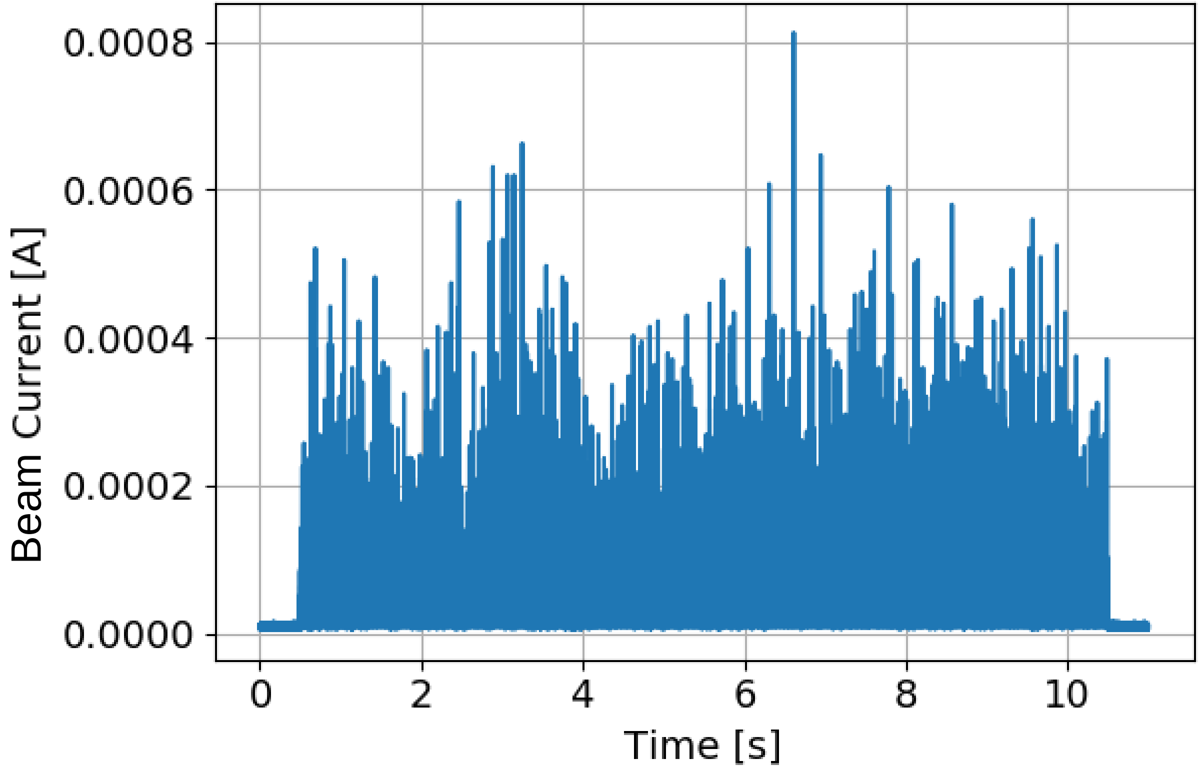
This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under GA No 101004730.

Measuring Small AC Ripple on Strong DC Currents

Slow Extraction Workshop 2024-02-11 - 15

Frank Stulle, Laurent Dupuy, Hervé Bayle (Bergoz Instrumentation)

Motivation



D. Prokopovich et al., “Slow Extraction at MedAustron”, I.FAST REX Kick-Off Meeting, Feb 2021

Stability of slowly extracted beams

⇳

Stability of magnet power supplies

⇳

Quality of feedback regulation

⇳

Precision of power supply current measurement

Development Objective

- I.FAST Work Package 5, Task 5.3:
  "Improvement of resonant slow extraction spill quality"

- I.FAST proposal: measure magnet currents to $\frac{\Delta I}{I_{\mathrm{DC,max}}} < 10^{-6}$

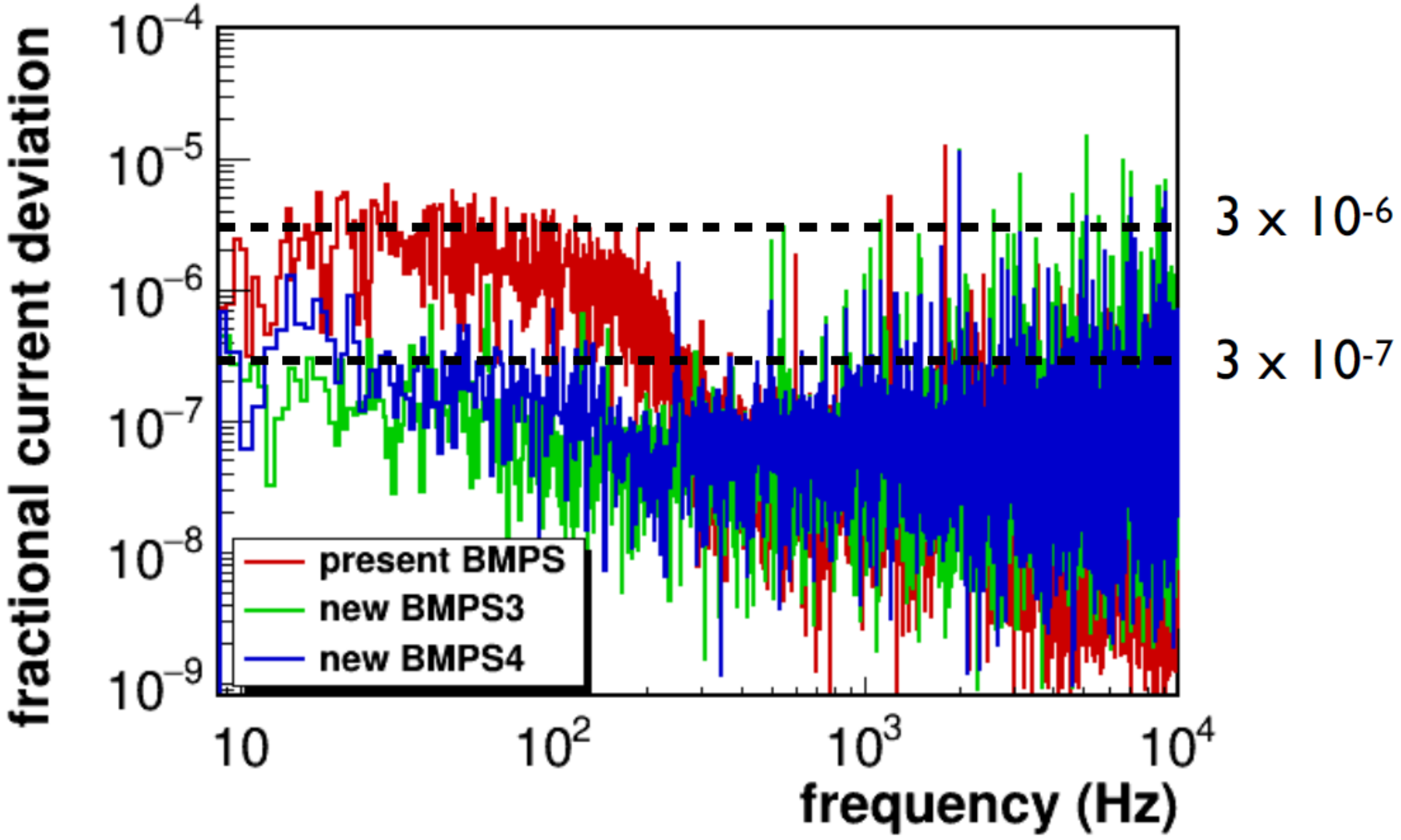
- Later communication: measure magnet currents to $\frac{\Delta I}{I_{\mathrm{DC,max}}} \approx 10^{-7}$

Short Interlude

Rewind to Monday 2024-02-12 16:30

Ryotaro Muto, “Spill structure with newly upgraded main magnet power supplies in J-PARC Main Ring”

Short Interlude



Question by audience:
"Does your DCCT really have 10^{-7} resolution?"

Short Interlude

- My answer: “Be careful!”
- Spectral amplitudes may be at such low levels.
- But to get resolution we need to apply the inverse Fourier Transform.
- Since spectrum has a certain bandwidth, what we get in time domain is a signal averaged over a certain time window.

- Trade-off: good amplitude resolution vs good time resolution!

- To my knowledge, there is no current measurement system available that achieves close to 10^{-7} resolution with >100 Hz bandwidth.

Short Interlude

Fast Forward to Wednesday 2024-02-14 14:00

Development Objective

- Measurement bandwidth $10\ \mathrm{Hz}$ to $40000\ \mathrm{Hz}$
- Magnet currents up to $I_{\mathrm{DC,max}} = 10000\ \mathrm{A}$
- Current modulations up to $I_{\mathrm{AC,max}} \approx 1\%\ I_{\mathrm{DC}}$

- Collaboration consists of several groups with very different accelerators and very different magnets.
- That means, any development must be adaptable to very different requirements.

Development Starting Point

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

$$\frac{\sigma_{\mathrm{I,AC}}}{I_{\mathrm{DC,max}}} \approx 10^{-7} \text{ (}\Rightarrow\text{ 140dB dynamic range)}$$

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

$$\frac{\sigma_{\mathrm{I,AC}}}{I_{\mathrm{AC,max}}} \approx 10^{-5} \text{ (}\Rightarrow\text{ 100dB dynamic range)}$$

- Required DC accuracy and resolution not properly specified, but certainly a lot less stringent than 10^{-7}.

$\Rightarrow$ It seems advantageous to separate DC and AC measurements.

Development Starting Point

- We are current transformer specialists.
- Hence, we decided to base the development on a current 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 1×10^{-5} resolution.

Challenge

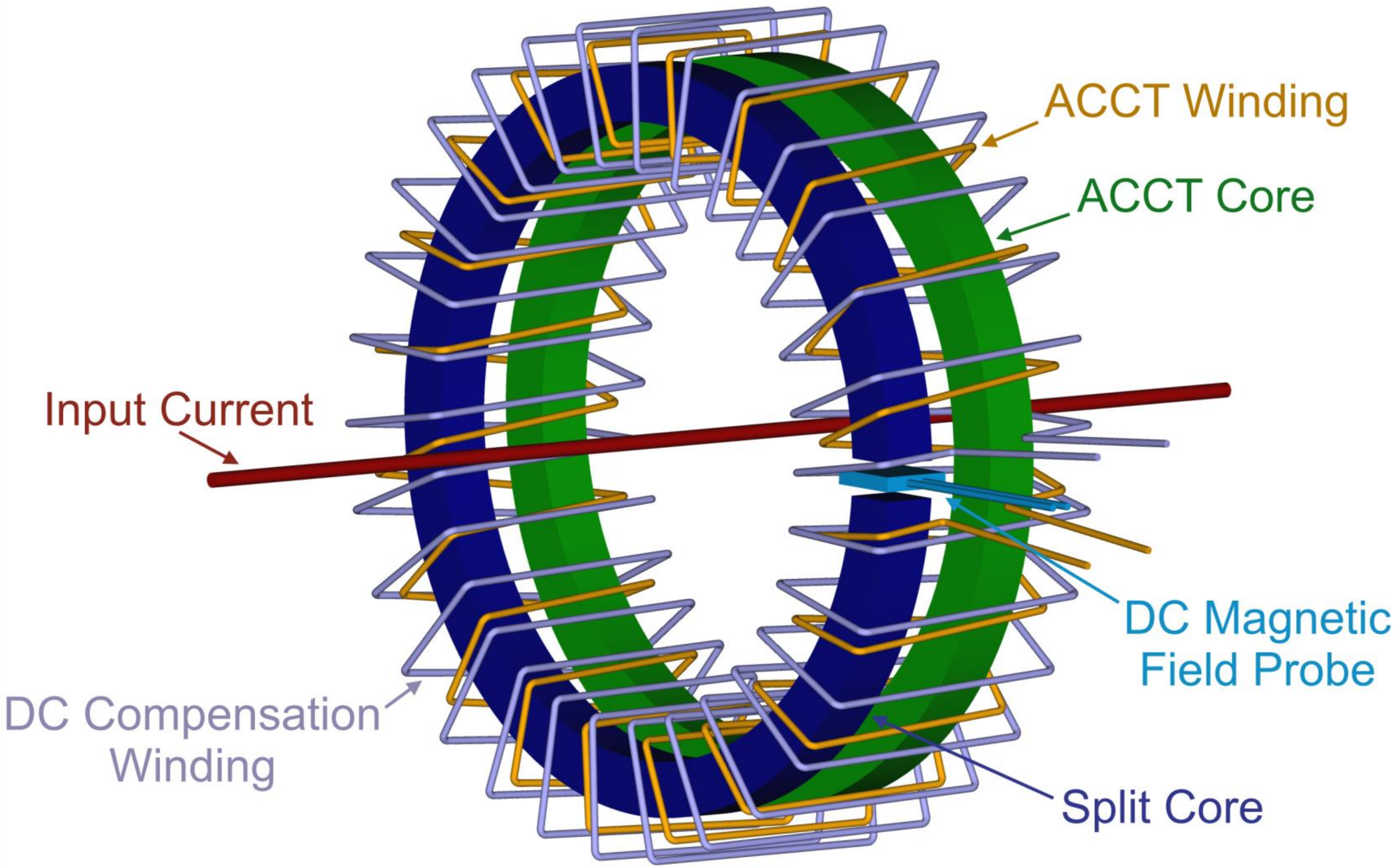
- Presence of strong DC currents, i.e. strong magnetic fields
  ⇒ saturation of magnetic materials used in current transformers

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

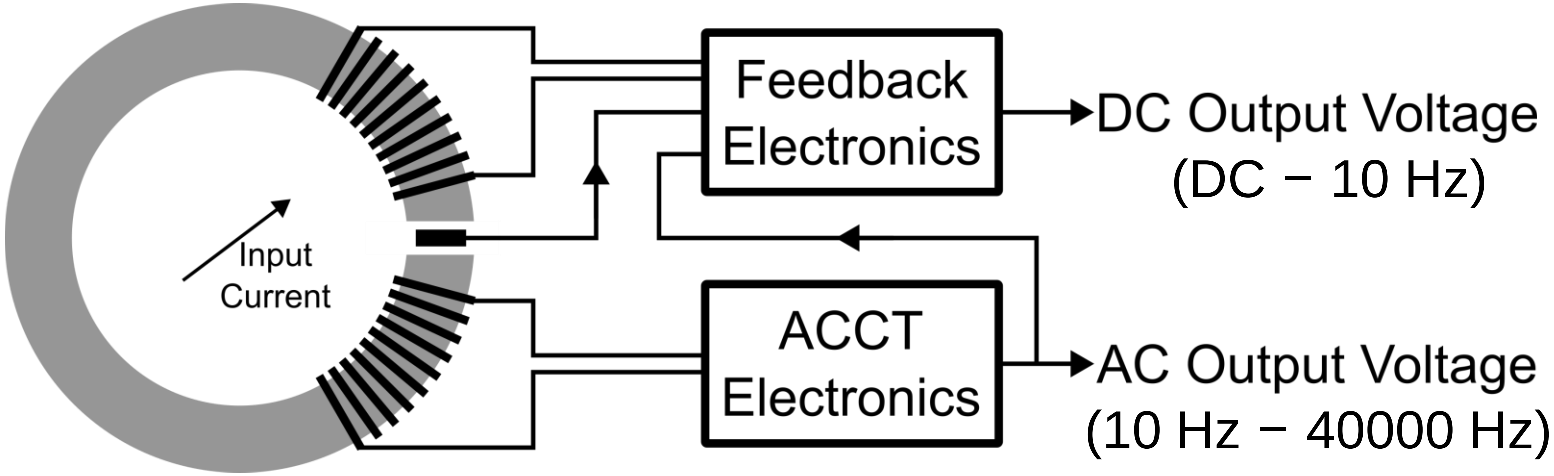
- Need to wrap the current transformer in a DC compensation coil.

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

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):

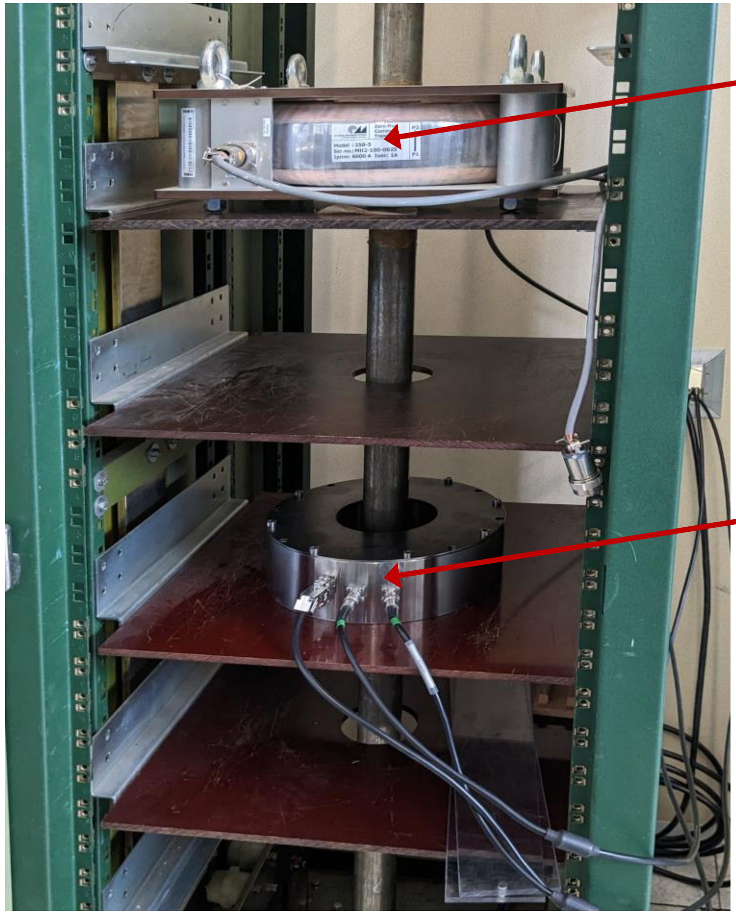
$$I_{\mathrm{in}}(f) = g_{\mathrm{DC}}\, U_{\mathrm{DC}}(f) + g_{\mathrm{AC}}\, U_{\mathrm{AC}}(f)$$

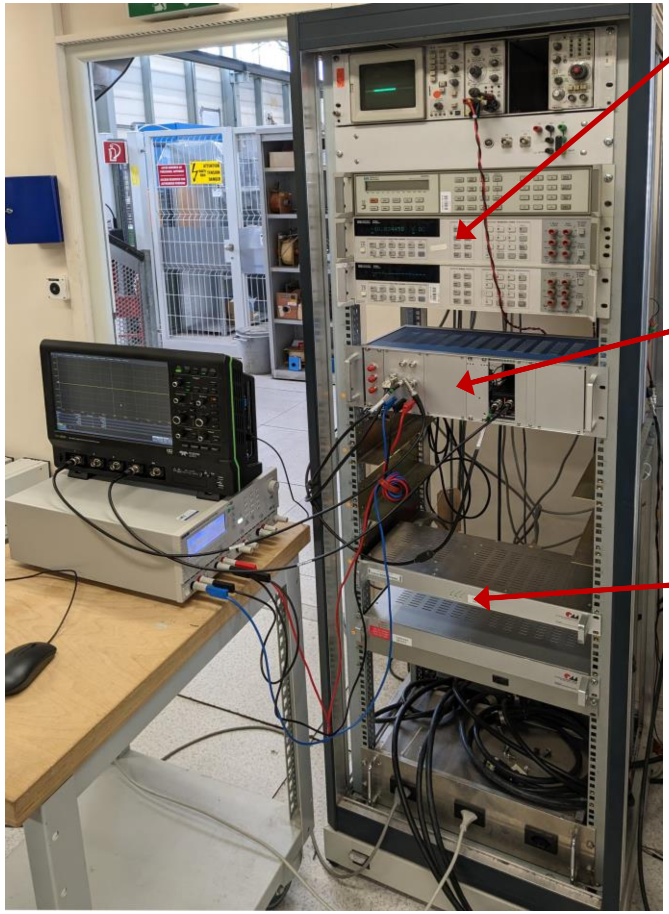
Prototype Specifications

- DC: 8 V for 6000 A, DC – ~10 Hz
- AC: 10 V for 60 A, ~10 Hz – ~40000 Hz
- Two windings, each 1500 turns
- 110 mm aperture
- 260 mm outer diameter
- 80 mm height

Prototype Tests at CERN

6000 A DC Test Stand





Reference Fluxgate DCCT

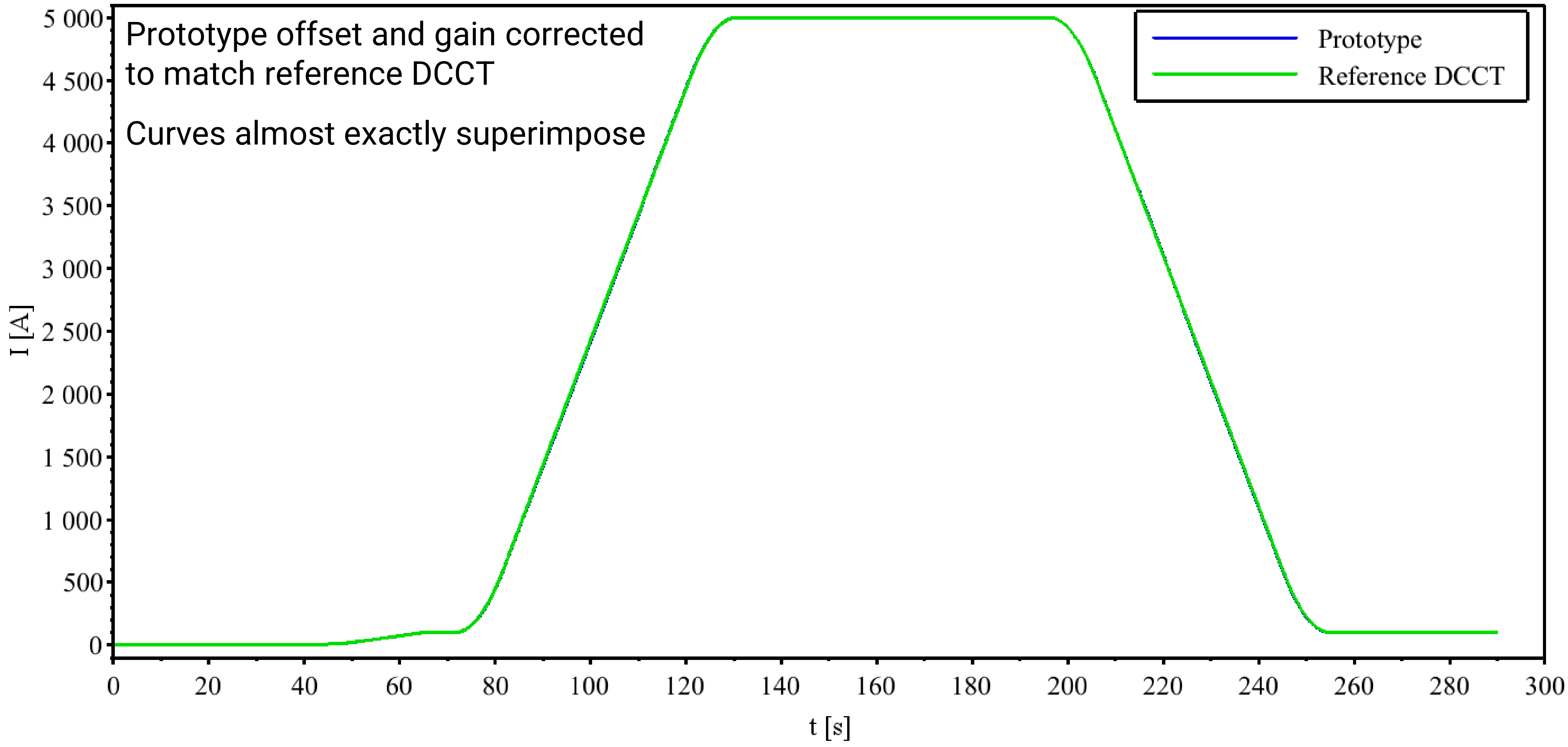
Prototype Sensor

Precision Voltmeters

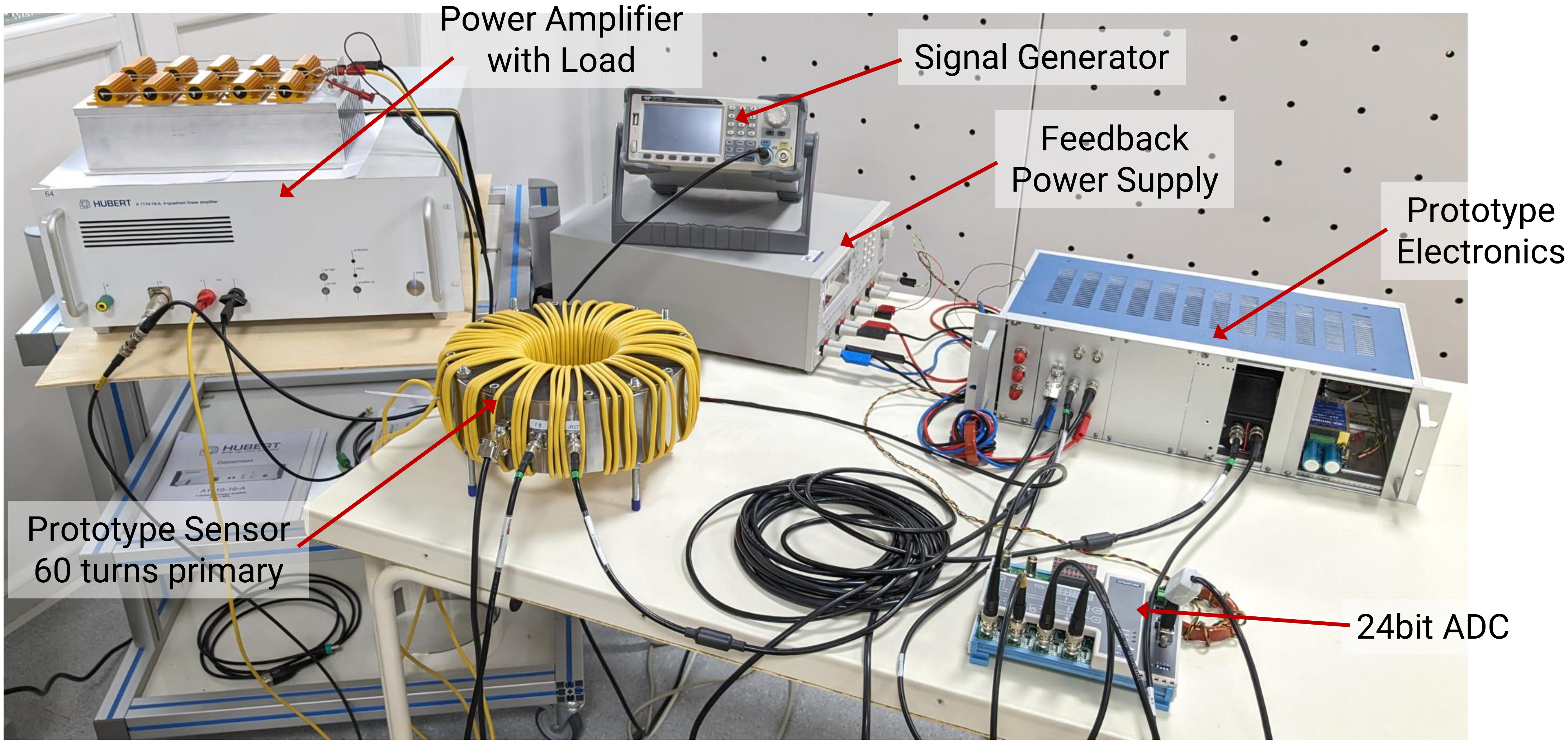
Prototype Electronics

Reference Fluxgate DCCT Electronics

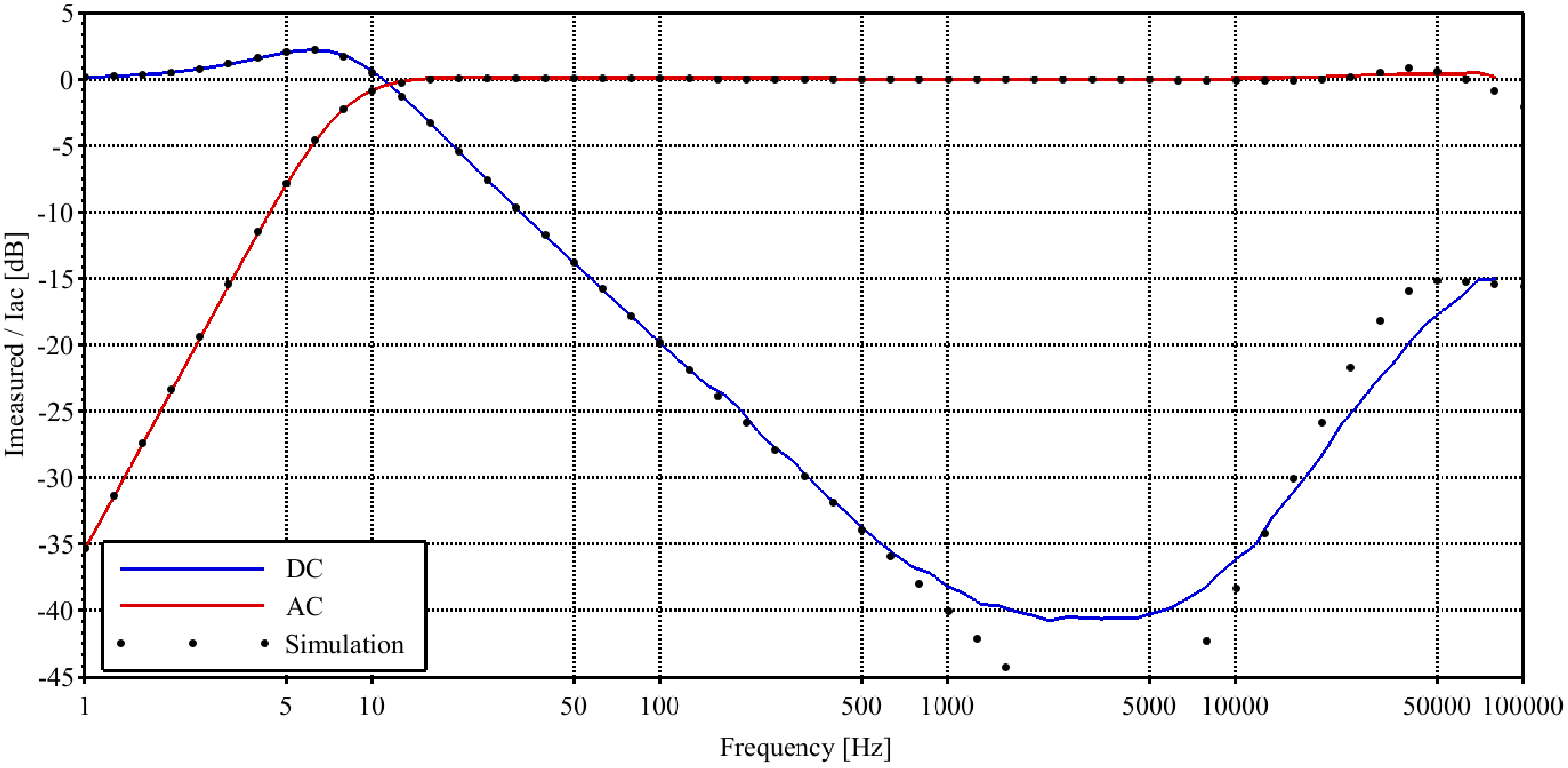
DC Ramp Up and Down



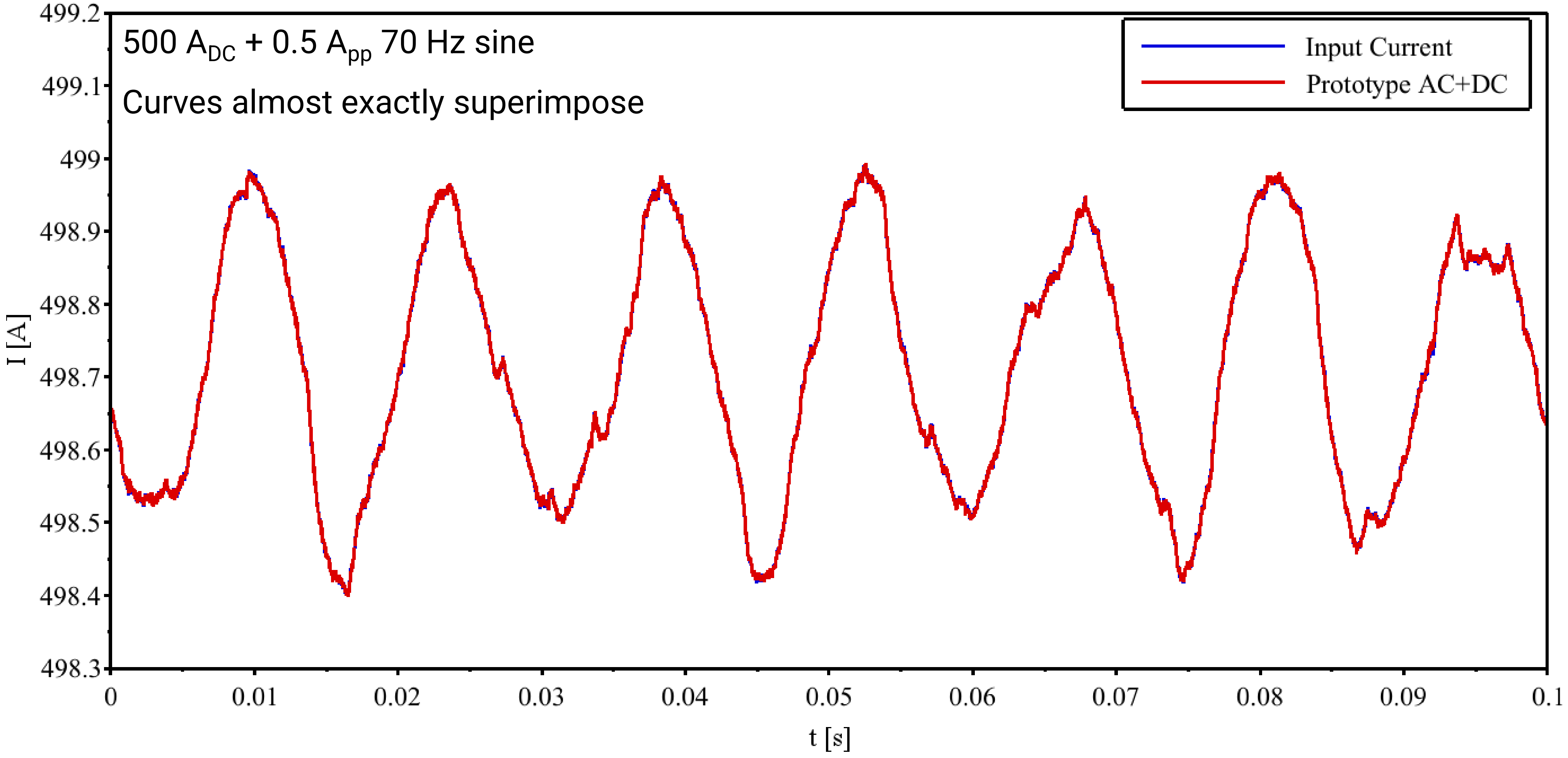
Prototype Tests at BI



Frequency Response



DC + Small AC



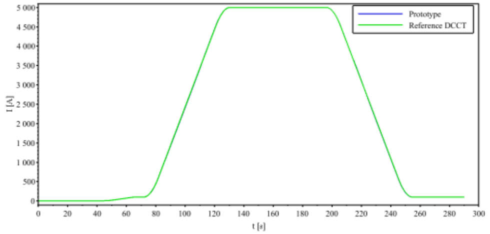
500 A$_{DC}$ + 0.5 A$_{pp}$ 70 Hz sine
Curves almost exactly superimpose
Input Current
Prototype AC+DC
I [A]
t [s]
499.2
499.1
499
498.9
498.8
498.7
498.6
498.5
498.4
498.3
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1

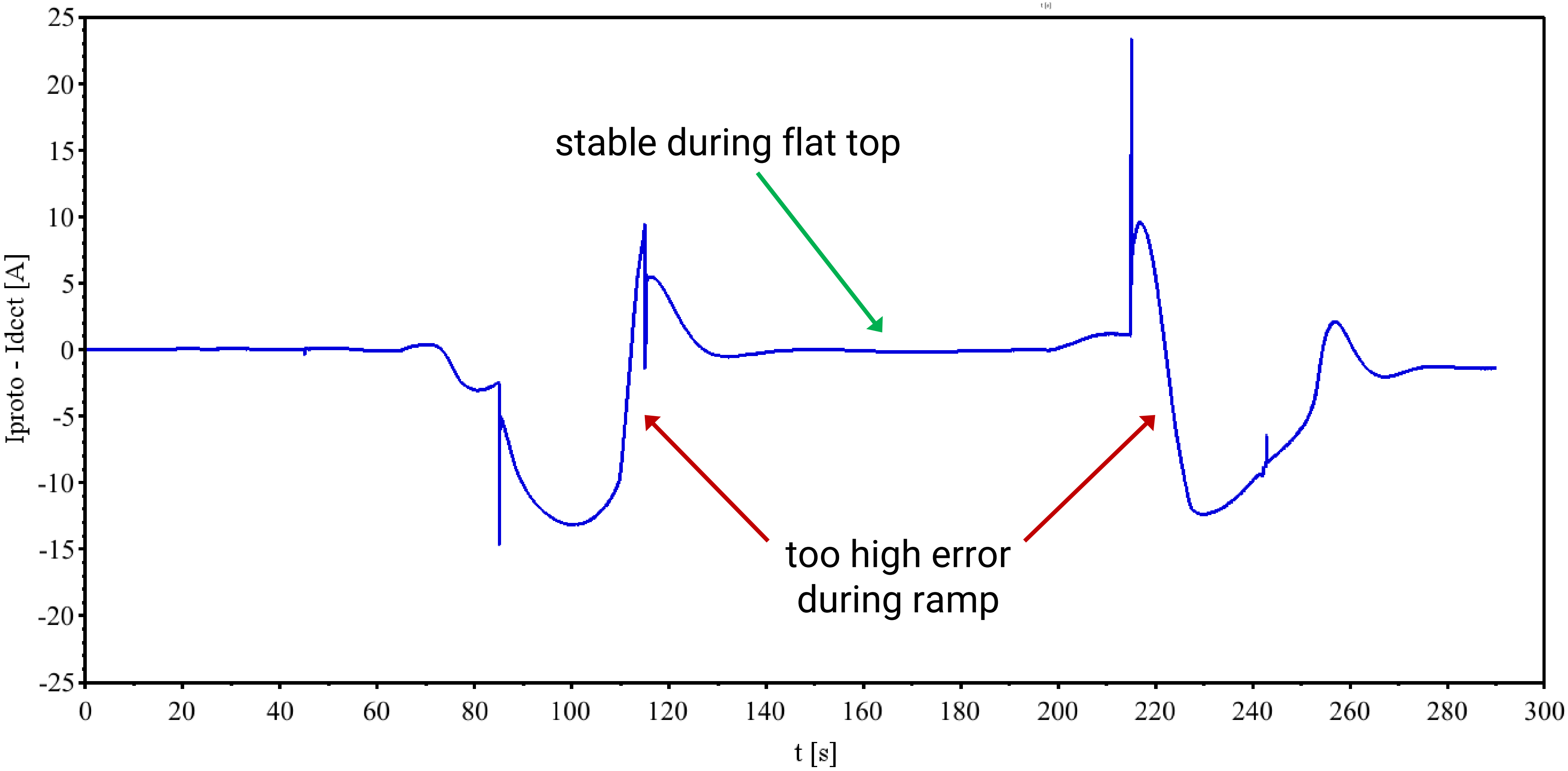
Measurements Close-Up

What went → well?

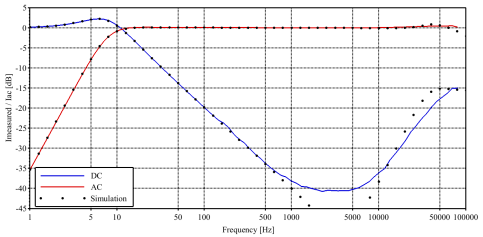
What went → wrong?

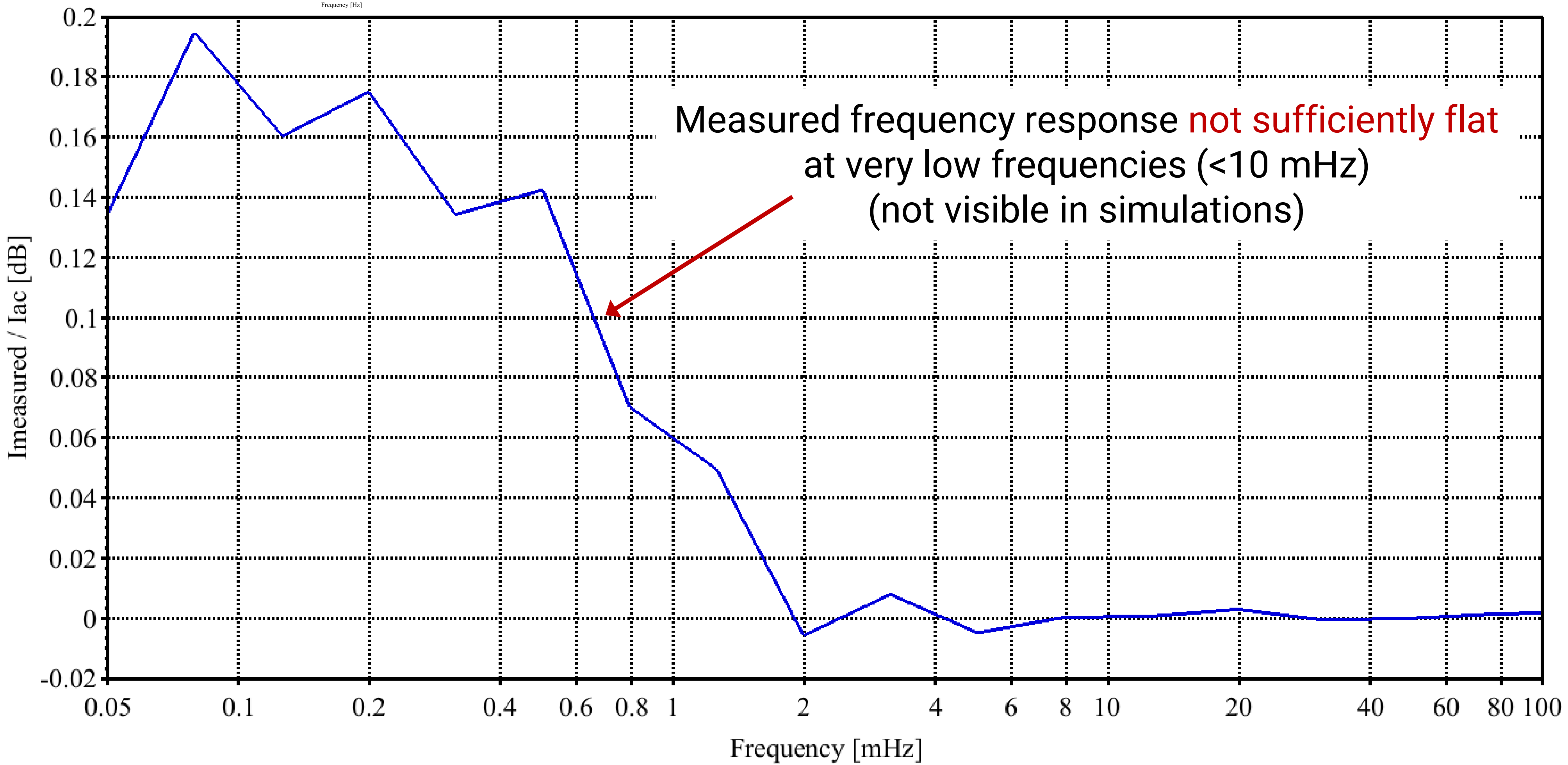
Close-Up DC


Prototype
Reference DCCT


stable during flat top
too high error
during ramp
Iproto - Idcct [A]
t [s]

Close-Up Frequency Response

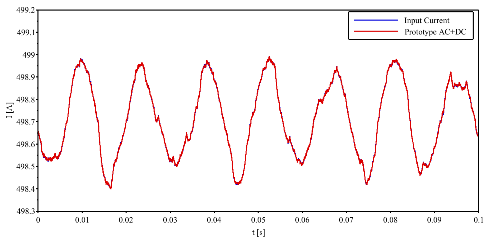




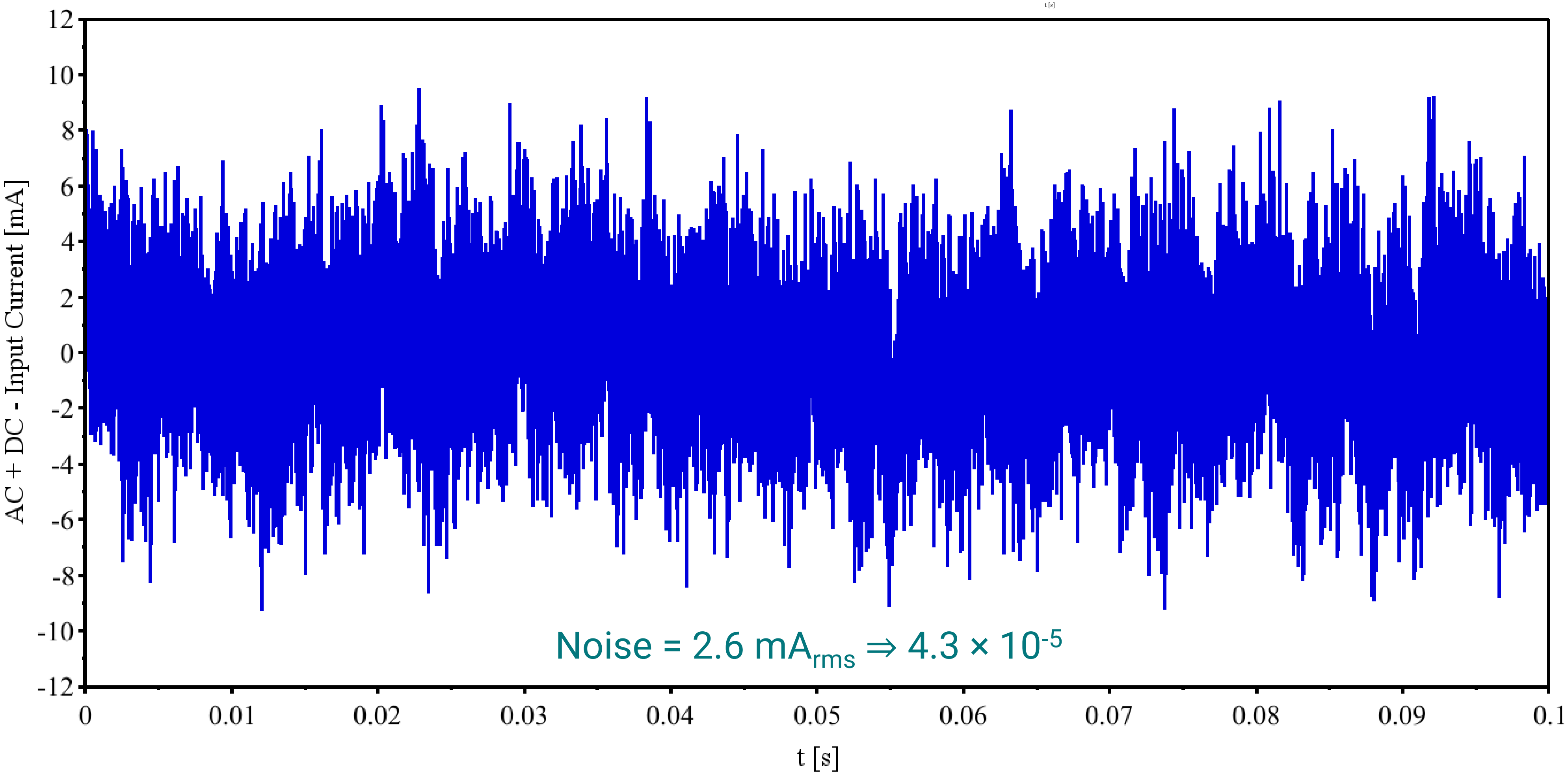
Close-Up DC / Frequency Response

- Apparently, DC compensation was behaving slightly wrong during measurements at CERN.
- Some shortcomings were quickly found, others were well hidden.
- Nothing was fundamentally wrong.
- Re-designed electronics for improved signal accuracy and stability.
- New electronics is being assembled now and will be tested soon.

Close-Up AC



Input Current
Prototype AC+DC
I [A]
t [s]



AC + DC - Input Current [mA]
t [s]
Noise = 2.6 mA$_{rms}$ ⇒ 4.3 × 10^{-5}

Close-Up AC

- Input Current: 500 A_{DC} + 0.5 A_{pp} 70 Hz sine

  AC Noise: $\sigma_{I,AC} = 2.6\ \mathrm{mA_{rms}},\ \frac{\sigma_{I,AC}}{I_{AC,max}} = 4.3 \times 10^{-5}$

same with 0 A input current

Spec: $10^{-5} < \frac{\sigma_{I,AC}}{I_{AC}} < 10^{-4}$, 40 kHz BW

- DC Feedback=Off , Input Current: no DC, ≥0 A_{AC}

  AC Noise: $\sigma_{I,AC} = 0.33\ \mathrm{mA_{rms}},\ \frac{\sigma_{I,AC}}{I_{AC,max}} < 5.6 \times 10^{-6}$

Summary

- High resolution, high dynamic range current measurement system in development for stabilization of magnet power supplies.

- Prototype measurements were rather satisfactory.
- Bandwidth surpasses specifications.
- Measured AC resolution is (almost) within specifications.
  And there seems to be potential for further improvements.

- However, DC compensation worked less well than expected.

- Some corrections and improvements have been implemented already.
- New electronics will be finished this week.

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