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The CERN Accelerator School

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Basics of Accelerator Science and Technology at CERN

Power supplies for Particle accelerators

Jean-Paul Burnet

The CERN Accelerator School

- Definition
- Basic electricity
- The loads
- The circuits
- The power supply specification
- Power electronics, how does it works?
- Examples of power supplies and applications
- Energy saving
- Power supply control
- Summary

Definition

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

Power supplies are everywhere: computer, electronics, inside any modern electrical equipment (washing machine, …), motor drives,…

Electricity provider

Power supply

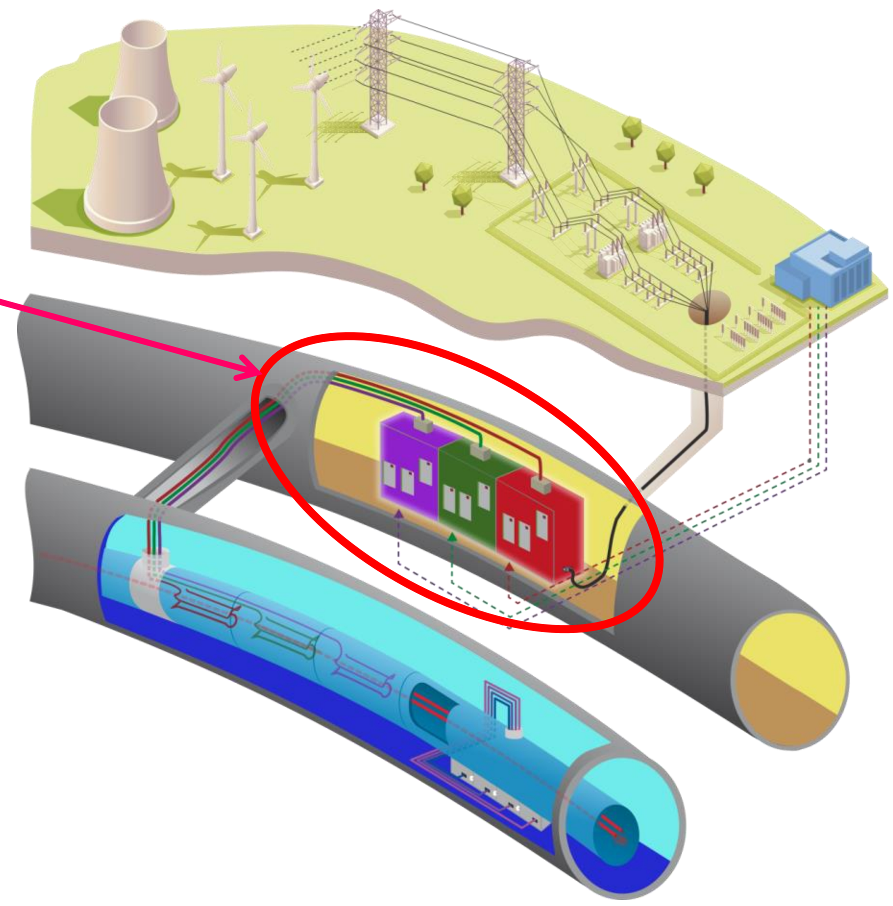
Load

Definition

Where can we find power supplies in a particle accelerator?

Everywhere ! Everything is powered by electricity !

This presentation covers the magnet power supplies which are specifics for particle accelerators :



Power supply or power converter?

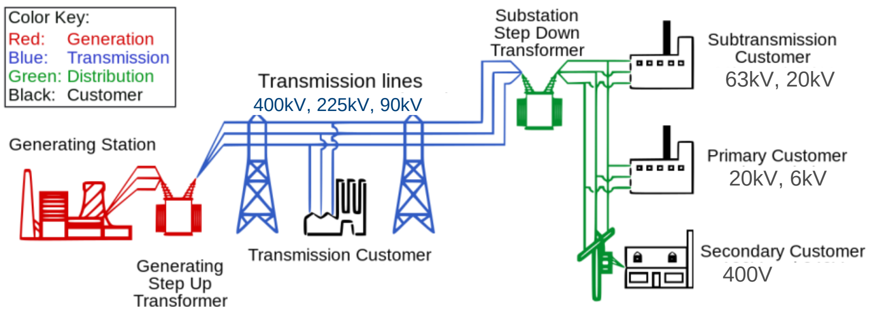
US labs use magnet power supply

CERN accelerators use power converter

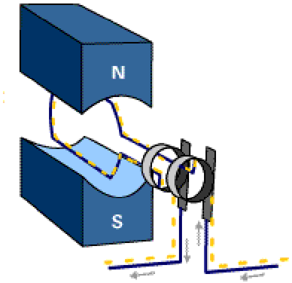
CERN experiments use power supply

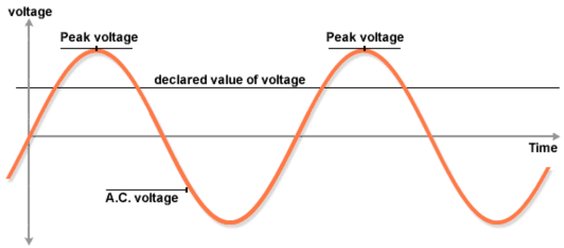
Electrical power

Electricity is mainly produced by rotating machines, generating alternative voltage.



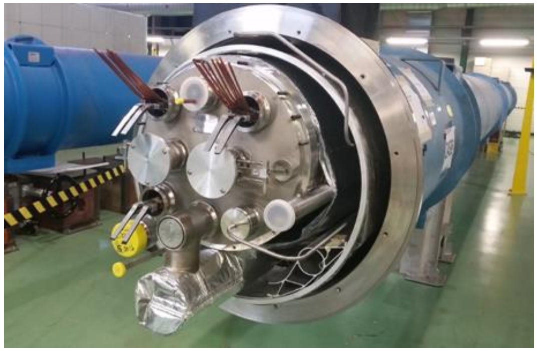
Alternative voltage





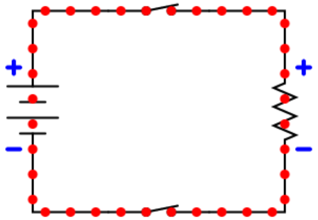
http://content.tutorvista.com/physics_12/content/media/ac_gen.swf

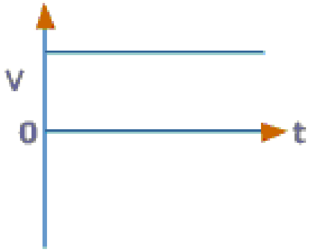
The accelerator magnets need a DC current.



DC current

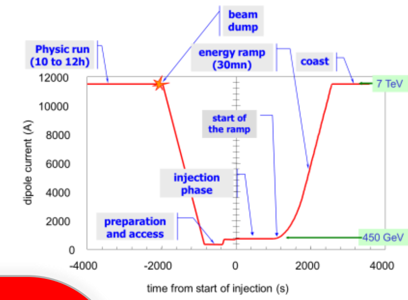
Direction of electron motion





Power supply functions

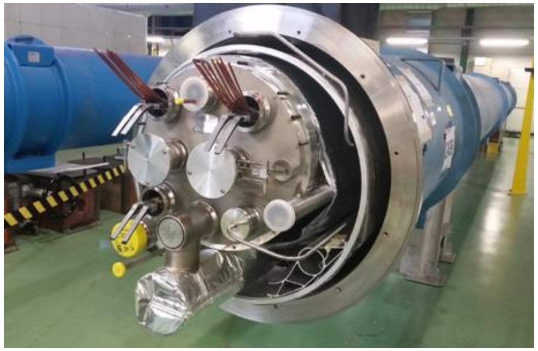
The tasks of a power supply are to process and control the flow of electric energy by supplying voltage and current in a form that is optimally suited for user loads.



Energy source

Control by
beam operation team

Application



Basic electricity

An **electric current** is a flow of electric charge. In electric circuits, this charge is often carried by moving electrons in a wire.

Voltage is the difference in electric potential energy between two points per unit electric charge. The voltage between two points is equal to the work done per unit of charge against a static electric field to move the test charge between two points and is measured in units of volts (a joule per coulomb).

Power (Watt) = Voltage (Volt) * Current (Ampere)

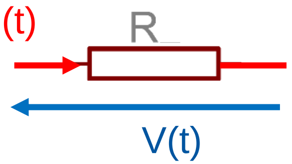
Energy (Joule) = Power (Watt) * time (second)

Matter:

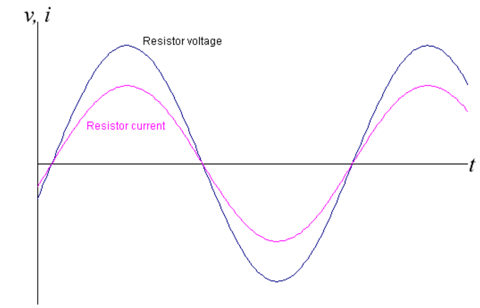
- Conductor = electrons flow easily. Low resistance.
- Semiconductor = electrons can be made to flow under certain circumstances.
- Insulator = electrons flow with great difficulty. High resistance.

Basic components

Resistor:



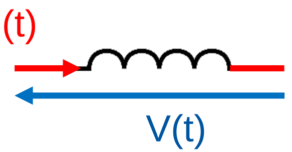
current is proportional to voltage



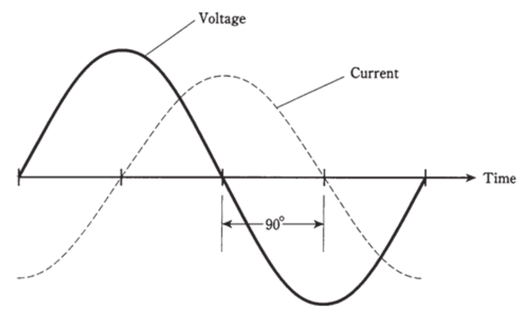
$$\mathrm{V(t)} = \mathrm{R} \times I(t)$$

R = resistance in ohm

Inductor:



Difficult to change the current



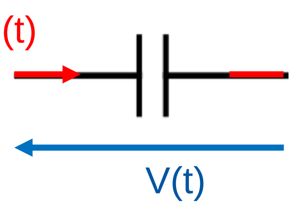
$$\mathrm{V(t)} = \mathrm{L} \times \frac{dI(t)}{dt}$$

L = inductance in Henry

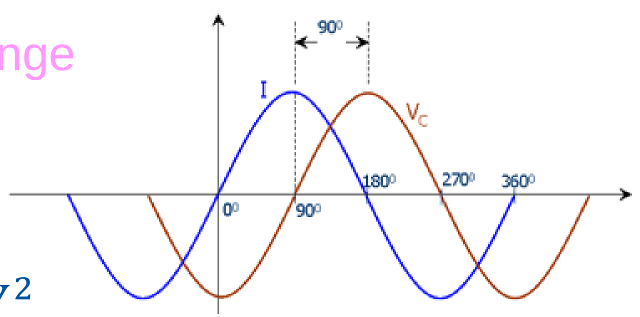
E_L = Stored energy

$$E_L = \frac{1}{2} \times L \times I^2$$

Capacitor



Difficult to change the voltage



$$\mathrm{I(t)} = \mathrm{C} \times \frac{dV(t)}{dt}$$

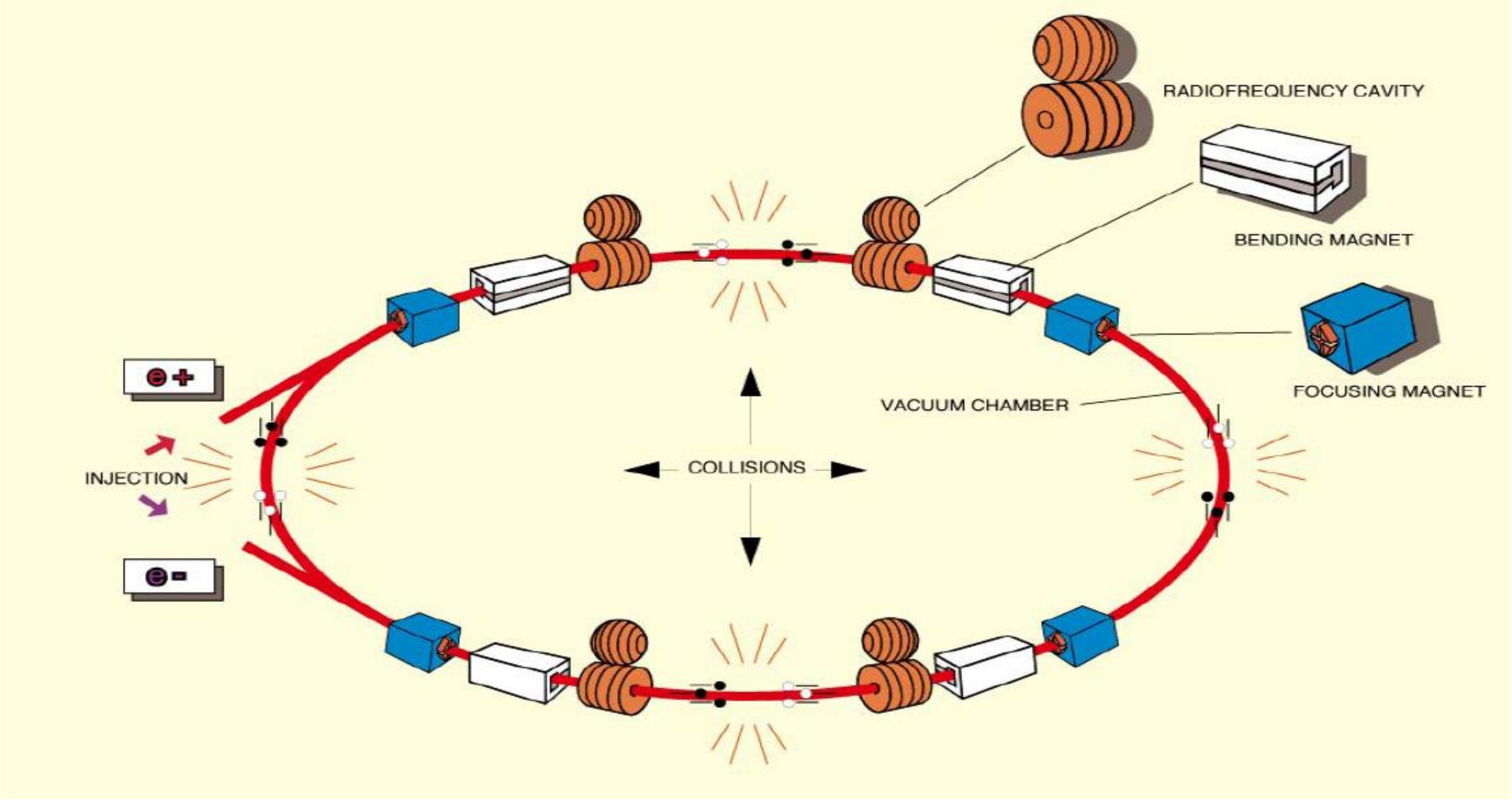
C = capacitance in Farad

E_c = Stored energy

$$E_C = \frac{1}{2} \times C \times V^2$$

What are the main loads?

The **main loads** of a particle accelerator are the magnets and the radiofrequency systems.
It is also the devices which control the beams.

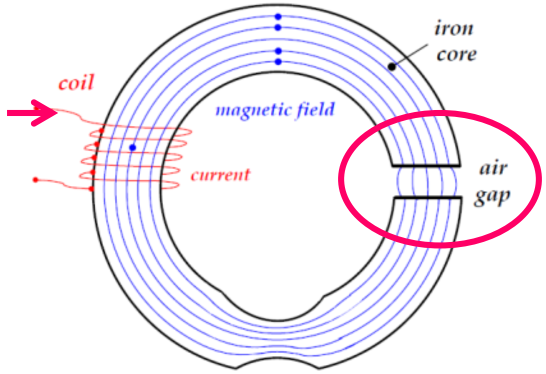


Are the magnet power supplies critical?

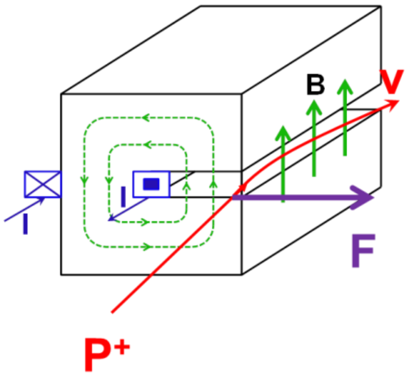
In a synchrotron, the beam energy is proportional to the magnetic field of the dipole magnets.

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

Magnet current

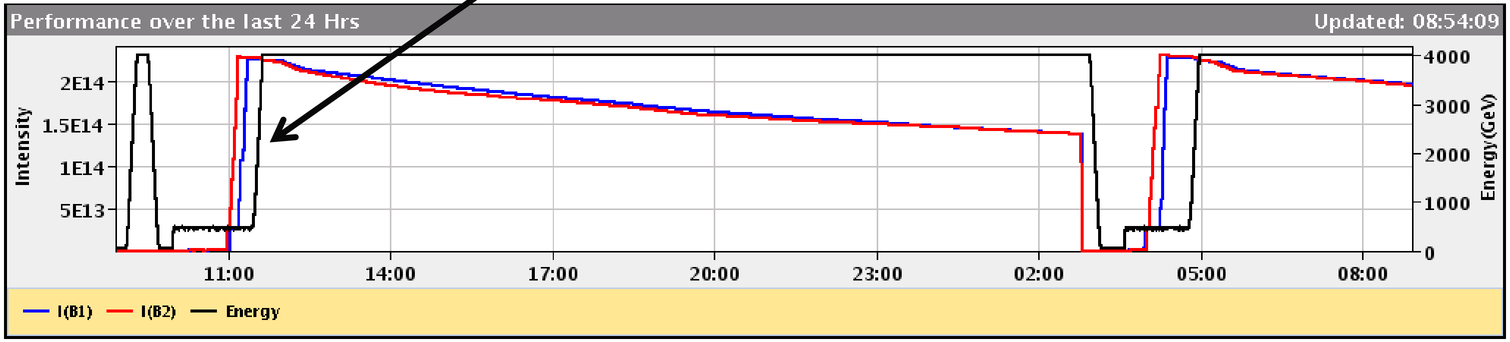


Magnetic field in the air gap



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

LHC vistar : Beam Energy = Dipole Current



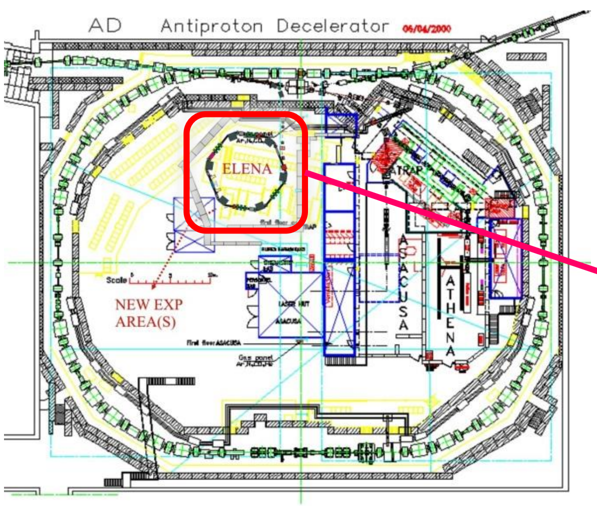
The magnet power supplies control the beam optics.

First step, identify the load

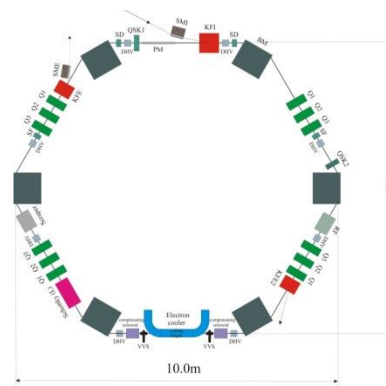
Before any design of power supplies, the first step is to write a **functional specification** which describes the powering of the accelerator and the performance required by the power supplies.

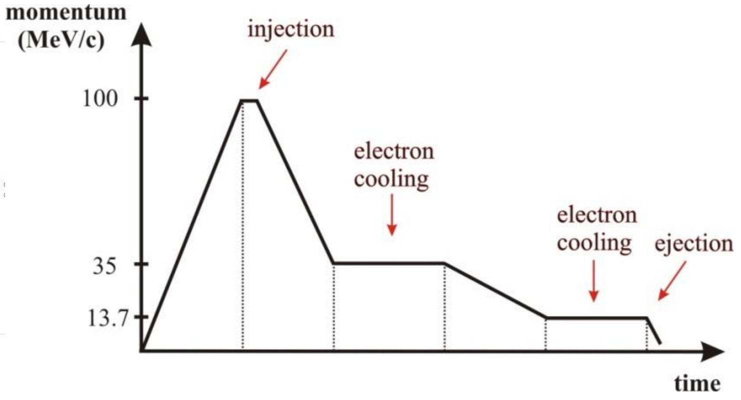
Many technical points have to be clarified to define all the power supply parameters.

What do we need for a new particle accelerator like ELENA?



ELENA: Extra Low Energy Antiproton Ring

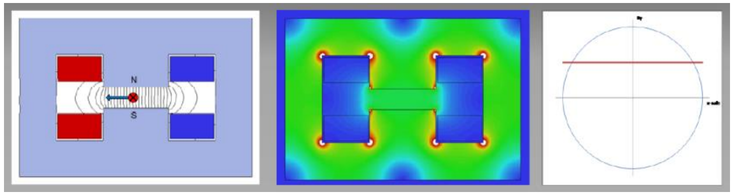




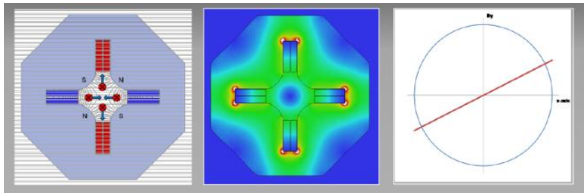
The loads: magnets

The magnet families are :

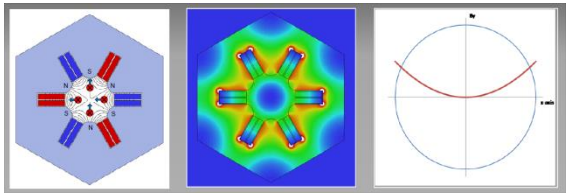
Dipole: Bend the beam



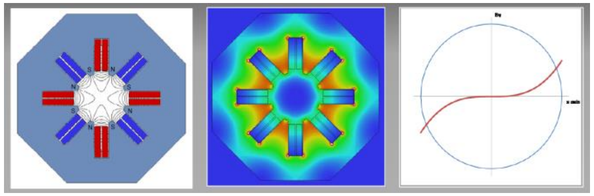
Quadrupole: focus the beam



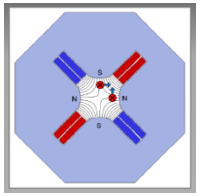
Sextupole: correct chromaticity



Octupole: Landau damping



Skew: coupling horizontal & vertical betatron oscillations

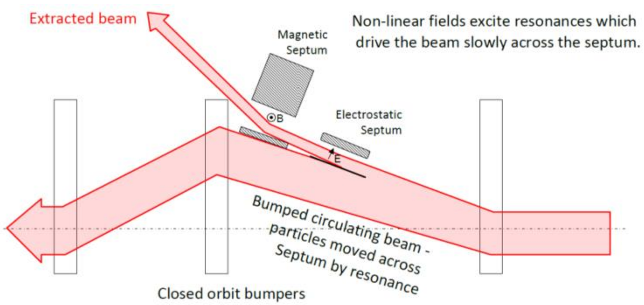


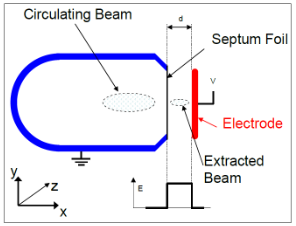
http://cas.web.cern.ch/CAS/Belgium-2009/Lectures/Bruges-lectures.htm

The loads, special magnets

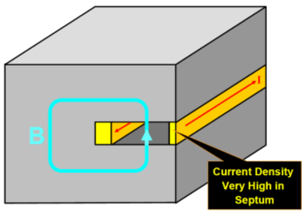
For beam transfer, special magnets are needed. The families are :

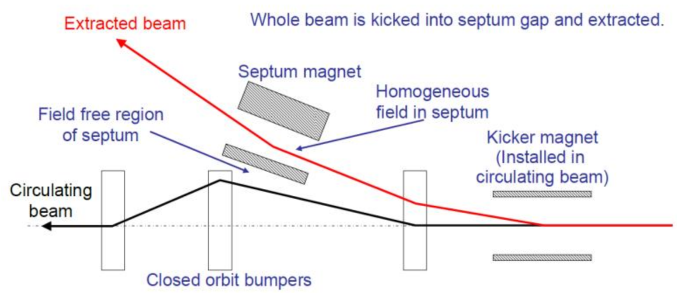
Electrostatic septum





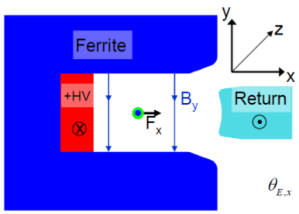
Septum magnet





Kicker Magnet

Rise time # 10ns-1µs



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

http://cas.web.cern.ch/cas/IET2017/IET-advert.html

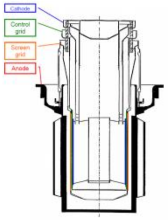
The loads, RF amplifiers

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

The families of RF power amplifiers are :

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

Present with the new SPS RF 200MHz

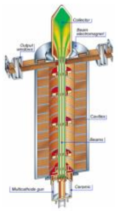


Tetrode, Medium power, 10kV, 100kW

Present in PS, SPS

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

Present in SPS



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

Present in LINAC4, LHC

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

Circuit layout, how many power supplies?

The magnets can be powered individually or in series.

Individually:

- increase flexibility of beam optics
- 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 in the magnet series
- Rigid optic
- Need trim power supplies to act locally
- Global cost reduced, less DC cables, less power supplies but bigger in power rating

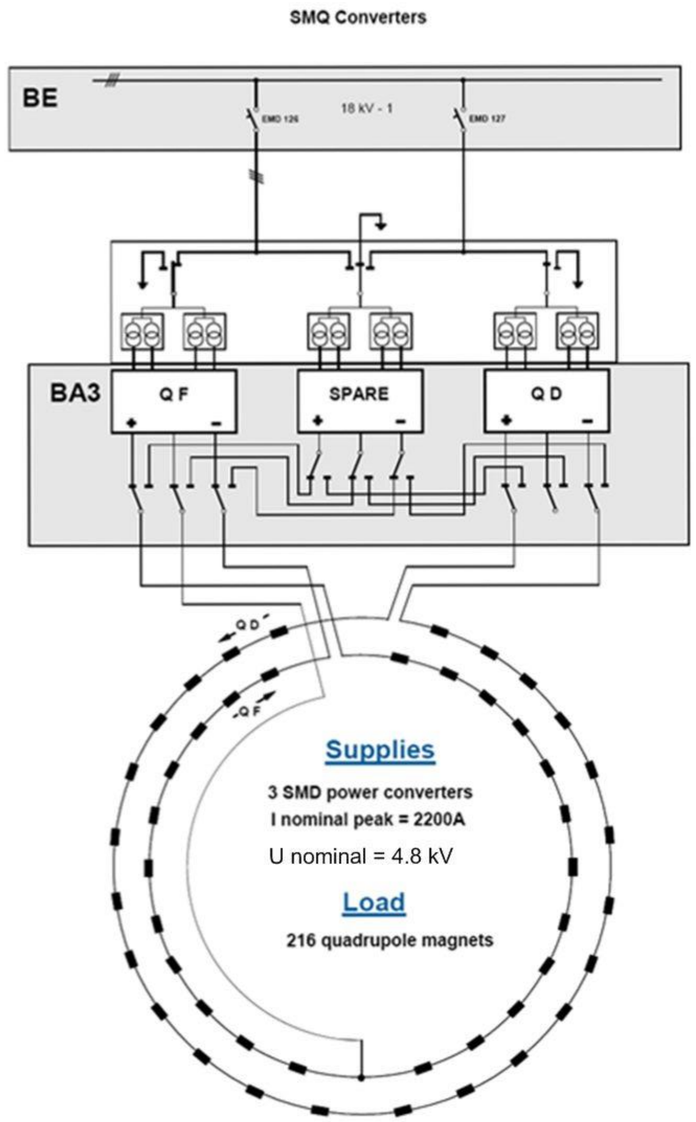
-

Magnet in series

To get the same B-field in a family of magnets as requested by accelerator physicists, the classical solution is to put all the magnets in series.

Generally done with dipole and quadrupole.

Example of SPS quadrupole

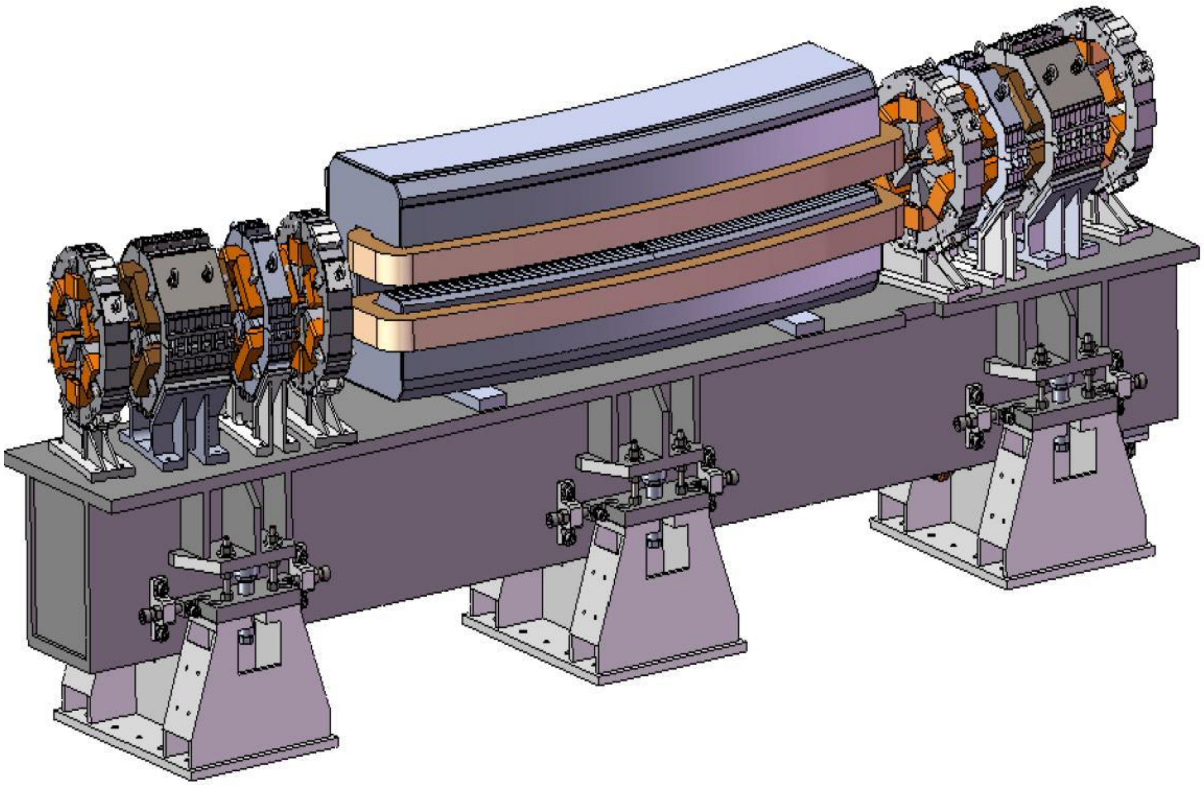


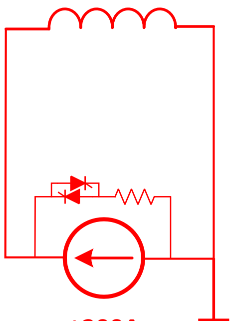
Lead to high power system for dipole and quadrupole, up to 120MW for SPS !!!

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.

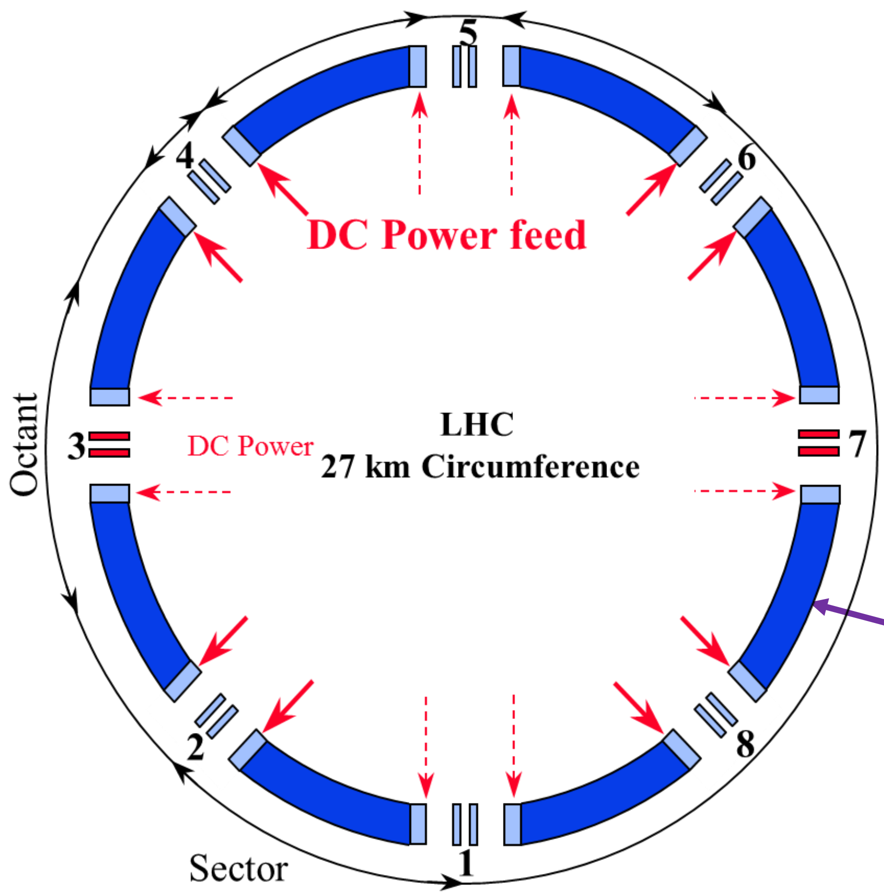




Splitting the magnet circuit

When the power is becoming too high, the circuits have to be split.

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



Tracking between sector !

1.2 GJ stored energy in dipole circuit per sector!

8 power supplies: 13kA / 200V

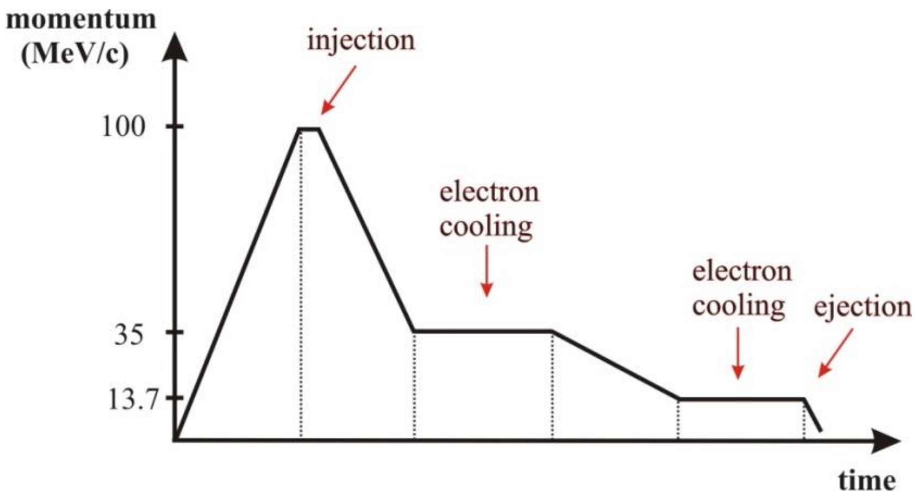
Powering Sector:

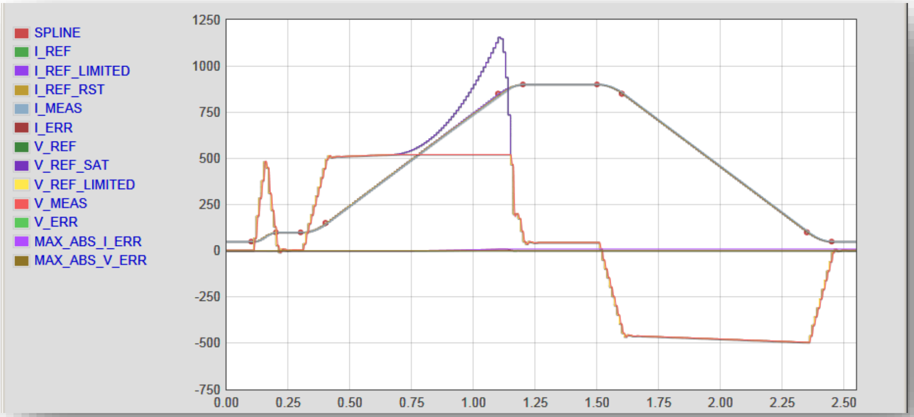
154 dipole magnets total length of 2.9 km

Power supply specification

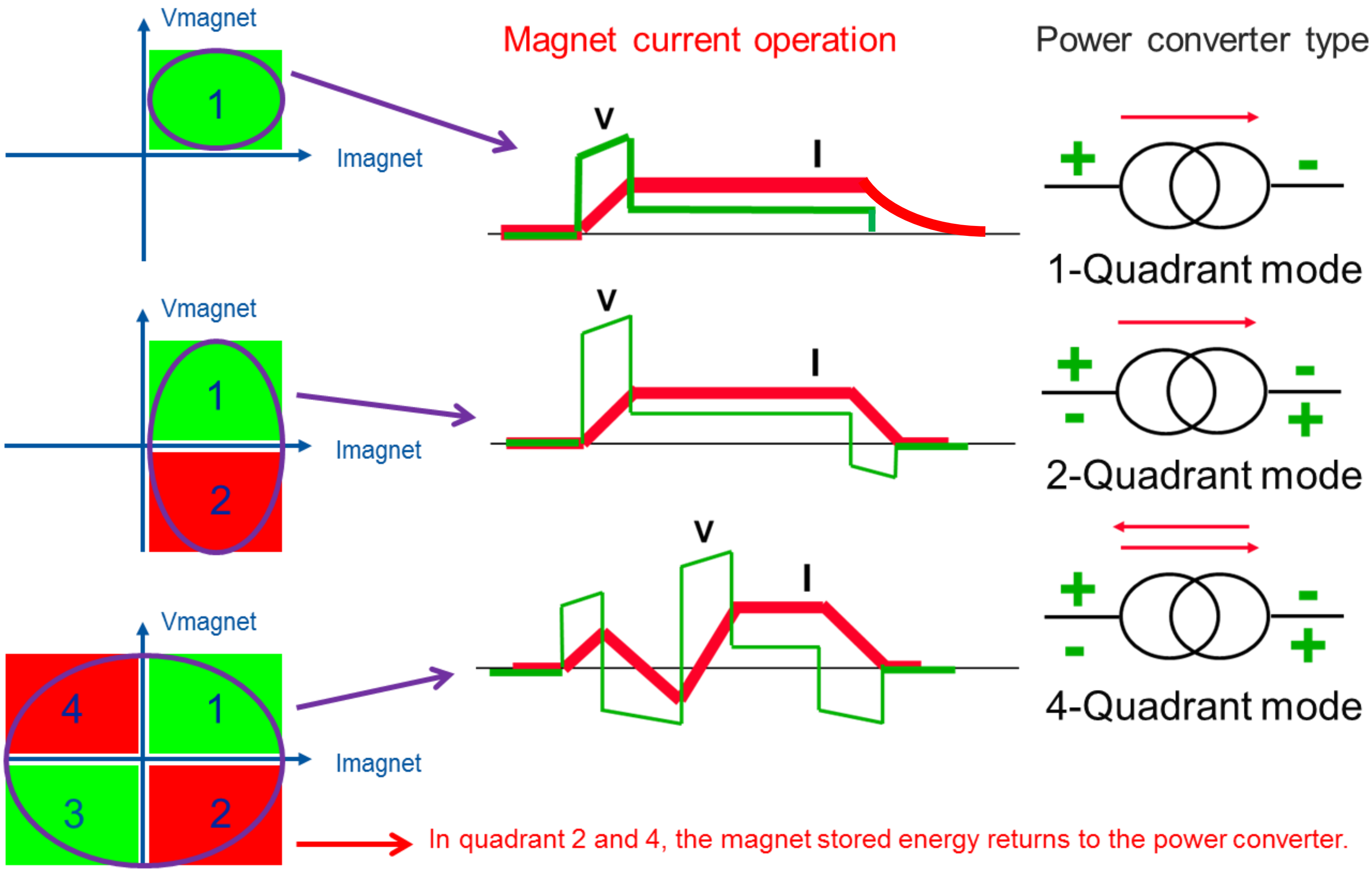
The way that the magnets will be operated has to be defined from the beginning.

- Type of control: Current control
- 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 versus magnet cycles



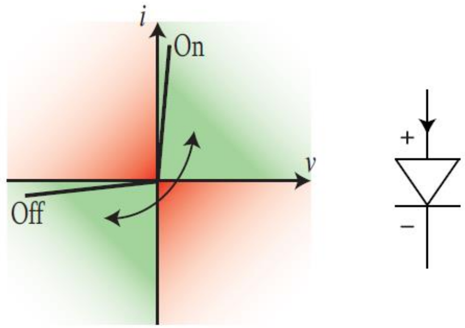
In quadrant 2 and 4, the magnet stored energy returns to the power converter.

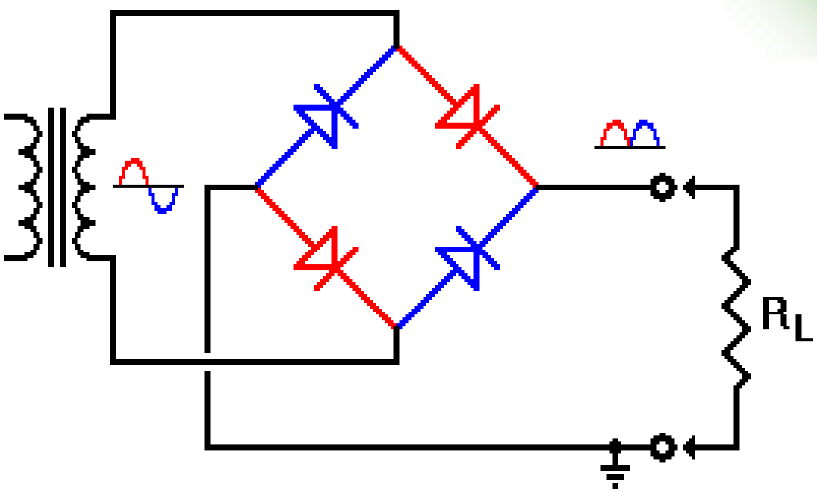
Origin of power electronics

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

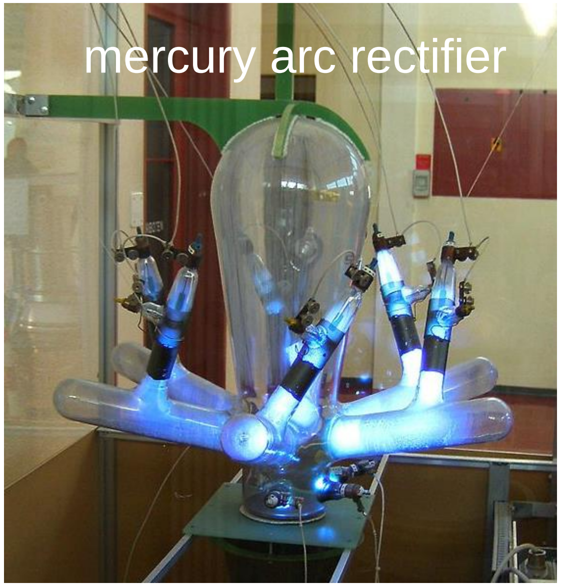
Power electronics started with the development of mercury arc rectifier. Invented by Peter Cooper Hewitt in 1902, the mercury arc rectifier was used to convert alternating current (AC) into direct current (DC).

Diode



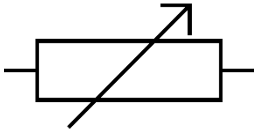


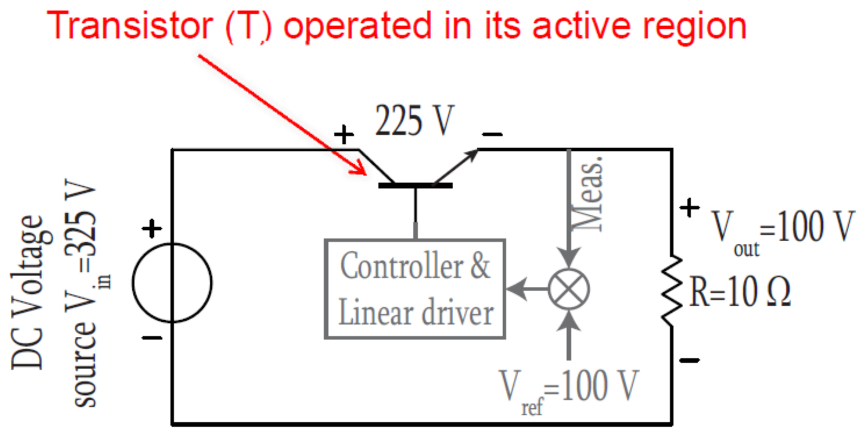
1902-1970



Middle age power electronics

Vacuum tube or transistor used as a variable resistor (linear regulator).





- Analysis:

P_{in}=325 V x 10 A=3.25kW

P_{out}=100Vx10A=1kW

P_T=P_{in}-P_{out}=225Vx10A=2.25kW

Efficiency:

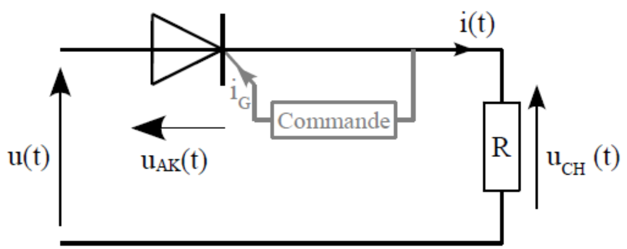
$$\eta = \frac{P_{out}}{P_{in}} = \frac{1}{3.25} = 0.3 \longrightarrow \mathbf{30}\%!$$

Vacuum tube or valve
1907-1970

transistor
1947-1980

Hippie power electronics

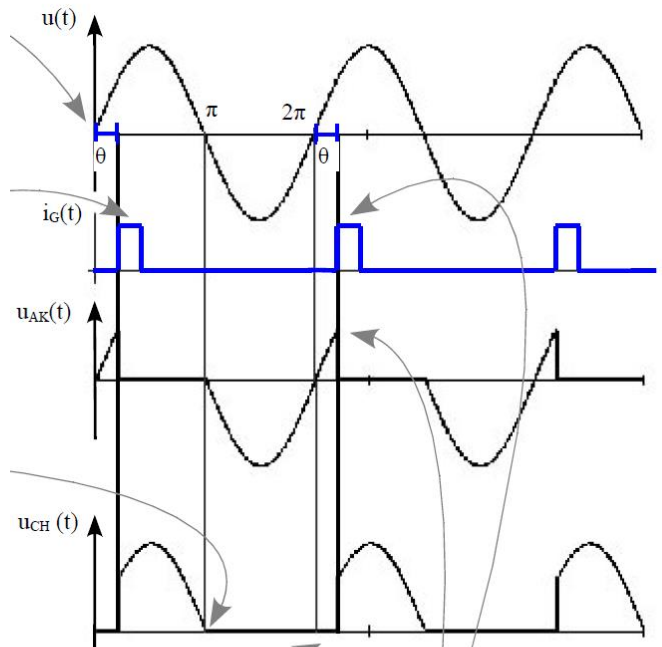
Thyristor (1956): once it has been switched on by the gate terminal, the device remains latched in the on-state (*i.e.* does not need a continuous supply of gate current to remain in the on state), providing the anode current has exceeded the latching current (I_L). As long as the anode remains positively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



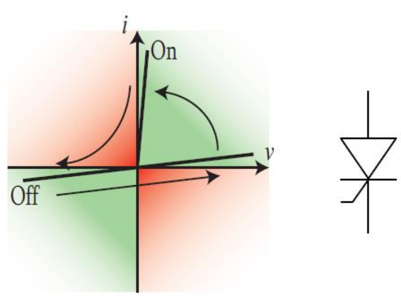
Thyristor Blocked

Thyristor turn ON

Thyristor turn OFF
At zero current



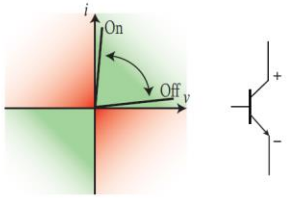
Thyristor



Thyristor
1957-2000

Turn ON possible when positive voltage

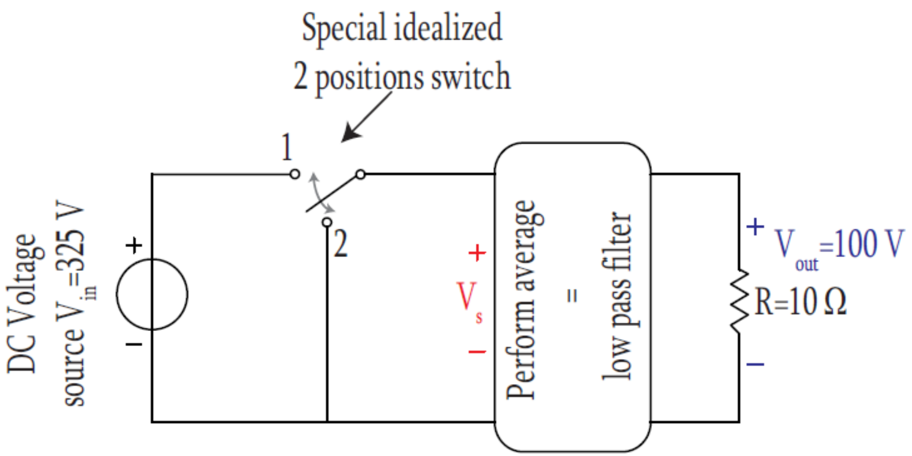
Modern power electronics

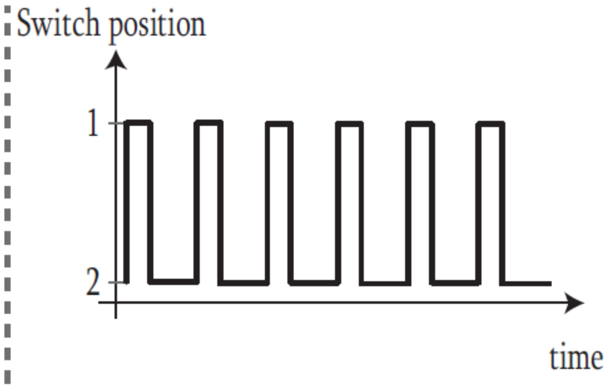


Use semiconductors as switches

ON – OFF states only

Switch-mode power supply





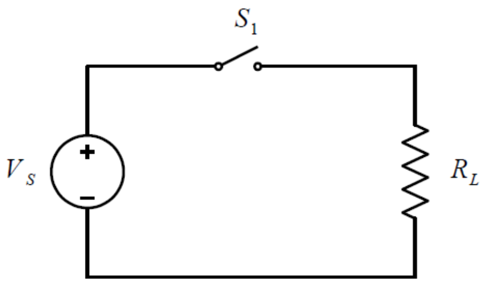
A square voltage waveform is generated by the switch.
The energy transferred to the load is controlled by modulating the duty cycle D.

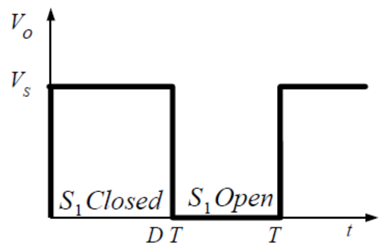
D is the fraction of one period in which the switch is ON.

Transistor, MOSFET, IGBT
1980 until now

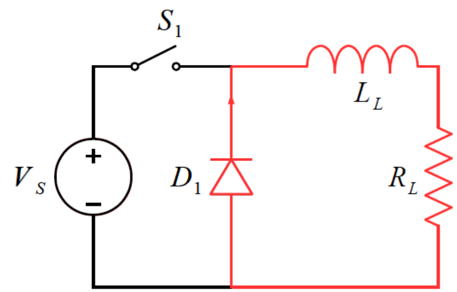
Basic principle

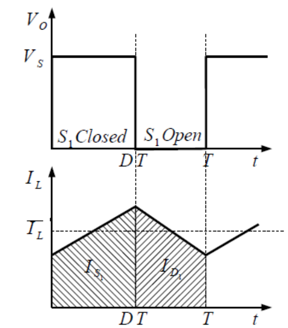
Resistive load





Inductive load





$$\overline{V_{Rl}} = \frac{DT}{T} \times V_s$$

$$\frac{1}{T} = switching\ frequency$$

$$\overline{I_{Rl}} = \frac{DT}{T} \times \frac{Vs}{R_L}$$

$$\boxed{\overline{V_{Rl}} = D \times V_s}$$

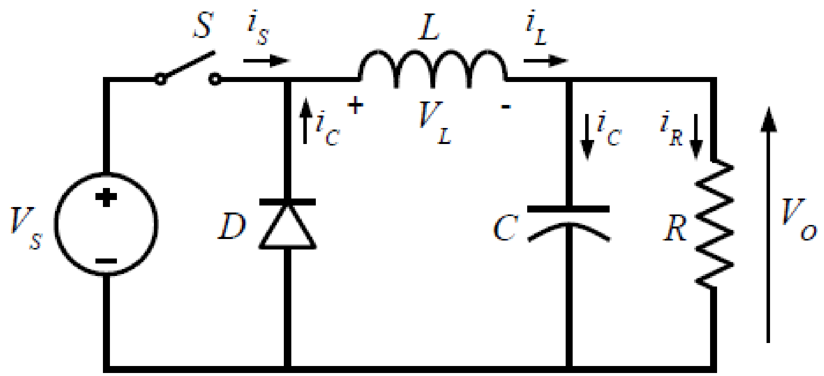
D = *Duty cycle*

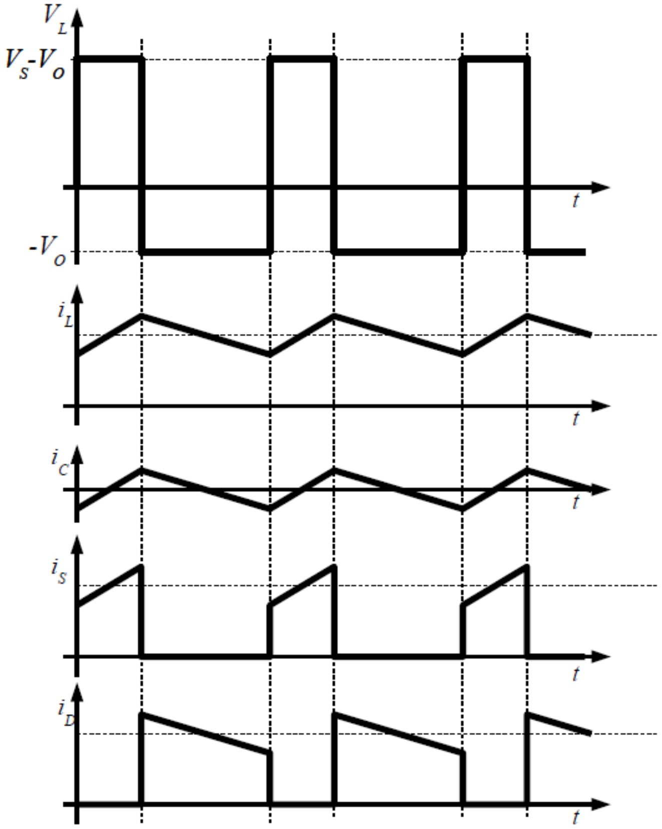
$$\boxed{\overline{I_{Rl}} = D \times \frac{Vs}{R_L}}$$

Simple buck converter

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

Example of a BUCK converter:





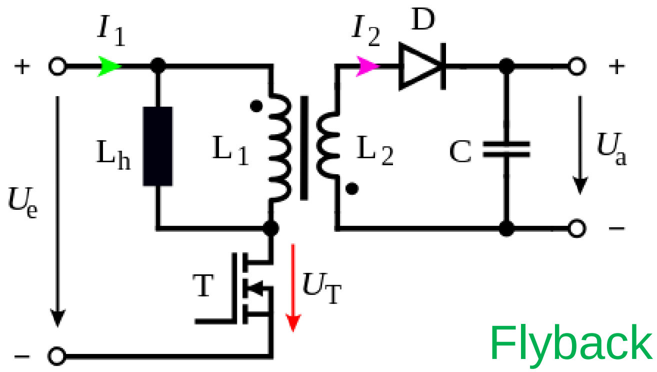
$$\bar{V_o} = \frac{DT}{T} \times V_s$$

$$\boxed{\bar{V_o} = D \times V_s}$$

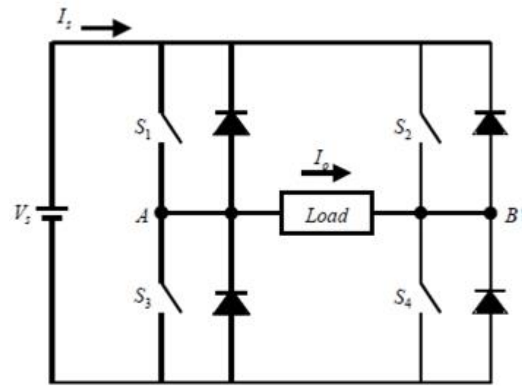
The voltage applied to the load can be changed by playing with the duty cycle.

Topologies

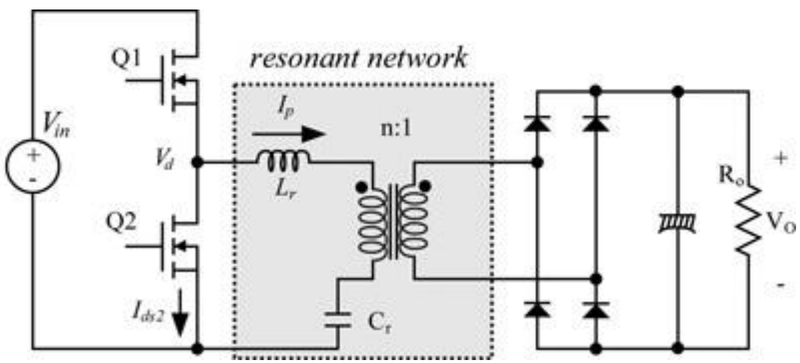
Many topologies exist to build a switch-mode power supply and new topologies appear every years!



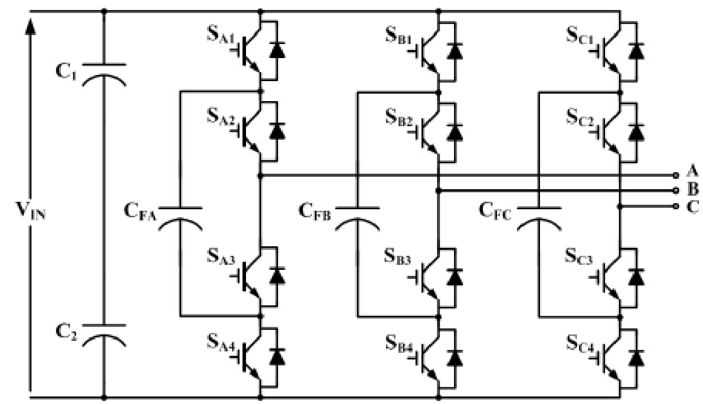
Flyback



Full bridge



LLC resonant



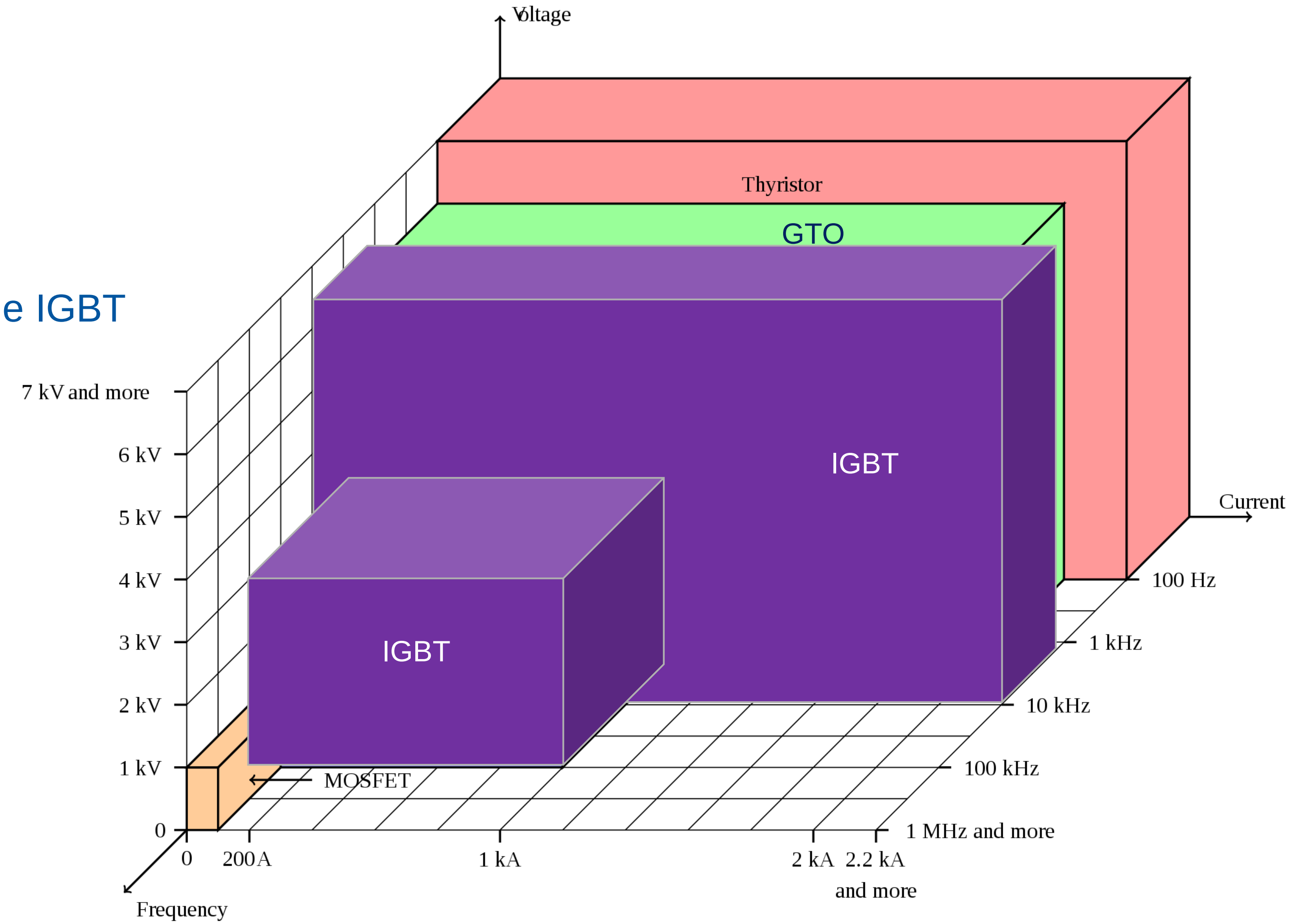
Multilevel

Switching devices

Nowadays, the main power semiconductors are:

- Diode
- MOSFET
- IGBT
- Thyristor

The most popular is the IGBT



IGBT, the most popular device

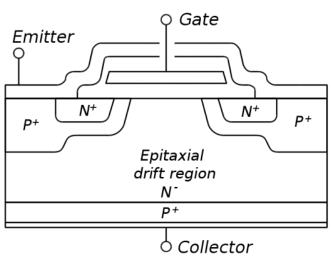
What is an IGBT ?

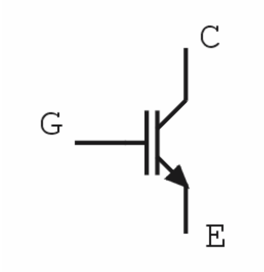
The IGBT combines the simple gate-drive characteristics of the MOSFETs with the high-current and low-saturation-voltage capability of bipolar transistors.

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

Many topologies can be built using IGBT.

Largely produced since 1990.





10A

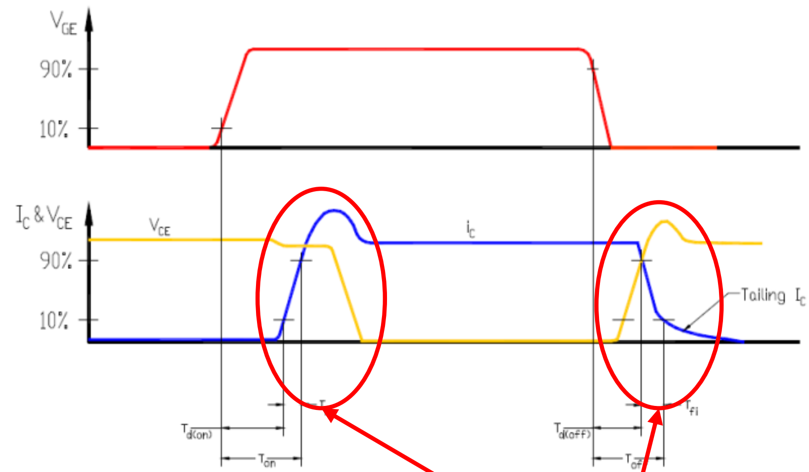
200A

1kA

3kA

IGBT

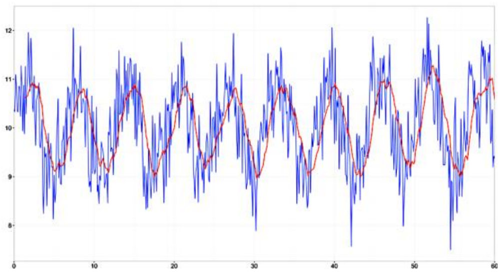
Real IGBT turn-on and turn-off:



Switching losses

Very fast di/dt, dv/dt => generate electrical noise

Electromagnetic compatibility (EMC) is challenging!



Switching losses => thermal limitation

The switching frequency depends on:

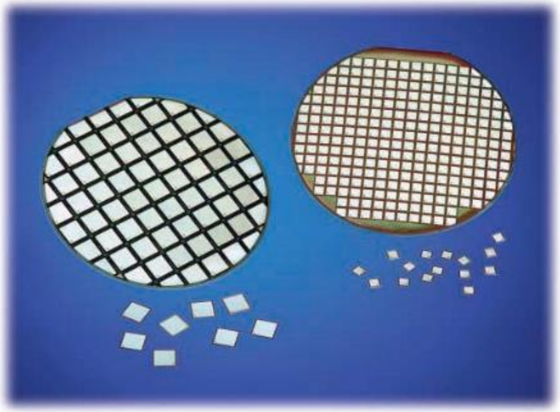
- The turn-ON and turn-OFF time of the switch
- The maximum losses dissipated by the switch

Typical switching frequency depending on the power rating:

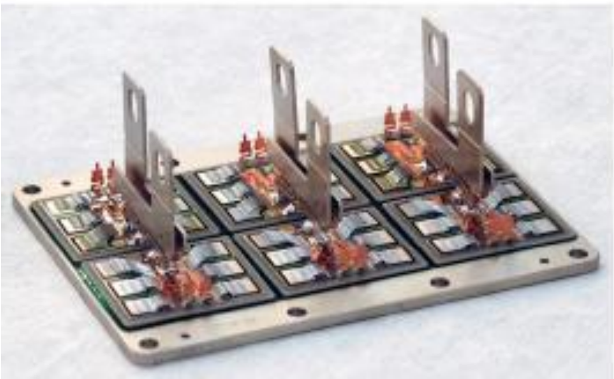
1kW range	100kHz
100kW range	10kHz
1MW range	1kHz

IGBT

IGBT dies



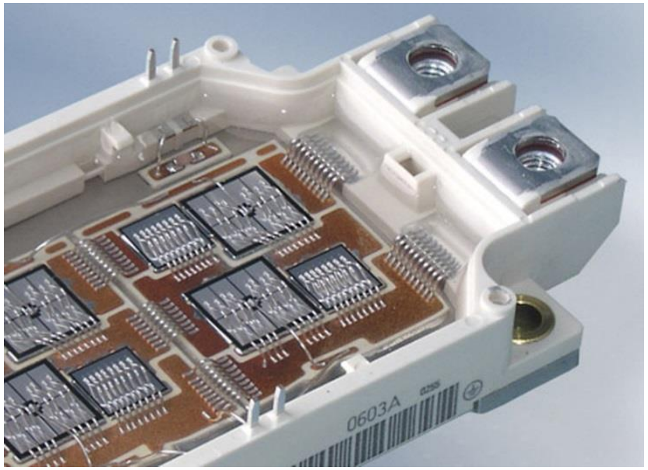
Inside a Module



IGBT dies exist only from 25A to 150A for 1.2kV and 1.7kV.

IGBT have good thermal and electrical coefficients which allow to place them in parallel.

IGBT modules have many dies in parallel to increase their current rating.



Topologies based on IGBT

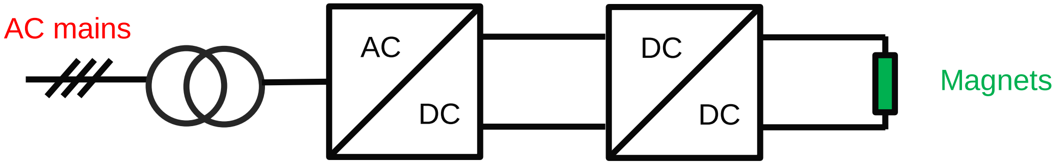
The magnets need DC current.

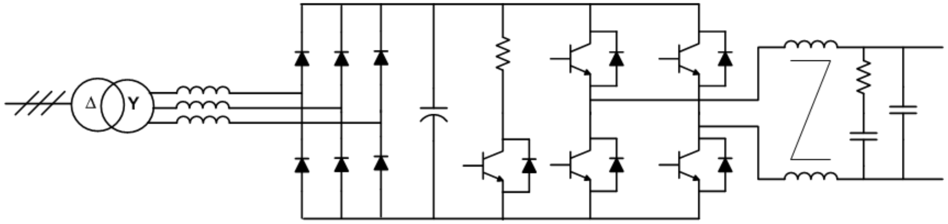
The magnet power supplies are always AC/DC.

The topologies are build with many stages of conversion.

The magnets need also a galvanic isolation from the mains.

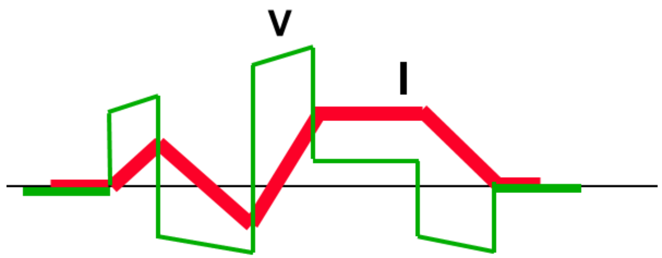
cases with 50Hz transformer

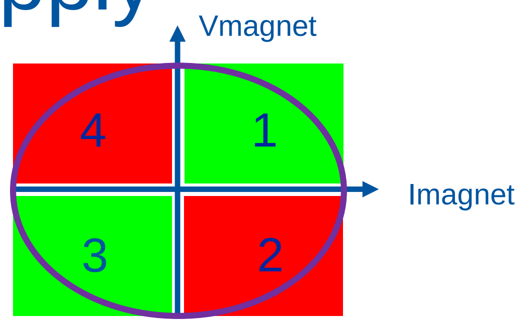


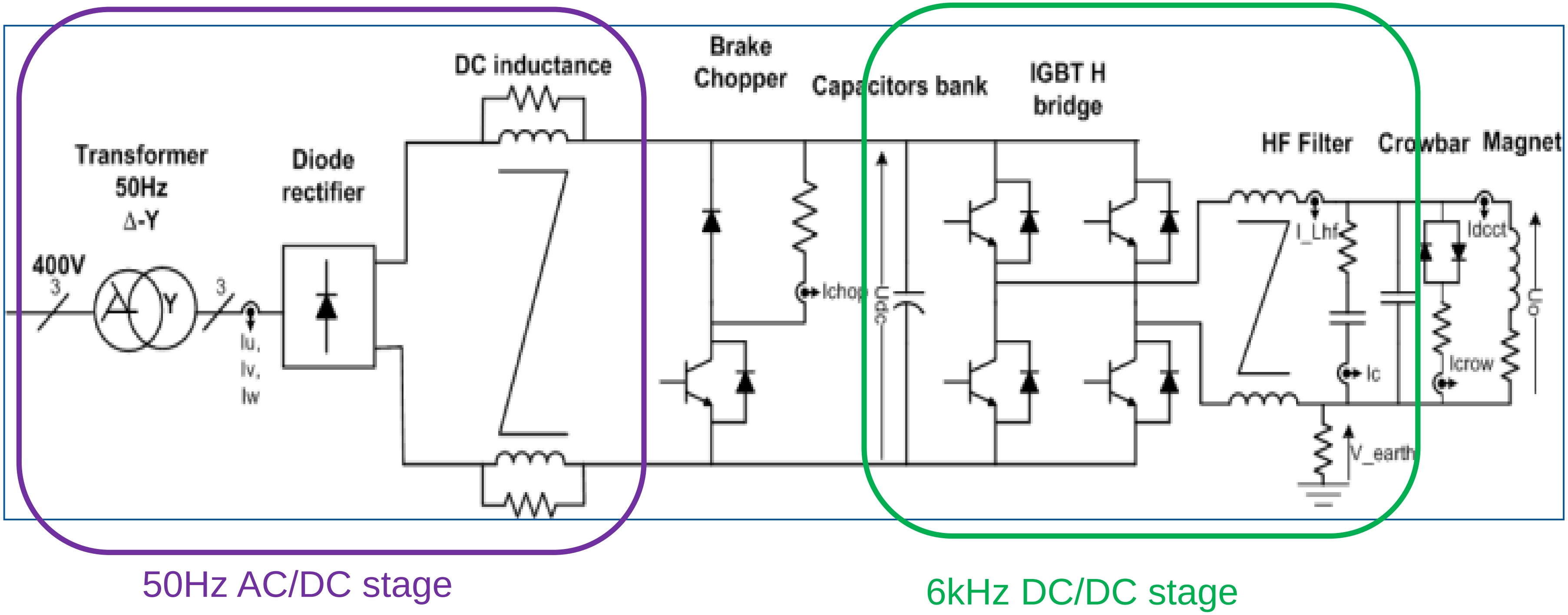


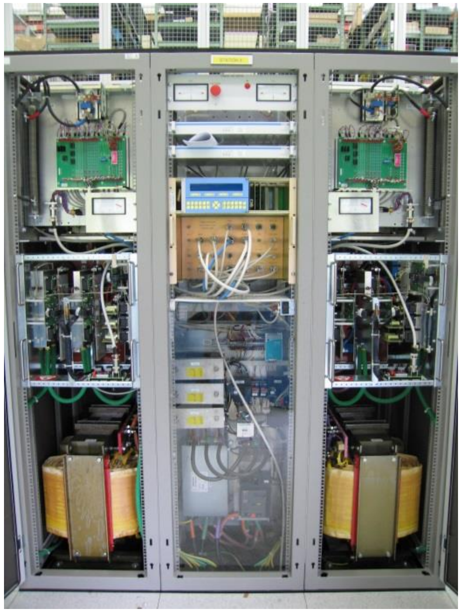
Switch-mode power supply

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









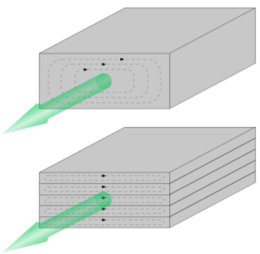

1
3
2
4

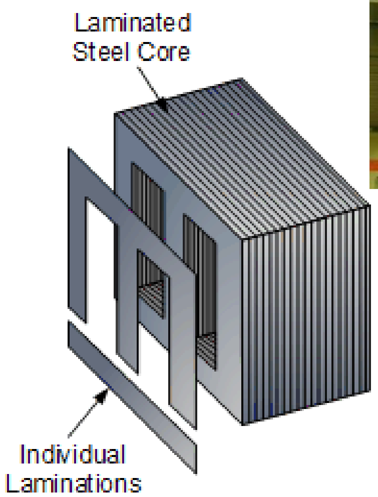
Transformer technologies

Two technologies are used for power transformers:

laminated magnetic core (like magnet):

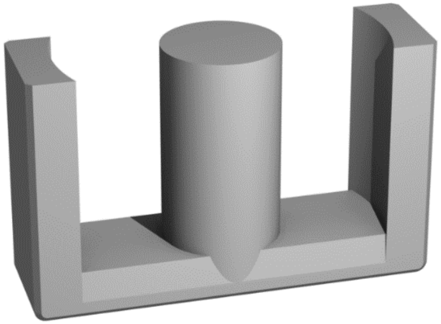
- 50Hz technology
- High field (1.8T)
- Limitation due to eddy current
- Low power density
- High power range

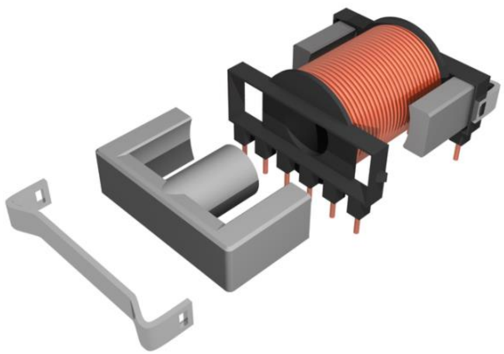




Ferrite core (like kicker):

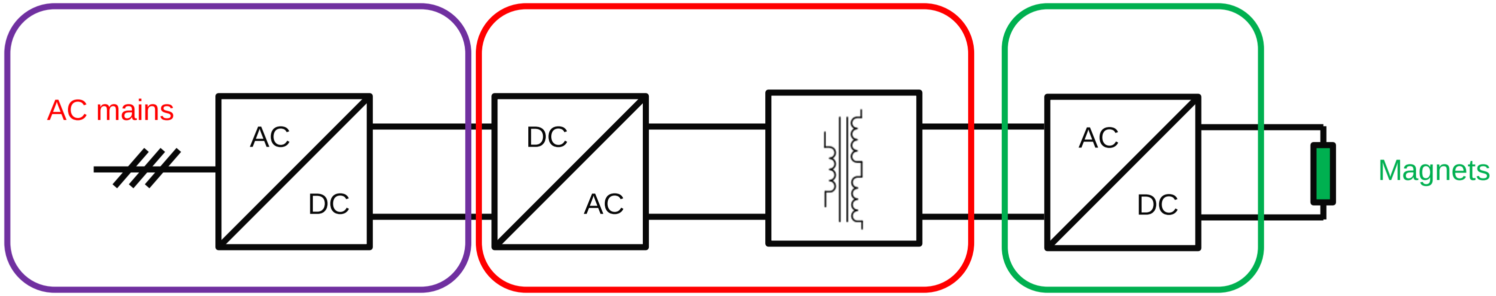
- kHz technology
- Low field (0.3T)
- Nonconductive magnetic material, very low eddy current
- High power density
- Low power range (<100kW)





Topologies with HF transformer

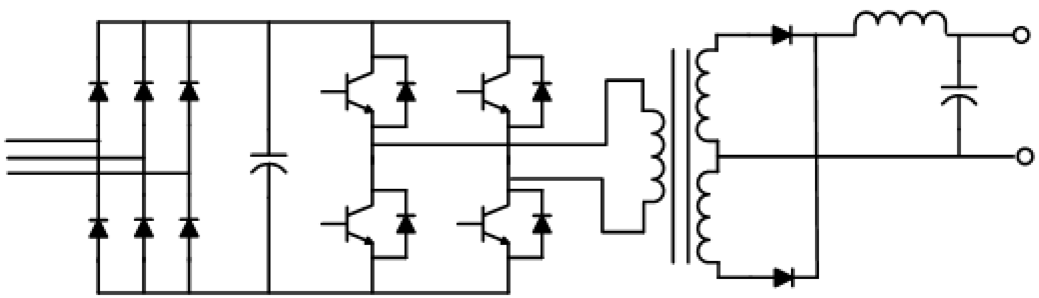
In this case, it is multi-stages converter with high-frequency inverters



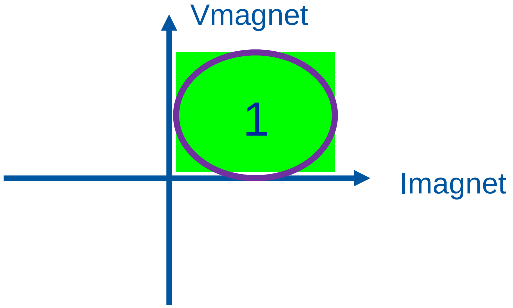
50Hz rectifier

20kHz inverters & transformer

20kHz rectifier & filter

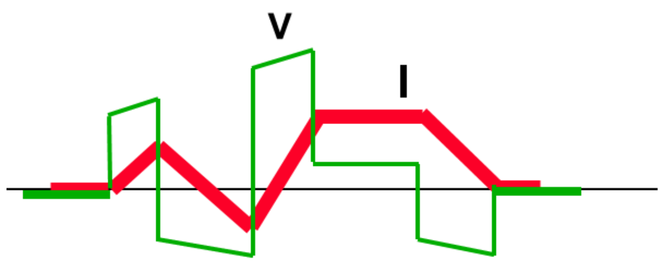


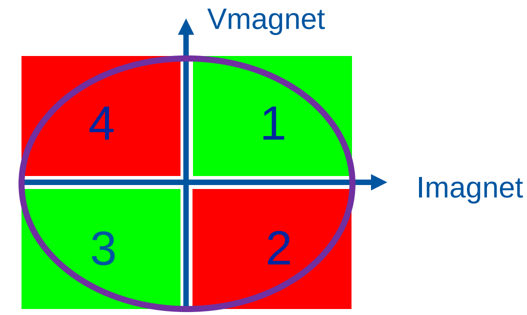
20kHz transformer

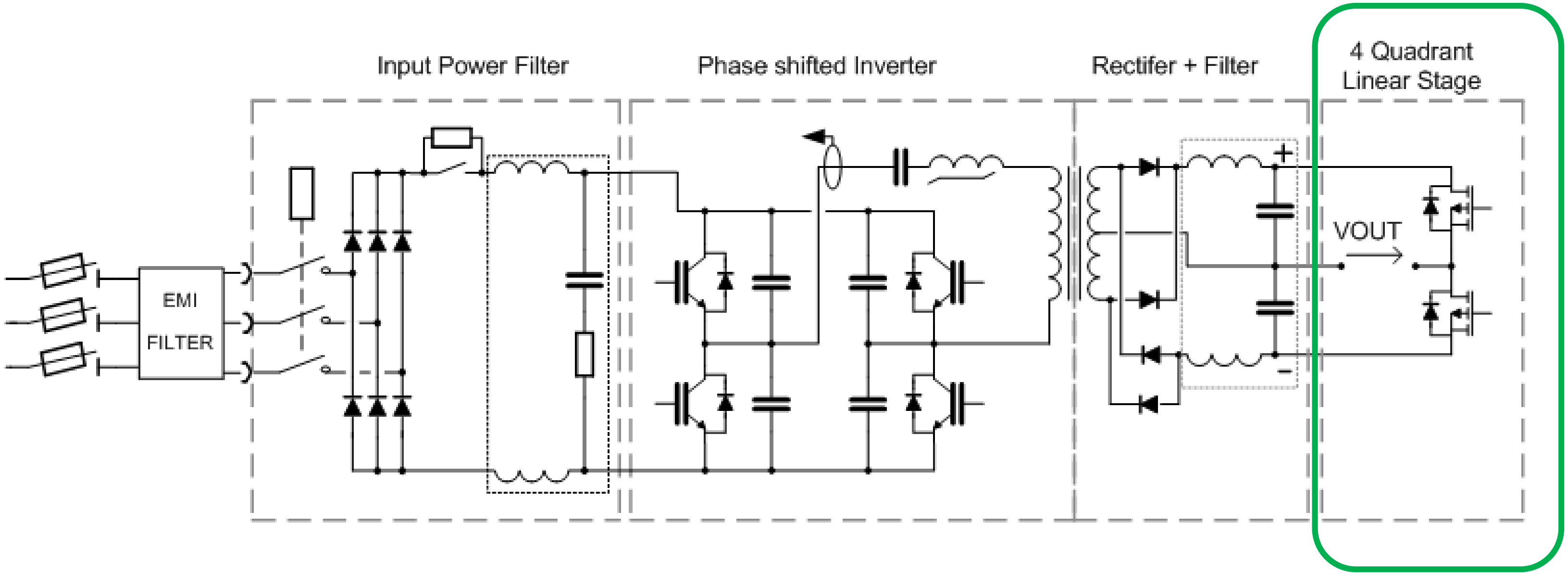


Switch-mode power supply with HF inverter

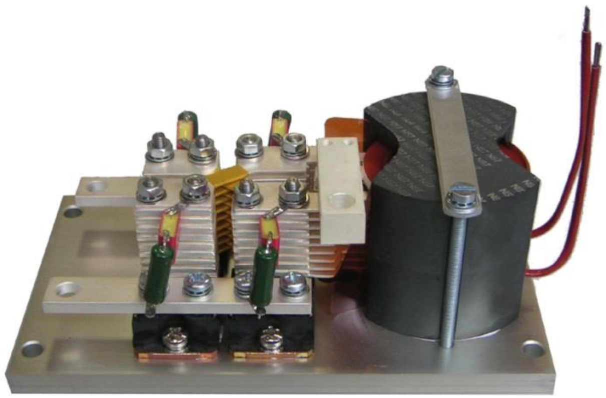
Example: LHC orbit corrector, ±120A/±10V

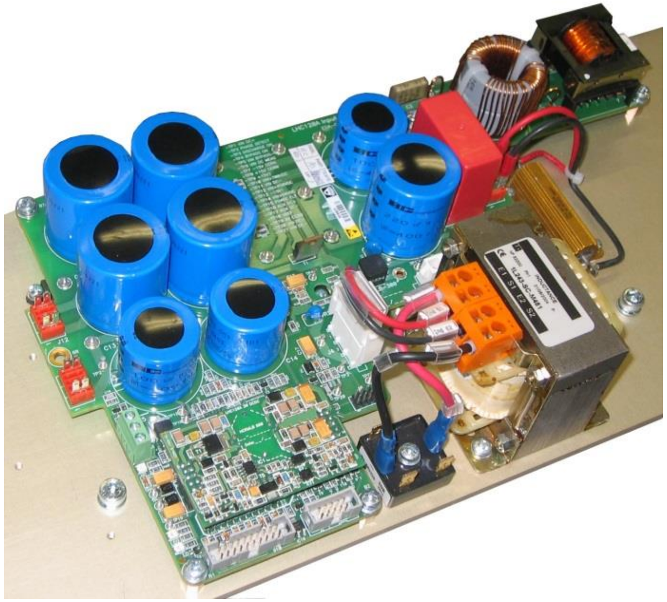






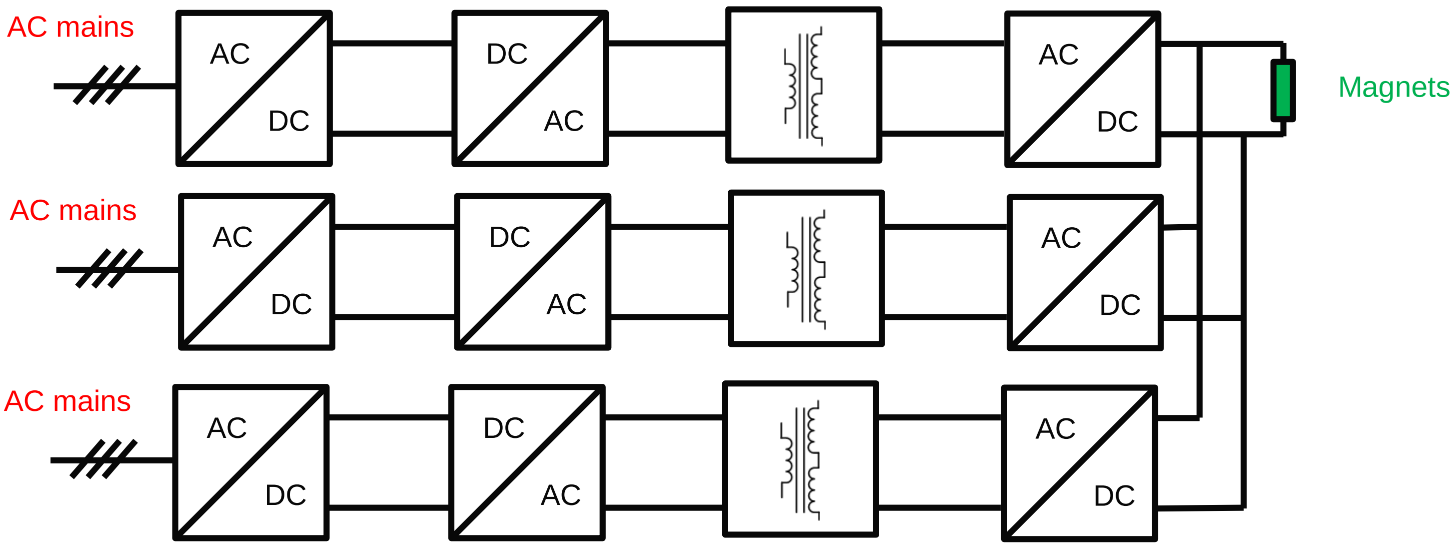
Linear stage to get low voltage ripple!





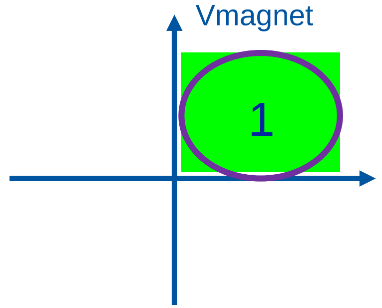
Converter association

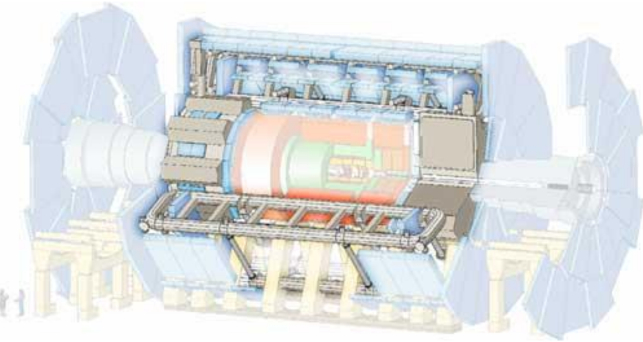
When the power demand increases above the rating of the power semiconductors, the only solution is to build a topology with parallel or series connection of sub-systems.



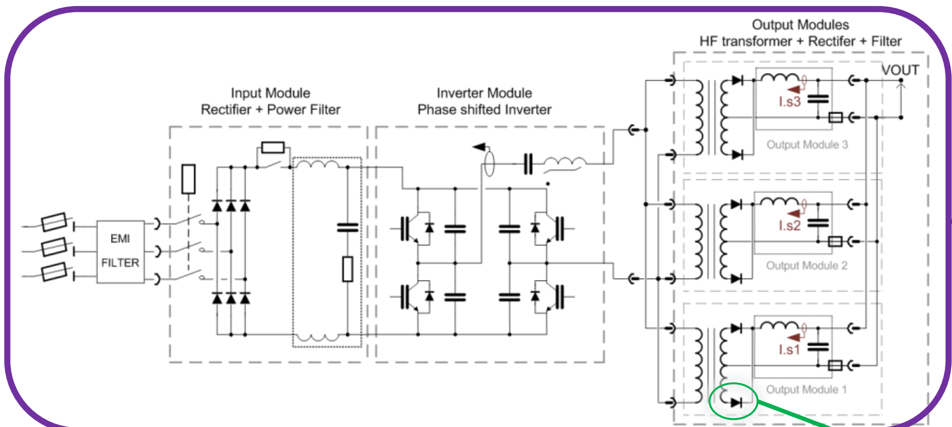
Parallel connection of sub-converters

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

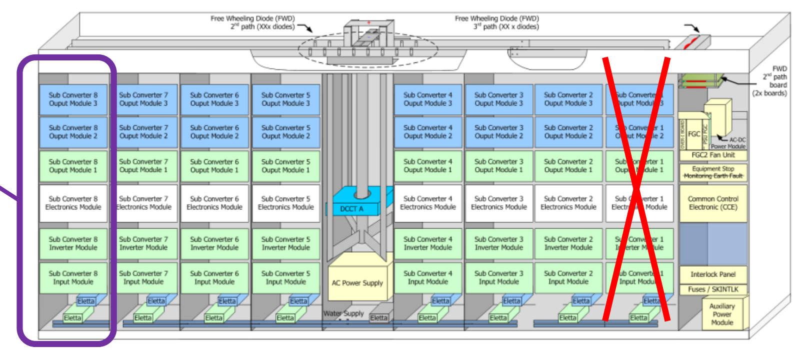




3.25kA/18V sub-converter



8 sub-converters in parallel



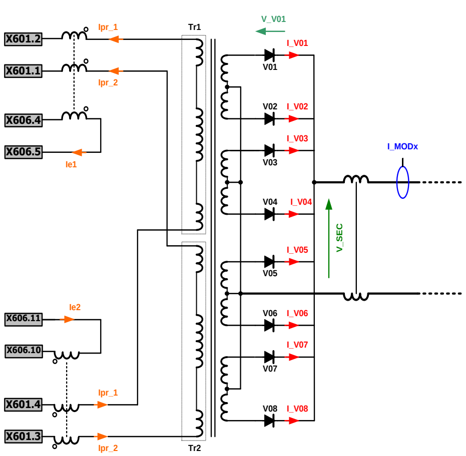
3.25kA/18V

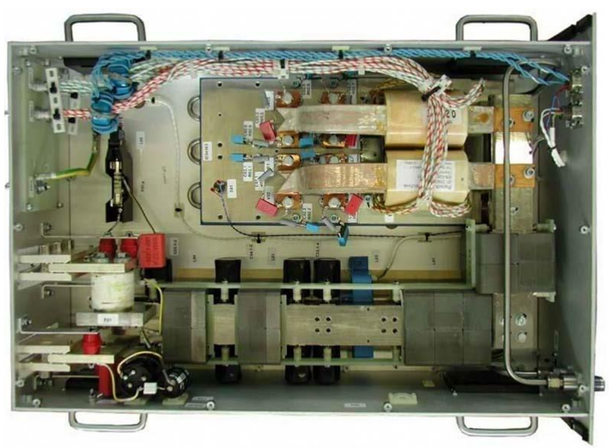
Redundancy implementation, n+1 sub-converters

Can work with only n sub-converters

250A max


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

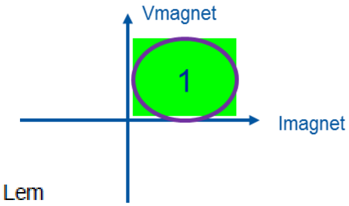

X601.2
Ipr_1
Tr1
V_V01
I_V01
V01
X601.1
Ipr_2
X606.4
X606.5
Ie1
V02
I_V02
I_V03
V03
I_MODx
V04
I_V04
V_SEC
I_V05
V05
Ie2
X606.11
X606.10
V06
I_V06
I_V07
V07
Ipr_1
X601.4
V08
I_V08
X601.3
Ipr_2
Tr2

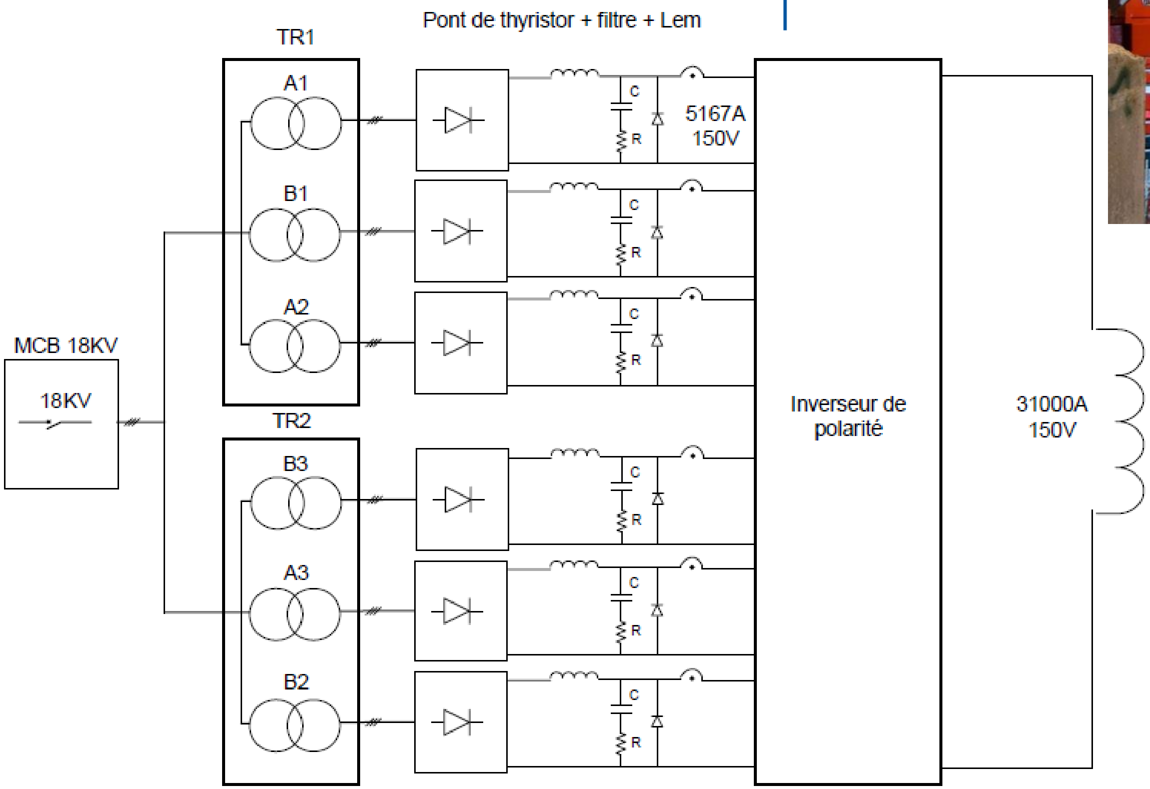


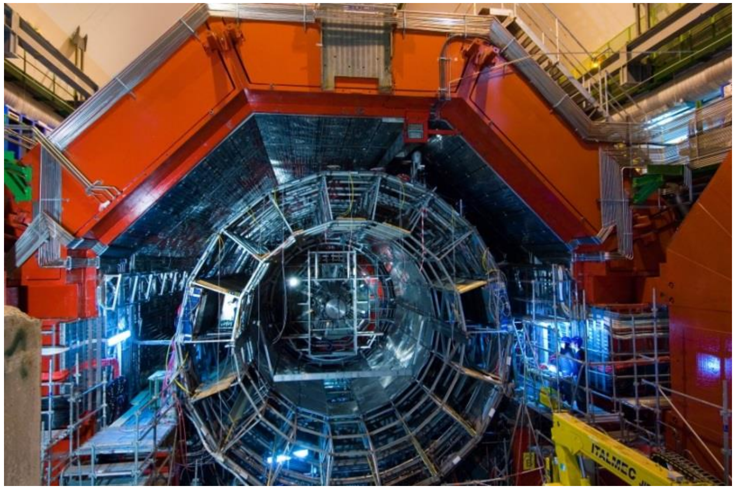

PWC-T

Parallel connection with thyristor rectifier

Example: Alice Dipole, 31kA/150V

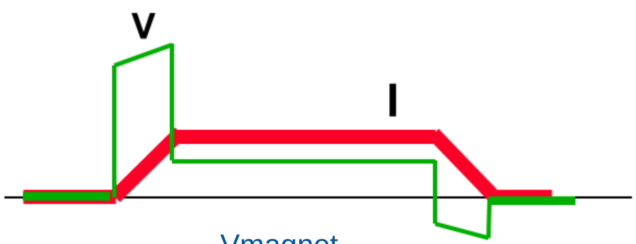


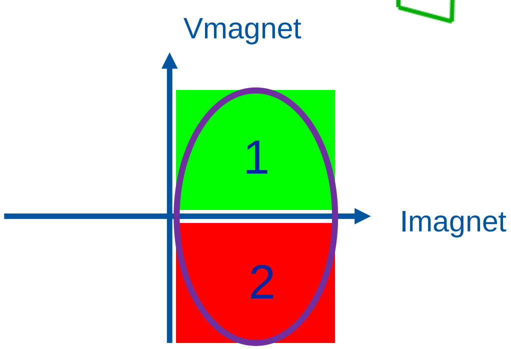


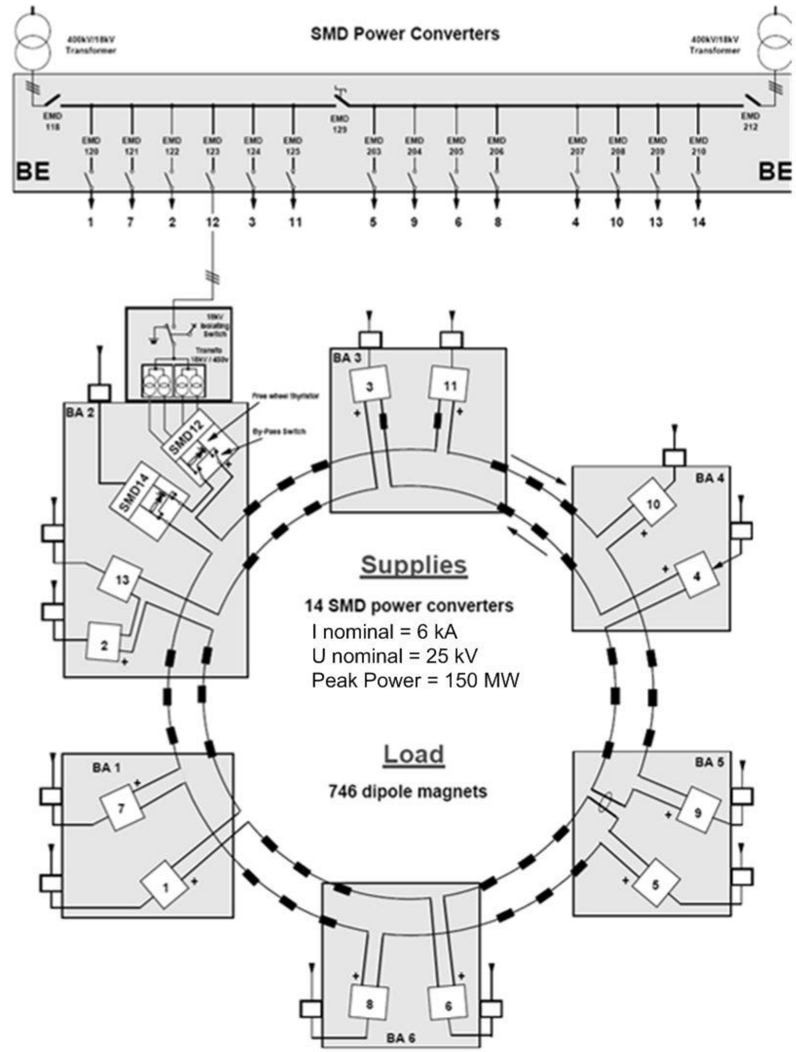


Series connection of sub-converters

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



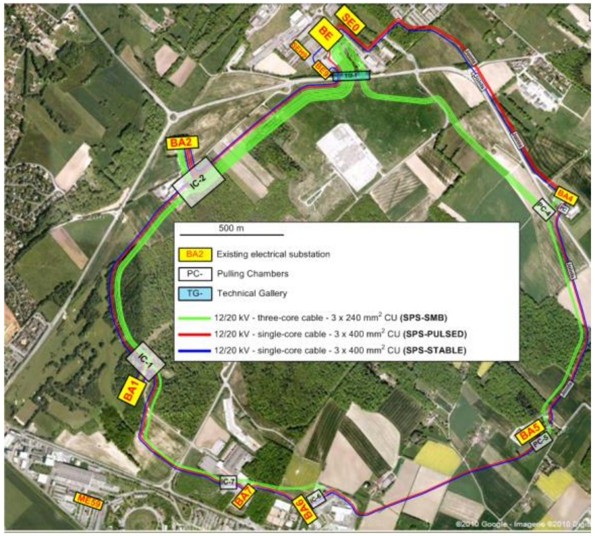




12 power supplies in series between magnets.

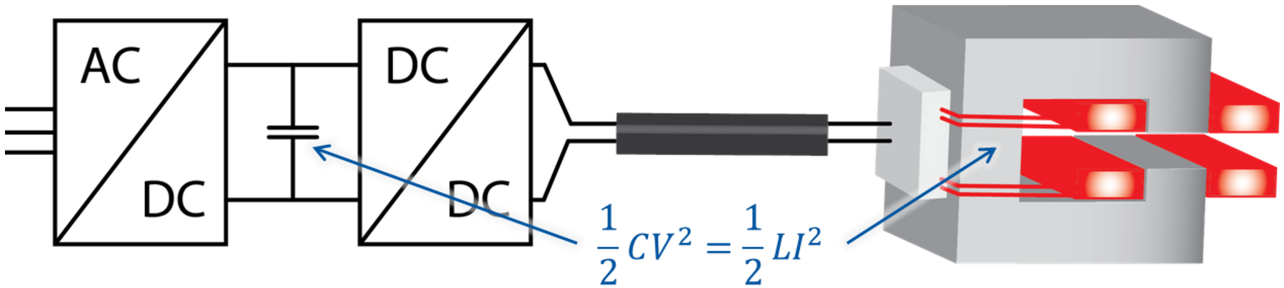
Each power supply gives 6kA/2kV.

In total 24kV is applied to the magnets.


BA2
IC-2
IC-1
BA1
BA4
BA5
PC-4
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)

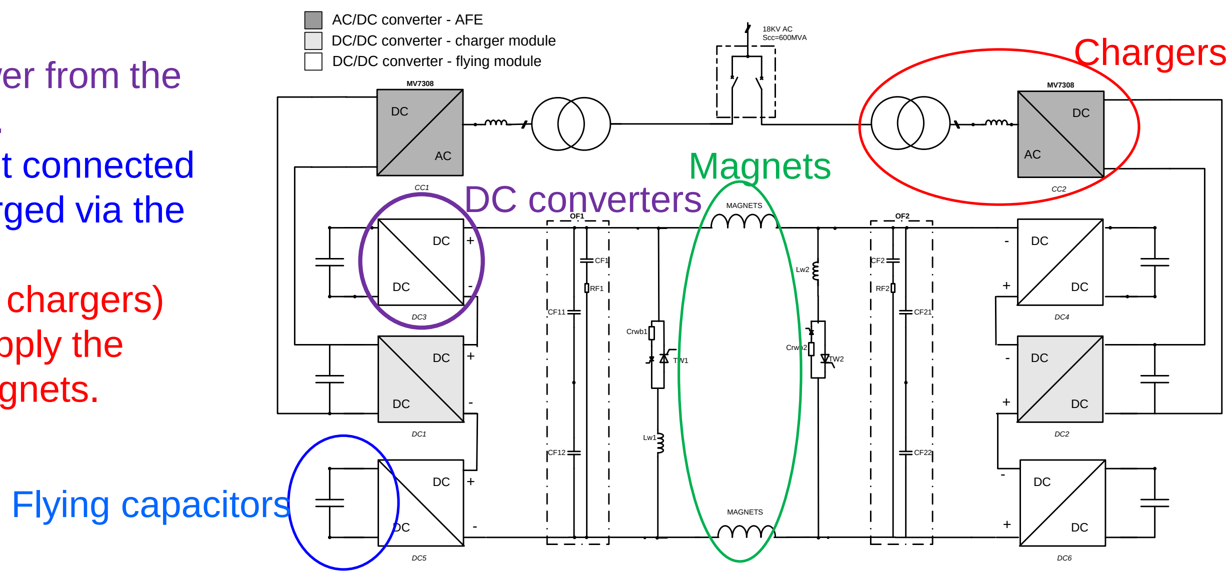
New concept for energy management

Local exchange of energy between magnets and energy storage devices inside the power supply. Done with capacitor banks integrated in the power supply.



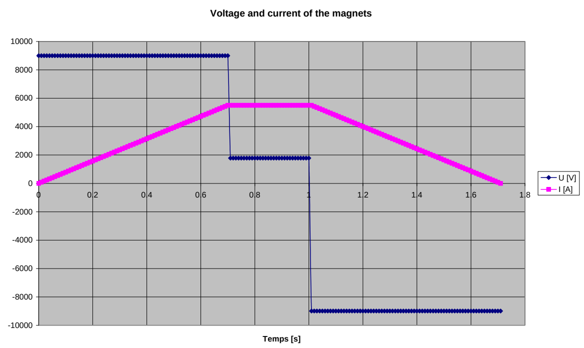
First application with POPS (PS main power system).

- 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.

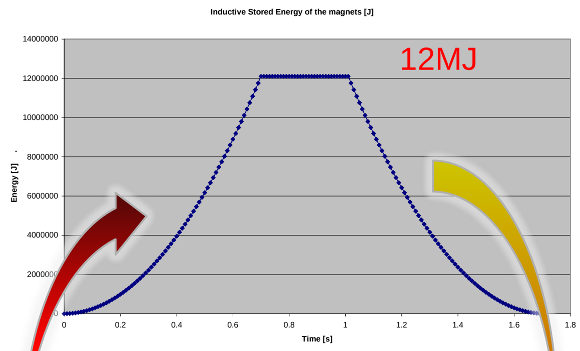


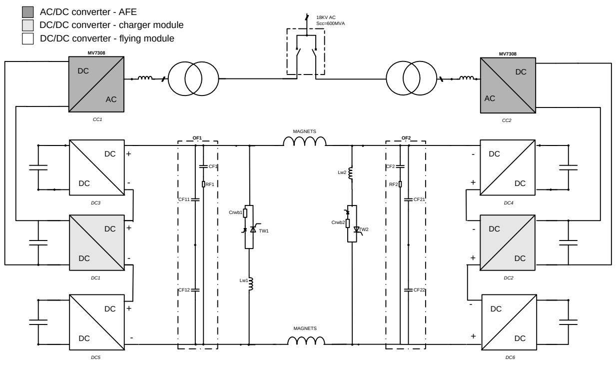
New concept for energy management

Magnets current and voltage

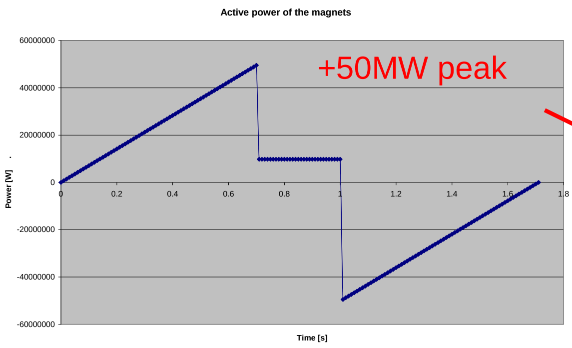


Stored magnetic energy

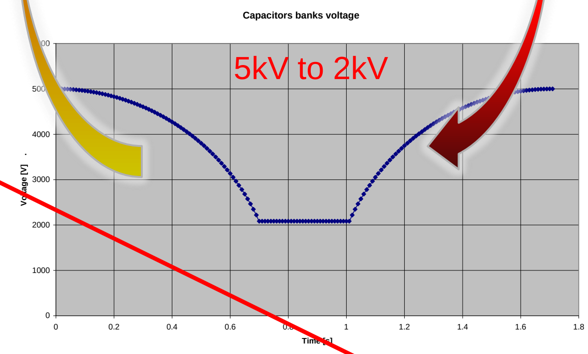




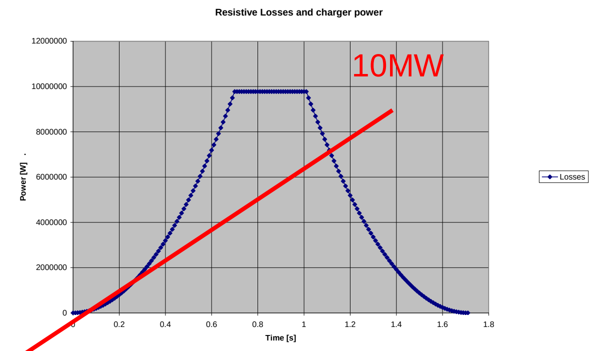
Power to the magnets



Capacitor banks voltage



Power from the mains = Magnet resistive losses



Acts as peak shaving for pulsed loads!

POPS example

Example: POPS 6kA/±10kV

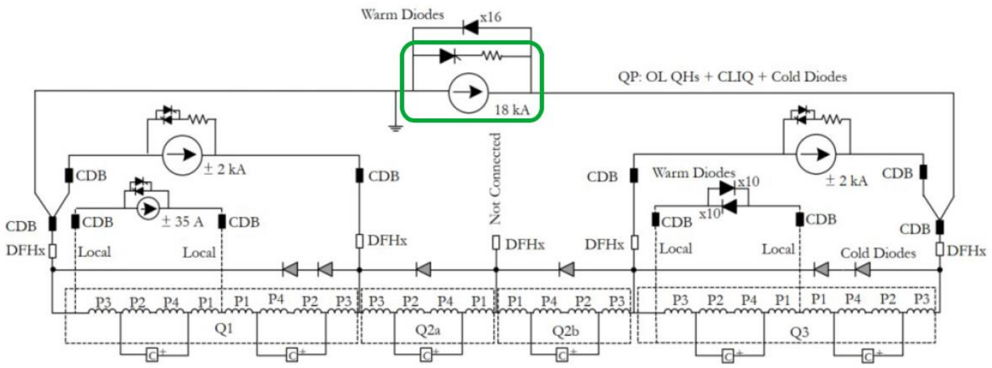
60 tons of capacitors for 18.5MJ
Equivalent to 0.5L of gasoline!

Control room Electrical room Cooling tower Power transformers Capacitor banks

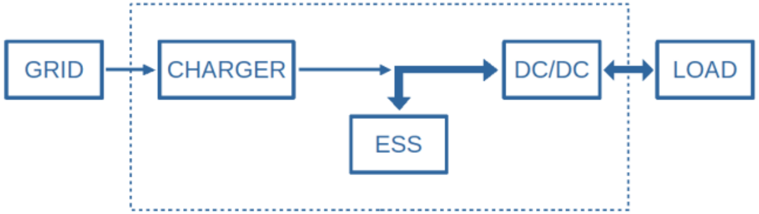
HL-LHC inner triplet

New inner triplet superconducting magnet
Lmag=255mH
Emag=11,5kWh (41MJ)
Rcircuit=0.026mΩ

PC= 18kA/±10V
Power converter topology including energy storage system



Converter	PC1	PC2	PC3	PC4
Output current [A]	18000	±2000	±2000	±35
Output voltage [V]	±10	±10	±10	±10

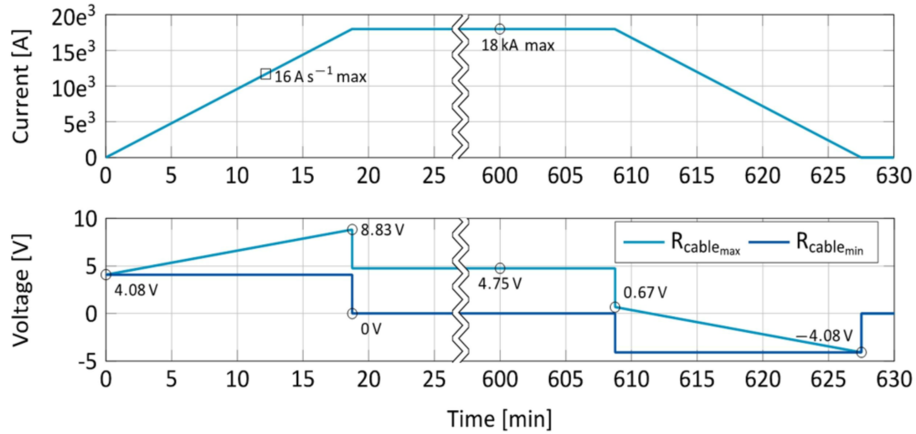


Why to use an Energy Storage System (ESS)?

- Reduce the peak power drawn from the network
- Increase the immunity to grid perturbations
- Recover the magnets energy during ramp down and supply it back during ramp up
- Ease the control of the power flow
- Modularity and N+1 redundancy can be implemented

HL-LHC inner triplet

New inner triplet:18kA/±10V



The number of cycles per year is 5000

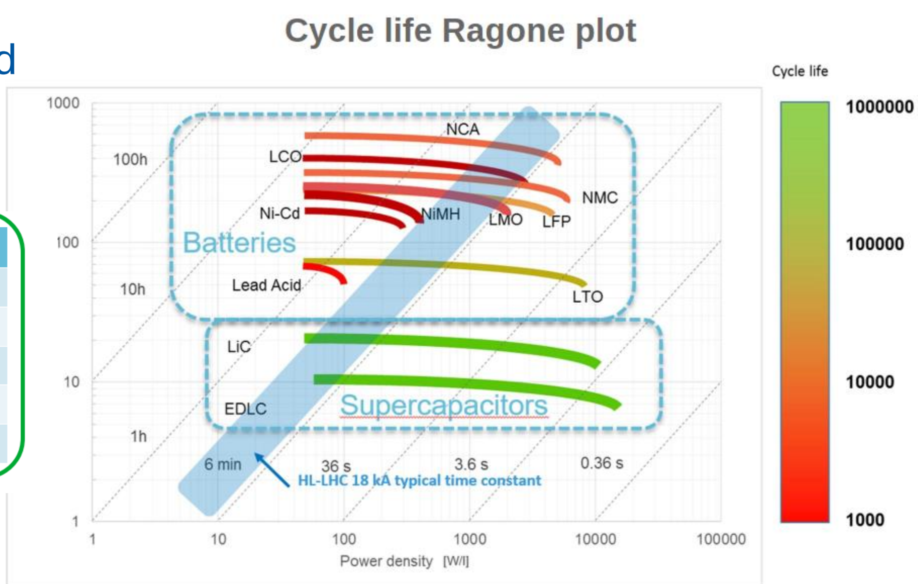
Classical Lion batteries can't be used!

Capacitors too bulky!

Supercaps can be used up to 100k cycles.

Lithium Titanate Oxide(LTO) best compromised between cost and number of cycles

11 kWh example	EDLC Supercaps	LiC Supercaps	LTO Batteries
Weight [kg]	2500	1390	900
Volume [l]	2550	1200	700
Number of racks	5	2-3	2
Total cells price [€]	250k	216k	40k + BMS
Cycle life	1M	>200k	>75k



HL-LHC inner triplet

New inner triplet superconducting magnet

Lmag=255mH

Emag=11,5kWh (41MJ)

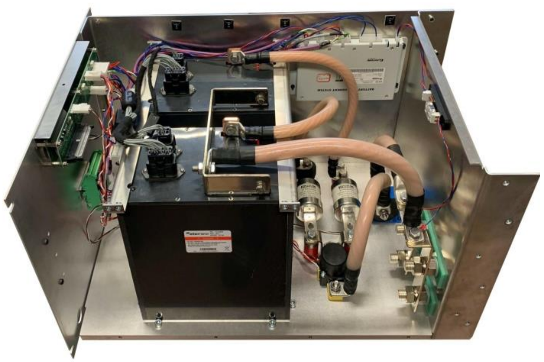
Rcircuit=0.026mΩ

ESS with LTO batteries

Voltage range = [17; 27.5] V

- Typical capacity = 67 Ah
- Typical energy = 1.45 kWh
- Maximum (dis)charge current = 500 A
- Typical internal resistance = 4 mΩ
- Self-discharge = 1 % per year
- Dimensions (L x W x H) = 28 x 16 x 30 cm
- Weight = 28 kg

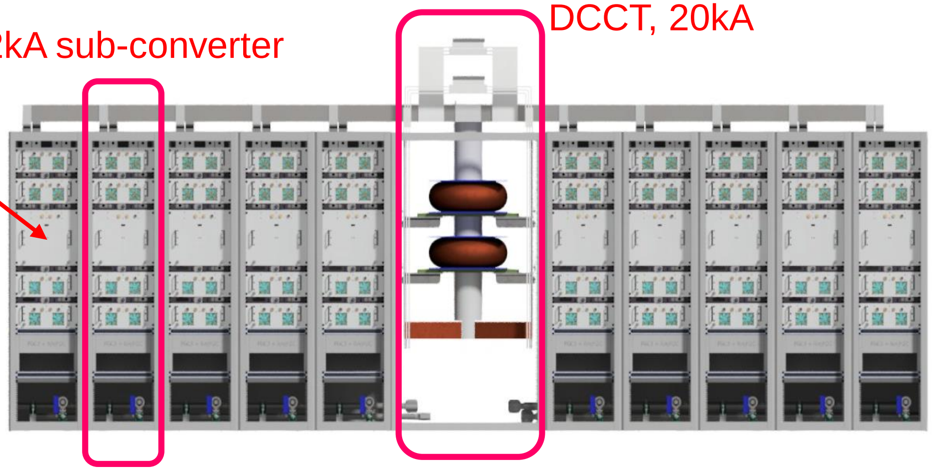
2 LTO batteries, 2.9kWh



70kg

2kA sub-converter

DCCT, 20kA



Power supply control

The power supply are controlled by the global control system.

They need to be synchronized => Timing

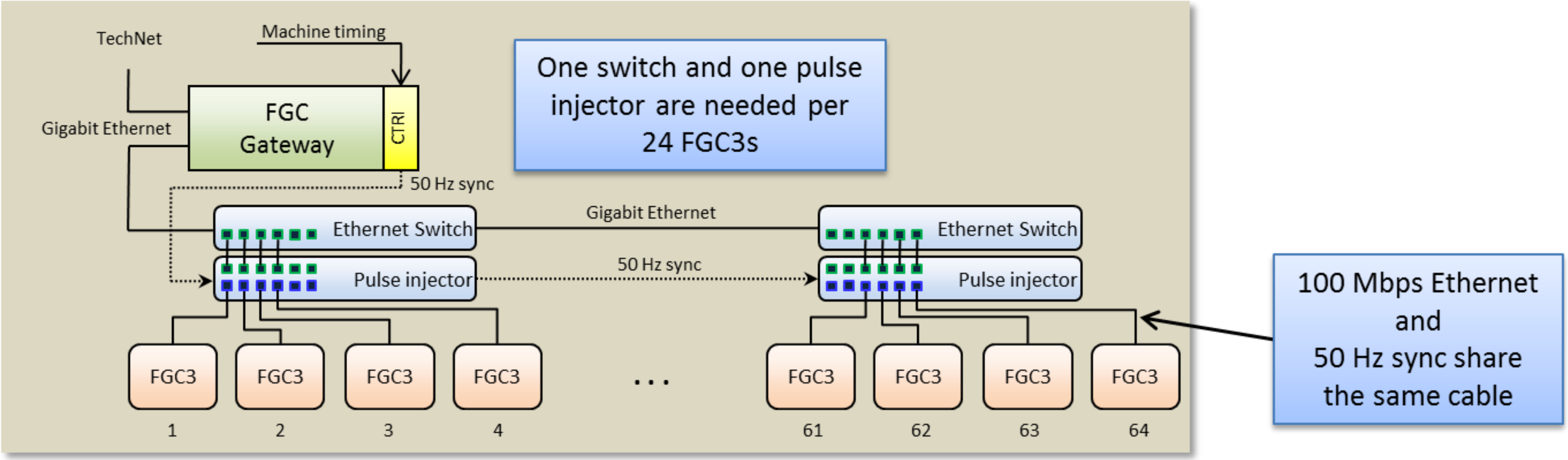
Locally, a fieldbus (must be deterministic) is used to communicate with a gateway,

WORLDFIP in the LHC

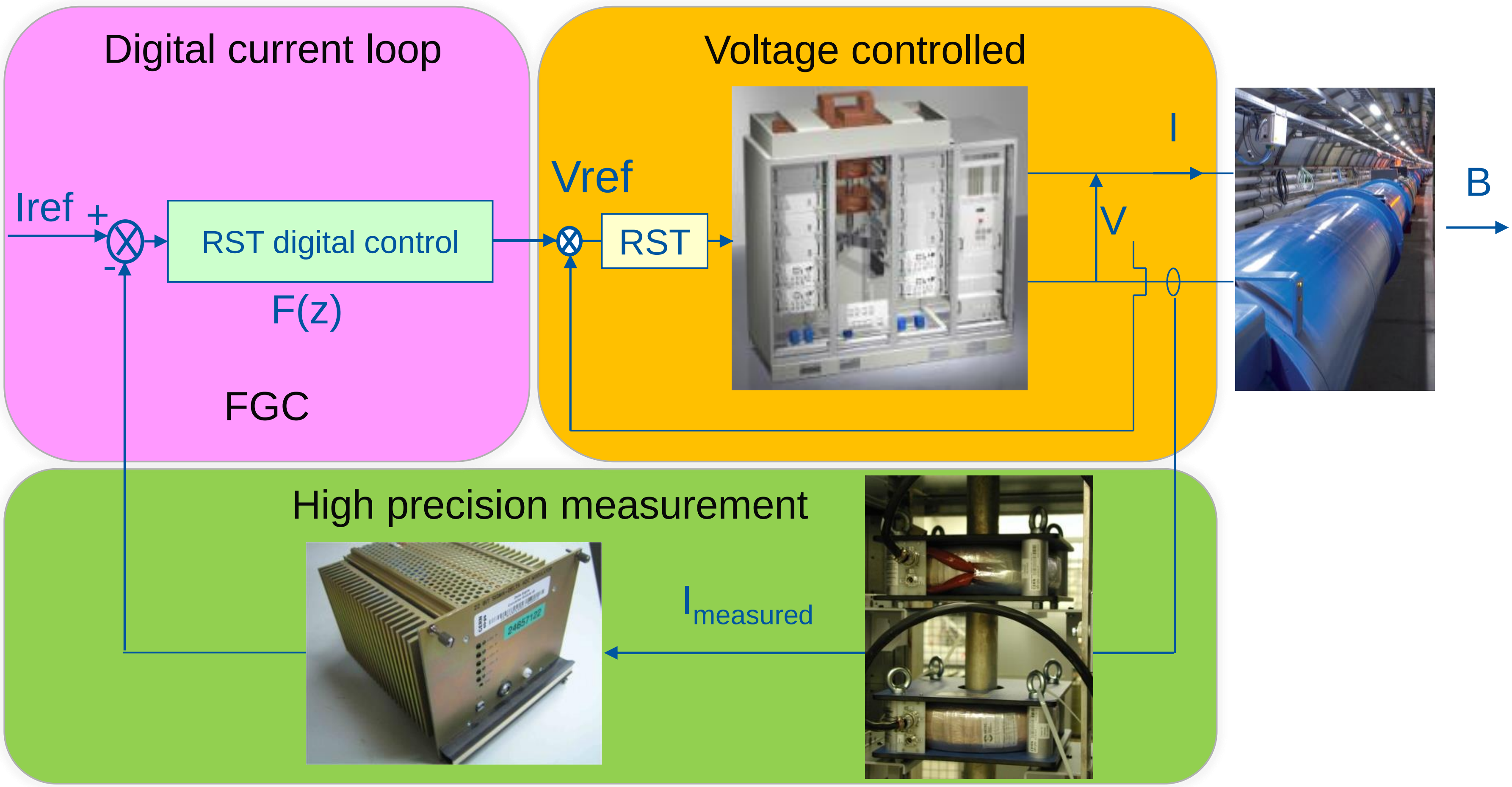
ETHERNET for LINAC4

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



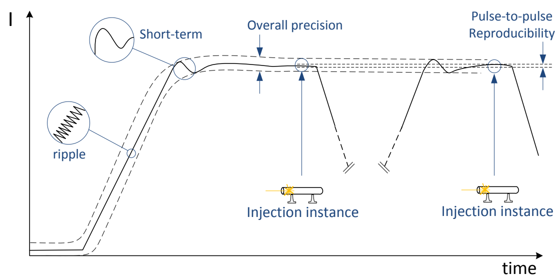
High-precision definition

Accuracy

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

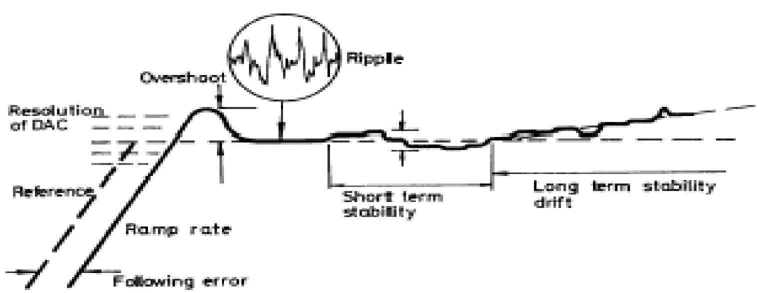
Reproducibility

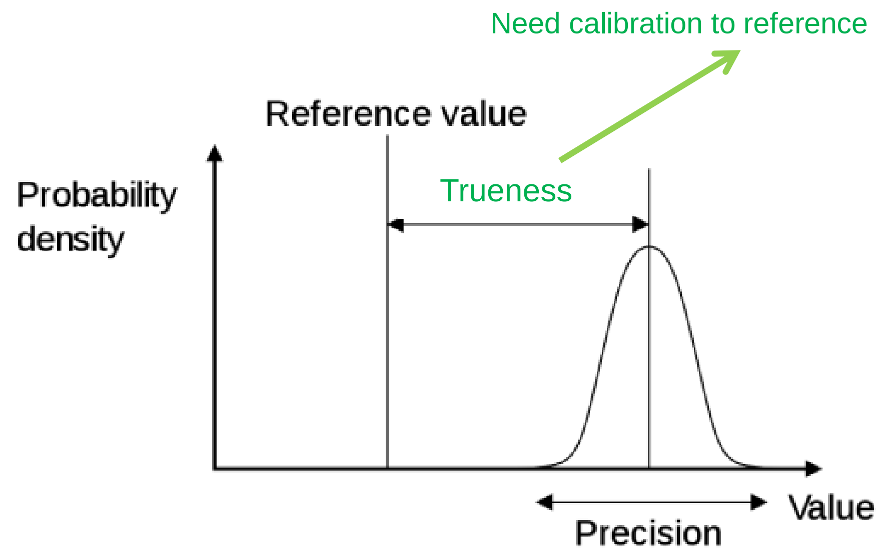
Uncertainty when returning to a set of previous working values from cycle to cycle of the machine.

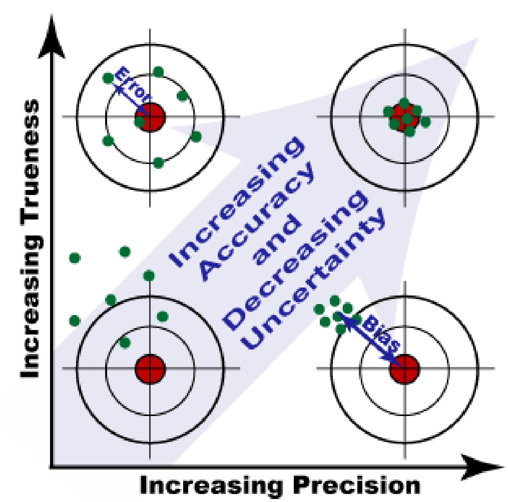


Stability

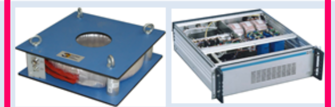
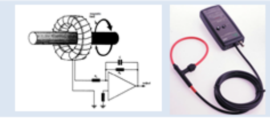
Maximum deviation over a period with no changes in operating conditions.







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

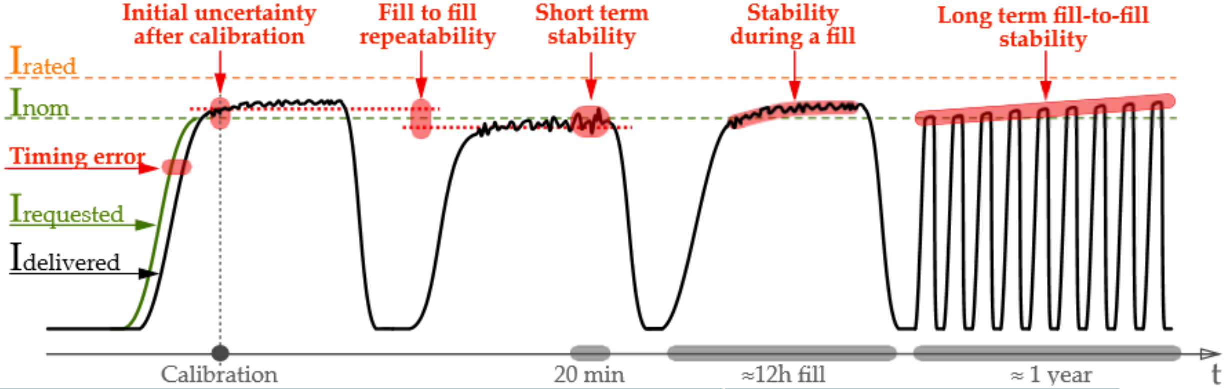
DCCT: invented by CERN for particle accelerators

LHC class specification

Best achievements

Converter category	Accuracy Class	½ hour stability [ppm]	24h stability [ppm]	1 year stability [ppm]
Main Dipoles 13kA-190V	Class 1	3	5	50
Main quadrupoles 13kA-18V	Class 1	3	5	50
Inner Triplets 8kA-8V	Class 1	3	5	50
Separation dipoles, Insertion quadrupoles 4-6-8kA-8V	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

HL-LHC class 0 requirements



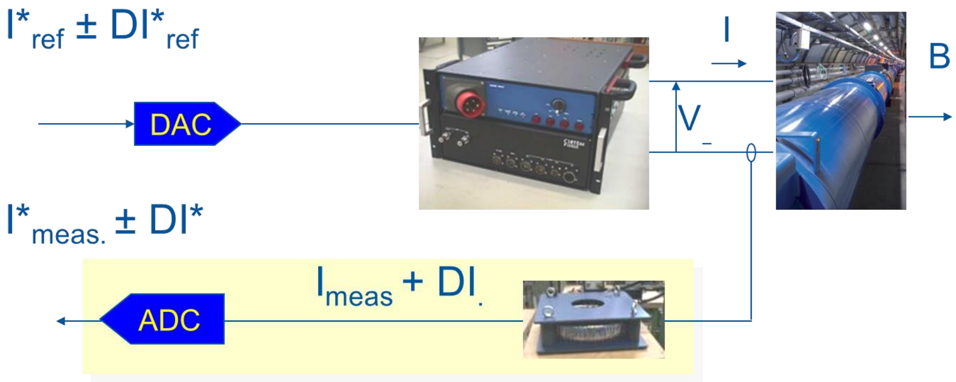
	Class 0		
	total PC	ADC	
Setting resolution [ppm]	0.5	0.2	T = *const.*
Initial uncertainty after cal. [2xrms ppm]	2.0	1.0	
Linearity [ppm] [max abs ppm]	2.0	1.0	
Stability during a fill * (12h) [max abs ppm]	**0.7**	**0.2**	
Short term stability (20min) [2xrms ppm]	**0.2**	**0.1**	
Noise (<500Hz) [2xrms ppm]	**3.0**	**1.0**	
Fill to fill repeatability [2xrms ppm]	**0.4**	**0.1**	
Long term fill to fill stability [max abs ppm]	8.0	4.0	
Temperature coefficient [max abs ppm/C]	**1.0**	**0.2**	ΔT = 0.5 ºC

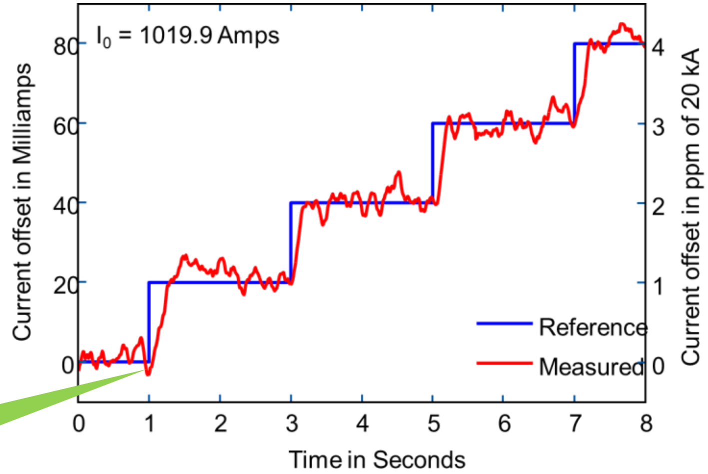
[4] M. C. Bastos. HL-LHC Power Converter Requirements. EDMS 2048827 v.2
[5] D. Gamba *et al*. Update of beam dynamics requirements for HL-LHC electrical circuits. CERN-ACC-2019-0030

** Contains a sub-specification for the first 5 minutes after ramp-up, which concerns only the DCCT*

Resolution

Resolution is the smallest increment that can be induced or discerned.
The resolution is expressed in ppm of maximum DCCT current.
Resolution is directly linked to ADC performance.





Best resolution achieved = 1ppm

Power supply workflow

From power supply functional specification

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

Power supply design

simulation

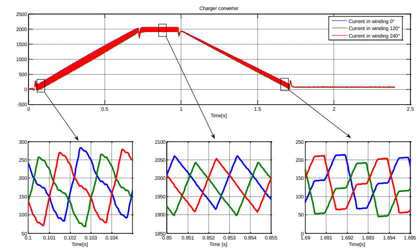
Component design

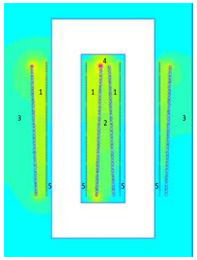
3D mechanical integration

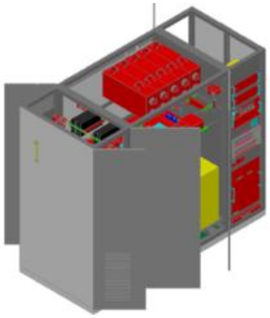
Production

Laboratory Tests

On site commissioning







Minimum 18 months
Up to 5 years when special development is needed.

What is special with magnet power supplies?

The magnet power supplies are high-precision current control.

The technical solutions are out the industrial standard

Custom power supplies

- 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 control electronics

Summary

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

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

Their performances have a direct impact on the beam quality.

Creativity is required in many technical fields!

More information:

Special CAS on power converters

May 2014 Baden (CH)