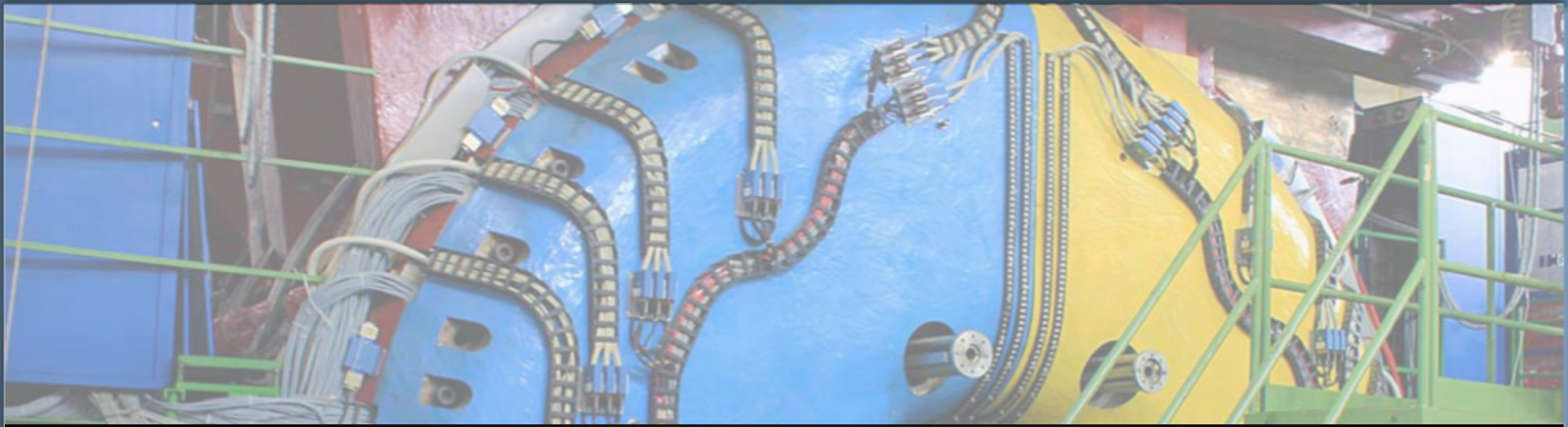
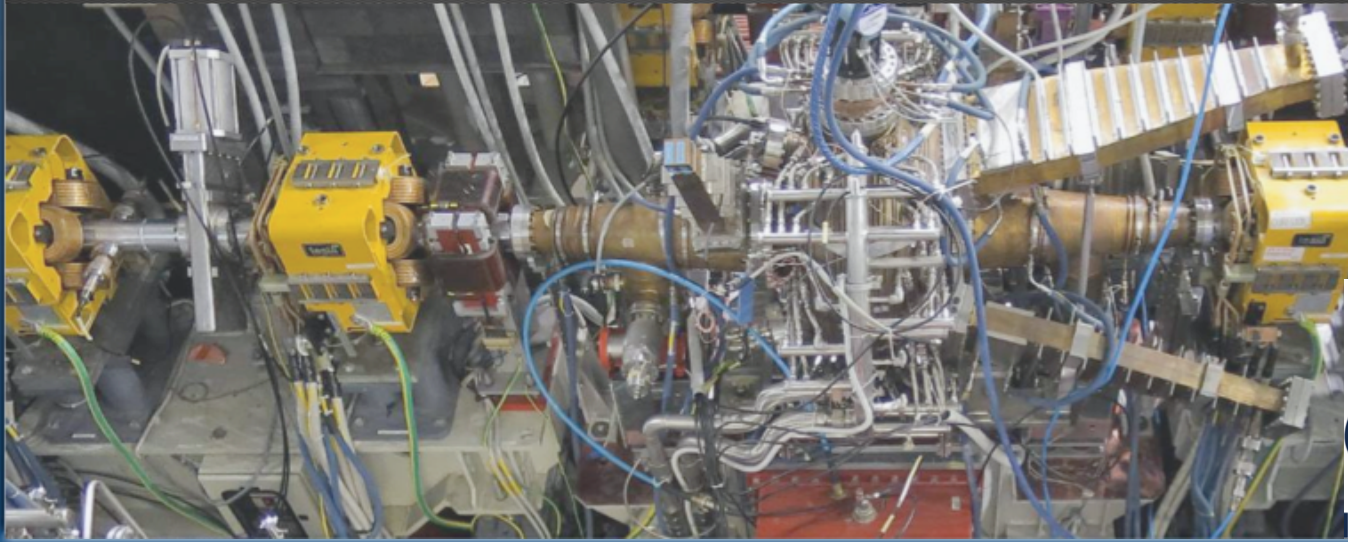


Accelerator Laboratory

Magnets in Particle Accelerators

Carlo Ligi, Alessandro Vannozzi



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Materials for electromagnets: Magnetization

The spin of an electron, combined with its orbital angular momentum, results in a magnetic dipole moment and creates a magnetic field.

In many materials (with a filled electron shell), the total dipole moment of all the electrons is zero.

Atoms with **partially filled shells** can experience a net magnetic moment in the absence of an external field. Ferromagnetic materials contain many atoms with unpaired spins.

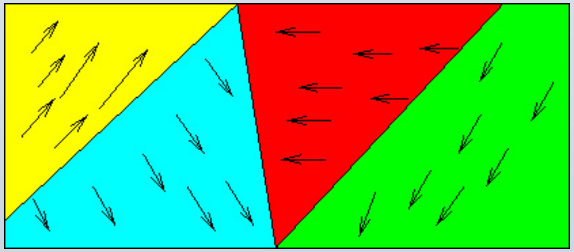
Elettroni 3*d* spaiati	Atomi	Numero di elettroni	Configurazione elettronica orbitali 3*d*					Elettroni 4*s*
3	V	23	↑	↑	↑			2
5	Cr	24	↑	↑	↑	↑	↑	1
5	Mn	25	↑	↑	↑	↑	↑	2
4	Fe	26	↑↓	↑	↑	↑	↑	2
3	Co	27	↑↓	↑↓	↑	↑	↑	2
2	Ni	28	↑↓	↑↓	↑↓	↑	↑	2
0	Cu	29	↑↓	↑↓	↑↓	↑↓	↑↓	1

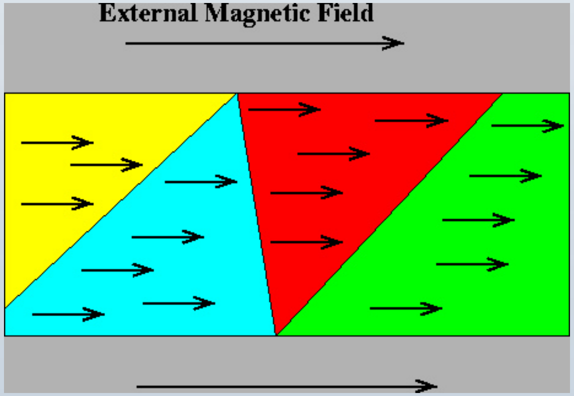
Materials for electromagnets: Ferromagnetism

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

In small WEISS domains (10^{-3} – 10^{-8} m) the magnetic dipole moments of the atoms tends to align. The domains are randomly oriented.

In presence of an external B, all the domains tends to align with it.

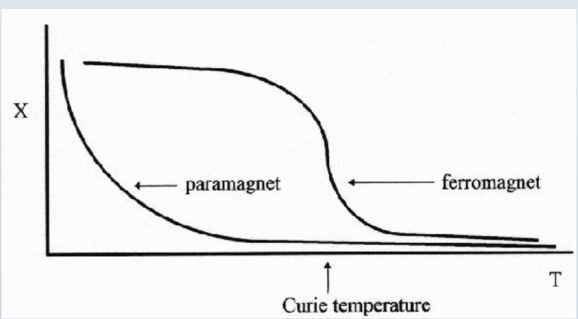


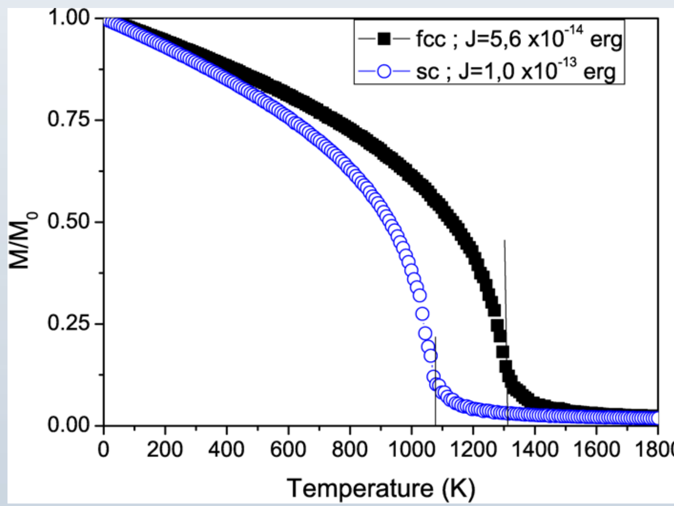


Materials for electromagnets: Ferromagnetism

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

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





Fe:	Tc=1043K
Ni:	Tc=627K
Co:	Tc=1388K
$FeOFe_2O_3$:	Tc=858K
$NiOFe_2O_3$:	Tc=858K
$CuOFe_2O_3$:	Tc=728K
$MgOFe_2O_3$:	Tc=713K
MnBi:	Tc=630K
MnSb:	Tc=587K
$MnOFe_2O_3$:	Tc=573K
$Y_3Fe_5O_{12}$:	Tc=560K
CrO_2:	Tc=386K
MnAs:	Tc=318K
Gd:	Tc=292K

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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%.

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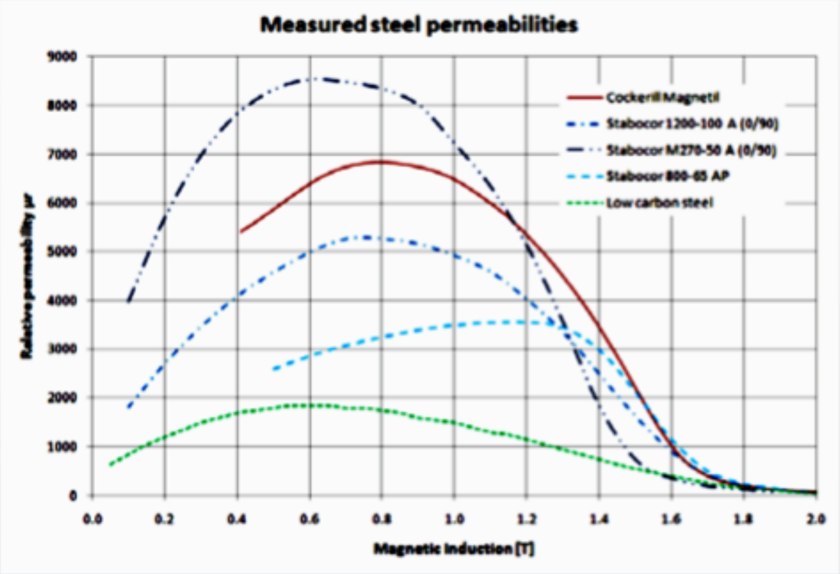
Materials for electromagnets: Ferromagnetism

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:

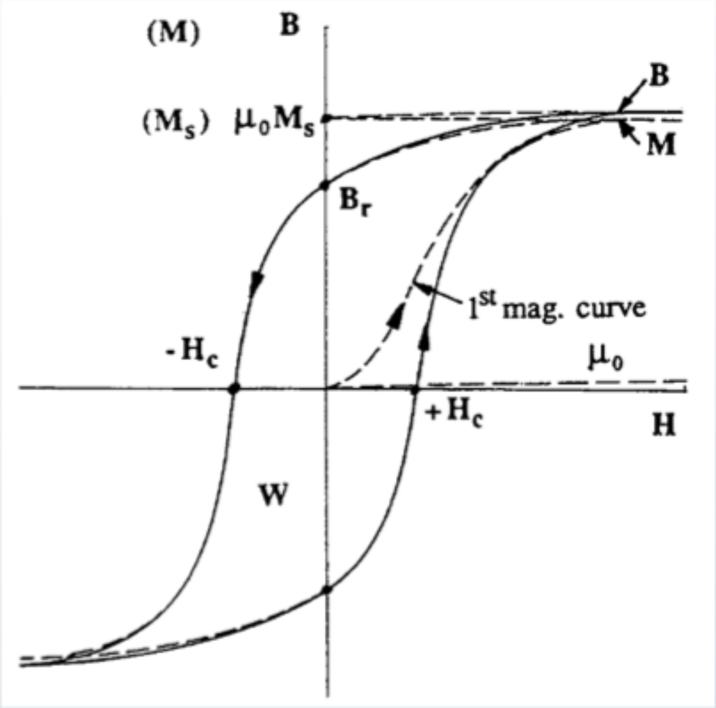
$B = \mu(B)\, H = \mu_r(B)\, \mu_0\, H$



Materials for electromagnets: Ferromagnetism

The hysteresis loop

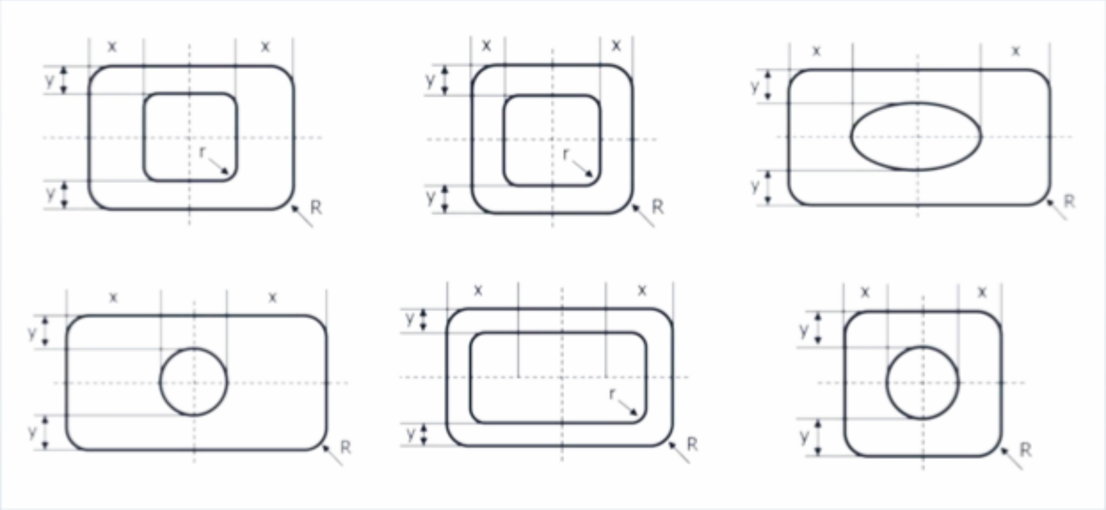
(B_r = residual induction, H_c = coercive force)



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



Materials for electromagnets: Conductors

Coil design should take in account some requirements as:

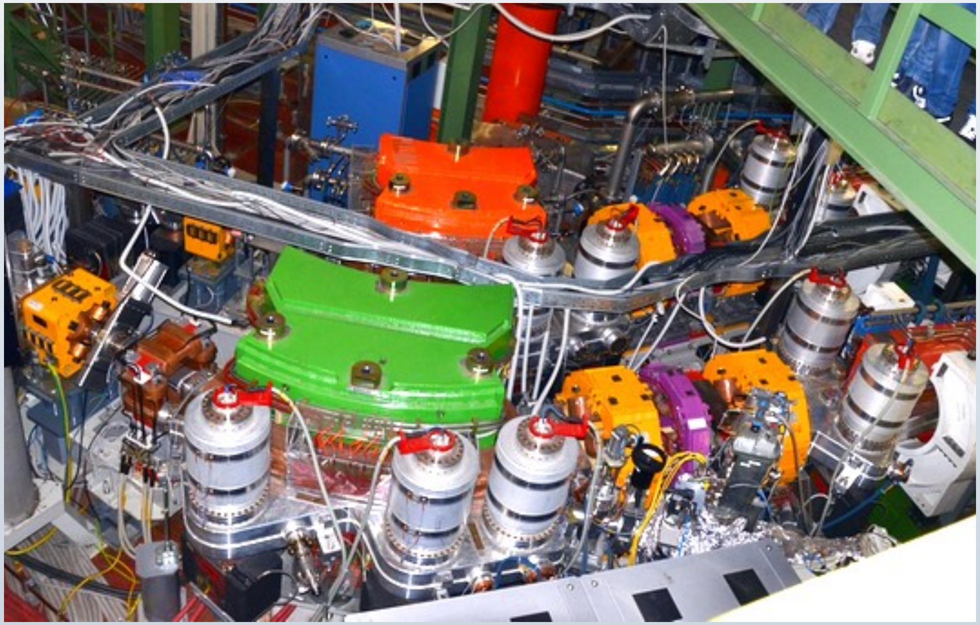
- Low power consumption, which is related with the yoke design
- Sufficient cooling performance (Water/Air cooling)
- Adequate insulation thickness
- Manufacturing Cost

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.



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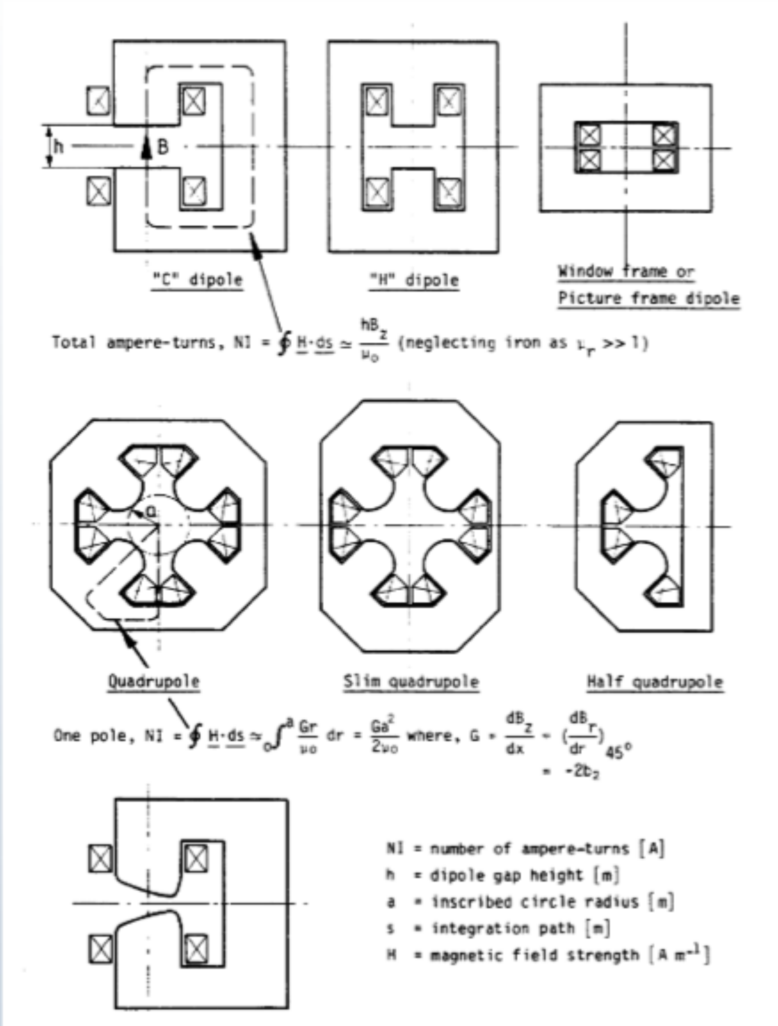
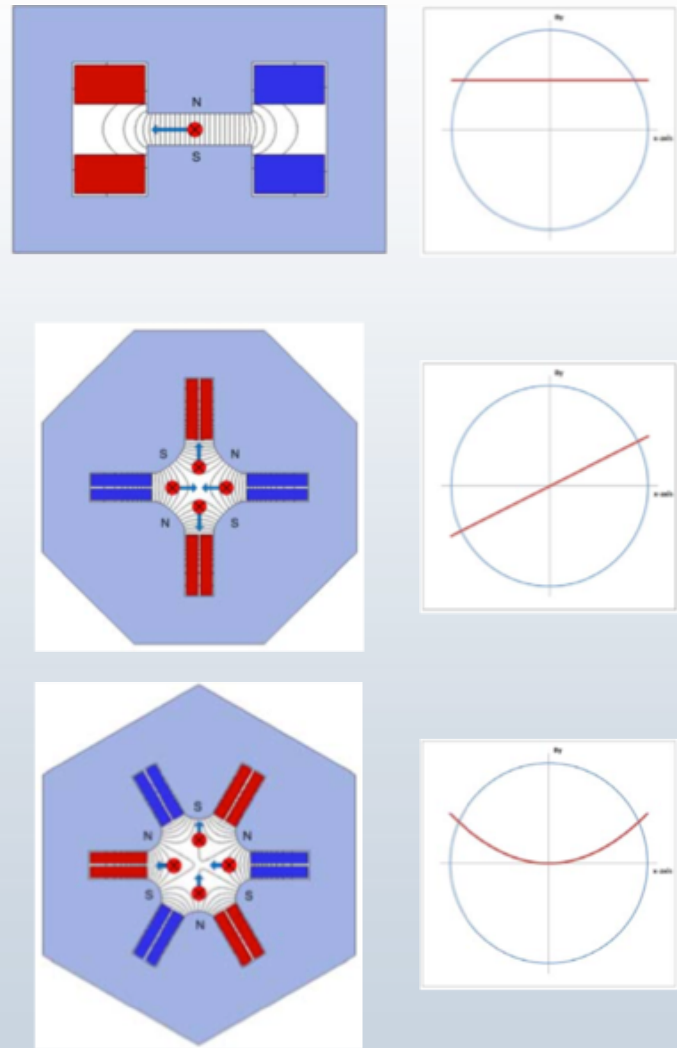
Magnets in Accelerators:





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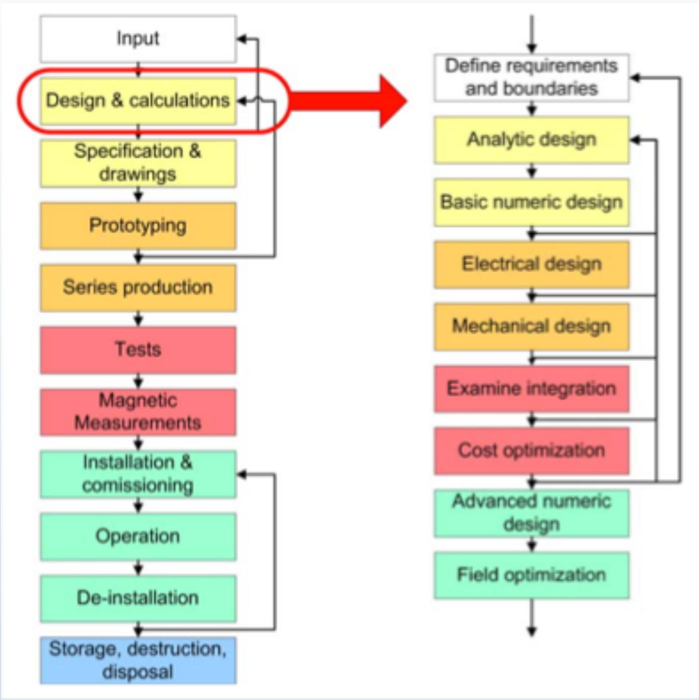
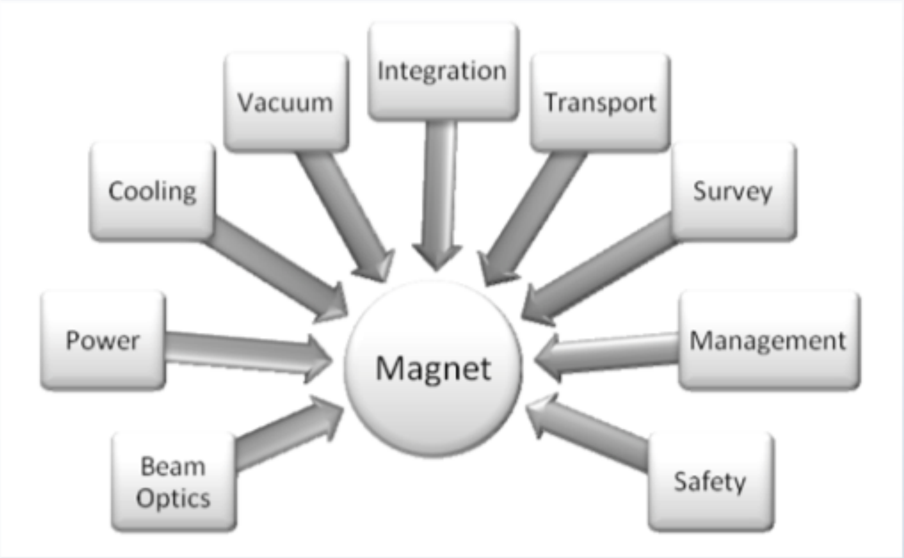
Magnetic design

Keyword: integration between services!





Magnetic design

General requirements

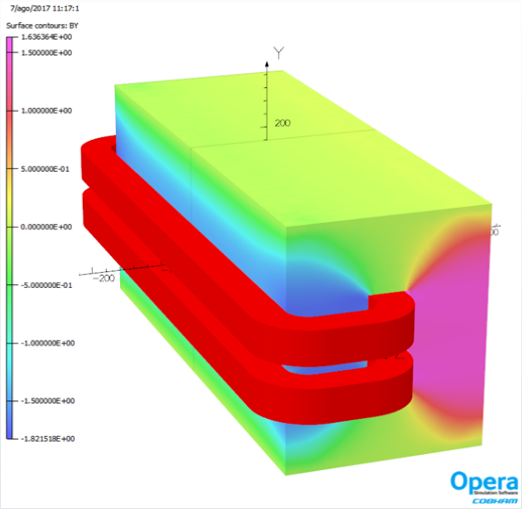
- Beam parameters (mass, charge, energy, deflection angle...)
- Magnetic field (integrated field or integrated gradient)
- Aperture (physical aperture and *good field region*)
- Operation mode (continuous, pulsed, fast pulsed, ramped...)
- Field quality (field uniformity)
- Available space

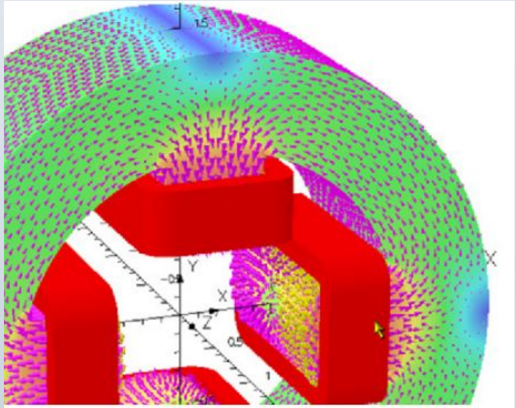
2-D and 3-D Simulations

Some finite elements computational codes:

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

Magnetic design – Finite Element Analysis (F.E.A.) Softwares





Opera 3D simulations

Pre-Processing

- Define geometry of all the regions (Coil, Iron, Air)
- Define material properties (B-H curve)
- Define mesh (region discretization)
- Define Ampere-Turns in the coils region
- Define symmetries

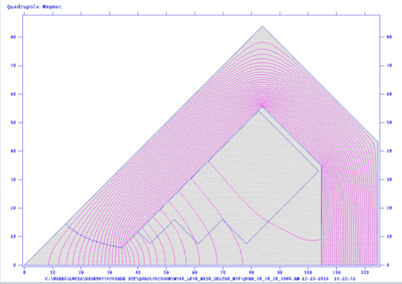
Solver

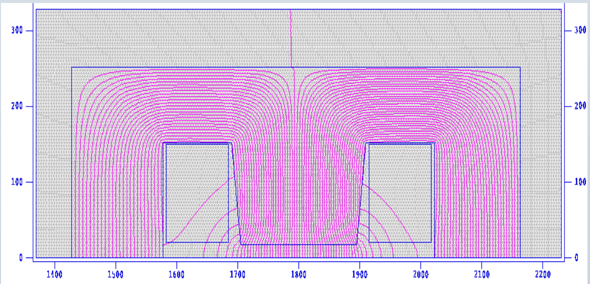
- Linearization of Maxwell Equation
- Definition of magnetic potential (thus flux density) in the mesh nodes

Post-Processing

Results analysis:

- Flux density in the air gap
- Flux density in the iron
- Gradient (for a quadrupole) etc. ...

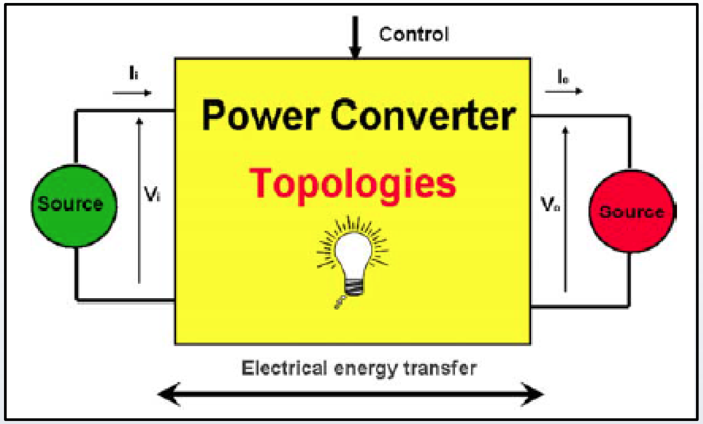


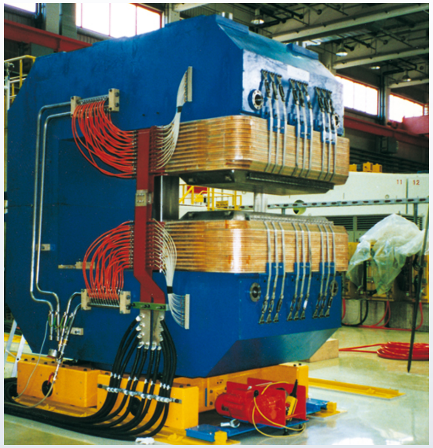


Poisson Superfish Simulations

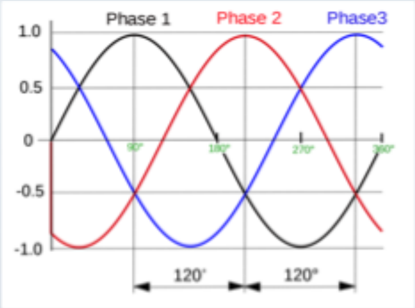
Power Supplies for Magnets

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





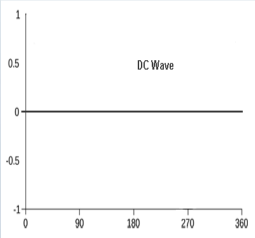
Magnets DC or Pulsed. **Current Source** needed

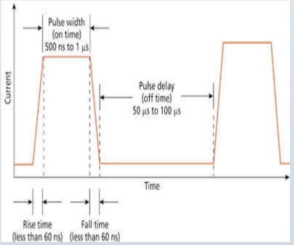


Voltage Source
Imposes a voltage independently of the current flowing through it.

Power Converter Performance

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





Current Source
Imposes a current independently of the voltage at its terminals.

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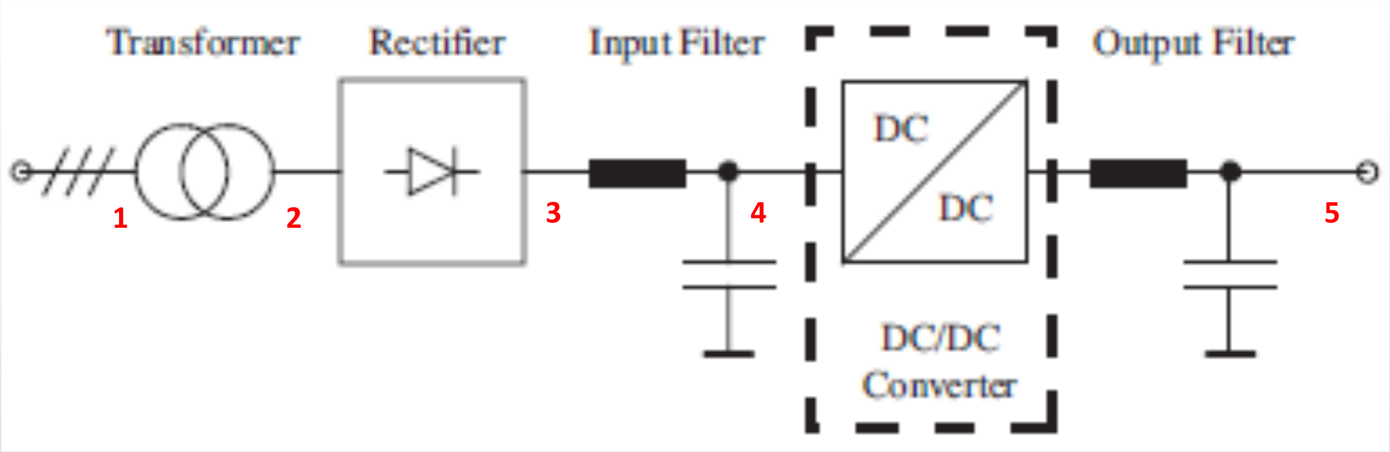
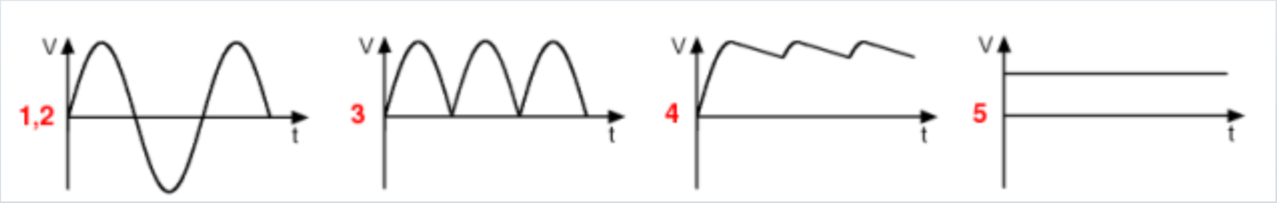
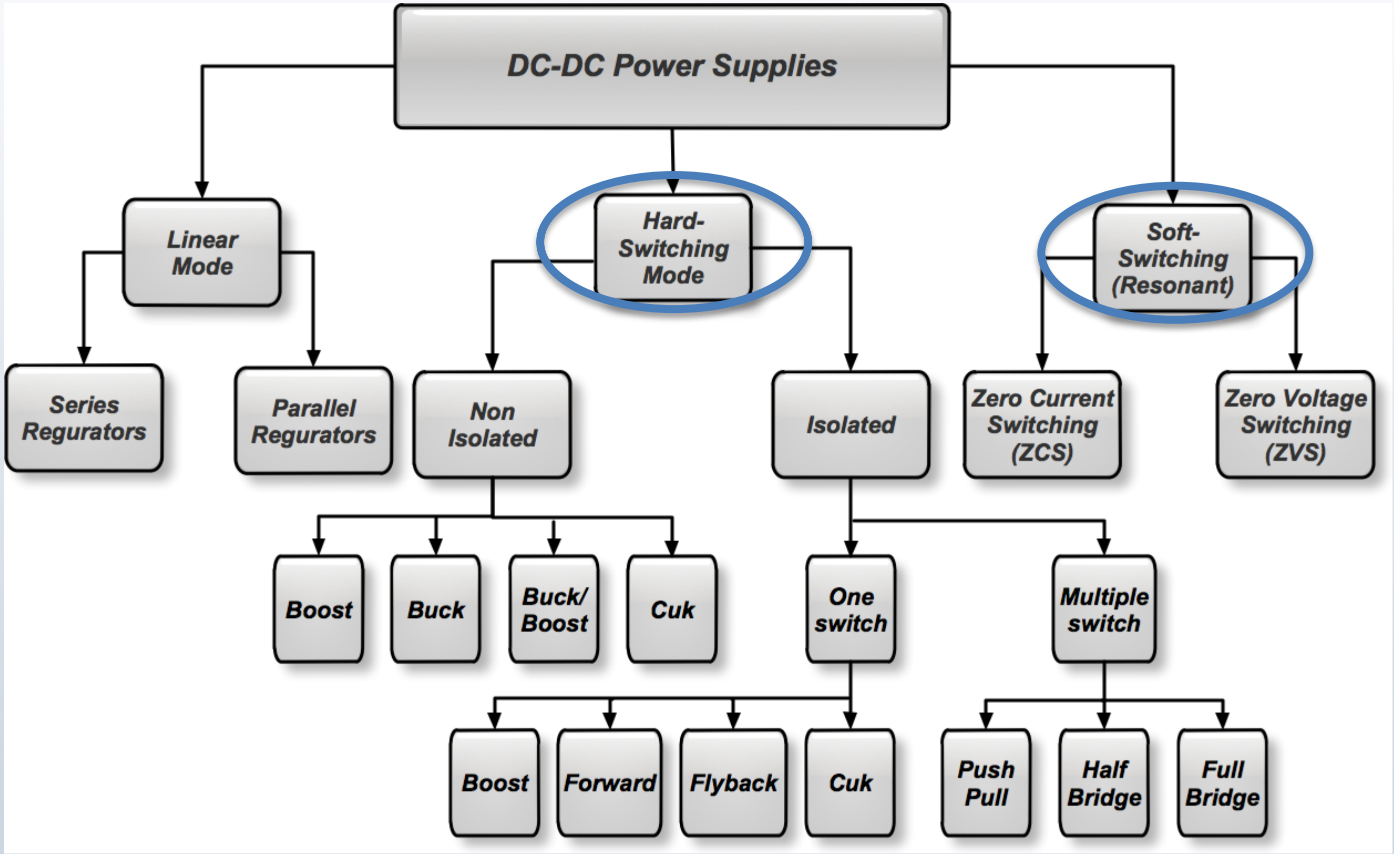
Power Supply: General Layout

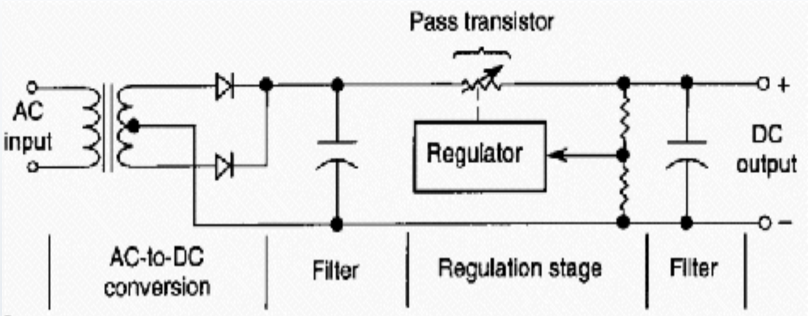


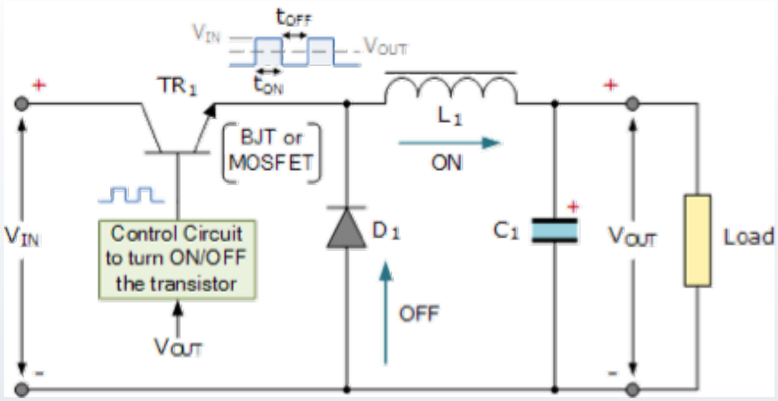


Power Supplies for Magnets



Linear mode Converter vs Switched Mode Converter





Linear Converter

- ☺ High dynamic for the output voltage regulation
- ☺ Poor output voltage ripple
- ☹ Low Efficency → Loss proportional to I_{LOAD} and non-zero $V_{TRANISITOR}$)

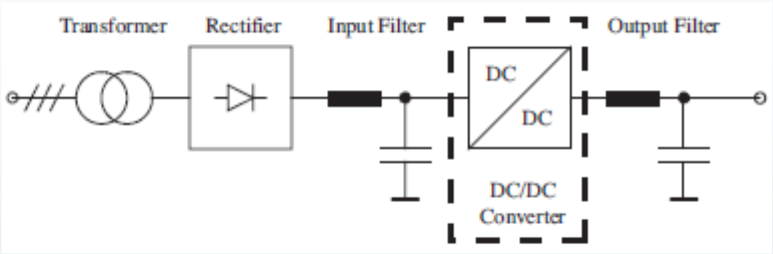
Mainly used in low-power application

Switched-Mode Converter

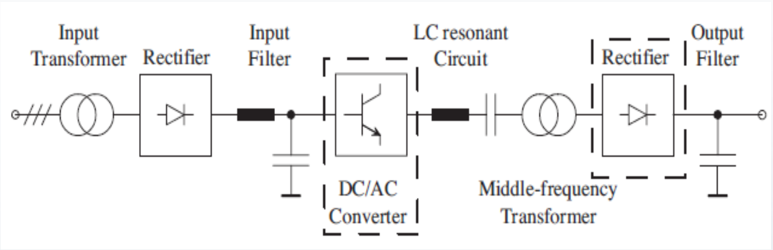
- ☺ High Efficency and High power density → Loss related only to the swittching losses and low conduction losses
- ☹ EMC emission
- ☹ Needed output filter to reduce output voltage ripple

Used in low and high power applications.

Switched Mode Converter



Direct DC/DC converter



DC/DC Converters with an intermediary AC stage

Direct DC/DC Converter

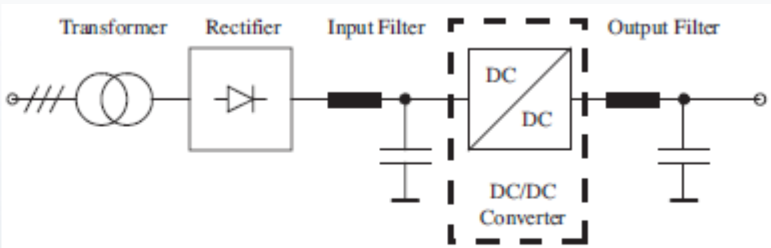
Only SINGLE stage is used to adjust voltage levels. They are classified according to the galvanic insulation of a transformer

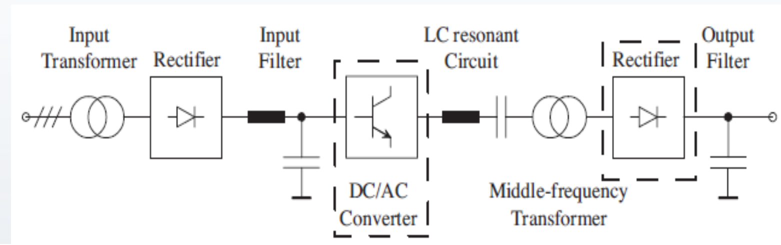
- Insulated
  - Forward DC/DC converter
  - Flyback DC/DC converter
- Non insulated
  - Buck
  - Boost
  - Buck/Boost
  - Cuk

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 te DC/AC converter in order to maximise its efficency

Switched Mode Converter





Optimization of Switched Mode Power Converter

1. Reduction of switch stress
2. Reduction of conduction loss
3. Optimization of switch frequency

age

Dir

mediary

Only SINGLE stag
They are classifie
insulation of a tra

ed by the

- Insulated
  - Forward DC/DC converter
  - Flyback DC/DC converter
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  - Cuk

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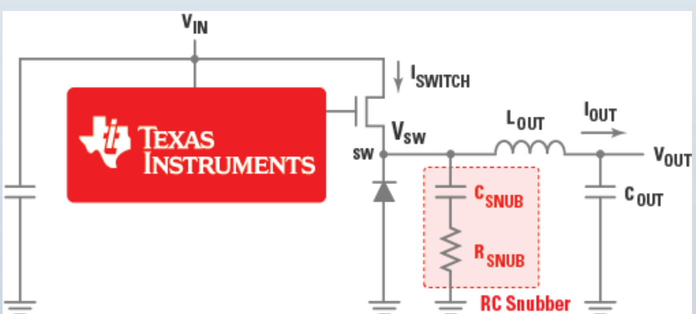
Hard Switching vs Soft Switching Power Supplies

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
- ☹ Overall Power supply efficiency doesn't change respect to the configuration without snubber



Soft Switching

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- ☺ Attenuation of harmonics in the range of tens of kHz

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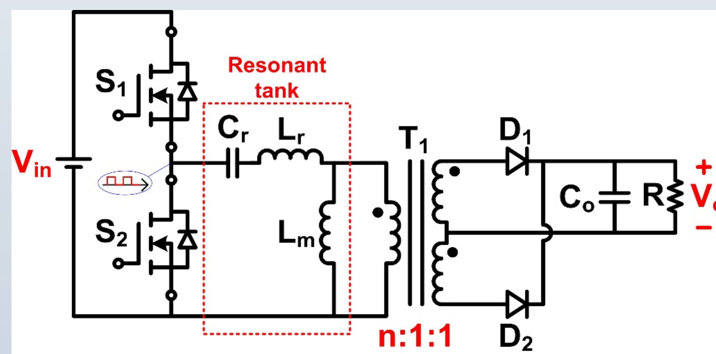

Hard Switching vs Soft Switching Power Supplies

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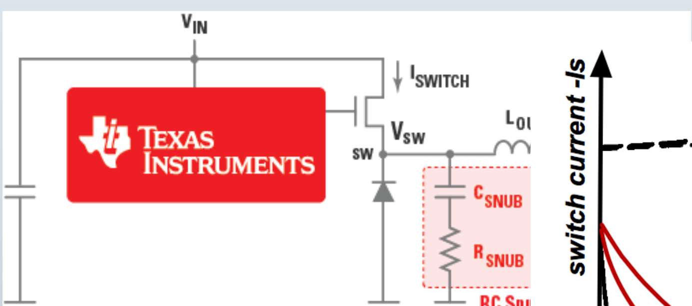
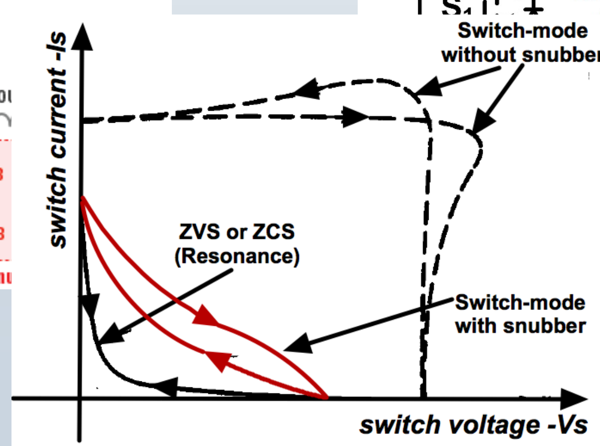
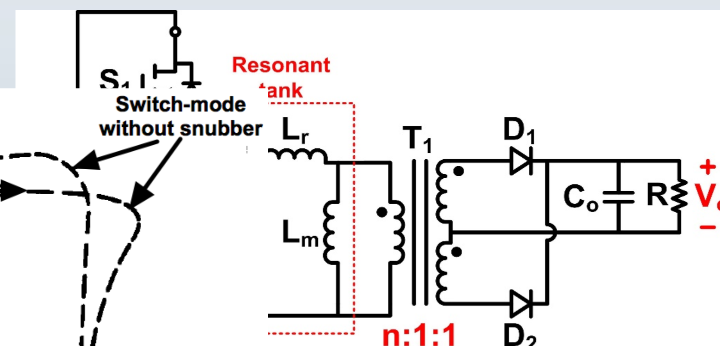
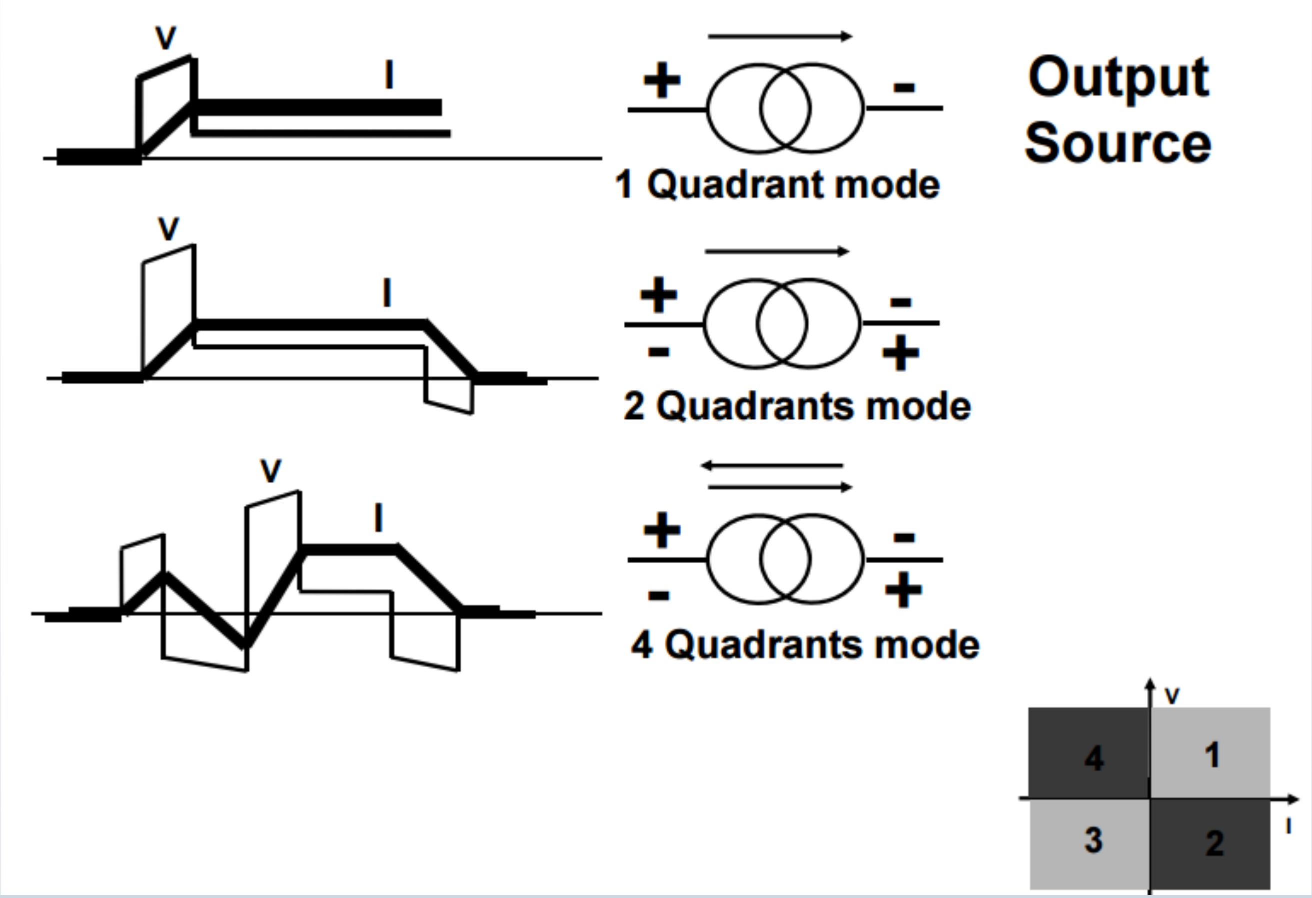


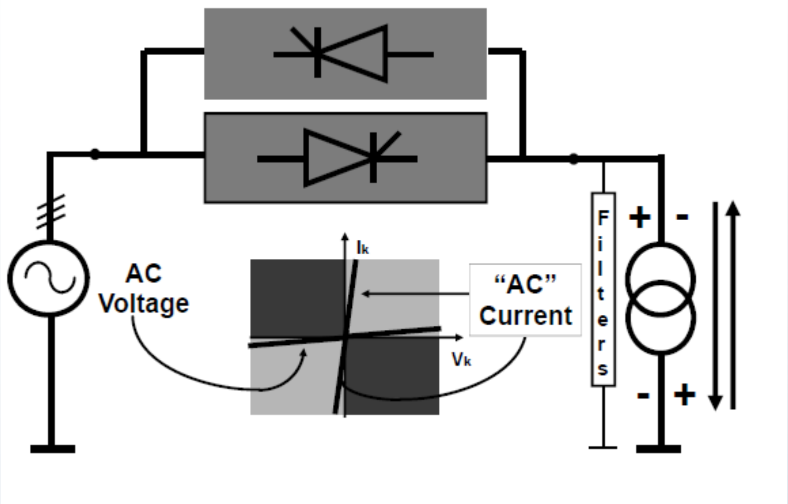




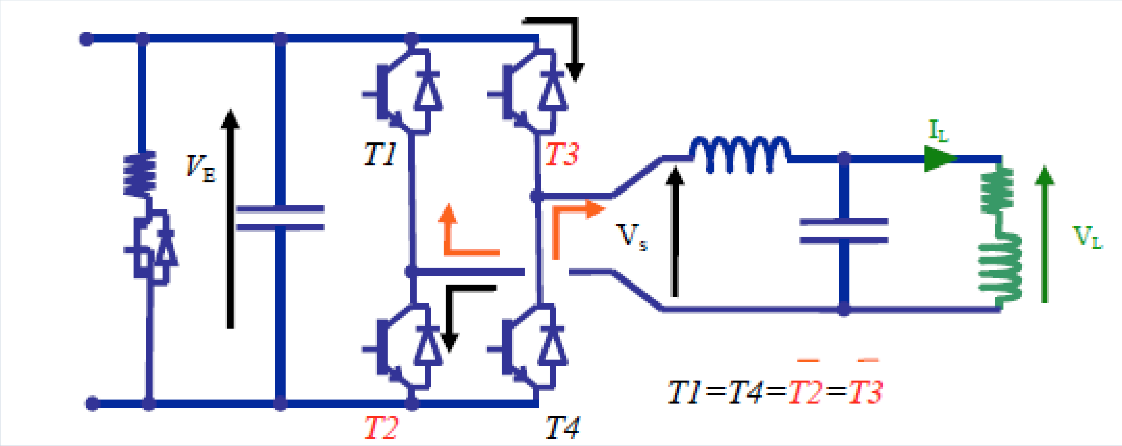
Operating Modes



Power Supply - 4 Quadrants mode

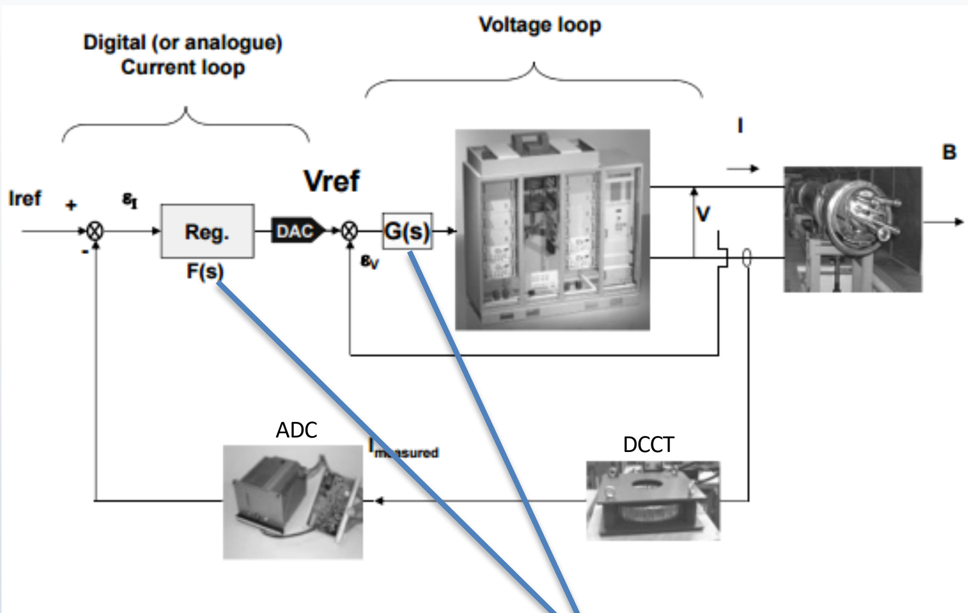


Direct Converter: Antiparallel Thyristor Bridge

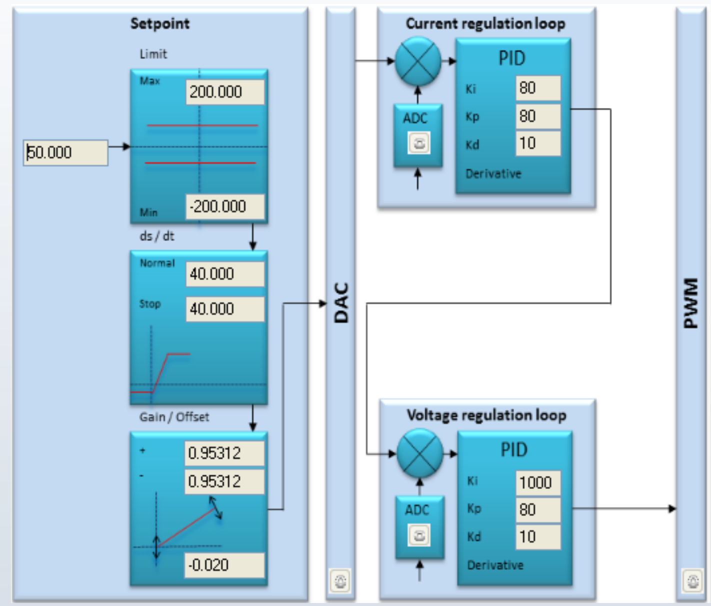


Full bridge

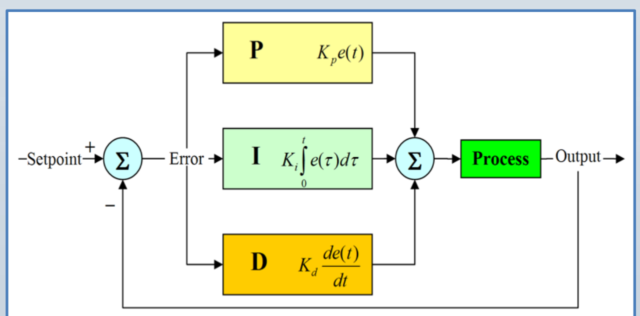
Power Converter Control



Power Converter Control Diagram



Power Converter Control GUI

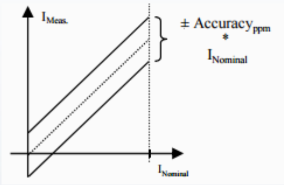


P.I.D. Block Scheme

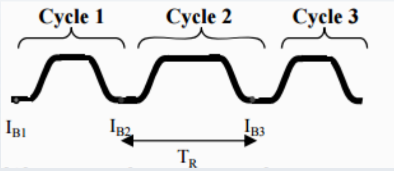
Power Converter for Magnets – Performance Requirements

PRECISION

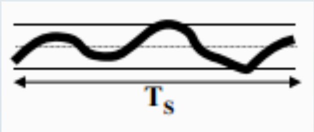
Accuracy
Long term setting or measuring uncertainty taking into consideration the full range of permissible changes of operating and environmental conditions.



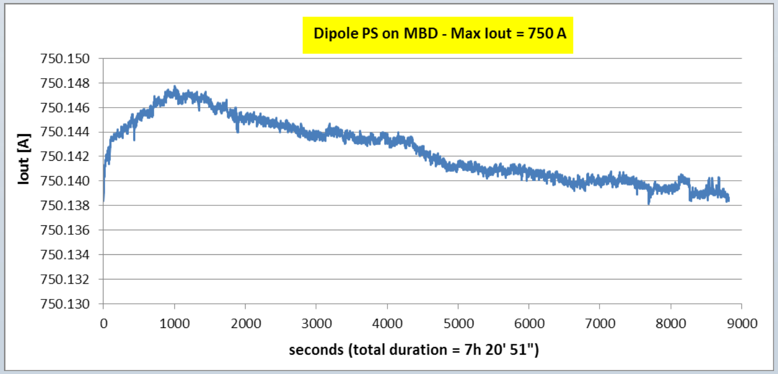
Reproducibility
Uncertainty in returning to a set of previous working values from cycle to cycle of the machine.



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)

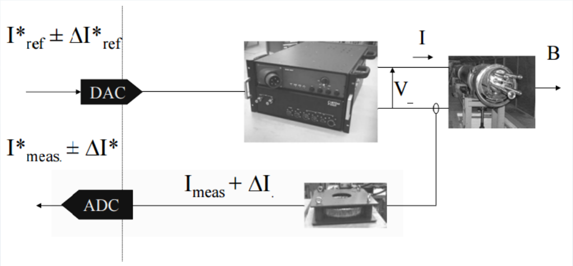


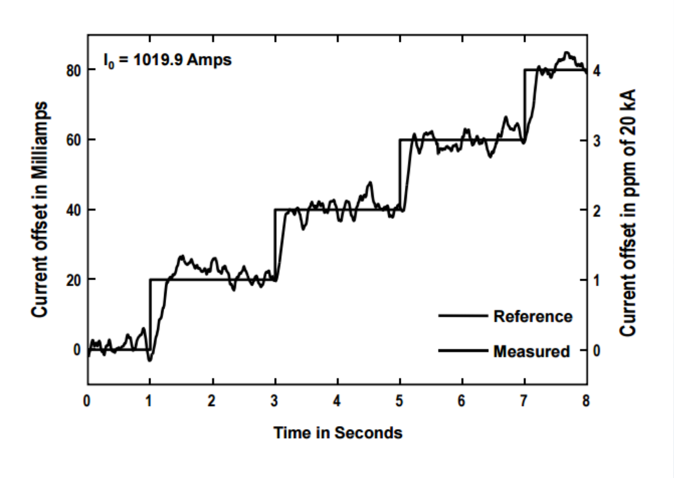
Power Supply Long term stability test

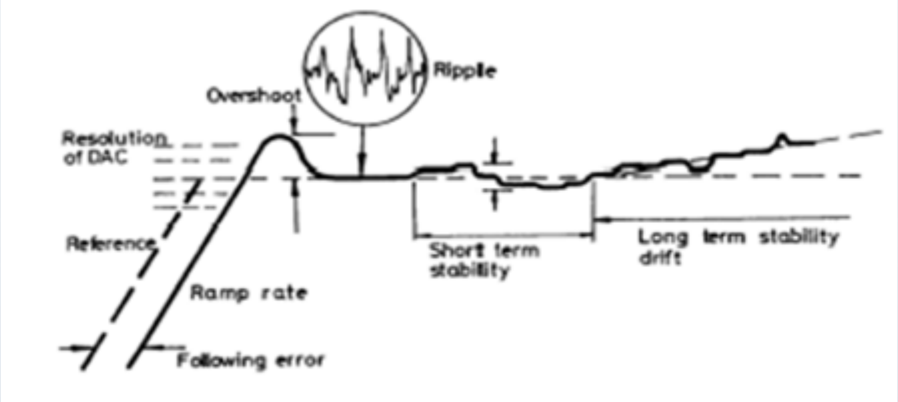
Power Converter for Magnets – Performance Requirements

Resolution

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



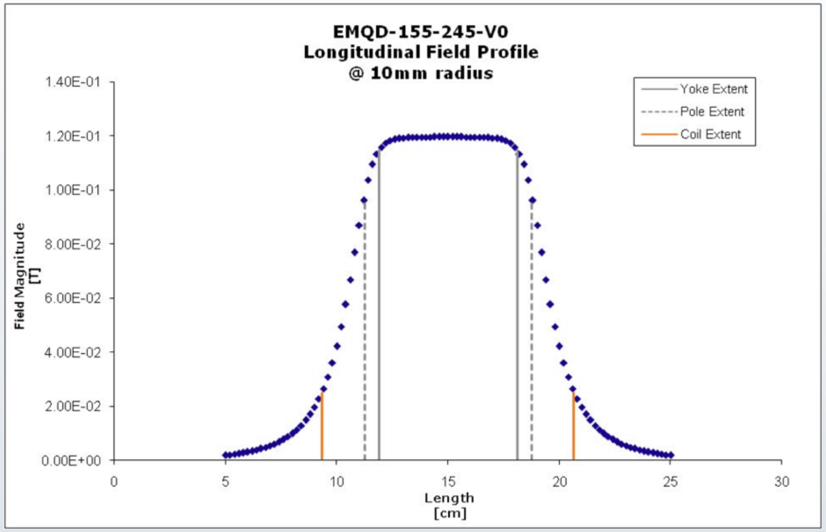




Magnetic length

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):

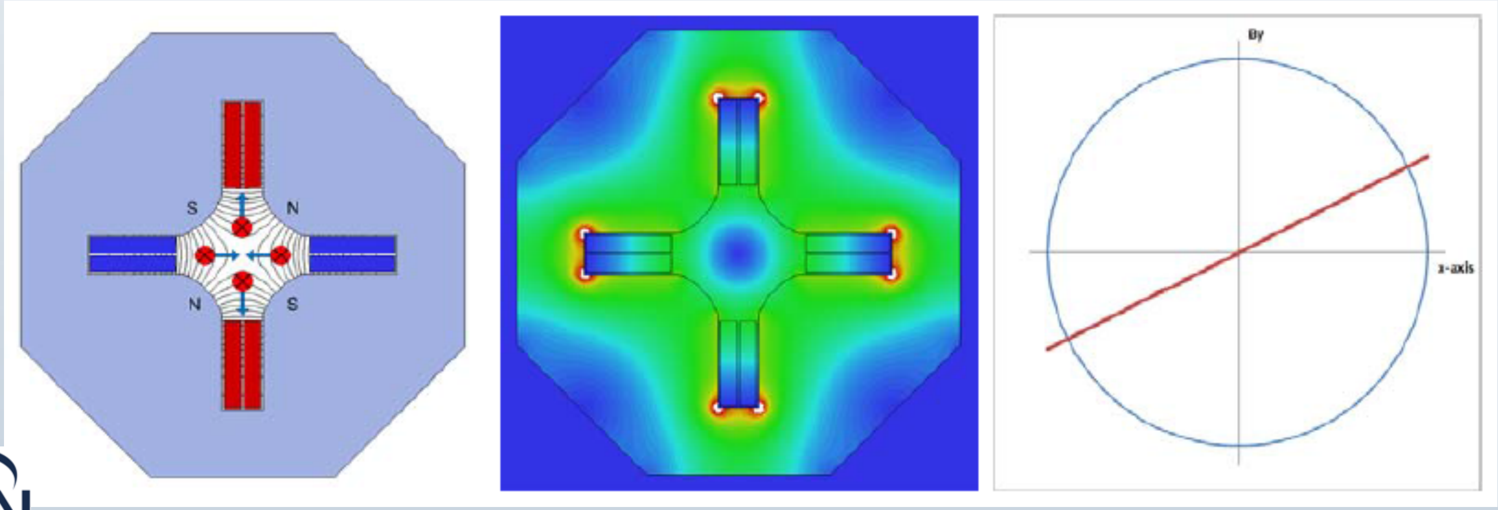
$$B_z = Gx$$

$$B_x = Gz$$

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.

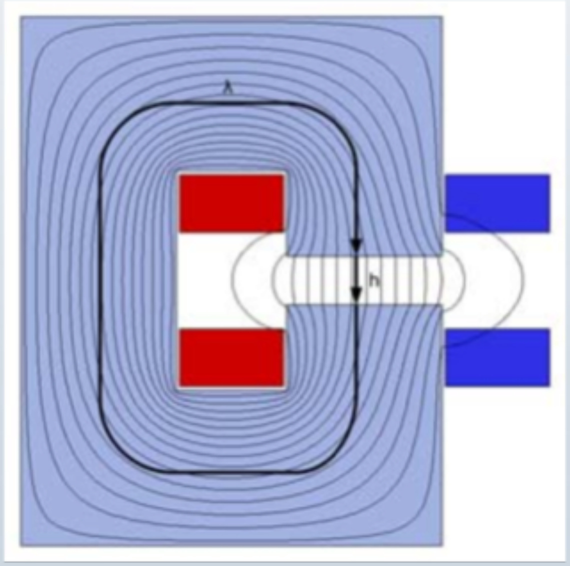
In our coordinate system: $G = \frac{dB_z}{dx}$



B vs I (dipole)

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

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



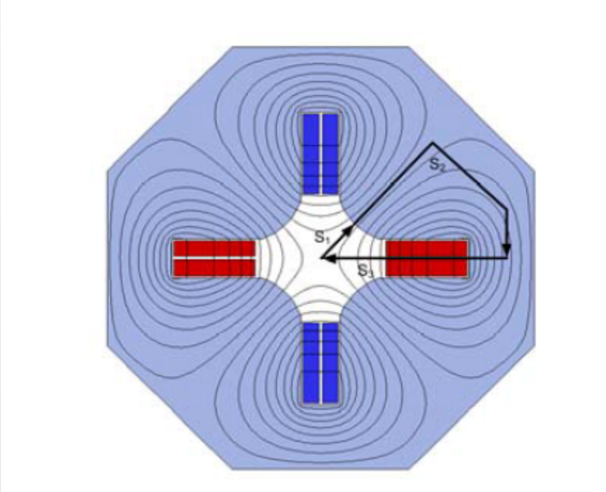
B vs I (quadrupole)

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…)

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**
   - current scan at a fixed position

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

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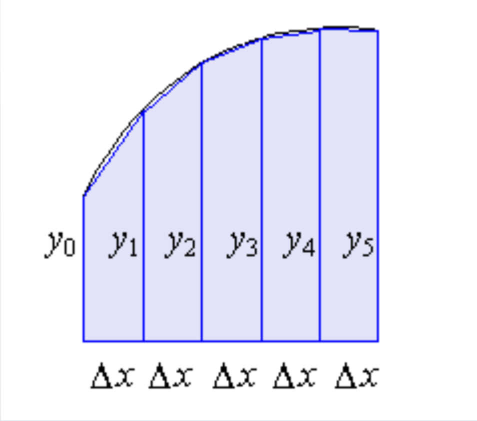
Trapezoidal rule to evaluate with Excel the general integral

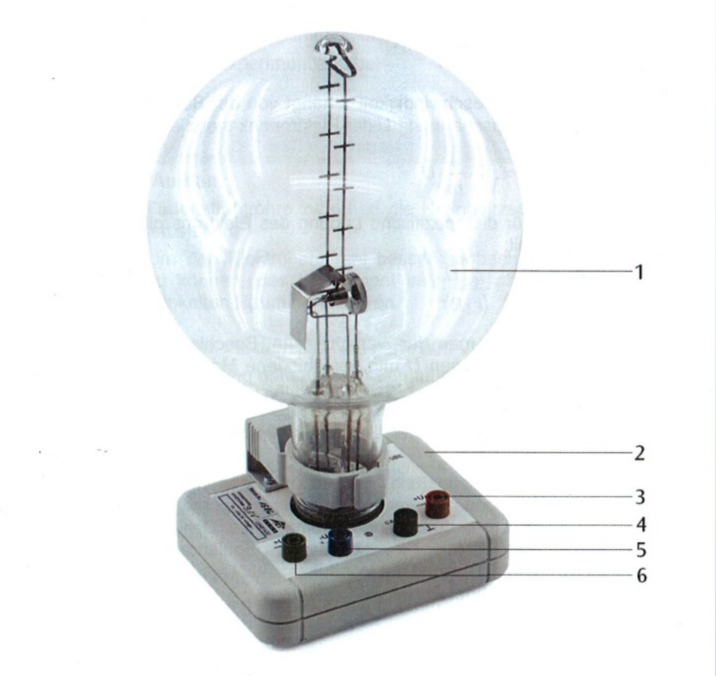
$$\int y dx = \frac{\Delta x}{2}(y_1 + 2y_2 + 2y_3 + \cdots + 2y_{n-2} + 2y_{n-1} + y_n)$$



Measurement of the e/m ratio

An electron gun, placed inside a glass bulb filled with neon gas, emits an electron beam. The gas atoms are ionized and a straight luminescent beam is produced.

When a homogeneous magnetic field is applied, the electrons deflect, and the trajectory radius can be measured



Helmholtz coils

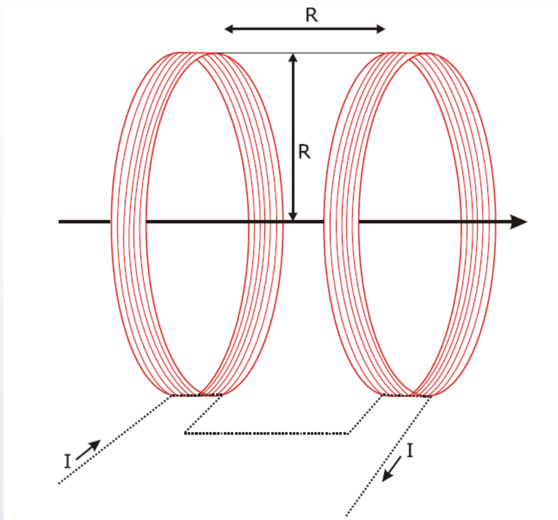
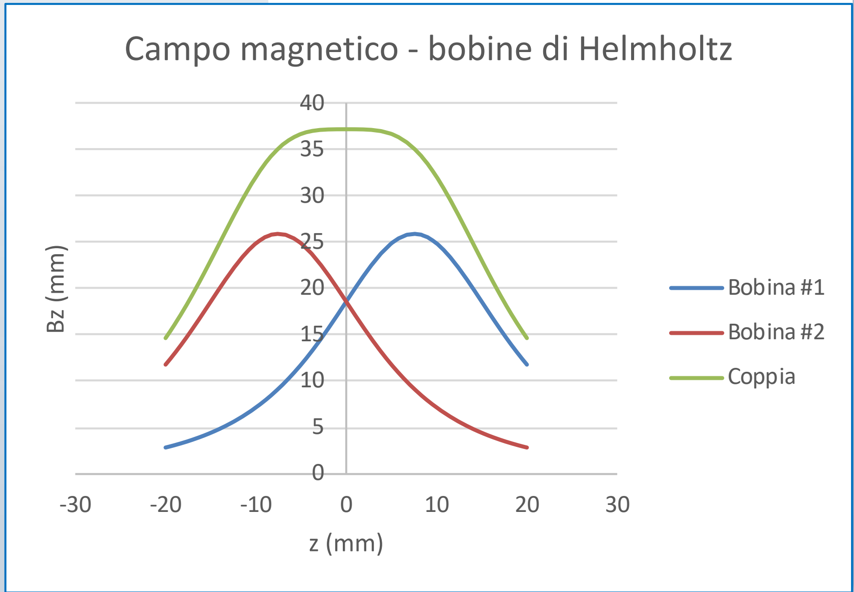


Fig. 1 Bobine nella geometria di Helmholtz

Two narrow coils with radius R are placed in parallel at a distance R. Combining the magnetic fields produced, we get a volume with a reasonably uniform magnetic field

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



In our setup:

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

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Measurement of the electron specific charge

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

  → $m\frac{v^2}{r} = evB$
- v is related to the gun accel. voltage: $\frac{1}{2}mv^2 = q\Delta V = eU$

So, we get: $v = \sqrt{\frac{2eU}{m}}$

Putting v in the equation:

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

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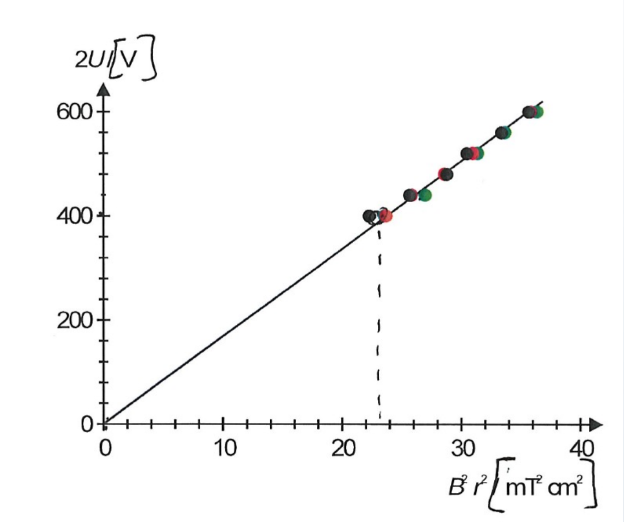
Measurement of the electron specific charge

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

A variation of B (changing the supply voltage) will modify the radius r.

- Graph U vs r^2B^2 for several B values.
- Calculate e/m.



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