Greek Teachers Programme 2014

Energy & Power Conversion

Konstantinos Papastergiou | Technology Department
CERN – European Organisation for Nuclear Research

Summary

- **Energy consumption at CERN**
  - How is energy spent?
  - Electricity, Water and Gas
- **From Electrical to Kinetic Energy**
  - How is electricity converted to acceleration?
- **Key electrical consumers?**
  - Components with power requirements
- **Electronics and Power Electronics**
  - What is the difference
- **Power Conversion Principle**
  - Why and how is energy converted
- **Accelerator Power Electronics**
  - Real world systems – how do they look
- **Research Challenges**
  - The future in powering accelerators

CERN και ενέργεια

Electricity at CERN

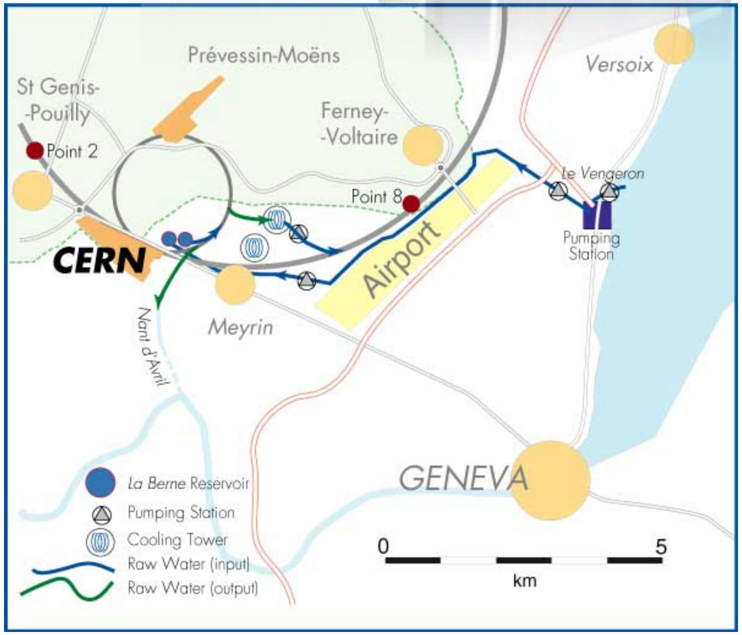
- Interconnections to both France and Switzerland
- Approximately 80% of electricity from France
  - (nuclear mostly)
- Special contract terms with EDF and SIG
- 1000 high voltage circuit breakers in operation
- Consumption
  - as high as all households in Geneva area
  - 1/10th of the canton (11.3TWh).

Energy Facts & Figures

- **Total consumption 1 000 000 000 kWh/yr**
  - 43% consumed by the LHC
    - Up to 14% by superconductive magnet cooling
    - Up to 9% equipment cooling and tunnel ventilation
  - 11% by its Experiments
  - 30% by SPS
    - 7% at its experiments
  - 3% PS-booster-Linac
  - 6% Data Centers
  - 7% in offices, restaurants etc.

Water

- 6 million m3 of water
- Closed circuit of demineralised water and secondary circuit of raw water cooled in cooling towers.
- Industrial process water
  - Surface treatment
  - Production of demineralised water

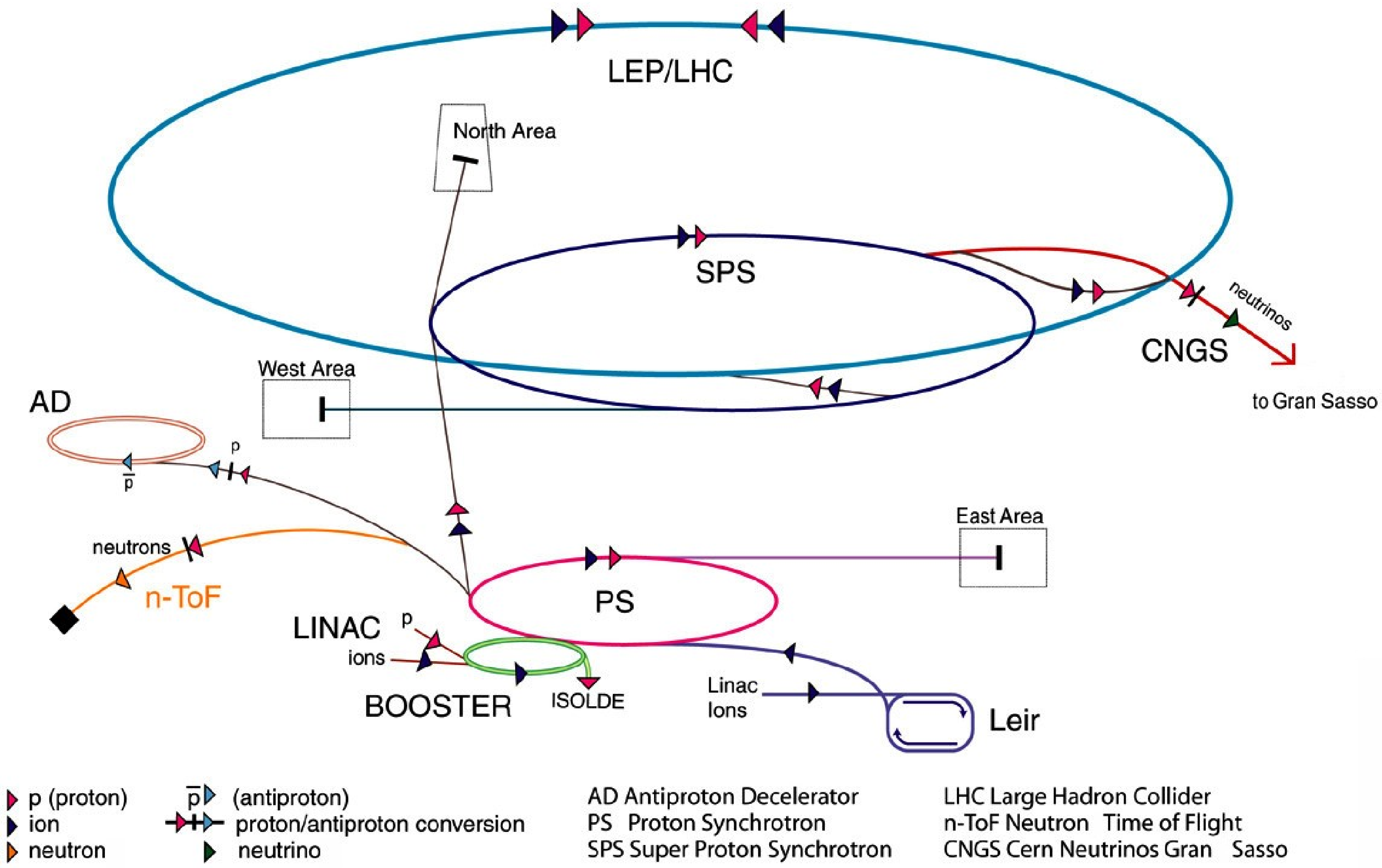


Natural Gas

- Heating stations at Meyrin 8 million m^3
- Heating station at Prevessin – 1.5million m^3
- Operated by external companies
  - Monitor dust, CO, CO2, nitrogen oxides and sulphur oxides

η ενέργεια στους επιταχυντές

Accelerators at CERN



Key Energy Consumers

- **Direct Energy to the beam**
  - RF cavities - Klystron
  - Magnets
- **Environmental Conditioning**
  - Cryogenics
  - Systems cooling
  - Tunnel air filtering
- **Data**
  - Measurements
  - Processing
- **Infrastructure**
- **Other**

(c) Rey.Hori / KEK

Force on a particle

The force on a charged particle is proportional to the charge, the electric field, and the cross product of the velocity vector and magnetic field:

Lorenz force:

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

Where q is the electrons (positrons, protons…) elementary charge:

$$q = e_0 = 1.602 \cdot 10^{-19} \text{ [C]}$$

For conservative forces (work done independent of the path) the work done by a force F along the path s_1->s_2 transversed by the particle is:

$$W = \int_{s1}^{s2} \vec{\mathbf{F}} \cdot d\vec{\mathbf{s}}$$

by differentiating:

$$dE/dt = q \cdot (\vec{\mathbf{v}} \cdot \vec{\mathbf{E}} + \vec{\mathbf{v}} \cdot (\vec{\mathbf{v}} \times \vec{\mathbf{B}})) = q \cdot \vec{\mathbf{v}} \cdot \vec{\mathbf{E}}$$

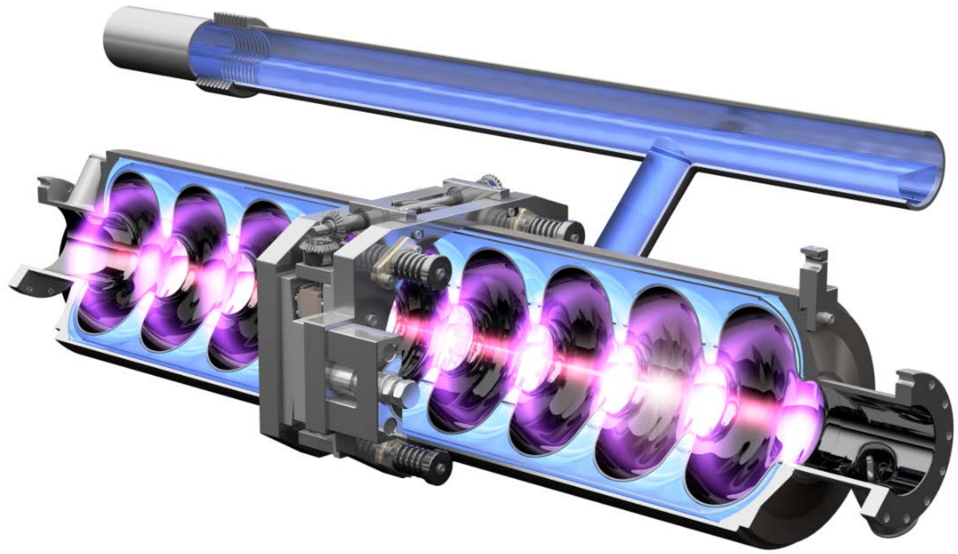
Conclusion the magnetic field does not produce any work on the direction of the vector s travelled by the charged particle. Energy (acceleration) is only gained under the effect of electric field.

RF Cavities - Klystron

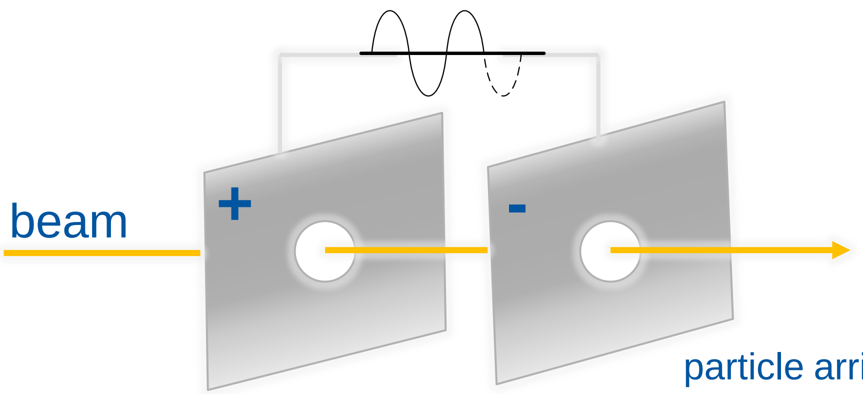
Functions:

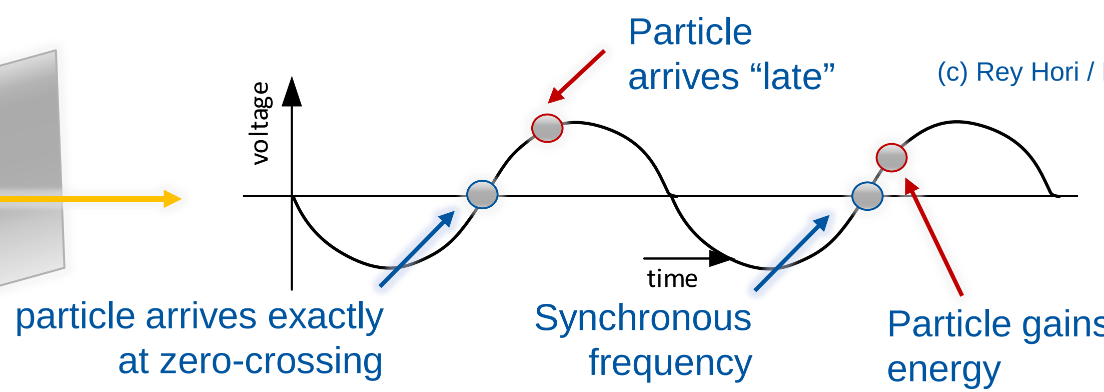
- Particle acceleration

$$\frac{dE}{dt} = q \cdot \vec{\mathbf{v}} \cdot \vec{\mathbf{E}}$$



* The rythm with which particles energy builds up depends on its rotation speed





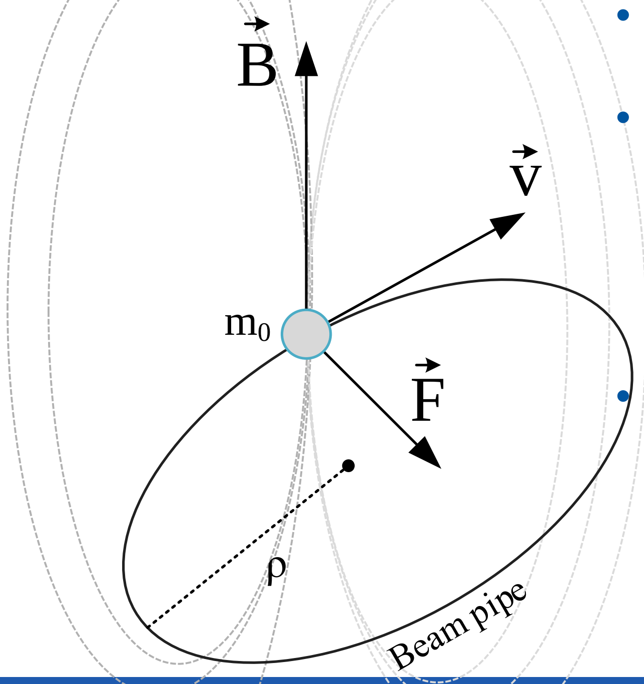
(c) Rey Hori / KEK

Electro-magnets

Functions:

- Beam steering

$$\vec{\mathbf{F}} = q \cdot (\vec{\mathbf{v}} \times \vec{\mathbf{B}})$$



- At first sight F is not dependent on mass
- Since v on a circle of radius ρ-> F = centripetal force

$$\vec{\mathbf{F}} = q \cdot (\vec{\mathbf{v}} \times \vec{\mathbf{B}}) = m_r \cdot \vec{a}_C = \frac{m_r \cdot \vec{v}^2}{\rho}$$

$$m_r = \gamma \cdot m_0$$

* γ : lorenz factor ($\gamma = 1/(1-v^2/c^2)$)

- Rearanging yields the beam rigidity i.e. a measure of the force needed to bend the charge direction
- And the bending angle inside a magnet field

$$\vec{B} \cdot \rho = \frac{m \cdot \vec{v}}{q} = \frac{\vec{p}}{e}$$

$$a = \frac{\int \vec{B} \cdot ds}{B \cdot \rho}$$

- The integrated field is a magnet property also given by Amperes law:

$$\oint_C \vec{B} \cdot ds = \mu_0 \cdot \iint_A \vec{J} \cdot dA = \mu_0 \cdot I_C$$

*μ_0: magnetic permeability of the air

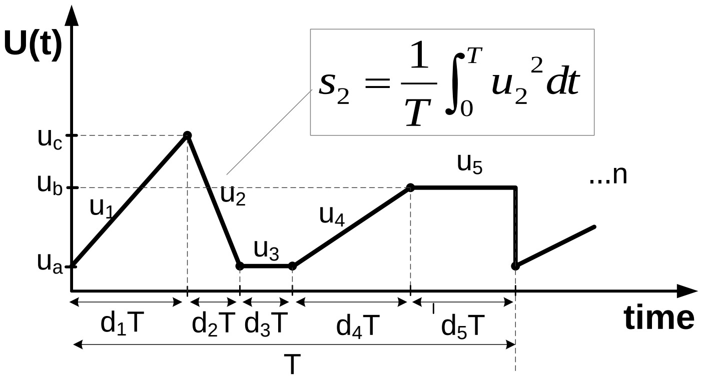
Dipole magnet

Functions:

- Beam steering

- Stores energy $E=0.5\ L\ I^2$
- Consumes power $P=I^2\ R$


(c) Rey Hori / KEK

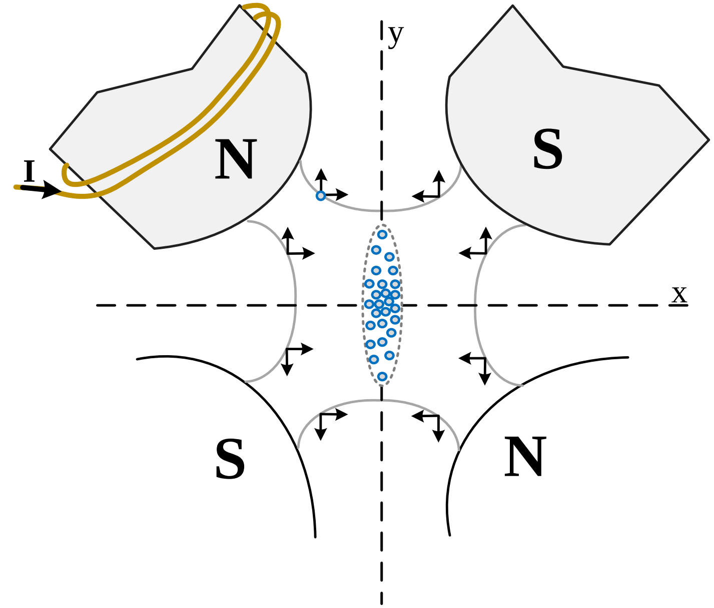


$$s_2 = \frac{1}{T}\int_0^T {u_2}^2 dt$$

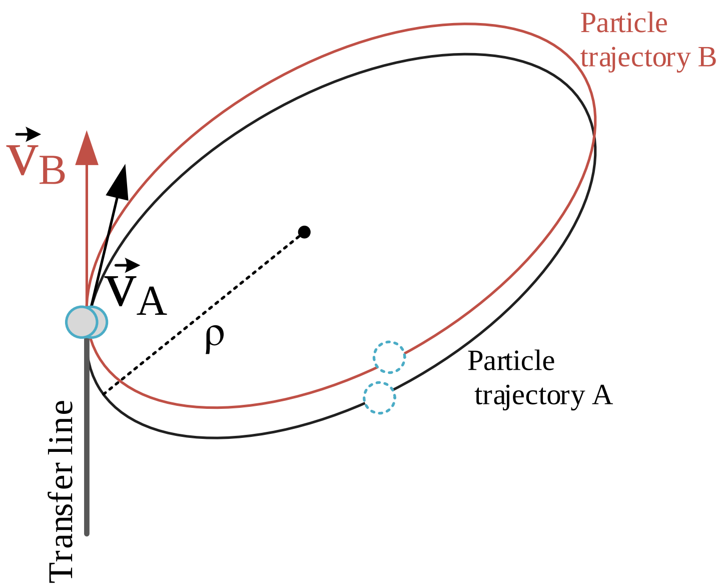
Quadrupole magnets

Functions:

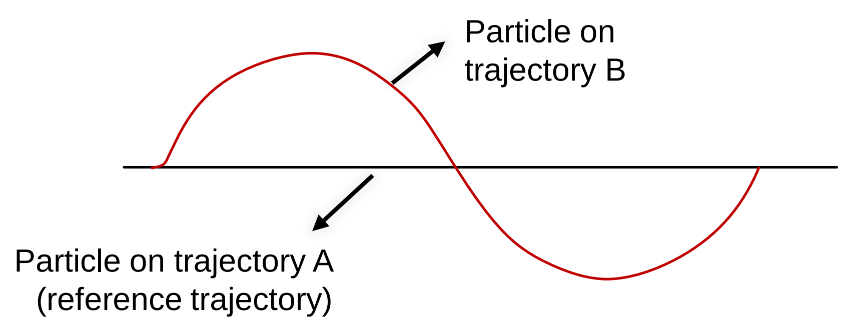
- Focussing-defocusing



Two particles enter in the accelerator with different velocity vectors:



Betatron Oscillation



Cryogenics

(c) Rey Hori / KEK

- Cryogenic pumps are the largest single electrical consumer at CERN
- Total power: 27.5MW
- 6 weeks to cool down Helium to 1.8K to 4.2K

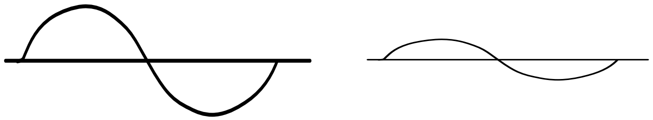
1880s

the war of currents

Thomas Edisson VS George Westinghouse

- Direct VS alternating current

- AC has two key advantages
  - Voltage/current can be transformed
  - Current can be interrupted



- Whereas DC is:
  - Less dangerous* but
  - May not be interrupted with standard switches
  - Could not be transmitted in long distances due to the lack of dc transformers

- Westinghouse won the battle!!!
  - Alternating current is standard and can be transformed, transmitted to distances of several hundred kilometres and may be interrupted with standard mechanical breakers.
  - It took us a century to develop technology for handling DC currents!

* If compared to a similar voltage level 50Hz alternating current of which the fluctuations can induce arrhythmia and eventually result in ventricular fibrillation of the heart

Edisson VS Westinghouse

- Electrical power is P_{tot}=voltage (v) x current (i)
- Using conductors to transmit power hence R_{copper}
- Power is lost on the way $P_{loss}=I^2R$
- Hence useful power is $P_{useful}=P_{tot}-P_{loss}$

Notice! Ploss is a function of I and R. Decreasing I by a factor of 2 decreases power loss by 4

- 2 Solutions to save energy:
  - Voltage rise -> voltage transformation
  - resistance reduction-> superconductive conductors

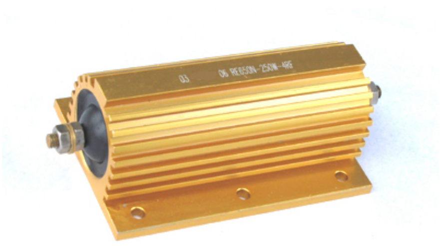
Εισαγωγή στους Μετατροπείς Ισχύος

Electronics & Power Electronics

- Electronics is the art of manipulating the flow of electrons to perform certain functions
  - Receive, transmit and store information
  - Generate electromagnetic waves (heat,light)
  - Convert electricity to kinetic energy (motors

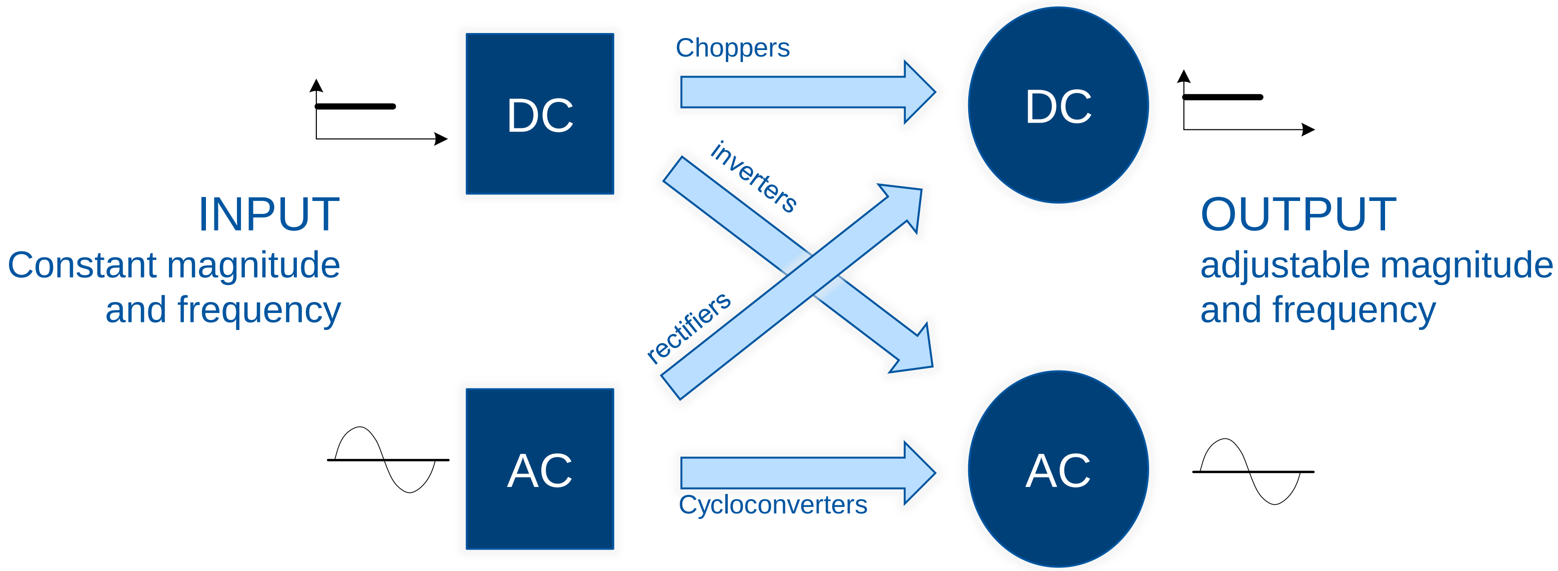
Analog &
Digital Electronics


Power Electronics

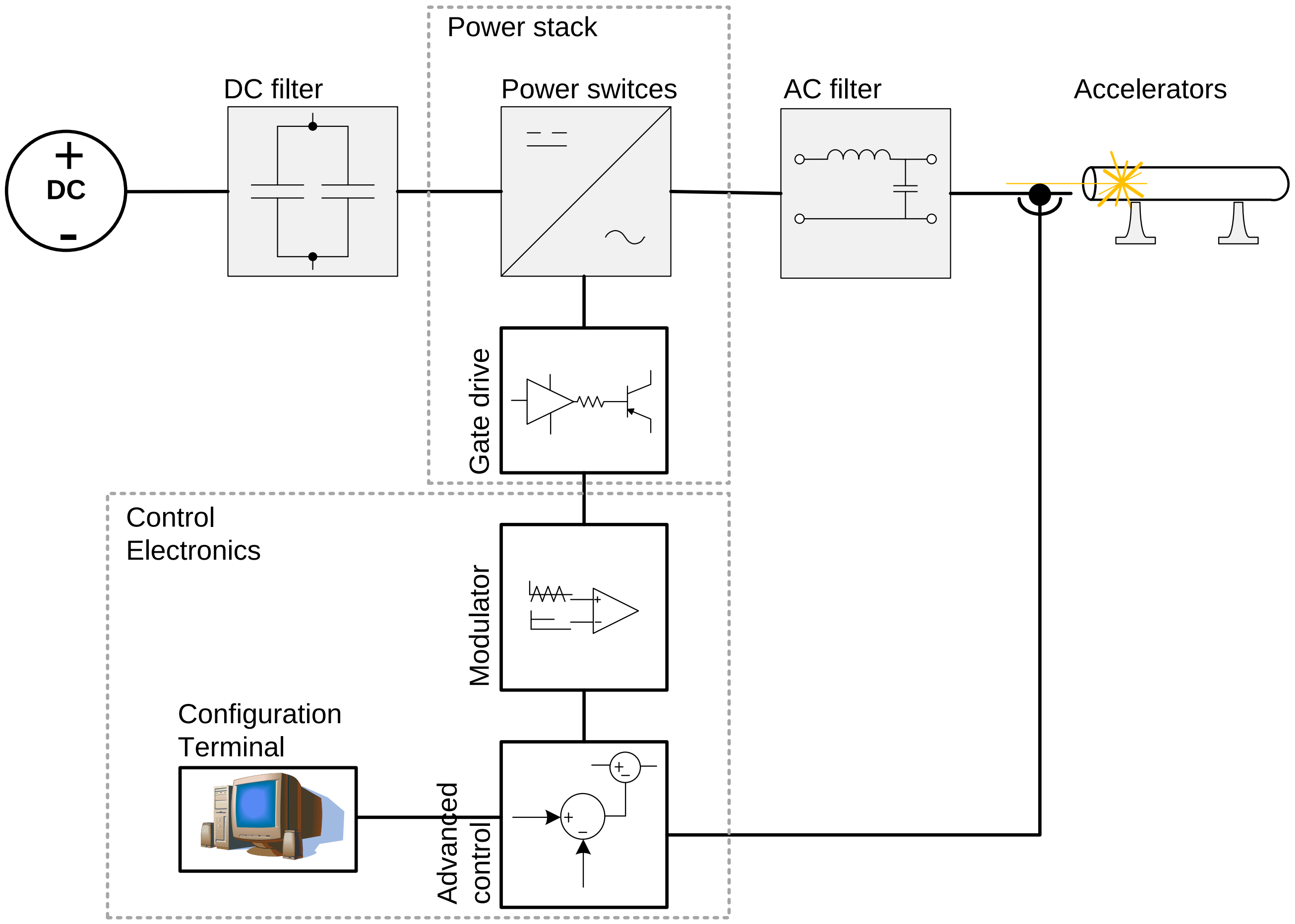


Power Conversion

- Electrical voltage needs to be transformed
  - From direct to alternating current and the opposite
  - From one voltage to another
  - From one frequency to another

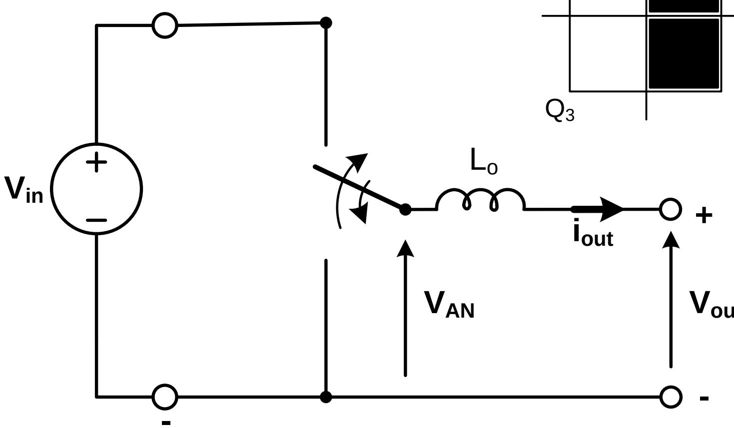


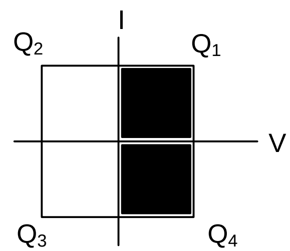
Power Converter Structure

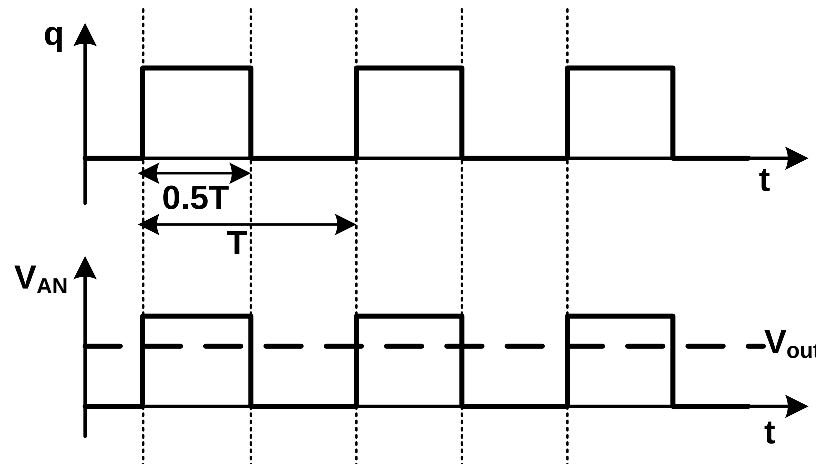


The basic power converter

- Voltage regulator operation based on switching on and off the input source with a duty cycle D.
- Inductor operates as averaging device

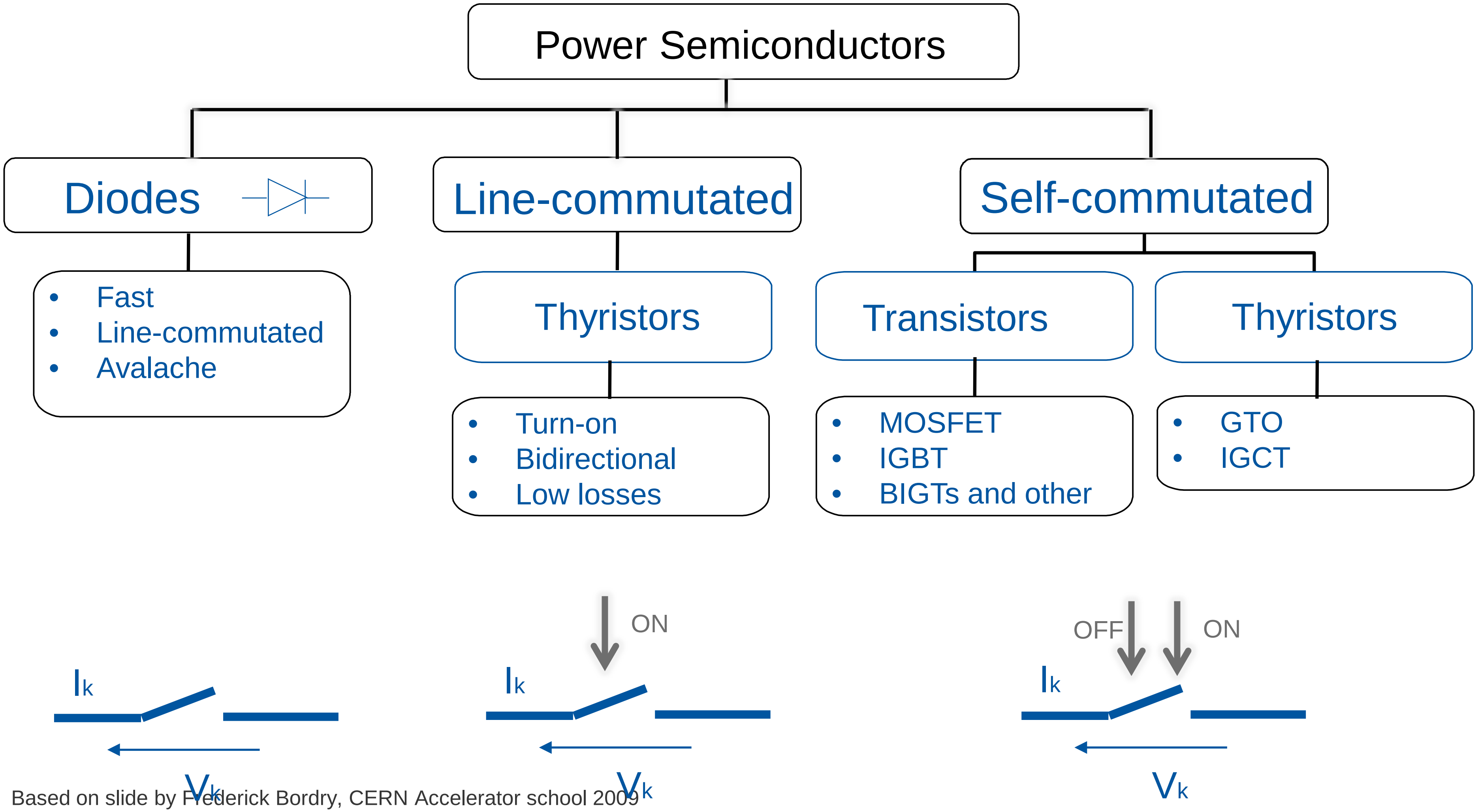






$$V_{out} = D.V_{in} \qquad 0 < D < 1$$

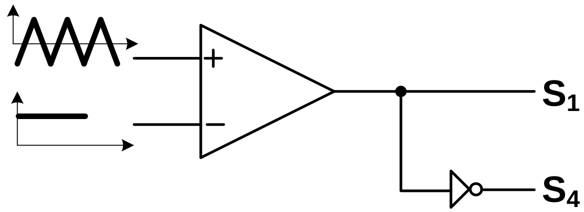
Power Semiconductors

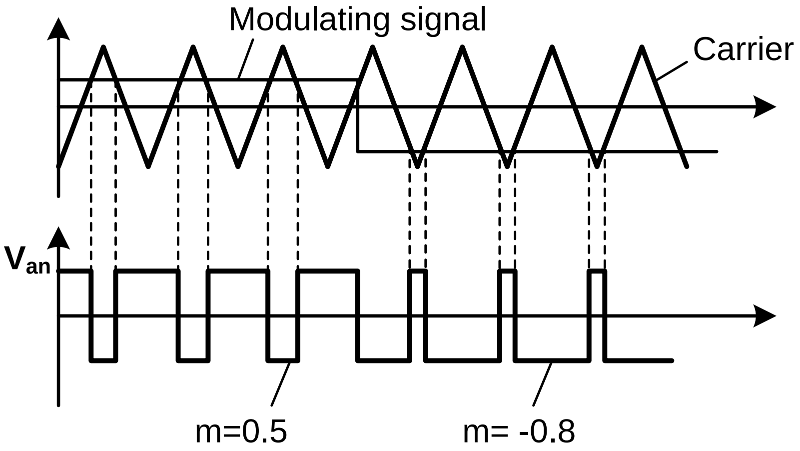


Based on slide by Frederick Bordry, CERN Accelerator school 2009

Modulation

- Control of the fundamental frequency component (ac or dc) by varying the switch duty ratio





Figures of merit in PE

- Power conversion efficiency
  - Expresses the effective-ness of a converter in converting input power to useful output power (with less wasted power in the process)

$$n_c = \frac{P_{out,dc}}{P_{in}}$$

- Input Power factor
  - A high power factor typically indicates a lower input current for delivering a certian output power level. (as usually input sources have a stiff voltage magnitude)

$$cos\varphi = \frac{P_{in}}{S_{in}}$$

- Ripple factor
  - Is a measure of the voltage or current ripple magnitude in dc voltage or current waveform

$$RF = \frac{V_{ac,rms}}{V_{dc}}$$

- Total Harmonic Distortion (THD)
  - is a measure of its RMS power of the harmonic components in comparison with the RMS power of the fundamental component of a voltage or current waveform.

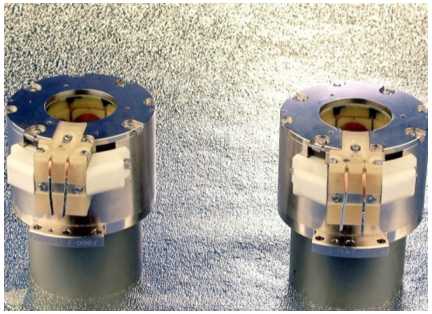
$$THD = \frac{V_{h,rms}}{V_{1,rms}}$$

LHC – the Large Hadron collider

- **The beams are controlled by:**
  - **1232 SC Main Dipole magnets to bend the beams**
  - **392 SC Main Quadrupole magnets to focus the beams**
  - **124 SC Quadrupole / Dipole Insertion magnets**
  - **6340 SC Corrector magnets**
  - **112 Warm magnets**
  - **SC RF Cavities to accelerate and stabilize the beam**

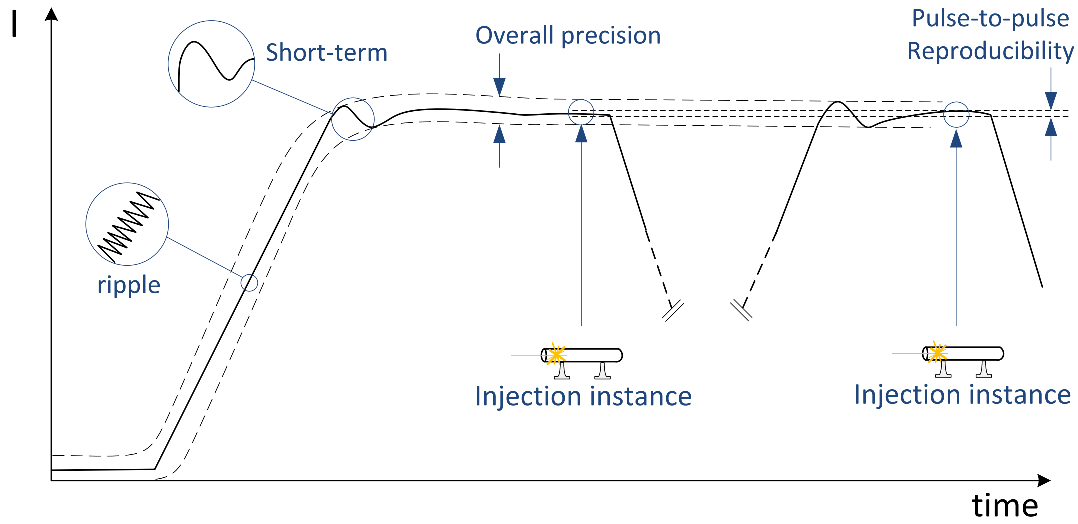
- (in 196 circuits of ~ 6 kA)
- (in 1460 circuits 60 to 600A)
- (in 38 circuits 600 to 900A)

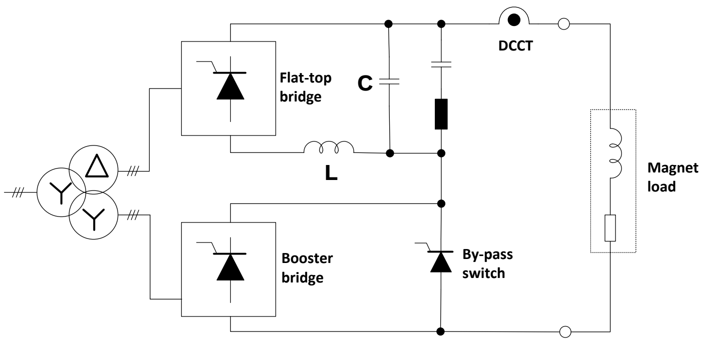
All ~8000 magnets need to be powered in a very controlled and precise manner



Current Regulation Precision

Current in a transfer line magnet



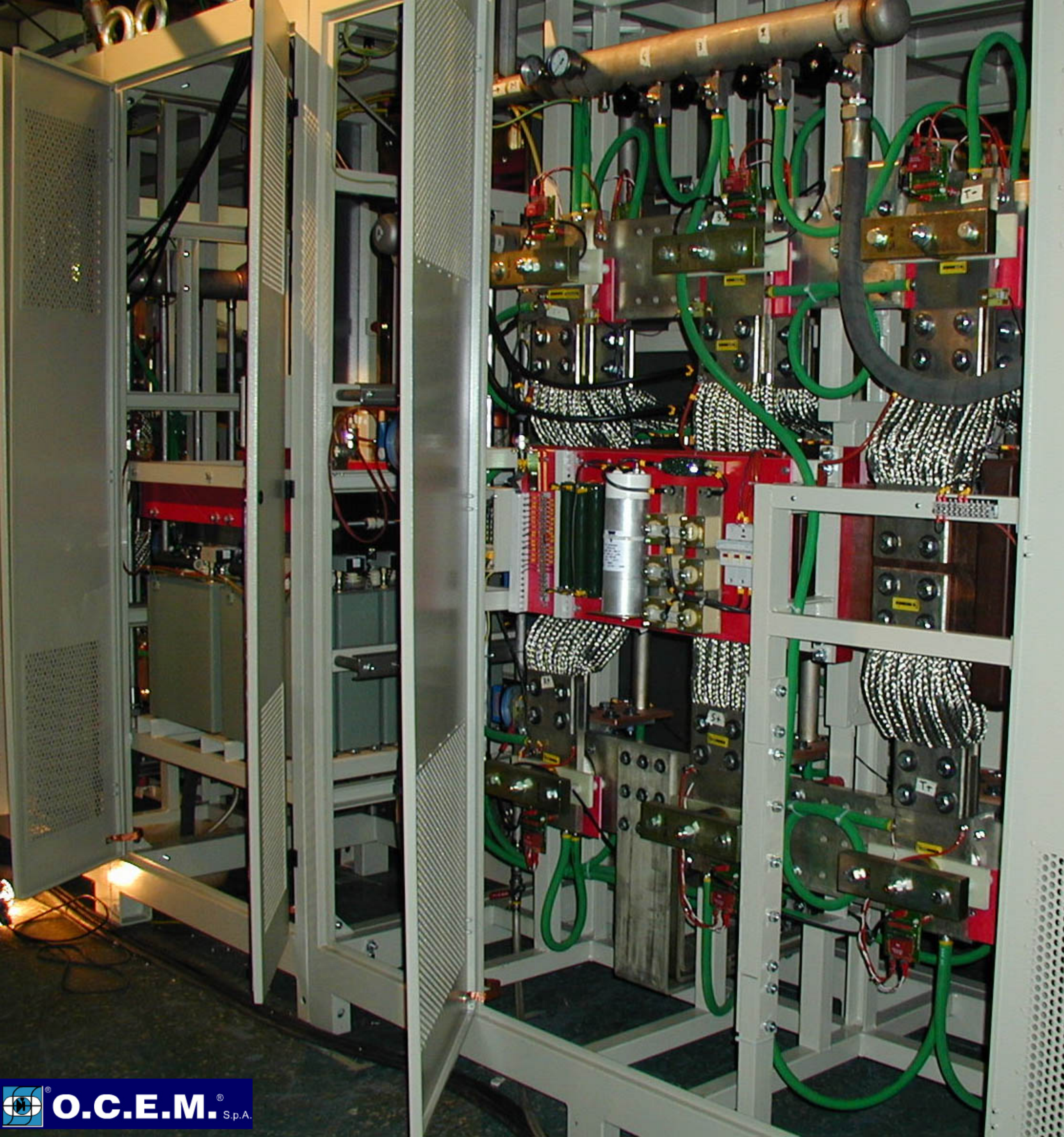


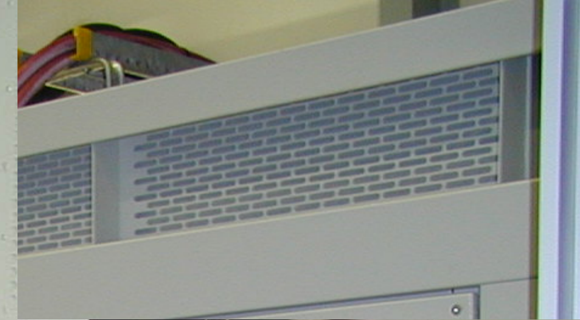
Precision components:

- Current ripple
- Short-term (dynamic behaviour)
- Long term (reproducibility)

Typical requirements:

- 1-100ppm depending on application





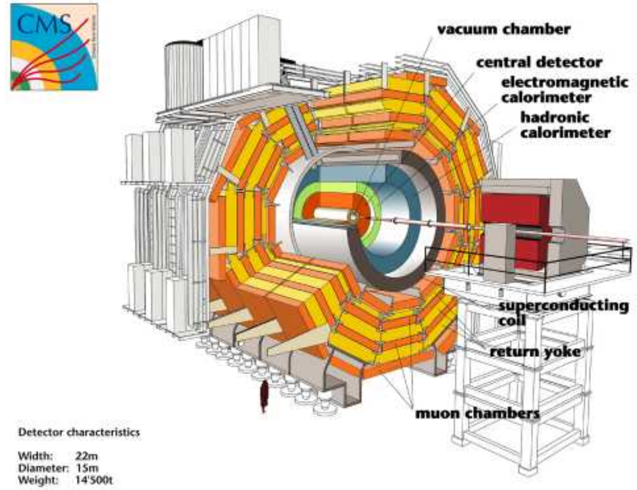
O.C.E.M.® S.p.A.

20kA power converter -CMS Solenoid

The load

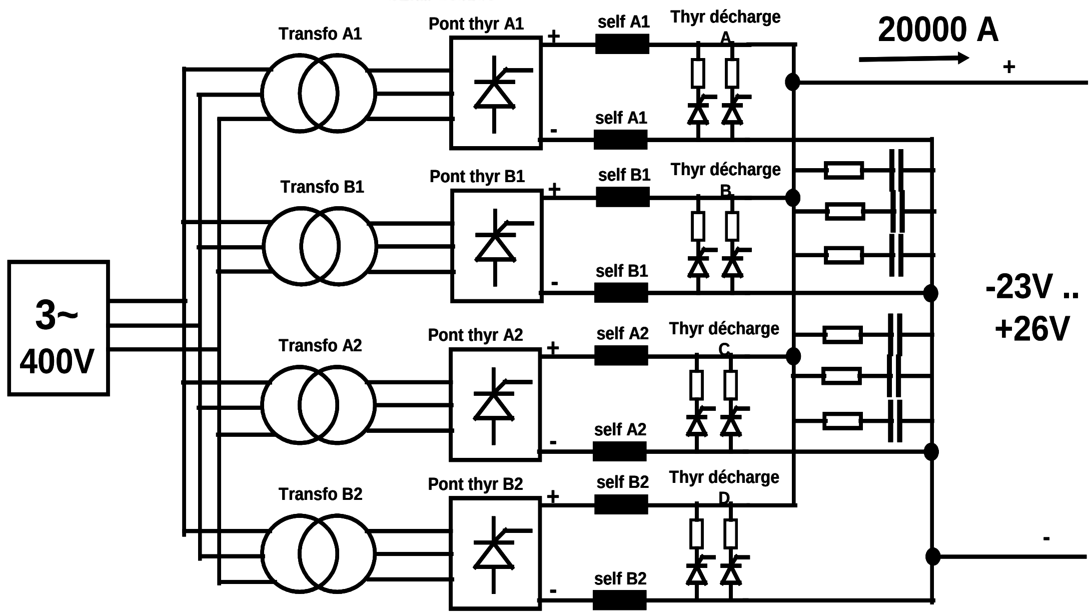
- **Superconducting magnet: L= 14H**
- **Nominal current: 20 kA**
- **Stored energy: 2.8 GJ**
- **Time constant: 39 hours**
- **Time for current ramping up: 3h15m**

- **Energy extraction system (resistor bank, not shown)**



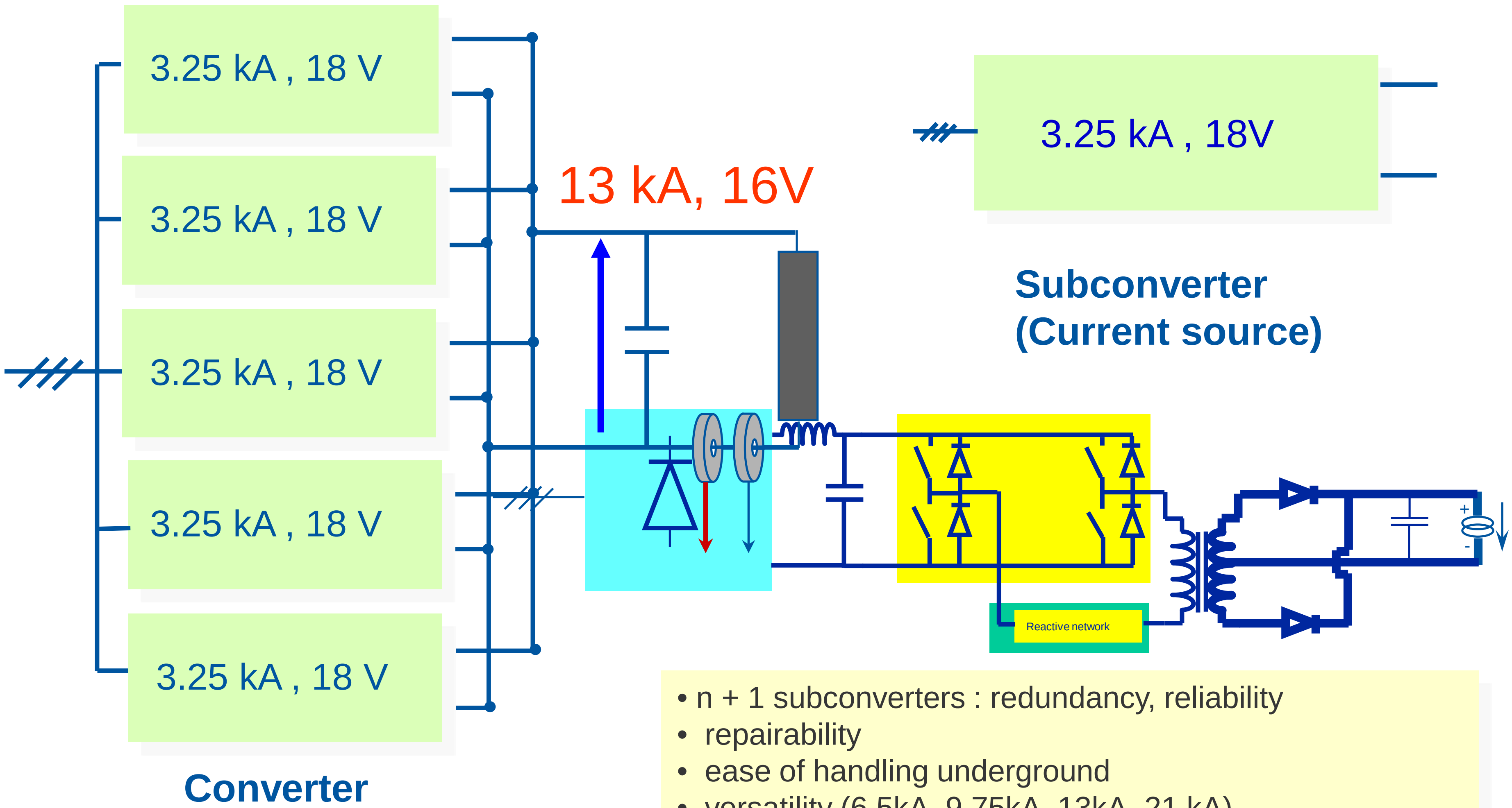
The power converter

Equipaggiamenti Elettronici Industriali



Slide by Frederick Bordry, CERN Accelerator school 2009

Converter modularisation

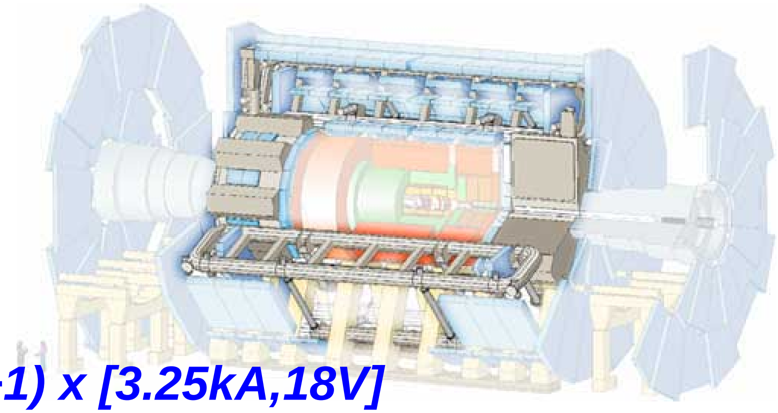


- n + 1 subconverters : redundancy, reliability
- repairability
- ease of handling underground
- versatility (6.5kA, 9.75kA, 13kA, 21 kA)

20.5kA power converter – ATLAS solenoid

The load

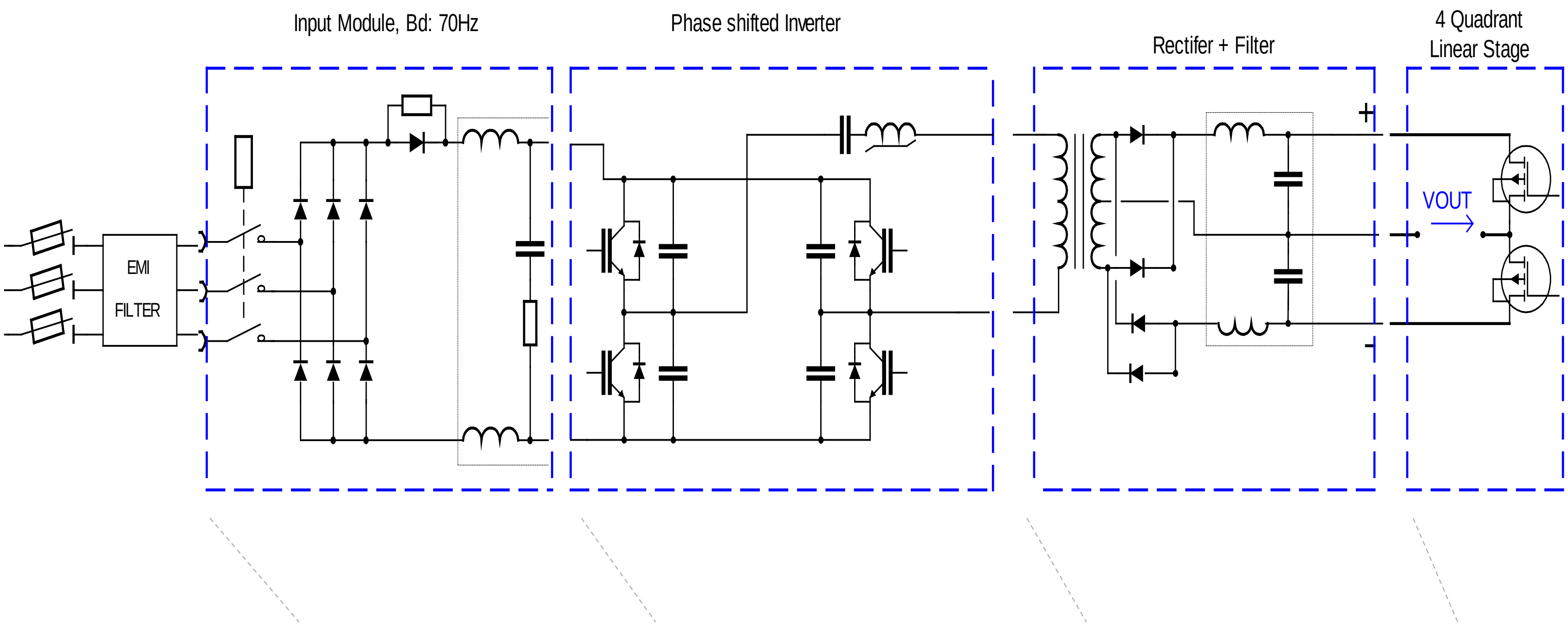
- **Superconducting magnet: L= 7.5 H**
- **Nominal current: 20.5 kA**
- **Stored energy: 1.6 GJ**
- **Time constant: 37’500 s**



The power converter : [20.5 kA, 18V] ; (7+1) x [3.25kA,18V]

TRANSTECHNIK

Typical Converter topology (120A,10V)

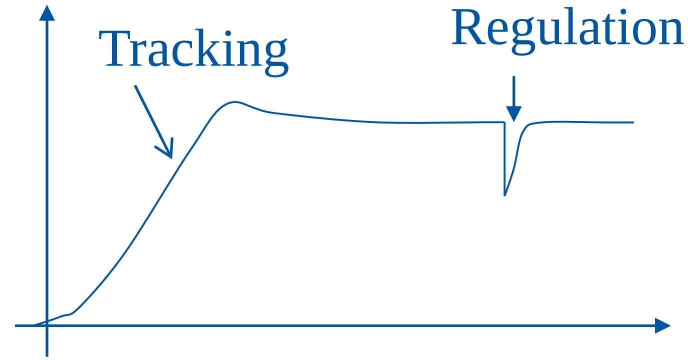


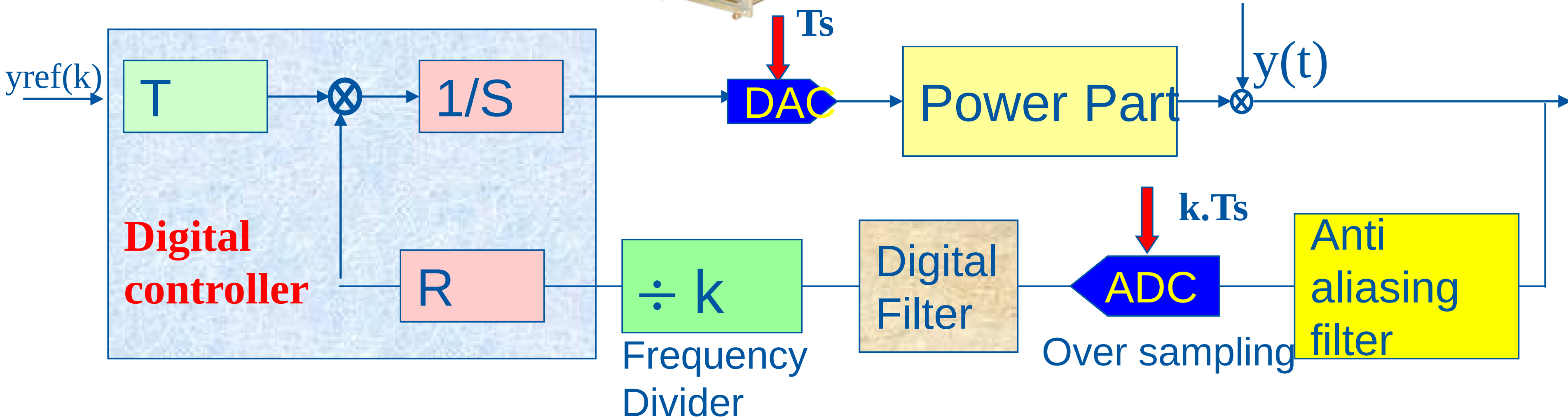
BREAKER & CONTACTOR	INPUT FILTER & SOFT-START	SOFT COM. INVERTER, 50kHz..100kHz	ISOLATION & RECTIFIER + FILTER	4Q.L.S.

Slide by Frederick Bordry, CERN Accelerator school 2009

Digital control design

Tracking and Regulation with independent objectives

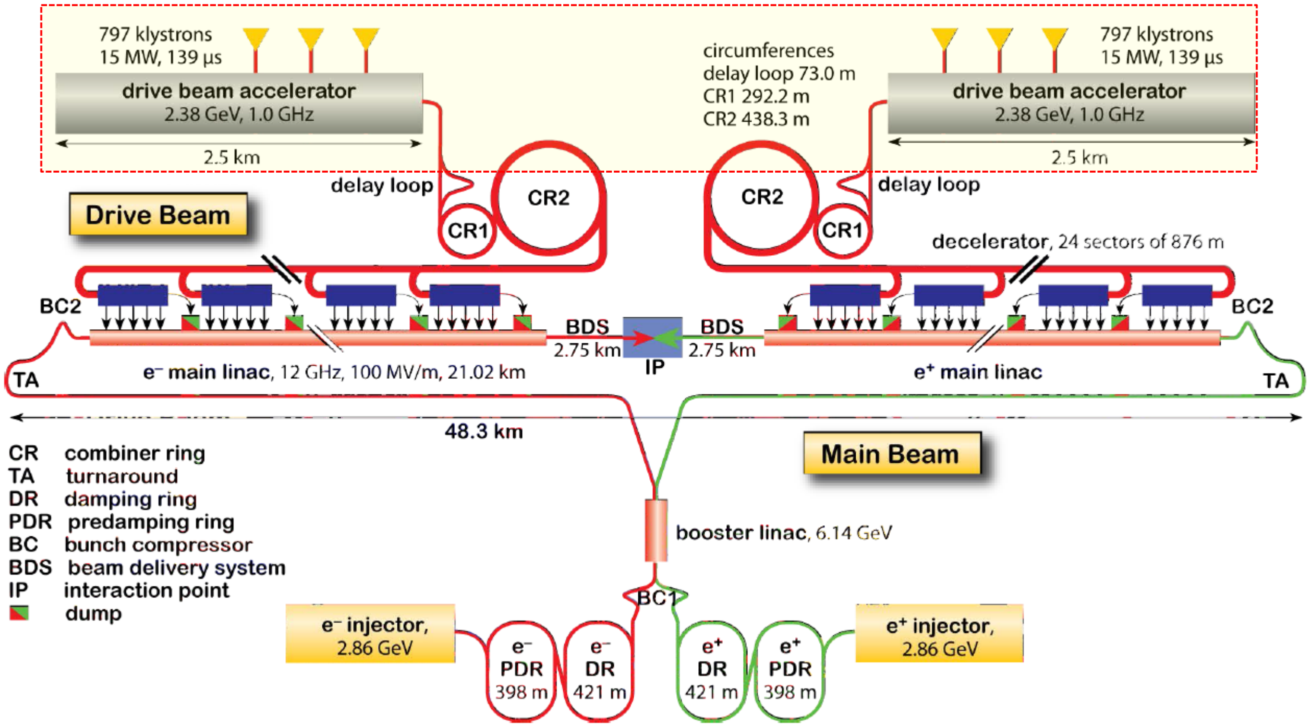




Slide by Frederick Bordry, CERN Accelerator school 2009

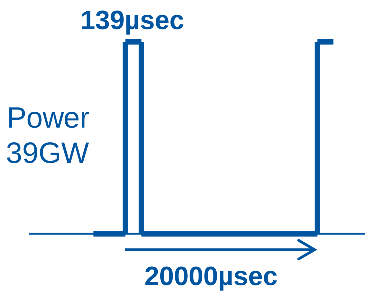
Έρευνα: πιο αποδοτικά συστήματα τροφοδοσίας

Compact Linear Collider (CLIC)

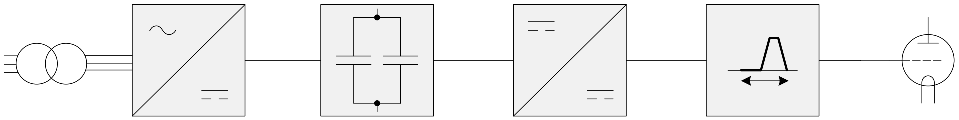


RF modulators are the primary electrical power consumer

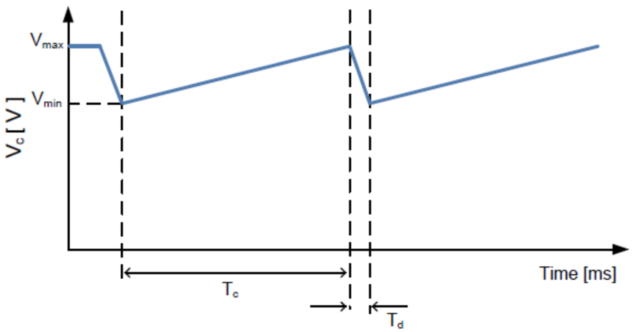
Pulses of 139us 150kV and 160A resulting in bursts of 24MW per modulator



CLIC Specifications



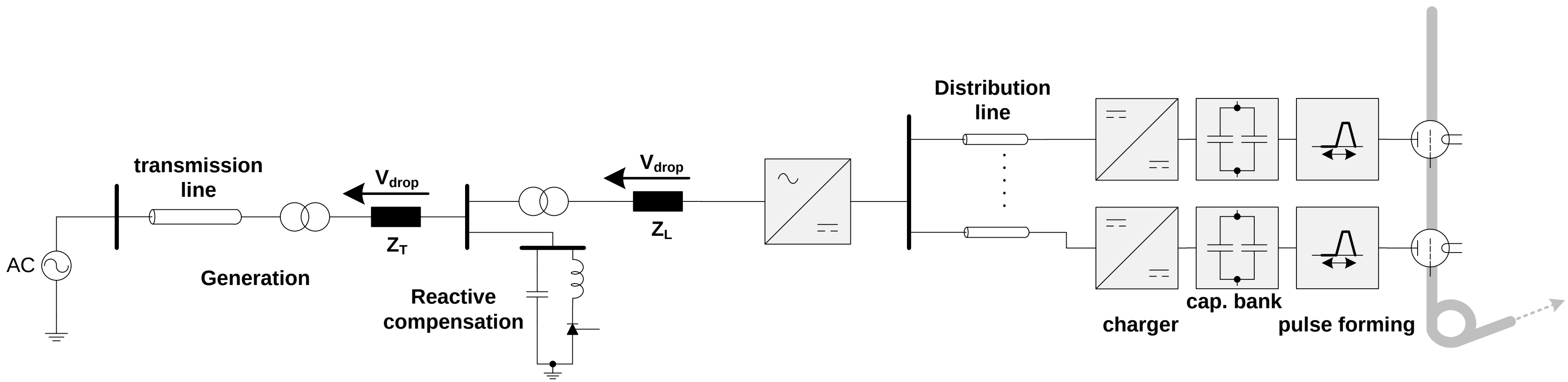
Modulator's output pulse specification			
Nominal pulse voltage	V_{kn}	150	kV
Nominal pulse current	I_{kn}	160	A
Pulse peak power	P_{mod_out}	24	MW
Rise & fall times	t_{rise}, t_{fall}	3	μs
Settling time	t_{set}	5	μs
Flat-top length	t_{flat}	140	μs
Repetition rate	$REPR$	50	Hz
Voltage overshoot	V_{ovs}	1	%
Precisions			
Flat-Top Stability	FTS	0.85	%
Reproducibility (6kHz-4MHz)	PPR	10	ppm
Efficiencies			
Charger electrical efficiency	η_{ch}	96	%
PFS electrical efficiency	η_{pfs}	98	%
Pulse efficiency	η_{pulse}	95	%
Modulator global efficiency	η_{mod_global}	90	%

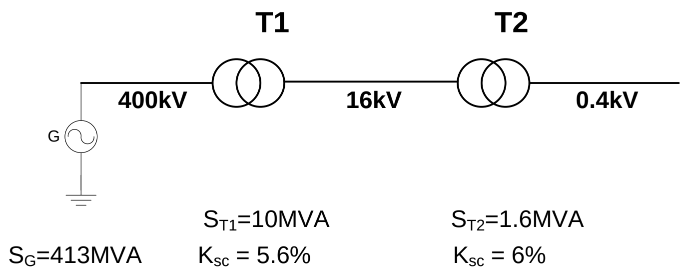


Application parameters:

- The load is 1638 Klystron tubes
- 150kV/160A 140µs flat-top required -> 24MW peak per Klystron -> 39.3GW peak load
- Average power per klystron modulator 168kW
- Accounting for a 90% efficiency (plug to drive beam) -> total average power 275MW

CLIC Grid interface

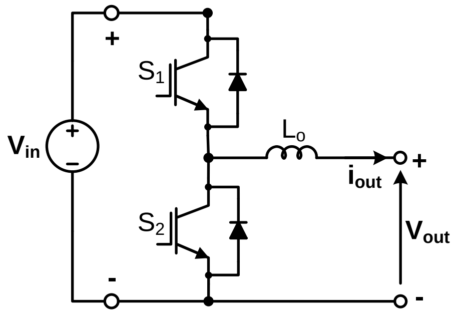


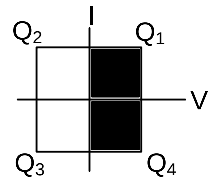


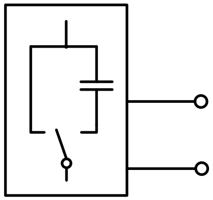
$$\frac{1}{S^{SC}} = \frac{1}{S_G^{SC}} + \frac{1}{S_{T1}^{SC}} + \frac{1}{S_{T2}^{SC}} = \frac{1}{413} + \frac{1}{179} + \frac{1}{26} = \frac{1}{21.5}$$

- The network impedance limits the power that can be drawn.
- At the rated power network impedance will be responsible for <10% voltage drop.
- Drawing 39000MVA out of a 300MVA transformer would collapse the voltage (hence tripping the protections)

From 2Q to multilevel

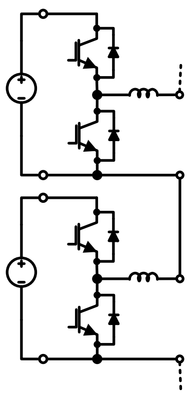




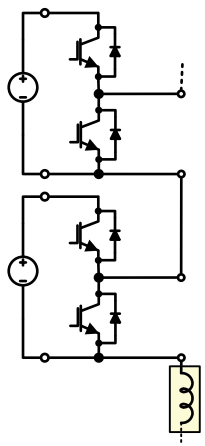


Q1: V: positive
I: positive

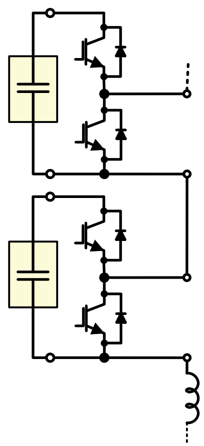
Q2: V:positive
I:negative



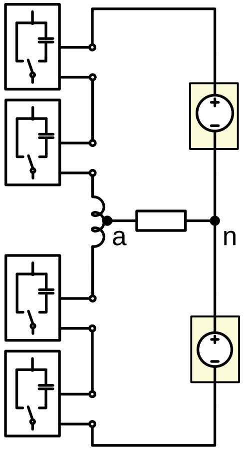
Series-connection of 2Q dc/dc



Lumped inductor



Capacitors in place of voltage sources

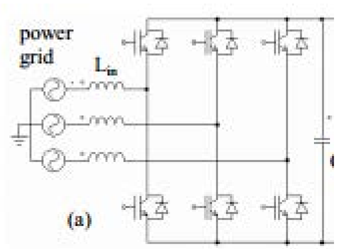


DC-supply added

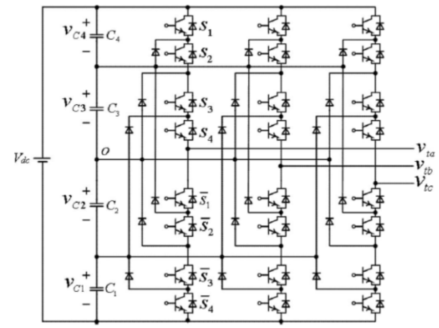
AFE Concepts

Topology comparison for:

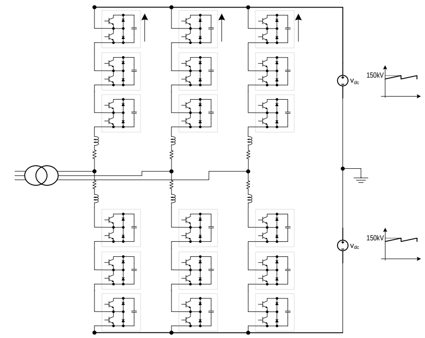
- high voltage (>20kV) and
- high power (>20MW) applications



Three phase-bridge



Five level NPC



Modular-multilevel-converter (MMC)

	Three phase-bridge	Five level NPC	Modular-multilevel-converter (MMC)
AC Filter size	◆	◆◆	◆◆◆
Control system	◆◆◆	◆◆	◆◆
Reliability ★	◆◆	◆◆	◆◆⬩
Spares inventory	◆◆	◆	◆◆◆⬩
Power range	□□□	□□□□	□□□□□
Mechanical integration	◆◆◆	◆	◆◆

★particularly interesting at higher voltage/power applications

- Ερωτήσεις;

Life at CERN

CERN

www.cern.ch