



MSC Seminar, 17th of May 2016

Power converters for particle accelerators at CERN: design and operation challenges

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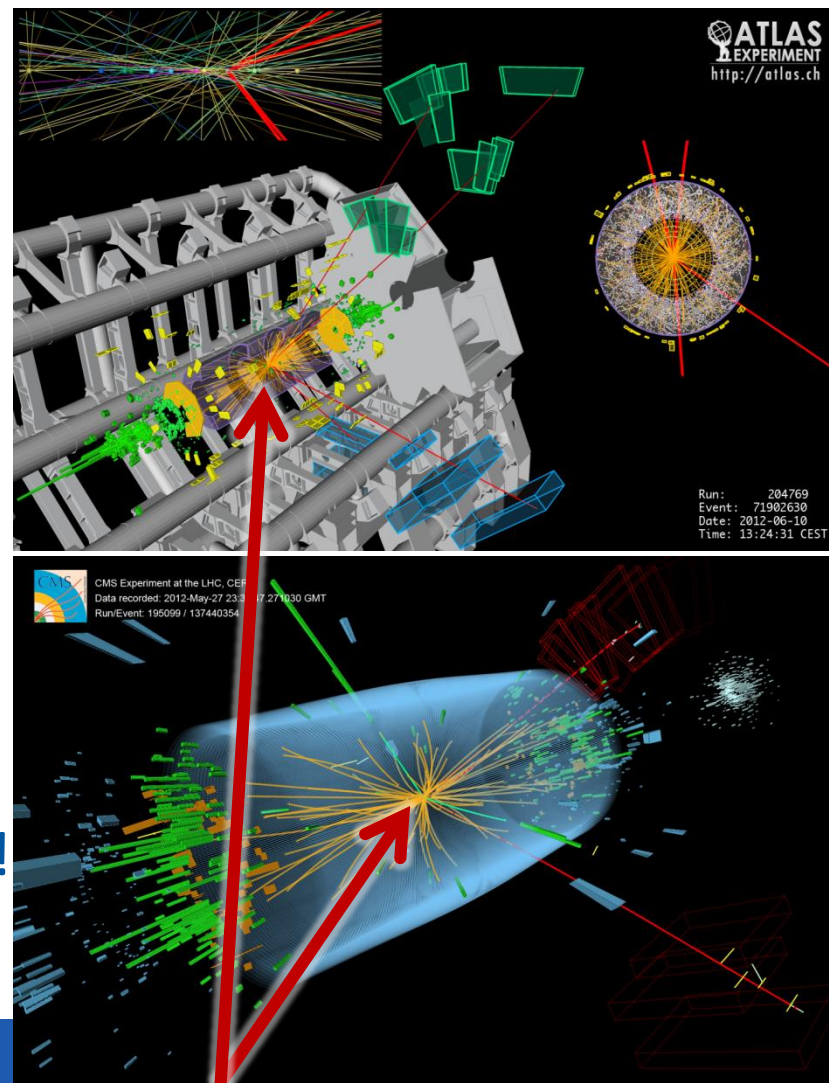
Today's menu

- Why power converters in accelerators?
- Basic principles in power electronics
- Power converters design challenges at CERN
- Design examples
- Typical power converter design procedure
- Electric Power Converter group in a nutshell
- Conclusion (@ slide No. 39)

Why power converters in accelerators?

Why power converters in accelerators?

- **Reminder:** Objective is to produce particles, observe their behaviour (matter, forces)
- **Mass energy equivalence**
 $E = mc^2$
The more we accelerate particles, increasing their energy, the more mass they gain
- According to the mass and energy conservation principle, collisions between accelerated particles generate a multitude of elementary particles, some of which can be new!



Example of proton collision⁵

Why power converters in accelerators?

- To accelerate and guide a beam of charged particles (q) forces shall be applied:

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

Acceleration

Particles pass through an electrical field oriented in the direction of their movement.



Need for HV to create strong electric fields



Power Converters

Trajectory control

As the energy of particles increases the magnetic field controlling the trajectory must also increase



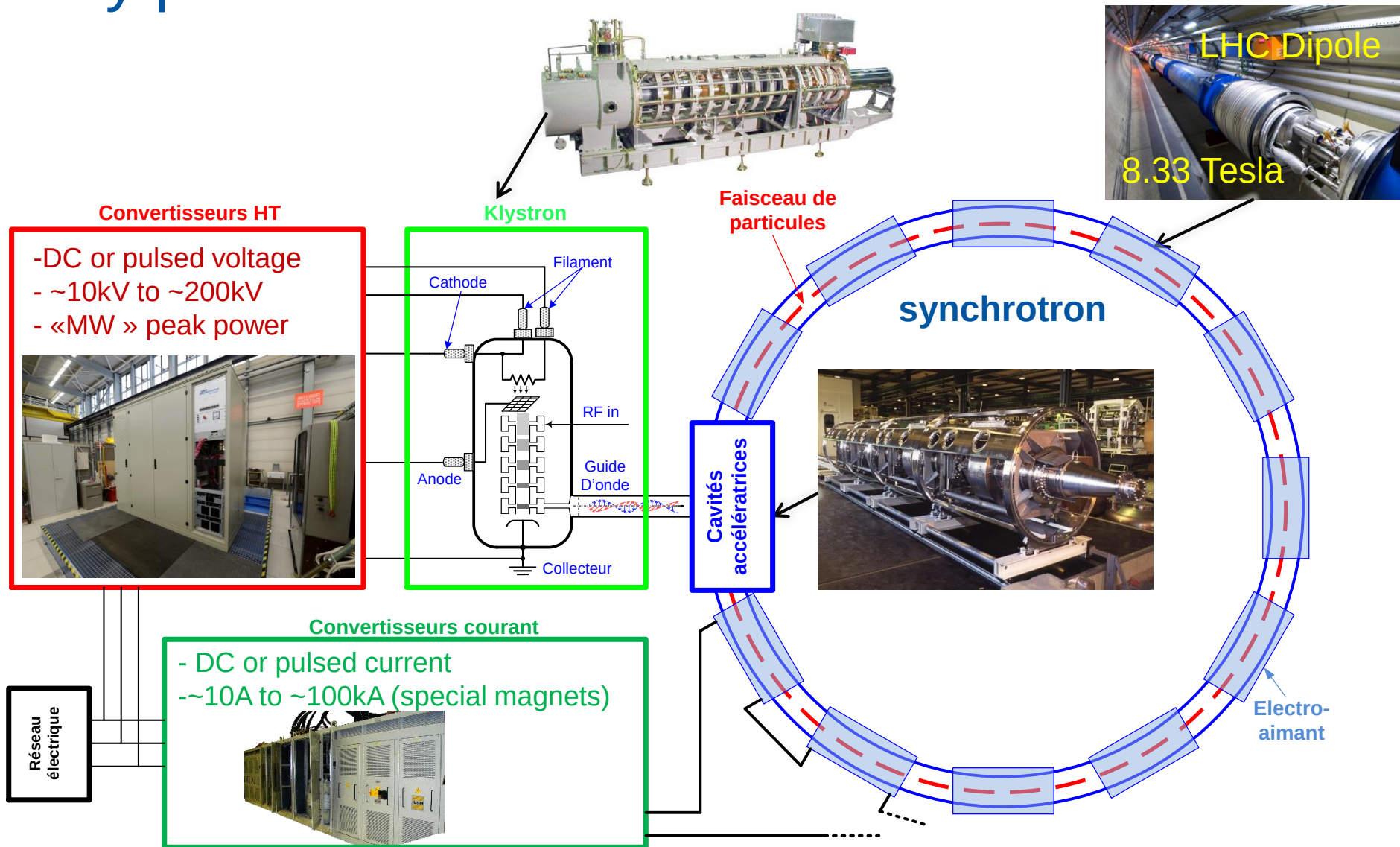
Need for strong magnetic fields:
Electro magnets are used



Power converters

At CERN ~6000 dedicated converters

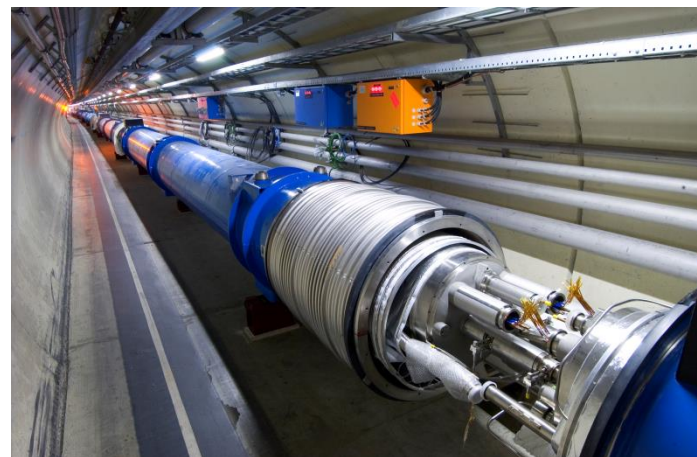
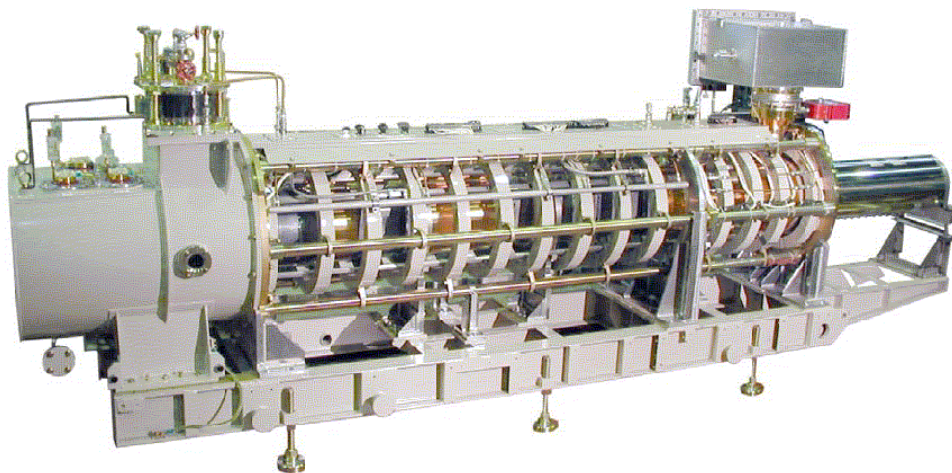
Why power converters in accelerators?



Why power converters in accelerators?

- Supply of several accelerator's equipment:
 - Normal conducting and superconducting magnets
 - Electronic tubes for RF production (klystrons, tetrodes, etc.)
 - Particles sources (protons, electrons, ions)
 - All auxiliary / standard DC supplies
(measurements, control electronics, etc.)

~6000 dedicated
converters at
CERN

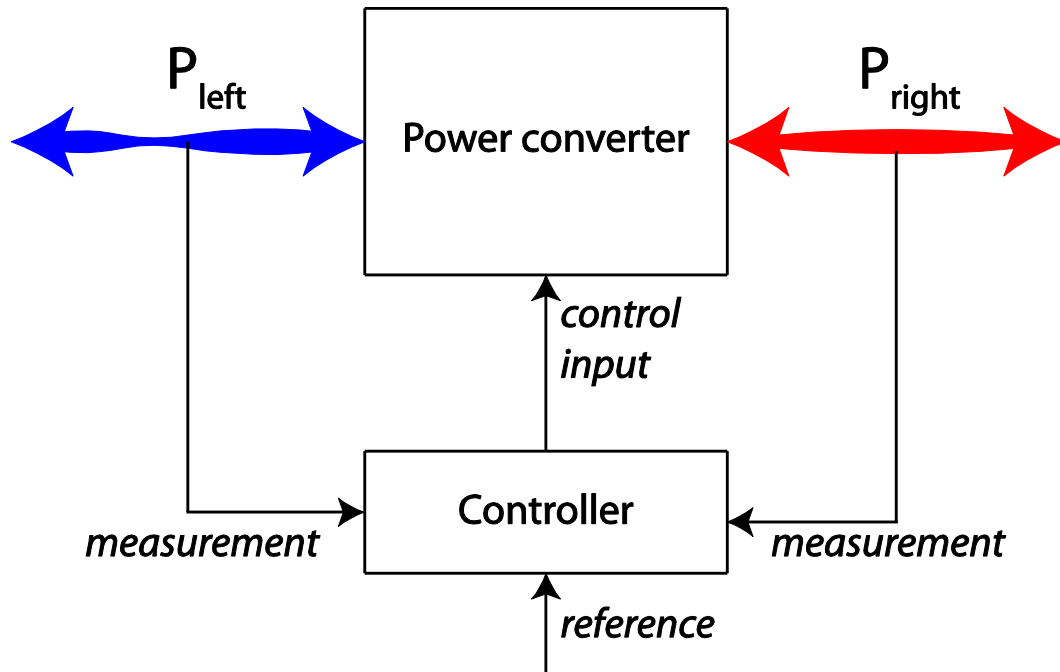


All the energy used to accelerate and guide the particle beams
passes through power electronics converters!

Basic principles in power electronics

Basic principles in power electronics

- What is a power converter? What is its task?
 - *The task of a power converter is to process and control the flow of electric energy by supplying voltages and currents in a form that is optimally suited for user loads.*



- Control is most of the time needed (precision), but one could set the reference without control (open loop)
- Depending on converter type, power can go in one or both directions
- Low losses = high efficiency η : small size and weight!

Basic principles in power electronics

- Applications in a wide power (P) range. Examples:
 - $P \sim W$: battery-based portable equipment
 - $10W < P < 1kW$: computers & office equipment
 - $1kW < P < 10MW$: variable speed drives (motors & generators)
 - $10MW < P < 1GW$: high power transmission systems (HVDC, UPFC, etc.)

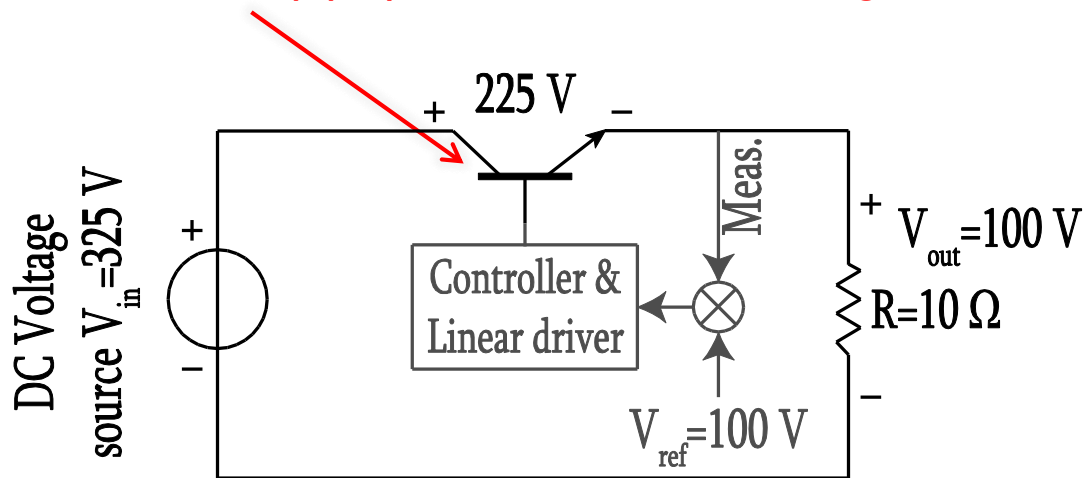


Basic principles in power electronics

- Old times: Linear voltage/current regulation for DC-DC conversion

A step-down voltage regulator example – 325V in – 100V out – 10A:

Transistor (T) operated in its active region



- Analysis:

$$P_{in} = 325\text{ V} \times 10\text{ A} = 3.25\text{ kW}$$

$$P_{out} = 100\text{ V} \times 10\text{ A} = 1\text{ kW}$$

$$P_T = P_{in} - P_{out} = 225\text{ V} \times 10\text{ A} = 2.25\text{ kW}$$

Efficiency:

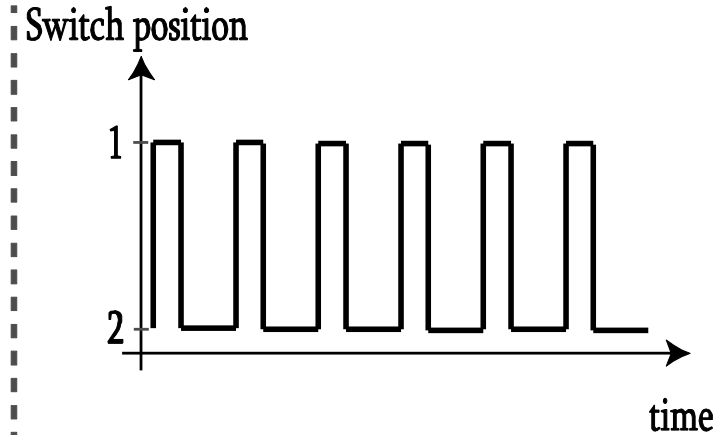
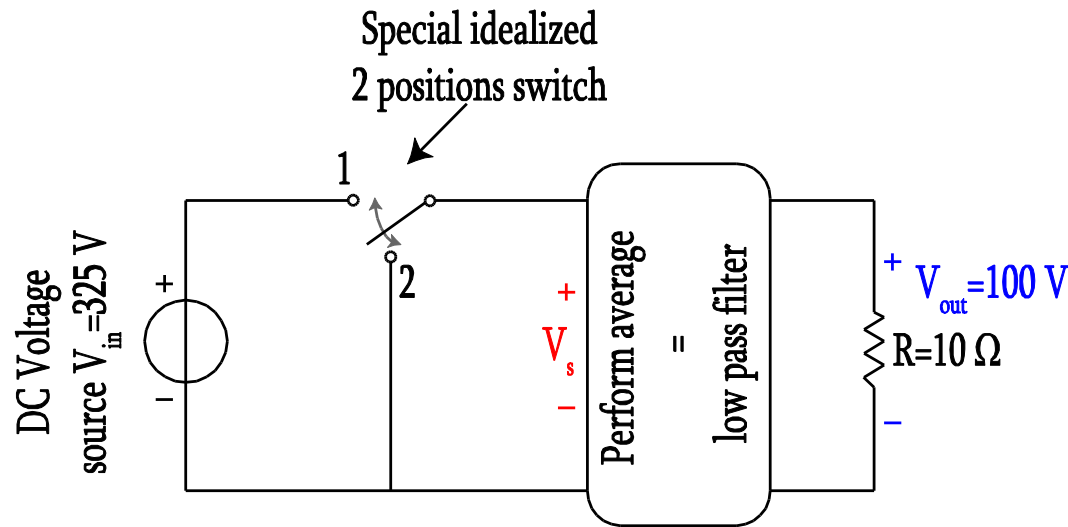
$$\eta = \frac{P_{out}}{P_{in}} = \frac{1}{3.25} = 0.3 \longrightarrow \mathbf{30\%!}$$

- Used until 1960s (still used in special applications: audio, high precision, HF, ...)
- Drawbacks: low efficiency – dissipate losses – step-down only – no DC insulation

Basic principles in power electronics

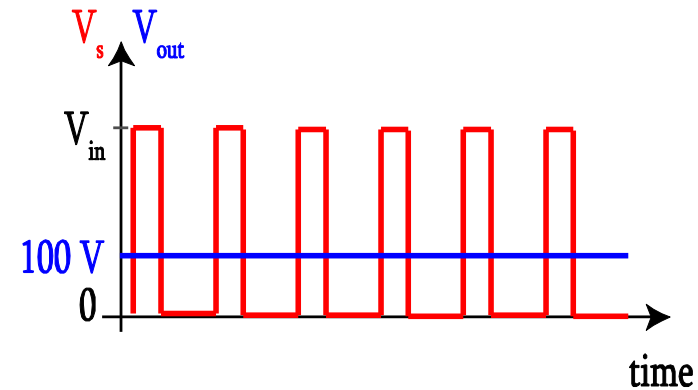
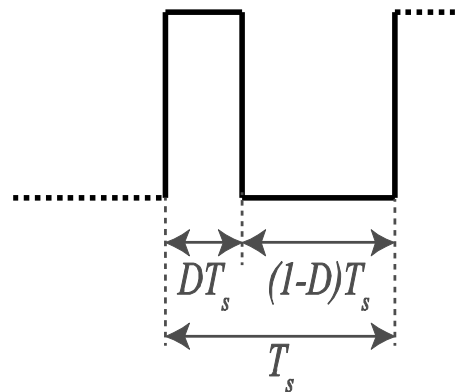
- Modern power converters: switching principle (On – Off states only)

No losses!



T_s : switching period
 $f_s = 1/T_s$: switching frequency
 D : duty cycle

$$V_{out} = \frac{1}{T_s} \int_0^{T_s} V_{in}(t) dt = DV_{in}$$



Basic principles in power electronics

- **The use of switches: states**

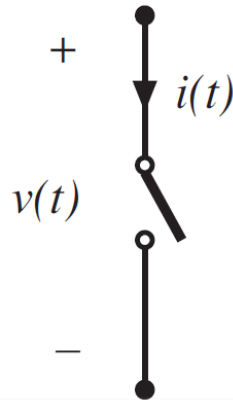
Two switch states:

Closed (On) : $v=0$

Open (Off): $i=0$

In each state $p=vi=0$

No losses in ideal switch!



Static
characteristic

Off state: open

Reality

On state: closed

Ok, some
losses...

- state change – transition (example of 2 segments switches)

Spontaneous commutation

Quadrant change

auto turn-on;
auto turn off

No switching losses

Controlled commutation

No quadrant change

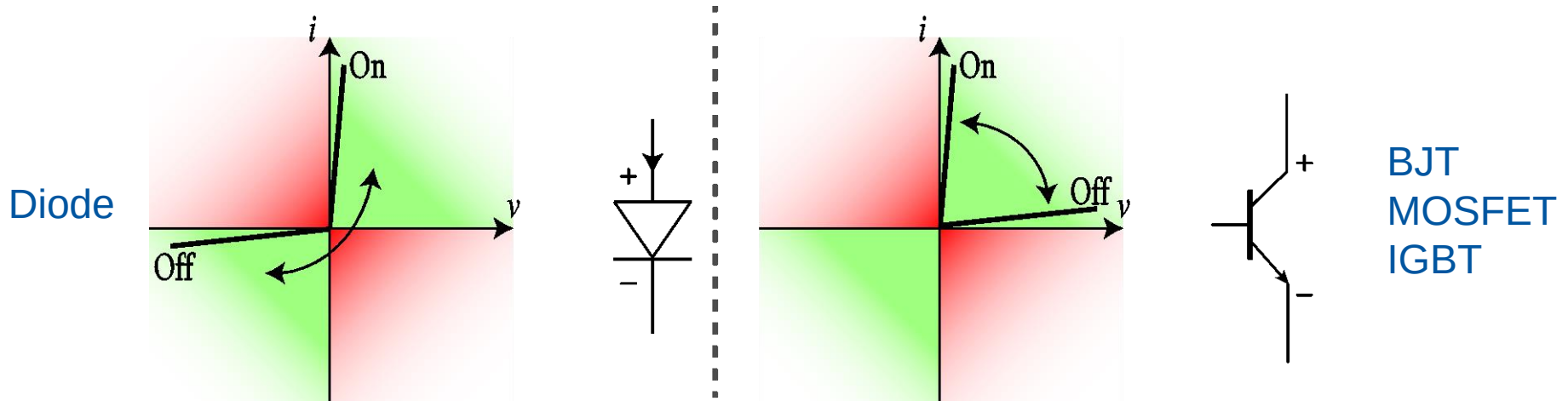
controlled turn-on;
controlled turn off

Switching losses

Control Gate!

Basic principles in power electronics

- Basic 2 segments switches (many other exist)



Example of a 1.7kV – 2.4kA switch (IGBT)

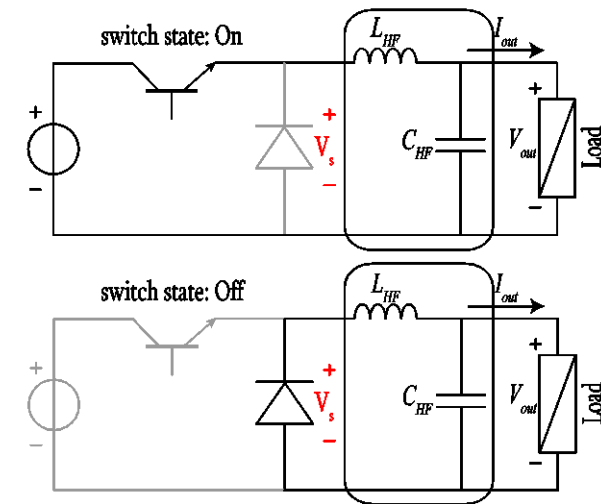
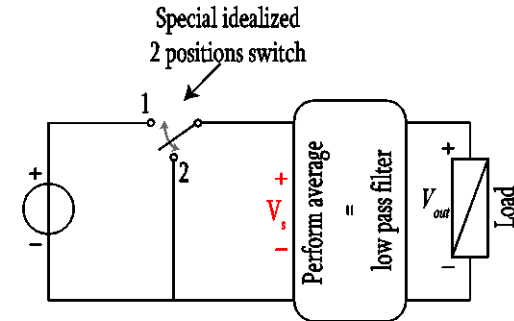
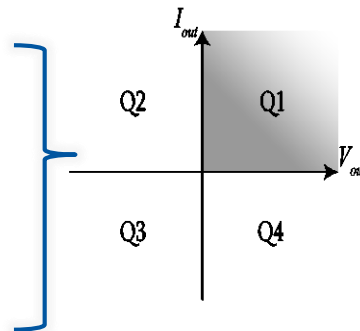
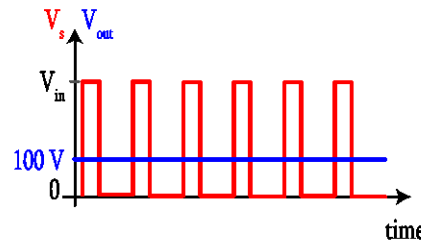
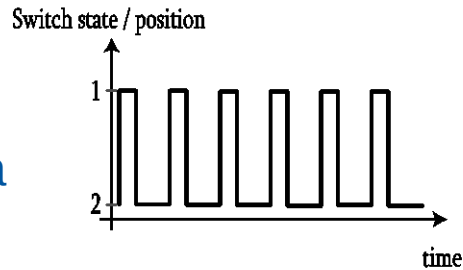
- At nominal current and voltage this IGBT can switch from ON to OFF states and vice-versa at a frequency of $\sim 10\text{kHz}$
- Losses occur during ON state (conduction) and transitions (switching) – Some losses need to be evacuated (heat-sink or water cooling plate)



Basic principles in power electronics

- From idealised principle converter to real circuit

- The 2 position switch is performed by a transistor and a diode
- This is called a buck, or DC/DC step down, converter
- Current in transistor and diode cannot be reversed
- V_s & V_{load} can be positive or 0V – never negative
- This is a one quadrant DC/DC converter, output voltage and current always positive!
- Power and energy can flow in one direction only



Basic principles in power electronics

- Many converter types

Extensively used in
particles
accelerators

Direct
conversion

Indirect
conversion

Conversion type

Family name

AC/DC

Rectifier

DC/DC

Chopper

DC/AC

Inverter

AC/AC

Cyclo-converter

AC/DC/AC

DC-link converter

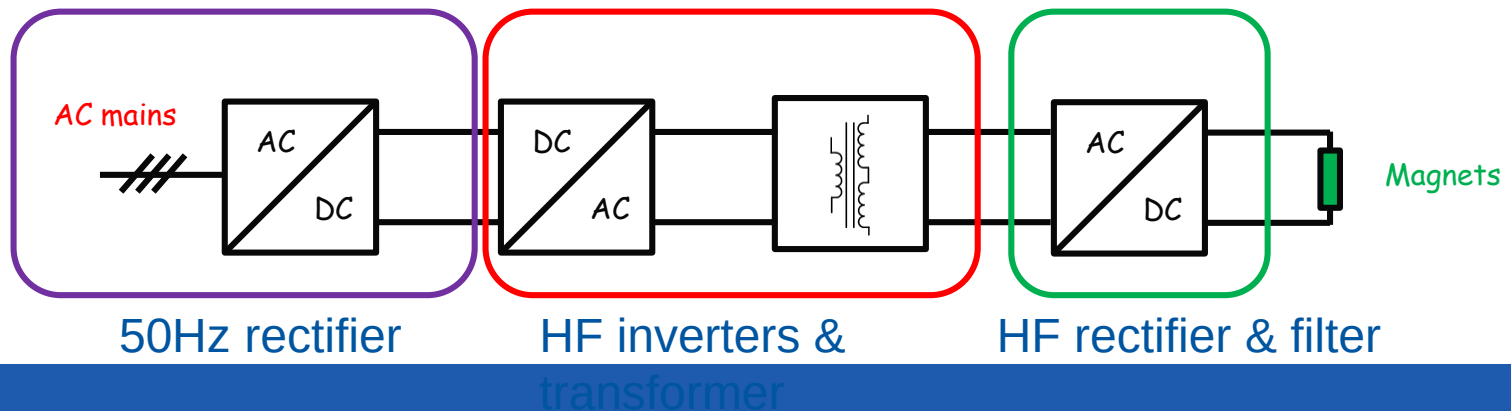
AC/DC/DC

DC-link converter

DC/AC/DC

AC-link converter

...and all kind of associations...



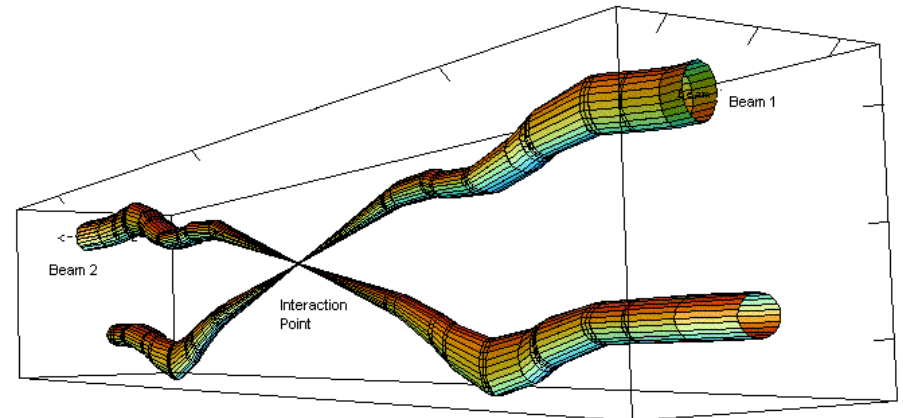
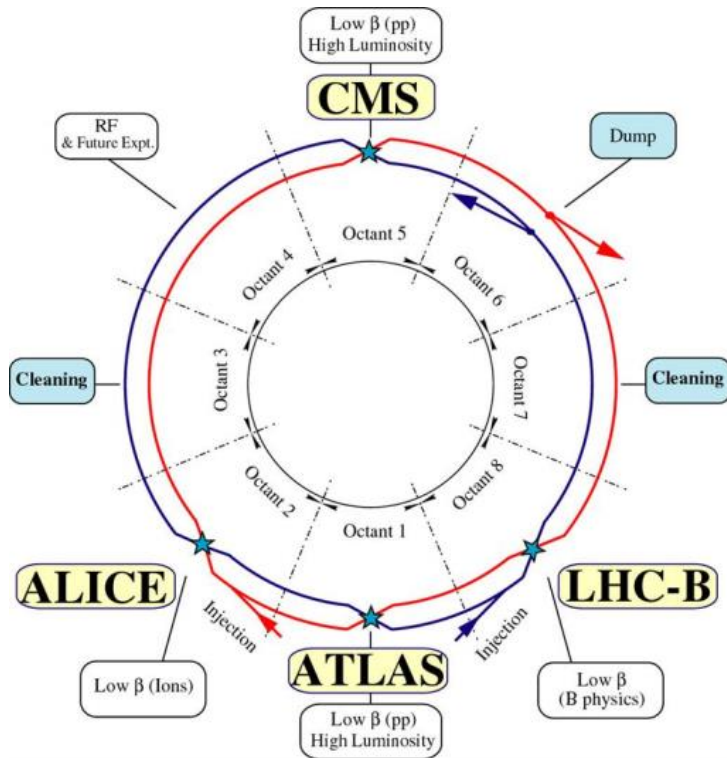
Power Converter Design Challenges at CERN

Power Converter Design Challenges at CERN

- Precision (LHC case)

Trajectory precision $\equiv$ magnet current precision

LHC collisions need beam perfectly aligned, their diameter being $\sim 50\mu\text{m}$ ($\sim$ hair diameter)



Relative beam sizes around IP1 (Atlas) in collision

- 600M collisions/second if beams aligned
- To perfectly aligned beams, currents in different LHC sectors must match to the part per million (ppm)

Power Converter Design Challenges at CERN

- Precision (LHC case)

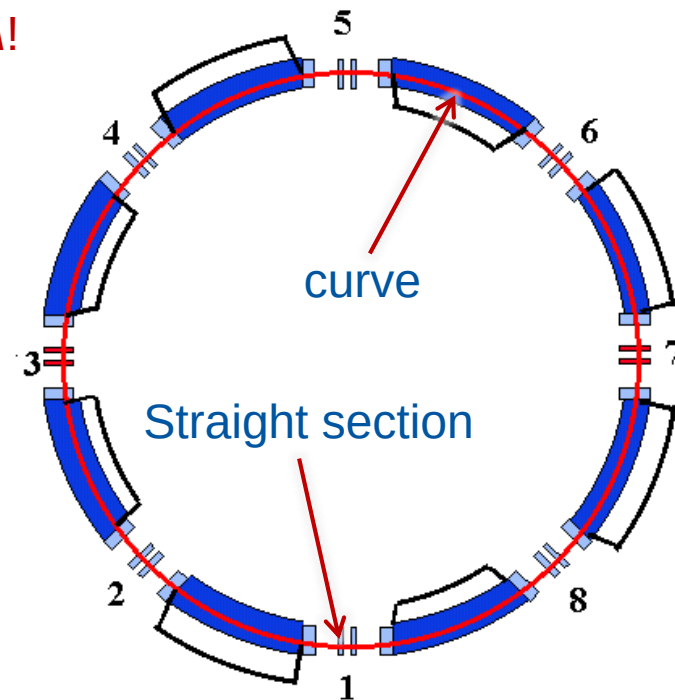
LHC main circuits divided in 8 powering sub sectors due to high energy stored in the magnets and to powering distribution constraints.

For the beam to follow its trajectory without being disturbed when going from one sector to the other the current in all sectors must be the same to better than a part per million – **13mA on 13kA!**

As a consequence the current in the different sector power supplies must track to the ppm.

Approach:

1. The same current reference is sent to all sectors (over 27km) with a time «jitter» of $>1\mu s$ (dedicated PLL over WorldFIP).
2. High precision measurement (DCCT)
3. High performance digital regulation loop (RST with practically no tracking error)



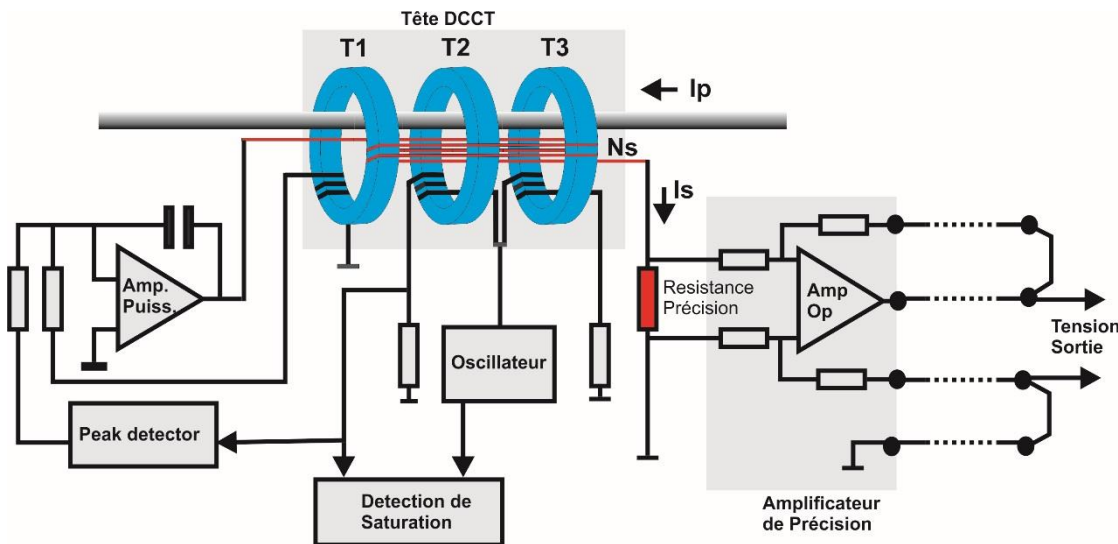
Power Converter Design Challenges at CERN

- Precision (LHC case)

To obtain ppm precision in the magnet current the current measurement must be even more precise. High Precision DCCTs (*DC Current Transducer*) were developed by industry in collaboration with CERN.

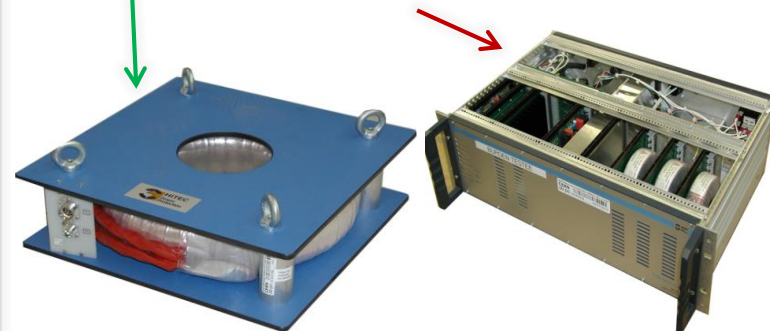
DCCT principle (zero flux)

- AC feedback loop – closed loop CT
- DC feedback loop – zero flux detector



LHC DCCT 13kA magnetic head equipped with extra winding for calibration

DCCT electronics providing a voltage signal, which is then digitized by an ADC



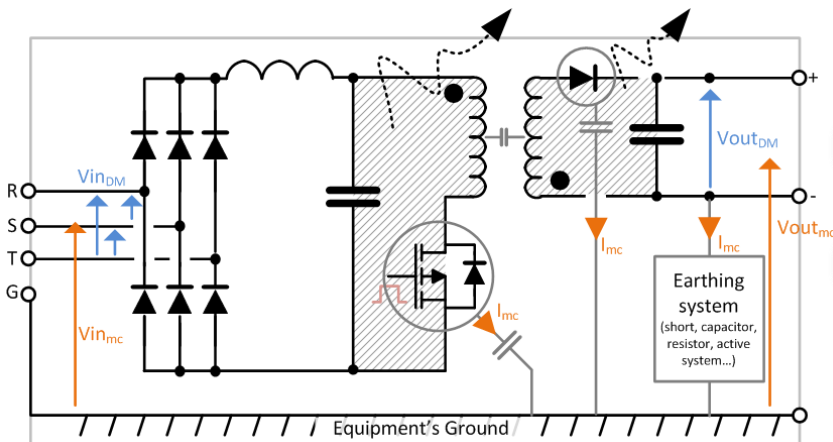
Power Converter Design Challenges at CERN

- Precision (LHC case)

Electromagnetic compatibility is essential in high precision power converters

Weak EMC $\equiv$ precision is compromised!

Eg. ppm regulation with % measurement noise is impossible!



1700 switching converters:

➔ 1700 noise sources

km of analogue cables:

➔ many coupling channels for noise

Ex.: 1m cable pile



- Immunity is essential!
- A single EMI event in a converter can cause the loss of the beam

Power Converter Design Challenges at CERN

- Efficiency and volume (LHC case)

In average the LHC is at 100m underground
So to decrease cost (copper losses in warm cables) the converters are underground

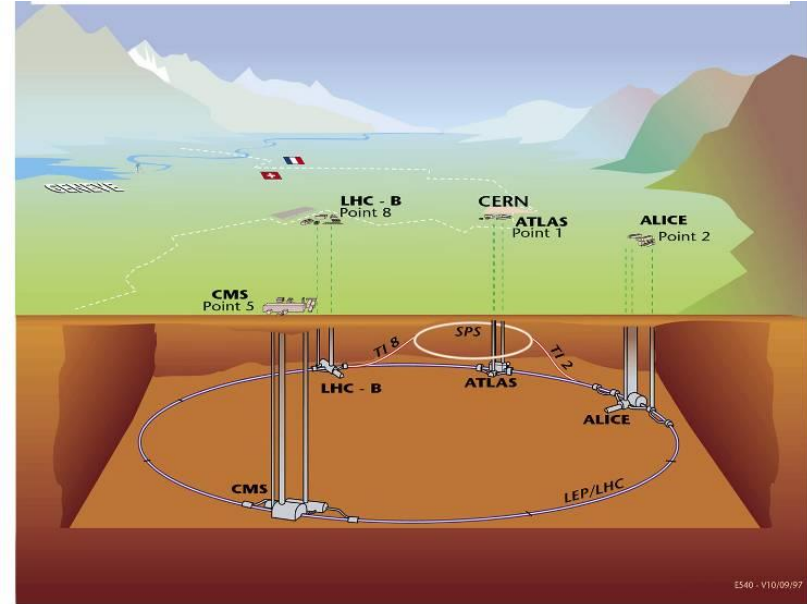


High efficiency required!
Losses evacuated through water cooling

- Radiation

Certain corrector magnet converters are placed very close to the accelerator. Losses in the beam can irradiate the electronics (digital and power) with negative consequences!

Today studies are still being carried out at CERN to improve power converter tolerance to radiation



ES40 - V10/09/97

Power Converter Design Challenges at CERN

- Operation constraints (LHC case)
reliability, Modularity, redundancy $\equiv$ LHC availability!

Converters underground mean big access time for repair. To minimize it:

1. Reliable and modular design
2. Redundancy: module lost – operation continues
3. Module weight minimized
4. Remote diagnostic essential

LHC Module



Design examples

Design examples

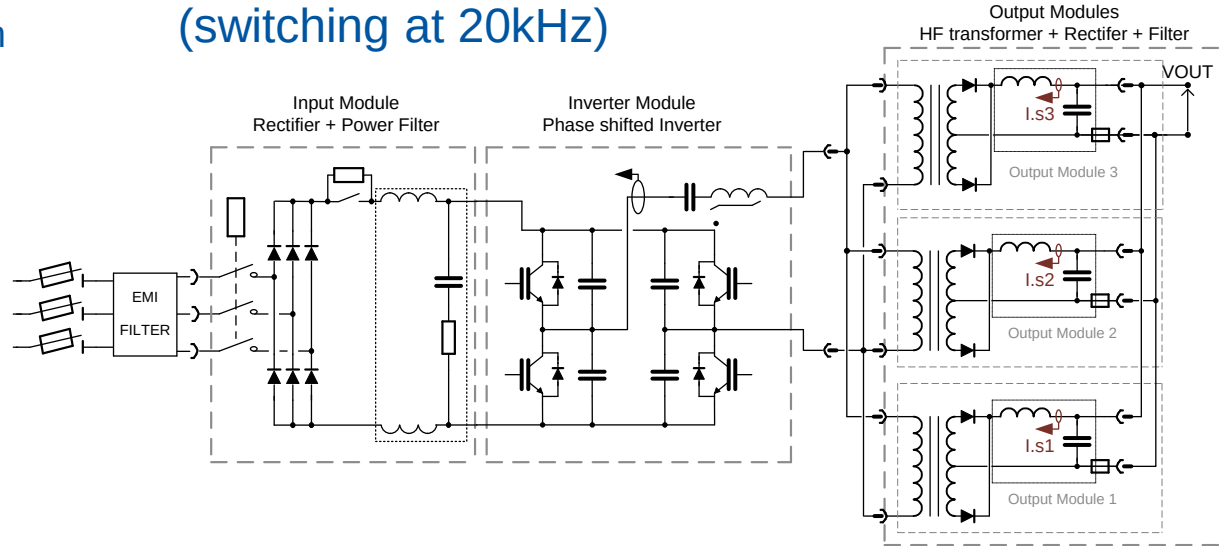
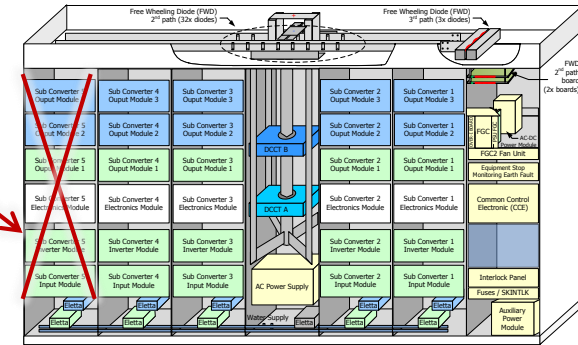
- LHC quadrupole power supplies

Specifications:

I_{out}	13kA
V_{out}	18V
24h current uncertainty	5ppm
30min current uncertainty	3ppm
Resolution	<1ppm

- Redundancy n+1 modules
- Phase shift in ZVS&ZCS

Module 3.25kA, 18V
(switching at 20kHz)

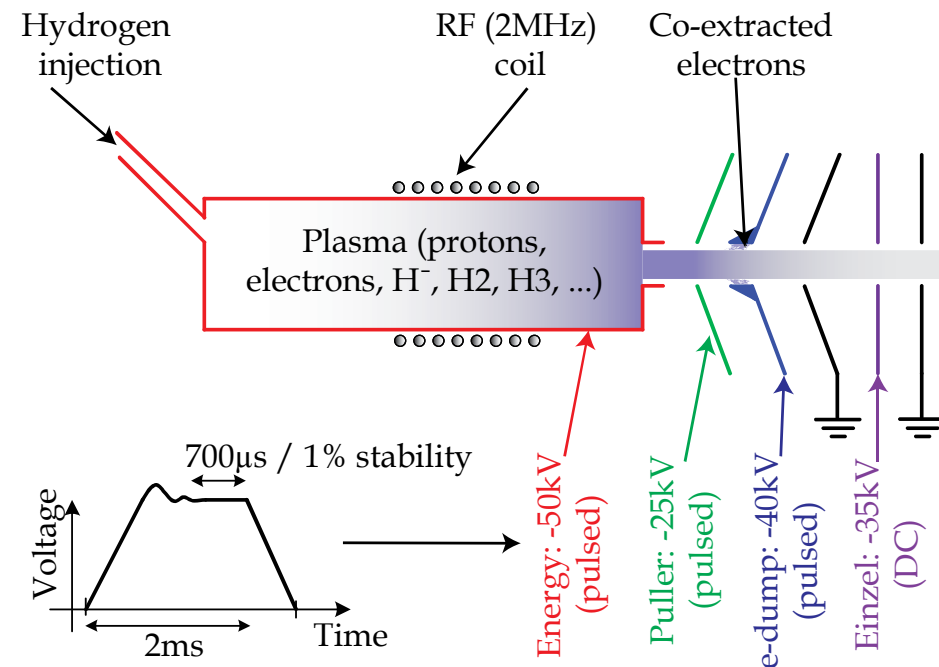


Design examples

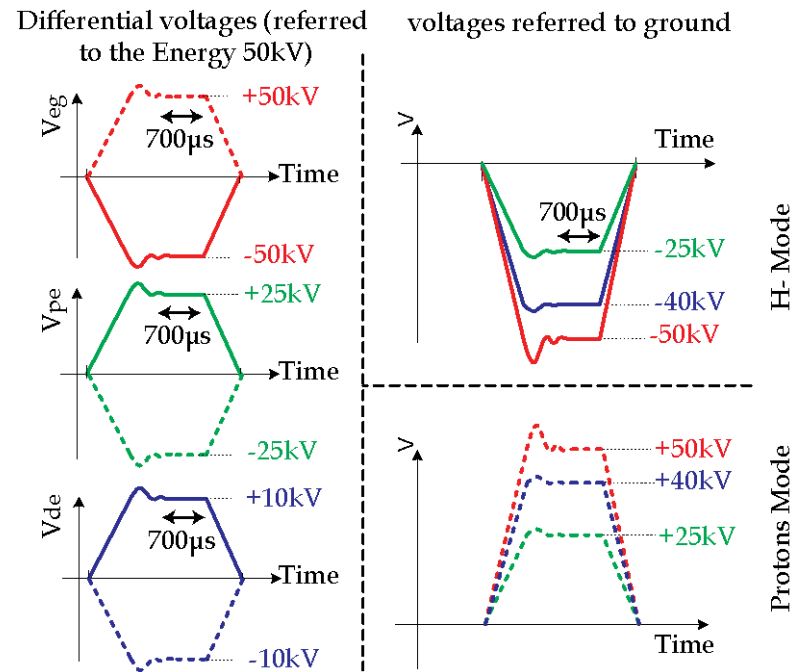
- H⁻ ions source power supply

- A new linear accelerator in under construction (Linac4) to provide protons for the CERN complex
- Linac4 accelerates hydrogen ions from which electrons are then removed to produce protons.

Principle of H⁻ source



Voltage power supplies specification

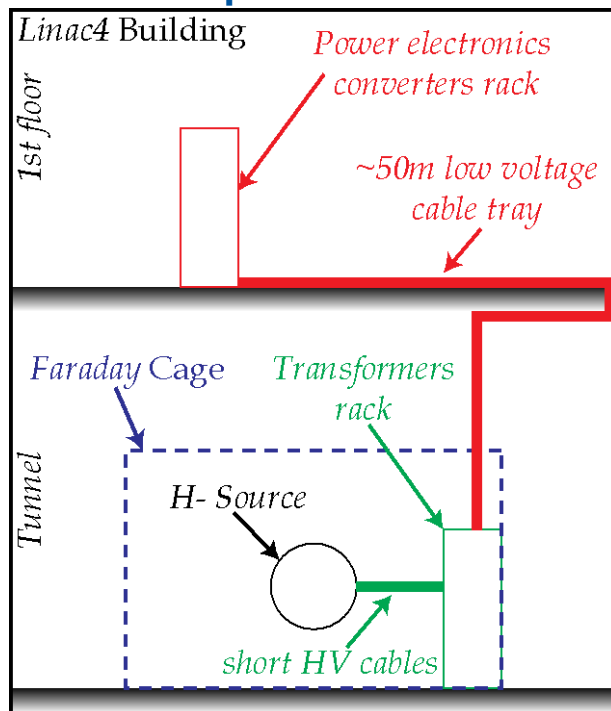


Design examples

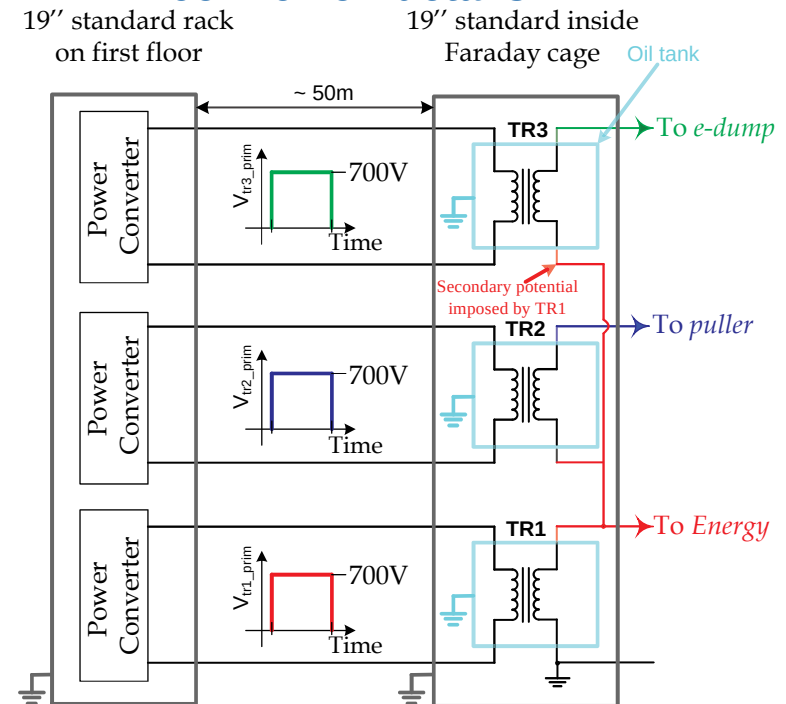
- H⁻ ions source power supply

Integration in the building and cable lengths define the general topology of the power supply! In pulsed mode HV cable length needs to be minimized (stray caps)

Solution for short HV cables and rapid intervention:



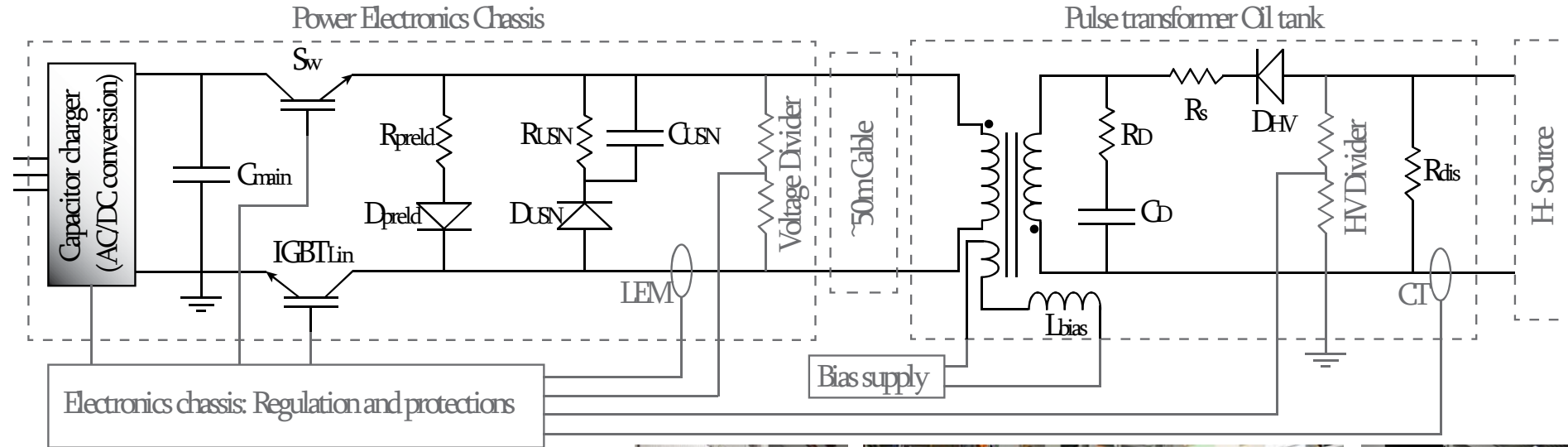
HV transformers inter-connexion details



Design examples

- H⁻ ions source power supply

Topology choice: simple (reliability), no ripple (IGBT in linear mode)

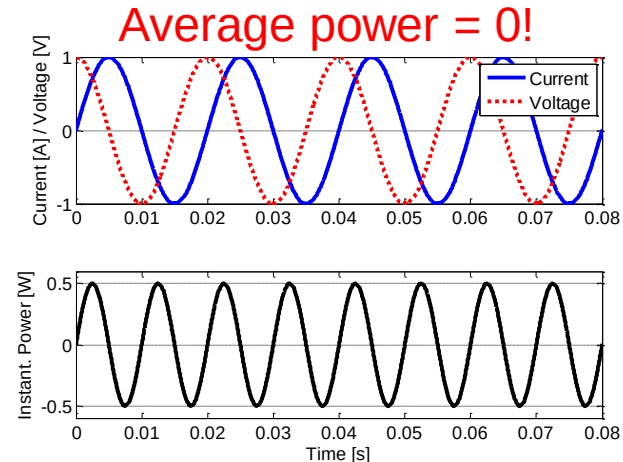
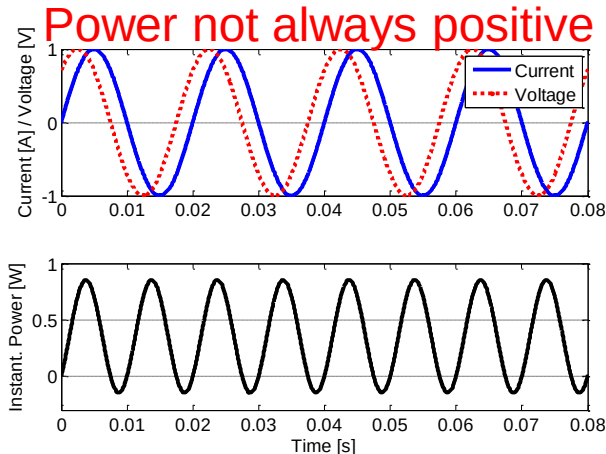
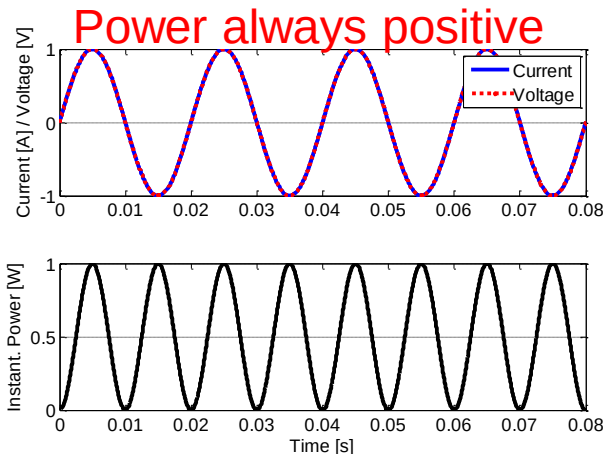


Quick access to the elements of the transformer for interventions in the tunnel – «custom».



Design examples

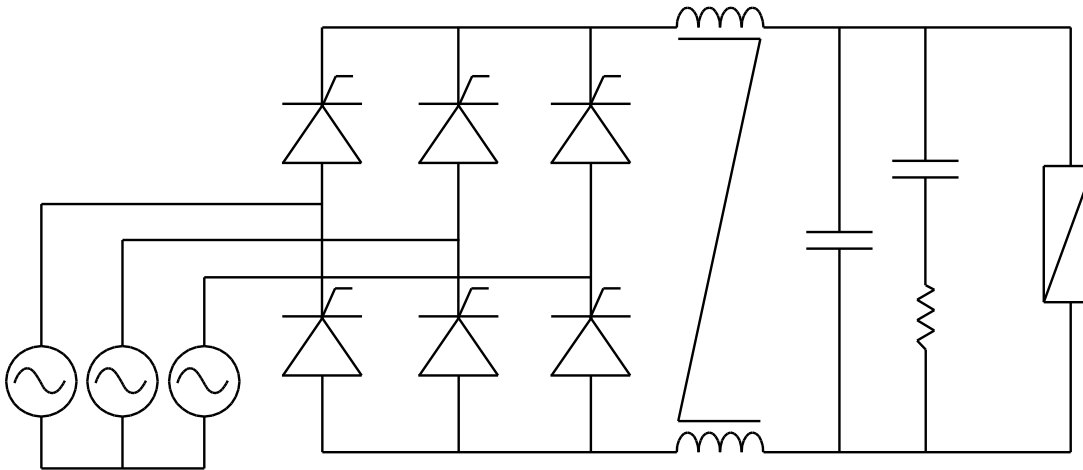
- Smooth connection to the grid –reactive power compensation
 - Instantaneous power defined by $v(t) \cdot i(t)$
 - In DC instantaneous and long terms energy flow are the same
 - In AC instantaneous energy flow direction depends on current to voltage phase displacement. Sometimes transmitted energy is 0!



- Active power relates to the average transmitted power/energy – the one we pay!
- Reactive power relates to the short-term power/energy “going back and forth” for nothing! – we do not pay reactive power, but shall be minimized/cancelled since it creates losses (non zero current) and voltage stability issues
- Some AC electrical elements create reactive power, such as some types of power converters

Power converter topologies – AC/DC conversion

- Line commutated AC/DC converters: controlled rectifiers (three-phase)



Can control the bridge output voltage by changing the firing angle α :

$$V_{out} = \frac{3}{\pi} \hat{V}_{in,L-L} \cos(\alpha)$$

Bi-directional output voltage, 2 quadrants converter.

Current is shifted by α (fundamental)

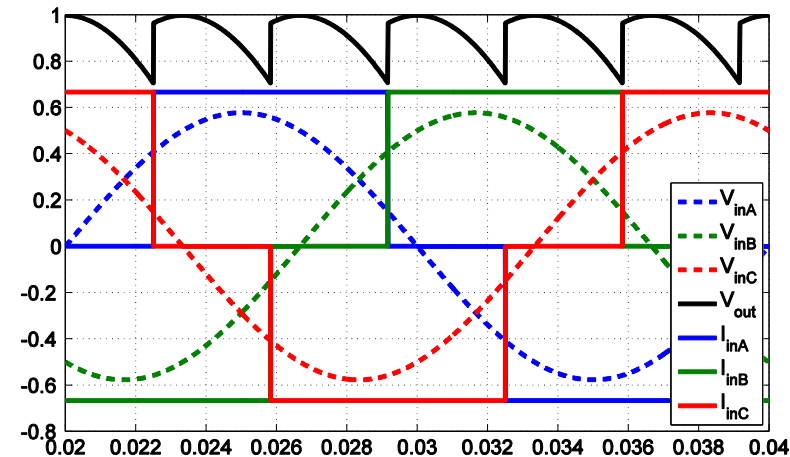
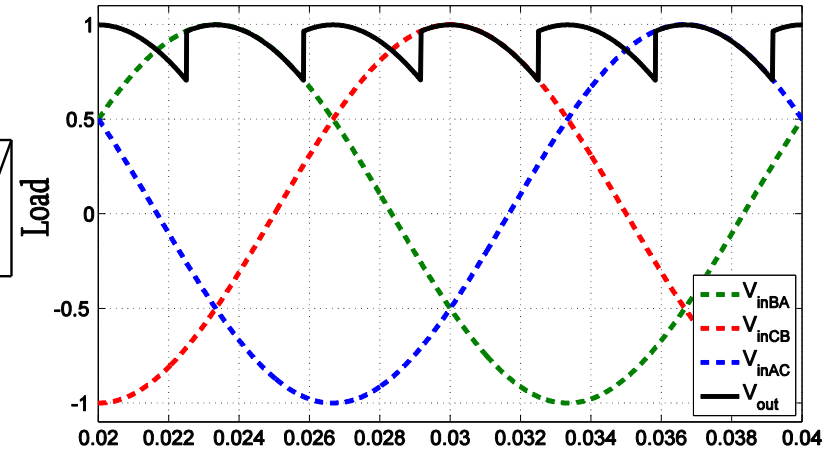
AC side active and reactive power (neglecting harmonics):

$$P = 3 * V_{phase} * I_{line} * \cos(\alpha)$$

$$Q = 3 * V_{phase} * I_{line} * \sin(\alpha)$$



Huge reactive power
at low DC voltages...



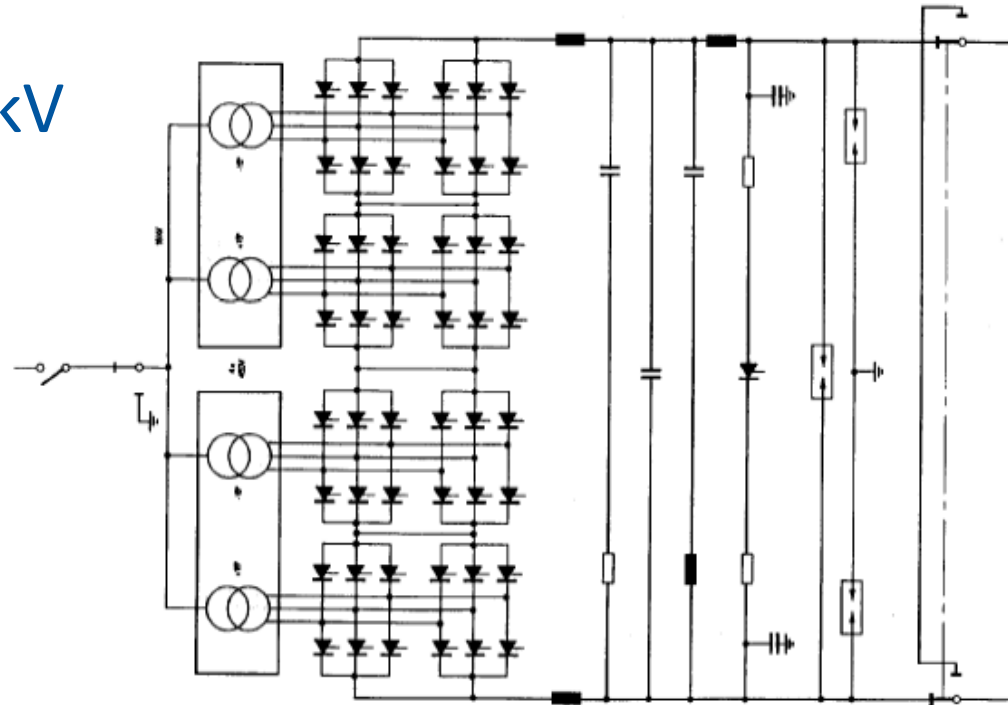
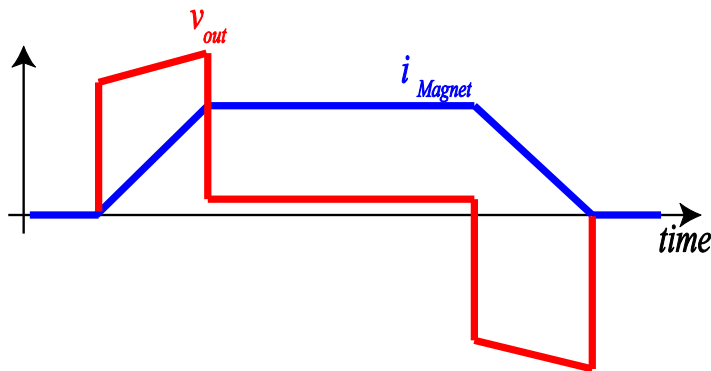
Design examples

Some converters produce enormous reactive power – shall be compensated!

- e.g. main SPS Magnet powering

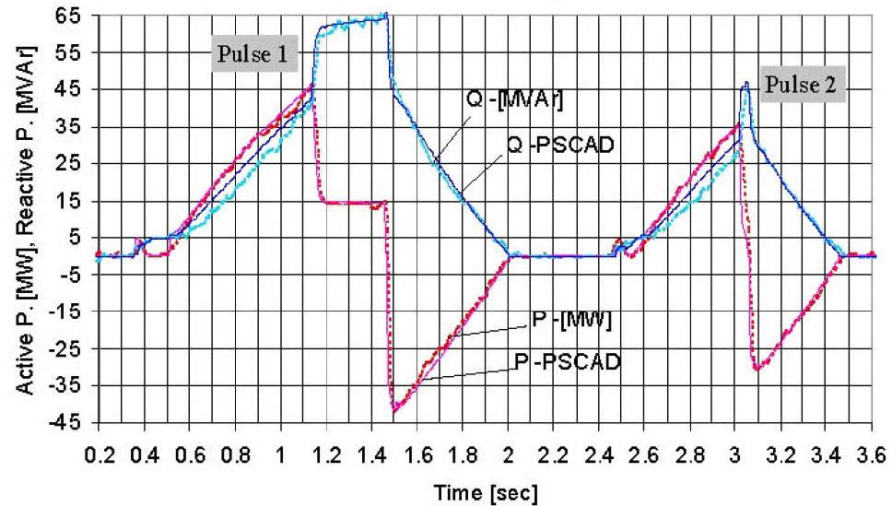
Thyristors topology

12 converters of 6kA, ± 2 kV



Design examples

- This is what we measure...

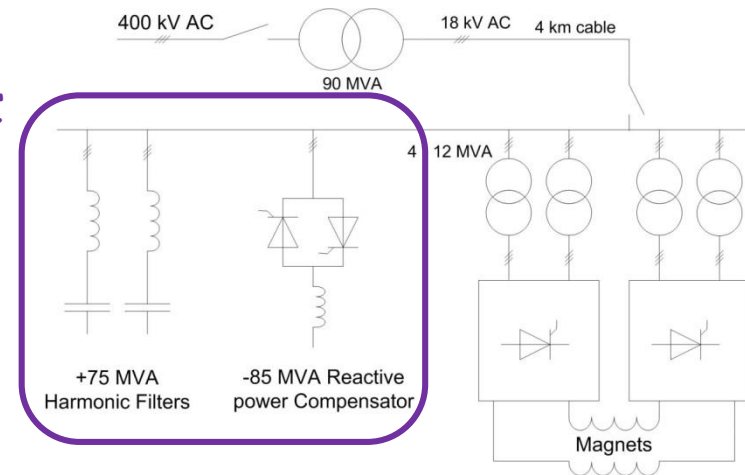


This topology manages more *reactive* (MVar) than *active* (MW) power!

A Static Var Compensator (SVC) has been necessary to connect to the grid



SVC



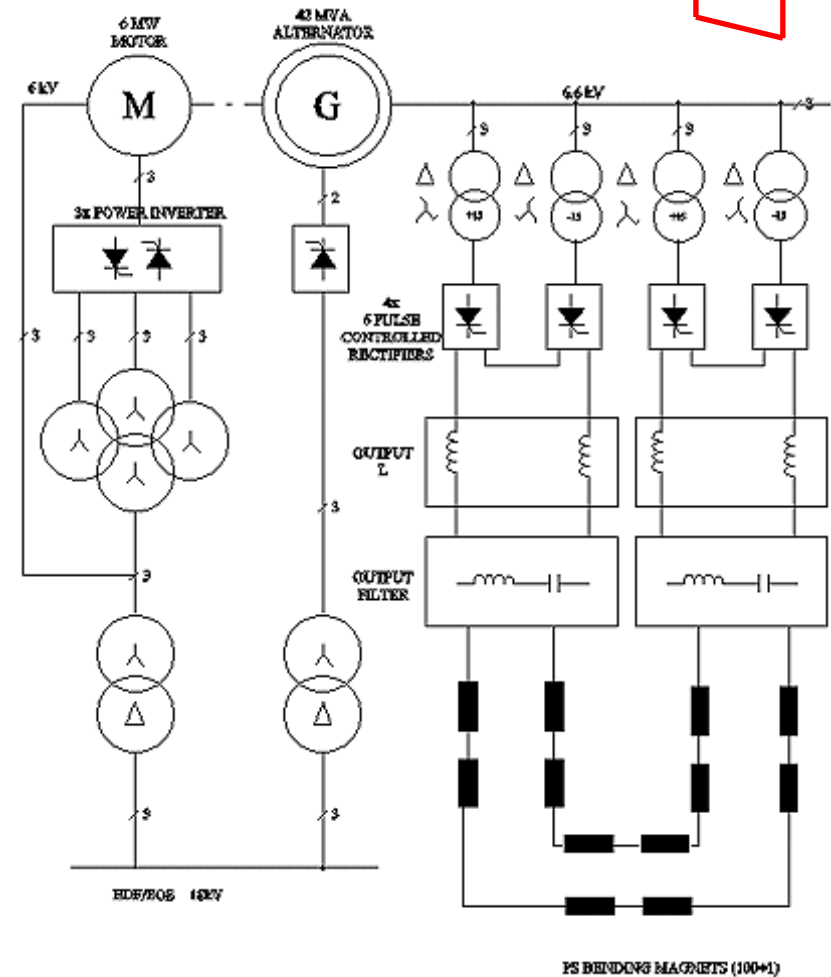
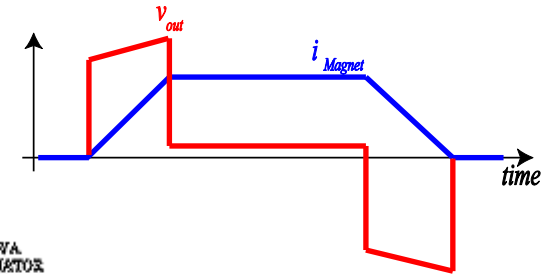
The SVC stabilises the 18kV at $\pm 1\%$

Design examples

- PS main magnets power supply (before)



- Inertia of synchronous generator stocks energy ($230MJ$ at $1000rpm$) for magnets ($12MJ$).
- Motor ($6MW$) ensure the production of the losses for all the system.

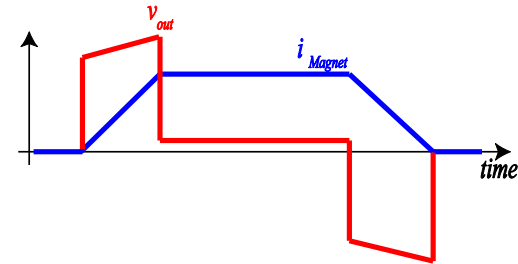


Design examples

- PS main magnets power supply (after)

One can store the magnet energy in capacitors instead!

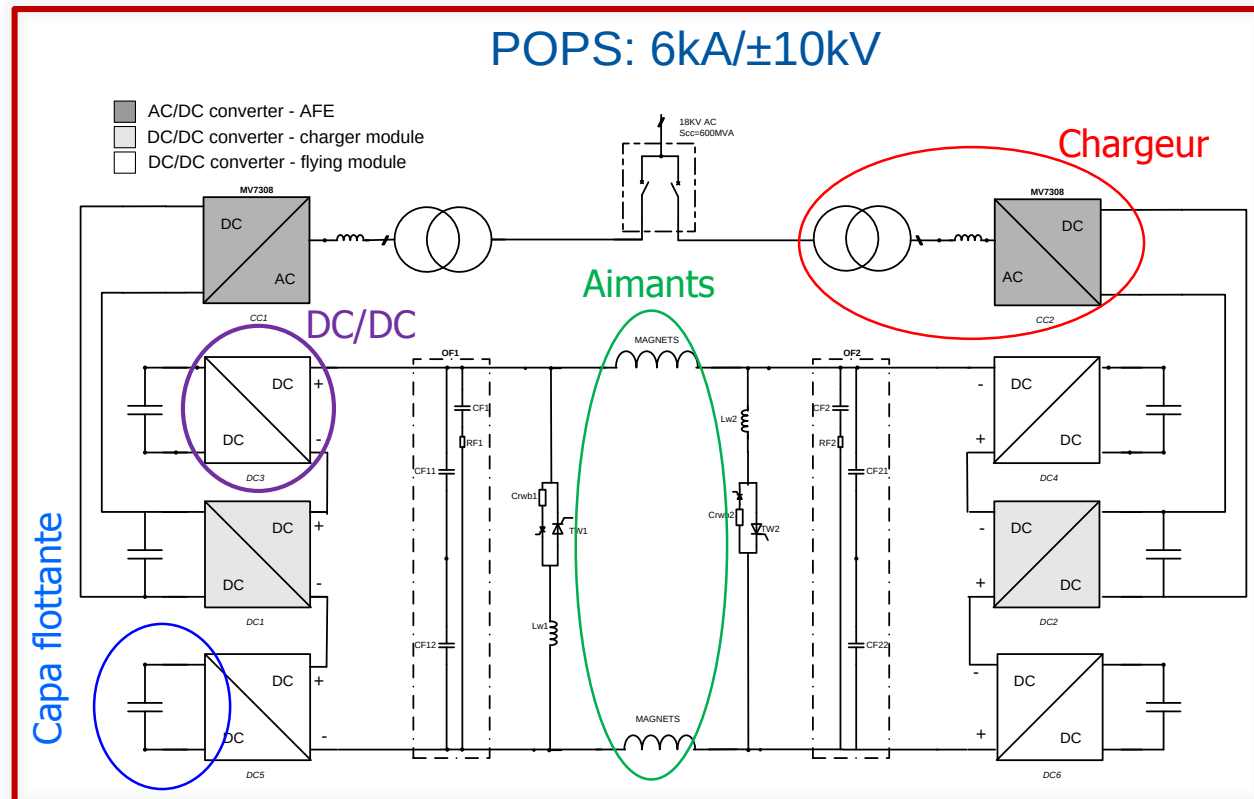
Energy for magnets supplied by banks of capacitors during $di/dt > 0$, and returned during $di/dt < 0$. The network doesn't see power fluctuation!



- Generator inertia replaced by banks of capacitors
- Motor replaced by AC/DC converters that supply the system losses only

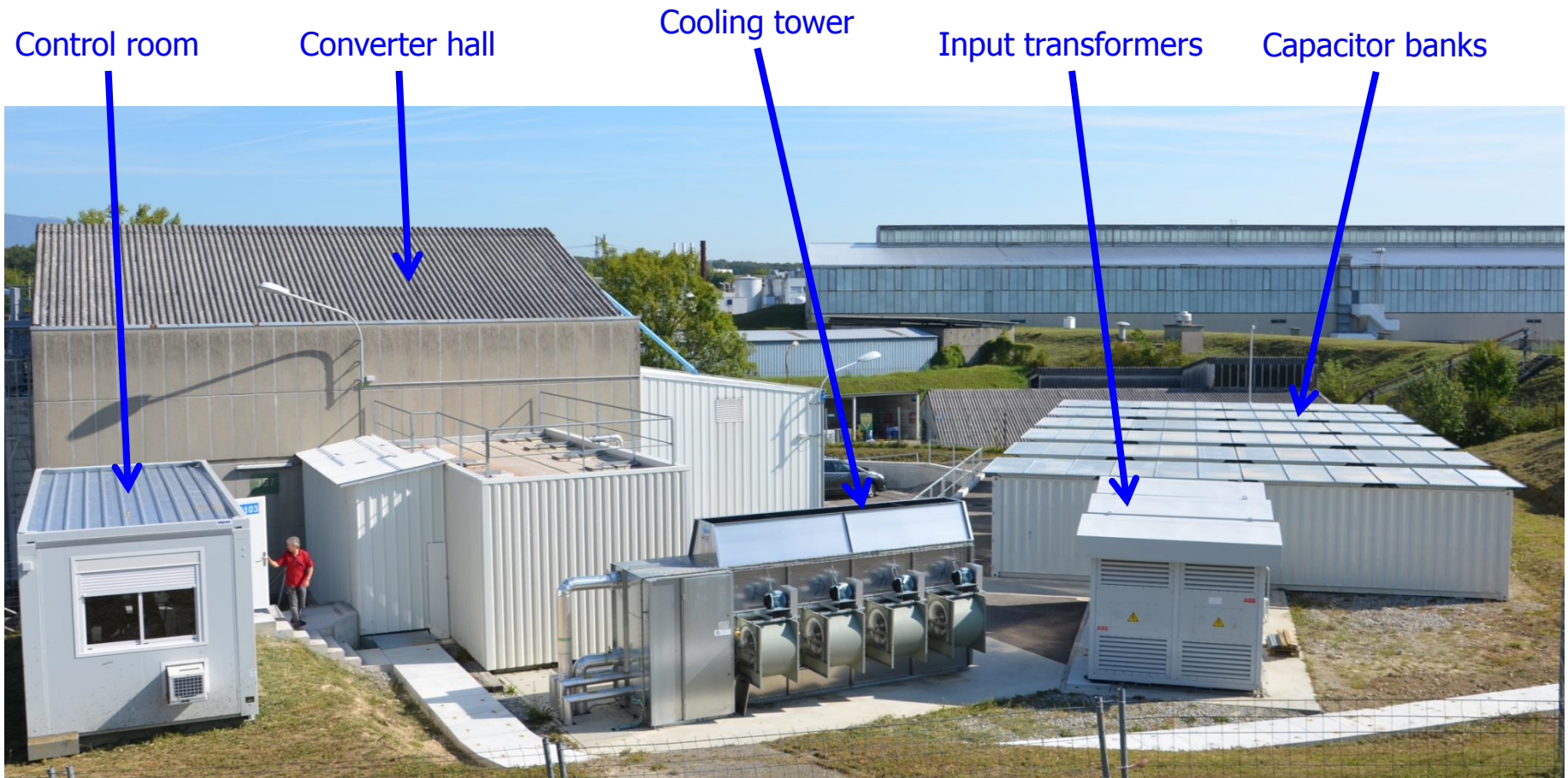
Patent

European Patent Office, Appl. Nr:
06012385.8 (CERN & EPFL)



Design examples

- PS main magnets power supply (view of system)



Typical power converter design procedure

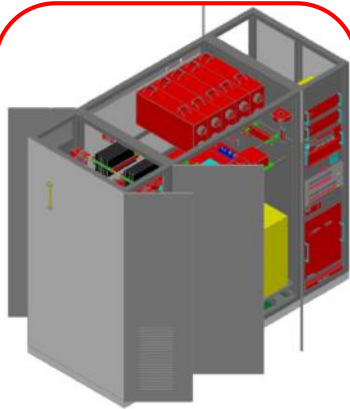
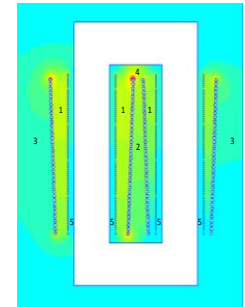
Efficiency, cost, volume, EMI,..., **specs**

Utility grid specs
(Voltage, power quality,...)

Specs analysis for topology selection
(1,2,4 quadrants, active/passive converter – closed/open loop regulation, switches technology, ...)

Numerical verification of selected topology
(dedicated numerical simulations for general converter functionality)

Components design and/or specifications
(analytical or numerical approaches)



3D Mechanical integration & construction



Laboratory tests



On site commissioning

Load specs

(L, R, C values, precision, ...)

Load examples:

- Magnet (high current)
- Klystron (High Voltage)
- Particles source (HV)
- RF equipment (HV)

Staff Members

~70 Staff
 + ~20 Fell
 + ~15 COAS/PhDs

J.P. BURNET

Group Leader

V. MONTABONNET

Deputy

Secretariat : S. GARDETTE

D. NISBET

Fast Pulsed
Converters
FPC

D. AGUGLIA

J.M. CRAVERO
 N. DAVID
 S. JOFFE
 Ch. MACHADO
 J. PARRA-LOPEZ
 S. PUTZ

High Power
Converters
HPC

K. KAHLE

J.M. BERNAL
 A. BESSONNAT
 F. BOATTINI
 D. DENUZIERE
 Y. GAILLARD
 X. GENILLON
 C. GENTON
 A. HARLE
 O. MICHELS
 G. SKAWINSKI

High Precision
Measurements
HPM

M. CERQUEIRA BASTOS

O. FOURNIER
 G. HUDSON
 M. MARTINO
 G. RAMSEIER

Converter Controls
Software
CCS

Q. KING

M. DUDEK
 M. MAGRANS DE ABRIL
 R. MURILLO GARCIA

Operation &
Maintenance Support
OMS

V. MONTABONNET

P. BAILLY
 M. BOMONT
 C. COUPAT
 A.L. DILLENSCHNEIDER
 D. DUREY
 L. GERMAIN-BONNE
 H. KADIR
 D. MATHIEU
 C. MUGNIER
 C. RUIZ LLAMAS
 J. SPILLER
 M. TIGNOLET

POWER

Power is nothing
 without precise control

Medium Power
Converters
MPC

G. LE GODEC

J.A. BAILLIE
 J. BLANC
 E. COULOT
 L. DE OLIVEIRA
 B. DUBOIS
 I. JOSIFOVIC
 C. MUTIN
 K. PAPASTERGIOU
 S. REIGNIER
 H. THIESEN

Low Power
Converters
LPC

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CONTROL

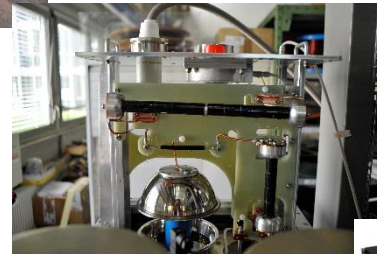
To keep properly running
 we need support

JANUARY 2015

Conclusion

- Power electronics challenges result from unique environment at CERN
- Most converters cannot be found “off the shelf ” in industry
- The load is often made or specified by CERN (magnet, klystron, RF tubes, etc.). Working with the designers is essential to find optimal solutions!
- Specifications sometimes require new approach, new technologies
- We operate our own converters... design challenges? Practical, reliable, easily replaceable, re-usable $\equiv$ Maintainable!

Thank you for your attention!





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Power Converter Design Challenges at CERN

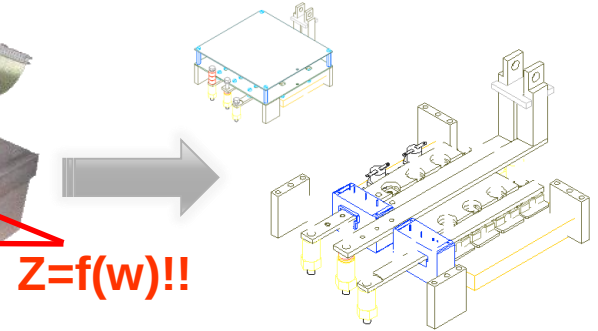
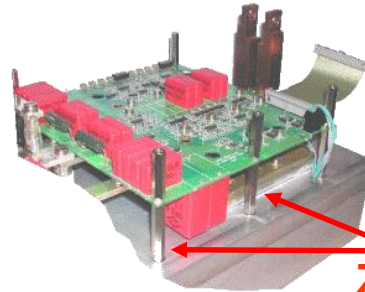
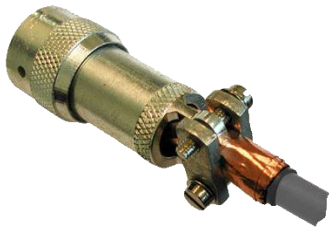
- Precision (LHC case)

EMC: find good solutions!

- **Reduce noise sources:**

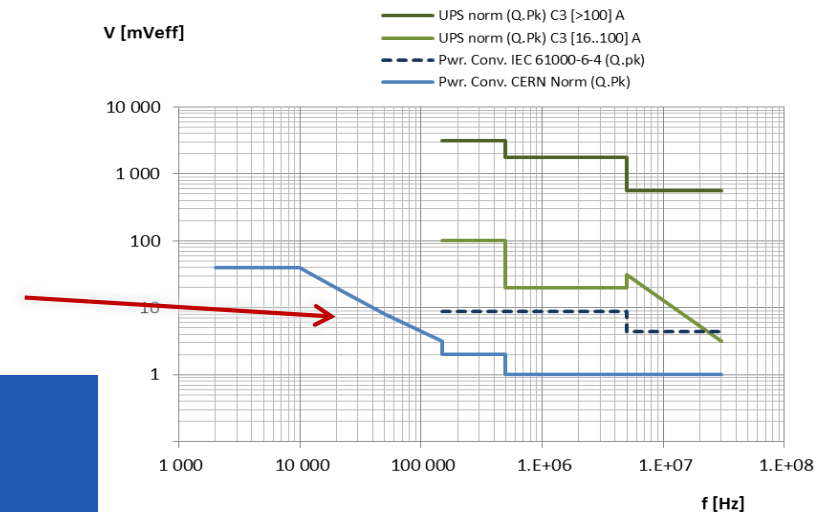
Power converter topologies with low EM emission → **ZVS and ZCS**

- **Ensure an excellent reference ground – A SINGLE GOOD GROUND**



$Z=f(w)!!$

- EMC from design stage
- EMC testing respecting international standards and more restrictive CERN standards!

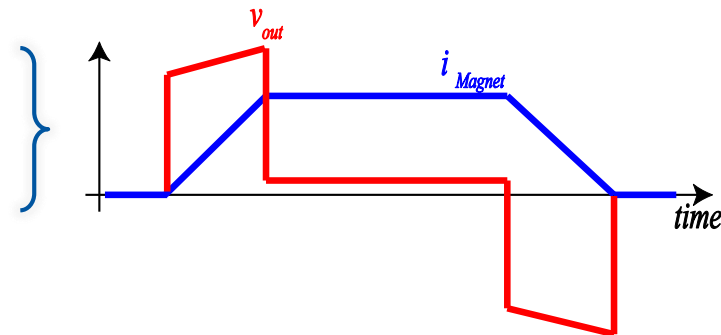


Power Converter Design Challenges at CERN

Pulsed converters

A lot of pulsed magnets are used to inject or eject the beam from one accelerator to the other and therefore pulsed converters are required. Pulsed magnets are also used for loss reduction.

Typical current/voltage waveform in many CERN magnets – 2 to 4 quadrant topologies not easily available in industry

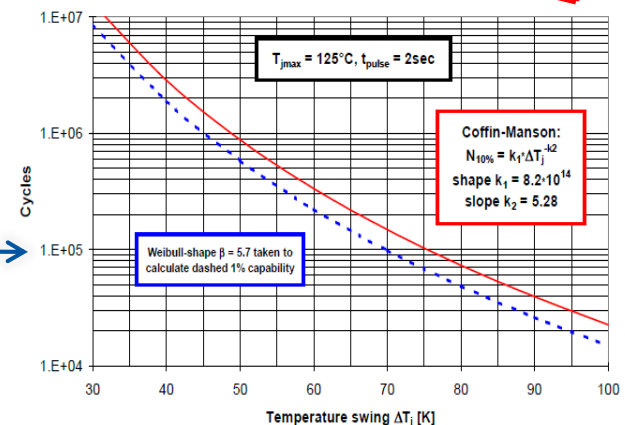


challenges:

1. High currents (~100A to 10kA) – pulsed adaptation transformers – global optimization
2. High bandwidth (big signal)
3. Small current ripple (seen by beam)
4. Thermal cycling must be considered



Interleaved topologies (series and parallel)

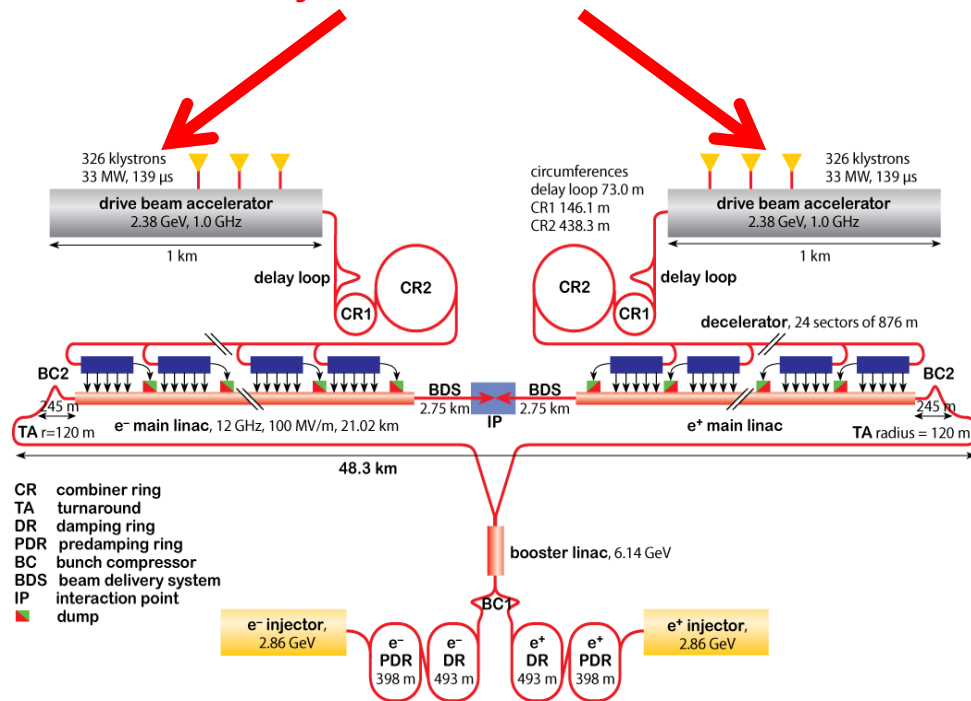


Design examples

- CLIC klystron modulators

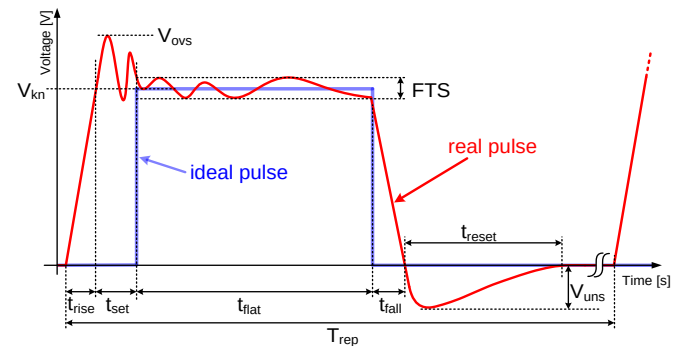
CLIC – *Compact Linear Collider* – linear accelerator under study at CERN

~1300 klystron modulators



Spécifications

Pulsed voltage	V_{kn}	180	kV
Pulsed current	I_{kn}	160	A
Peak power	P_{out}	29	MW
Rise/fall time	t_{rise}	3	μ s
Flat top length	t_{flat}	140	μ s
Repetition rate	Rep_r	50	Hz
Flat top stability	FTS	0.85	%
Pulse repeatability	PPR	10-50	ppm



Design examples

- CLIC klystron modulators

Simultaneous operation of all modulators

➔ 29 MW x 1300 klystrons = **38GW!**

Absorbed AC power must be constant to stabilise the distribution voltage!

General topology of modulator:

- Capacitive storage and discharge
- Voltage drop compensator
- Fast HV pulsed transformer

Even with the energy storage, a power fluctuation on the AC side. Active compensation of these fluctuations is under study.

