High Resolution Power Supply Ripple Measurements

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Collaboration

- Development performed within EU project “I.FAST”, Work Package 5, Task 5.3, “Improvement of resonant slow extraction spill quality”
- Collaboration consists of several groups with different accelerators and magnets.

iFAST

bergoz INSTRUMENTATION

MedAustron

CERN

GSI

SEE IIST South East European International Institute for Sustainable Technologies

barthel HF-Technik

CNAO Centro Nazionale di Adroterapia Oncologica

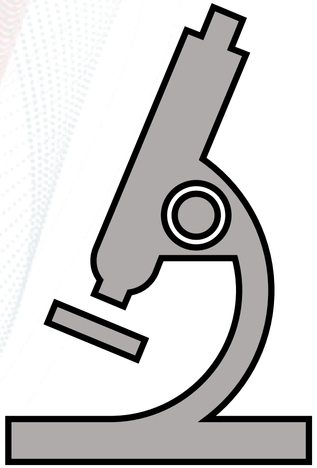
HIT Heidelberger Ionenstrahl-Therapiezentrum

Objective

- Measure power supply current with a resolution of

$$\frac{\Delta I}{I_{\mathrm{DC,max}}} \approx 10^{-7} \qquad \left(\text{official spec: } \frac{\Delta I}{I_{\mathrm{DC,max}}} < 10^{-6}\right)$$

- Maximum DC current: $I_{\mathrm{DC,max}} = 5000\ \mathrm{A}$
- Maximum AC modulation: $I_{\mathrm{AC,max}} = 1\%\ I_{\mathrm{DC,max}} = 50\ \mathrm{A}$
- Measurement Bandwidth: $10\ \mathrm{Hz}\ -\ 40000\ \mathrm{Hz}$

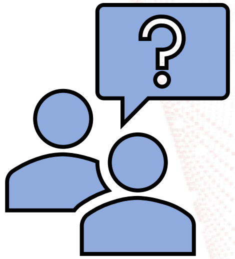


Challenge

- Required measurement resolution relative to $I_{\mathrm{DC,max}}$:

$$\frac{\Delta I}{I_{\mathrm{DC,max}}} \approx 10^{-7}$$

- Since specified bandwidth covers AC only,
wouldn't it be enough to measure AC only and forget about DC?



- Required measurement resolution relative to $I_{\mathrm{AC,max}}$:

$$\frac{\Delta I}{I_{\mathrm{AC,max}}} \approx 10^{-5}$$

(Too) Quick Solution

- 10^{-5} is a rather realistic resolution that should be reachable with a variant of an existing transformer.

- AC resolution and bandwidth are almost achieved by ACCT:
  ACCT bandwidth 1 Hz – 1 MHz
  ACCT resolution <5×10^{-5} relative to full scale current
- Assuming flat noise spectrum, low pass filtering to 40000 Hz should result in <10^{-5} resolution.

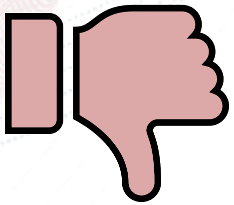
Extra Complication

- Presence of strong DC currents, i.e. strong DC magnetic fields
  ⇒ saturation of magnetic materials used in current transformers

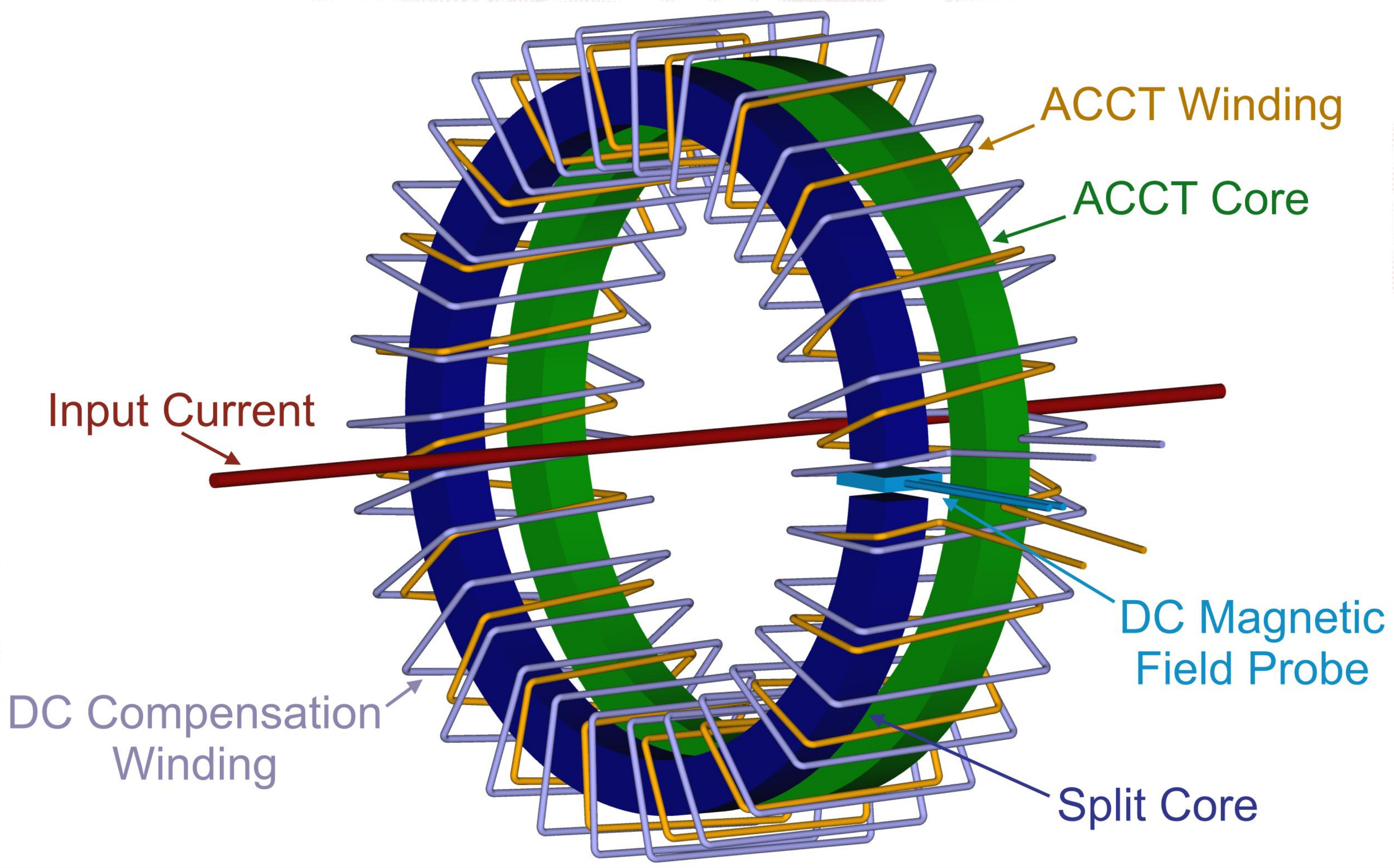
- A few Amperes suffice to saturate high performance magnetic materials.

- Must wrap the current transformer in a DC compensation coil.

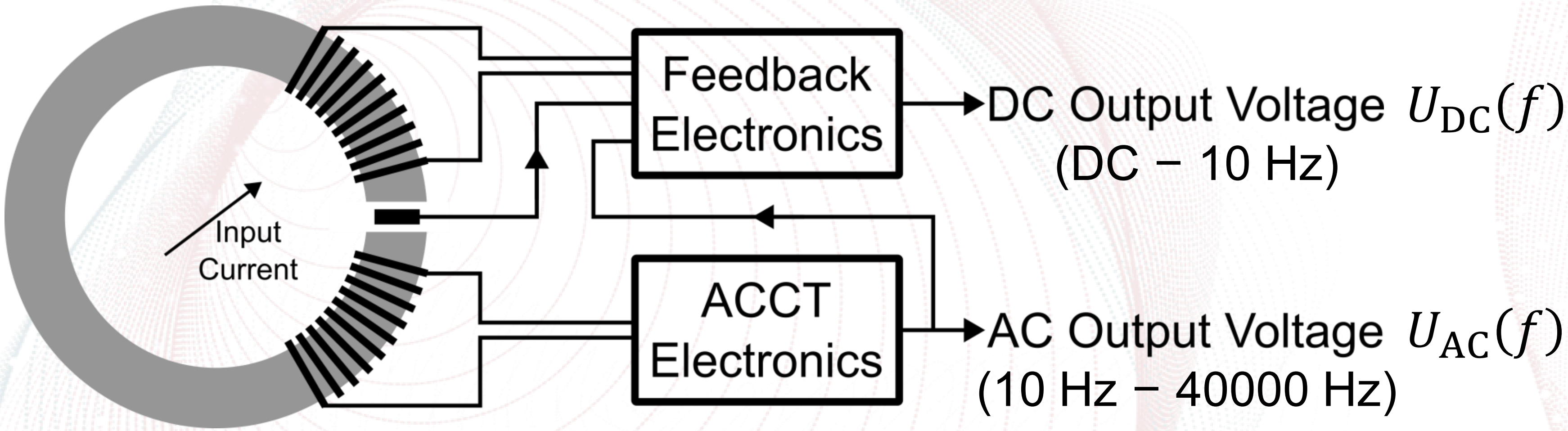
- Required compensation accuracy: $\lesssim 1\ \mathrm{A} \Rightarrow \frac{\Delta I_{\mathrm{DC}}}{I_{\mathrm{DC,max}}} \lesssim 2 \times 10^{-4}$



Basic Principle



Basic Principle



- Design choice: both output signals shall be properly in phase
- That means, to reconstruct the full input current spectrum (DC – 40000 Hz):

$$I_{in}(f) = g_{DC}\, U_{DC}(f) + g_{AC}\, U_{AC}(f)$$

Last Year's Status and Advancements

- I reported on very nice measurements already during last year's SlowEX workshop.
- However, given the tight requirements "very nice" is insufficient.
- We had to improve the electronics.
- And the sensor.

Second Prototype Electronics

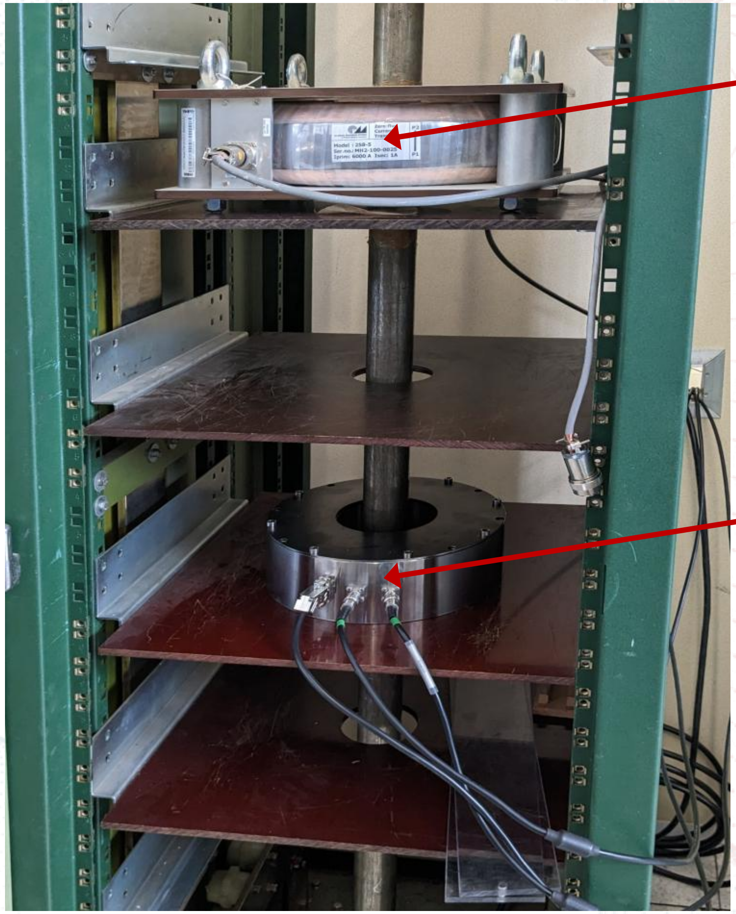
DC feedback + ACCT electronics external power supply

Second Prototype Sensor

2x 1500turns transformer with integrated DC magnetic field probe

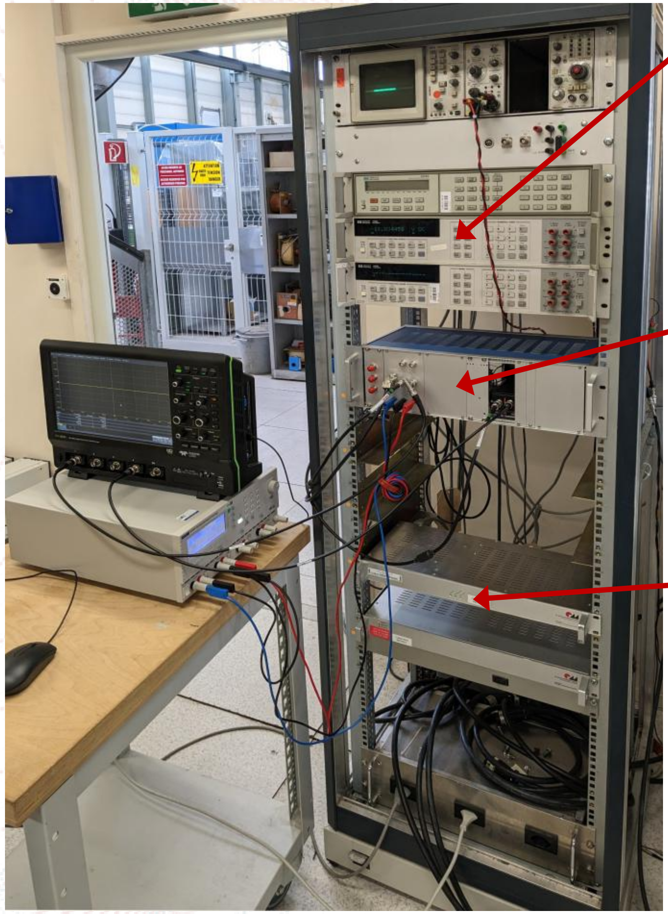
Prototype Tests at CERN

6000 A DC Test Stand



Reference Fluxgate DCCT

(First) Prototype Sensor



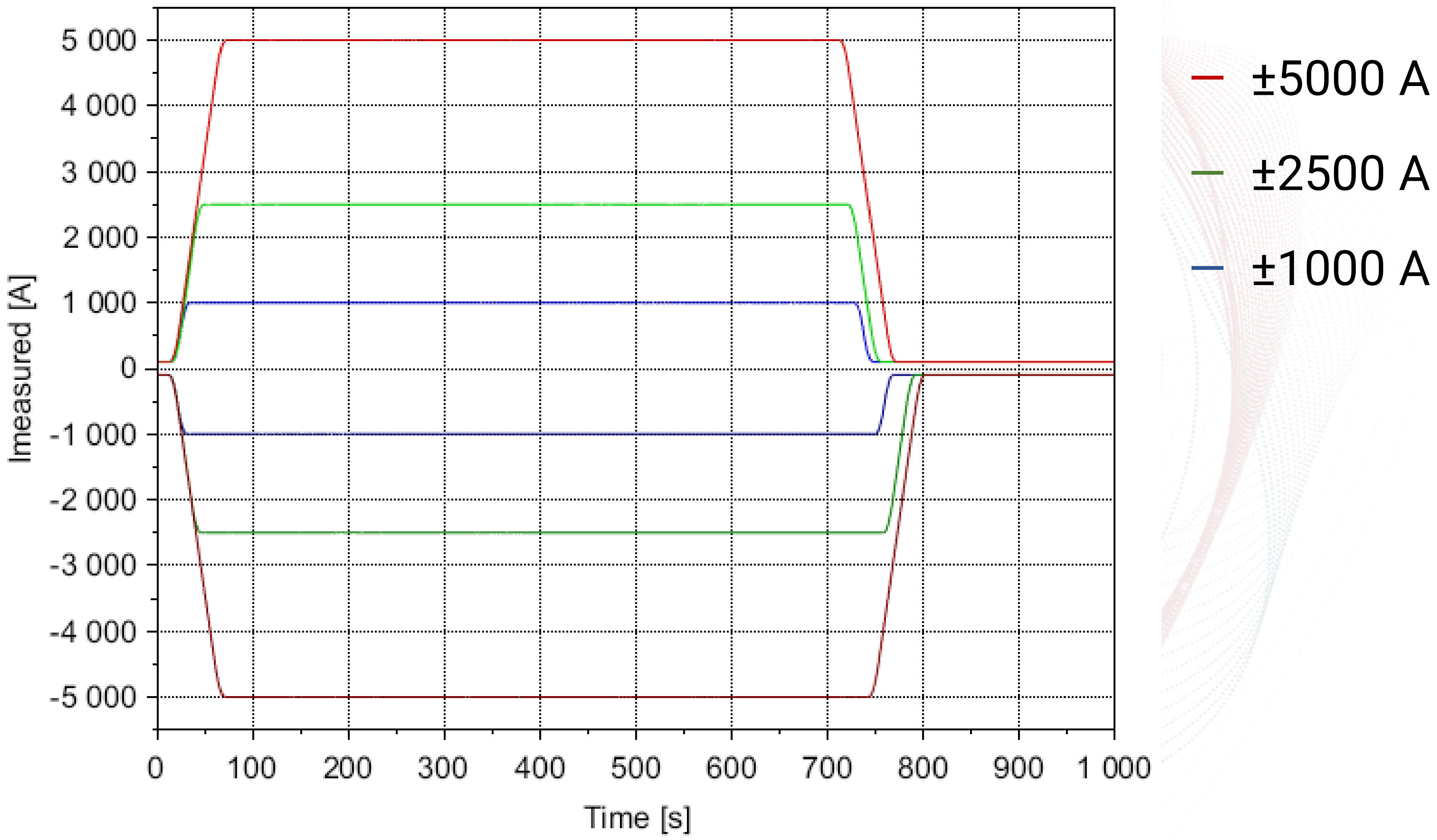
Precision Voltmeters

(First) Prototype Electronics

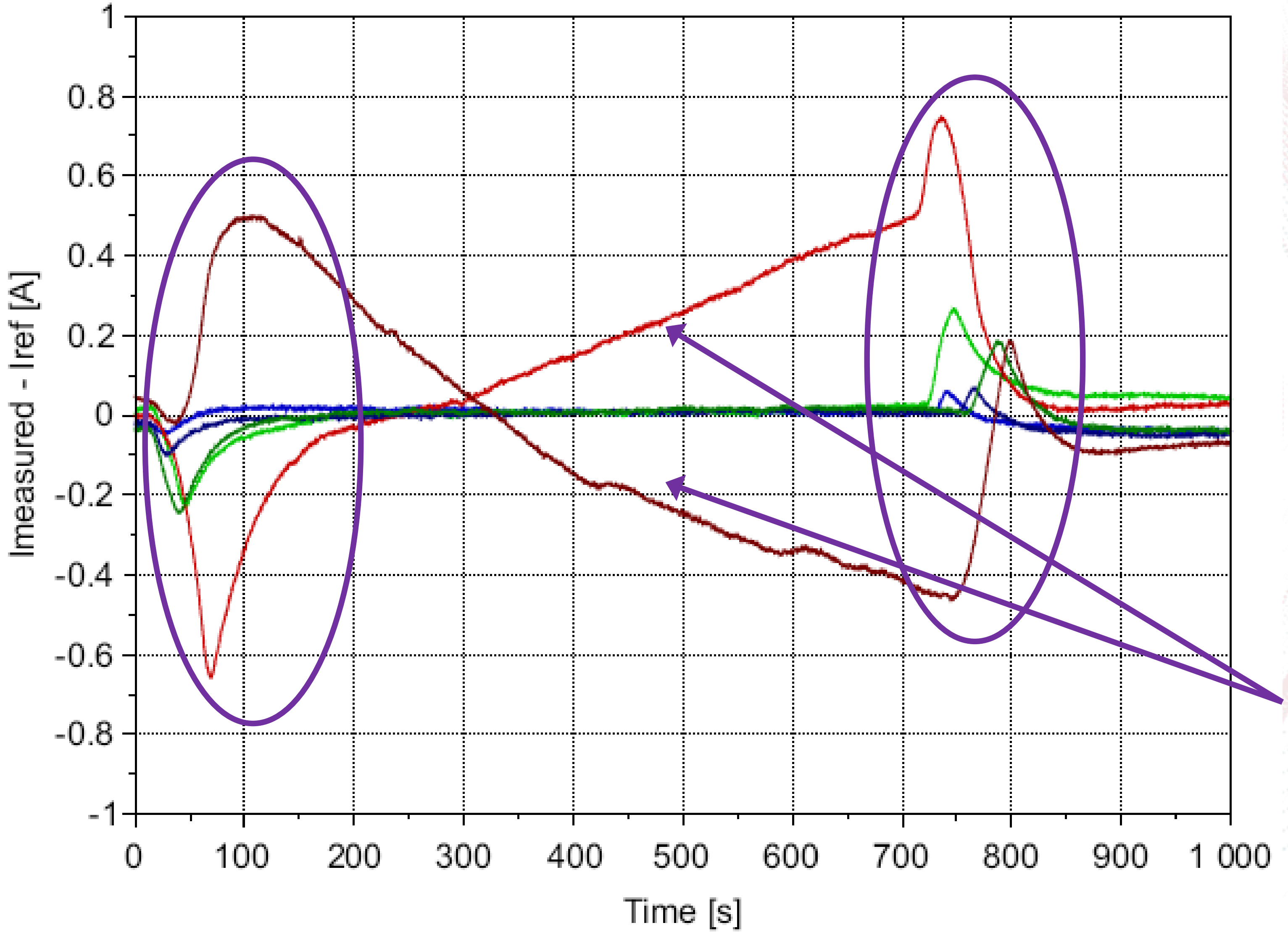
Reference Fluxgate DCCT Electronics

Not visible on photos: parallel loop for AC current injection and
24bit digitizer for high-resolution and high-bandwidth measurements

Second Prototype Measurements @ CERN



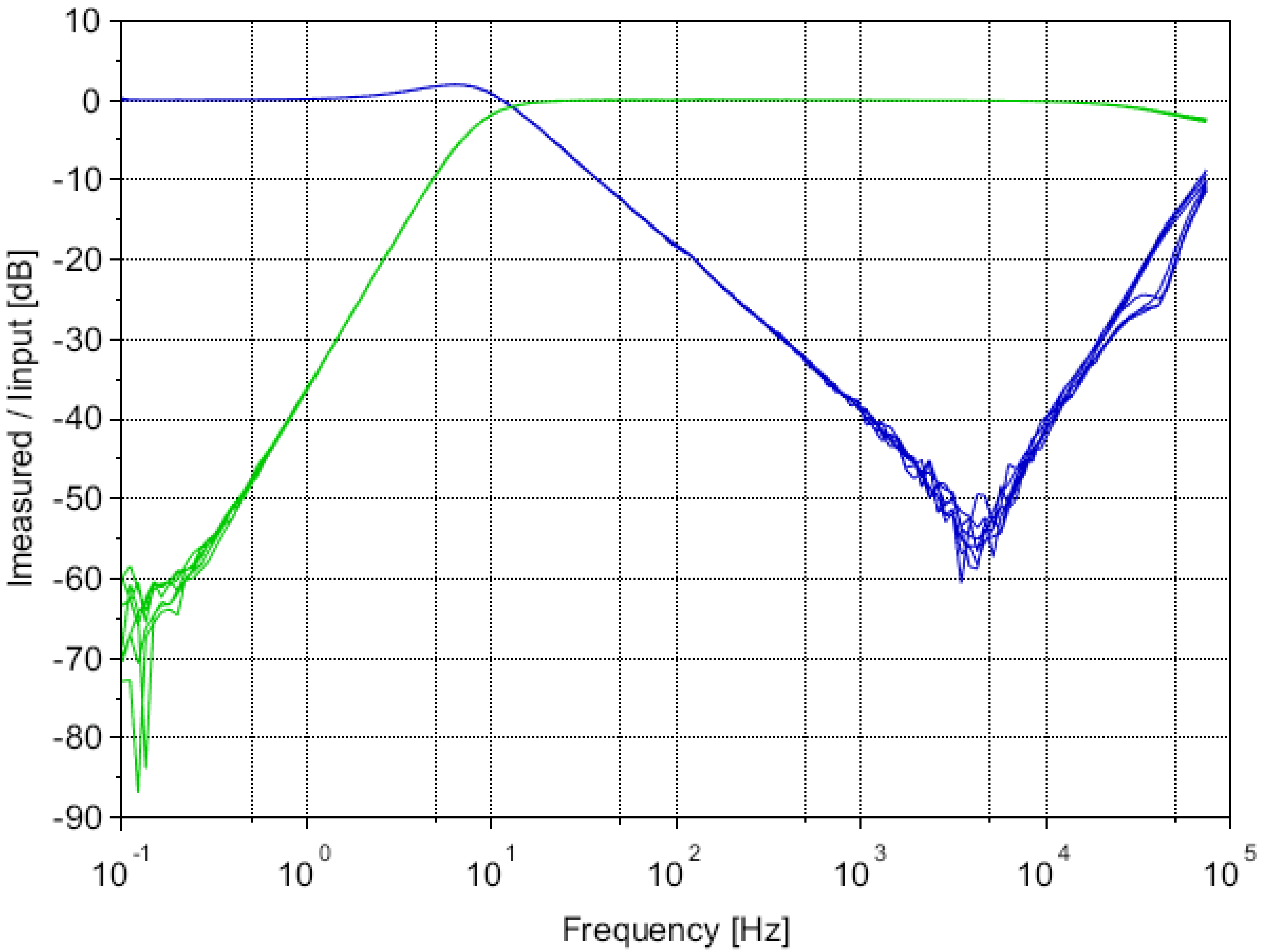
Second Prototype Measurements @ CERN



Small deviations are expected during ramp, all within specs.

Related to heating, mainly electronics, can be reduced by active cooling, further investigations required.

Second Prototype Measurements @ CERN

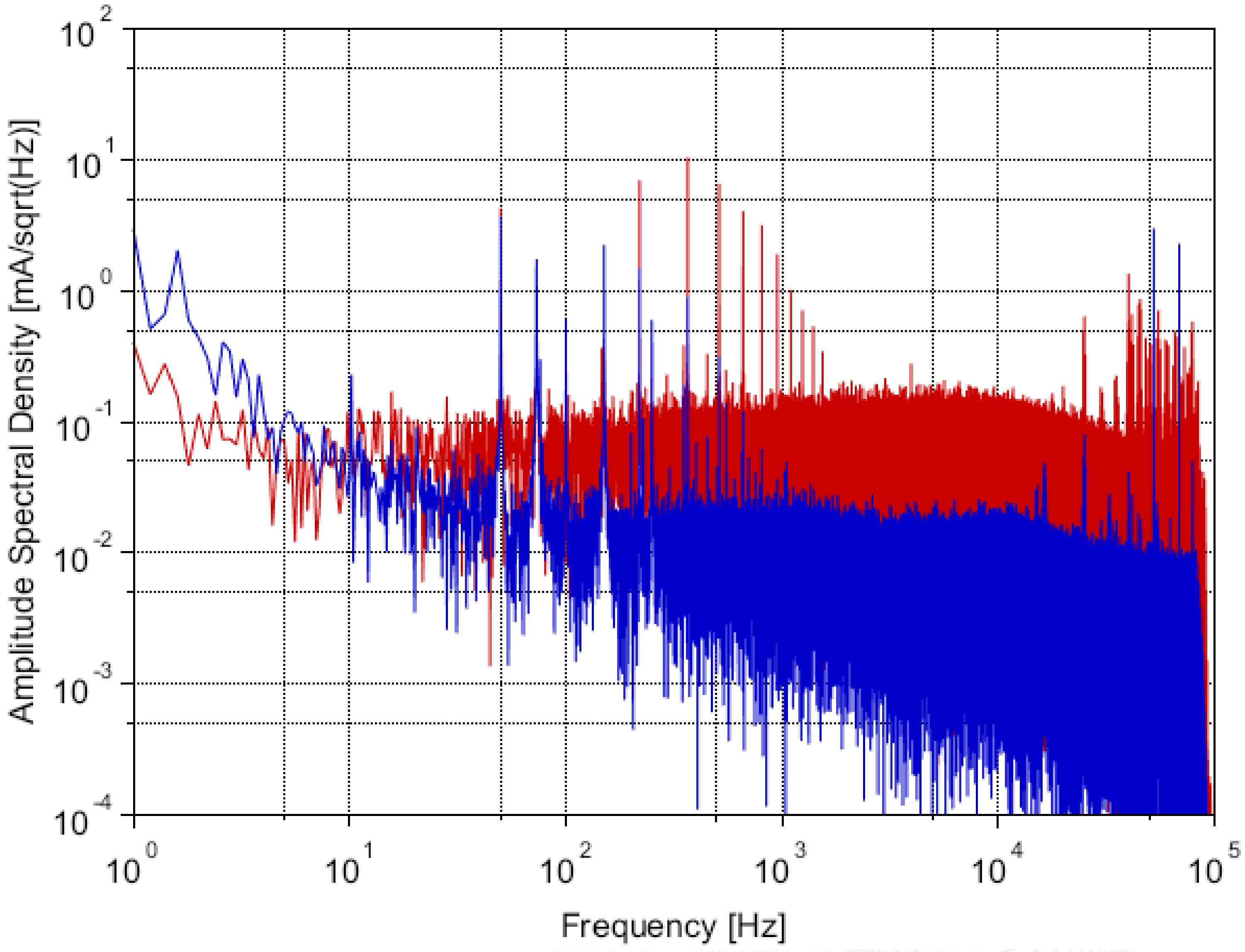


- DC Output
- AC Output

Frequency responses measured at DC offsets of 0 A, ±1000 A, ±2500 A and ±5000 A.

Traces overlap, i.e. they are independent of DC offset.

Second Prototype Measurements @ CERN



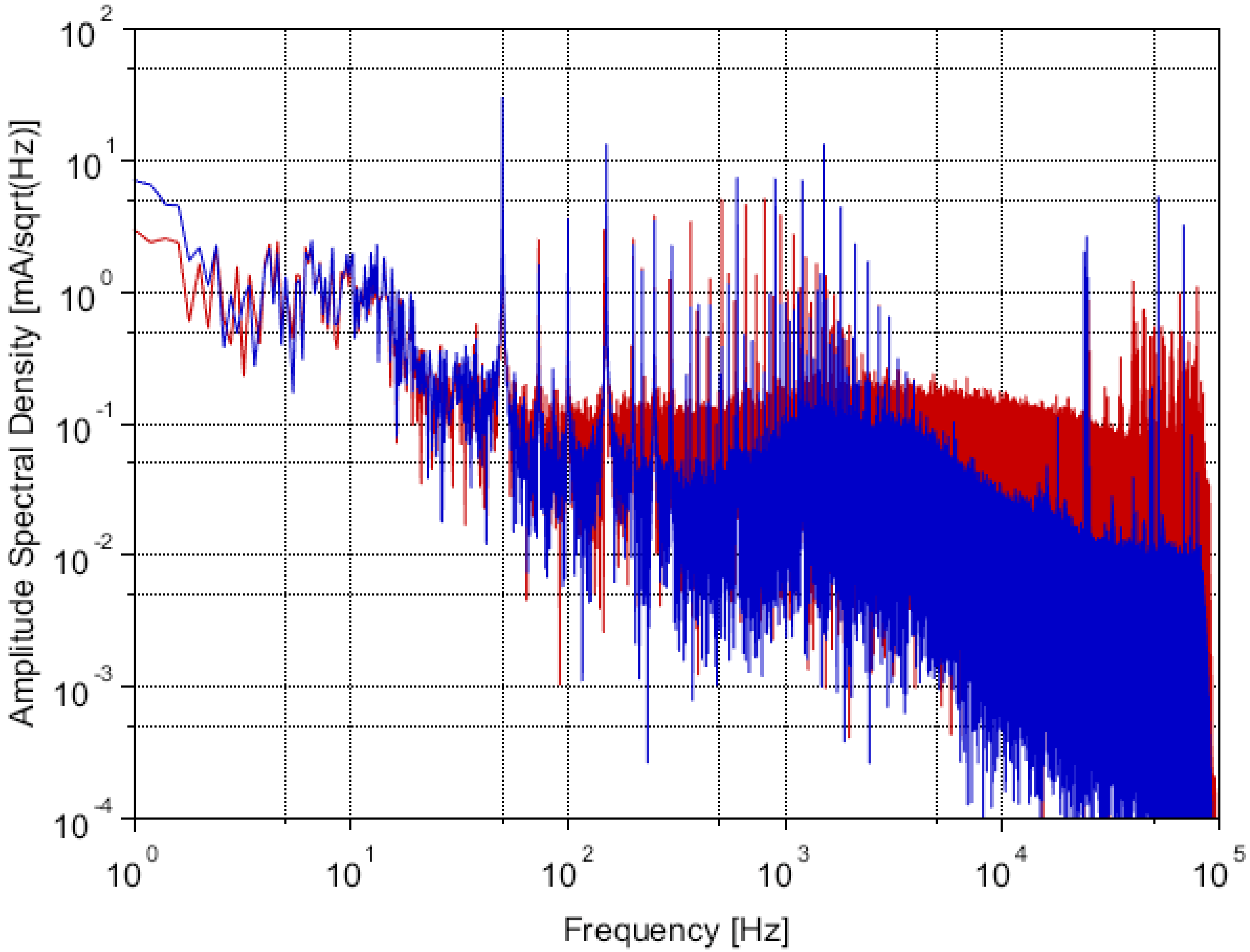
- IFast Sensor (AC + DC)
- Reference DCCT

0 A primary current (i.e. power supply off, but bus-bar still connected).

Below ~10 Hz the reference DCCT has less noise.

Above ~10 Hz the IFast sensor has less noise.

Second Prototype Measurements @ CERN



— IFast Sensor (AC + DC)

— Reference DCCT

5000 A primary current

A lot noise is common to both traces, i.e. it stems from input signal or environment.

Several spectral rays come from 50 Hz + harmonics and DCCT excitation frequency + harmonics.

Achieved AC Resolution @ CERN

$$\text{at } 0\ \text{A}_{\text{DC}} \Rightarrow\ \Delta I < 2\ \text{mA}_{\text{rms}} \Rightarrow \frac{\Delta I}{I_{\text{DC,max}}} < 4 \times 10^{-7}$$

$$\text{at } 5000\ \text{A}_{\text{DC}} \Rightarrow\ \Delta I < 4\ \text{mA}_{\text{rms}} \Rightarrow \frac{\Delta I}{I_{\text{DC,max}}} < 8 \times 10^{-7}$$

- To deduce resolution, features common to IFast sensor and reference DCCT were removed from the noise spectra.
- Unfortunately, this is neither simple nor unambiguous.
- And it yields at best an upper limit for the resolution.

?

Achieved AC Resolution @ Bergoz

- We also deduced resolution from lab measurements, hoping that we could better determine input signal and that environmental noise would be lower.
- But we had the same problems as at CERN.

$$\text{at } 0\ \mathrm{A_{DC}} \Rightarrow \Delta I < 1.5\ \mathrm{mA_{rms}} \Rightarrow \frac{\Delta I}{I_{\mathrm{DC,max}}} < 3 \times 10^{-7}$$

$$\text{at } 1000\ \mathrm{A_{DC}} \Rightarrow \Delta I < 2\ \mathrm{mA_{rms}} \Rightarrow \frac{\Delta I}{I_{\mathrm{DC,max}}} < 4 \times 10^{-7}$$

- However, results are basically the same.
  Which makes us confident that they are realistic.

Specifications fulfilled!

Summary

- A high-resolution measurement system for magnet power supplies was developed and tested.

- Exceptional AC resolution was achieved for a bandwidth of 10 Hz to 40000 Hz:

$$\frac{\Delta I_{\mathrm{AC}}}{I_{\mathrm{DC,max}}} < 3 \times 10^{-7}$$

- DC measurement accuracy is also very good:

$$\frac{\Delta I_{\mathrm{DC}}}{I_{\mathrm{DC,max}}} < 2 \times 10^{-4}$$

Outlook

- I.FAST project (officially) comes to an end in a few weeks.
- Work continues.

- Next step is the installation at GSI.
- This will allow to evaluate long-term performance in a real accelerator environment.