Conventional Accelerator Magnets

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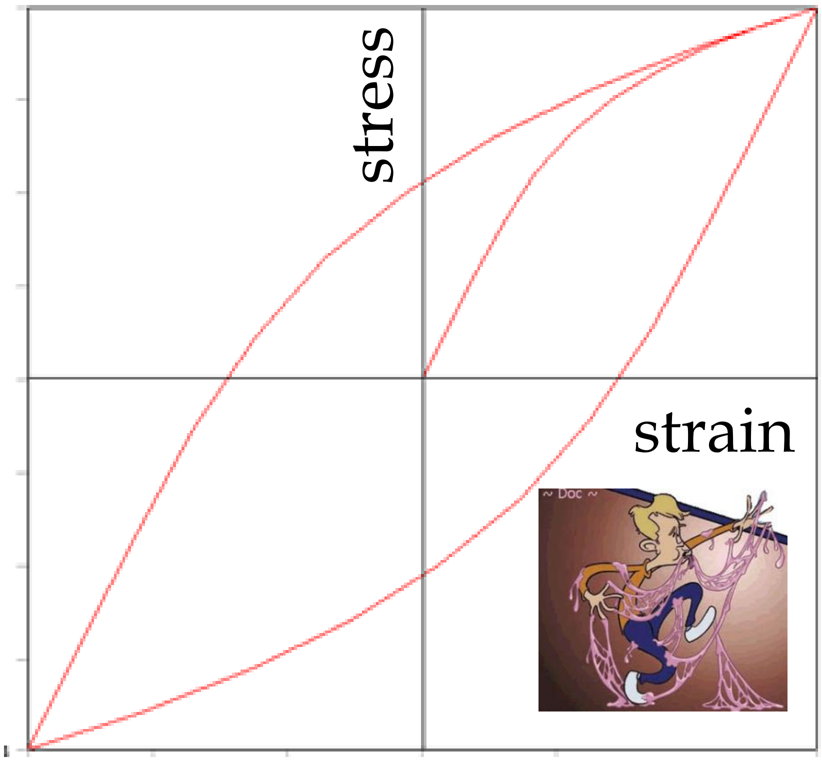
CERN

- Basic principles
- Magnet types
- Elementary design (dipole)
- Manufacture
- Resistive magnets in CERN accelerators

Basic principles : mechanics



To squeeze or elongate an object you need a press

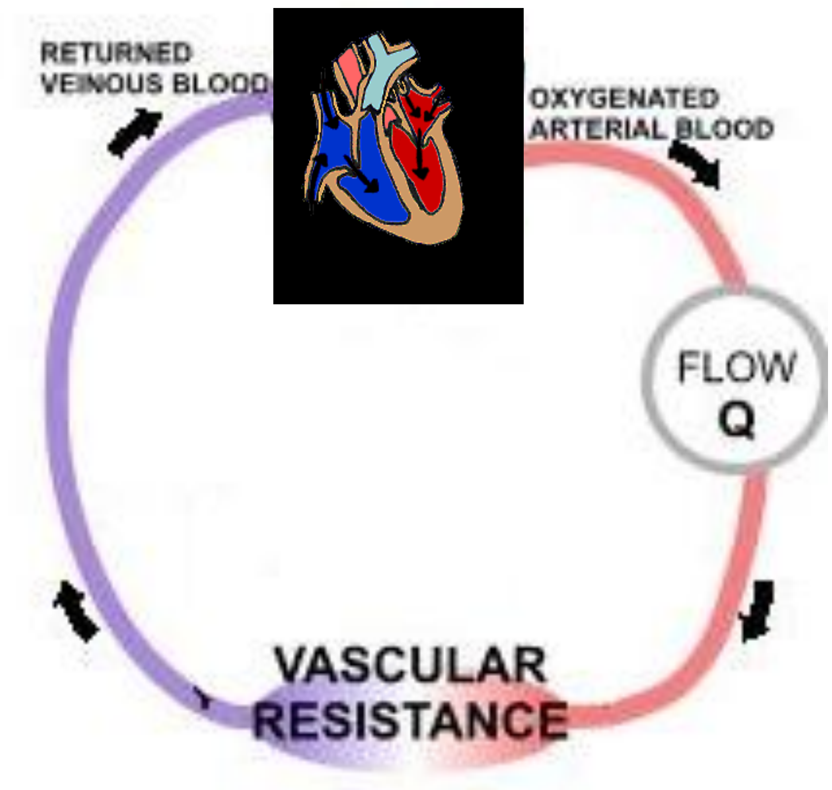
An elongation or compression creates a force

FORCE = pressure x section

F = P x A

$\Delta L = (1/\mathcal{K}) \times F$

Basic principles : hydraulic circuit



To make a fluid circulating you need a pump

A difference of pressure creates a flow

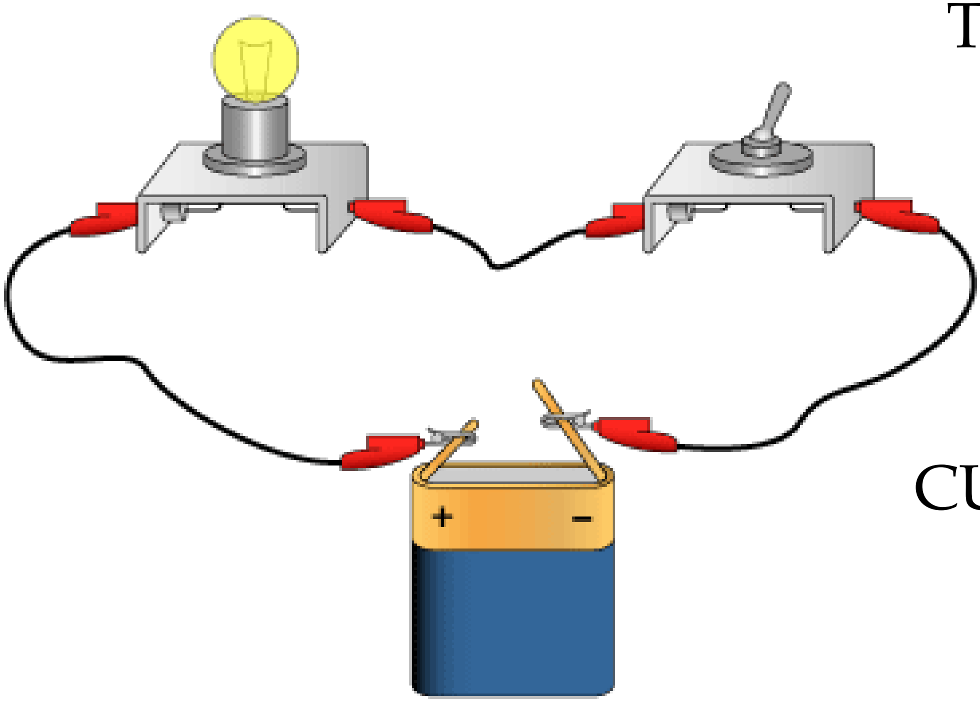
FLOW = speed x section

$Q = v \times A$

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

Little **pressure drop** across the main vessels, most is in tissues/organs

Basic principles : electric circuit



To produce electrical current you need a generator

A difference of voltage creates a current flow

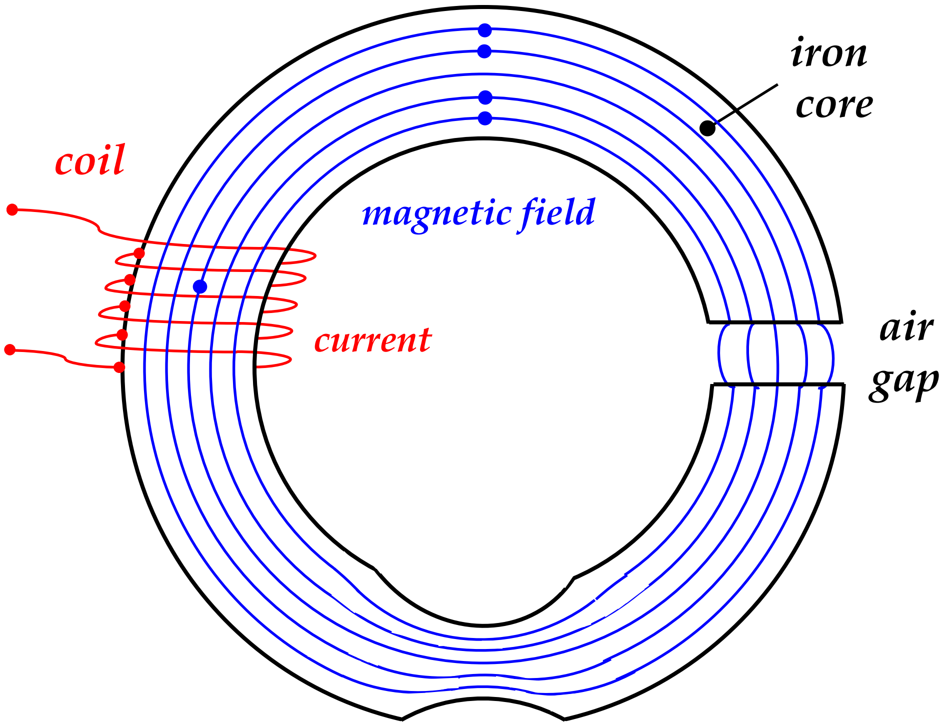
CURRENT = $C_{density}$ x section

$I = J \times A$

$\Delta V = R \times I$

Little **voltage drop** across the wires, most is in the bulb

Basic principles : magnetic circuit

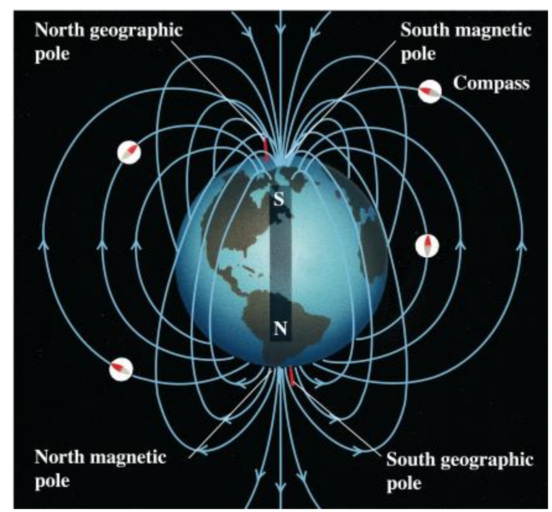


To produce a magnetic field you need a coil

A magnetomotive force creates a magnetic flux

FLUX = field x section

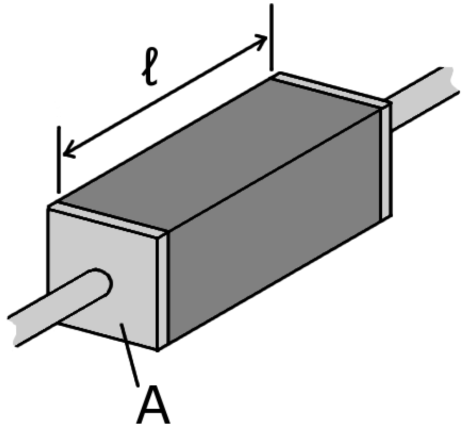
$\Phi = B \times A$



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

Little **magnetomotive force** is used in the iron, most is used in the air gap

Basic principles : constitutive equations



R = length /(electrical conductivity x section)

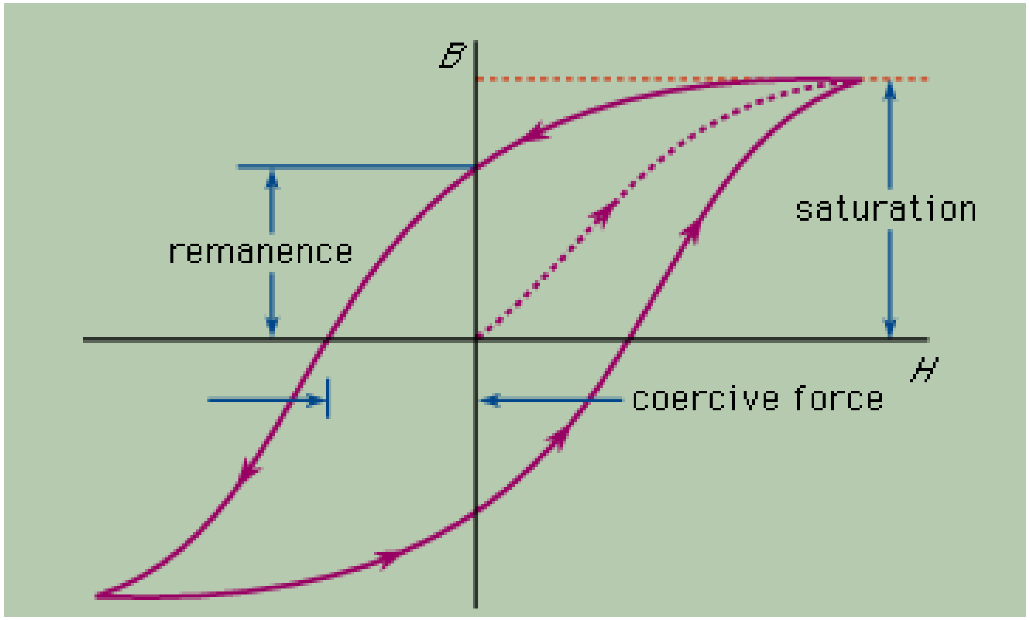
$\mathcal{R}$ = length/ (magnetic permeability x section)

$$R = \rho \frac{l}{A} \qquad \Re = \frac{l}{\mu A}$$

Electrical Magnetic

$$B = \mu_0 \mu_r H$$

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



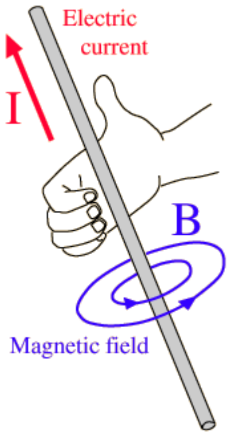
magnetomotive force is in reality "magnetizing work density"

$$NI = \oint H \cdot dl \text{ (Ampère's law)}$$

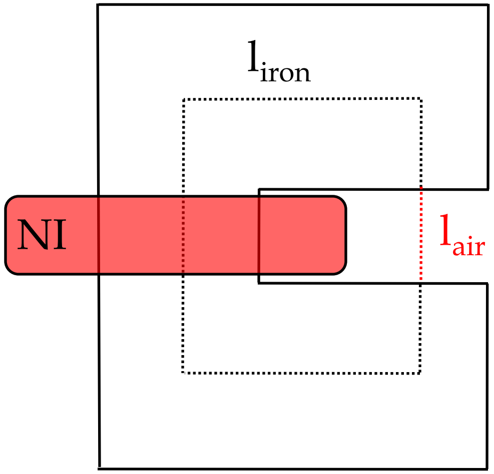
$$\mathcal{R} \times \Phi \text{ (Hopkinson's law)}$$

H can be interpreted as "magnetizing pressure"
In ferromagnetic materials small **H** creates high **B**

Basic principles : magnetic field generation



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



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

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

Basic principles : forces

Work (energy) done by a force is :

$$W = \Delta E = \int \vec{F} \cdot d\vec{s}$$

In case of a uniform magnetic field

$W_m = ½ B·H·V = ½ B·H·S·x$

$F = dW/dx = ½ B·H·S$

in air $H = B/\mu_0$

Magnetic force is then ≈ $B^2 \cdot 4\ kg_f/cm^2$

A key ($2\ cm^2$) in

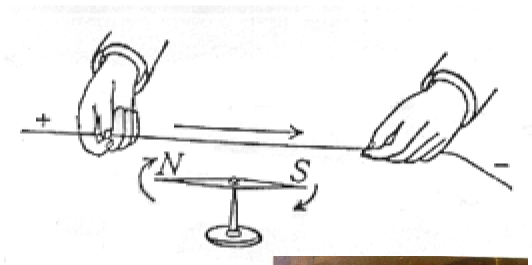
$B = 1T \Rightarrow F = 8\ kg_f$

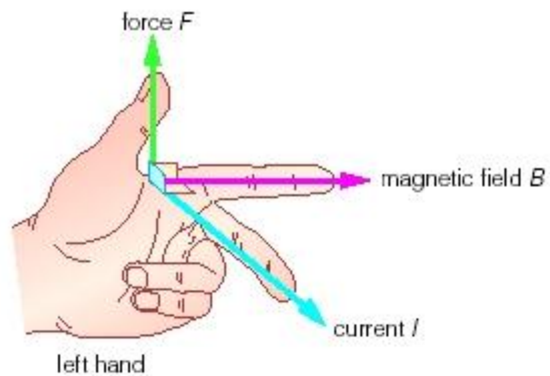
$B = 2T \Rightarrow F = 32\ kg_f$

Basic principles : forces

On a conductor immerged in magnetic field

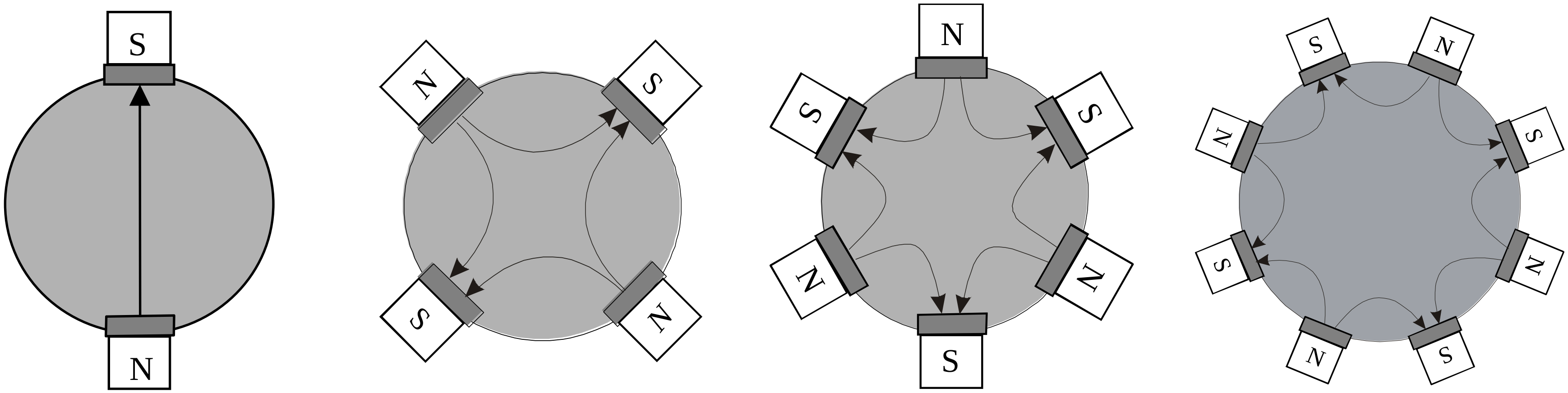
$$\mathbf{F} = \mathrm{I}\cdot\mathbf{L}\times\mathbf{B}$$



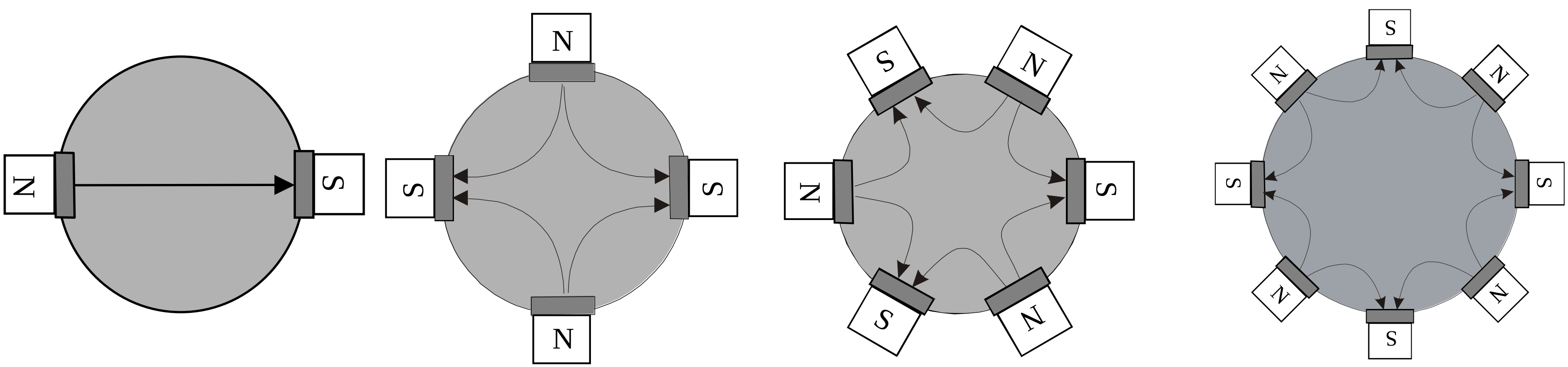


For example if a coil of 3 m length with NI= 50 000 A is immersed in a perpendicular field of B= 0.5 T

$$F= 50000\cdot 3\cdot 0.5 = 75000\ \mathrm{N} = 7.5\ \mathrm{tons_f}$$



NORMAL : vertical field on mid-plane



SKEW : horizontal field on mid-plane

Magnet types : operation

Operation can be in steady state (DC), cycled, pulsed

A varying magnetic field produces a voltage difference (Faraday law)
This effect acts against the variation (Lenz law)

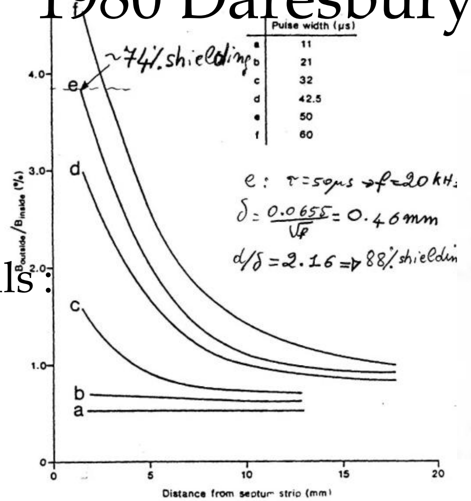
$$V = -\, \partial\Phi / \partial t$$

Currents are generated in electrical conducting materials :

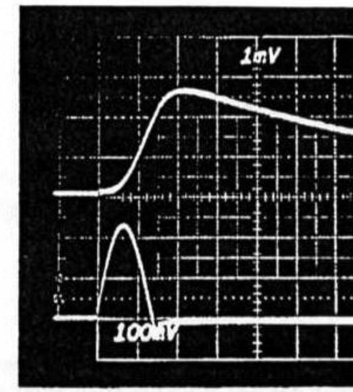
- opposing to the penetration of the magnetic field
- producing losses

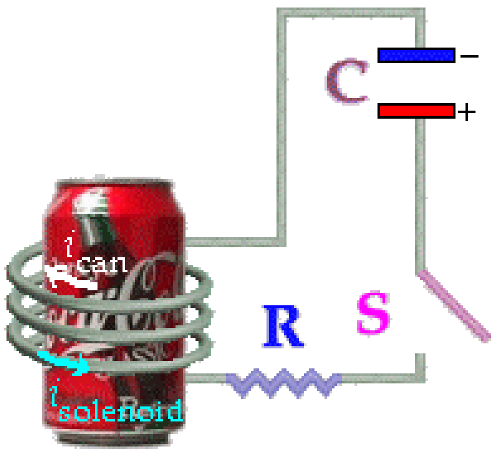
$$\delta = (\pi\mu\sigma f)^{-1/2}$$

1980 Daresbury

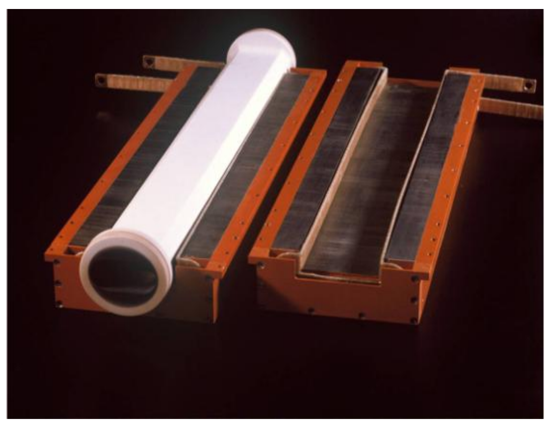


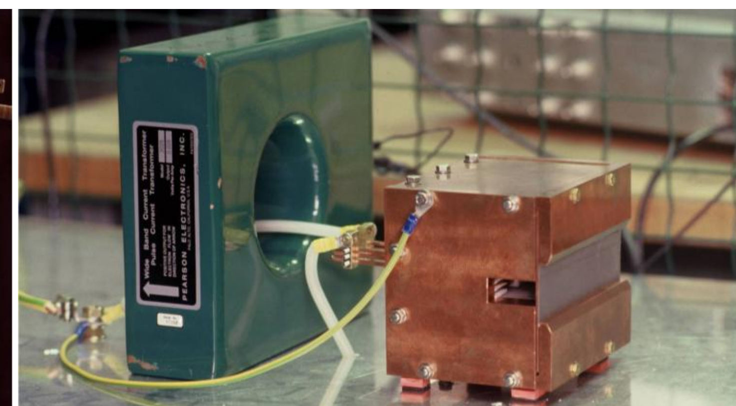
1990 ESRF





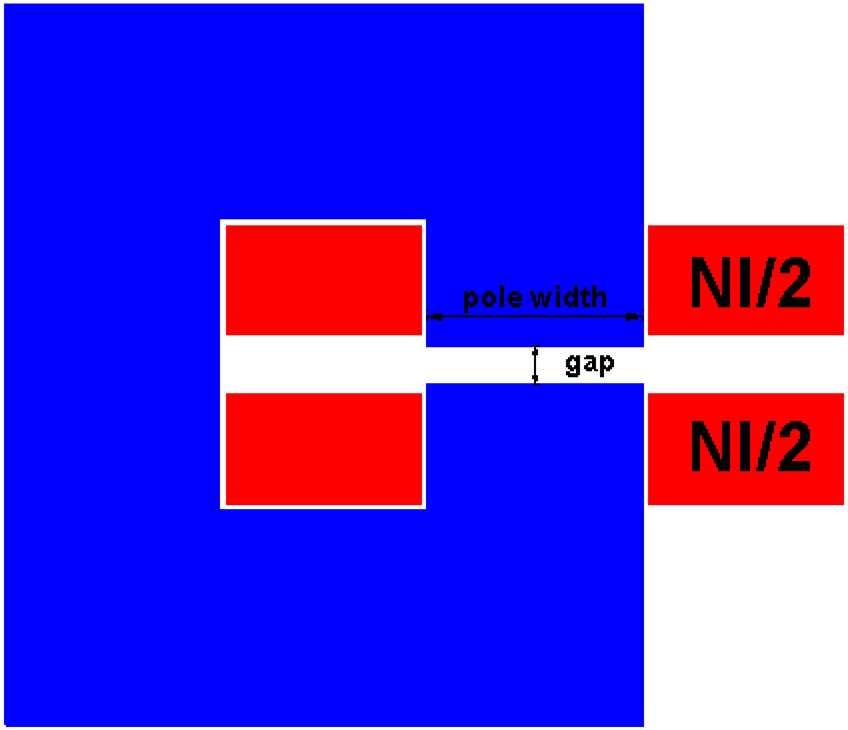
1990 ELETTRA





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

Elementary design : a C-dipole

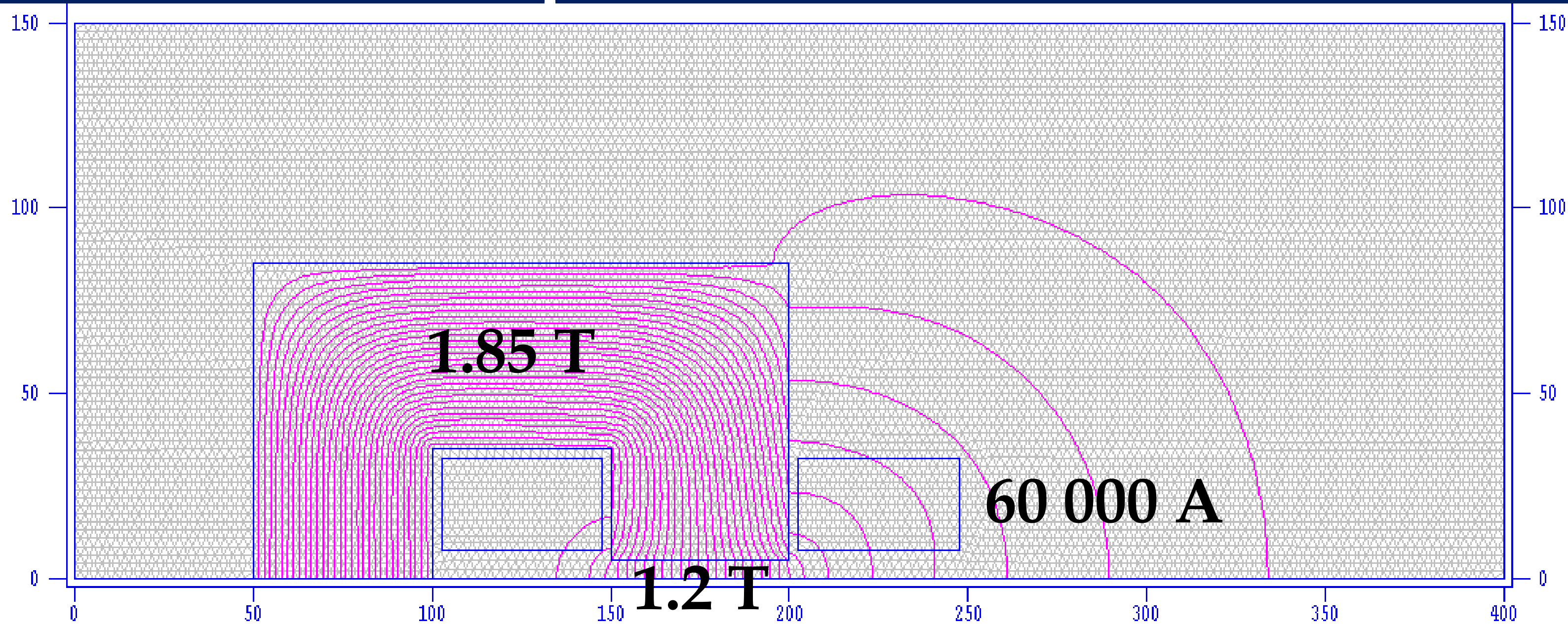


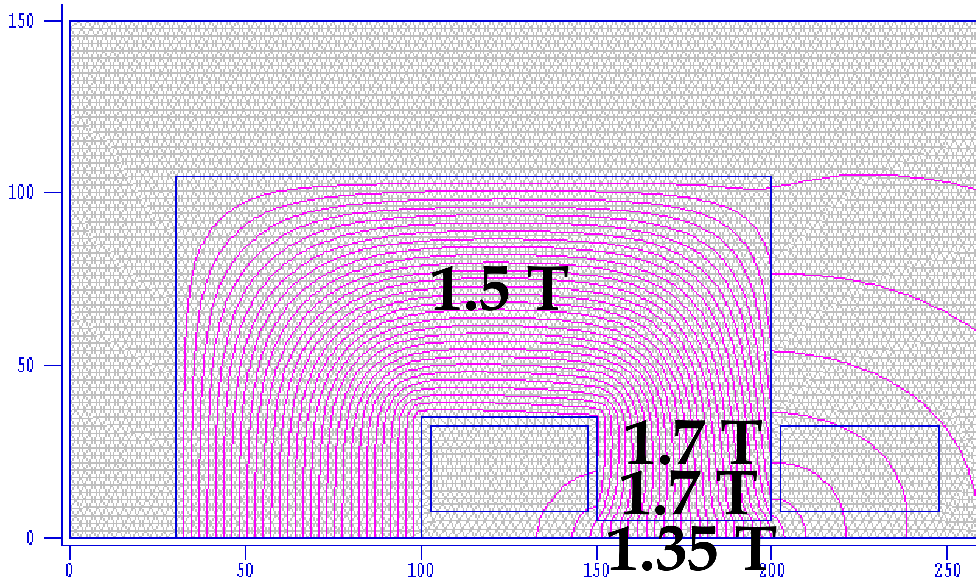
tentative pole width ~ good field region + 2.5•gap

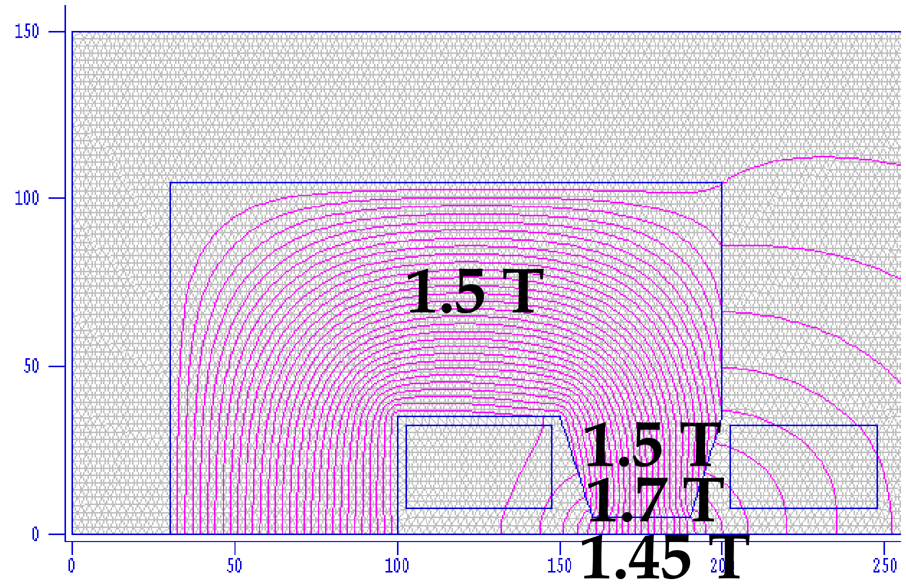
Considering the reluctance of iron negligible with respect to that of air, NI = $\mathcal{R}$ xΦ = [gap/(μ_0xA)]x(BxA)=gap·B/μ_0

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

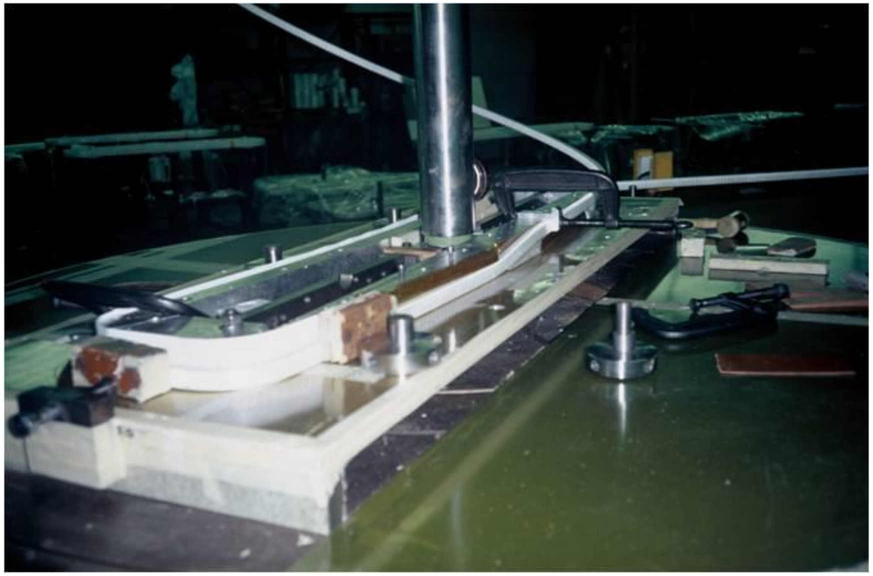
The C-dipole: saturation of iron

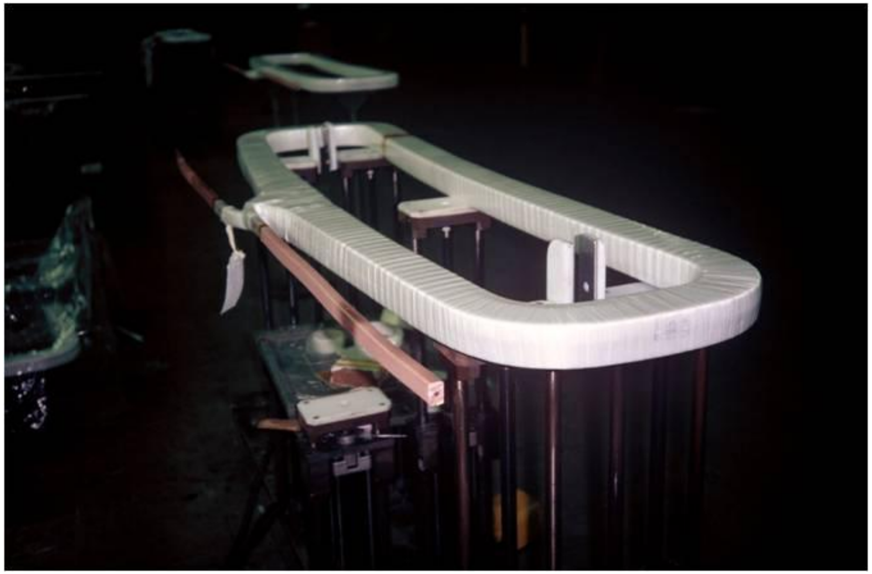




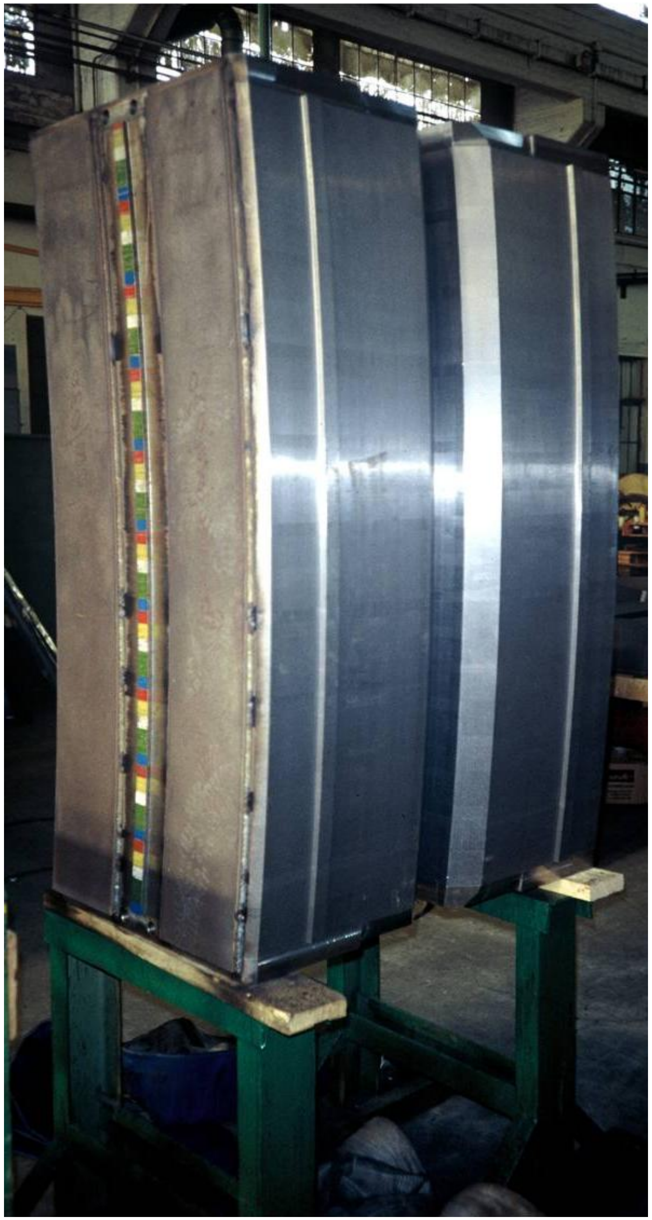


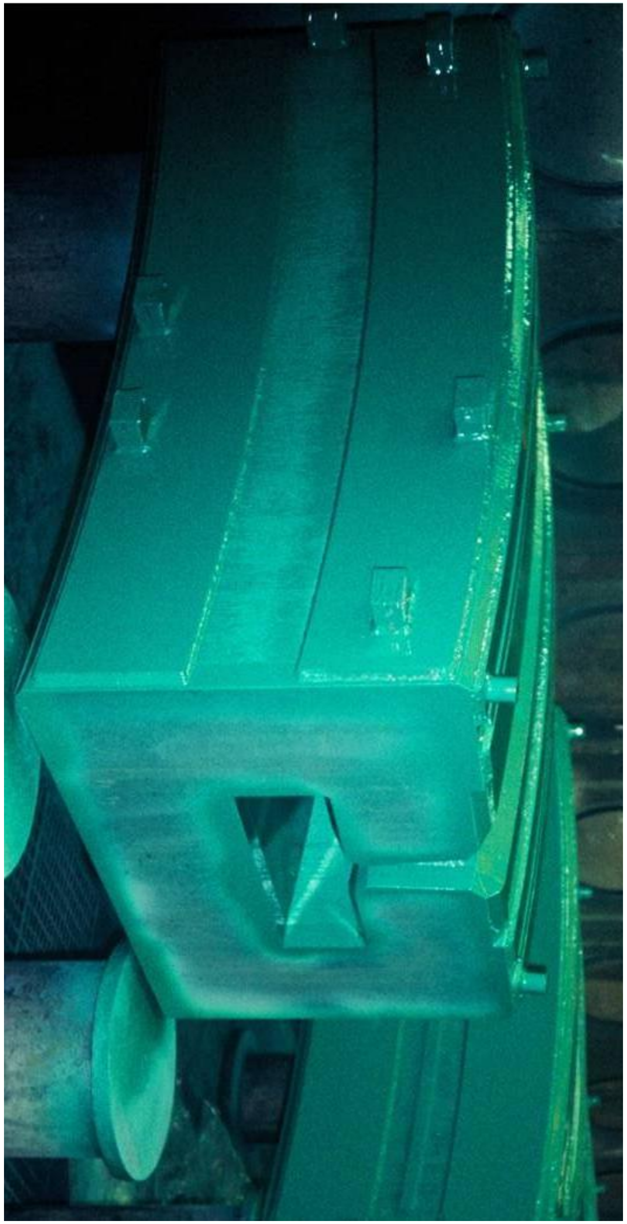
Manufacture : coils



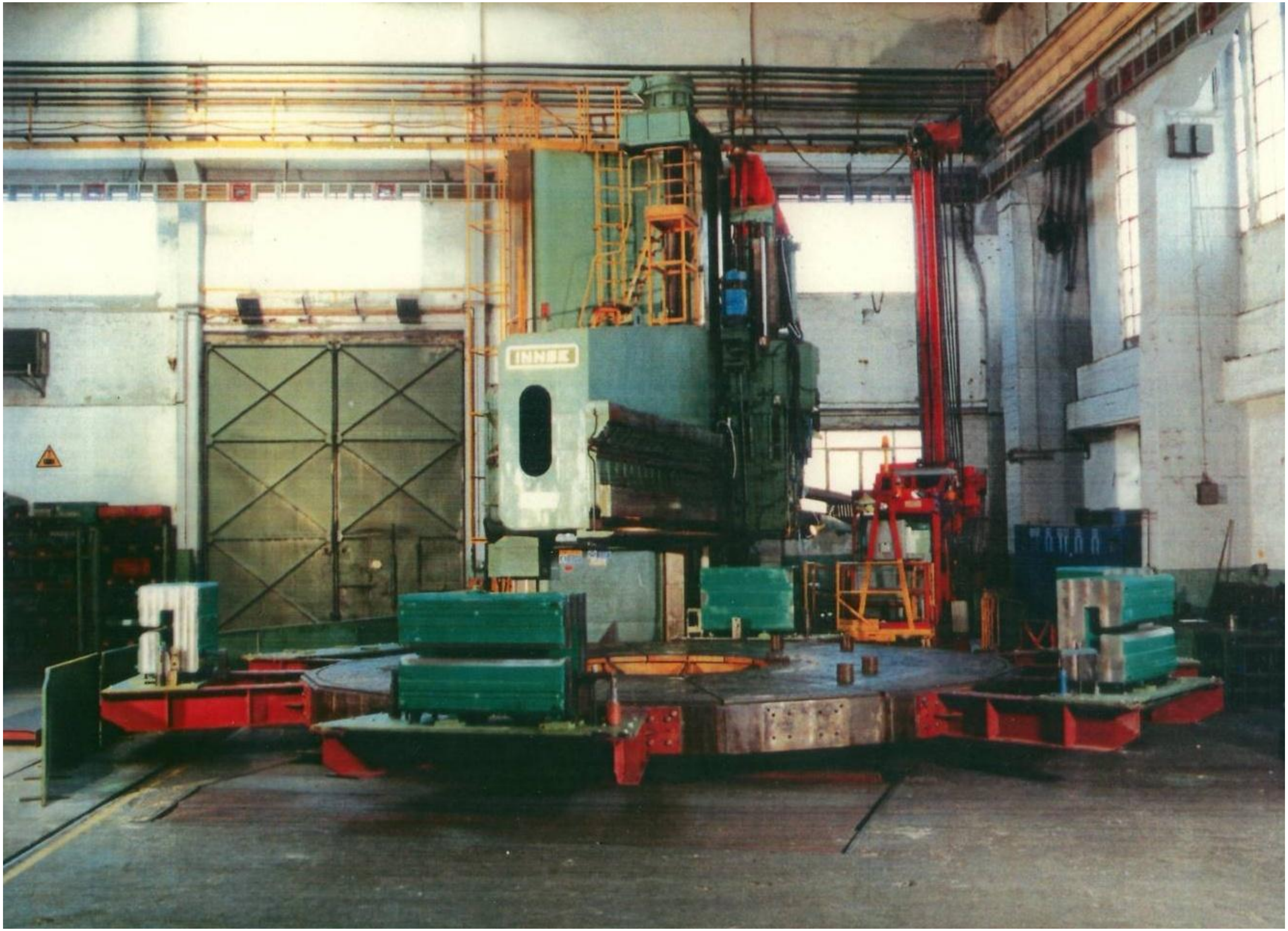


Manufacture : yoke

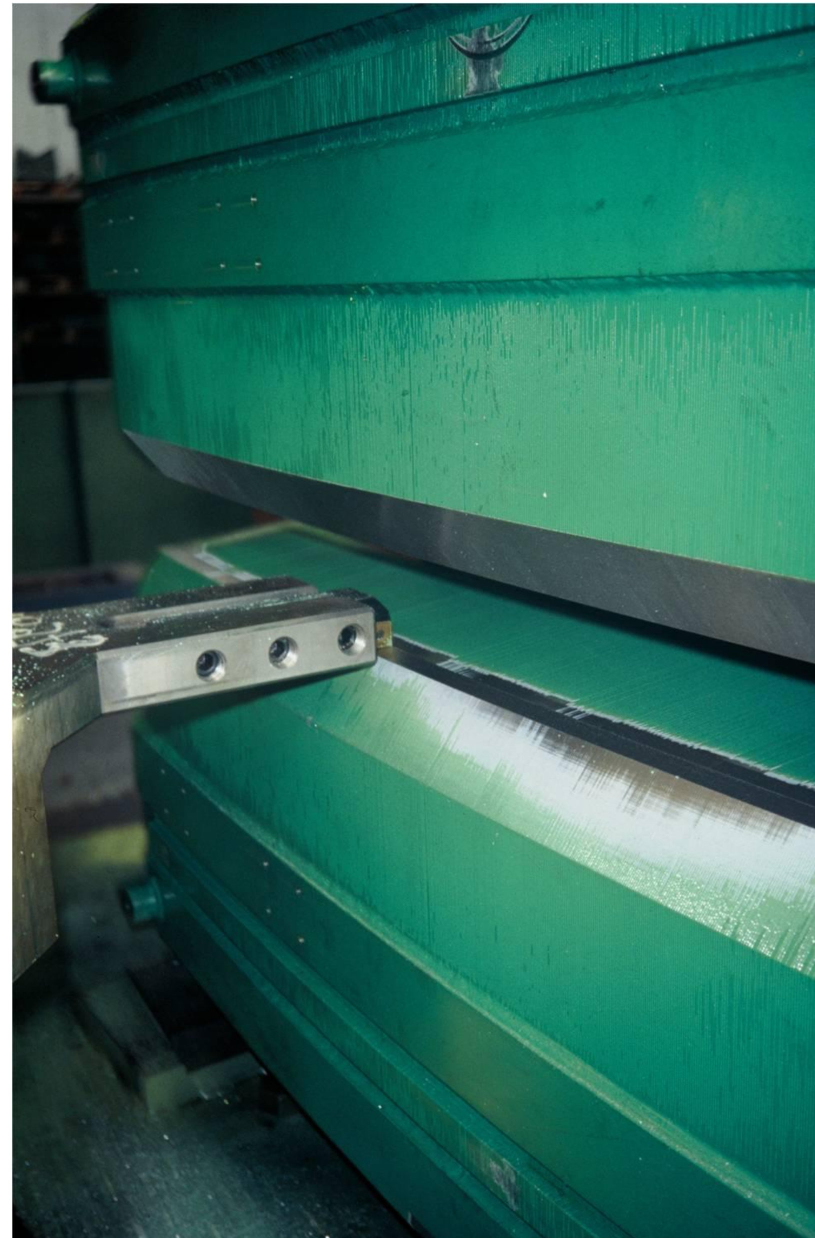




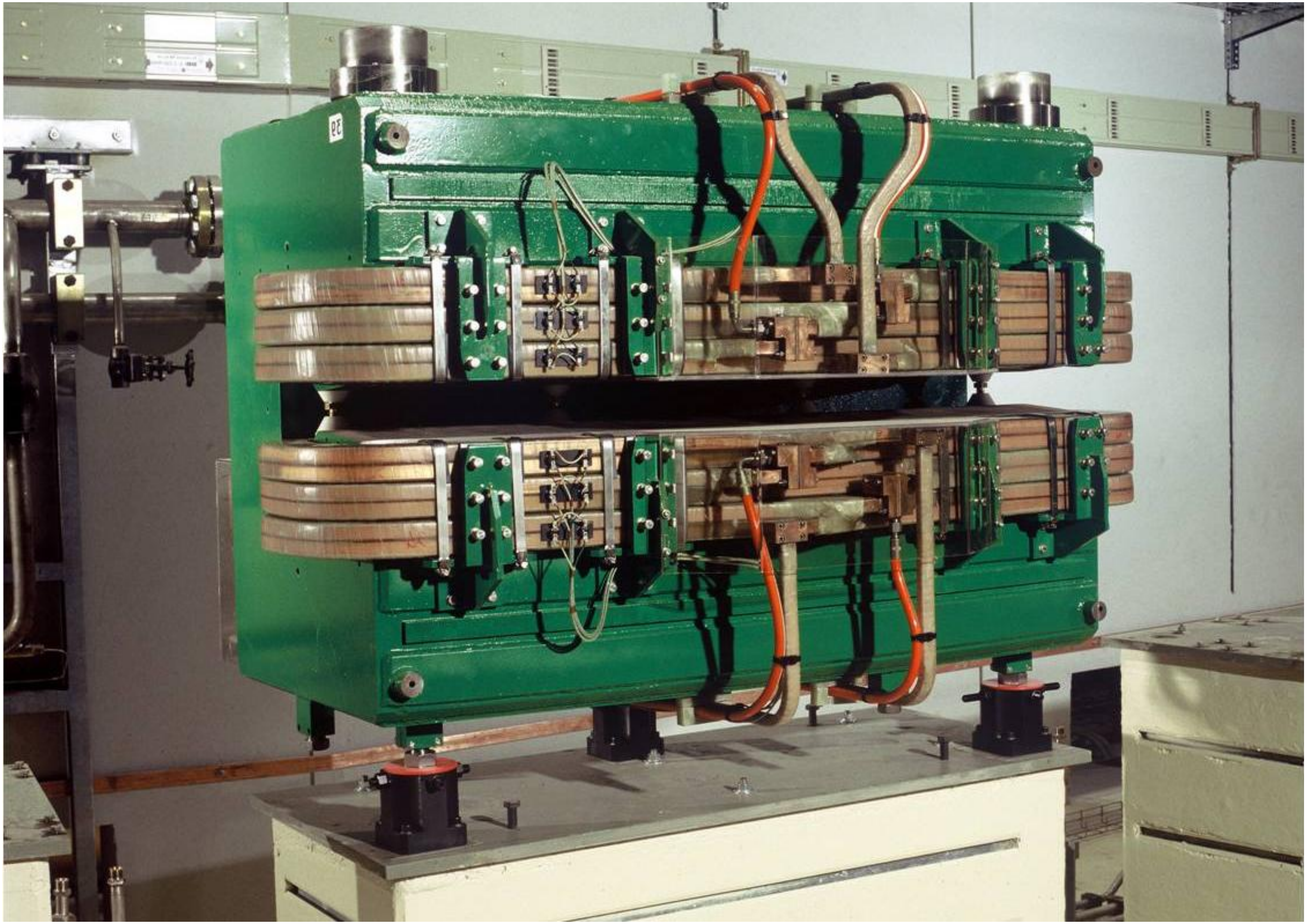
Manufacture : yoke



Manufacture : yoke



Manufacture : yoke



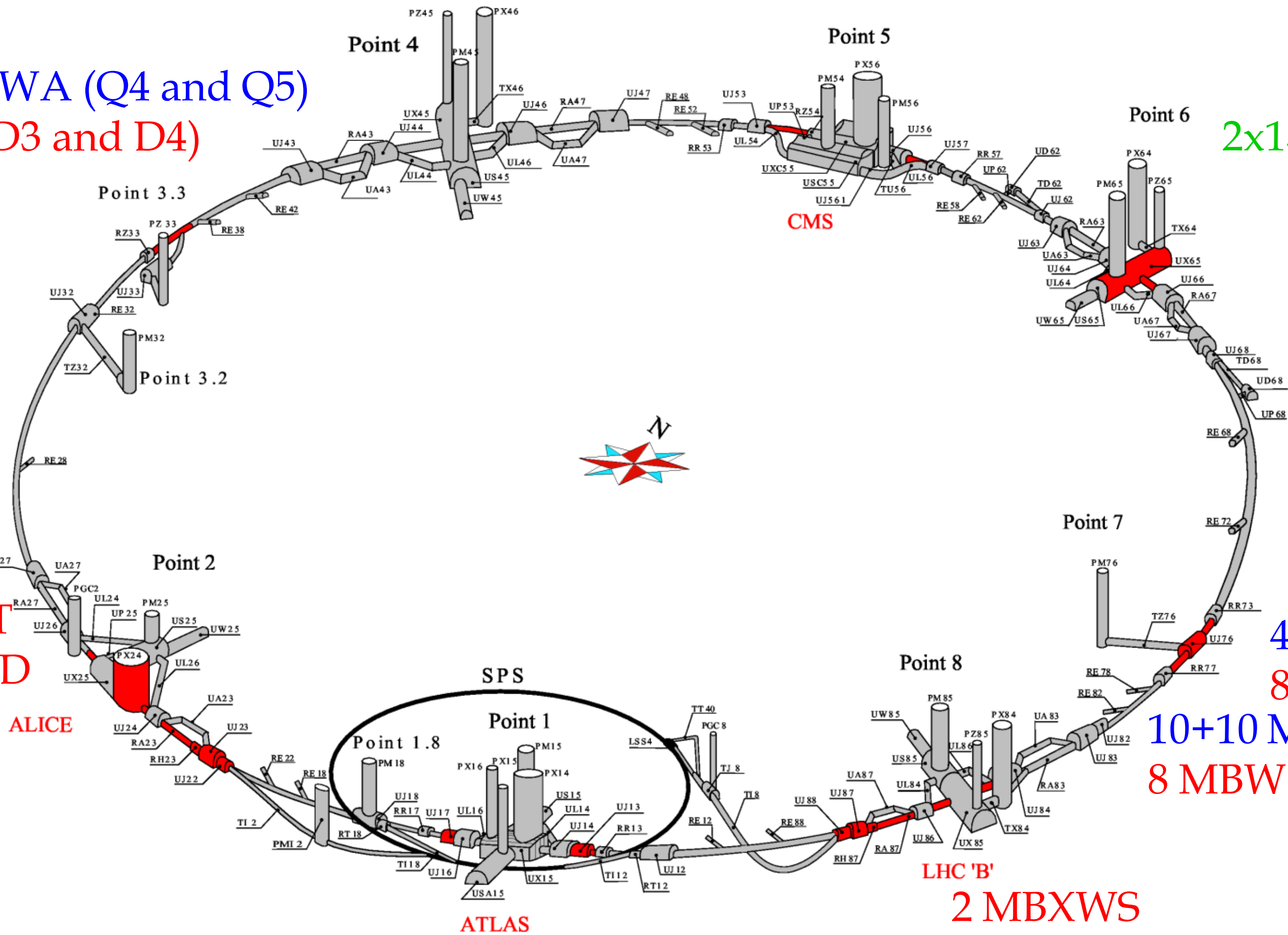
Normal Conducting LHC Magnets

12 MBXW (D1)

10+10 MQWA (Q4 and Q5)
12 MBW (D3 and D4)

4 MQWB
8 MCBW

2x15 MSD



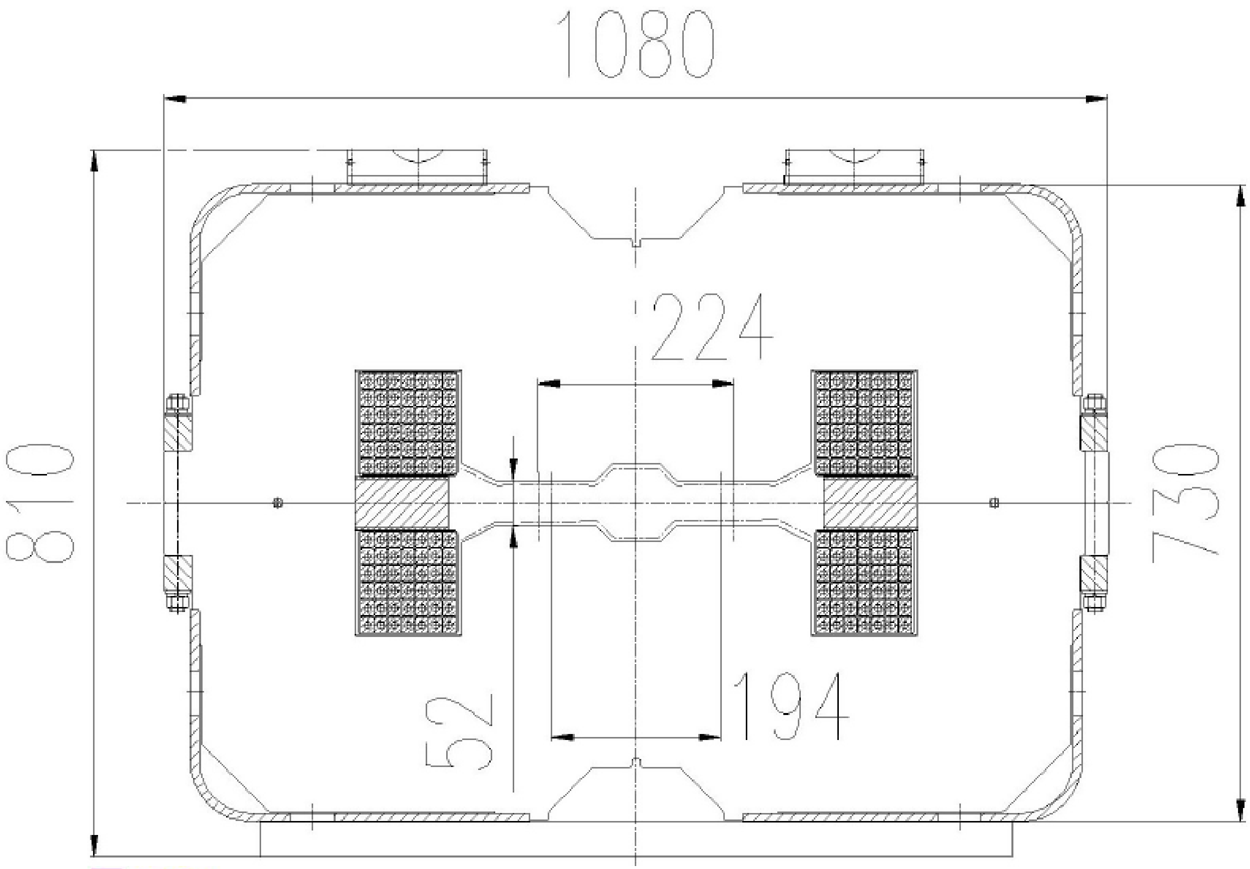
2 MBXWT
1 MBWMD
5 MSI

4 MQWB
8 MCBW
10+10 MQWA (Q4, Q5)
8 MBW (D3, D4)

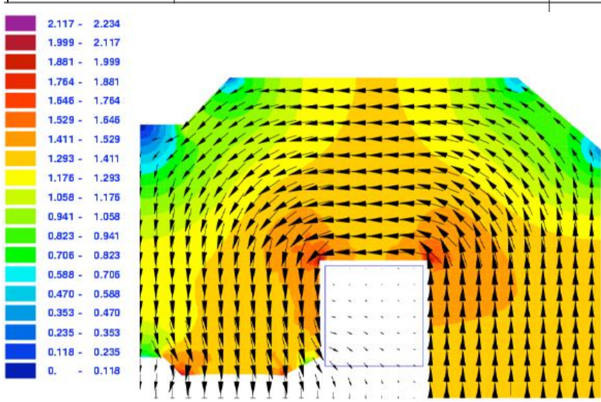
12 MBXW (D1)

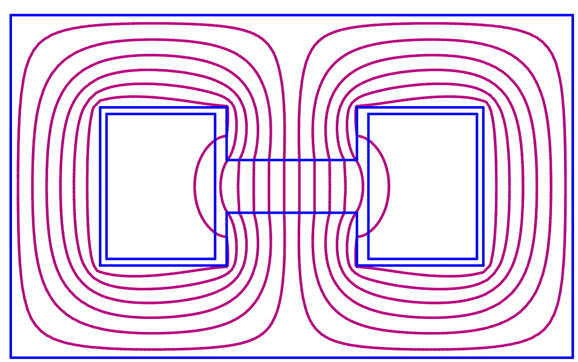
2 MBXWS
1 MBXWH
5 MSI

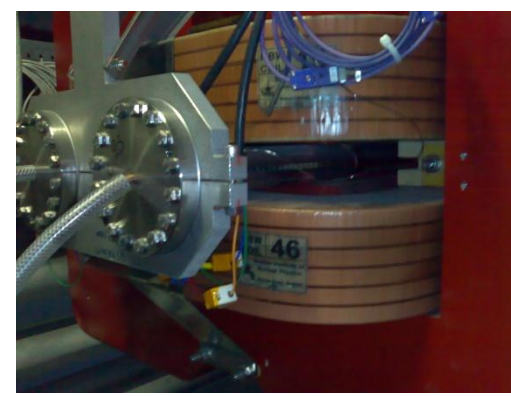
MBW in the LHC : H-type dipole / 1



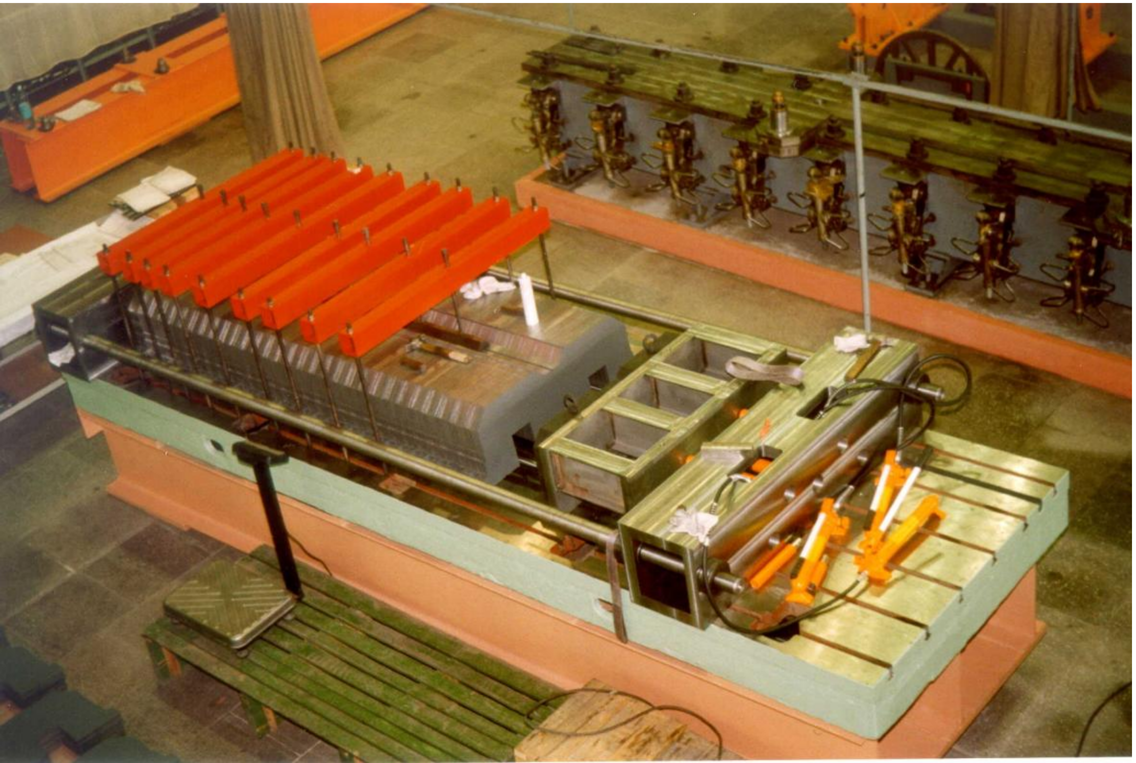
Parameter	Value
Aperture	52 mm
Nominal field	1.42 T
Magnetic length	3.4 m
Weight	18 t
Water flow	19 l/min
Power	29 kW

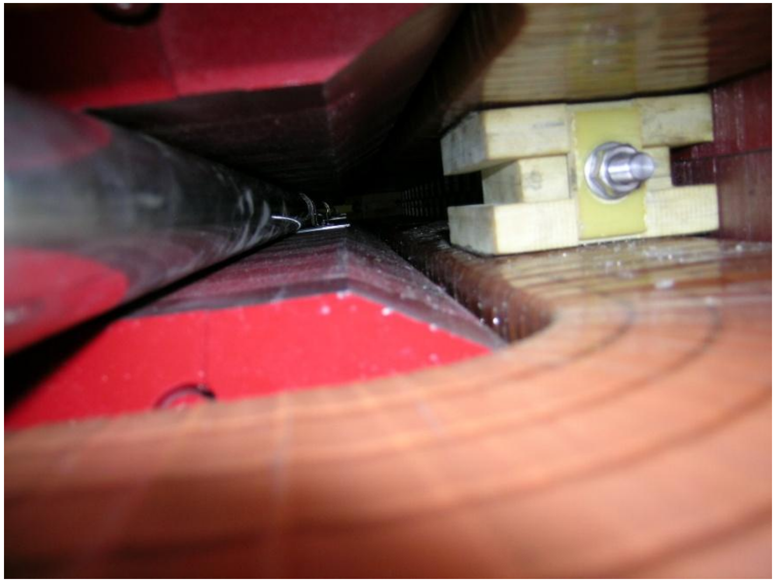


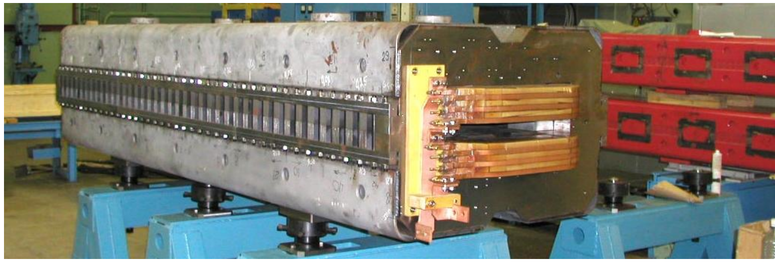




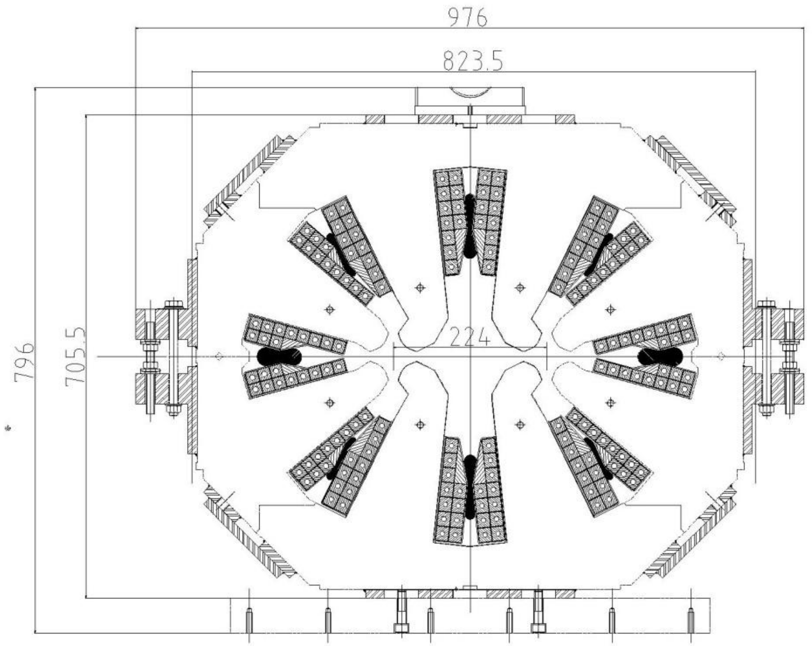
MBW in the LHC : H-type dipole / 2

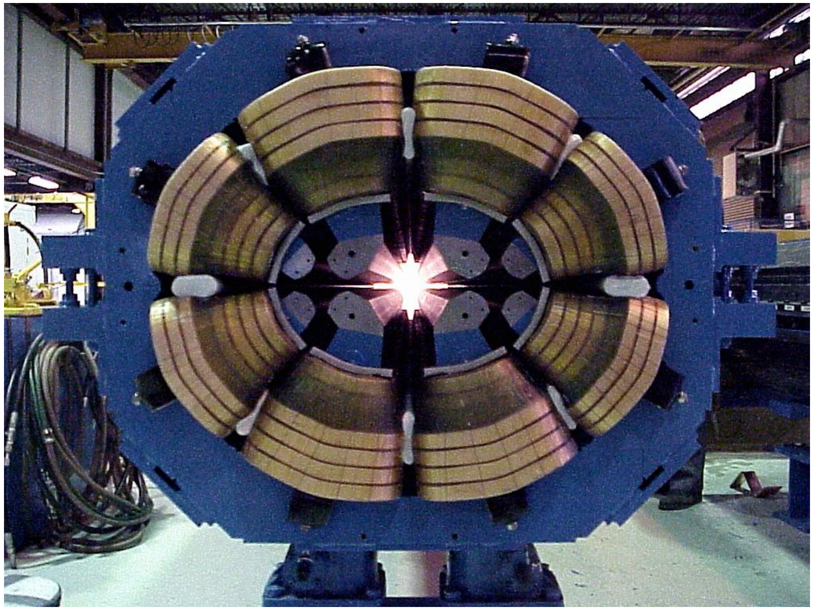


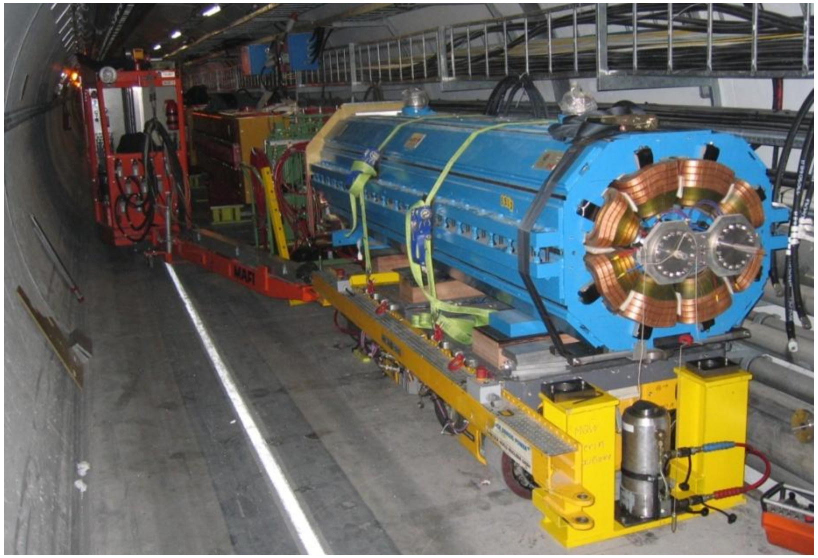




MQW Magnets



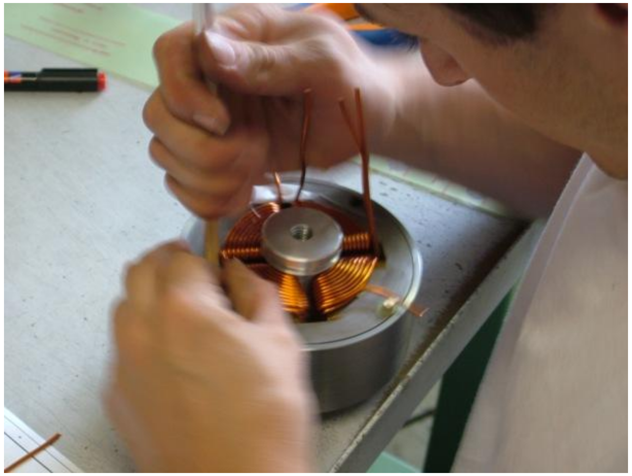




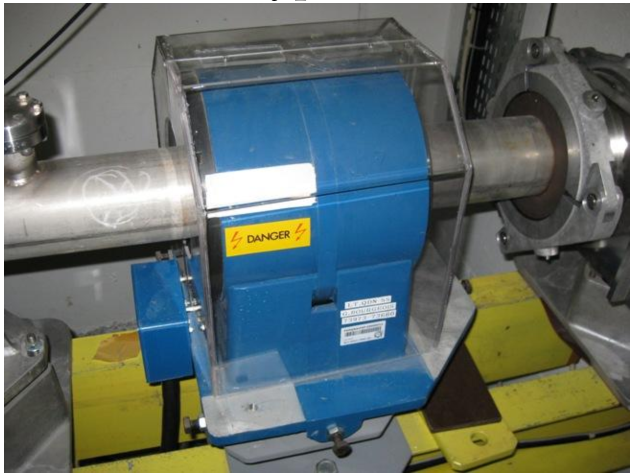
LINAC-2 Quadrupoles

Type III

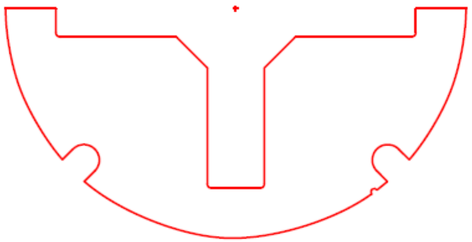
Type III - Assembly



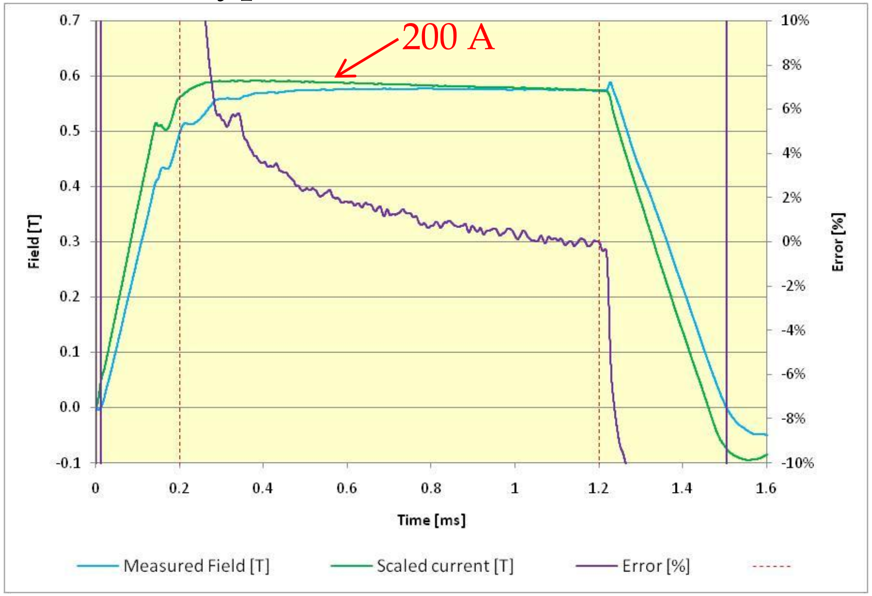
Type VII



Quadrupole Lamination



Type III – Field Measurement

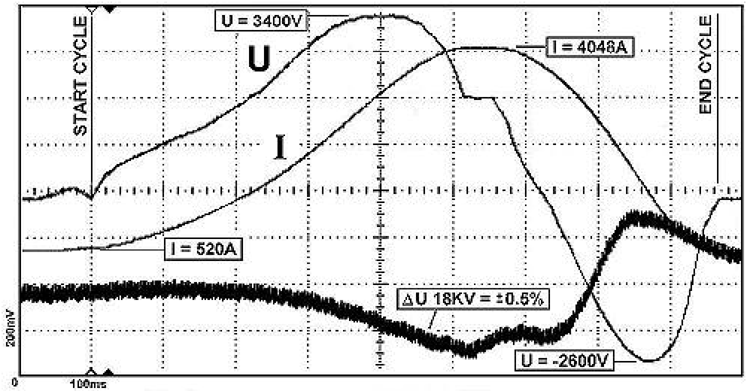


Types - I to X
Core O.D. - 113 to 245 mm
Core Length - 25 to 203 mm
Aperture Diameter - 22 to 103 mm

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

PS Booster Dipoles

1.4 GeV Magnet Cycle



Spare Booster Dipole

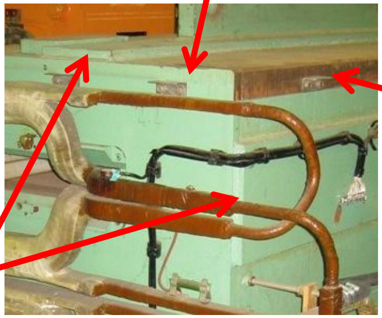
Installed Booster Dipole

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

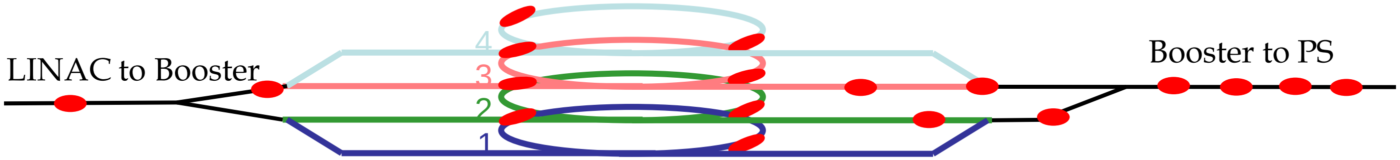
BDL correction Windings compensate the 1% difference between the inner and outer rings.



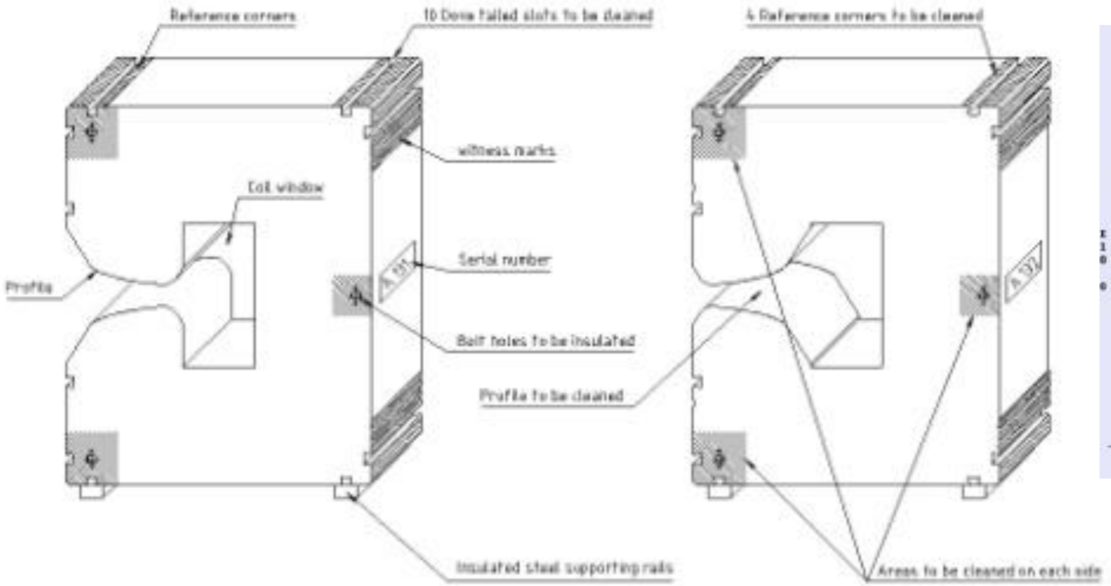
Laminations

Welded tie Bars

Booster Ring



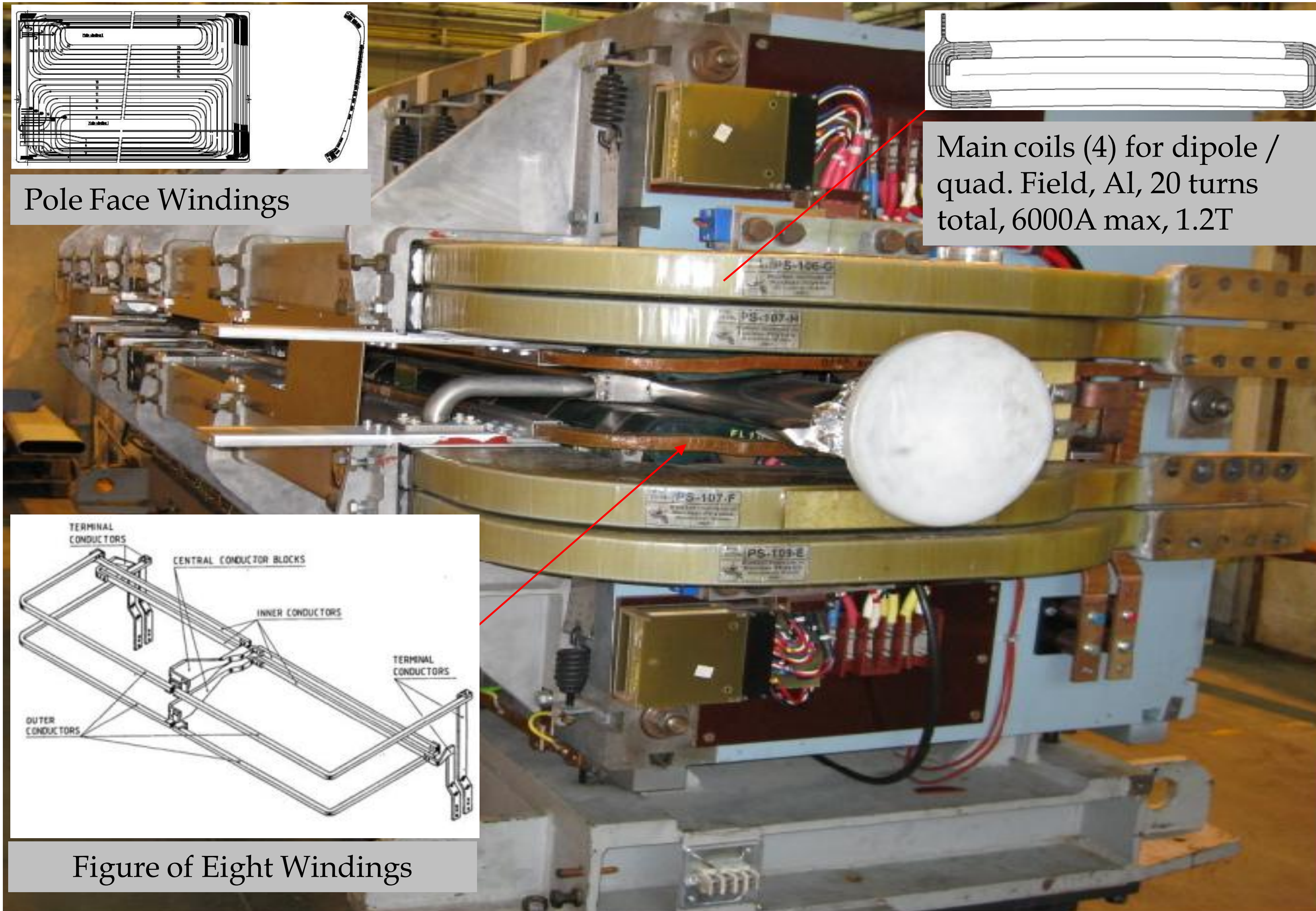
Main units PS, combined function



Typical "TSTLHC" cycle for LHC

1.256T, 900 ms, 25.08 GeV

Combined function dipole / quadrupole, PS machine



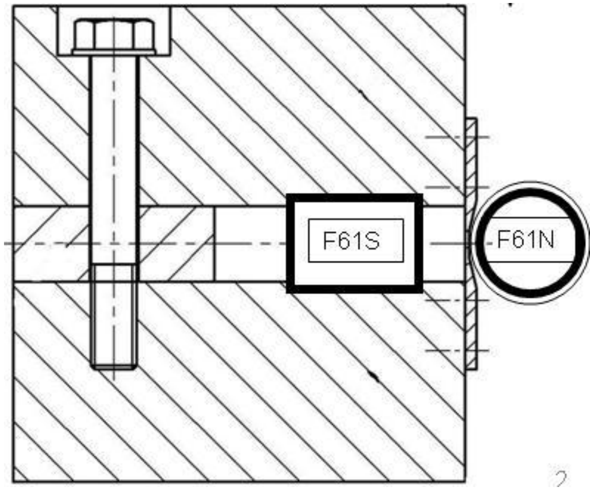
Pole Face Windings

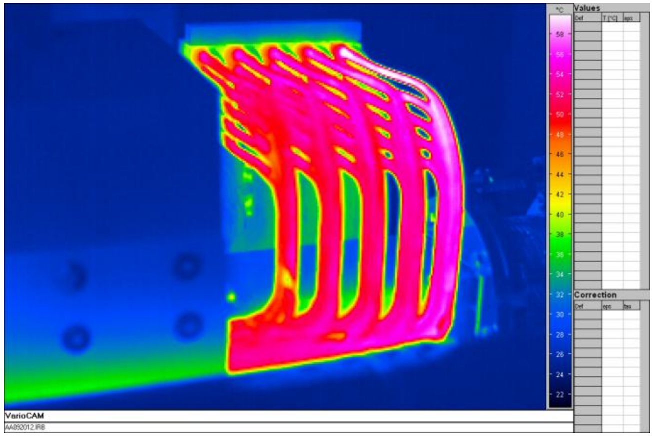
Main coils (4) for dipole / quad. Field, Al, 20 turns total, 6000A max, 1.2T

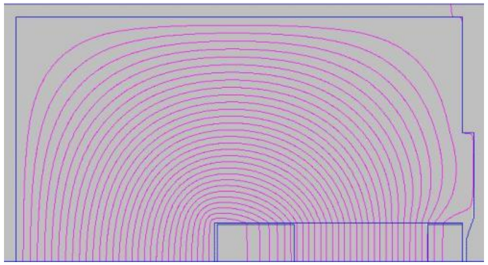
Figure of Eight Windings

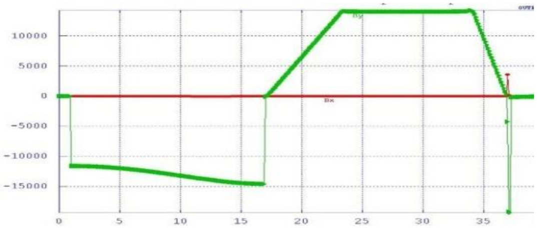
Massive yoke, DC operated, 1.4 T in the gap, ferromagnetic chamber with μ-metal shield around the north beam

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



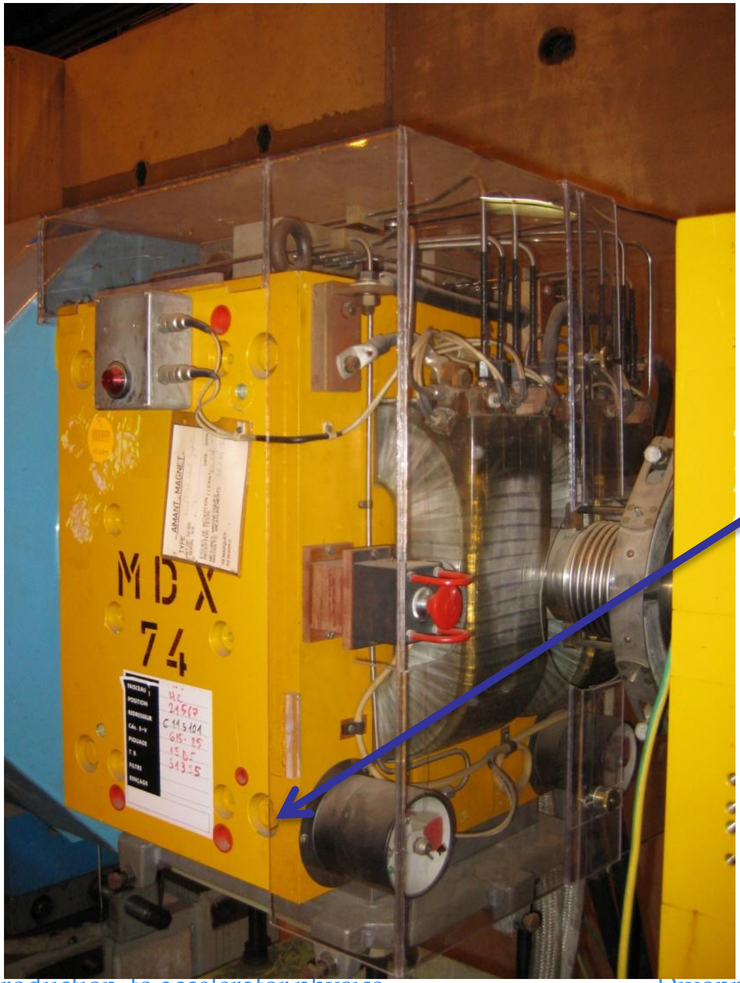






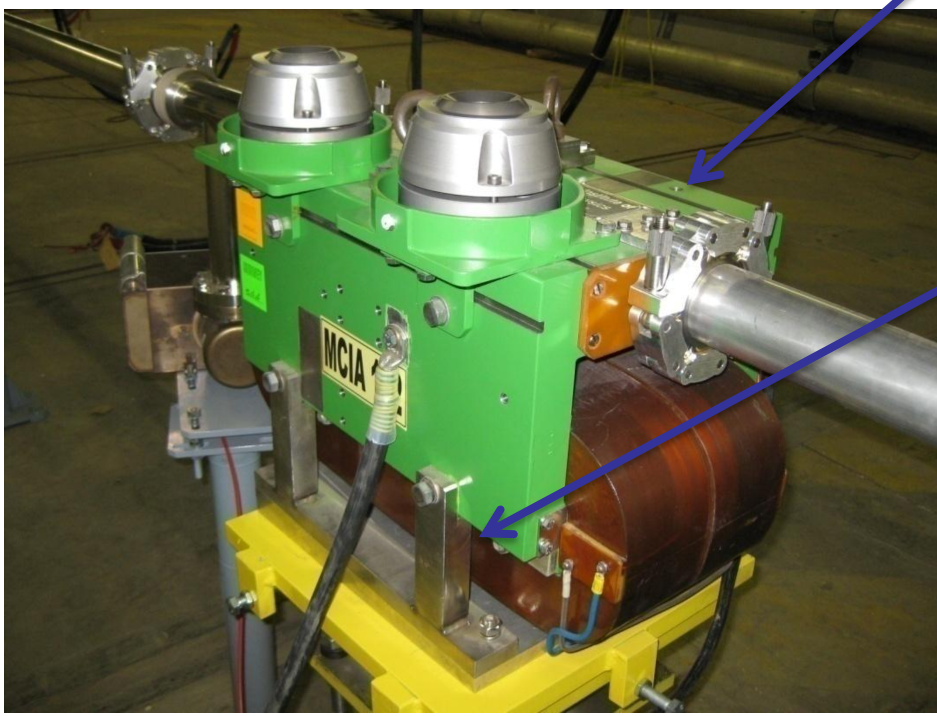
Corrector dipole North Experimental area

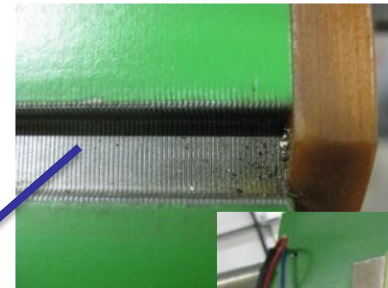
Magnet with solid yoke parts assembled with bolts.



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

Magnet with glued laminated yokes assembled with bolts.

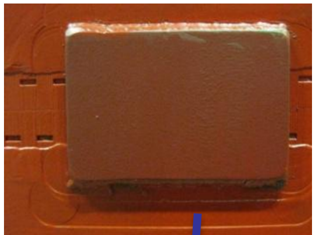


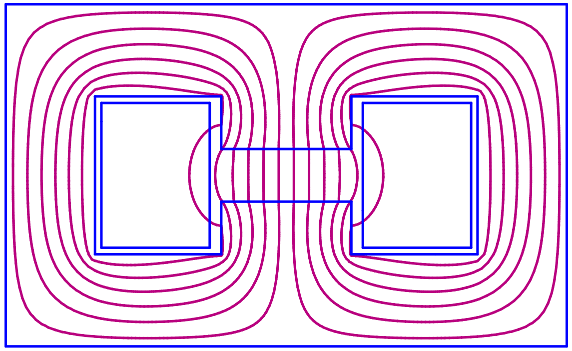


Main parameters	
Name	MCIA V
Type	Vertical correcting dipole
Nominal peak field [T]	0.26
I_{max} [A]	3.5
N. Of turns	1014
Résistance [Ω]	13.9
Yoke lenght [mm]	450
Gap [mm]	32.5
Total weight [kg]	300

Main dipole in the SPS

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

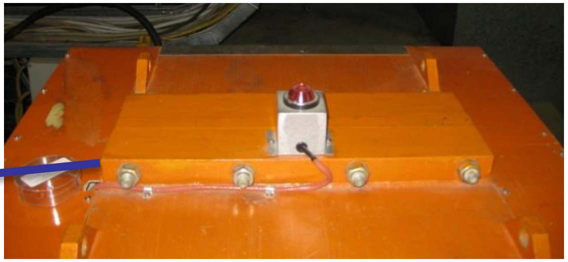




Main parameters	
Name	MBB
Type	Bending dipole
Nominal peak field [T]	1.8
I_{max} [A]	4900
N. Of turns	16
Résistance [Ω]	4.46 . 10^{-3}
Inductance [H]	0.018
Yoke lenght [mm]	2225
Gap [mm]	52
Total weight [kg]	17400

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

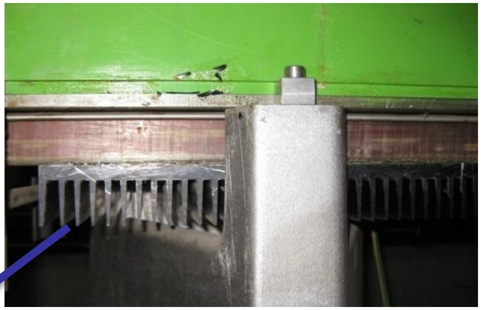
Corrector dipole for BBLR experiment in SPS

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

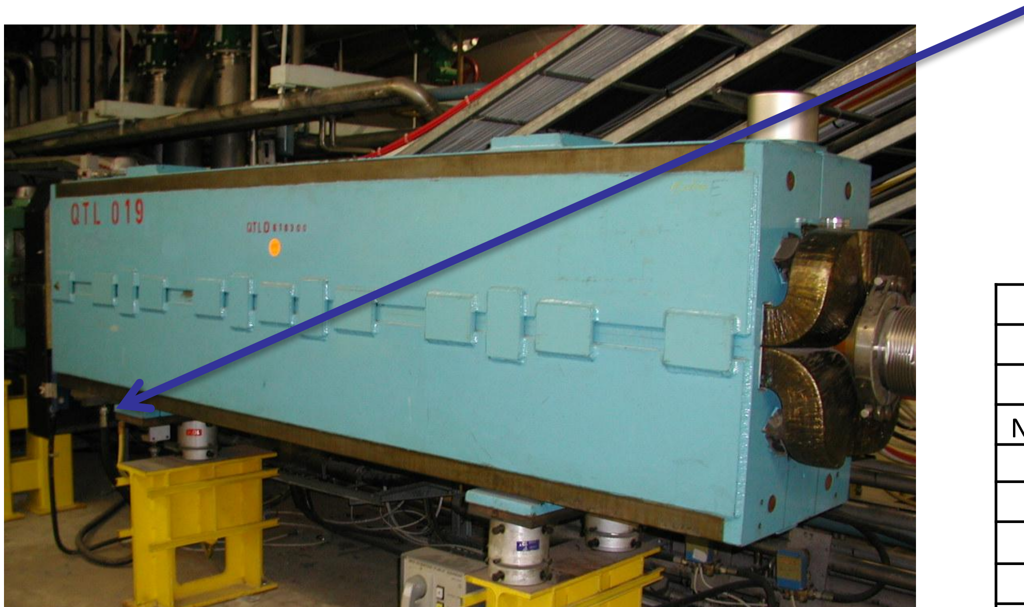
Air-cooled magnet



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

Water-cooled magnet with insulators

Moulded insulating distributor

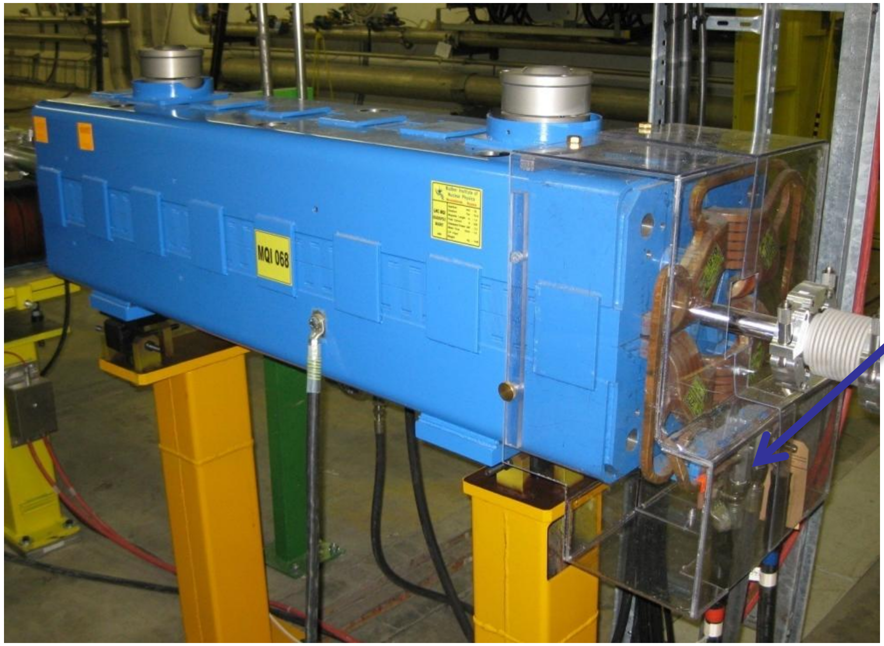


Separated insulators

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

Quadrupole of TI2 injeciton line to the LHC

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
Power	750 kW

Recommended reading