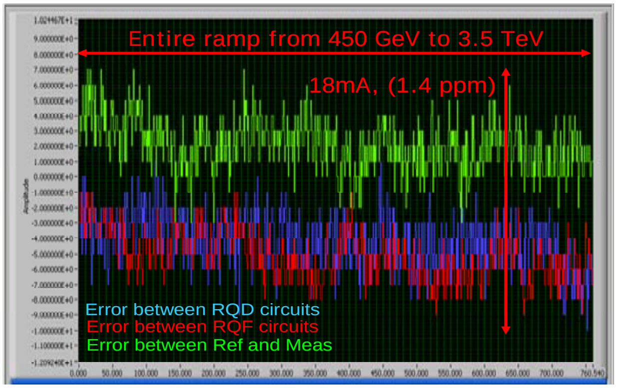
HIGH PRECISION PERFORMANCE OF LHC POWER CONVERTERS



POCPA Conference
14..16 June @ CERN

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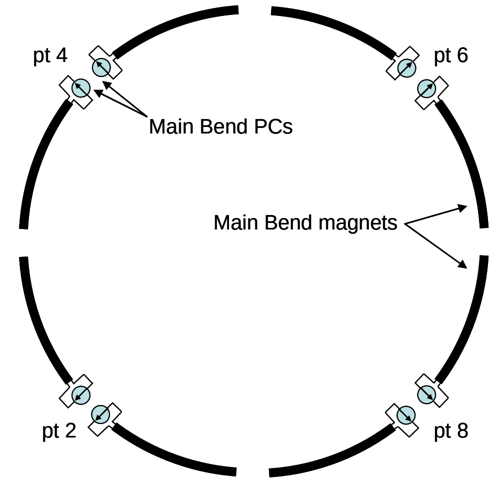
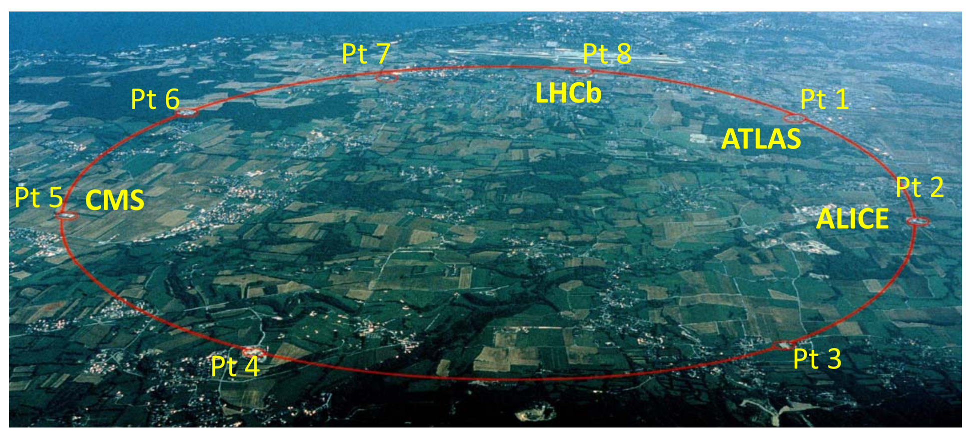
LHC powering challenge



- 8 independent powering sectors, each with one main dipole circuit and two main quadrupole circuits
- A multitude of circuits with different powering and accuracy requirements !

The “high-precision” challenge:

- Generate and synchronise 24 different current reference functions for the main power converters –> main dipoles and quadrupoles -> power converter: Inom=13kA
- Control the currents in all the main circuits within a few parts per million (ppm) of nominal current (1ppm = 13mA):
  - High accuracy current measurement
  - No tracking error
  - No overshoot



LHC powering -> a multitude of circuits with different powering and accuracy requirements !

Where to start ?

- Converters grouped in few categories
- Accuracy classes defined at early design stage

Converter category	Accuracy class	1/2 hour stability ppm	24 hour reproducibility ppm	1 year accuracy ppm
Main dipoles, quads, inner triplets	Class 1	3	5	50
Separation dipoles, insertion quadropoles	Class 2	5	10	70
600 A multipole correctors	Class 3	10	50	200
60/120 A orbit correctors	Class 4	50	100	1000
Beam transfer main converters	BT1	20	50	200
Beam transfer aux. converters	BT2	100	200	1000

LHC ±120A,±10V
300 Units
ACCURACY CLASS 4

- Inner Triplet (IT) correctors, dipole orbit correctors
- CERN Design
- Switch-mode converter

LHC ± 600A,± 10V
400 Units
ACCURACY CLASS 3

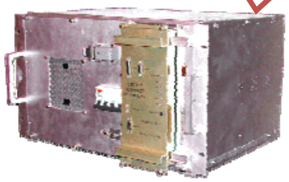
- Multipole correctors
- External Design
- Switch-mode converter

LHC 4..6kA,08V
200 Units
ACCURACY CLASS 2

- Separation dipoles, insertion quadrupoles
- External Design
- Switch-mode converter

LHC 60A,08V
752 Units
ACCURACY CLASS 4

- Dipole orbit correctors
- CERN Design
- Switch-mode converter



LHC 13kA,18V
16 Units
ACCURACY CLASS 1

- Main quadrupoles
- External Design
- Switch-mode converter

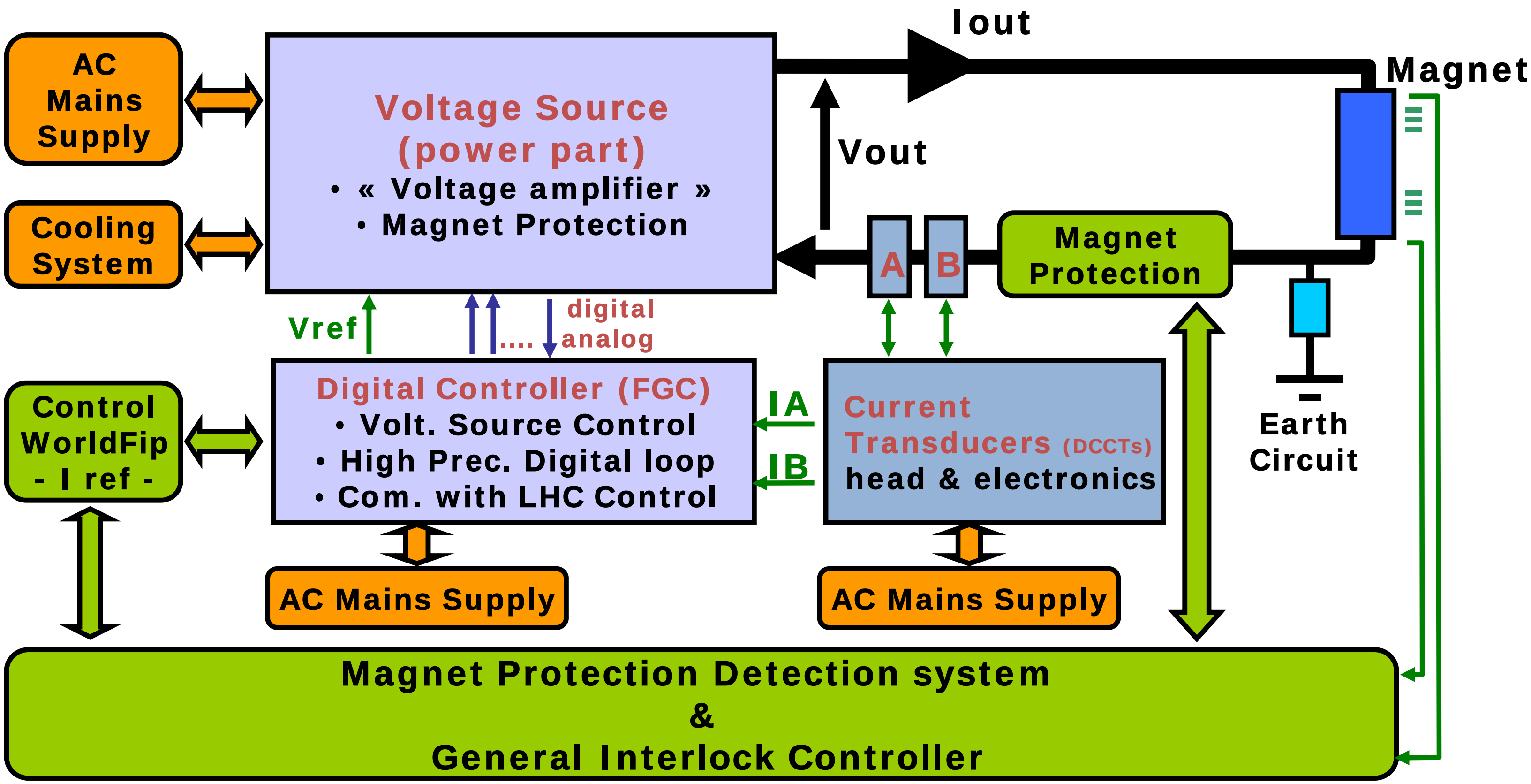
LHC13kA,±190V
8 Units
ACCURACY CLASS 1

- Main dipoles
- External Design
- Thyristor converter

Calibration/Precision Rack
16 locations
ACCURACY CLASS 1

Used with:
- LHC 13kA 18V
- LHC13kA ±190V
- Inner Triplet converters

- High performance requires a **subsystem approach**
- LHC power converters are composed of **3 main subsystems:**
  1. Voltage Source (power part)
  2. Digital control electronics (**FGC**) -> **high performance current loop**
  3. Current transducers (**DCCTs**) -> **high performance current loop**



DIGITAL CONTROL ELECTRONICS - FGC

- **FGC [Function Generator Controller]**
  - Reference function generation, digital current regulation, measurement acquisition
  - Only 2 types for all LHC converters !
    The difference is the internal ADC board:
    - **FGC-COD** -> **SAR ADC** for **lower precision** [only used for LHC60A-08V > **accuracy class 4**]
    - **FGC-Generic** -> **Delta-Sigma ADC** for **medium to high precision** [**accuracy class 2, 3 and 4** converters]

The FGC- Function Generator controller

For the very high precision (**accuracy class 1**): main dipoles, main quadrupoles and inner triplet converters, a generic FGC is used but a dedicated external ADC is used instead of the internal one:

- **22-bits DELTA-SIGMA ADC**
  - CERN Design
  - Output signal transmitted by fibre-optics to the FGC
  - Installed in an separate EMC, temperature controlled rack

The CERN 22 bit Delta Sigma ADC

Class 1-2 High Precision: 4-13kA DCCT

- Separate head (magnetic part) and electronics
- Five ratings of nominal currents (4kA, 5kA, 6kA, 7kA, 13kA)
- Head equipped with a **calibration winding for calibration**: calibration by injection of a reference current in the cal winding !

4..13kA DCCT Magnetic Head

Class 3 - Medium Precision: 600A DCCT

- Separate head (magnetic part) and electronics
- Electronics located in the FGC chassis
- Local calibration using a special calibration chassis

4..13kA DCCT Electronics

Class 4 - Low Precision: 120A DCCT

- Integrated Head and Electronics
- Initial calibration done locally using a reference DCCT

600A DCCT head

600A DCCT Electronics

120A Hitec DCCT

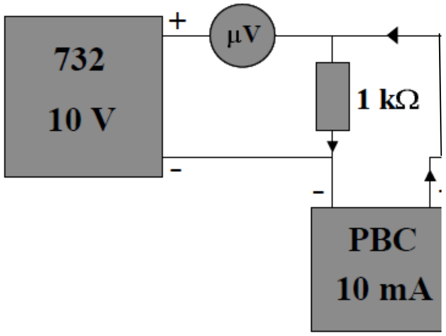
120A Ritz DCCT

A **complete calibration infrastructure** was built to cope with the LHC requirements for high precision current measurement:

- The **CERN standards laboratory** which keeps a set of eleven 10V reference standards and resistance standards (1Ω..10k Ω), traceable to national standards

- A unique **10mA transportable reference standard** especially develloped for CERN (called **PBC**), traceable to national standards via 1kOhm and 10V standards. This device is at the basis of CERN's current calibration infrastructure.

A set of CERN's transportable 10mA, 10V current standards, traceable to international standards



10mA-> 10V, 1kΩ traceability

TESTING AND CALIBRATION INFRASTRUCTURE

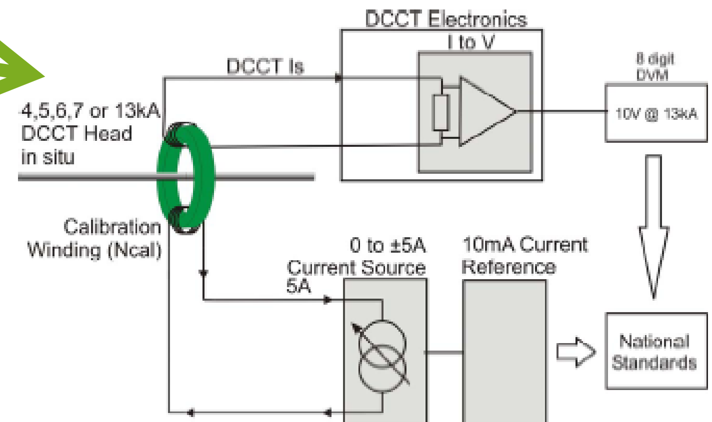
- **High accuracy DCCT measurement test-beds** (600A, 6kA, 20kA) equipped with **reference DCCTs** -> a group of selected and specially improved high-current DCCTs used as reference devices)

- The **CDC** (**C**ERN **D**CCT **C**alibrator): a 0 to ±5A programmable reference current source with ppm accuracy, designed at CERN. The CDC is used for calibration of DCCTs with calibration windings.

DCCTs under test

The 6kA DCCT testbed

The CERN Current Calibrator

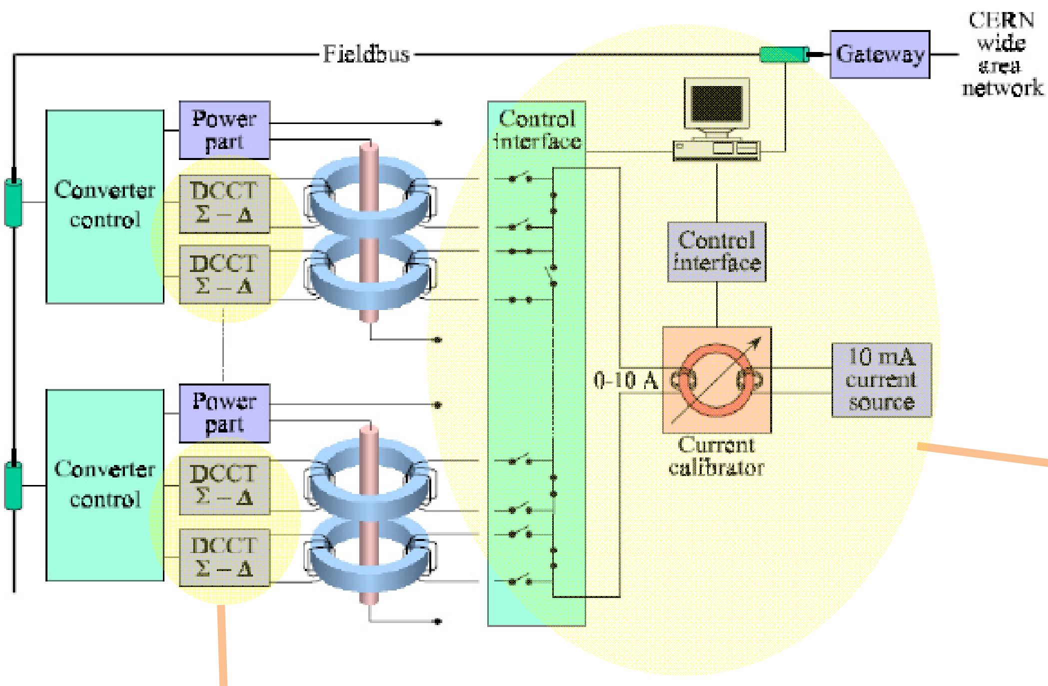


DCCT calibration and traceability

TESTING AND CALIBRATION INFRASTRUCTURE

- For **accuracy class 1** a fixed calibration system using the CDC has beeen foreseen **in the tunnel** for **remote calibration** of the power converters.
- For the other converters, **mobile calibration** units have been foreseen, for easy calibration of the power converters in the tunnel

A Mobile calibrator used to calibrate a 6kA converter



Accuracy 1 fixed calibration system installed in special EMC, temperature controlled racks

- In the **FGC**, a number of properties implement a **model** of the **ADC and DCCT errors.**

- Calibrations are done by **memorising calibration constants** in the FGC. In operation, the FGC continuously recalculates the output value of the device being corrected.

- An image of the FGC configuration properties is stored **in a central database** and a synchronisation scheme ensures that the properties in the database remain a faithful image of the FGC properties at all times.

- Some of these properties are modified during calibrations (DCCT, ADC errors). Others are used as read-only properties (TC, temperature, etc).

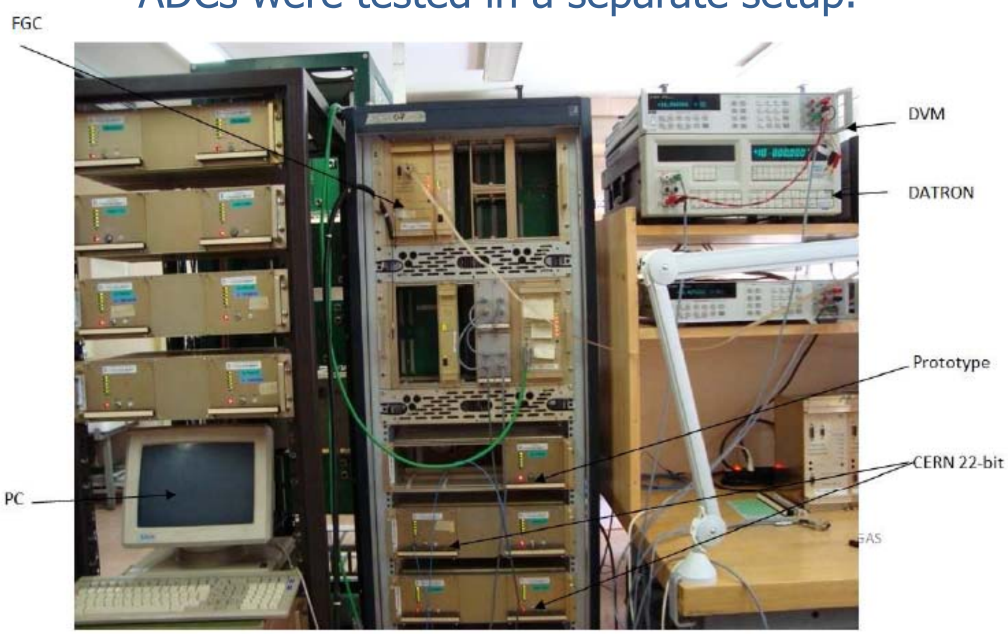
- **The power converter output current accuracy is largely determined by DCCT and ADC employed.**
- These components were thoroughly tested before installation and need to be maintained over the life of the accelerator. Six interventions can be discerned:
    - **Testing of subsystem by manufacturer**
    - **Reception tests at CERN**
    - **Converter Integration tests**
    - **Commissioning tests**
    - **Calibration after repair or exchange of the subsystem**
    - **Periodic calibration to guarantee long-term accuracy**
- High Precision DCCTs: **calibration** performed by injection of a reference current in the calibration windings.
- ADCs: **calibration** performed by applying a reference voltage to the input of the ADCs. For the FGC internal ADCs this is done automatically each 24h when the converter is OFF. The reference voltages are verified every year using DVMs which themselves are calibrated using 10V reference standards -> traceability.

- All DCCTs, were tested in special testbeds on arrival at CERN. **4000** DCCTs were tested in total.

Type	4-13kA	600A	120A
Quantity	450	1050	2450
Time/DCCT	8 hours	4 hours	2 hours
Nr of param	30	30	23
Reject rate	4.7%	7.2%	12.5%
Precision class	2ppm	10ppm	100ppm

- **2000** FGCs were tested and burnt in in a special facility receiving 200 FGCs at a time

- **100** CERN 22bit ADCs individually tested on a dedicated testbed. Internal ADCs were tested in a separate setup.

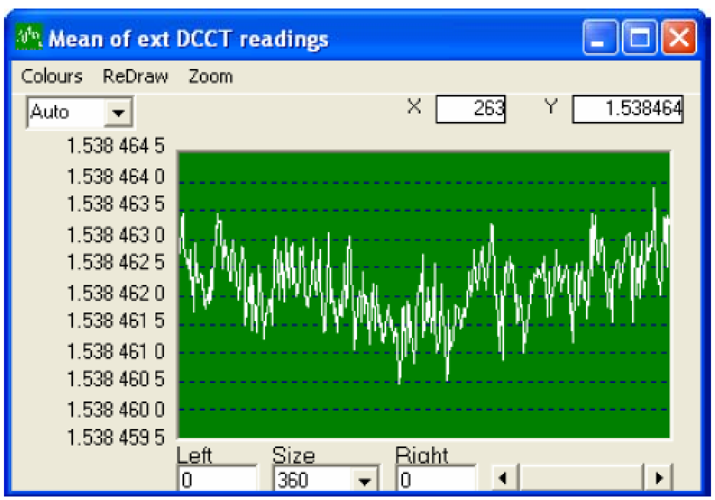


- Once all subsystems were integrated into the power converters, the overall high precision performance was tested in specially-built test-beds, equipped with reference DCCTs

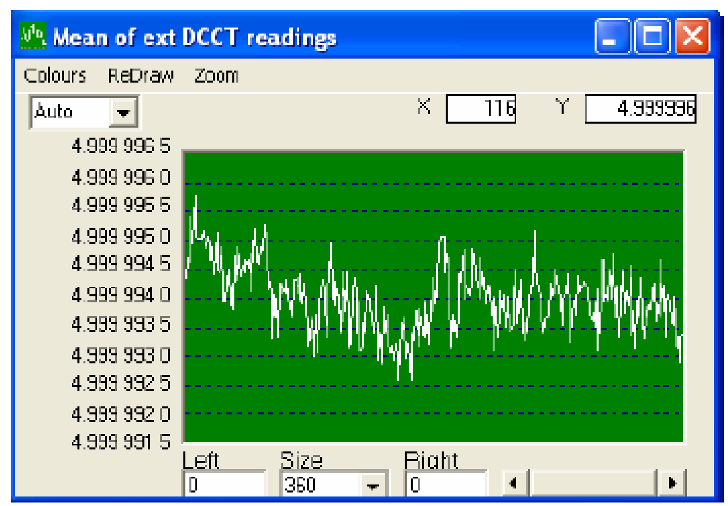
- After installation in the tunnel, performance type tests were performed in all types of converters using the current calibrator or a reference DCCT

Parameter	13kA	4-7 kA	600A	120A	60A
Stability @ I_{min}	0.8±0.3	0.4±0.2	0.4±0.2	0.6±0.2	3±1.3
Noise @ I_{min}	1±0.2	3±1.5	2.1±0.3	2.5±0.7	10.8±1.9
Stability @ I_{max}	1.5±0.9	2.3±1.3	1.7±0.7	4.5±2.0	8.2±3.2
Noise @ I_{max}	1.4±0.6	5.7±2	5.0±0.6	6.7±1.0	14.8±3.2
Reproducibility	0.4±0.5	0.5±0.3	0.5±0.3	0.8±0.4	3.3±1.5

Integration tests results in ppm peak-to-peak for short term stability, LF noise, reproducibility

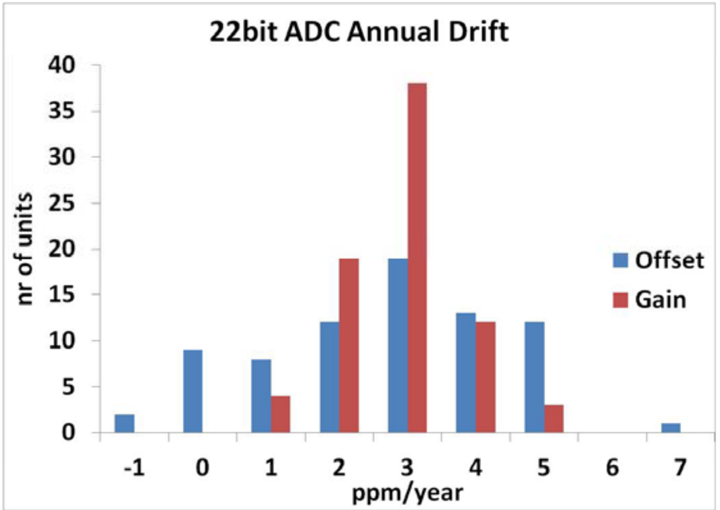


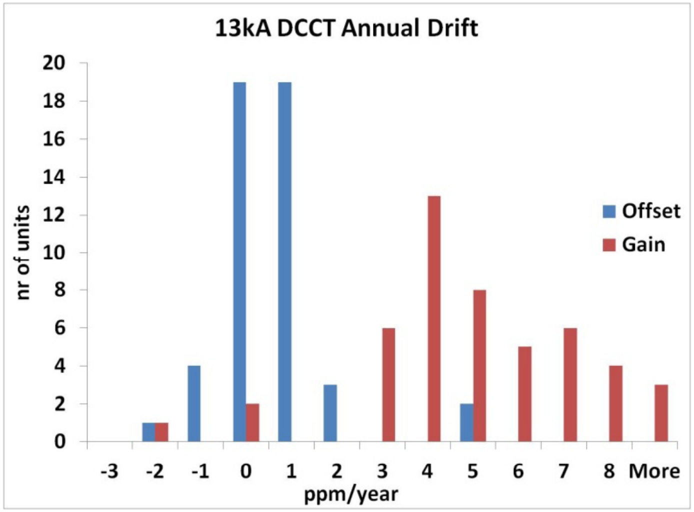
main dipole power supply 30min stability at 2kA -> within 0.3 ppm !!

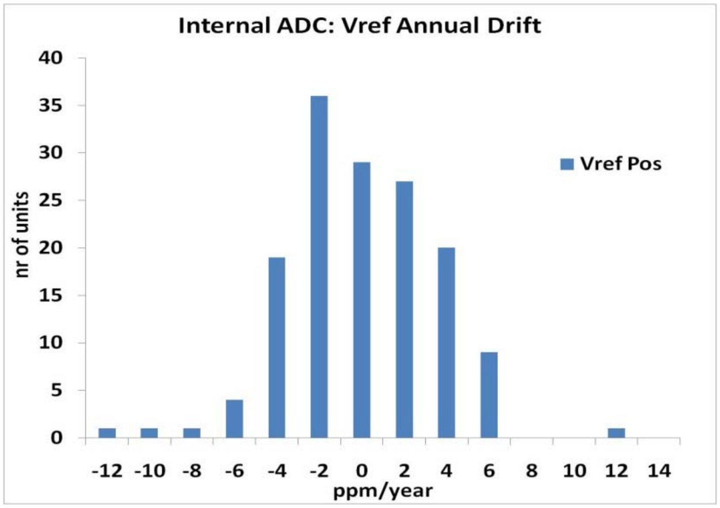


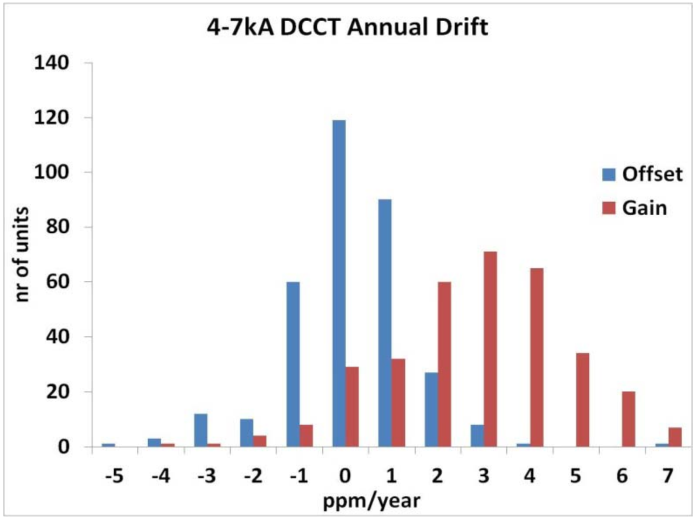
main quadropole power supply 30min stability at 6.5kA -> within 0.3 ppm !!

Converter category	Accuracy class	1 year accuracy (ppm)
Main dipoles, quads, inner triplets	Class 1	50
Separation dipoles, insertion quadrupoles	Class 2	70



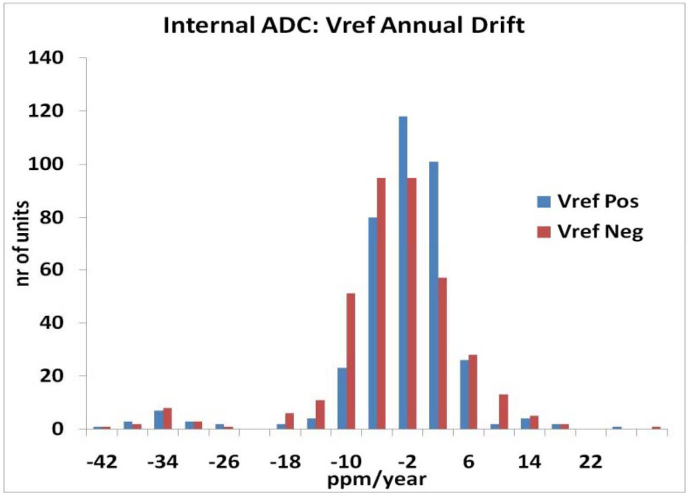


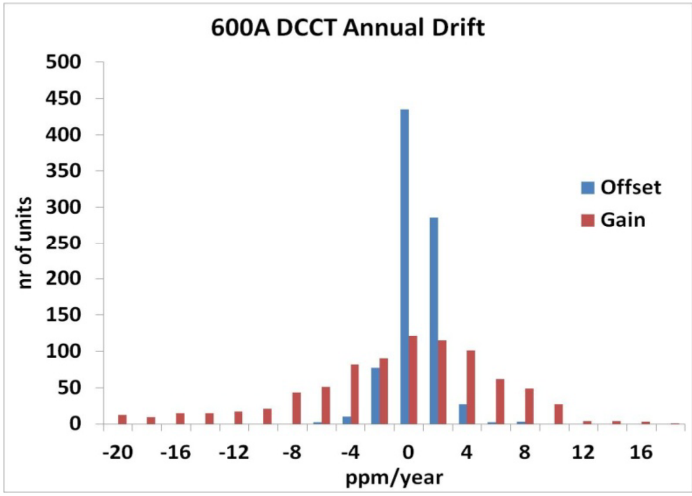


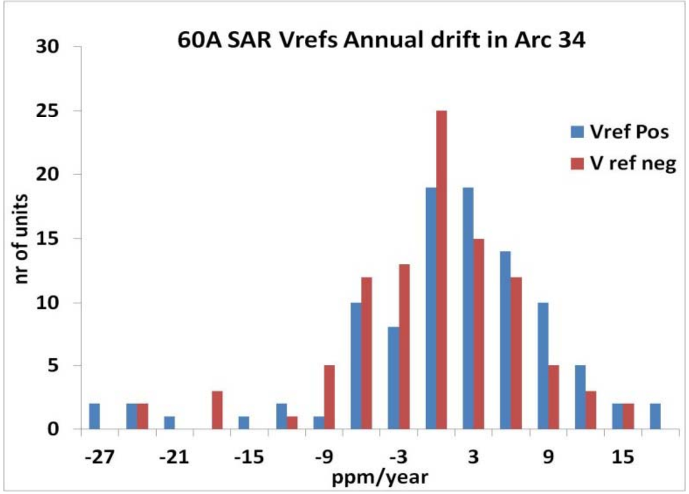


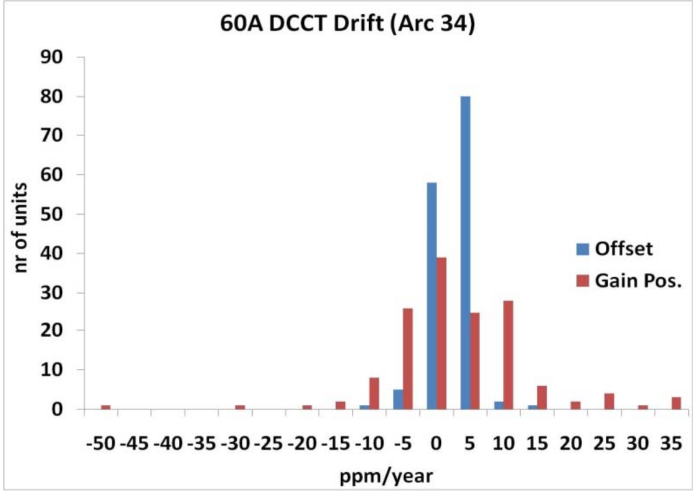
CALIBRATIONS IN THE TUNNEL

Converter category	Accuracy class	1 year accuracy (ppm)
600 A multipole correctors	Class 3	200
60/120 A orbit correctors	Class 4	1000

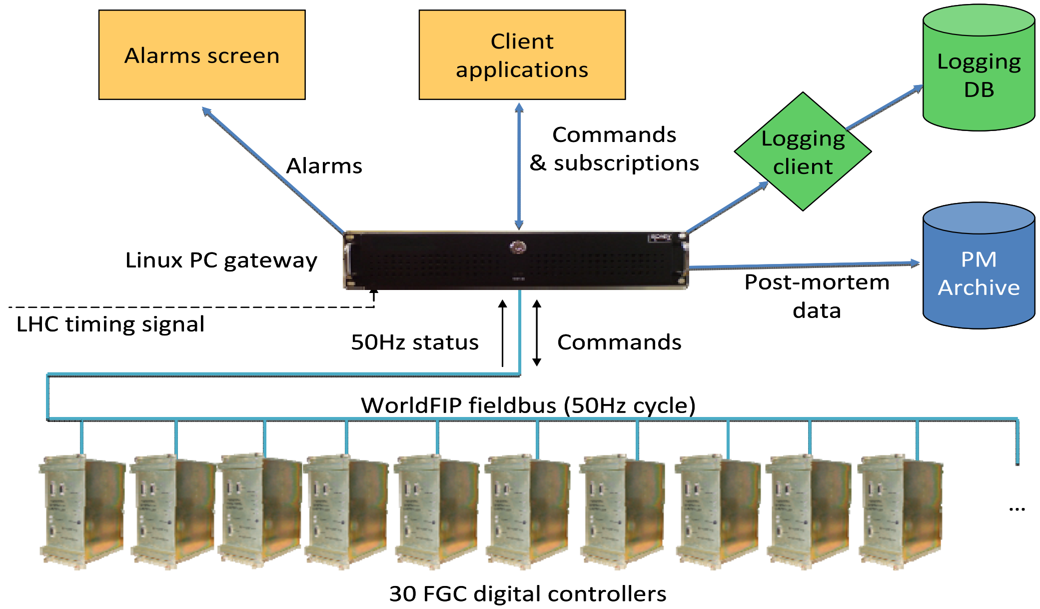








- Control of the LHC requires that all of the power converters be controlled together and their operation synchronised
- In order to achieve synchronised control of the converters, the FGCs are connected by groups of 30 units to 73 x **WorldFIP** real-time fieldbus segments
- Each one of this WFIP segments is connected to the **LHC controls ethernet** by a **gateway** front-end computer
- The power converters are controlled using **client applications** that send commands to the gateways which then relay the commands to the FGCs over the WorldFIP.

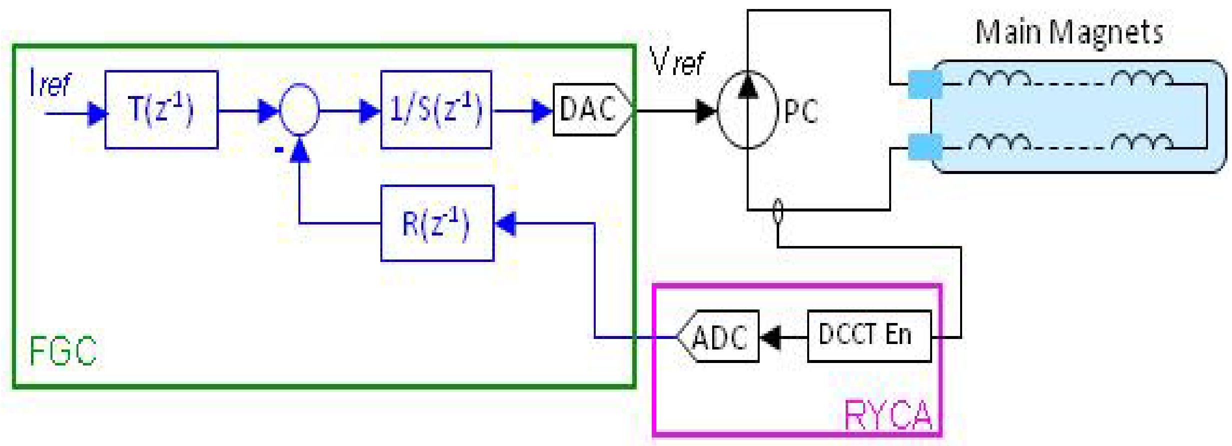


How is the reference generation in all FGCs synchronised?

- Each gateway has a timing receiver connected to the **LHC timing network**, providing GPS-synchronised UTC time and LHC timing event data
- The timing signal is used to generate a 50Hz trigger signal to synchronise the cycles of all WorldFIP buses
- Each FGC uses the start of each WorldFIP cycle in a phase-locked loop to synchronise its local clock to within 1E-7, with jitter of less than 1E-6 s
- Synchronisation of the starting and aborting of references is achieved using **timing events** sent over the LHC timing network.

Gateway PCs installed in an LHC access point

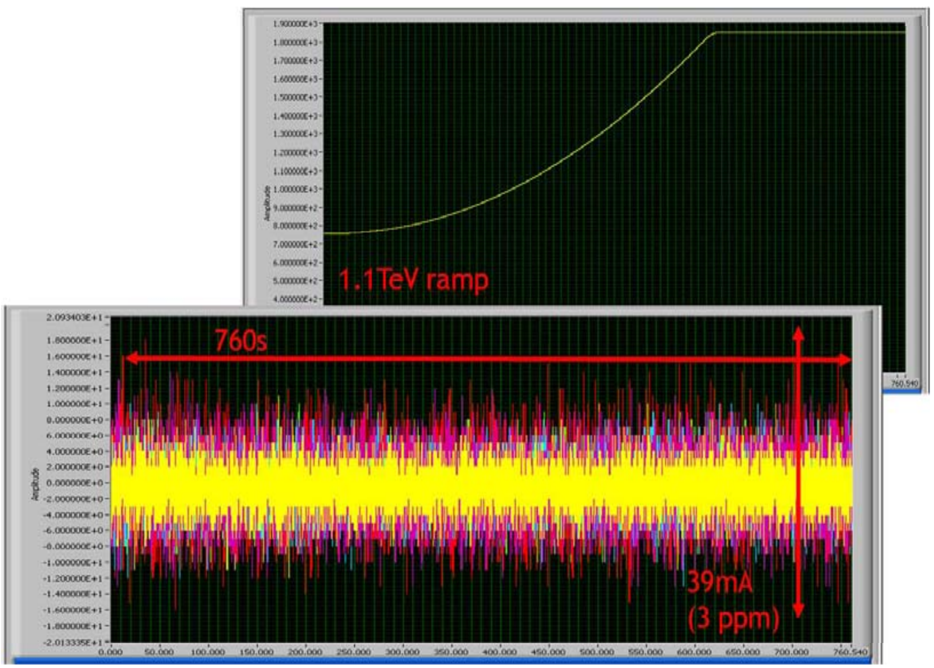
- To achieve the high precision requested for the control of the currents in the LHC, an **RST digital current loop** is implemented within each power converter's FGC
- This type of current loop has the advantage of decoupling the problem of the tracking of the reference from the problem of regulation (rejection of perturbations).
- This control strategy allows the current reference to be followed with high precision **without tracking error or overshoot** and minimizes voltage noise at the power converter output



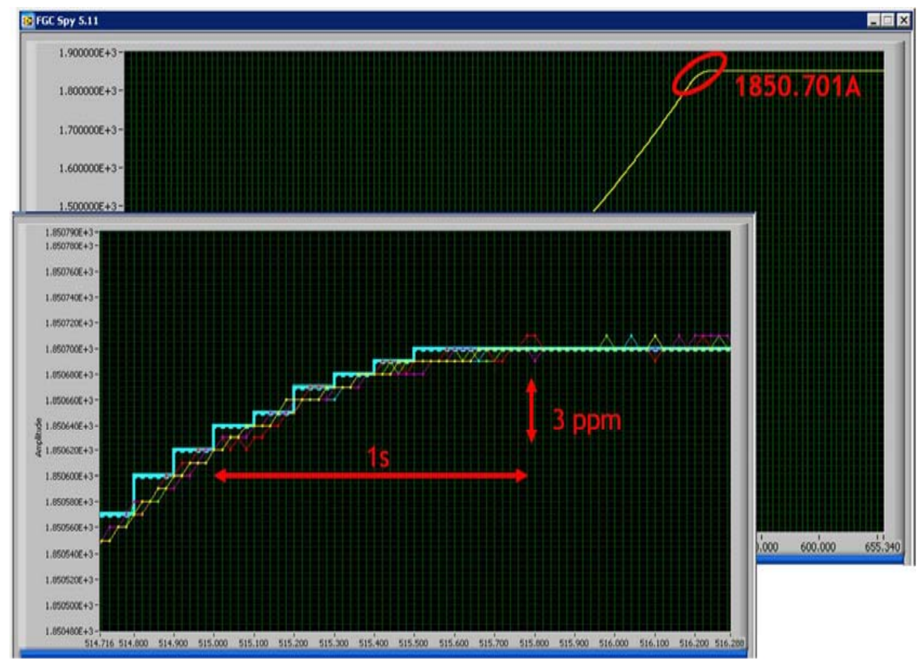
Current regulation loop in main LHC power converters

- The role of the current loop is to follow the current reference sent by the LHC control room with high precision and to compensate for the imperfections in the circuit model.

- The bandwidth of the current loop can be relatively low (0.4..1 Hz) and current loop sampling period large (0.1 s). The RST loop is well adapted to the LHC as inductances and time constants are high (16.6H and 20’000s for MD and 0.25H and 250s for MQ).



Regulation error in 1.1TeV ramp for main dipole and quadrupole power converters of sectors 12 and 23



Zoom on the following of the current reference (blue) by main dipole and quadrupole power converters of sectors 12 and 23 at the end of a 1.1TeV ramp.

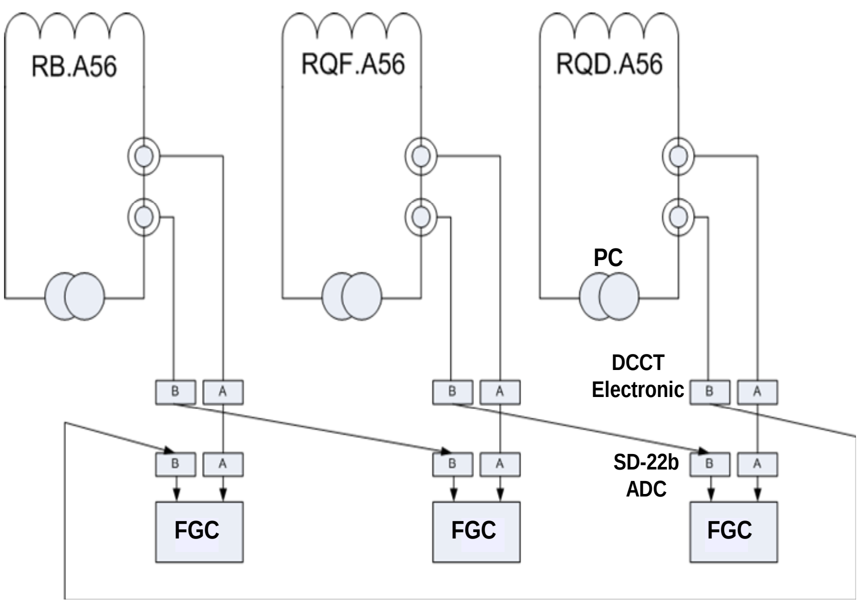
- These tests were carried out to validate the **tracking** of the same current reference by different power converters from the same sector and from **adjacent sectors**.

Test Method for a single sector:

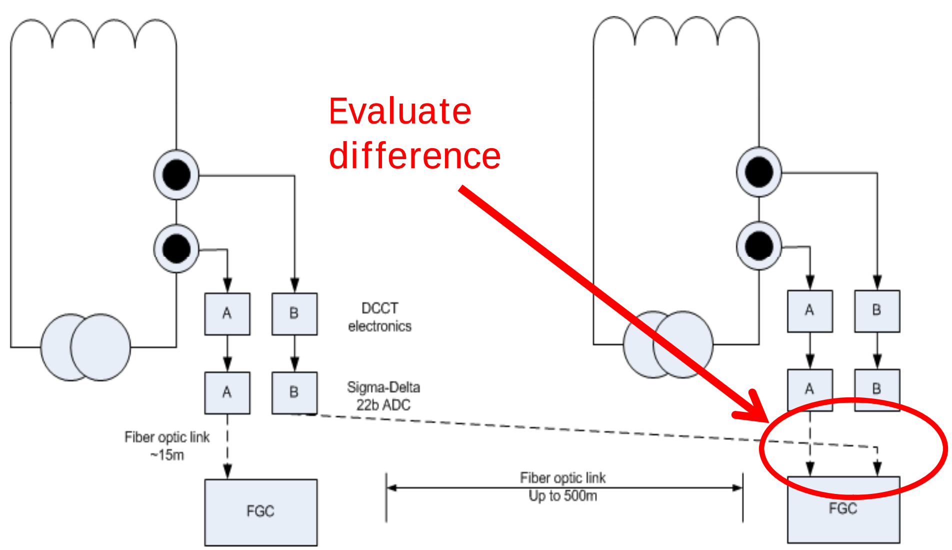
- Regulation with Channel A
- Channel B cabled to 'neighboring circuit'

Test Method for a single sector:

- Regulation with Channel A
- Channel B cabled to the other circuit
- 'Post Mortem Timing Event' used to trigger across several sectors
- Uses fiber optic link (output of 22bit Delta sigma), so propagation time is negligible

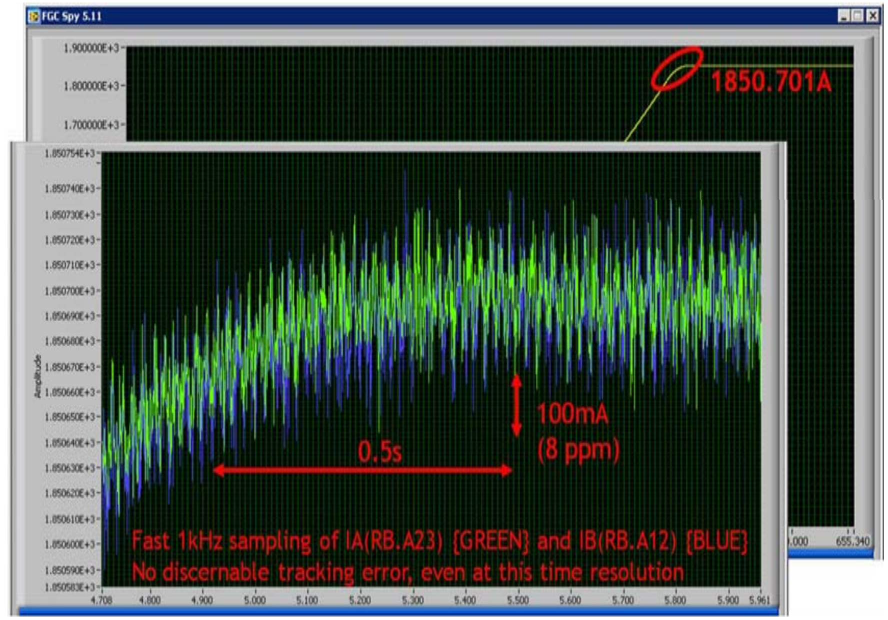


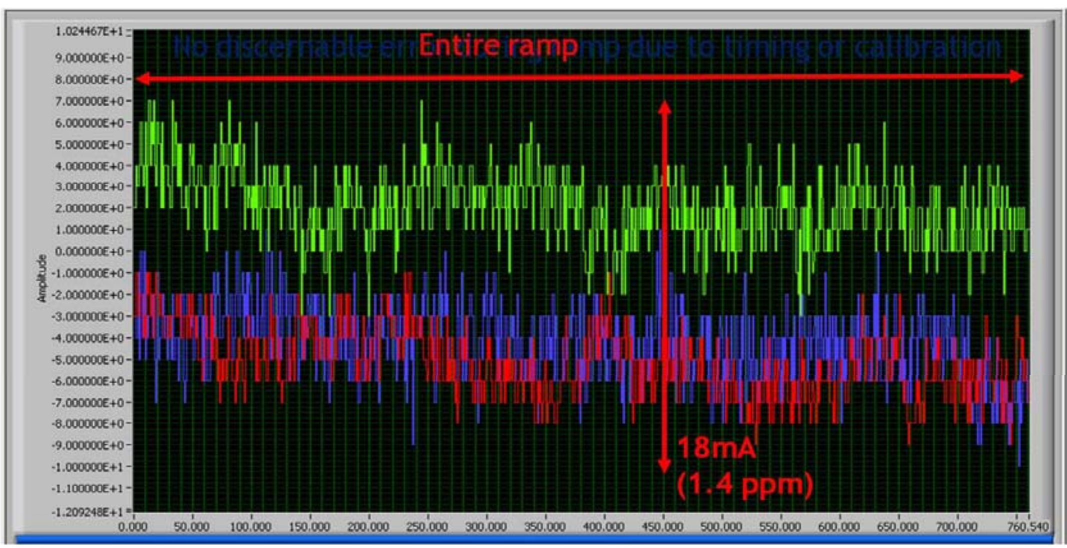
Test setup for tracking test in same sector



Test setup for tracking test in adjacent sectors

TRACKING TESTS





RED(ref): error RQD.A23 (A / B)

BLUE: error RB.A12 / RB.A23

GREEN: error RQF.A12 / RQF.A23

CONCLUSIONS

The LHC requires unprecedented precision for the control of the main circuit currents, mainly due to the division of the machine powering into eight independent sectors.

This presentation has shown how the objective has been achieved and how the main challenges have been solved.

Thank you for your attention !