The Upgraded CERN DC-current Calibrator

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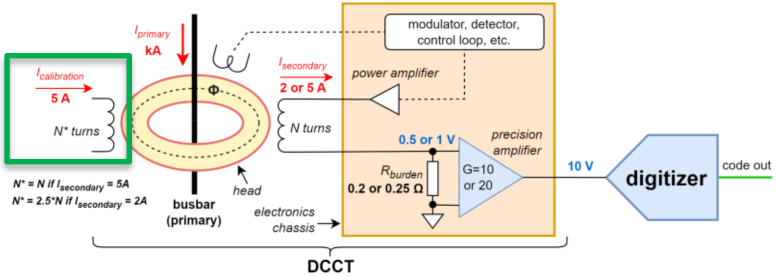
Introduction

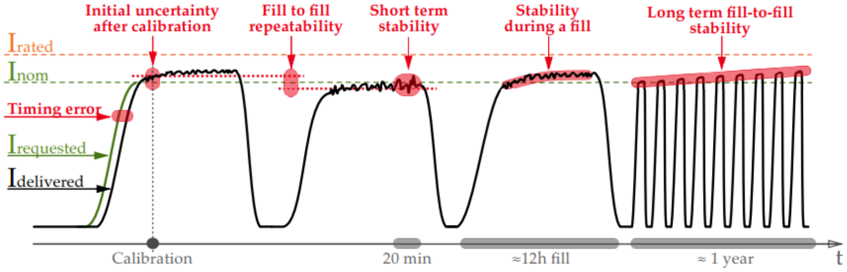
- Extremely precise **(ppm-level)** high currents **(kA)** are needed for magnet powering
- The high (primary) current is stepped down to a lower (secondary) current using a **D**irect **C**urrent **C**urrent **T**ransformer (**DCCT**)
- The secondary current is converted to voltage, then digitized.
- A digital current regulation loop is closed around the power converter / magnet circuit. The measurement chain (DCCT + digitizer) directly determines the precision of the delivered primary current
- DCCTs can be tested / calibrated by injecting a reference current in an auxiliary winding to simulate primary current
- There are **no commercial current sources or meters** with the required precision and stability, either at the primary (kA) or secondary (few A) current levels → the **CERN DC-current Calibrator (CDC)** was developed for LHC [1]



$$U_{out(DCCT)} = \frac{I_{primary}}{N_{turns}} \times R_{burden} \times G_{precision\,amp}$$

Accuracy class	Circuits	$I_{primary}$ (kA)	$I_{secondary}$ (A)	N turns	R_{burden} (Ω)
LHC Class 1	main dipoles, main quadrupoles	13	5	2600	0.2
LHC Class 1 & 2	inner triplets, insertion quads, separation/ recombination dipoles	4 5 6 7	2	2000 2500 3000 3500	0.25
HL-LHC Class 0	separation/ recombination dipoles	14	5	2800	0.2
HL-LHC Class 0	inner triplet quadrupoles	18	5	3600	0.2

HL-LHC Class 0 DCCT Requirements



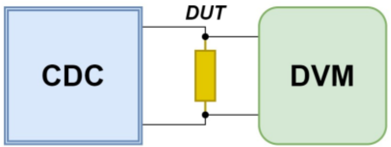
Parameter	DCCT
Initial uncertainty after cal [2xrms ppm]	1.0
Linearity [|.|max ppm]	1.0
Stability during a fill (12h) [|.|max ppm]	0.5
Short term stability (20min) [2xrms ppm]	0.1
Noise (<500Hz) [2xrms ppm]	2.0
Fill to fill repeatability [2xrms ppm]	0.3
Long term fill to fill stability [|.|max ppm]	4.0
Temperature coefficient [max abs ppm/°C]	0.8

isothermal

- Stricter precision powering requirements than existing in LHC [2]. In particular:
  - short-term stability (20 minutes)
  - fill stability (12 hours)
  - noise
  - fill-to-fill repeatability
  - temperature coefficient
- New ADC developed [7] and already presented at the 92nd HL-LHC TCC (13.02.2020)
- Improved DCCT test infrastructure needed, targeting the enhanced performance
- Performance and functional improvements needed for the >20 year-old CDC

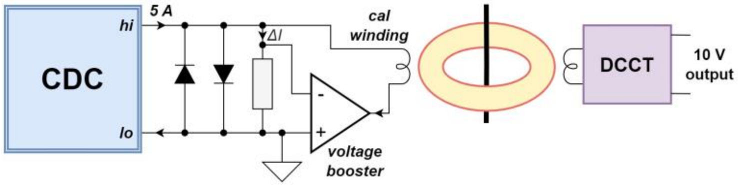
How the CDC is used

1) **Direct measurements** of burden resistors at ppm level (characterization - temperature/power coefficient)

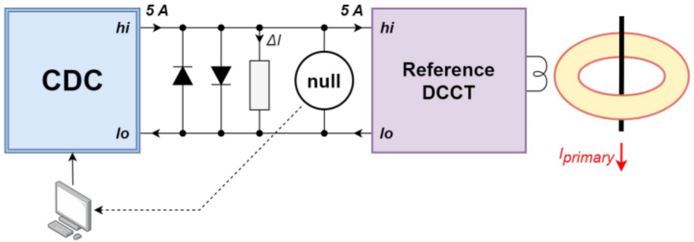


2) **Testing and calibration of DCCTs**

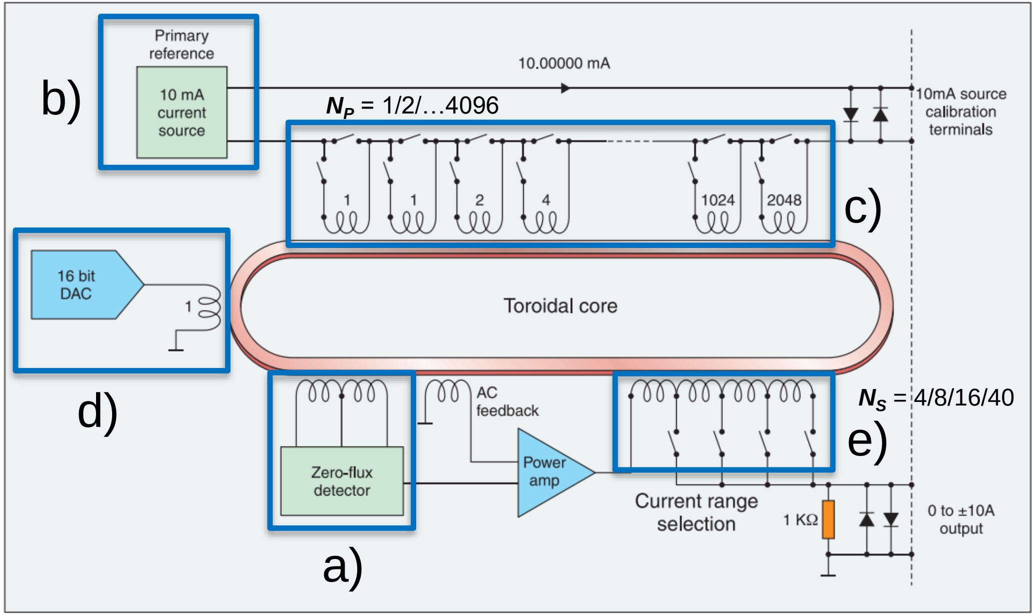
- Feeding the calibration winding of a DCCT with precise current (using a voltage booster)
- e.g. in-situ calibration of LHC dipole magnet current measuring chain
- Back-to-back measurement (compensation of DCCT secondary current) – excludes the burden



3) **Measurement of primary current** using the back-to-back method [3]



Principle of operation



a) **Zero Flux Detector (ZFD)**
- two matched cores, modulated in opposite directions
- 2nd harmonic proportional to DC flux
- closed-loop system with DC and AC feedback paths

b) **10 mA primary reference current**

Resolution: >24 bits (theoretically 28 bits)

c) coarse: binary-encoded windings (12 b)

d) fine: one-turn DAC (16 b)

e) **Output ranges:**

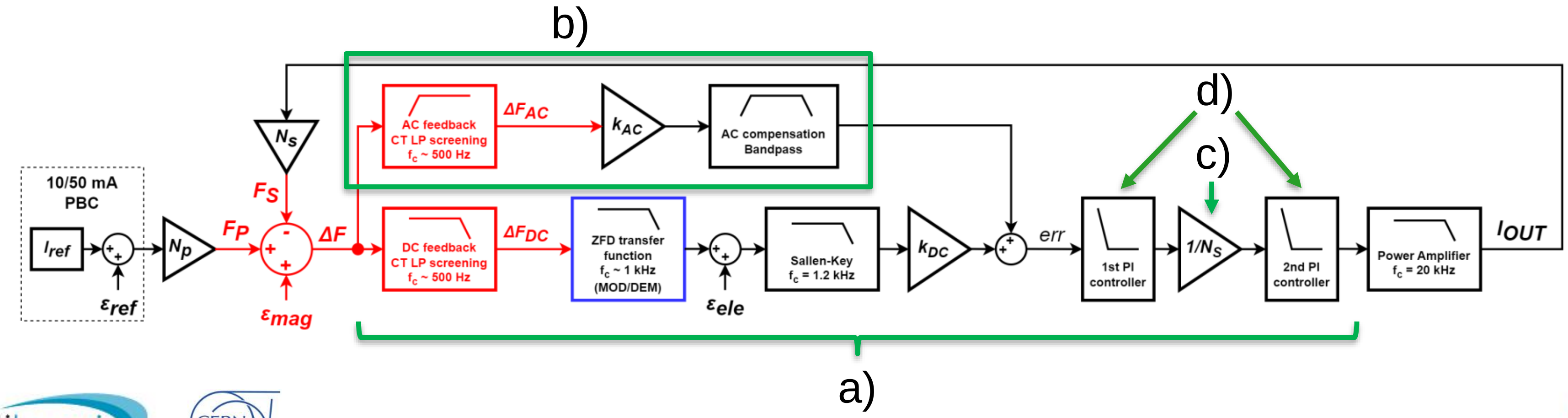
Current (A)	±1	±2.5	±5	±10
N_S (turns)	40	16	8	4
N_P / N_S at full scale ($N_P = 4096$)	102.4	256	512	1024

Nominal (DCCT)

The control loop

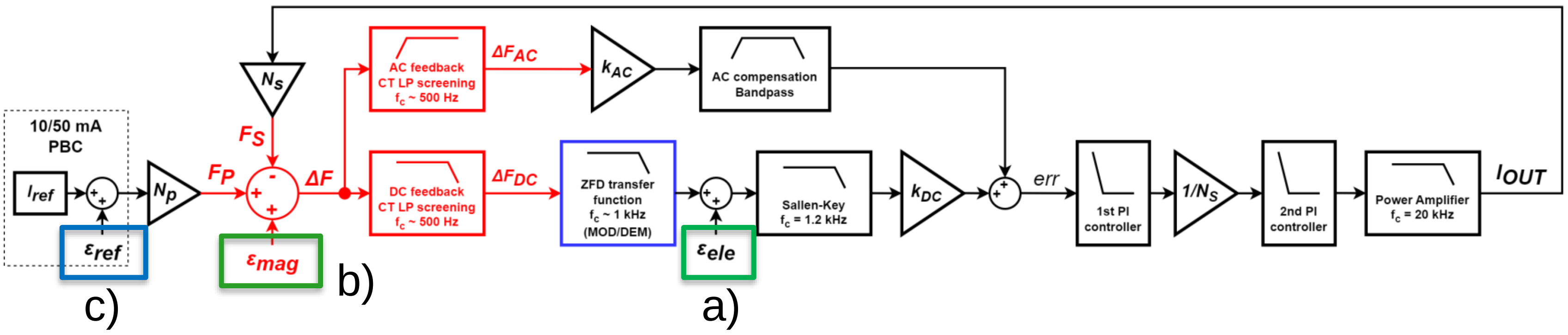
- **Objectives:**

a) High DC gain – minimize steady-state error
b) Very good AC response – reduce the effects of transients during the primary relay actuations
c) Variable gain – due to different output ranges (numbers of secondary turns)
d) Integrator clamps – during startup and range changes



Error sources – low-frequency noise

Origin	Sources	Scaling (at low frequencies)
a) Electronics	1/f noise of the operational amplifiers, offset, drift, thermal noise, ground sensing	$\frac{\varepsilon_{ele_2}}{\varepsilon_{ele_1}} = \frac{N_{S_1}}{N_{S_2}}$
b) Magnetics	Magnetic (Barkhausen) noise, BH curve temperature dependence, remanence	$\frac{\varepsilon_{mag_2}}{\varepsilon_{mag_1}} = \frac{N_{S_1}}{N_{S_2}}$
c) Primary current reference	Internal voltage reference (LTZ1000 or ADR1000), U→U conversion (~7 V to 10 V), U→I conversion (10 V to 10 mA)	$\frac{\varepsilon_{ref_2}}{\varepsilon_{ref_1}} = \frac{N_{P2}N_{S1}}{N_{P1}N_{S2}}$



Improvement of low-frequency noise

- LF noise directly determines the short-term stability of I_{out} and contributes significantly to mid-term stability
- Tests confirmed that the dominant sources are **magnetic noise** and **current noise of the primary current reference**
- Solutions:

a) **Improve the 10 mA primary current reference**

b) *then magnetic noise becomes the limit*

c) **Operate with higher I_{ref} on a lower range**

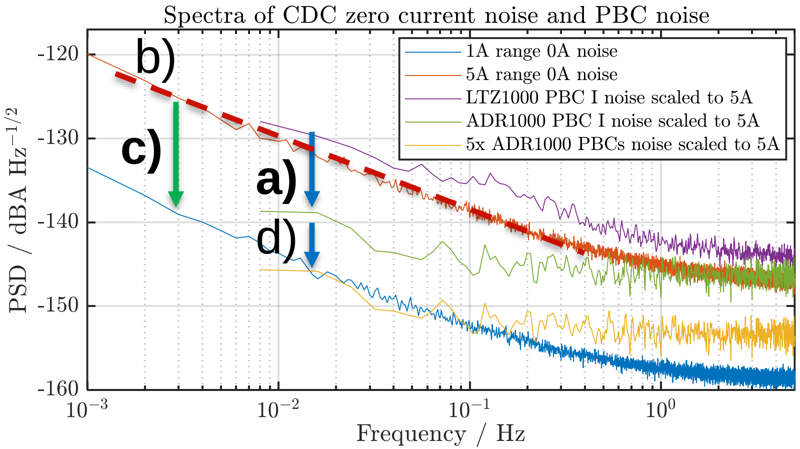
50 mA on 1 A range → I_{out} **= 5 A**

→ magnetic noise is 5x lower

d) Use of 5 x 10 mA reference current sources

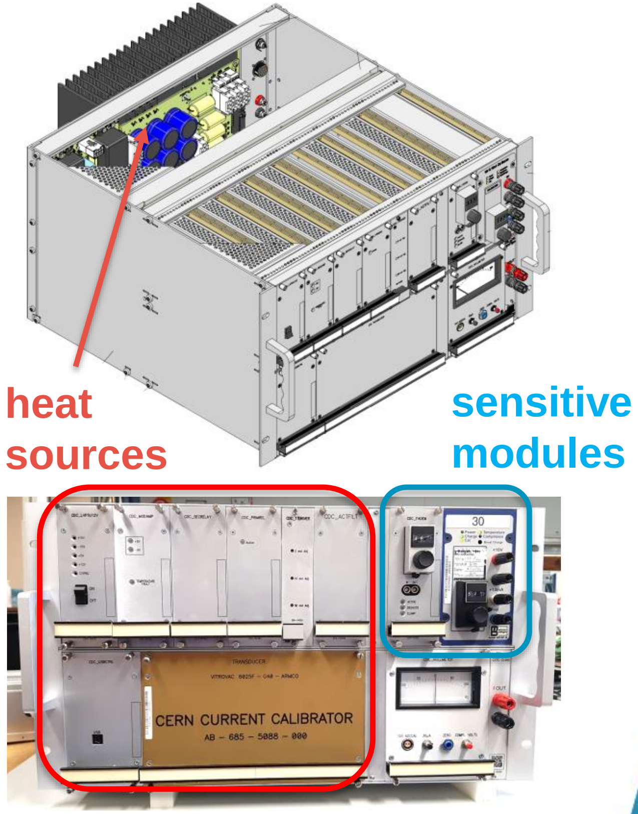
→ Further improvement by $\sqrt{5}$

→ Estimated equal contributions of both noise sources



The upgrade of the CDC

- **Electronics**
  - redesign of all modules (12 in total)
  - controller – new System on Chip-based module, new software
  - new primary current reference
- **ZFD module**
  - improved secondary windings (to reduce heating)
- **Integration**
  - optimized module placement for reduced thermal coupling
  - 1-wire bus for local temperature monitoring
  - thermal decoupling between the power amplifier heatsink and chassis



Upgrade of the electronic modules

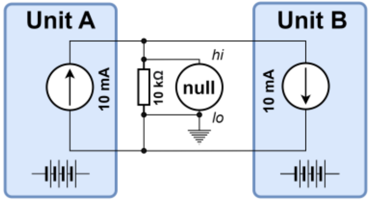
- Replacement of obsolete components (CPLD, power amplifiers, etc.)
- Use of modern components, particularly precision auto-zero operational amplifiers in the DC signal path
- The most sensitive DC signal path is kept within a single module
- Differential signaling between modules for lower noise and better EMI immunity
- Differential drive for the ZFD cores → reduced modulation noise
- Higher flexibility due to local FPGAs, e.g. for generation of the 10 kHz modulation waveform

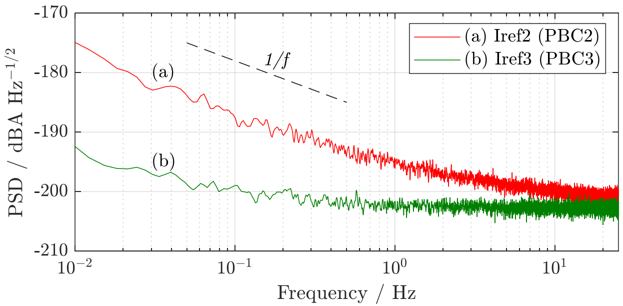
  (but basic architecture remains analog)
- Improved linear power supply for lower CM noise at mains frequencies

New primary current reference

- Developed together with Metron Designs Ltd., based on the previous version developed for LHC in the early 2000s
- Lower-noise voltage reference: Analog Devices Inc. **ADR1000** (vs LTZ1000)
- Improved 6.665 V → 10 V and 10 V → 10 mA conversion stages
- Overall improvement: 3 – 5 times lower LF current noise compared to the older LTZ1000-based variant
- Chassis with 5 units (50 mA) was prepared for the upgraded CDC

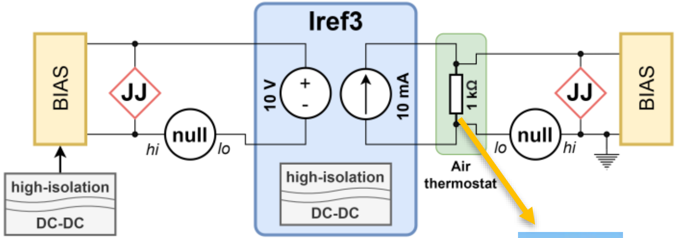
(additional bonus of external chassis: separation from CDC heat sources)

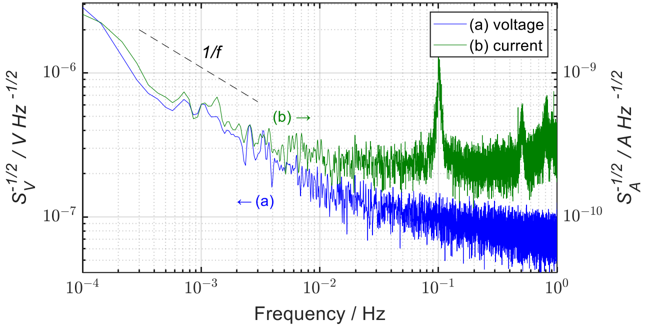


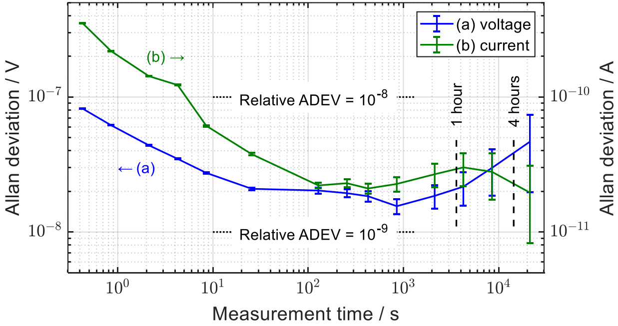


New primary current reference

- Test with **two** Josephson systems at PTB - Braunschweig
- Ultimate confirmation of short-term stability of both outputs (10 V and 10 mA) on the level of few times **10^{-9}**
- *Probably the lowest-noise non-quantum current standard ever built and tested*
- Also presented at CPEM-2024 [4]

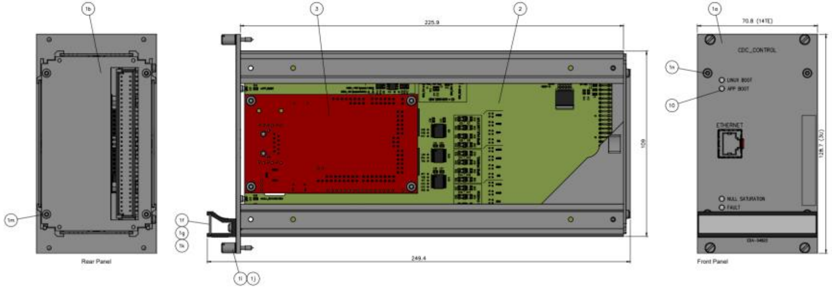






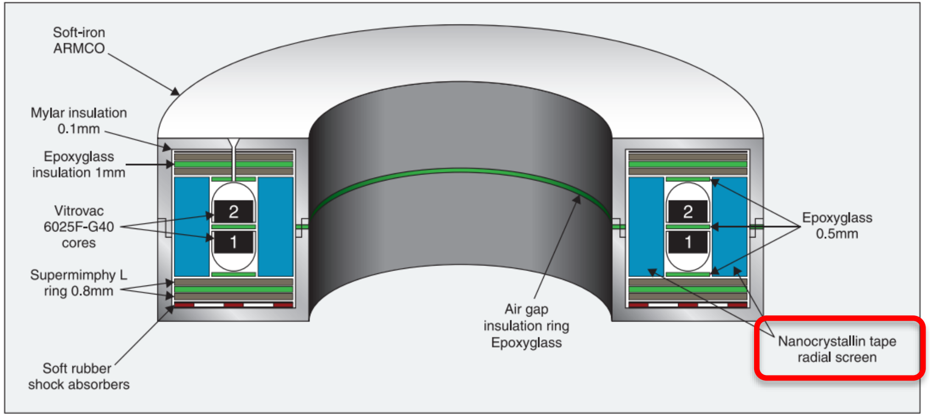
New controller board and software

- Based on Xilinx Zynq-7000 System-on-Chip
- Supports Ethernet network connection
- Programmable Logic (FPGA) – controls the other modules through SPI (2x FPGAs, 1 DAC, 1 ADC)
- Processing System (ARM core) – runs Python software on Linux, parses and executes commands sent over TCP
- More information available in [5]

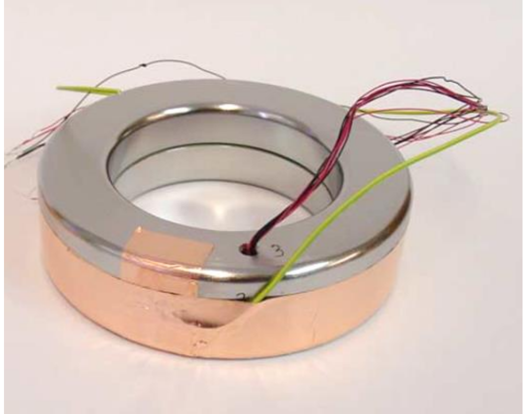


The ZFD assembly

- The availability of magnetic materials has been declining over the years
- As of 2024 the assembly can be produced, but there is no replacement yet for the obsolete radial shield material (Nanophylm)
- The cross-section of the secondary windings was increased to reduce heating when using 40 turns in the 1 A range for 5 A output



from [6]



Preliminary characterization results

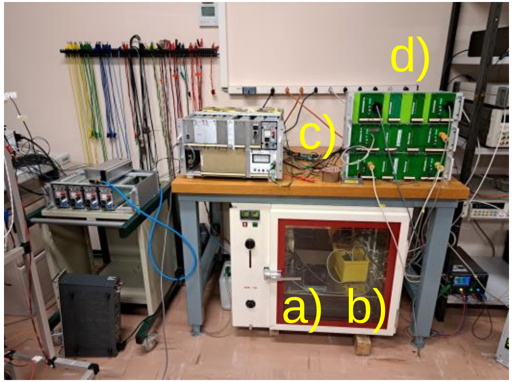
a) Precision 0.2 Ω resistor (Alpha FNP series) on heatsink + fan, temperature-stabilized in an oven and pre-heated with 5 A from a power supply prior to the CDC test

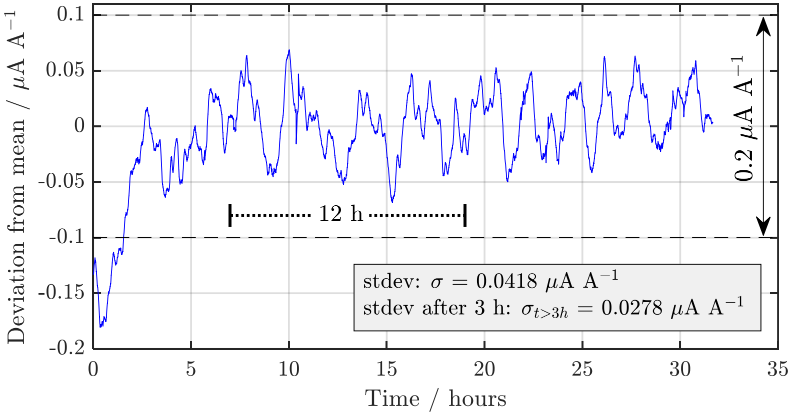
b) Precision auto-zero amplifier with G = 10 V/V

c) MOSFET bridge for CDC output current reversals

d) 5x HPM7177 metrology-grade digitizers [7], digital reconstruction of signal from the recorded data

- Disregarding the initial thermal transient in the 0.2 Ω resistor, the output current stability is within the 12-hour target of 0.2 µA/A p-p, but the measurement is still limited by the test setup [5]



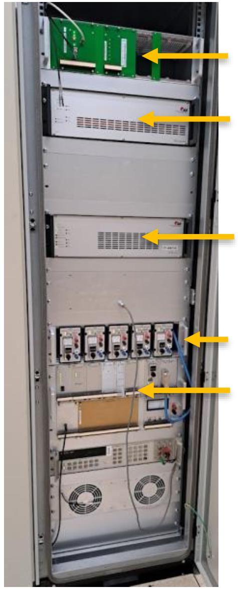


Time scale	Target	Measured
20 min	0.05 µA/A rms	<0.026 µA/A rms
12 hours	0.2 µA/A p-p	<0.14 µA/A p-p

Preliminary results of PC tests

Regulation DCCT head

HL-LHC 14 kA prototype PC



ADC chassis

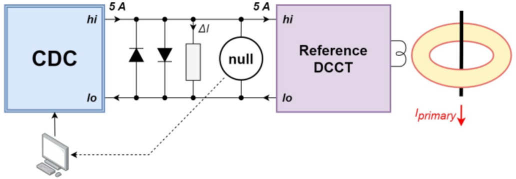
Regulation DCCT chassis

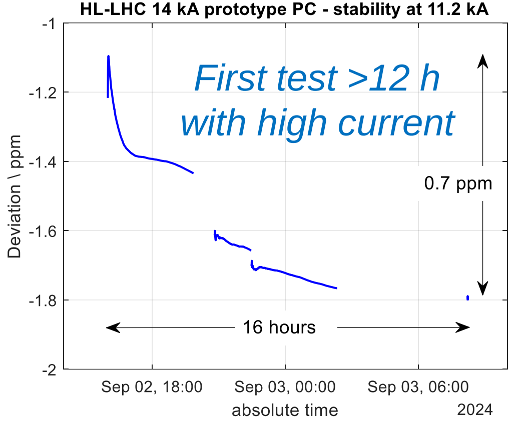
Reference DCCT chassis

5x 10 mA PBCs

Upgraded CDC

Temperature-controlled rack





Conclusions

- The CDC was improved in terms of functionality and performance
- The new design is not constrained by electronic component obsolescence or backward compatibility issues
- The upgraded CDC is now functionally tested, and preliminary performance tests show good results
- Further characterization is needed to fully qualify the upgraded CDC for testing of HL-LHC Accuracy Class 0 DCCTs
- The upgraded CDC was already used for testing the prototype 14 kA power converter in P-hall

References

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Thank you!