30.08.2013 – Greek Teachers Programme

Energy & Modern Technology

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CERN – European Organisation for Nuclear Research

κδπ

Summary

- **Energy consumption at CERN**
  - How is energy spent?
  - Electricity, Water and Gas
- **From Electrical to Kinetic Energy**
  - How is electricity converted to speed?
- **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

Ποιος ενδιαφέρεται για το CERN?

trends.google.com

cern

Δεδομένα: Παγκόσμια – 2008

Δεδομένα: Παγκόσμια – 2004-σήμερα

Regional interest

Switzerland	100	▬▬▬▬▬▬▬▬▬▬
Greece	93	▬▬▬▬▬▬▬▬▬
Italy	34	▬▬▬
Austria	30	▬▬▬
Denmark	23	▬▬
Norway	21	▬▬
Turkey	21	▬▬
Croatia	20	▬▬
Ireland	19	▬▬
Germany	18	▬▬
Denmark	10	▬

Electricity at CERN

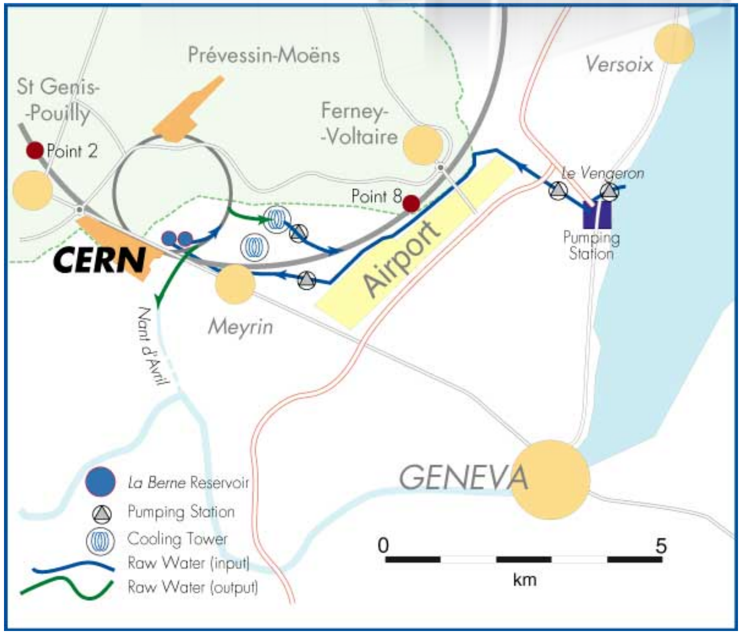
- Interconnections to both France and Switzerland
- Approximately 80% of electricity from France
  - (nuclear mostly)
- Special contract terms with EDF and SIG
- 1000 high voltage circuit breakers in operation
- Consumption
  - as high as all households in Geneva area
  - 1/10th of the canton (11.3TWh).

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

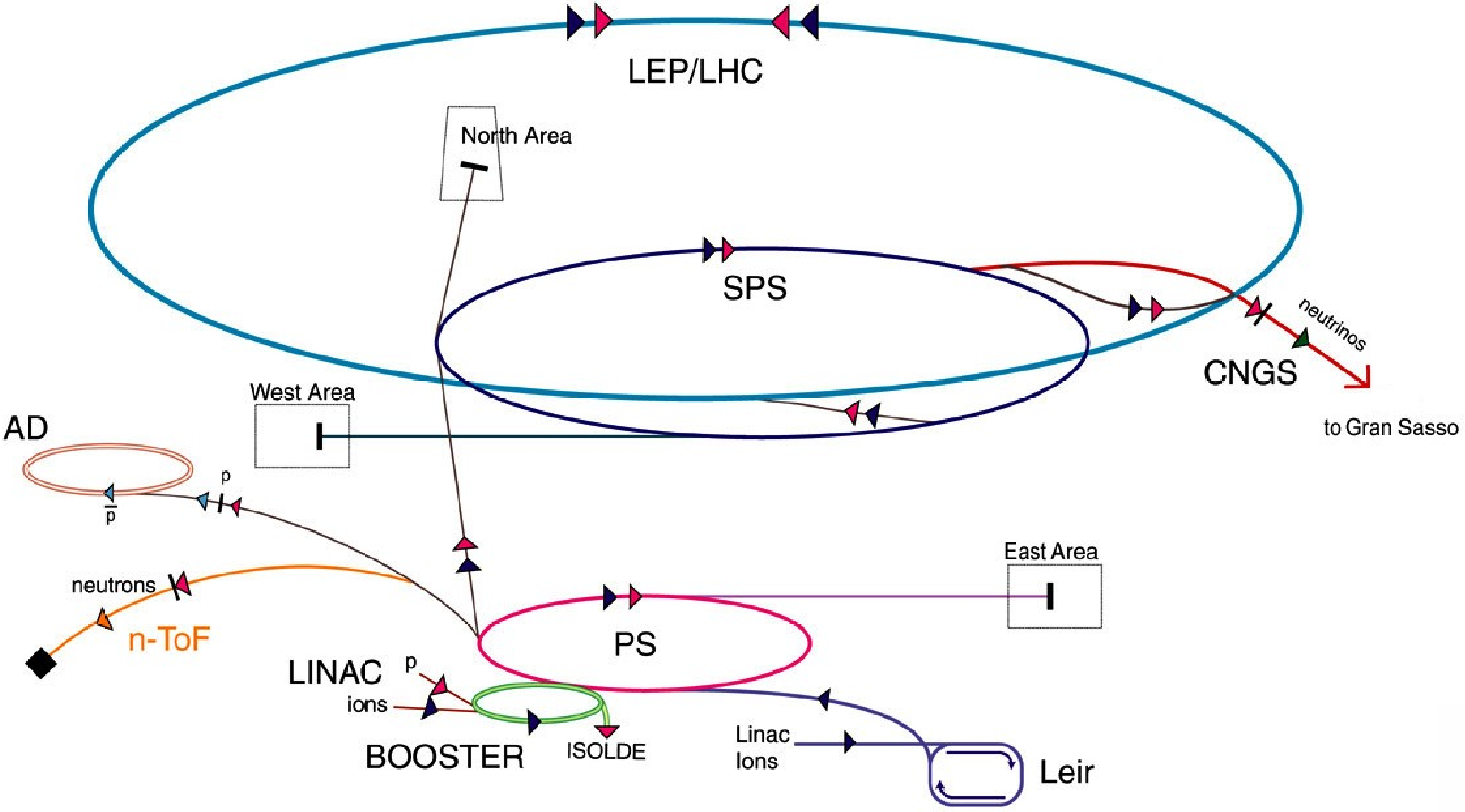
- 6 million m3 of water
- Closed circuit of demineralised water and secondary circuit of raw water cooled in cooling towers.
- Industrial process water
  - Surface treatment
  - Production of demineralised water



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

Accelerators at CERN



▶ p (proton)
▶ ion
▶ neutron

$\bar{p}$ ▶ (antiproton)
→▶|▶ proton/antiproton conversion
▶ neutrino

AD Antiproton Decelerator
PS Proton Synchrotron
SPS Super Proton Synchrotron

LHC Large Hadron Collider
n-ToF Neutron Time of Flight
CNGS Cern Neutrinos Gran Sasso

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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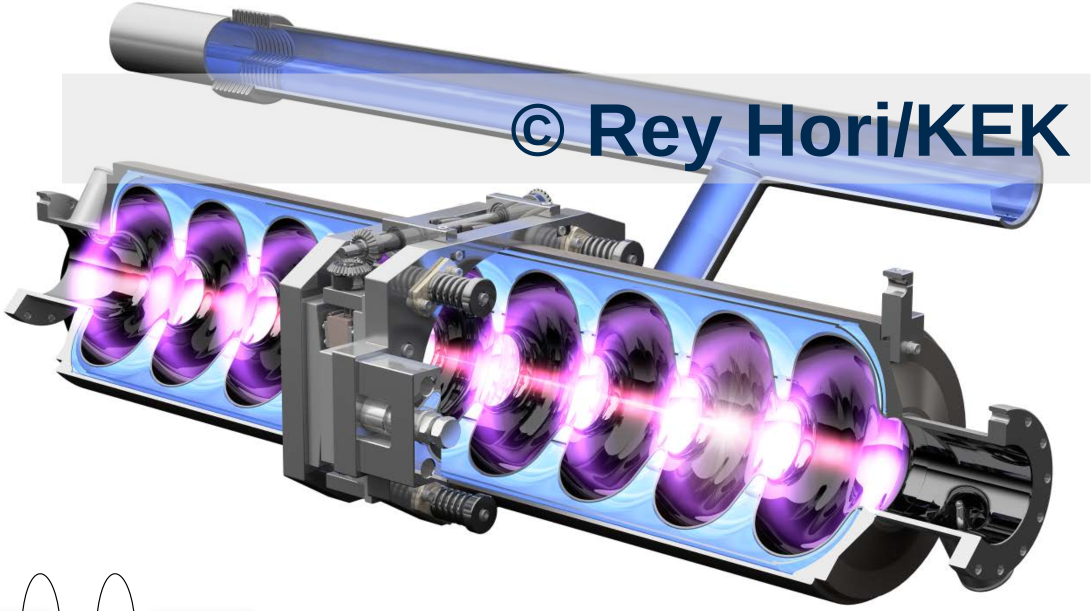
RF Cavities - Klystron

Functions:

- Particle acceleration



© Rey Hori/KEK

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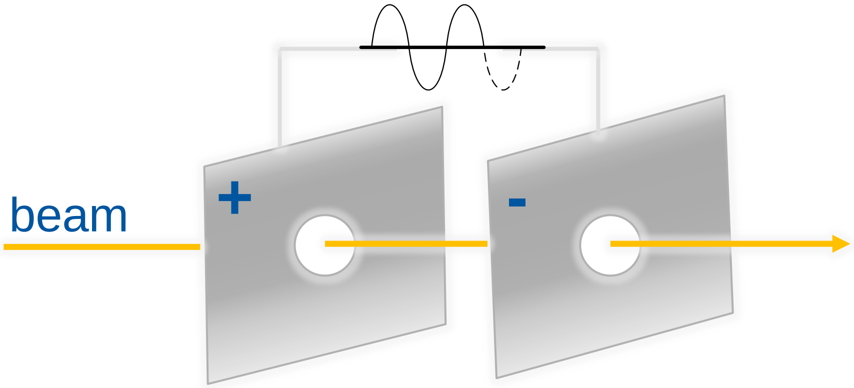
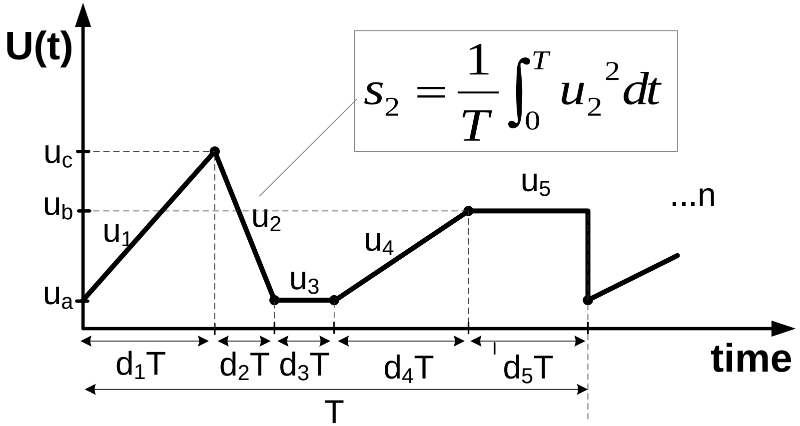


Electro-magnets

Functions:

- Beam steering
- Beam focussing-defocussing
- Beam gymnastics

(c) Rey Hori / KEK



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

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

Cryogenics

(c) Rey Hori / KEK

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

Electronics & Power Electronics

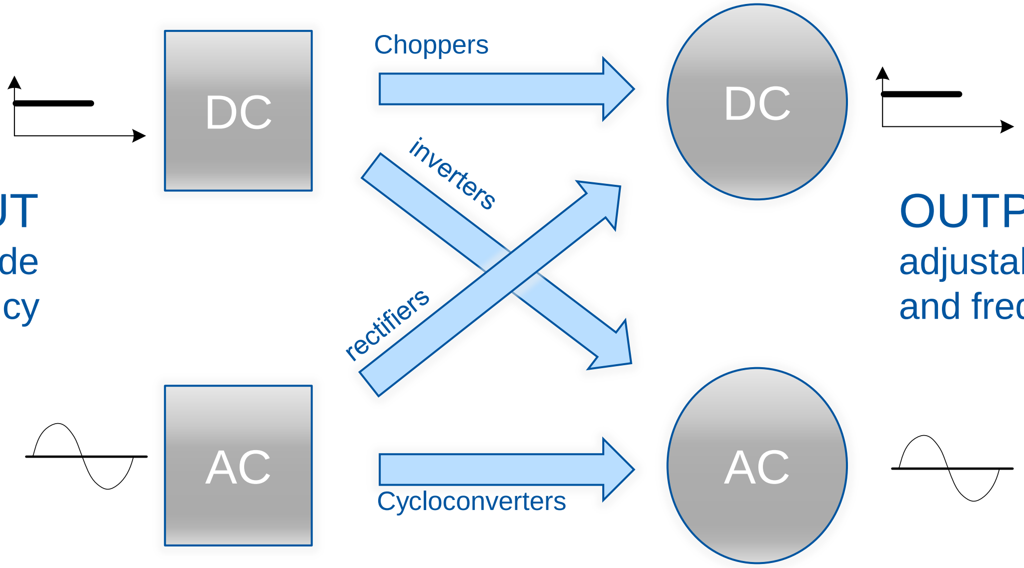
- Electronics is the art of manipulating the flow of Electrons to perform certain functions
  - Receive, transmit and store information
  - Generate electromagnetic waves (heat, light)
  - Convert electricity to kinetic energy

Analog & Digital Electronics

Power Electronics

Power Conversion

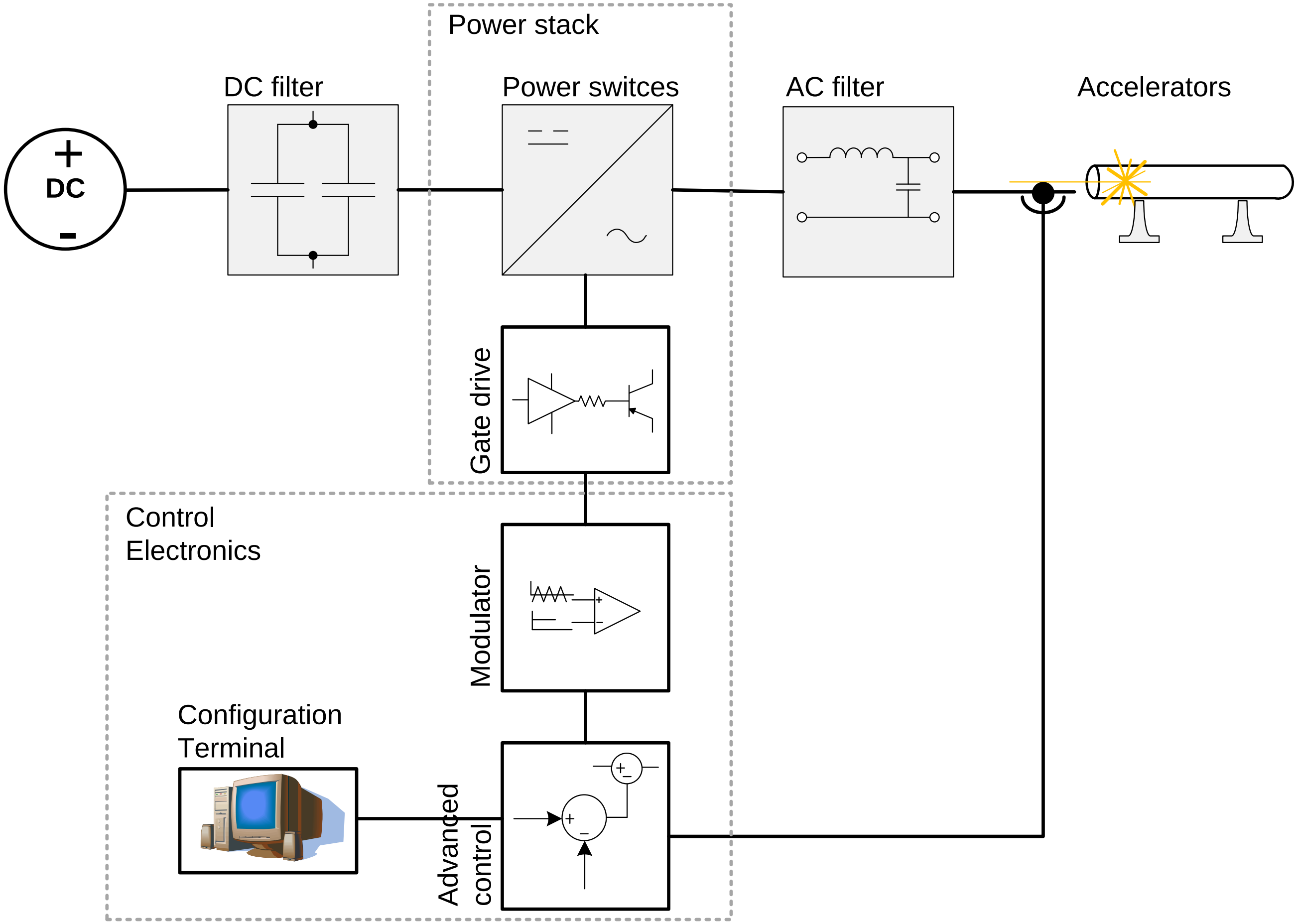
- Electrical voltage needs to be transformed
  - From dc to ac and the opposite
  - From one voltage to another
  - From one frequency to another



INPUT
Constant magnitude
and frequency

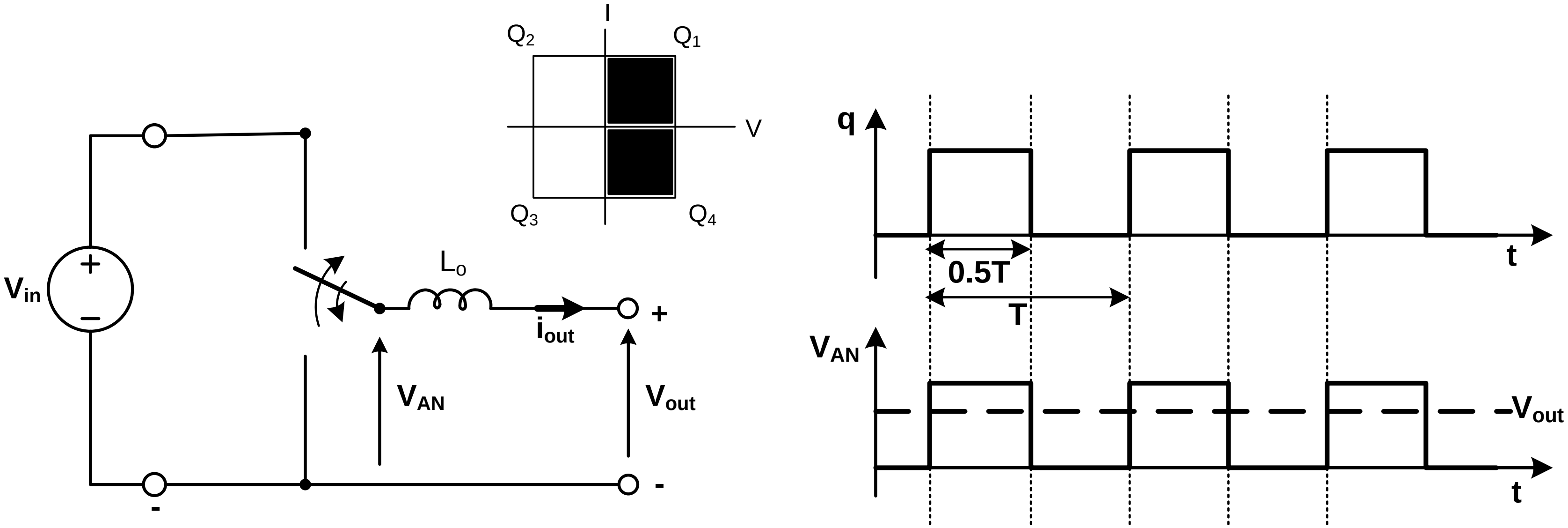
OUTPUT
adjustable magnitude
and frequency

Power Converter Structure



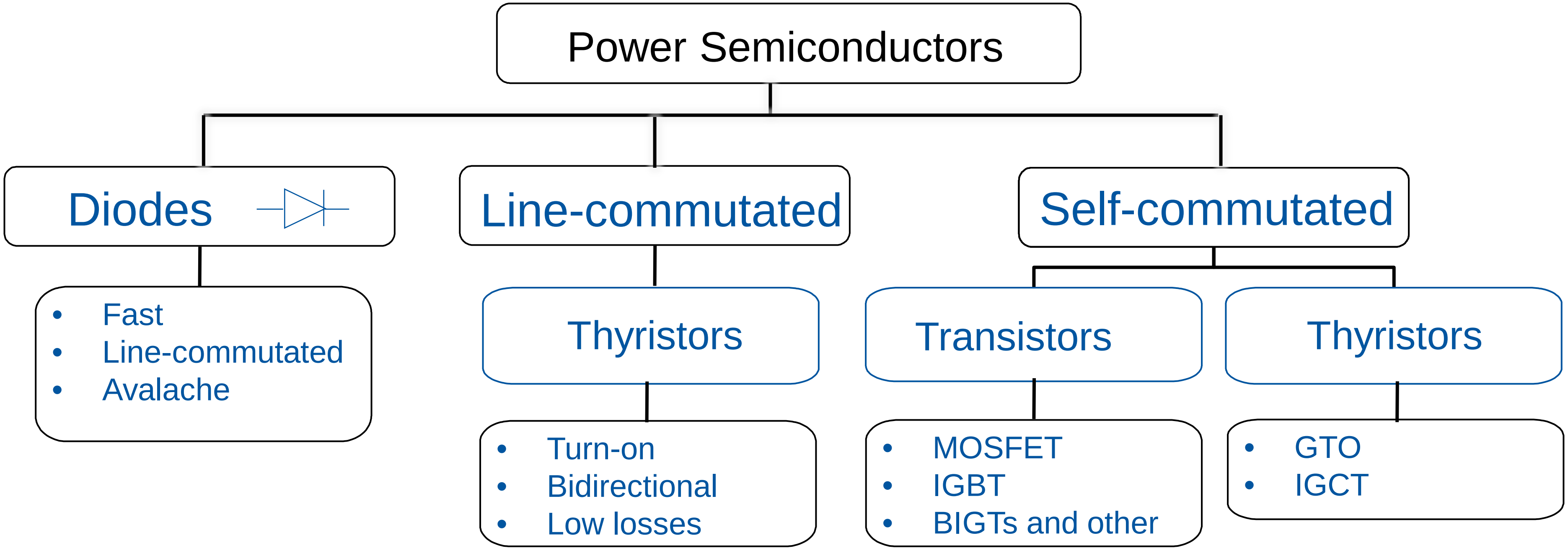
The basic power converter

- 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



Power Semiconductors

Diodes

- Fast
- Line-commutated
- Avalache

Line-commutated

Thyristors

- Turn-on
- Bidirectional
- Low losses

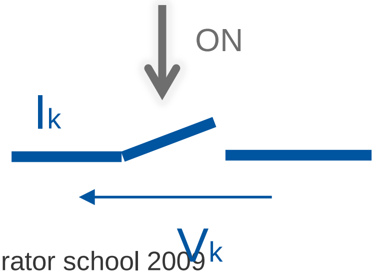
Self-commutated

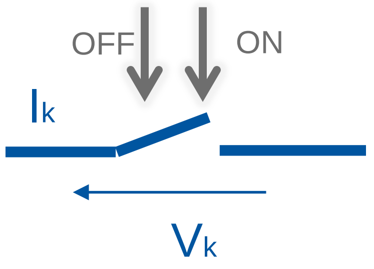
Transistors

- MOSFET
- IGBT
- BIGTs and other

Thyristors

- GTO
- IGCT

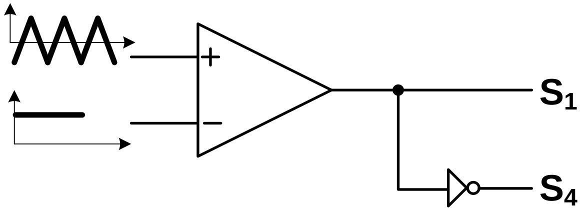


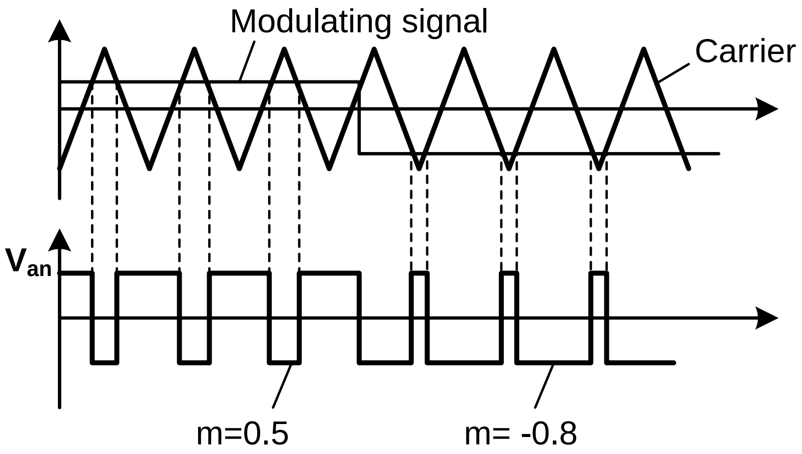


Based on slide by Frederick Bordry, CERN Accelerator school 2009

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 effectiveness 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.

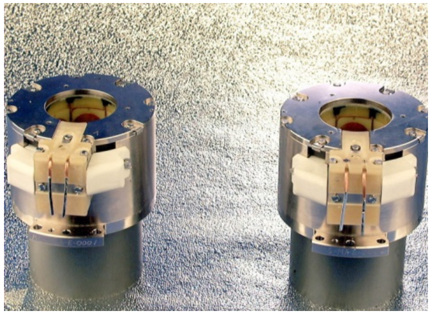
$$THD = \frac{V_{h,rms}}{V_{1,rms}}$$

LHC – the Large Hadron collider

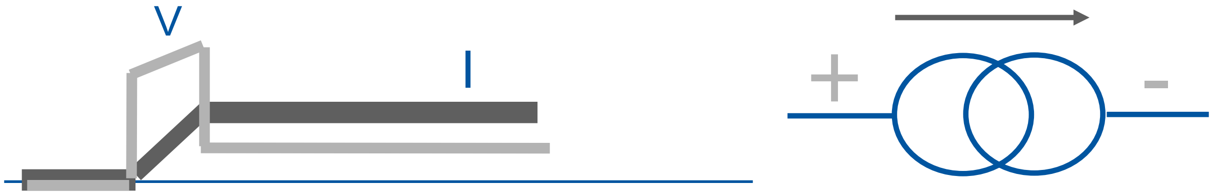
- **The beams are controlled by:**
  - **1232 SC Main Dipole magnets to bend the beams**
  - **392 SC Main Quadrupole magnets to focus the beams**
  - **124 SC Quadrupole / Dipole Insertion magnets**
  - **6340 SC Corrector magnets**
  - **112 Warm magnets**
  - **SC RF Cavities to accelerate and stabilize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

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

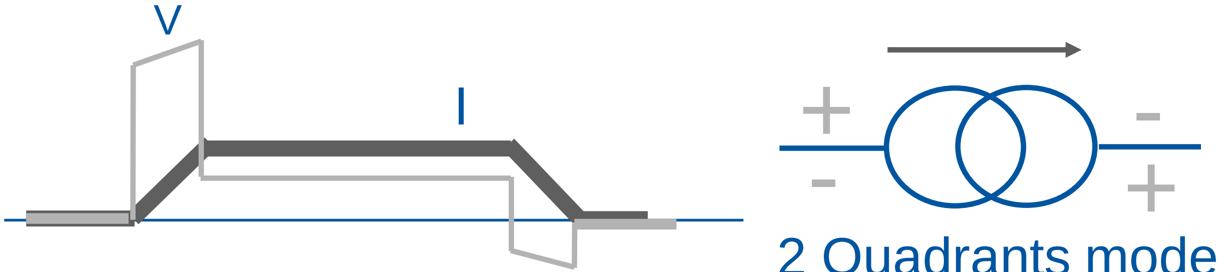
All ~8000 magnets need to be powered in a very controlled and precise manner



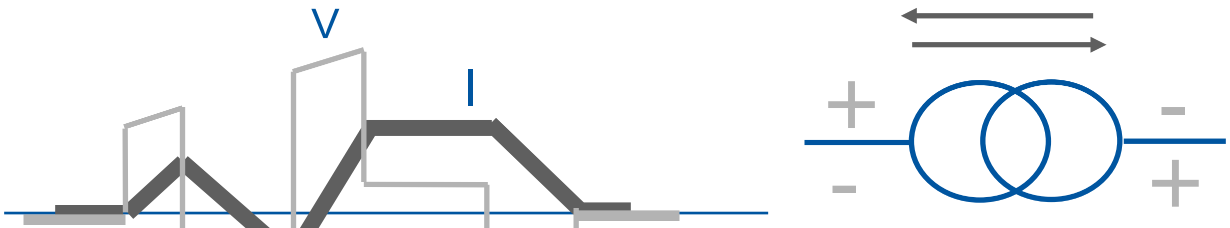
Converter operating modes



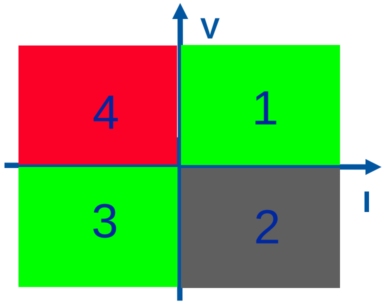
1 Quadrant mode



2 Quadrants mode



4 Quadrants mode



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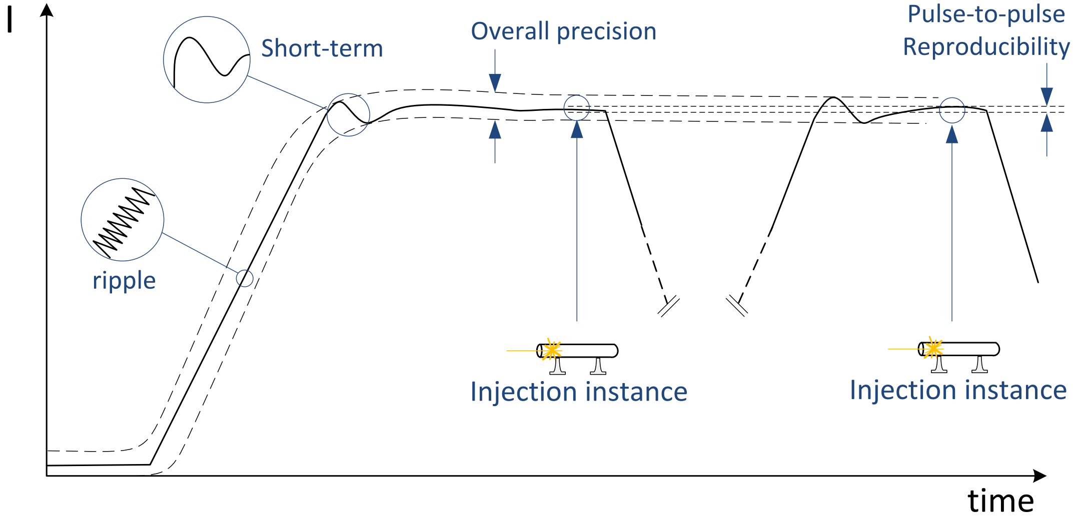
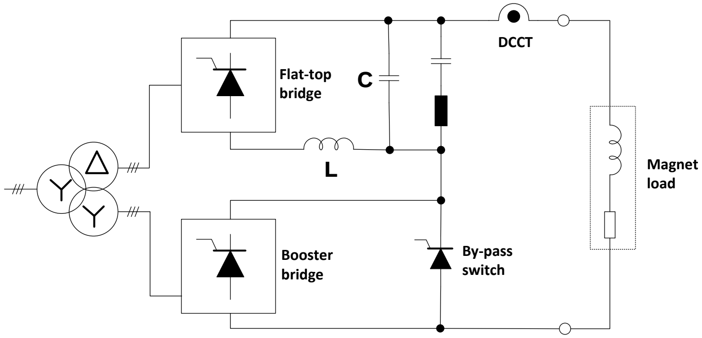
Current Precision

Current in a transfer line magnet





Precision components:

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

Typical requirements:

- 1-100ppm depending on application

LHC Powering Challenges

- **Installation (LEP infrastructure) and Operation**
  - ⇨ volume (a lot of converter shall be back-to-back)
  - ⇨ weight (difficult access) => modular approach
  - ⇨ reparability and rapid exchange of different parts
  - ⇨ radiation for [±60A,±8V] converters
  - ⇨ losses extraction : high efficiency (>80%) , water cooling (90% of the losses)
  - ⇨ high reliability (MTBF > 100’000 h)
  - ⇨ EMC : very close to the other equipment ; system approach

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LHC Power Converters

- A- Elementary module [3.25 kA, 18V], [2kA,8V] :
  - Switch Mode Converter (25-40 kHz, soft commutation)
  - Modular approach : 4.0 kA (28) , 6.0 kA (160) , 8.0 kA (8) , 13 kA (18)
  - Redundancy; small volume and weight

- B- Unipolar and Bipolar converters 600A
  - [± 600 A,± 10 V] : (~ 400)
  - [± 600 A,± 40 V] : (~ 40)
  - Energy dissipation SMPC : soft commutation ; 50-100 kHz

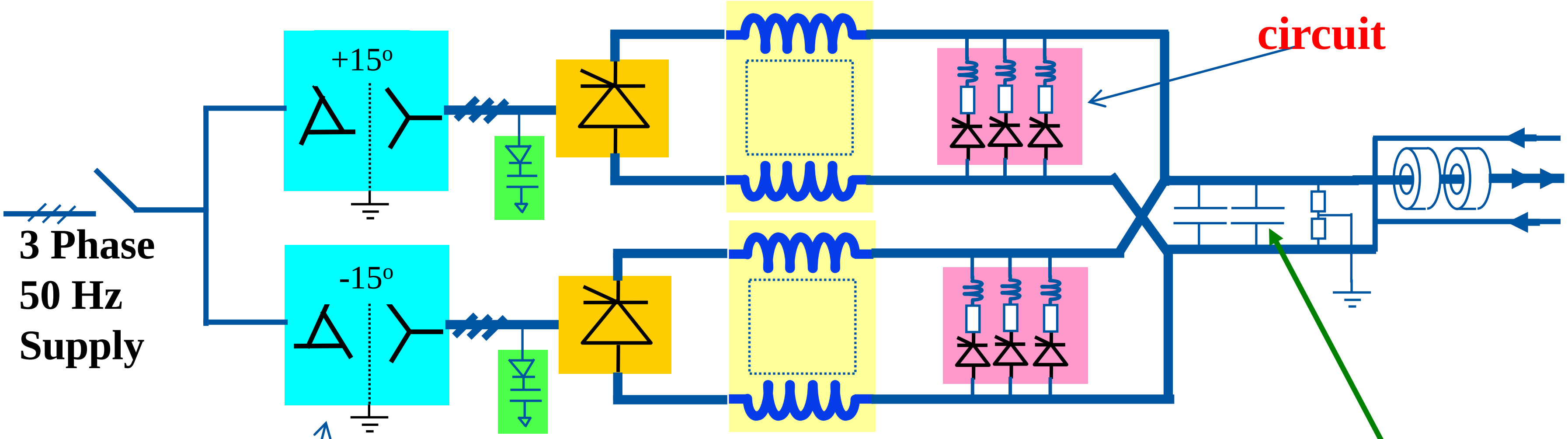
- C- Bipolar converter [±60 A, ± 8 V] and [±120A,±10V]
  - SMPC : soft commutation SMPC : soft commutation
  - High reliability, radiation resistance (tunnel installation)

- D- High voltage power converter [13 kA, ±180 V] (8)
  - High power SCR converter and Topology studies
  - Ramp (up and down) : [13 kA, ± 180 V] Flat bottom and flat top : [13 kA, 18 V]
  - SCR converter : [13 kA, ± 180 V] with Active filter : ±600A,±12V

Power Converter topologies

Two Quadrant Phase Controlled Rectifiers for high current SC magnets:

- Used for booster of Main Bend and large warm magnets



Freewheel circuit

3 Phase 50 Hz Supply

Good Symmetry

-Voltage bandwidth < 70Hz
- Well proven
- Inversion possible
- Active filter **(4% of the output voltage)**

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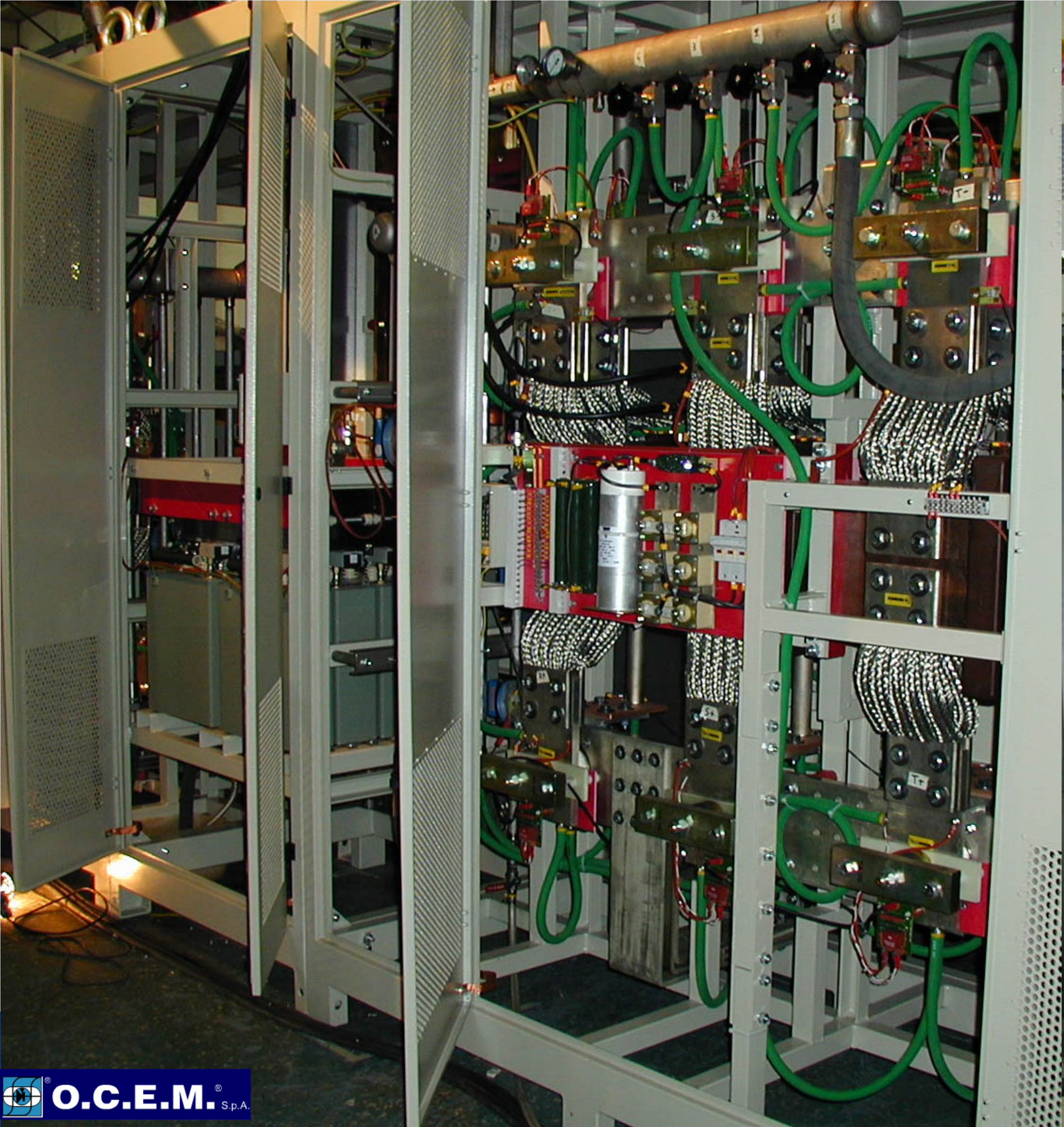


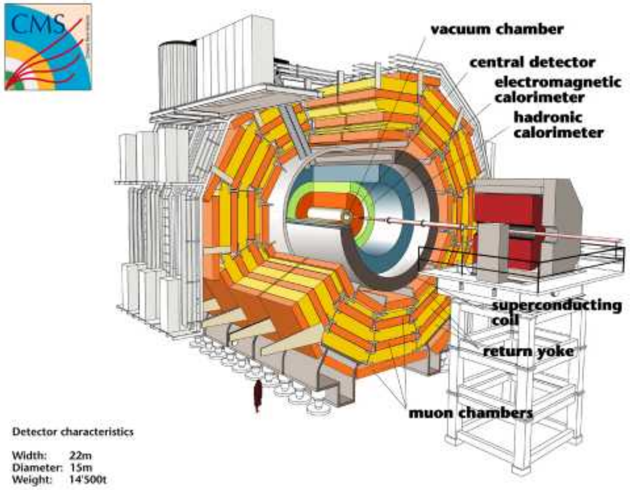
O.C.E.M.® S.p.A.

20kA power converter -CMS Solenoid

The load

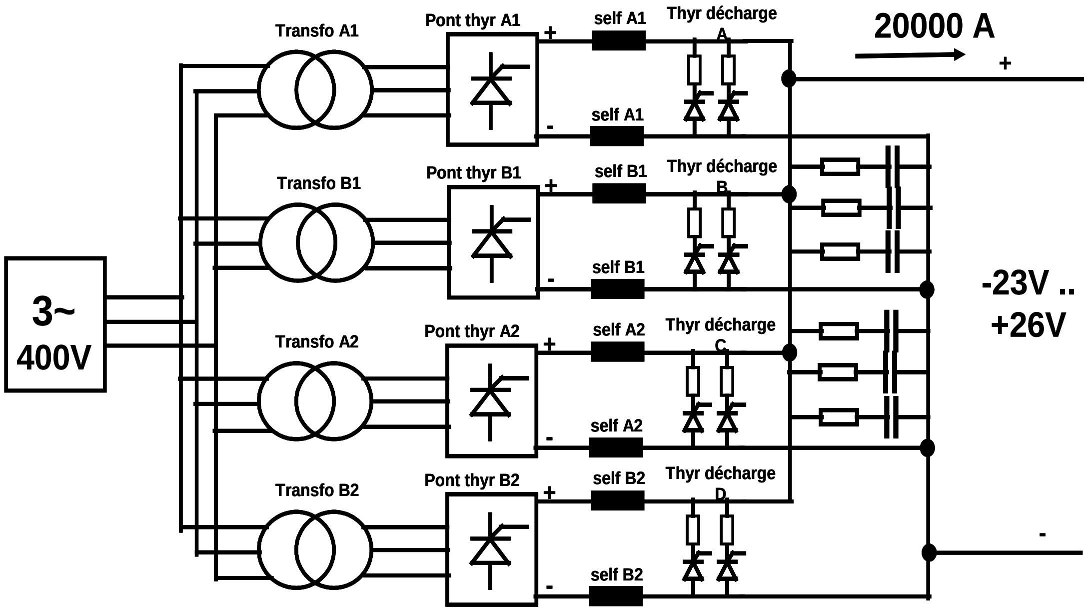
- **Superconducting magnet: L= 14H**
- **Nominal current: 20 kA**
- **Stored energy: 2.8 GJ**
- **Time constant: 39 hours**
- **Time for current ramping up: 3h15m**

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



The power converter

Equipaggiamenti Elettronici Industriali



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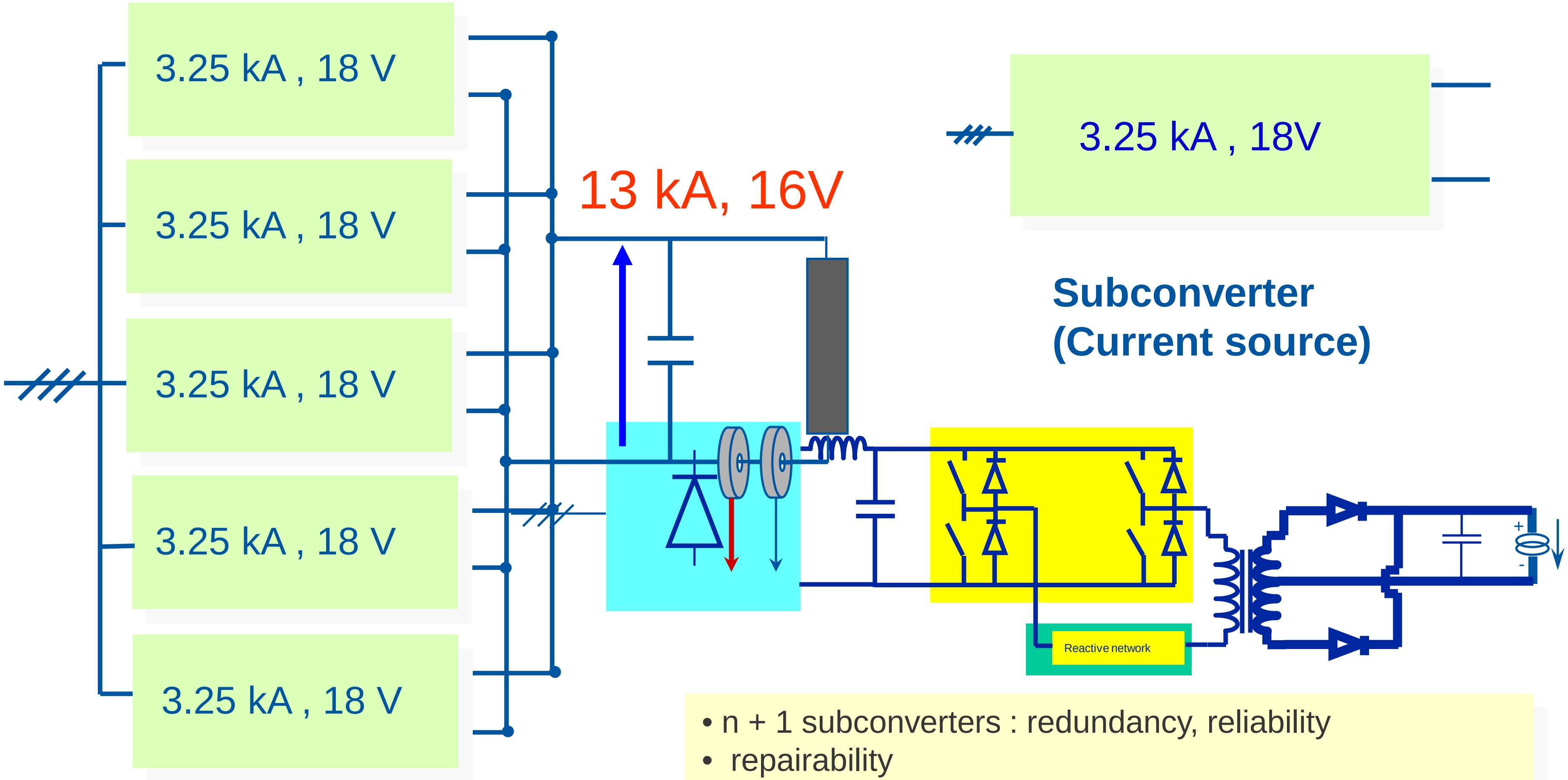
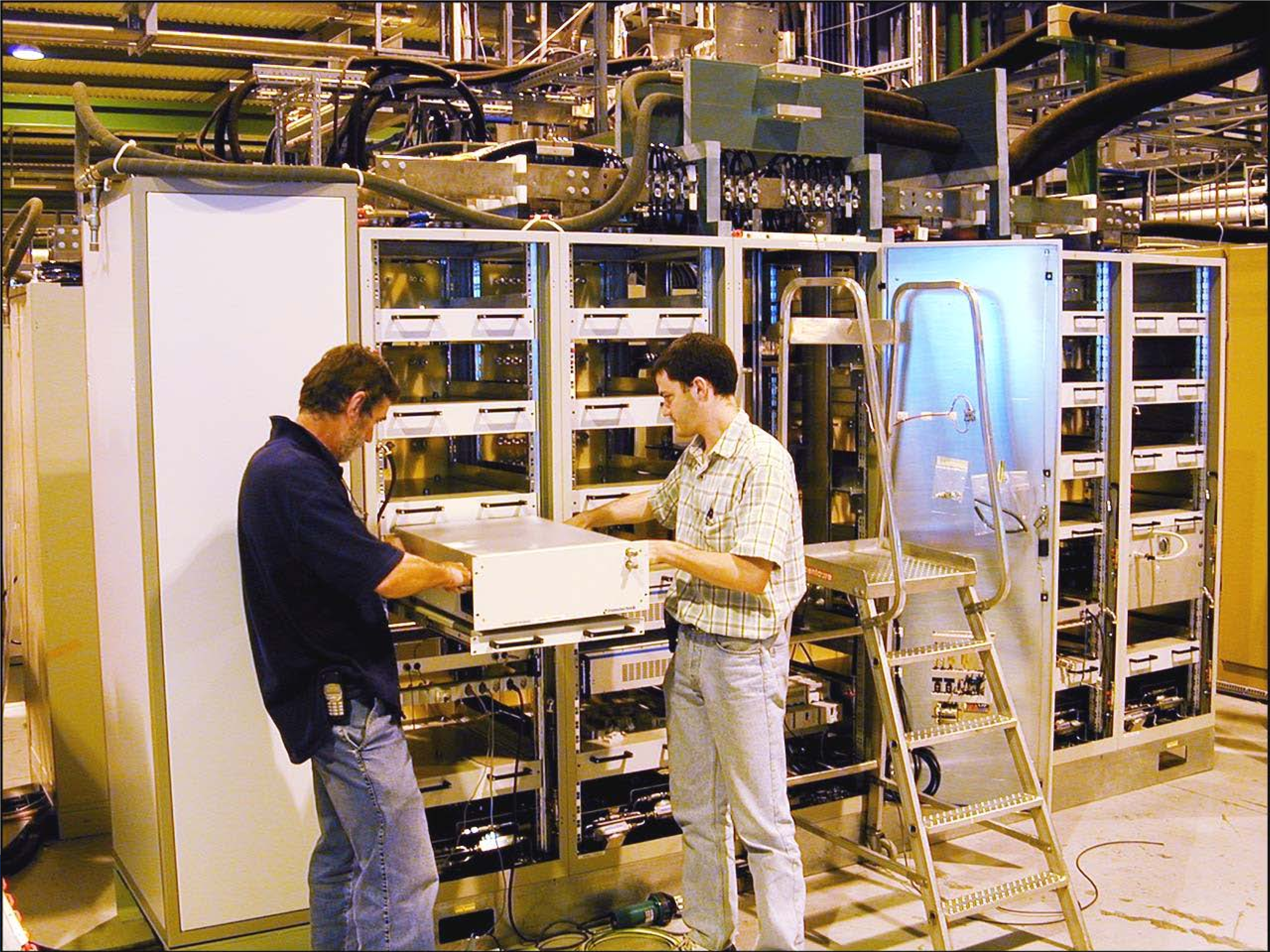
Converter modularisation



Converter

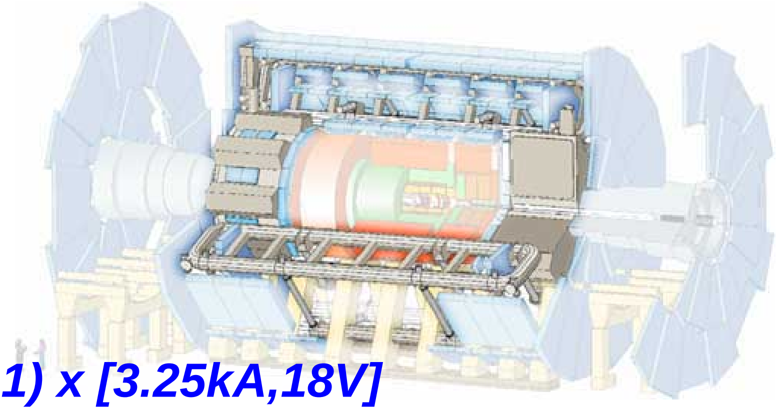
- n + 1 subconverters : redundancy, reliability
- repairability
- ease of handling underground
- versatility (6.5kA, 9.75kA, 13kA, 21 kA)



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]

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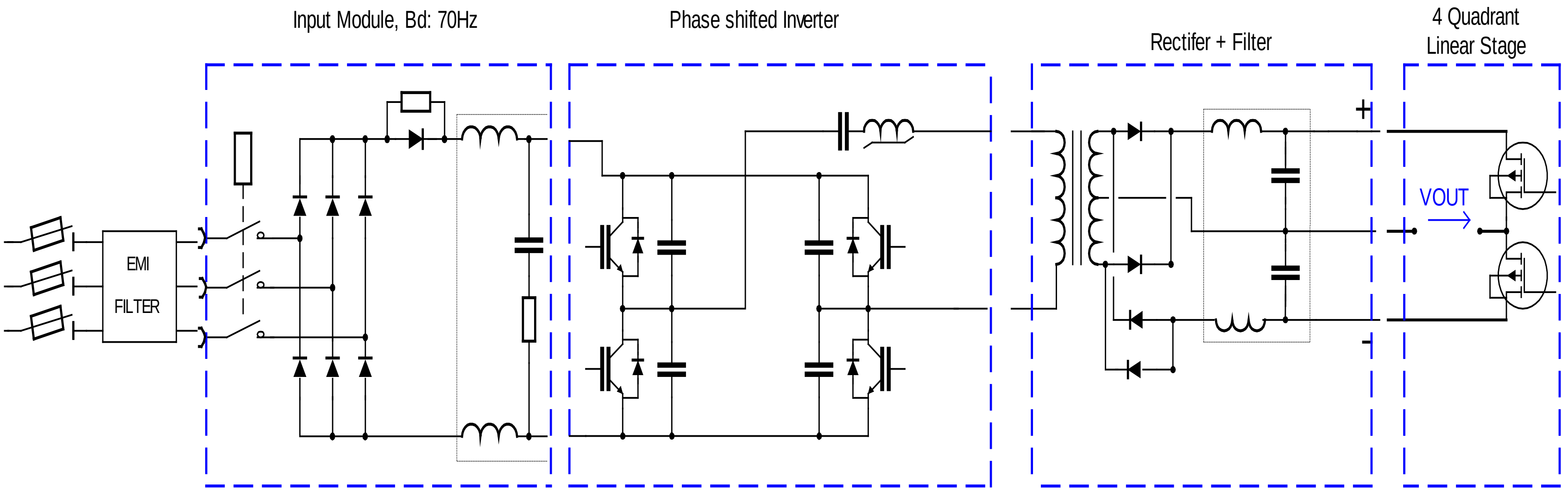
Typical Converter topology (120A,10V)



BREAKER &
CONTACTOR

INPUT FILTER &
SOFT-START

SOFT COM. INVERTER,
50kHz..100kHz

ISOLATION &
RECTIFIER + FILTER

4Q.L.S.

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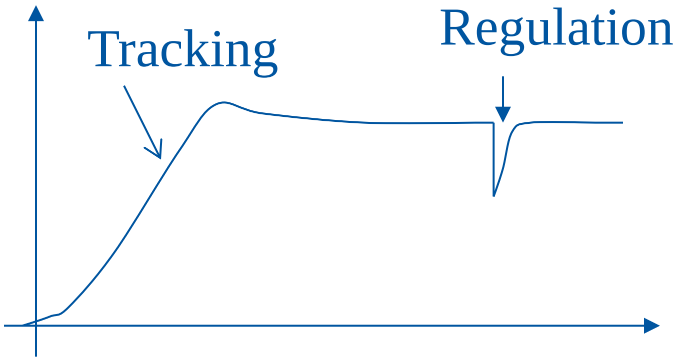
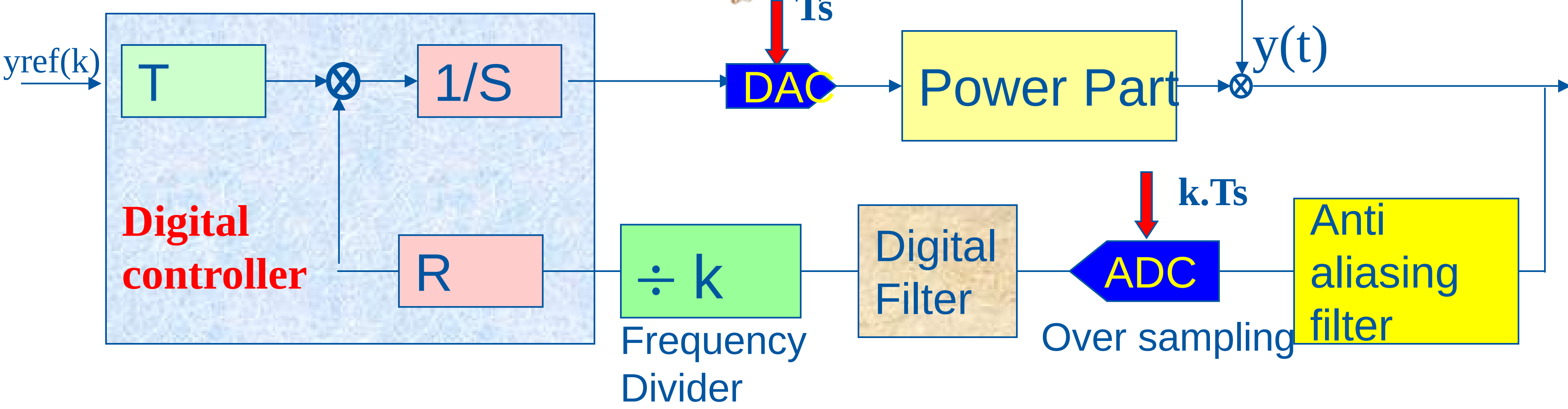
Digital control design

Tracking and Regulation with independent objectives





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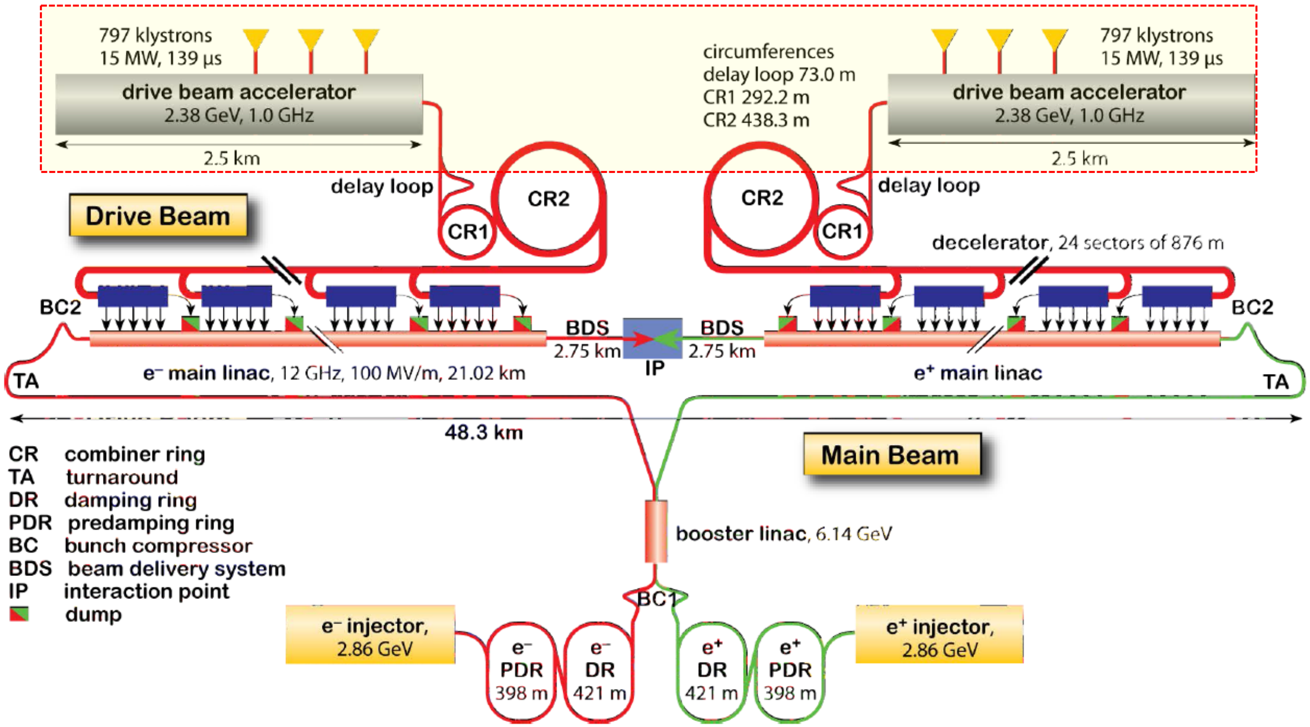
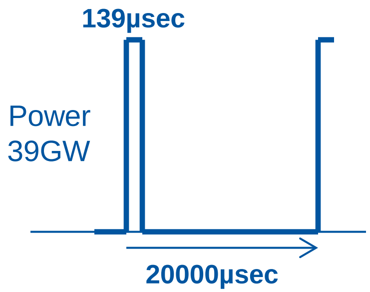
Power Electronics for the Future Accelerators

Compact Linear Collider (CLIC)

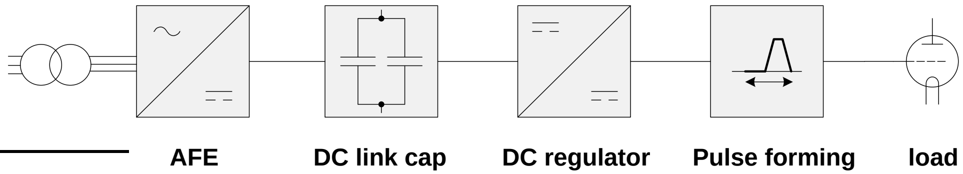


RF modulators are the primary electrical power consumer

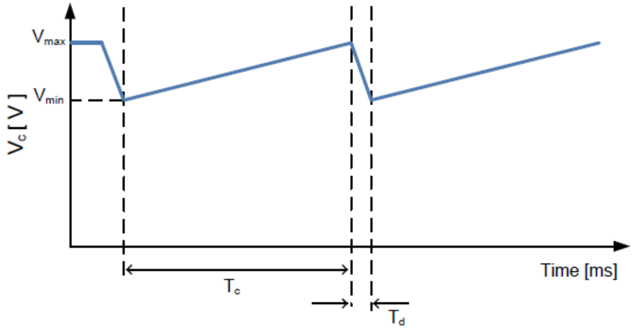
Pulses of 139us 150kV and 160A resulting in bursts of 24MW per modulator



CLIC Specifications



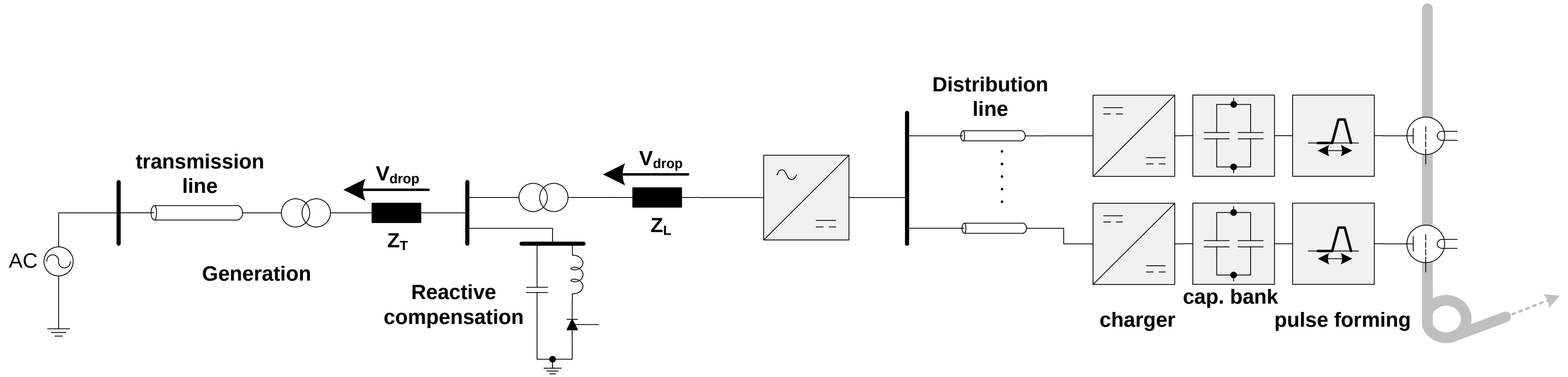
Modulator's output pulse specification			
Nominal pulse voltage	V_{kn}	150	*kV*
Nominal pulse current	I_{kn}	160	*A*
Pulse peak power	P_{mod_out}	24	*MW*
Rise & fall times	t_{rise}, t_{fall}	3	μs
Settling time	t_{set}	5	μs
Flat-top length	t_{flat}	140	μs
Repetition rate	*REPR*	50	*Hz*
Voltage overshoot	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	%

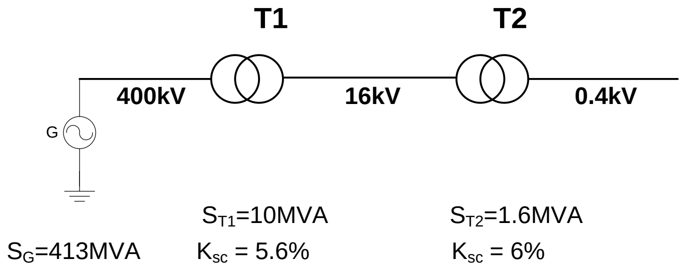


Application parameters:

- 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

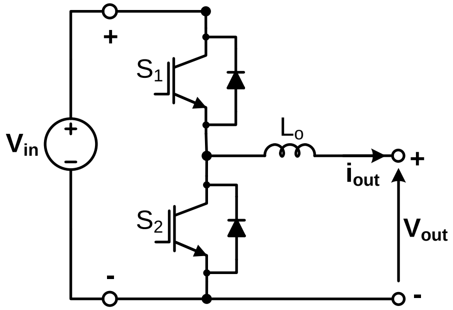


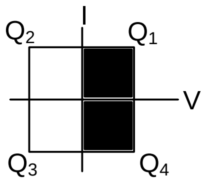


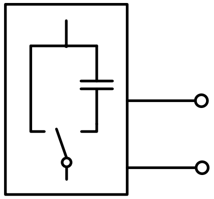
$$\frac{1}{S^{SC}} = \frac{1}{S_G^{SC}} + \frac{1}{S_{T1}^{SC}} + \frac{1}{S_{T2}^{SC}} = \frac{1}{413} + \frac{1}{179} + \frac{1}{26} = \frac{1}{21.5}$$

- 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

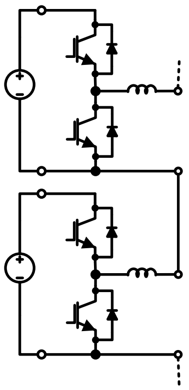




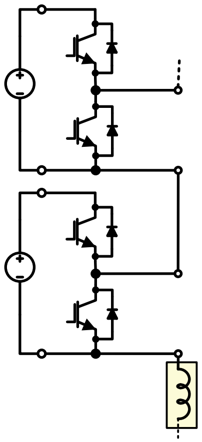


Q1: V: positive
I: positive

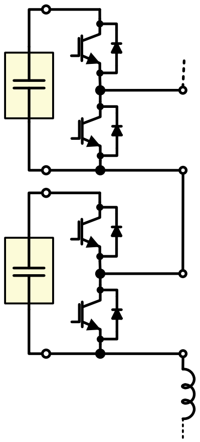
Q2: V:positive
I:negative



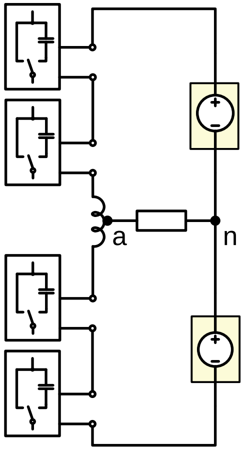
Series-connection of 2Q dc/dc



Lumped inductor



Capacitors in place of voltage sources

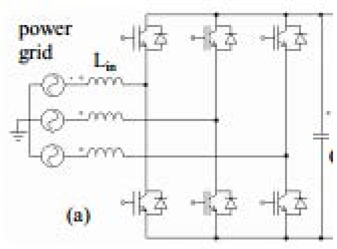


DC-supply added

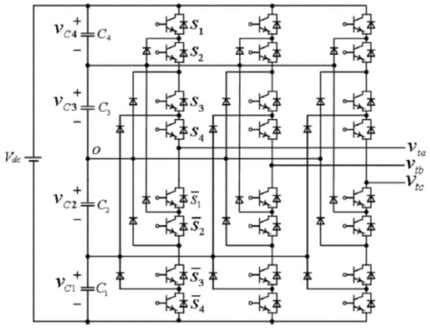
AFE Concepts

Topology comparison for:

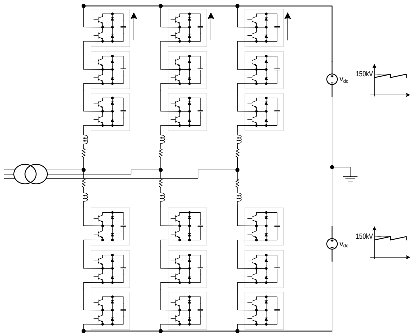
- high voltage (>20kV) and
- high power (>20MW) applications



Three phase-bridge



Five level NPC



Modular-multilevel-converter (MMC)

AC Filter size	◆	◆◆	◆◆◆
Control system	◆◆◆	◆◆	◆◆
Reliability ★	◆◆	◆◆	◆◆⬩
Spares inventory	◆◆	◆	◆◆◆⬩
Power range	🟩🟩🟩	🟩🟩🟩🟥	🟩🟩🟩🟥🟥
Mechanical integration	◆◆◆	◆	◆◆

★particularly interesting at higher voltage/power applications

- Any questions?
- Aftervisit reading: http://www.cern.ch/aftervisit

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