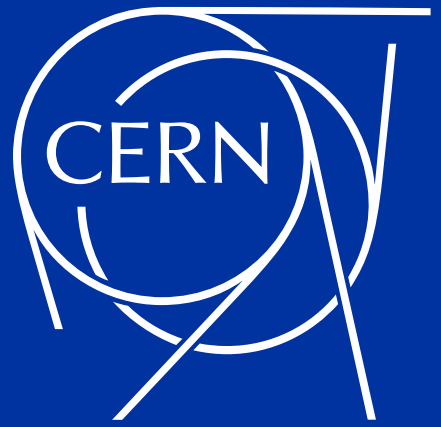


Electrical Power Converter challenges at CERN

Miguel Cerqueira Bastos

10/09/2024

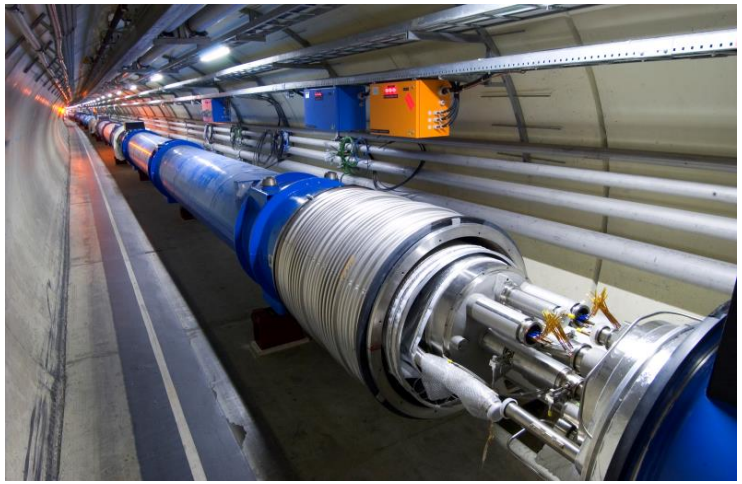
Electrical Power Converter challenges at CERN

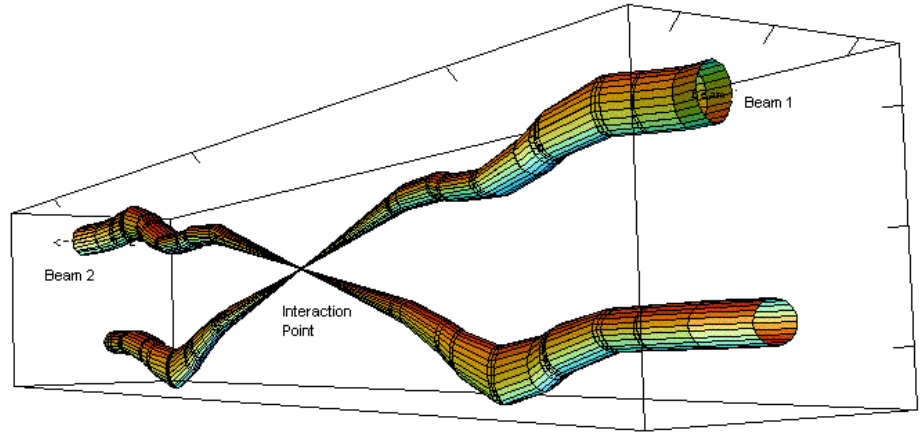
- High Precision, stability and accuracy
  - Motivation
  - Control
  - Current measurement
  - Digitizing
- EMC
- Cycling converters
- Efficiency, volume
- Availability, reliability, maintenance
- Radiation

High precision, stability, accuracy

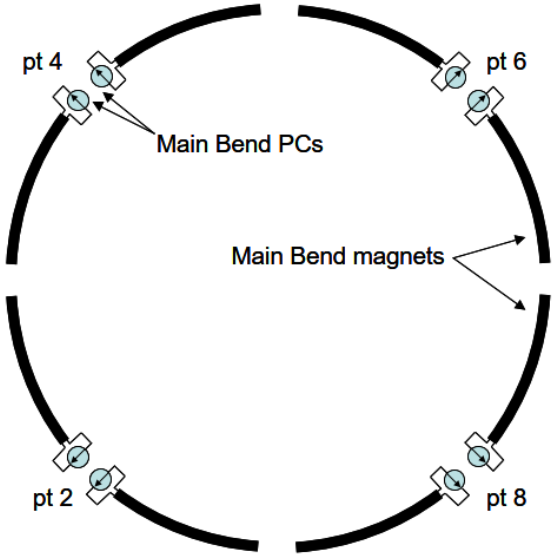
Motivation (LHC)

- Proton beams in the LHC are steered by the **magnetic field** in electro-magnets powered by **electrical power converters**
- **Precision and stability of beam** trajectory linked to **precision and stability of power converters**
- Collisions need perfectly aligned beams and beam diameter ~50µm => **part per million precision and stability** of power converter currents
- LHC divided in 8 powering sub sectors => currents in dipole, quadrupole magnets of sub sectors **need to match** to ensure magnetic fields match
- **Part per million (ppm) relative accuracy** is therefore required for the current between sectors



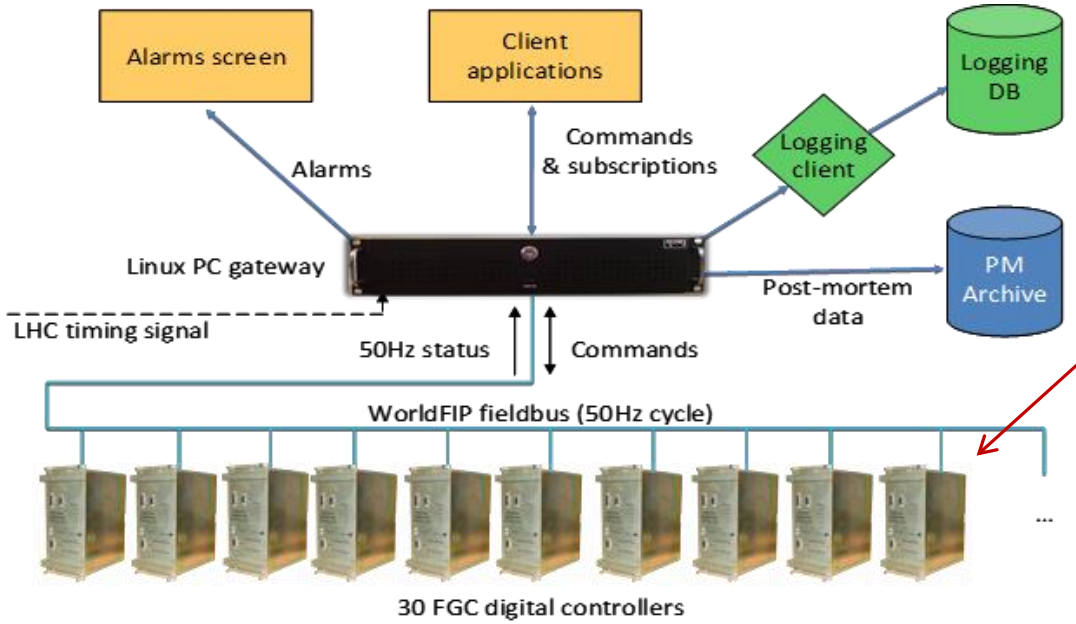


Relative beam sizes around IP1 (Atlas) in collision



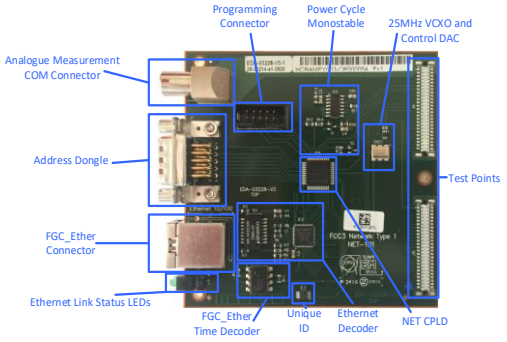
Control requirements

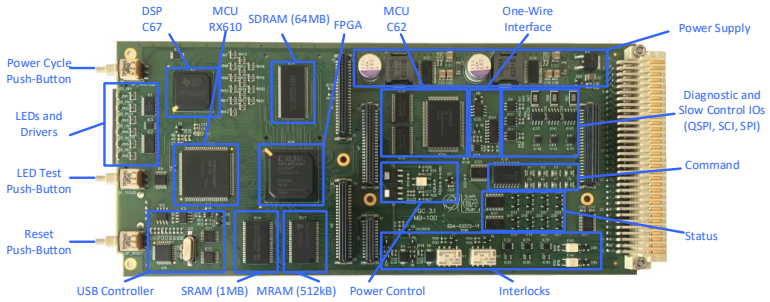
- Converters in the LHC must follow the same current reference over 27 km with a time «jitter» of < 1ms
- Synchronisation of the reference in the LHC is achieved using timing events sent over the LHC timing network
- The **converter controller** receives timing events via its gateway computer and **controls the current** in the power converters
- Complexity of control & unique requirements led to the early development of the **CERN Function Generator Controller (FGC)**
- The **FGC** allows for **standardisation of control systems** across thousands of converters at CERN

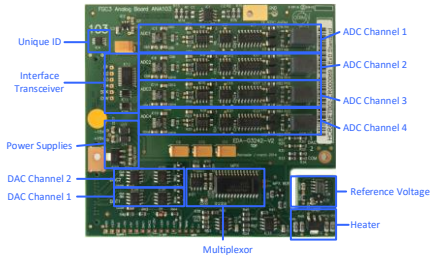


FGC3 controller

FGC2 controller





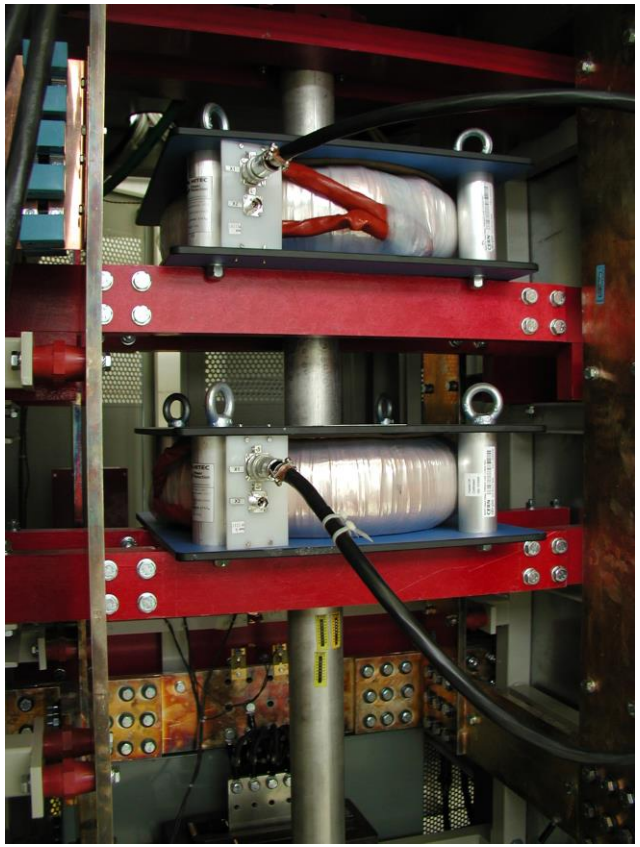


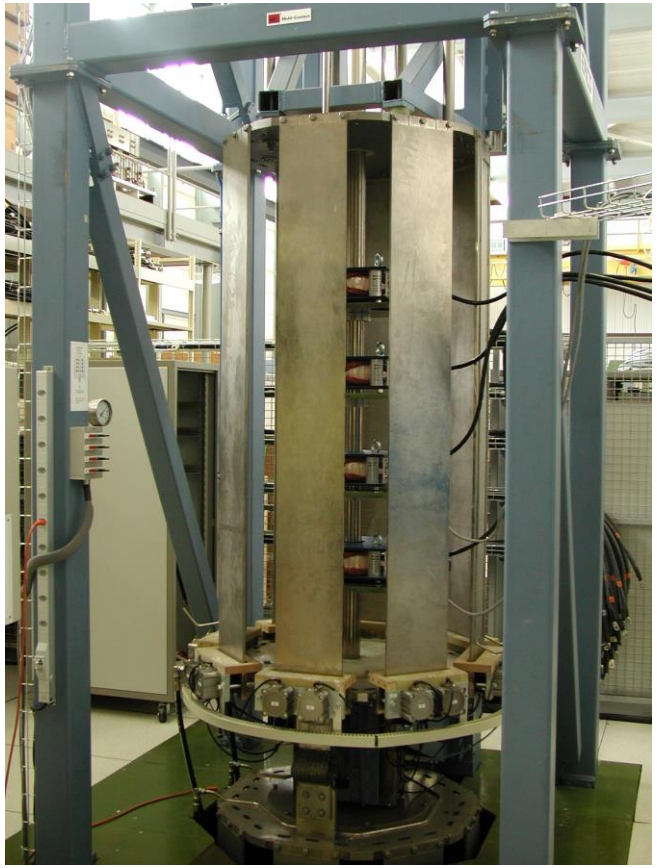
High precision current measurement

- Power Converter output current is measured using DCCTs (Direct-Current Current Transducers)
- DCCT operation is based on Zero Flux Detection in a feedback loop + closed loop Current Transformer (Hereward transformer)
- DCCTs are supplied by industry, but improved in collaboration with CERN
- CERN has unique test facilities for evaluation of DCCTs: 20kA testbed with part per million uncertainty

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

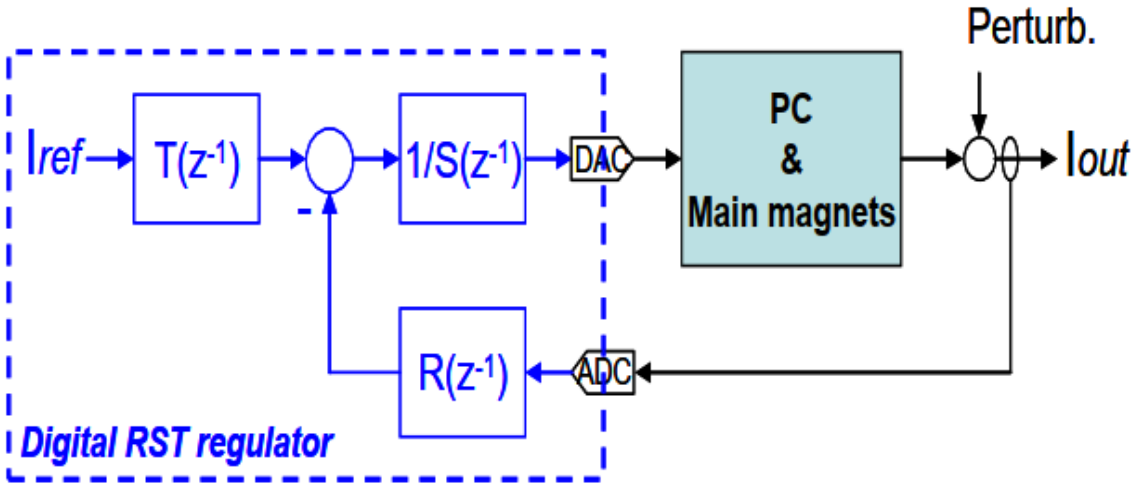
DCCT electronics: provides a voltage signal, which is then digitized by an ADC

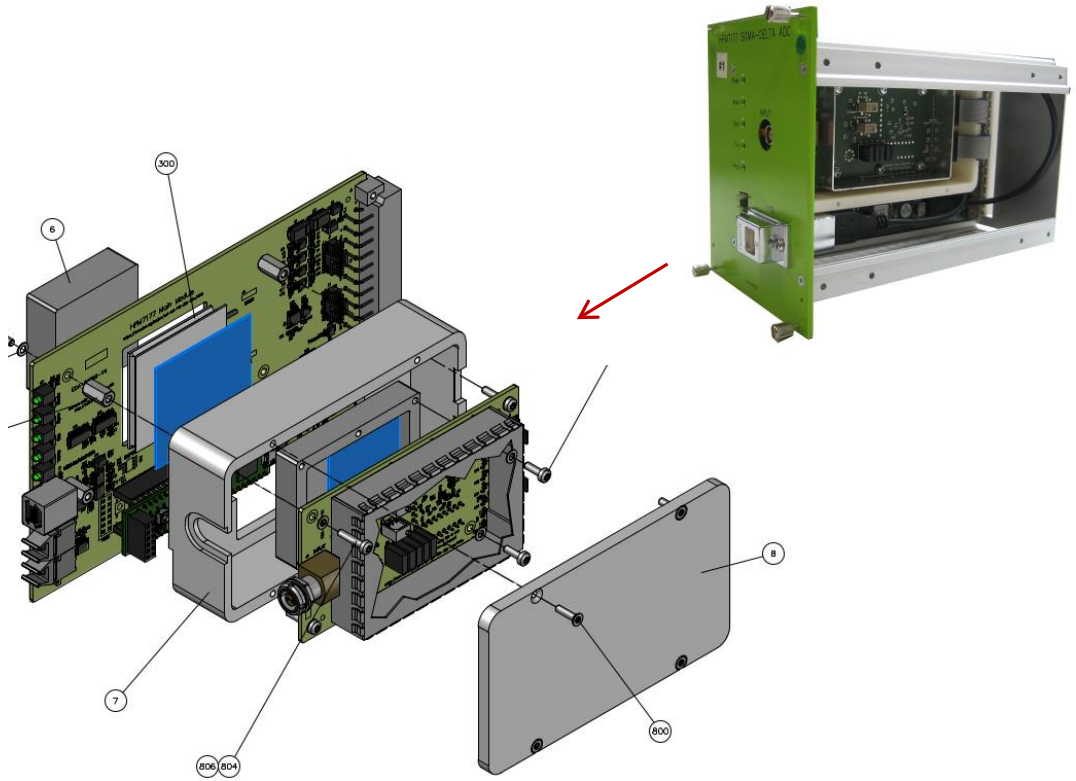




High precision digitizers and regulation

- CERN-developed **high precision digitizers** are used to convert the DCCT signal into a digital signal
- A careful design in a temperature controlled and thermally isolated enclosure, **allows for sub ppm performance**
- The digitized measurement is used in a digital loop implemented in the FGC to control the converter
- The digital loop uses RST control to allow decoupling of tracking (following reference) from regulation (rejection of perturbations)





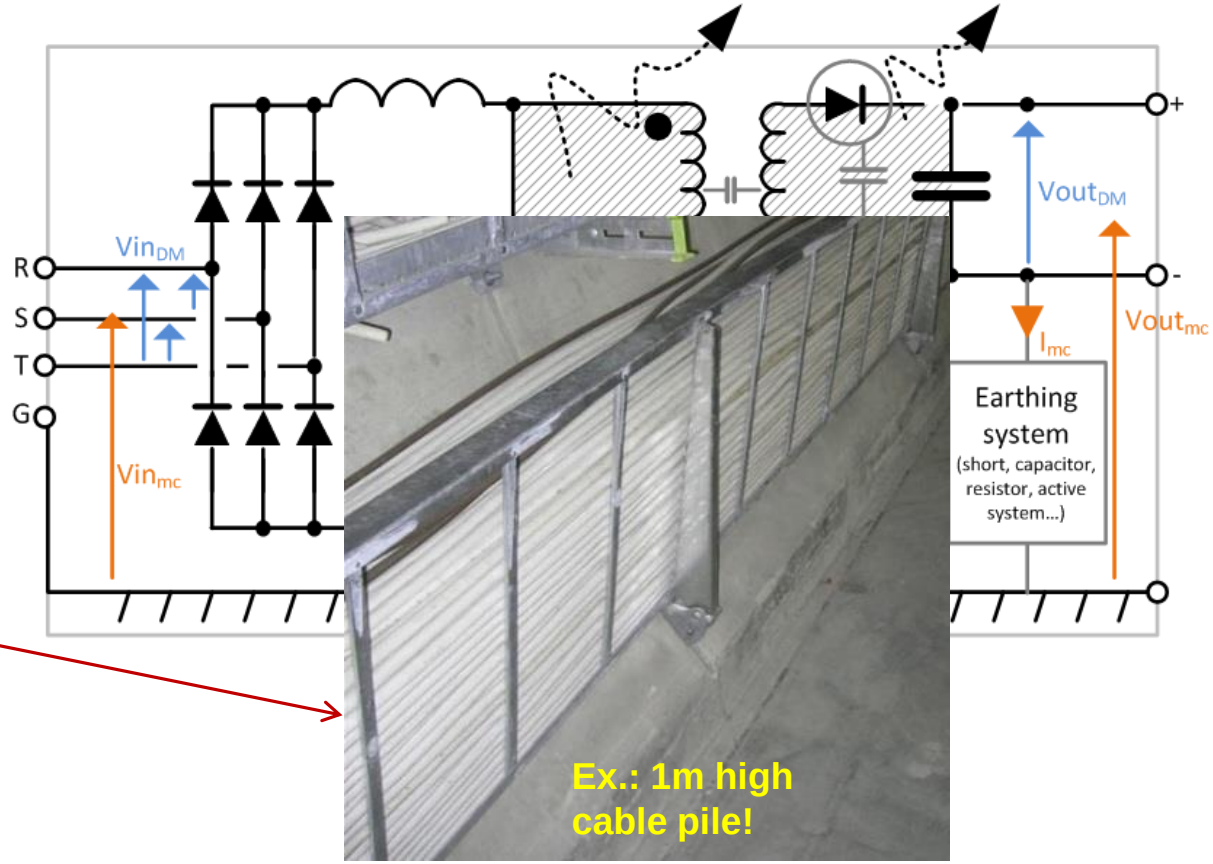
Electro Magnetic Compatibility

- EMC an essential aspect in guaranteeing the high precision performance of power converters !

Weak EMC ≡ high precision is compromised!

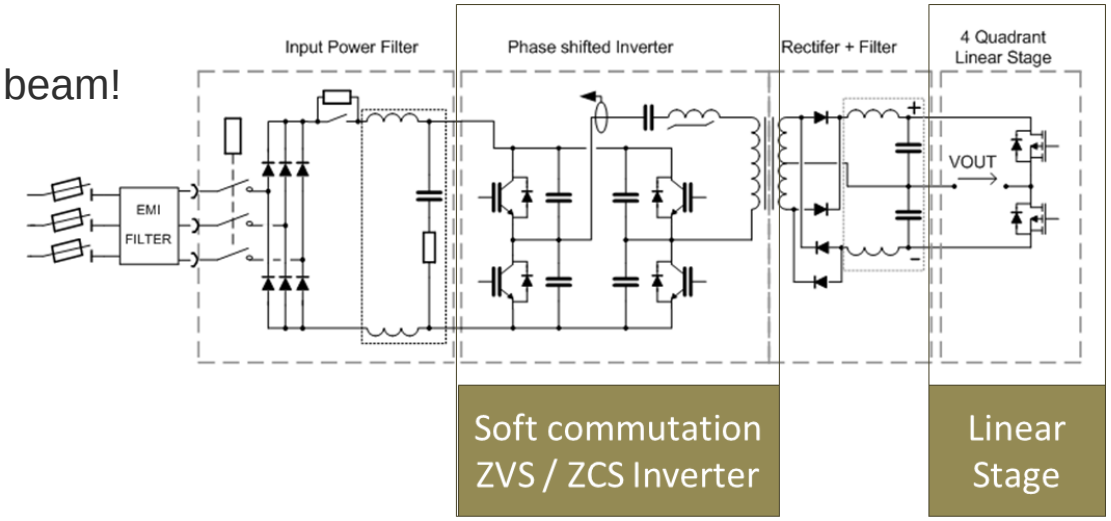
ppm regulation with % measurement noise is impossible without good EMC!

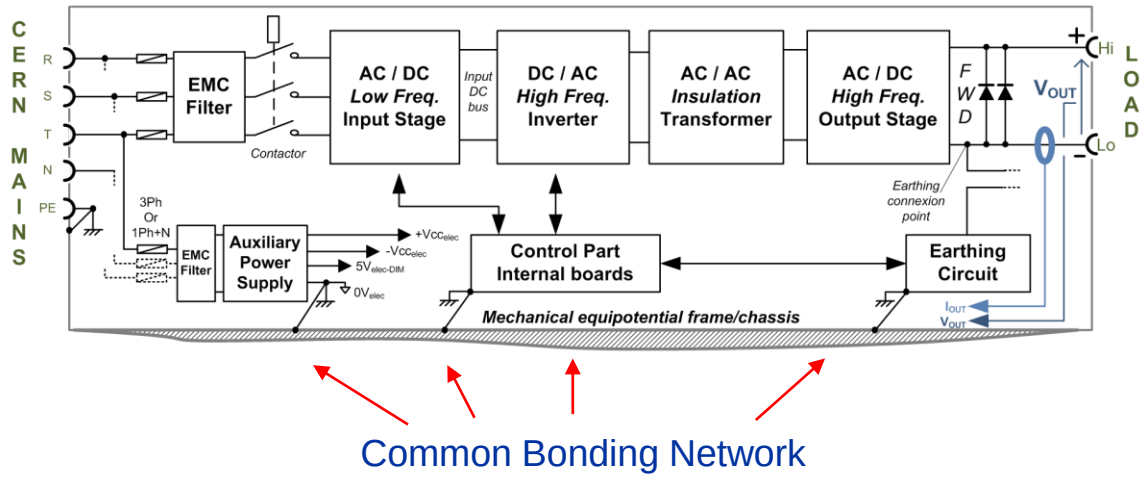
- Thousands of switching converters:
  - thousands of noise sources!
- km of analogue cables:
  - many coupling channels for noise!
  - grounding issues, common mode!
- Unique environment:
  - RF systems
  - pulsed converters (@ 400 kA/µs)
  - etc
- Unique installations with upgrades over many decades
  - Old components and designs “pre-EMC”



Electro Magnetic Compatibility - design

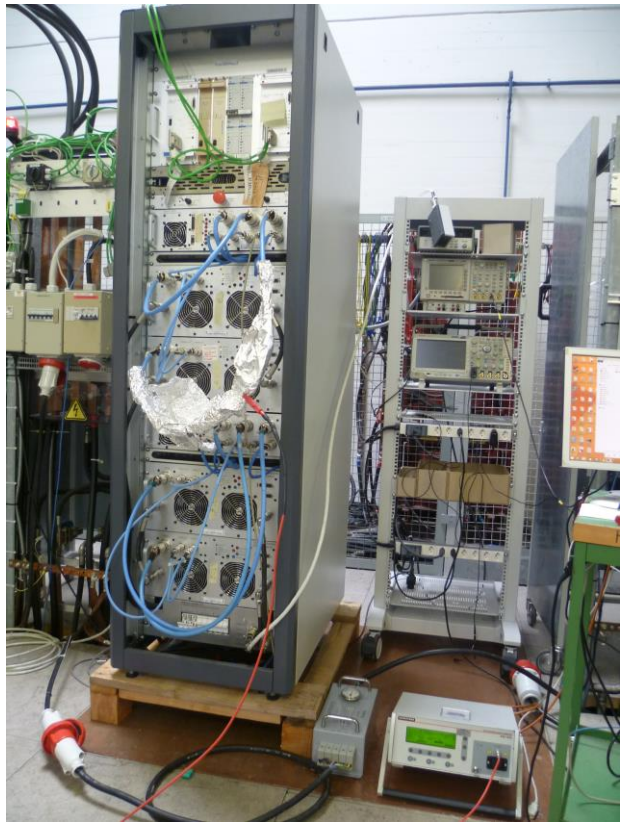
- Immunity & emissions control is essential
  - A single EMI event in a converter can cause the loss of particle beam!
- EMC considerations from design phase!
  - Topology: limiting noise sources
    - ✓ Soft-commutation-only (ZVS, ZCS)
    - ✓ Linear stage for 4-quadrant converters,
    - ✓ Management of impedance to ground of switching cells (capacitive coupling to heatsink)
    - ✓ etc…
  - Robust Common Bonding Network (CBN) – equipotentiality
  - Single reference potential (0V), strongly connected to CBN
  - Coherent electrical shielding strategy (cables, enclosures)
  - EMC testing …

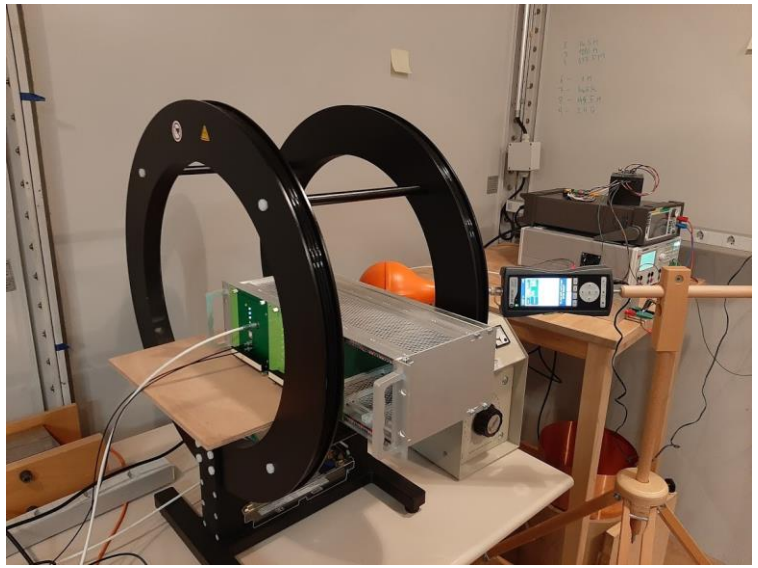




Electro Magnetic Compatibility - testing

- EMC test equipment @ CERN for:
  - Pre-compliance EMC testing of current transducers and digitizers
  - Pre-compliance EMC testing of complete power converters

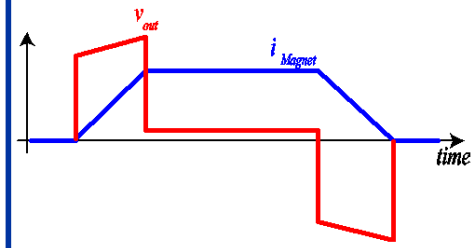


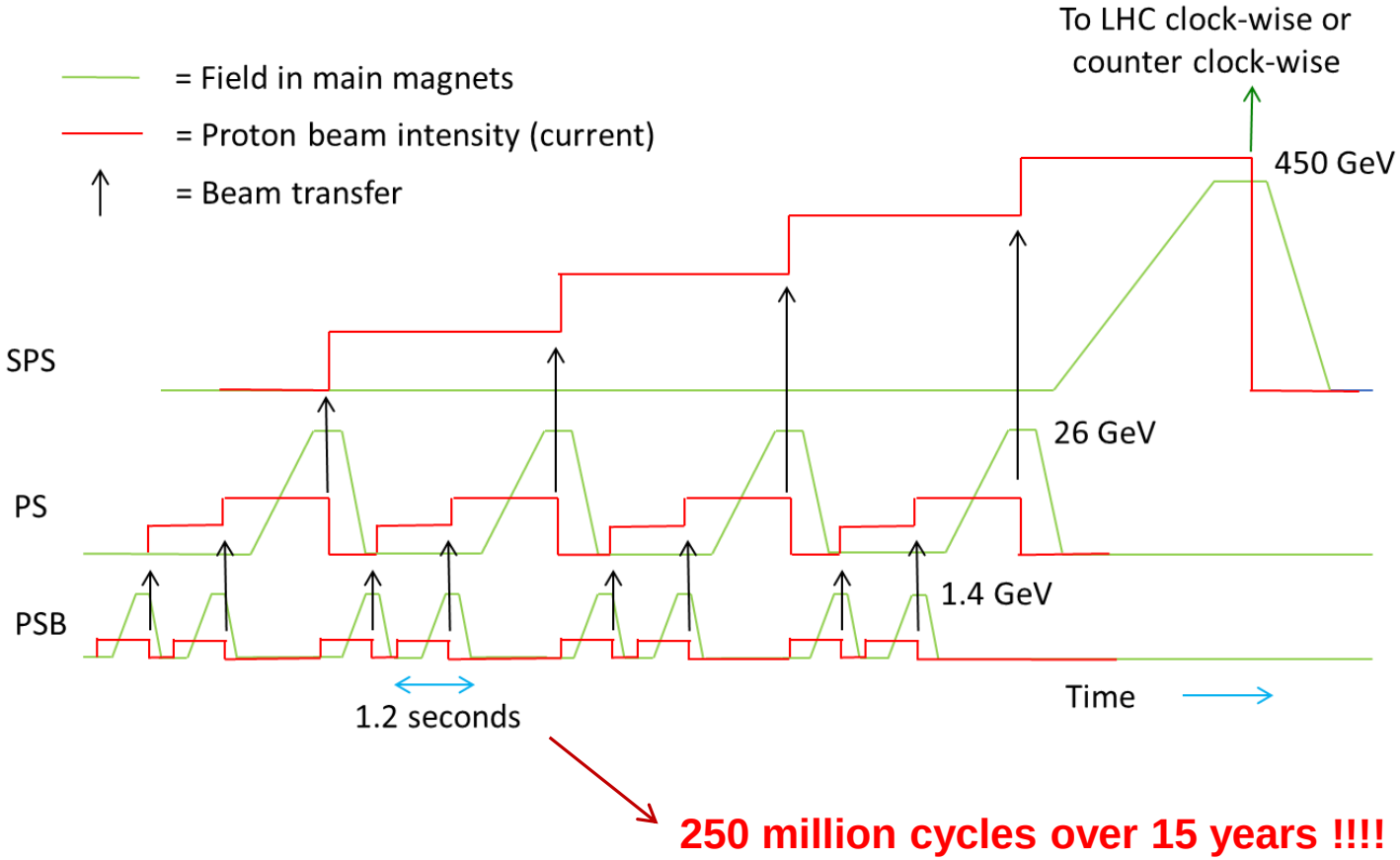


Cycling power converters

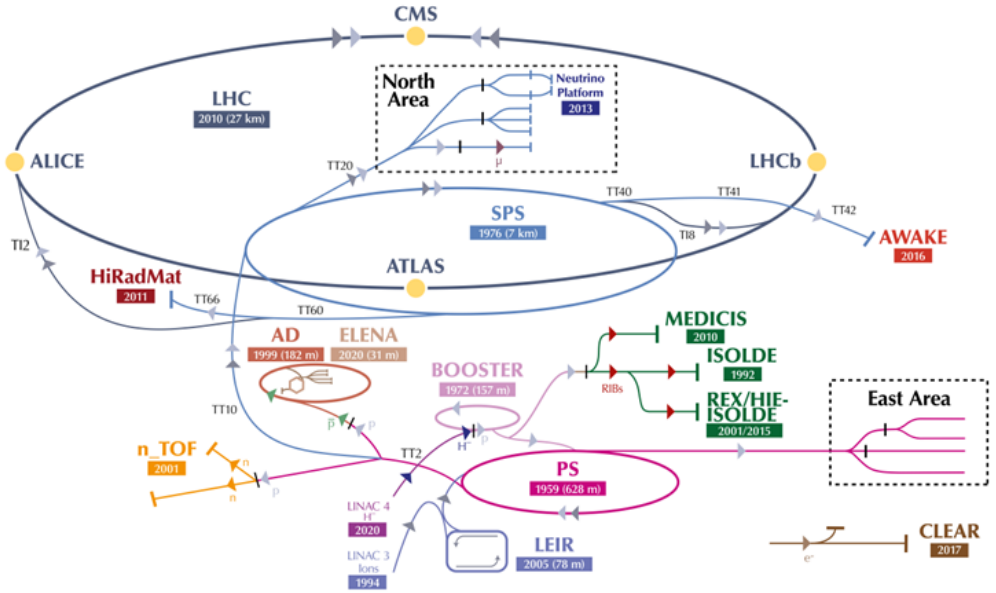
- Accelerators are often cycling – currents in the magnets are **cycled with different shapes**
  - **Thermal cycling** of semiconductors pose specific challenges
  - **Mechanical forces** generated by cycling cause mechanical stresses
  - **Capacitor selection** is not trivial as operation mode is neither DC nor AC

Typical voltage & current shapes applied to magnets:





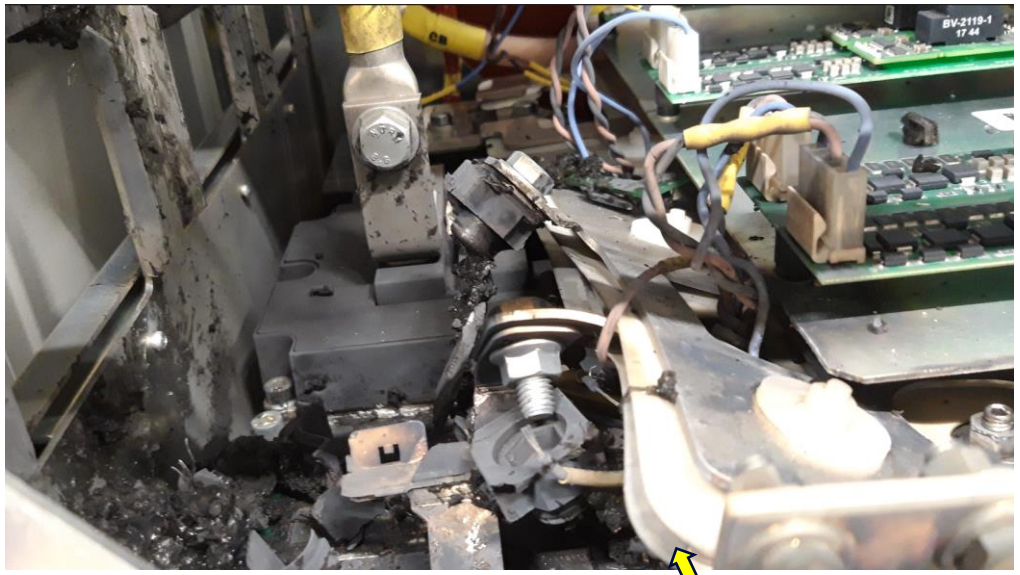
250 million cycles over 15 years !!!!



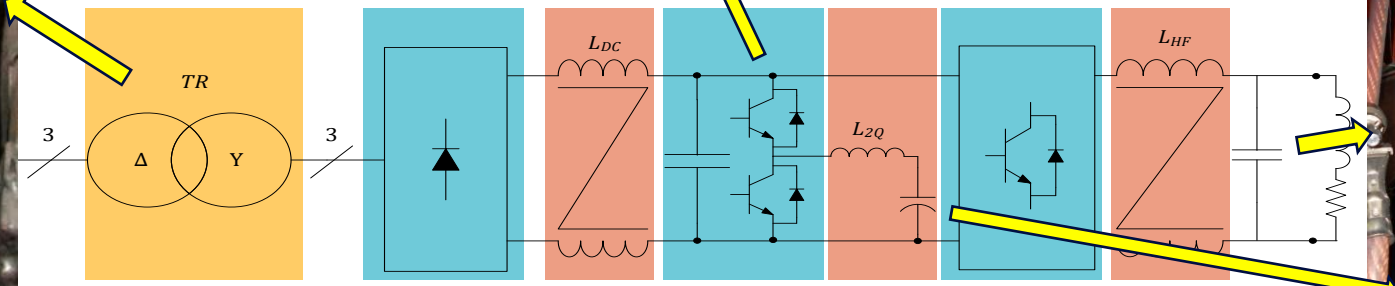
Cycled power converters

- Consequences of **cycling**… we have learnt the hard way!
- mid and long-time effects need to be considered carefully !!!!

Mechanical stress



IGBT failure

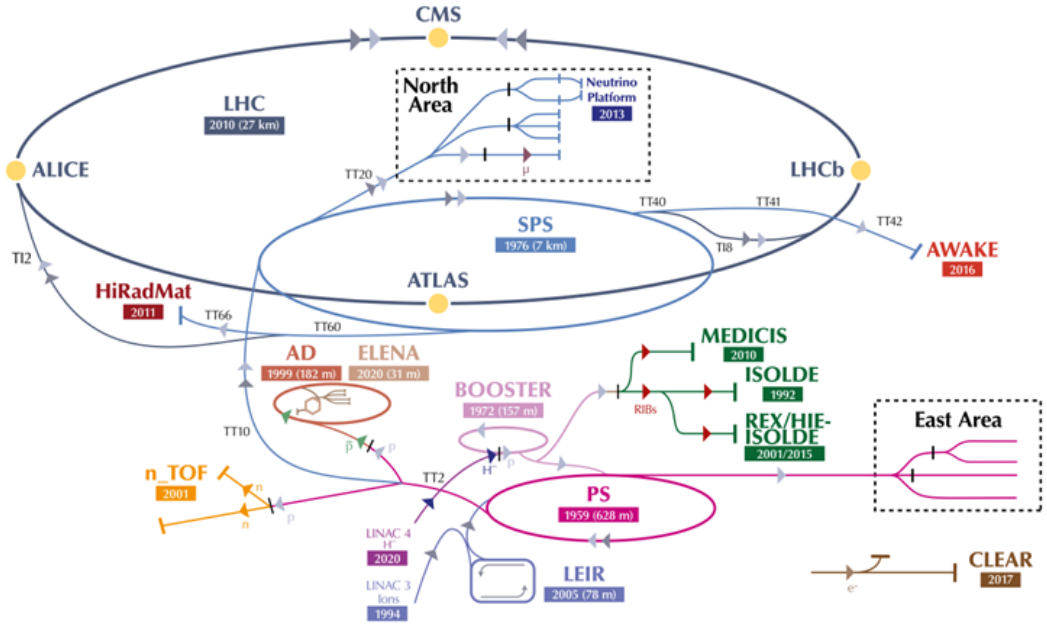


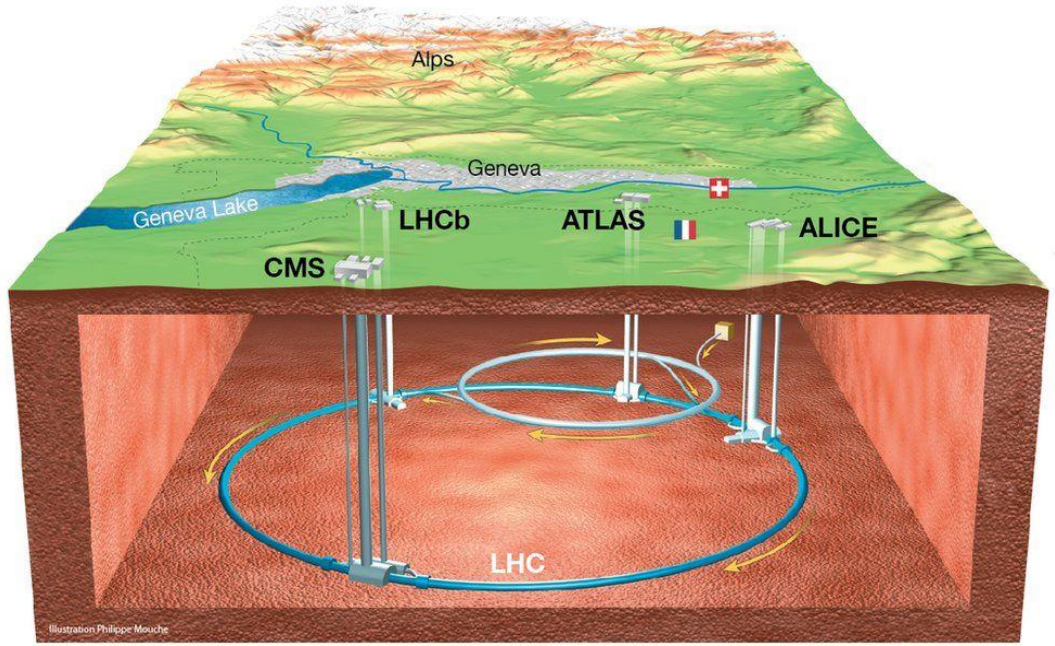
Loss of capacitance value

Energy Storage explosion

Efficiency and volume

- Large accelerator complex, wide geographical distribution, LHC installed 100m underground
- To **decrease copper loses and minimize cost**, converters are also installed underground
  - **High efficiency** required!
  - Losses evacuated through water cooling
  - Volume needs to be optimized to fit in underground galleries
- Incidentally, locating the converters underground **exposes them to radiation**… (we'll see in the next slides…)

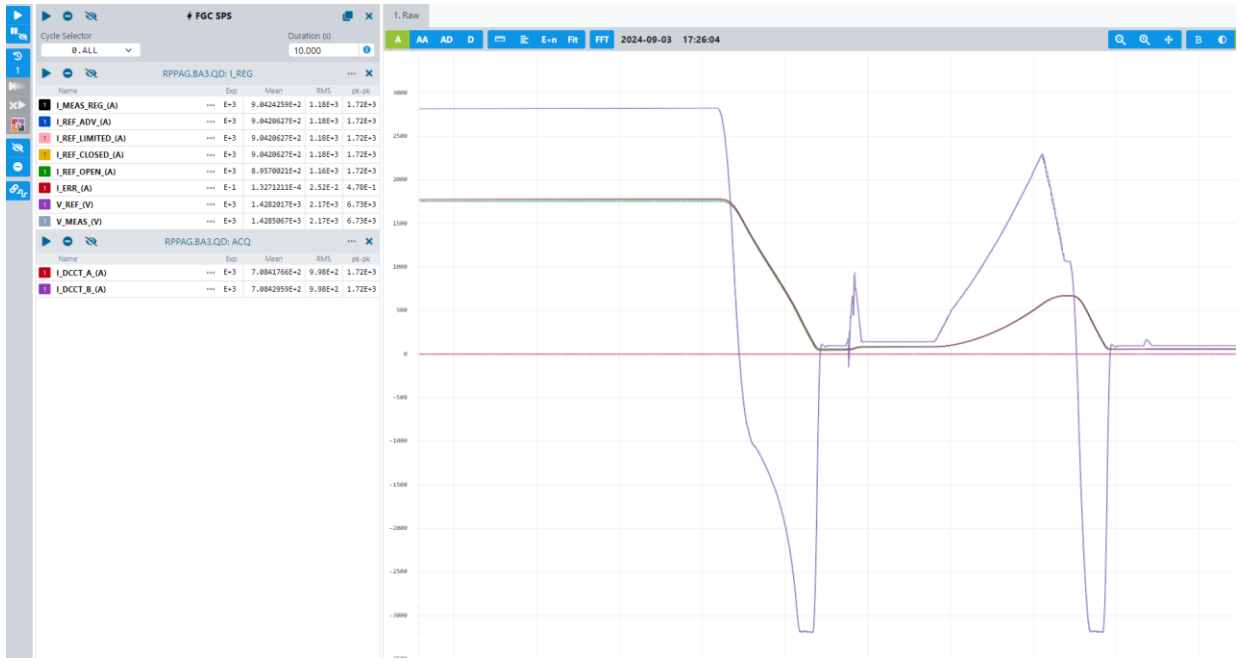




Availability, reliability, maintenance

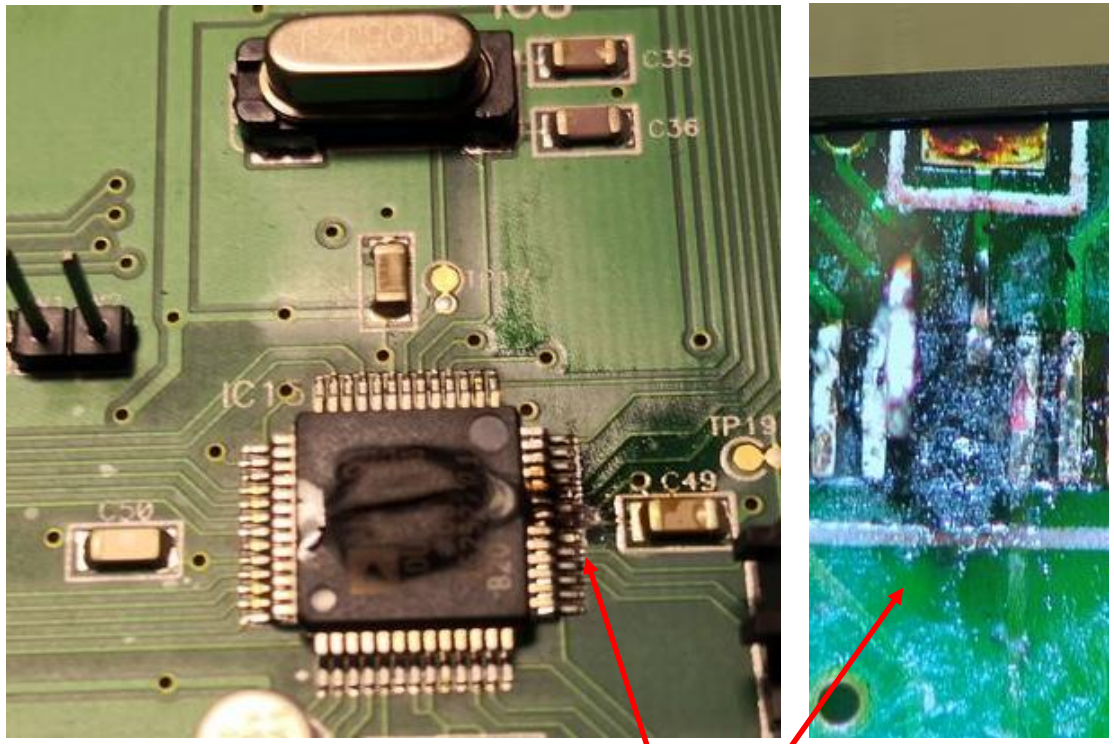
- **Availability is critical in accelerators!**
  - **> 5’000 converters** in operation at CERN! need to run reliably for **20-30 years** as converter failures lead to beam dumps!
  - Underground equipment + long distances + radiation => **minimize access underground**, **minimize repair times**
    - **Modular** designs for **low MTTR** & using **n + 1** redundancy
    - **Hot swap** (modules automatically put into operation)
- **Maintenance**
  - Predictive: monitoring of critical parameters and statistics on common failures
  - Preventive: preventive actions during annual shut-downs
- **Diagnosis:** Advanced remote diagnosis tools essential !

redundancy
n+1 modules



Radiation Tolerant Converters

- Many converters need to operate in **radioactive** areas!
- Radiation at CERN due to losses caused debris from collisions, beam gas interaction, beam cleaning,…
- 3 different types of radiation effects are considered:
  - T.I.D. : Total Ionising Dose
  - N.I.E.L. : Non-Ionising Energy Loss or displacement damage
  - S.E.E. : Single Event Effect
- Single Event failure (destructive **Single Event Latchup** or **Single Event Burn Out**) can lead to beam dumps
- Shielding, relocation are possible but not enough
- CERN designed radiation tolerant power converters and controller based on **Commercial Off The Shelf - COTS components**



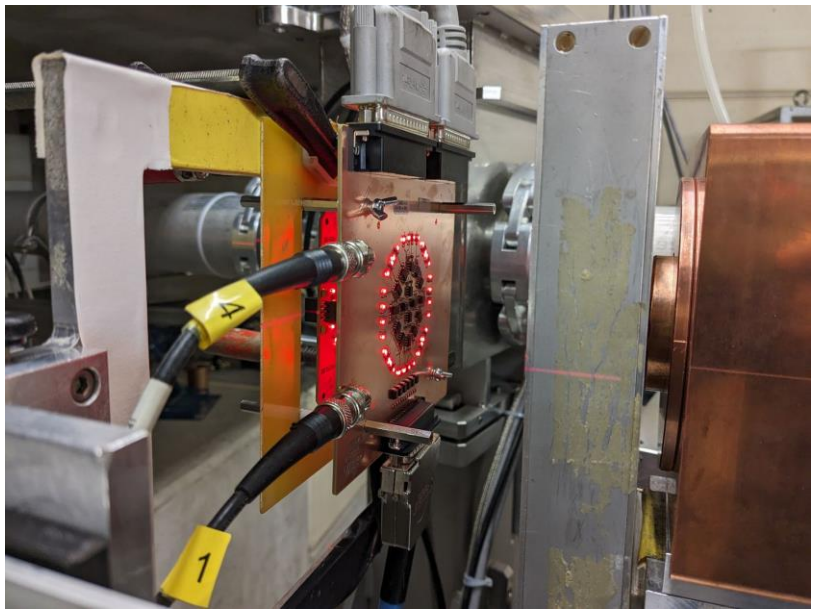
Destructive effect of Single Event Latchup

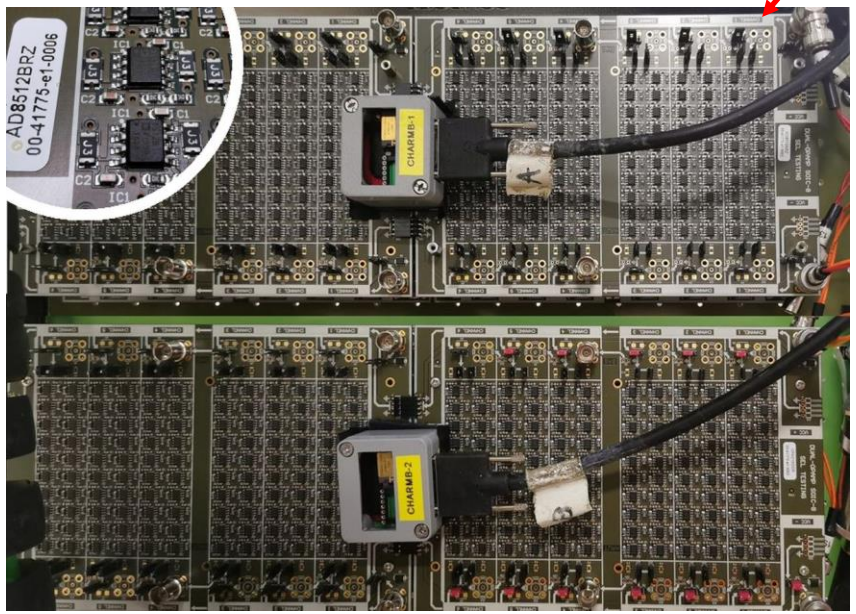
Component testing under radiation

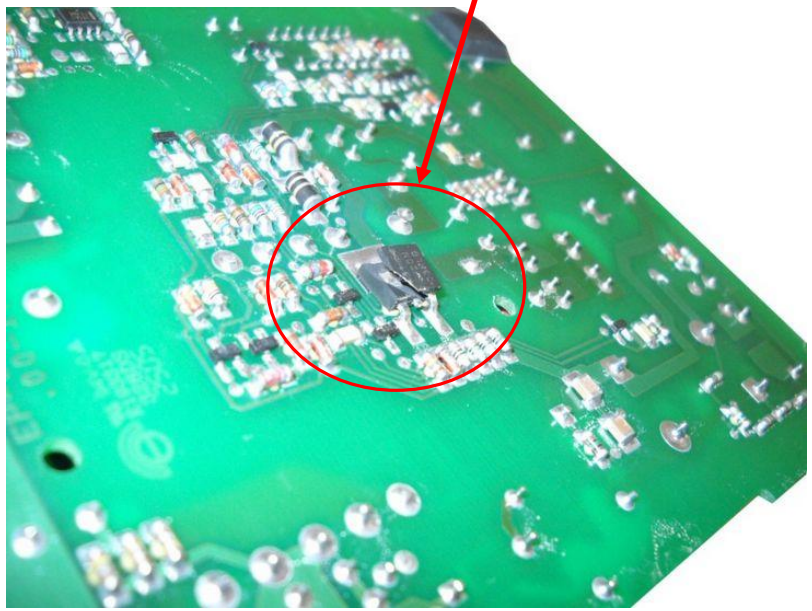
Radiation tolerant converters with **Commercial Off The Shelves - COTS** components

testing, testing, testing !

- Component testing – **thousands of component references** tested at different test facilities for different effects (TID, Displacement Damage, SE):
  - H4IRRAD (CERN), CHARM (CERN), CNRAD (CERN), PSI





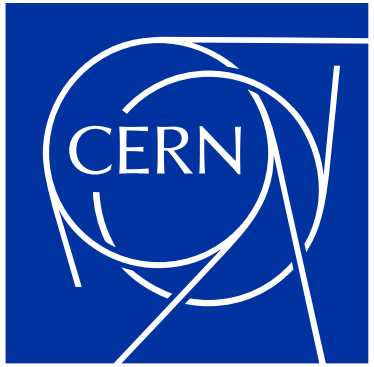


System testing under radiation

Radiation tolerant converters with **Commercial Off The Shelves - COTS** components
testing, testing, testing !

- System testing – **full converter testing** at CHARM
- **Heavy operation**:
  - power converter dimensions
  - water cooling,
  - electrical distribution,
  - automated transport to minimize exposure
  - …

Thank you for your attention!



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