Czech Metrology Institute

Digital Sampling Impedance Bridge for 1 MHz

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CMI coordinates EMPIR project TracePQM
Traceable Power Quality Measurements

- Modular measurement system for power and PQ
- Open SW tool
- Good practice guide

- **Improved transducer calibration up to 1 MHz**
  - Target exp. uncertainty **< 800 µrad/MHz** on phase angle
  - Target exp. uncertainty **< 100 µA/A** on ac-dc

Project web:
http://tracepqm.cmi.cz/

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

100 kHz bridge

CMI 100 kHz digital sampling (2016):

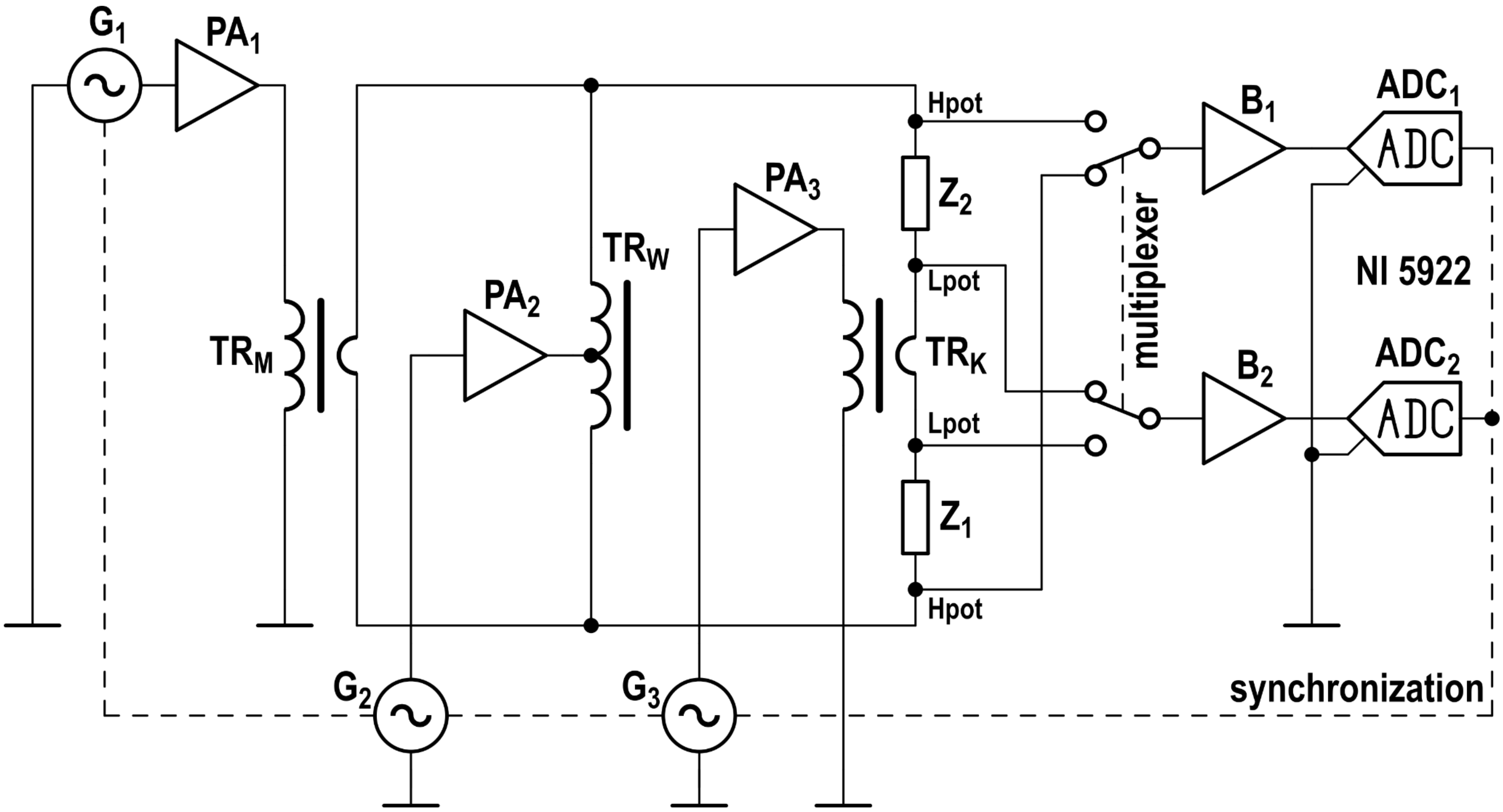
- Digital sampling topology with time multiplex
- Frequency 20 Hz to 100 kHz
- Impedances below 100 kΩ
- 4TP or 2P configuration
- Ratio uncertainty below 35 μΩ/Ω (*k* = 2)
- Phase uncertainty below 50 μrad (*k* = 2)

S. Mašláň, M. Šíra, V. N. Zachovalová and J. Streit, "*Digital Sampling Setup for Measurement of Complex Voltage Ratio*," in *IEEE Transactions on Instrumentation and Measurement*, vol. 66, no. 6, pp. 1355-1363, June 2017. doi: 10.1109/TIM.2017.2649899

Four Terminal Pair Digital Sampling Impedance Bridge up to 1 MHz (2018):

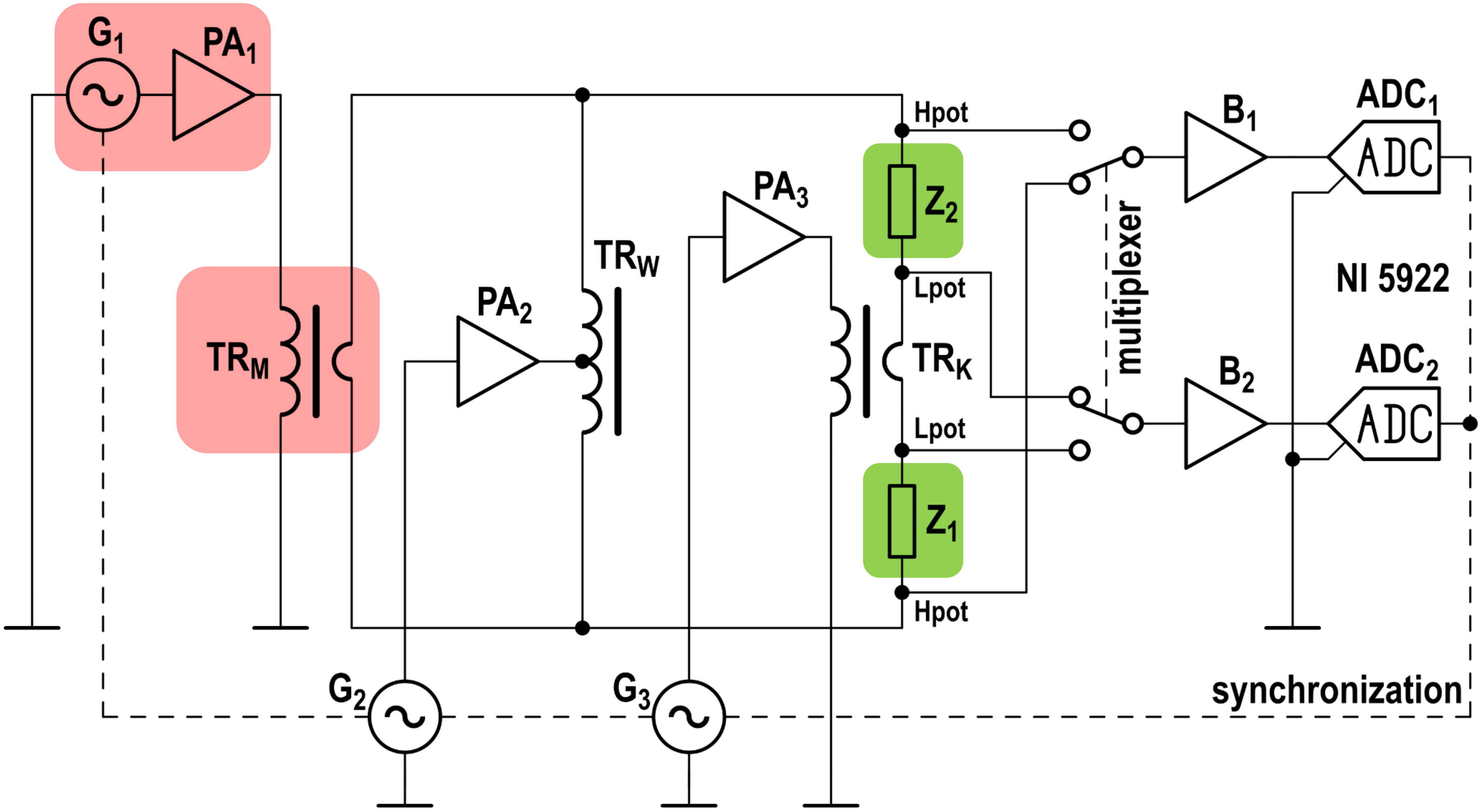
S. Mašláň, M. Šíra, T. Skalická and T. Bergsten, "Four Terminal Pair Digital Sampling Impedance Bridge up to 1 MHz," in *IEEE Transactions on Instrumentation and Measurement*. doi: 10.1109/TIM.2019.2908649

Digital sampling impedance bridge



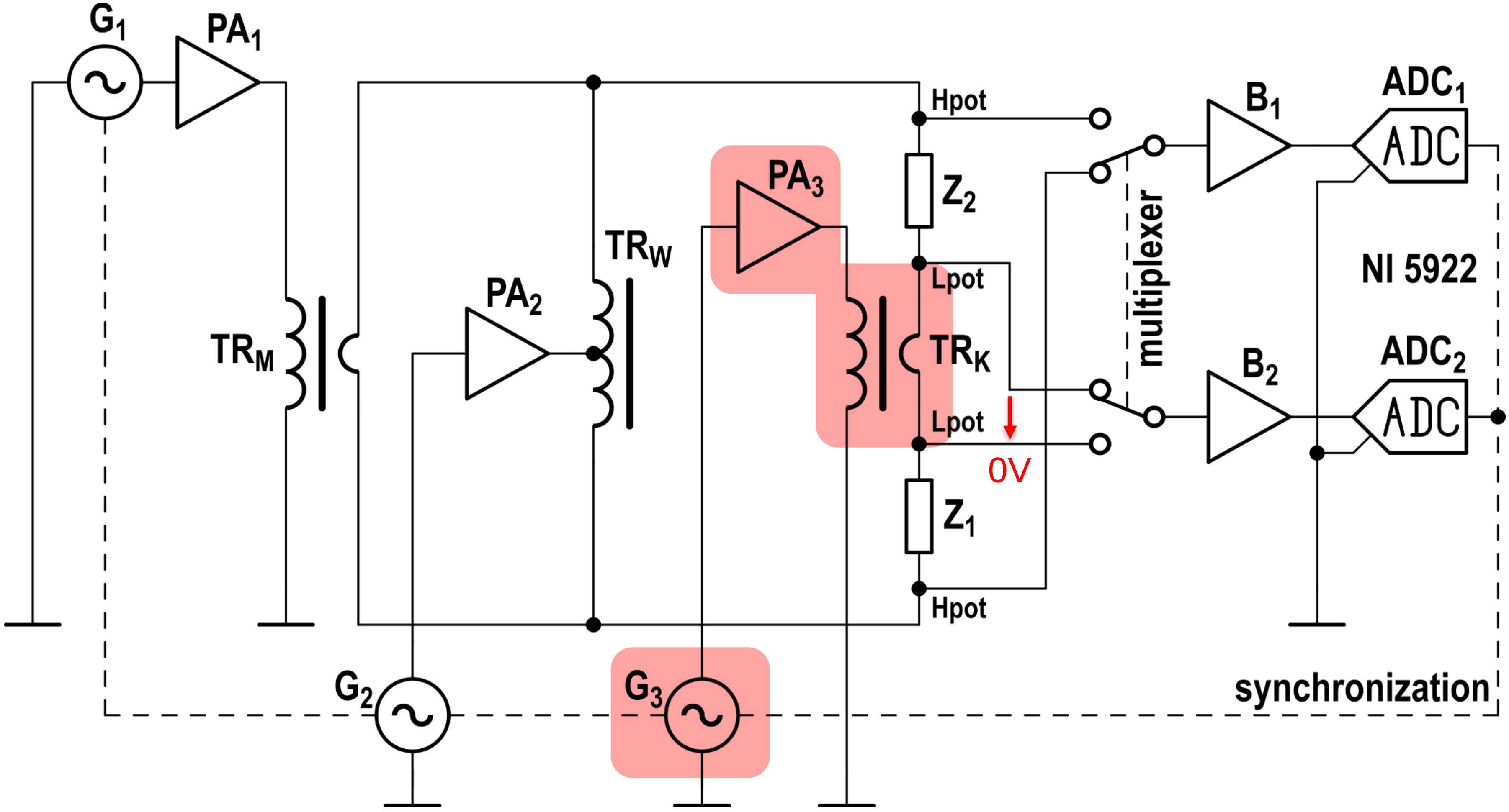
DDS generator: CMI design, low jitter
ADC: National Instruments 5922

Digital sampling impedance bridge



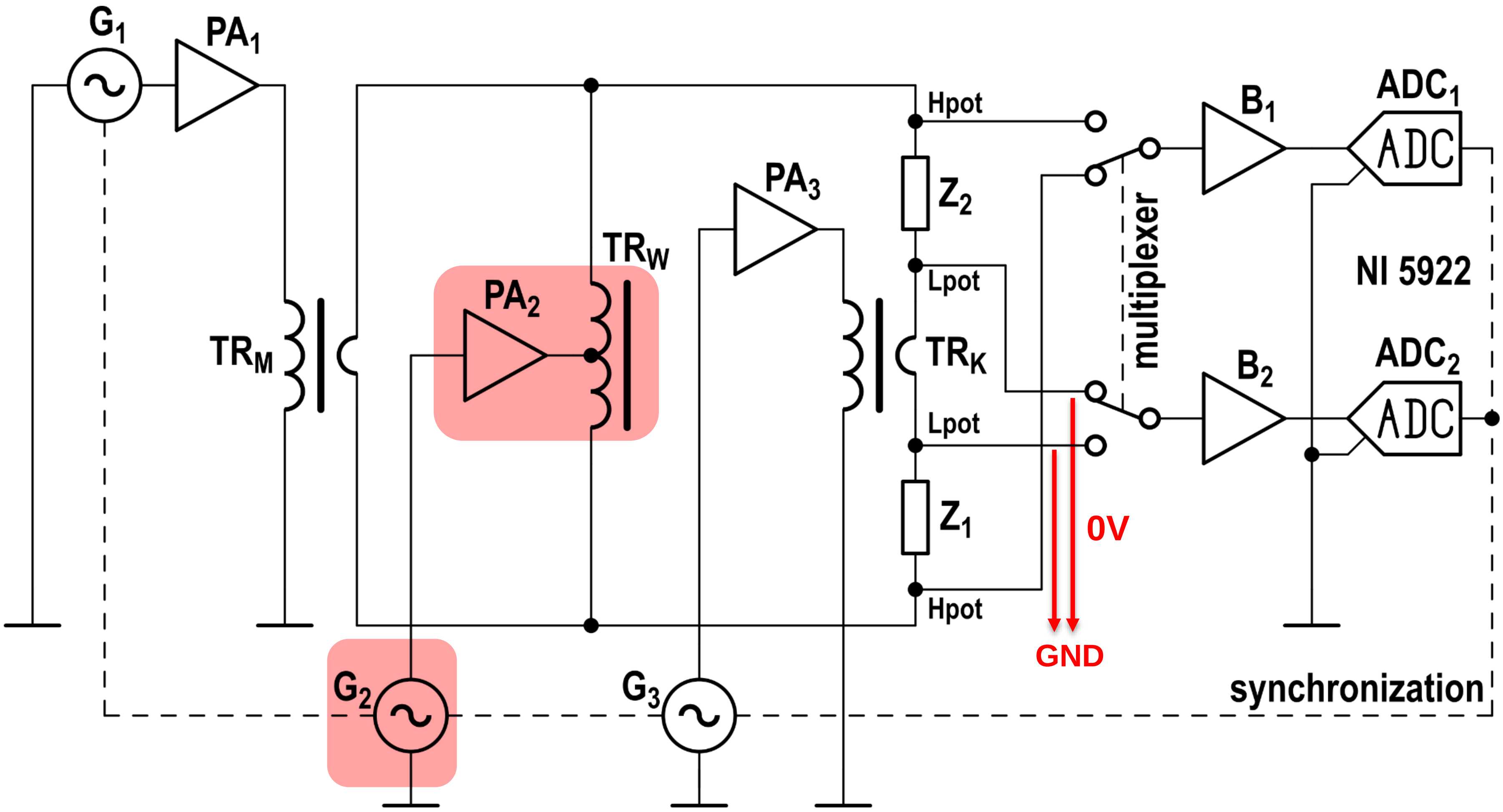
Supply: LT1210 amplifier, 3:1 transformer, I < 3 A at 1 MHz

Digital sampling impedance bridge



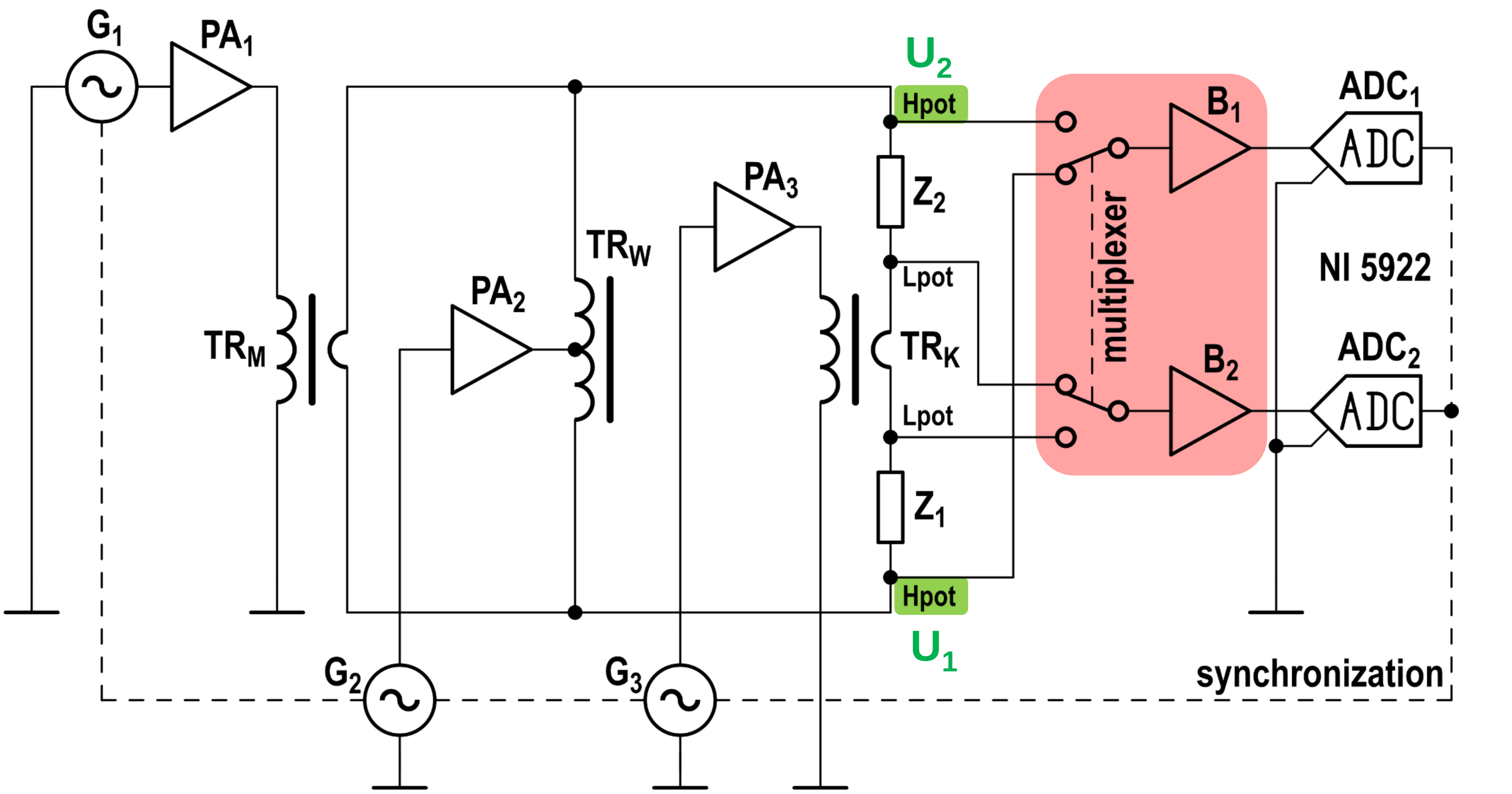
Kelvin circuit: LT1210 amplifier, 3:1 transformer, I < 3 A at 1 MHz

Digital sampling impedance bridge



Wagner circuit: LT1210 amplifier, optional IVD TR_W

Digital sampling impedance bridge

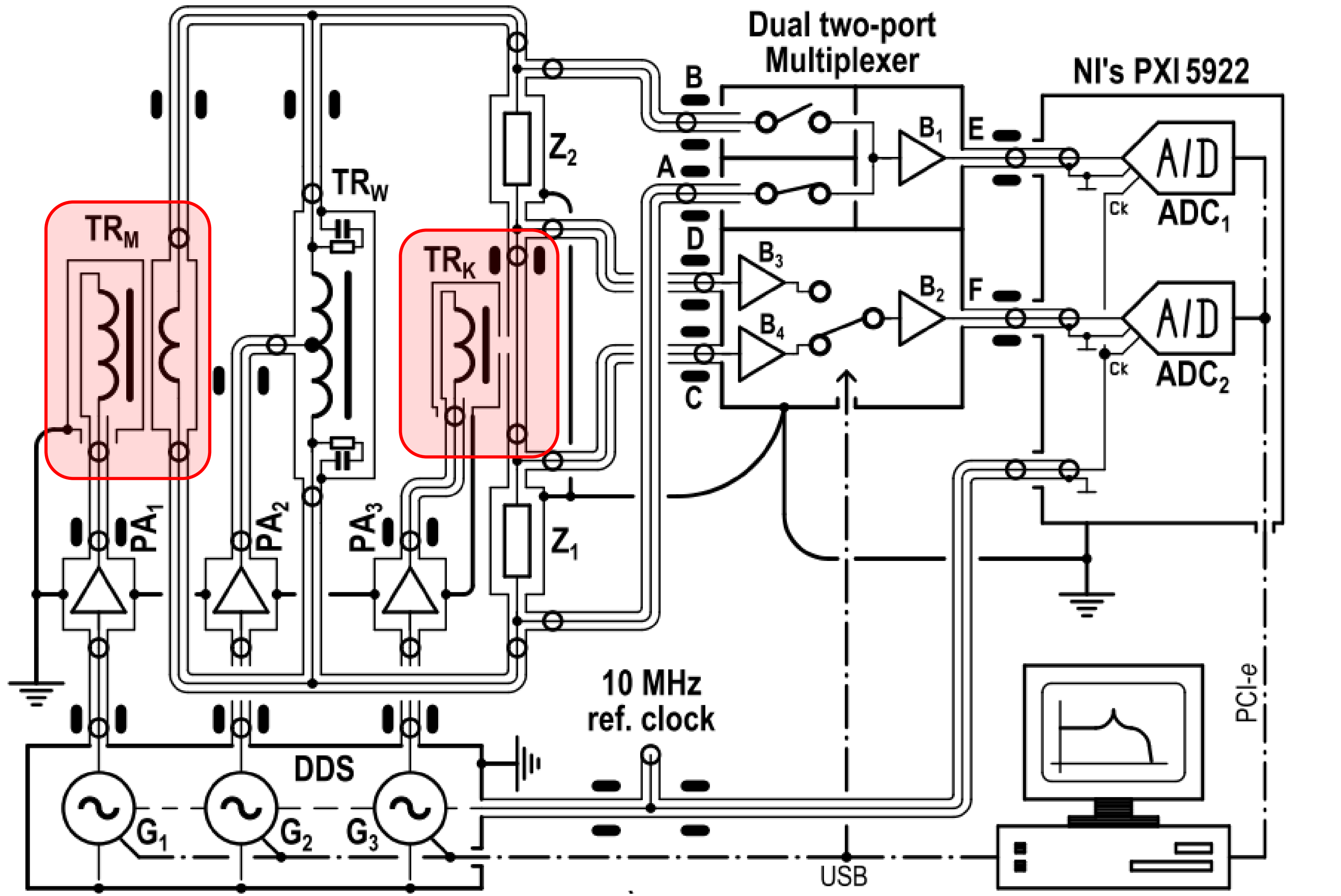


Multiplexer:

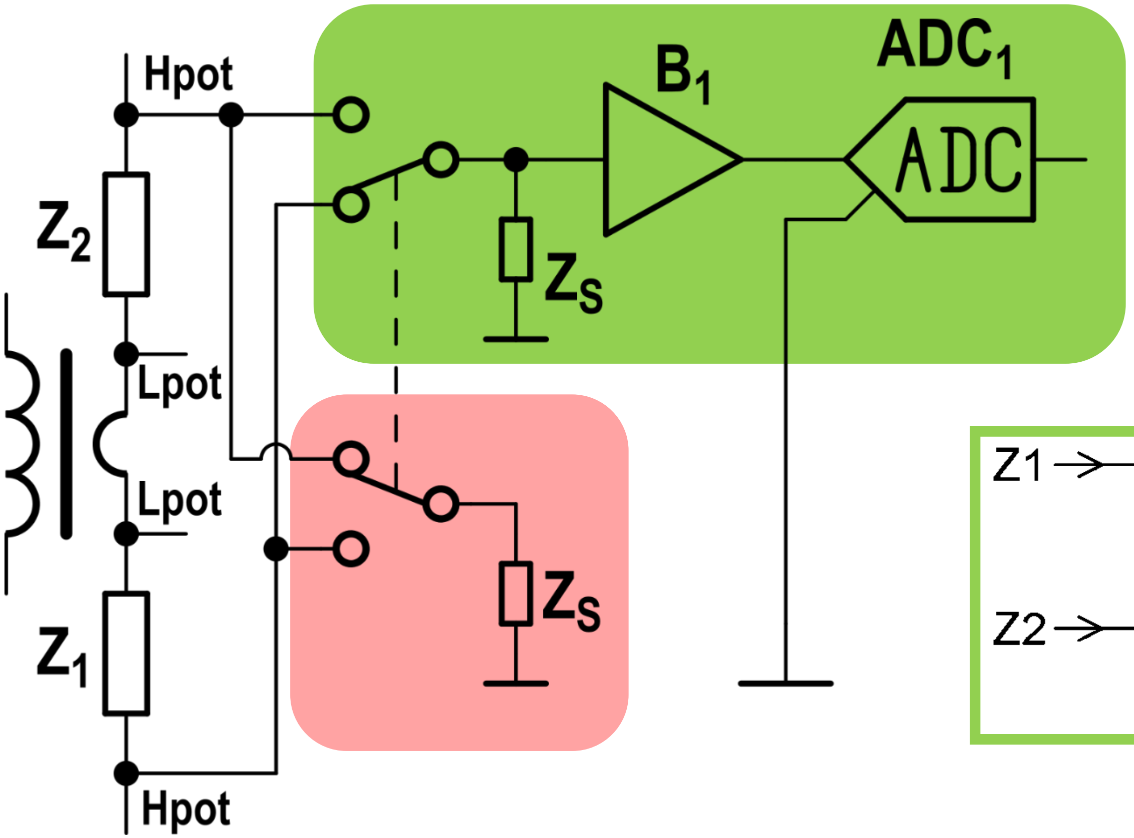
main channel for H_{POT} voltages

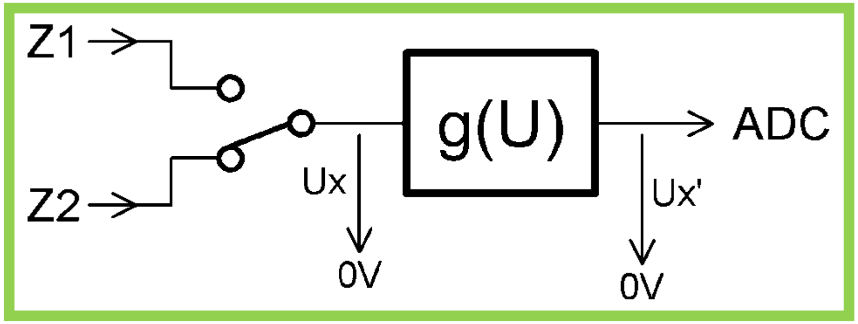
aux channel for residual L_{POT}

Digital sampling impedance bridge



Multiplexer

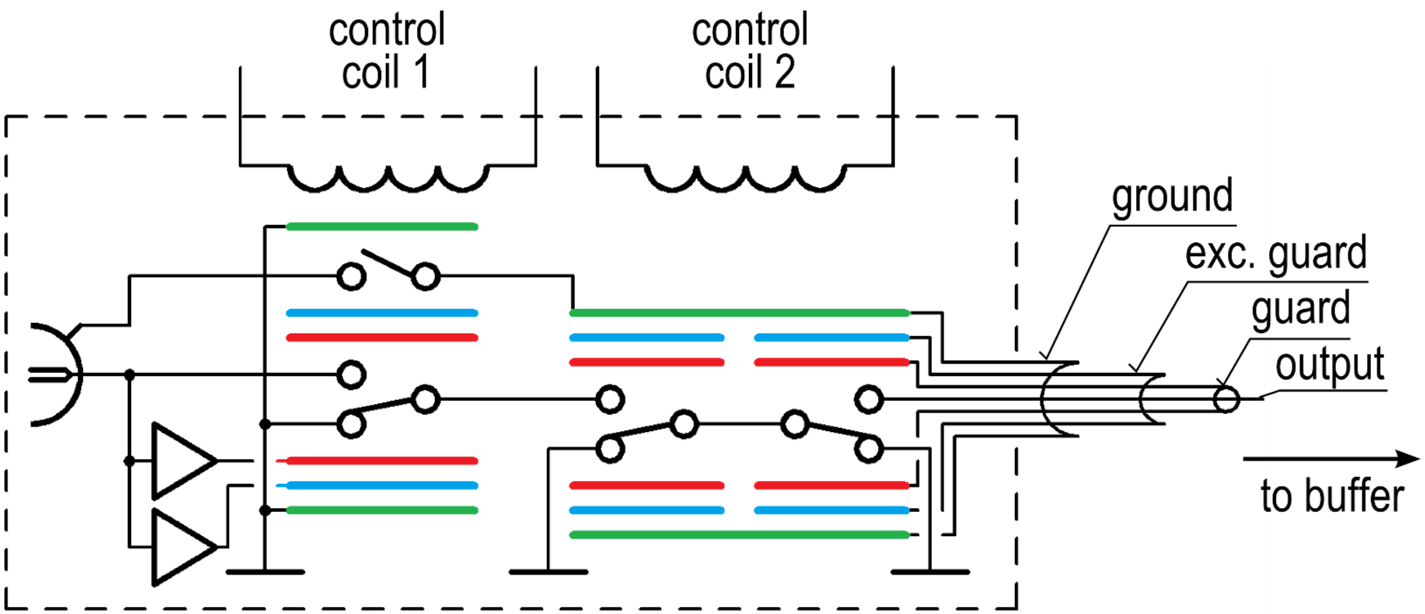


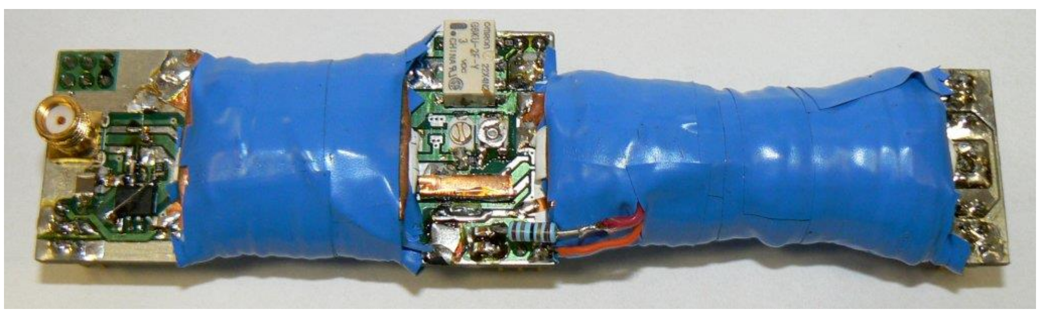


Multiplexer:

- **Buffer at output.**
- **Identical non-linearity g(*U*)** for both inputs.
- **Substitution network Z_S.**
- **Constant input shunting admittance.**

Multiplexer

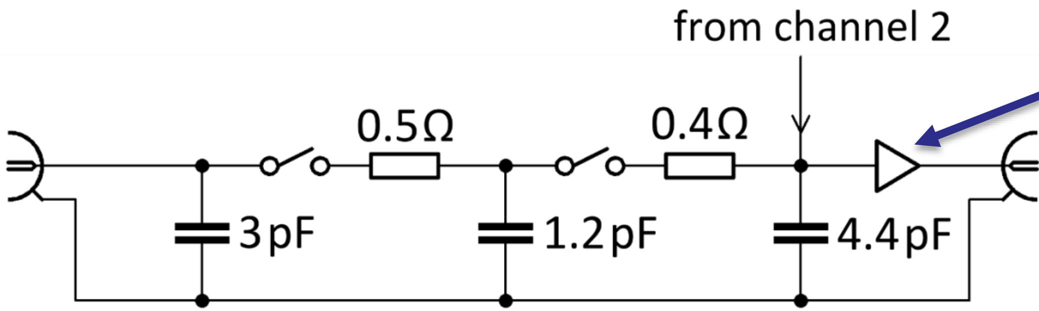




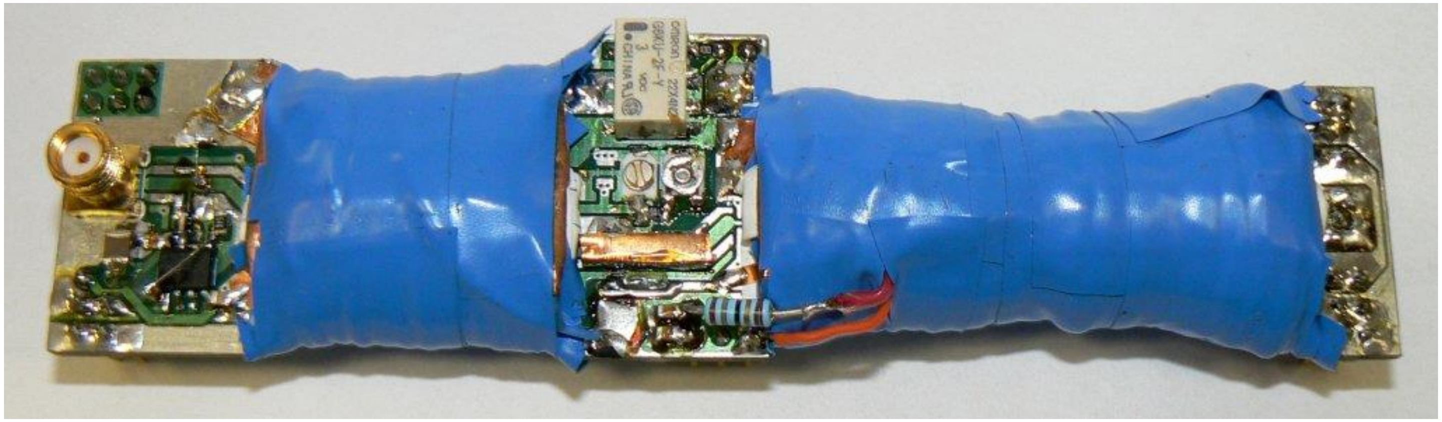
Multiplexer:

- Two identical modules.
- 3 groups of **reed** contacts.
- 3 groups of guards.
- **Two staged guarding**.
- Control coils around shields.
- Settling **< 30 ms**.
- Almost indestructible.

Multiplexer



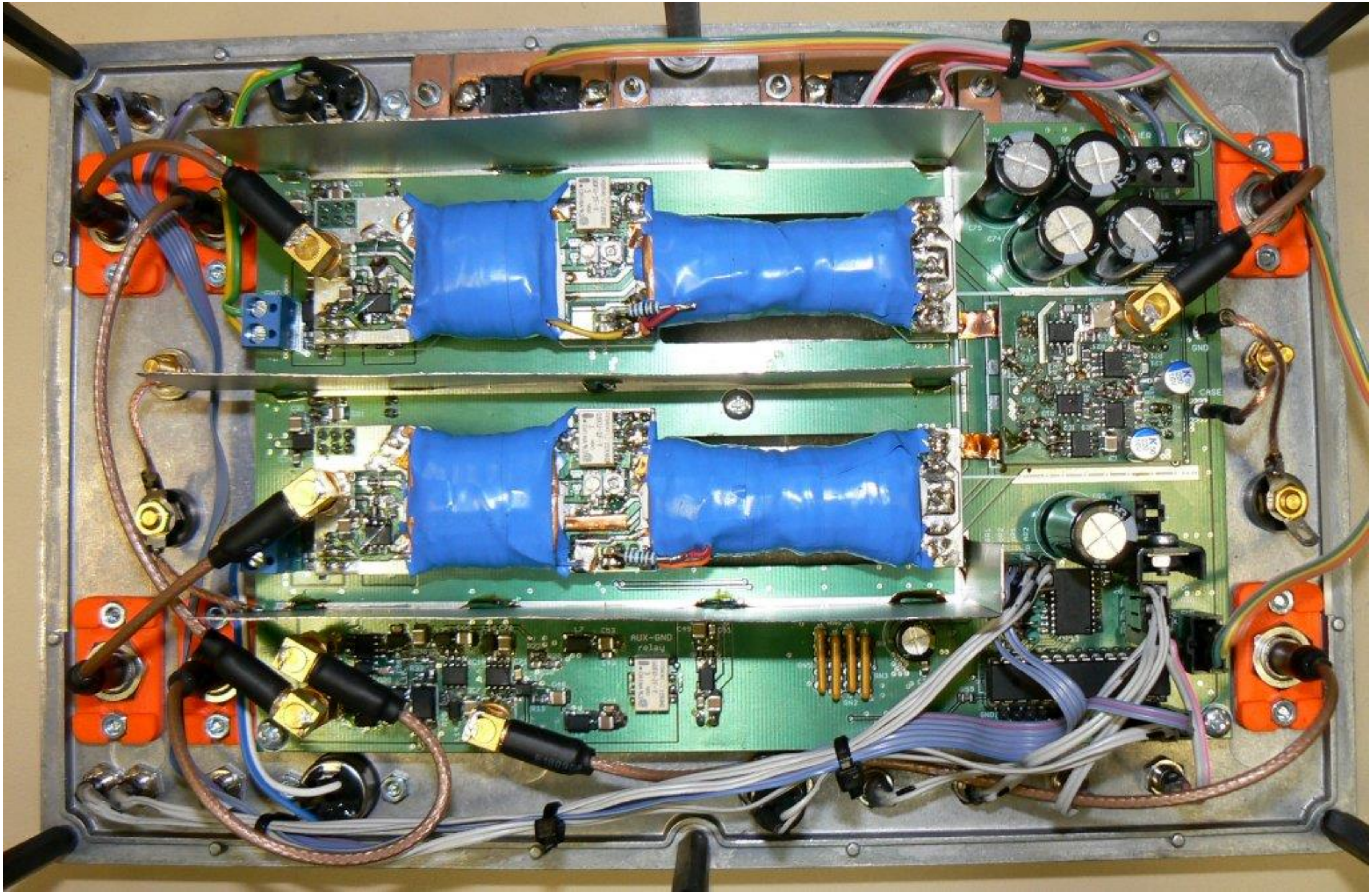
QuADC buffer



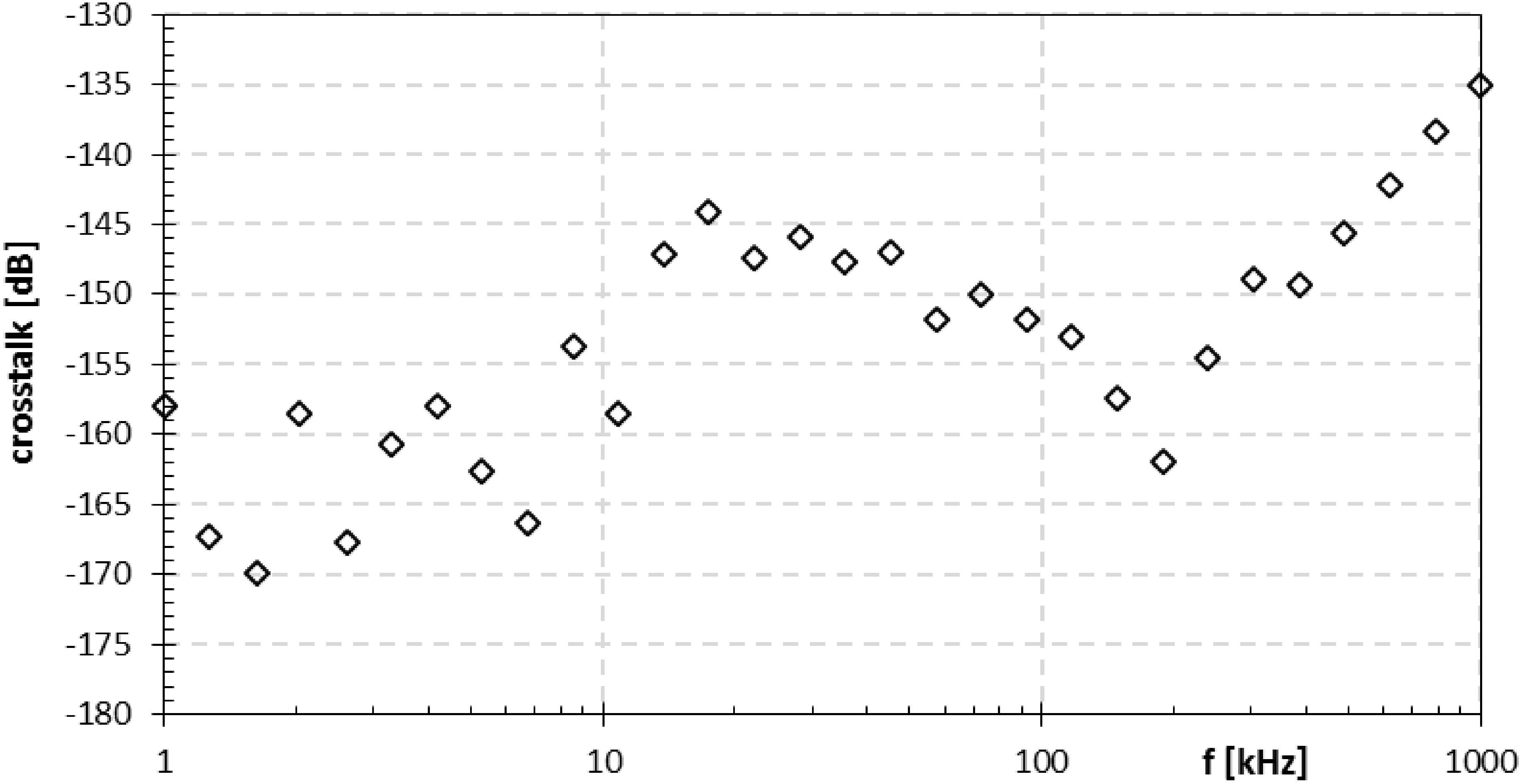
Multiplexer:

- Total distributed shunting capacitance ~6 pF.
- Closed loop impedance ~1 Ω at 1 MHz.
- Reasonable injection loss.
- Acceptable phase angle stability.

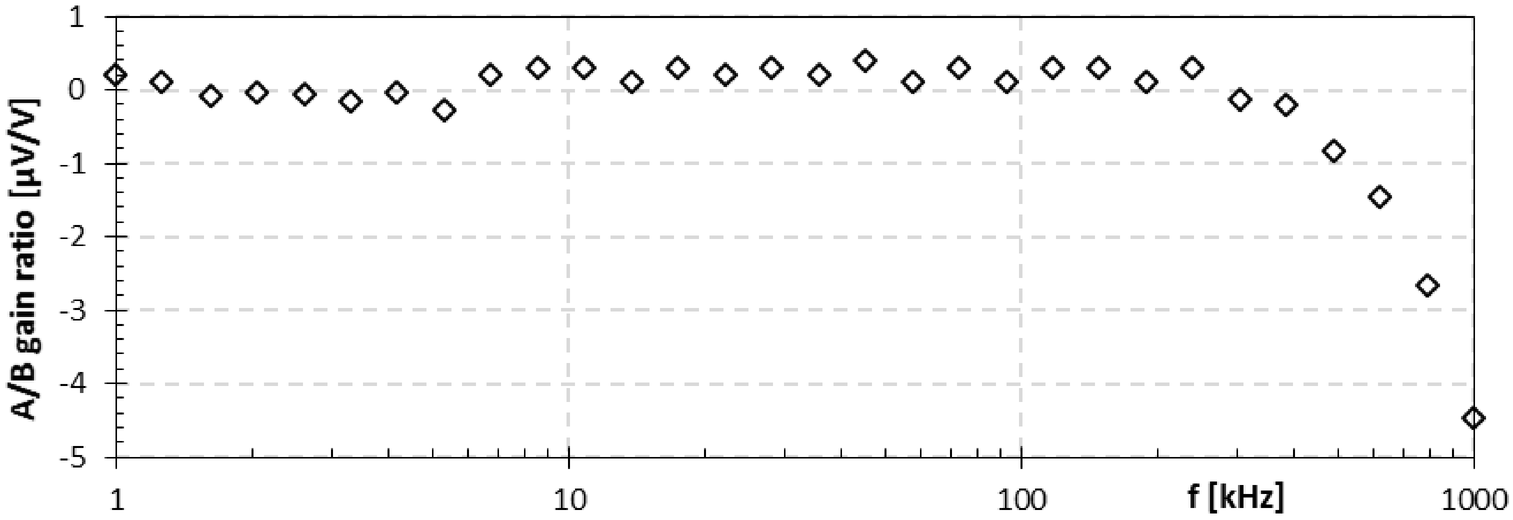
Multiplexer

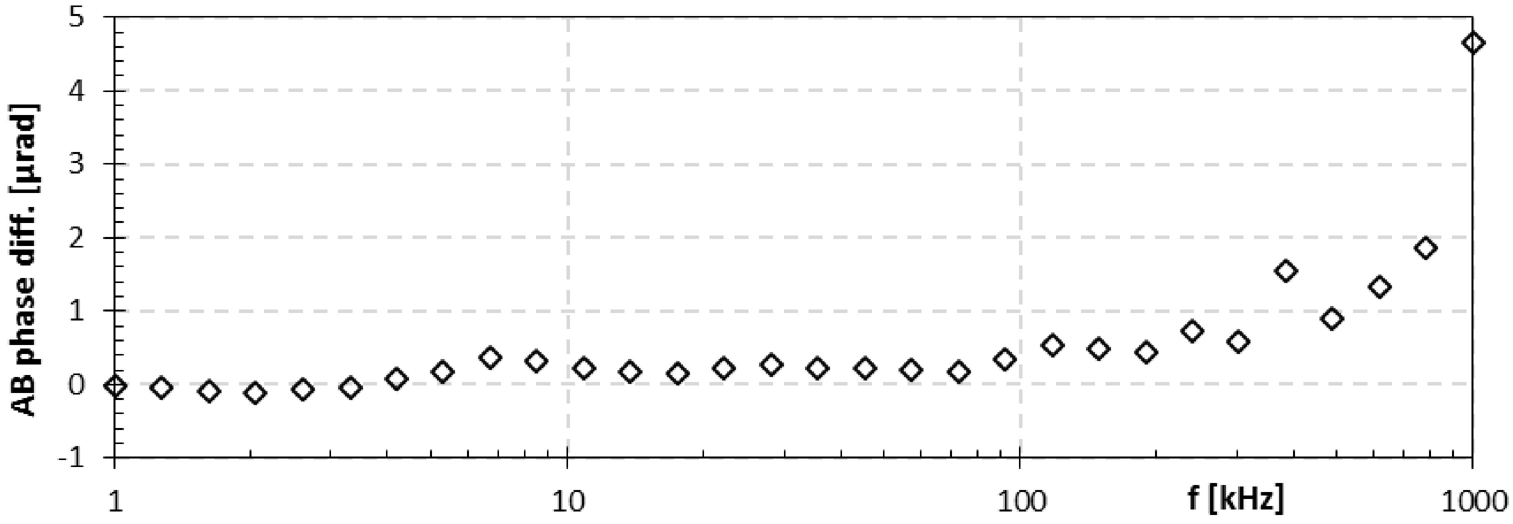


Crosstalk with 100 Ω load:



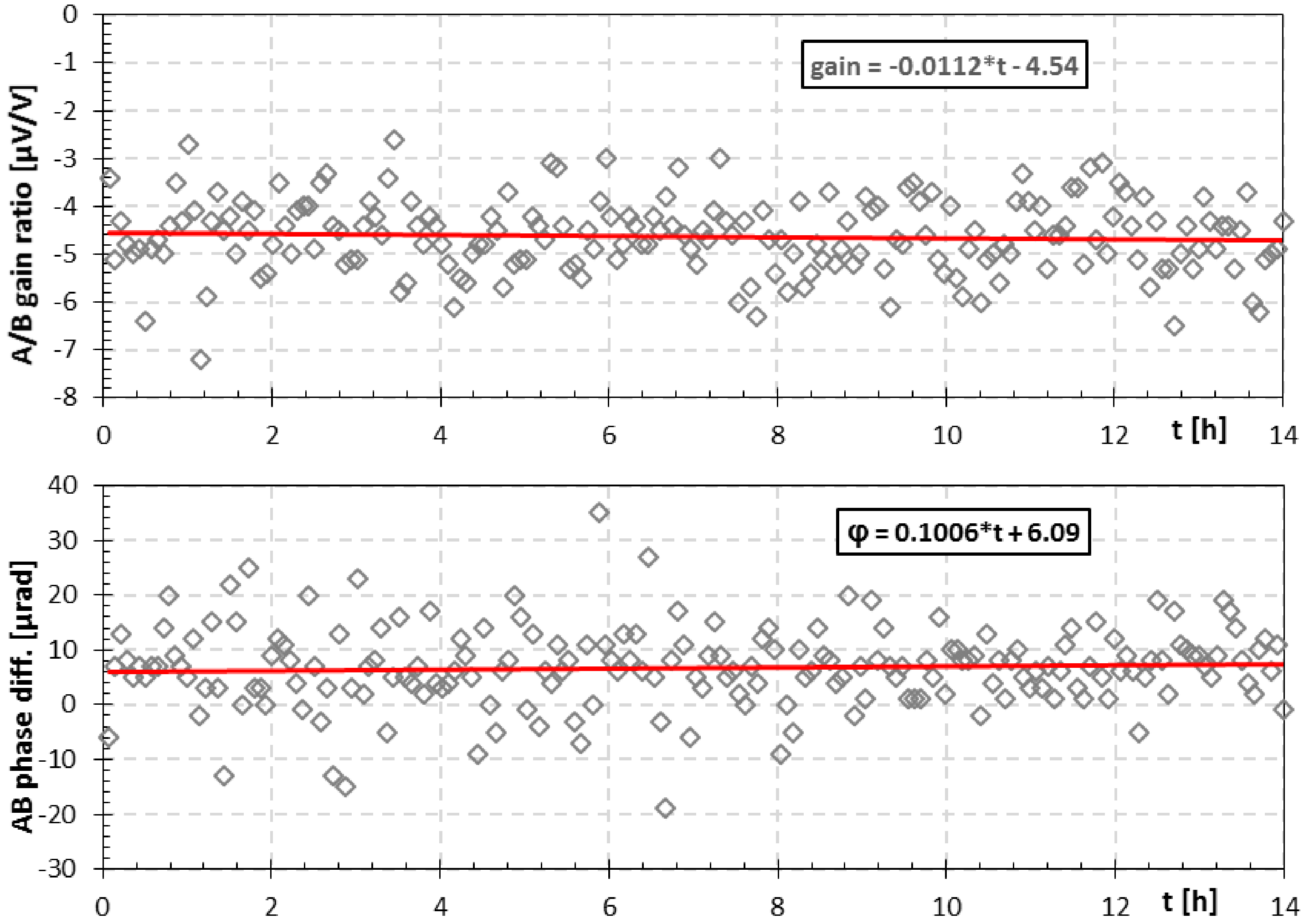
A-to-B channel transfer:





A-to-B channel transfer stability:

f = 1 MHz, time = 14 hours



Processing:

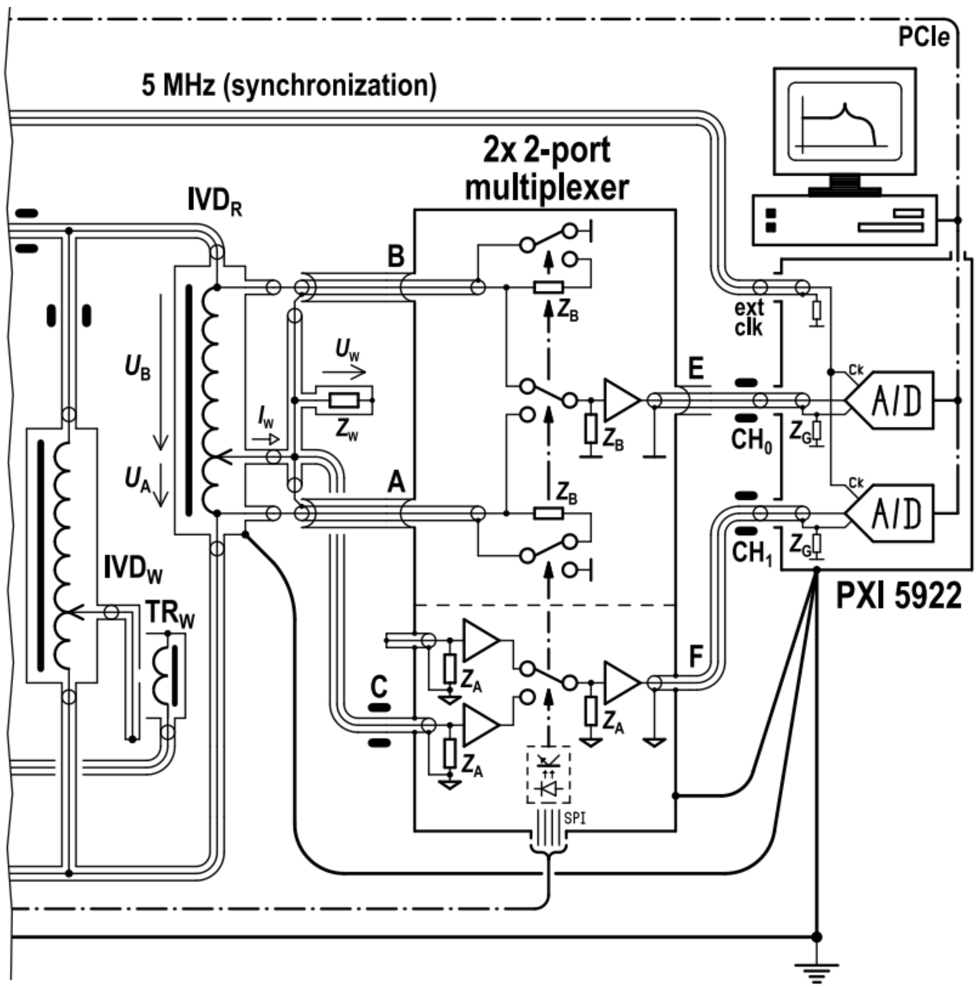
- Coherent sampling – **FFT**.
- Identical to 100 kHz bridge (see paper TIM 2016).

Corrections:

1) Crosstalk.
2) Inter-channel differential transfer.
3) **Linearity correction.**
4) Kelvin circuit correction:
    - Compensates asymmetry in the Kelvin arm.
5) **Loading correction:**
    - Emulates 4TP defining conditions.

Method for 100 kHz bridge:

- One decade IVD to simulate known A:B ratio.



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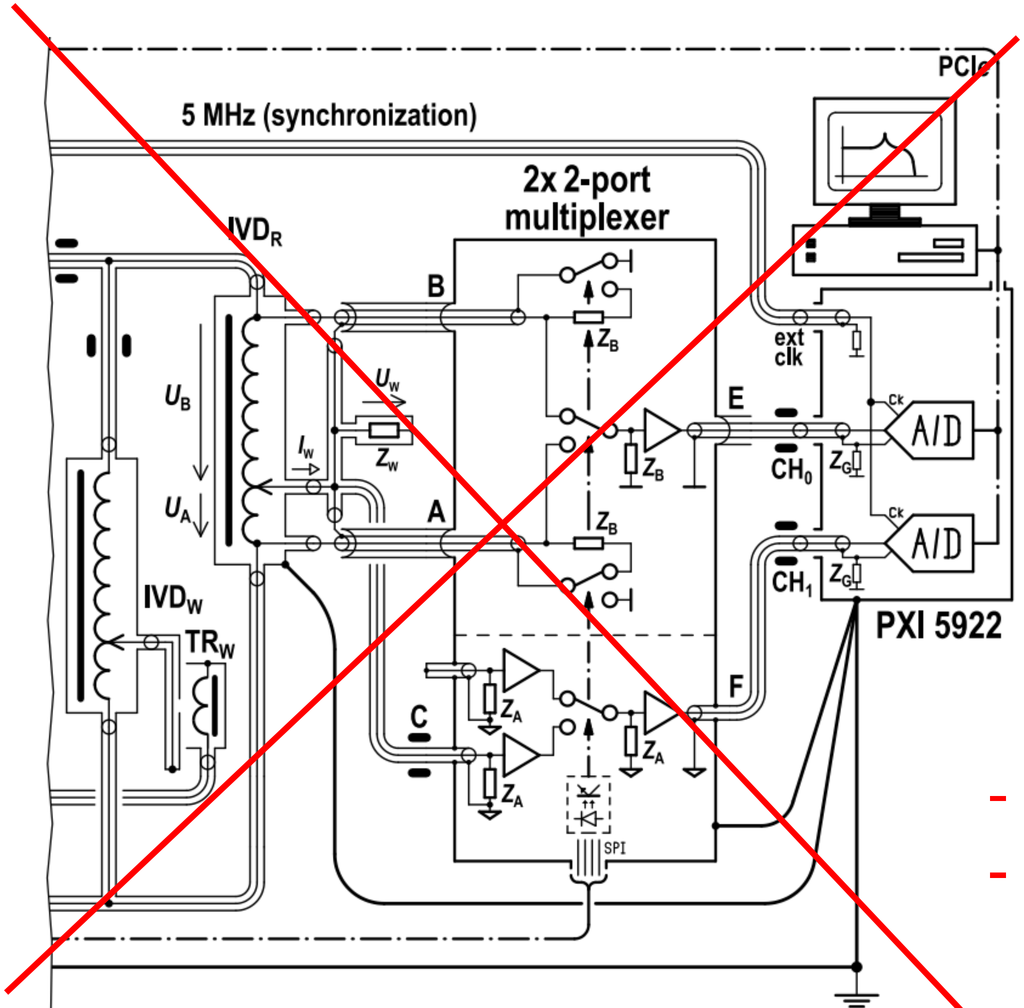


- Bad solution for HF
- Needs operator

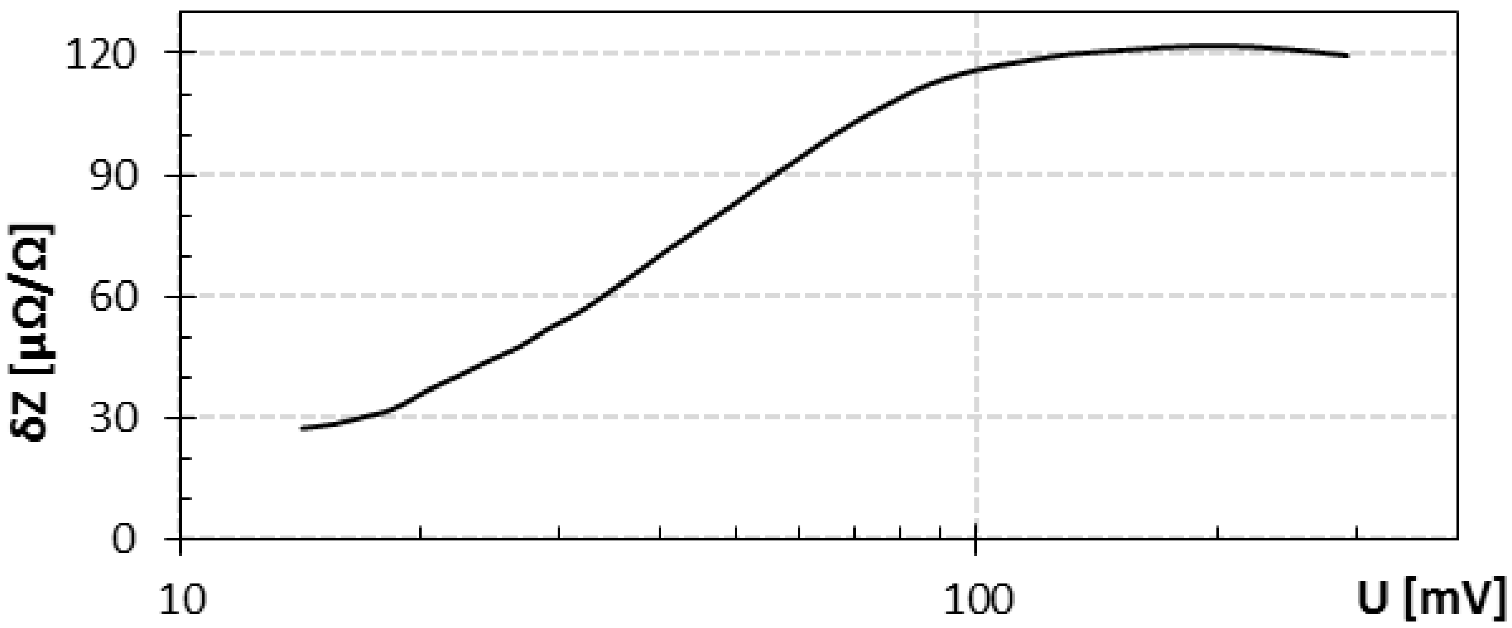
Method:

- **Two calculable resistors**, e.g.: 100 Ω, 10 Ω, ratio **10:1**.
  (or any other **known fixed ratio device**, e.g. IVD)

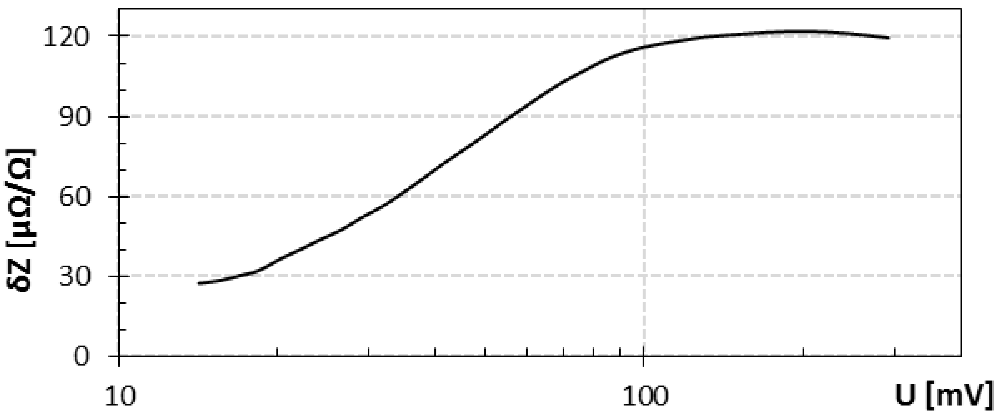
Method:

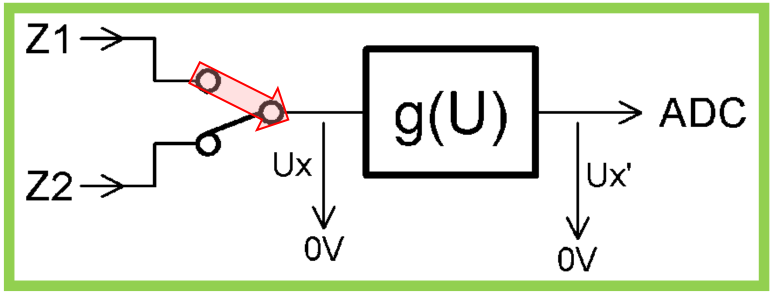
- **Two calculable resistors**, e.g.: 100 Ω, 10 Ω, ratio **10:1**.
- Measure voltage dependence of bridge error ***δZ*(*U*)**.

10:1 ratio at 1 MHz



Linearity correction



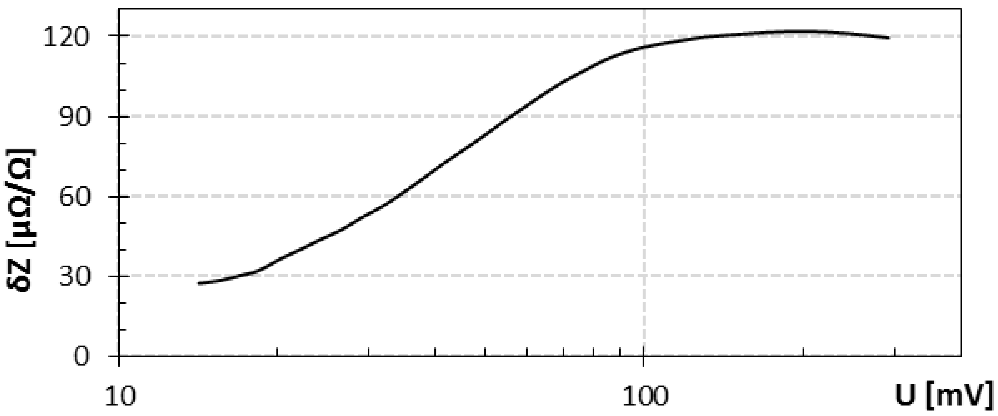


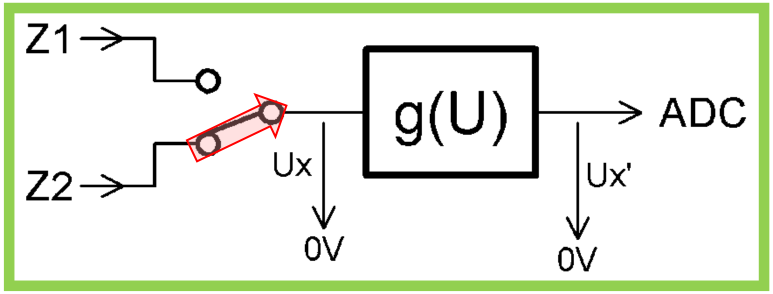
Non-linearity

$$\hat{U}_1' = \hat{U}_1 \cdot g\left(\left|\hat{U}_1\right|\right)$$

Corrected channel 1 voltage

Linearity correction





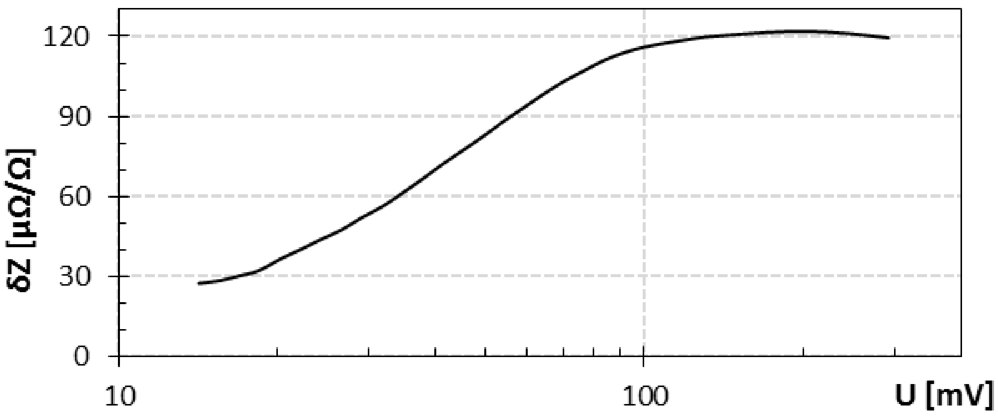
Non-linearity

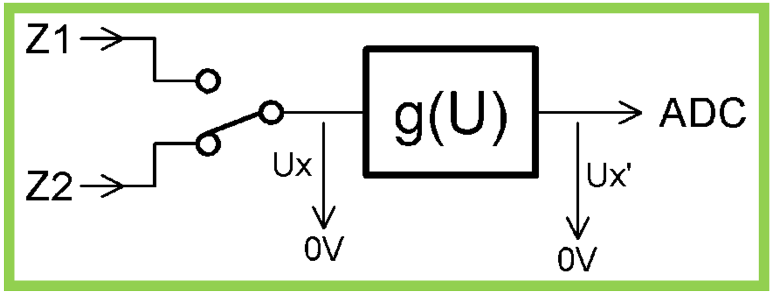
$$\widehat{U}_1' = \widehat{U}_1 \cdot g\left(\left|\widehat{U}_1\right|\right)$$
$$\widehat{U}_2' = \widehat{U}_2 \cdot g\left(\left|\widehat{U}_2\right|\right)$$

Corrected channel 1 voltage

Corrected channel 2 voltage

Linearity correction





Non-linearity

$$\hat{U}_1' = \hat{U}_1 \cdot g\left(\left|\hat{U}_1\right|\right)$$

Corrected channel 1 voltage

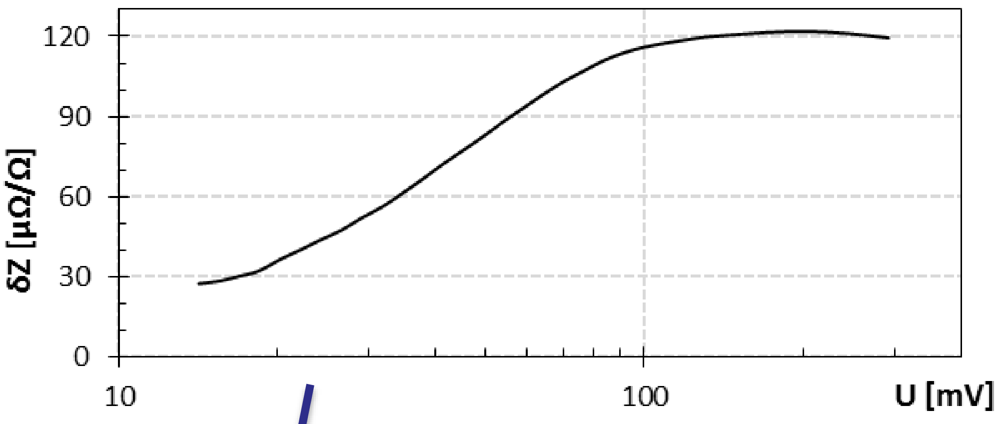
$$\hat{U}_2' = \hat{U}_2 \cdot g\left(\left|\hat{U}_2\right|\right)$$

Corrected channel 2 voltage

$$\frac{\hat{U}_2{}'}{\hat{U}_1{}'} = \frac{\hat{Z}_2}{\hat{Z}_1}$$

Corrected impedance ratio

Linearity correction



$$\hat{U}_2' = \hat{U}_2 \cdot g\left(\left|\hat{U}_2\right|\right)$$

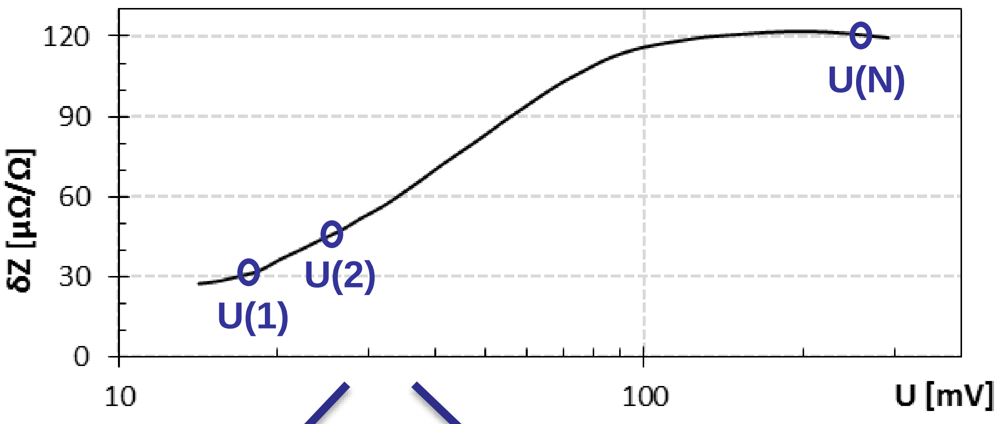
$$\hat{U}_1' = \hat{U}_1 \cdot g\left(\left|\hat{U}_1\right|\right)$$

$$\frac{\hat{U}_2'}{\hat{U}_1'} = \frac{\hat{Z}_2}{\hat{Z}_1}$$

Measured by bridge

$$\left[\frac{\hat{U}_2 \cdot g\left(\left|\hat{U}_2\right|\right)}{\hat{U}_1 \cdot g\left(\left|\hat{U}_1\right|\right)} = \frac{\hat{Z}_2}{\hat{Z}_1}\right]$$

Linearity correction



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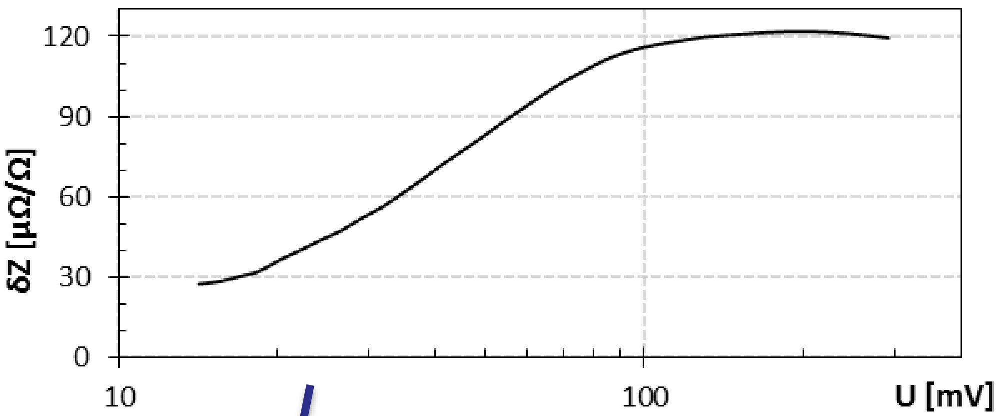
$$\hat{U}_1' = \hat{U}_1 \cdot g\left(\left|\hat{U}_1\right|\right)$$
$$\frac{\hat{U}_2{}'}{\hat{U}_1{}'} = \frac{\hat{Z}_2}{\hat{Z}_1}$$

$$\left[\begin{array}{c}
\dfrac{\hat{U}_2(1) \cdot g\left(\left|\hat{U}_2(1)\right|\right)}{\hat{U}_1(1) \cdot g\left(\left|\hat{U}_1(1)\right|\right)} = \dfrac{\hat{Z}_2}{\hat{Z}_1} \\
\dfrac{\hat{U}_2(2) \cdot g\left(\left|\hat{U}_2(2)\right|\right)}{\hat{U}_1(2) \cdot g\left(\left|\hat{U}_1(2)\right|\right)} = \dfrac{\hat{Z}_2}{\hat{Z}_1} \\
\vdots \\
\dfrac{\hat{U}_2(N) \cdot g\left(\left|\hat{U}_2(N)\right|\right)}{\hat{U}_1(N) \cdot g\left(\left|\hat{U}_1(N)\right|\right)} = \dfrac{\hat{Z}_2}{\hat{Z}_1}
\end{array}\right]$$

Linearity correction



Measured by bridge

Known ratio of calculable R

$$\left[\frac{\hat{U}_2 \cdot g\left(\left|\hat{U}_2\right|\right)}{\hat{U}_1 \cdot g\left(\left|\hat{U}_1\right|\right)} = \frac{\hat{Z}_2}{\hat{Z}_1}\right]$$

$$\hat{U}_2' = \hat{U}_2 \cdot g\left(\left|\hat{U}_2\right|\right)$$
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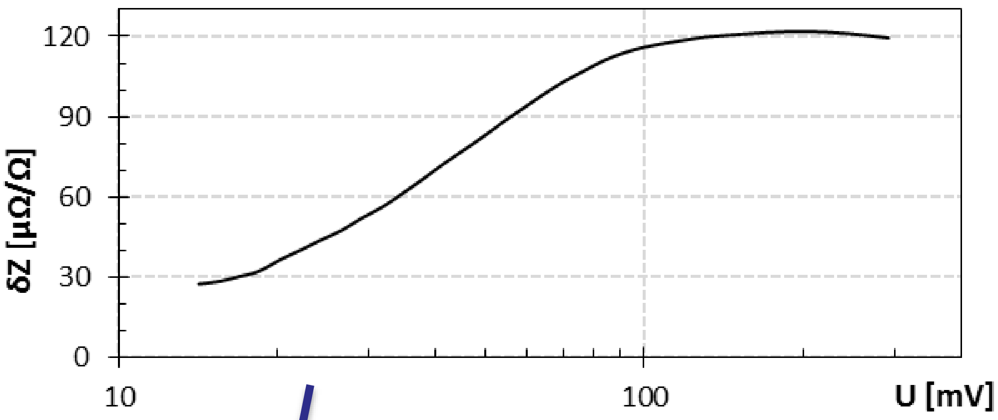
$$\frac{\hat{U}_2{}'}{\hat{U}_1{}'} = \frac{\hat{Z}_2}{\hat{Z}_1}$$

Linearity correction



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Measured by bridge

Known ratio of calculable R

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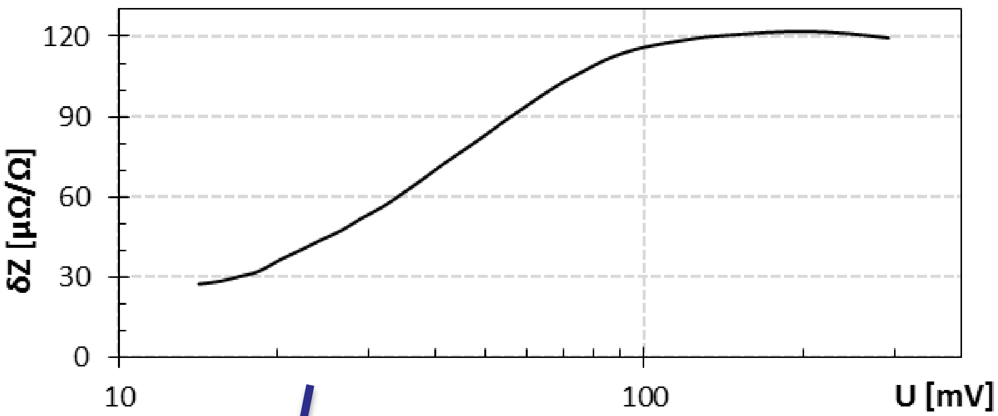
Non-linearity Function to find

Linearity correction



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Measured by bridge

Known ratio of calculable R

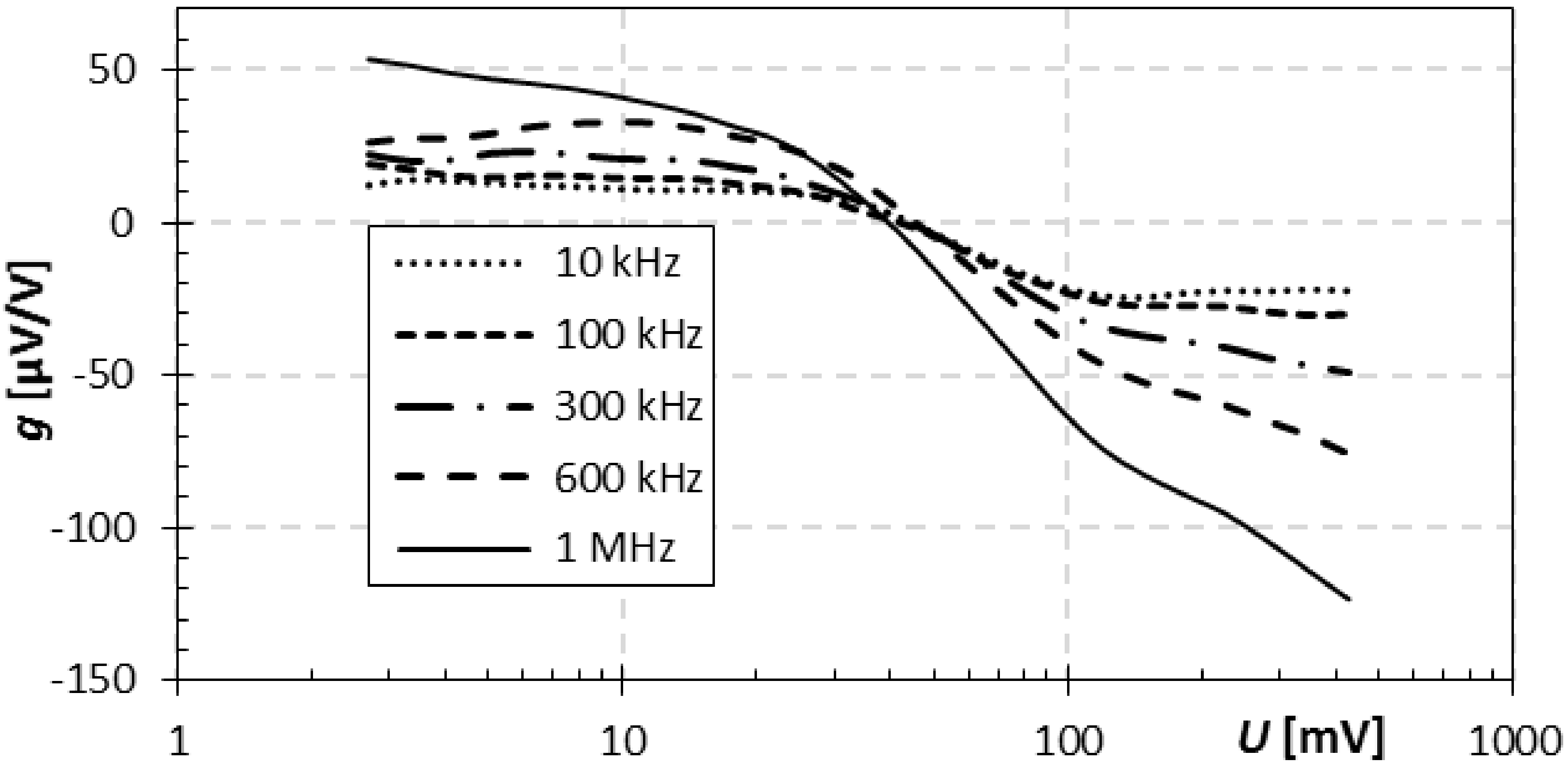
$$\left[\frac{\widehat{U}_2 \cdot g\left(\left|\widehat{U}_2\right|\right)}{\widehat{U}_1 \cdot g\left(\left|\widehat{U}_1\right|\right)} = \frac{\hat{Z}_2}{\hat{Z}_1}\right] \rightarrow$$

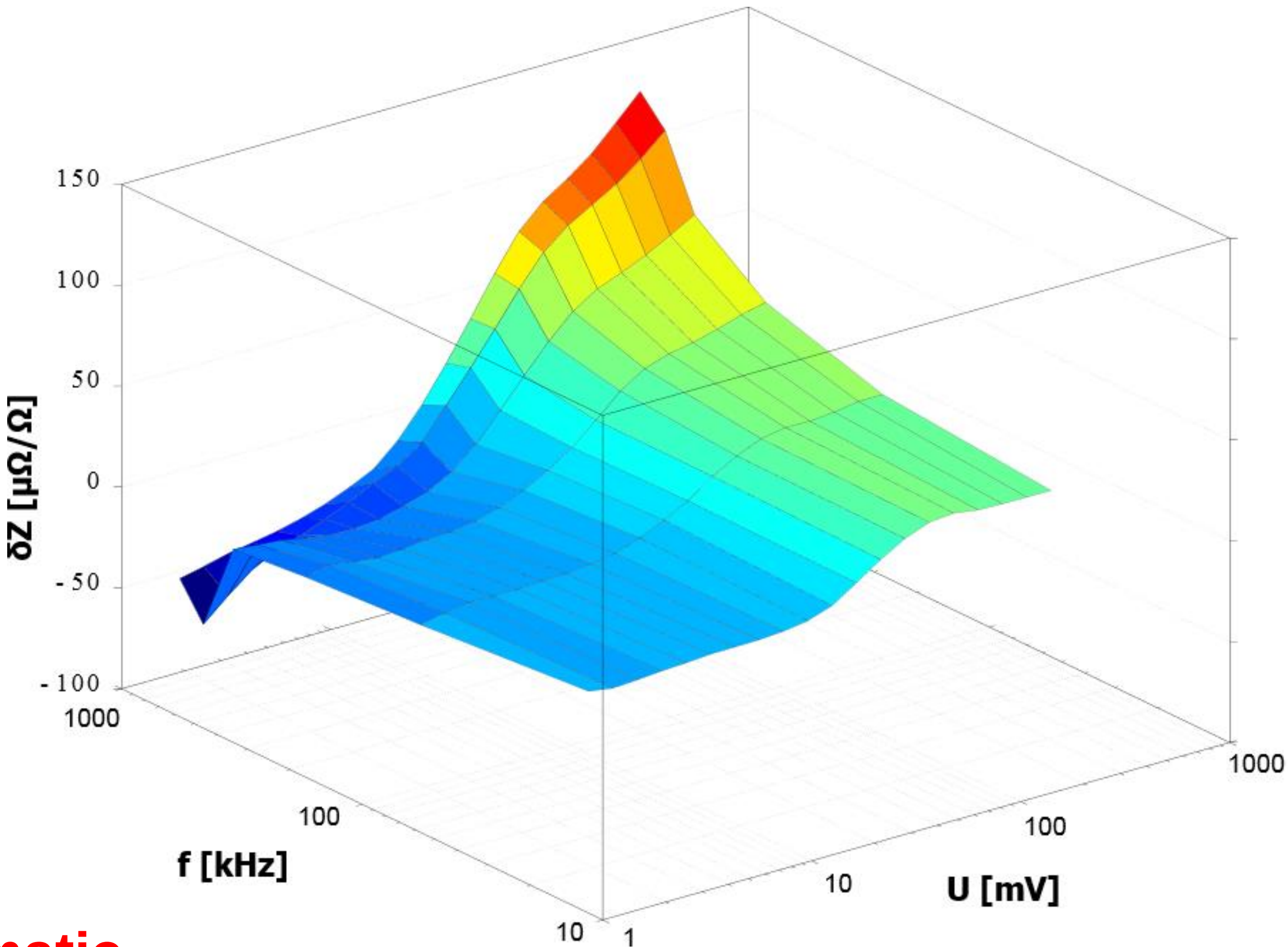
Non-linearity Function to find

Set of equations:

- one for each measured spot ***δz***
- ***g()*** chosen as piecewise function
- Solved by **least square method**

Linearity correction



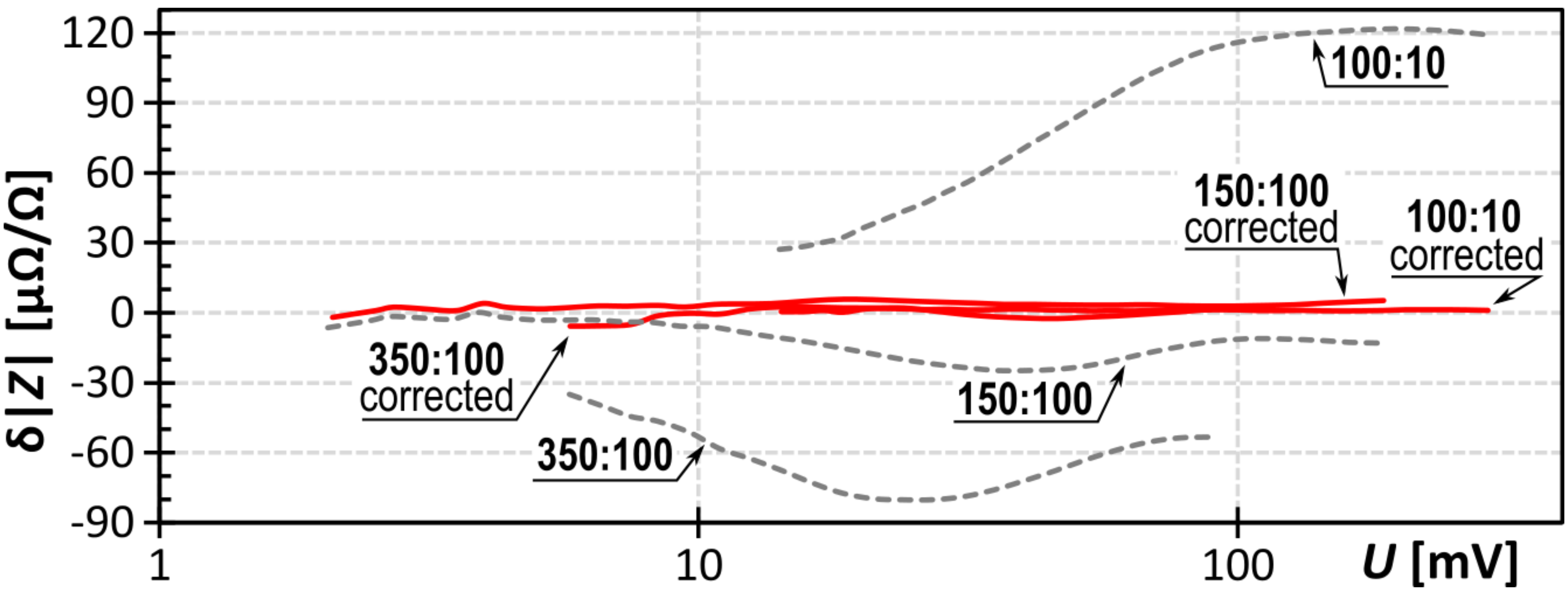


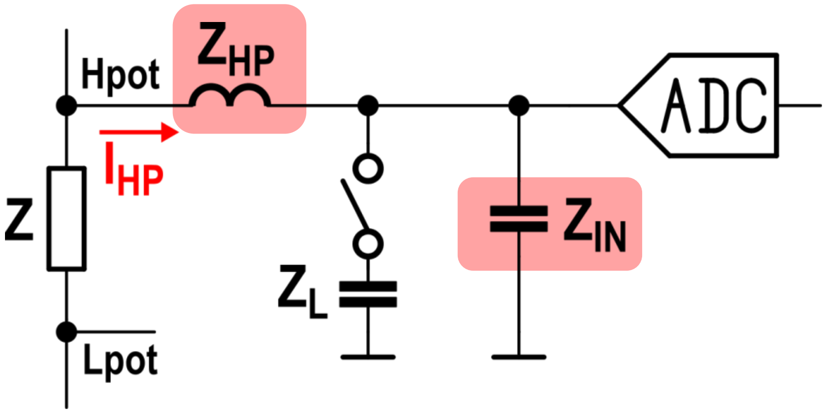
Summary:

- **Fully automatic**
- Takes roughly **8 hours** for all frequencies.

Linearity correction

Corrected errors below 10 ppm for any ratio below 1:20 at 1 MHz

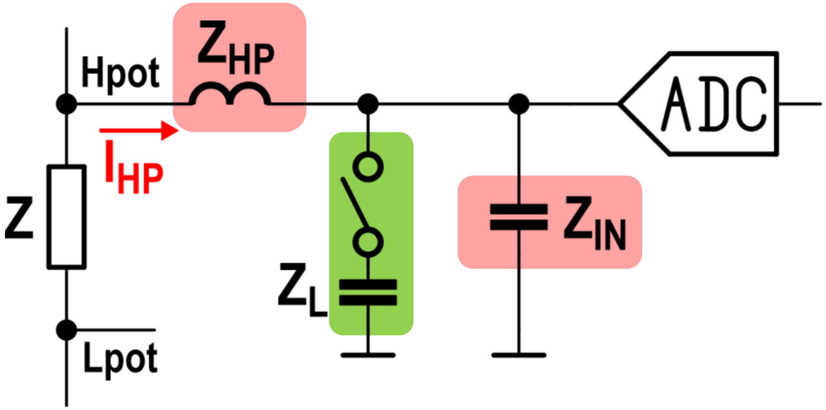




4TP defining conditions:
- Zero voltage at **Lpot** terminal
- No current from **Hpot**

Loading error:
- **Z_{HP}** and **Z_{IN}** resonates
- High error on amplitude
  > 100 µΩ/Ω at 1 MHz
- Minor errors on phase

Loading correction



4TP defining conditions:
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Loading error:
- Z_{HP} and Z_{IN} resonates
- High error on amplitude **> 100 µΩ/Ω** at 1 MHz
- Minor errors on phase

Correction:
- **Loading Hpot** by known Z_L
- Evaluating Z_{HP} from change of measured value
- Using known Z_{HP} and Z_{IN} to **emulate zero Hpot current**
- Std. uncertainty ~12 µΩ/Ω

Uncertainty budget:

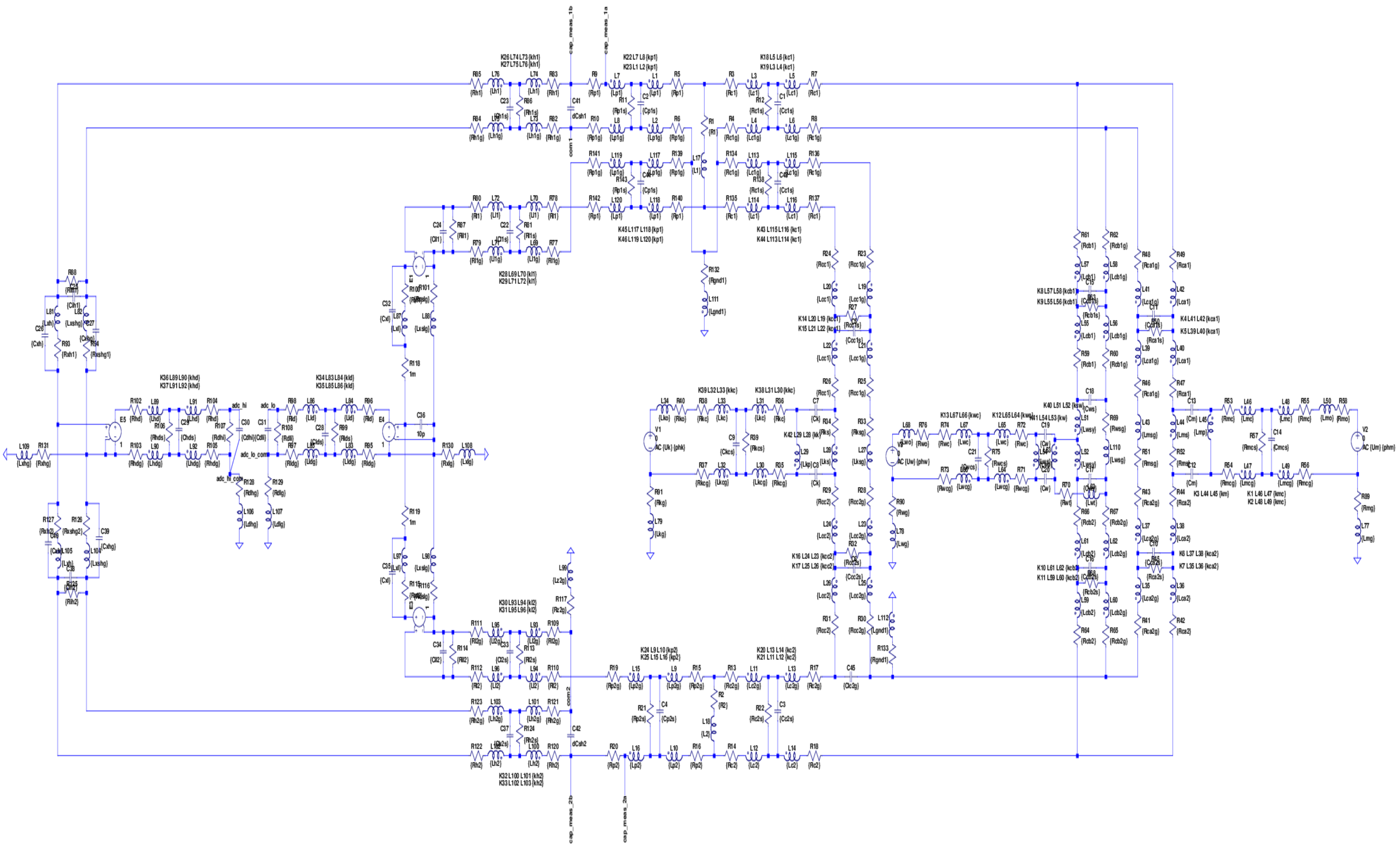
- For ratios below 1:16
- Voltage above 20 mV

For near 1:1 ratio:

- U(ratio) ~ 20 μΩ/Ω

	100 kHz	**1 MHz**		**100 kHz**	**1 MHz**	
Linearity	4	**19**	μΩ/Ω	16	160	μrad
Kelvin circuit	1.5	8	μΩ/Ω	5	50	μrad
Inp. Z variation	1	9	μΩ/Ω	2	20	μrad
Loading effect	0.1	**12**	μΩ/Ω	6	60	μrad
Crosstalk	0.5	0.5	μΩ/Ω	8	8	μrad
Coaxial network	0.7	2.5	μΩ/Ω	0.7	2.5	μrad
Repeatability	2	5	μΩ/Ω	3	30	μrad
Total	*4.9*	*26*	*μΩ/Ω*	*20*	*180*	*μrad*
Total (k = 2)	***9.8***	***52***	***μΩ/Ω***	***40***	***360***	***μrad***

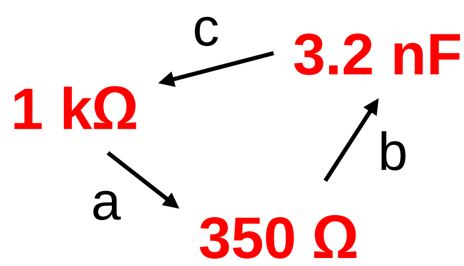
Uncertainty budget



Measurements

Triple ratio test:

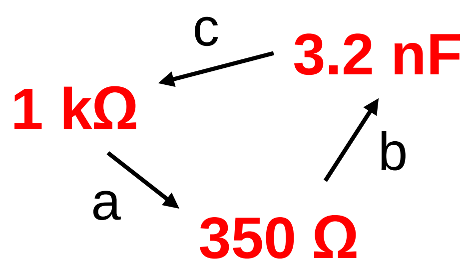
- ratios up to **1:20**
- **quadrature** ratios tested



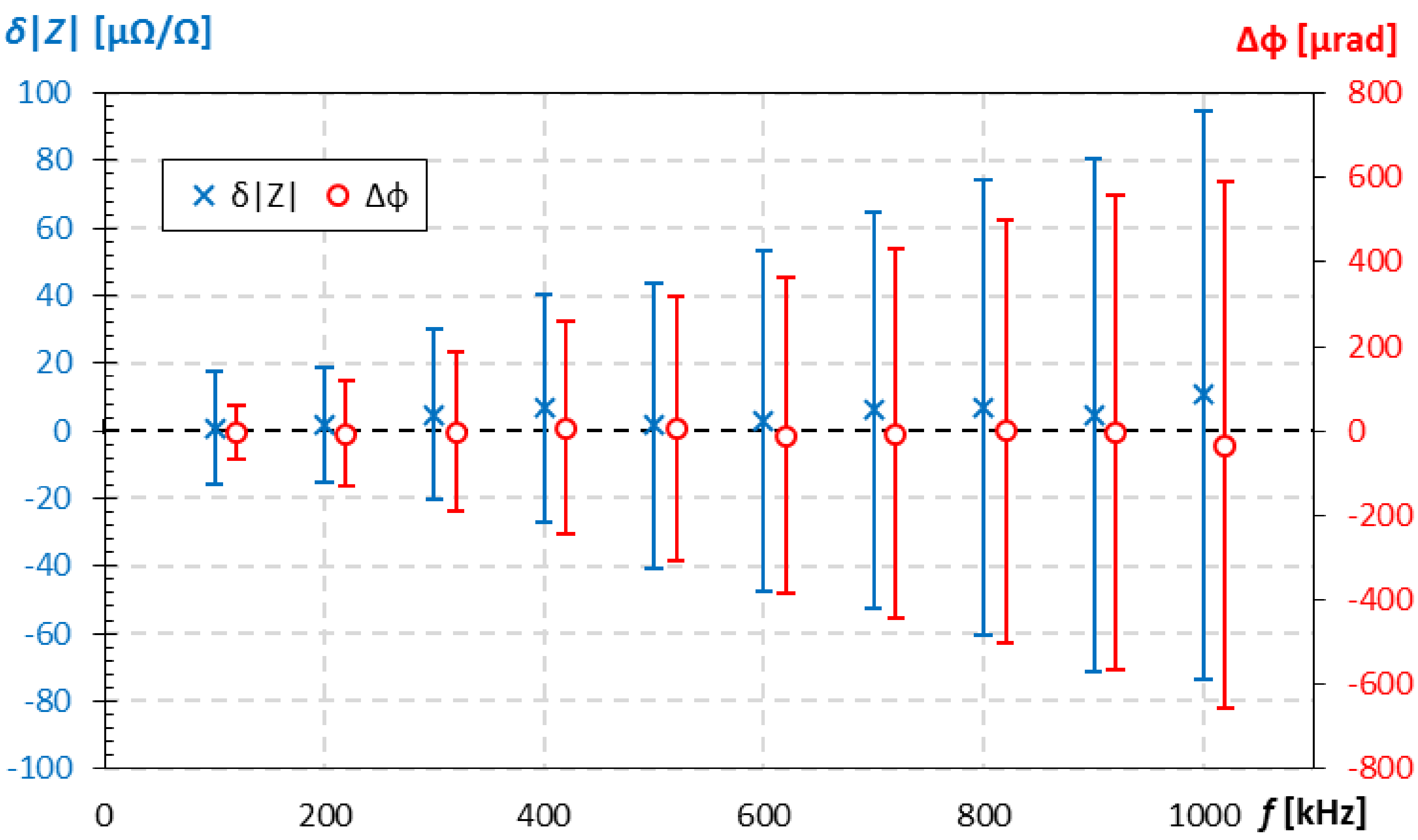
$$\boxed{\delta\hat{Z} = \hat{a}\cdot\hat{b}\cdot\hat{c} - 1}$$

Triple ratio test:

- ratios up to **1:20**
- **quadrature** ratios tested



$$\delta\hat{Z} = \hat{a}\cdot\hat{b}\cdot\hat{c} - 1$$



Triple ratio test:

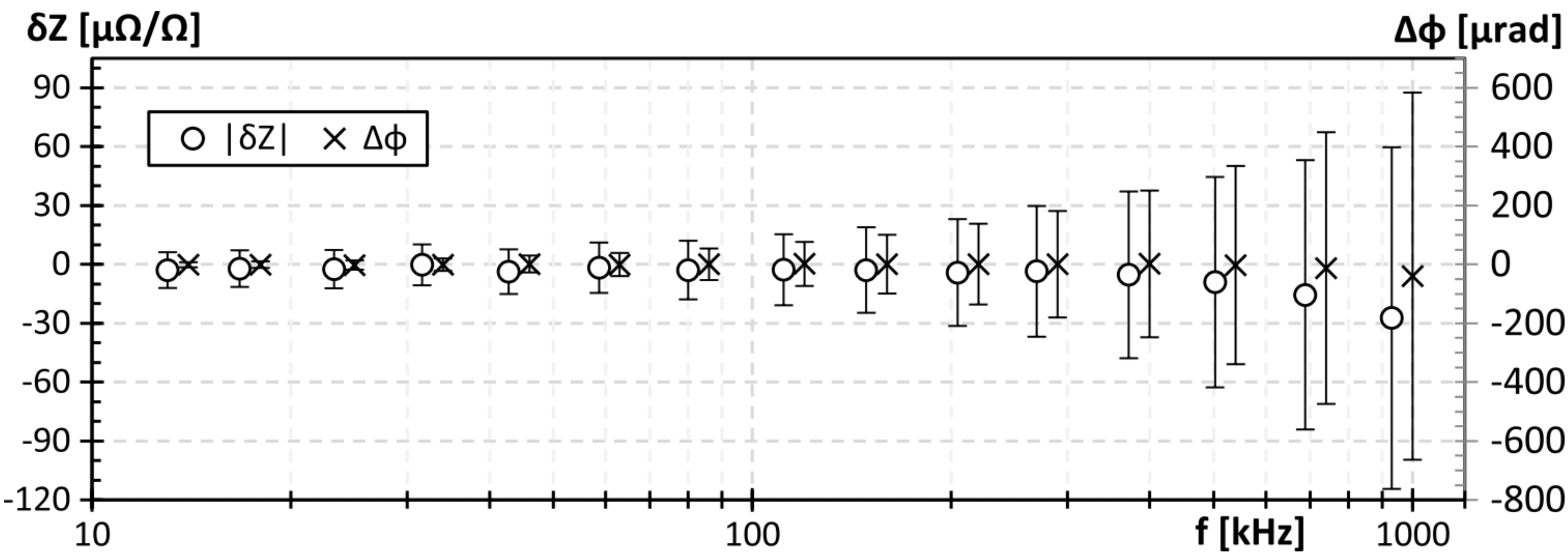
- ratios up to **1:5**
- current 1 A

c **120 mΩ**

600 mΩ b

a **200 mΩ**

$$\boxed{\delta\hat{Z} = \hat{a}\cdot\hat{b}\cdot\hat{c} - 1}$$



Capacitor HP16384A, 1000 pF compared to C and calculable R

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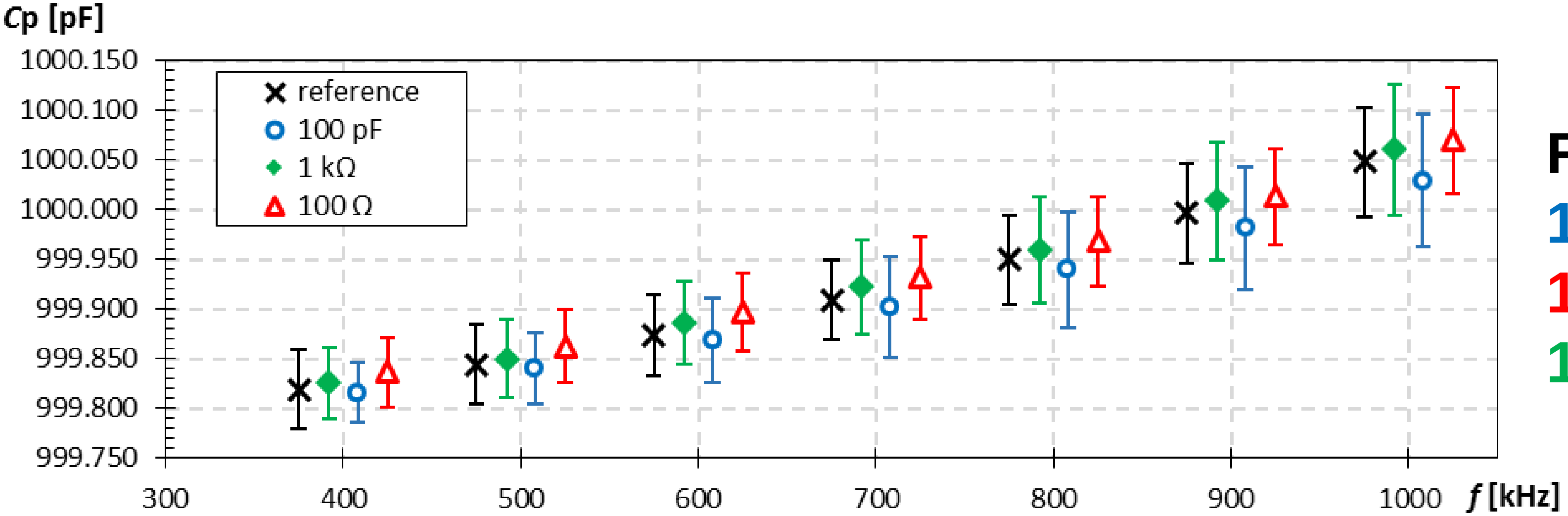


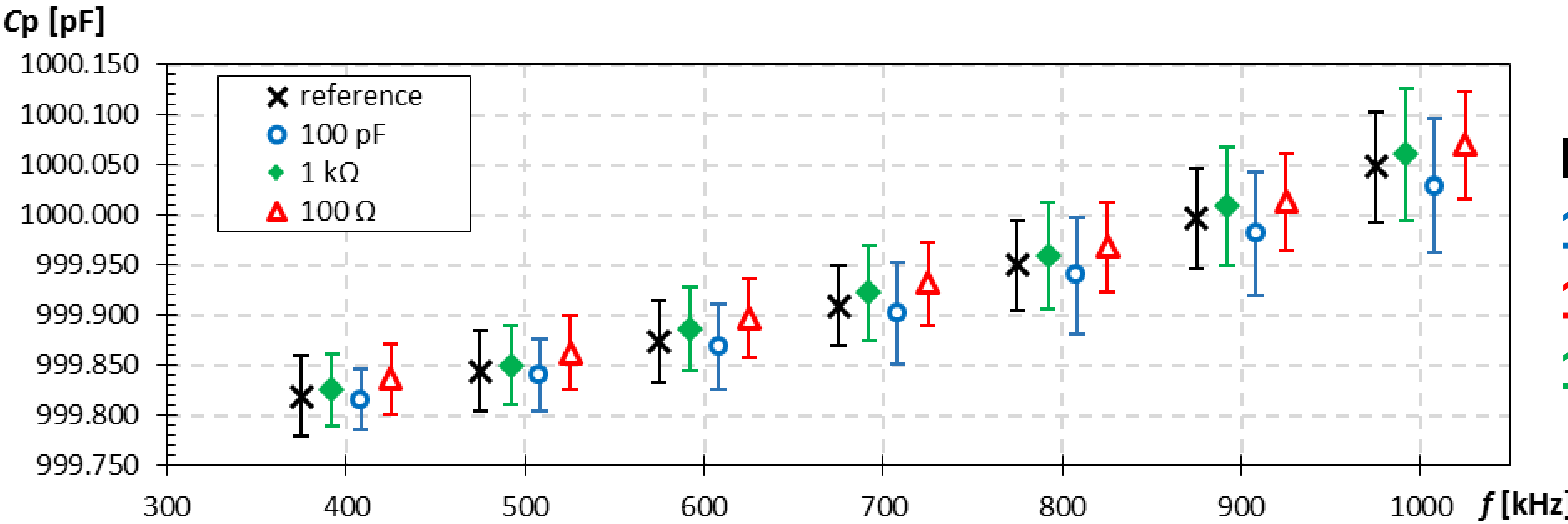
Ratios:

10:1

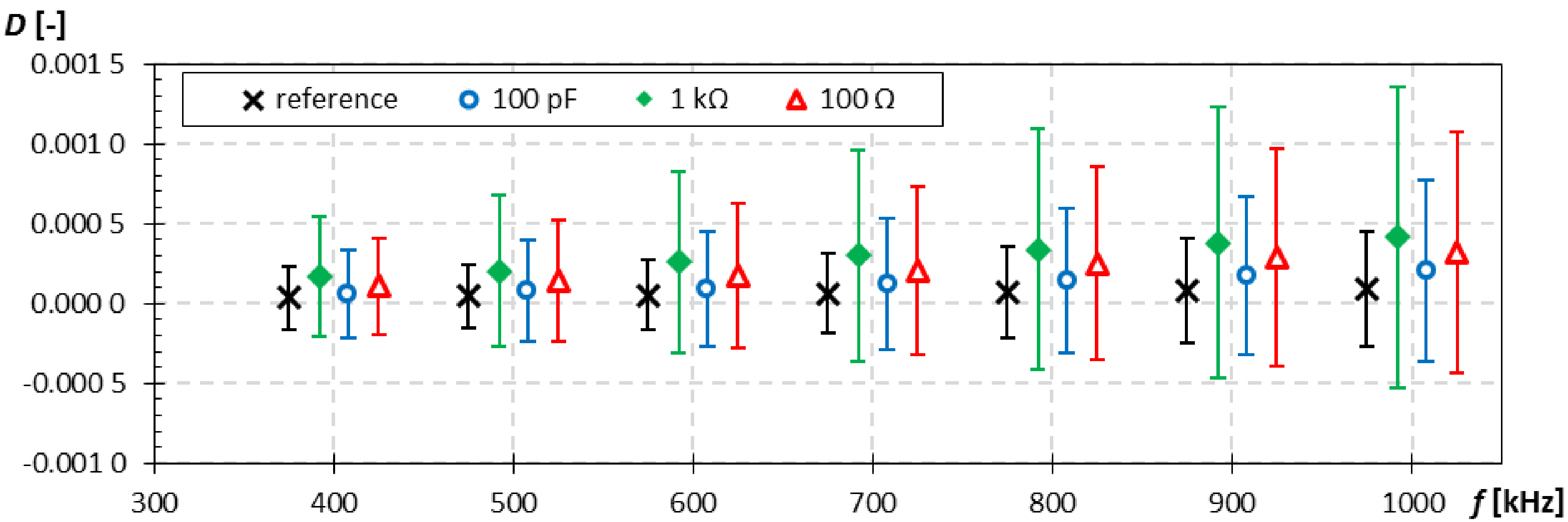
1:4 to 1:1.6

1.6:1 to 4:1

Capacitor HP16384A, 1000 pF compared to C and calculable R



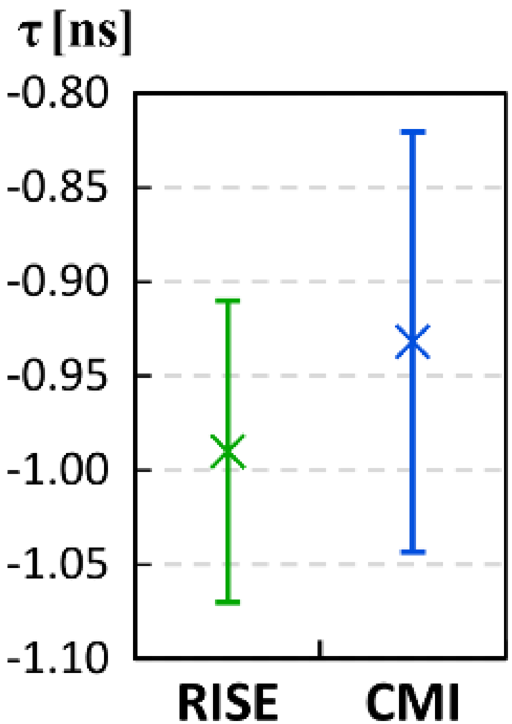
Ratios:
10:1
1:4 to 1:1.6
1.6:1 to 4:1



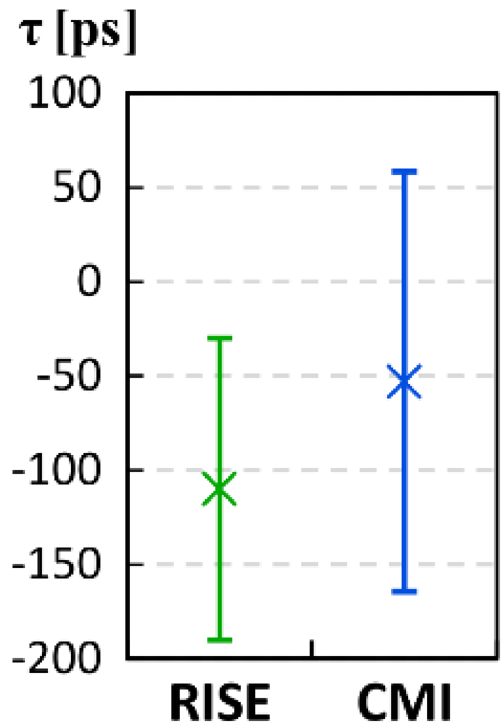
Comparison of timeconstant RISE – CMI:

- Three shunts compared 100 mA, 300 mA and 1 A
- Deviation **~ 55 ps** (350 µrad at 1 MHz)

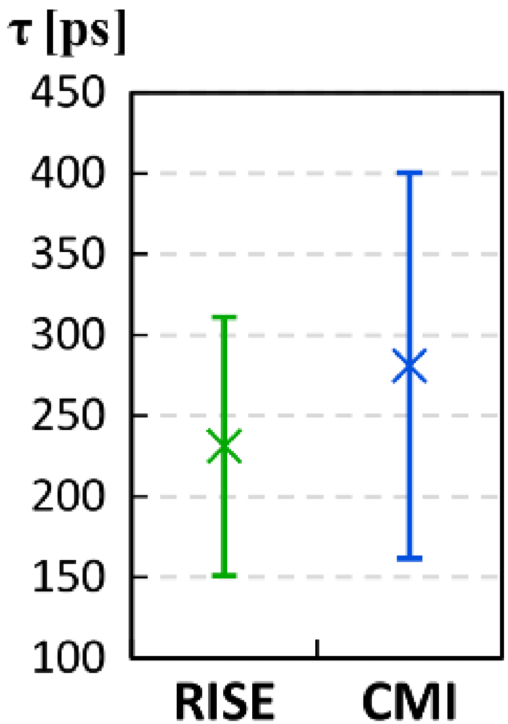
6 Ω shunt



2 Ω shunt

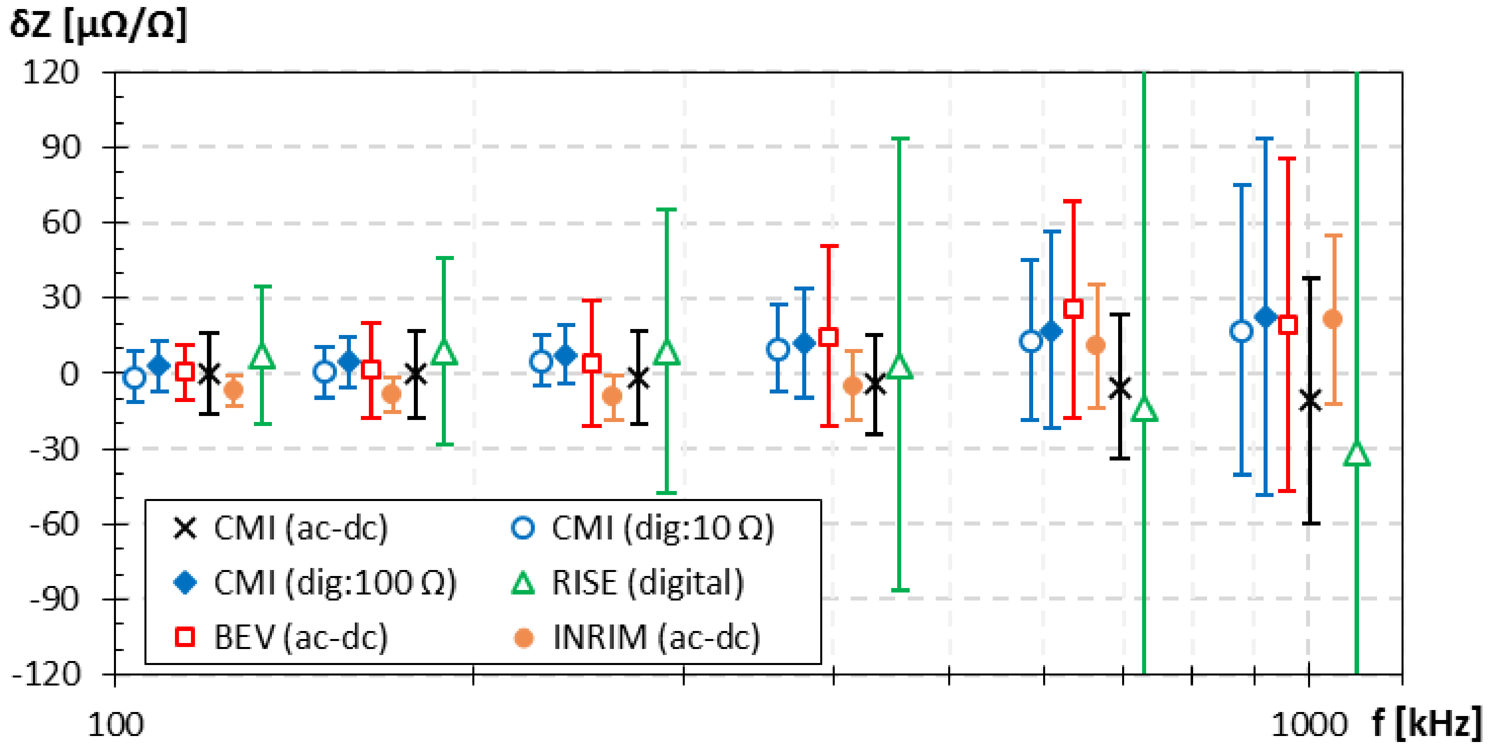


0.6 Ω shunt

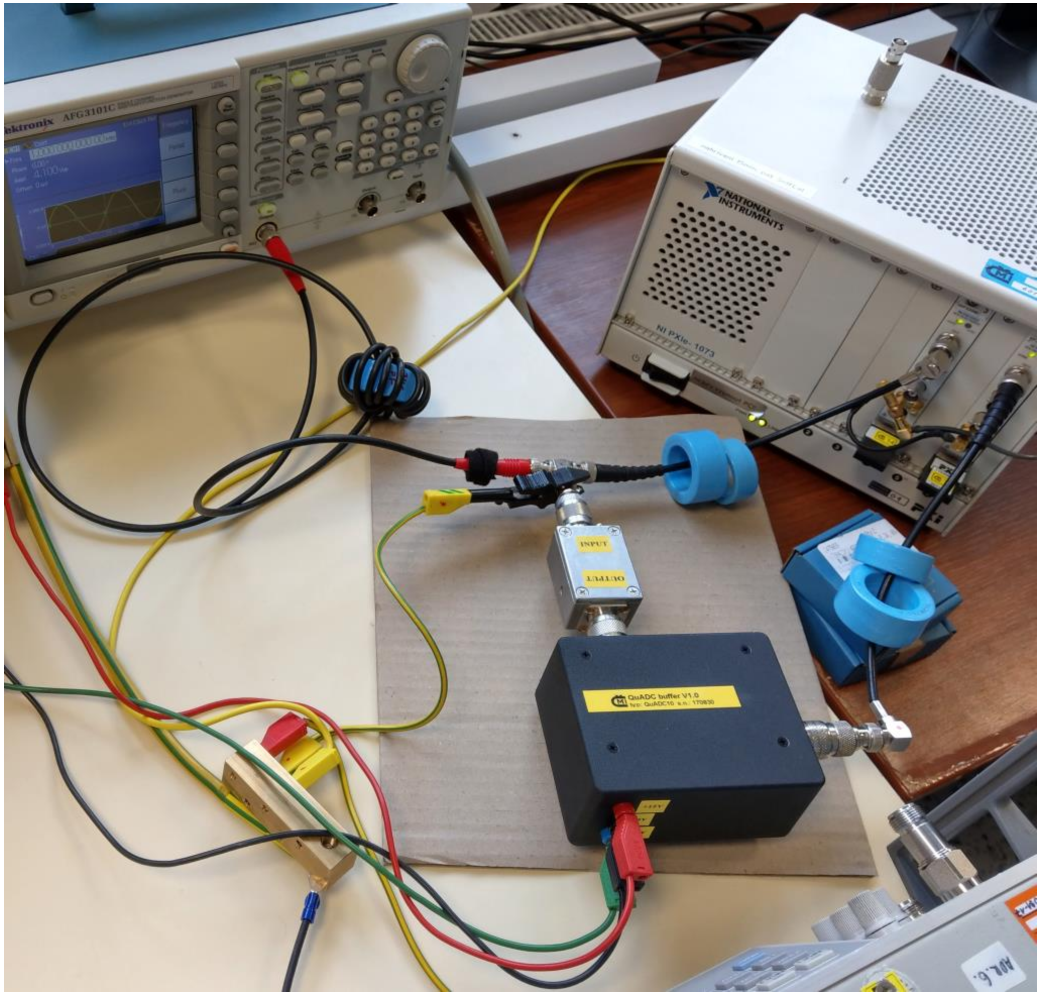


Comparison of ac-dc of 100 mA shunt (6 Ω):

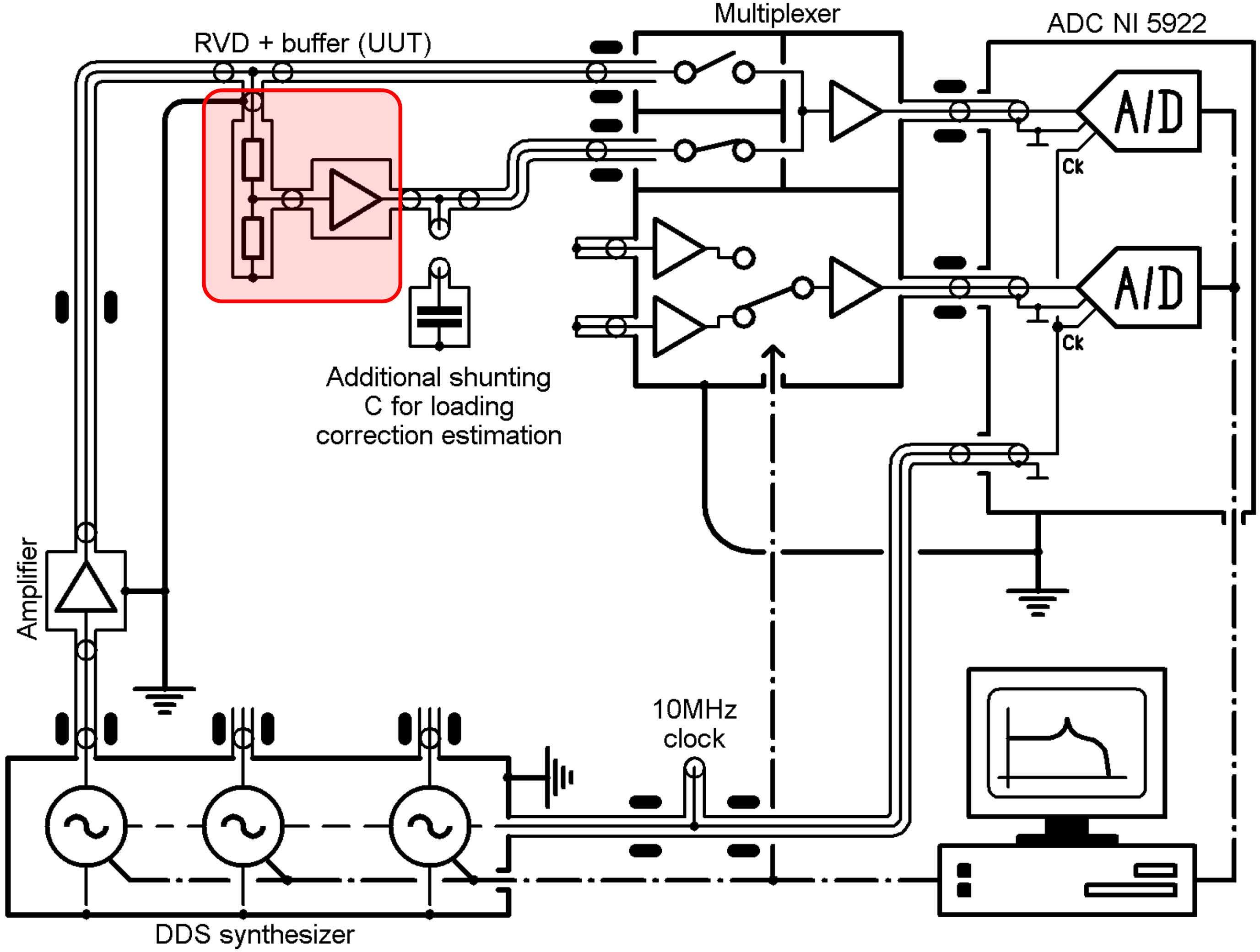
- **CMI:** compared to **10 Ω** and **100 Ω** resistors and **ac-dc method**
- **BEV: ac-dc difference**
- **RISE: digital setup**
- **INRIM: ac-dc**



Comparison of ac-dc and phase of RVD 1:15:



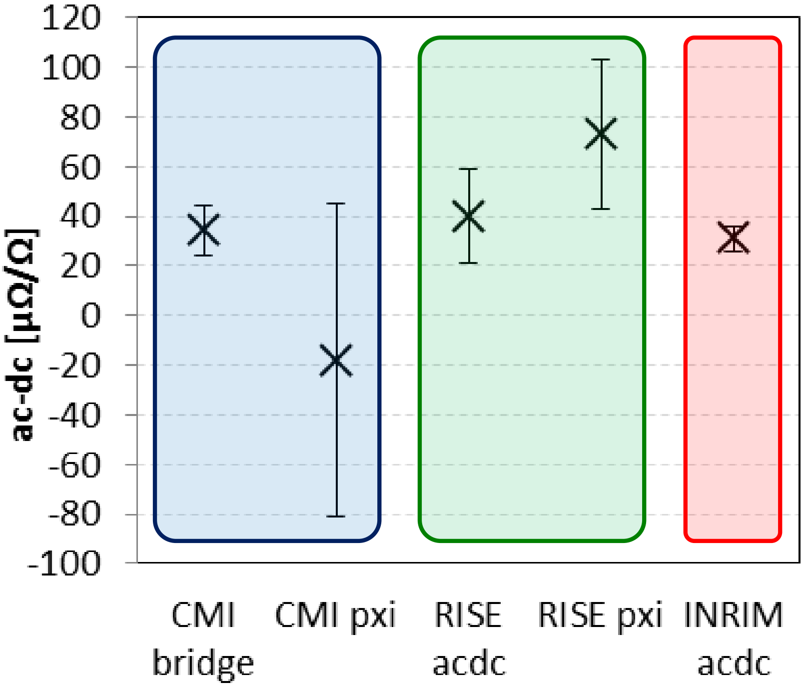
Comparison of ac-dc and phase of RVD 1:15:



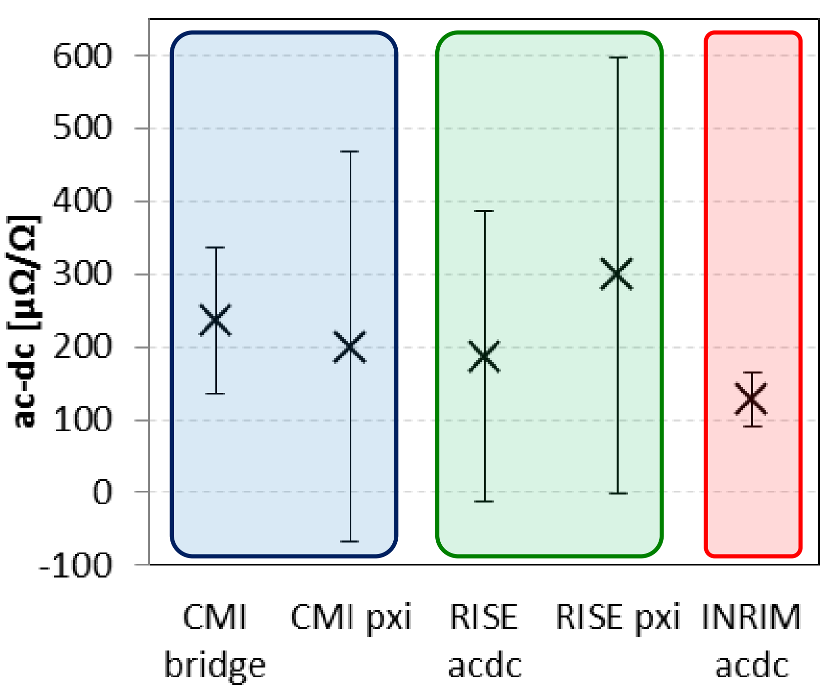
Comparison of ac-dc and phase of RVD 1:15:

- **CMI: digital sampling bridge and PXI system**
- **RISE: PXI setup and ac-dc**
- **INRIM: ac-dc**

f = 100 kHz:



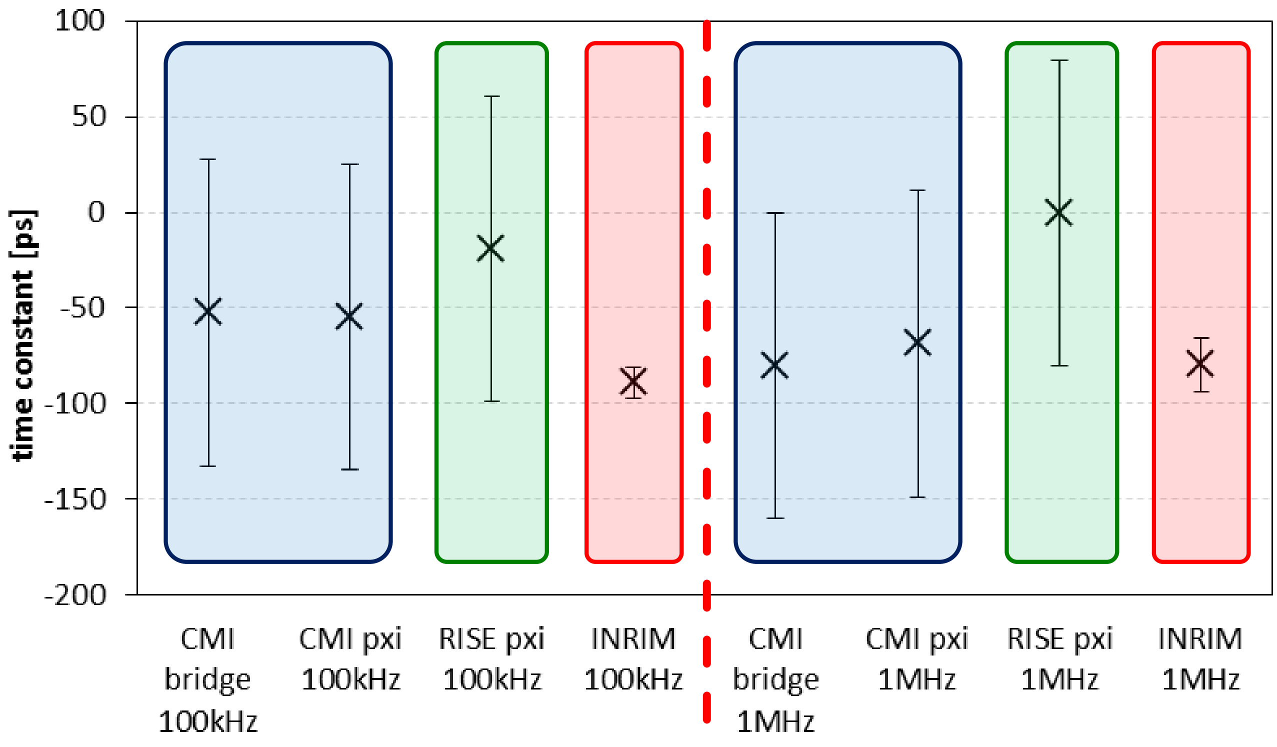
f = 1 MHz:



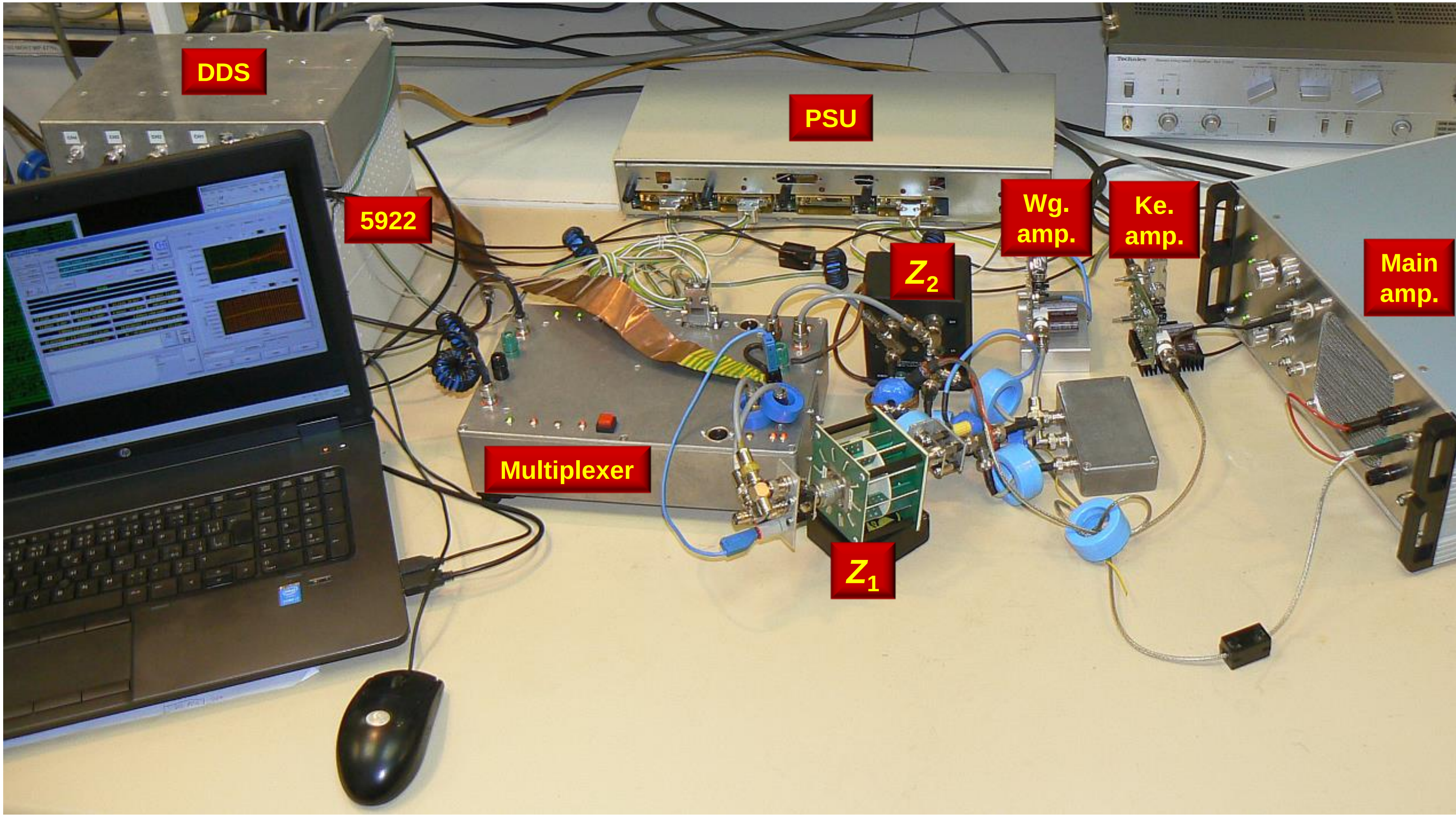
Comparison of ac-dc and phase of RVD 1:15:

- **CMI: digital sampling bridge and PXI system**
- **RISE: PXI setup**
- **INRIM: digital**

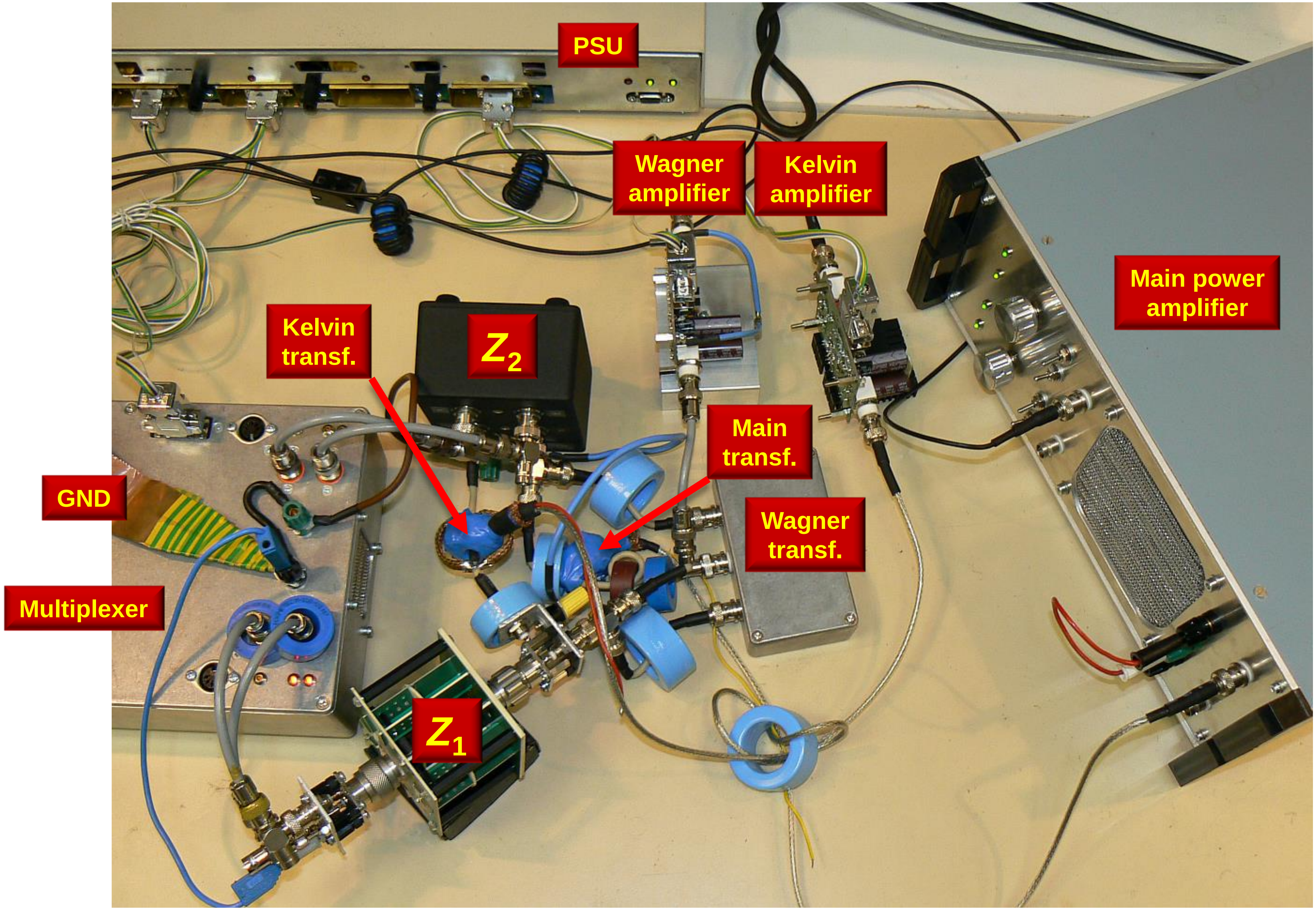
f = 100 kHz: **f = 1 MHz:**



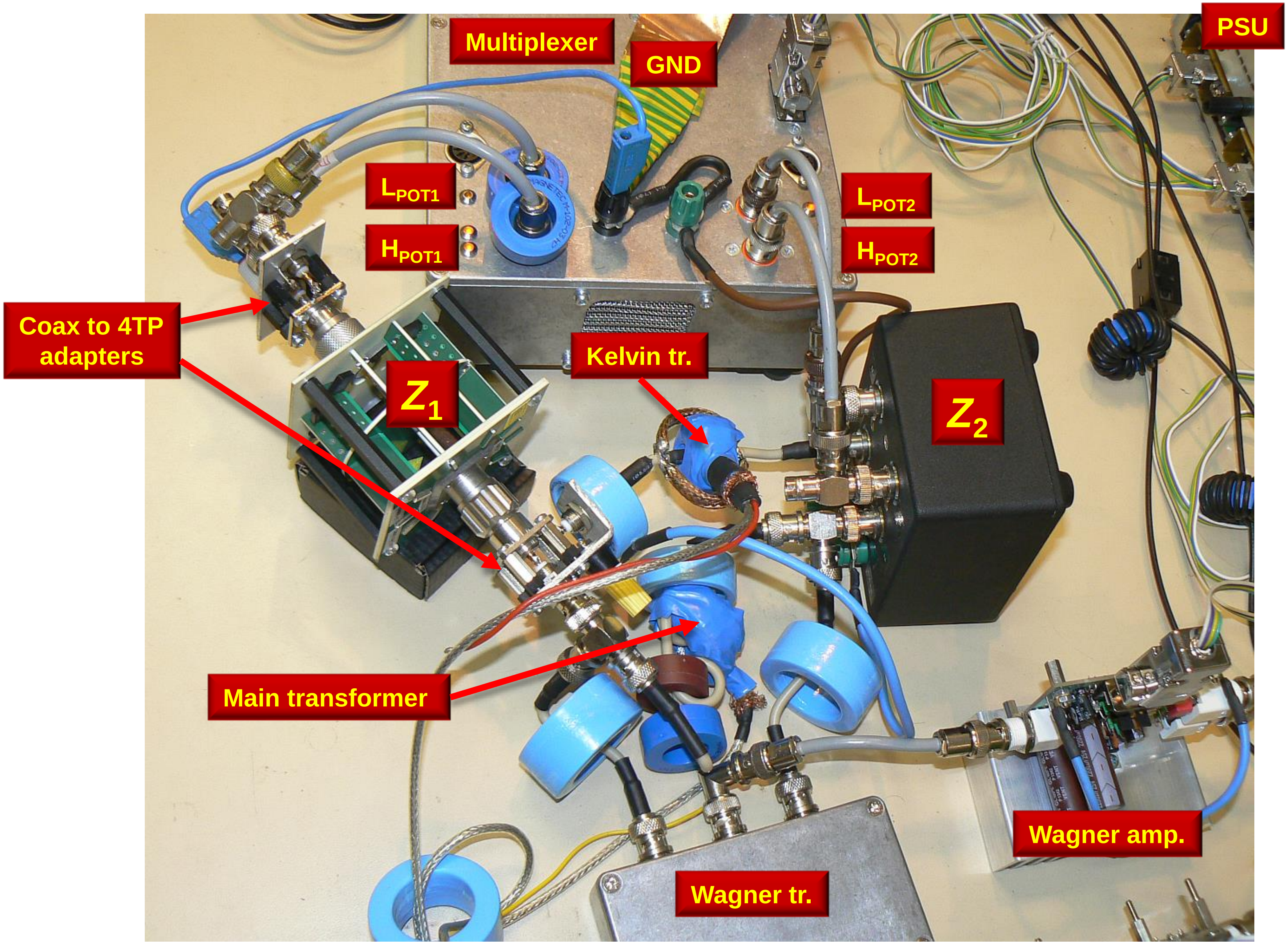
The bridge



The bridge


PSU
Wagner amplifier
Kelvin amplifier
Main power amplifier
Kelvin transf.
Z_2
Main transf.
Wagner transf.
GND
Multiplexer
Z_1

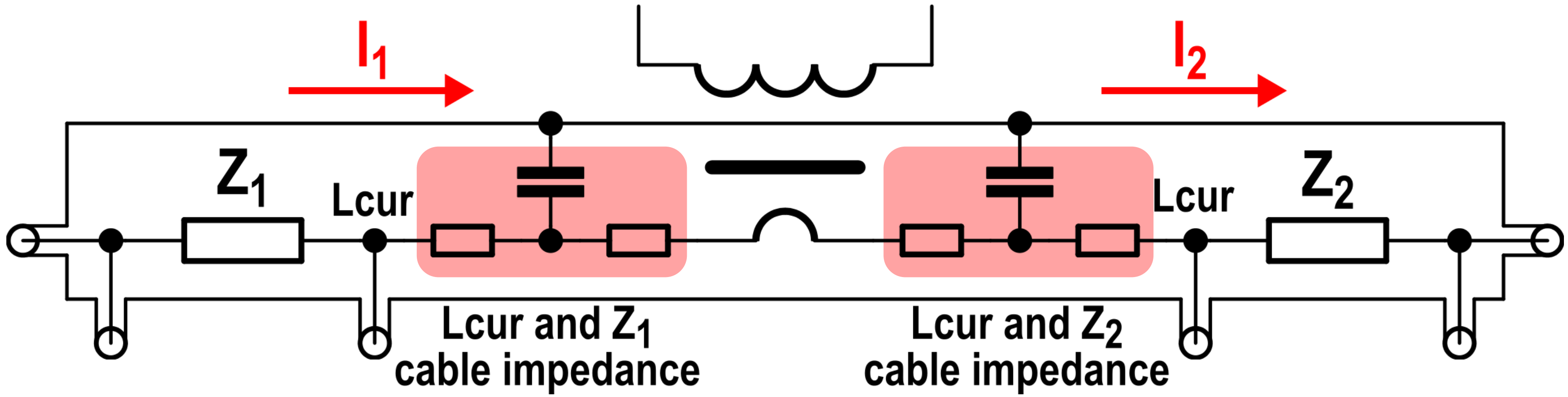
The bridge



Multiplexer
GND
PSU
L_{POT1}
H_{POT1}
L_{POT2}
H_{POT2}
Coax to 4TP adapters
Z_1
Kelvin tr.
Z_2
Main transformer
Wagner amp.
Wagner tr.

Thank you.

Kelvin asymmetry correction



Kelvin asymmetry error:

- **Lcur** terminal series impedances are **not symmetric**
- Currents $\mathbf{I_1}$ and $\mathbf{I_2}$ **are not equal**
- Typical errors below **30 µΩ/Ω** at 1 MHz
- Corrected by modeling the circuit