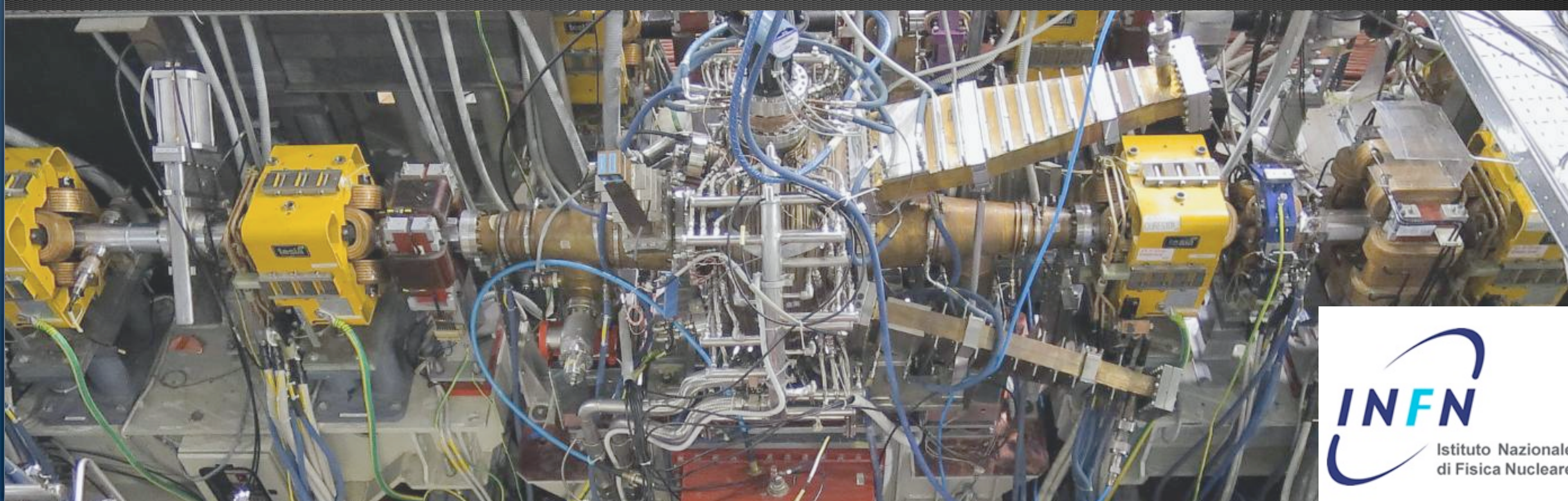
Accelerator Laboratory

Magnets in Particle Accelerators



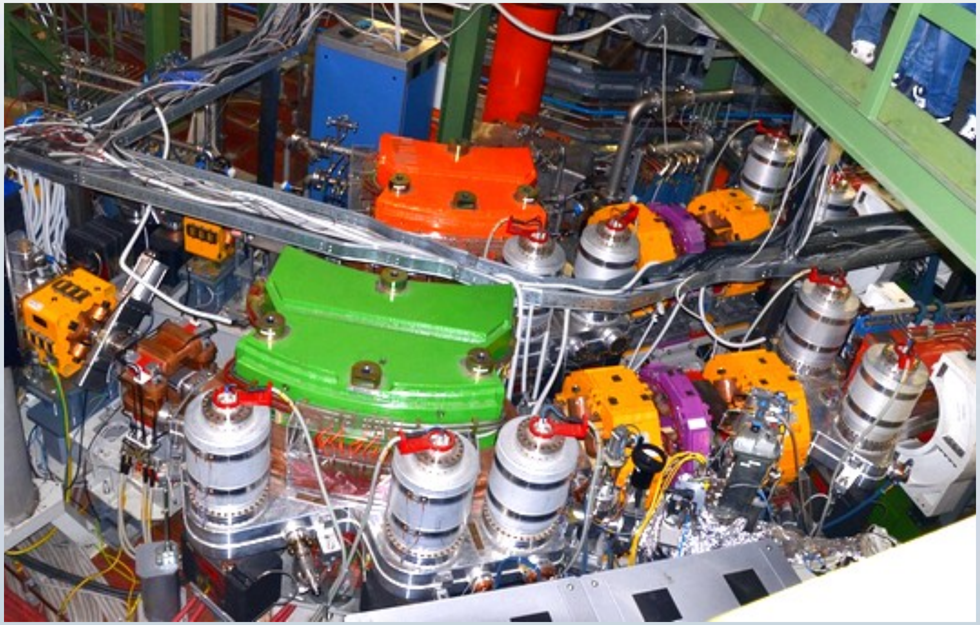
INFN
Istituto Nazionale
di Fisica Nucleare

Magnets in Accelerators:

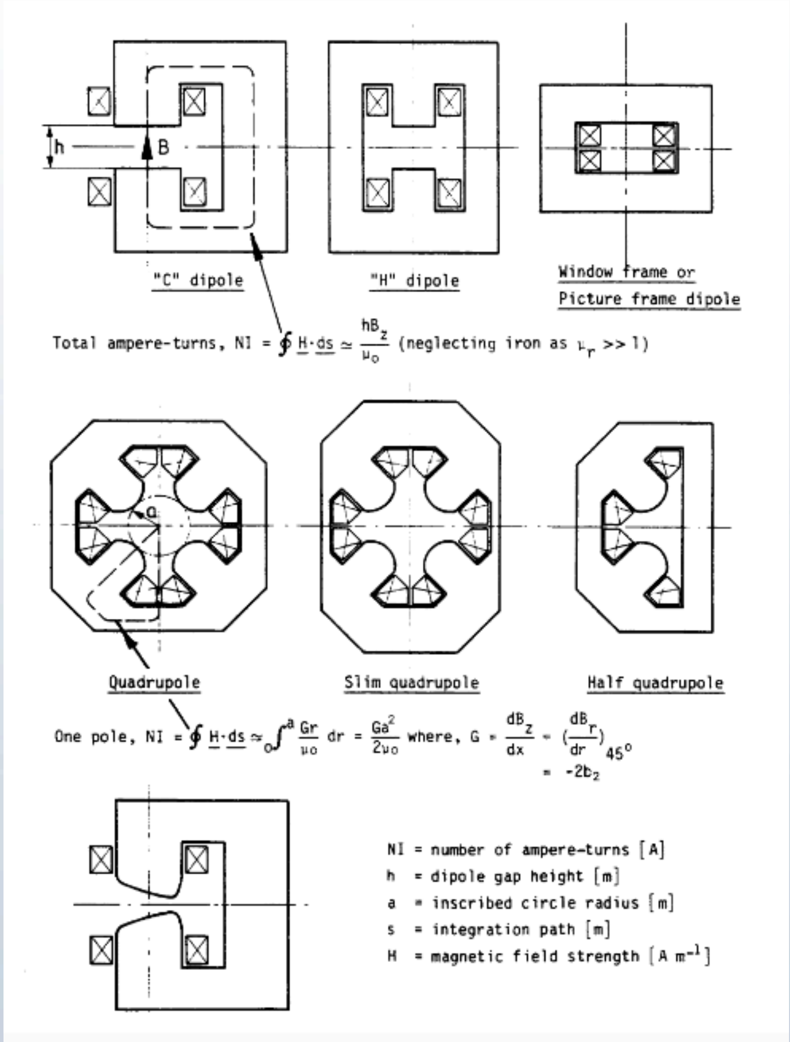
- ✓ Electromagnets
  - ○ Normal Conducting
    - ○ D.C.
    - ○ A.C.
  - ○ Superconducting
- ✓ Permanent Magnets

Accelerator's Magnets

- Dipoles
- Quadrupoles
- Sextupoles
- Octupoles
- Wigglers
- Solenoids
- Combined-function, etc.



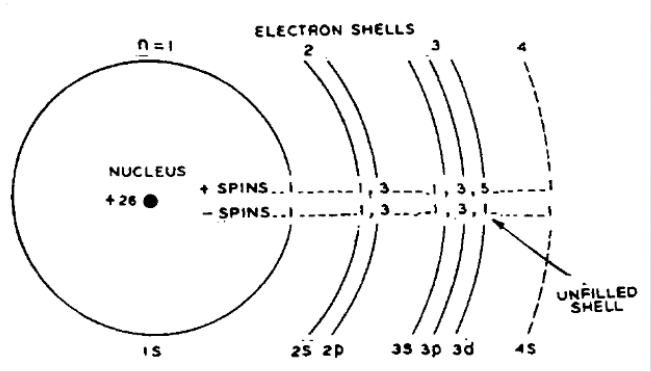
Magnets in Accelerators:



Materials for electromagnets: Ferromagnetism

Ferromagnetism is the property of some materials that exhibit a spontaneous magnetization.

It is mostly due to a strange behavior of electrons.



Iron, Cobalt, Nickel (Z = 26, 27, 28) are ferromagnetic elements, together with some of their alloys and some compounds of rare-earth metals.

The effect is a function of T and disappears when the material is heated over the *Curie Temperature*, which depends on the material.

Materials for electromagnets: Ferromagnetism

High-purity iron (impurities < few 100 ppm) such as ARMCO *(American Rolling Mill Company)* iron is the most used magnetic steel for yokes, which can be either massive or laminated.

Solid yokes support eddy currents hence cannot be cycled rapidly. Moreover, laminated steel assure better reproducible steel quality.

Laminated steel is generally cheaper than solid steel but require more tooling for the production.

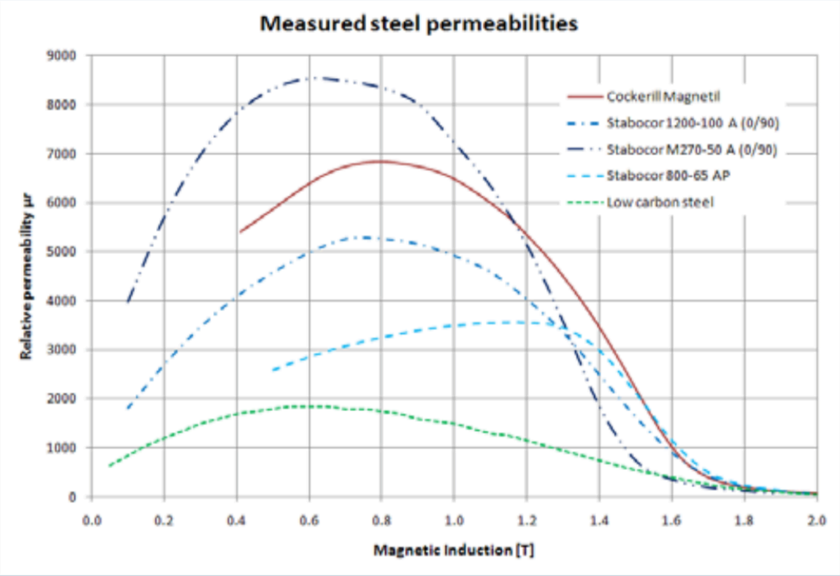
Typical sheet thickness is in the range 0.3 – 1.5 mm, the filling factor being around 97%.

Materials for electromagnets: Ferromagnetism

Magnetic steel is the most used material for yokes, which can be massive or laminated (solid yokes support eddy currents hence cannot be cycled rapidly).

Inside a ferromagnetic material the *permeability* is a function of the magnetic induction B:

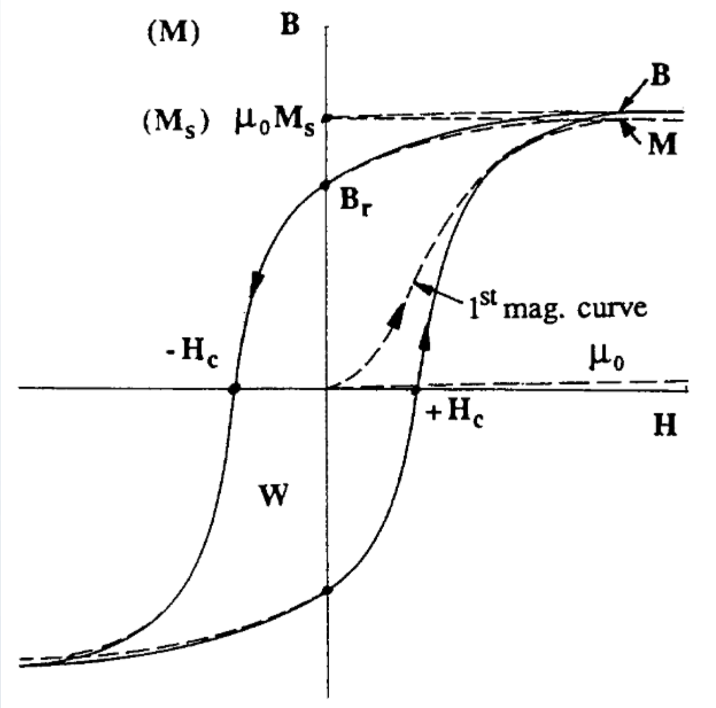
$B = \mu(B)\, H = \mu_r(B)\, \mu_0\, H$



Materials for electromagnets: Ferromagnetism

The hysteresis loop

(B_r = residual induction, H_c = coercive force)



Materials for electromagnets: Conductors

Common materials used for the coil fabrication are basically OFHC Copper and Aluminum (NbTi and Nb_3Sn for superconducting coils)

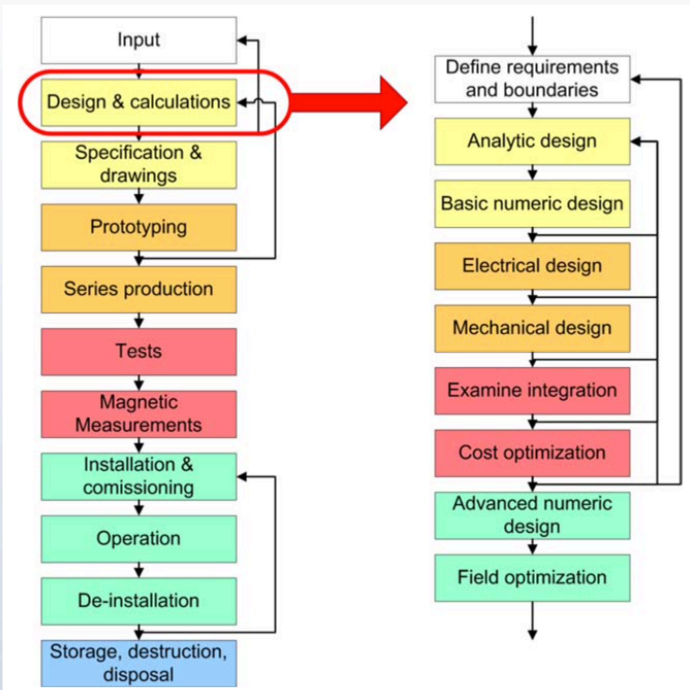
Property	Aluminium	Copper (OF grade)
Purity	99.7%	99.95%
Resistivity at 20°C	28.3 nΩ m	17.2 nΩ m
Thermal resistivity coefficient	0.004 K^{-1}	0.004 K^{-1}
Density	2.70 kg/dm^3	8.94 kg/dm^3
Thermal conductivity	237 W/m K	391 W/m K
Approx. price	4.7 €/kg	11 €/kg

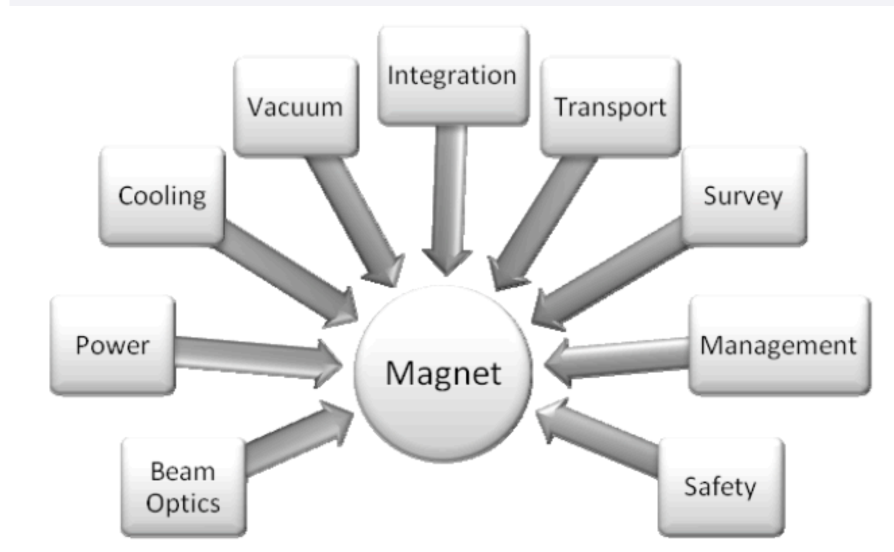
Coil design should take in account some requirements as:

- Low power consumption, which is related with the yoke design
- Sufficient cooling performance (Water/Air cooling)
- Adequate insulation thickness
- Manufacturing Cost

Magnetic design

Keyword: integration between services!



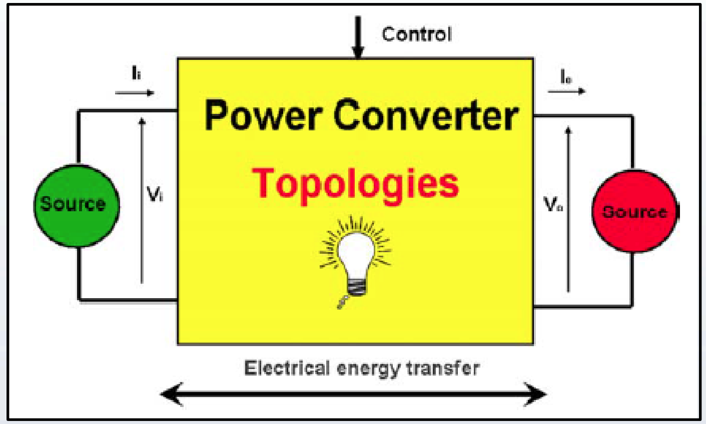


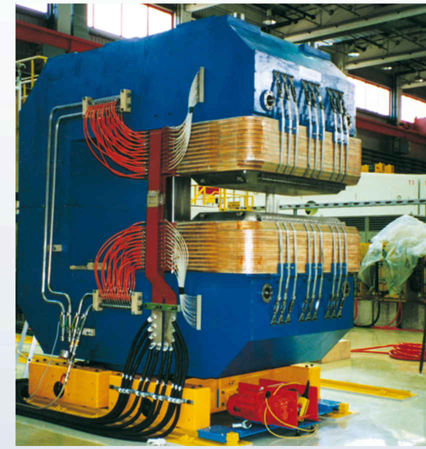
Some finite elements computational codes:

- POISSON (2-Dimensional)
- OPERA, ANSYS (2 and 3-Dimensional)
- ROXIE (2 and 3D superconducting)

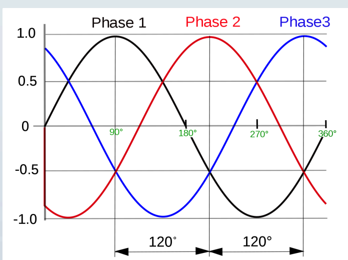
Power Converter for Magnets

Voltage Source
(Power Grid) 3 Phase
50 Hz – 60 Hz



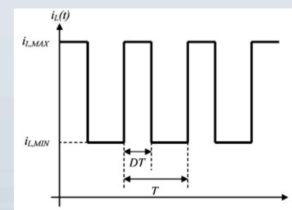


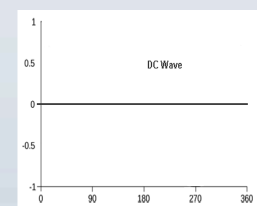
Current Source (Magnets) DC or Pulsed



Power Converter Performance

- Ripple
- Stability
- Accuracy
- Reproducibility
- Resolution
- Efficency
- EMC
- Reliability (MTBF), Reparability (MTTR)

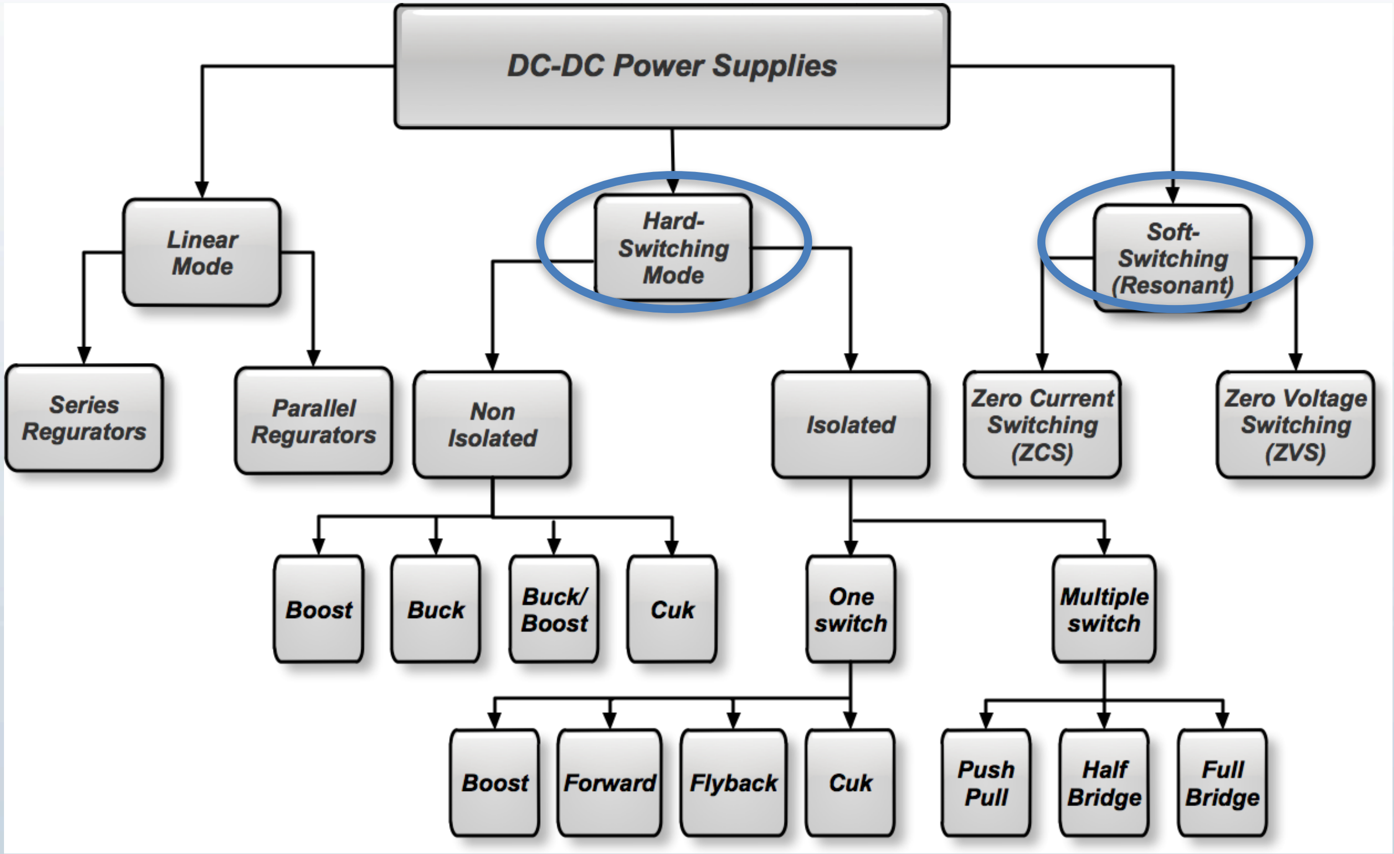




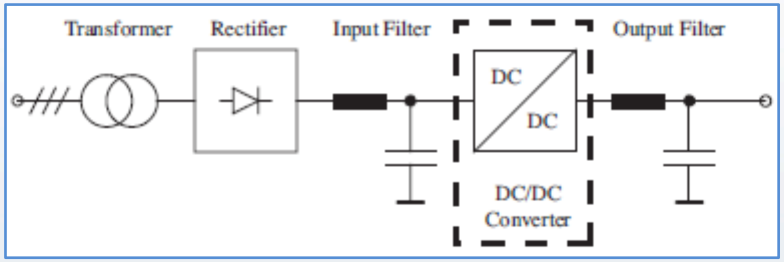
Voltage Source
Imposes a voltage independently of the current flowing through it. This implies that the series impedance of the source is zero (or negligible in comparison with the load impedance)

Current Source
Imposes a current independently of the voltage at its terminals. This implies that the series impedance of the source is infinite (or very large in comparison with the load impedance)

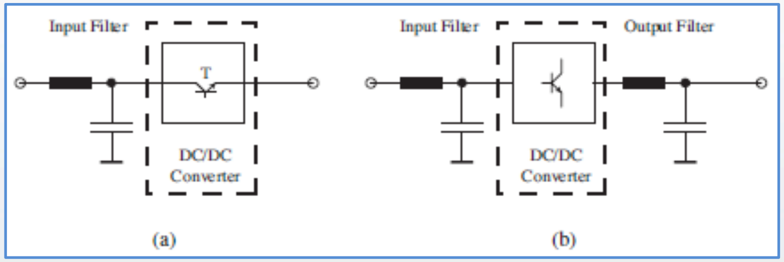
Power Converter for Magnets – Topology



Linear mode PS vs Switched Mode PS



General Scheme of a DC supply



DC/DC converters (a) Linear Converter
(b) Switched-mode Converter

Linear PS

☺ High dynamic for the output voltage regulation

☺ Poor output voltage ripple

☹ Low Efficency →Loss proportional to I_{LOAD} and non-zero Voltage)

Mainly used in low-power application

Switched-Mode PS

☺ High Efficency and High power density → Loss related only to the swittching losses and low conduction losses

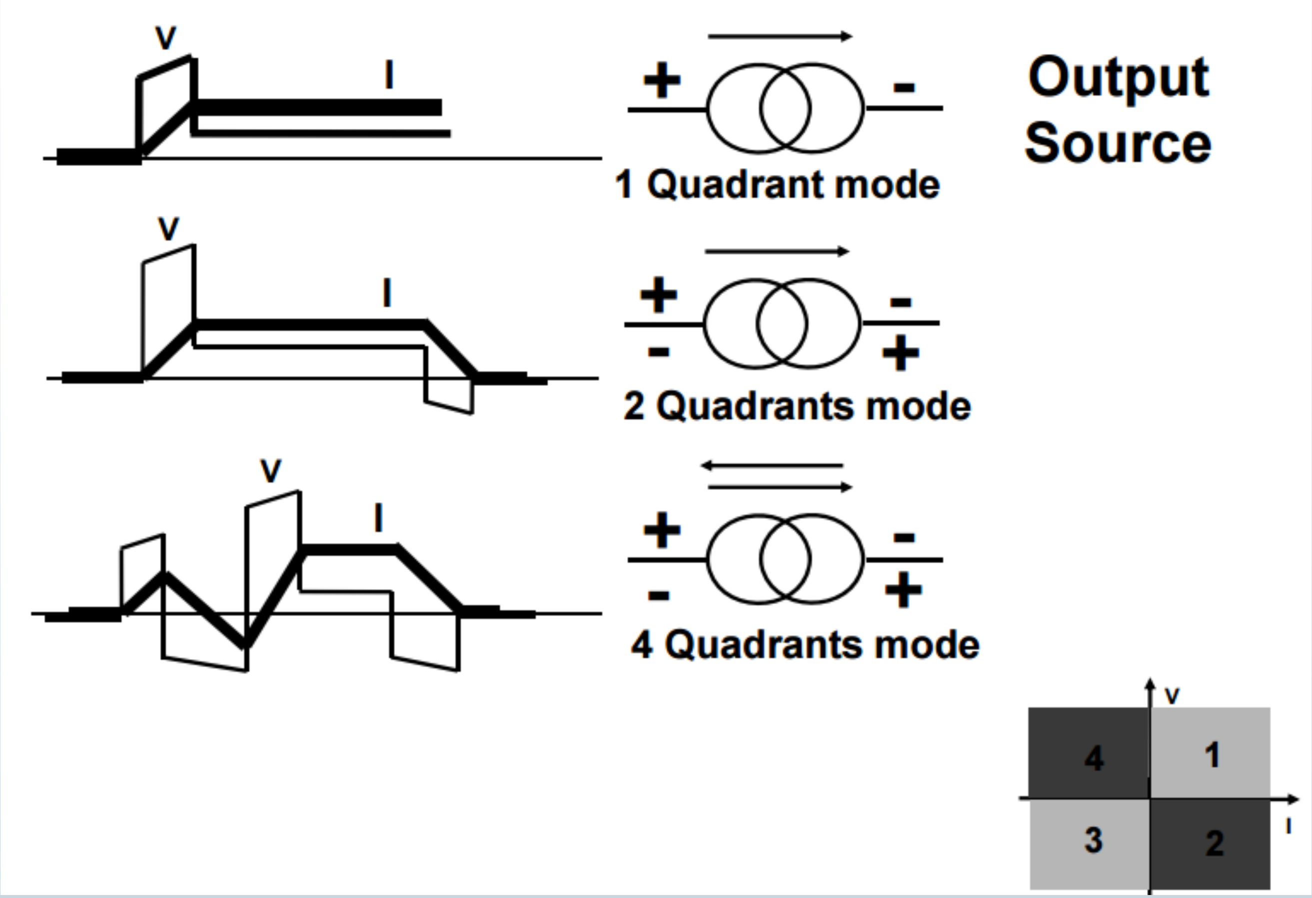
☹ EMC emission

☹ Needed output filter to reduce output voltage ripple

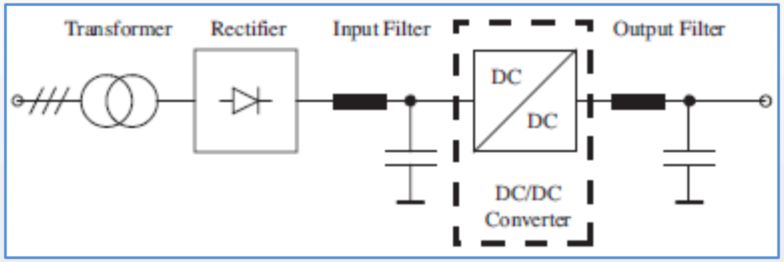
Used in low and high power applications.
Can have one, two or four quadrants

We'll focus on one quadrant Power Converter

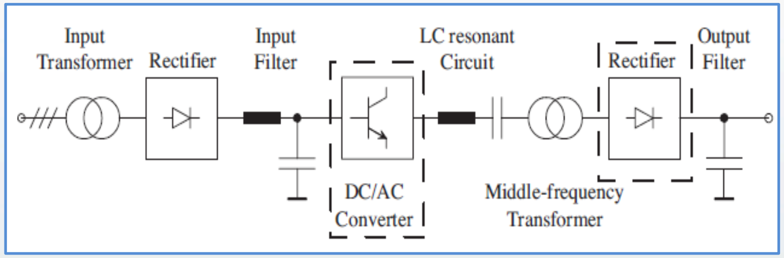
Operating Modes



Switched Mode Converter



Direct DC/DC converter



DC/DC Converters with an intermediary AC stage

Direct DC/DC Converter

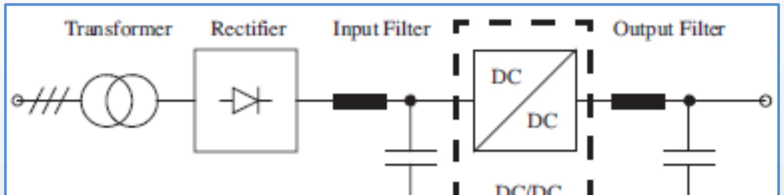
Only SINGLE stage is used to adjust voltage levels. They are classified according to the galvanic insulation of a transformer

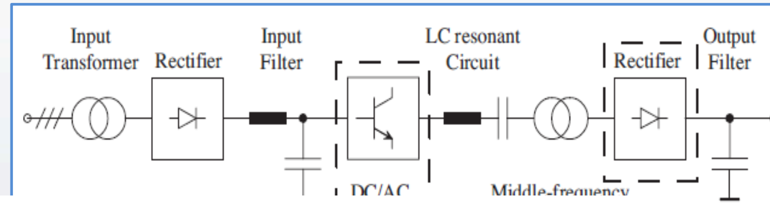
- Insulated
  - Forward DC/DC converter
  - Flyback DC/DC converter
- Non insulated
  - Buck
  - Boost
  - Buck/Boost
  - Cuk

DC/DC Converters with an intermediary AC stage

- Output voltage regulation achieved by the control of the DC/AC converter
- LC resonant circuit should be used to enable soft-switching condition for the DC/AC converter in order to maximise its efficency

Switched Mode Converter





Direct

Optimization of Switched Mode Power Converter

1. Reduce switch stress
2. Reduce the conduction loss
3. Optimize the switching frequency

Direct ... iary

Only SINGLE stage is
They are classified a ... y the
insulation of a trans

- Insulated
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  - Flyback DC/DC converter
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  - Boost
  - Buck/Boost
  - Cuk

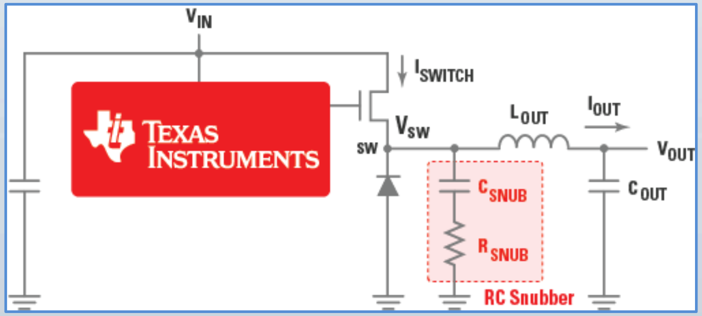
- LC resonant circuit should be used to enable soft-switching condition for the DC/AC converter in order to maximise its efficency

Hard Switching vs Soft Switching Power Supplies

Hard Switching

- ☺ Switching losses reduction
- ☺ Magnetics parts size reduction
- ☺ Higher efficency
- ☺ Attenuation of harmonics in the range of tens of kHz

- ☹ Increased control complexity
- ☹ EMI and RFI problems
- ☹ High cost
- ☹ Snubber circuit to reduce the losses at high switching frequencies



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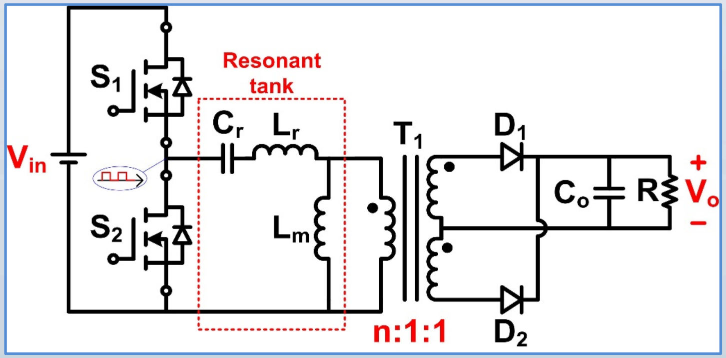

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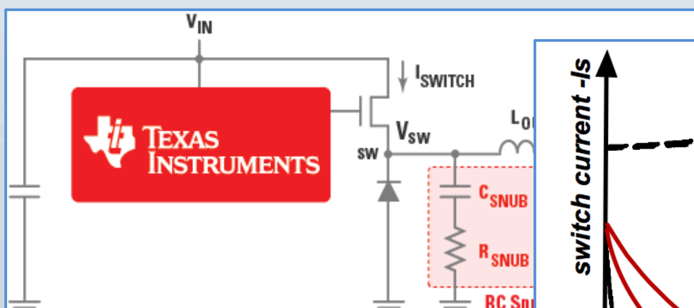
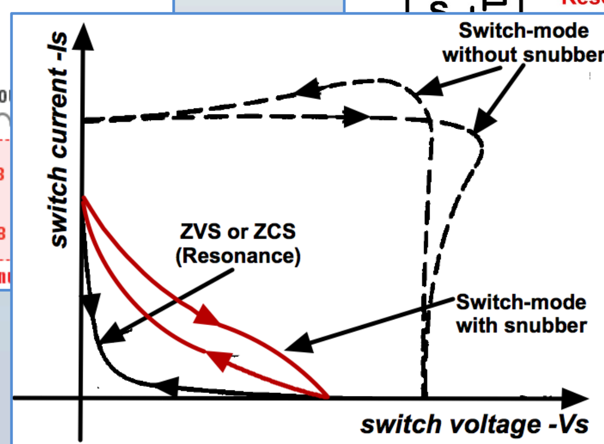
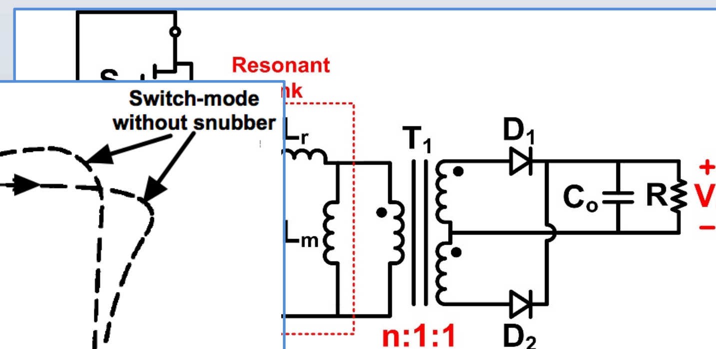
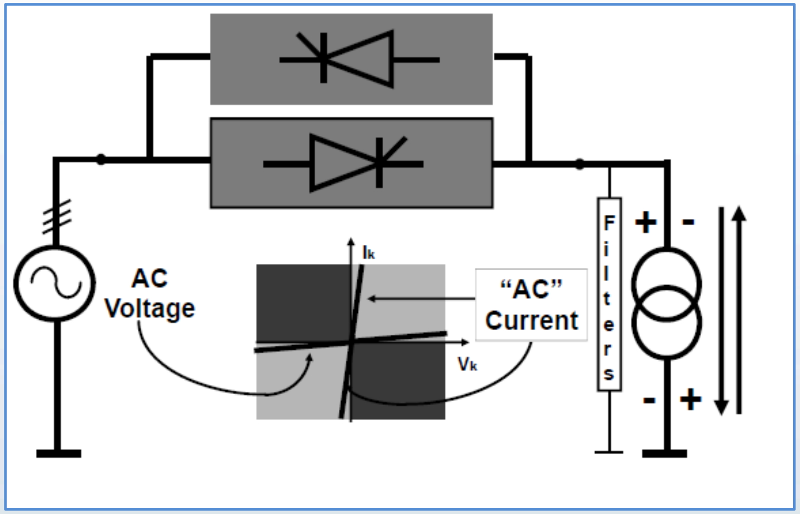


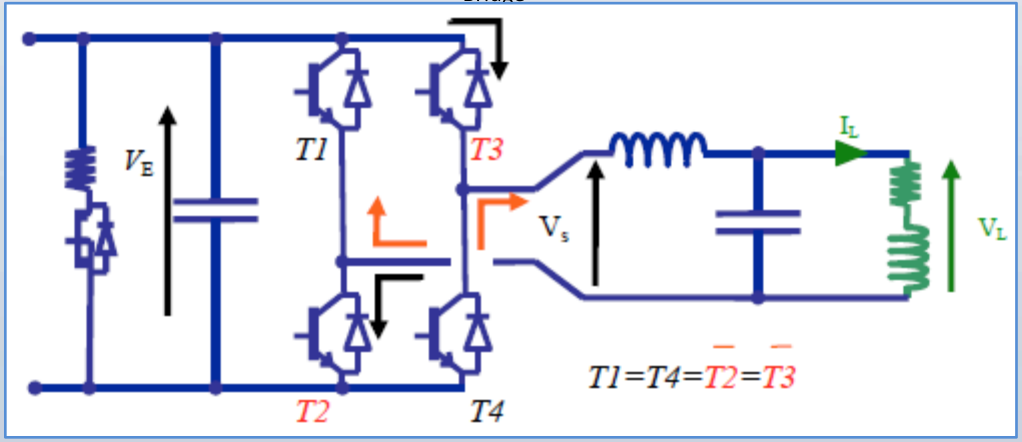




Power Supply - 4 Quadrants mode

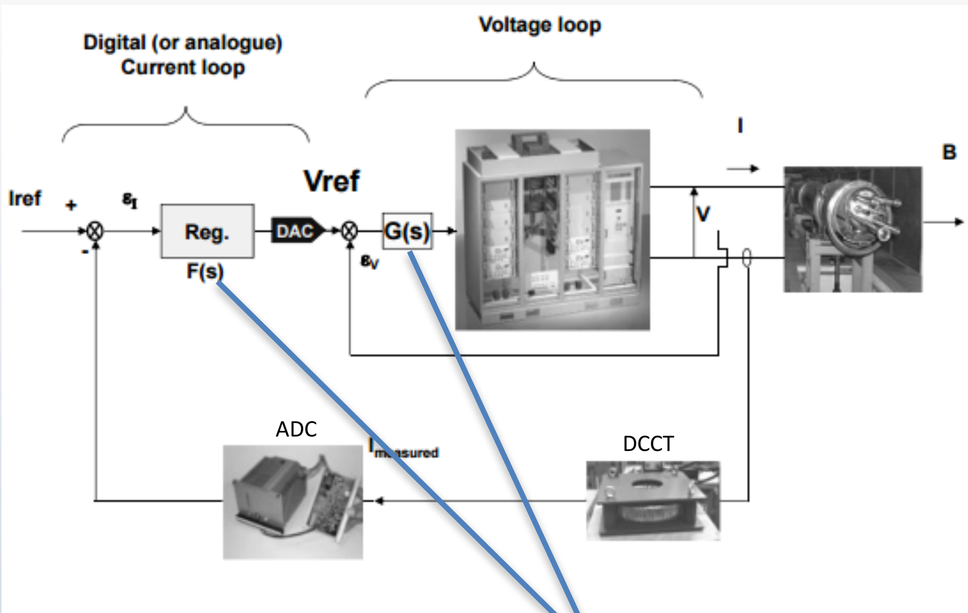


Direct Converter: Antiparallel Thyristor Bridge

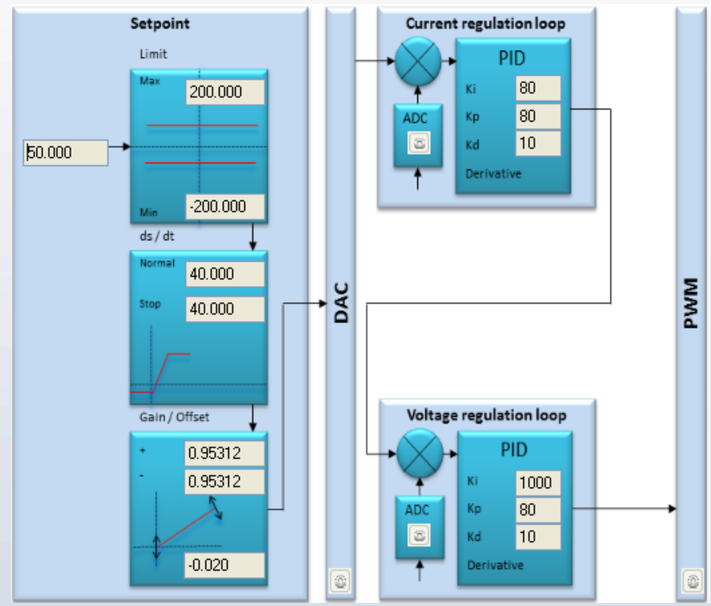


Full bridge

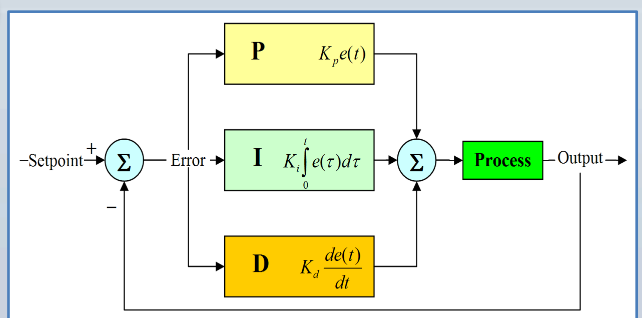
Power Converter Control



Power Converter Control Diagram



Power Converter Control GUI

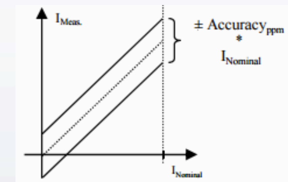


P.I.D. Block Scheme

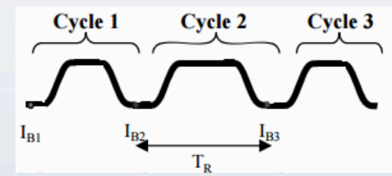
Power Converter for Magnets – Performance Requirements

P R E C I S I O N

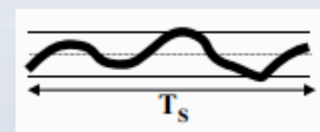
Accuracy
Long term setting or measuring uncertainty taking into consideration the full range of permissible changes of operating and environmental conditions.



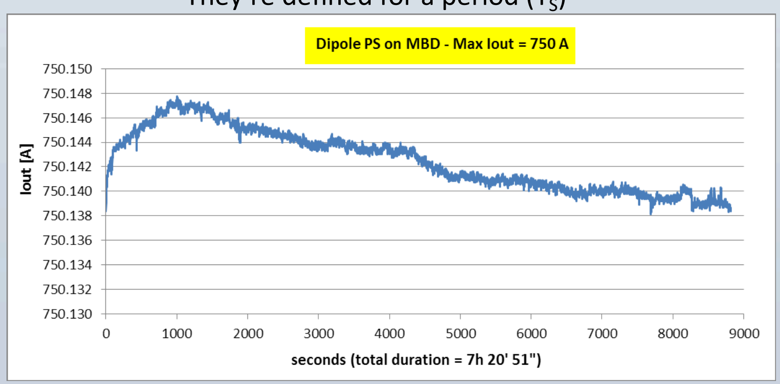
Reproducibility
Uncertainty in returning to a set of previous working values from cycle to cycle of the machine.



Stability
Maximum deviation over a period with no changes in operating conditions.



Accuracy, Reproducibility and Stability are quantitative parameters (measured in p.p.m. of In)
They're defined for a period (T_S)

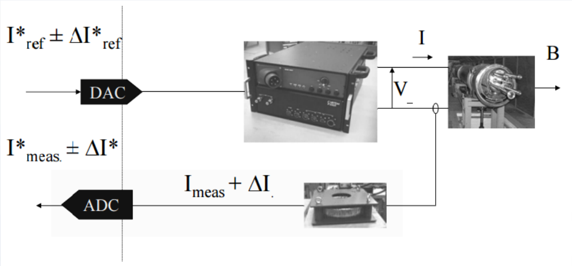


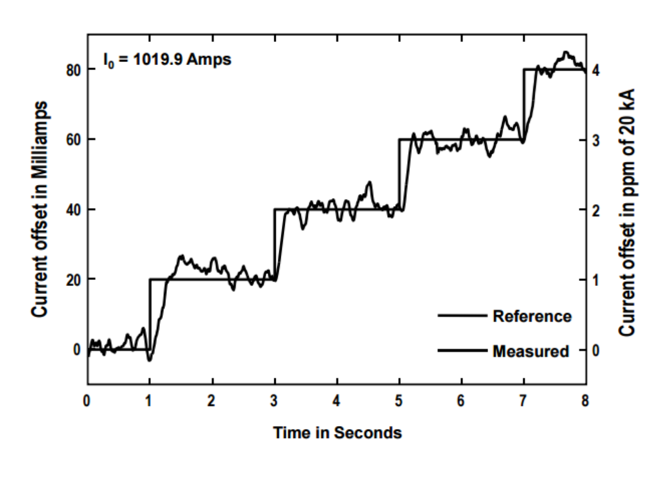
Power Supply Long term stability test

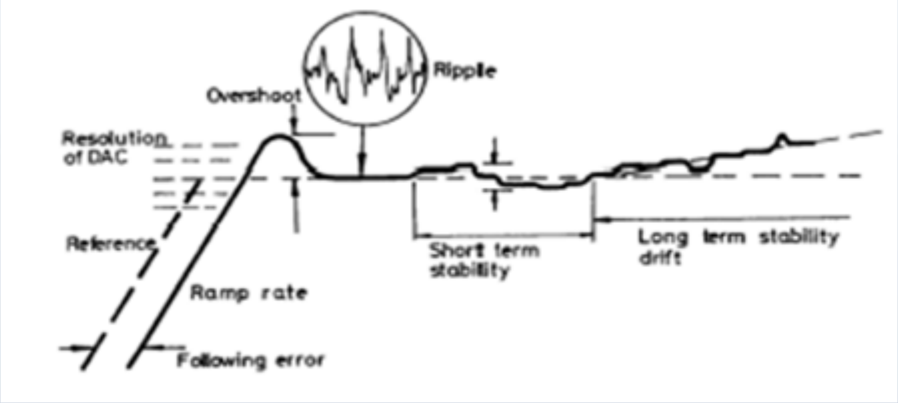
Power Converter for Magnets – Performance Requirements

Resolution

Minimum set current step of power supply
It is expressed in ppm of In
Directly linked to A/D system







Power Converter Performance

- Ripple
- Stability
- Accuracy
- Reproducibility
- Resolution
- Efficency
- EMC
- Reliability (MTBF), Reparability (MTTR)

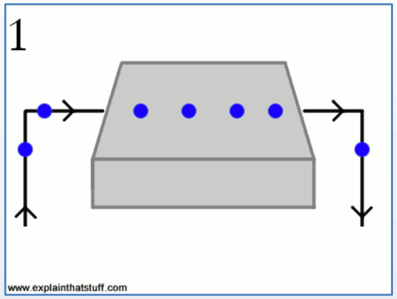
Magnetic measurements: Hall probe

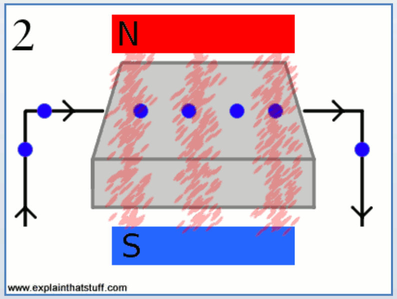
A *Hall probe* is a transducer that varies its output voltage in response to a magnetic field (Hall effect).

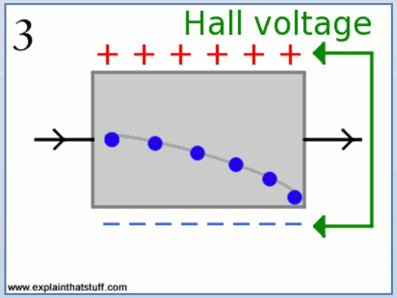
1. When an electric current flows through a material, electrons move through it in pretty much a straight line.
2. Put the material in a magnetic field. The Lorentz force acts on the electrons and makes them deviate from their straight-line path.
3. The electrons in this example would bend as shown. With more electrons on one side of the material than on the other, there would be a difference in potential (a voltage) between the two sides. The size of this voltage is directly proportional to the size of the electric current and the strength of the magnetic field.

PROs: fast response, very simple electronics, compact

CONs: temperature dependence



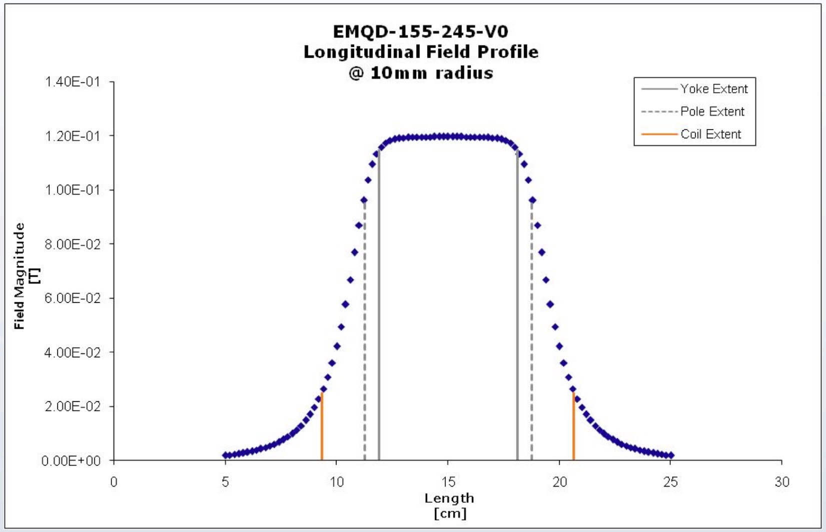




Magnetic length

Magnetic length (*effective* length) is always larger than the actual iron length (*mechanical* length):

$$L_{mag} = \frac{\int_{-\infty}^{+\infty} B_z(y)dy}{B_0}$$



Dipole: $l_{mag} \approx l_{iron} + 2hk$

h: magnet gap

k: geometrical factor, typically 0.3÷0.6

Quadrupole: $l_{mag} \approx l_{iron} + 2rk$

r: aperture radius

k: geometrical factor, typically ~0.45)

Quadrupole: Gradient

In a quadrupole, the components of the ideal magnetic field in the plane transverse to the beam are given by (general equations):

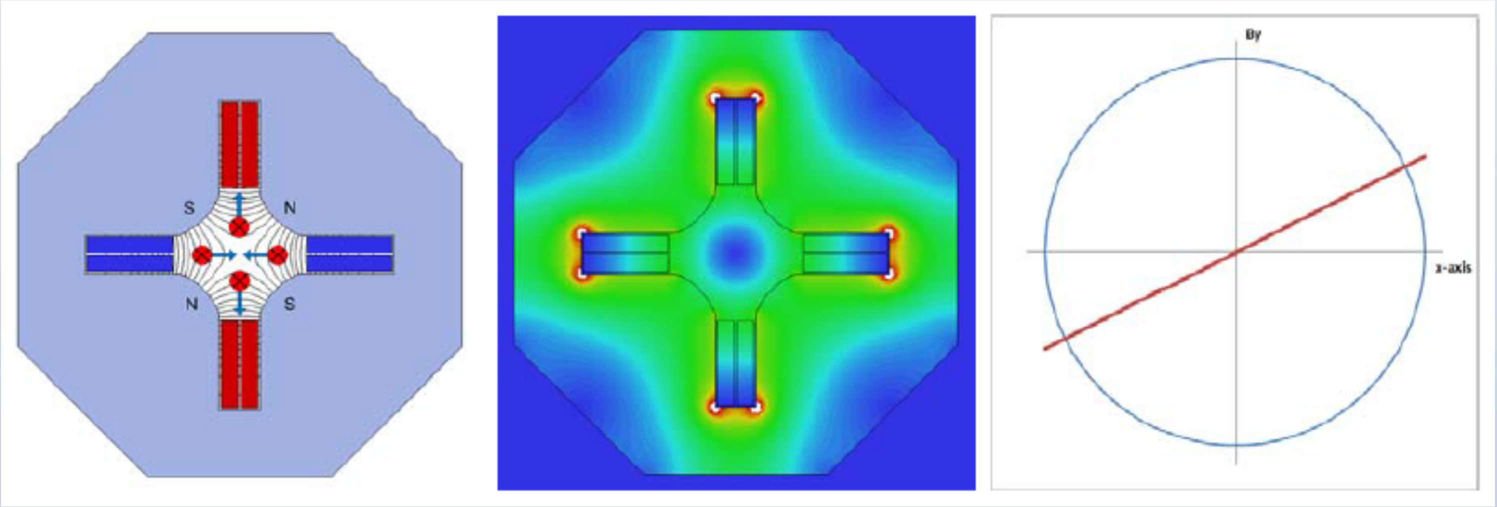
$$B_z = Gx$$

$$B_x = Gz$$

G (T/m) is the field gradient of the vertical component in the horizontal direction (or equivalently, the gradient of the horizontal component in the vertical direction).

Sign of G: the quadrupole focuses or defocuses.

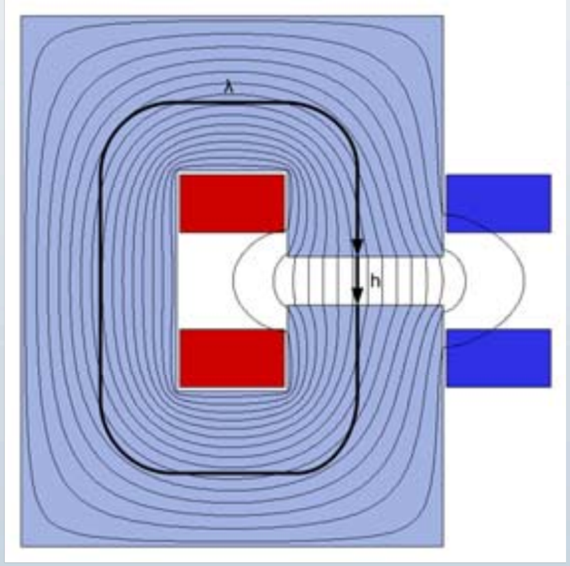
In our coordinate system: $G = \frac{dB_z}{dx}$



B vs I (dipole)

The flux density in the air gap is proportional to the excitation current.

$$NI = \oint \vec{H}\overrightarrow{dl} = \oint \frac{\vec{B}}{\mu}\overrightarrow{dl} = \int_{gap} \frac{\vec{B}}{\mu_{air}}\overrightarrow{dl} + \int_{yoke} \frac{\vec{B}}{\mu_{iron}}\overrightarrow{dl} = \frac{Bh}{\mu_{air}} + \frac{B\lambda}{\mu_{iron}} \approx \frac{Bh}{\mu_0}$$



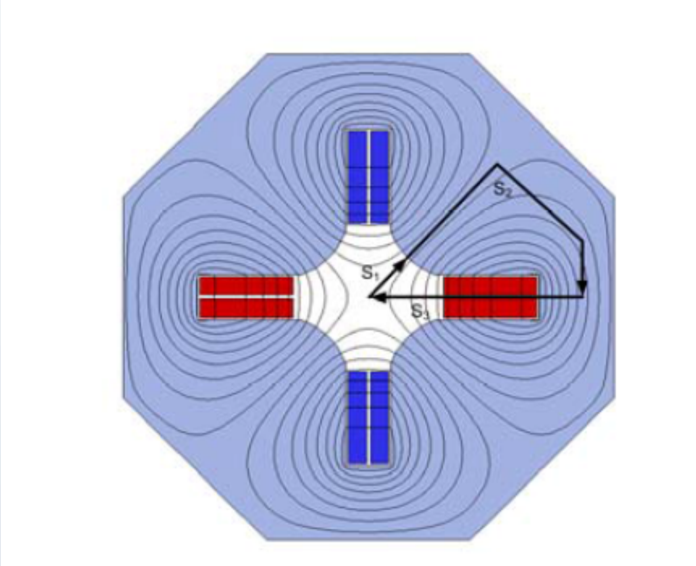
B vs I (quadrupole)

The gradient in the air gap is proportional to the excitation current.

$$H(r) = \frac{B'}{\mu} r \quad (B' \text{ costant in ideal quadrupole})$$

$$NI = \oint \vec{H}\vec{dl} = \frac{B'}{\mu_0} \int_{gap} r\vec{dr} + \frac{B'}{\mu_{iron}} \int_{yoke} r\vec{dr} + \frac{B'}{\mu} \int_{X\ axis} r\vec{dr} \approx \frac{B'}{\mu_0} \int_0^R r\vec{dr} = \frac{B' r^2}{2\mu_0}$$

$$B_z = B'_z \cdot x \propto I$$



Field quality estimation

A simple method to judge the field quality of a magnet is to evaluate the homogeneity of the field (for dipoles) or of the gradient (for quadrupoles) in the defined good field region (GFR):

Dipole:

$$\frac{\Delta B}{B_0} = \frac{B_z(x,z) - B_z(0,0)}{B_z(0,0)} \leq 0{,}01\%$$

Quadrupole:

$$\frac{\Delta B'}{B_0'} = \frac{B_z'(x,z) - B_z'(0,0)}{B_z'(0,0)} \leq 0{,}1\%$$

Magnetic measurements

Equipment:
- Quadrupole
- Axes movement control system
- Hall probe
- Power supply
- PC (Labview, Excel…)

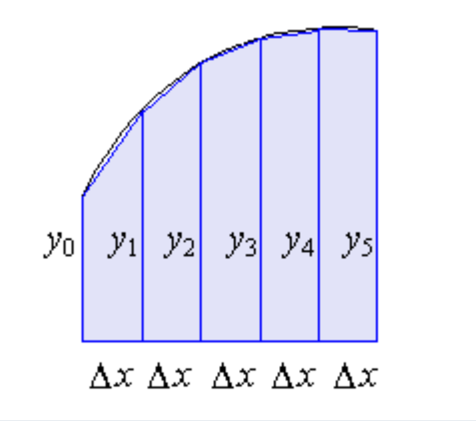
QUADRUPOLE	Mag No 91544.4
Aperture	53 mm
Gradient	?? T/m
Effective length	?? mm
Focussing power	0.41 T
Nominal voltage	2.2 V
Nominal current	15.5 A

We will evaluate the following parameters:

1. **magnetic length**
   - longitudinal scans at different x
2. **magnetic gradient**
   - radial scan at magnet center
3. **B vs I**
4. **field quality**
   - Calculate the field quality by evaluating the gradient next to the magnet center and in another point.

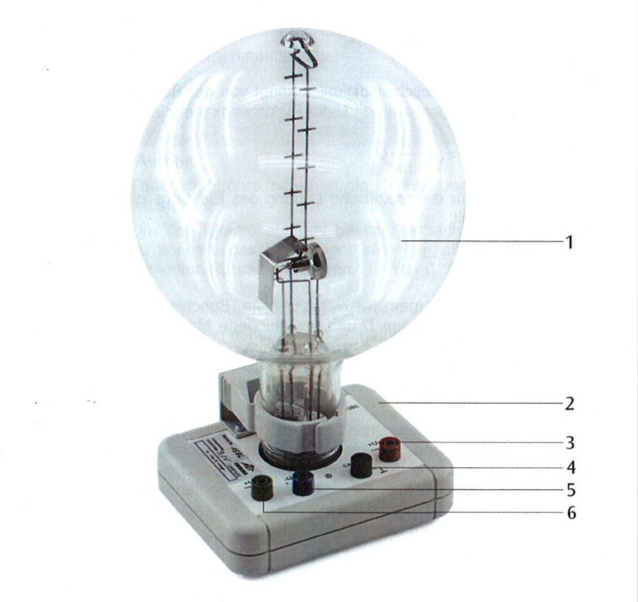
Trapezoidal rule to evaluate with Excel the general integral

$$\int y dx = \frac{\Delta x}{2}(y_1 + 2y_2 + 2y_3 + \cdots + 2y_{n-2} + 2y_{n-1} + y_n)$$



Descrizione

Il tubo a fascio filiforme serve per l'analisi della deflessione dei fasci di elettroni nel campo magnetico formato dalla coppia di bobine di Helmholtz. Verrà usato per la determinazione quantitativa della carica specifica dell'elettrone e/m.



In un'ampolla è presente un cannone elettronico, composto da un catodo di ossido riscaldato, un cilindro di Wehnelt per la focalizzazione del fascio, e un anodo in un'atmosfera di neon. Gli elettroni vengono estratti dal catodo, accelerati verso l'anodo e focalizzati; gli atomi di neon vengono ionizzati lungo la traiettoria degli elettroni e si forma un fascio visibile. Il campo magnetico deflette questo fascio e si può misurare il diametro della traiettoria percorsa.

Bobine di Helmholtz

Due bobine corte con ampio raggio R vengono posizionate parallelamente sullo stesso asse alla distanza R. Attraverso la sovrapposizione dei due campi, tra le due bobine si ottiene un’area con campo magnetico ampiamente uniforme.

$$B = kI_H = \left(\frac{4}{5}\right)^{\frac{3}{2}} \frac{\mu_0 N I_H}{R}$$

Nel nostro apparato sperimentale:

$$k \cong 0{,}756\ \mathrm{mT/A}$$

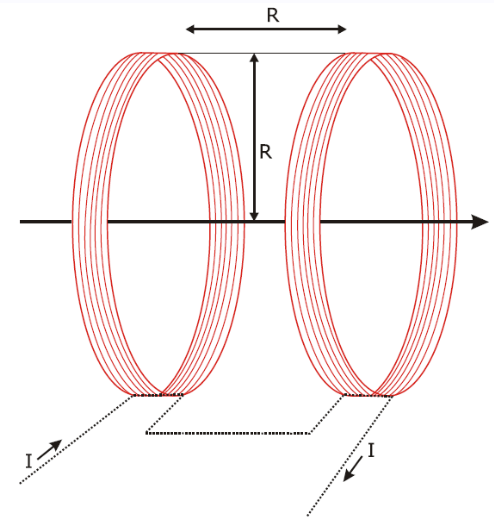
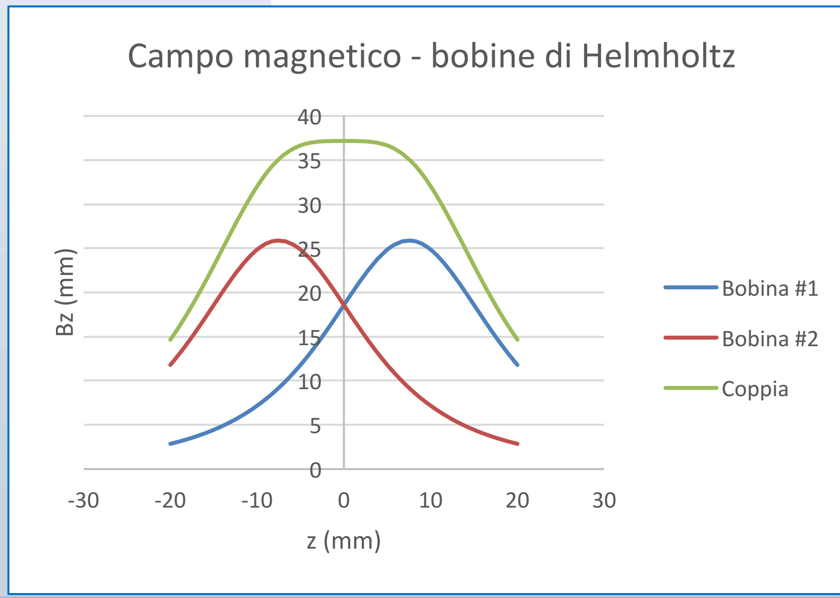


Fig. 1 Bobine nella geometria di Helmholtz



Determinazione quantitativa della carica specifica dell'elettrone

- Forza di Lorentz: $\vec{F} = q\vec{v}\text{x}\vec{B}$
- Forza centripeta: $F = m\frac{v^2}{r}$

→ Uguagliando le due: $m\frac{v^2}{r} = evB$

La velocità è legata alla tensione di accelerazione del cannone:

- $\frac{1}{2}mv^2 = q\Delta V = eU$

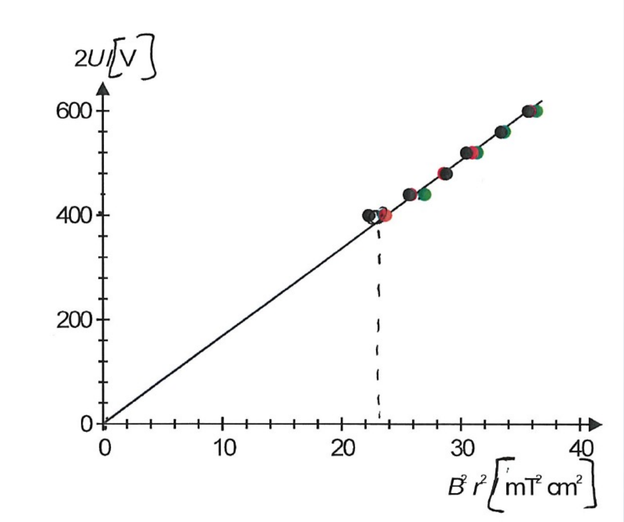
Si ricava quindi la velocità: $v = \sqrt{\frac{2eU}{m}}$

Si inserisce nell'equazione e si risolve: $\frac{e}{m} = \frac{2U}{r^2B^2}$

Determinazione quantitativa della carica specifica dell'elettrone

Quindi: $$\frac{e}{m} = \frac{2U}{r^2B^2}$$

Al variare di B (variando la corrente di alimentazione) si osserva una variazione di r.



- Realizzare un grafico *2U* vs r^2B^2 per vari valori di B.
- Determinare il valore di *e/m*.