the magnetic field has to be quickly changed you want to keep the inductance low, typically by reducing the number of coil turns.

Basic principles : forces

In case of a uniform magnetic field

$$E_m = ½\, B·H·V = ½\, B·H·S·x$$

$$F = dE/dx = ½\, B·H·S$$

in air $H=B/\mu_0$

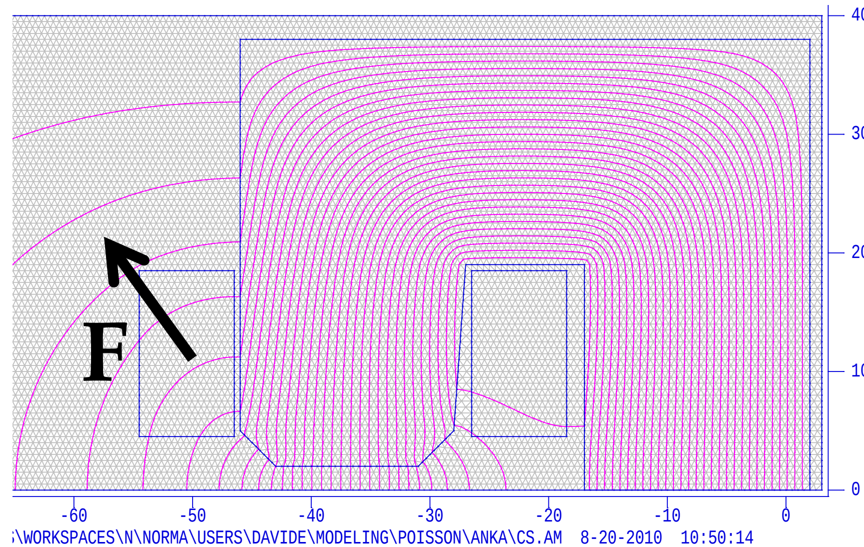
The magnetic force is then $\approx B^2·4\ kg_f/cm^2$

A key ($2\ cm^2$) in
$B = 1T \Rightarrow F = \ \ 8\ kg_f$
$B = 2T \Rightarrow F = 32\ kg_f$

Basic principles : force

On a conductor immerged in magnetic field

$$\mathbf{F} = \mathrm{I}\cdot \boldsymbol{L} \times \mathbf{B}$$



Example for the Anka dipole:
On a the external coil side with N=40 turns, I= 700A, L~2.2 m
in an average field of B= 0.25 T

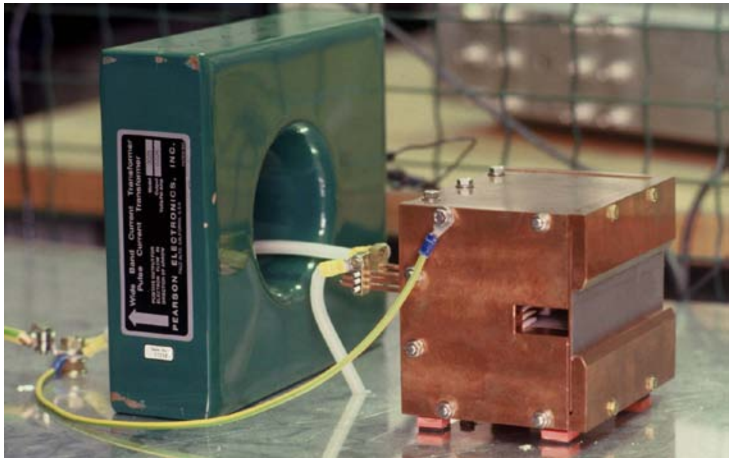
$$F= 40\cdot 700 \cdot 2.2\cdot 0.25 = 15400 \text{ N} \sim 1.5 \text{ tons}_f$$

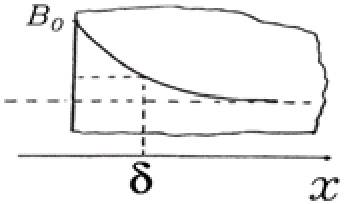
Basic principles : time varying fields

Varying magnetic field → voltage difference (Faraday law)
This effect acts against the variation (Lenz law)

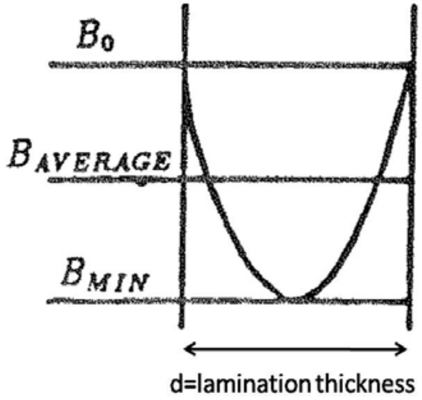
$$V = - \partial\Phi / \partial t$$

Currents are generated in electrical conducting materials :
- opposing to the penetration of the magnetic field
- producing losses





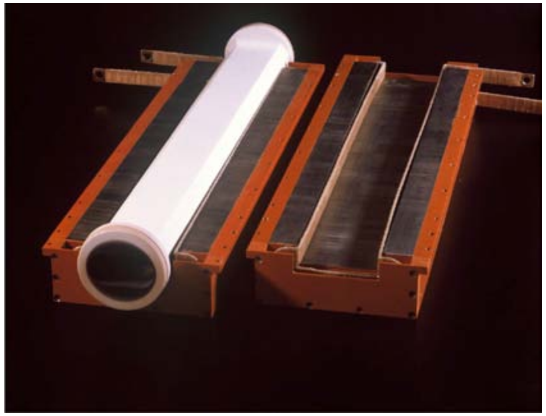
$$B(x) = B_0 \cdot e^{-x/\delta} \qquad \delta[m] = \frac{1}{\sqrt{\pi \cdot \mu_0 \cdot \mu_r \cdot f \cdot \sigma}}$$



Penetration of a time varying field in a lamination

$$\frac{B_{average}}{B_0} = \frac{\delta}{2 \cdot d} \cdot (1 + (a - b) \cdot (a + 2 \cdot c) + b \cdot (a + b))$$

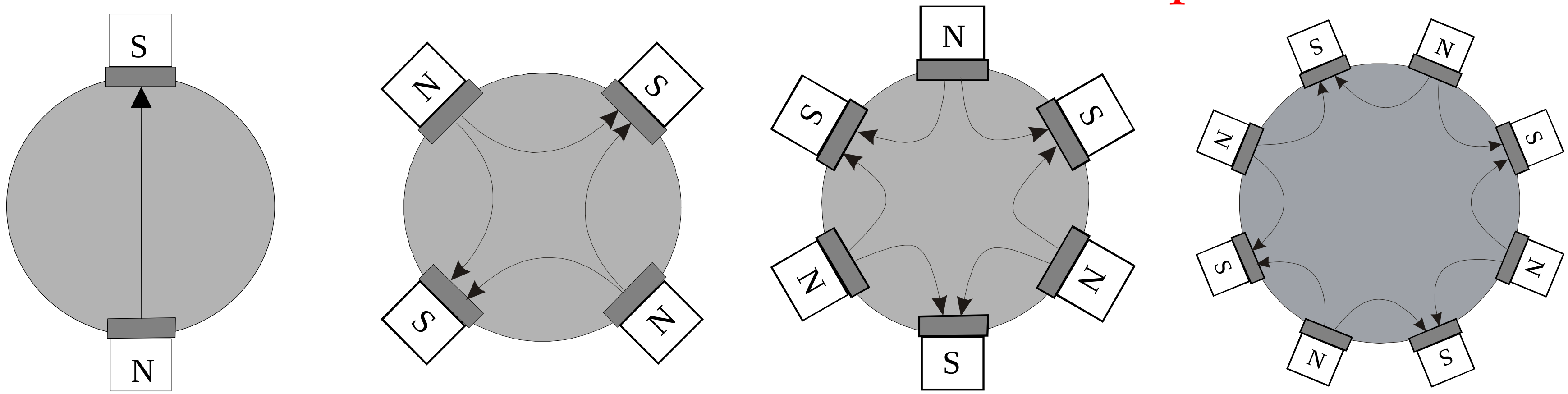
$$a = \sin(\frac{d}{\delta})\,;\, b = \cos(\frac{d}{\delta})\,;\, c = e^{-d/\delta}$$



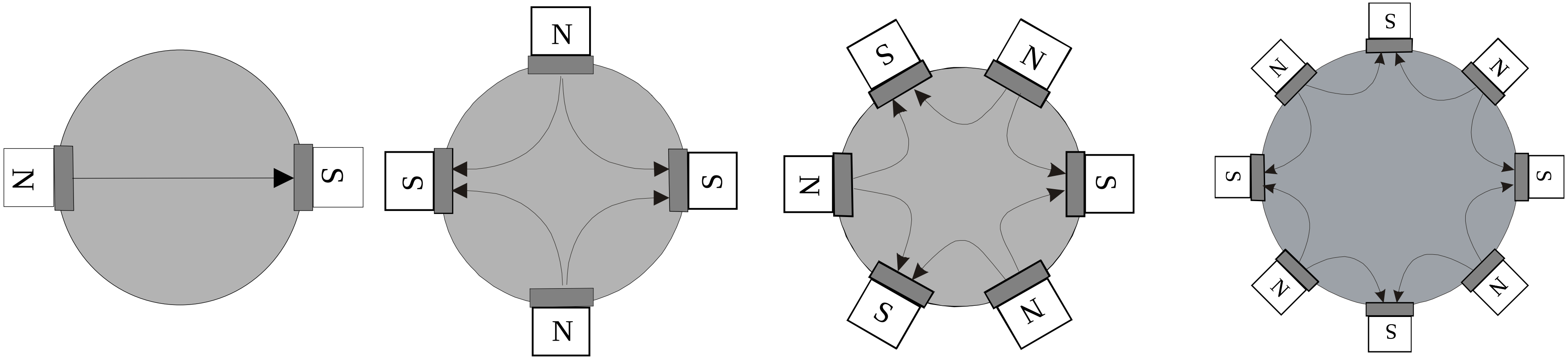
When magnetic field varies use laminations, possibly with silicon (1-4%) to increase resistivity

Magnet types

NORMAL : vertical field on mid-plane



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

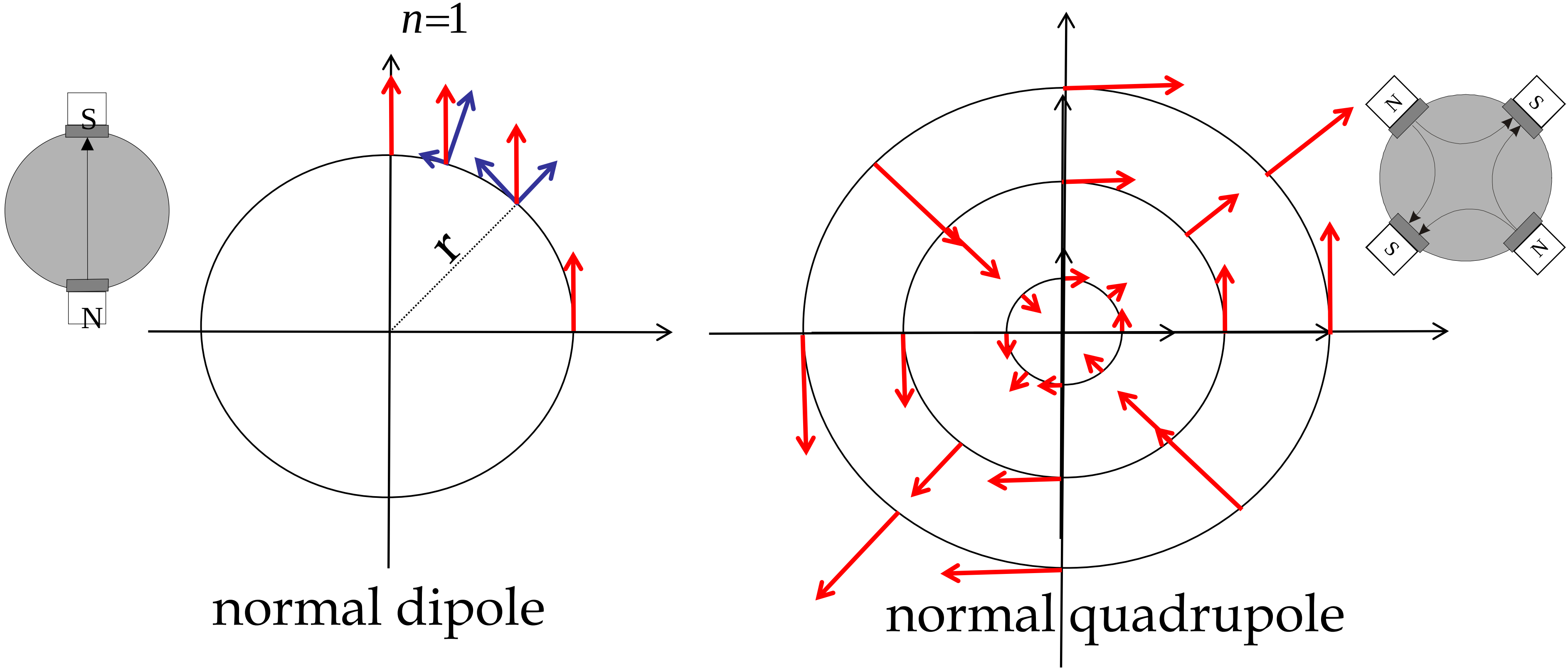


SKEW : horizontal field on mid-plane

Field Harmonics

$$B_r(r,\vartheta) = \sum_{n=1}^{\infty} r^{n-1}\left[N_n \cdot \sin(n\vartheta) + S_n \cdot \cos(n\vartheta)\right]$$

$$B_\vartheta(r,\vartheta) = \sum_{n=1}^{\infty} r^{n-1}\left[N_n \cdot \cos(n\vartheta) - S_n \cdot \sin(n\vartheta)\right]$$

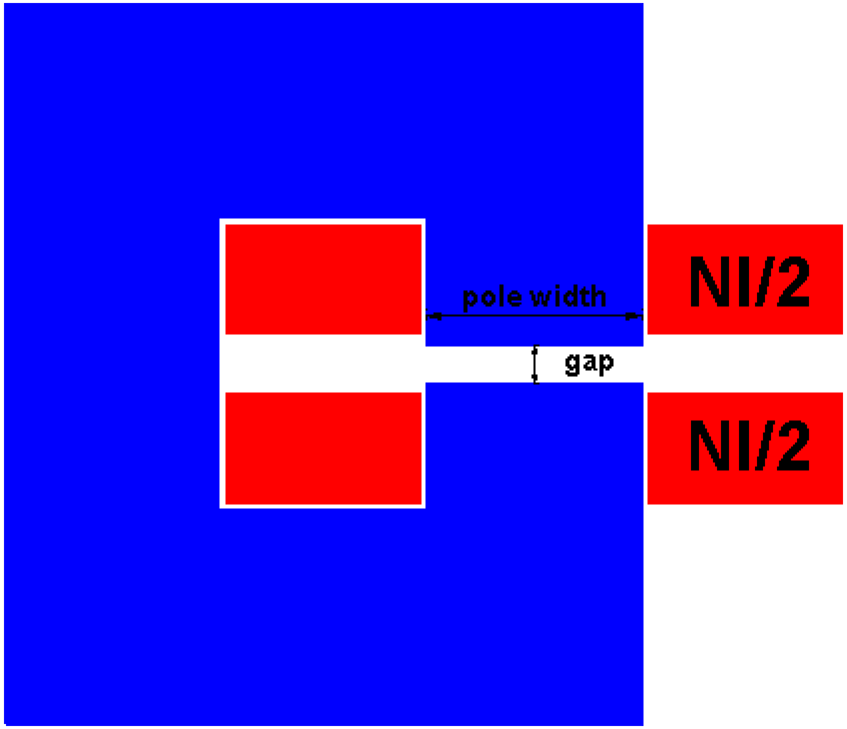


Requirements of an accelerator magnet

- operation mode
- physical constraints (space, transport, weight ...)
- strength
- good field region (may depend on working point)
- field quality at the different working conditions
- physical aperture
- power supply
- cooling
- radiation
- alignment
- reliability
- protection

understand, understand, understand & discuss

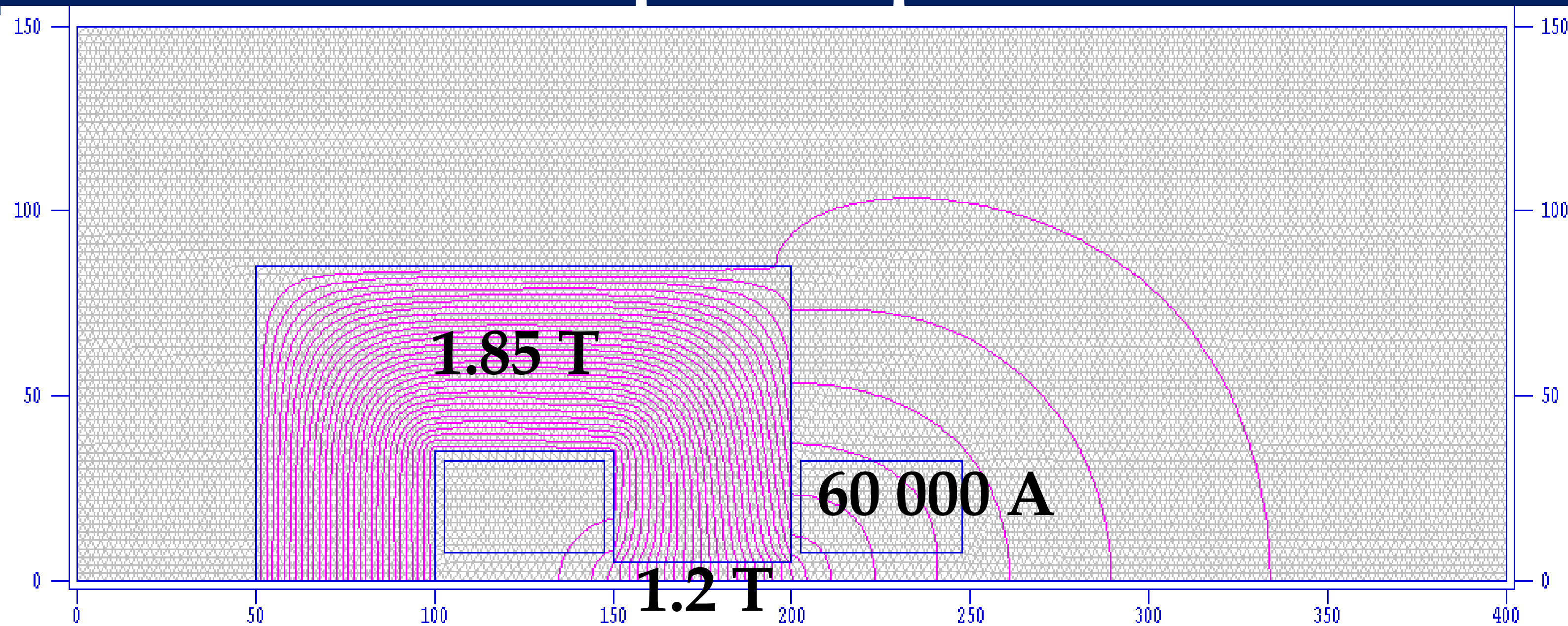
0. BE SURE OF THE REQUIREMENTS

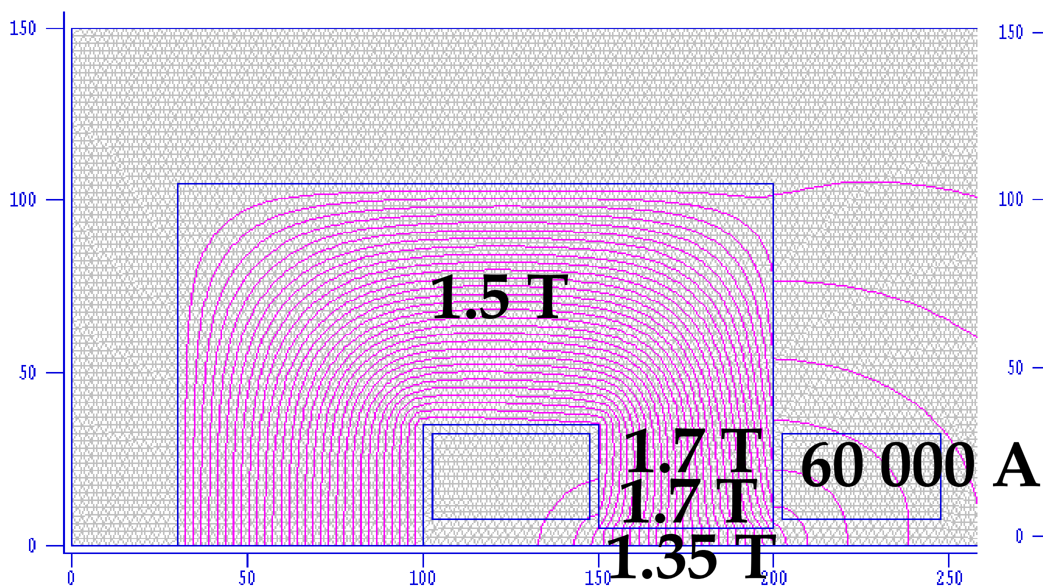


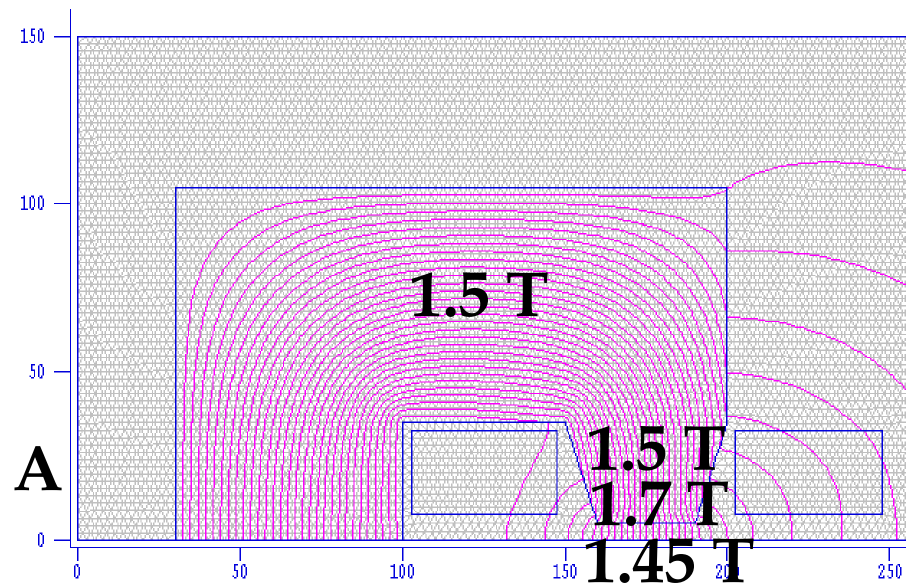
1. ***determine the required amperturns***
   neglecting the amperturns spent in the iron
   $NI = gap \cdot B/\mu_0$
2. ***determine the required pole width***
   tentative ~ good field region + 2.5•gap
3. ***determine the coil section***
   tentative ~ 1 (air) 5 (water) A/mm²
4. ***draw a tentative cross section***
   equi-flux section
5. ***use FE code***
   2D, possibly 3D if magnet is short

B= 1.5 T, gap = 0.1 m ⇒ NI = 120 000 A

The C-dipole: optimization



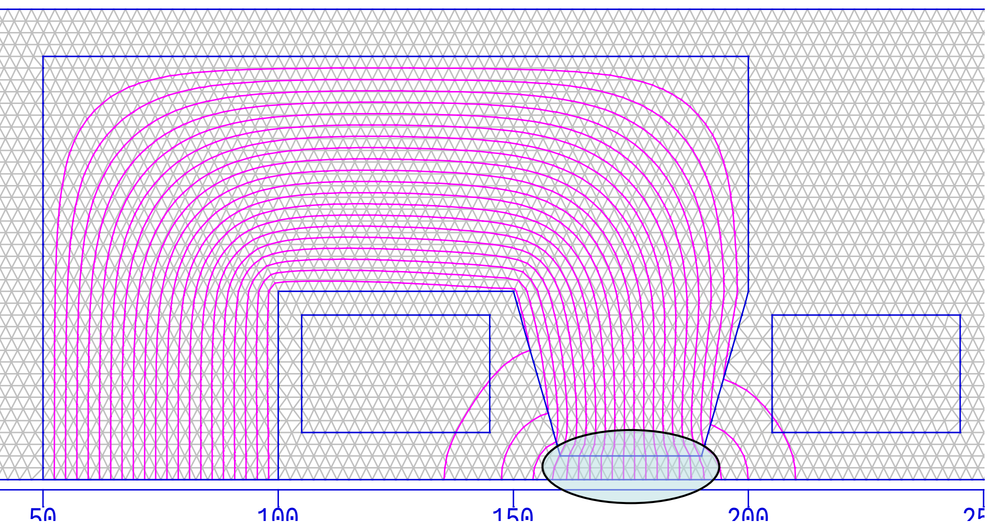


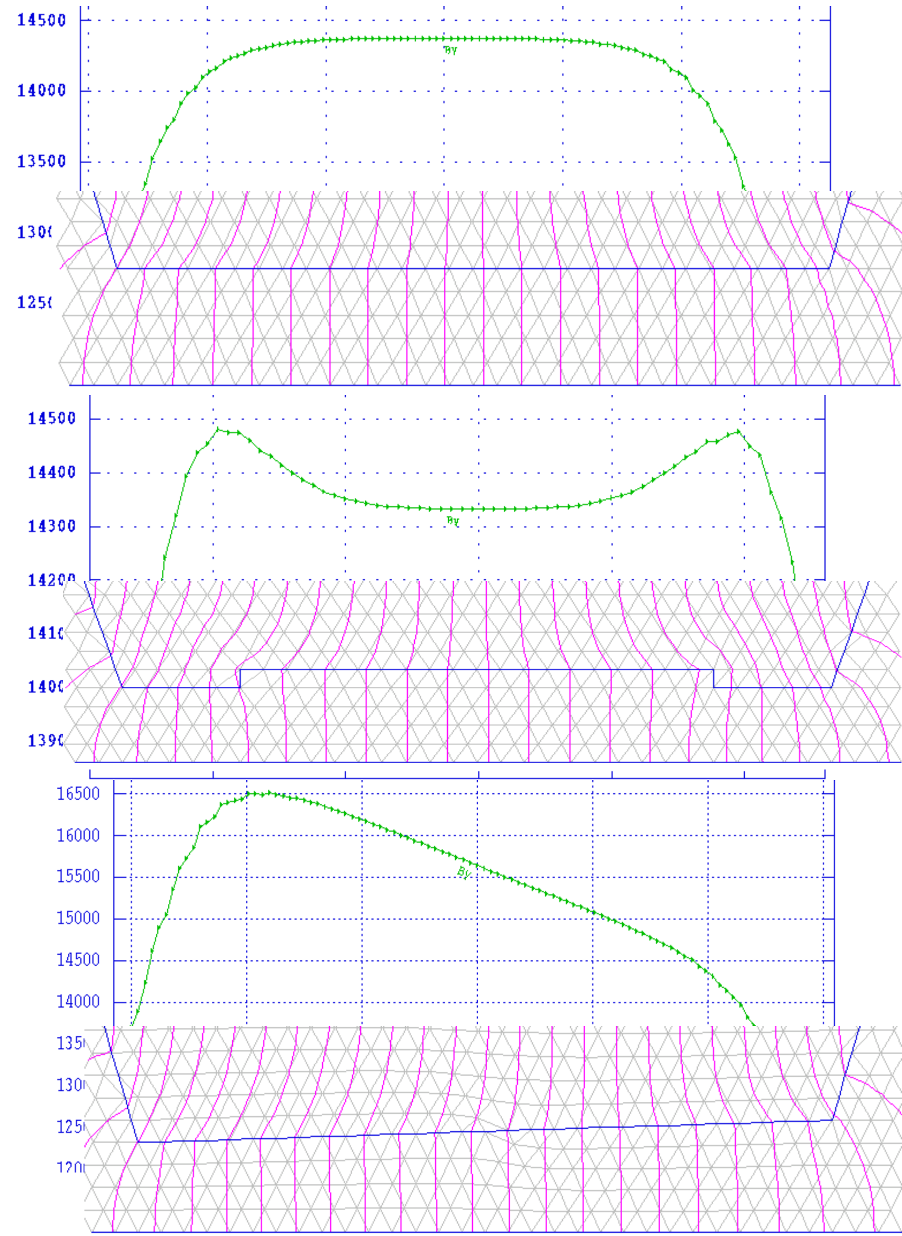


Field harmonics

"ALLOWED" FIELD HARMONICS

Magnet Type	Harmonics	Example
Dipole, n_0=1	$n=n_0+2i$	3,5,7,...
Quadrupole, n_0=2	$n=n_0+4i$	6,10,14,...
Sextupole, n_0=3	$n=n_0+6i$	9,15,21,...
Octupole, n_0=4	$n=n_0+8i$	12,20,28,...





Design : losses

- In a coil of cross section *S*, total current *I*, per unit of length *l*,

$$P/l\,[W/m] = \frac{\rho}{S}\cdot I^2$$

$$\rho_{cu} = 1.72\cdot(1+0.0039\cdot(T-20))\cdot 10^{-8}\,\Omega\cdot m$$

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

- In the yoke we have losses due to:
  - hysteresis: up to 1.5 T we can use the Steinmetz law

$P[W/kg] = \eta\cdot f\cdot B^{1.6}$ with $\eta = 0.01 \div 0.1$, about 0.02 for silicon steel

  - eddy currents: for silicon iron, an approximate formula is

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

where d_{lam} is the lamination thickness in mm

Design : cooling with water

To increase the temperature of 1 kg of water by 1°C we need 1 kcal=1/4.186 kJ.

$$Q[l/\min] = 14.3 \cdot \frac{P[kW]}{\Delta T} \approx 15 \cdot \frac{P[kW]}{\Delta T}$$

To efficiently cool a pipe you need the fluid velocity be greater than zero on the wall, i.e. the flow being moderately turbulent (Reynolds > 2000):

$$R_e = \frac{d \cdot v}{\upsilon} \sim 140 \cdot d[mm] \cdot v[m/s] \text{ for water at} \sim 40°\text{C}$$

Small pipes need high velocity, however attention to erosion (v>3m/s)!

As cooling pipes in magnets can be considered smooth, a good approximation of the pressure drop ΔP as a function of the cooling pipe length L, the cooling flow Q and the pipe hole diameter d is derived from the Blasius law, giving:

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

Design : cost

Manufacture

- Design
- Tooling (punching, stacking, winding, molding)

} fixed

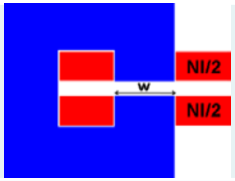
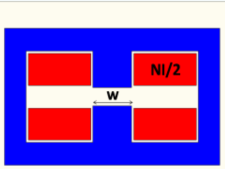
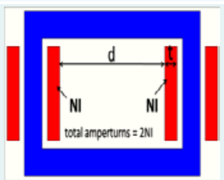
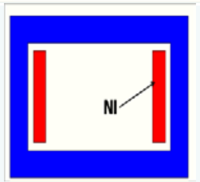
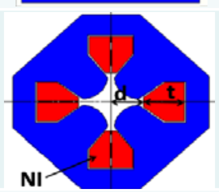
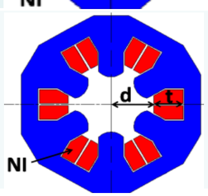
- Materials
- Manufacture
- Assembly + ancillaries + tests

} unitary

Other costs to consider

- Other systems (cooling, power converters & distribution)
- Running costs (electric power, maintenance)

Basic magnets

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	$3x^2y-y^3=R^3$	$B(r)=S\cdot r^2=\frac{1}{2}B''\cdot r^2$ $S=3\mu_0 NI/R^3$	$L=20\mu_0 N^2 A/R$ $A \approx (d+1/3t)\cdot(l+1/2R)$

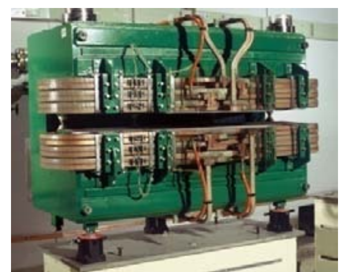
~0.95 efficiency may be introduced in the transfer function

SR facilities : storage ring dipoles

	ELETTRA	ALS	ESRF	ANKA	ASP	ALBA	SOLEIL	SPRING-8	SLS	DIAMOND
Bending radius [m]	5.5	∞	23.37	5.56	∞	7.05	5.36	39.27	5.73	7.16
N. of magnets	24	36	64	16	28	32	32	88	36	48
Dipole field [T]	1.21	1.35	0.86	1.5	1.3	1.42	1.71	0.68	1.4	1.4
Gradient [T/m]	2.86	5.19	0	0	3.35	5.65	0	0	0	0
Gap [mm]	70	50	54	41	42	36	37	64	41	46.6
Current [A]	1420	924	700 ?	660	695	530	538	1090	557	1337

ANKA

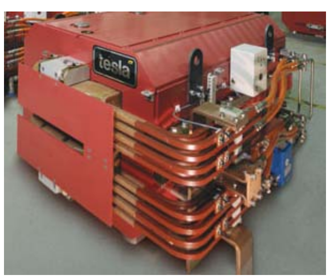
ALBA



ELETTRA

SLS

SPRING-8

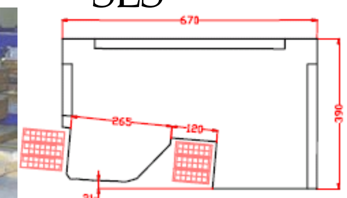


SOLEIL

DIAMOND

CLS

Gap=45 mm B= 1.35 T G= 3.8T/m

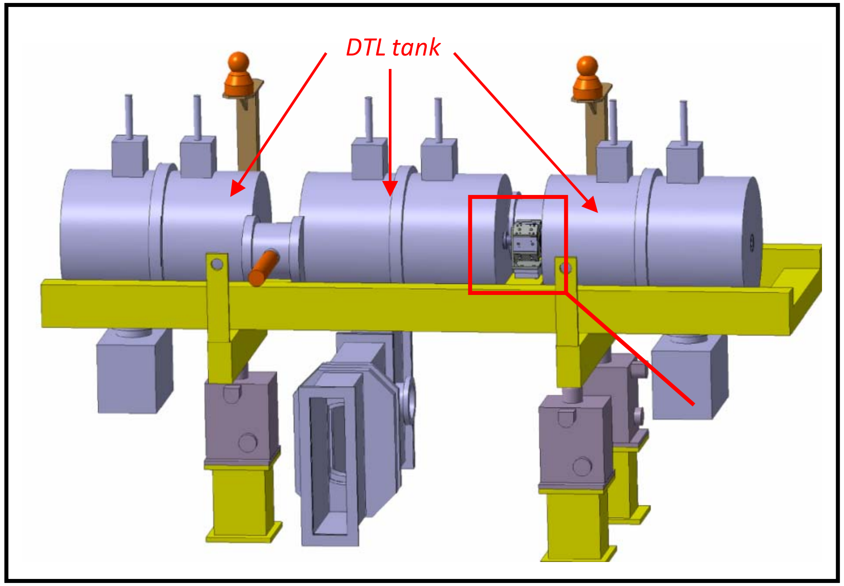


ASP

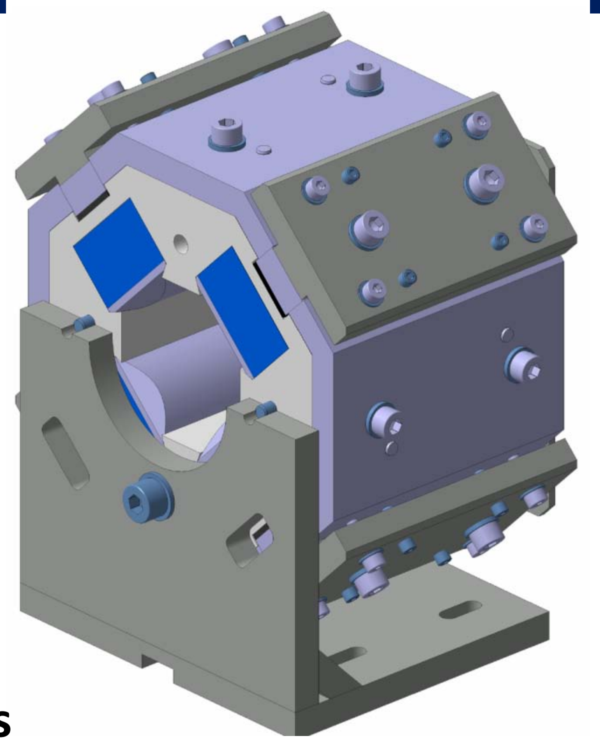
SPEAR3

Gap = 50 mm B= 1.4 T G= 3.6 T/m

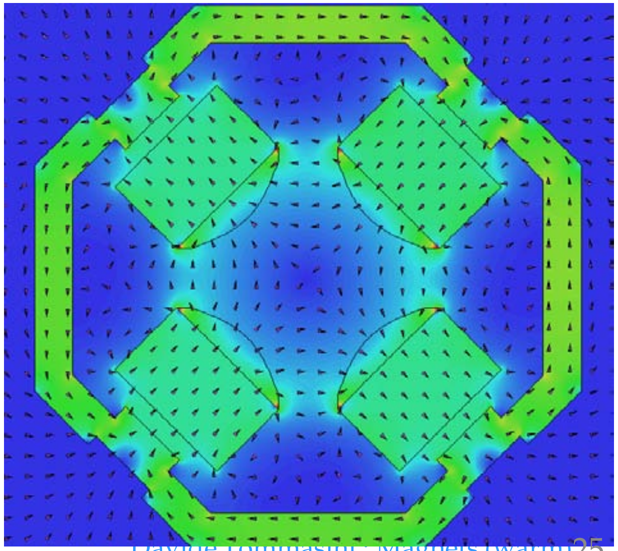
Permanent Magnets : LINAC 4



Pictured : Cell-Coupled Drift Tube Linac module.

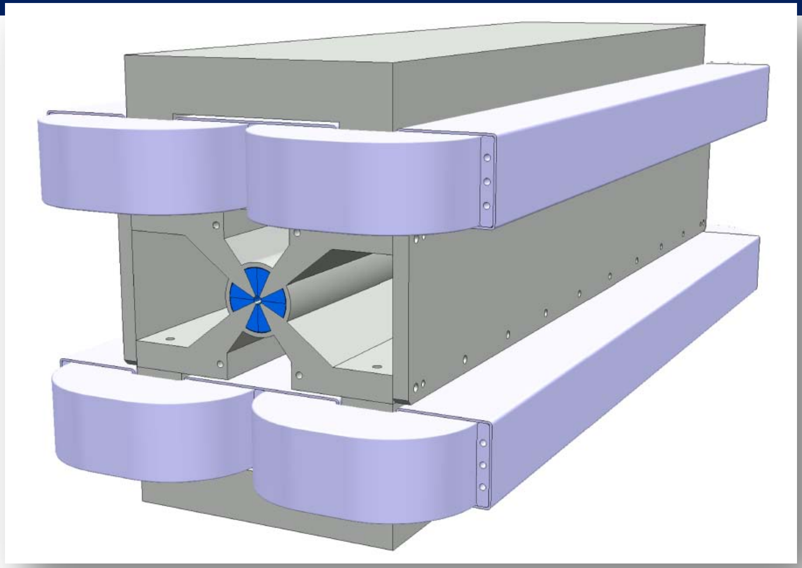


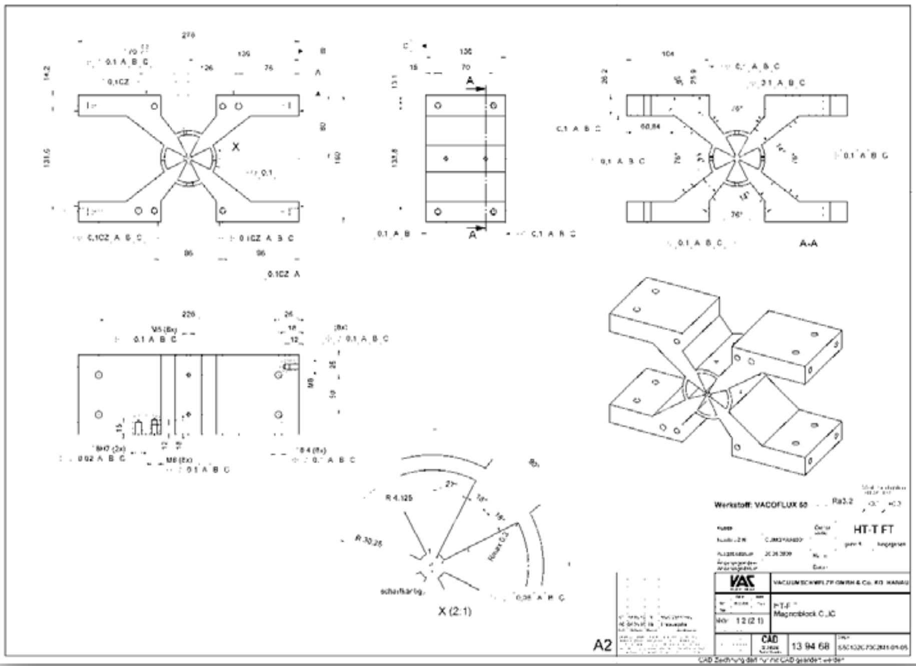
- Permanent magnet because of space between DTL tanks
- Sm_2Co_{17} permanent magnets
- Integrated gradient of 1.3 to 1.6 Tesla
- 15 magnets
- Magnet length 0.100 m
- Field quality/amplitude tuning blocks

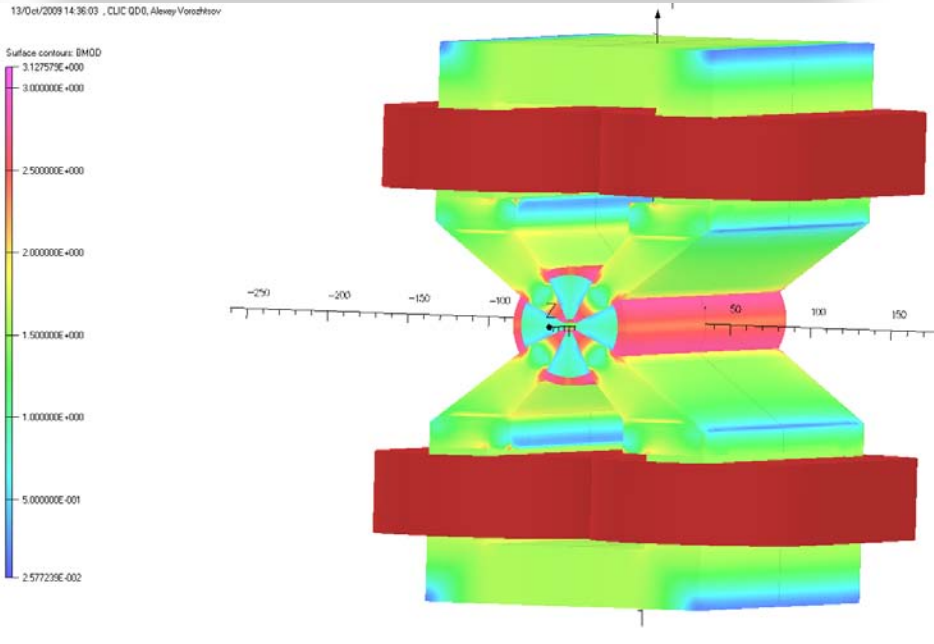


Hybrid Magnets : CLIC final focus

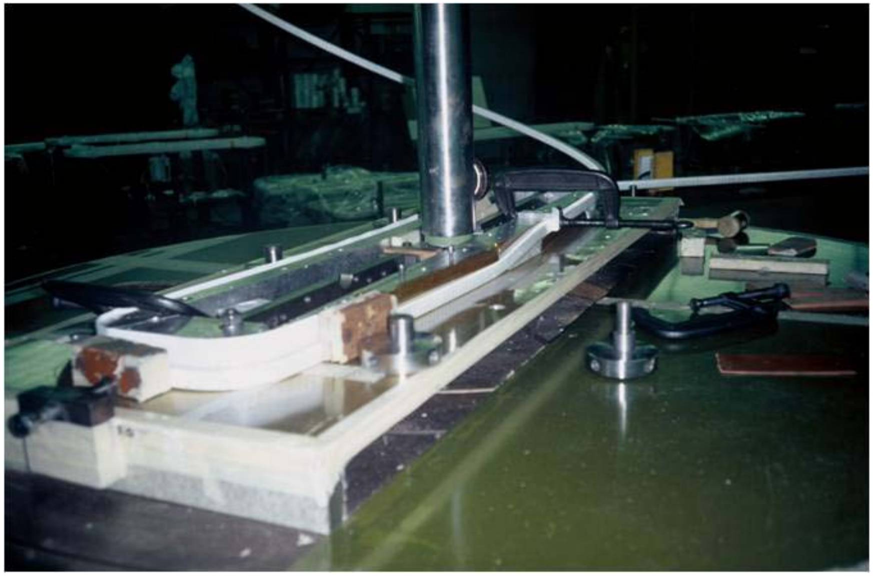
Gradient: > *530 T/m*
Aperture Ø: *8.25 mm*
Tunability: *10-100%*

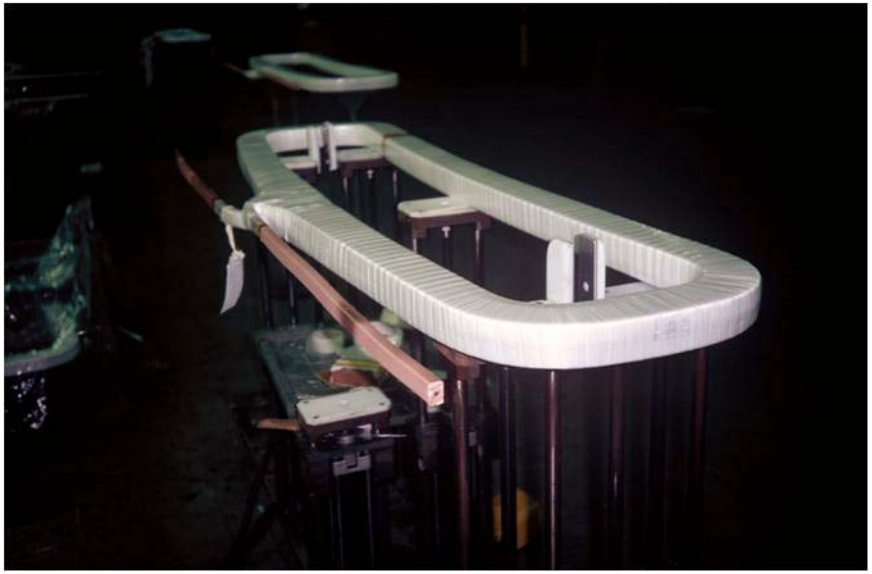




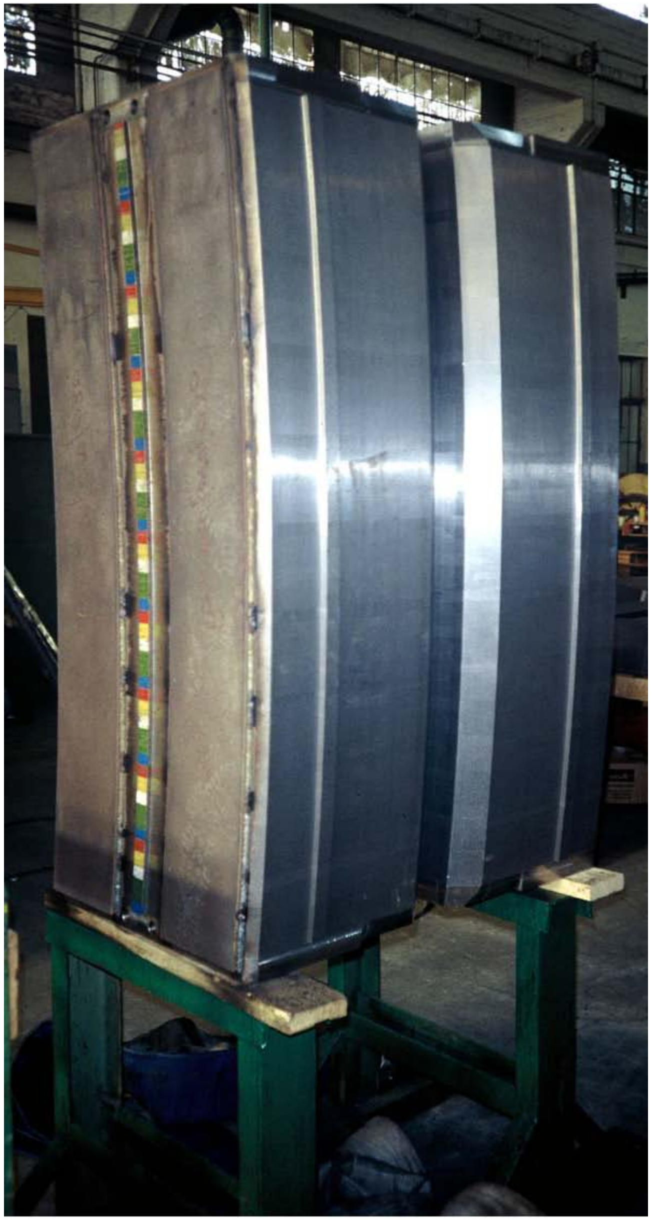


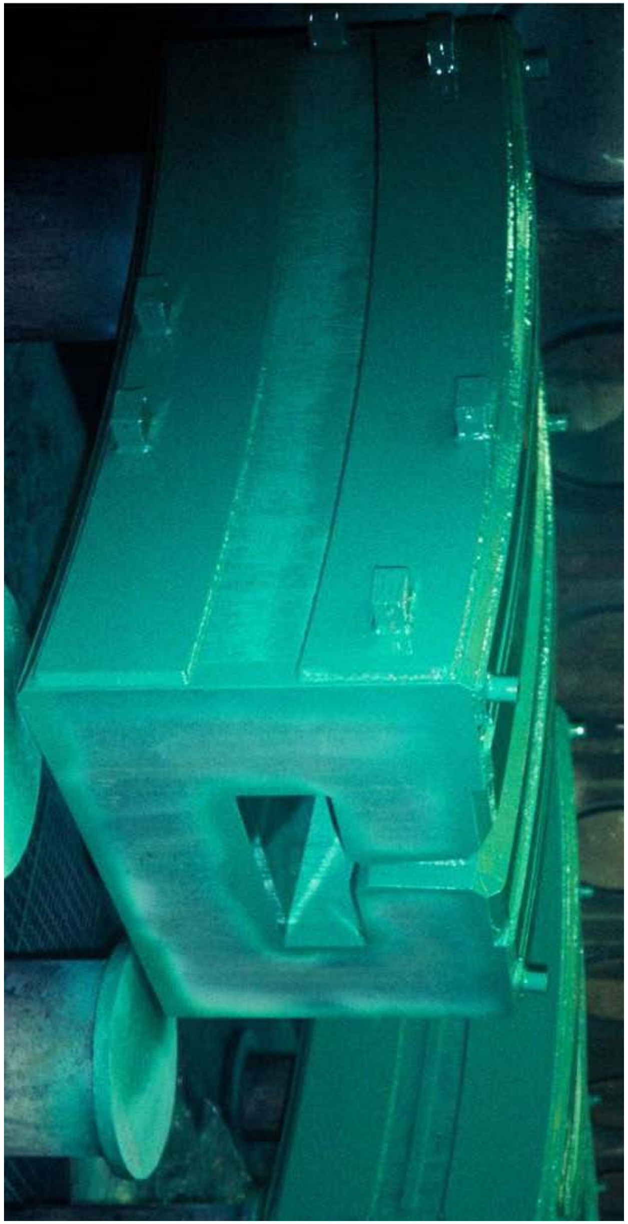
Manufacture : coils



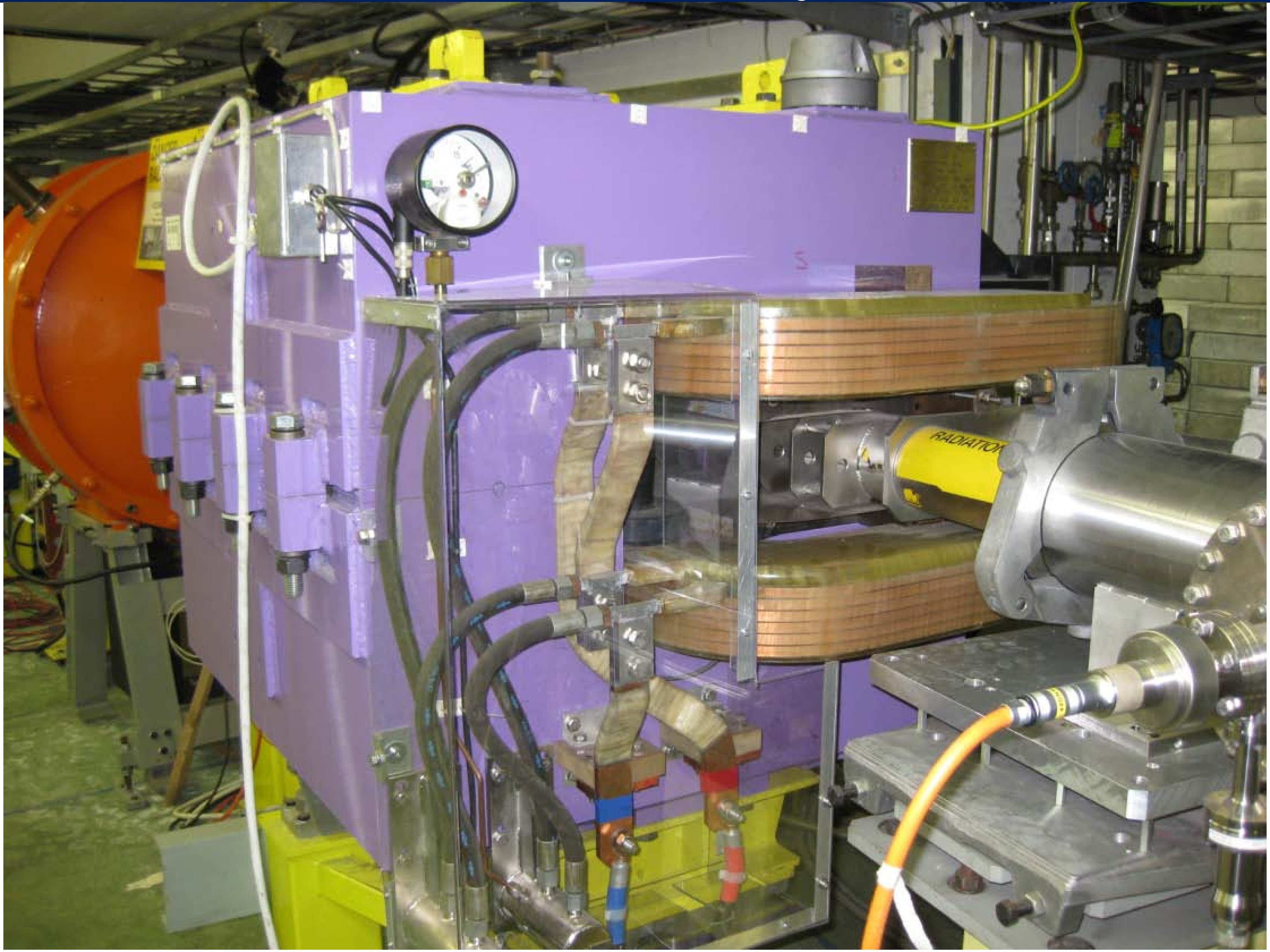


Manufacture : yoke

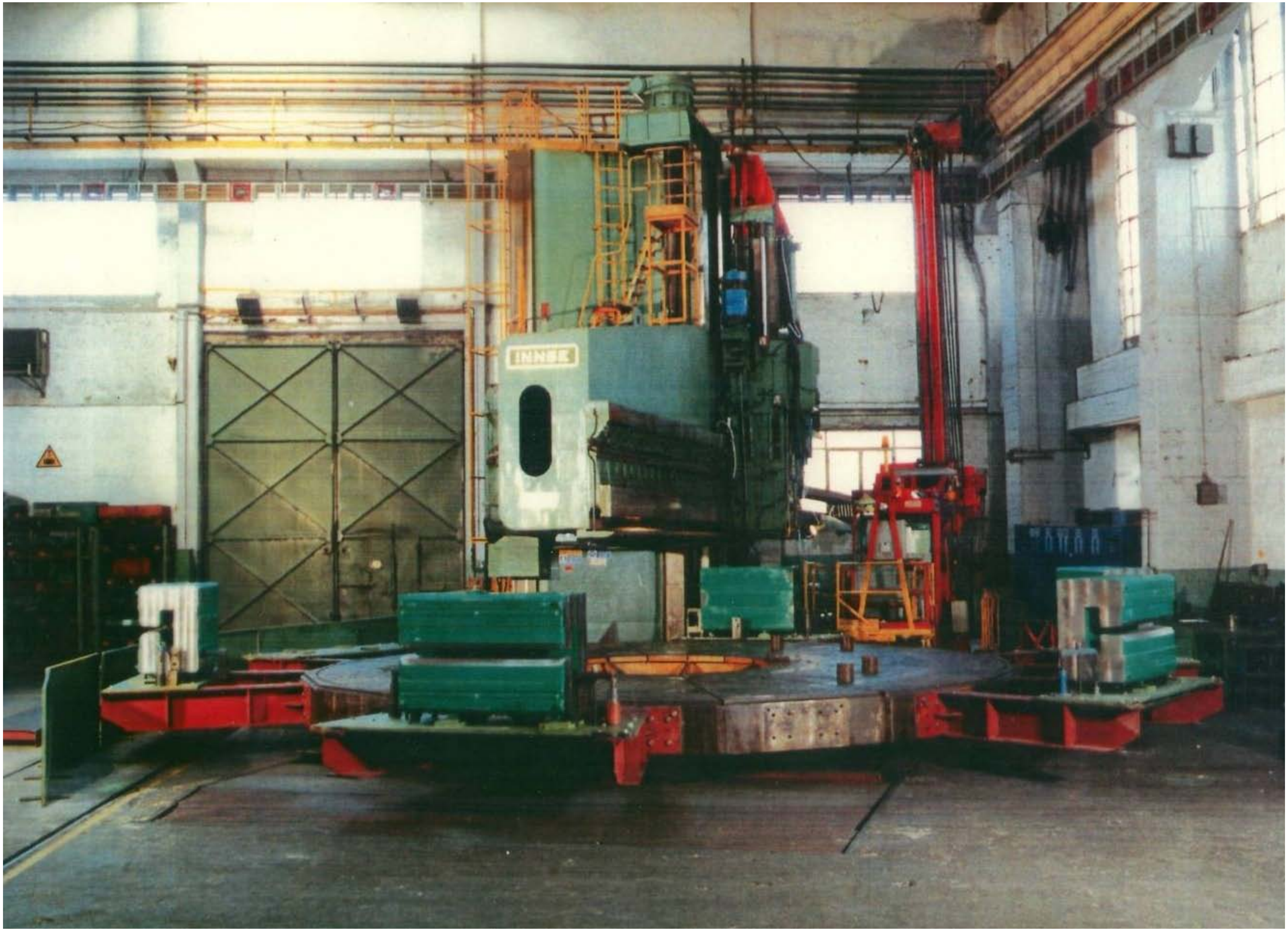




Manufacture : yoke

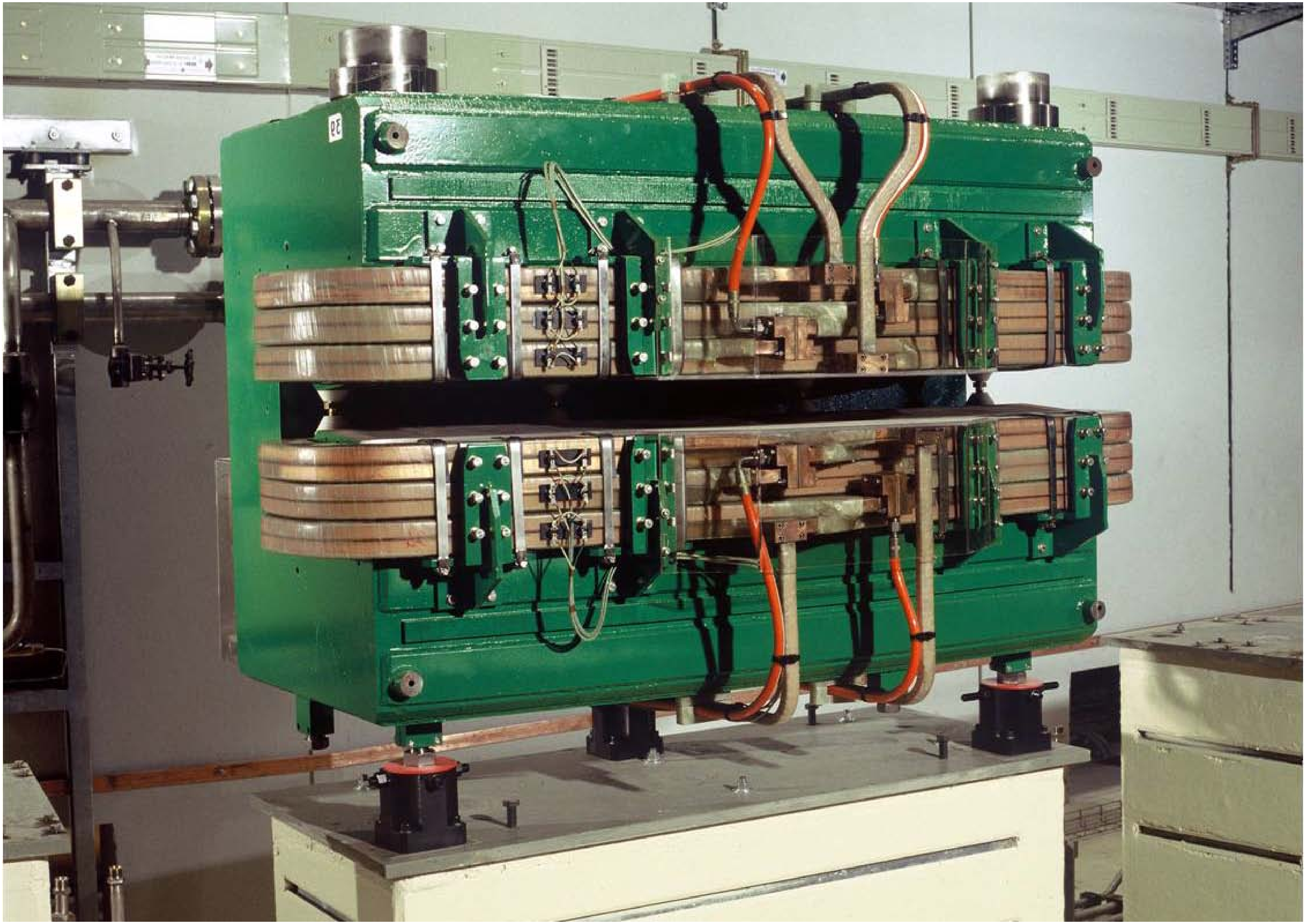


Manufacture : yoke

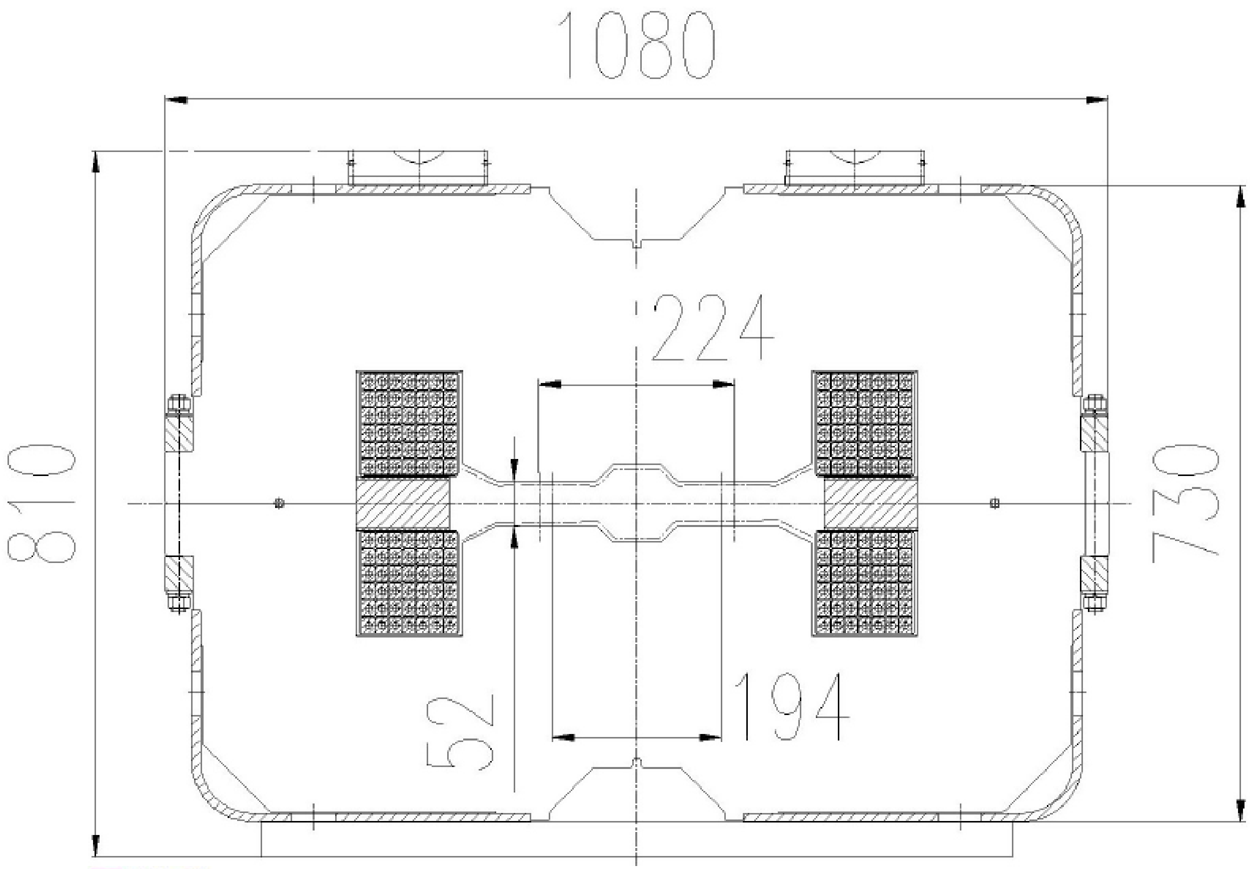


Manufacture : yoke

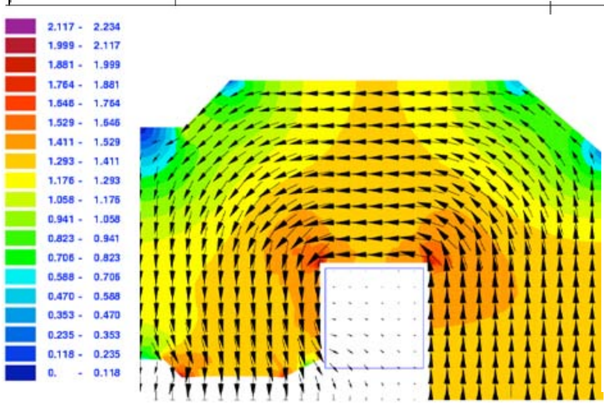
Manufacture : yoke

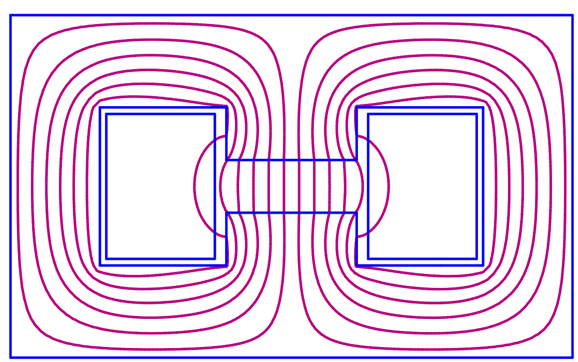


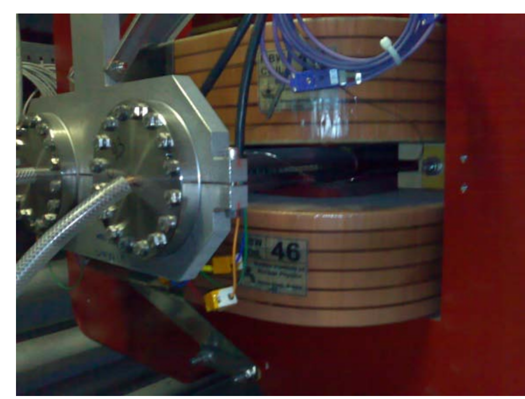
MBW in the LHC : H-type dipole / 1



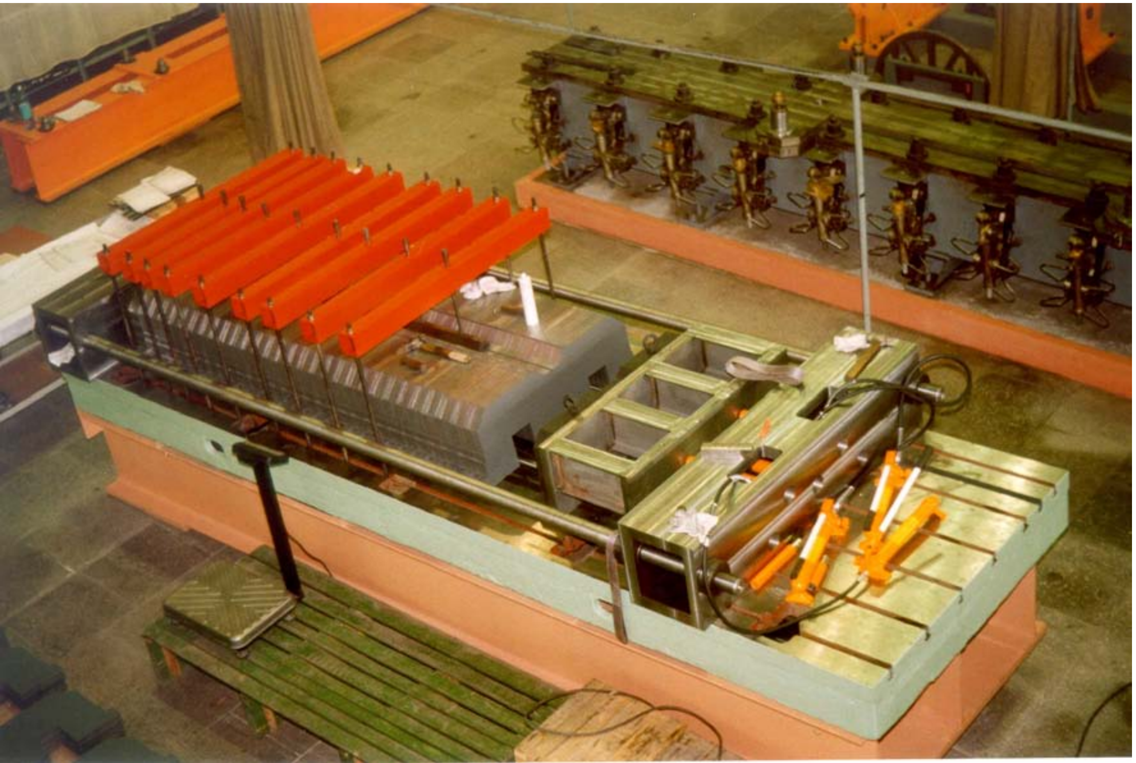
Parameter	Value
Aperture	52 mm
Nominal field	1.42 T
Magnetic length	3.4 m
Weight	18 t
Water flow	19 l/min
Power	29 kW

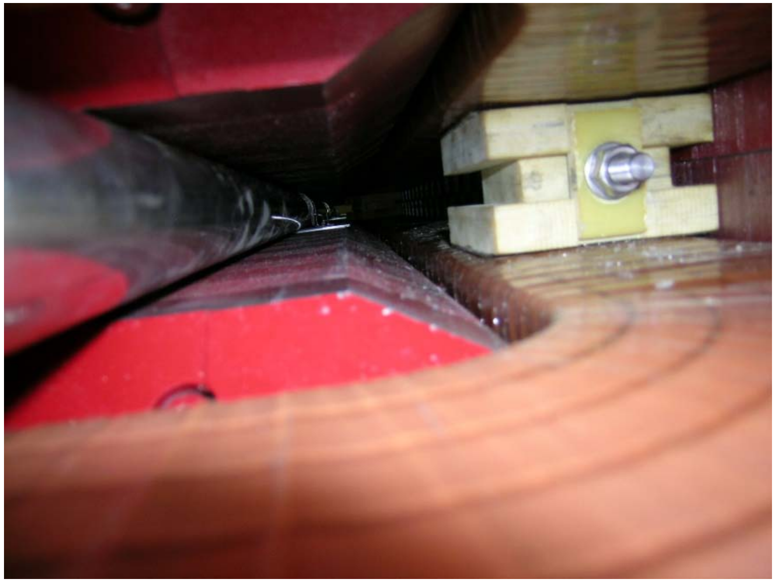


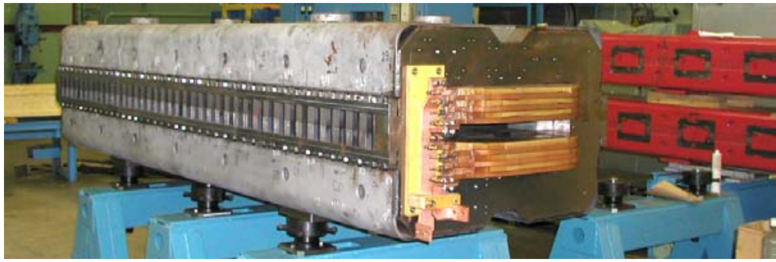




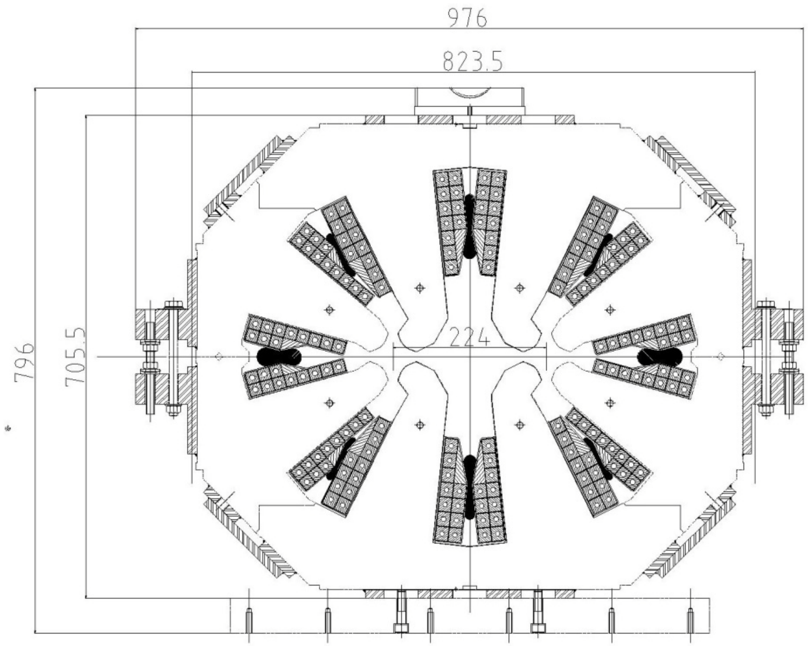
MBW in the LHC : H-type dipole / 2

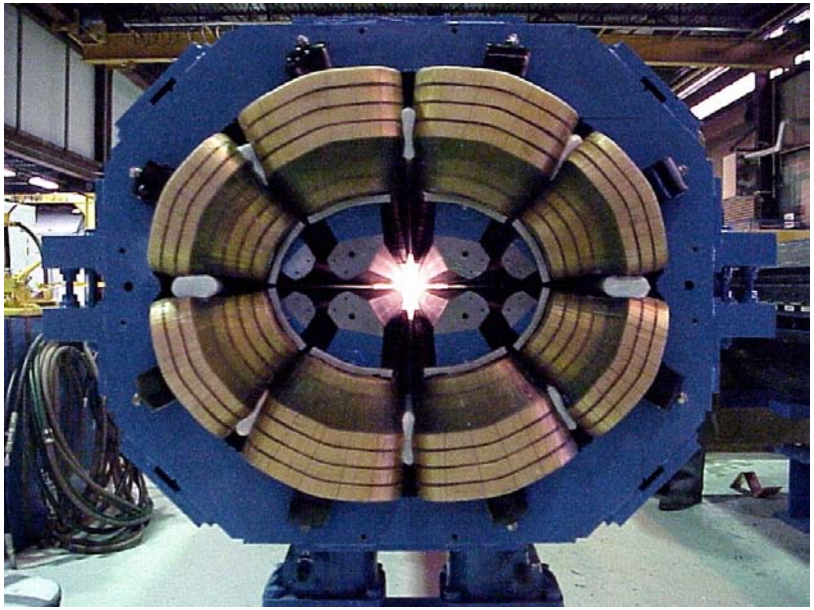






MQW Magnets

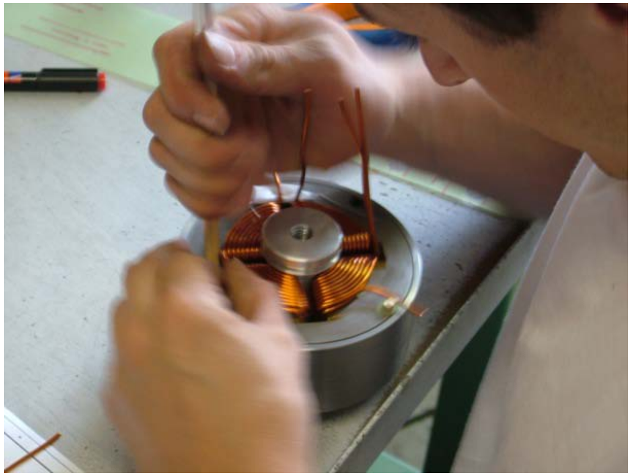




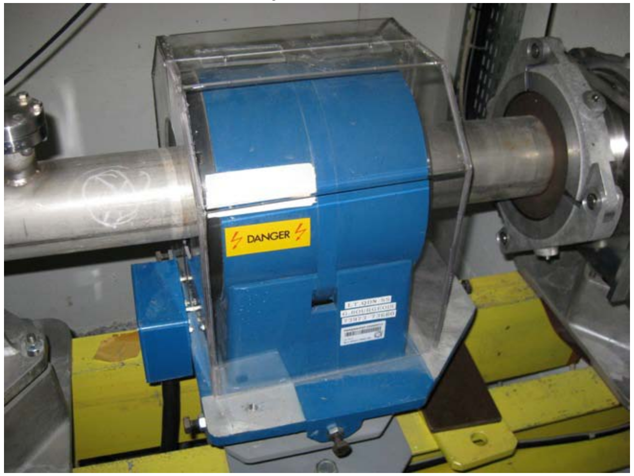
LINAC-2 Quadrupoles

Type III

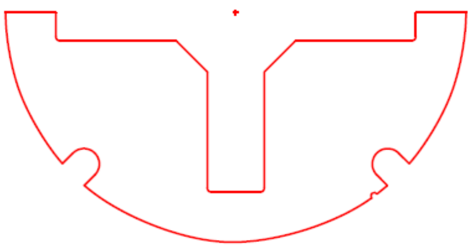
Type III - Assembly



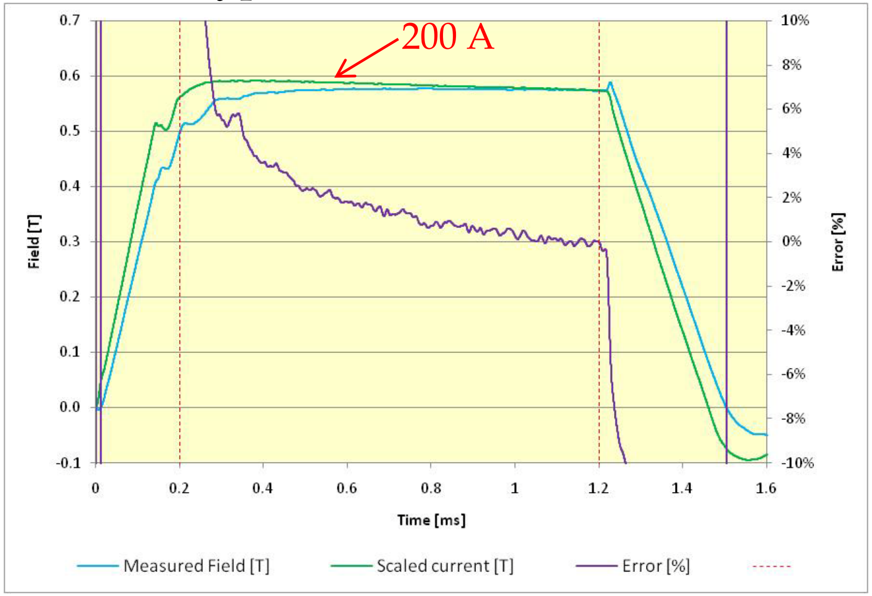
Type VII



Quadrupole Lamination



Type III – Field Measurement

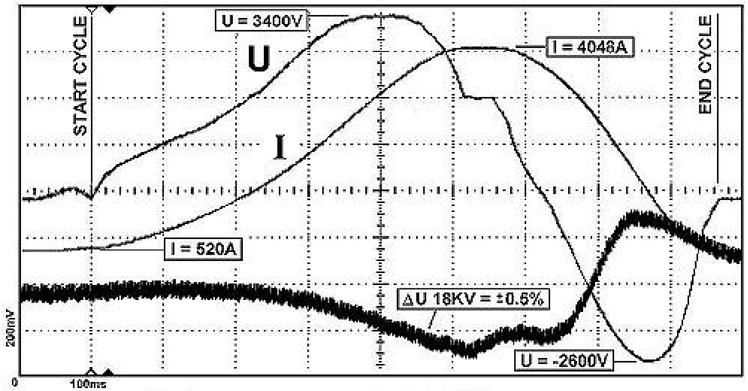


Types - I to X
Core O.D. - 113 to 245 mm
Core Length - 25 to 203 mm
Aperture Diameter - 22 to 103 mm

Yoke half - stacked and glued 0.65 mm laminations assembled with shrunk fit outer ring then potted.

PS Booster Magnets

1.4 GeV Magnet Cycle



Spare Booster Dipole

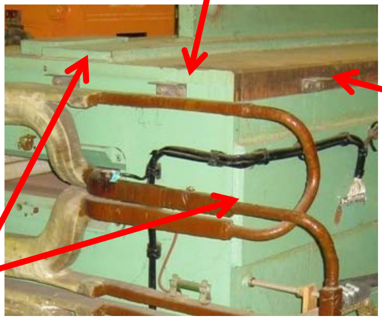
Installed Booster Dipole

32 Dipole magnets for Booster Ring
Magnet Weight - 12000 Kg
Core Length - 1537 mm
Aperture - 103 mm
Magnetic flux @ 1.4 GeV operation 1.064 T

Yoke construction:
Laminated core stacked between 'thick' end plates assembled using external welded tie bars. Lamination insulation achieved through a phosphatizing process.

'Thick' End Plate

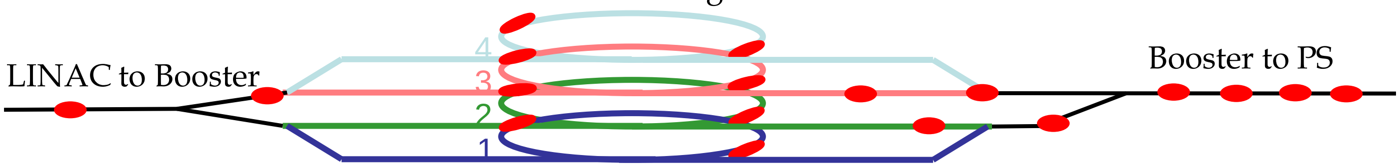
BDL correction Windings compensate the 1% difference between the inner and outer rings.



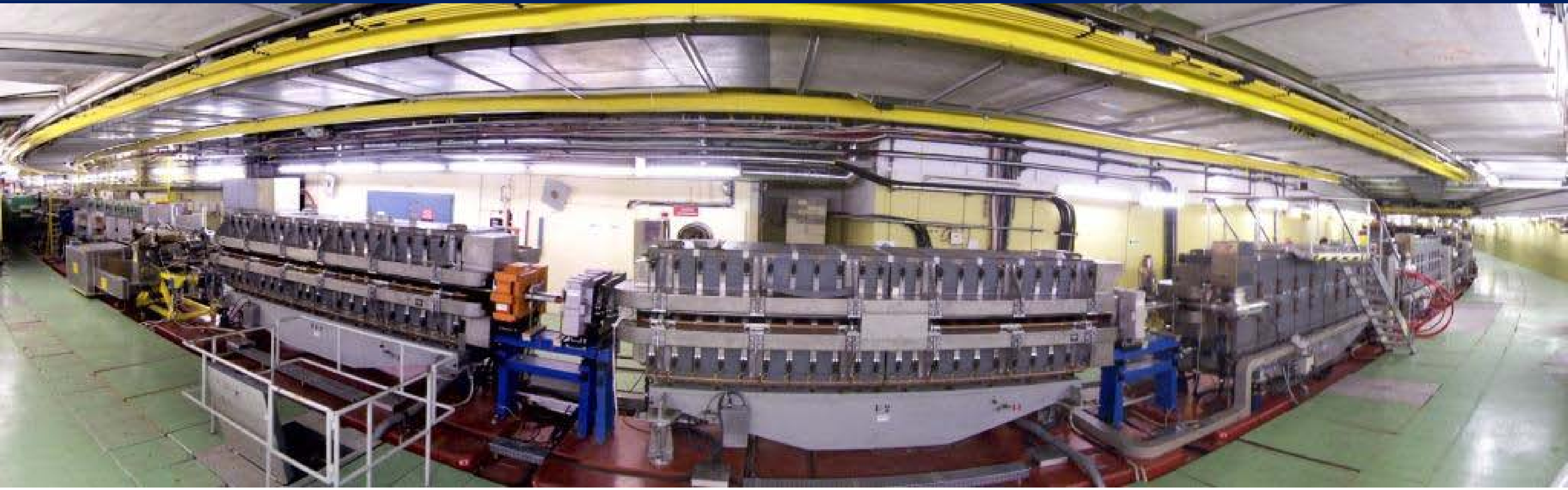
Laminations

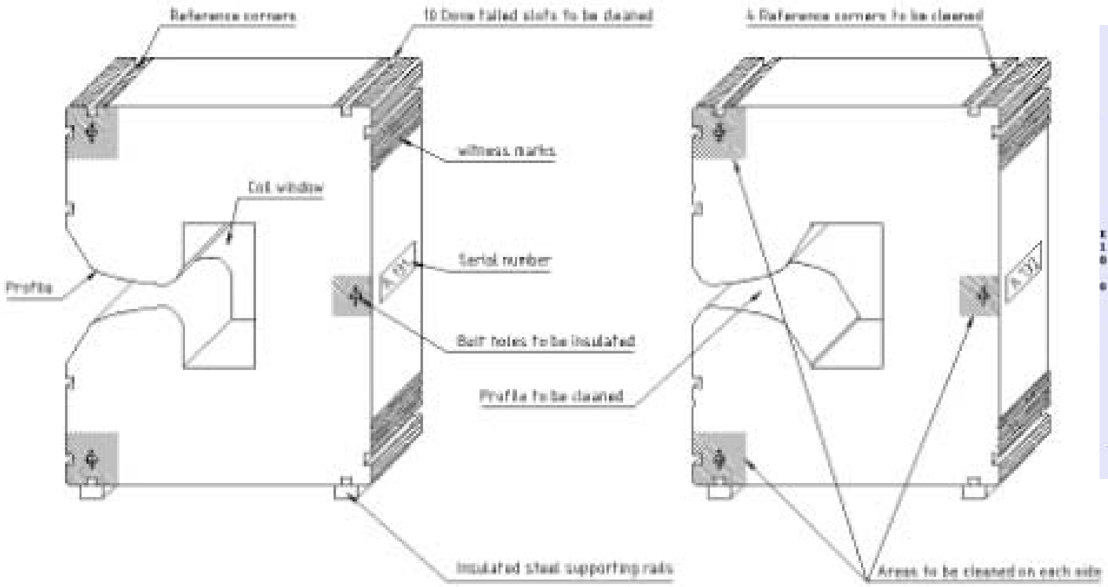
Welded tie Bars

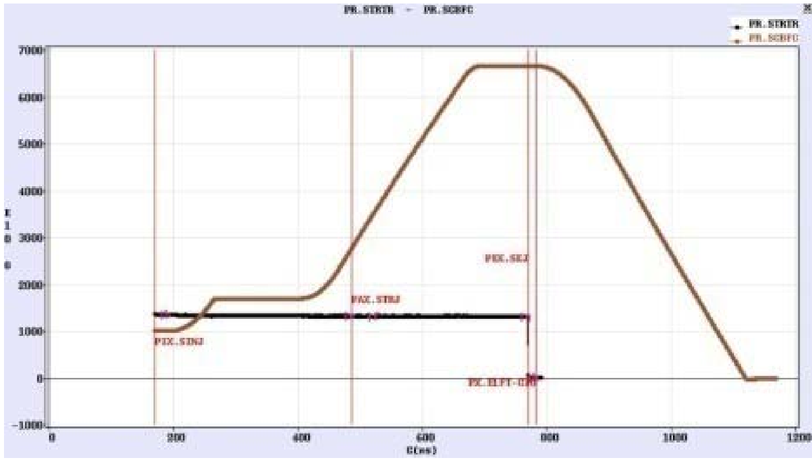
Booster Ring



Main units PS, combined function



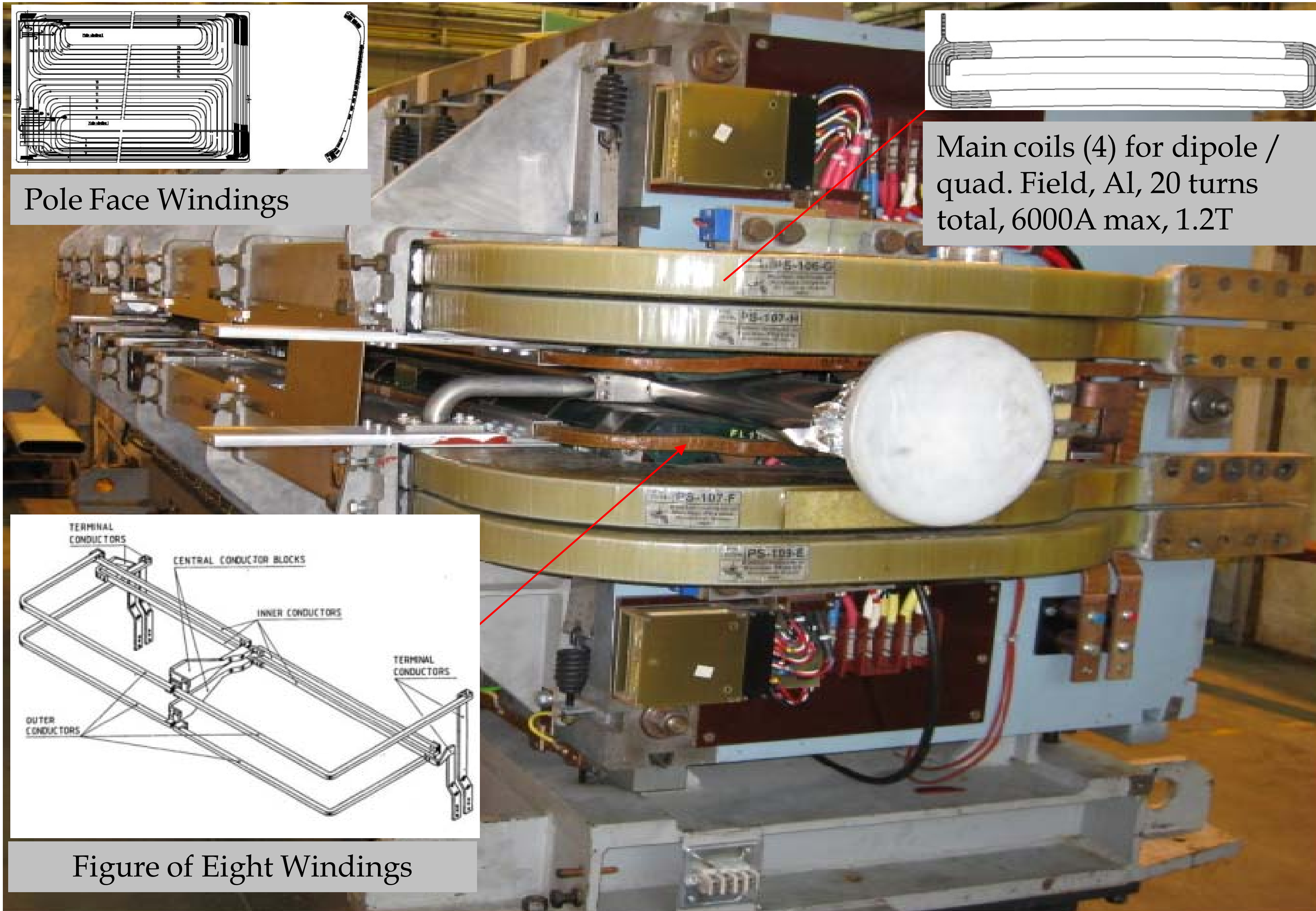




Typical "TSTLHC" cycle for LHC

1.256T, 900 ms, 25.08 GeV

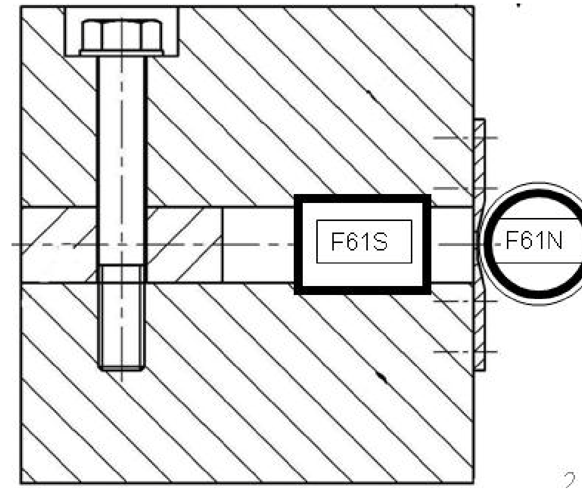
Combined function dipole / quadrupole, PS machine

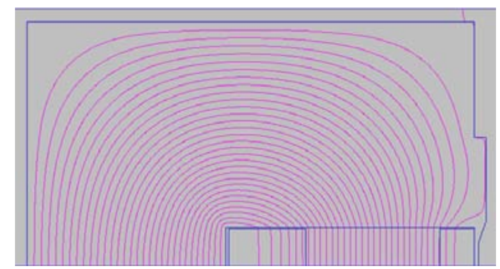


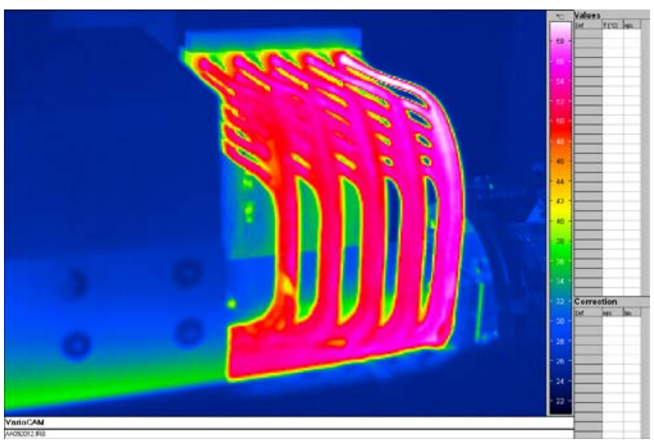
Septum magnet East Experimental area

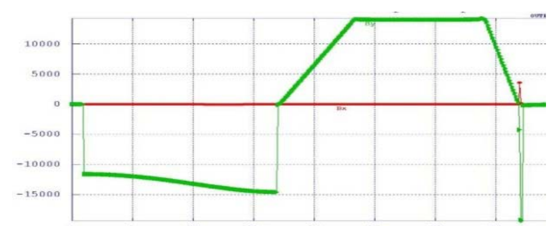
Massive yoke, DC operated, 1.4 T in the gap, ferromagnetic chamber with μ-metal shield around the north beam

High current density (80 A/mm2), 50 turns, 1300A, high cooling capacity of 15.6 m3/h

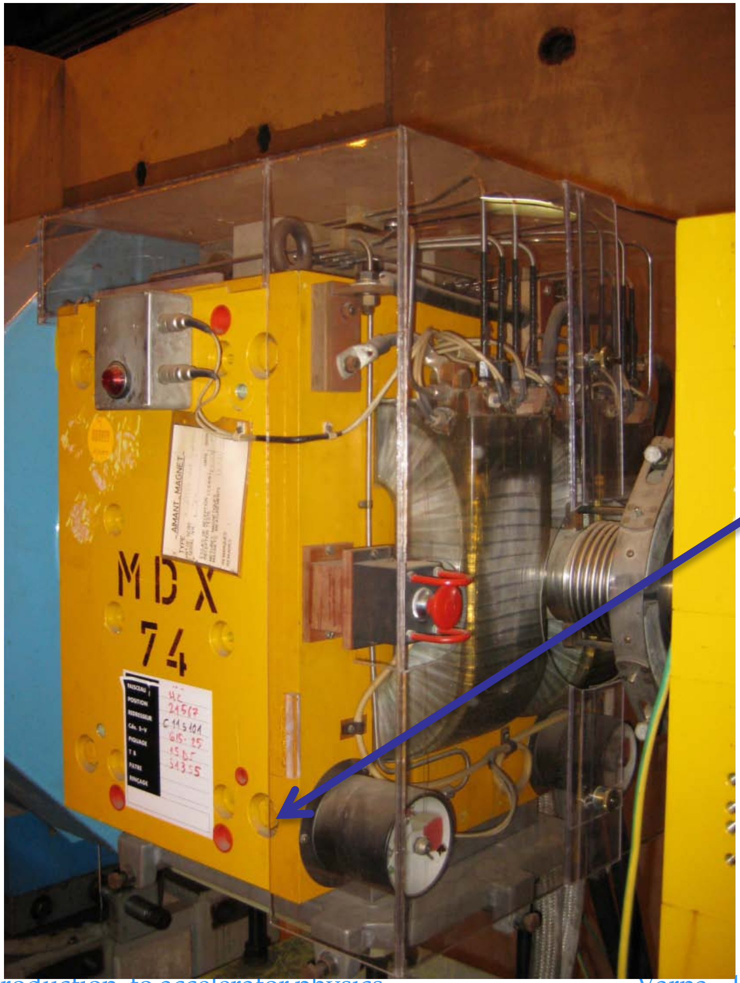








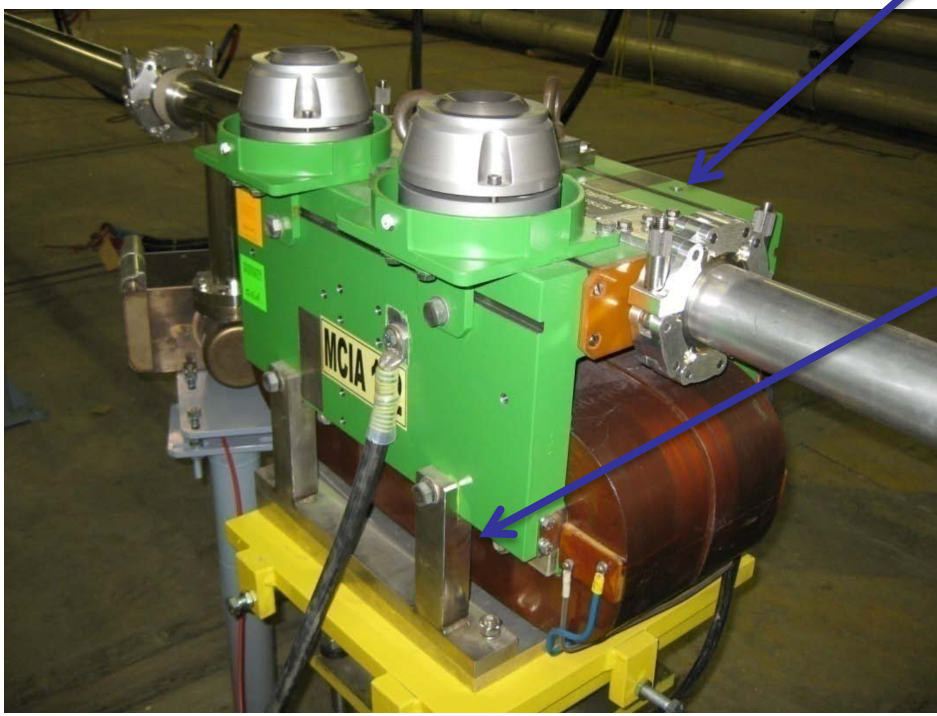
Magnet with solid yoke parts assembled with bolts.

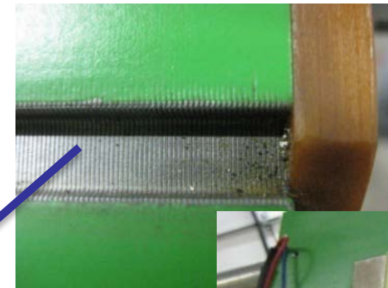


Main parameters	
Name	MDX
Type	Vertical correcting dipole
Installation	SPS experimental area
Nominal peak field [T]	1.33
I_{max} [A]	240
Résistance [Ω]	0. 305
Inductance [H]	0. 221
Yoke lenght [mm]	400
Gap [mm]	80
Total weight [kg]	1000

Corrector dipole in TI2 and TI8 LHC injection lines

Magnet with glued laminated yokes assembled with bolts.

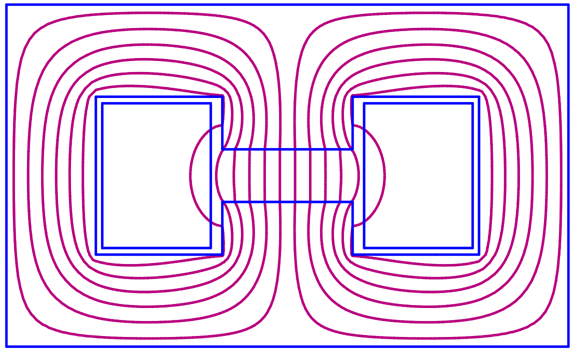


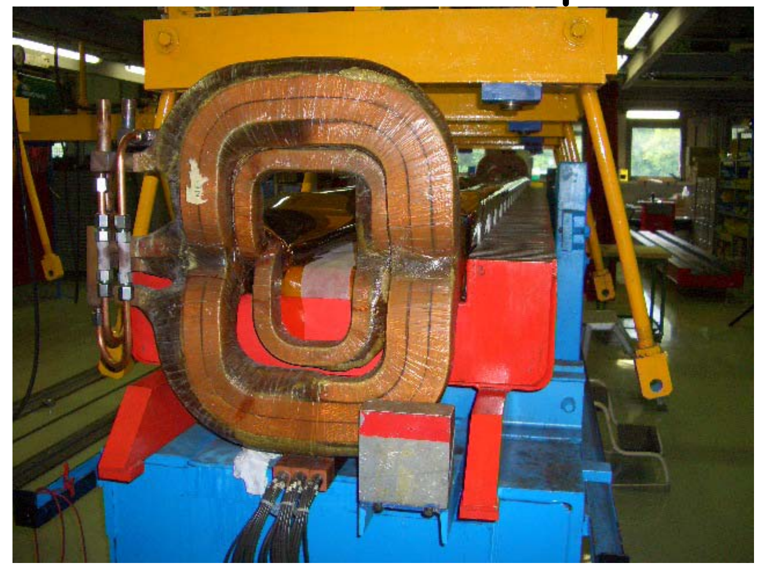


Main parameters	
Name	MCIA V
Type	Vertical correcting dipole
Nominal peak field [T]	0.26
I_{max} [A]	3.5
N. Of turns	1014
Résistance [Ω]	13.9
Yoke lenght [mm]	450
Gap [mm]	32.5
Total weight [kg]	300

Main dipole in the SPS

Magnet with laminations welded in a steel envelope
H-type dipole, half-yokes assembled with welded plates

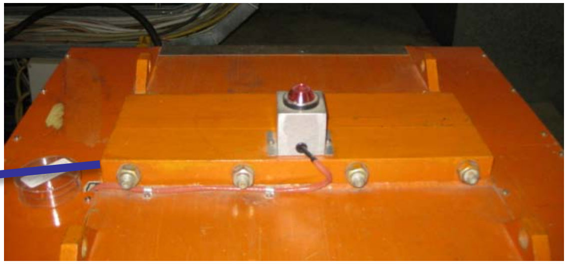




Main parameters	
Name	MBB
Type	Bending dipole
Nominal peak field [T]	1.8
I_{max} [A]	4900
N. Of turns	16
Résistance [Ω]	$4.46 \,.\, 10^{-3}$
Inductance [H]	0.018
Yoke lenght [mm]	2225
Gap [mm]	52
Total weight [kg]	17400

Corrector dipole for E-Cloud experiment in SPS

Magnet with laminations welded in a steel envelope
half-yokes assembled with bolts.



Main parameters	
Name	MDVW
Type	Vertical correcting dipole
Nominal peak field [T]	0.266
I_{max} [A]	55
N. Of turns	2 x 50
Résistance [Ω]	1.76
Inductance [H]	1.12
Yoke lenght [mm]	429
Gap [mm]	200
Total weight [kg]	1100

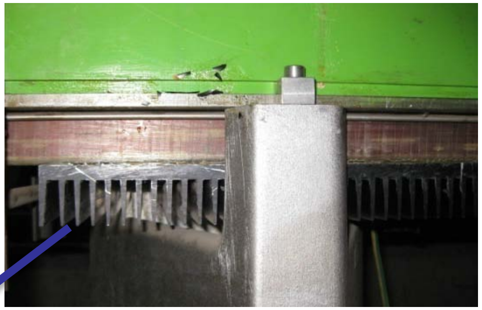
Corrector dipole for BBLR experiment in SPS

Water-cooled magnet with plain conductor coils equipped with external water circuit.

Main parameters	
Name	MCVA
Type	Vertical correcting dipole
Nominal peak field [T]	0.059
I_{max} [A]	5
Résistance [Ω]	12.5
Yoke lenght [mm]	400
Gap [mm]	170
Total weight [kg]	130

Corrector dipole for BBLR experiment in SPS

Air-cooled magnet



Main parameters	
Name	MCVA
Type	Vertical correcting dipole
Nominal peak field [T]	0.059
I_{max} [A]	5
Résistance [Ω]	12.5
Yoke lenght [mm]	400
Gap [mm]	170
Total weight [kg]	130

Quadrupole of TT40 (SPS to CNGS)

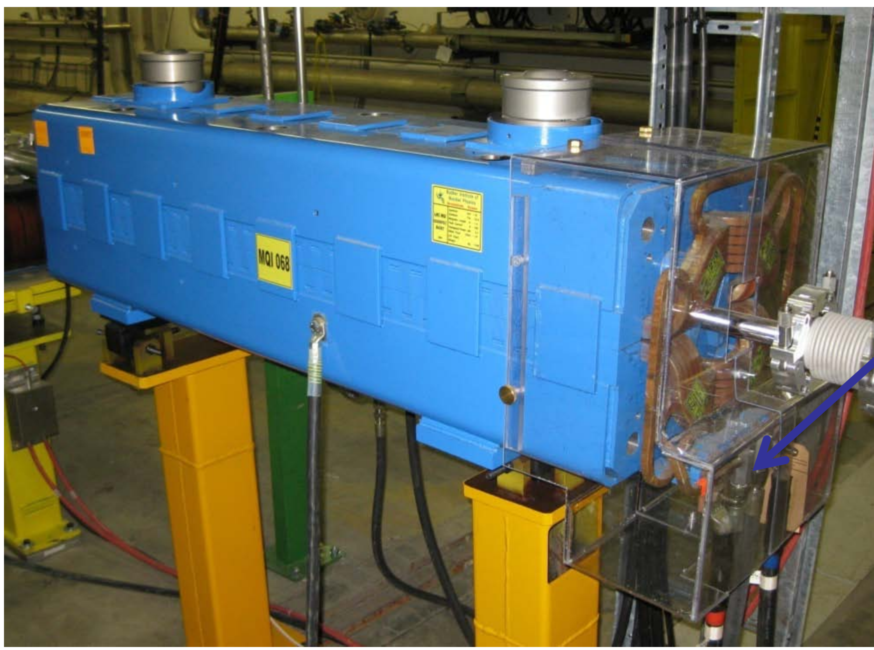
Water-cooled magnet with insulators

Moulded insulating distributor

Separated insulators

Main parameters	
Name	QTL
Type	Quadrupole
Nominal gradient field [T/m]	24
I_{max} [A]	416
N. Of turns	4 x 42
Résistance [Ω]	0.276
Inductance [H]	0.390
Yoke lenght [mm]	2990
Inscribed radius [mm]	80
Total weight [kg]	9900

Water-cooled magnet without insulators (insulating hoses).



Main parameters	
Name	MQI
Type	Quadrupole
Nominal gradient field [T/m]	≥ 53.5
I_{max} [A]	530
N. Of turns	4 x 11
Résistance [Ω]	0.036
Inductance [H]	0.013
Yoke lenght [mm]	1400
Inscribed radius [mm]	16
Total weight [kg]	1070

Spectrometer magnet in T7 line (LHCb)of East Hall

Parameter	Value
Aperture	500 mm
Nominal field	1.4 T
Pole width	1000 mm
Pole length	1000 mm
Weight	65 t