CERN

Basics of Accelerator Science and Technology at CERN

Magnet power supplies

Jean-Paul Burnet

- Definition
- What is special for powering magnets?
- Power supplies requirements
  - Circuit parameters
  - Circuit optimization
  - Power supplies ripples
  - Grounding
  - Magnet protections
  - Current cycles
  - Power supply types
- Power electronics
  - Thyristor technology
  - IGBT technology
  - Power supply association
  - Nested circuits
  - Energy management
  - Discharged power supplies
- Power supply control
  - Control architecture
  - High precision measurement
  - Current regulation
- What should specify an accelerator physicist?

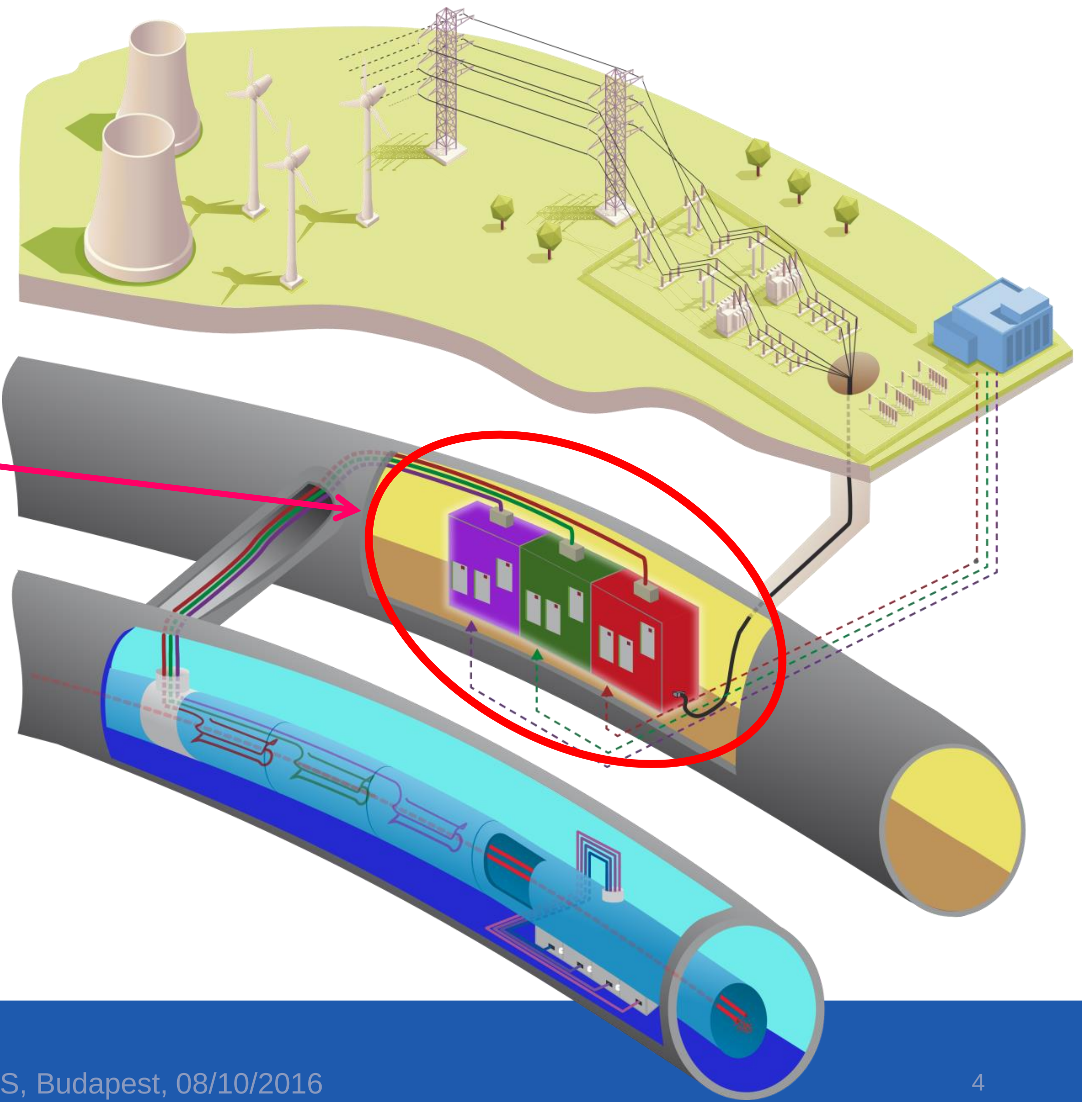
Definition

Wikipedia: A power supply is a device that supplies electric power to an electrical load.

Power supplies are everywhere:

Computer, electronics, motor drives,…

Here, the presentation covers only the very special ones for particles accelerators : Magnet power supplies



Power supply # power converter

US labs uses magnet power supply

CERN accelerator uses power converter

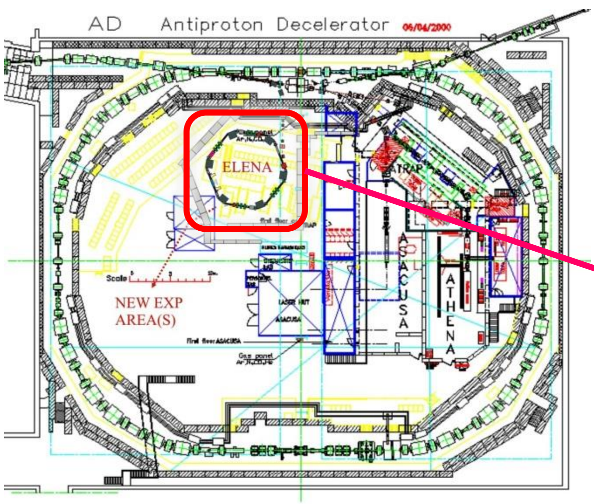
CERN experiment uses power supply

Introduction

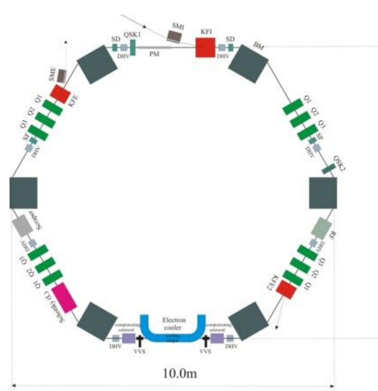
This talk will describe the beginning of a project for a new particles accelerator.

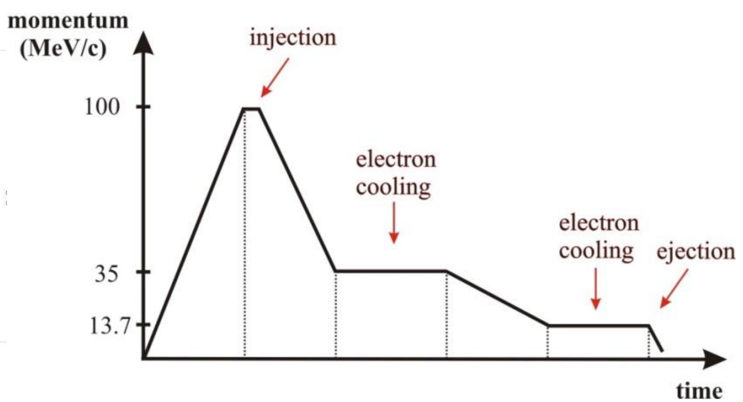
Before any design of power supplies, the first step is to write a functional specification which describes the powering of the accelerator and the performance required by the power supplies.

Many technical points have to be raised and worked for optimization.



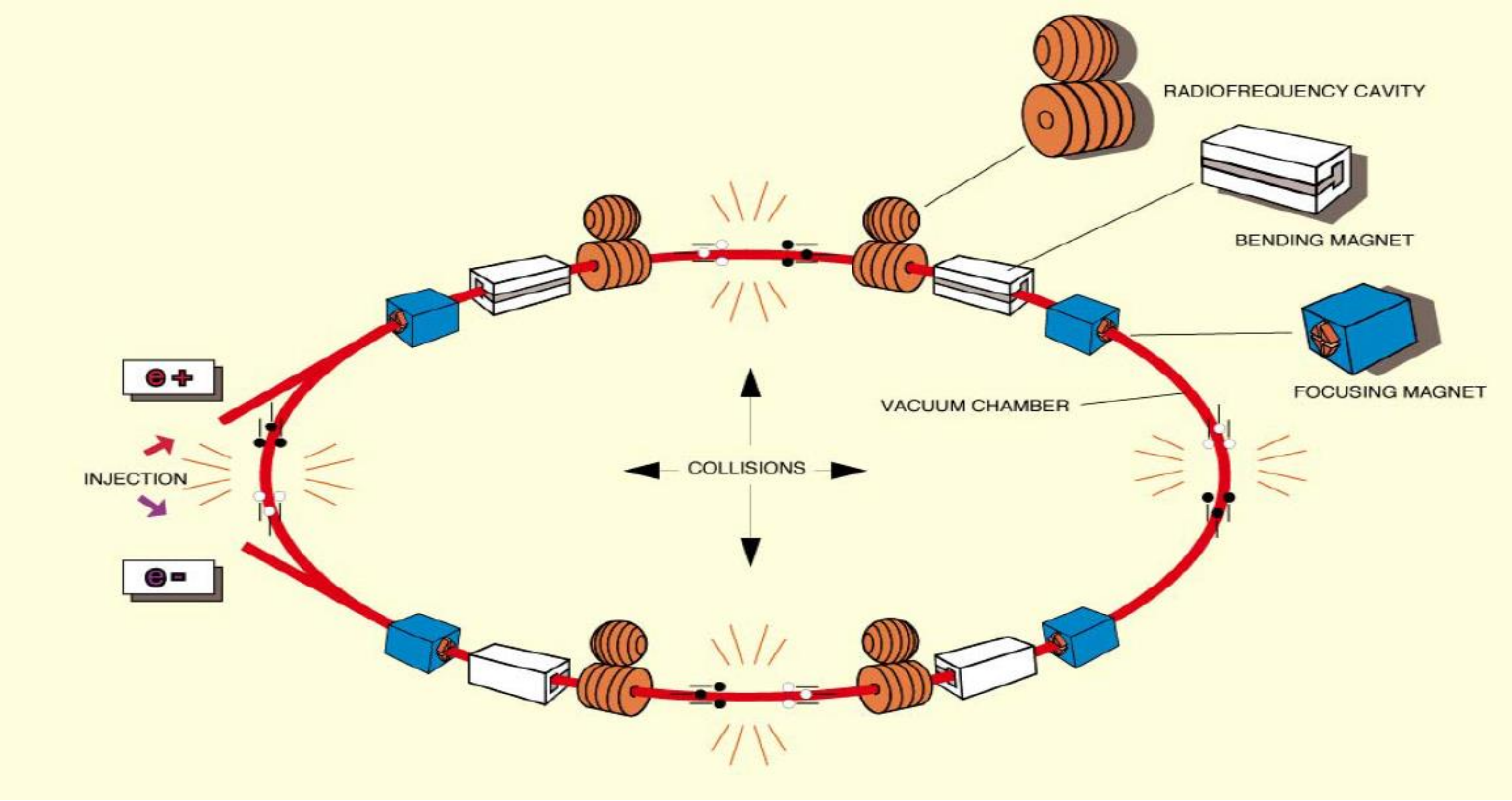
ELENA: Extra Low Energy Antiproton Ring





What do we power?

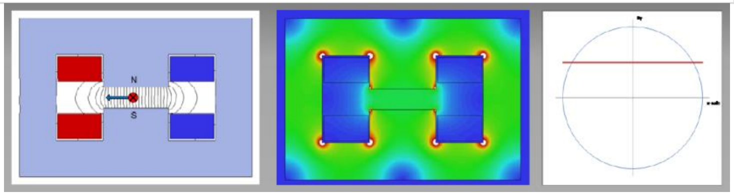
The **main loads** of a particles accelerator are the magnets and the radiofrequency system.



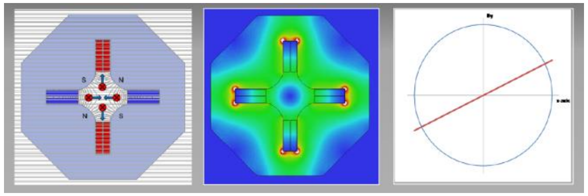
What do we power?

The magnet families are :

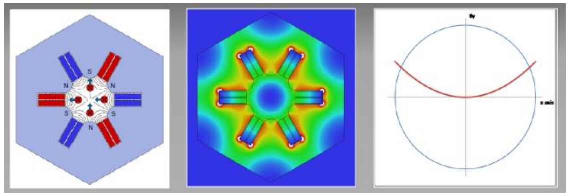
Dipole: Bend the beam



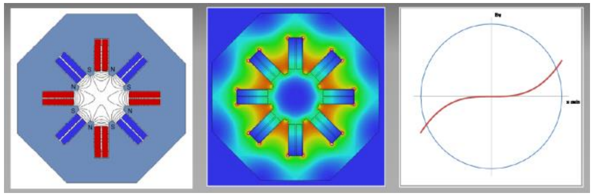
Quadrupole: focus the beam



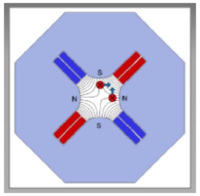
Sextupole: correct chromaticity



Octupole: Landau damping



Skew: coupling horizontal&vertical betatron oscillations

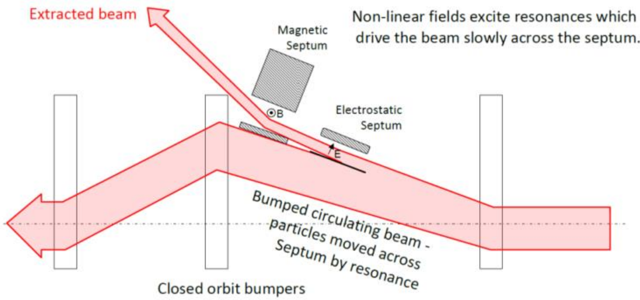


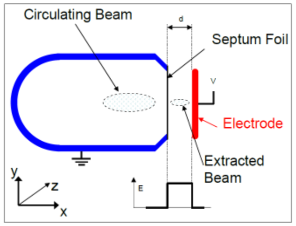
http://cas.web.cern.ch/CAS/Belgium-2009/Lectures/Bruges-lectures.htm

What do we power?

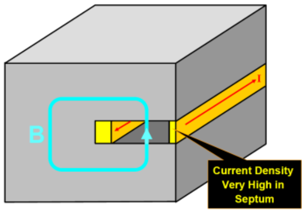
For beam transfer, special magnets are needed. The families are :

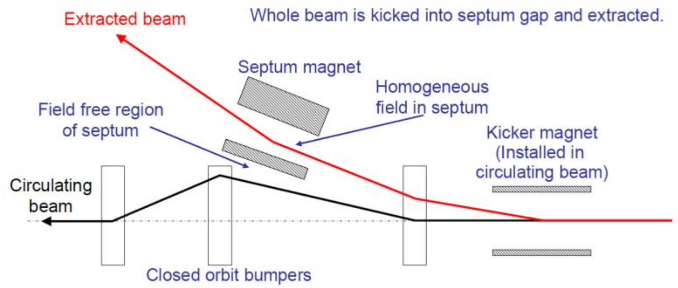
Electrostatic septum





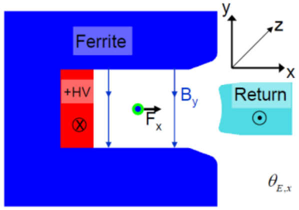
Septum magnet





Kicker Magnet

Rise time # 10ns-1µs



Kicker generators are very special and generally handled by kicker people.

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

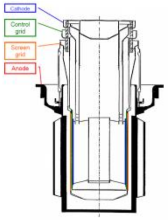
What do we power?

For the radio frequency system, the RF power comes through power amplifiers.

The families of RF power amplifiers are :

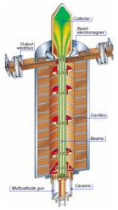
Solid state amplifier, Low power, 100V, 1–100kW

Tetrode, Medium power, 10kV, 100kW



IOT, Medium power, 20-50kV, 10-100kW

Klystron, High power RF, 50-150kV, 1-150MW



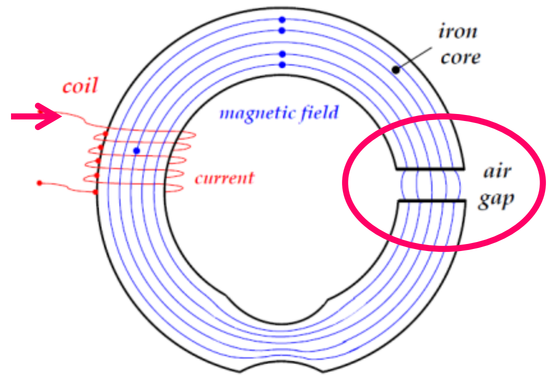
http://cas.web.cern.ch/CAS/Denmark-2010/Lectures/ebeltoft-lectures.html

What is special for powering magnet?

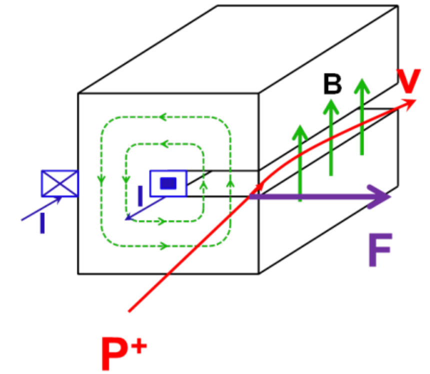
In a synchrotron, the beam energy is proportional to the magnetic field.

The magnet field is generated by the current circulating in the magnet coils.

Magnet current

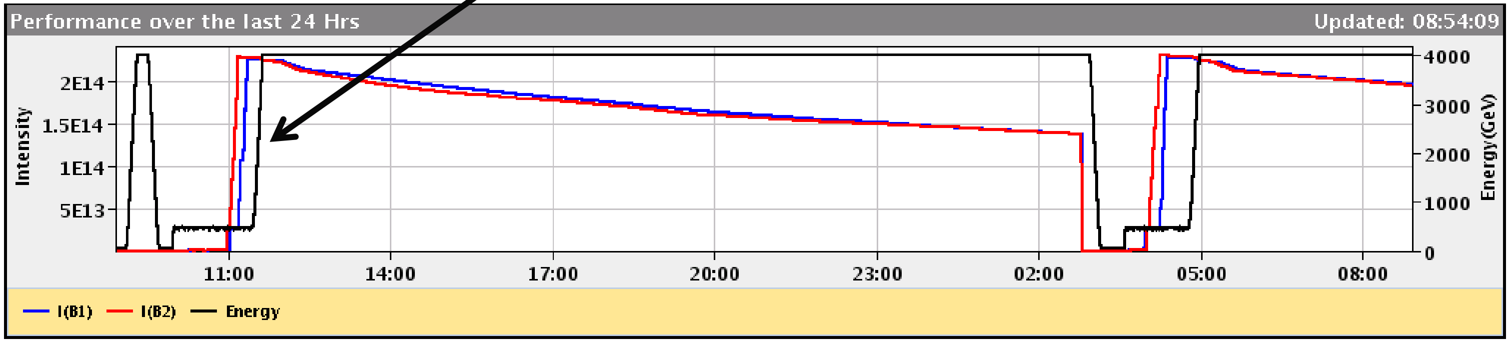


Magnetic field in the air gap



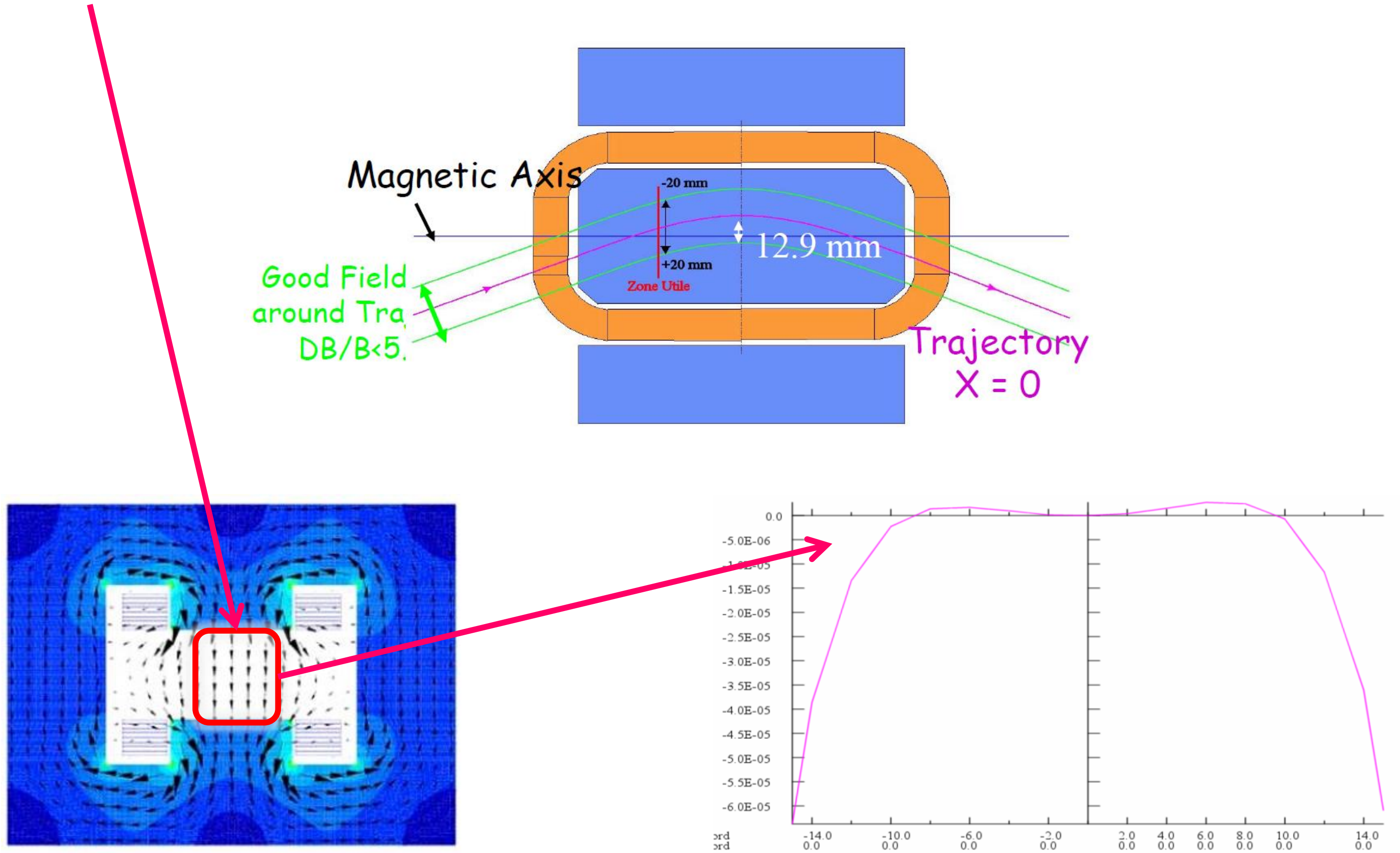
$$NI = \mathcal{R} \times \Phi$$

LHC vistar : Beam Energy = Dipole Current



What is special for powering magnet?

The dipole magnets shall have a high field homogeneity which means a high current stability.
The good field region is defined typically within ±10^{-4} ΔB/B.

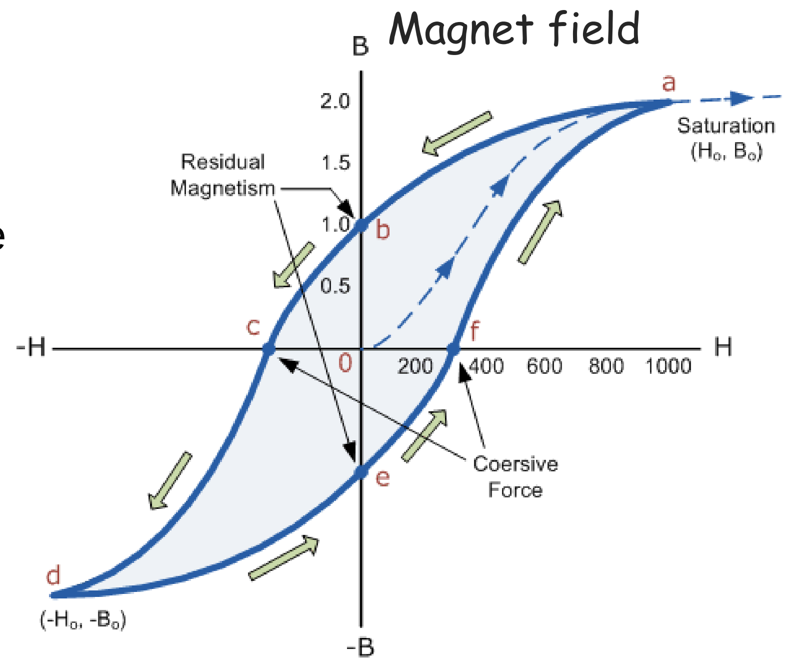


What is special for powering magnet?

The relation between the current and B-field isn't linear due to magnetic hysteresis and eddy currents.

In reality, Beam Energy = kf×Dipole field ≠ ki×Dipole Current

Classical iron yoke

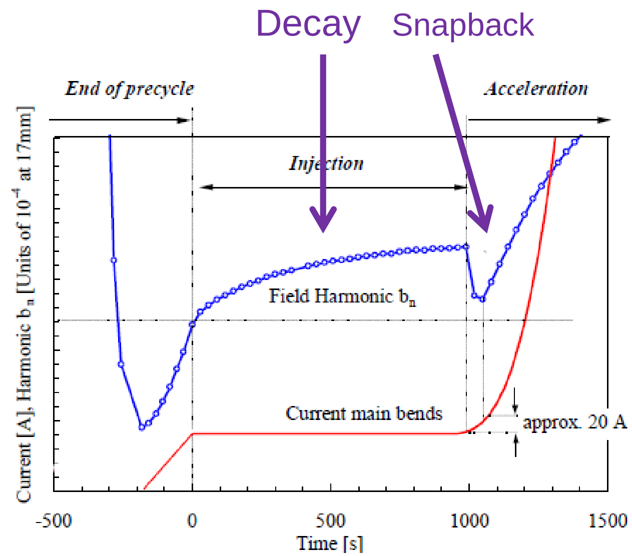


Magnet current

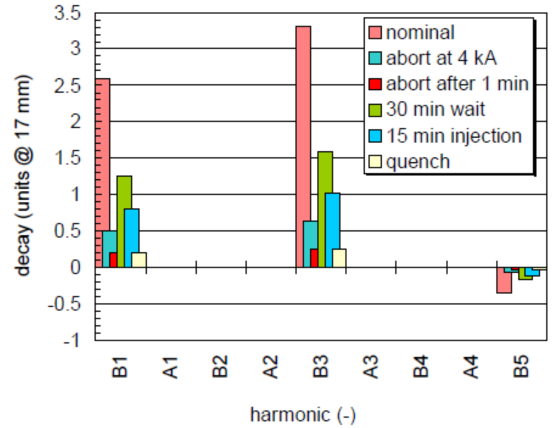
What is special for powering magnet?

For superconducting magnet, the field errors (due to eddy currents) can have dynamic effects.

$$\vec{B}_y + i\vec{B}_x = \sum_{n=1}^{\infty} C_n \left(\frac{z}{R_{ref}}\right)^{n-1} = B_1 \sum_{n=1}^{\infty} \frac{(b_n + i a_n)}{10^4} \left(\frac{z}{R_{ref}}\right)^{n-1}$$



Decay is characterised by a significant drift of the multipole errors when the current in a magnet is held constant, for example during the injection plateau. When the current in a magnet is increased again (for example, at the start of the energy ramp), the multipole errors bounce back ("snap back") to their pre-decay level following an increase of the operating current by approximately 20 A.
For the energy ramp such as described in [3], the snapback takes 50-80 seconds but this can vary if, for example, the rate of change of current in the magnet is changed.



http://accelconf.web.cern.ch/accelconf/e00/PAPERS/MOP7B03.pdf

What is special for powering magnet?

Measuring the magnetic field is very difficult and needs a magnet outside the tunnel.

In most of the synchrotrons, all the magnets (dipole, quadrupole, sextupole, orbit correctors,…) are current control.

The beam energy is controlled by the current of the dipole magnet.

To operate a synchrotron, operator needs to measure the beam position with pick-up.

From control room:

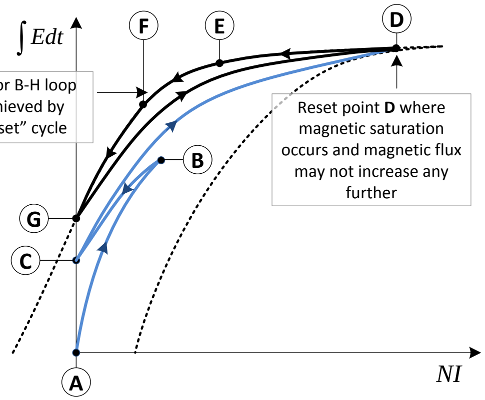
Is my accelerator an Ampere meter ?

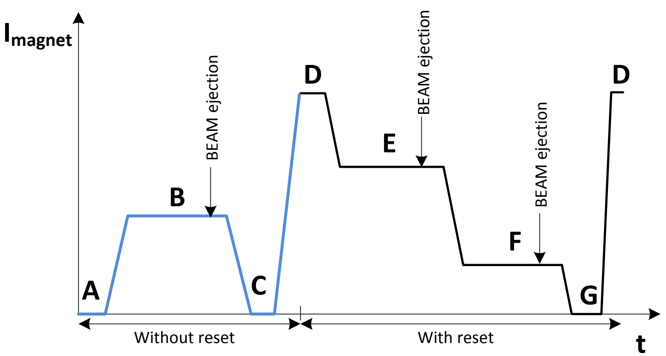
Solutions for magnetic field control

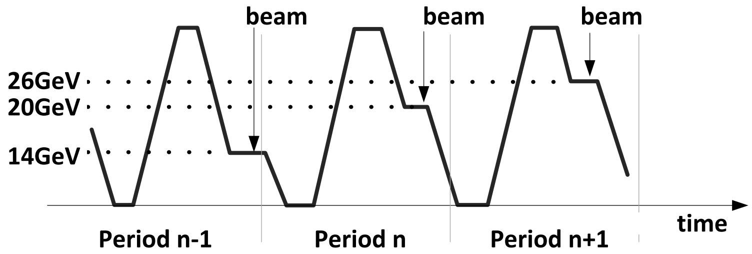
To solve this problem of hysteresis, the classical degauss technique is used.

For a machine working always at the same beam energy, few cycles at beam energy will degauss the magnets. Example LHC precycle.

For machine or transfer line with different beam energies, the degauss has to take place at each cycle. Solution, always go at full saturation in each cycle.







Solutions for magnetic field control

Measuring the magnetic field is very difficult and need a magnet outside the tunnel equipped with magnetic sensors.

In most of the synchrotrons, all the magnets (quadrupole, sextupole, orbit correctors,…) are current control and the beam energy is controlled by the dipole magnet current.

For higher performance, the solutions are :

- Get a high-precision magnetic field model (10^{-4})
- Real time orbit feedback system
- Real time tune feedback
- Real time chromaticity feedback
- Or
- Real-time magnetic field measurement and control (10^{-4})

How an operator change the beam energy with a synchrotron?

To ramp up, the operator increases the dipole magnetic field.

The radiofrequency is giving the energy to the beam, but the RF is automatically adjusted to follow the magnetic field increase (Bdot control).

Power supply requirements

Now, you know that accelerators need high precision power supplies.

What are the main parameters you should define with

accelerator physicists
&
magnet designers?

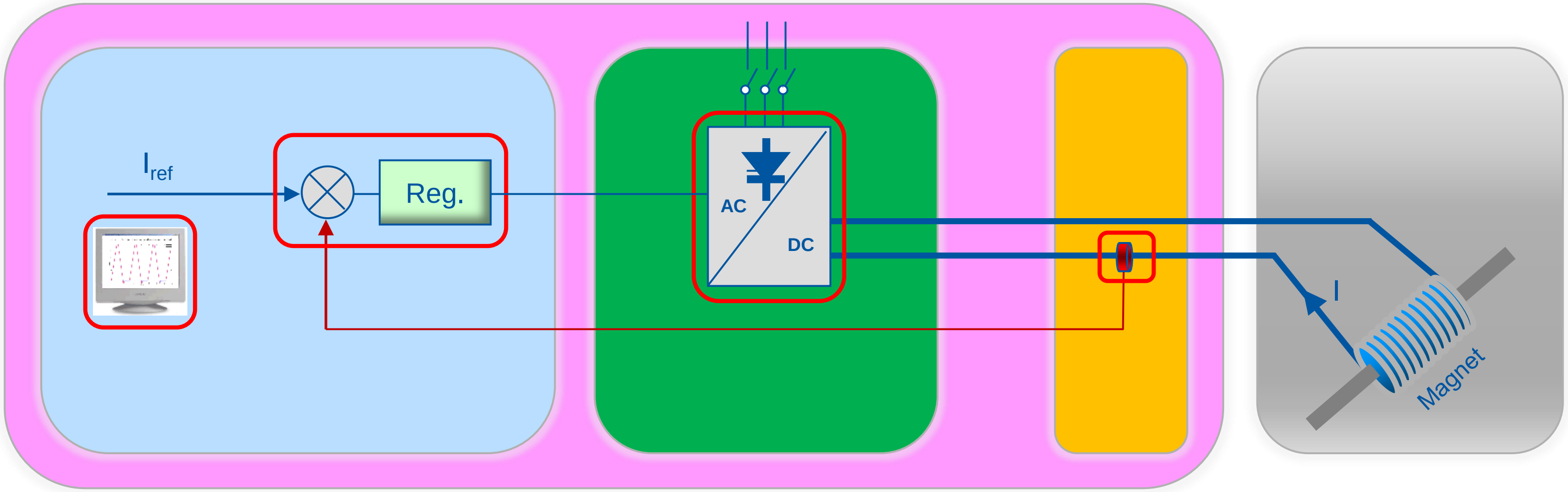
Don’t let the accelerator physicists work alone with the magnet designers.

Powering optimization plays with magnet parameters

The power engineers have to be included in the accelerator design from the beginning!

Power supply requirements

Many points need to be defined :



Power supply control

Power part

Power supply performance

Magnet & circuit optimization

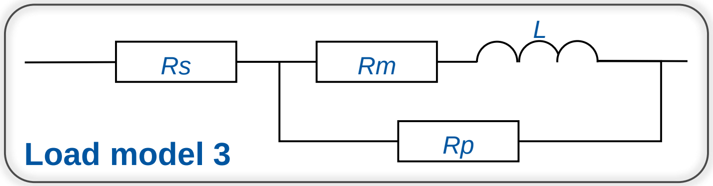
Power supply infrastructure

Magnet parameters

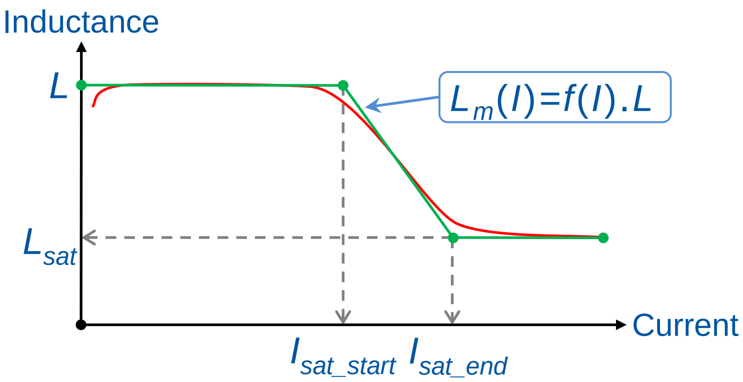
Magnet parameters seen by the power supplies:

- Inductance, in mH
- Resistance, in mΩ
- Current limits
- Voltage limits (insulation class)
- di/dt limits

much better, magnet model including saturation effect.



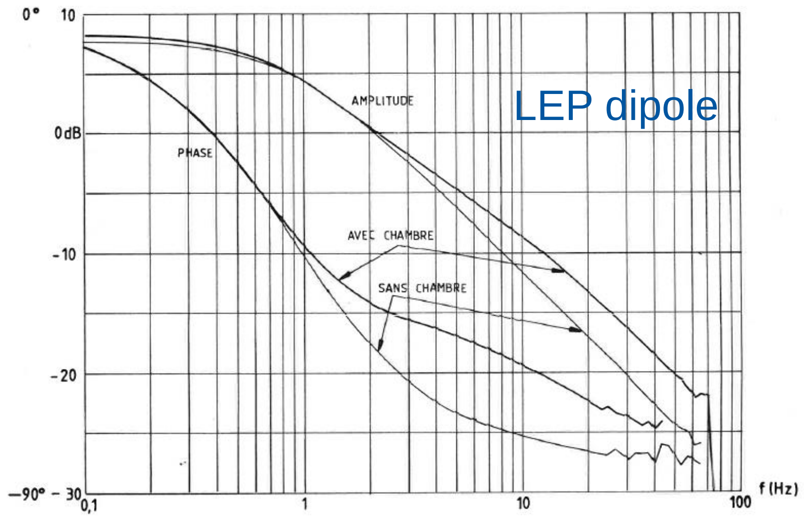
Load Saturation model



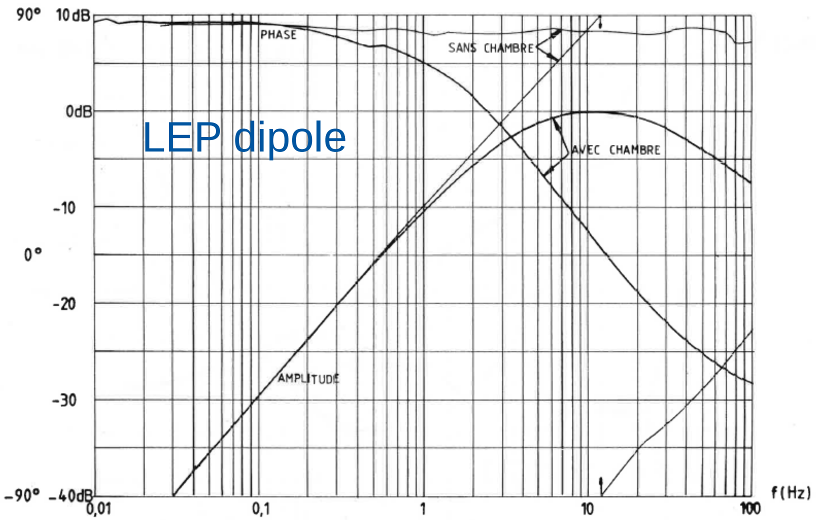
Magnet parameters

Even better, magnet model between B-field and current (impact of the vacuum chamber).

Impact of the vacuum pipe on the magnet transfer function



Impact of the vacuum pipe on the magnetic field



Power supply & magnet optimization

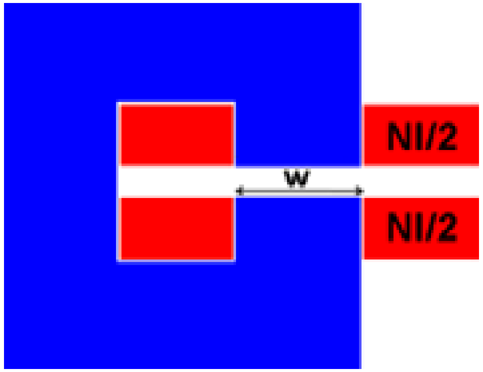
The powering optimization plays with the magnet parameters, the power supply parameters and the circuit layout.

For the same integral field, the magnet can be done in different ways.

The magnet parameters are:

- Number of turns per coil N
- Maximum current I
- Current density in the conductor J
- Length/field strength of the magnet

$B = \mu_0 NI / g$



g: vertical gap

Advantages of large N

- Lower I
- Lower losses in DC cables
- Better efficiency of power supply

Drawbacks of large N

- Higher voltage
- Magnet size (coil are bigger due to insulation)

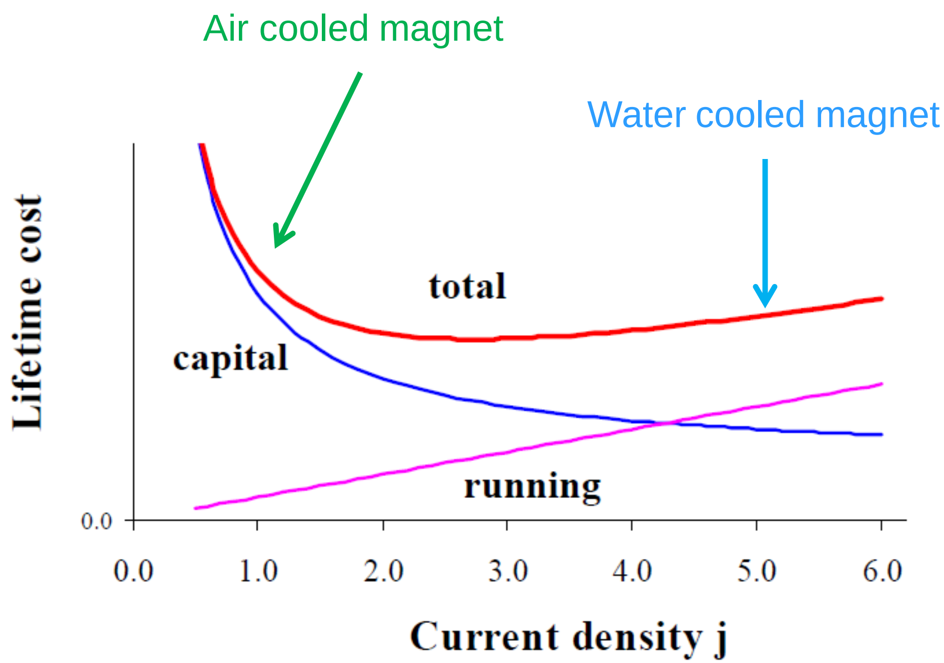
Magnet optimization

Advantages of lower J

- Lower losses in magnet
- Less heat to dissipate in air or water

Drawbacks

- Higher capital cost
- Larger magnets

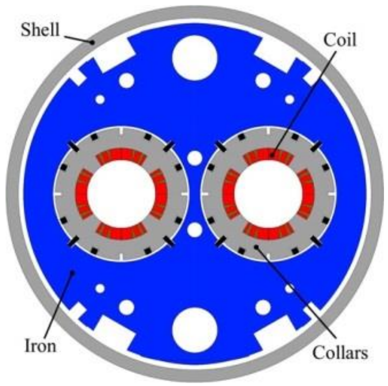


Global optimization shall be done including capital investment, cooling system and energy consumption.

Example of magnet optimization

HL-LHC new Q4 (quadrupole magnet in the interaction region).

First design with single coil layer: L_{manget} = 6mH, $I_{nominal}$ =15.6kA



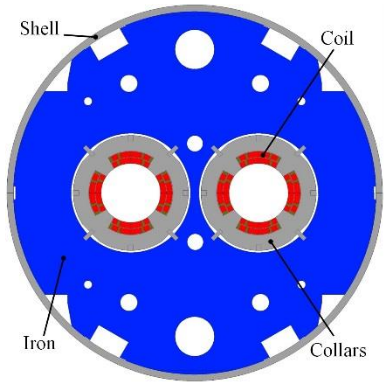
Advantage:

- simple coil

Drawback:

- High current = costly powering system
- Low inductance = poor stability of the magnet current

Second design, with double coil layer: L_{manget} = 74mH, $I_{nominal}$ =4.5kA



Advantage:

- High current stability (1ppm)
- Low powering cost

Drawbacks:

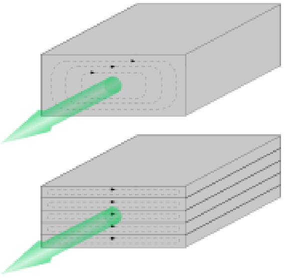
- Magnet more complex
- Magnet more expensive

Global cost reduced and performance required by accelerator physicists reached.

Magnet cost versus energy consumption

DC magnets have a solid yoke which prevents to pulse it. They are used for economical raisons in experimental areas or transfer lines.

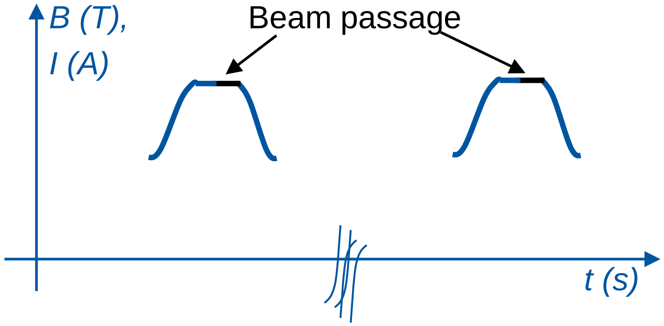
Their eddy currents need a long decay time to disappear (tens of second to minutes). The yoke represents ~50% of the magnet cost.



If the beam isn't present all the time, then big saving can be achieved by pulsing the magnets. The energy consumption is proportional to beam duty cycle.

DC magnet advantages

- Cheap magnets
- Simple powering scheme



DC magnet Drawback

- High energy consumption

One example of study for EAST Area at CERN, where a energy reduction of 90% could be achieved. https://edms.cern.ch/document/1255278/1

Circuit layout

The magnets can be powered individually or in series.

Individually:

- increase flexibility of beam optic
- B-field can be different depending of the cycles (hysteresis)
- Global cost is higher, more DC cables, more power supplies
- Needed when the voltage goes too high (>10kV magnet class)
- Needed when the energy stored is too big (superconducting magnets)

Series connected:

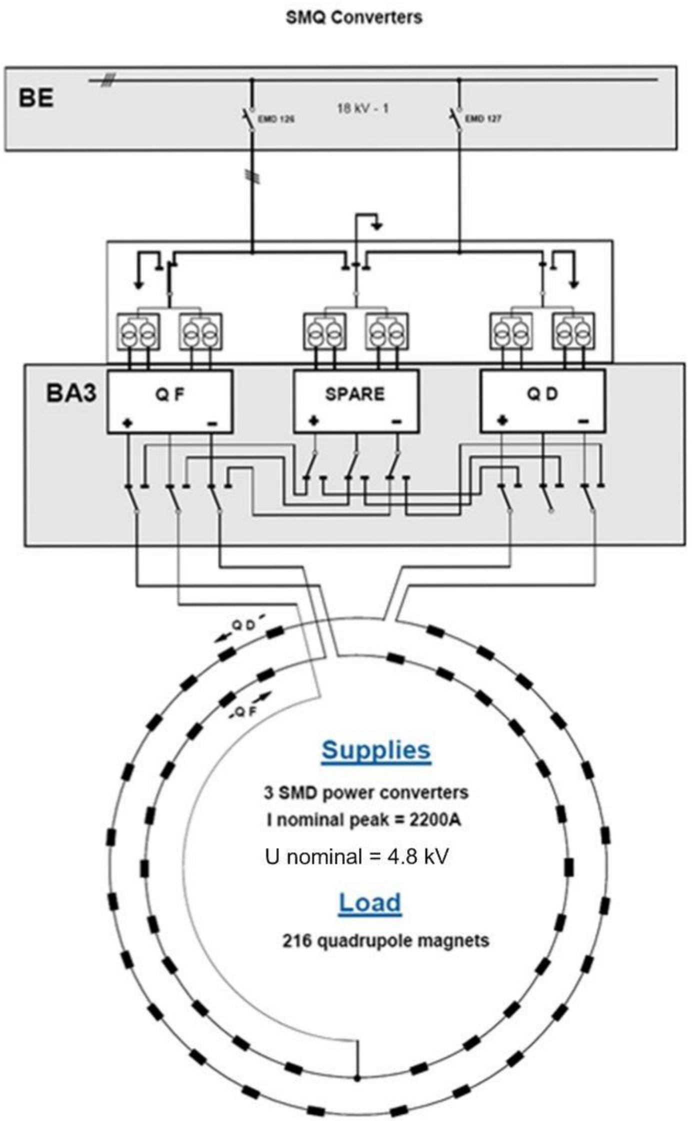
- B-field identical
- Rigid optic. Need trim power supplies to act locally.
- Global cost reduced, less DC cables, less power supplies but bigger in power rating.

Magnet in series

To get the same B-field in all the magnets, the classical solution is to put all the magnets in series.

Generally done with dipole and quadrupole.

Example of SPS quadrupole

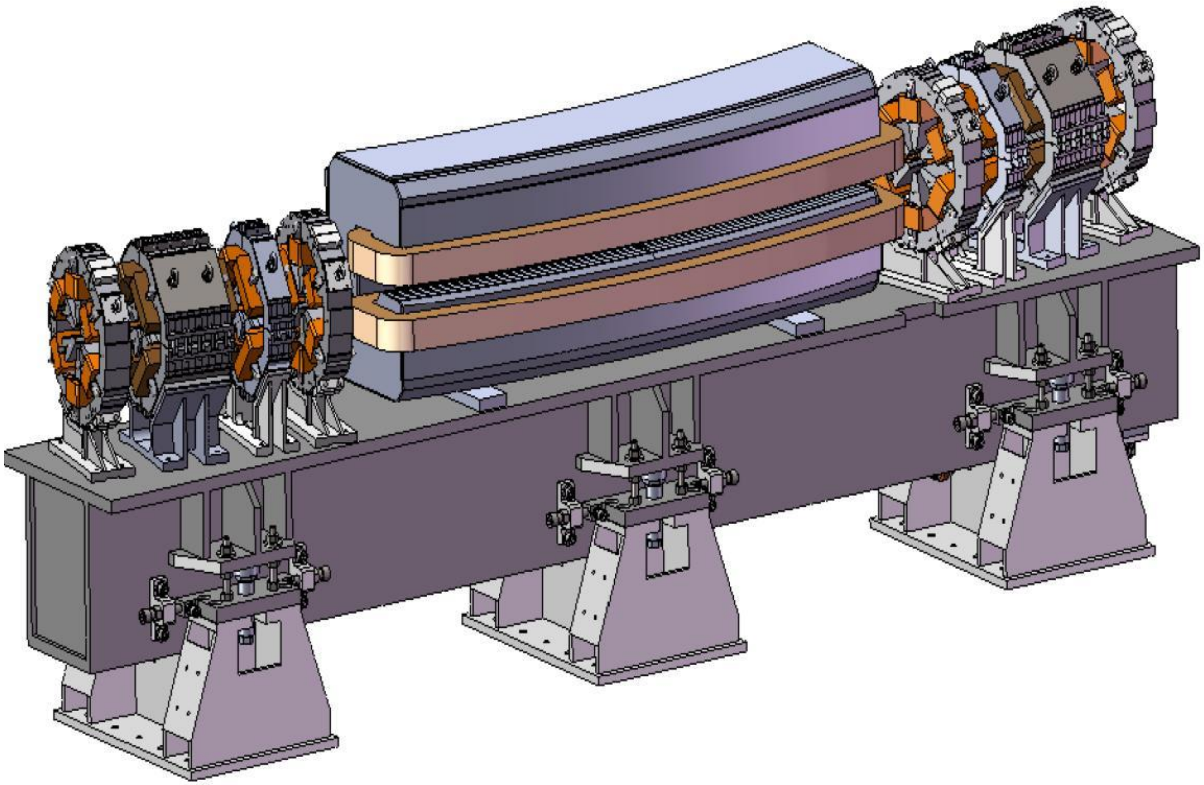


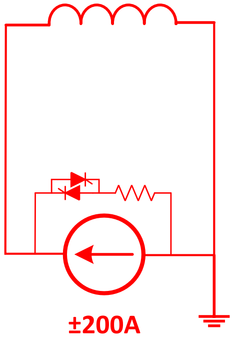
Lead to high power system for Dipole and quadrupole.

Individual powered magnet

For synchrotron source lights, the quadrupole are generally individually powered to adjust the beam size (beta function) for each users (corresponding to a Fodo cell).

Example, SESAME cell.

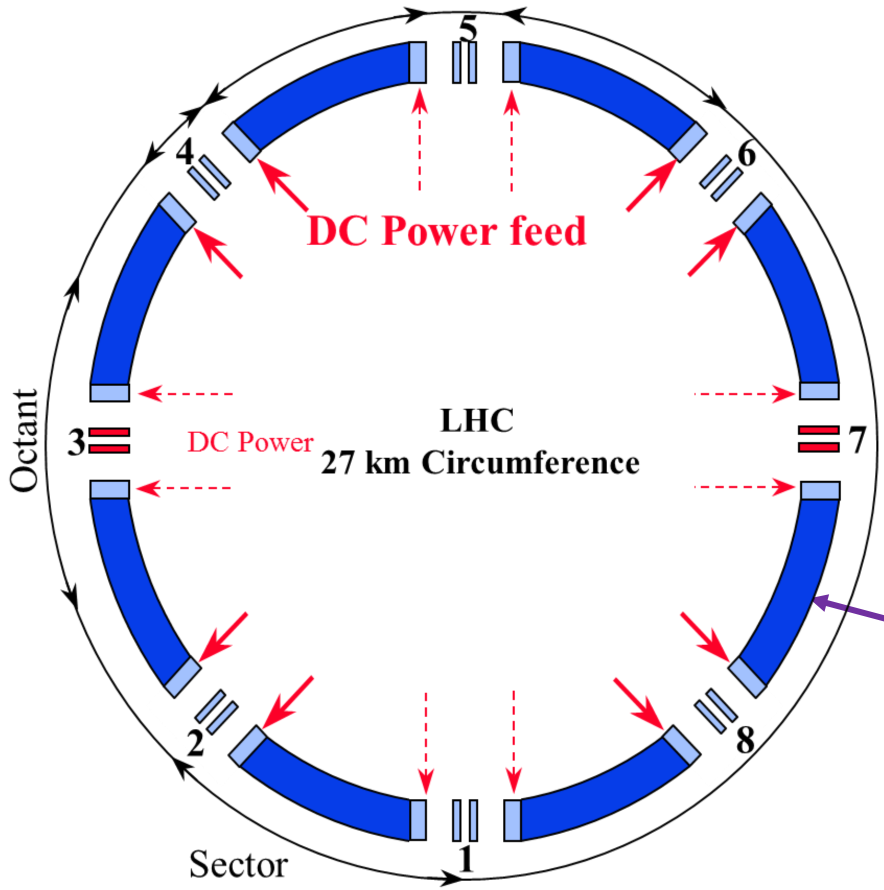




Splitting the magnet circuit

But when the power is becoming too high, the circuit can be split.

First time with LHC in 8 sectors. All magnet families cut in 8



Tracking between sector !

1.2 GJ stored energy per sector!

Powering Sector:

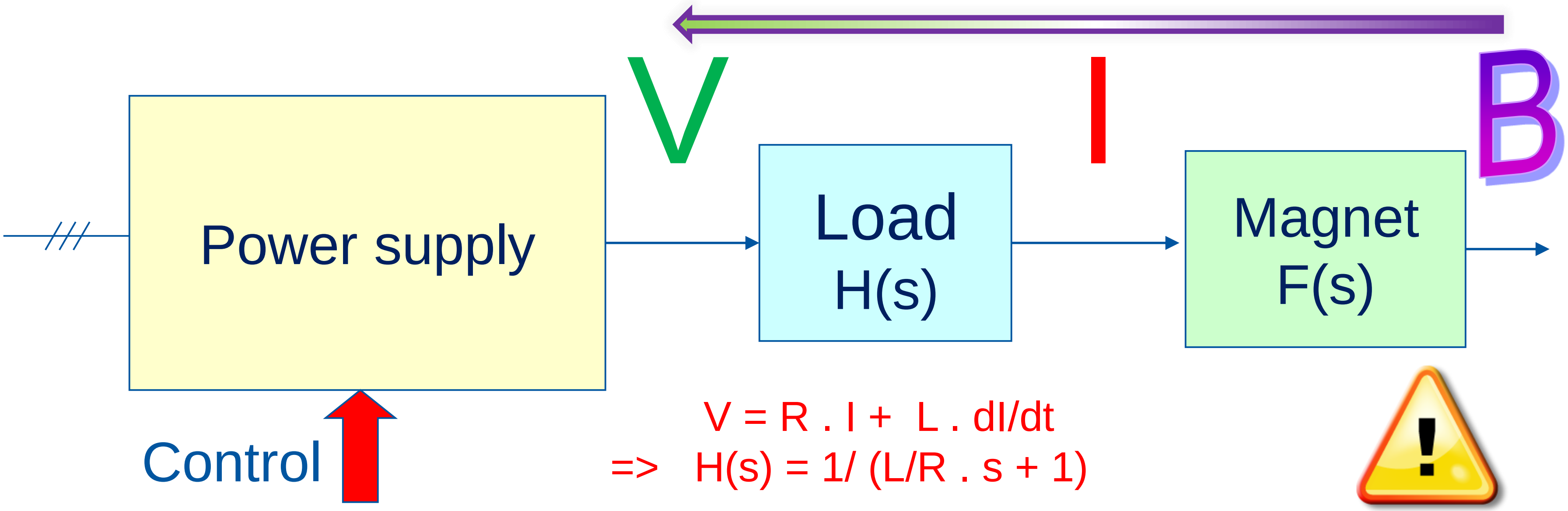
154 dipole magnets
total length of 2.9 km

Power supply ripples

The acceptable current ripple has to be fixed by the accelerator physicists.

In fact, it is the maximum B-field ripple which needs to be determined.

From the B-field ripple, we can determine the current ripple and then, fix the voltage ripple.



$$V = R \cdot I + L \cdot dI/dt$$

$$\Rightarrow \quad H(s) = 1/\,(L/R \cdot s + 1)$$

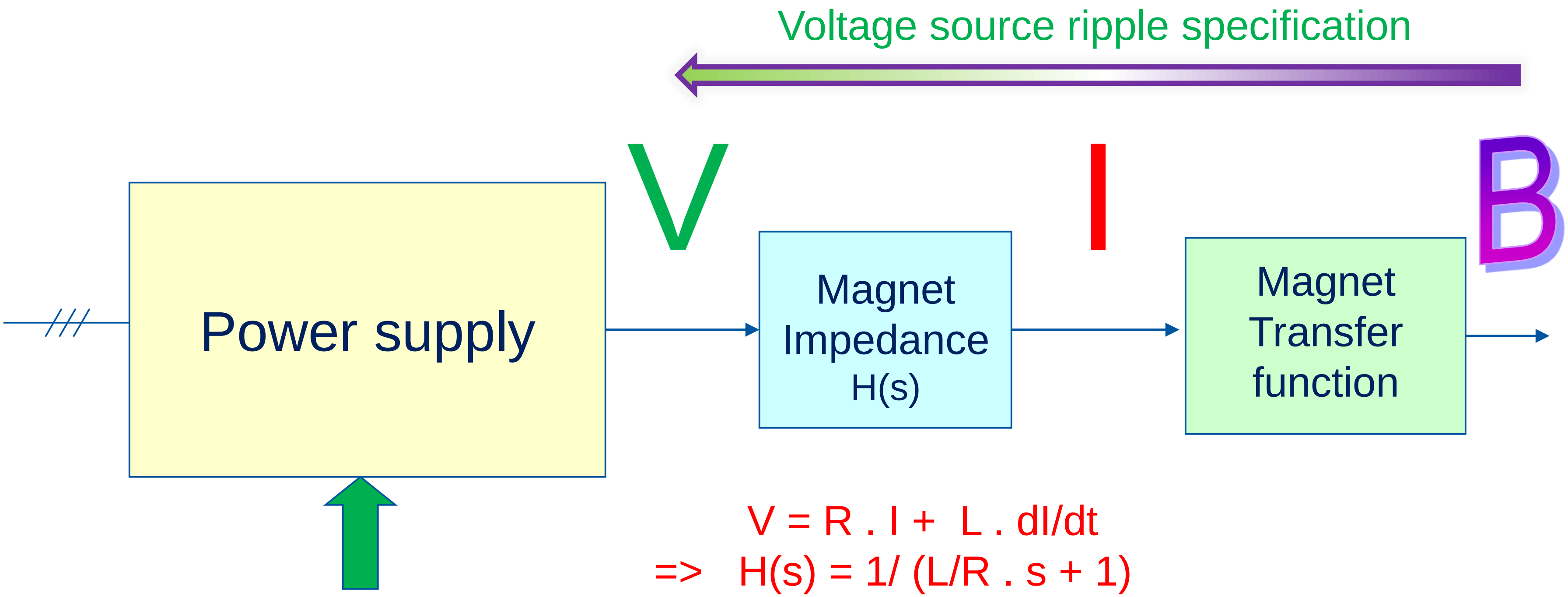
Current ripple
Depends of the load

Voltage ripple is generated by the power supply

Current ripple is defined by load transfer function (cables & magnet)

B-Field ripple is depends on magnet transfer function (vacuum chamber,…)

Power supply ripples



Voltage ripple
(source of the ripple)

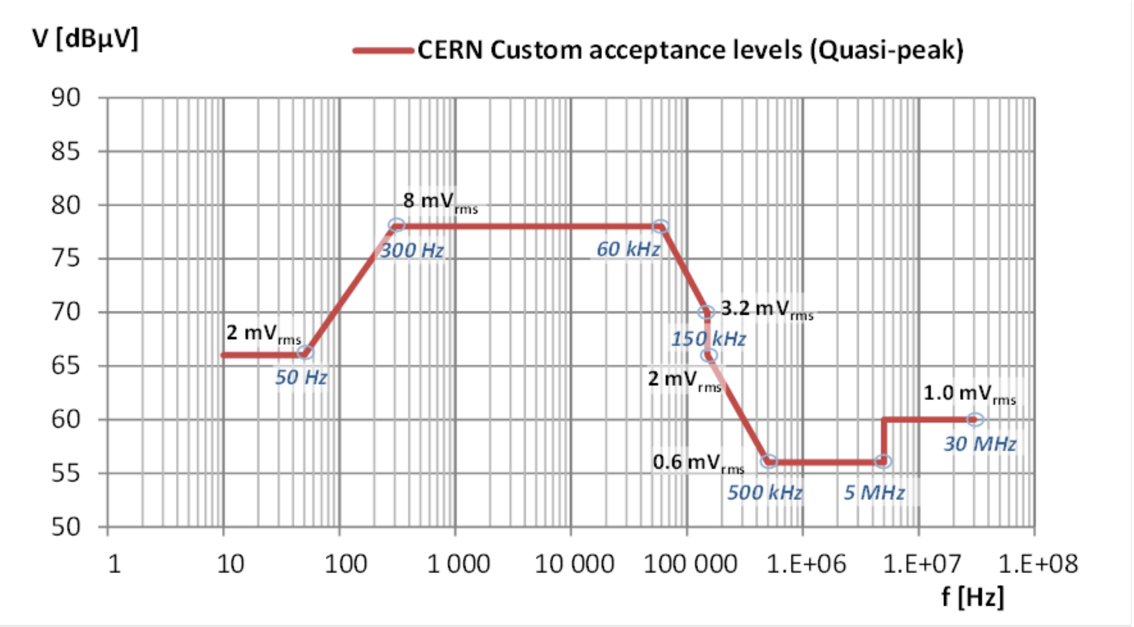
Current ripple

Magnetic field ripple
(Beam instability)

Power supply ripples specification

The voltage ripple has to be specified for all frequencies.

<50Hz: for regulation performance
50-1200Hz: for grid disturbance
1-150kHz: for power supply switching frequency
>150kHz: for EMC



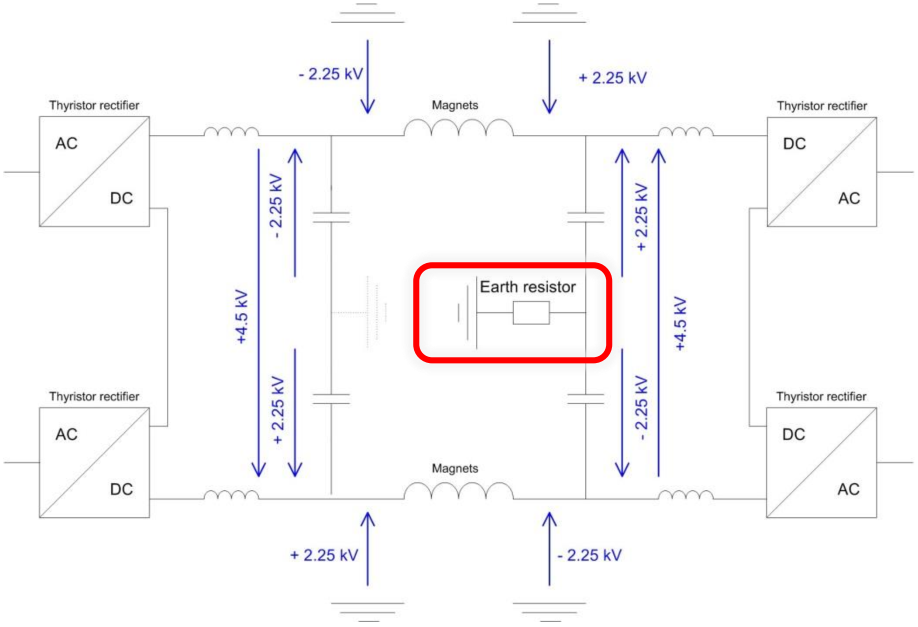
Magnet grounding

For safety reasons, the magnet shall be isolated from the mains. The power supply needs an insolation transformer in its topology.

The magnets shall be connected to the ground somewhere, they can't be left floating with parasitic capacitances.

One polarity can be connected directly to the ground, or via a divider for a better voltage sharing.

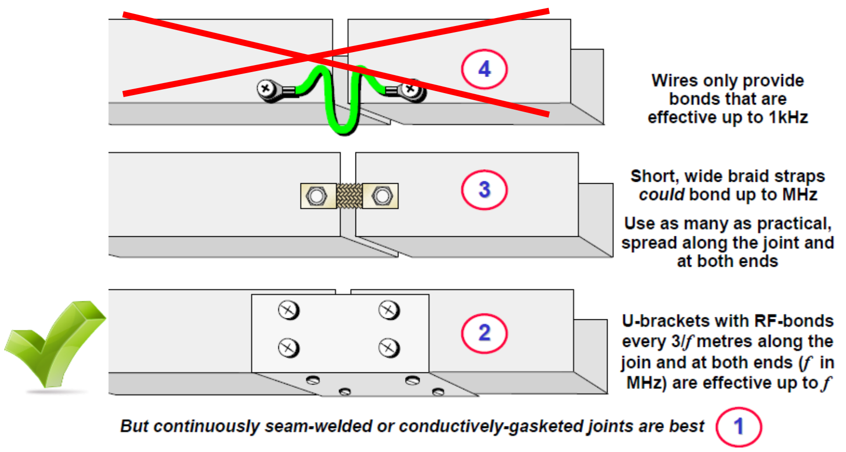
The ground current shall be monitor.

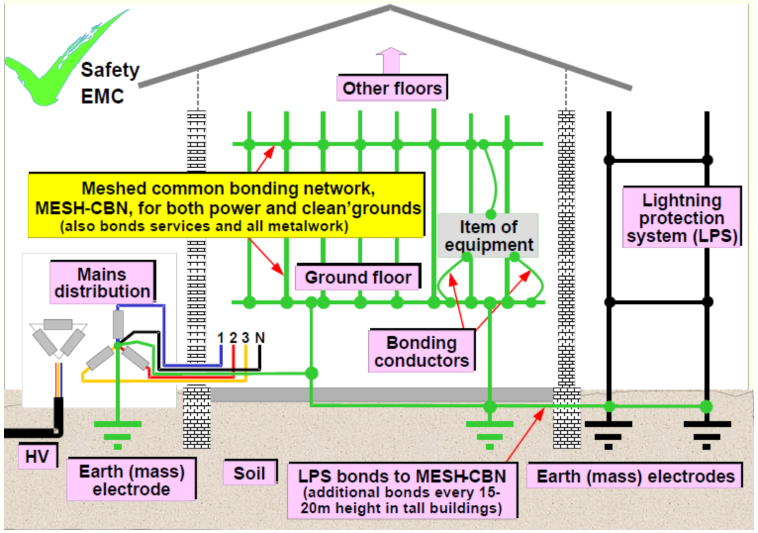


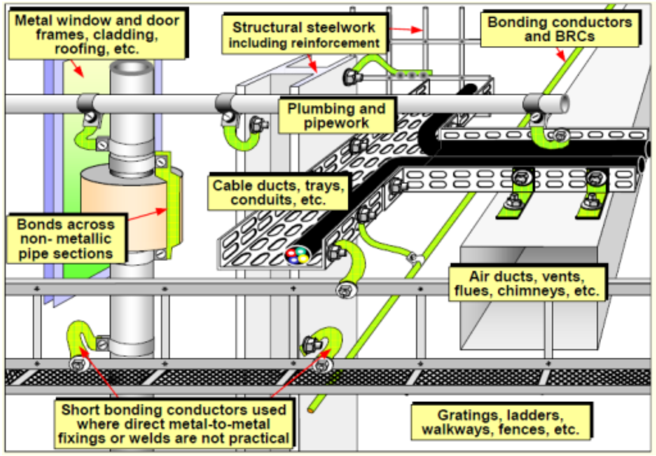
Grounding

Particles accelerators are very sensitive to EMC (conducted and radiated noise).

Need a meshed earth !



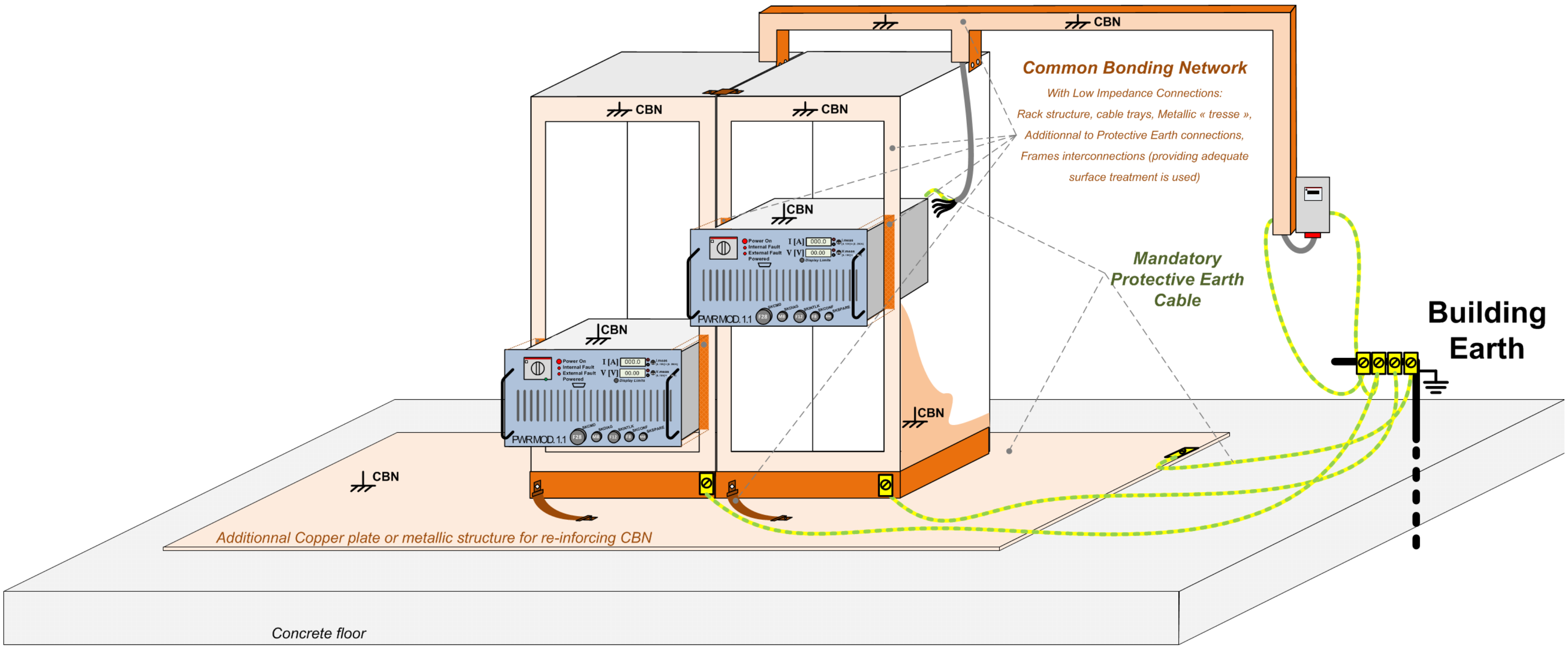




http://indico.cern.ch/getFile.py/access?contribId=44&sessionId=9&resId=0&materialId=slides&confId=85851

Grounding

Appling good EMC rules to power supplies:



Magnet protection

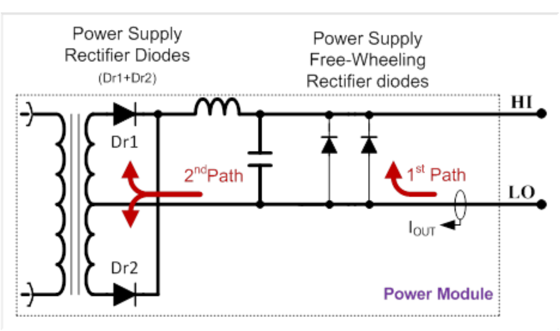
The magnets shall have its own interlock system.
For warm magnets, it is quite simple (water flow, thermostat, red button,…).
For superconducting magnets, it is quite complex (quench protection).

This interlock system shall request a power abort to the power supply.

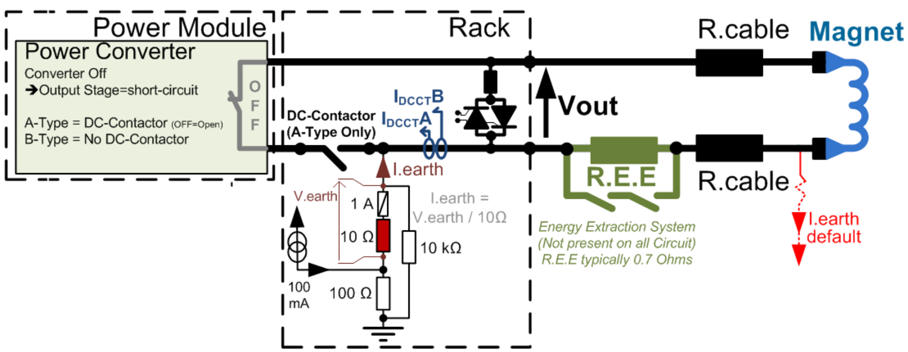
Be careful, magnets are inductive load, the circuit can't be opened !
The power supply shall assure a freewheeling path to the current.

It can be inside the power supply for warn magnet,
or outside for superconducting magnet.

Easy



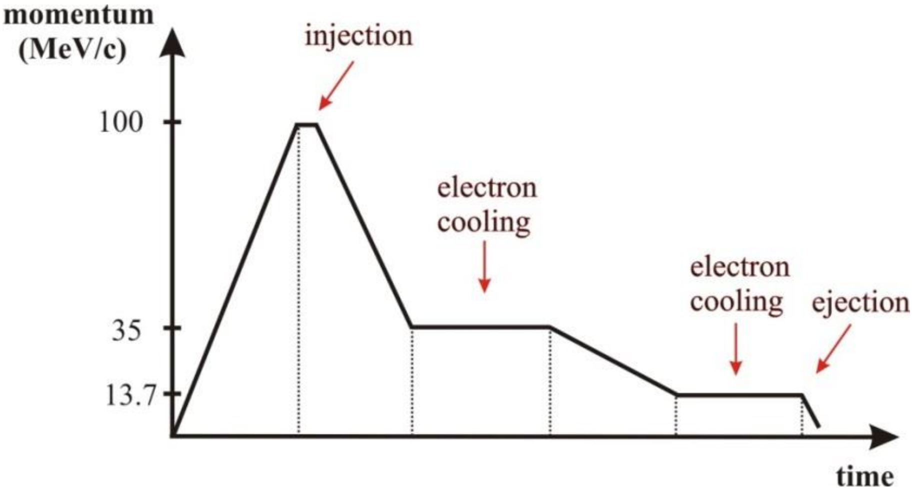
Complex

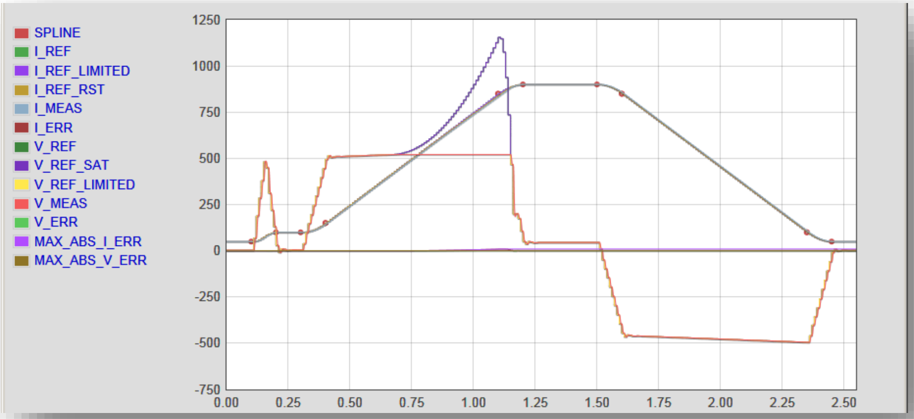


Magnet cycle

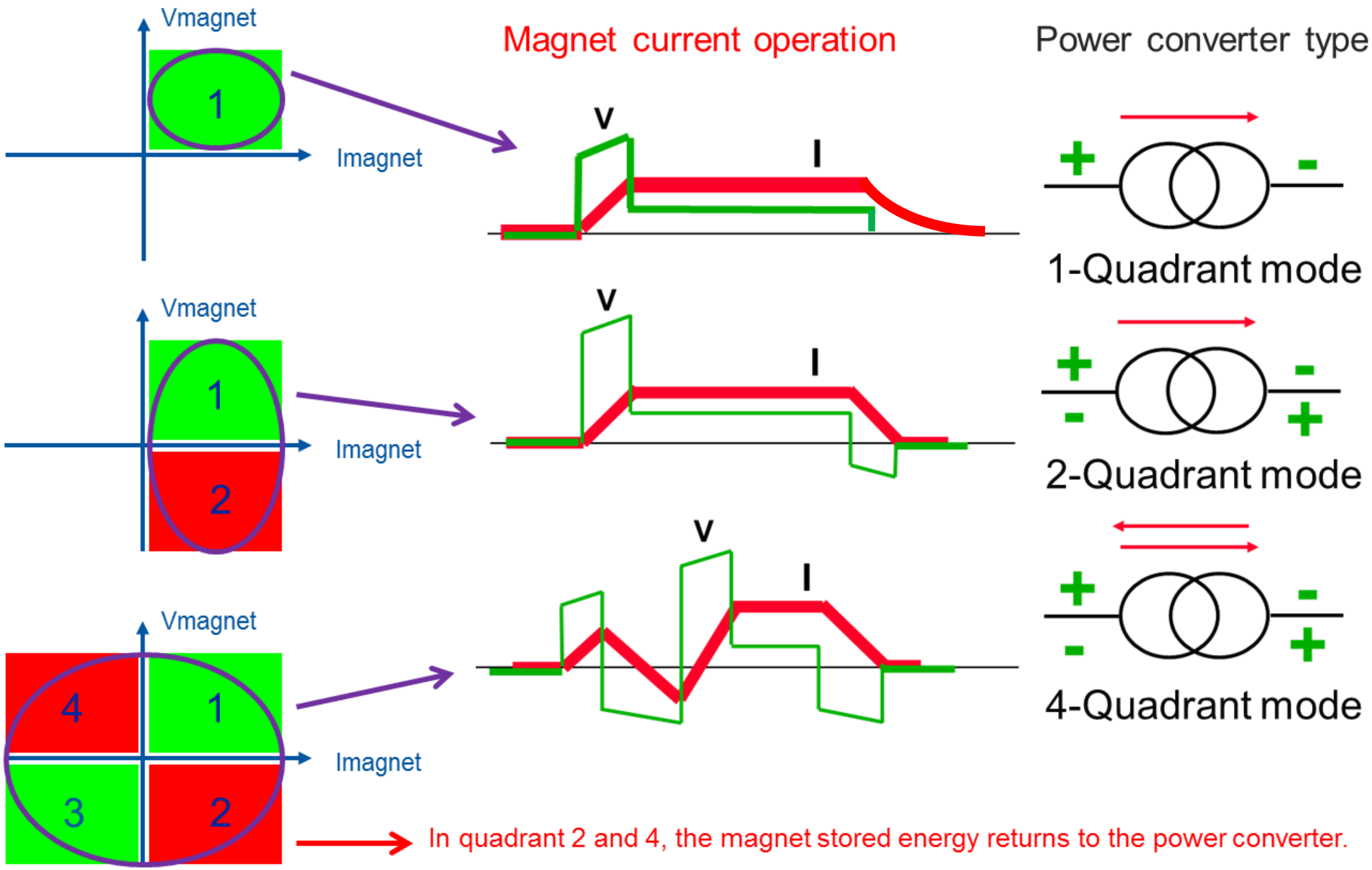
The way that the magnets will be operated has to be defined from the beginning.

- Type of control: Current / B-field
- Maximum – minimum current
- Complete cycle
  - Injection current
  - Maximum dI/dt, ramp-up
  - Maximum flat top current
  - Maximum dI/dt, ramp-down
  - Return current
  - Cycle time
- Degauss cycle / pre-cycle
- Standby mode





Power supply types

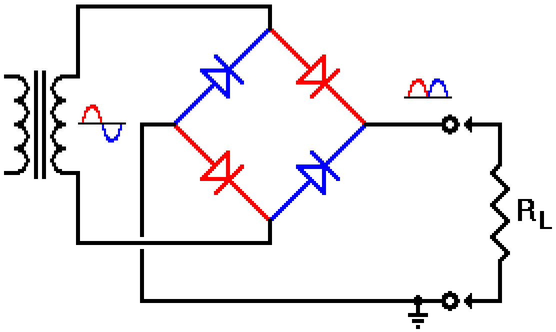


In quadrant 2 and 4, the magnet stored energy returns to the power converter.

Power electronics

Power electronics is the application of solid-state electronics for the control and conversion of electric power.

Power electronics started with the development of mercury arc rectifier. Invented by Peter Cooper Hewitt in 1902, the mercury arc rectifier was used to convert alternating current (AC) into direct current (DC).



The power conversion systems can be classified according to the type of the input and output power

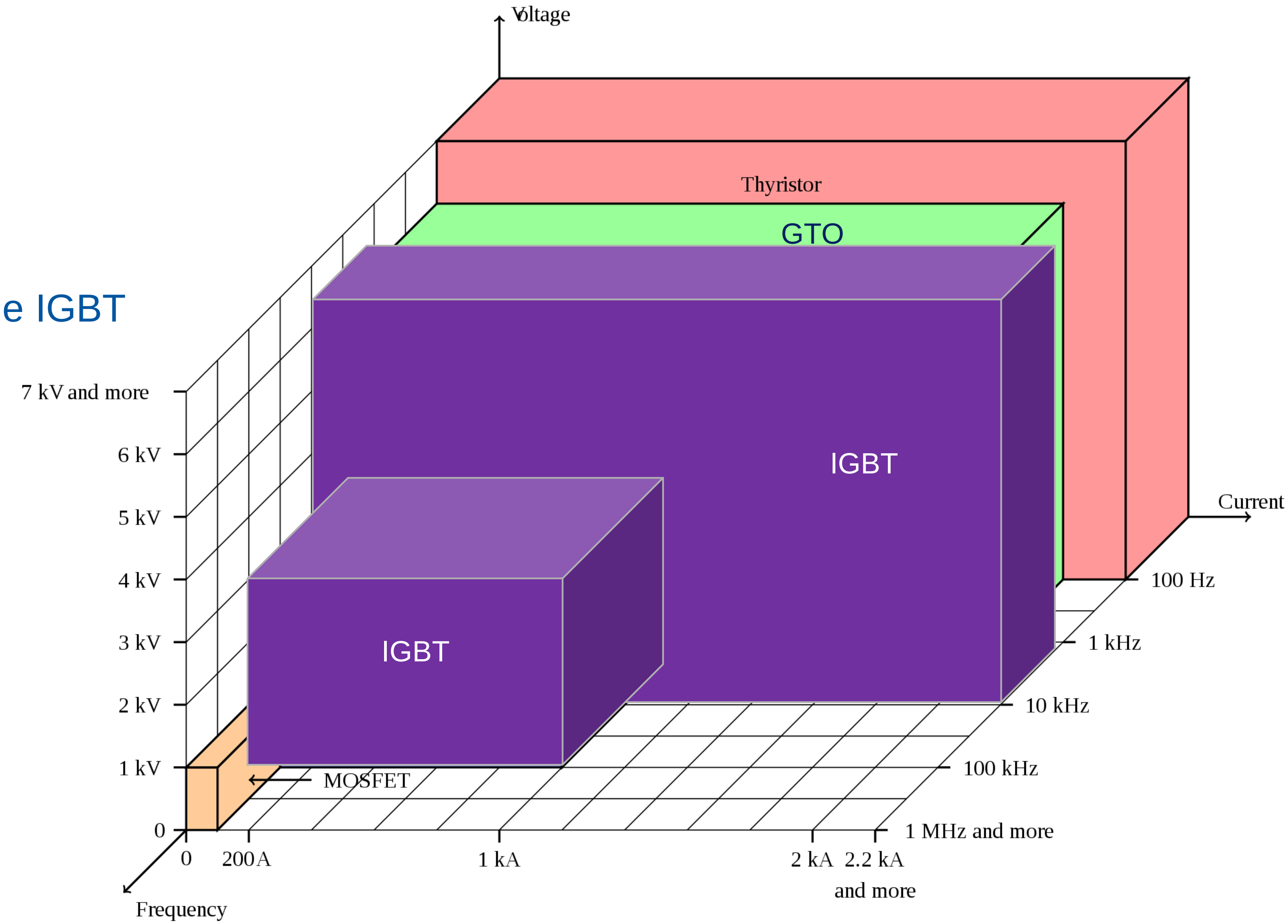
- AC to DC (rectifier)
- DC to AC (inverter)
- DC to DC (DC-to-DC converter)
- AC to AC (AC-to-AC converter)

Switching devices

Nowadays, the main power semiconductors are:

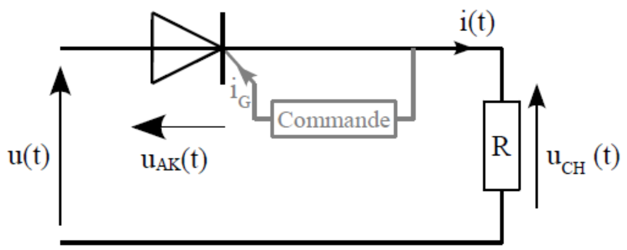
- Diode
- MOSFET
- IGBT
- Thyristor

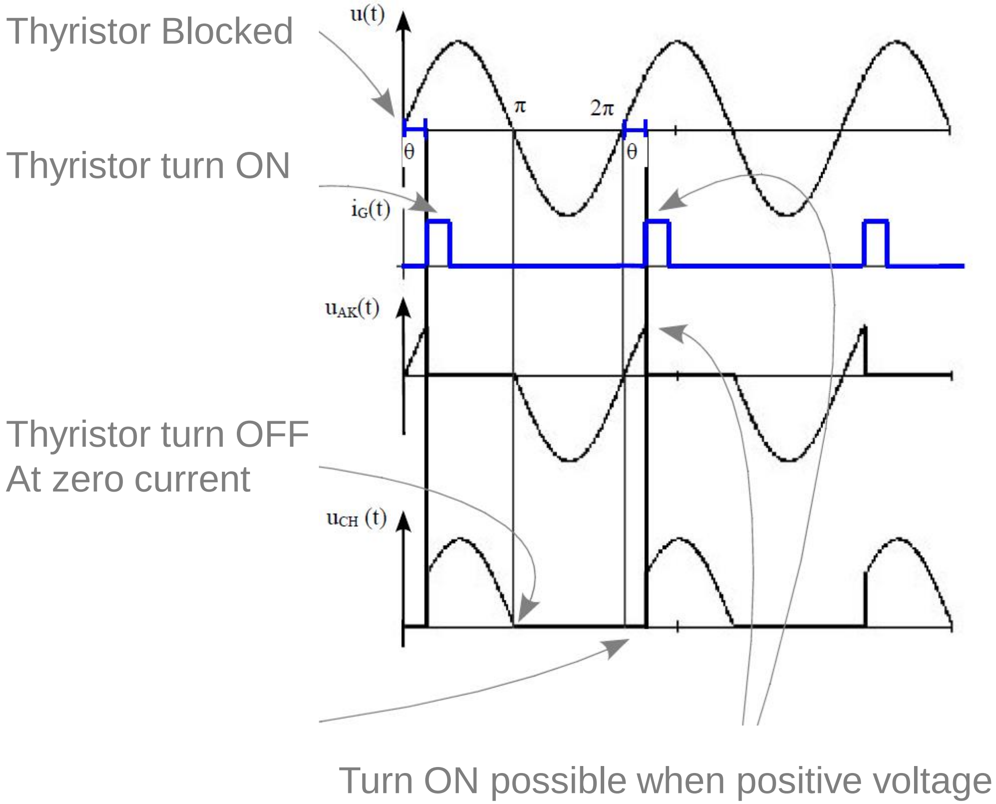
The most popular is the IGBT



Thyristor principle

Thyristor (1956): once it has been switched on by the gate terminal, the device remains latched in the on-state (*i.e.* does not need a continuous supply of gate current to remain in the on state), providing the anode current has exceeded the latching current (I_L). As long as the anode remains positively biased, it cannot be switched off until the anode current falls below the holding current (I_H).





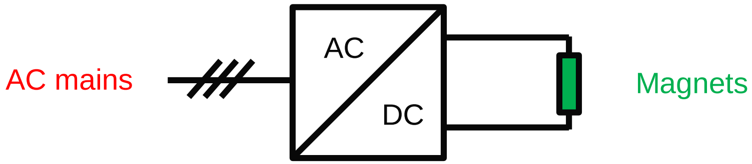
Topologies based on thyristor

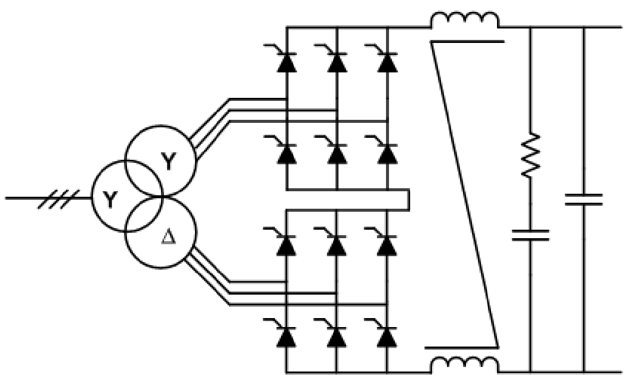
The magnets need DC current.

The magnet power supplies are AC/DC.

The magnets need a galvanic isolation from the mains: 50Hz transformer

The thyristor bridge rectifier is well adapted to power magnets.



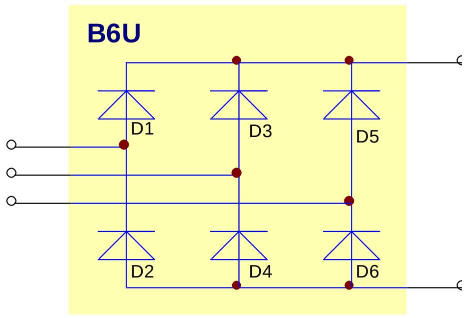


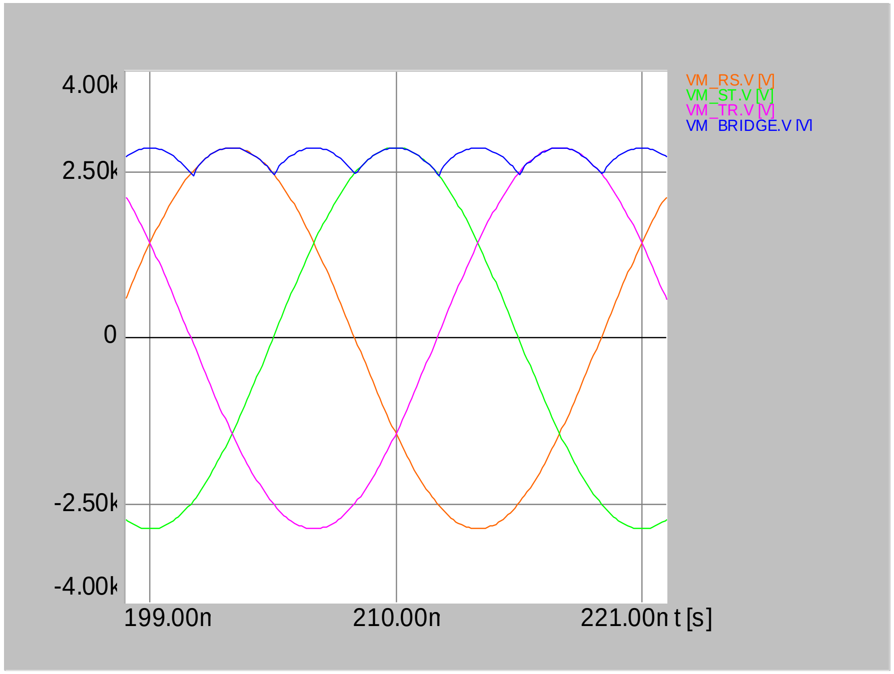
Thyristor advantages
- Very robust
- Cheap
- Low losses

Thyristor drawbacks
- Sensible to mains transients
- Low losses
- Low power density

Diode bridge rectifier

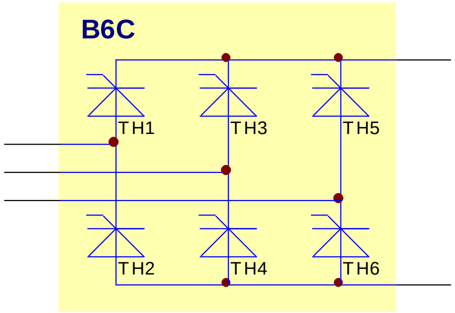
- 3 phases diode bridge voltage rectification
  - Bridge output voltage is fixed, $1.35 * U_{\text{line to line}}$

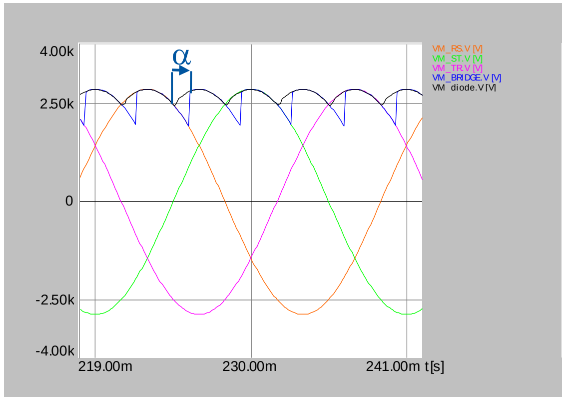


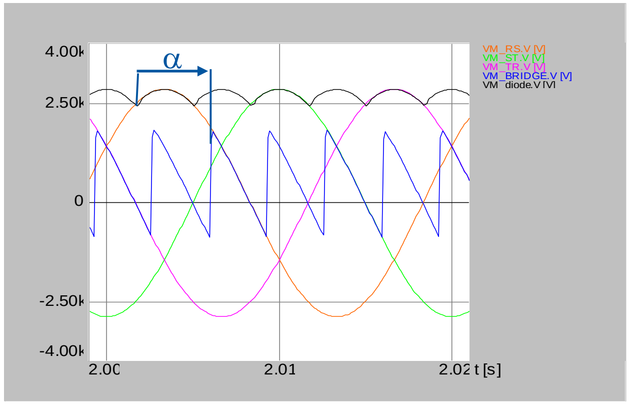


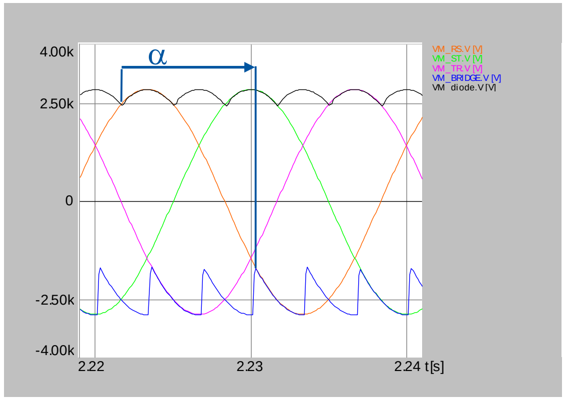
Thyristor bridge rectifier

- 3 phases Thyristor bridge voltage rectification
  - Can control the bridge output voltage by changing the firing angle α
  - Vout = Umax * cos α
    - α = 15°,   Vout = 0.96 * Umax
    - α = 70°,   Vout = 0.34 * Umax
    - α = 150°, Vout = -0.86 * Umax



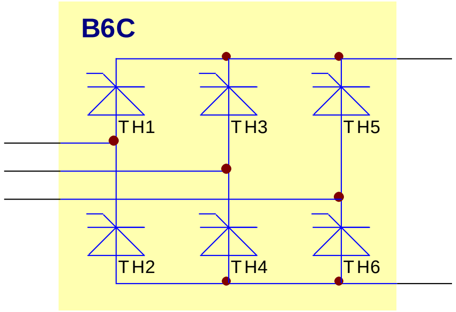


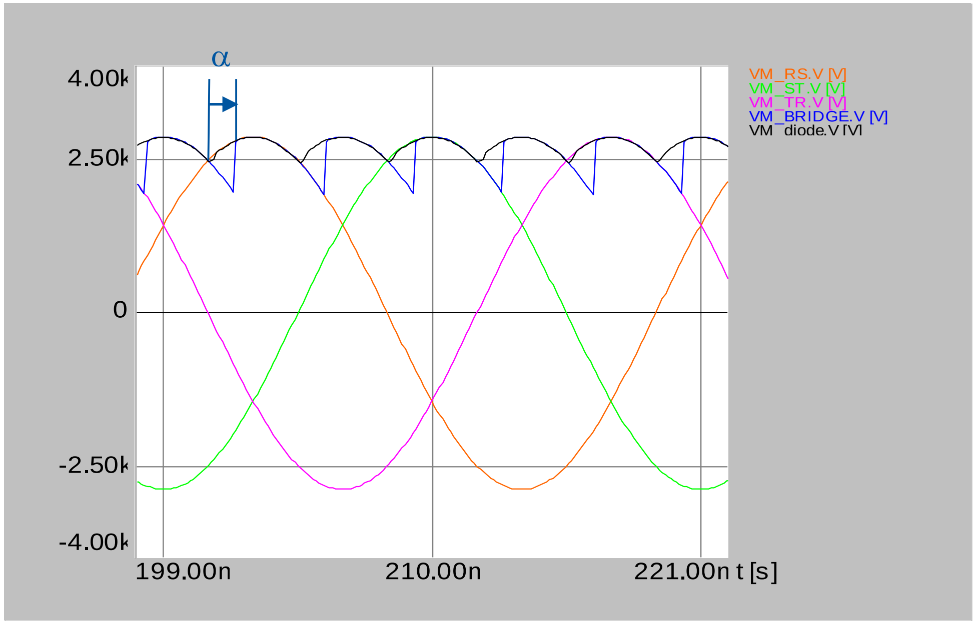




Thyristor bridge rectifier

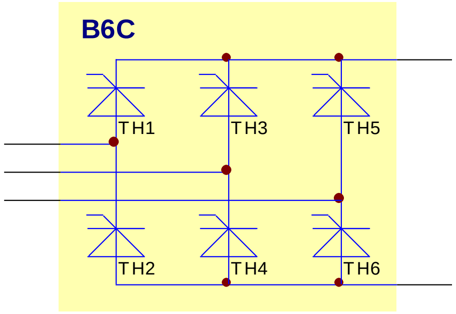
- Maximum voltage, α = 15°

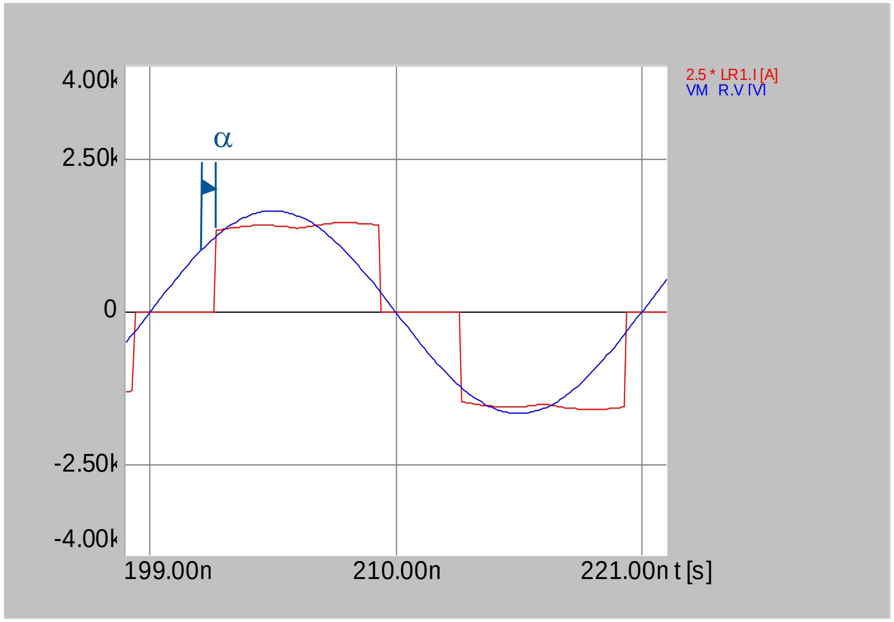




Thyristor bridge rectifier

- Transformer line current at maximum voltage, α = 15°
  - The diode bridge current is in phase with the voltage
  - For the thyristor rectifier, the AC line current is shifted with the angle α

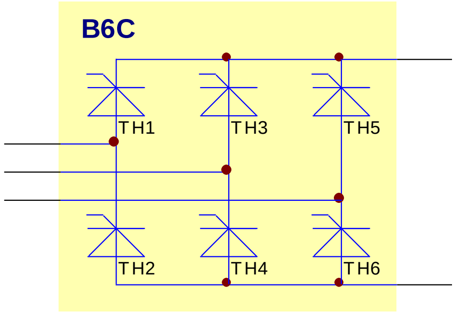


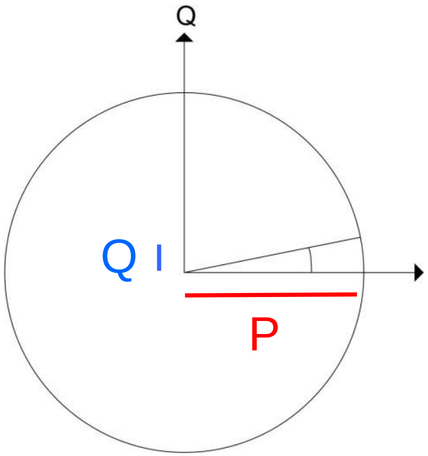


Thyristor bridge rectifier

- Power analysis
  - Power: $P(t) = V_r(t) * I_r(t) + V_s(t) * I_s(t) + V_T(t) * I_T(t)$
  - Active power: $P = 3 * V_r * I_{Line\ rms} * \cos\alpha$
  - Reactive power: $Q = 3 * V_r * I_{Line\ rms} * \sin\alpha$
  - Apparent power: $S = \sqrt{P^2 + Q^2}$
  - Power factor: $P/S = \cos\alpha$

- $\alpha = 15°$
  - Active power high
  - Reactive power low

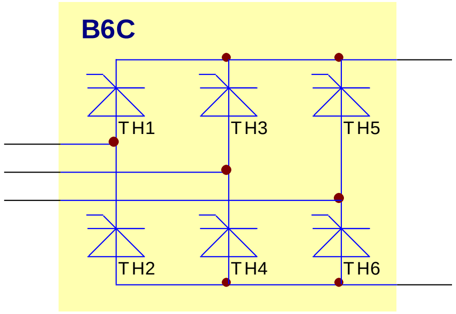


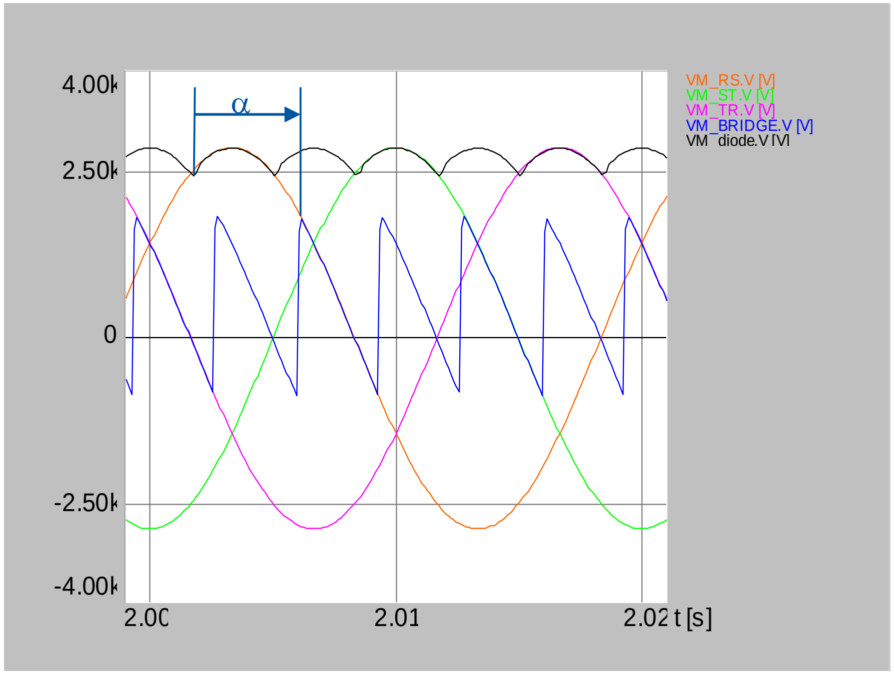


Thyristor bridge rectifier

- At flat top, α = 70°

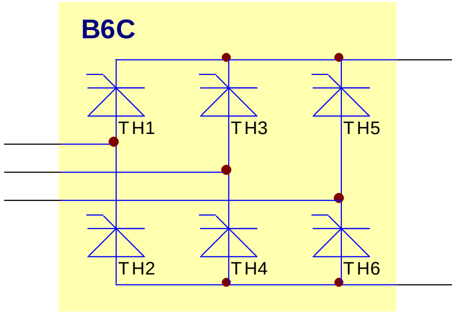
Full current / low DC voltage

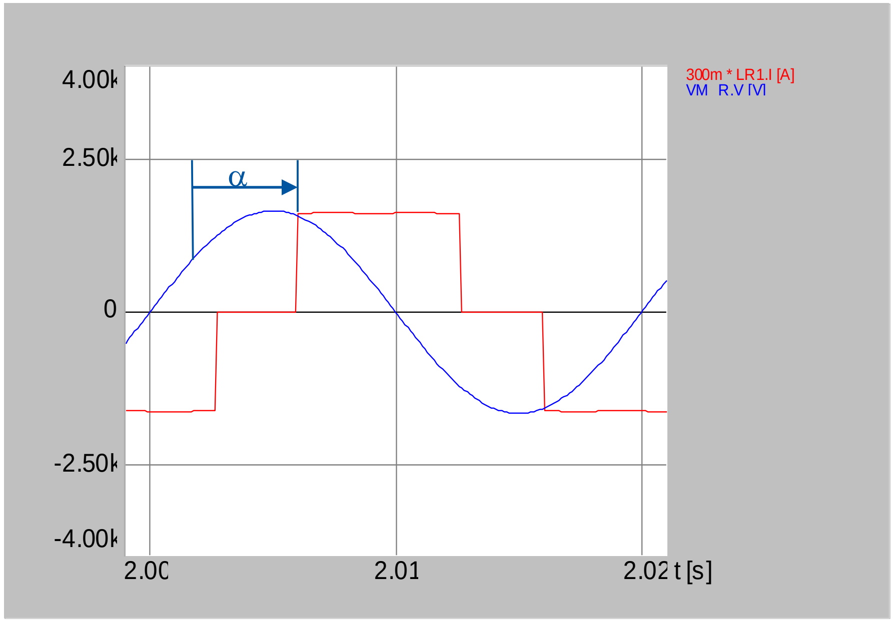




Thyristor bridge rectifier

- Transformer line current at flat top (at α = 70°)

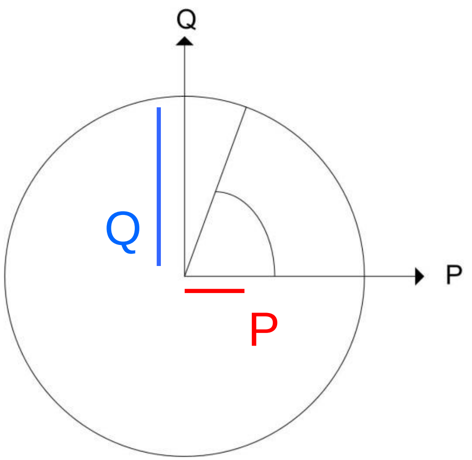


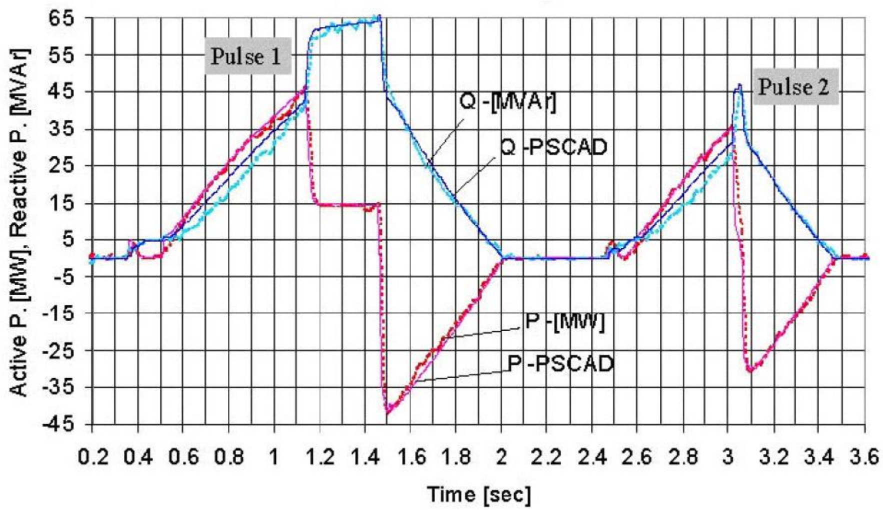


Thyristor bridge rectifier

- Power analysis
  - Active power: $P = 3 * V_r * I_{Line\ rms} * \cos\alpha$
  - Reactive power: $Q = 3 * V_r * I_{Line\ rms} * \sin\alpha$
  - Apparent power: $S = \sqrt{P^2 + Q^2}$

  - $\alpha = 70°$
    - Active power low
    - Reactive power high





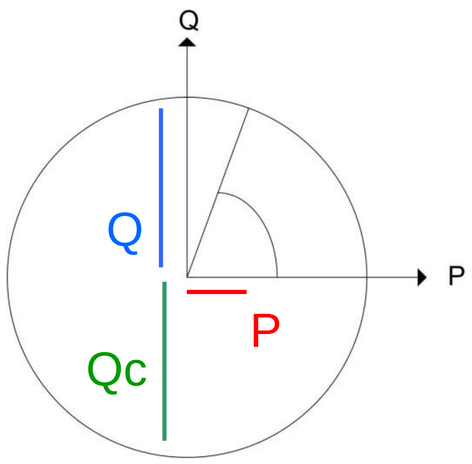
Reactive power compensation

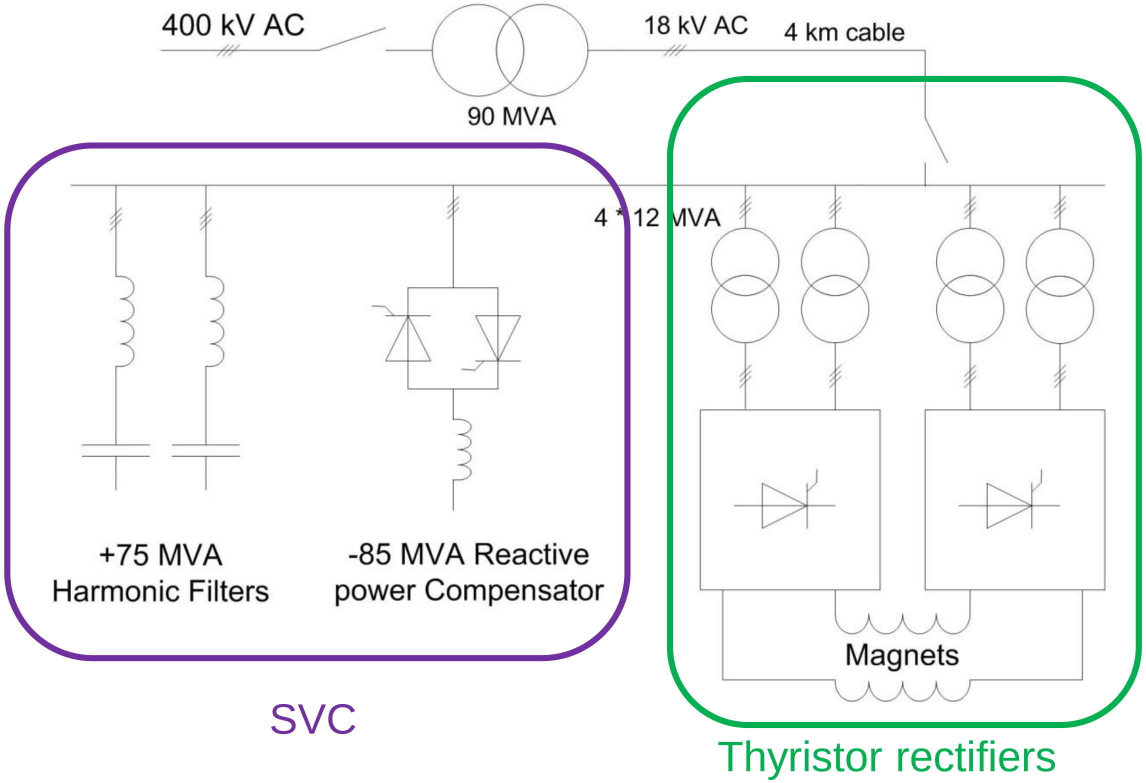
Reactive power must be compensated.

Power factor > 0.93 for EDF.

Affect the mains voltage stability.

Solution :SVC: Static VAR Compensator, Qc





Reactive power compensation

SVC role on the 18kV

- Compensate reactive power (Thyristor Controlled Reactor)
- Clean the network (harmonic filters)
- Stabilize the 18kV network (>±1%)

Thyristor rectifier example

Example: LHC dipole converter 13kA/180V

Magnet: L = 15.7H

R = 0.001Ω

Iultimate = 13kA

Magnet operation:

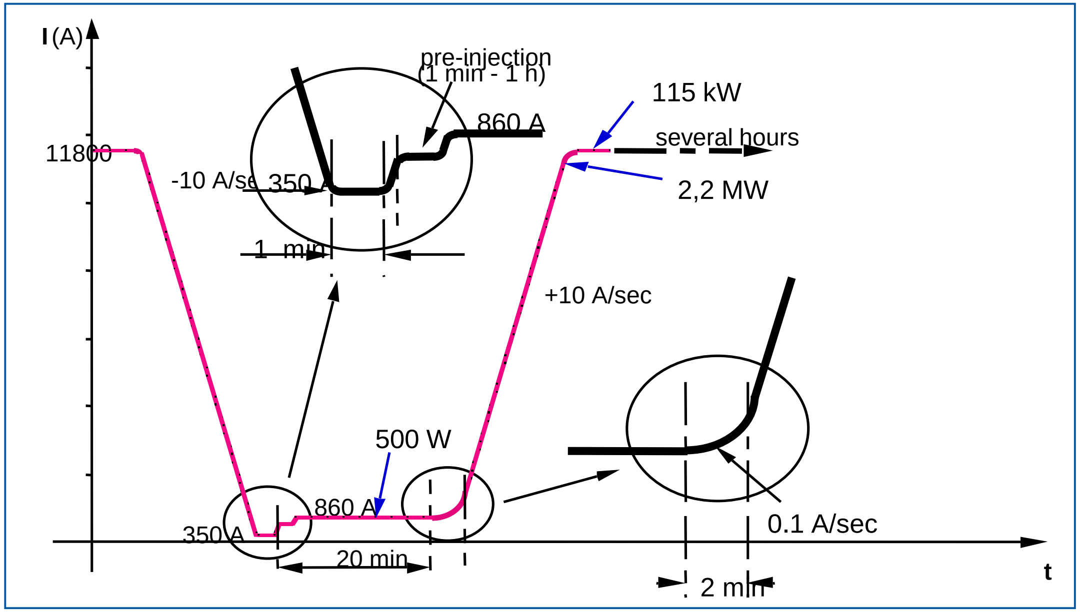
Injection = 860A

dI/dt = ±10A/s

I_{4TeV} = 6.9kA

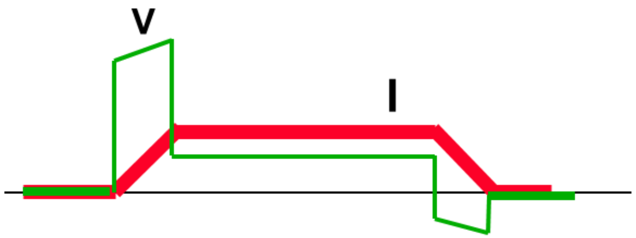
I_{7TeV} = 11.8kA

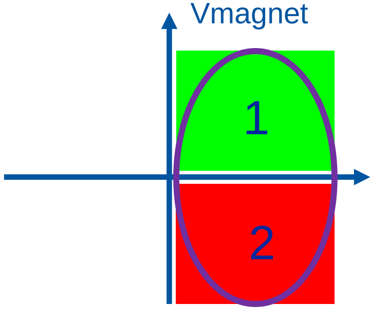
Magnet protected by external dump resistor



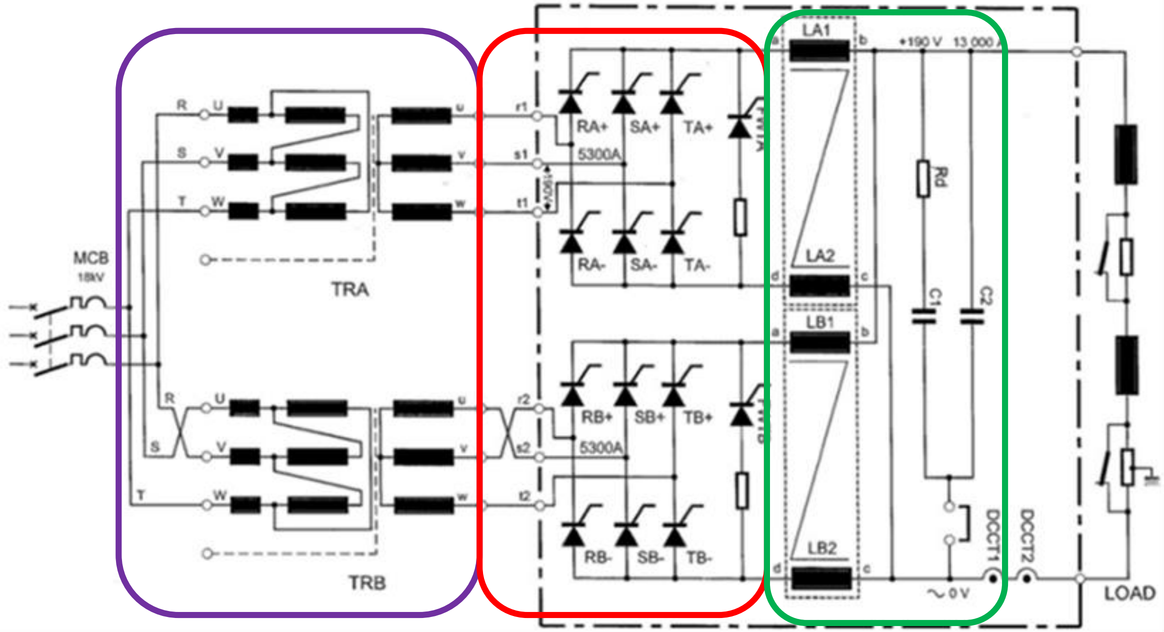
Thyristor rectifier example

Example: LHC dipole converter 13kA / 180V





18kV AC

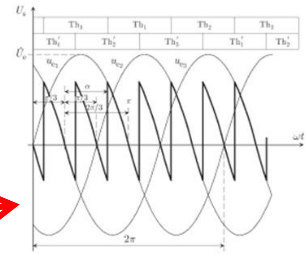


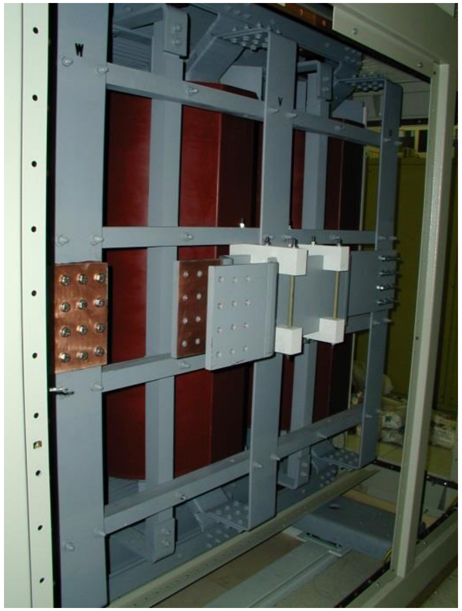
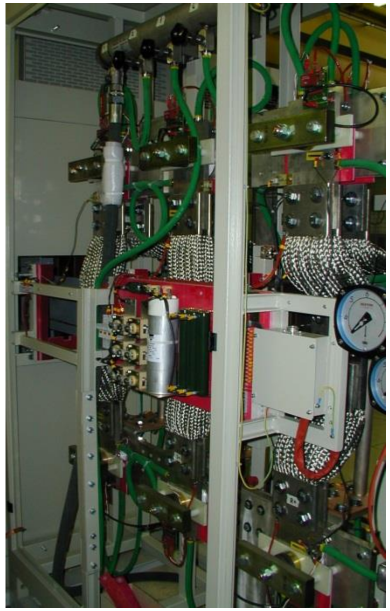
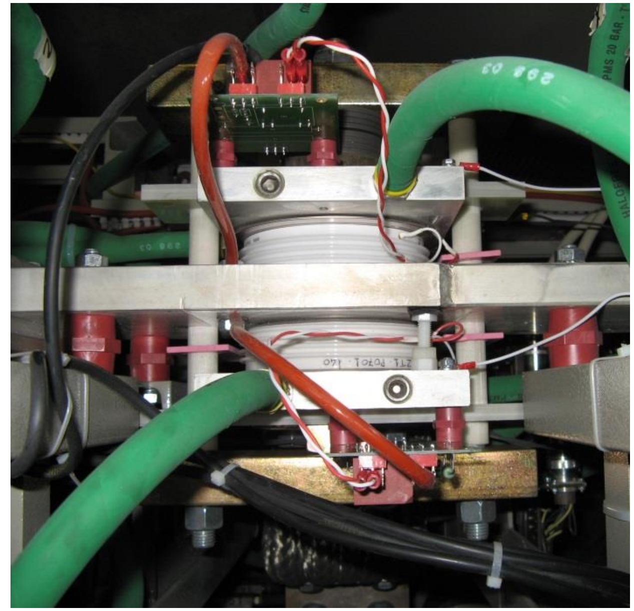
Magnets

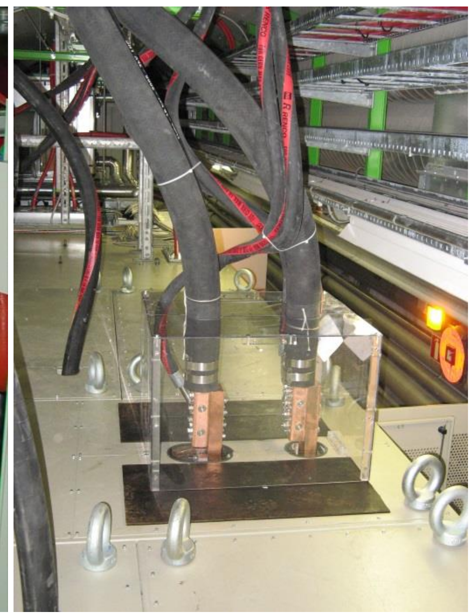
50Hz transformer

Output filter

Thyristor rectifier

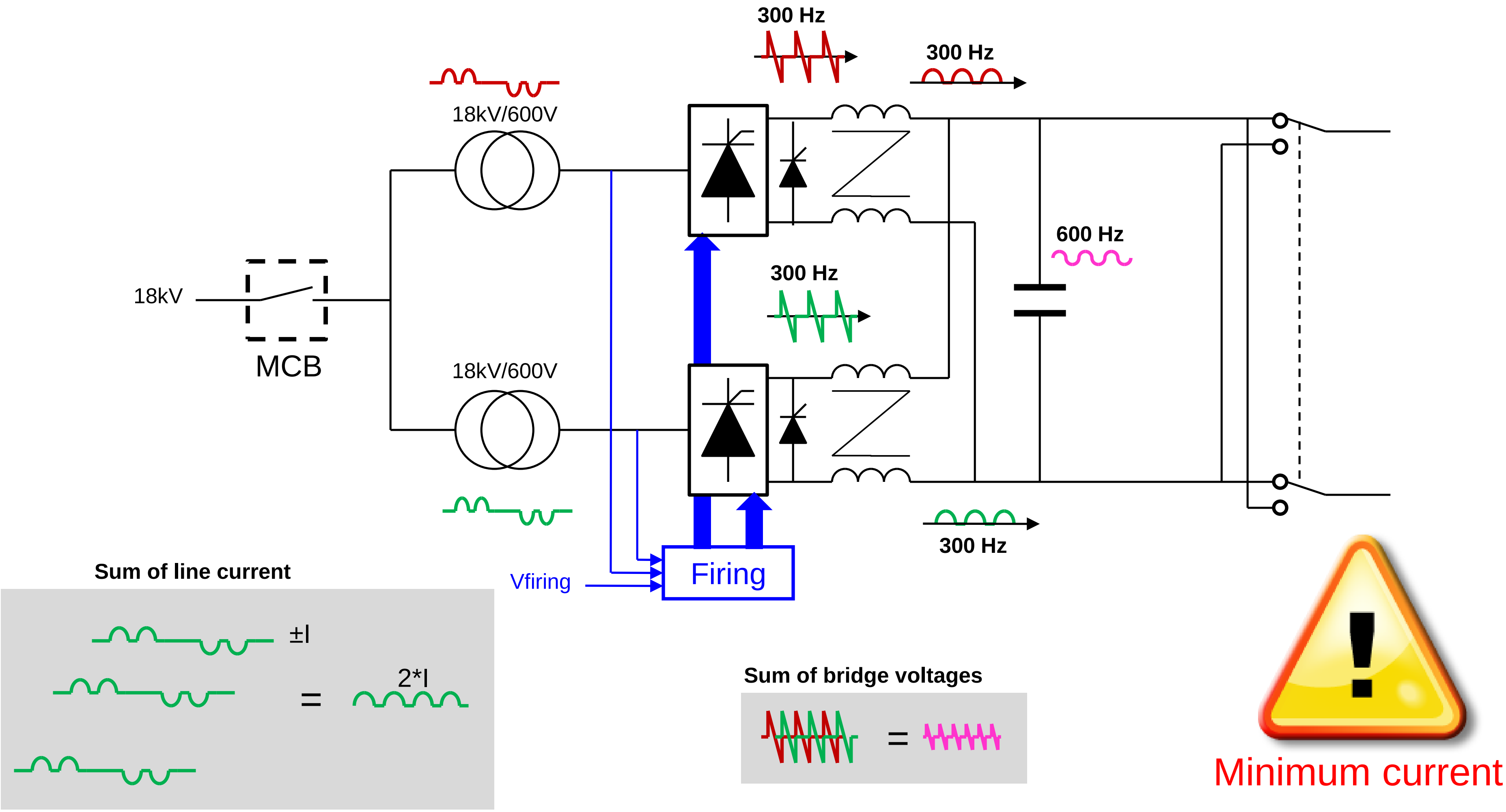



Thyristor rectifier

Limitation a low current due to discontinuity of current



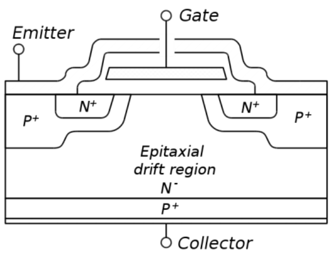
Topologies based on IGBT

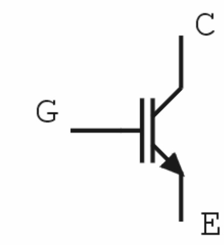
What is an IGBT ?

The IGBT combines the simple gate-drive characteristics of the MOSFETs with the high-current and low-saturation-voltage capability of bipolar transistors.

The main different with thyristor is the ability to control its turn ON and turn OFF.

Many topologies can be built using IGBT.





10A

200A

1kA

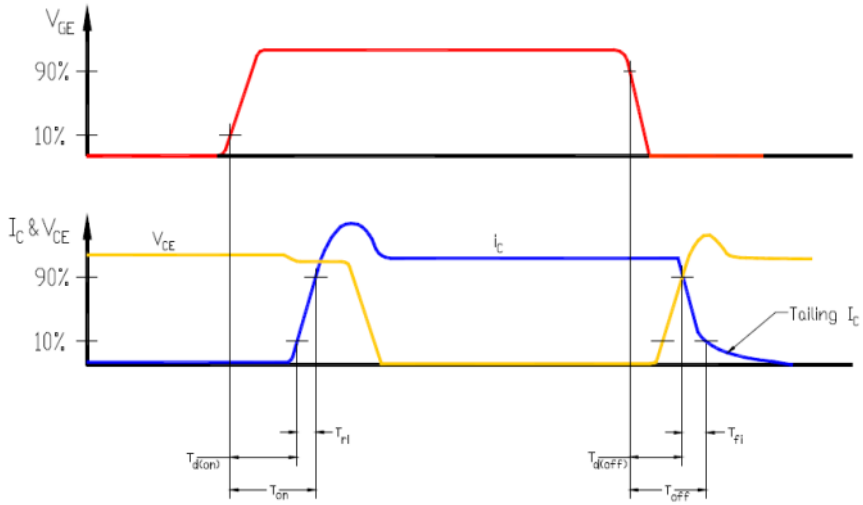
3kA

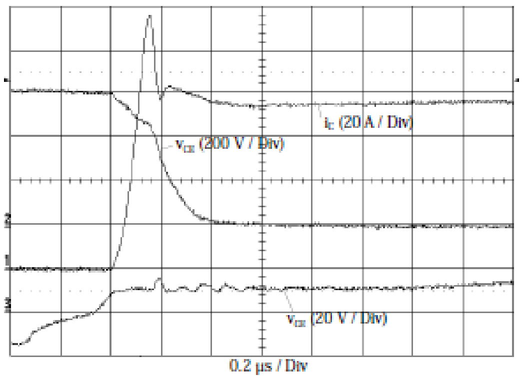
IGBT

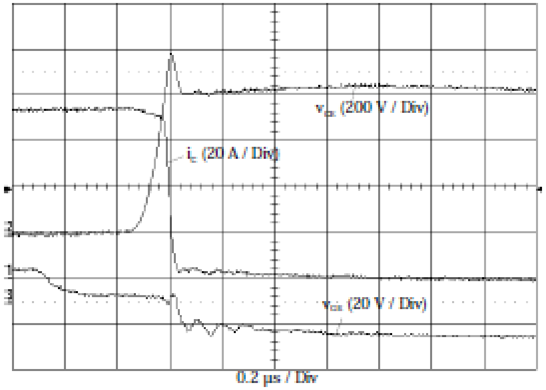
Real IGBT turn-on and turn-off:

Very fast di/dt, dv/dt => EMC

Switching losses => thermal limitation



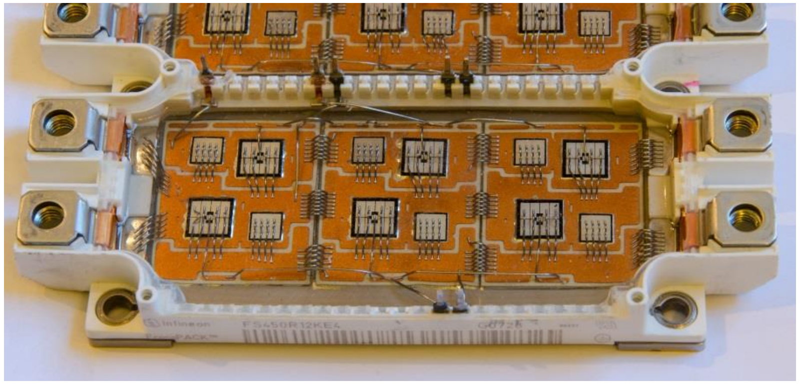


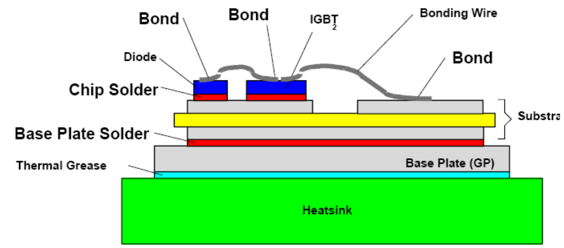


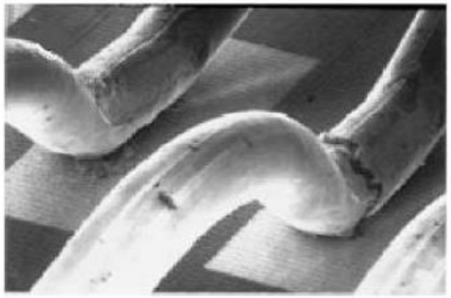
IGBT

Number of cycles

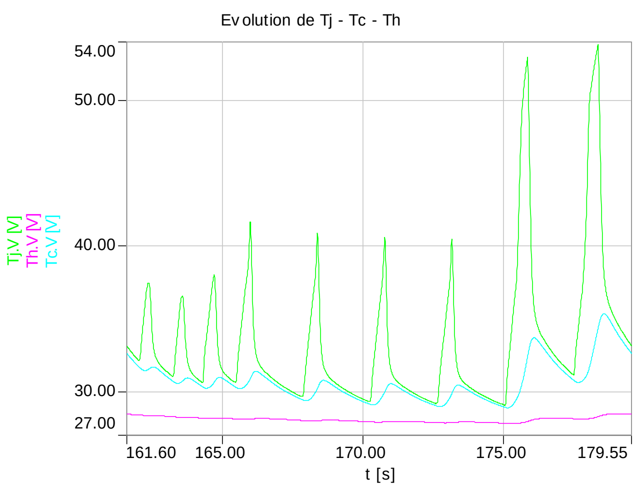
Thermal cycling of the IGBT

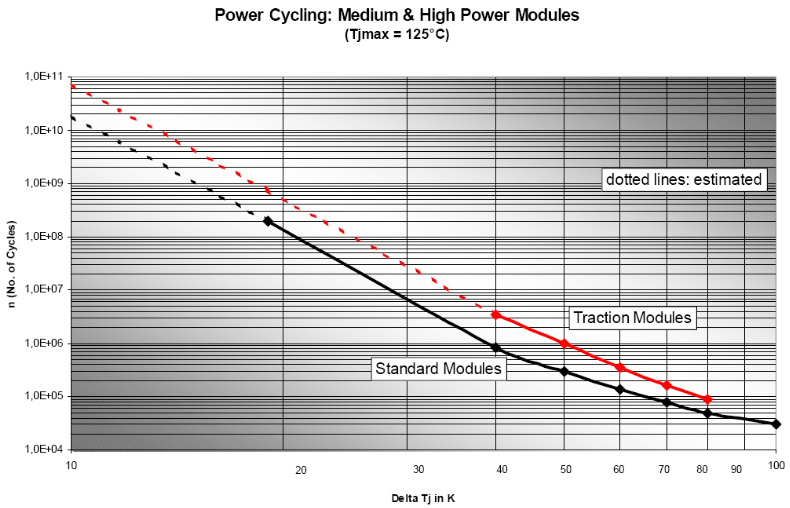






IGBT bonding can break after few thousand of thermal cycles

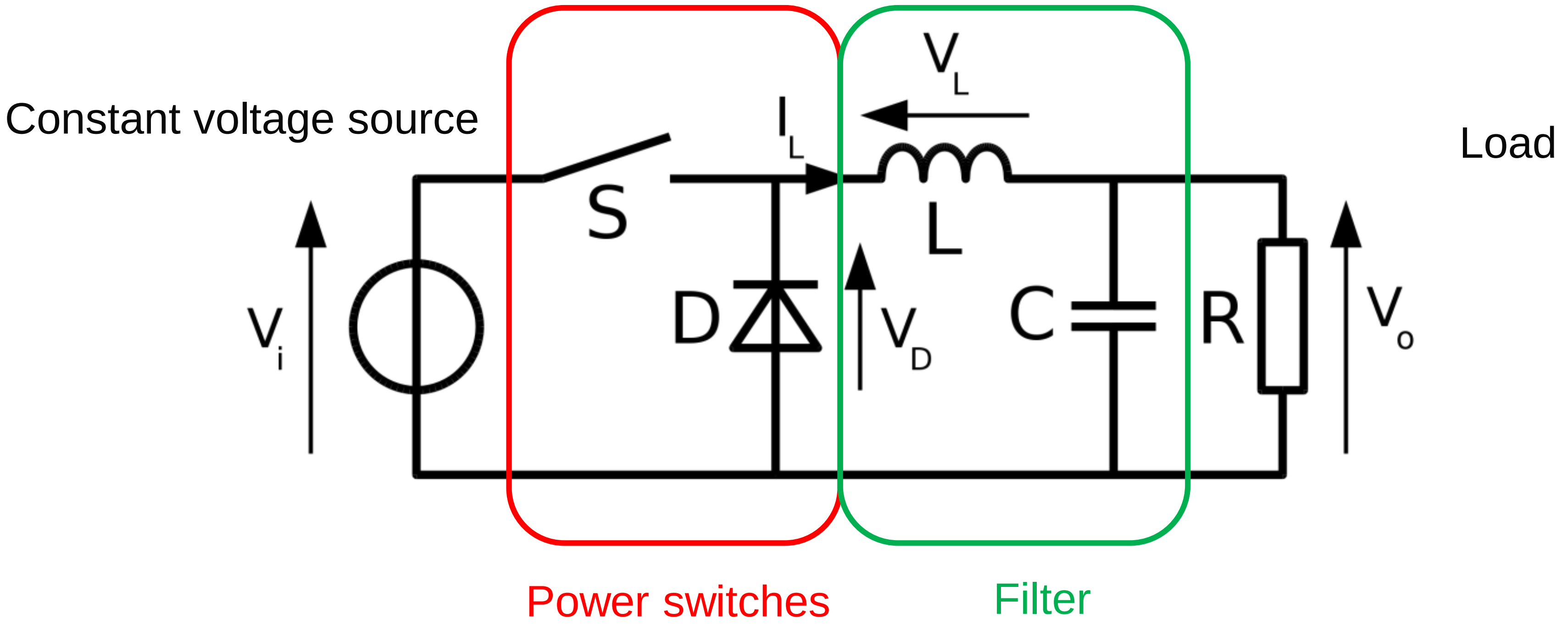




Power electronics basic concept

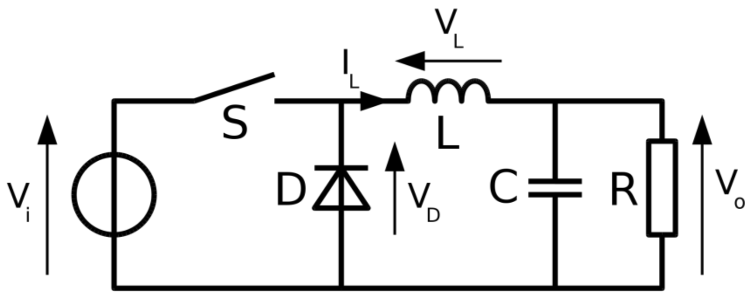
The basic principle is to command a switch to control the energy transfer to a load.

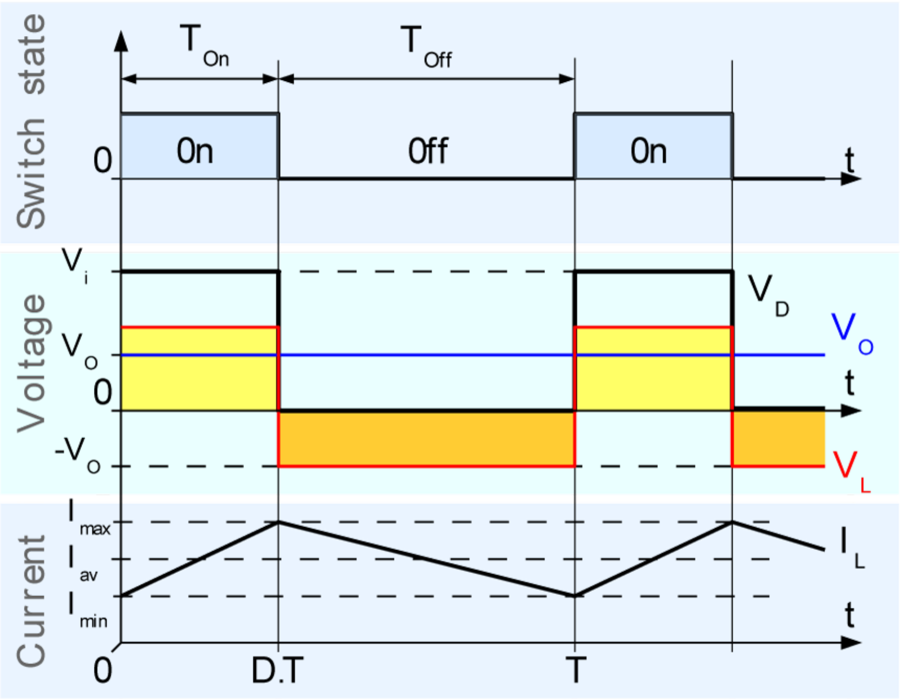
Example of a BUCK converter:



Power electronics basic concept

The switch S is switched ON during a short period which is repeated periodically.

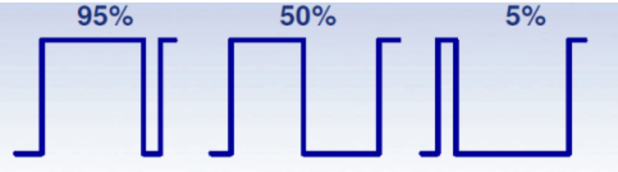




<Vo> = Ton/T × Vi

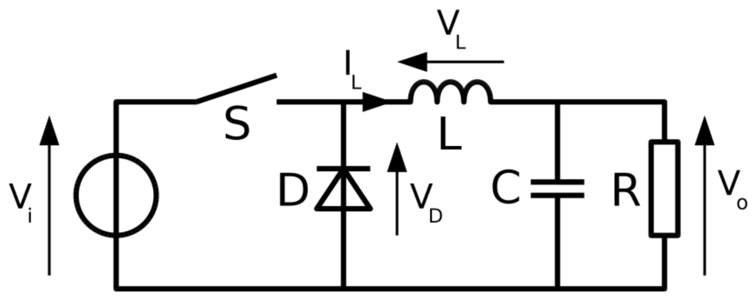
Vout = α × Vi

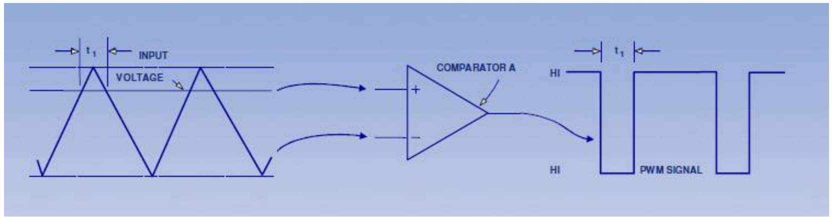
The output voltage can be controlled by playing with the duty cycle α.

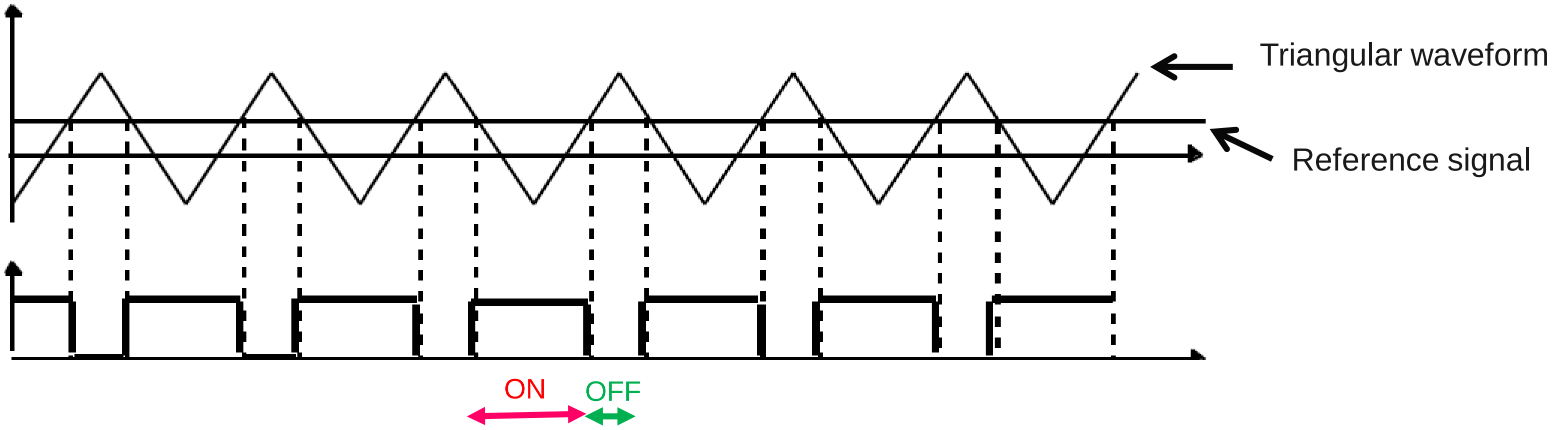


Power electronics basic concept

Most of the time, PWM (Pulsed Width Modulation) technique is used to control the switches. A triangular waveform is compared to a reference signal, which generates the PWM command of the switch.





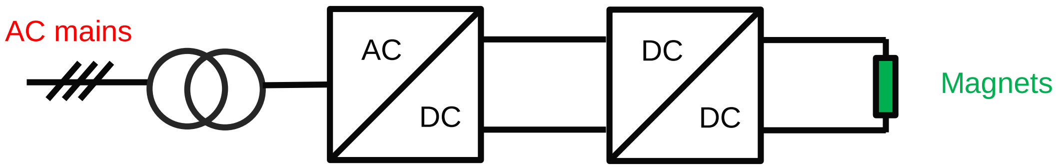


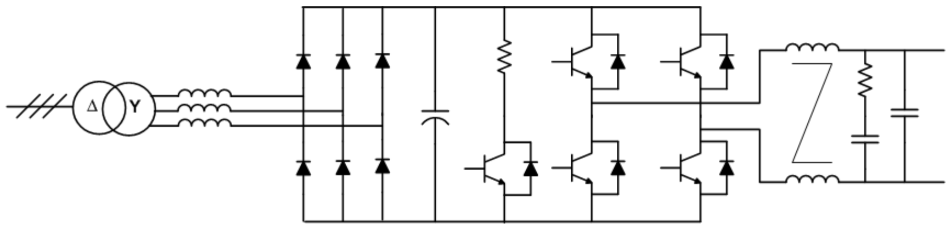
Topologies based on IGBT

The magnets need DC current.

The magnet power supplies are AC/DC.
The topologies are with multi-stages of conversion.

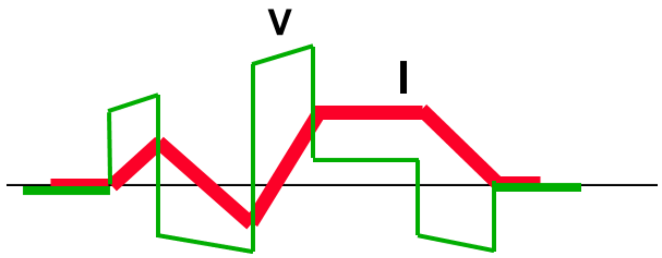
The magnets need a galvanic isolation from the mains: cases with 50Hz transformer

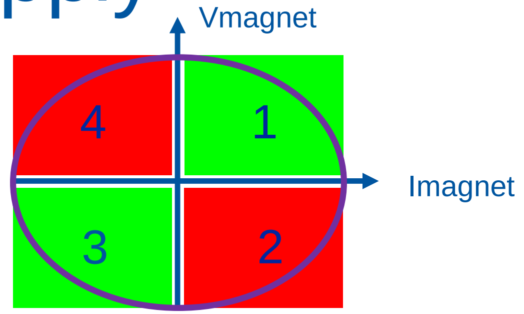


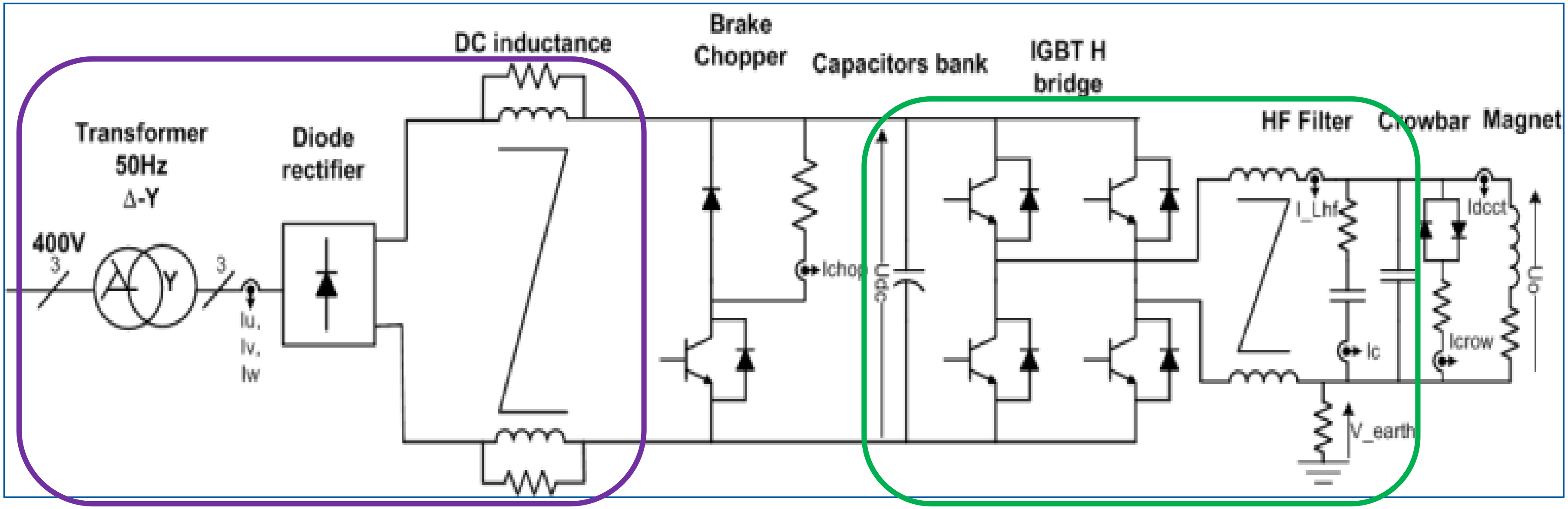


Switch-mode power supply

Example: PS converter: PR.WFNI, ±250A/±600V

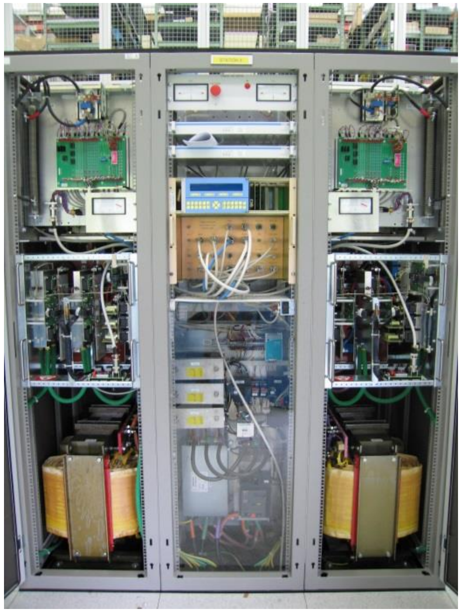






50Hz AC/DC stage

High-frequency DC/DC stage



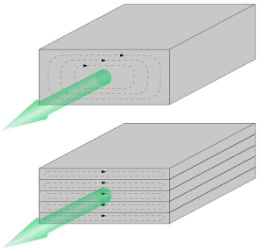

1
3
2
4

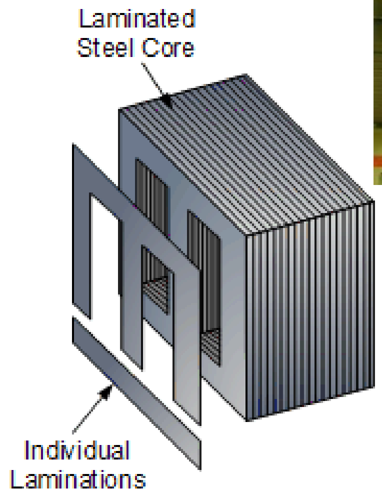
Transformer technologies

Two technologies are used for power transformers:

laminated magnetic core (like magnet):

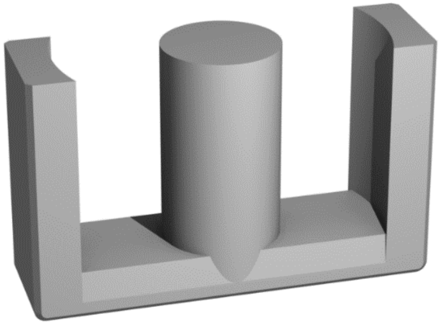
- 50Hz technology
- High field (1.8T)
- Limitation due to eddy current
- Low power density
- High power range

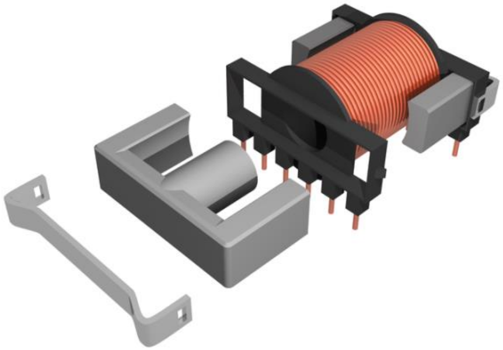




Ferrite core (like kicker):

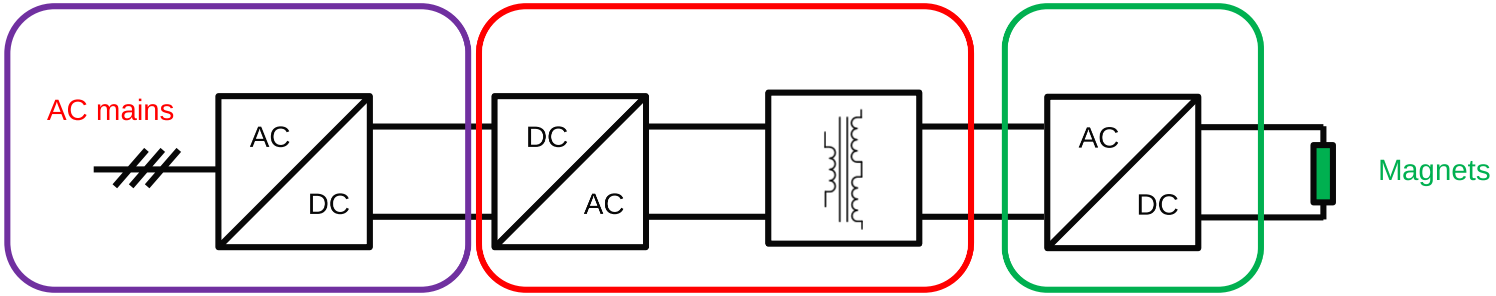
- kHz technology
- Low field (0.3T)
- Nonconductive magnetic material, very low eddy current
- High power density
- Low power range (<100kW)





Topologies with HF transformer

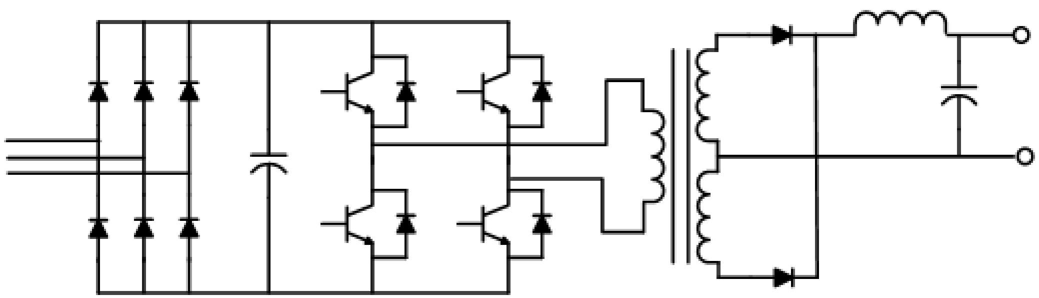
In this case, it is multi-stages converter with high-frequency inverters



50Hz rectifier

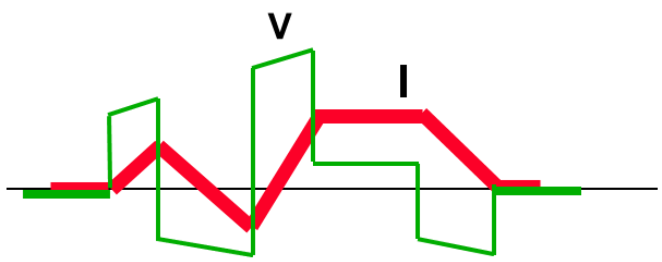
HF inverters & transformer

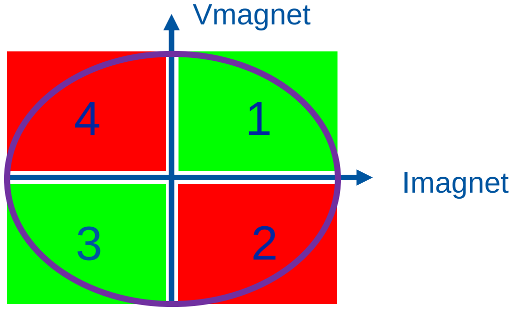
HF rectifier & filter

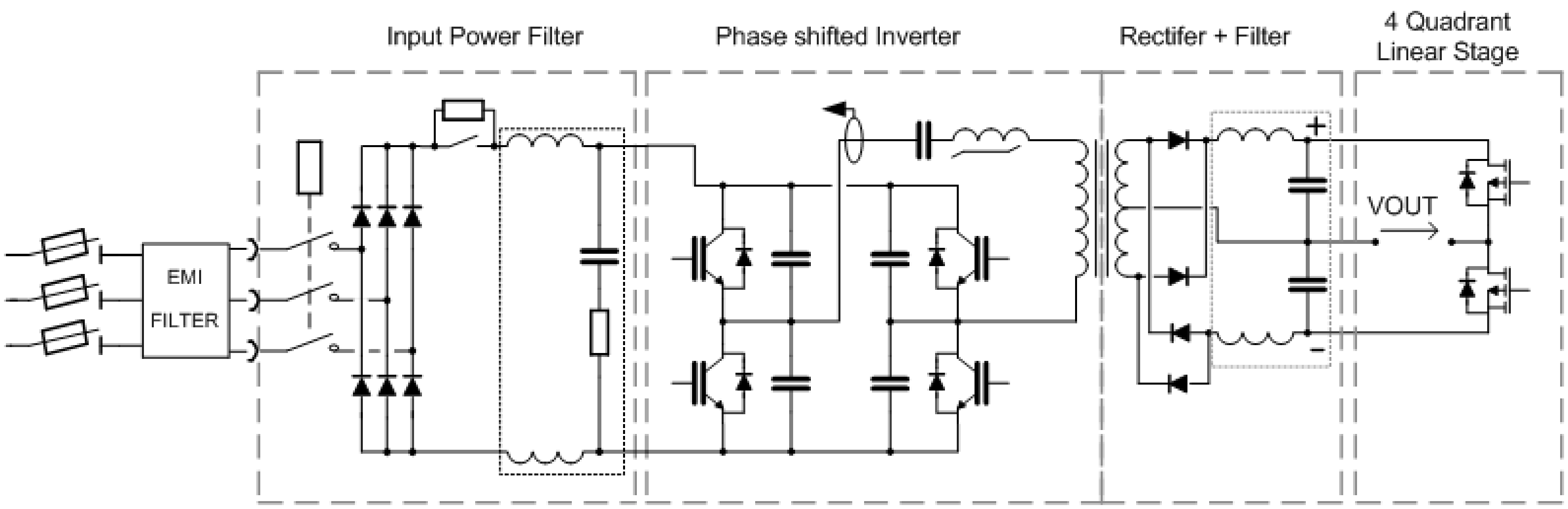


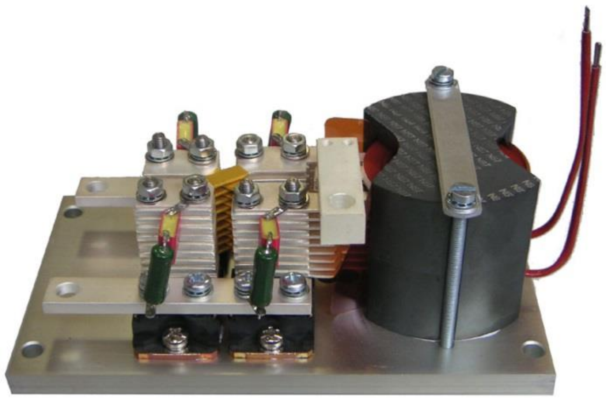
Switch-mode power supply with HF inverter

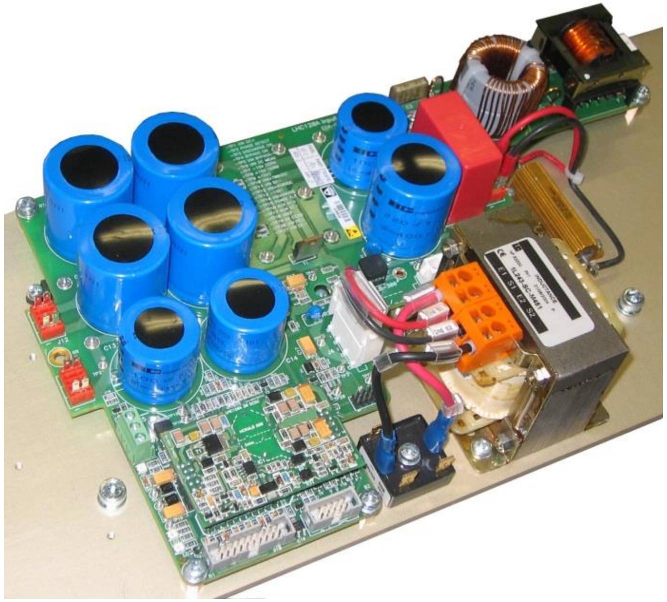
Example: LHC orbit corrector, ±120A/±10V





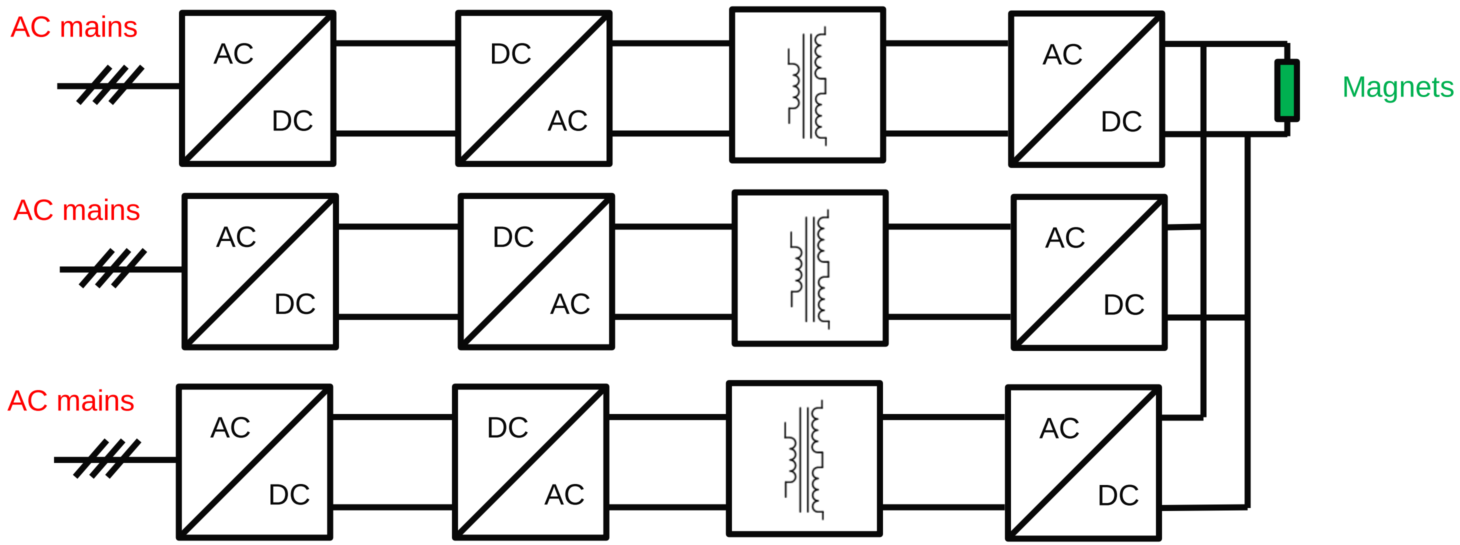






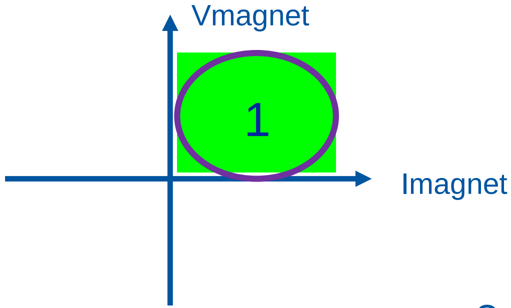
Converter association

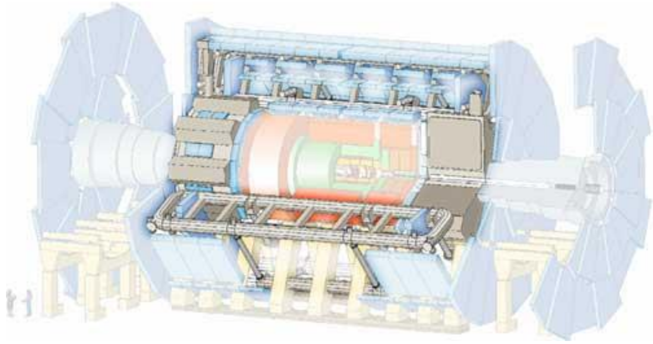
When the power demand increases above the rating of the power semiconductor, the only solution is to build a topology with parallel or series connection of sub-system.



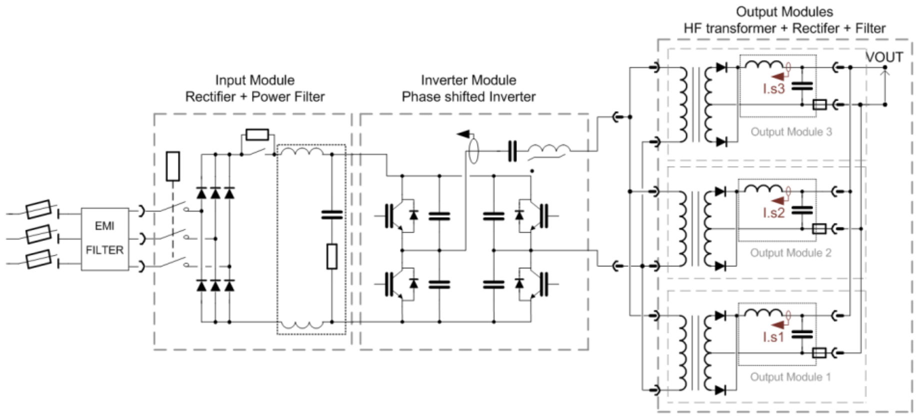
Parallel connection of sub-converters

Example: Atlas toroid magnet power supply 20.5kA/18V

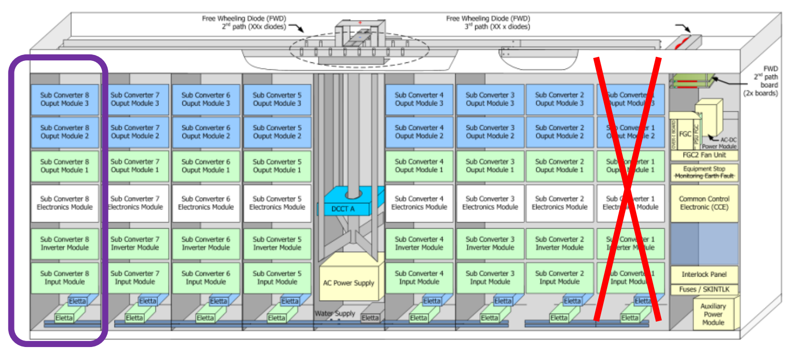




3.25kA/18V sub-converter



8 sub-converters in parallel

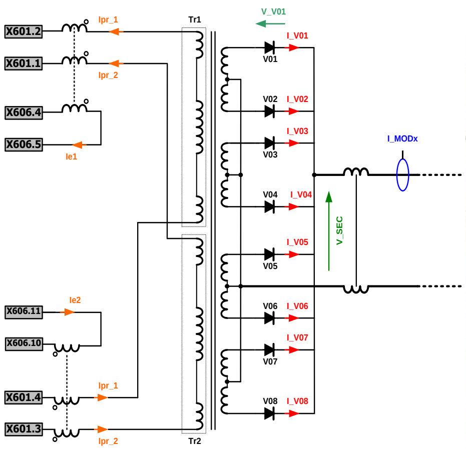


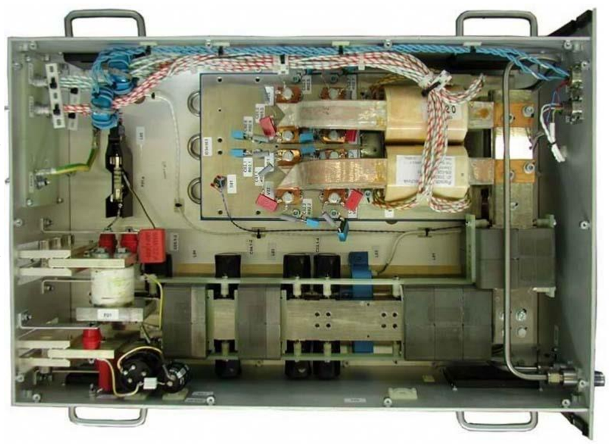
3.25kA/18V

Redundancy implementation, n+1 sub-converters

Can work with only n sub-converters


Sub. 8
Sub. 7
Sub. 6
Sub. 5
Power Connection Rack
TRANSTECHNIK
Sub. 4
Sub. 3
Sub. 2
Sub. 1
Electronics Rack

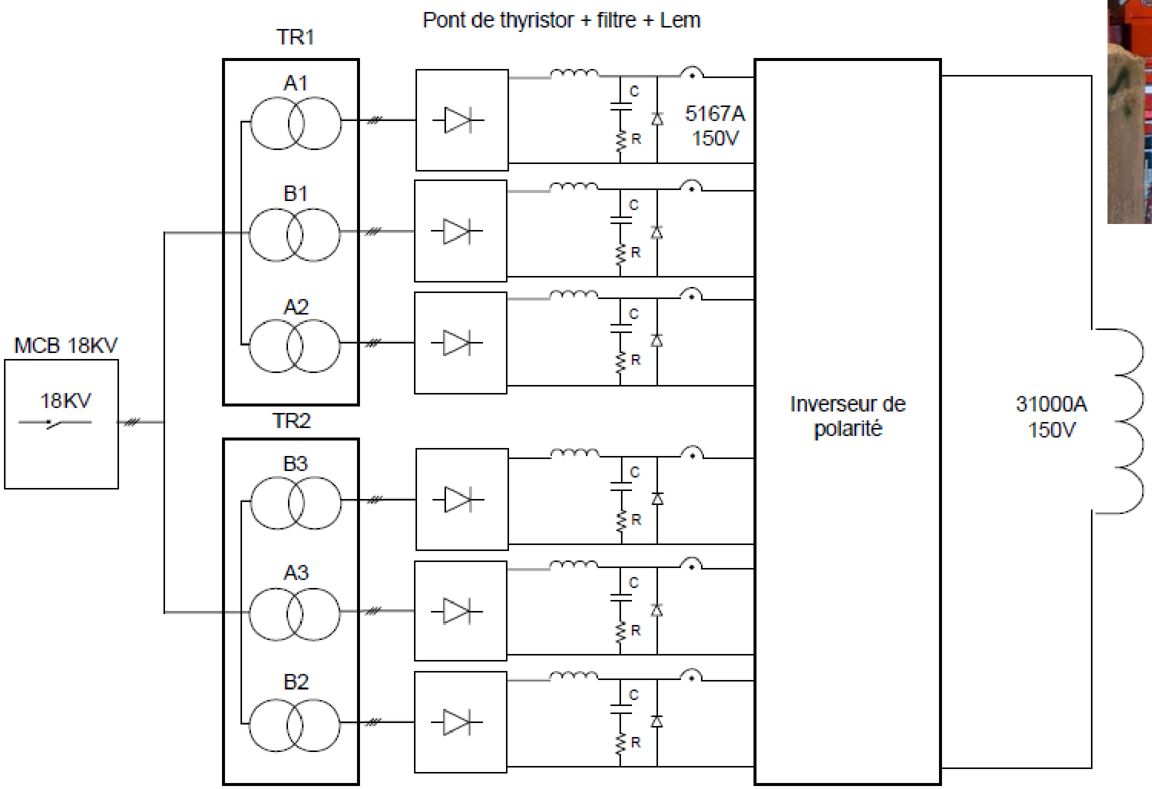

X601.2
X601.1
X606.4
X606.5
X606.11
X606.10
X601.4
X601.3
Ipr_1
Ipr_2
Ie1
Ie2
Ipr_1
Ipr_2
Tr1
Tr2
V_V01
I_V01
V01
V02
I_V02
I_V03
V03
V04
I_V04
I_V05
V05
V06
I_V06
I_V07
V07
V08
I_V08
V_SEC
I_MODx

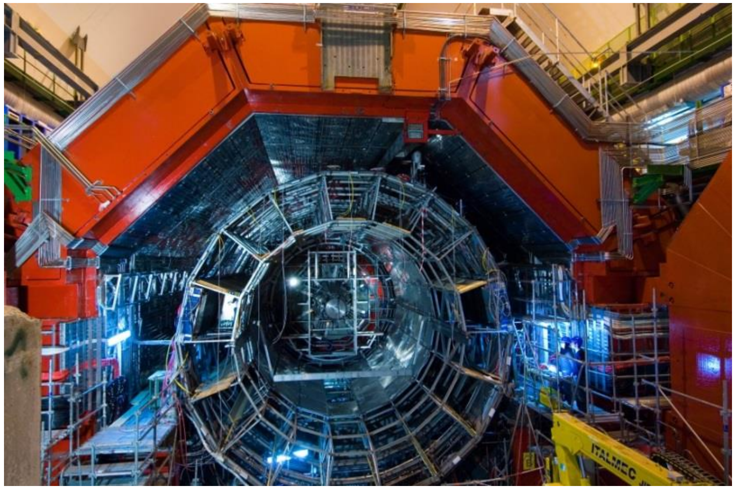



PWC-T

Parallel connection with thyristor rectifier

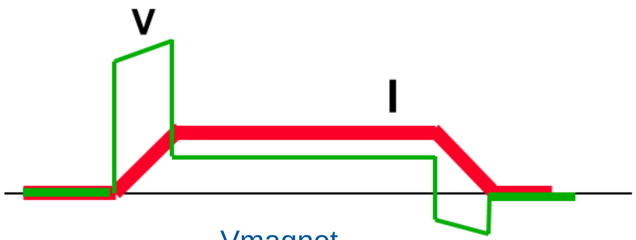
Example: Alice Dipole, 31kA/150V

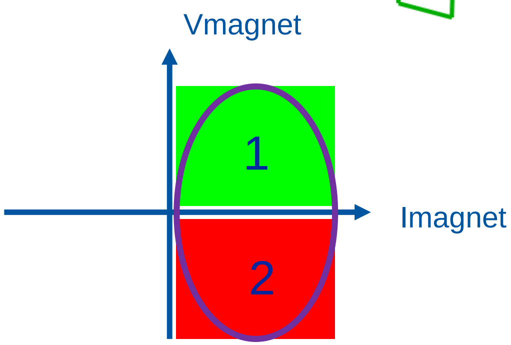


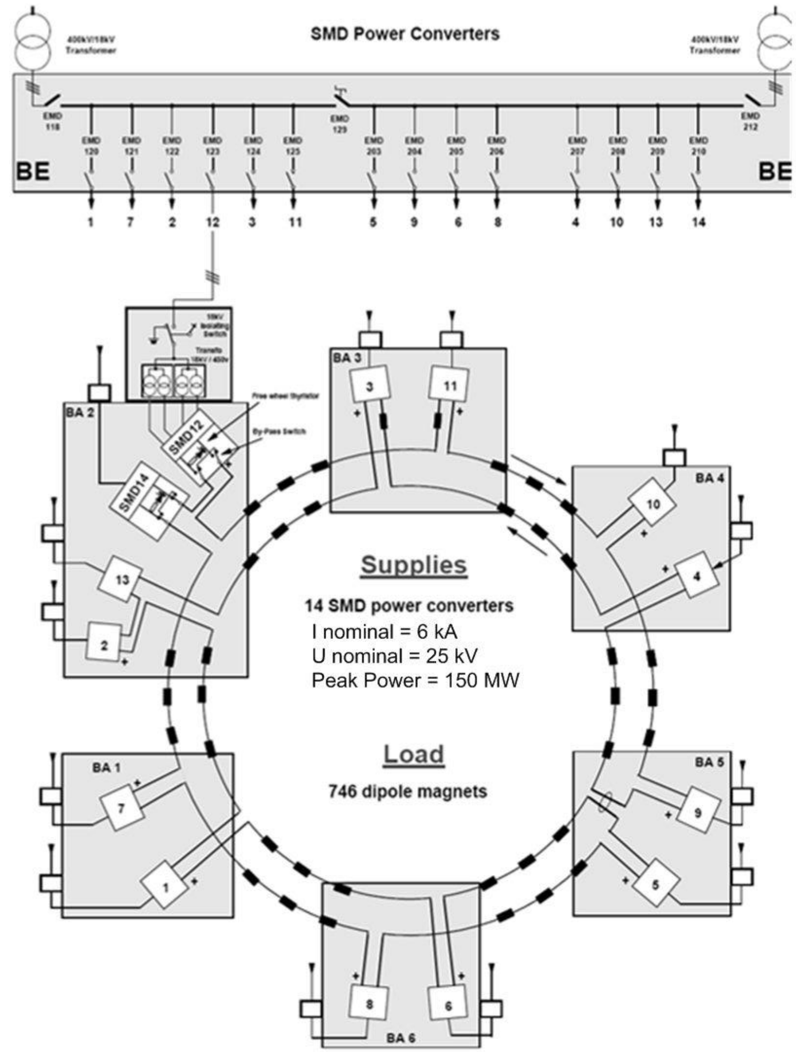


Series connection of sub-converters

Example: SPS dipole power supply, 6kA/24kV



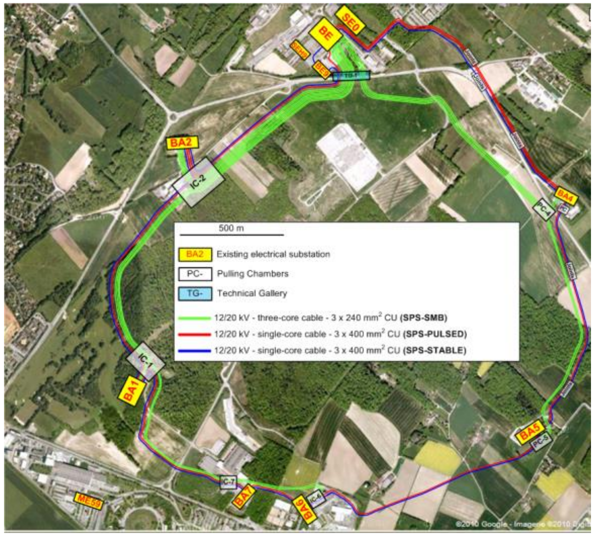




12 power supplies in series between magnets.

Each power supply gives 6kA/2kV.

In total 24kV is applied to the magnets.


BE
SE0
BA2
IC-2
PC-4
BA4
IC-1
BA1
BA5
500 m
BA2 Existing electrical substation
PC- Pulling Chambers
TG- Technical Gallery
12/20 kV - three-core cable - 3 x 240 mm2 CU (SPS-SMB)
12/20 kV - single-core cable - 3 x 400 mm2 CU (SPS-PULSED)
12/20 kV - single-core cable - 3 x 400 mm2 CU (SPS-STABLE)

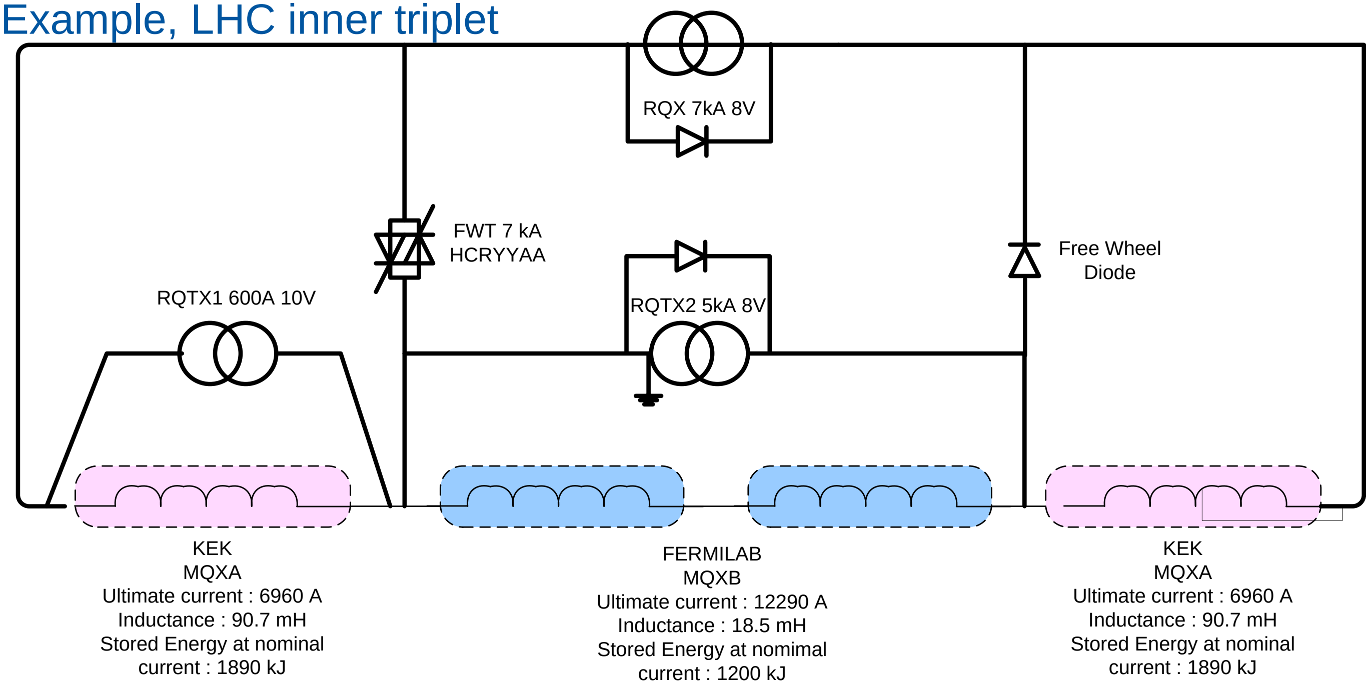
Nested circuits

Nested powering scheme is popular with accelerator physicists and magnet designers.

Allows association of different magnets or to correct local deviation over a long series of magnets.

Main reasons: saving on DC cables, current leads, lower power supply rating,…

Example, LHC inner triplet



Nested circuits

Nested powering scheme is a nightmare for power engineers !!

Very complex control, it is like a car with many drivers having a steering wheel acting on only one wheel.

Coupled circuits

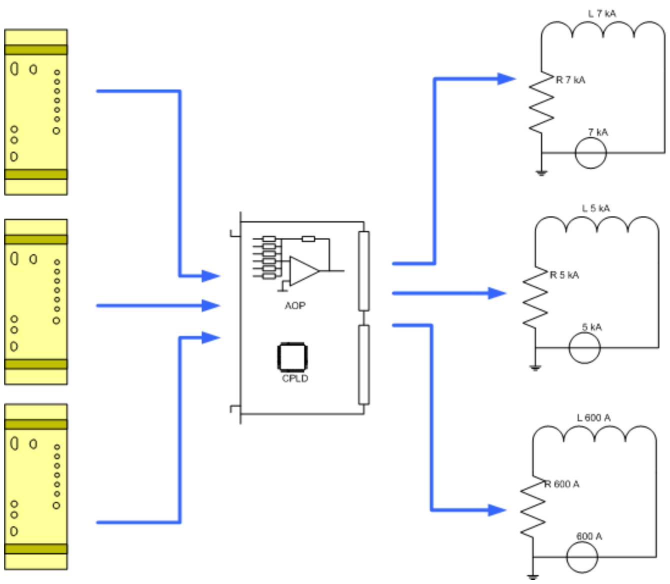
Nested circuits

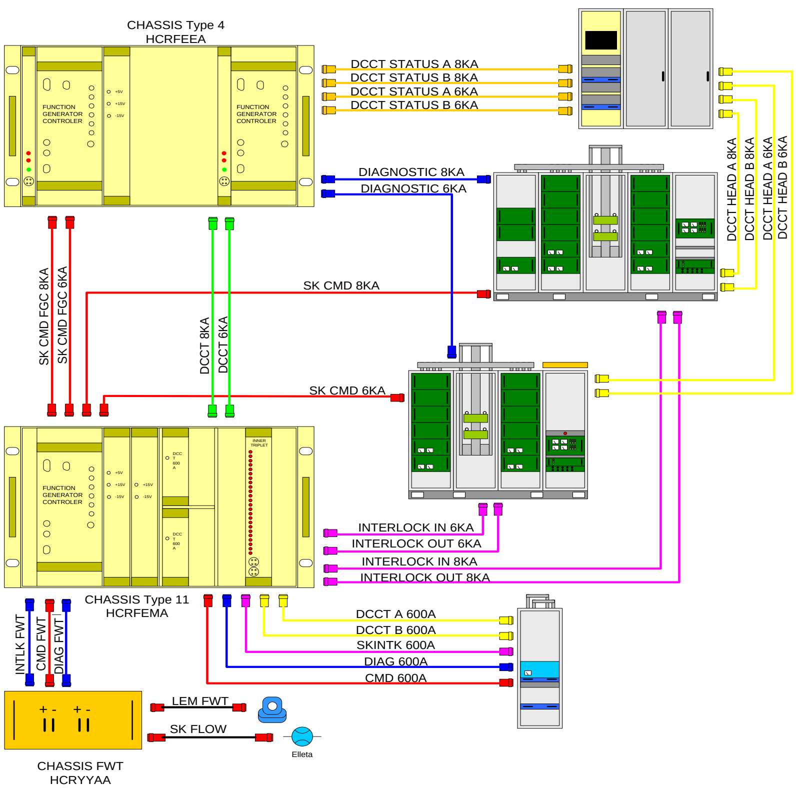
Very difficult to operate and repair, long MTTR.

Reduce investment but decrease availability!

All power supplies have to talk each others.

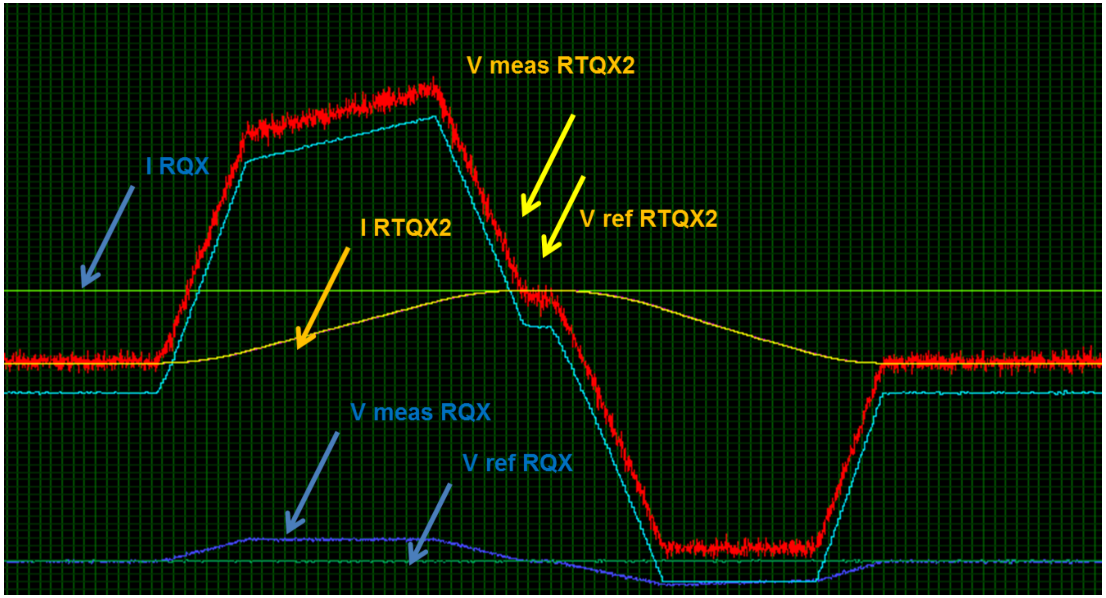
Need a decoupling control to avoid fight between power supplies !





Nested circuits

Look at the current and voltage of RQX while RTQX2 current is changing!



Nested circuits aren't RECOMMANDED !

LHC inner triplet works perfectly well but MTTR is very high.

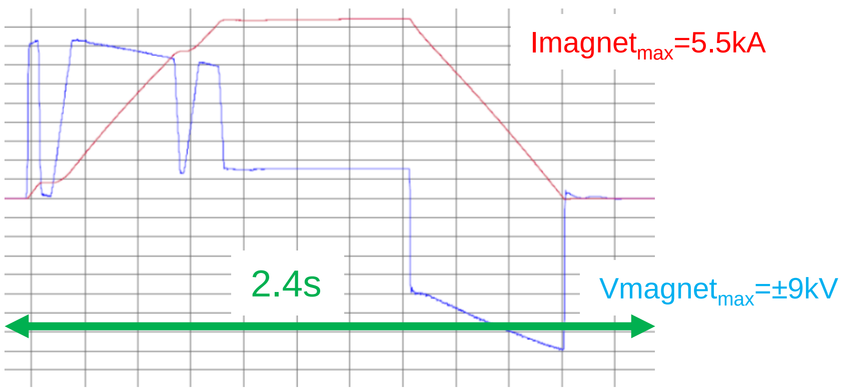
RHIC had many difficulties with nested circuits.

Energy management

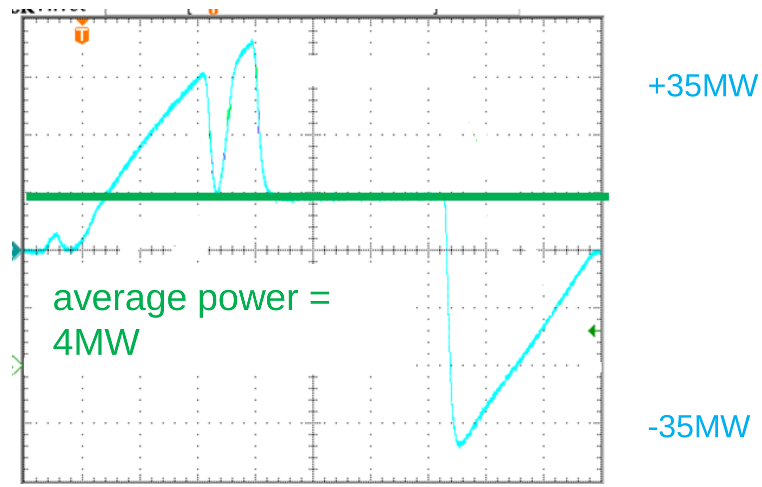
Magnets need voltage to move their current:

Vmagnet(t) = Rmg * Img(t) + Lmg * dImg(t)/dt

Example with the PS main magnets



Blue: Umagnet 1 kV / div
Red: Imagnet 500A / div



Light blue: Power_to_magnet 10 MW / div

Power(t) = I_magnet(t) x V_magnet(t)

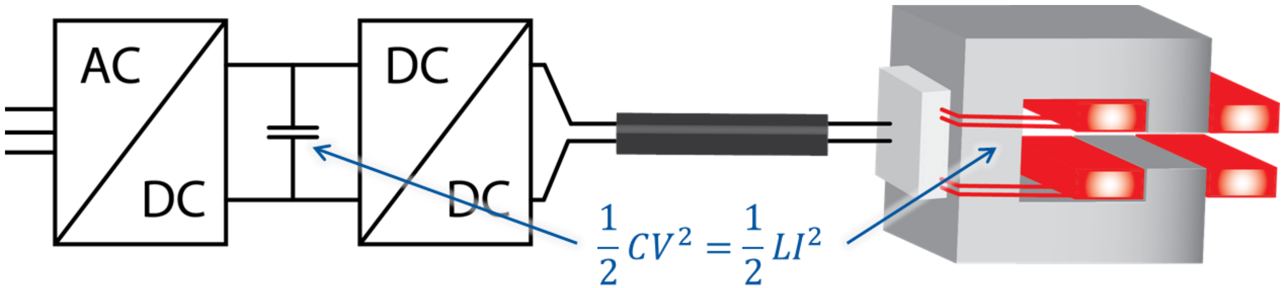
The peak power needed for the main magnets is ±40MW with a dynamic of 1MW/ms

The average power is only 4MW !!!

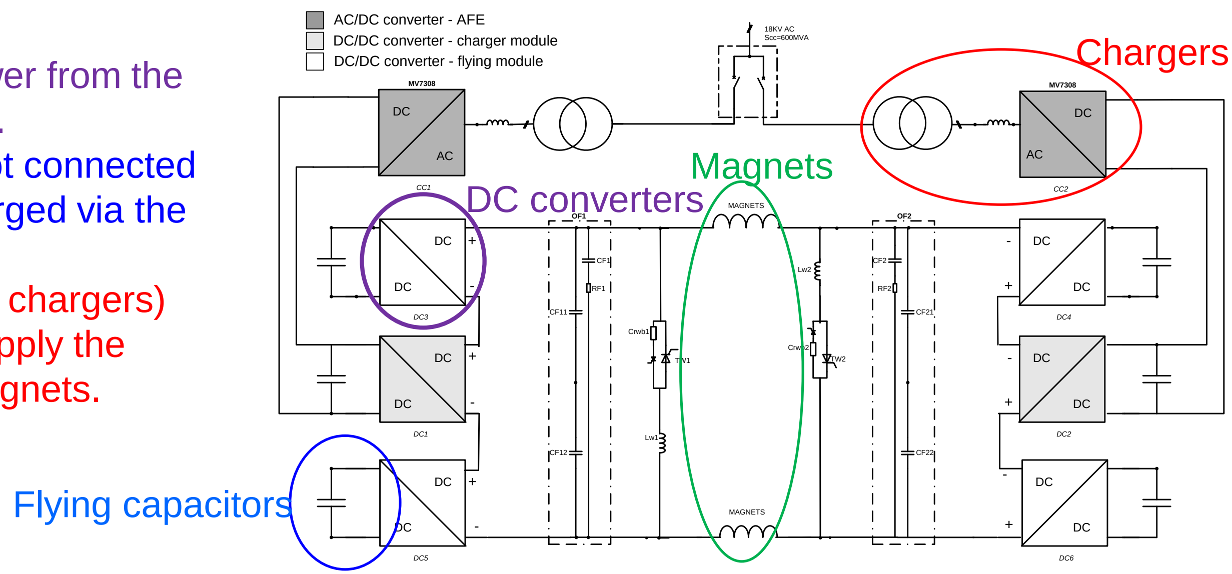
The challenge: Power a machine which needs a peak power 10 times the average power with a very high dynamic !!!

New concept for energy management

The energy to be transferred to the magnets is stored in capacitors
The capacitor banks are integrated in the power supply

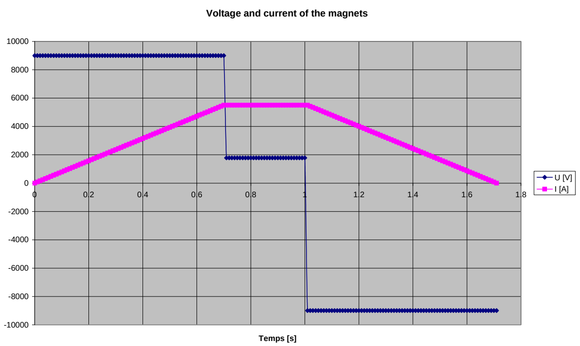


- DC/DC converters transfer the power from the storage capacitors to the magnets.
- Four flying capacitors banks are not connected directly to the mains. They are charged via the magnets
- Only two AC/DC converters (called chargers) are connected to the mains and supply the losses of the system and of the magnets.

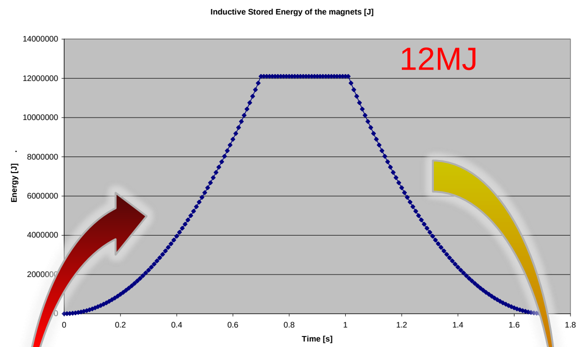


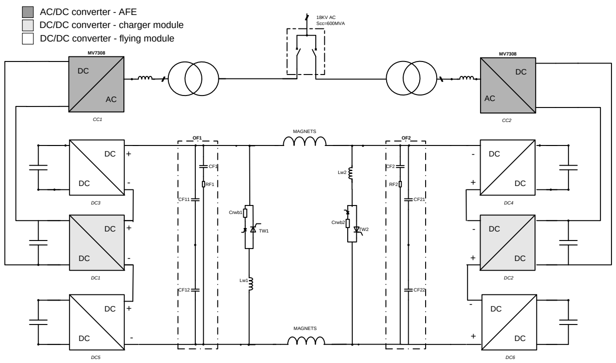
New concept for energy management

Magnets current and voltage

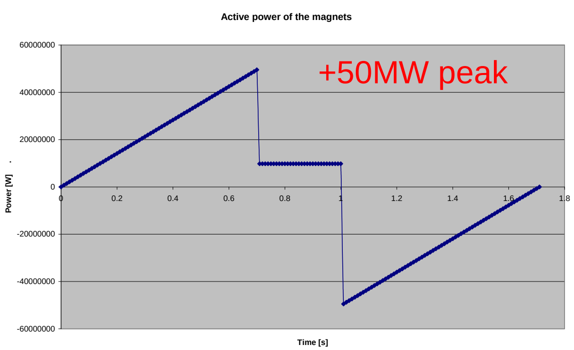


Stored magnetic energy

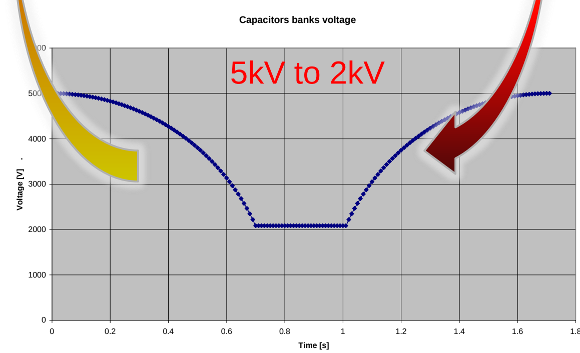




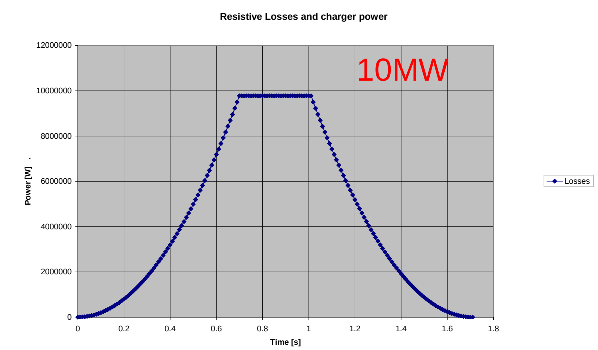
Power to the magnets



Capacitor banks voltage



Power from the mains = Magnet resistive losses



POPS: POwer converter for the PS main magnets.

POPS example

Example: POPS 6kA/±10kV

Control room | Electrical room | Cooling tower | Power transformers | Capacitor banks

Energy management

- Capacitor banks
  - 5kV Dry capacitors
  - Polypropylene metalized self healing
  - Outdoor containers: 2.5m x 12m, 18 tons
  - 0.247F per bank, 126 cans
  - 1 DC fuse
  - 1 earthing switch
  - 3 MJ stored per bank

- 60 tons of capacitors divided in
- 6 capacitor banks making in total 18.5MJ

- Up to 14MJ can be extracted during a cycle!

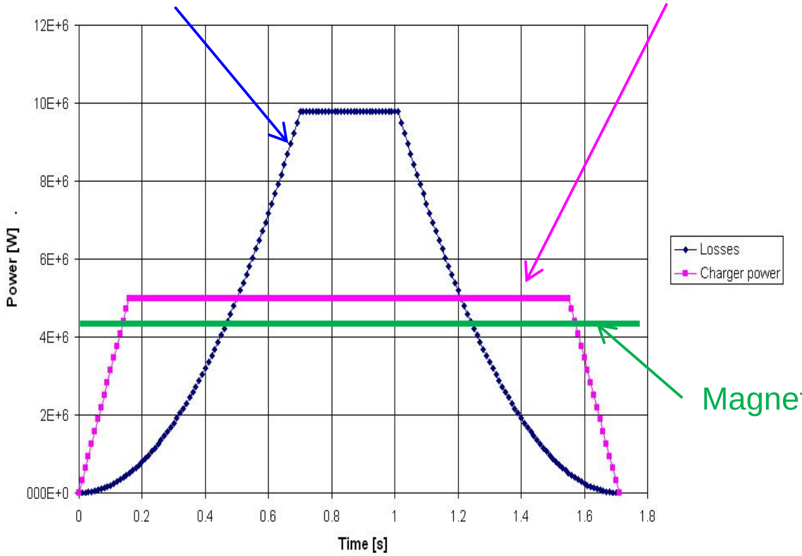
- The capacitors represent 20% of the total system cost.

Energy management

Best optimization : Max power taken on the mains # magnet average power

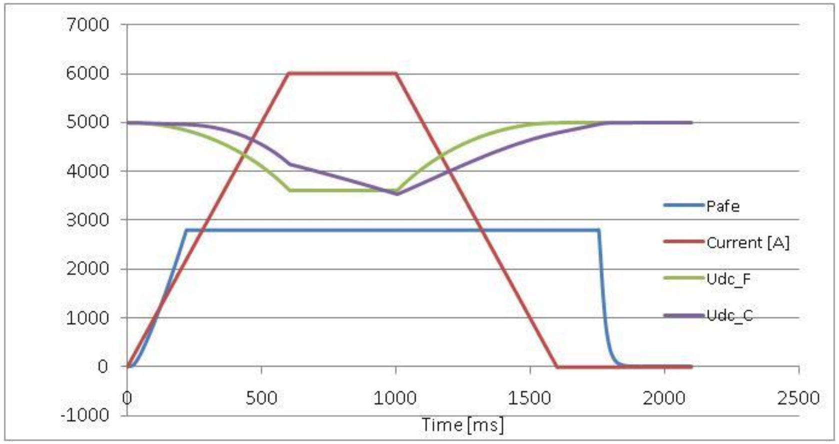
Resistive losses of the magnets

Power demand on the mains



Magnet average power

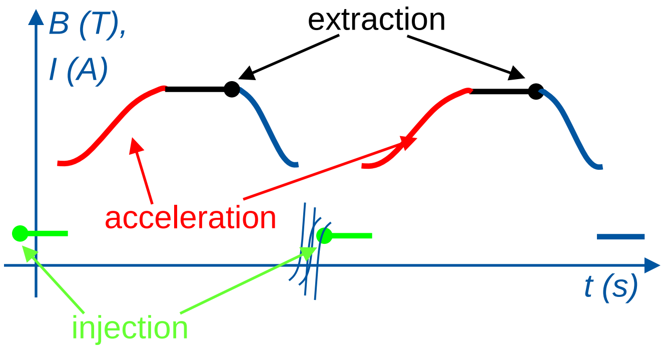
POPS energy management



Discharged power supplies

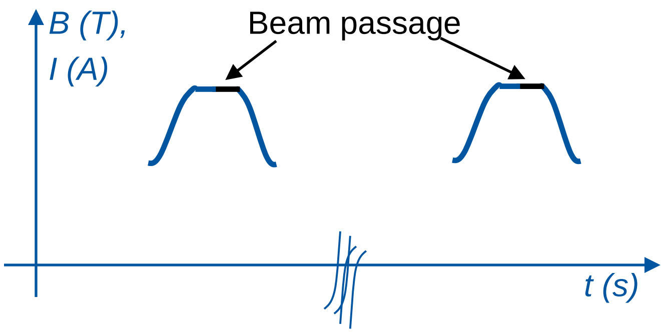
Synchrotrons

Beam is injected, accelerated and extracted in several turns



Linac's and transfer lines

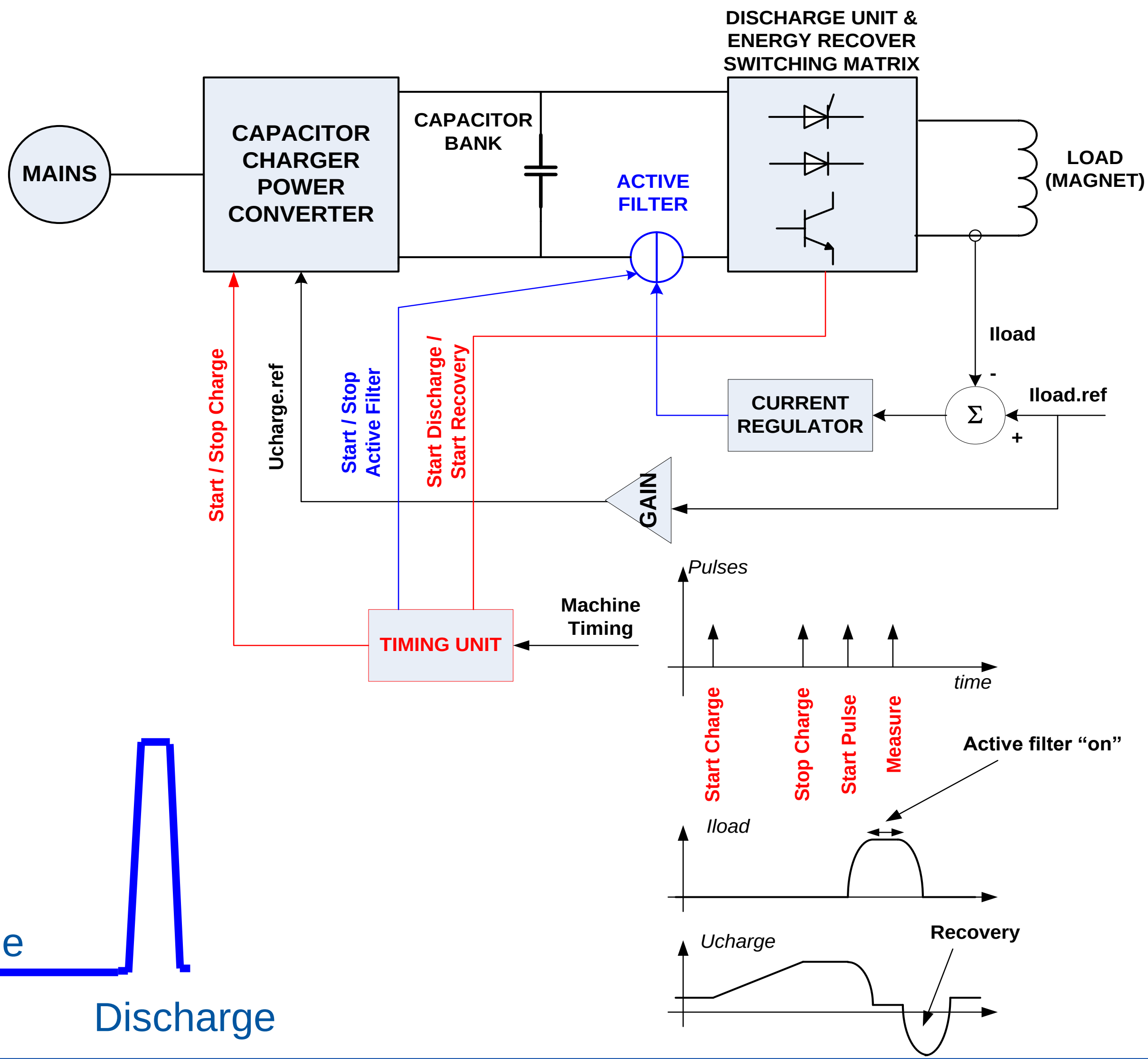
Beam is passing through in one shot, with a given time period;

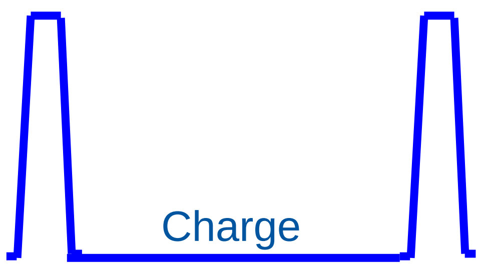


Rise and fall time < few ms

Direct Energy transfer from mains is not possible:
Intermediate storage of energy
Peak power : could be > MW
Average power kW

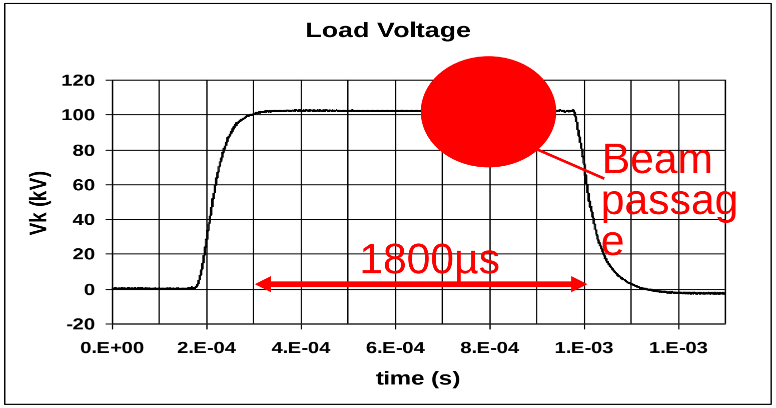
Discharged power supplies

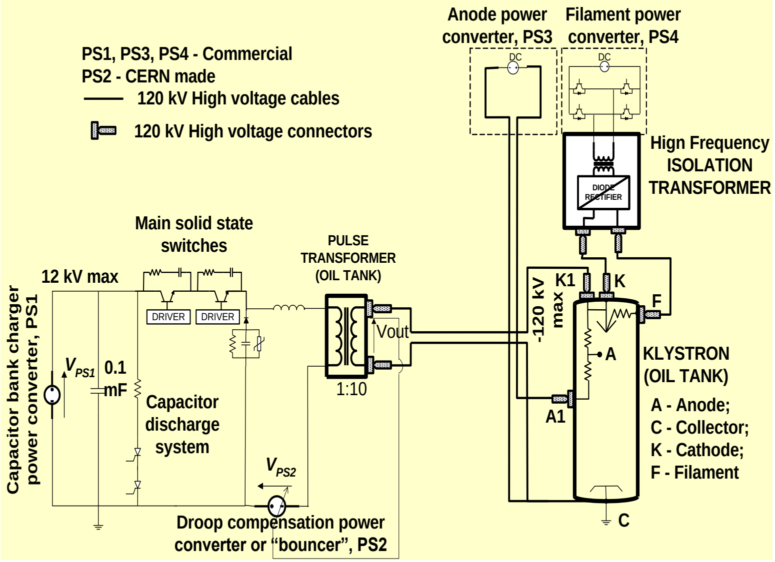




Example of LINAC4 Klystron modulator

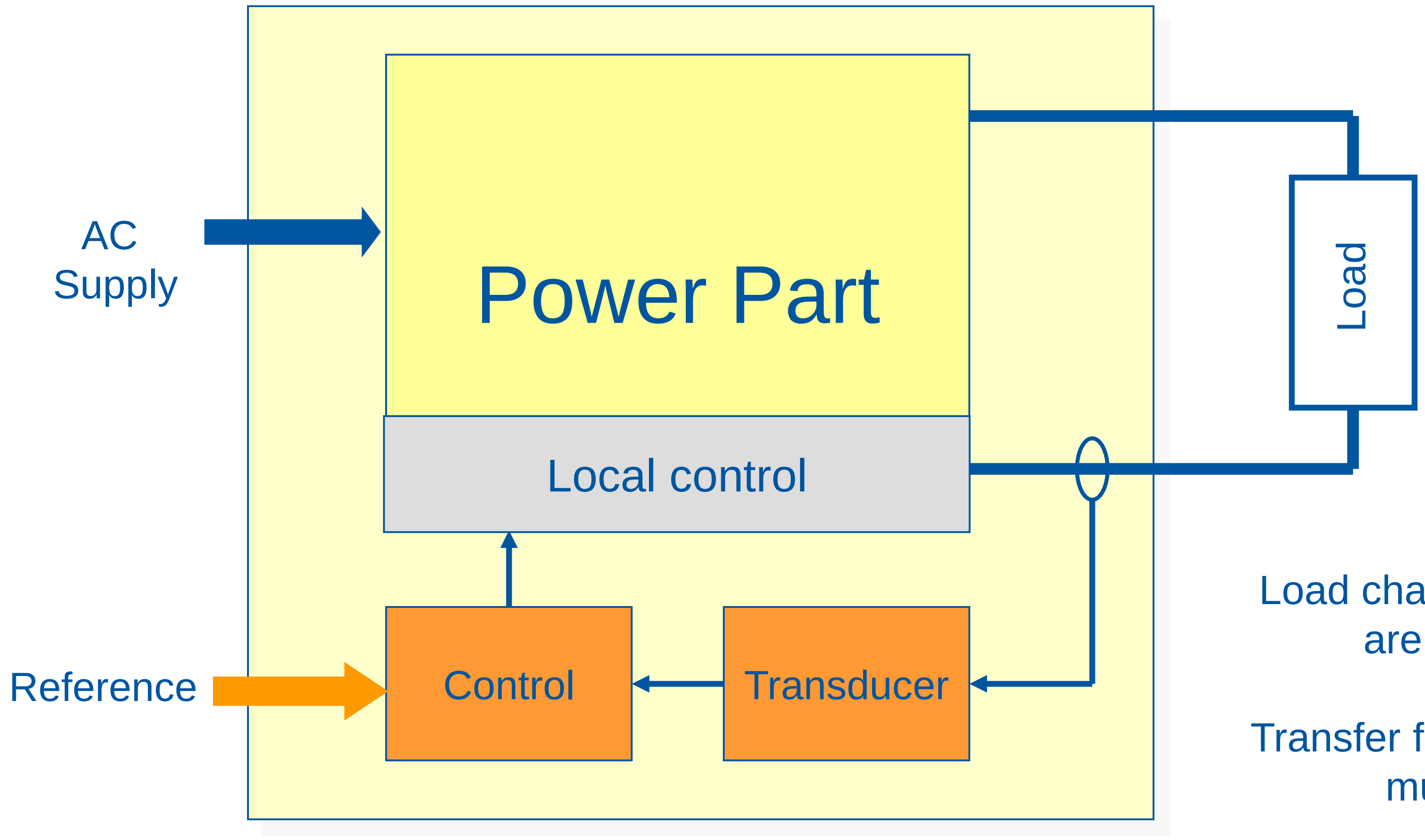
Specification	symbol	Value	unit
Output voltage	V_{kn}	110	*kV*
Output current	I_{out}	50	*A*
Pulse length	$t_{rise}+t_{set}+t_{flat}+t_{fall}$	1.8	*ms*
Flat-Top stability	*FTS*	<1	*5*
Repetition rate	$1/T_{rep}$	2	*Hz*





Peak power : 5.5MW
Average power: 20kW

Power supply control



Load characteristics are vital.

Transfer function is a must !

Power supply control

The power supply are controlled by the global control system.

They need to be synchronized => Timing

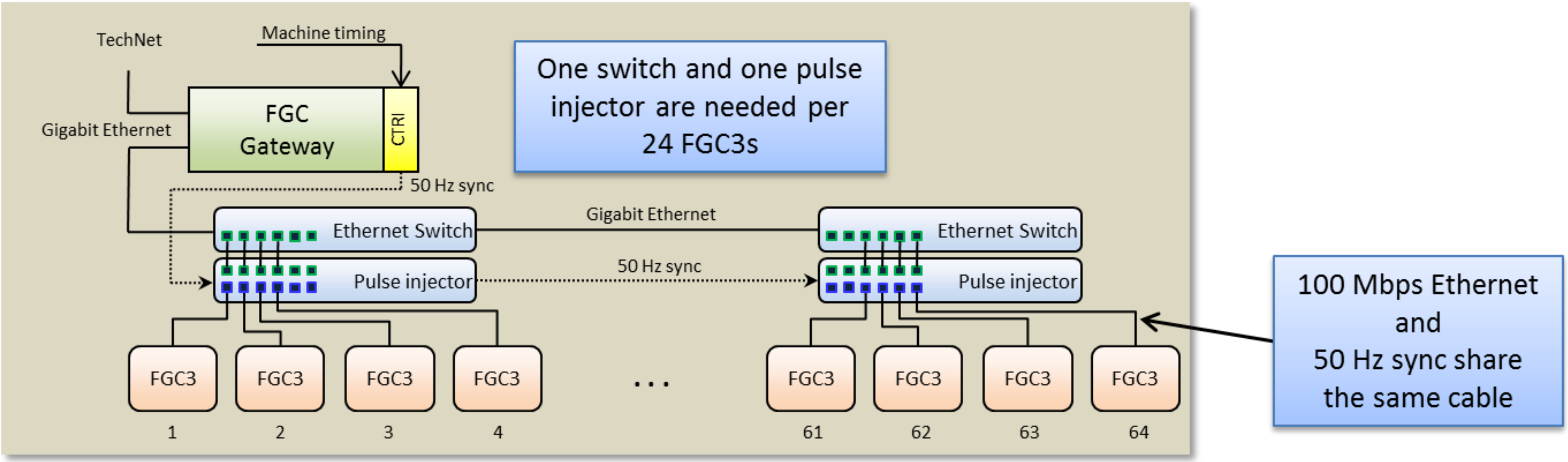
Locally, a fieldbus (must be deterministic) is used to communicate with a gateway,

WORLDFIP in the LHC

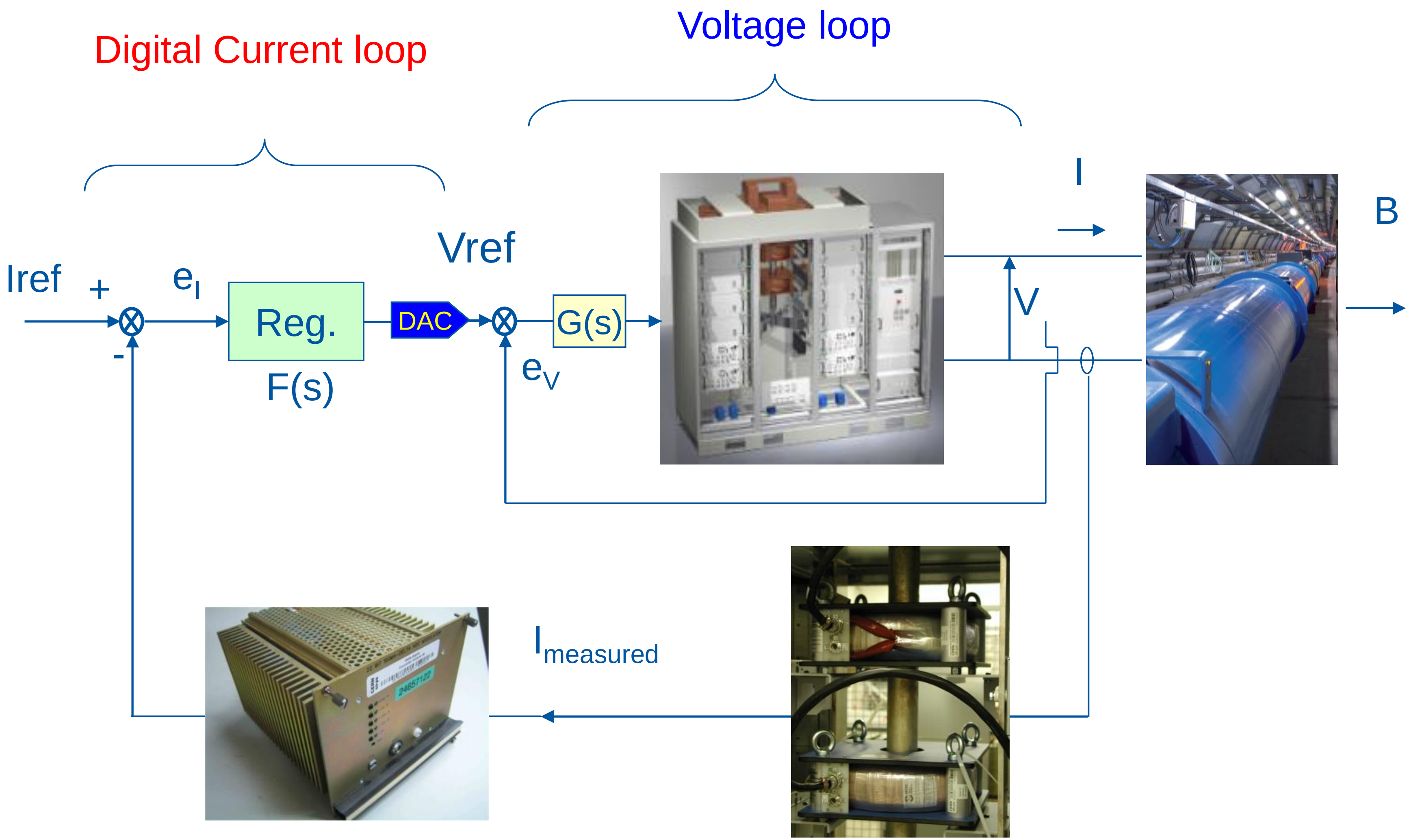
ETHERNET for LINAC4

In each power supply, an electronic box (FGC) manages the communication, the state machine and do the current control.

Real time software is implemented.



Power supply control



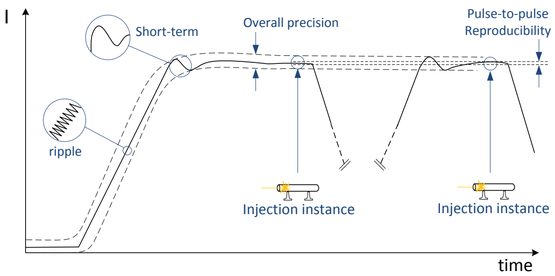
High-precision definition

Accuracy

The closeness of agreement between a test result and the accepted reference value. (ISO)

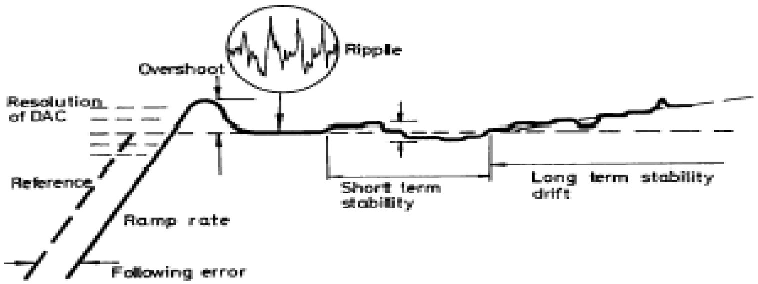
Reproducibility

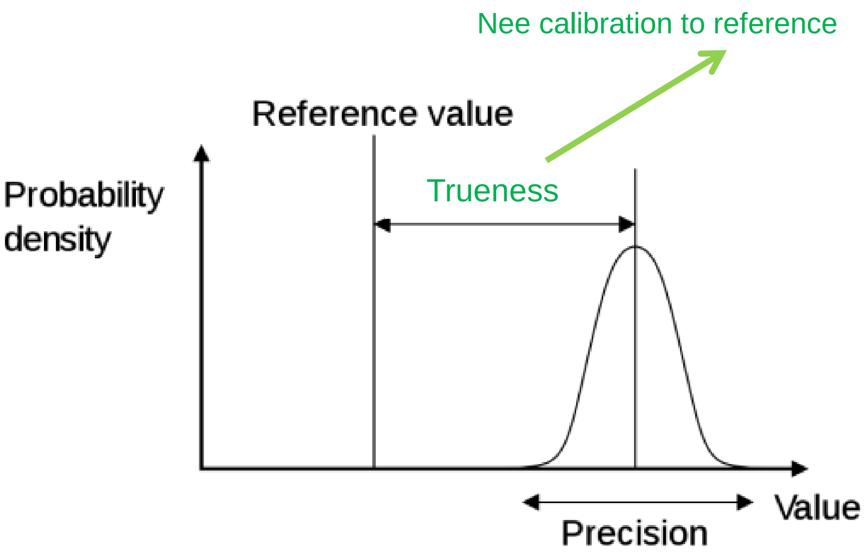
Uncertainty when returning to a set of previous working values from cycle to cycle of the machine.

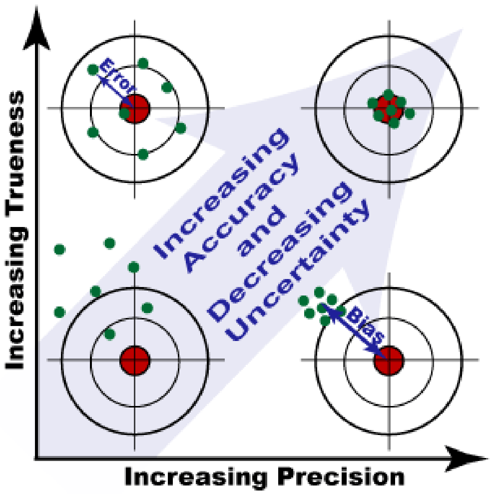


Stability

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







Accuracy characterisation

The term Accuracy is a qualitative concept, used to describe the quality of a measurement. At CERN (and elsewhere) a measurement's systems capability is often characterized in terms of Gain and Offset errors, Linearity, Repeatability, Reproducibility and Stability.

Linearity:

Difference in the systematic error of a measuring device, throughout its range.

Gain and Offset errors:

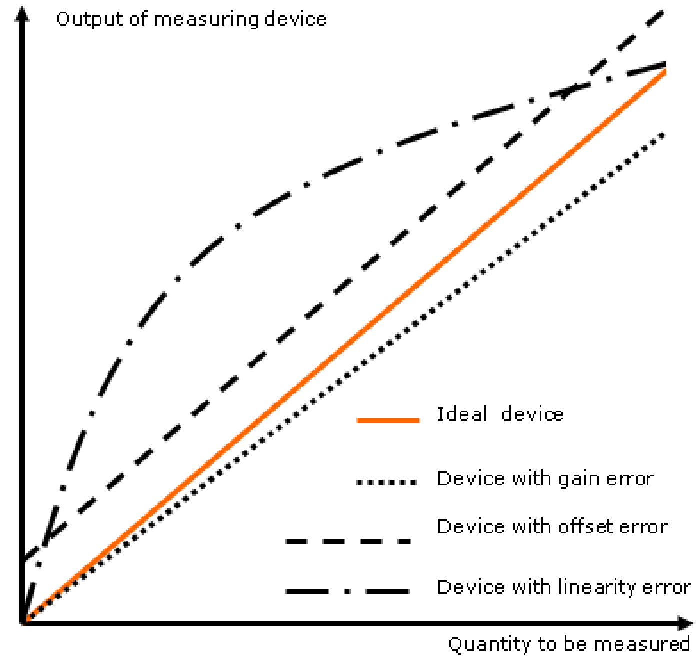
They are systematic errors that relate to the trueness of a measurement.

The offset error refers to the systematic error at zero and the gain error to the systematic error at full scale.

Stability:

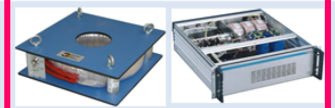
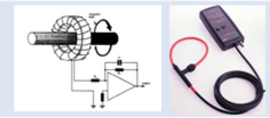
Measurement of the change in a measurement system's Systematic errors with time. We can more specifically refer to Gain Stability or Offset Stability.

Noise can also be seen as a measurement of a device's stability, although normally the term stability is used only for the low frequency range (≤Hz).

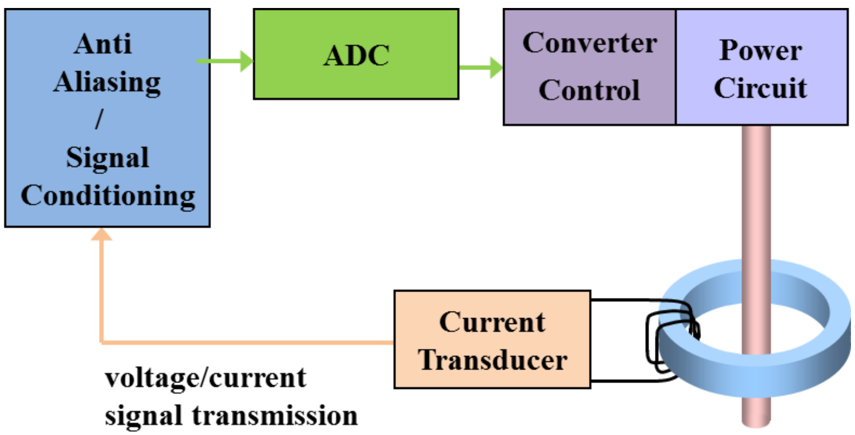


http://te-epc-lpc.web.cern.ch/te-epc-lpc/sensors/definitions.stm

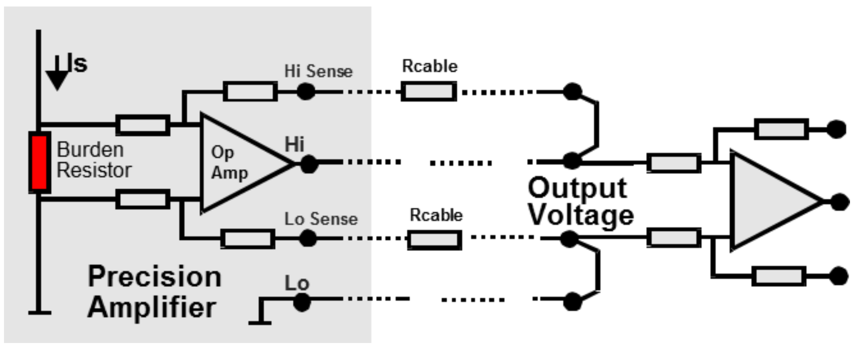
Current measurement technologies

	DCCTs	Hall effect	CTs	Rogowsky	Shunts
					
Principle	Zero flux detection	Hall effect	Faraday's law	Faraday's law	Ohm's law
Output	Voltage or current	Voltage or current	Voltage	Voltage	Voltage
Accuracy	Best devices can reach a few ppm stability and repeatability	Best devices can reach 0.1%	Typically not better than 1%	Typically %, better possible with digital integrators	Can reach a few ppm for low currents, <% for high currents
Ranges	50A to 20kA	hundreds mA to tens of kA	50A to 20kA	high currents possible, up to 100kA	From <mA up to to several kA
Bandwidth	DC ..kHz for the higher currents, DC..100kHz for lower currents	DC up to couple hundred kHz	Typically 50Hz up to a few hudreds of kHz	Few Hz possible, up to the MHz	Up to some hundreds of kHz with coaxial assemblies
Isolation	Yes	Yes	Yes	Yes	No
Error sources	**Magnetic** (remanence, external fields, centering) **Burden resistor** (thermal settling, stability, linearity, tempco) **Output amplifier** (stability, noise, CMR, tempco)	**Magnetic** **Burden resistor** **Output amplifier** **Hall sensor stability** (tempco, piezoelectric effect)	**Magnetic** (remanence, external fields, centering, magnetizing current) **Burden resistor**	**Magnetic** **Integrator** (offset stability, linearity, tempco)	Power coefficient, tempco, ageing, thermal voltages

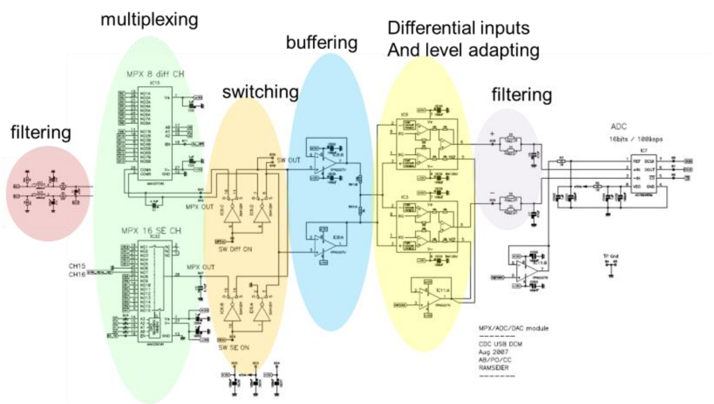
High-precision Current measurement chain



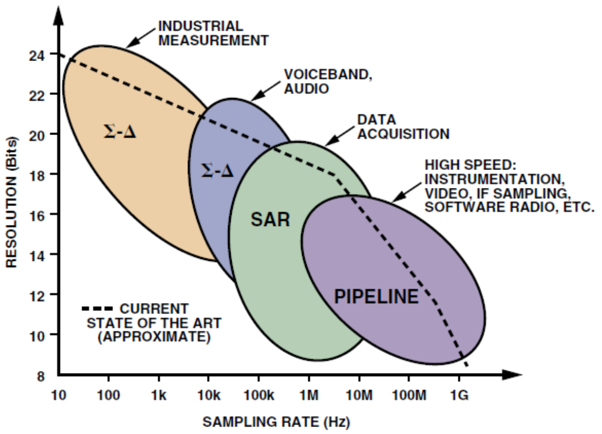
Precision amplifier and burden



Signal conditioning and filtering



High-resolution ADC



LHC class specification

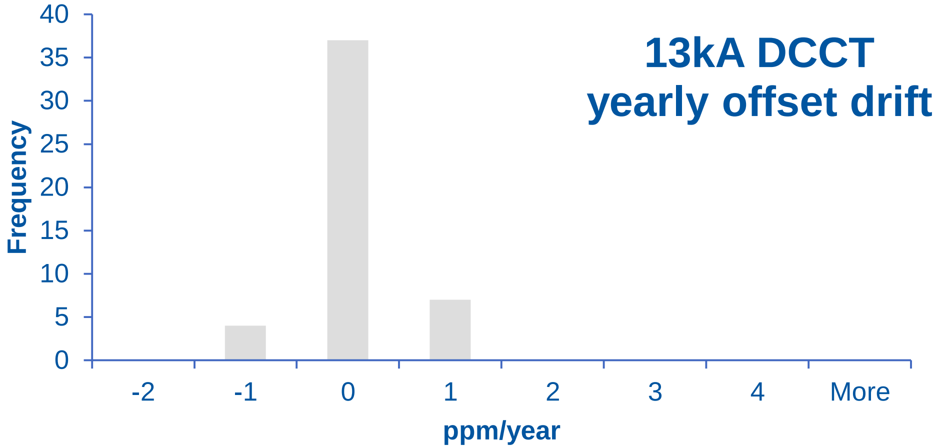
Converter category	Accuracy Class	½ hour stability	24h stability	1 year stability
Main Dipoles	Class 1	3	5	50
Main quadrupoles	Class 1	3	5	50
Inner Triplets	Class 1	3	5	50
Separation dipoles, Insertion quadrupoles	Class 2	5	10	70
600A multipole correctors	Class 3	10	50	200
120A orbit correctors	Class 4	50	100	1000
60A orbit correctors	Class 4	50	100	1000

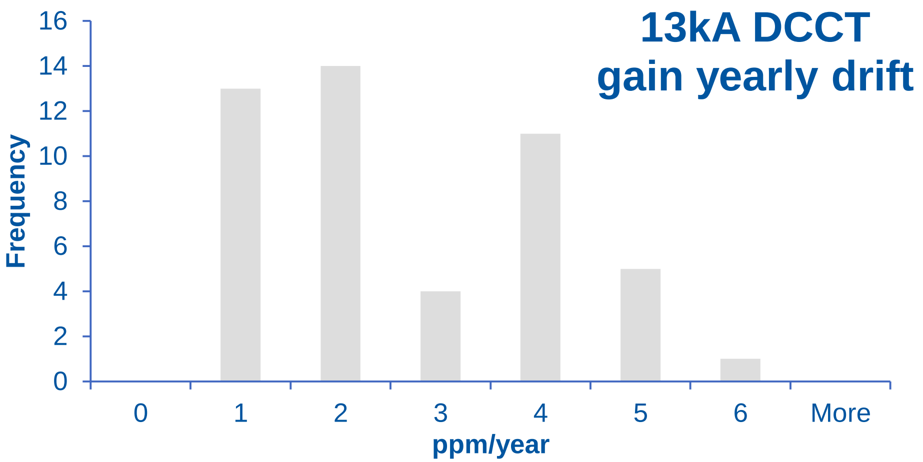
LHC class 1 DCCT

13kA DCCT Magnetic Head

13kA DCCT Electronics

DCCT specification	
Gain drift 1 year	5 ppm
Offset drift 1 year	5 ppm

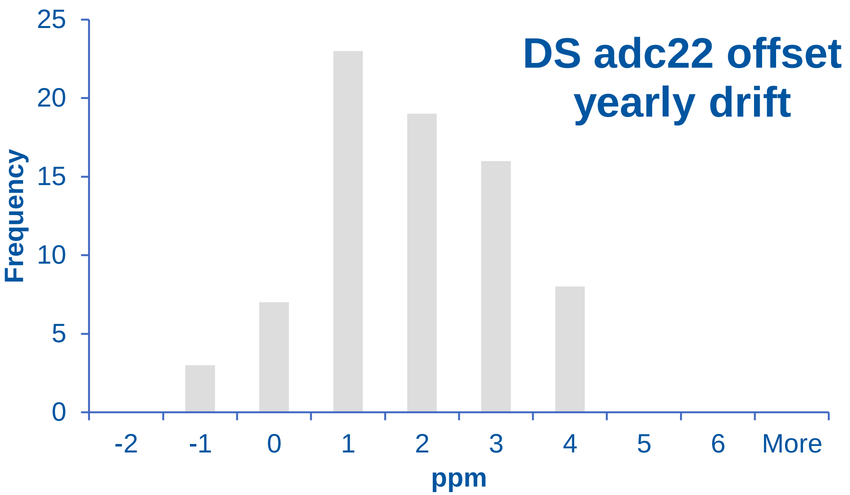


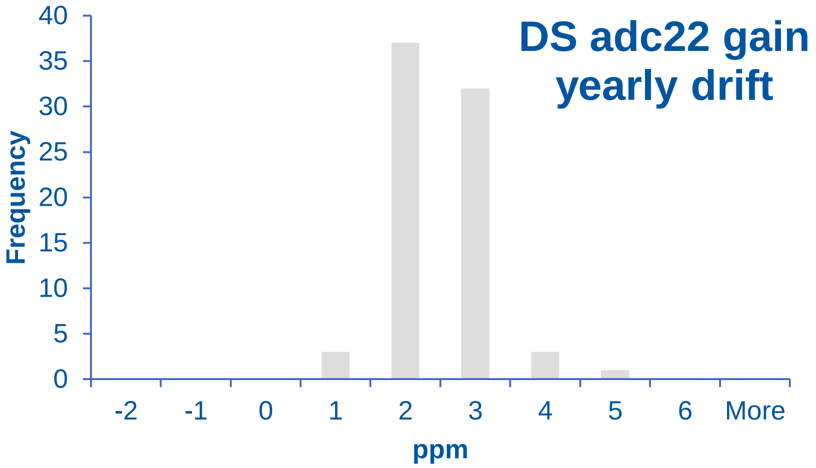


LHC class 1 ADC

The CERN 22 bit Delta Sigma ADC

DS22 specification	
Gain drift 1 year	20 ppm
Offset drift 1 year	10 ppm





LHC class 1 global accuracy

Converter category	Accuracy Class	1 year stability
Main Dipoles	Class 1	50

LHC specification

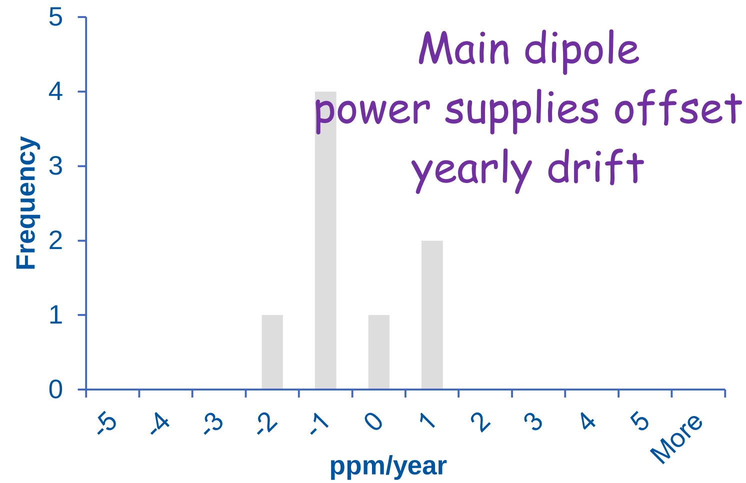
50ppm/year

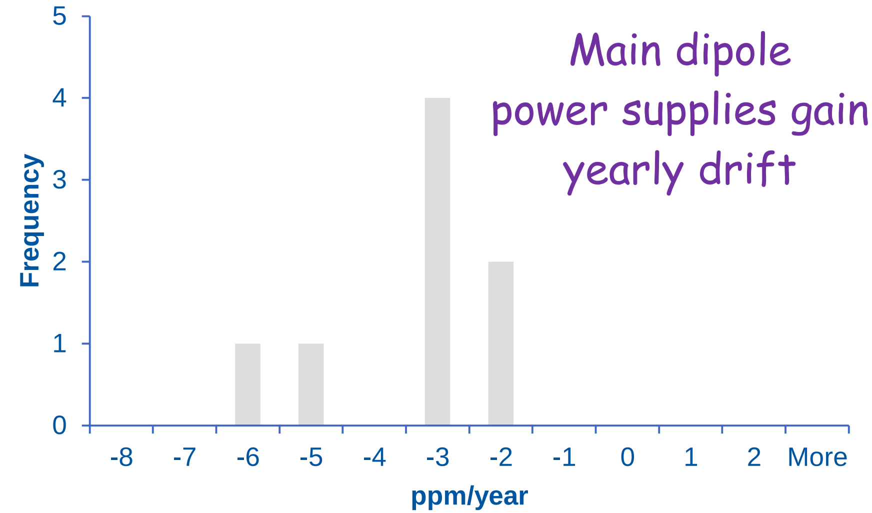
LHC result

< 10ppm/year with annual calibration

Possible improvement

< 2ppm/year with monthly calibration

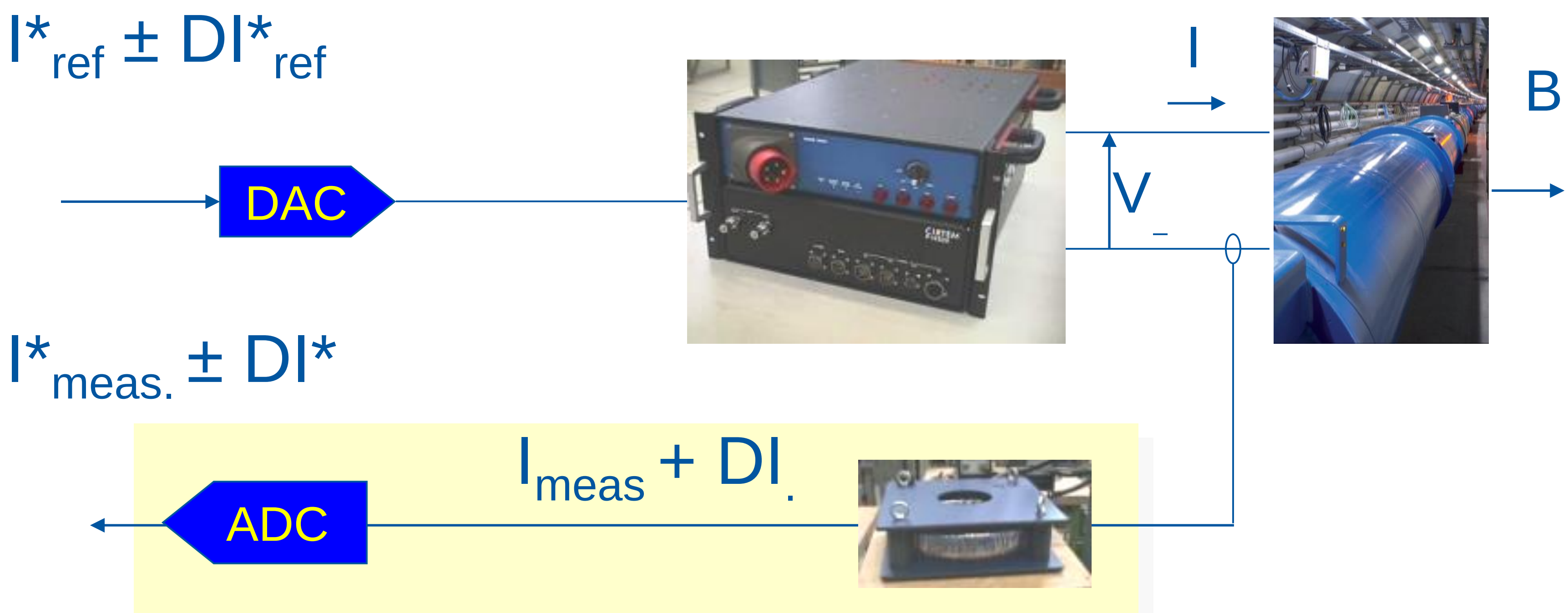




LHC resolution

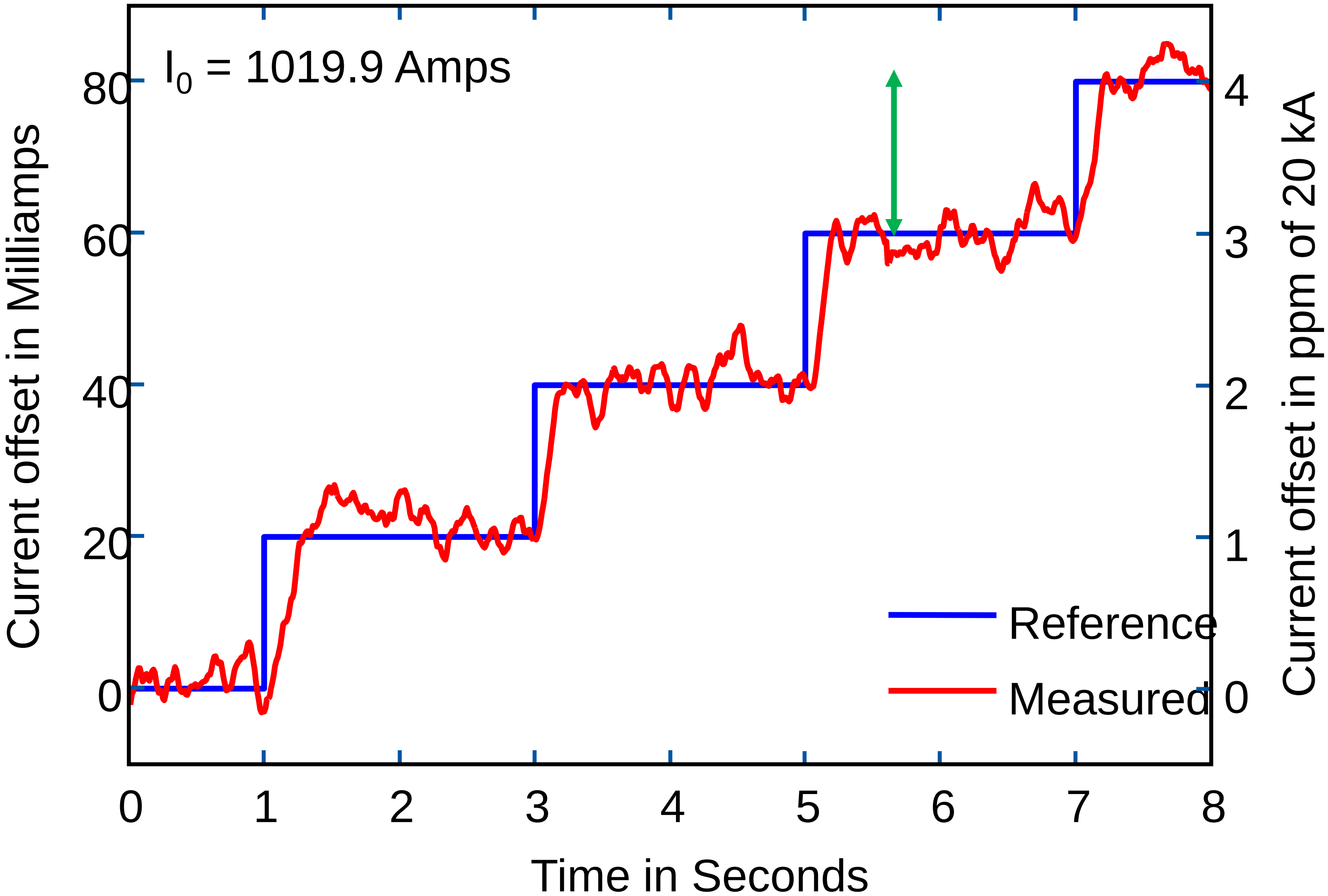
Smallest increment that can be induced or discerned.

The resolution is expressed in ppm of maximum DCCT current.
Resolution is directly linked to A/D system.



LHC resolution

Best resolution achieved = 1ppm

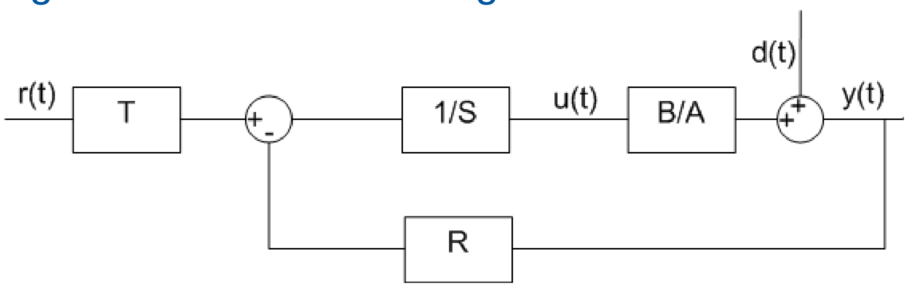


Current regulation

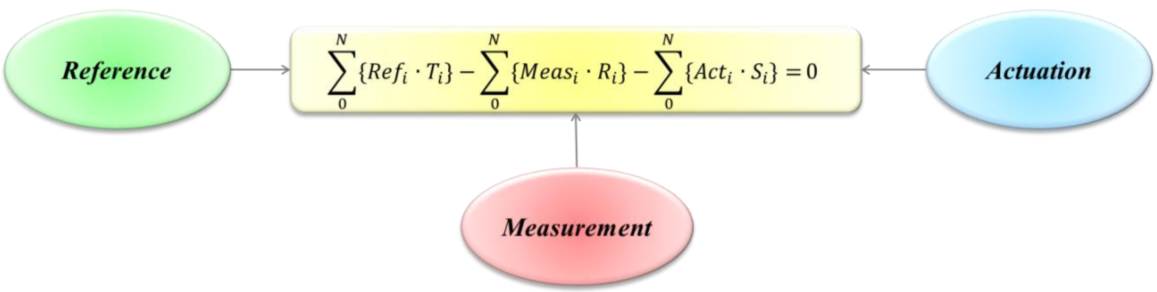
The performance of the current regulation is critical for a machine. Can be a nightmare for operators!

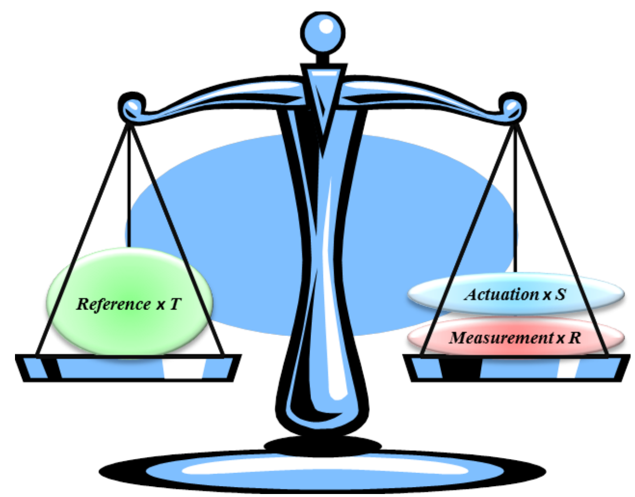
RST controller provides very powerful features:
Manage the tracking error as well as the regulation.

Iref
Current reference



Imeas
Current measurement



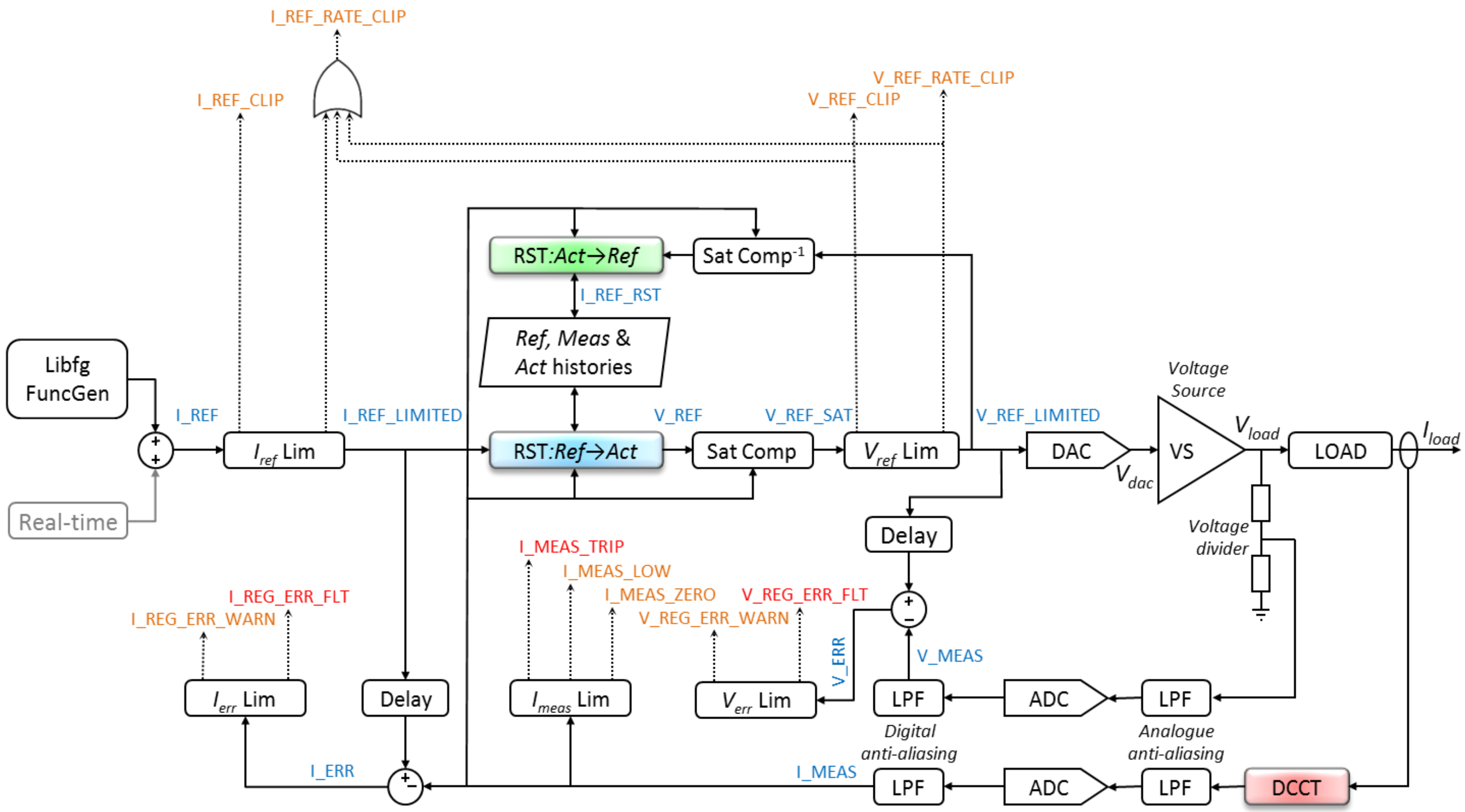


Current regulation

Anti-windup is needed to control the saturation of the loop.

→ complex control loop

The real controller is shown below:



Current regulation

Tutorial is proposed here on the FGC currant regulation

https://project-cclibs.web.cern.ch/project-cclibs/download_tutorial.htm

Here you can find some examples

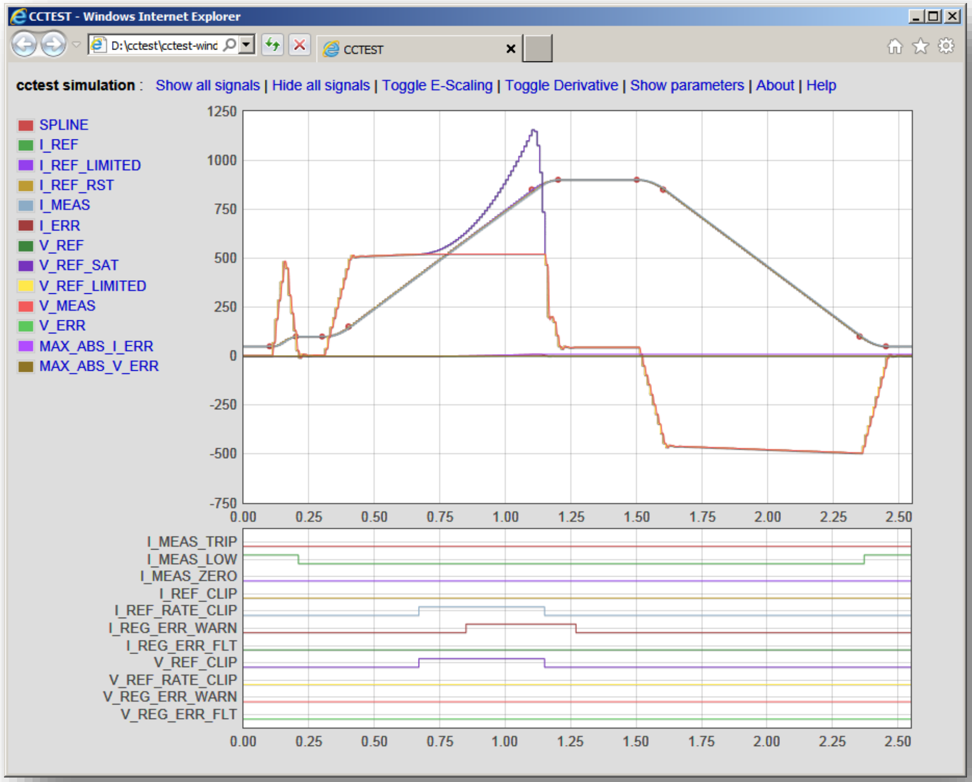
https://project-cclibs.web.cern.ch/project-cclibs/plots/tests/

What parameters should be specified ?

Magnet operation:

- Precision class
- Type of control: Current / B-field
- Maximum current ripple
- Complete cycle
  - Injection current
  - Maximum dI/dt, ramp-up
  - Maximum flat top current
  - Maximum dI/dt, ramp-down
  - Return current
  - Cycle time
- Degauss cycle / pre-cycle
- Magnet protection system

Power supply functional specification



What shall contain the functional specification?

Short description of the machine

Description of the loads

- Magnet layout
- Magnet parameters
- Optimization with integral cost and energy saving

Description of the operation duty cycle

- Machine cycles
- Minimum and maximum beam energy

Power supply requirements

- Power supply rating
- Current precision
- Current tracking
- Control system
- Energy management
- Lock-out and safety procedure
- Infrastructure (layout, Electricity, Cooling, handling…)

Purchasing and development strategy

Planning

Budget

Resource

Power supply delivery

From power supply functional specification

https://edms.cern.ch/document/829344/3

Power supply design

simulation

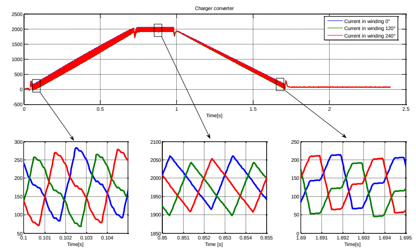
Component design

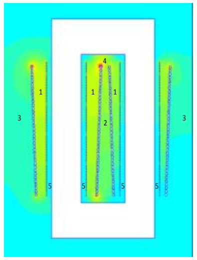
3D mechanical integration

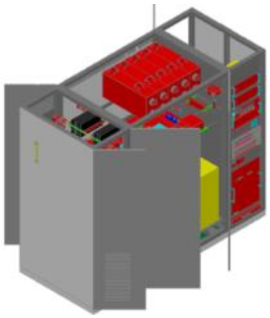
Production

Laboratory Tests

On site commissioning







Minimum 18 months
Up to 3 years when special development is needed.

Power supply procurement

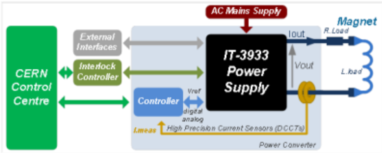
From power supply functional specification

- Power supply technical specification

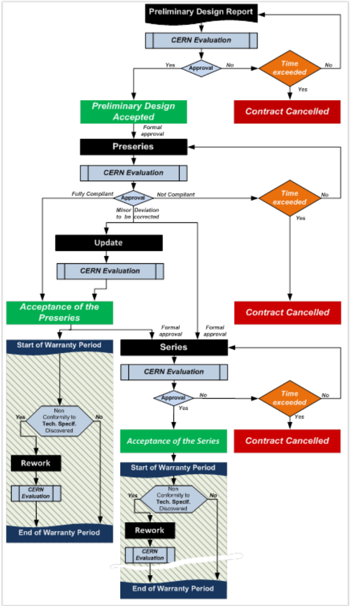
https://edms.cern.ch/document/1292325

Minimum 6 months

- Call for tender



- Award of contract
- Design report
- Prototype acceptance
- Series production
- On site commissioning



Minimum 12 months

What is special with magnet power supplies?

The magnet power supplies are high-precision current control.

To build it, the technical solutions are out the industrial standard:

- Need very low ripple
- Need current and voltage control over large range
- Operation in 1-2-4 quadrant

Special topologies

- Need high-precision measurement
- Need high-performance electronics
- Need sophisticated control and algorithm

Special electronics and control

Powering a magnet isn't classical, and few one the shelf products can be used

mainly custom power supplies

What is power electronics?

Summary

Power supplies are key devices for particles accelerators (like an engine in a car).

Operators in control room play with power supplies to control the beam.

Their performances have a direct impact on the beam quality.

Creativity is required in many technical fields!

More training :

last

Special CAS on power converters

7 – 14 May 2014 Baden (CH)