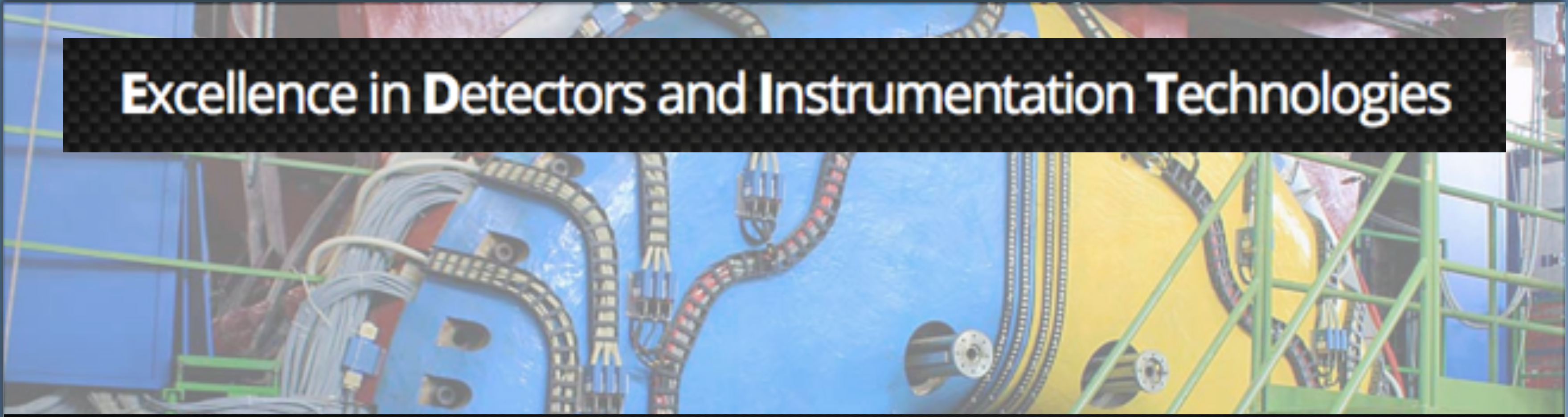
Excellence in Detectors and Instrumentation Technologies



ACCELERATOR LABORATORY

MAGNETS IN ACCELERATORS

INFN
Istituto Nazionale di Fisica Nucleare

EDIT 2015
INTERNATIONAL SCHOOL

CERN

Magnets in Accelerators:

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

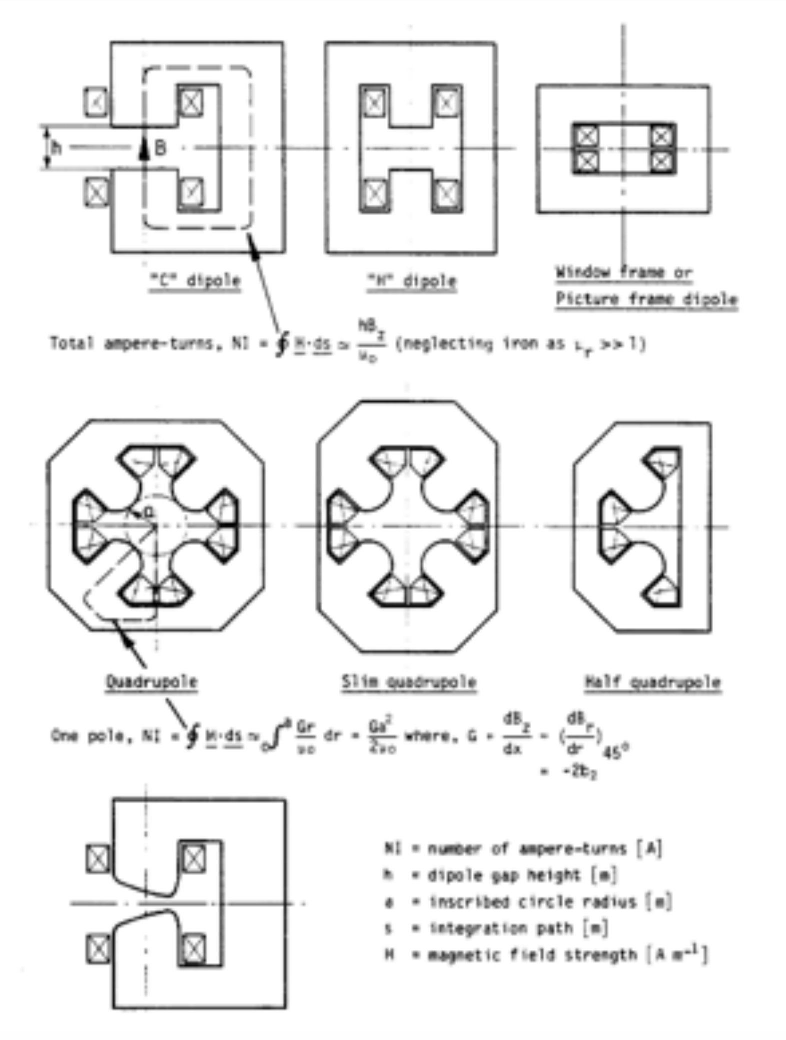
Accelerator's Magnets

- Dipoles
- Quadrupoles
- Sextupoles
- Octupoles
- Wigglers
- Solenoids
- …

Detector's Magnets

- Large Solenoids

Magnets in Accelerators:



Total ampere-turns, $NI = \oint \underline{H}\cdot\underline{ds} \simeq \frac{hB_z}{\mu_0}$ (neglecting iron as $\mu_r >> 1$)

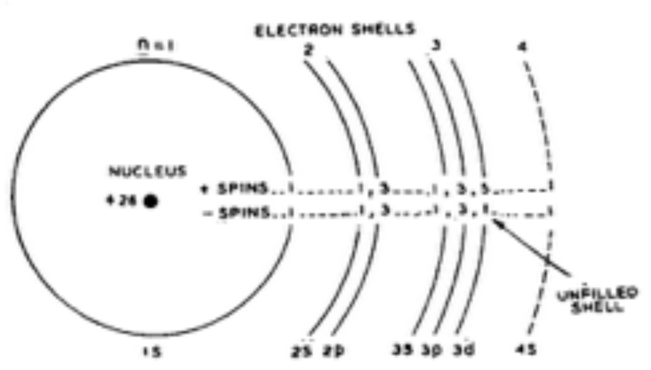
One pole, $NI = \oint \underline{H}\cdot\underline{ds} \approx \int_0^a \frac{Gr}{\mu_0}\, dr = \frac{Ga^2}{2\mu_0}$ where, $G = \frac{dB_z}{dx} = \left(\frac{dB_r}{dr}\right)_{45°}$
$= -2b_2$

NI = number of ampere-turns [A]
h = dipole gap height [m]
a = inscribed circle radius [m]
s = integration path [m]
H = magnetic field strength [A m^{-1}]

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 are the main ferromagnetic elements, together with some of their alloys and some compounds of rare-earth metals

The effect disappeares when the material is heated over a certain temperature, called Curie Temperature, which depends on the material

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. Moreover, laminated steel assure better reproducible steel quality.

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

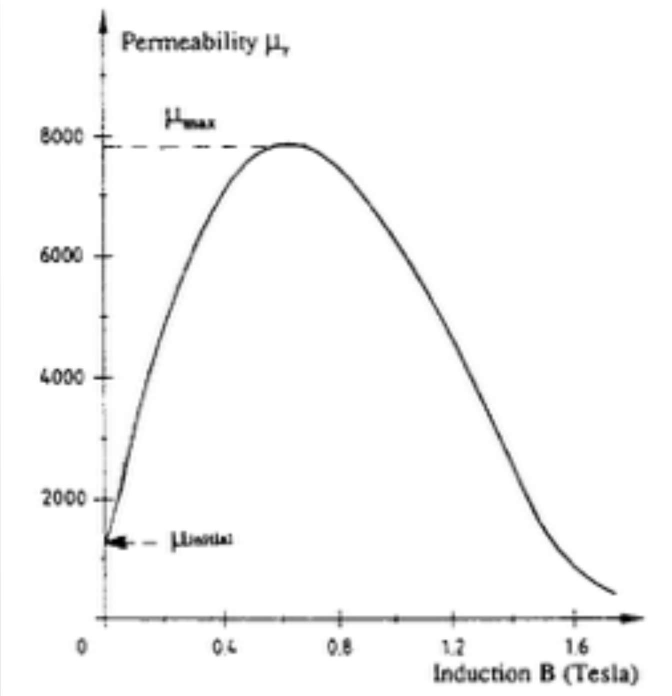
Typical sheet thickness is in the range 0.3 – 1.5 mm

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)

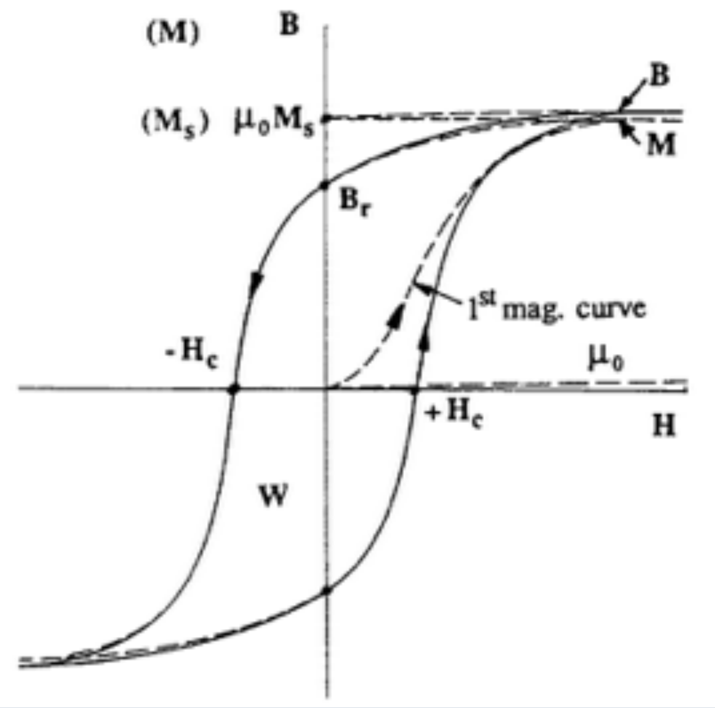
Inside a ferromagnetic material the permeability is a function of the magnetic induction B:

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



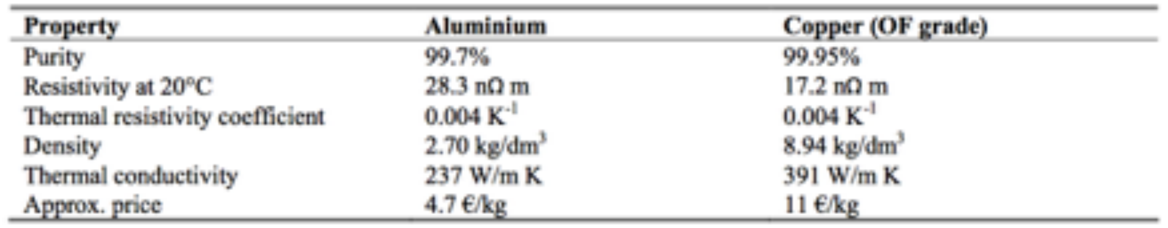
Materials for electromagnets: Ferromagnetism

The hysteresis loop



Materials for electromagnets: Conductors

Common materials used for the coil fabrication are basically OFHC Copper and Aluminum (NbTi and Nb$_3$Sn for superconducting coils)



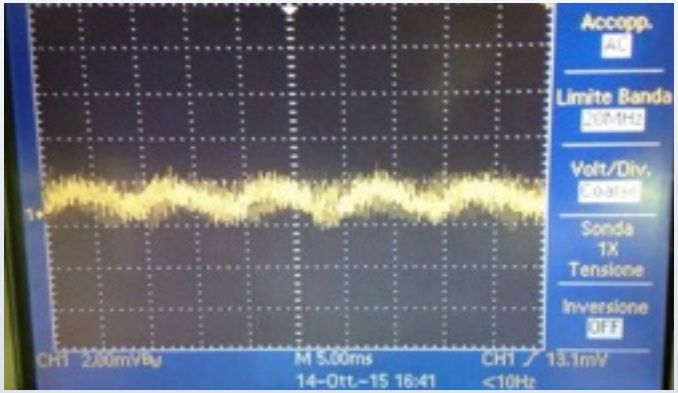
Property	Aluminium	Copper (OF grade)
Purity	99.7%	99.95%
Resistivity at 20°C	28.3 nΩ m	17.2 nΩ m
Thermal resistivity coefficient	0.004 K^{-1}	0.004 K^{-1}
Density	2.70 kg/dm^3	8.94 kg/dm^3
Thermal conductivity	237 W/m K	391 W/m K
Approx. price	4.7 €/kg	11 €/kg

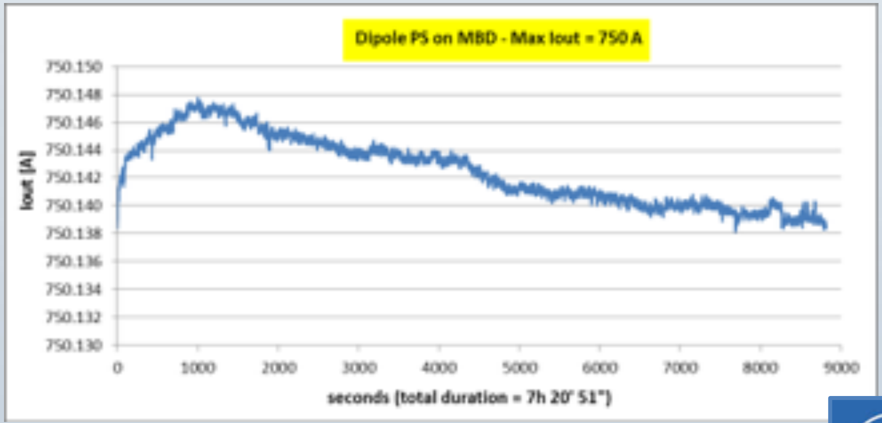
Coil design should take in account some requirements as:

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

MAGNETS POWER SUPPLIES MAIN REQUIREMENTS

- High accuracy in current setting
  - Low ripple
  - High current stability
- Power factor ≈1
- Accuracy
- EMC





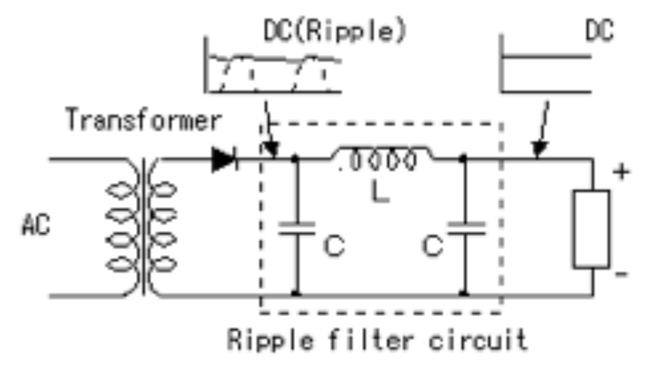
MAIN SCOPE OF POWER SUPPLIES DESIGNER

- Ripple and noise

- Slew rate

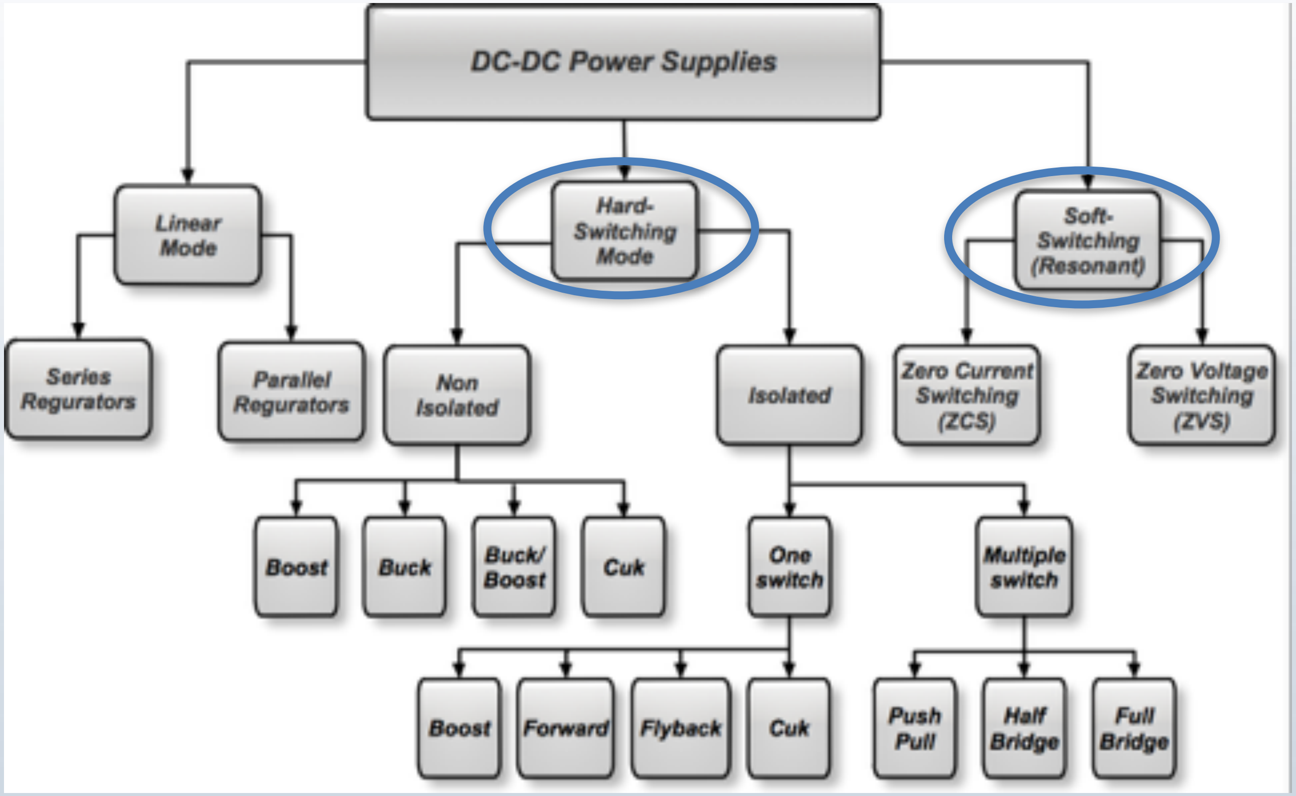
FILTER

- Transient response



Increasing of slew rate and transient response due to capacitances and inductances

POWER CONVERTERS TOPOLOGIES

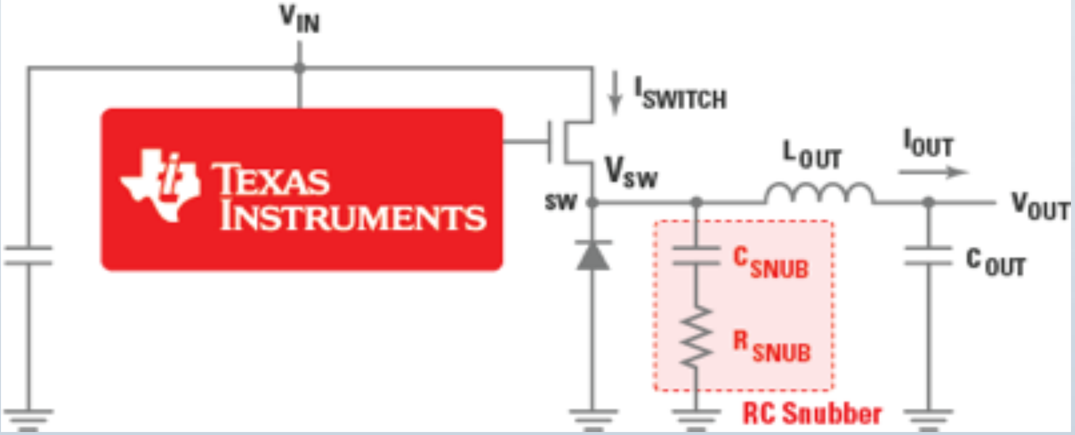


HARD SWITCHING VS RESONANT POWER SUPPLIES

HARD SWITCHING

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

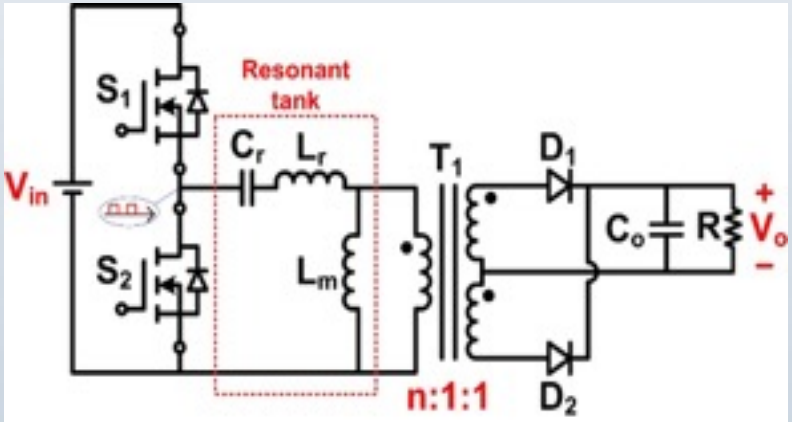
- DRAWBACKS
  - Increased control complexity
  - EMI and RFI problems
  - High cost
  - Snubber circuit to reduce the losses at high switching frequencies

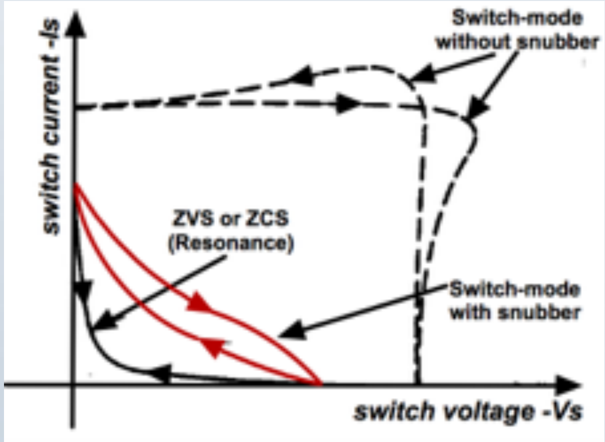


HARD SWITCHING VS RESONANT POWER SUPPLIES

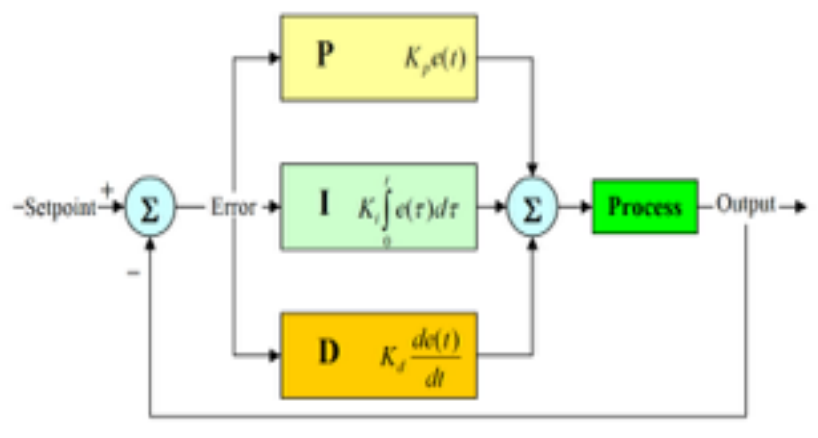
SOFT SWITCHING (resonant)

- ADVANTAGES
  - Switching losses reduction
  - Magnetics parts size reduction
  - Higher efficiency
  - Attenuation of harmonics in the range of tens of kHz
- DRAWBACKS
  - Increased control complexity
  - EMI and RFI problems
  - High cost





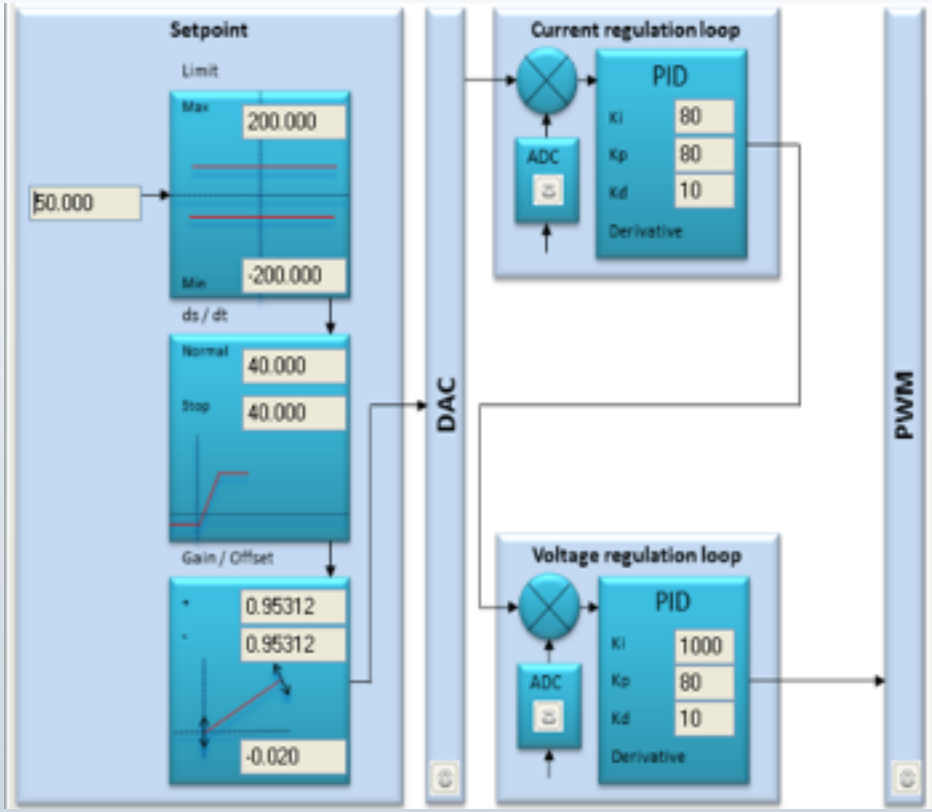
CONTROL METHODS: PID



VOLTAGE CONTROL

- Output voltage moves from its set-point in response to variation of output current.
- The voltage value is measured at the PS output and compared with a reference generating an error signal
- The error signal is applied to the input of a compensation PID-type block

CONTROL METHODS



Max 200.000
50.000
Min -200.000

ds / dt
Normal 40.000
Stop 40.000

Gain / Offset
+ 0.95312
- 0.95312
-0.020

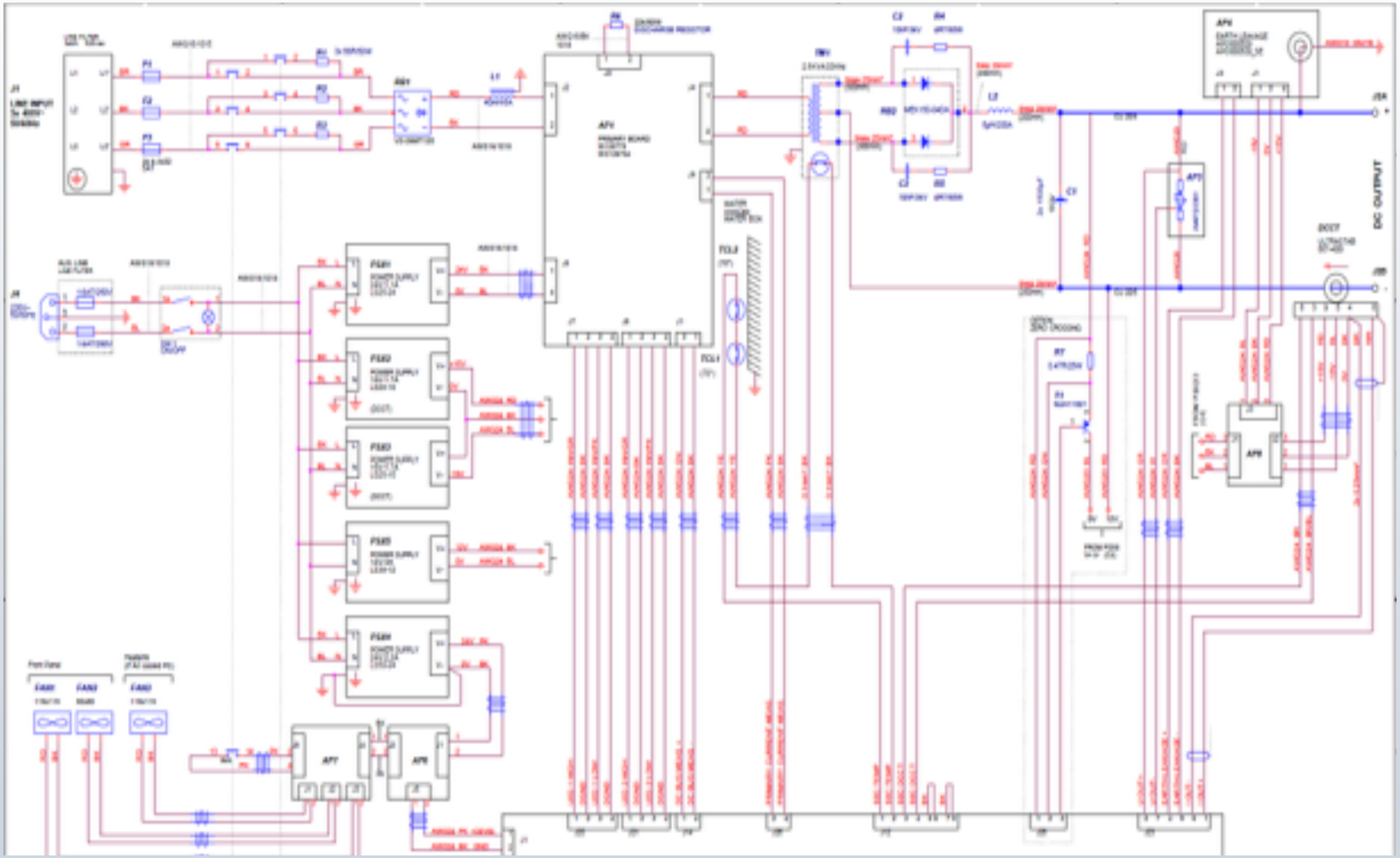
Current regulation loop
Ki 80
Kp 80
Kd 10

Voltage regulation loop
Ki 1000
Kp 80
Kd 10

CURRENT CONTROL

In current control an inductor current is used as a feedback state. However current and voltage reference values are not independent and they specifically require knowledge of the load. To overcome this obstacle, two loops of control are normally arranged, the outer loop manages the output voltage error by generating the necessary current reference whilst the inner loop makes the converter to act as a current source.

ELI-NP START 11 ELECTRICAL SCHEME DESIGN



Magnetic measurements

We will measure the following parameters of a quadrupole:

1. magnetic length
2. magnetic gradient
3. B vs I
4. estimation of field quality

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

Equipment:

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

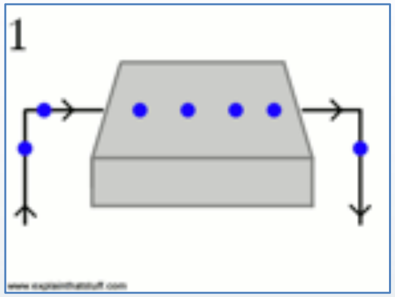
Hall probe

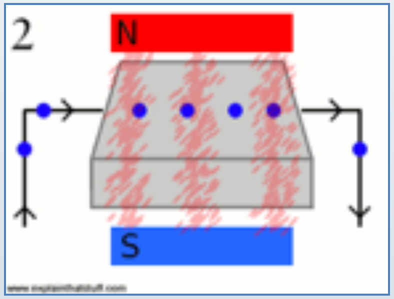
A *Hall probe* is a transducer that varies its output voltage in response to a magnetic field (Hall effect).

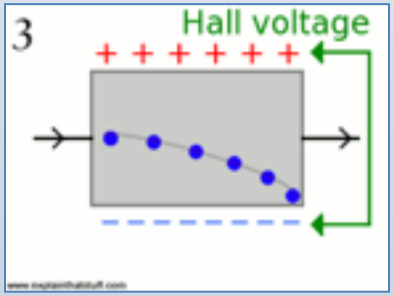
1. When an electric current flows through a material, electrons move through it in pretty much a straight line.
2. Put the material in a magnetic field. The Lorentz force acts on the electrons and makes them deviate from their straight-line path.
3. The electrons in this example would bend as shown. 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



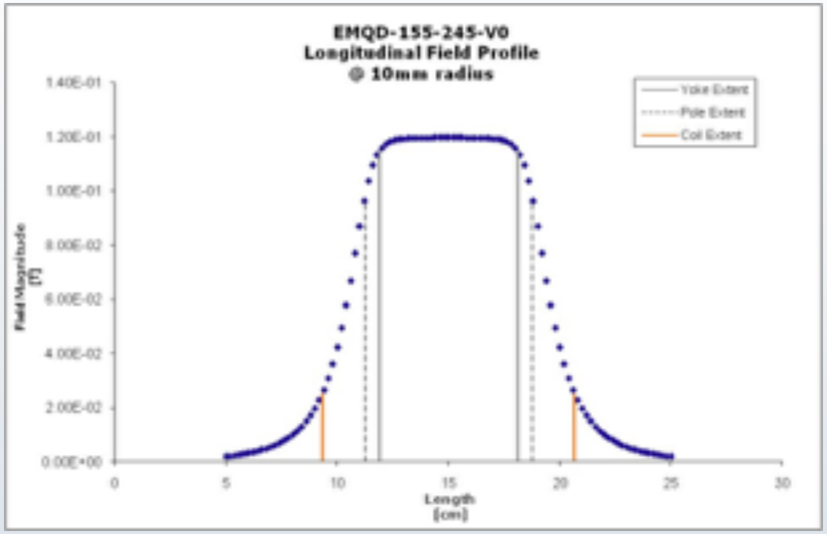




Magnetic length

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

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



Measurements:

- Longitudinal scans at different x (to check dependence on x position)
- Longitudinal scans at different I (to check dependence on excitation current)

Gradient

The components of the ideal magnetic field in the plane transverse to the beam are given by (general equations):

$$B_z = Gx$$

$$B_x = Gz$$

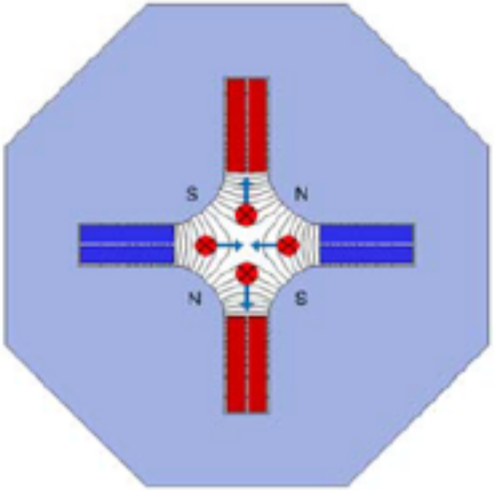
G (T/m) is the field gradient of the vertical component in the horizontal direction (or equivalently, the gradient of the horizontal component in the vertical direction). Sign of G: the quadrupole focuses or defocuses.

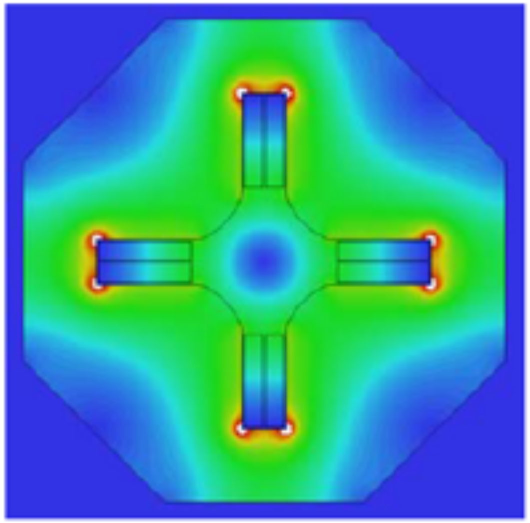
In our coordinate system: $G = \frac{dB_z}{dx}$

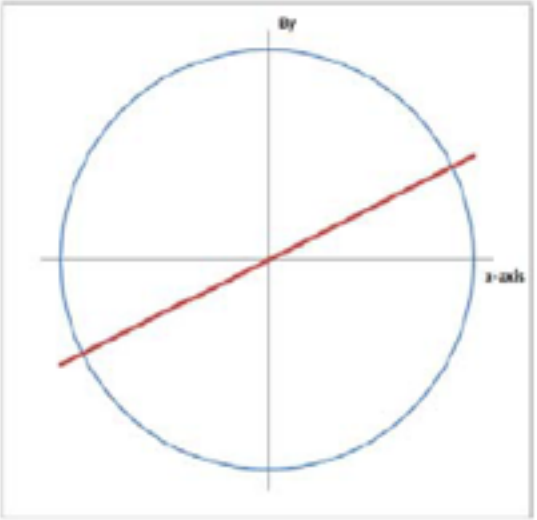
Measurements:

- Radial scan and evaluate the gradient
- Radial scan at different y (to check dependence on longitudinal position)
- Radial scan at different I

Gradient



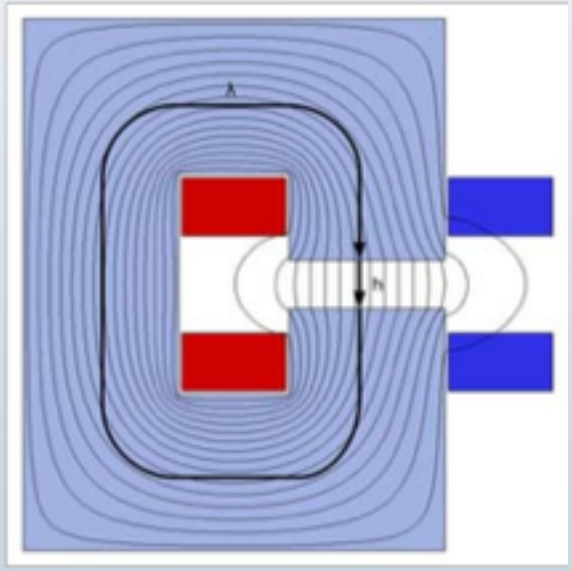




B vs I

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

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



Measurements:

- Choose a position and measure B_z at different I

Field quality estimation

A simple method to judge the field quality of a quadrupole is to evaluate the homogeneity of the gradient in the defined good field region:

$$\frac{\Delta B'}{B'_0} = \frac{B'_z(x,z) - B'_z(0,0)}{B'_z(0,0)}$$

Excercise:

- 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

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