10th January 2025

Power electronics for very high Energy Accelerators
–
Today’s and Tomorrow’s Challenges

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Accelerator System dept.

Electrical Power Converter Group

On the menu

CERN & the Electrical Power Converter Group

Why power converter in accelerators?

Specific design challenges

Wide variety of applications - Designs examples

Current & future projects involving R&D

Academic & industrial collaborations opportunities

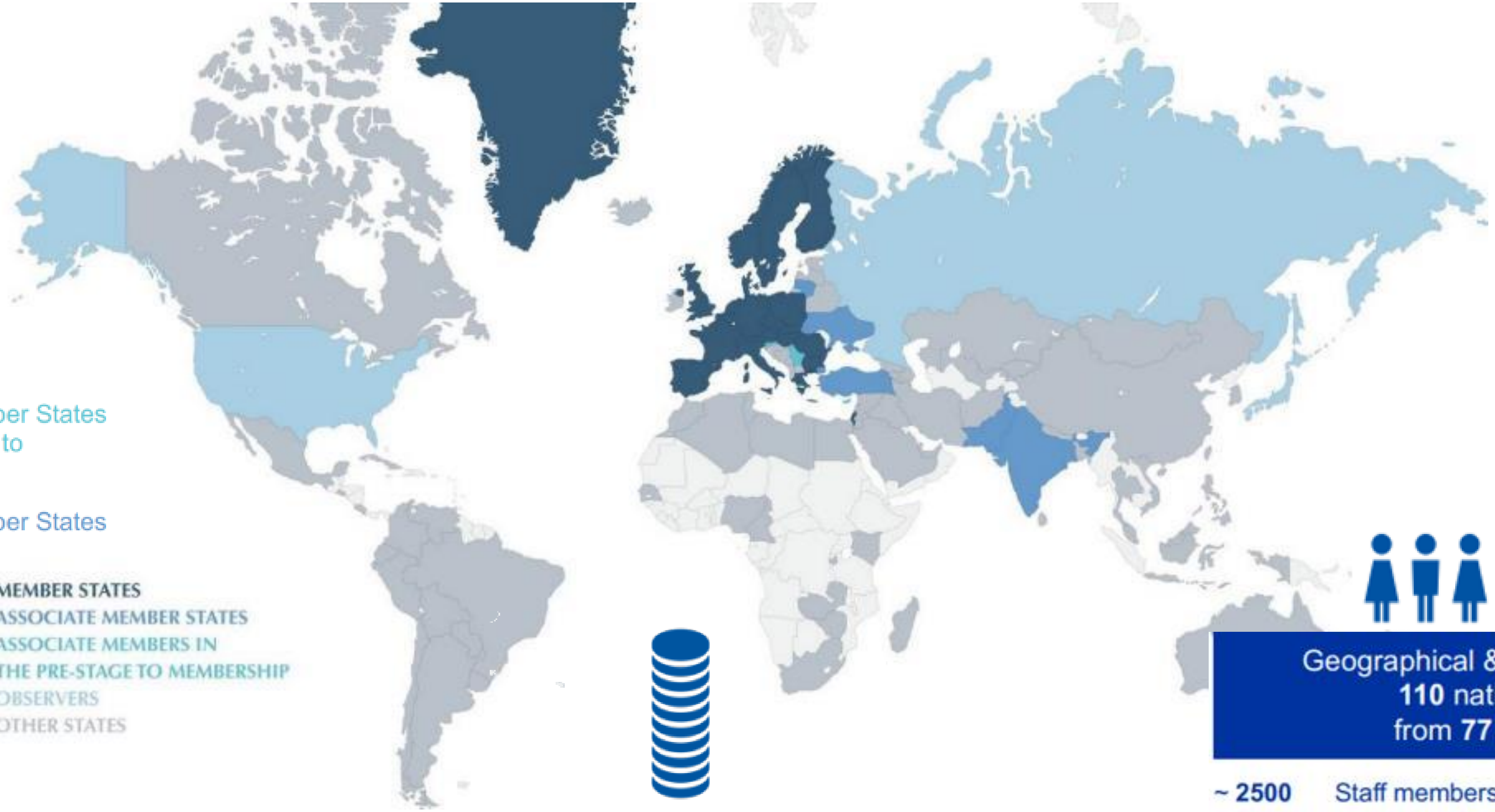
CERN
&
the Electrical Power Converter (EPC) Group

CERN in a nutshell

CERN ID

Name	*European Organization for Nuclear Research*
Surname	*CERN – Conseil Européen pour la Recherche Nucléaire*
Mother & Father	*UN and 12 member states*
Date of Birth	*29 September 1954 (proposals started in 1946)*
Purposes	*Probing fundamental structure of the Universe*
	Bringing nations together through science
	Advancing frontiers of physics and technology
	Educating scientists & engineers of tomorrow
Financed by	*23 European member states*
Disting. marks	*Multi-cultural / peaceful / ethic / creative / motivated*

Today CERN has 23 EU Member States and more…



23 Member States

3 Associate Member States in the pre-stage to membership

6 Associate Member States

Yearly budget ~ 1200 MCHF

Geographical & cultural diversity
110 nationalities,
from **77** countries

~ 2500	Staff members
~ 2000	contractors' employees
~ 13000	physicists /users


LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SUISSE
FRANCE
SPS 7 km
ALICE
CMS
LHC 27 km

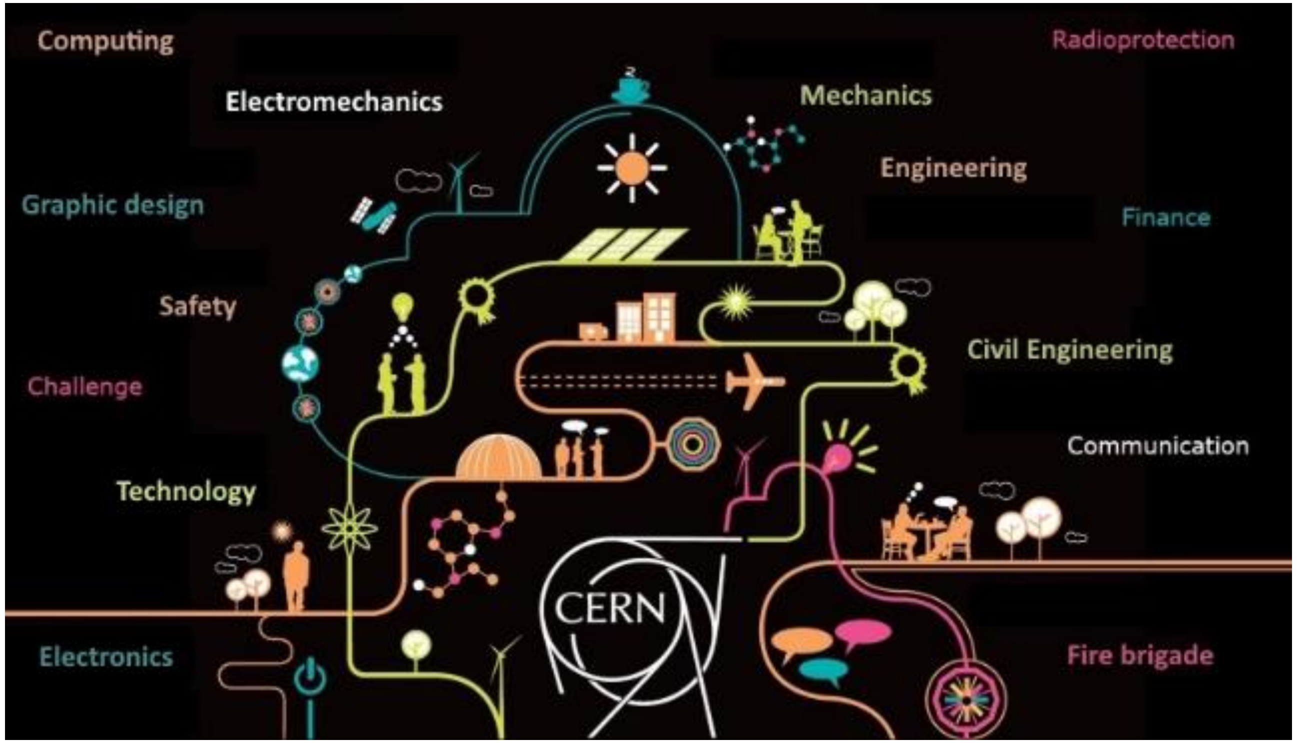
Who works at CERN ?

Several personnel categories

		Nb	Position /year
Professionals	**Scientific/Eng. Work Technical Work**	**1998**	150
	Theoret. physicists	082	
	Administr. work	420	
Graduates	Early / Experienced	800	400
Post-Docs	Research Fellows		40
	Technical /Administr. Students		250
	Doctoral Student		80
Students	Summer Students	400	300
	Short-term Interns		250
	Apprentices		

Wide professional variety

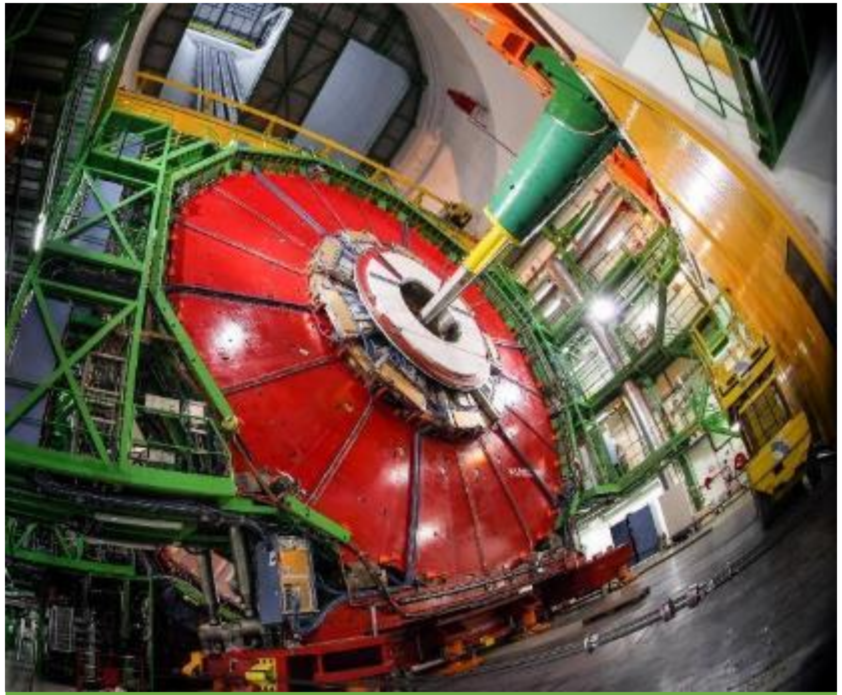
including in science, technology and engineering



https://careers.smartrecruiters.com/CERN/

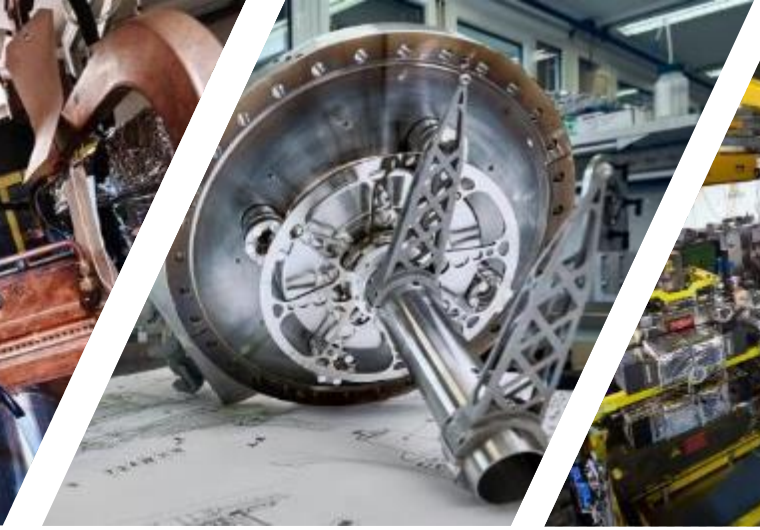
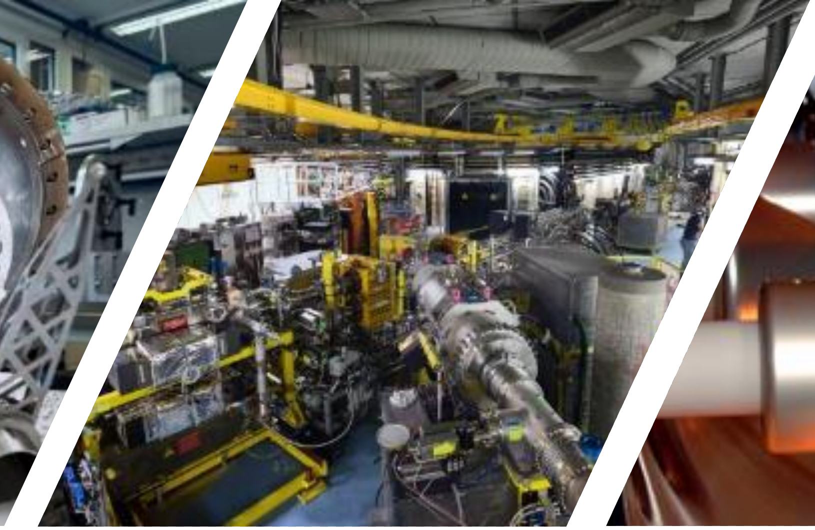
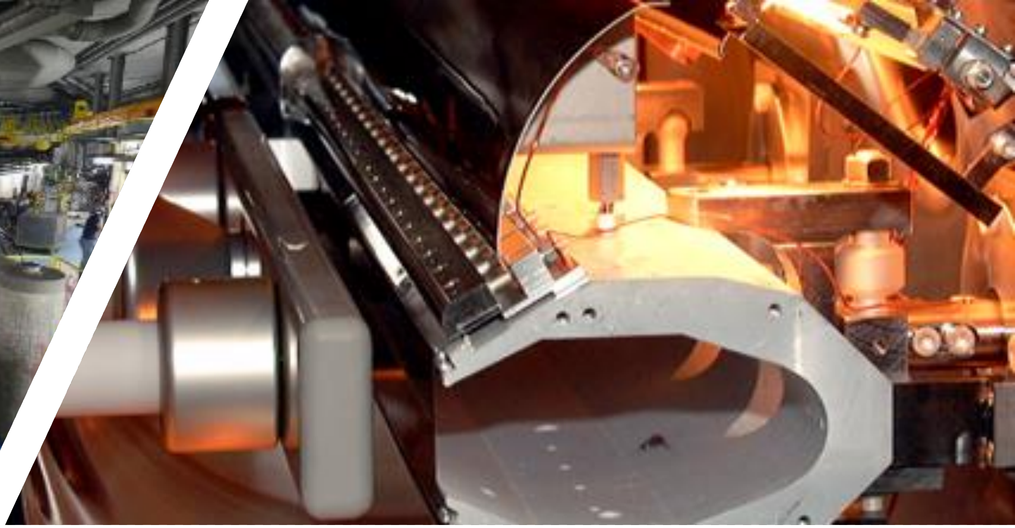
We develop technologies in three key areas

ACCELERATORS



DETECTORS

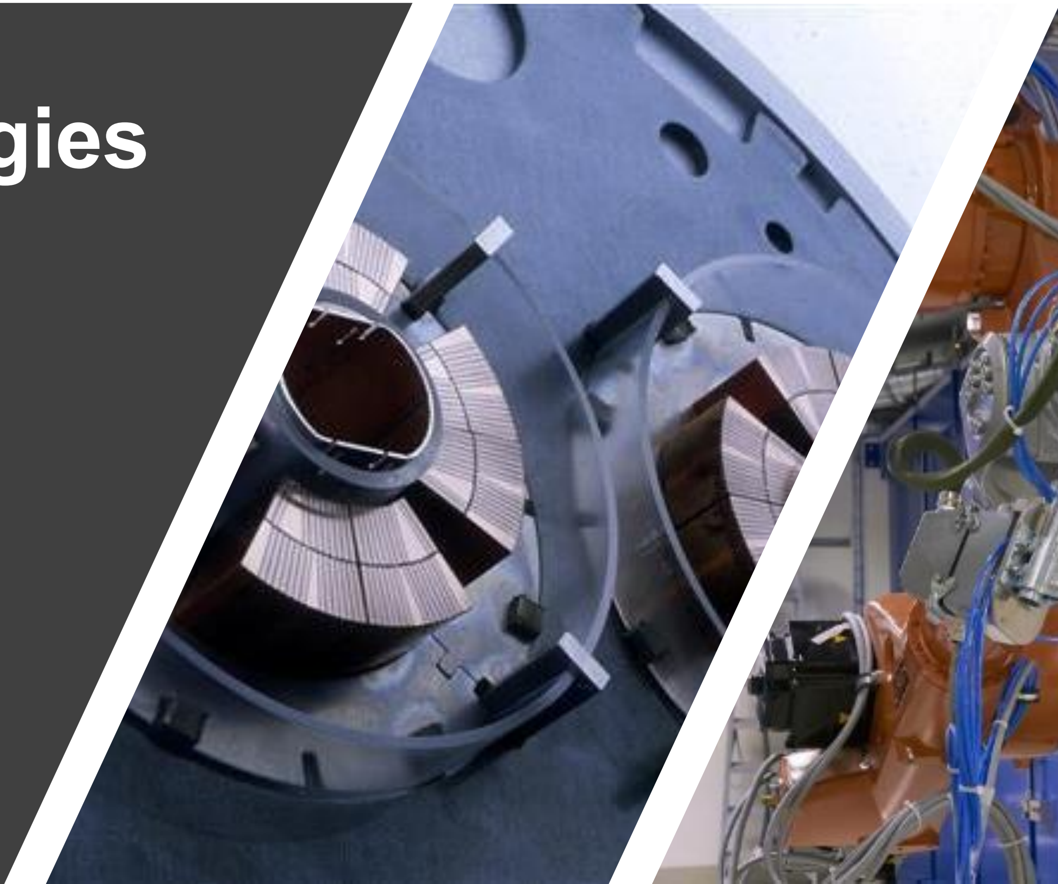
COMPUTING

Accelerator’s technologies

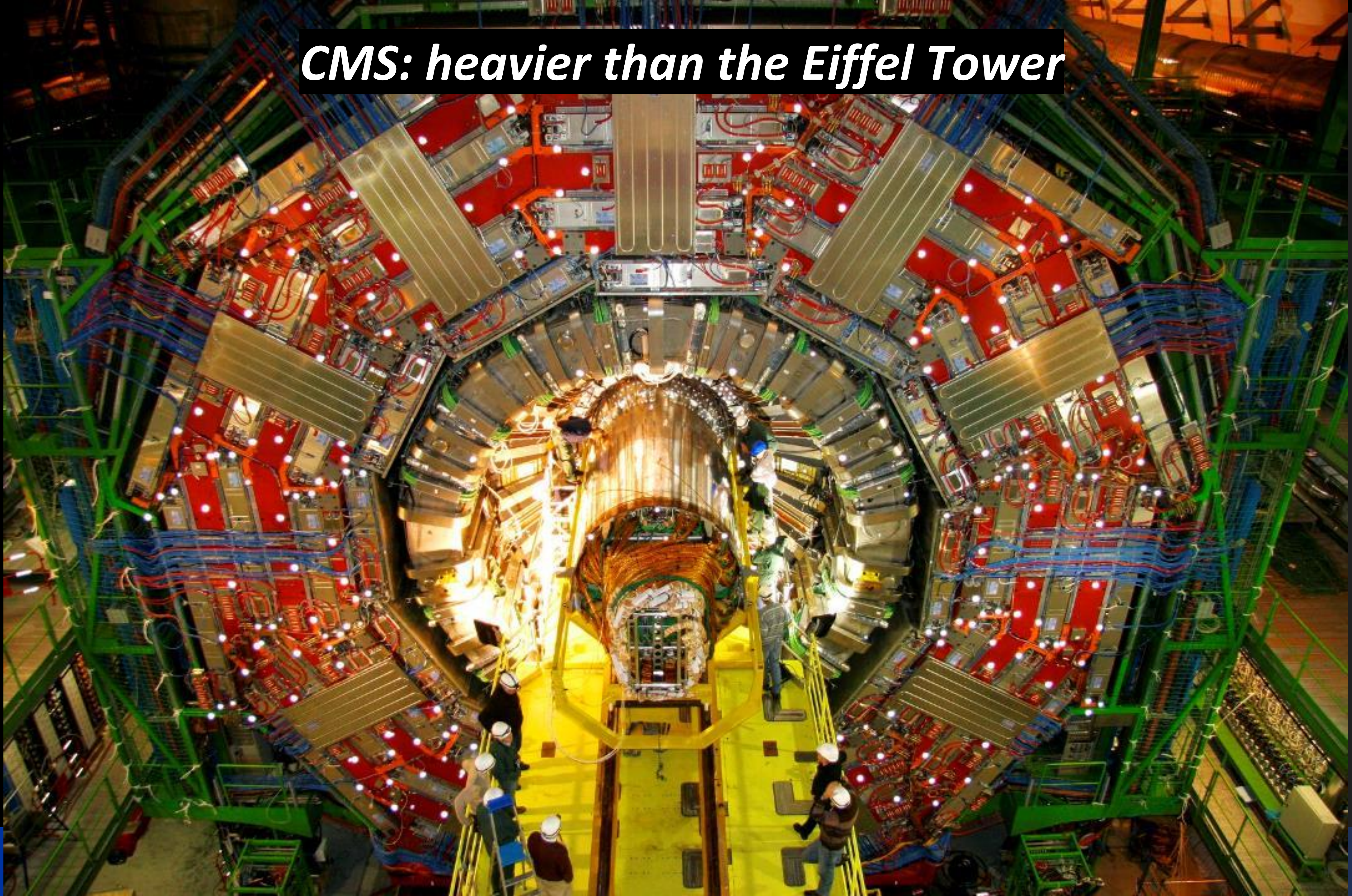
Beam must be:

- ➢ Accelerated
- ➢ Guided
- ➢ Measured (position, intensity)
- ➢ Controlled




ATLAS: as big as a 5-storey building

CMS: heavier than the Eiffel Tower



Electrical Power Converter group, our mandate

Responsible for:

- Design
- Installation
- Performance
- Operation & maintenance

of electrical power converter systems

Activities:

optimization

Numerical simulations

FAT

procurement

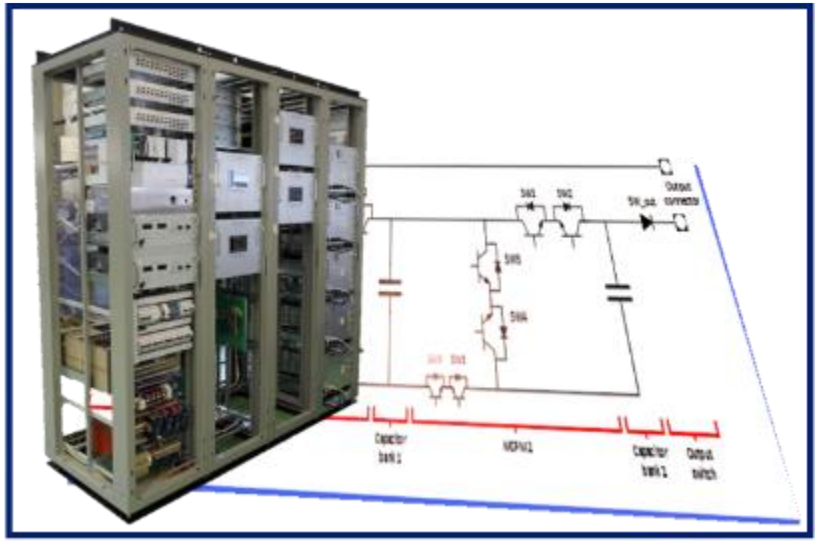
standardization

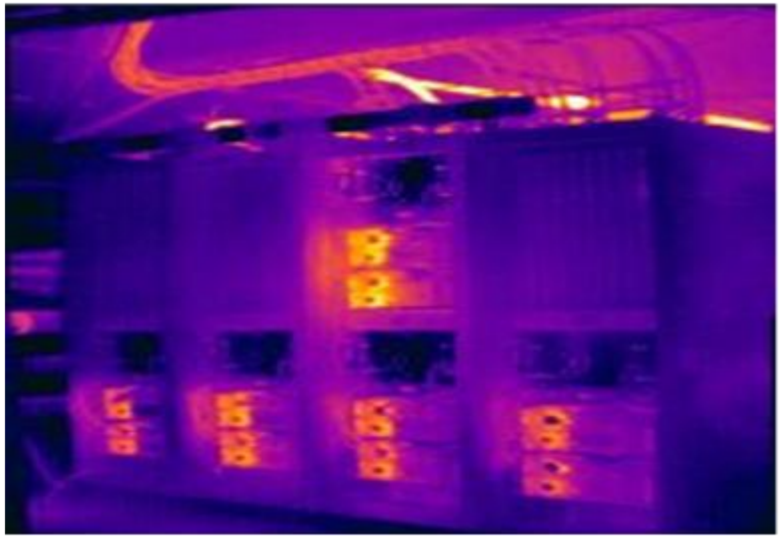
prototyping

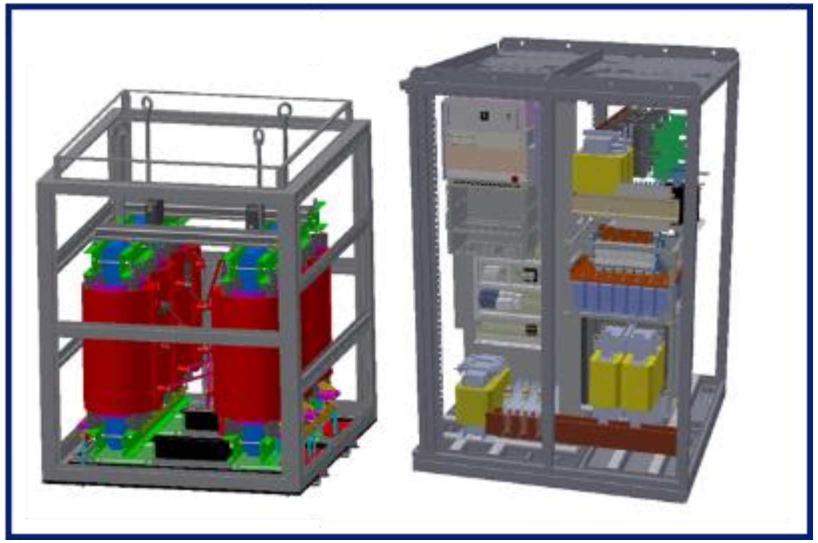
24/7 stand-by service

Lab. testing

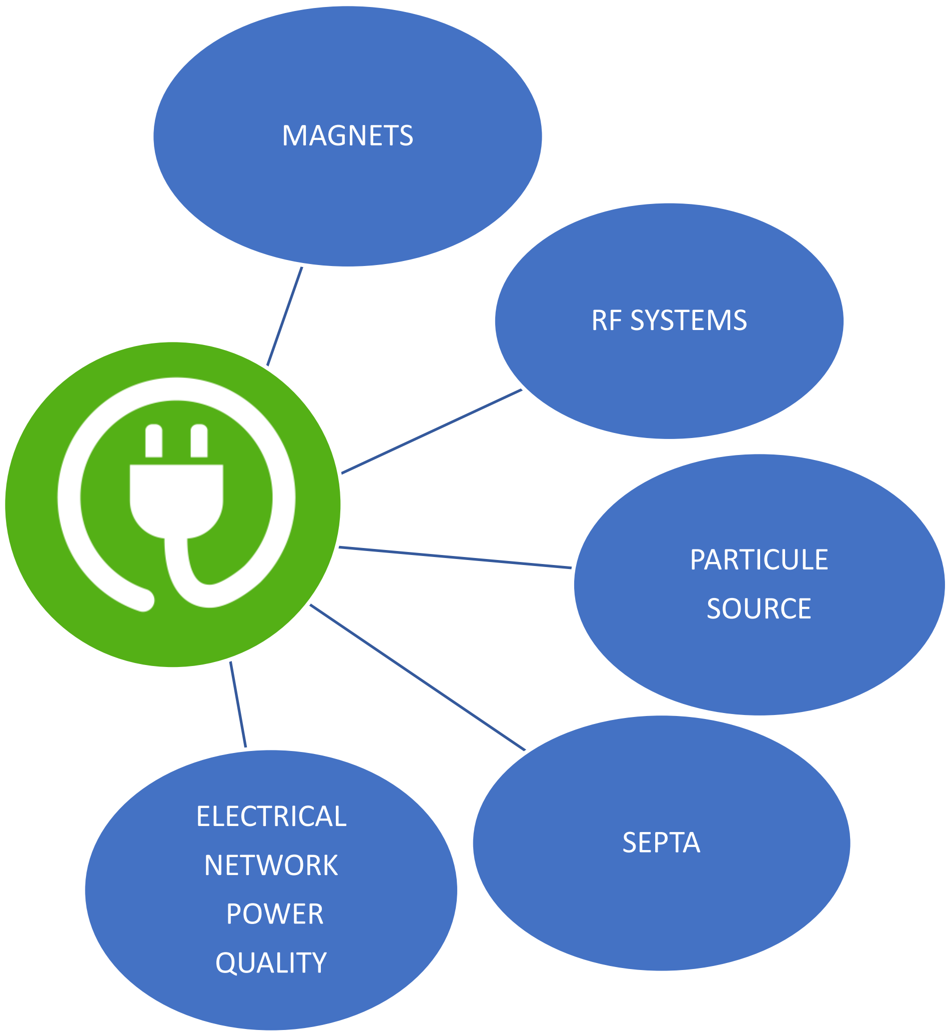
documentation







Electrical Power Converter group, a wide diversity



5300 power converters

from 100 W up to some MW

from 1A up to some kA

from V to some hundred kV

from DC to Cycled or Pulsed mode

from low to high-precision

Electrical Power Converter group, a powerful group !

69 STAFF
03 DOCT
27 GRADUATE
09 TECH/TRNE

104

CONTRACTORS

8 SECTIONS

- **- CCS - Converter Controls Software**
- **- LPC - Low Power Converters**
- **- MPC - Medium Power Converters**
- **- HPM - High Precision Measurement**
- **- CCE - Converter Controls Electronics**
- **- HPC - High Power Converters**
- **- FPC - Fast Pulsed Converters**
- **- OMS – Operation Maintenance Support**

EPC Video

Why power converters in accelerators?

Why power converters in acc.?

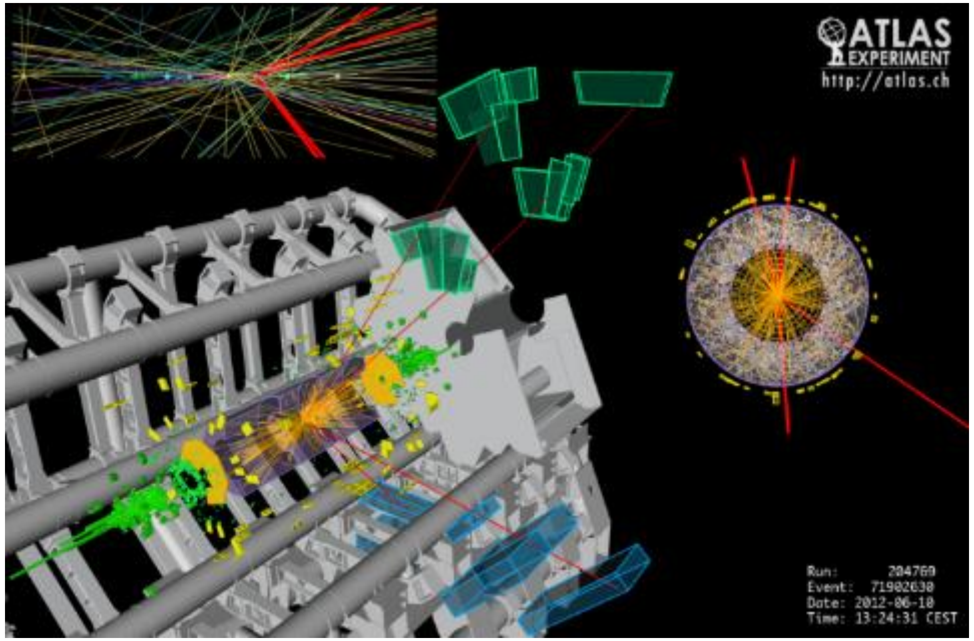
Why we accelerate particles?

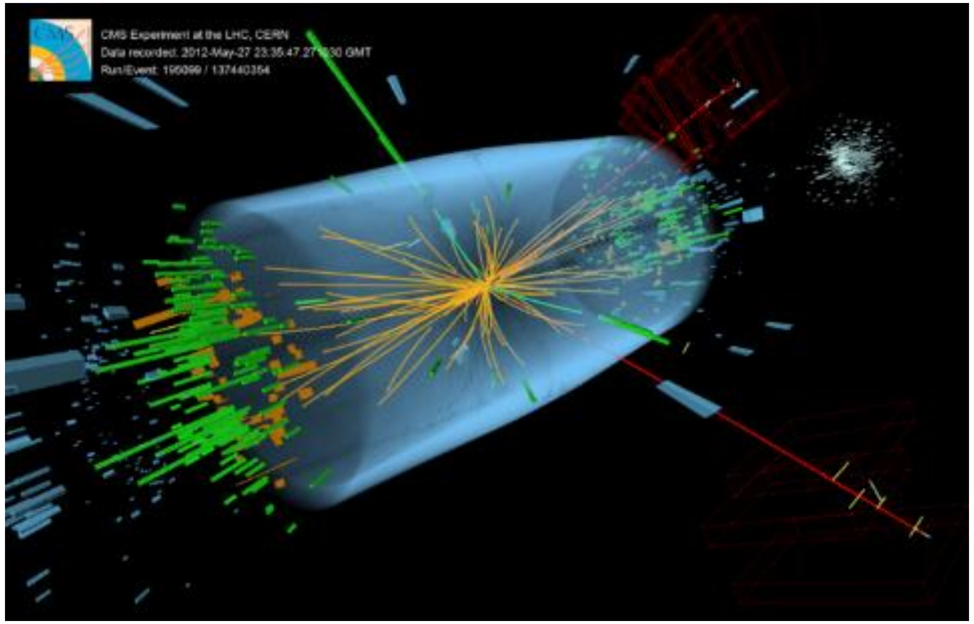
Reminder: mass-energy equivalence

$$E = mc^2$$

1. We accelerate to increase particles' mass
2. Then we smash them
3. Their big mass-energy are converted into a multitude of other particles at lower energies (energy conservation)
4. We study the behavior of these "produced" particles (some does not exist naturally on earth)

Particles that don't exist at rest energy (e.g. anti particles) appear; sometimes new things appear!

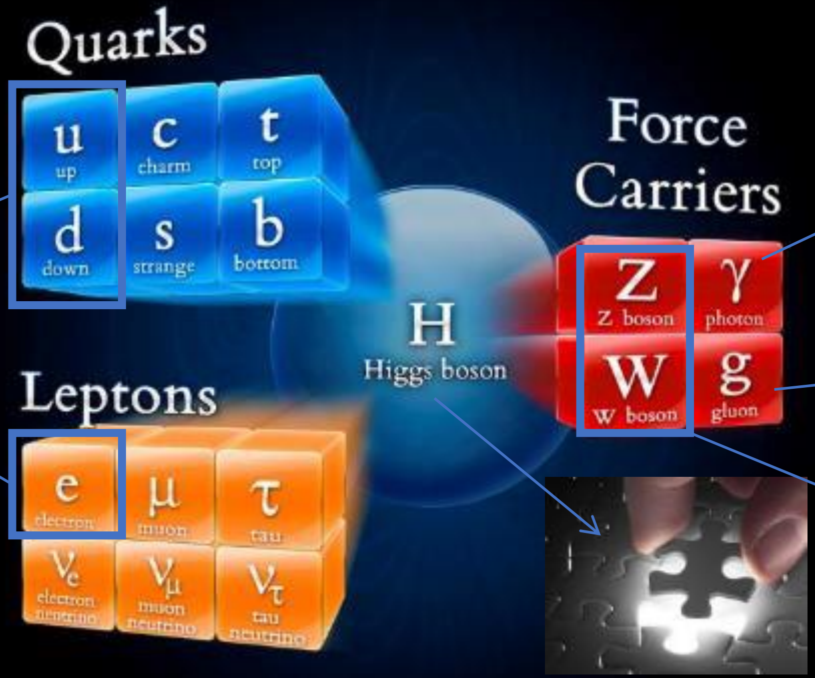




Example of what we «see» to study particles behavior (proton-proton collisions at the LHC)

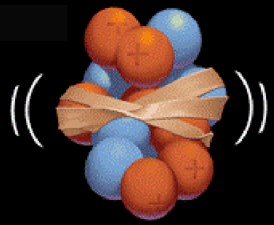
Few elementary particles naturally exist on earth

The Standard Model (no gravitation → « graviton »)



Electro-magnetic

Nuclear



Weak

Standard model explains 5% of visible-known matter

→ 95% of universe not know (72% Dark Energy & 23% Dark Matter)

→ Accelerators used to verify the model & discover (see) new matter of the unknown 96%!

Why power converters in acc.?

To accelerate and guide a beam of charged particles (*q*) forces are applied via Electric and Magnetic fields:

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

Acceleration

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

↓

Need for HV to create strong electric fields

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** ←

Specific design challenges

Power converters specific challenges

Reliability – Availability & Maintenance

- Availability
  - Modular designs for low MTTR & n+1 as much as possible
  - Hot spares modules (automatically put into operation) - LHC case
- Maintenance
  - Predictive maintenance: monitoring of critical parameters or statistics on common failures (when issues declared already)
  - Preventive maintenance: during annual shut-downs (e.g. Oil Transformers, dust cleaning, etc.)
- Faults during Operation
  - 24/24, 7/7 On call service for all our equipment's

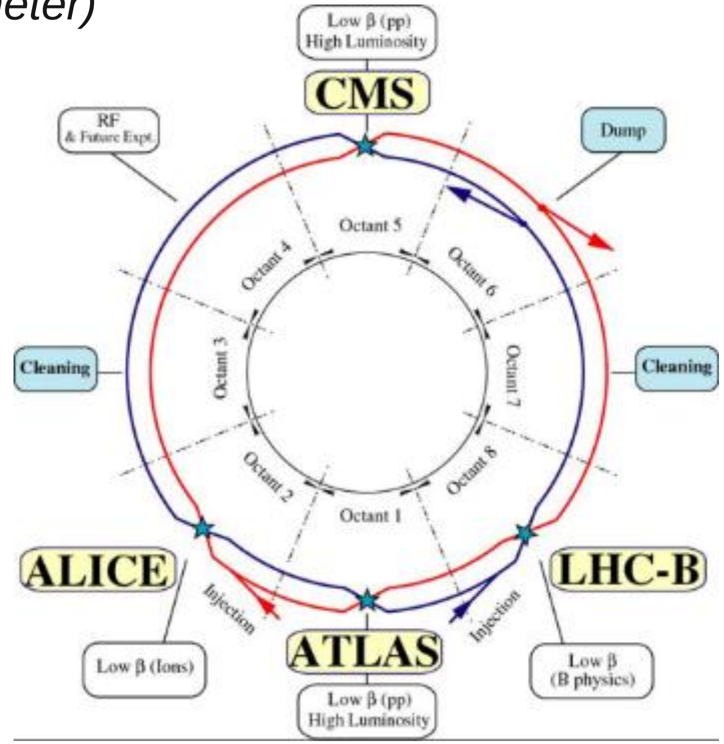
LHC power module

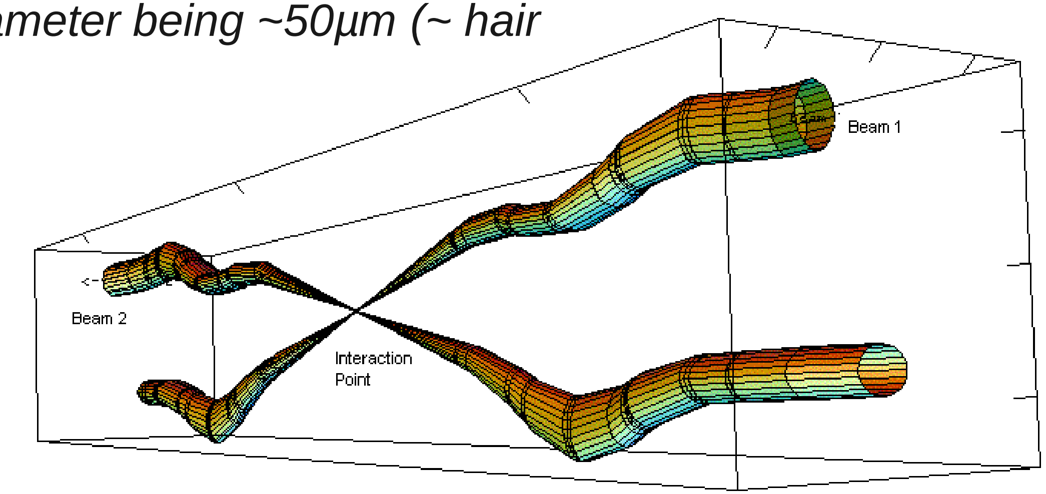
Power converters specific challenges

Precision

- Trajectory precision ≡ magnet current precision
- Beam position vibration ≡ magnet current ripple
- Beam position repeatability (cycle to cycle) ≡ Current stability and repeatability

LHC collisions need beam perfectly aligned, their diameter being ~50µm (~ hair diameter)





Relative beam sizes around IP1 (Atlas) in collision

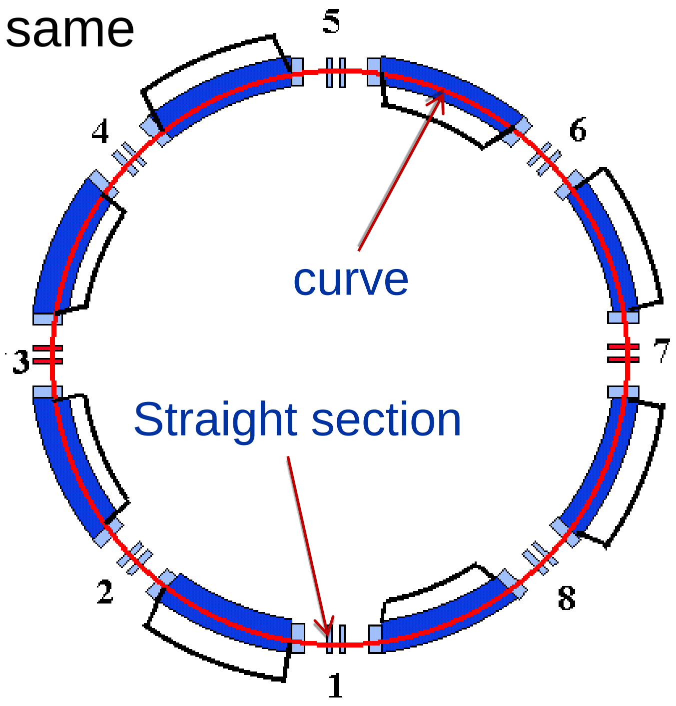
- 600M collisions/second if beams aligned
- To perfectly align beams, currents in different LHC sectors must match to the part per million (ppm) precision

Power converters specific challenges

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 – 13*mA* on 13*kA*!



Therefore, the current in the different sector power supplies must track to the ppm.
Approach:

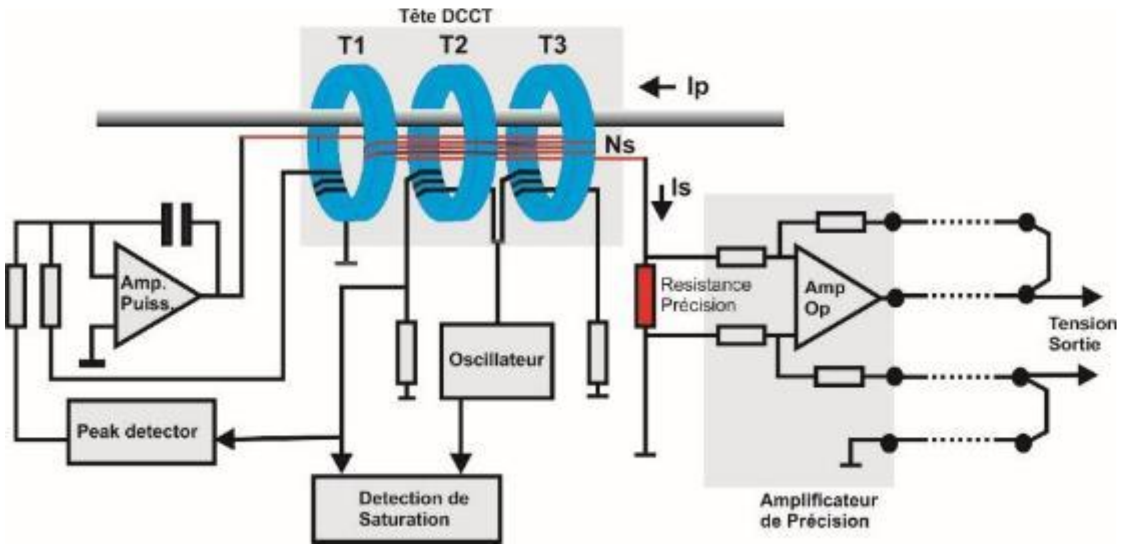
1. The same current reference is sent to all sectors (over 27*km*) with a time «jitter» of <1*μs* (dedicated PLL over WorldFIP).
2. High precision measurement (DCCT)
3. High performance digital regulation loop (RST with practically no tracking error)

Power converters specific challenges

High precision measurements

High beam position precision obtained via high precision current measurements. DCCT (*DC Current Transducer*) to measure currents (10 A – 10s kA) with very high precision required (developed in collaboration with industry).

DCCT principle (zero flux)



LHC's 13 kA DCCT head – equipped with supplementary calibration winding

High precision amplifier

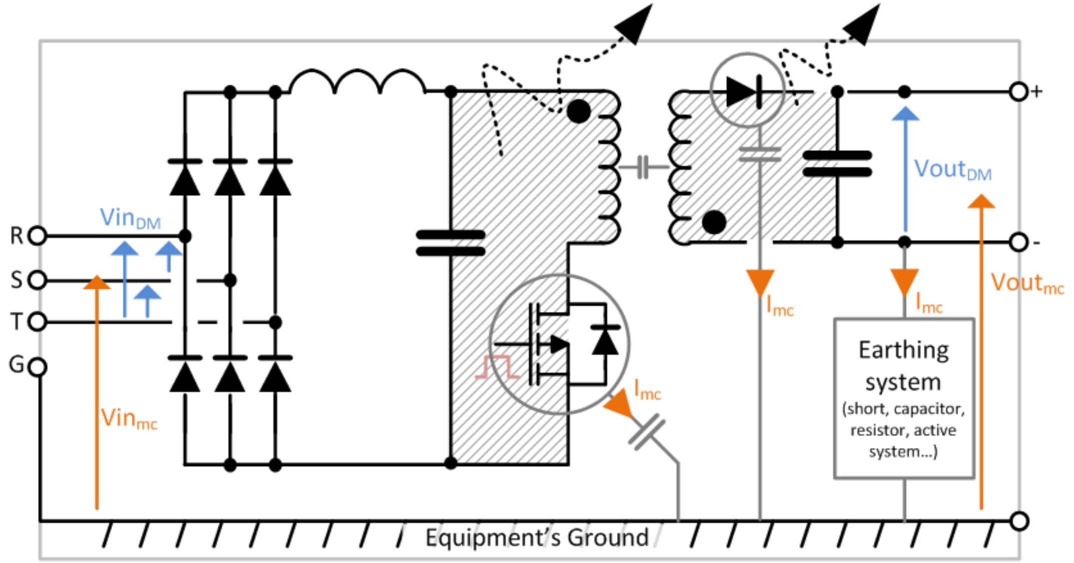
Power converters specific challenges

<u>Precision</u> (LHC case)

Electromagnetic compatibility is essential in high precision power converters

<u>Weak EMC ≡ precision is compromised!</u>

<u>Eg. *ppm* regulation with % measurement noise is impossible!</u>



1700 switching converters:

➡ 1700 noise sources

km of analogue cables:

➡ many coupling channels for noise

Ex.: 1m cable pile

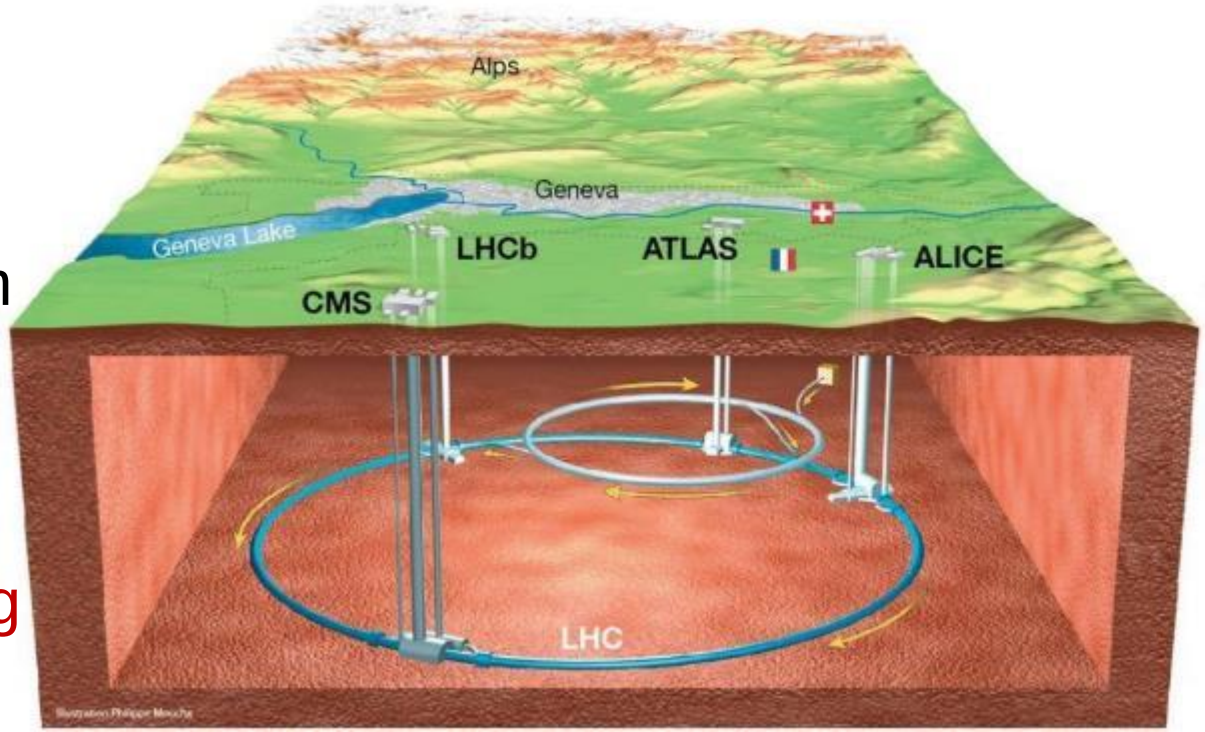
- Immunity is essential!
- A single EMI event in a converter can cause the loss of the beam

Power converters specific challenges

Efficiency and volume (LHC case)

LHC is at 100m underground
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!

Tolerance to radiation considered in design phases

Power converters specific challenges

CAPEX & OPEX: Standardization and modularity

- Wide variety of specs (small to big accelerators)
  - Reducing CAPEX with higher volume components
  - Reducing OPEX with fewer converter models

Example of a modular converter family covering a wide specs spectrum

Wide variety of applications - Designs examples

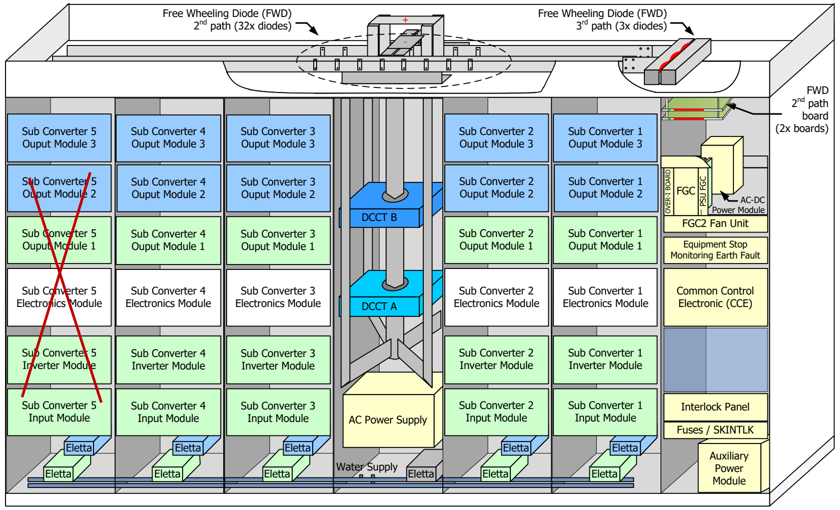
Wide variety of applications and designs - examples

LHC quadrupole power supplies

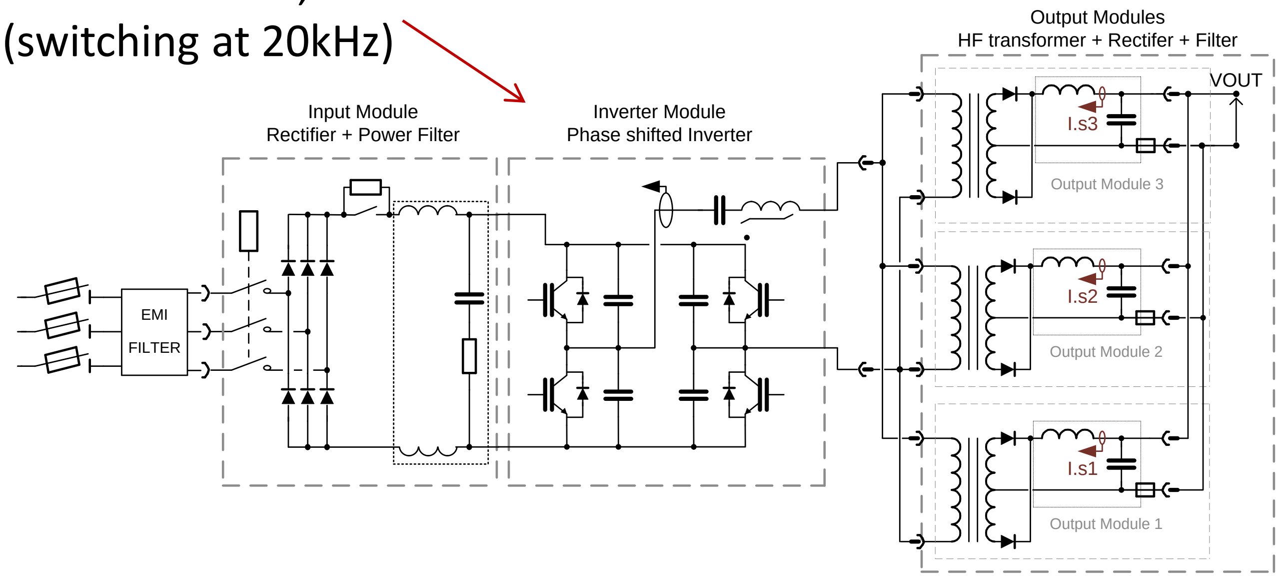
Specifications:

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

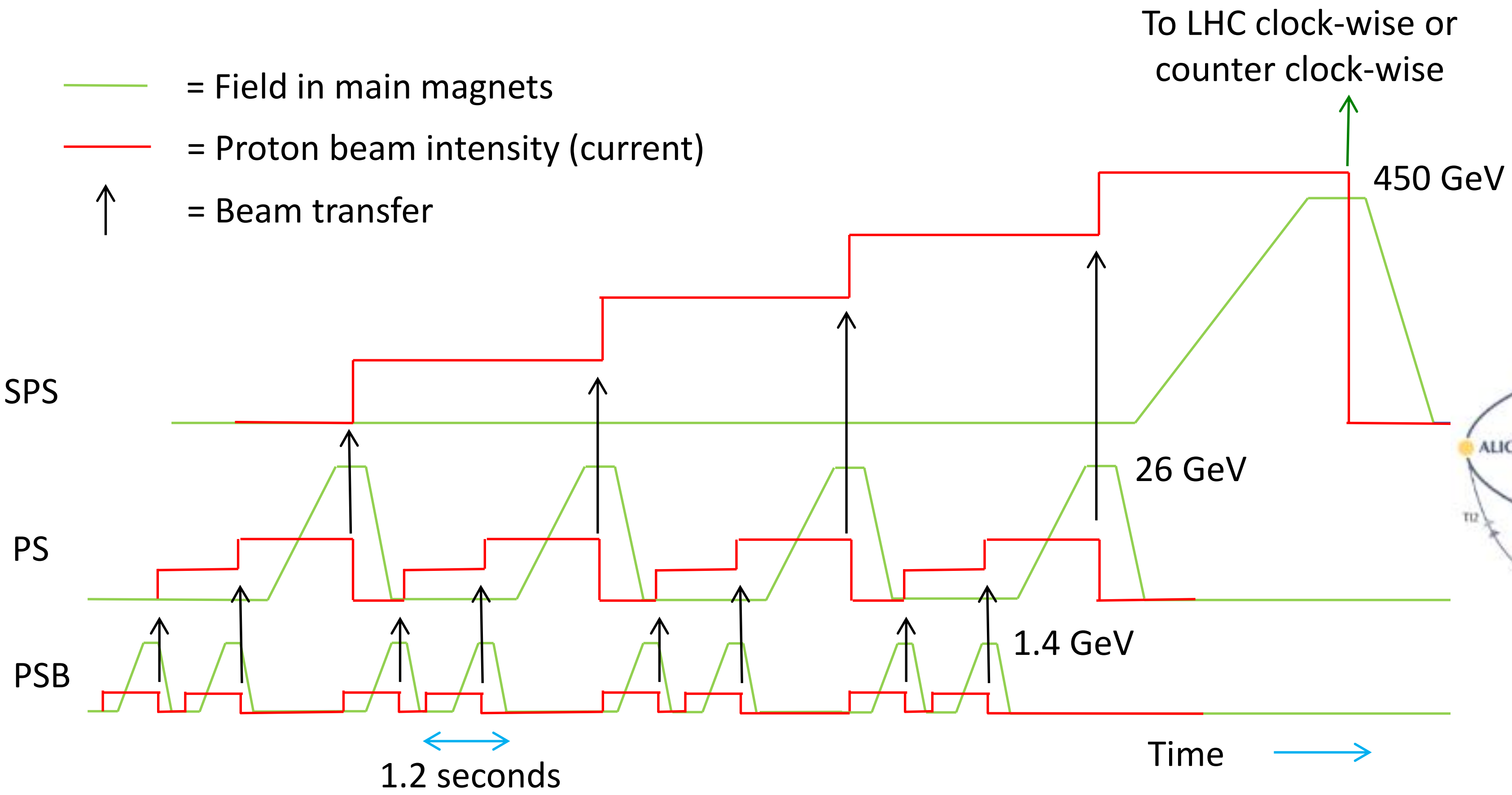


Module 3.25kA, 18V (switching at 20kHz)

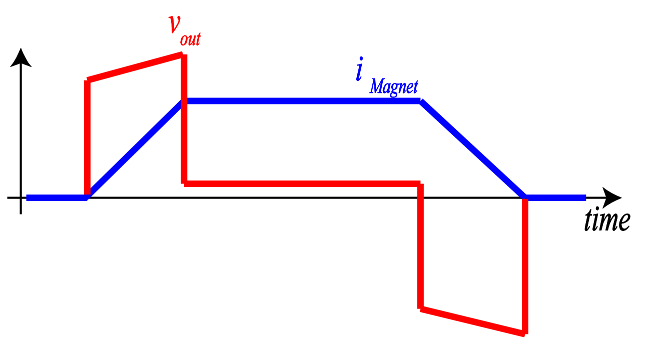


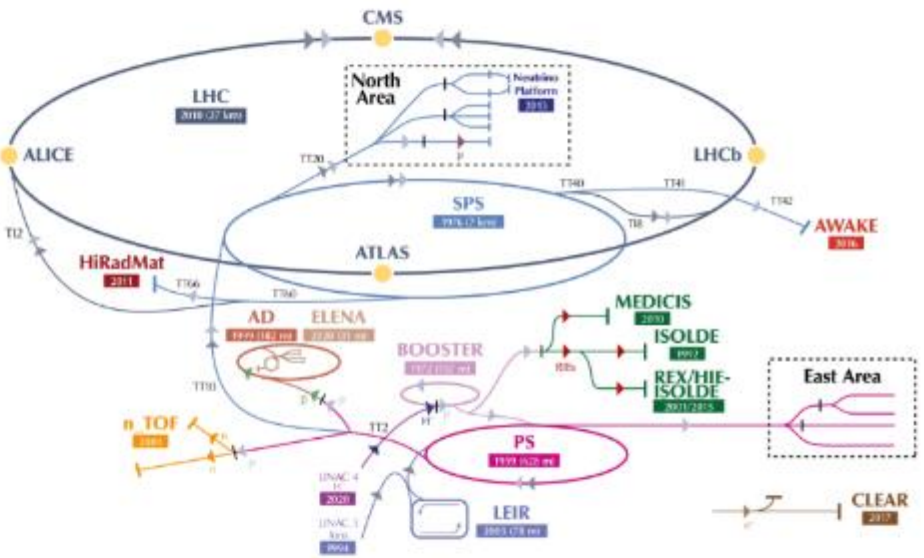
Wide variety of applications and designs - examples

Accelerators are cycling (with thermal cycling issues for power converters)



Typical voltage & current shapes applied to magnets:





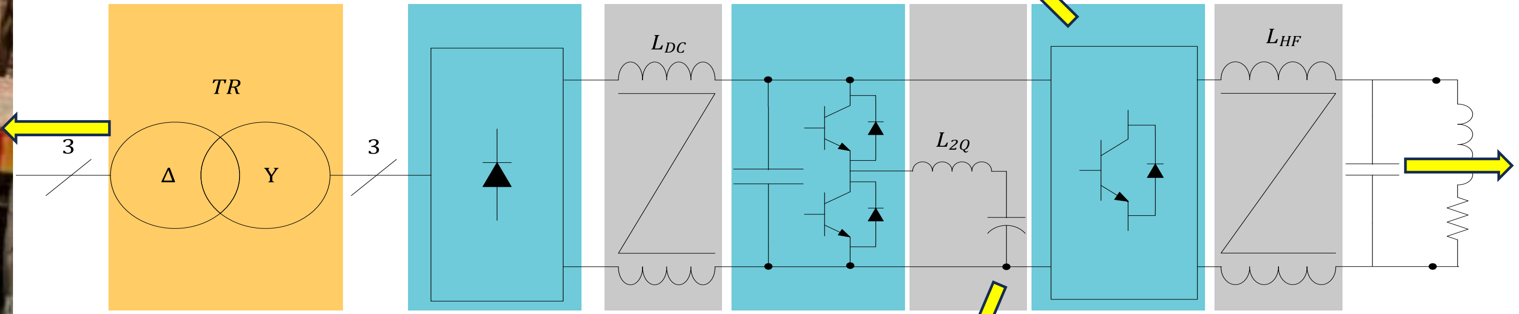
Wide variety of applications and designs - examples

Cycling consequences…

We have experience!

IGBT failure

Mechanical stress



Loss of capacitance value

Energy Storage explosion

Mid & long-term effects…
consequences on accelerators
availability of the accelerator complex

Wide variety of applications and designs - examples

Main SPS Magnet powering

12 series connected converters

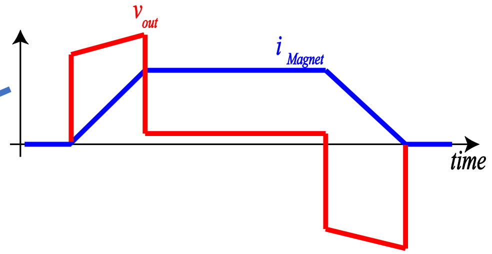
Each 6kA, ±2kV

Total of 144 MVA installed power

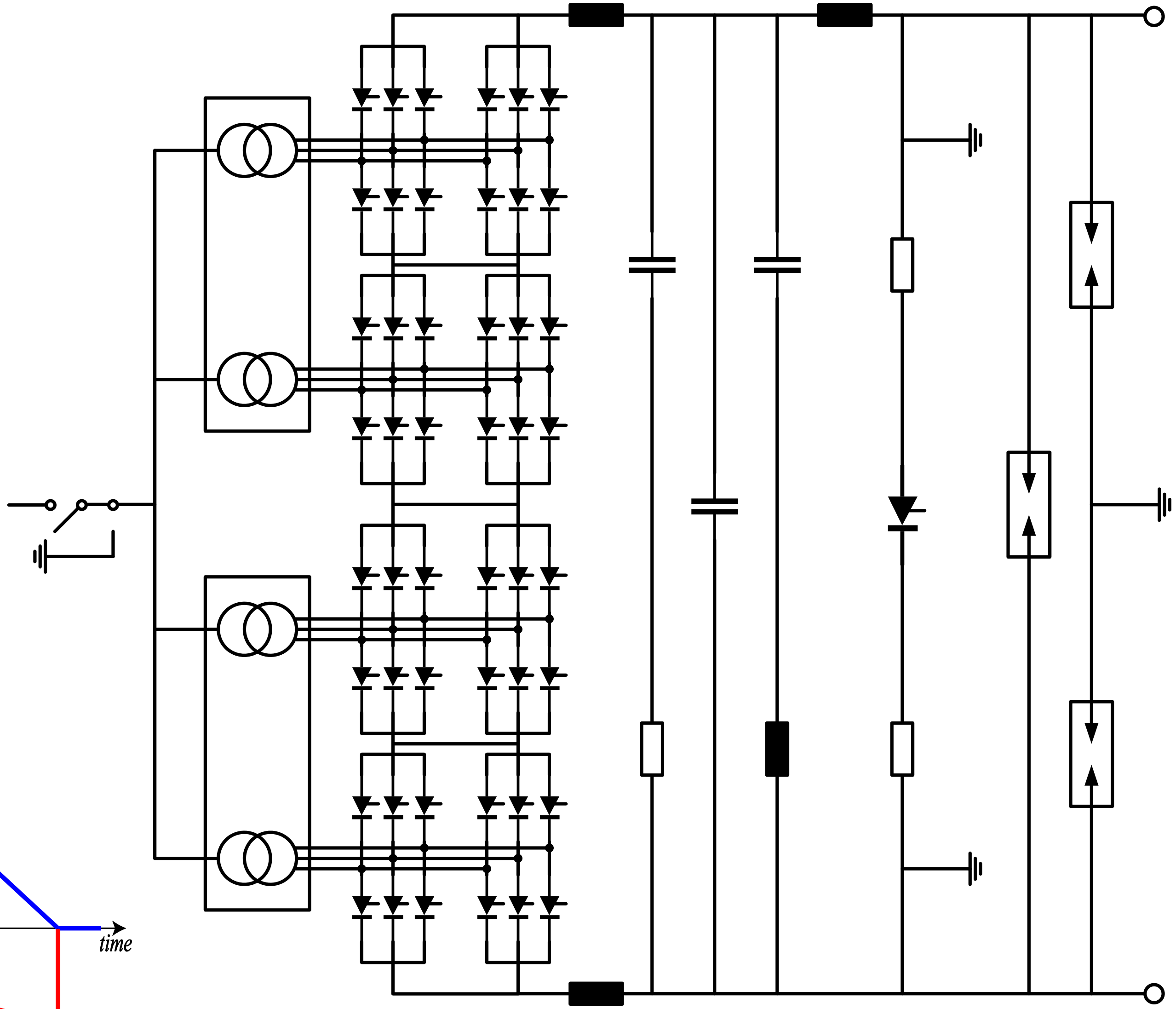
Remember that for thyristor rectifiers:

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

Bi-directional output voltage, 2 quadrants converter.
Current is shifted by α (fundamental)
AC side active and reactive power (neglecting harmonics):
$P=3*V_{phase}*I_{line}*\cos(\alpha)$
$Q=3*V_{phase}*I_{line}*\sin(\alpha)$

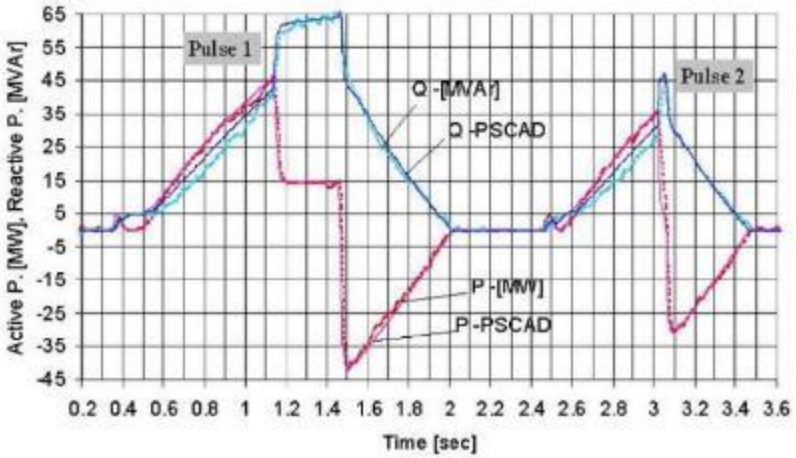


Huge reactive power
at low DC voltages…

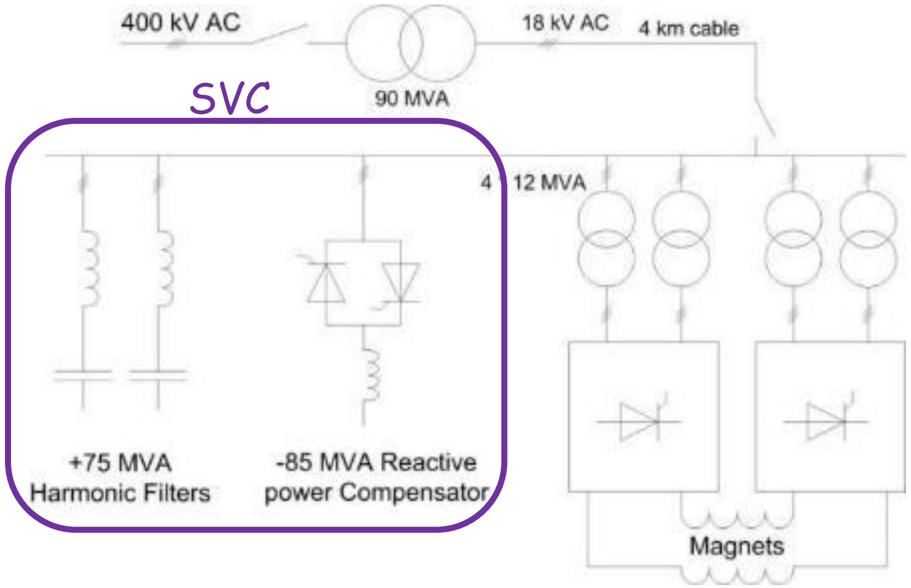


Wide variety of applications and designs - examples

This is what we measure…



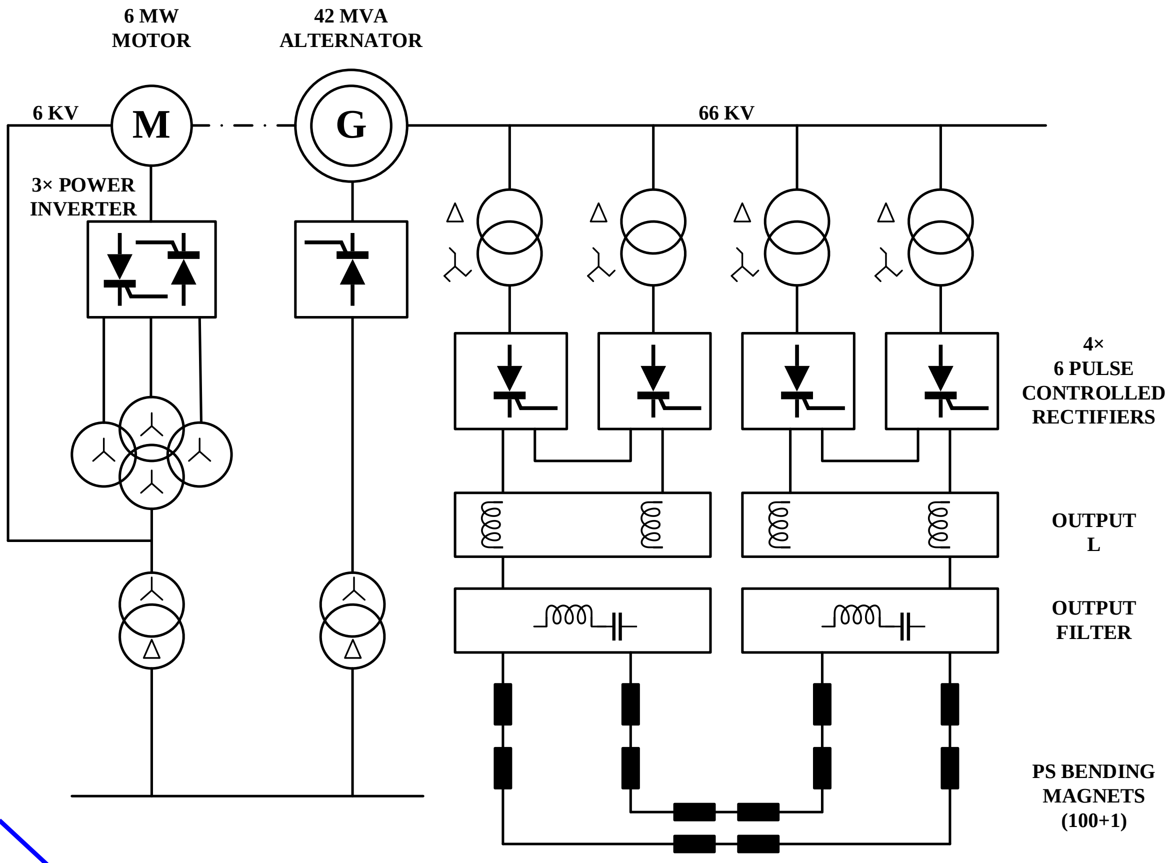
Static *Var* Compensator (SVC) are necessary to connect to the grid such converters with huge reactive power swings → need for network voltage stabilisation



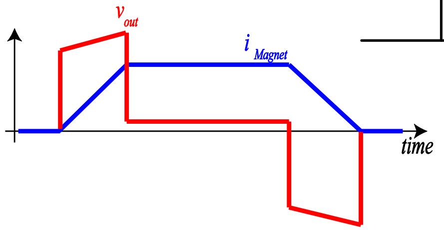
The SVC stabilises the 18kV at ±1%

Wide variety of applications and designs - examples

PS main magnets power supply (til 10 years ago)



Inertia of synchronous generator stocks 230*MJ at 1000rpm* for magnets supply (12*MJ*).



DFIM (6*MW*) constantly pushing for losses compensation

Wide variety of applications and designs - examples

PS main magnets power supply (today)

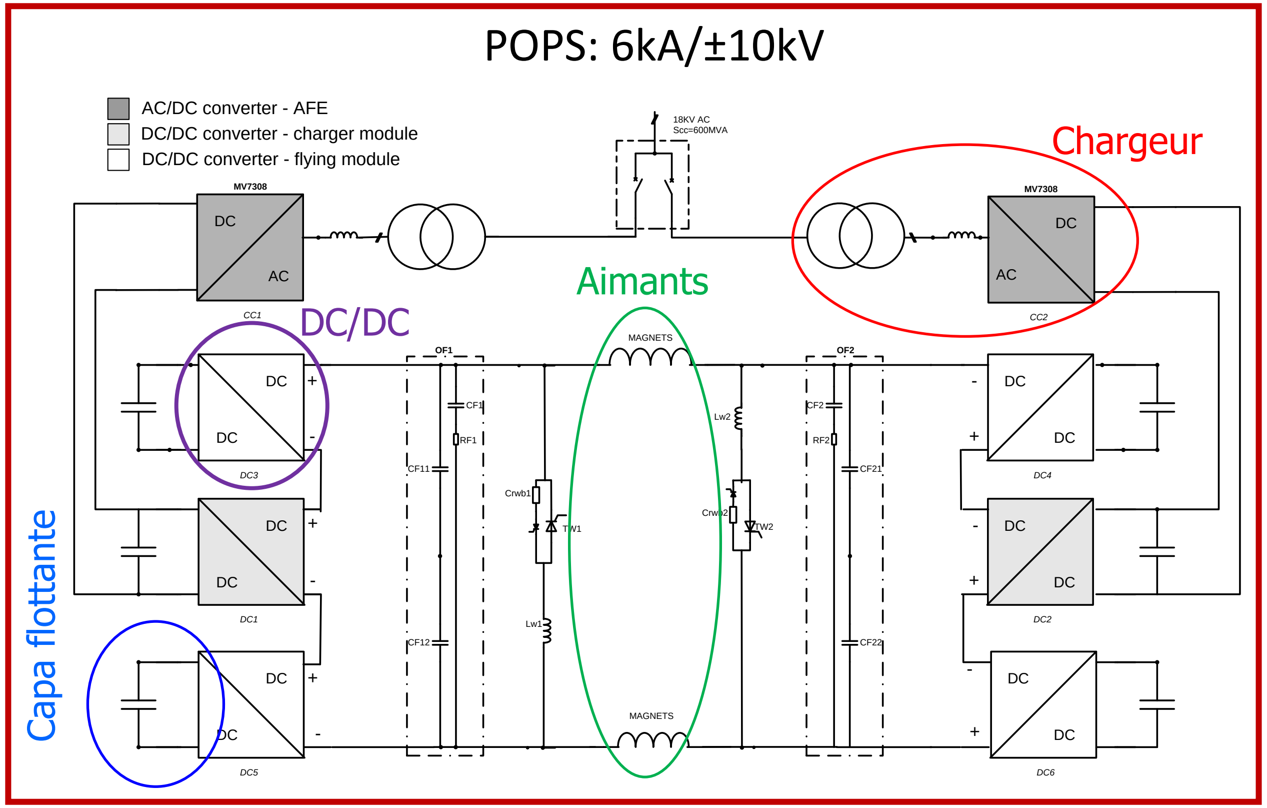
One can store the magnet energy in capacitors instead!

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!

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

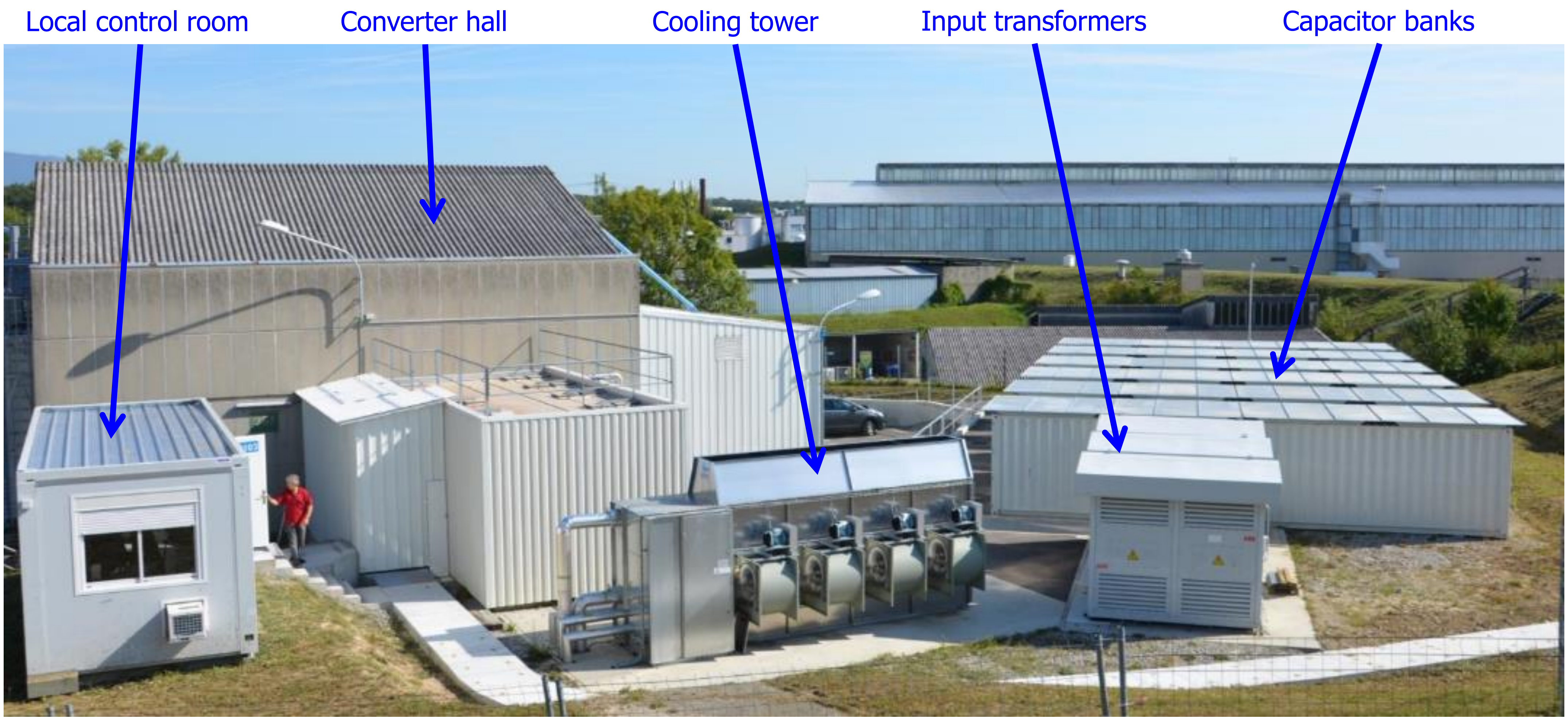
- Generator inertia replaced by banks of capacitors
- Motor replaced by AC/DC converters that supply the system losses only

Expertise's in capacitors technology and tests for cycled (bipolar voltage) operation



Wide variety of applications and designs - examples

PS main magnets power supply (system view)

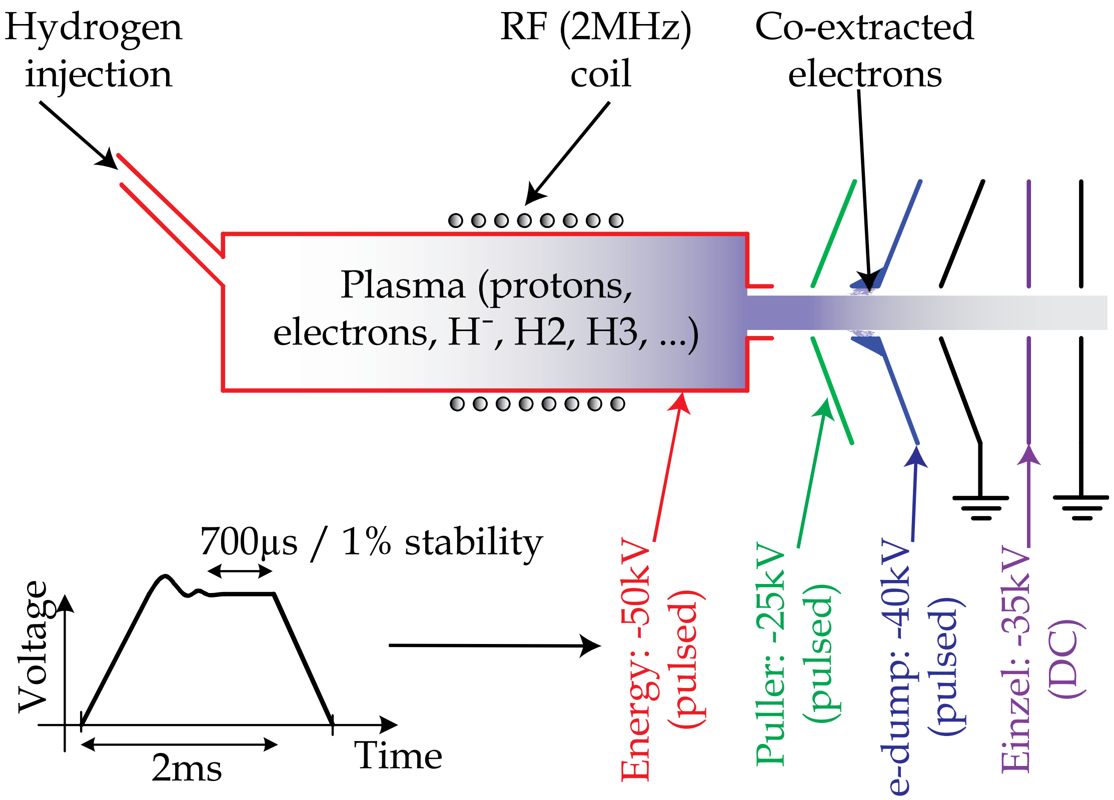


Wide variety of applications and designs - examples

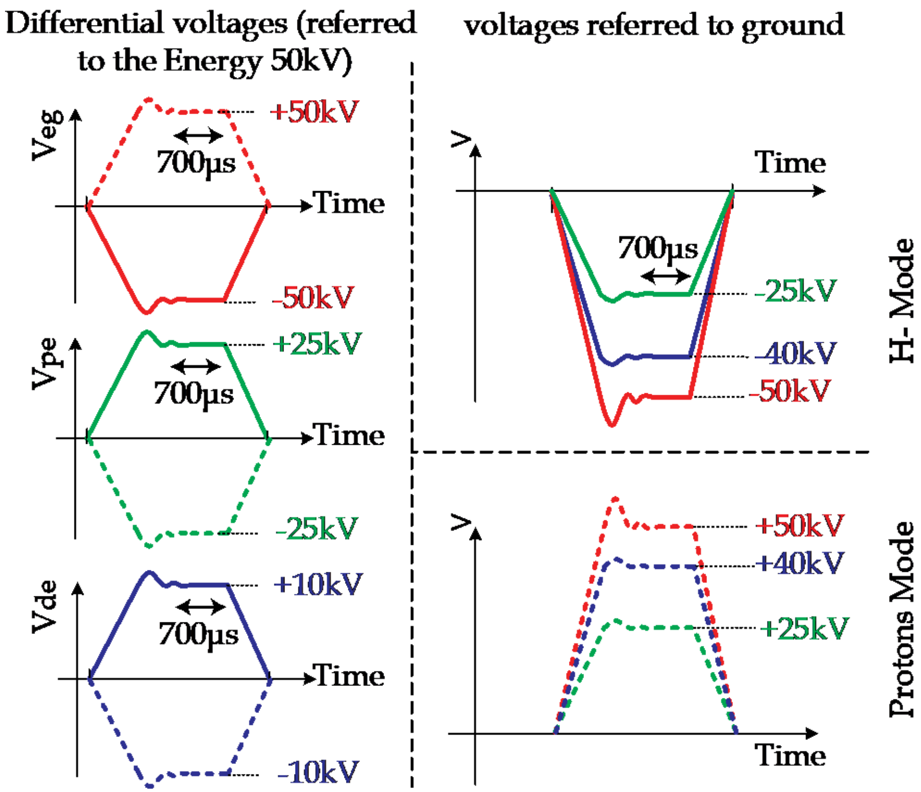
H^- ions source power supply

- Linear accelerator (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



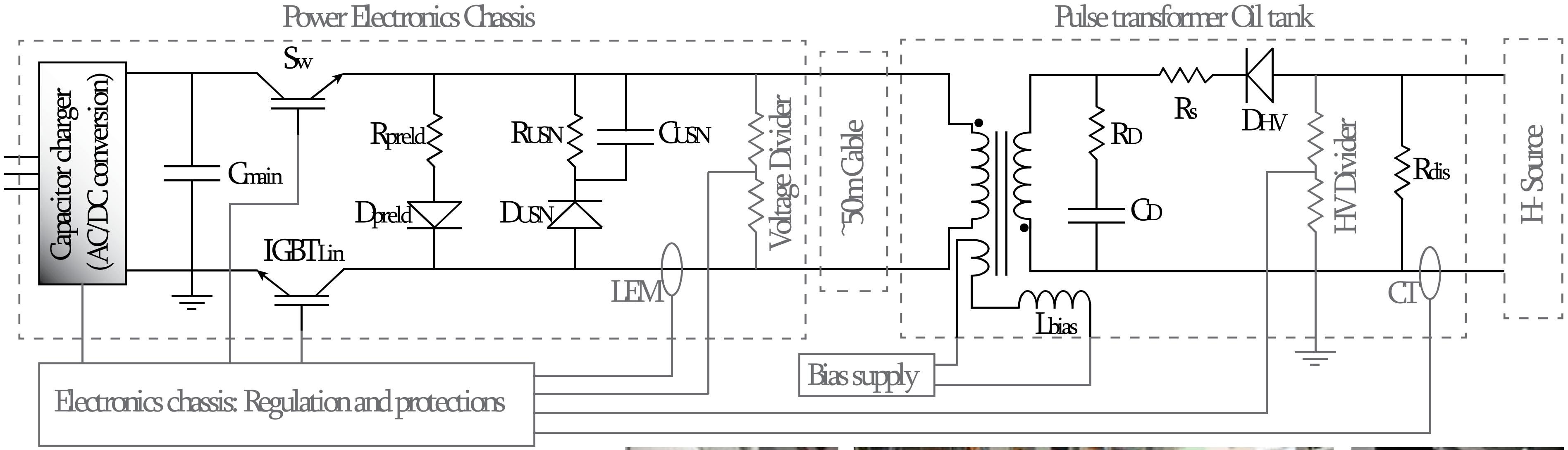
Voltage power supplies specification



Wide variety of applications and designs - 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».

Wide variety of applications and designs - examples

Control electronics as standard as possible in this jungle of converter types is mandatory

Standard boards with standardized software / Gateware (Firmware) by functionality

Assembles in standard chassis (chassis dedicated to converter type/family)

Current & future projects involving R&D

Current and future projects involving R&D

1. Consolidating and upgrading what we already have in place

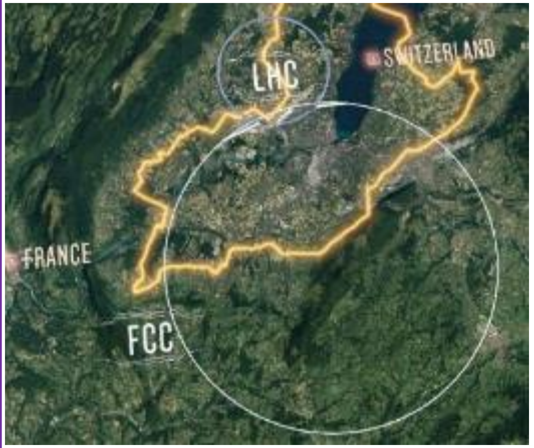
2. Studying the next accelerators at CERN (long term)

CONS – Consolidation projects

Renovate / consolidate / upgrade for:

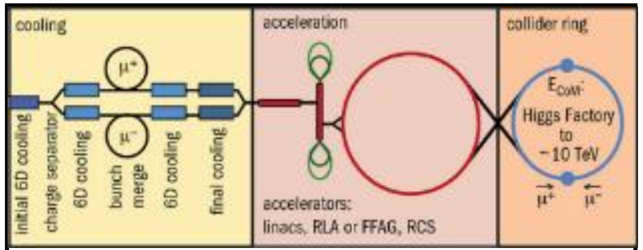
- Increasing reliability (ageing conv.)
- Improving performances
- Reducing maintenance costs
- Standardising power bricks & controls

FCC – Future Circular Collider



100 TeV hadron collider
91 km long accelerator/collider
2 stages approach (next slides)
Advantage: higher energies (hadrons)
Inconvenient: complex hadron collisions!

MC – Muon Collider



Muons are the holy grail of particles to be accelerated.
Combine advantages of point-like particles with negligible synchrotron radiation (high energy physics).

10 TeV muon collider
1 x accelerator (RCS) and 1 x collider
Inconvenient: Technically very challenging

- Specific/efficient muon cooling
- Fast acceleration required

Current and future projects involving R&D

- Consolidation projects
  - Development efforts to optimize resource's (HR & cost) via renovations
- Future accelerators
  - Pure R&D aiming at demonstrating their feasibility
  - Typical R&D needs:
    - Finding powering concepts via global optimisation
    - Power distribution integrating DC networks
    - Energy storage systems evaluation and their optimal integration
    - Energy recovery concepts evaluation
    - Develop cost and volume models
    - Integrating sustainable processes, materials, etc.

With some challenges!

Minimize capital & operational cost
Maximize accelerator availability (big implications on reliability and maintenance efficiency – remember: 100 km!)
- Ensure efficient monitoring
- Distance interventions and tests
- Modular approach (redundancy)
- Etc.

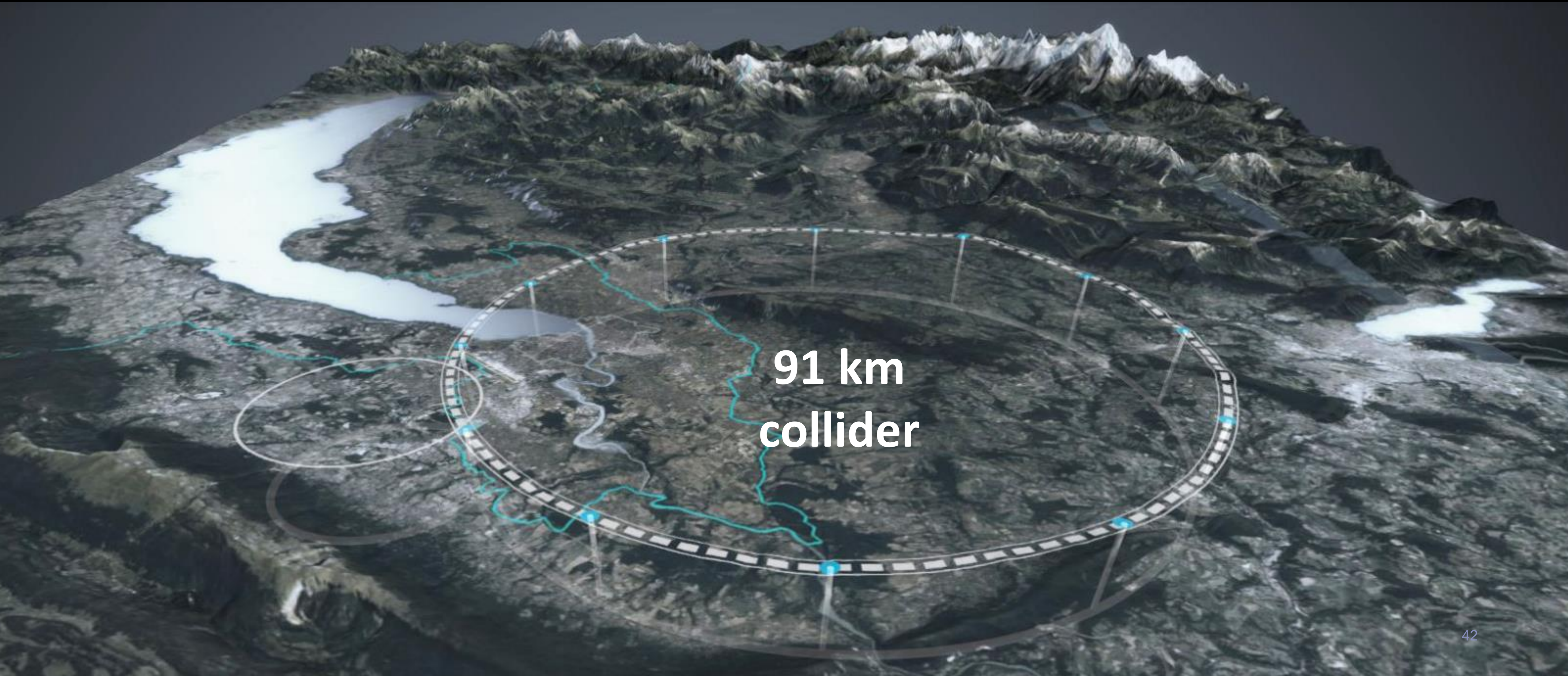
Ensure AC power quality
Etc.

The FCC feasibility study

Possible future collider to be constructed from ~2031

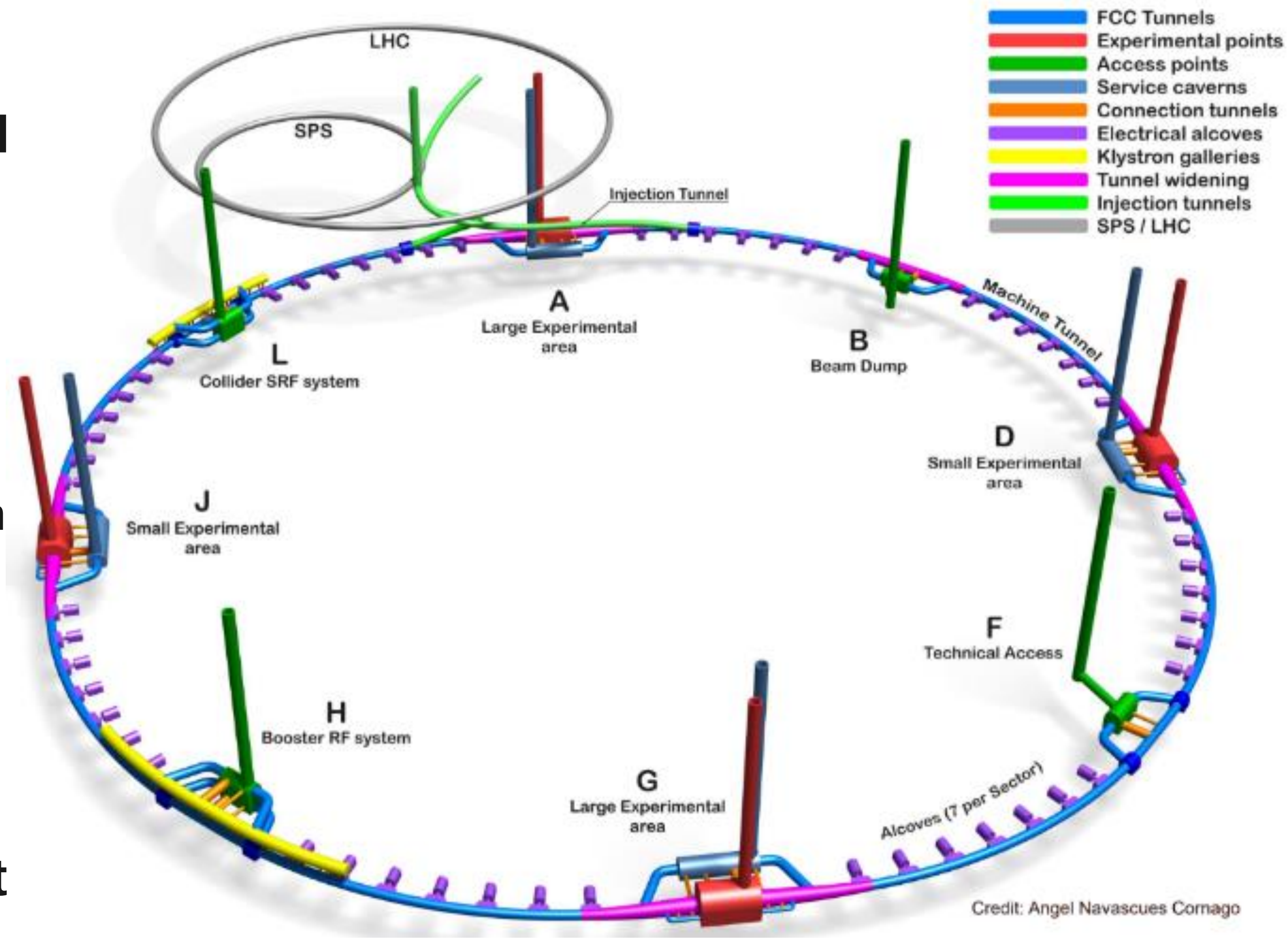
Physics exploitation from ~2044 to end of century

Decision in 2025-2026



Few numbers on FCC

- **> 35'000 magnet circuits to be powered**
  - From few kW to MWs
- **160 MW power converter for RF**
- **Need to reduce CAPEX+OPEX**
  - Global optimization needs (optimal integration and cross-domain specifications)
  - New switch techno to be evaluated to increase efficiency
  - High availability
- **Sustainability becoming a central point**



Academic & industrial collaborations opportunities

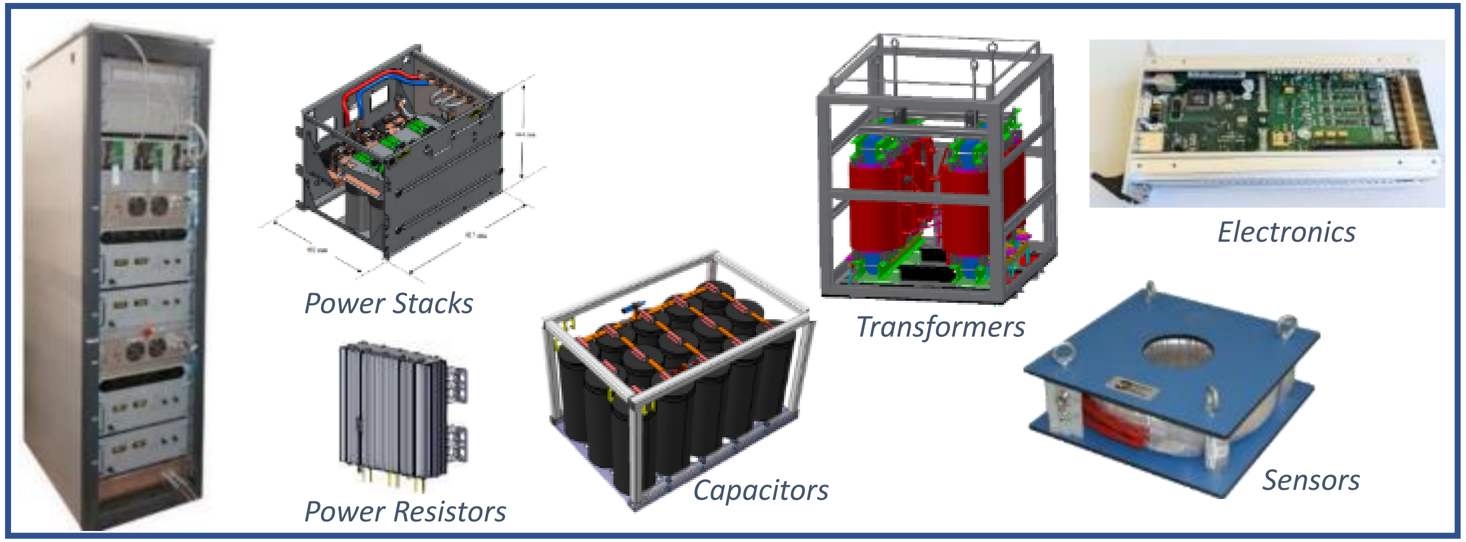
Collaborations with industry

Doing business with CERN

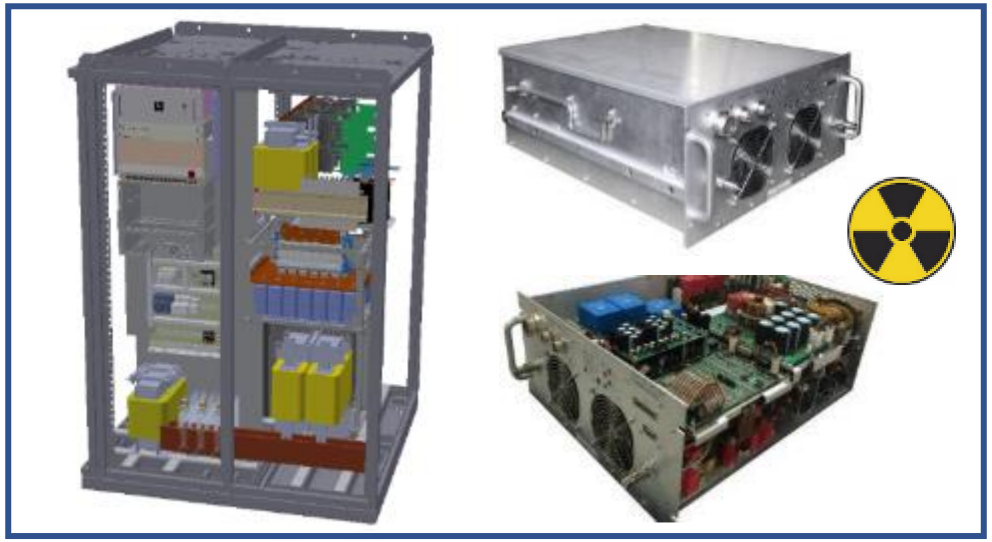
- If the product/system exist in industry → we buy turnkey systems, no design at CERN
- If specific (e.g. need for standardization, CERN control electronics, etc.) → Build to spec, CERN & industry design
- If extremely specific product (e.g. rad tolerant) → we detail design → ask industry for build to print, full CERN design

Turnkey System

Build to Spec

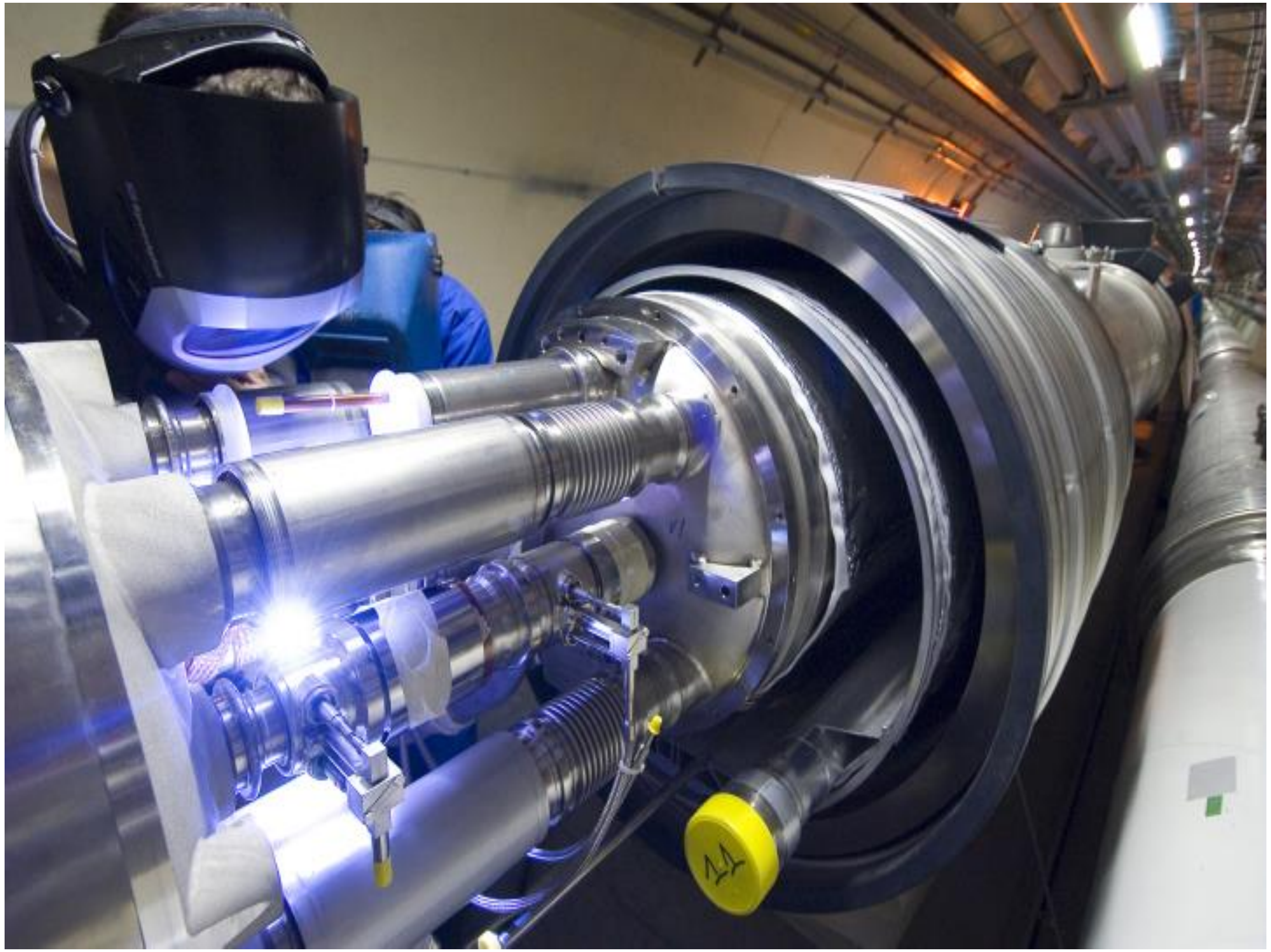


Build to Print



Not only power converters…

- Computing/IT
- Vacuum & cryogenics
- Electronics
- Electricity
- Magnets
- Mechanics
- Material Science
- Radio-Frequency
- Control Systems
- Measurements
- Civil Engineering
- Etc.



We need you …

…to continue the extraordinary CERN history

…to achieve extraordinary record of scientific and technological accomplishments

Industries	Research Institutes	Universities
		

Thanks for inviting us!

For more information:

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- https://careers.cern/alljobs (Search for all Job opportunities)
- https://careers.smartrecruiters.com/CERN/students (opportunities for students)
- https://sy-dep.web.cern.ch/ (Accelerators Systems Dept.)
- https://videos.cern.ch/ (animations & more)
- http://epc.web.cern.ch/ (EPC group website)

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