CERN

CERN Accelerator School

Putting it into Practice

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CERN

Introduction

In this talk,

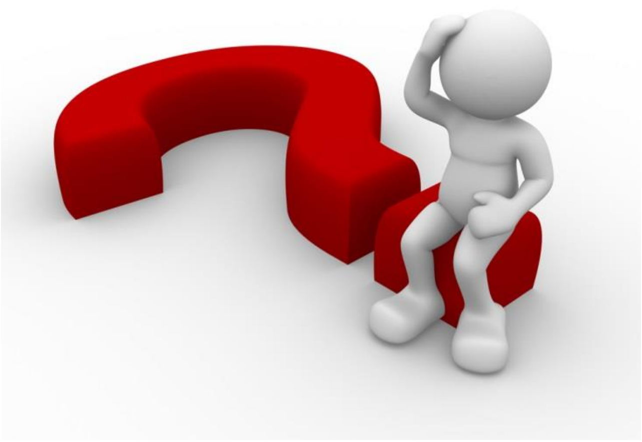
I will try to answer to questions raised in 'power converter requirements'

I will try to propose a list of solutions,

of tricks,

of recommendations,

of warnings….



- B-field uncertainty / accelerator operation
- Circuit layout
- Energy saving
- Capacitor ageing
- EMC / grounding
- IGBT ageing
- Control performance

Solution for B-field uncertainty

In most of the synchrotrons, all the magnets (quadrupole, sextupole, orbit correctors,…) are current control and the beam energy is controlled by the dipole magnet current.

To mitigate the B-Field uncertainty, the solutions are :

- Use the degauss or pre-cycle technique
- Get a high-precision magnetic field model (10^{-4})
- beam steering application for orbit and trajectory correction
- Real time orbit feedback system
- Real time tune feedback
- Real time chromaticity feedback

Or / and

- Real-time magnetic field measurement and control (10^{-4})

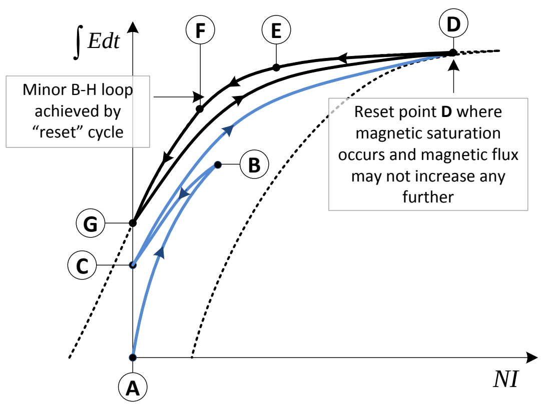
    needs an extra magnet outside the machine with instrumentation in its gap.

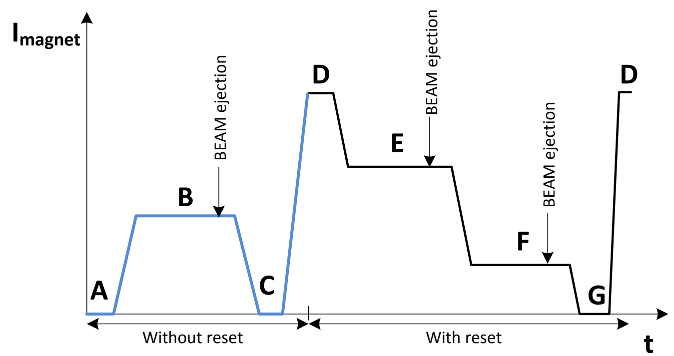
Solution degauss technique

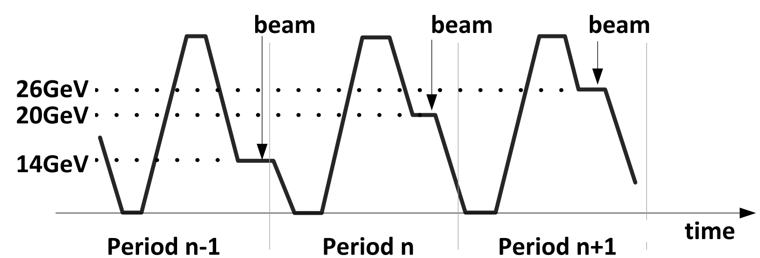
To solve this problem of hysteris, the classical degauss technique is used.

For a machine working always at the same beam energy, few cycles at beam energy will degauss the magnets. Example LHC precycle.

For machine or transfer line with different beam energies, the degauss has to take place at each cycle. Solution, always go at full saturation in each cycle.

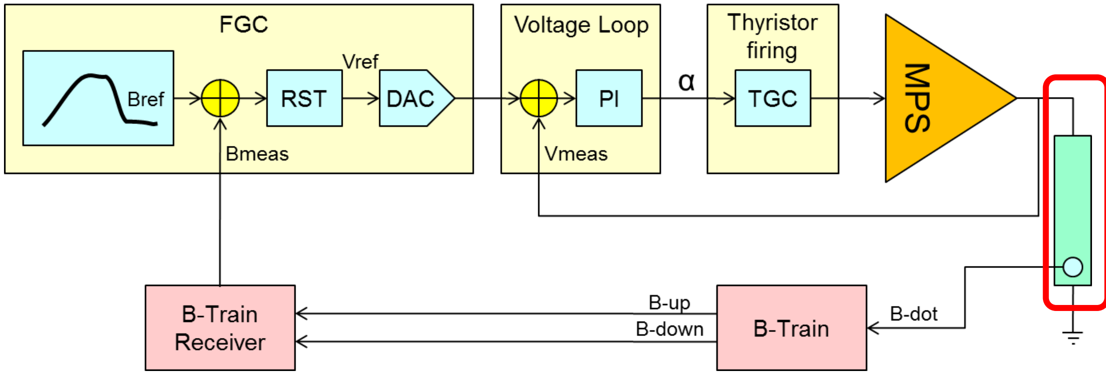


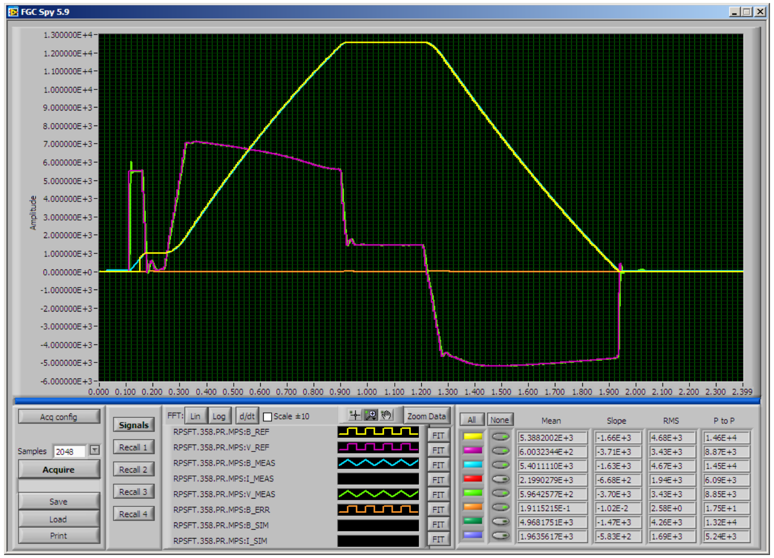


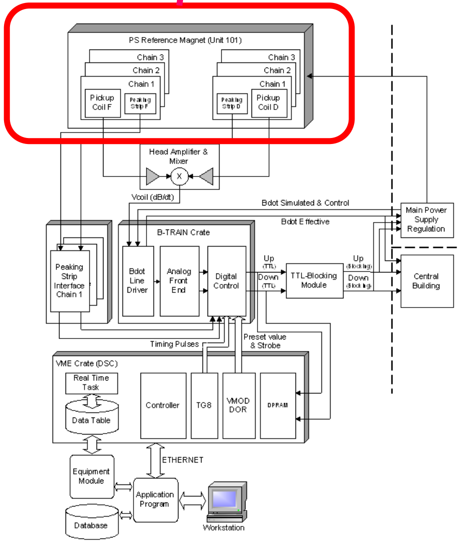


Solution B-field control

Reference magnet with B-field measurement.







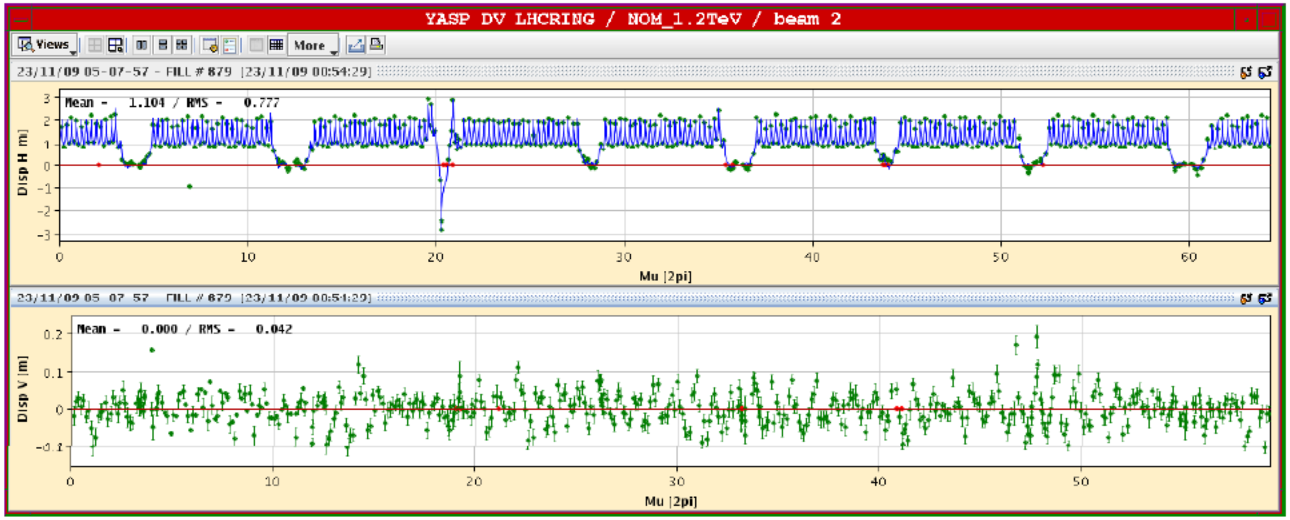
Solution: Magnetic Model

The LHC has a magnetic model.

Accelerator physicists use the FiDeL tool to generate the current reference.

The aim is to provide the integral transfer function (integral field vs. current) in a form suitable for inversion (current vs. integral field) for each circuit in the LHC. In addition, for the main ring magnets FiDeL will provides a prediction of the field errors to be used to set the corrector circuits.

https://lhc-div-mms.web.cern.ch/lhc-div-mms/tests/MAG/Fidel/



Measured dispersion in the LHC versus model [courtesy of R. Steinhagen]

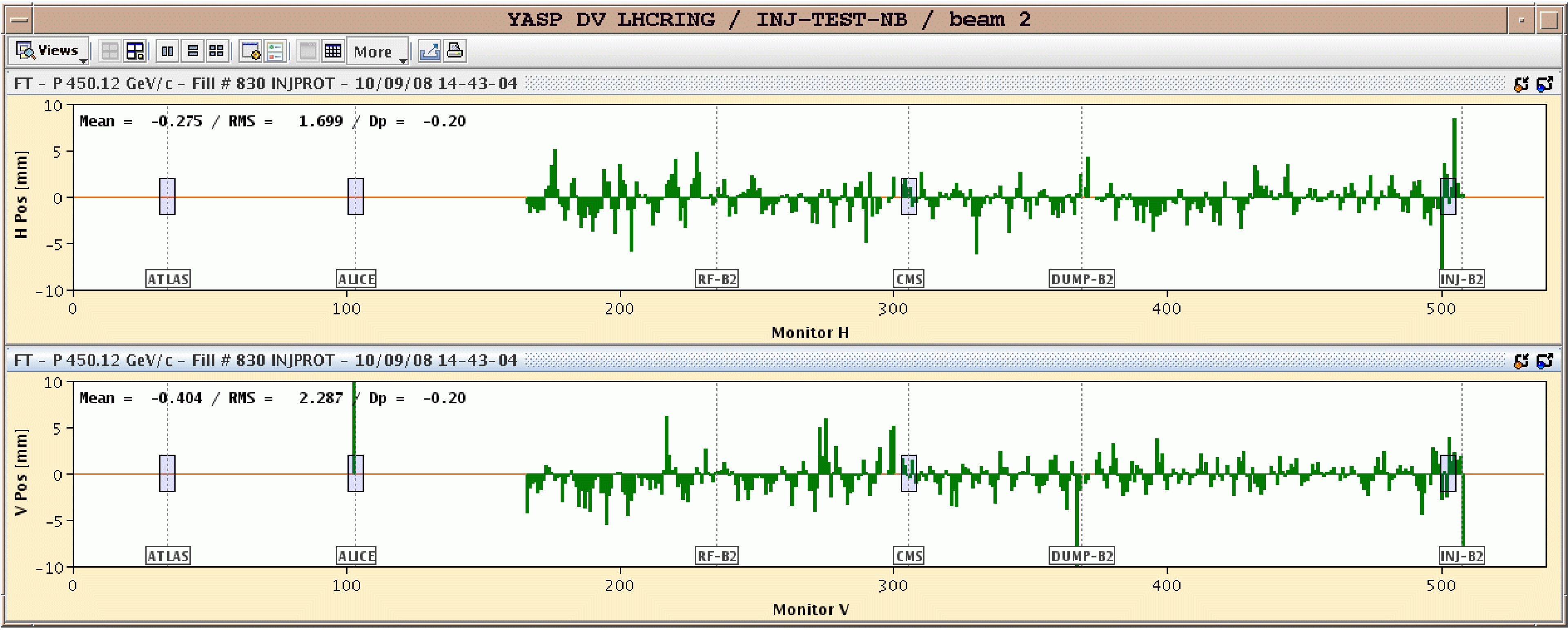
Solution: beam steering

beam steering application for orbit and trajectory correction
= operator tool

https://jwenning.web.cern.ch/jwenning/documents/YASP/YASP-user-guide.pdf

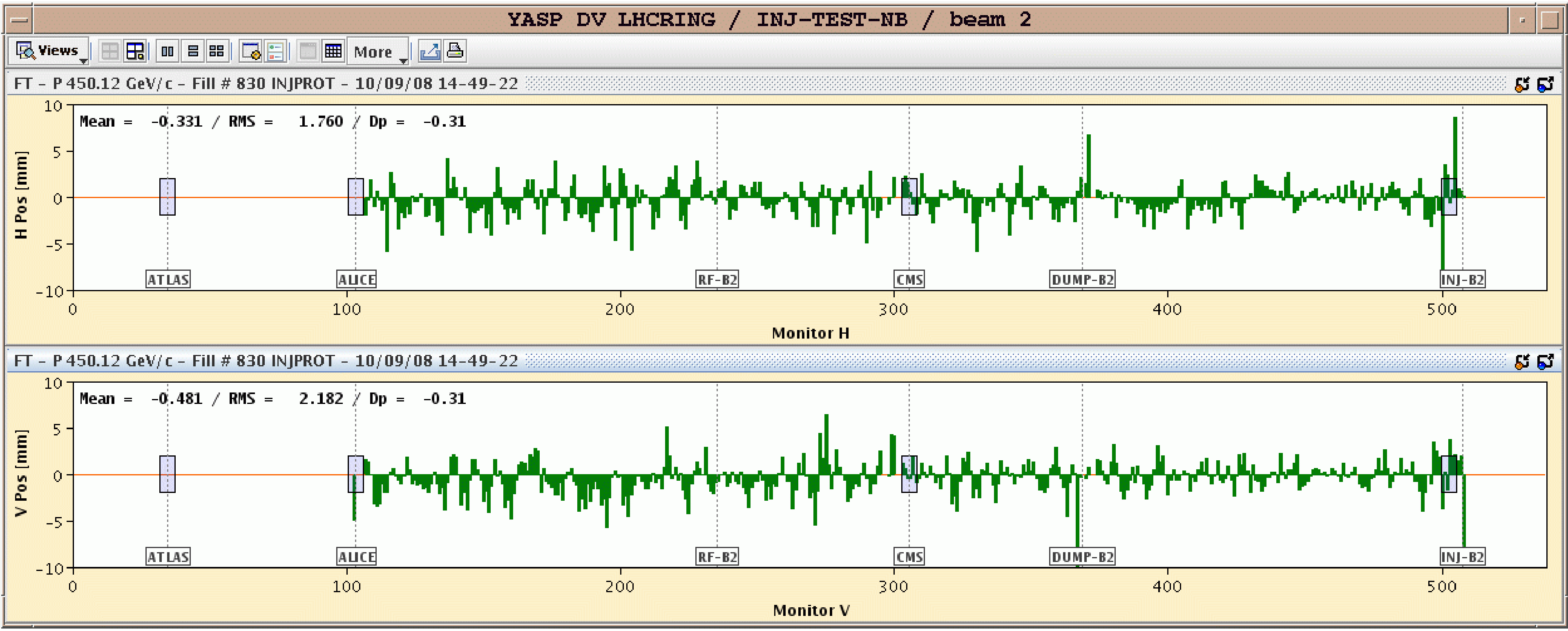
First LHC Beam 2 around the ring

1. Beam to TDI
2. Beam to IR7
3. Beam to IR6
4. Beam to CMS
5. Beam to IR3



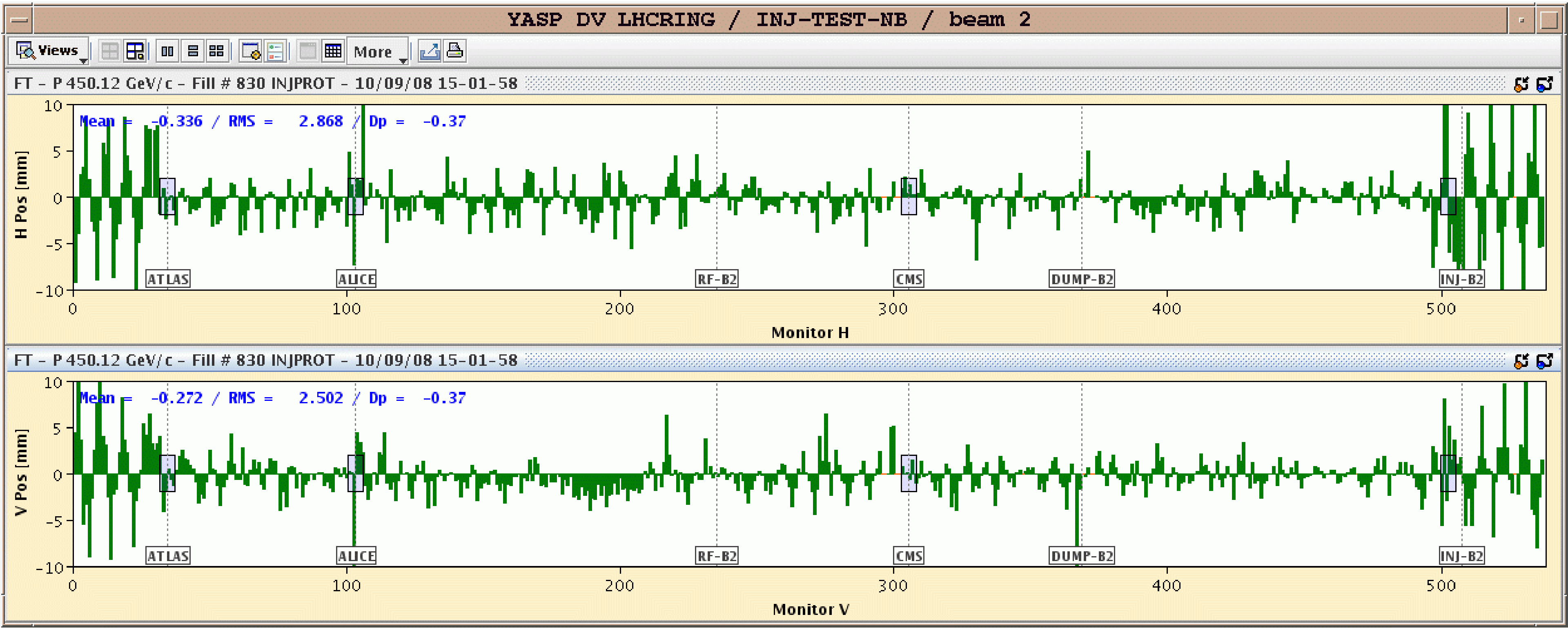
First LHC Beam2 around the ring

1. Beam to TDI
2. Beam to IR7
3. Beam to IR6
4. Beam to CMS
5. Beam to IR3
6. Beam to ALICE



First LHC Beam2 around the ring

1. Beam to TDI
2. Beam to IR7
3. Beam to IR6
4. Beam to CMS
5. Beam to IR3
6. Beam to ALICE
7. Beam to ATLAS
8. **Beam to LHCb – First Turn !**



Solution orbit feedback

The LHC has an orbit feedback system.

It needs BPM (Beam Position Monitors). The feedback controller acts on the orbit corrector magnets

http://cds.cern.ch/record/1054849/files/thesis-2007-058.pdf?version=1

https://jwenning.web.cern.ch/jwenning/documents/Orbit/FB/Snapb-EPAC02.pdf

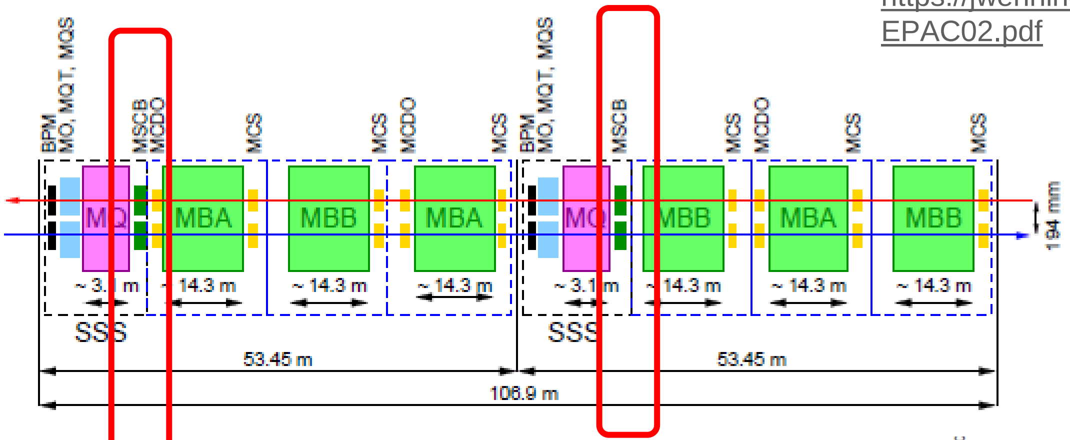


Figure 1.5: Standard LHC arc

Dynamic compensation

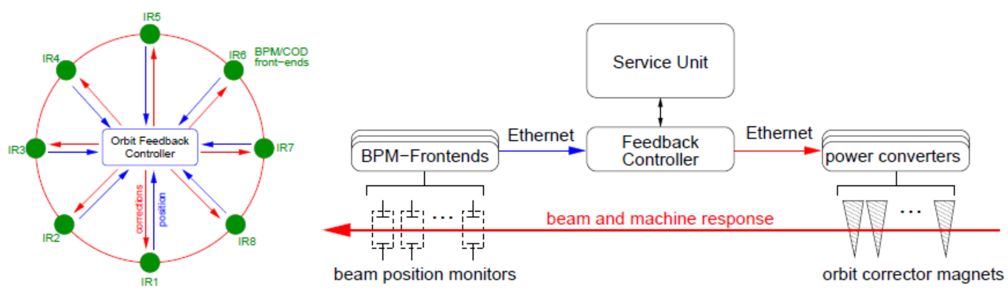


Figure 1.17: Schematic Feedback Overview

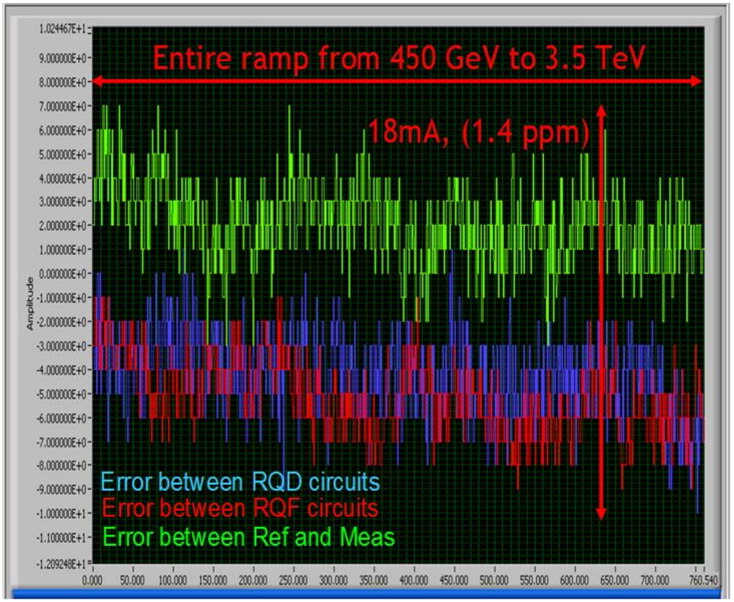
Solution for individual powering

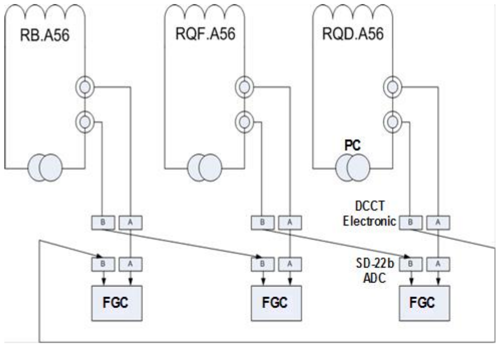
When the circuits are split:

- The tracking error shall be limited (control performance)
- The magnet hysteresis shall be reset (pre-cycle)

Recommendation:
Place the same controller in front of all the power converters.

Example:
LHC tracking error between the 8 sectors

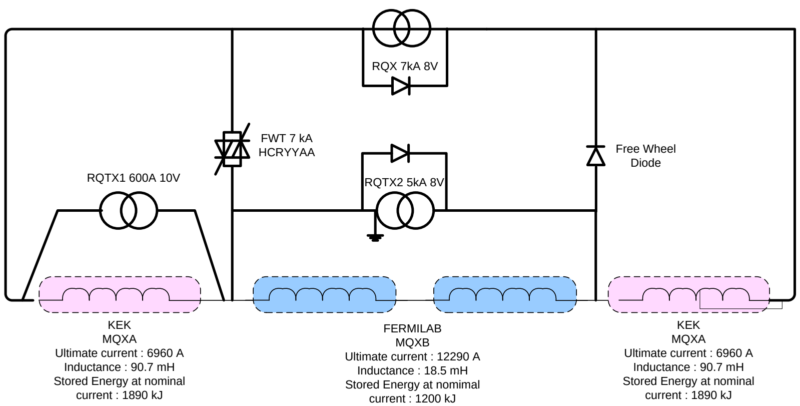




Solution for nested circuits

Nested powering scheme can be a nightmare for power engineers !!

Very complex control, it is like a car with many drivers having a steering wheel acting on only one wheel.



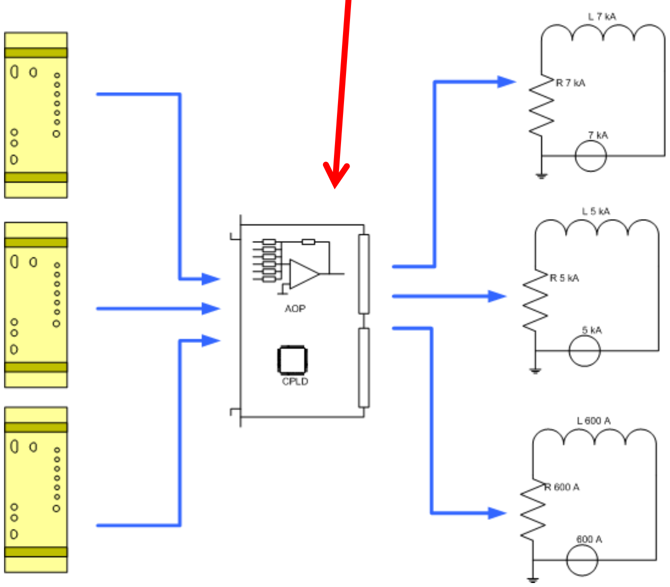
Reduce capital cost but decrease availability!

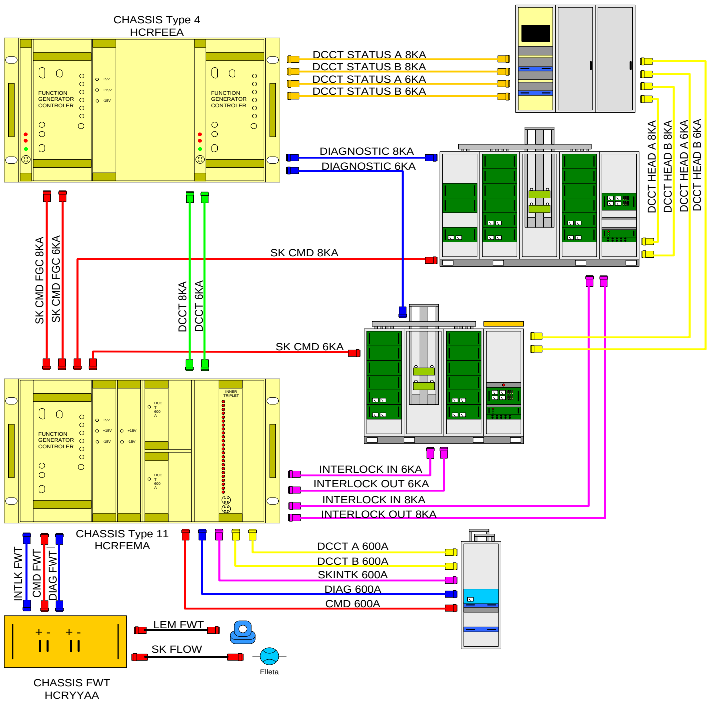
Solution for nested circuits

Very difficult to operate and repair, long MTTR.

All converters have to talk each others.

Need a <u>decoupling matrix</u> to avoid fight between converters !

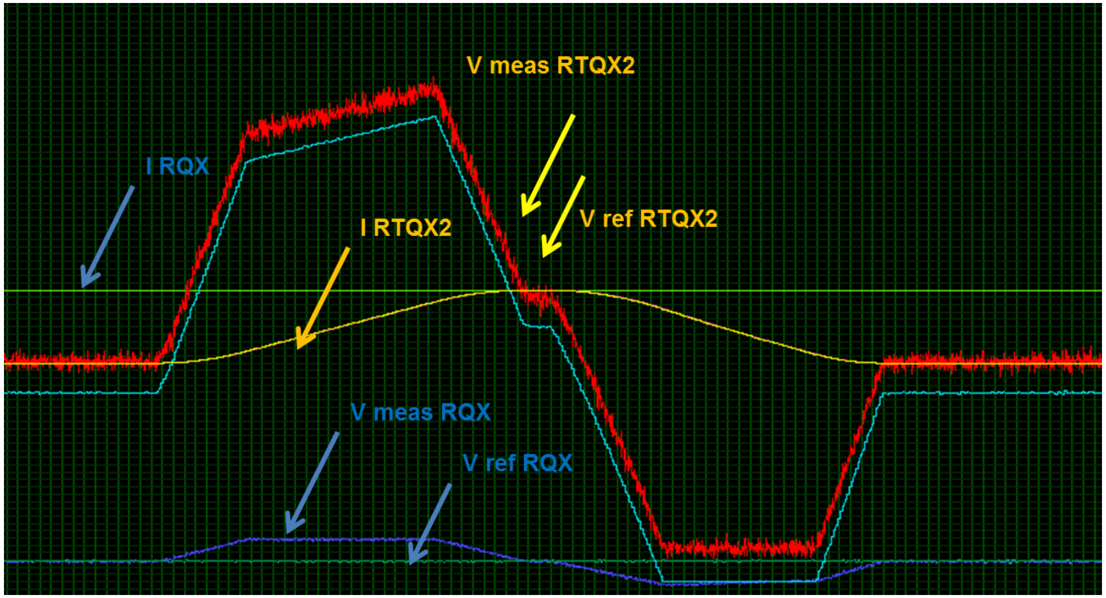




https://edms.cern.ch/file/1100412//LHC-Inner-Triplet-I_PAC_2010.pdf

Solution for nested circuits

Look at the current and voltage of RQX while RTQX2 current is changing!



Nested circuits aren't RECOMMANDED !

LHC inner triplet works perfectly well but MTTR is much higher.

RHIC had many difficulties with nested circuits.

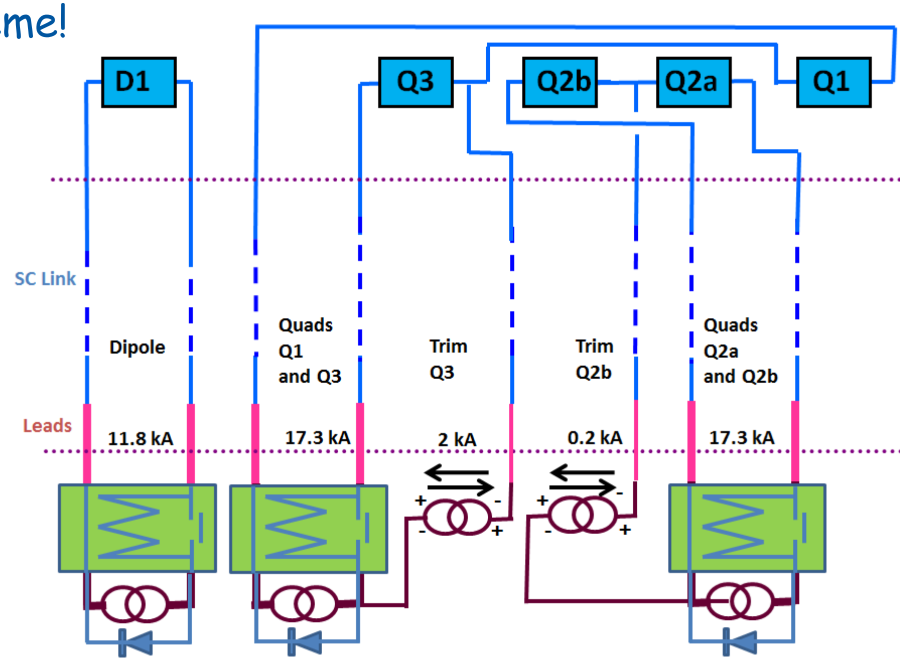
Solution for HL-LHC

For the LHC upgrade project (High-Lumi LHC), the inner triplet magnet will be replaced by new ones with a larger aperture.

The solution proposed is to have one power converter for Q2a-b magnets and one for Q1 – Q3 magnets!

It still requires trim power converters to have the full flexibility with beam optics.

Simpler powering scheme!

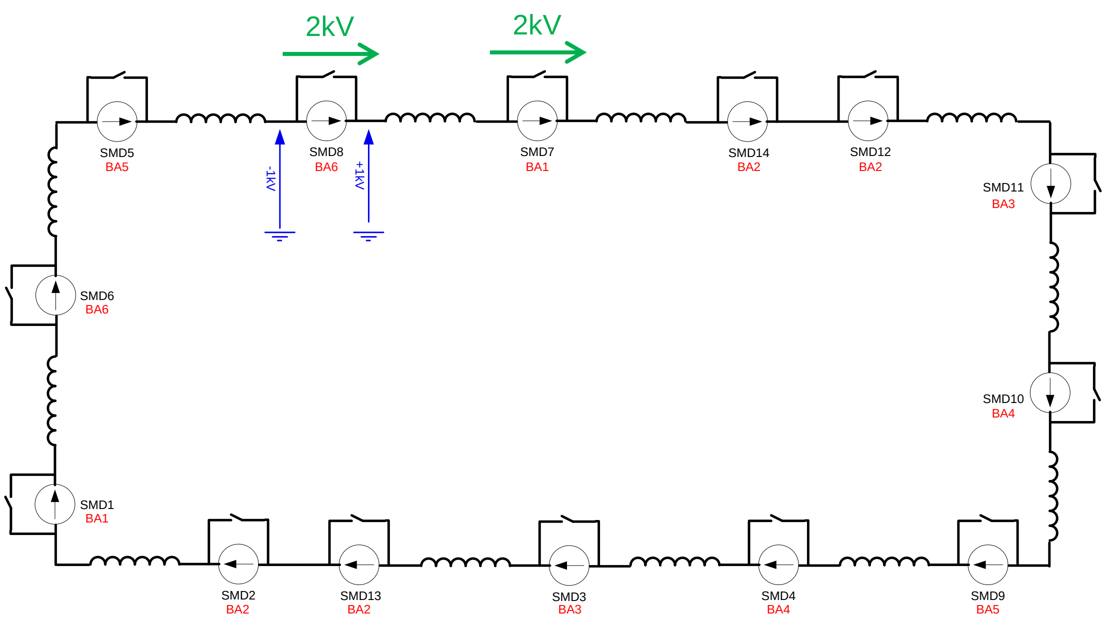


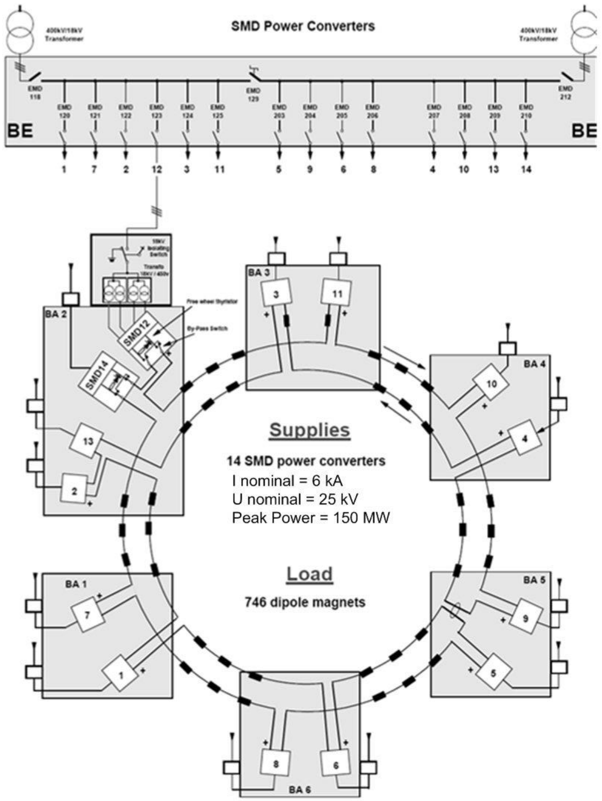
Solution for large dipole circuit

The SPS have 744 dipole magnets. The total voltage applied is 24kV for 6kA.

12 power converters are placed between series of magnets. Each power converter is rated at 2kV. The maximum voltage to ground of the magnet is then 2kV.

Large reduction of insulation constraint on the magnets!



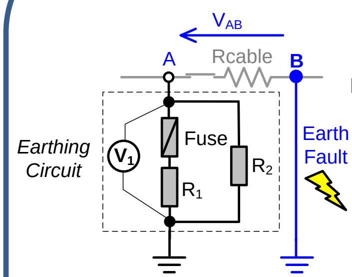


Solution for magnet grounding

With a resistor, an earth fault can't be detected close to the polarity connected to earth.

Solution: active detection https://edms.cern.ch/file/997662//PAC2009_Earth-Current-Monitoring-Circuit-for-Inductive-Loads.pdf

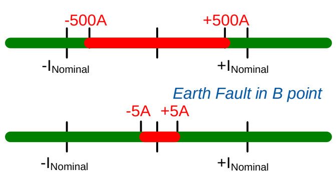
Earthing Circuit: Passive Detection



Earth fault: $|V_1|>0.5V$
$|I_{earth}|>50mA$

R1	10Ω
Fuse	1A
R2	10kΩ

R_{cables} 2mΩ



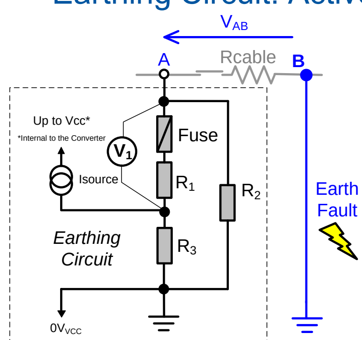
R_{cables} 200mΩ

Dead zones: $|V_{AB}| < 0.5V$

Advantages
- Simple

Drawbacks
- Fuse status unknown
- Dead zones for low voltage drops

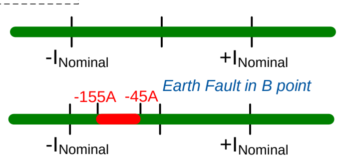
Earthing Circuit: Active Detection



Earth fault: $|V_1|>0.5V$
$|I_{earth}|>50mA$

R1	10Ω
R3	100 Ω
Fuse	1A
R2	10kΩ
I_{Source}	100mA

R_{cables} 2mΩ

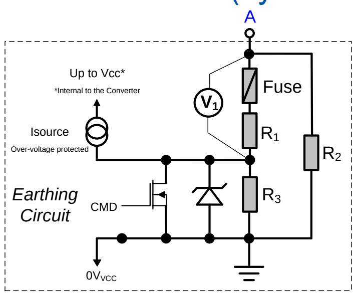


R_{cables} 200mΩ

Advantages
- Earth fault detection before energisation
- Fuse status known
- No dead zone for low voltage drops and 1-quadrant converters

Drawbacks
- Dead zones for high voltage drops since common mode voltage must be kept limited to few volts (safety reasons)

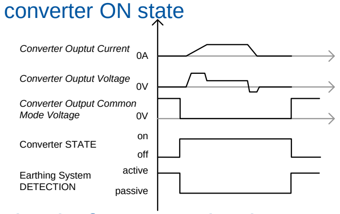
Earthing Circuit: Active / Passive Detection (dynamic selection)



Earth fault: $|V_1|>0.5V$
$|I_{earth}|>50mA$

R1	10Ω
R3	100 Ω
Fuse	1A
R2	10kΩ
I_{Source}	100mA

Dynamic selection through CMD signal:
- Active detection = converter OFF state
- Passive detection = converter ON state



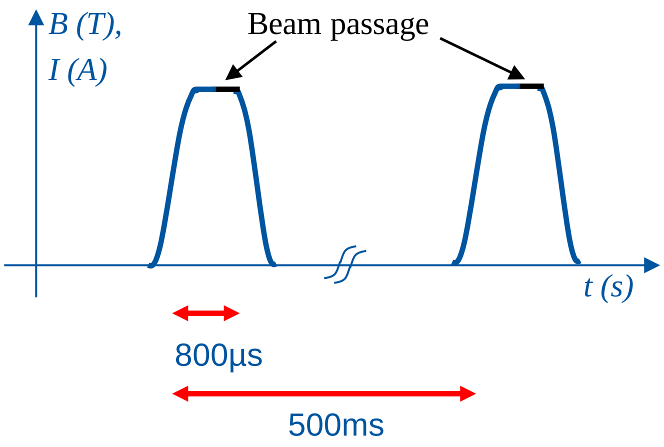
Advantages
- Earth fault detection before energisation
- Useful for high voltage drops when passive detection is preferable

Drawbacks
- Dead zones for low voltage drops

Solution for energy saving

<u>Linac's and transfer lines</u>

LINAC4 : Beam is passing through in one shot, with a given time period;



Beam duty cycle : 0.016%

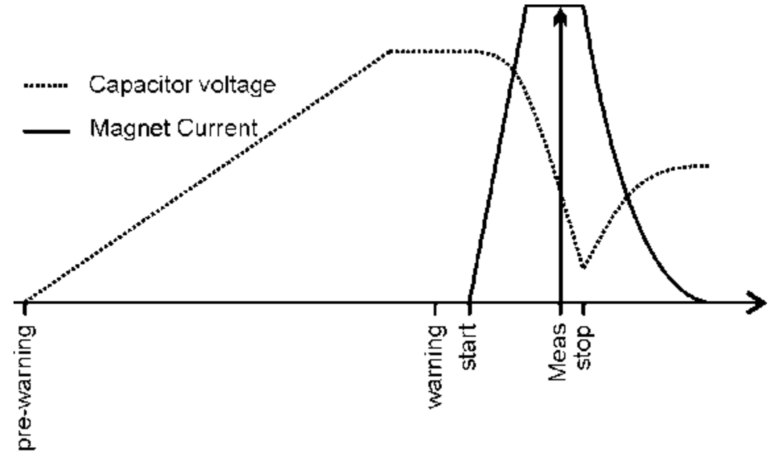
Most of the magnets and all klystrons are pulsed.

Solution for energy saving

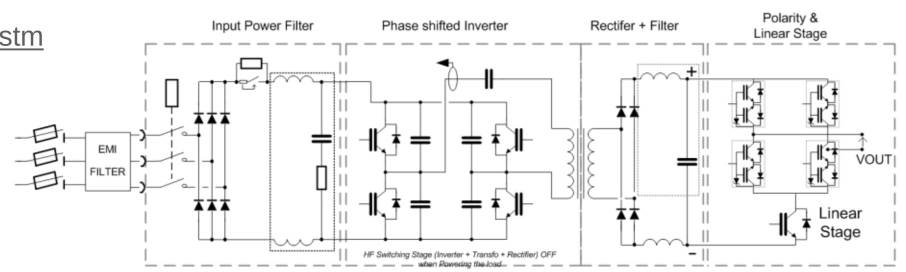
New topologies for discharged converters.

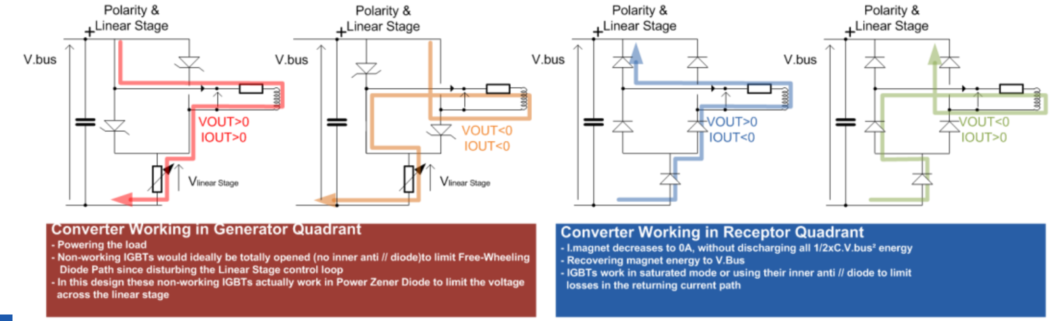
- Fast ramp-up (IGBT polarity switches)
- Flat top control (active filter or IGBT in linear mode)

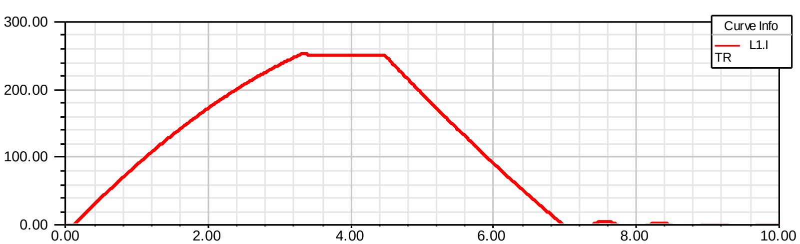
Energy saved compared to DC powering = 99.4%



http://te-epc-lpc.web.cern.ch/te-epc-lpc/converters/mididiscap/general.stm



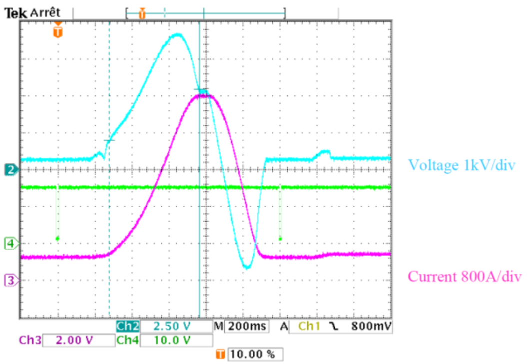


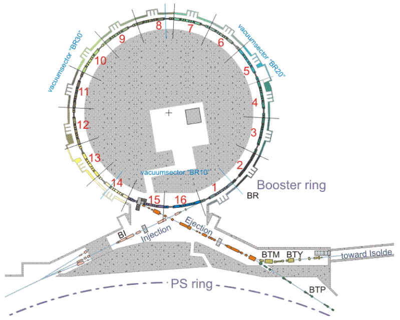


New concept for energy management

Project of beam energy increase at the Booster

Present power converter:
4 thyristor bridges in series, 4kA/4kV
With SVC
All magnet coils in series.





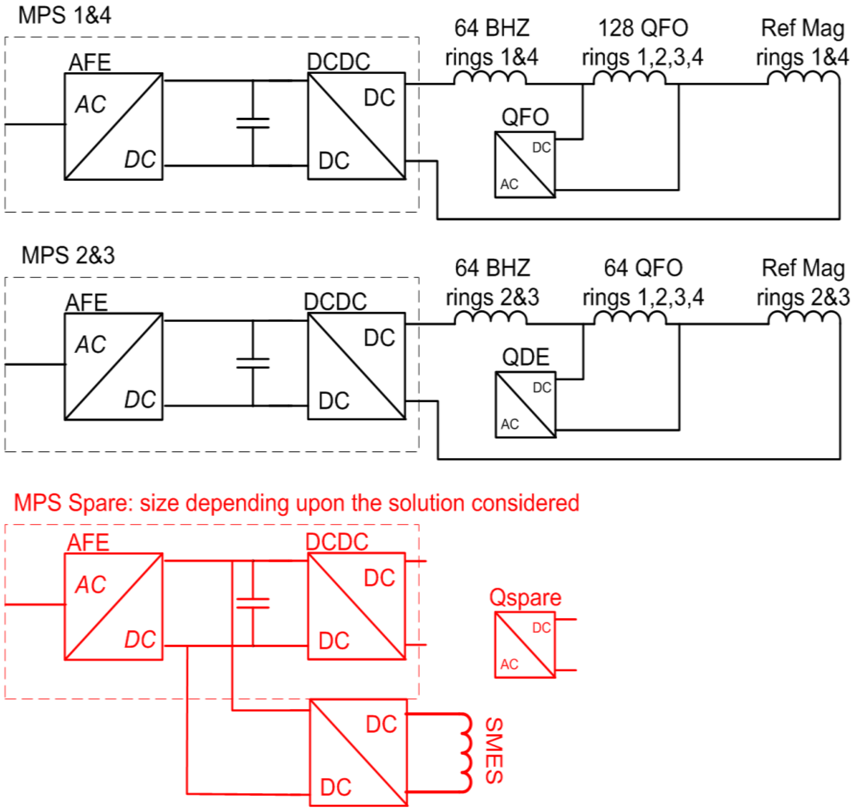
- From 1.4Gev to 2GeV → B-field: x1.3
- Magnet saturation effect → Peak Current: x1.5
- Same ramp-up time → Power: x1.8

Increase ramp-up time to keep the same RMS current in the magnets → Peak Power: x2

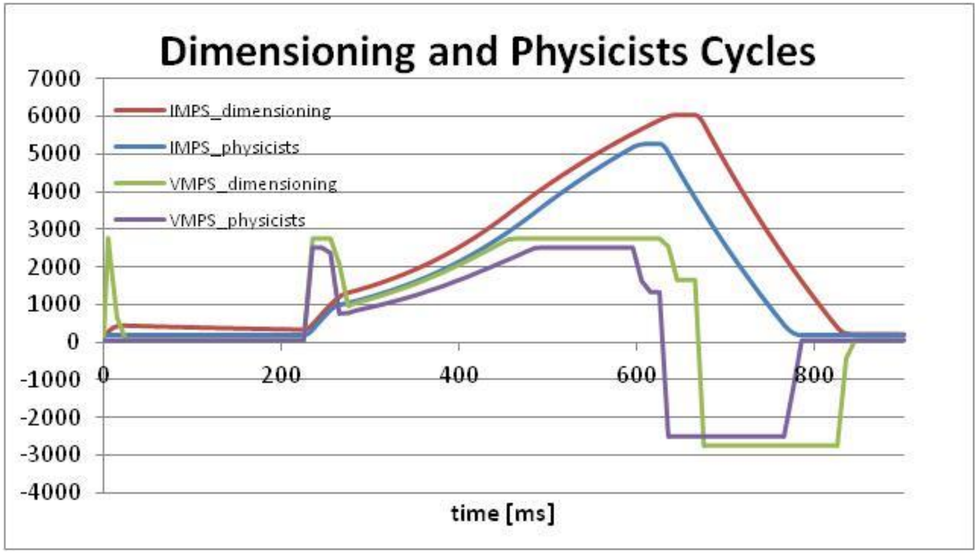
New challenging Main Power Supply

New concept for energy management

2 power converters + 1 full spare
IGBT converters with capacitive storage 3 * 2.6MJ
Peak power 2 * 14MW
Rms power 2 * 1.5MW



Separation of middle coils with the outer coils



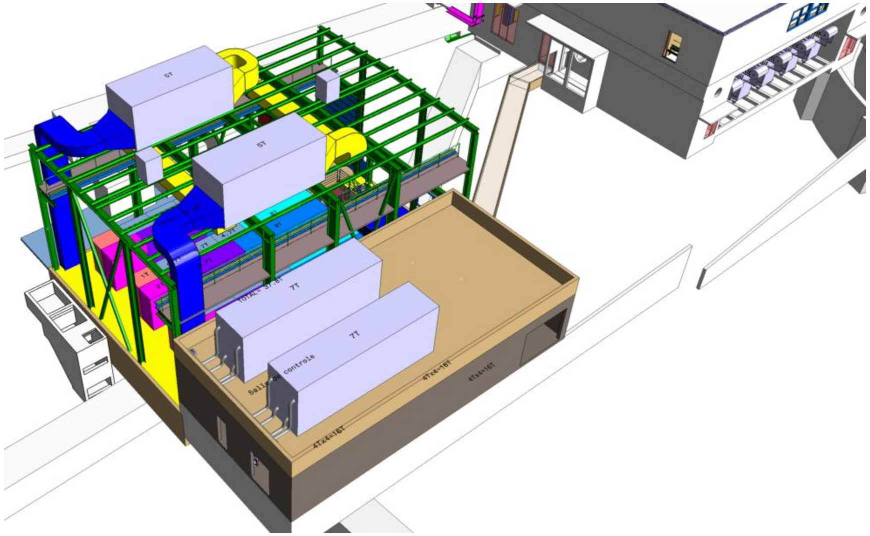
New concept for energy management

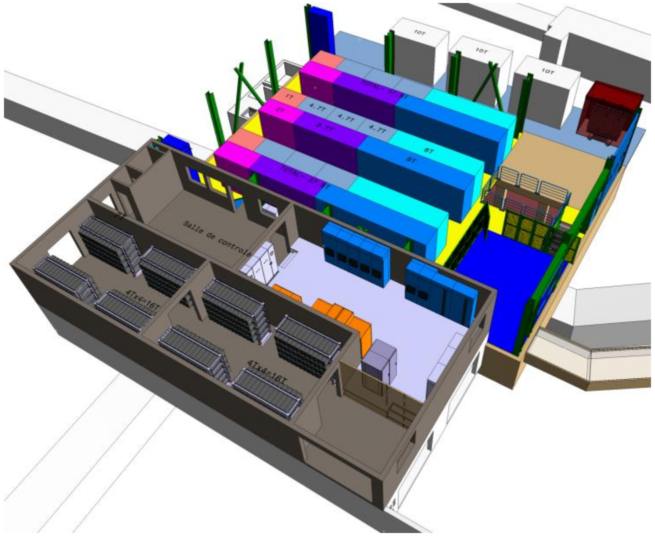
Present power system:

- Peak power applied to magnets: 14MW
- Peak power taken on the grid: 14MW + SVC 17MVar

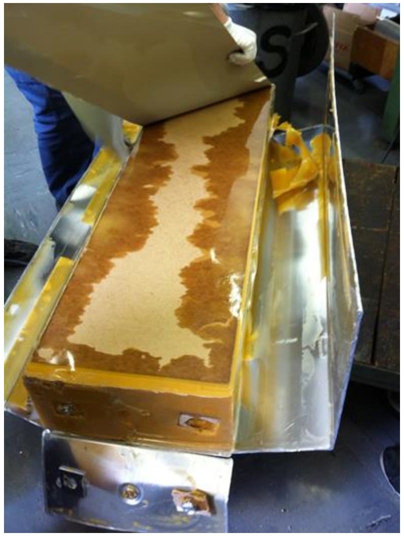
New power system

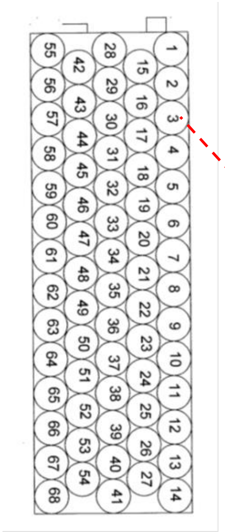
- Peak power applied to magnets: 28MW
- Peak power taken on the grid: 5MW + no SVC
- No increase of magnet losses! Same average power !



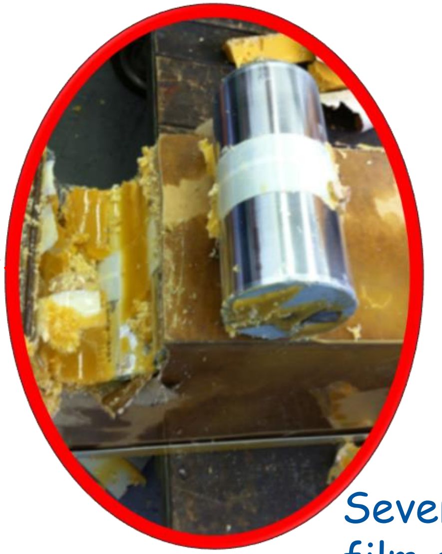


Capacitor ageing of POPS

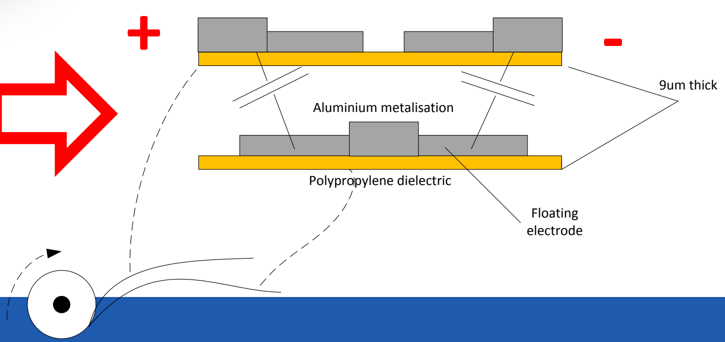




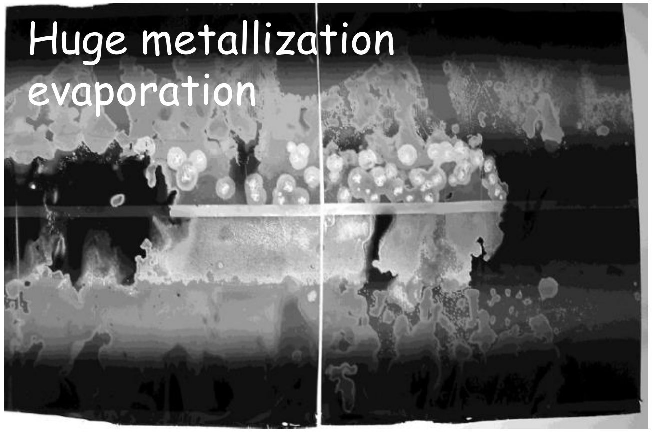
A capacitor unit is 2mF.
68 basic elements (cans) are connected in parallel

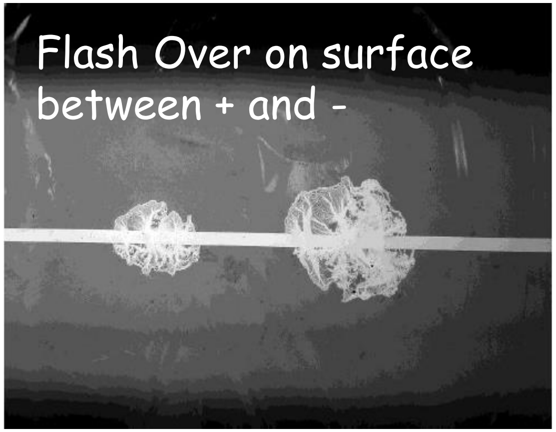


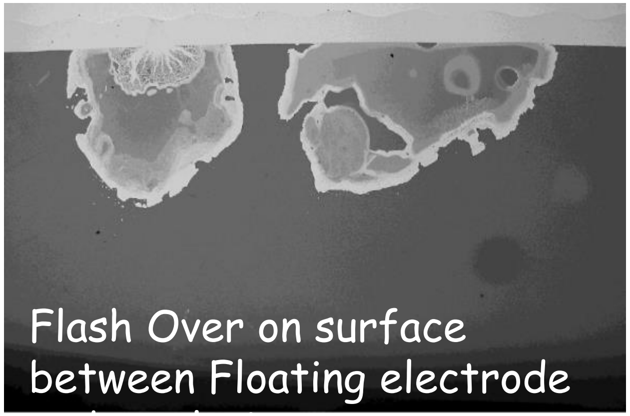
Several hundreds meters of double film are rolled-up.
The double film layer constitutes a series connection of 2 capacitors.

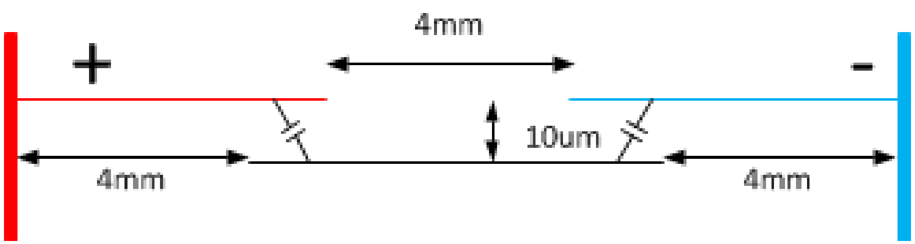


Capacitor ageing



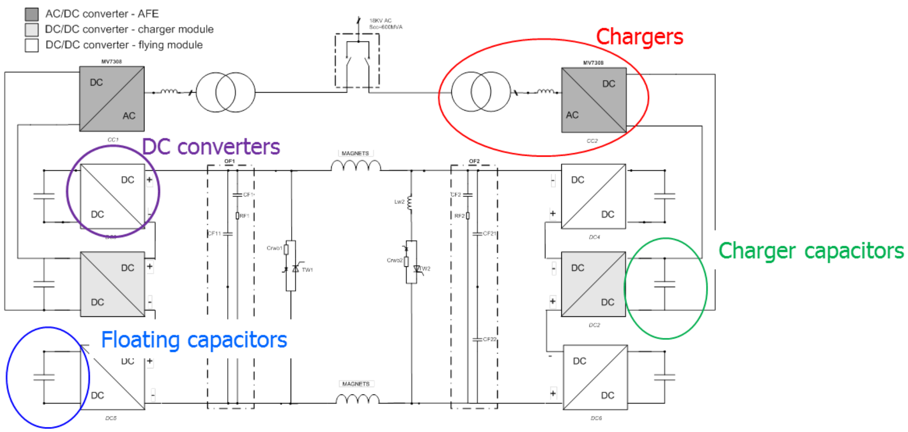


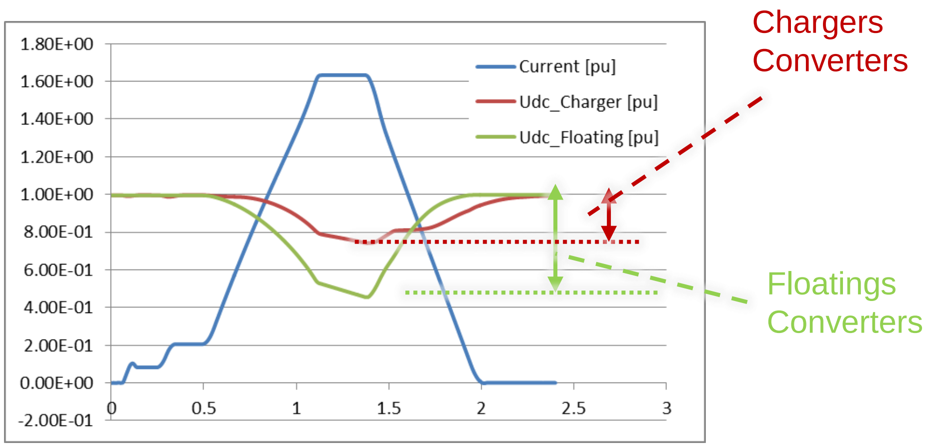




1. Electric stress on surface: 4mm for 5kV looks really tight (probably under dimensioned)
2. Electric stress in the dielectric: E=250V/um is generally considered a limiting value for real applications in pp.

Capacitor ageing





The first hypothesis is unexpected ageing caused by low frequency charge-discharge cycling.

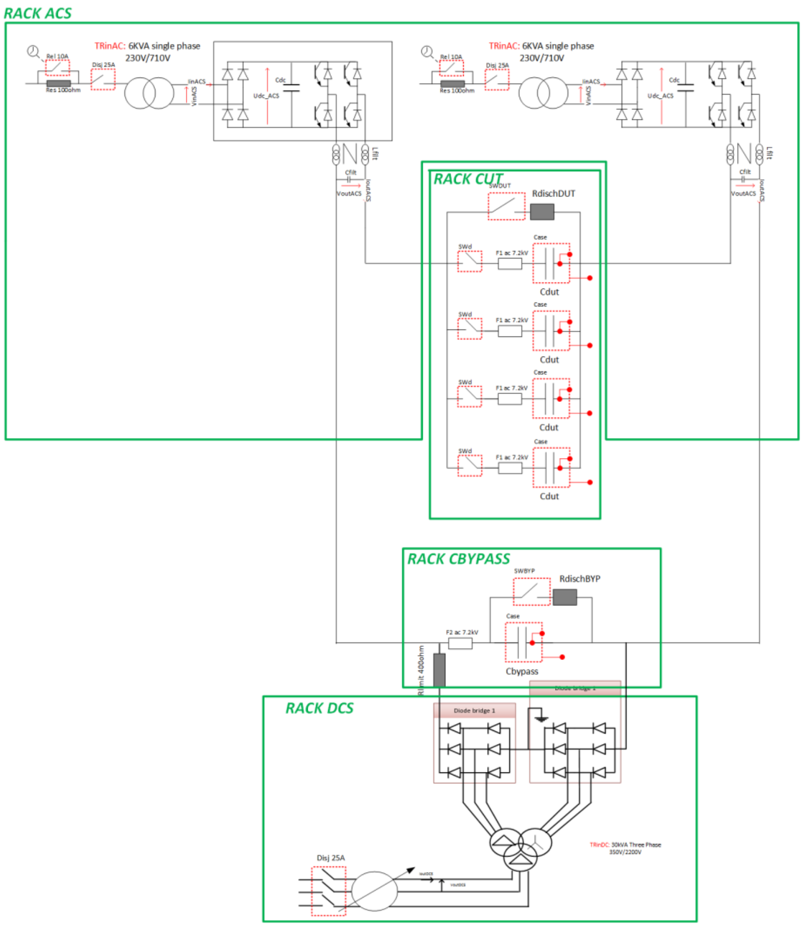
'film corrosion is due to partial discharged which demands on dv/dt.

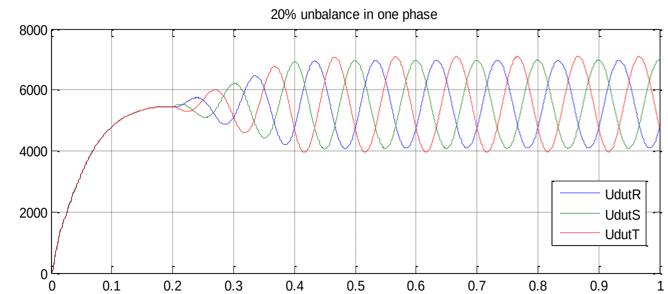
Capacitor manufacturers are under economical pressure, which leads to design without any margin.

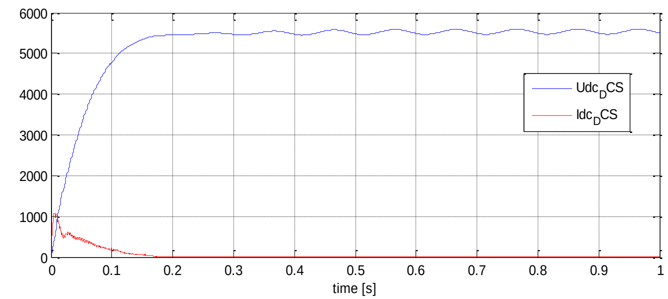
Put this margin in your specification.
For example, specify 6kV capacitors for operation at 5kV.

Capacitor ageing

CERN is building a test stand for accelerated testing of different capacitor technologies with a combination of DC+AC voltage.

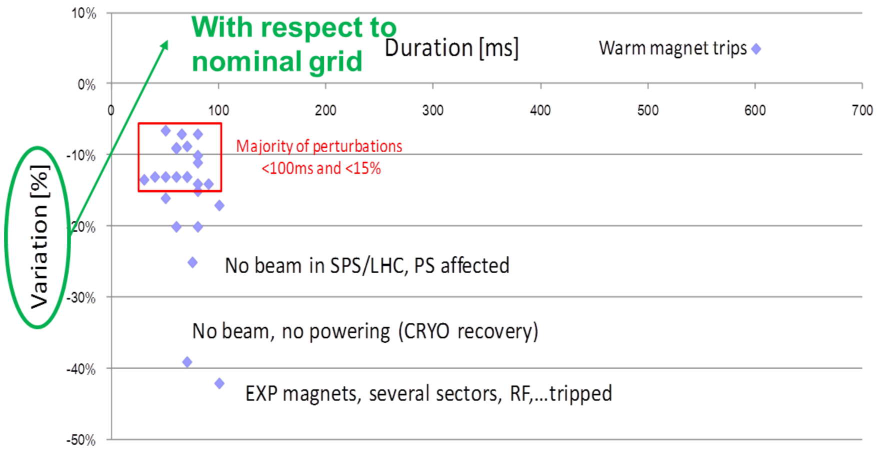






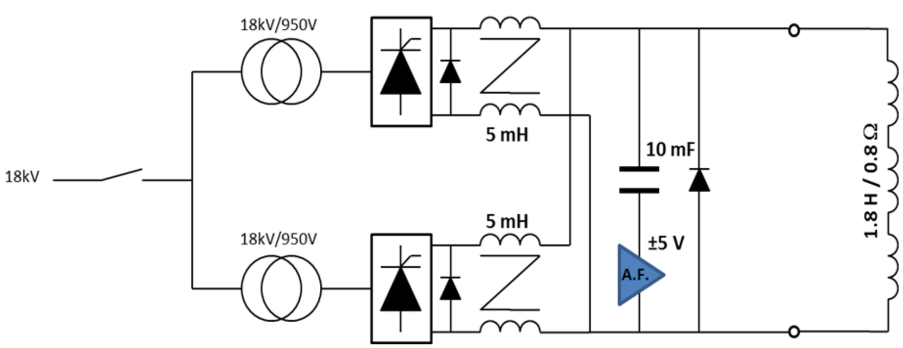
Sensitivity to grid perturbations

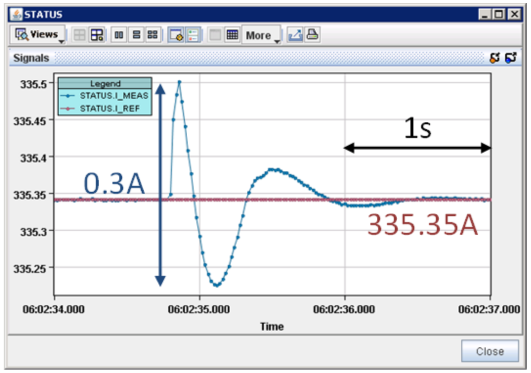
CERN is affected by grid perturbations.
The most sensible circuits are the warn magnets in LHC.



18kV grid

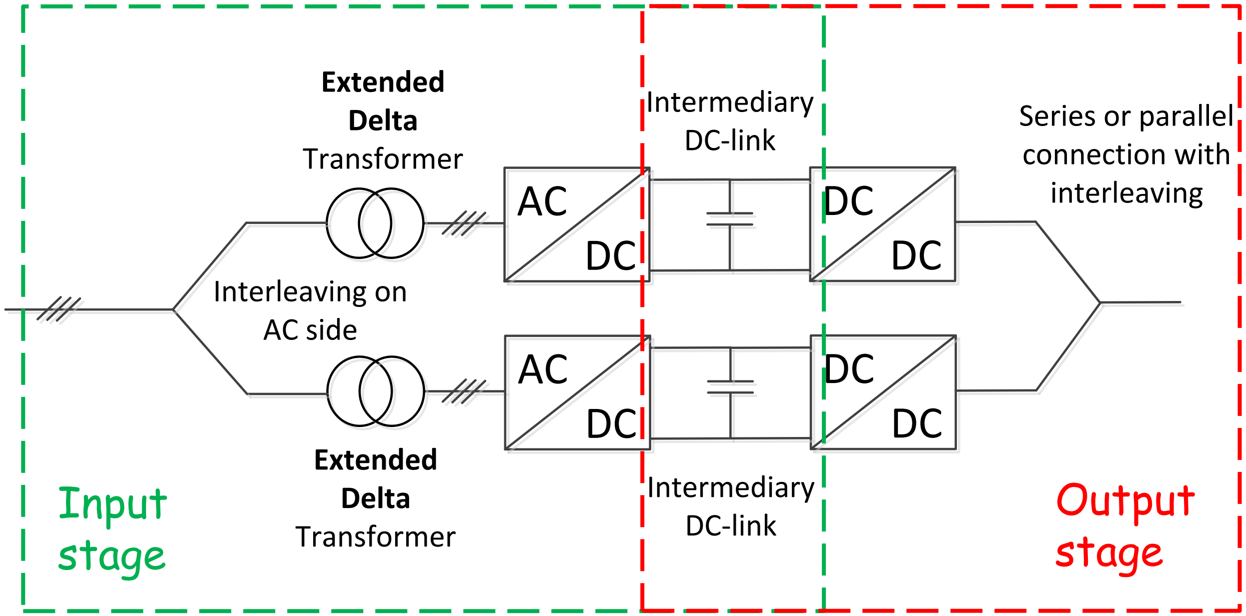
Trigger beam dump





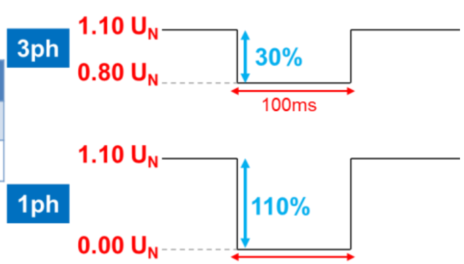
Sensitivity to grid perturbations

Classical topology but with special design to ovoid trip due to grid perturbations.



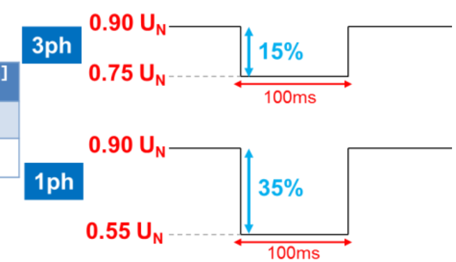
1.10 U_N permanent

Transient type	Transient step voltage [% of U_N]
Three phase	-30 %
Single phase	-110 %



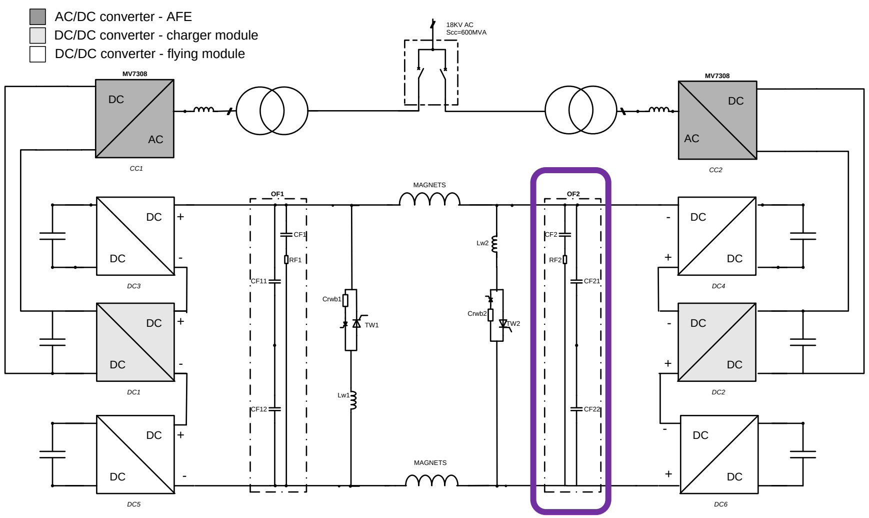
0.90 U_N permanent

Transient type	Transient step voltage [% of U_N]
Three phase	-15 %
Single phase	-35 %

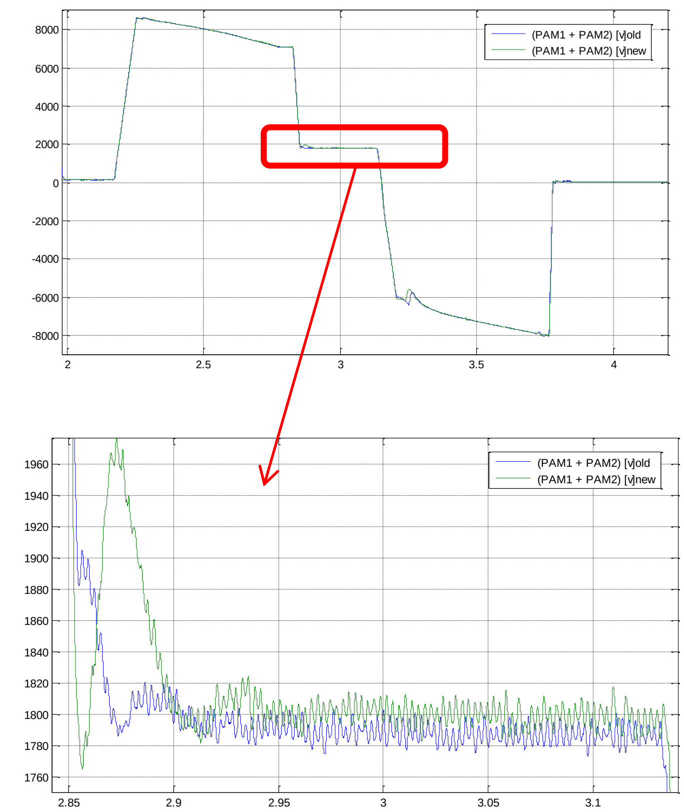


EMC: Common mode voltage

At the start of POPS, all the performance were verified in differential mode.
Everything was fine, but with the beam, the tune was disturbed.



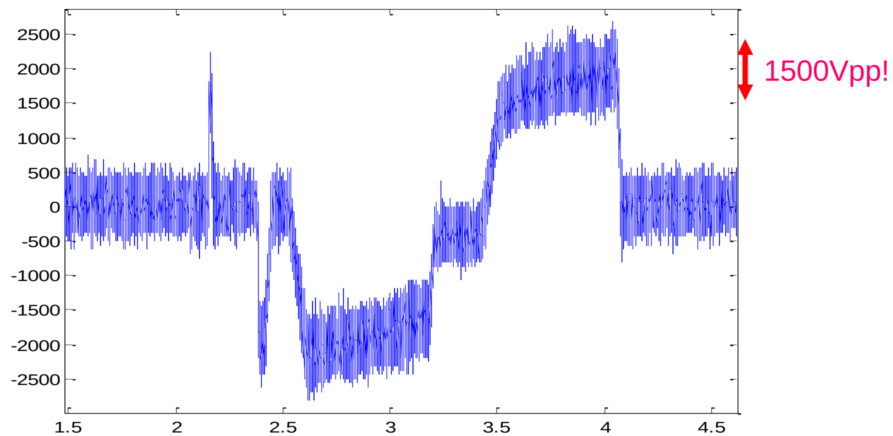
Differential voltage applied to magnet

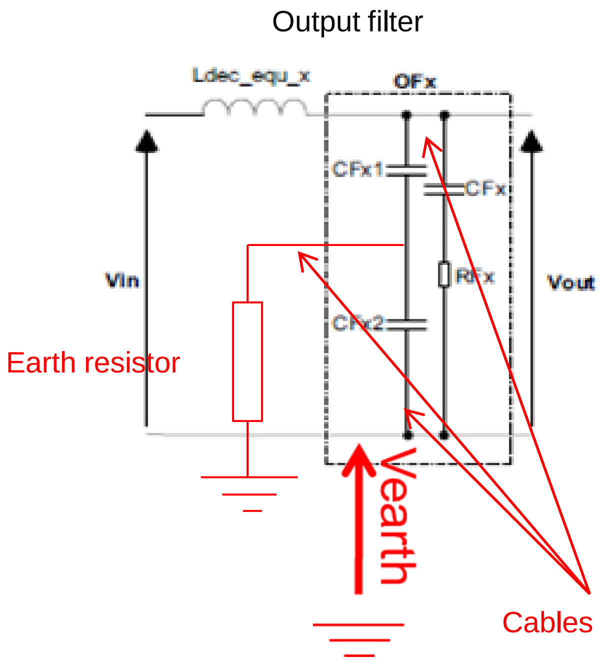


20Vpp as specified

EMC: Common mode voltage

Then, we looked at the common mode voltage (Between one polarity to ground).

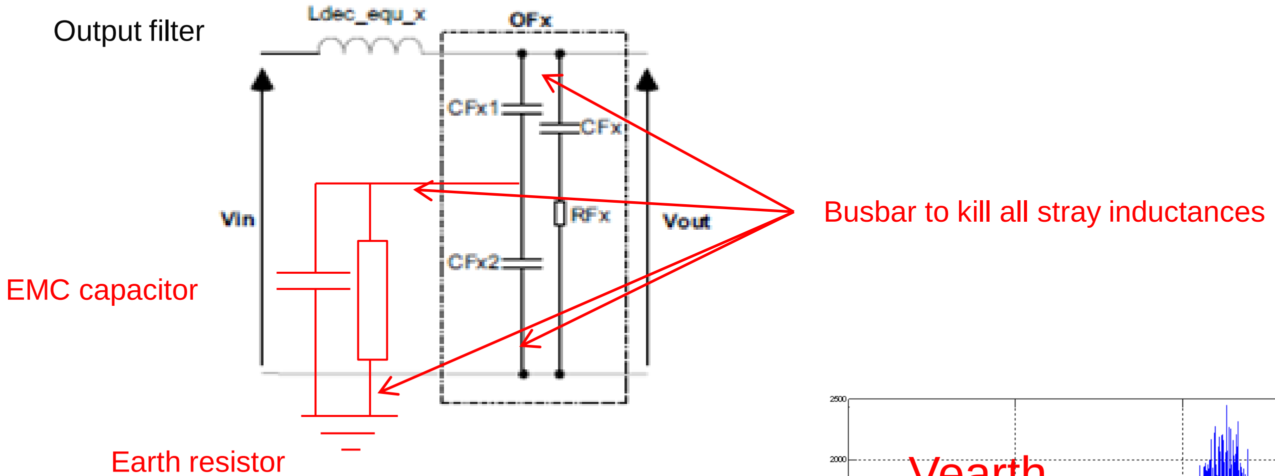


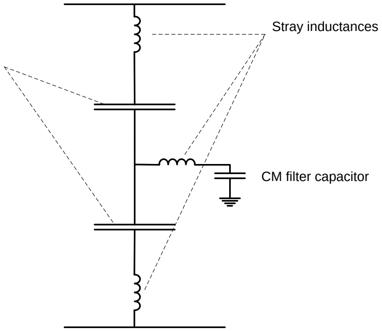


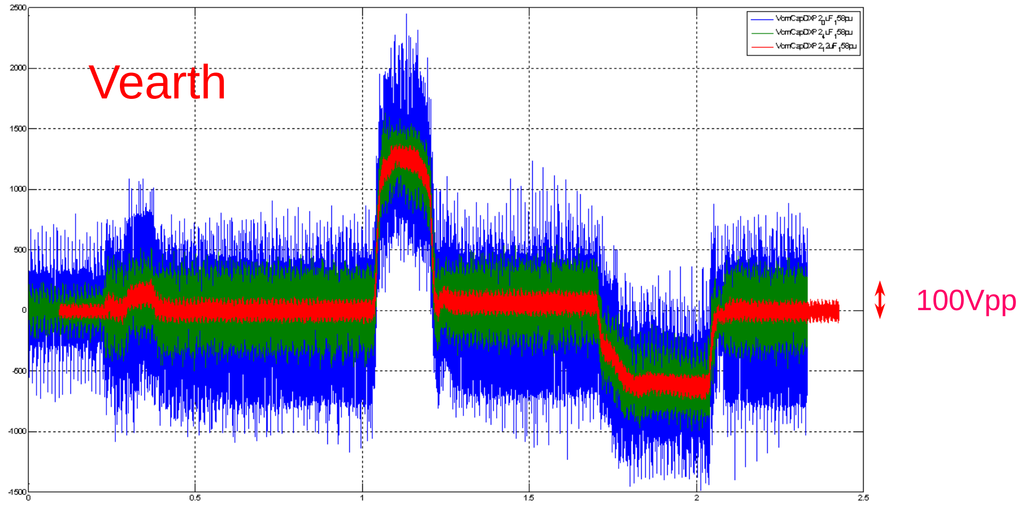
EMC: Common mode voltage

Solution: Place EMC capacitor to earth via busbar

Use metal plate, no wire or cable

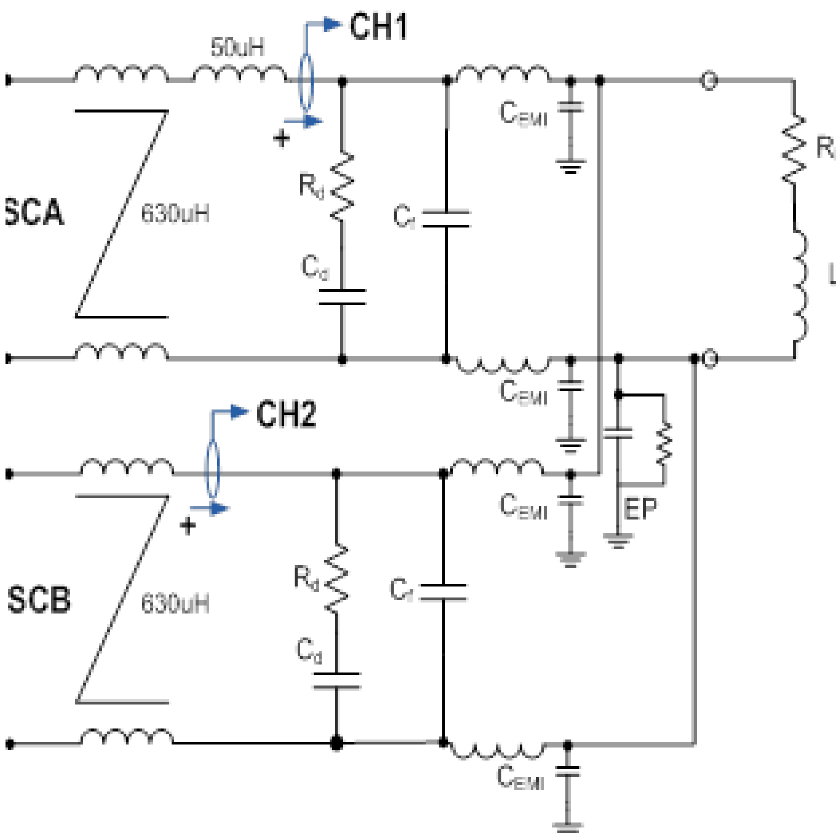


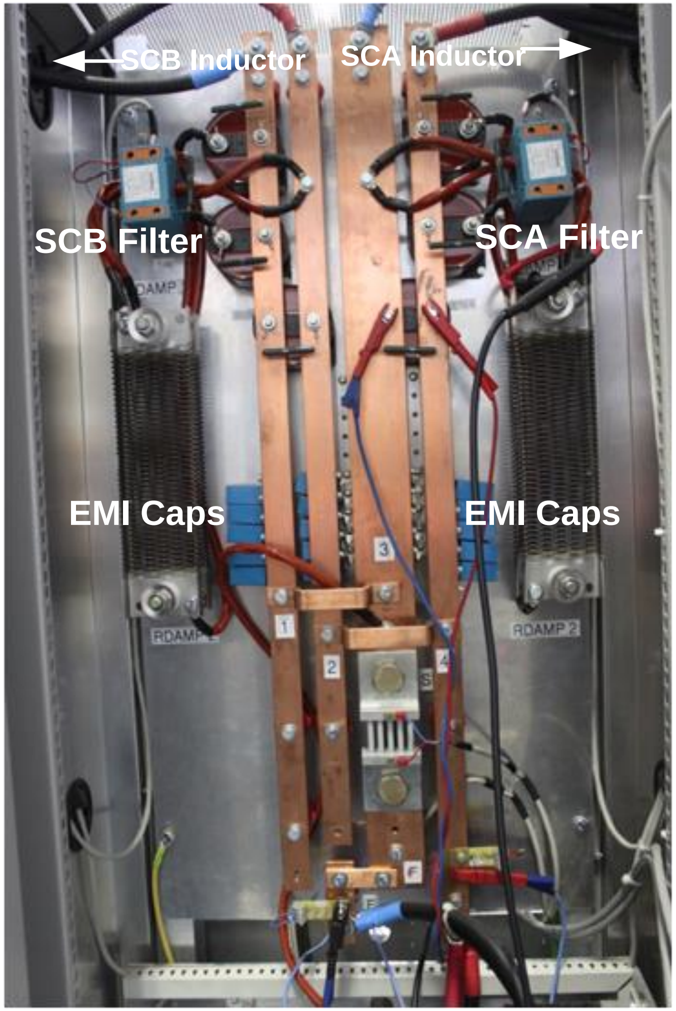




EMC: Common mode voltage

Example of DC filtering with EMC capacitor

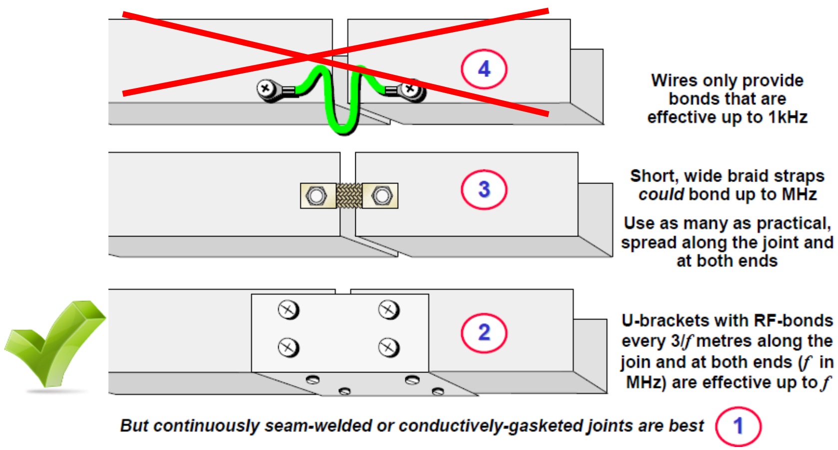


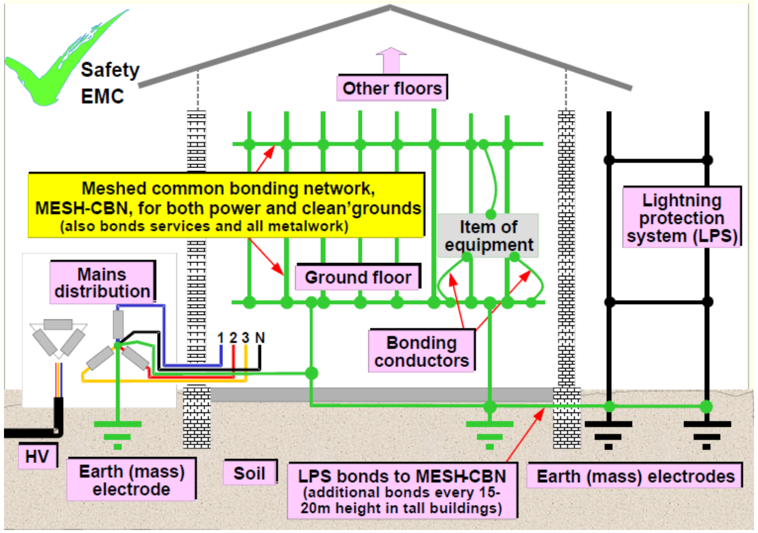


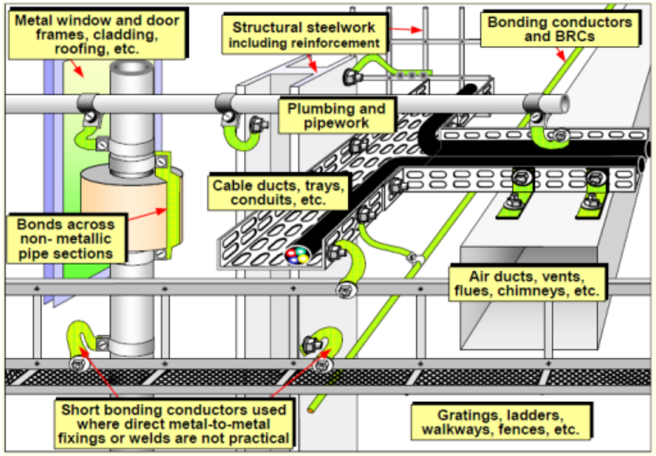
Grounding

Particles accelerators are very sensitive to EMC (conducted and radiated noise).

Need a meshed earth !







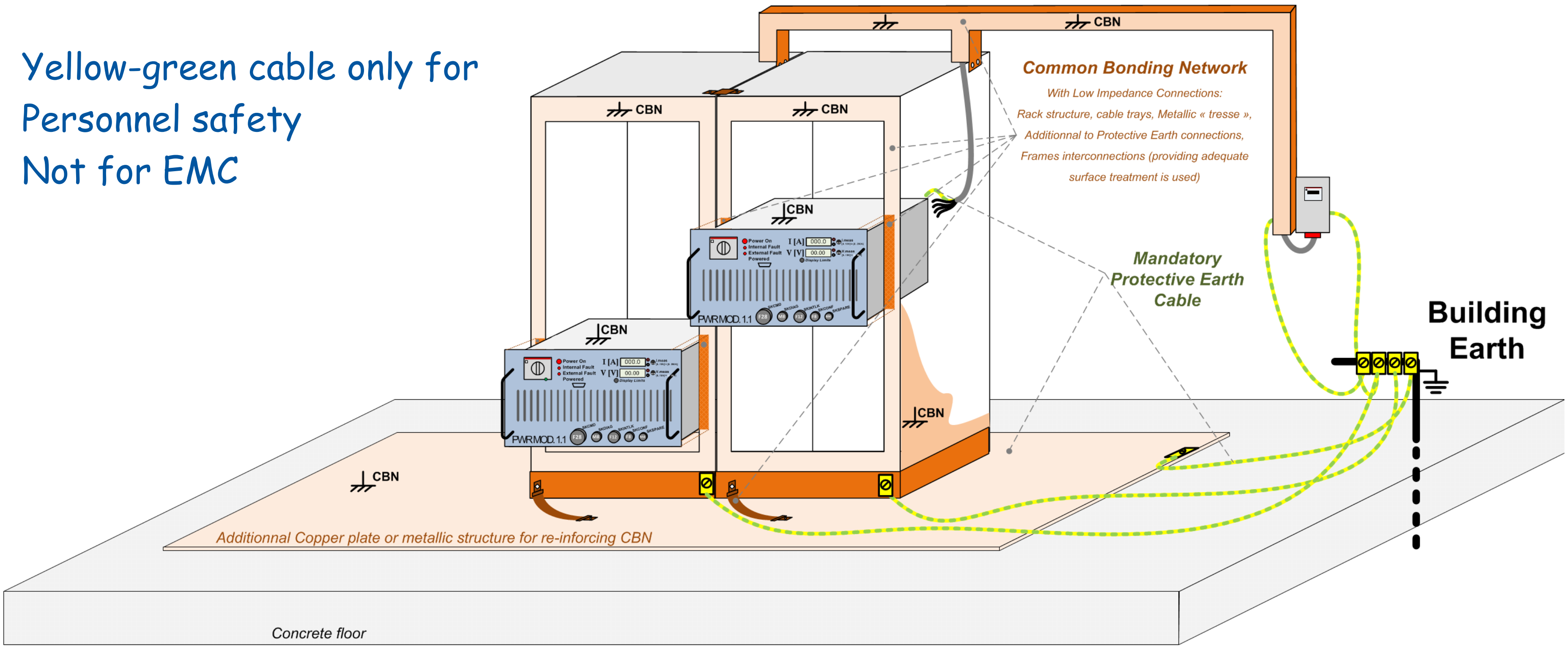
http://indico.cern.ch/getFile.py/access?contribId=44&sessionId=9&resId=0&materialId=slides&confId=85851

Grounding

Appling good EMC rules to power converters:

Use metal plate to interconnect and not cable.

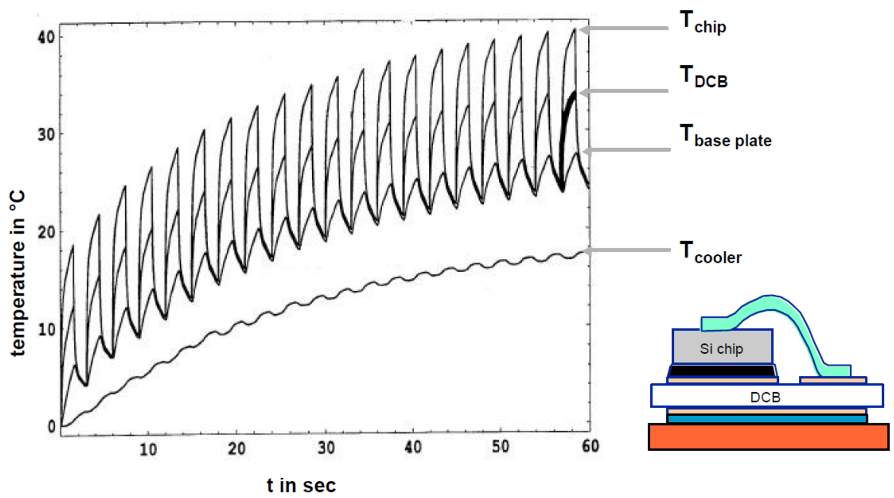
Yellow-green cable only for
Personnel safety
Not for EMC

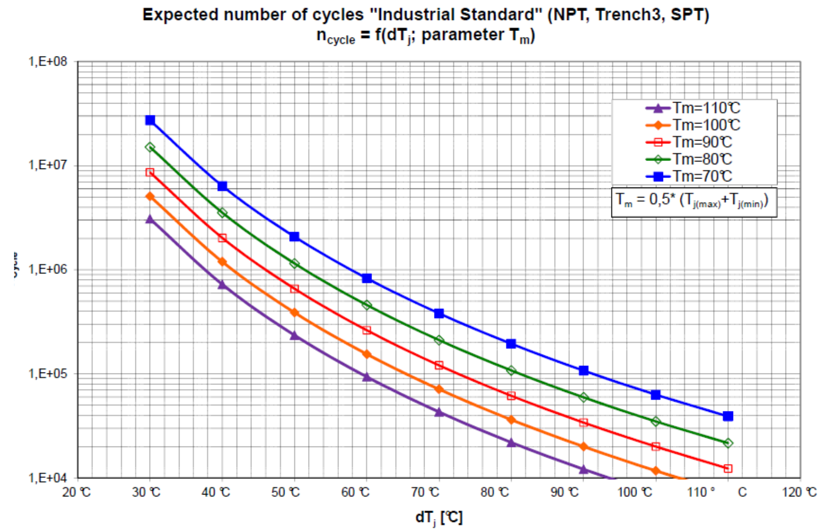


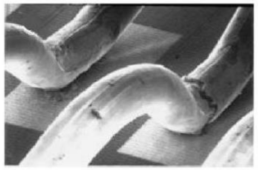
Solution for IGBT cycling

The life time of the IGBT is limited in number of thermal cycles.

IGBT manufacturers provide expected number of cycles depending of ΔTj







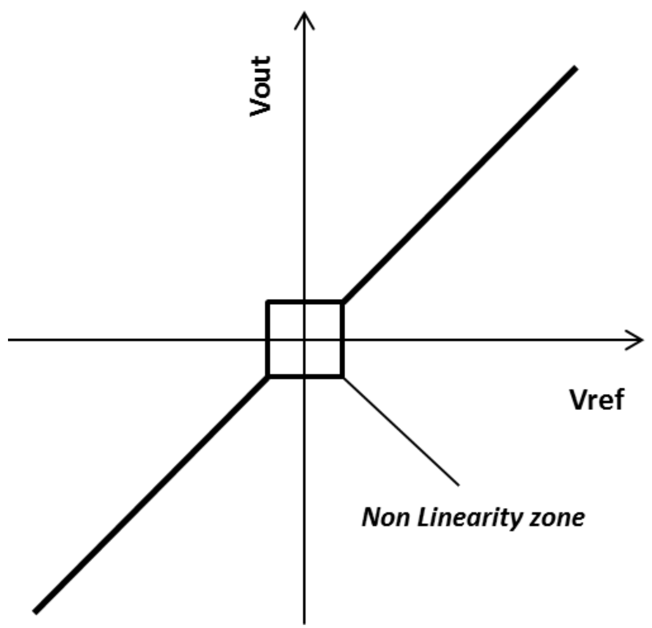
Solutions:

- reduce IGBT stress by interleaving technique (more cells in parallel)
- Oversize IGBT to decrease the ΔTj:

POPS example: 15 millions cycle / year → ΔTJ<25°C with press pack IGBT

Minimum duty cycle

The IGBT has a minimum pulse width and each IGBT leg needs dead time.
This creates non linearity in the PWM control at low voltage.



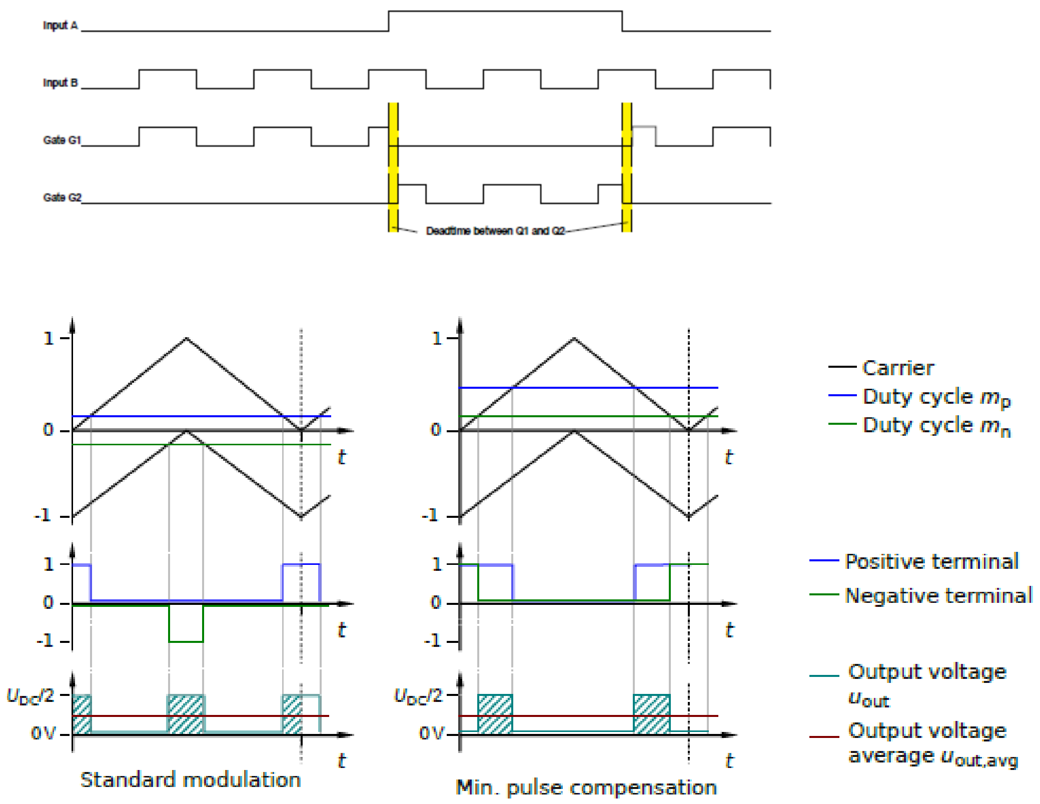
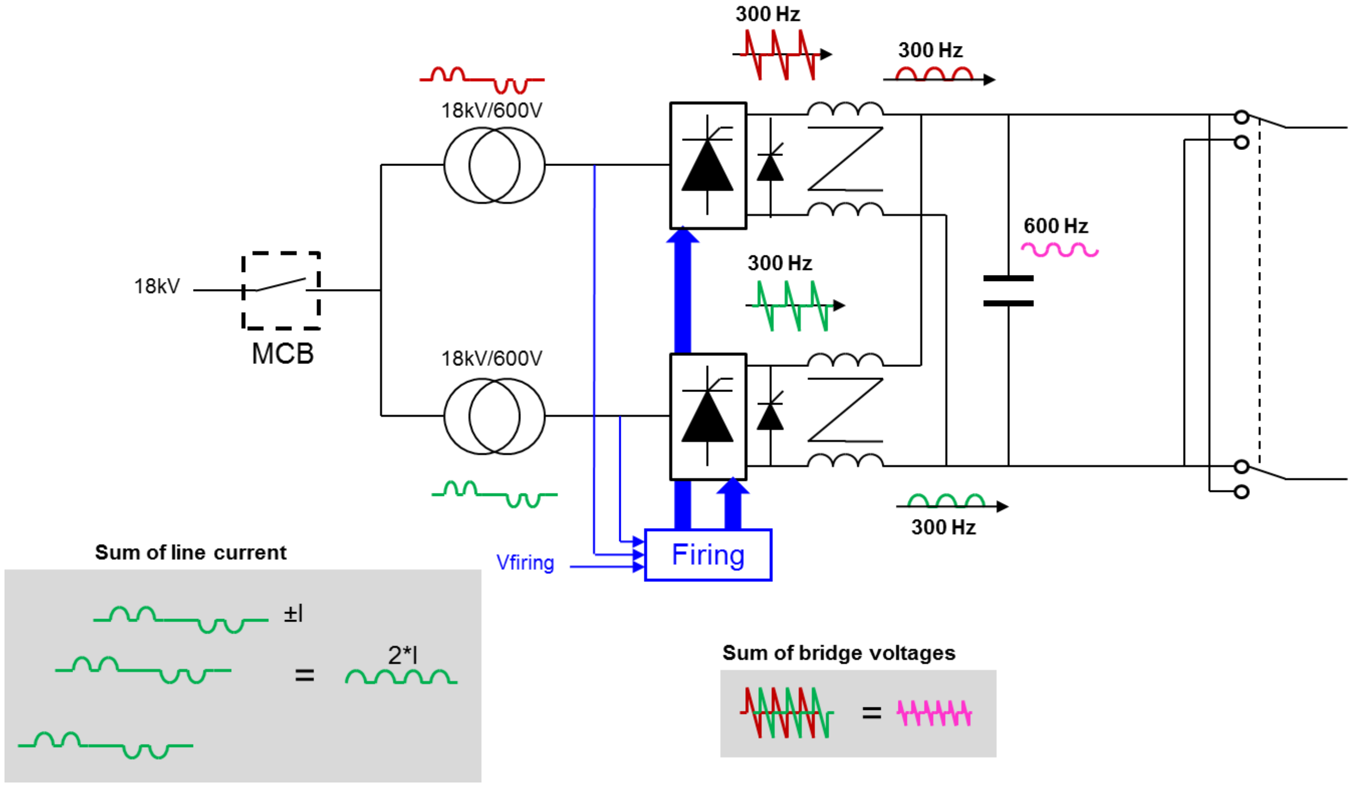


Figure 5.2: Principle of minimum pulse compensation on converter level

Minimum duty cycle

Thyristor have also a minimum turn ON time.

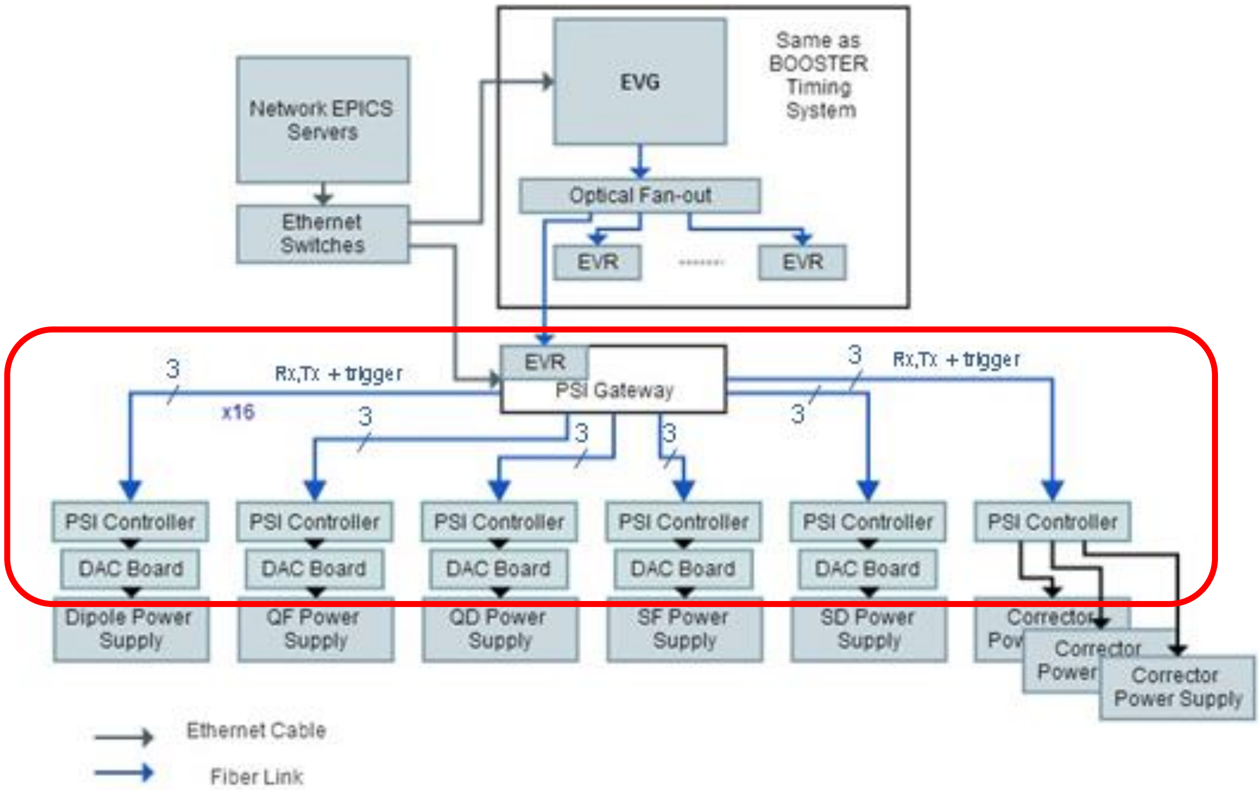
The discontinuity of the current in the choke is also limiting the minimum current of the converter.



Solution for accelerator control

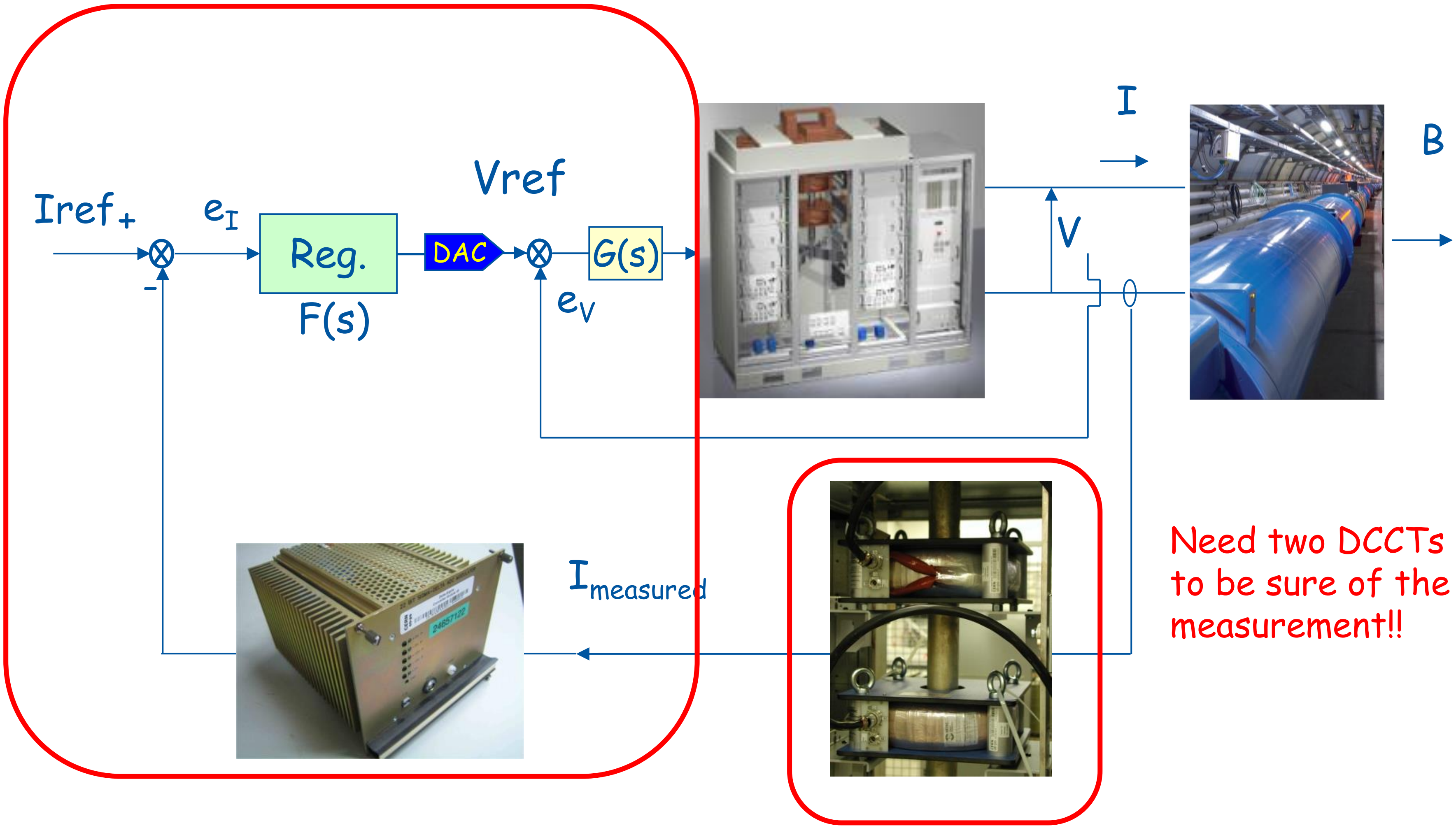
To facilitate the control of the accelerator, an identical controller shall be placed in front of all the power converters.

Example of SESAME with PSI controller



Power converter control

Need digital electronics to achieve high performance control



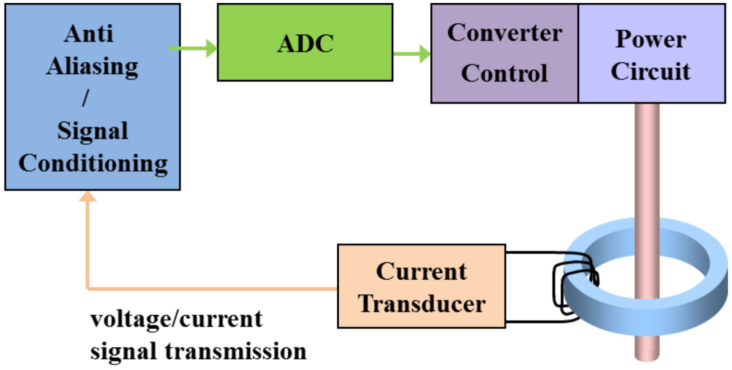
Need two DCCTs to be sure of the measurement!!

Current measurement

Do you need to calibrate your measurement chain?

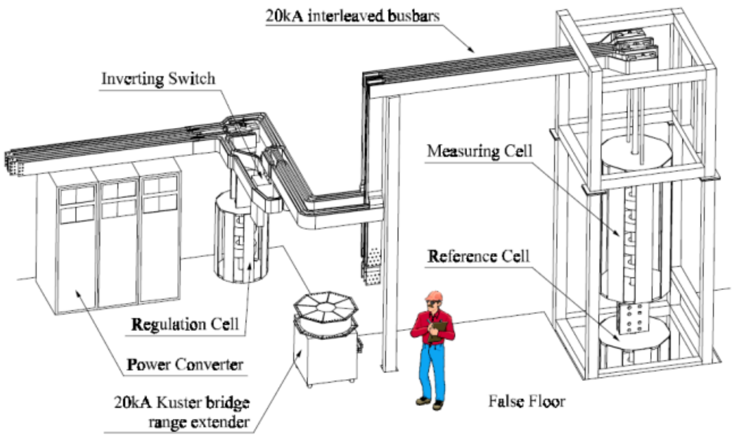
What?
When?
How?

Ask the specialists!



Do you need a standard lab?

Burden resistor
Reference voltage
Reference current source
Reference DCCT



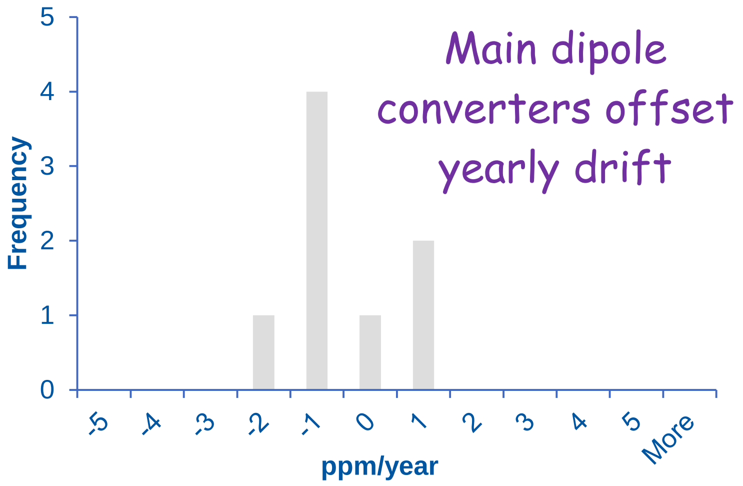
LHC class 1 global accuracy

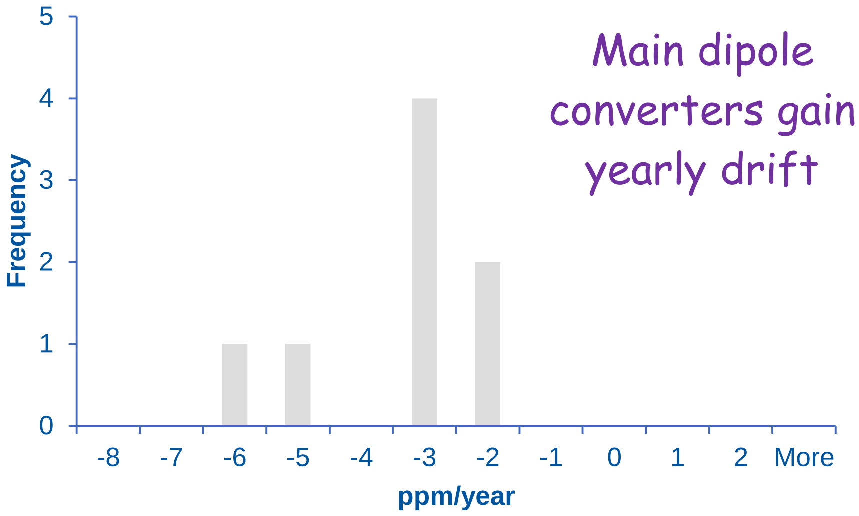
Converter category	Accuracy Class	1 year stability
Main Dipoles	Class 1	50

LHC specification
50ppm/year

LHC result
< 10ppm/year with annual calibration

Possible improvement
< 2ppm/year with monthly calibration

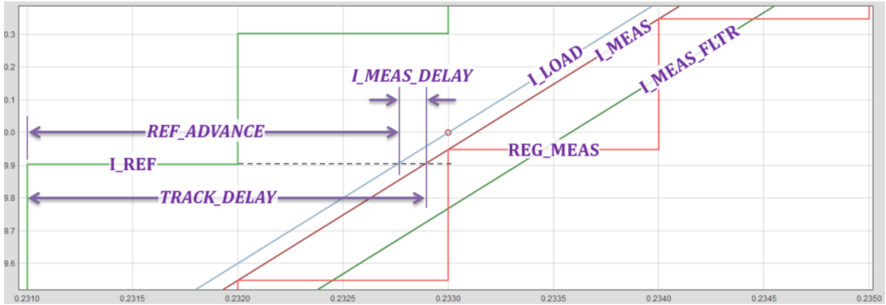


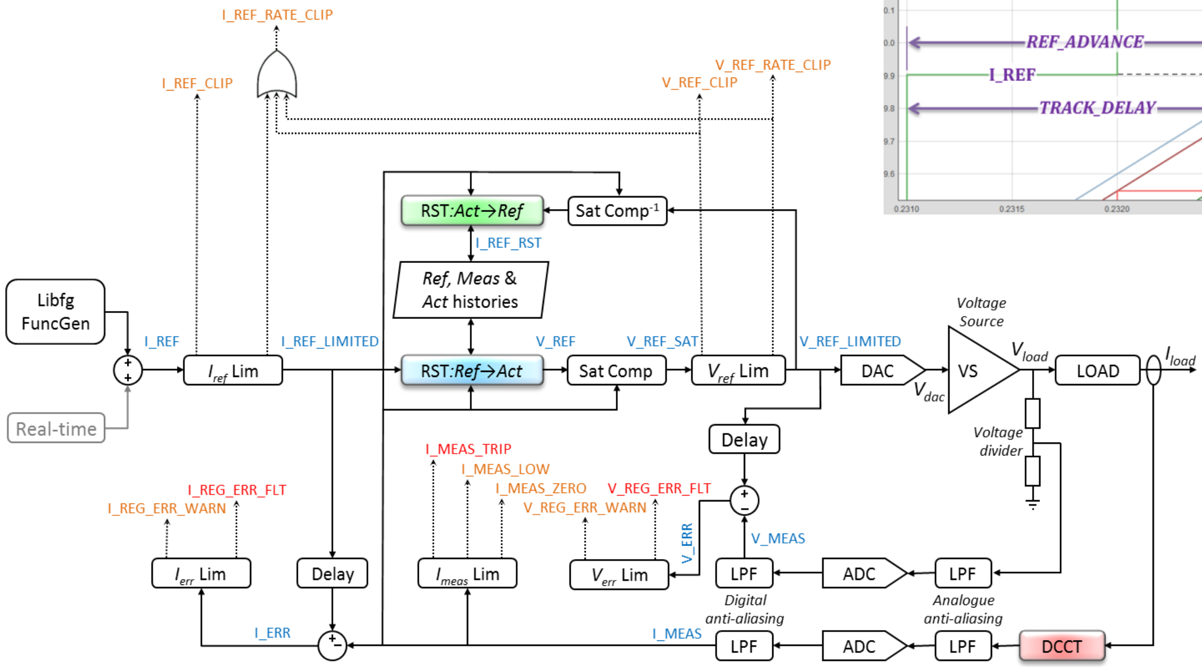


Current regulation

The performance of the current regulation is critical for a machine.

RST controller provides very powerful features.
Dead-beat control is a must for operation!
Anti-windup is needed to control the saturation of the loop.





Summary

The magnet power converters are driving the beam.

Their performance are very challenging for particles accelerators.

Particles accelerators need all your
creativity in many technical fields!

Experience sharing helps us to make it right !

Many thanks to all speakers!!

CAS organisation

Many thanks to

Roger Bailey

&

Barbara Strasser

The CERN Accelerator School

Many thanks to

PAUL SCHERRER INSTITUT

Linny Rivkin

&

René Künzi

Many thanks to all sponsors !!!

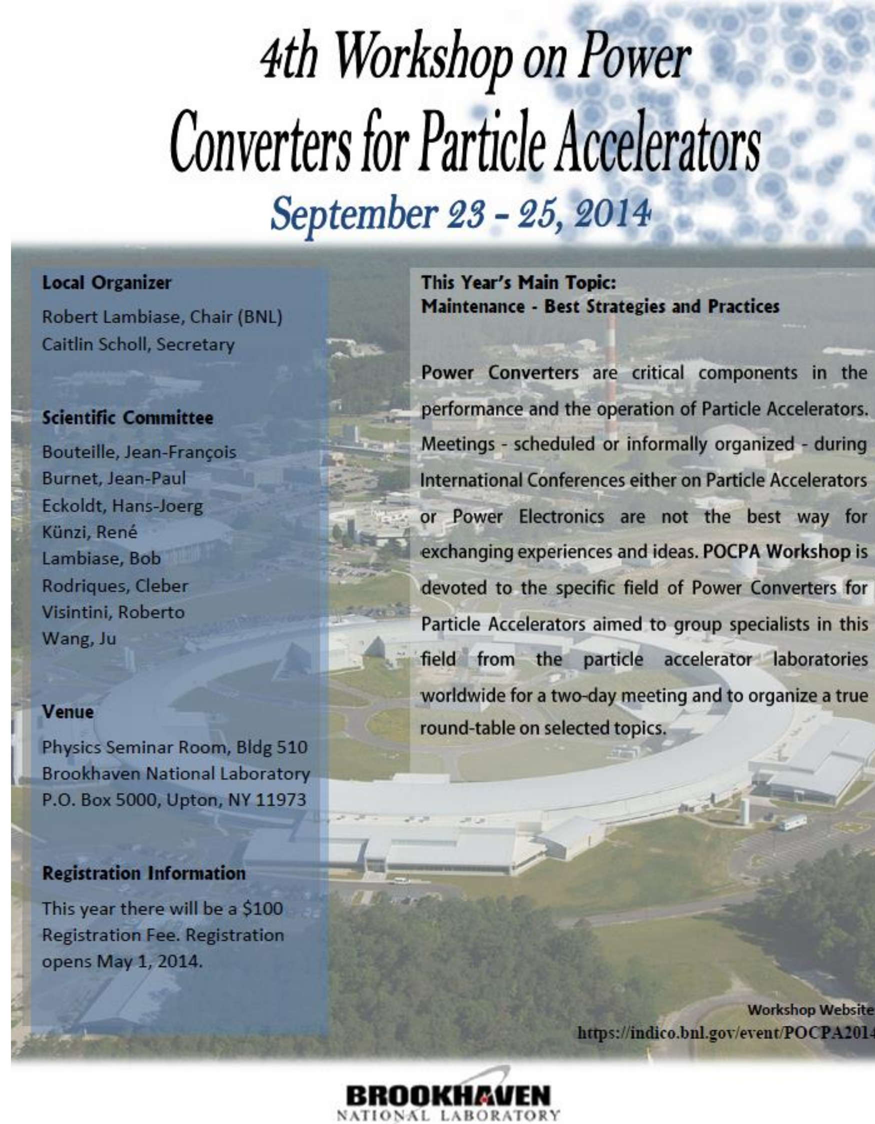
Next step

POCPA: Power Converters for Particles accelerators

This workshop is organized for power supply specialists from all labs every two years.

50 people participated to the Last event in DESY.

Join us!



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