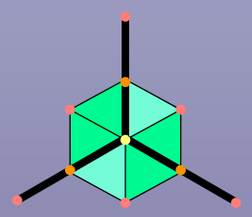

Novel Design of a Miniature High Precision Three Axis Hall Sensor

Christina Wouters

(Magnet Section, PSI Villigen)

PhD Supervisor: Prof. Dr. C. Hierold (Micro and Nanosystems Group, ETH Zürich)
Lead Research Partner: Prof. Dr. J. Gobrecht (Laboratory for Micro and Nanotechnology, PSI Villigen)
Mentor: V. Vranković (Magnet Section, PSI Villigen)
Project Manager: Dr. S. Sanfilippo (Magnet Section, PSI Villigen)
Implementation Partner: P. Keller (Metrolab)

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Prof. Dr. W. Wegscheider (Advanced Semiconductor Quantum Materials Group, ETH Zürich)
Dr. C. Rössler (Nanophysics Group, ETH Zürich)
Dr. I. Shorubalko (Micro and Nanotechnology, EMPA Dübendorf)
Dr. P. Reimann (Physics Technology Group, Universität Basel)
Dr. K. Jefimovs (Micro and Nanotechnology, EMPA Dübendorf)

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

UNI BASEL

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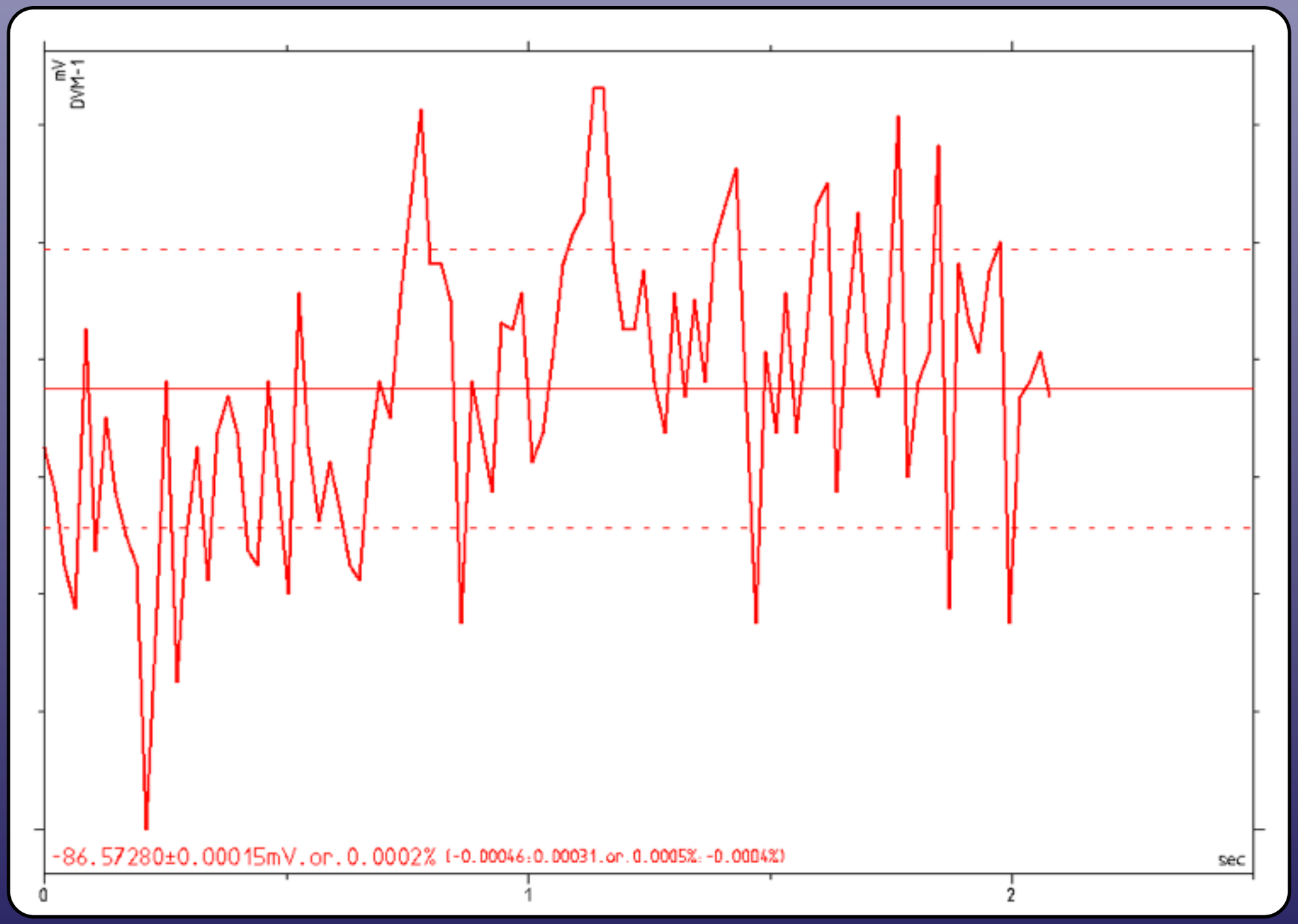
PSI

EMPA

Metrolab

Goal

Development of a 3D Hall sensor with unrivaled measurement precision (10^{-4} at 1 T)

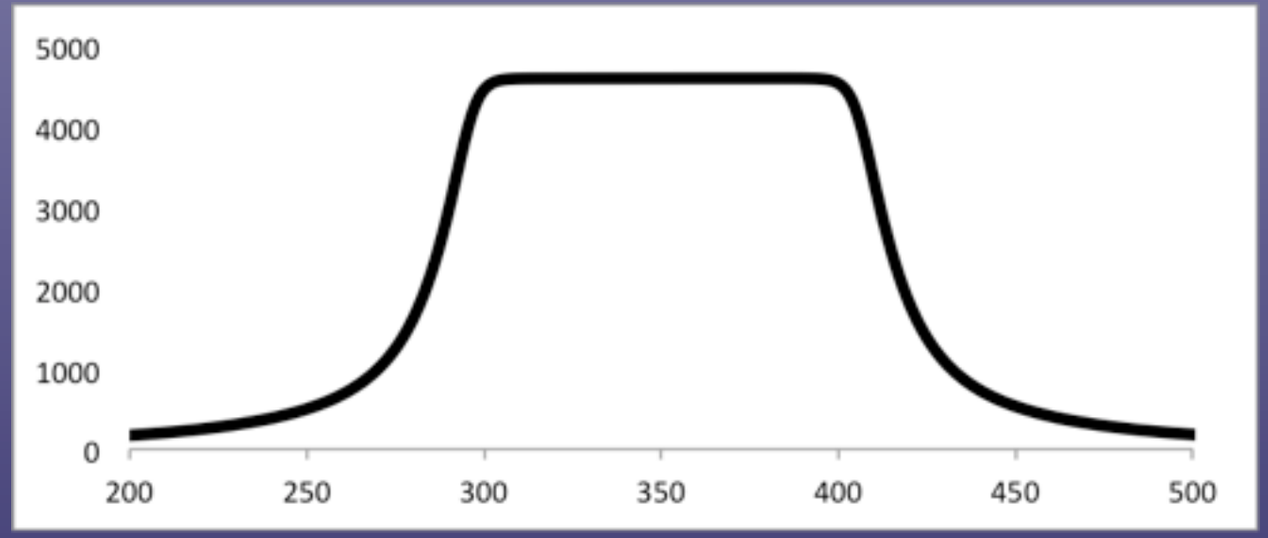


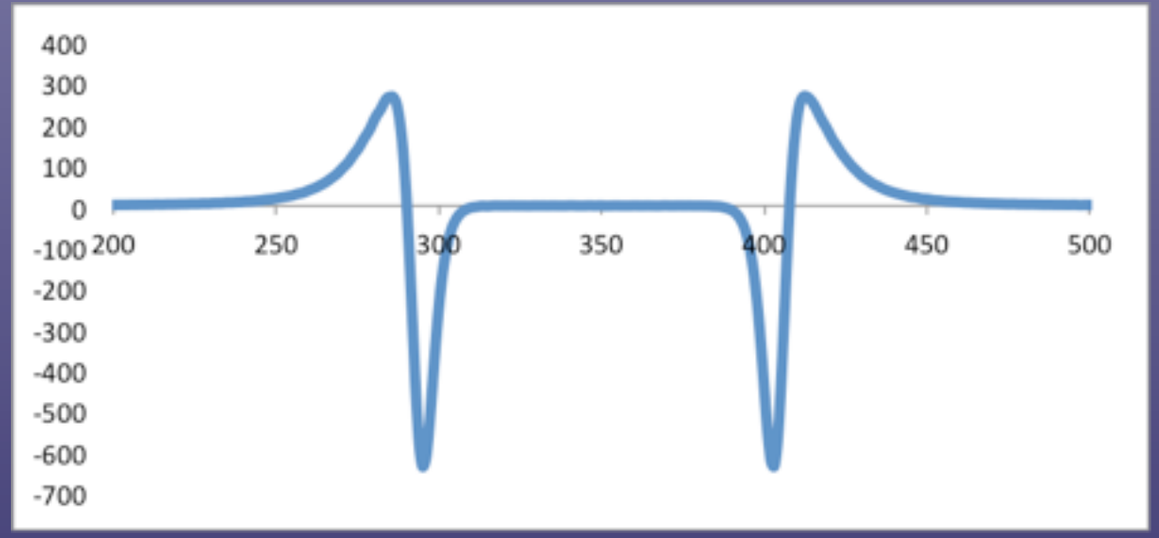
Goal

Development of a 3D Hall sensor with unrivaled measurement precision (10^{-4} at 1 T)

Assembly of “standard” 1D Hall probes

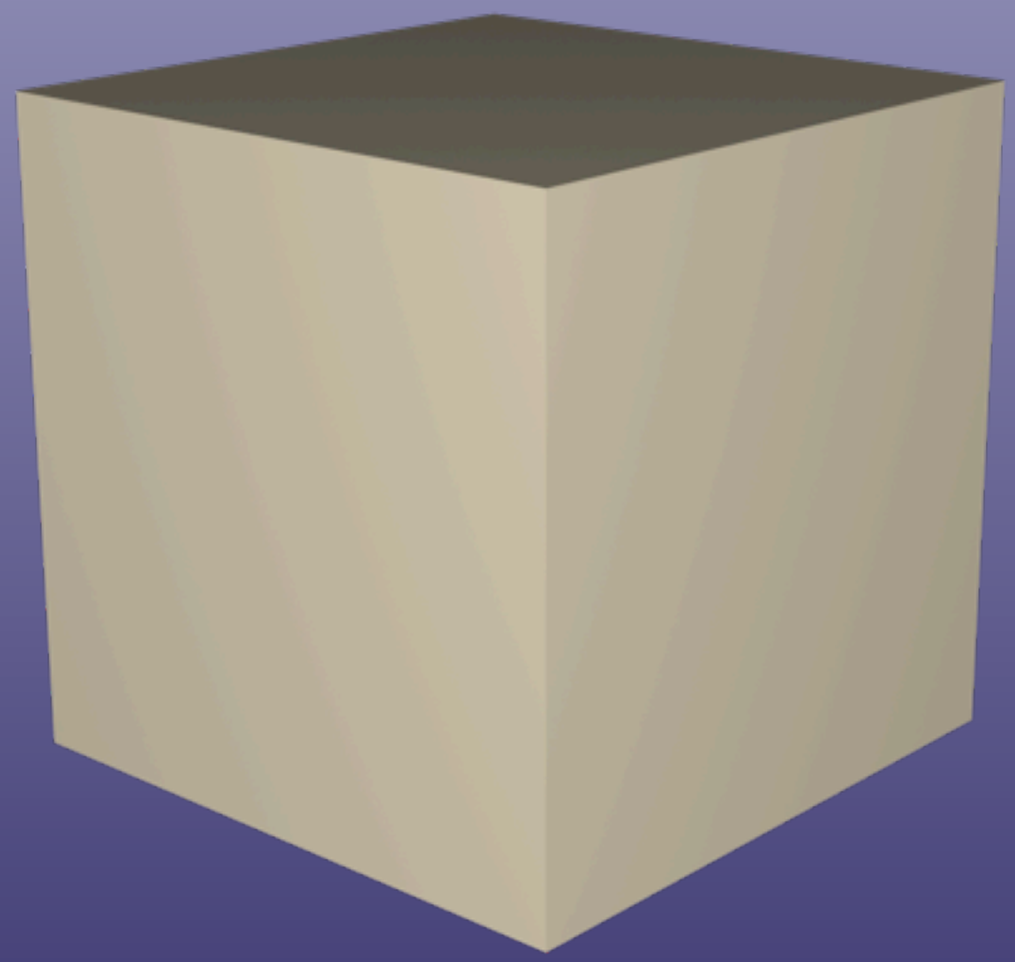
Combine standard and vertical Hall probes





Linear interpolation error < 0.5 Gauss
➔ d < 1 mm

3D HALL*cube*



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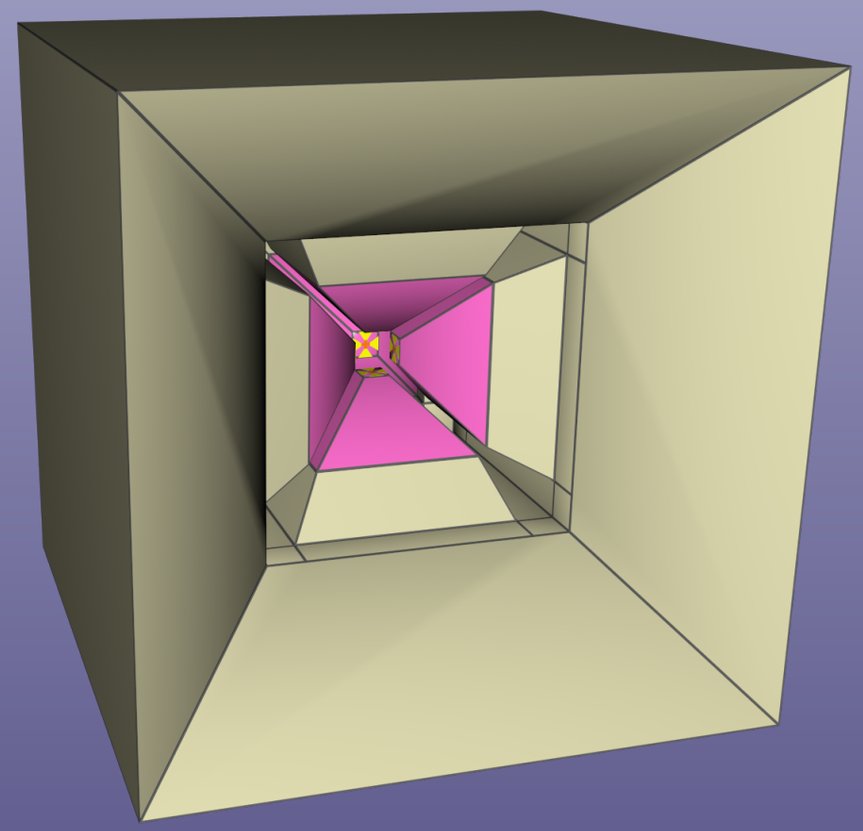
3D HALL*cube*

Concept (European patent pending)

Plate-like 1D Hall probes on 6 truncated pyramids

Inner cube volume: <200x200x200 μm^3

Outer cube volume: <4x4x4 mm^3



Hallmarks

Advantage in precision of single axis Hall probes

Elimination of parasitic Hall Planar Effect

Measurement of full field vector in a single point in time and space

Thermally insulated

Ideal for

Measuring small aperture magnets

Measuring weak magnetic side field components such as in search for a solenoid's magnetic axis

Precisely measuring highly inhomogeneous field such as in undulators

Magnetic measurements where high measurement precision of all three field components is essential

Challenges

Optimizing/improving semiconductor properties

Electrical contacting, wiring, and assembly

Effective calibration procedure

Commercially realizable sensor

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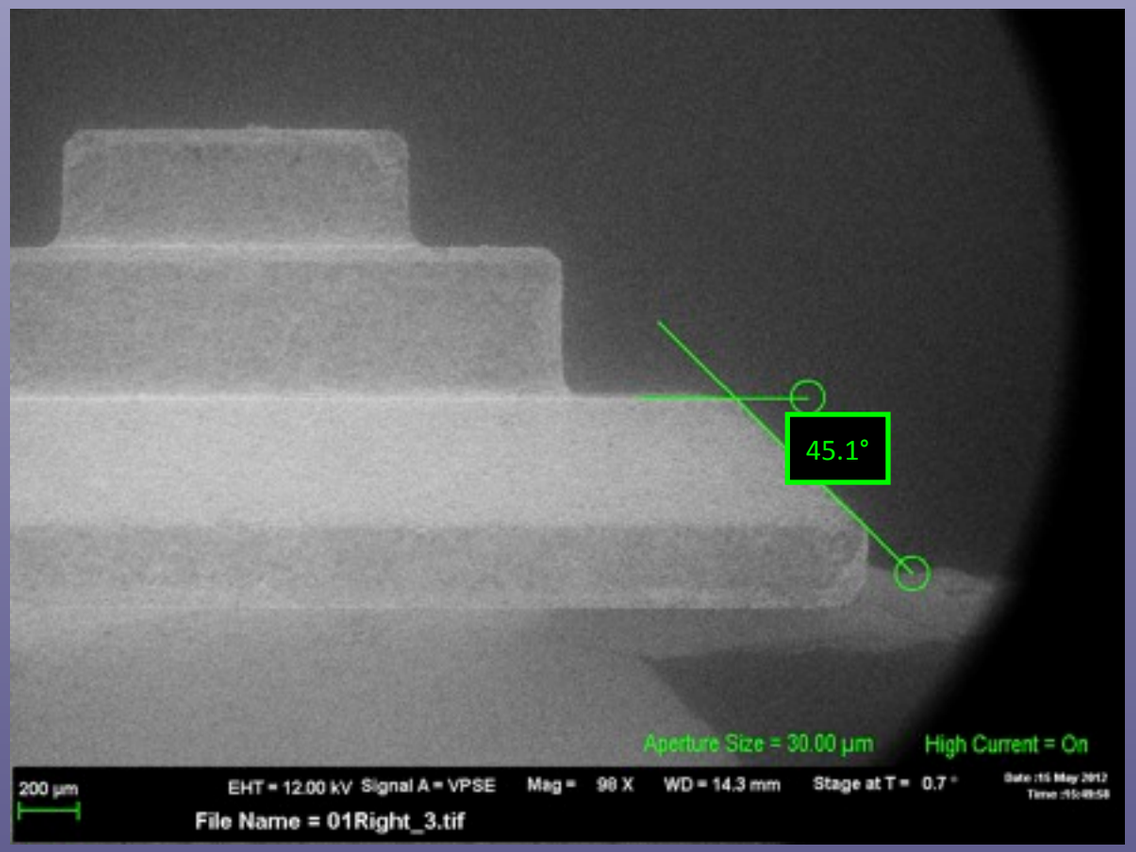
Pyramid base

Requirements:

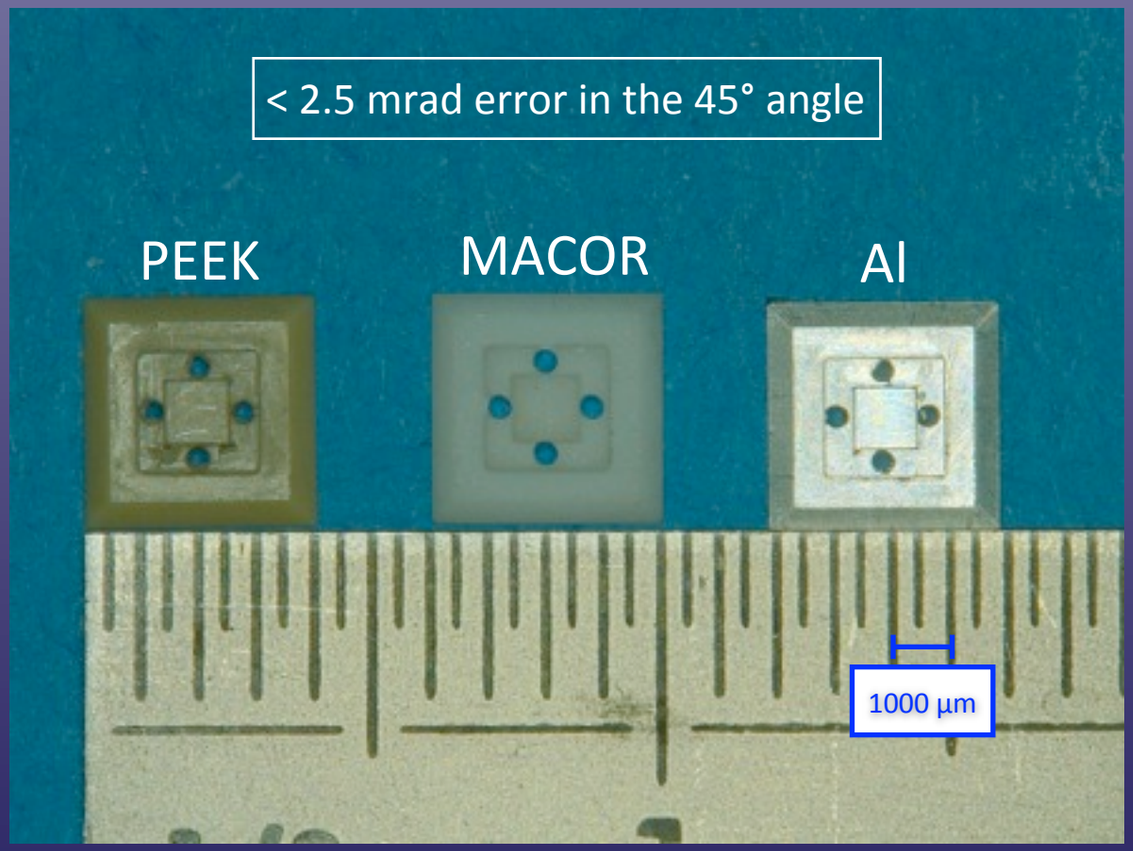
- Non-magnetic
- Non-conductive
- Stable
- Machinable with tight tolerances

Desirable:

- Low thermal conductivity
- Low thermal expansion
- Easy machinable
- Cheap



Courtesy of A. Weber (Paul Scherrer Institut)



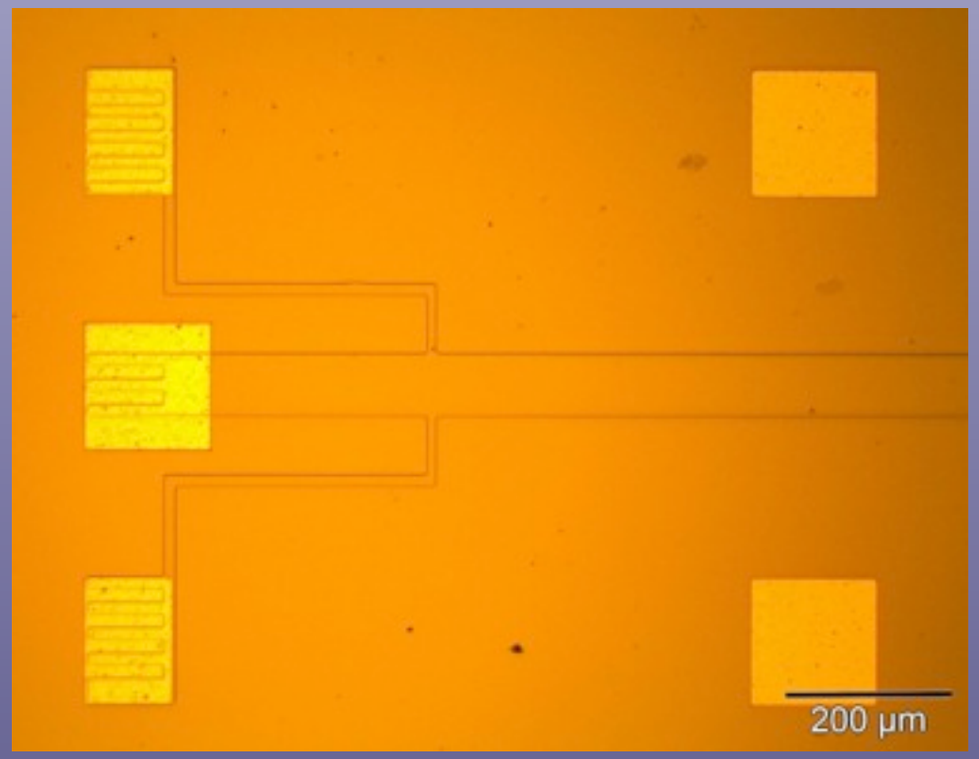
Courtesy of Dr. P Reimann (Universität Basel)

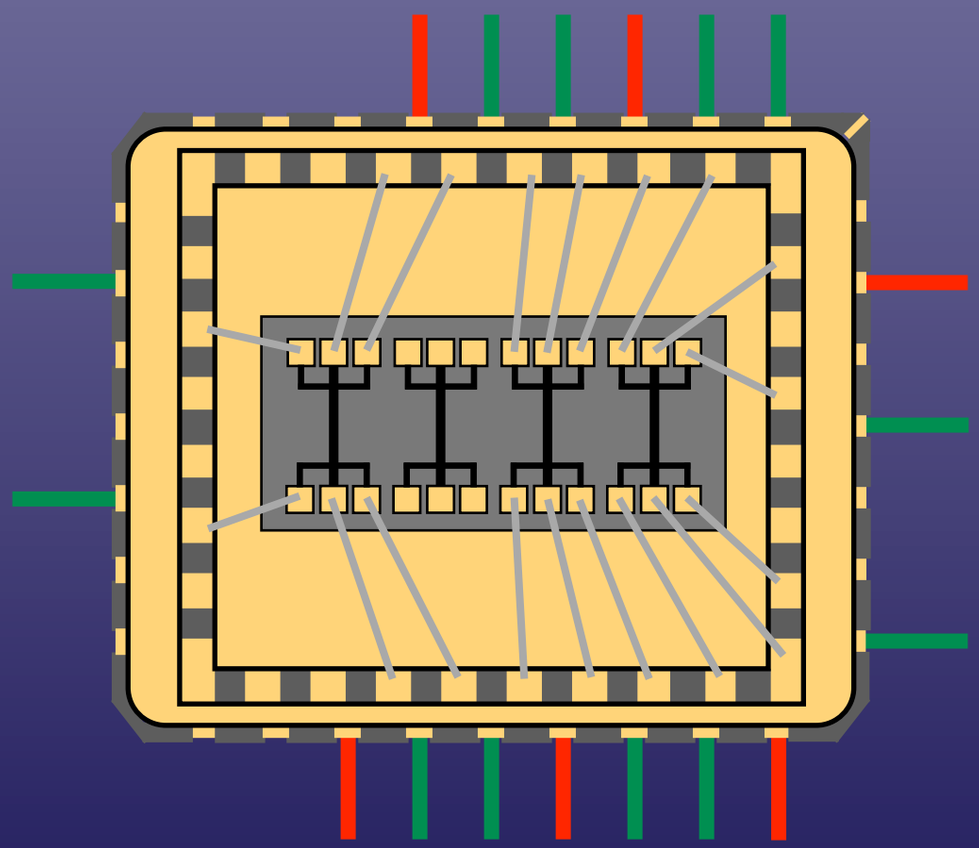
MACOR machinable ceramic

thermal conductivity: 1.46 $Wm^{-1}K^{-1}$

thermal expansion coefficient: 9.3 µm $m^{-1}K^{-1}$

Fabrication of a Hall bar

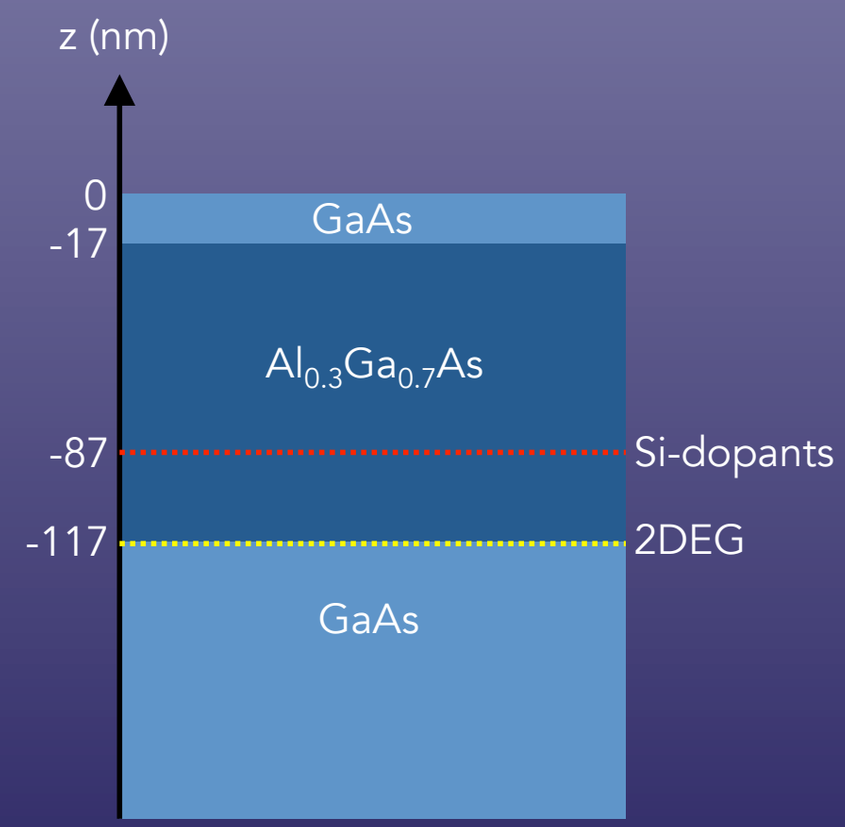




"HPF1" (version 0)

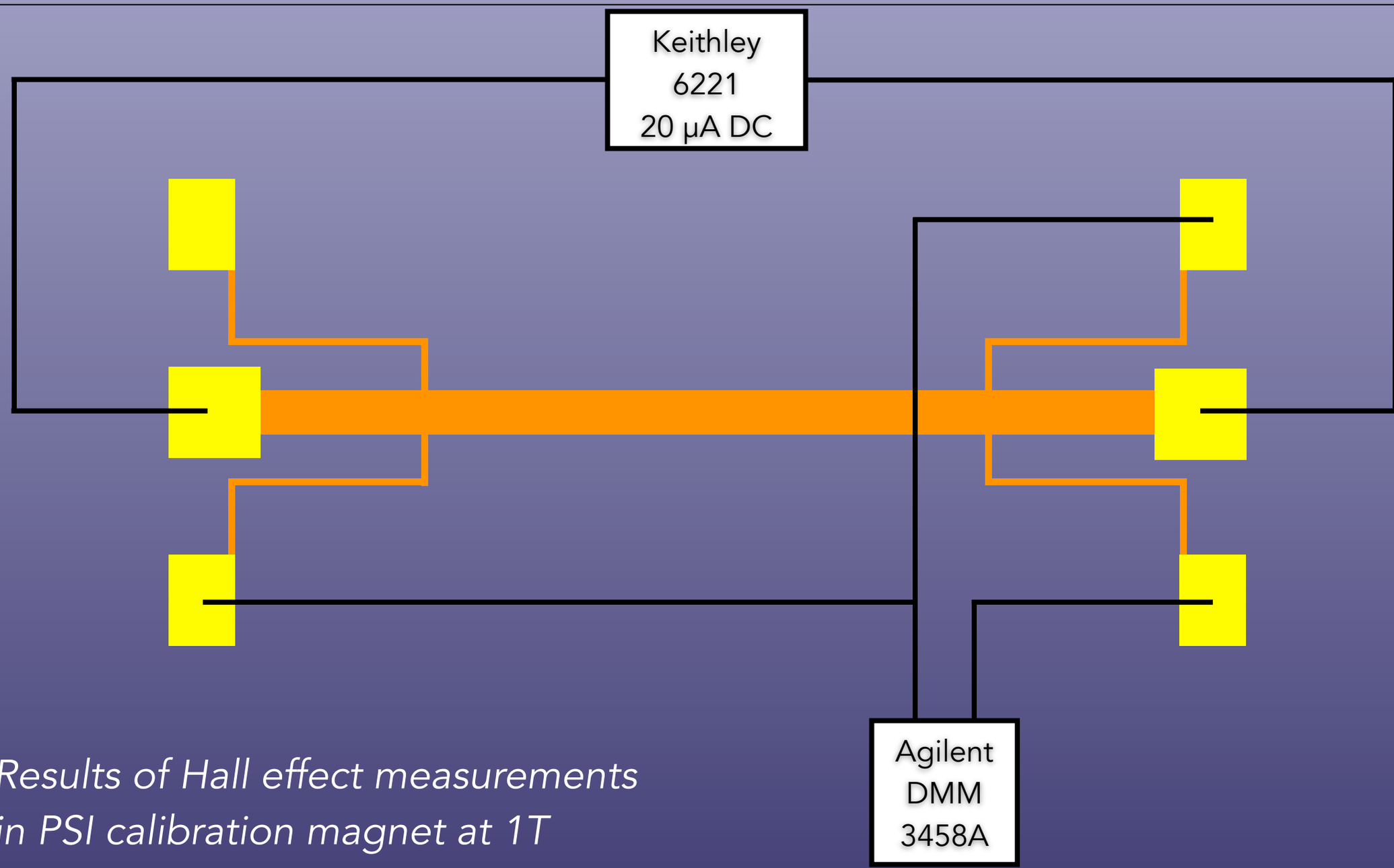
w = 100 µm; l = 1900 µm

2DEG from GaAs-AlGaAs heterostructure with Si doping



source: Dr. C Rössler, ETH Zürich (modified)

Hall bar measurements (I)



Results of Hall effect measurements in PSI calibration magnet at 1T

$n_{2D} \approx 3.5 \cdot 10^{11}\ cm^{-2}$

$\rho_{2D} \approx 2.2\ k\Omega \rightarrow R \approx 42\ k\Omega$

$\mu \approx 7800\ cm^2V^{-1}s^{-1}$

$$V_{Hall}/IB = \mu\rho_{2D} \approx 1750\ V\ T^{-1}A^{-1}$$

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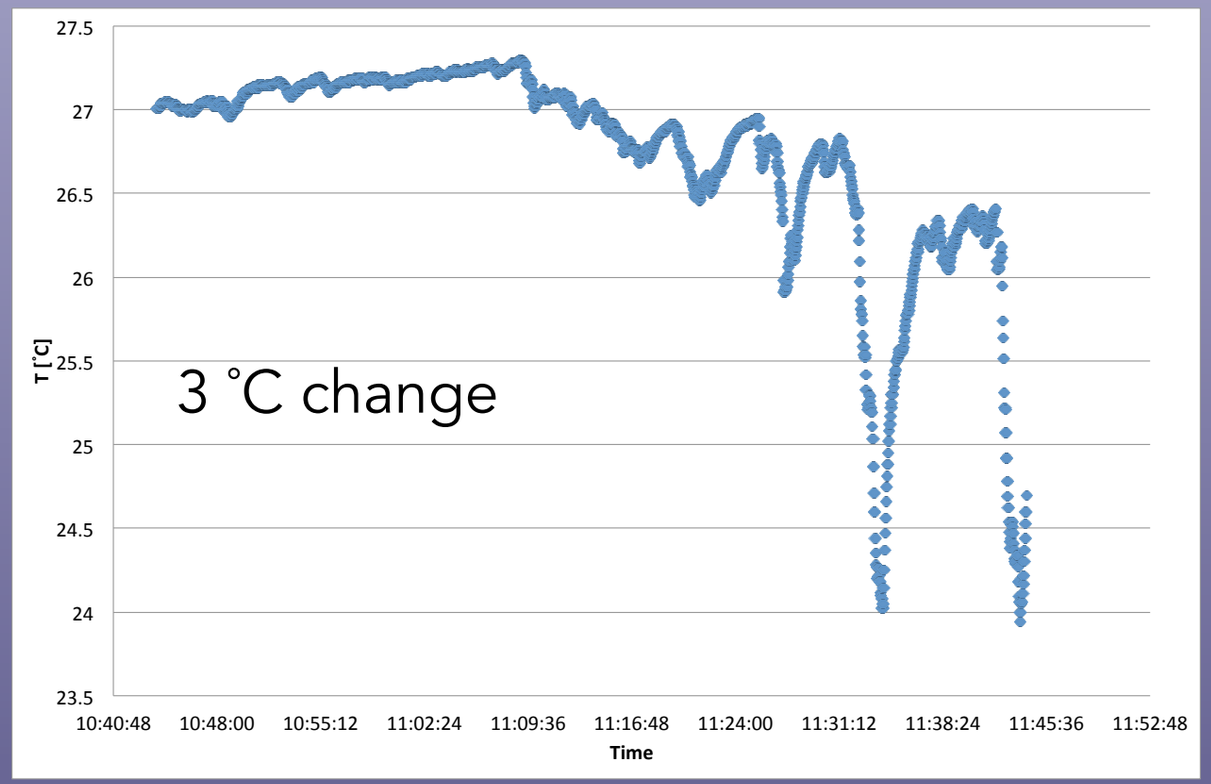
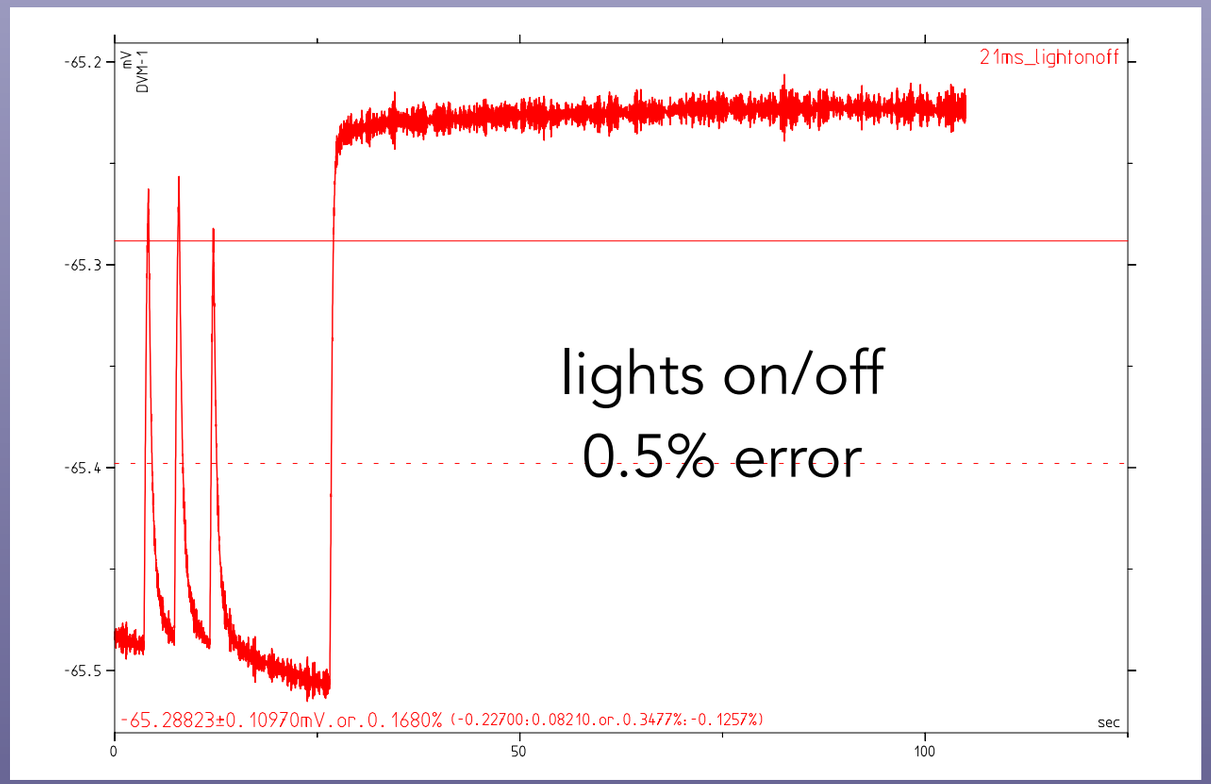
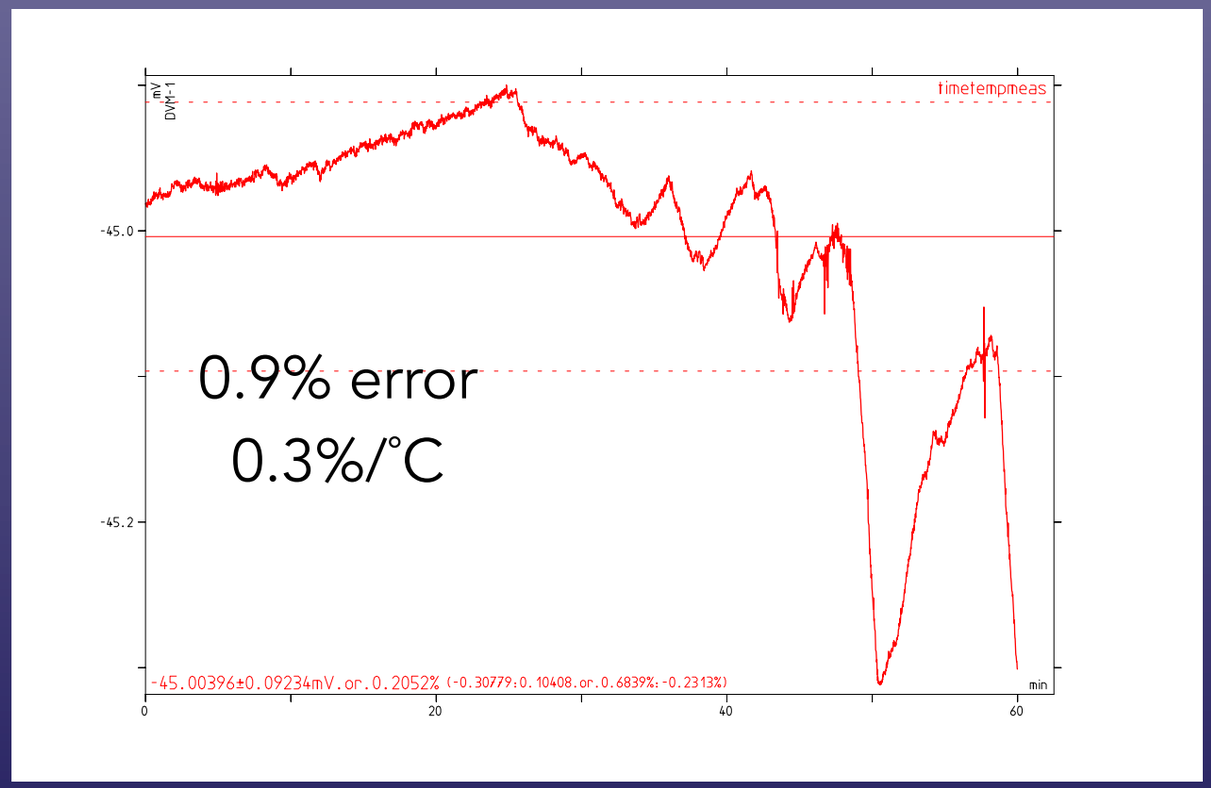
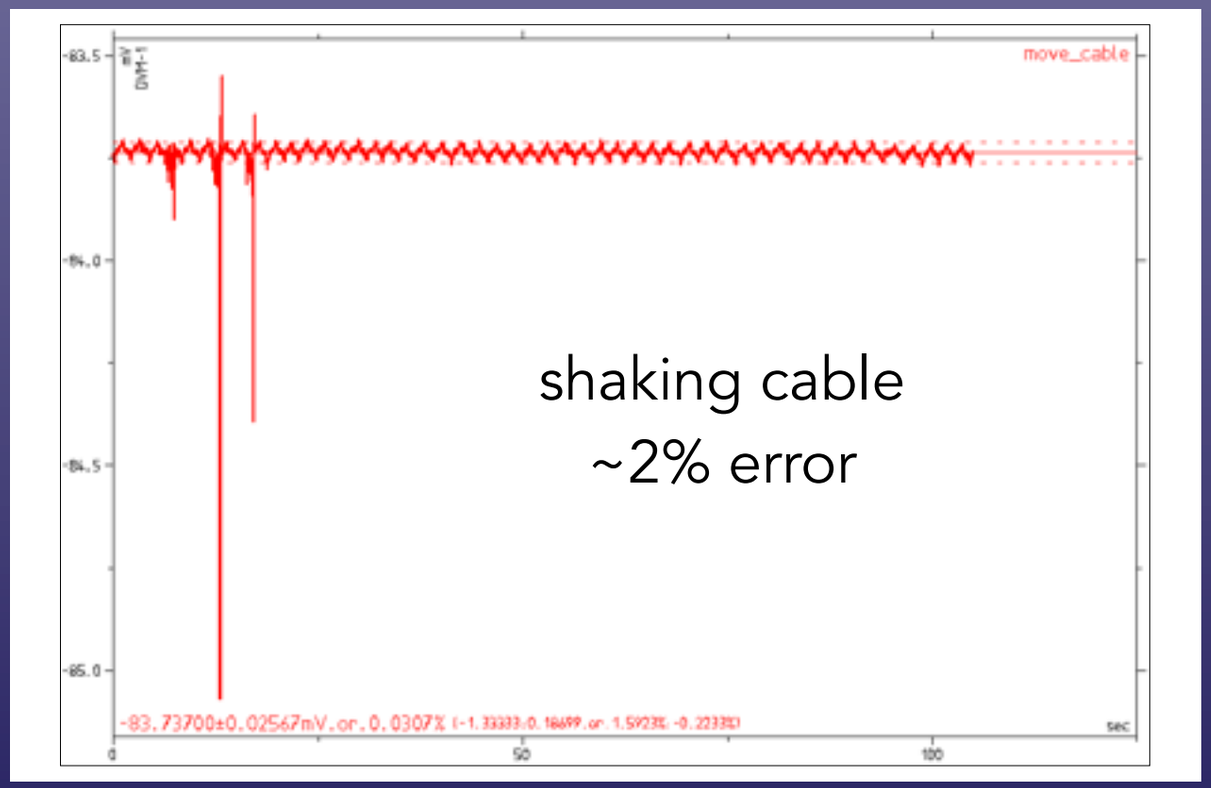
Hall bar measurements (II)









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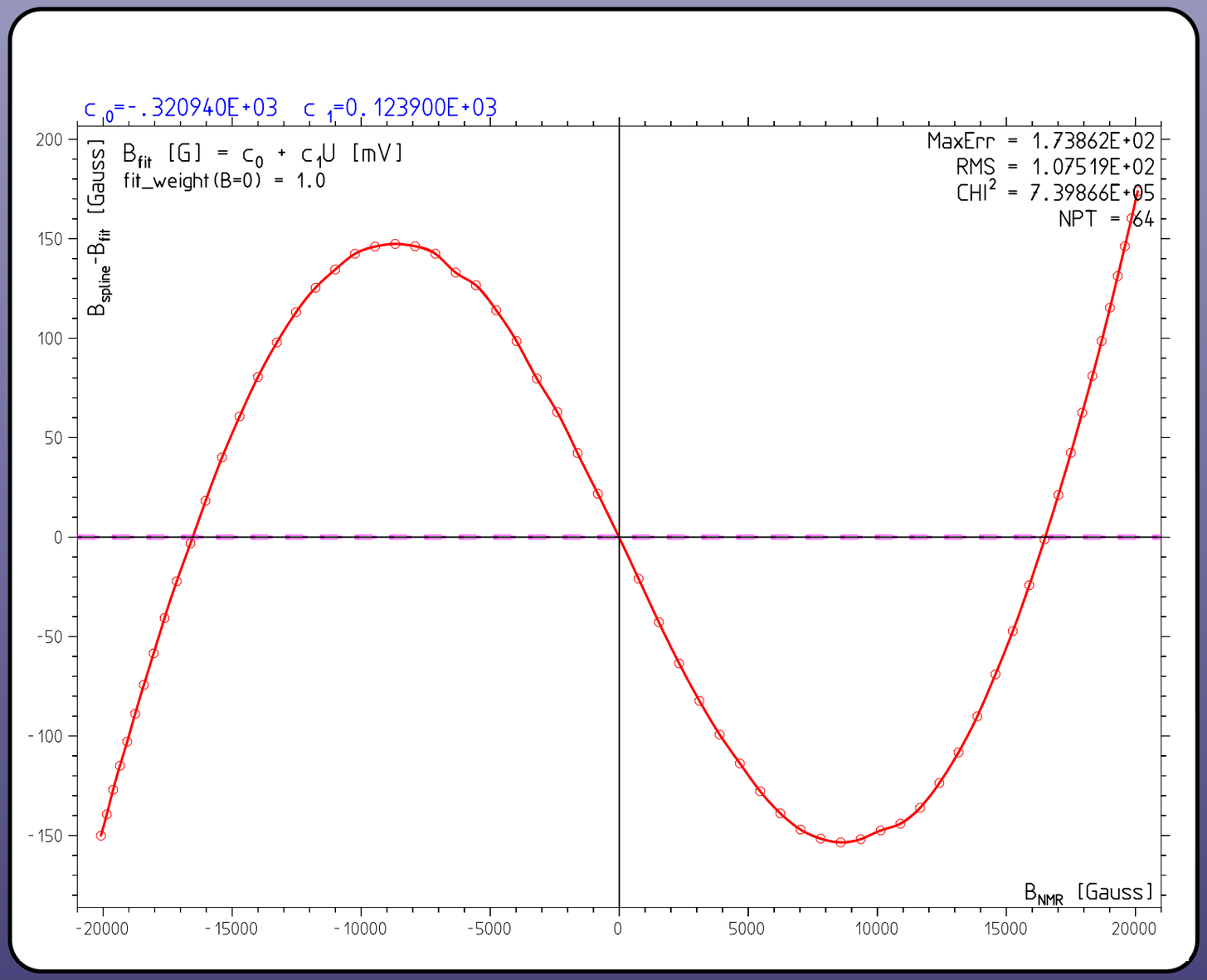
Hall bar calibration



Keithley 6221
I_{Hall}: 50 µA DC

Agilent DMM 3458A
aperture: 200 ms
N_{trig}: 15
meas. points: 64

Magnetic field: ±2 T (NMR)

T_{hutch} : 24.5 °C

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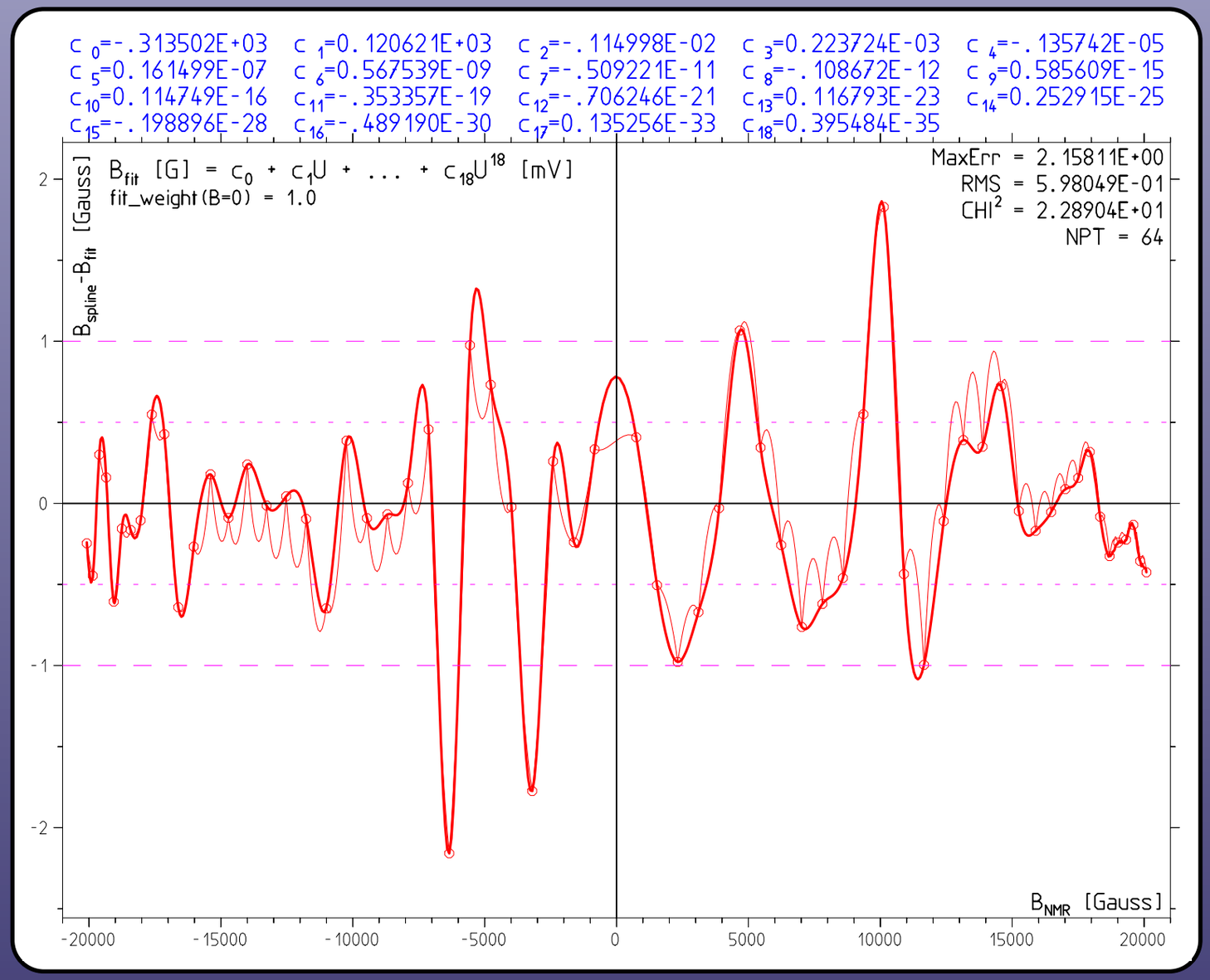
Hall bar calibration



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aperture: 200 ms
N_{trig}: 15
meas. points: 64

Magnetic field: ±2 T (NMR)

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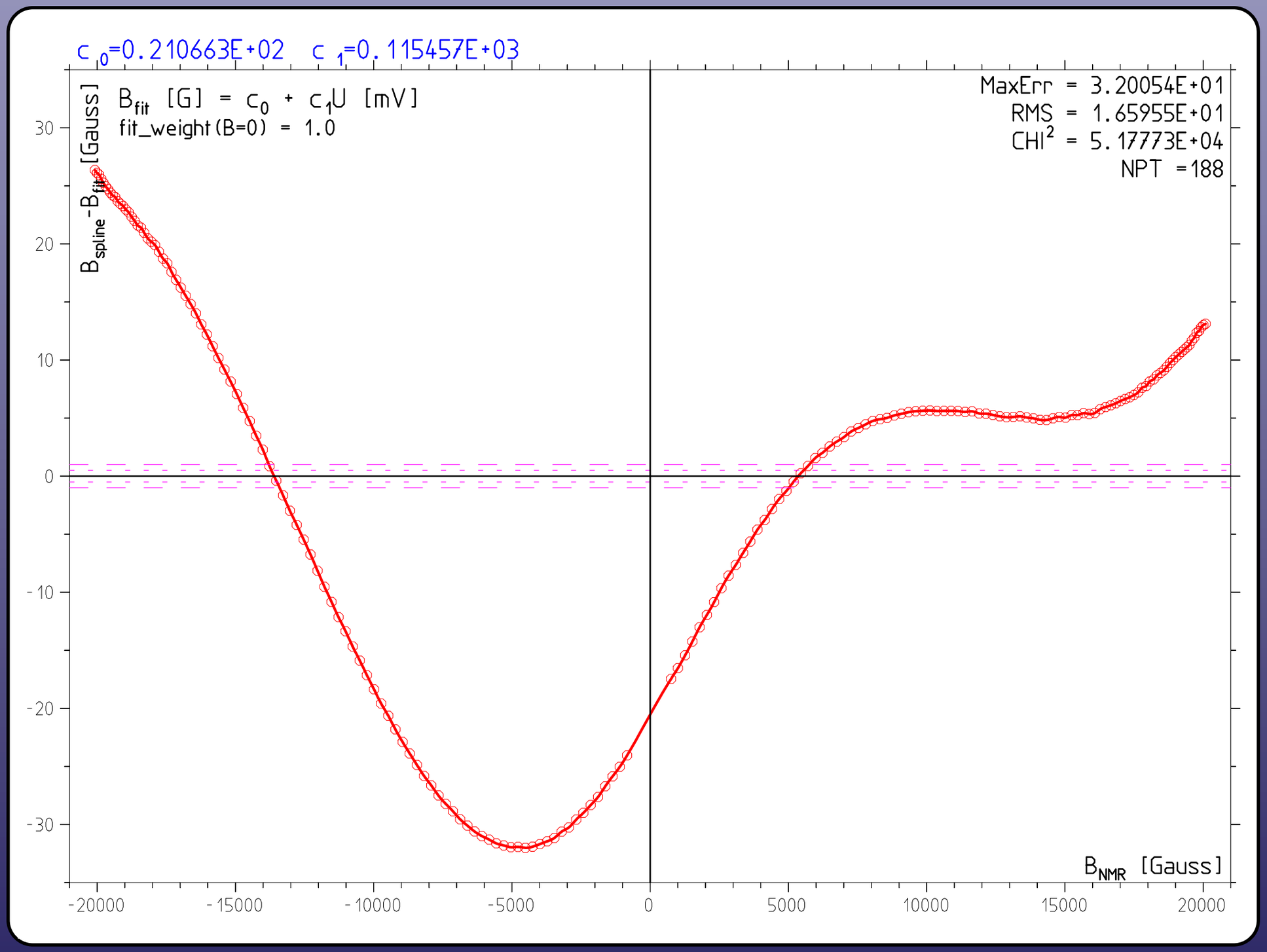
Siemens sbv-585



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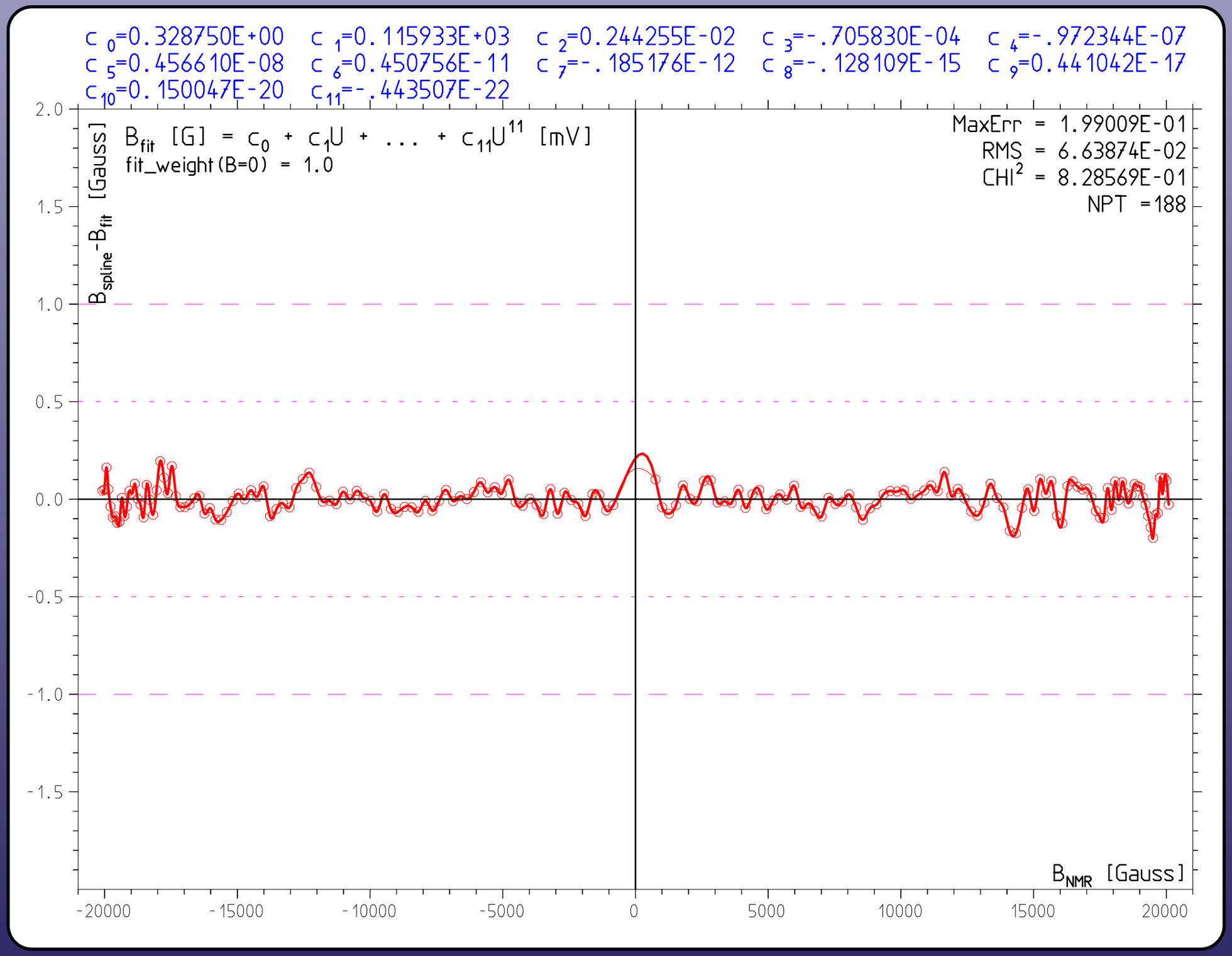
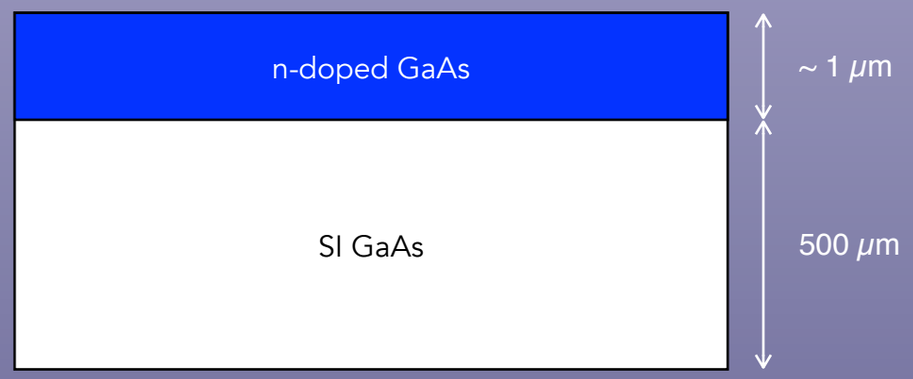
Siemens sbv-585

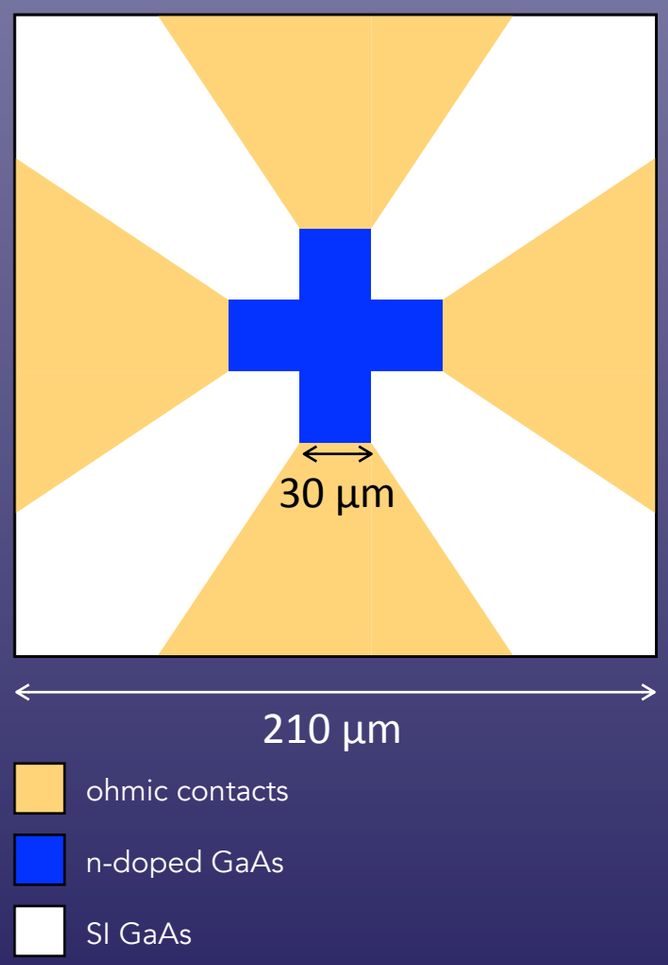


GaAs Hall sensor

GaAs has a high mobility *and* a low intrinsic carrier concentration



$$R = \rho \frac{l}{wd} = \frac{1}{nq\mu}\frac{3}{d} \qquad V_{Hall} = \frac{1}{nqd} IB = \frac{\mu\rho}{d} IB$$



The ideal Hall sensor:

- High sensitivity
- Low driving current
- Low resistance
- Low temperature coefficient
- Low offset
- High linearity
- Longterm stability

...compromise!

† D.C. Look, "Electrical Characterization of GaAs Materials and Devices", John Wiley and Sons 1989
‡ S.M. Sze, "Physics of Semiconductor Devices", John Wiley and Sons 2007

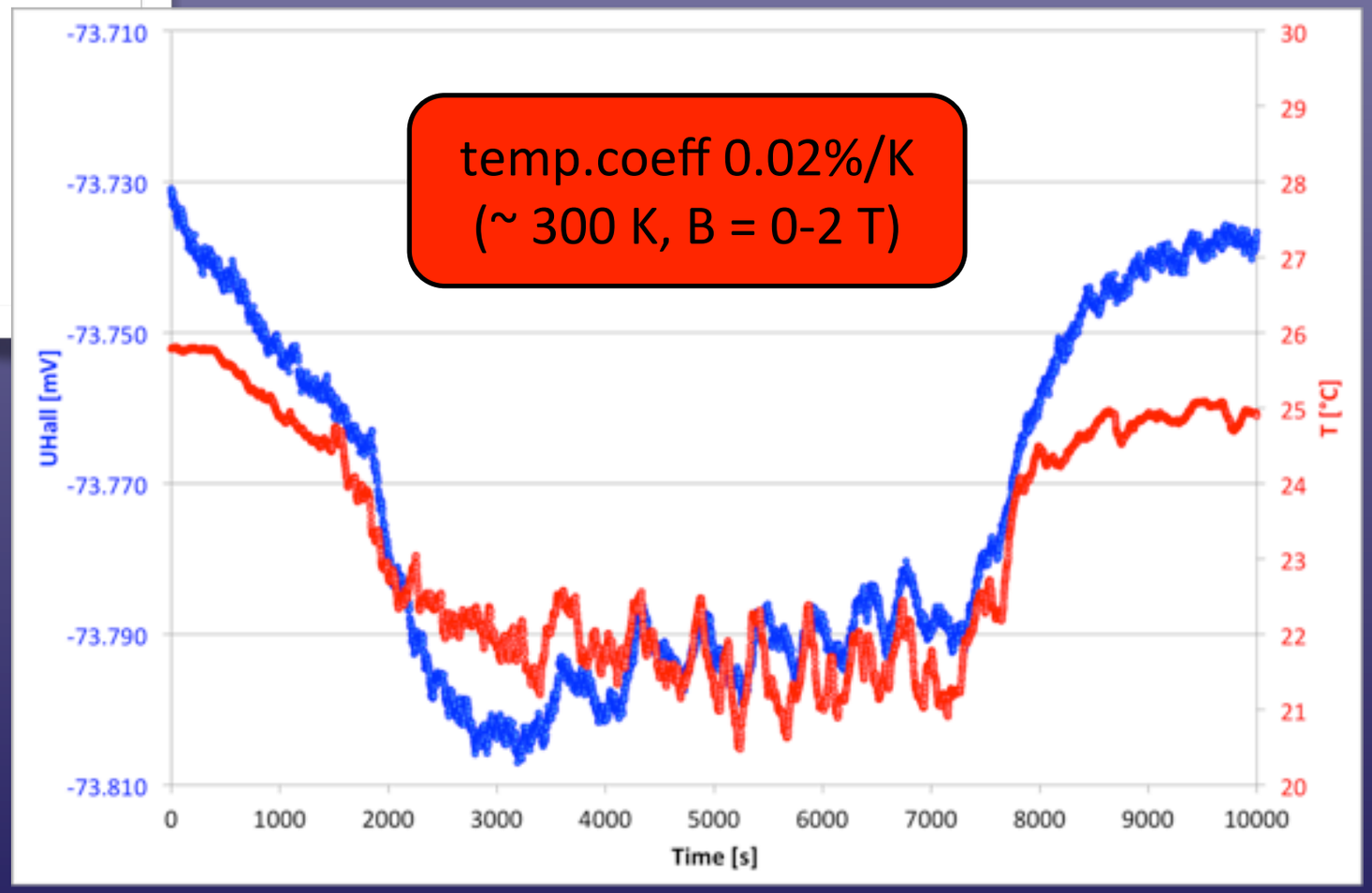
GaAs Hall sensor

"HPF1" (Version 0)
2DEG from GaAs-$Al_{0.3}Ga_{0.7}As$ heterostructure with Si-doping

✔ Very high sensitivity
✔ Very low driving current (tens of µA)
✘ High resistance (non-trivial cabling)
✘ Strong sensitivity of Hall voltage to ambient light
✘ Too high temperature coefficient of Hall voltage
✘ Noisy

"HPF2" (Version 1)
Si-doped (~10^{18} cm^{-3}) thin film GaAs (~1 µm) on semi-insulating GaAs substrate

✔ High sensitivity (70 V $T^{-1}A^{-1}$)
✔ Low driving current (1 mA)
✘ High resistance (~600 Ω)
✘ Sensitivity of Hall voltage to ambient light
✘ High temperature coefficient of Hall voltage



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GaAs Hall sensor

"HPF1" (Version 0)
2DEG from GaAs-$Al_{0.3}Ga_{0.7}As$ heterostructure with Si-doping

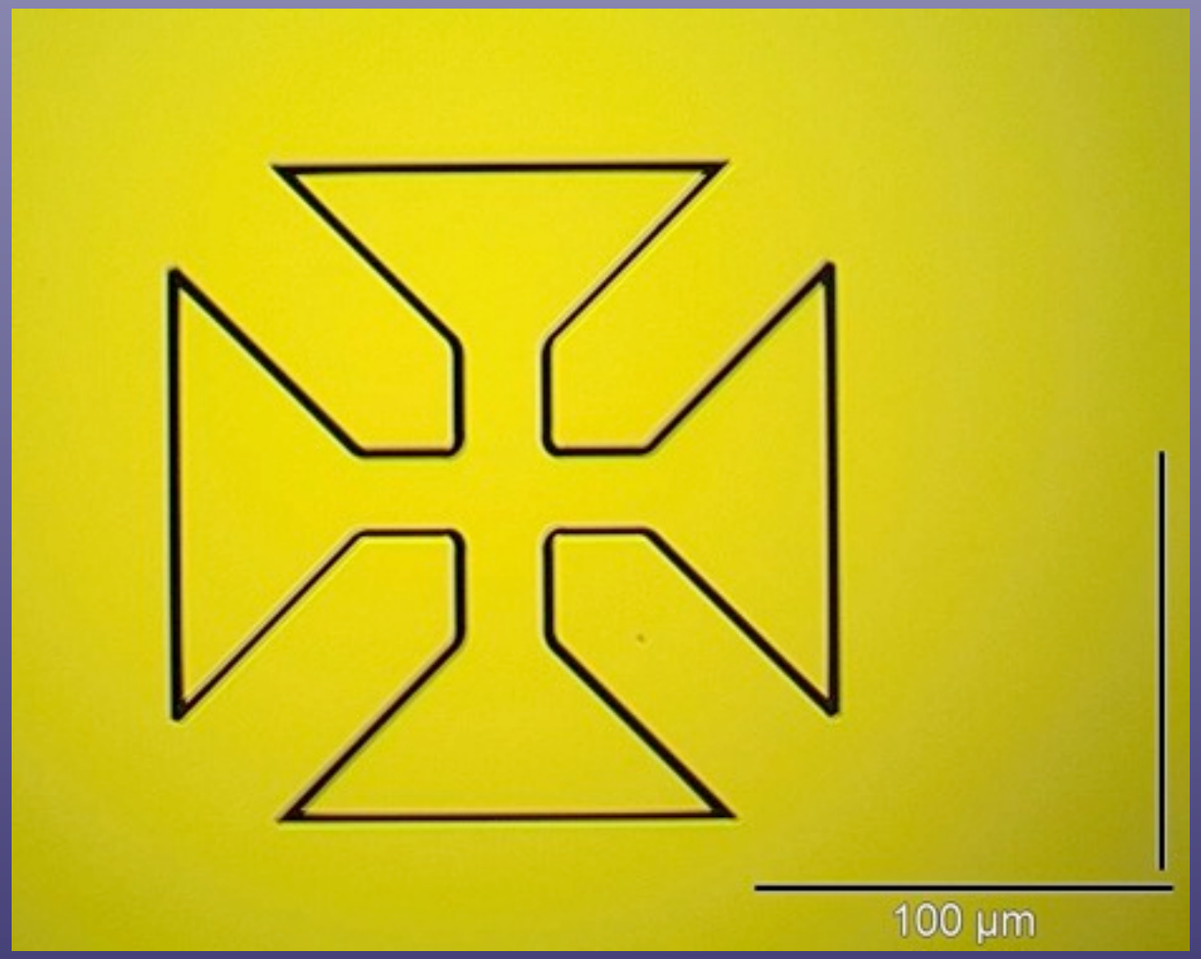
✔ Very high sensitivity
✔ Very low driving current (tens of µA)
✘ High resistance (non-trivial cabling)
✘ Strong sensitivity of Hall voltage to ambient light
✘ Too high temperature coefficient of Hall voltage
✘ Noisy

"HPF2" (Version 1)
Si-doped (~10^{18} cm^{-3}) thin film GaAs (~1 µm) on semi-insulating GaAs substrate

✔ High sensitivity
✔ Low driving current (1 mA)
✘ High resistance
✘ Sensitivity of Hall voltage to ambient light
✘ High temperature coefficient of Hall voltage

"HPF3" (Version 2)
Si-doped (~10^{19} cm^{-3}) thin film GaAs (~1 µm) on semi-insulating GaAs substrate

✔ Low resistance
✔ Low temperature coefficient of Hall voltage
✔ Very low sensitivity of Hall voltage to ambient light
✔ Very high linearity
✘ Moderate sensitivity



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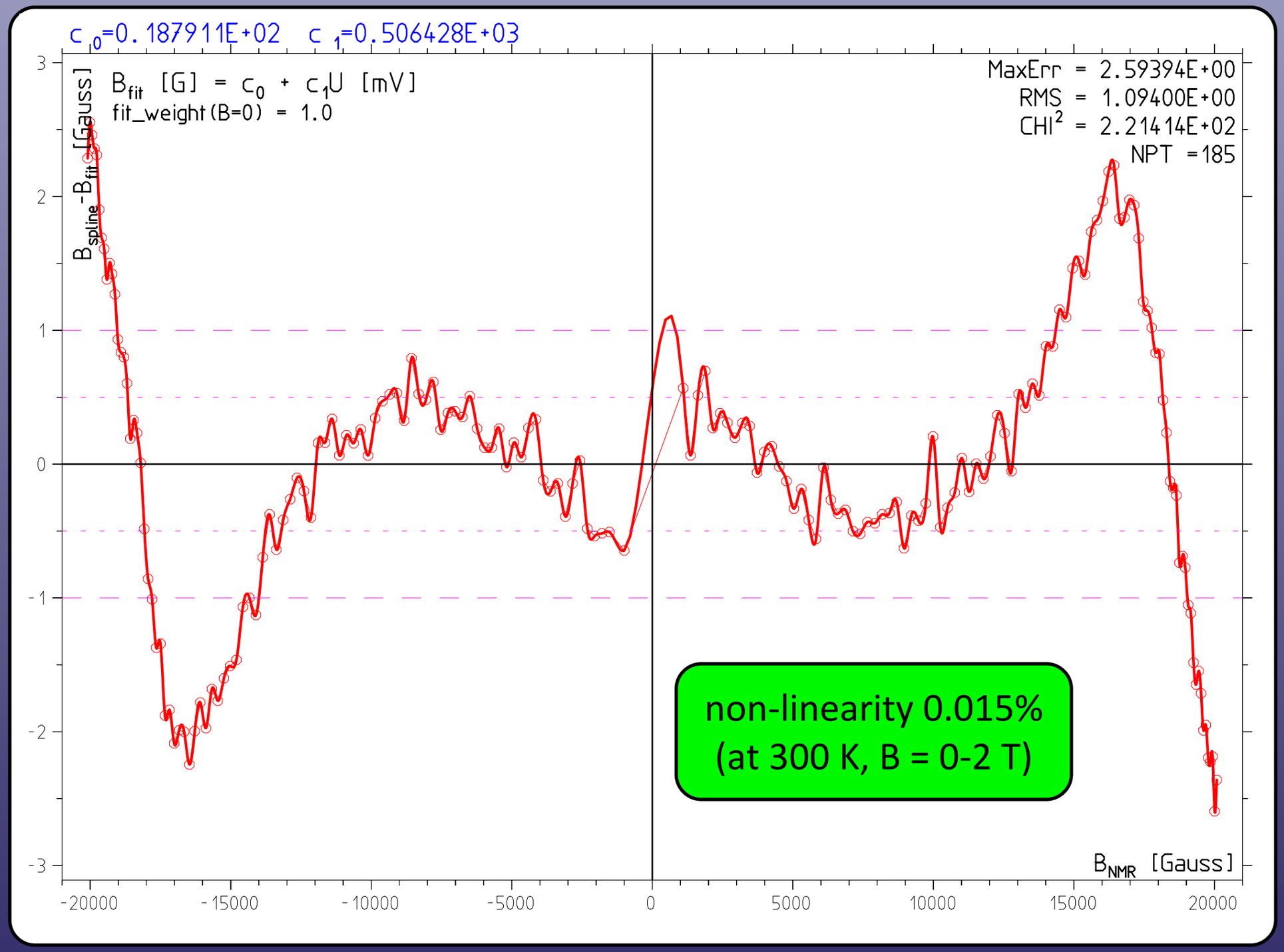
Calibration results "HPF3"



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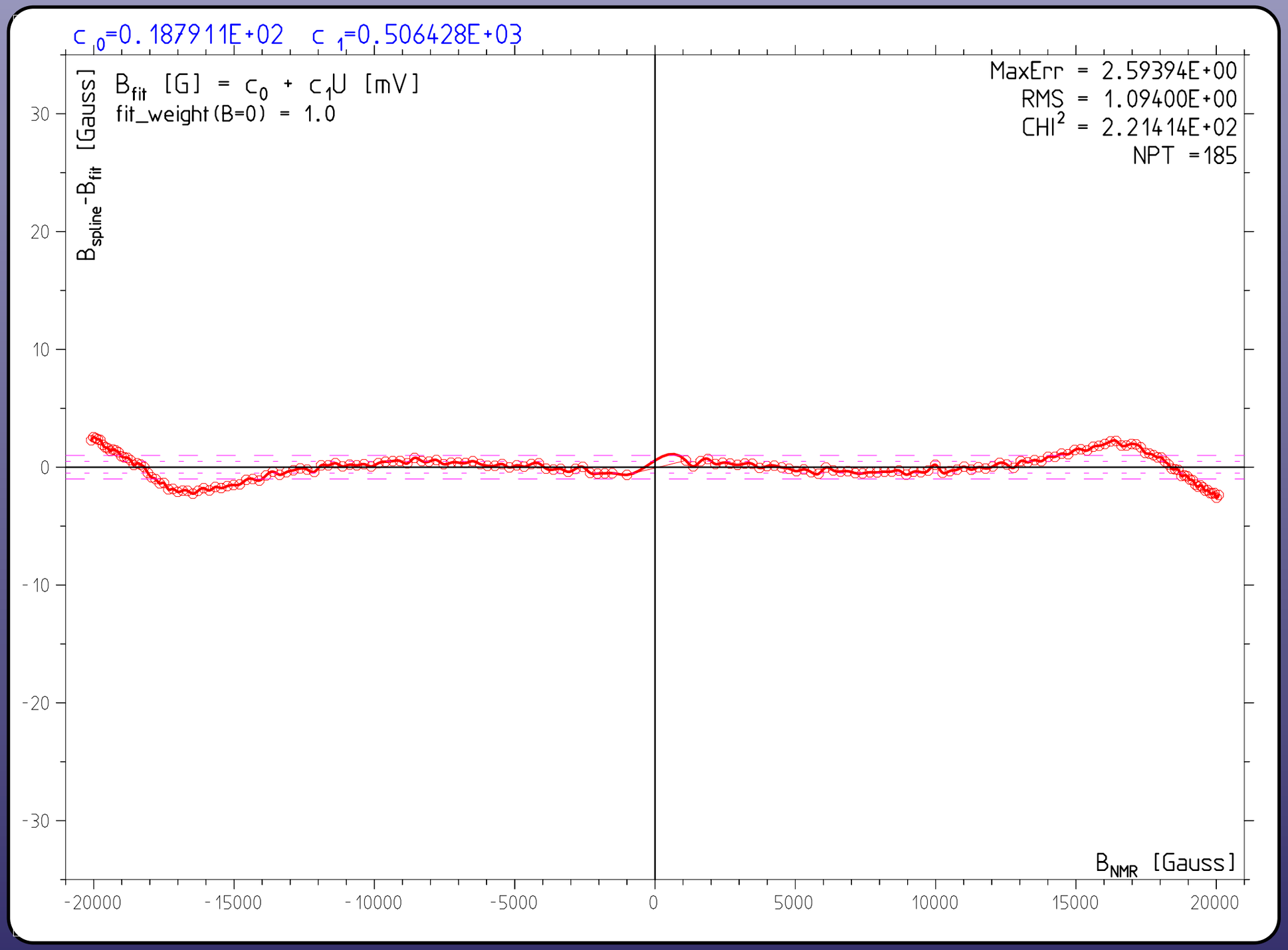
Calibration results "HPF3"



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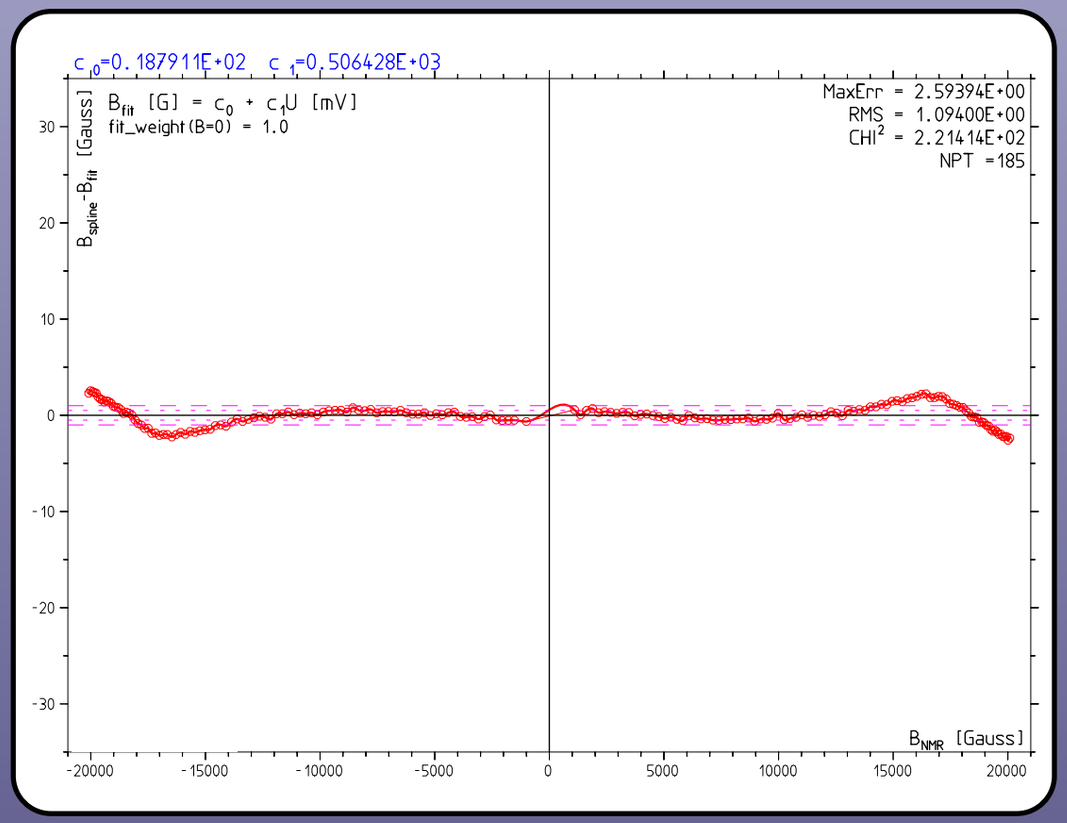
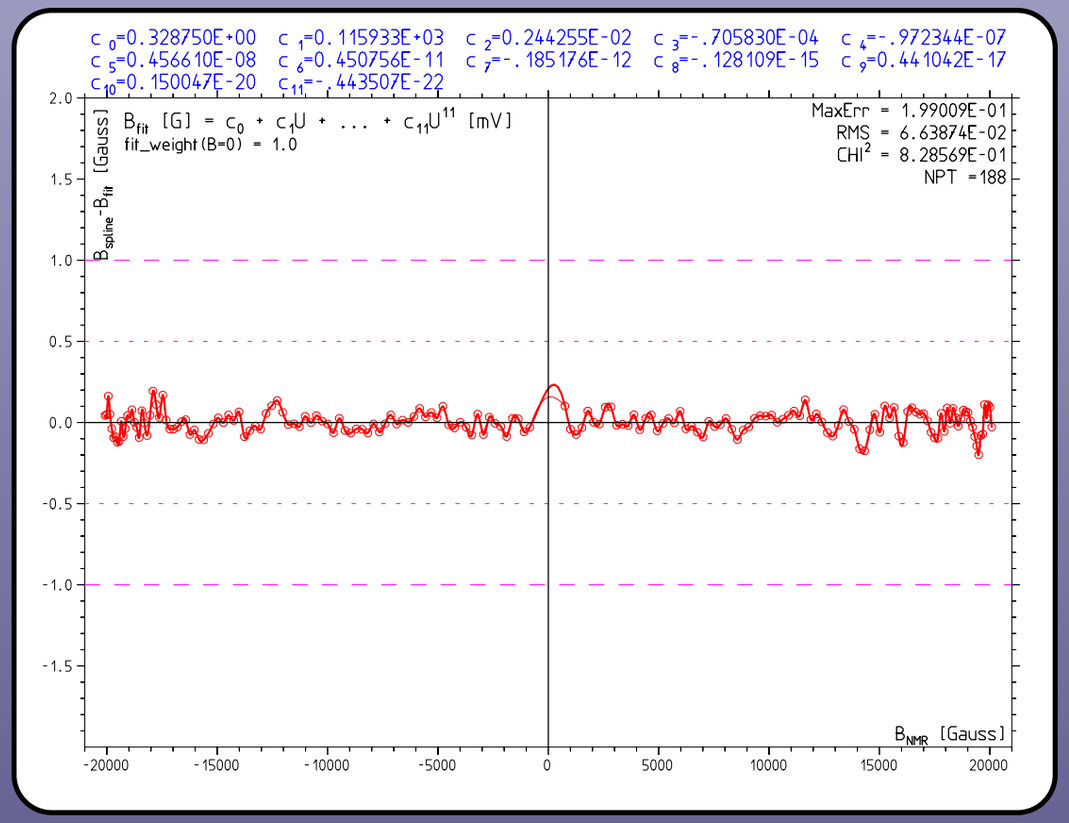
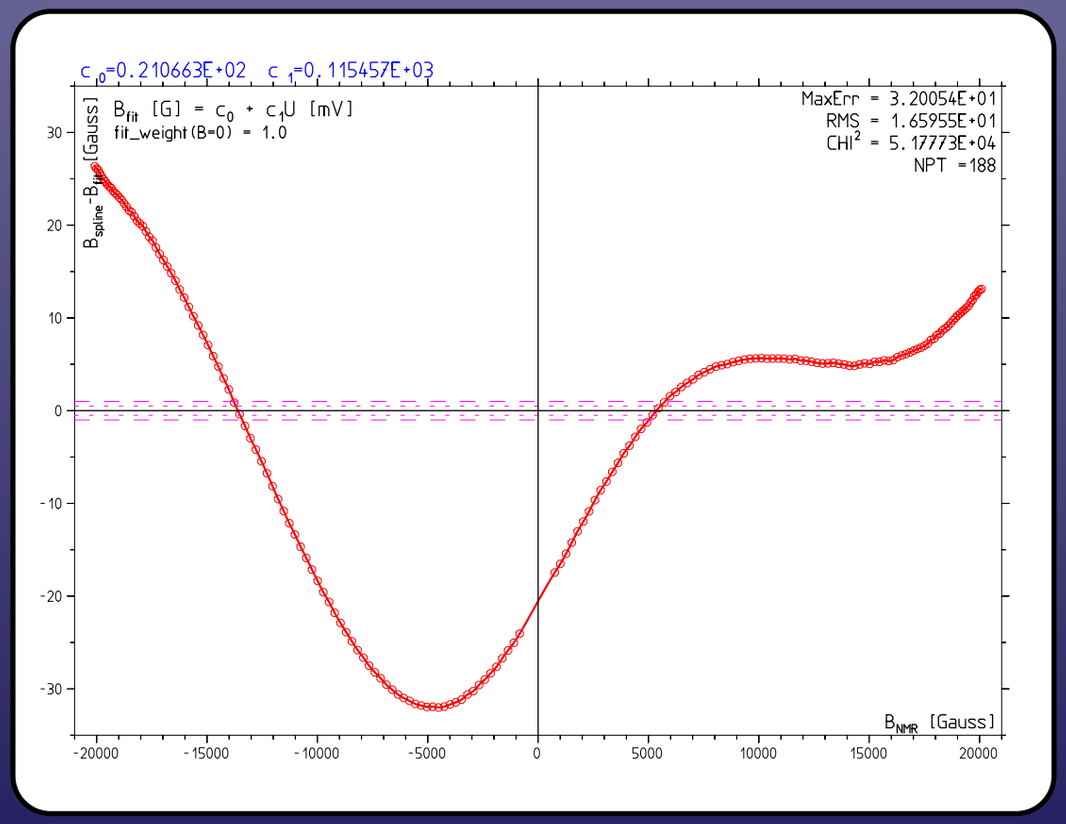
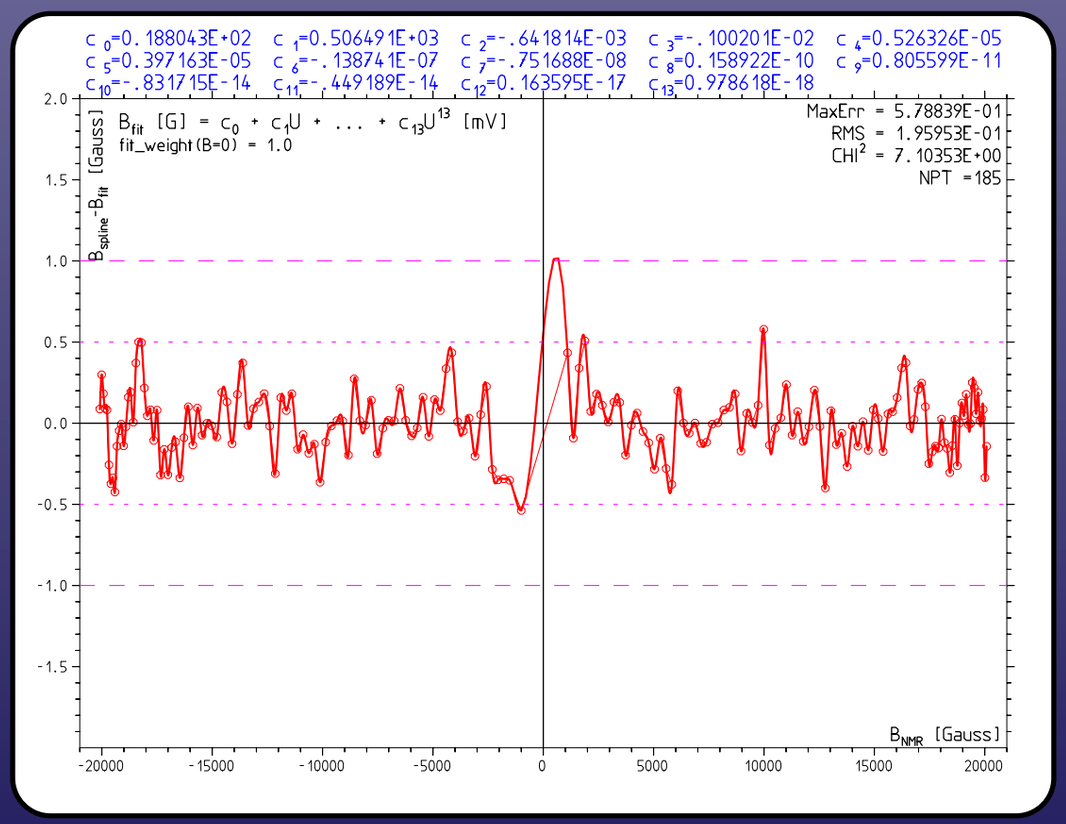
Calibration results “HPF3”

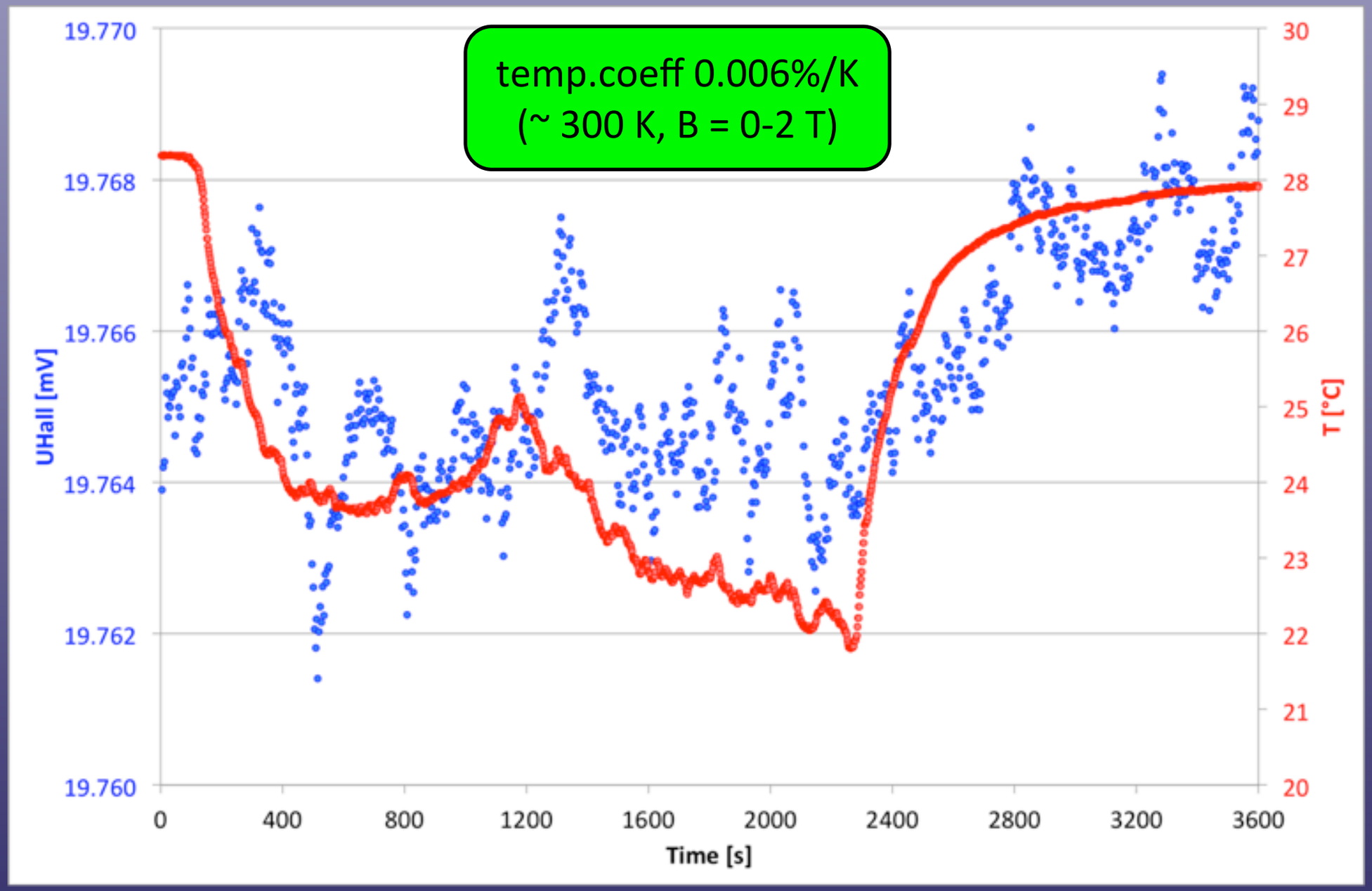








Results "HPF3"



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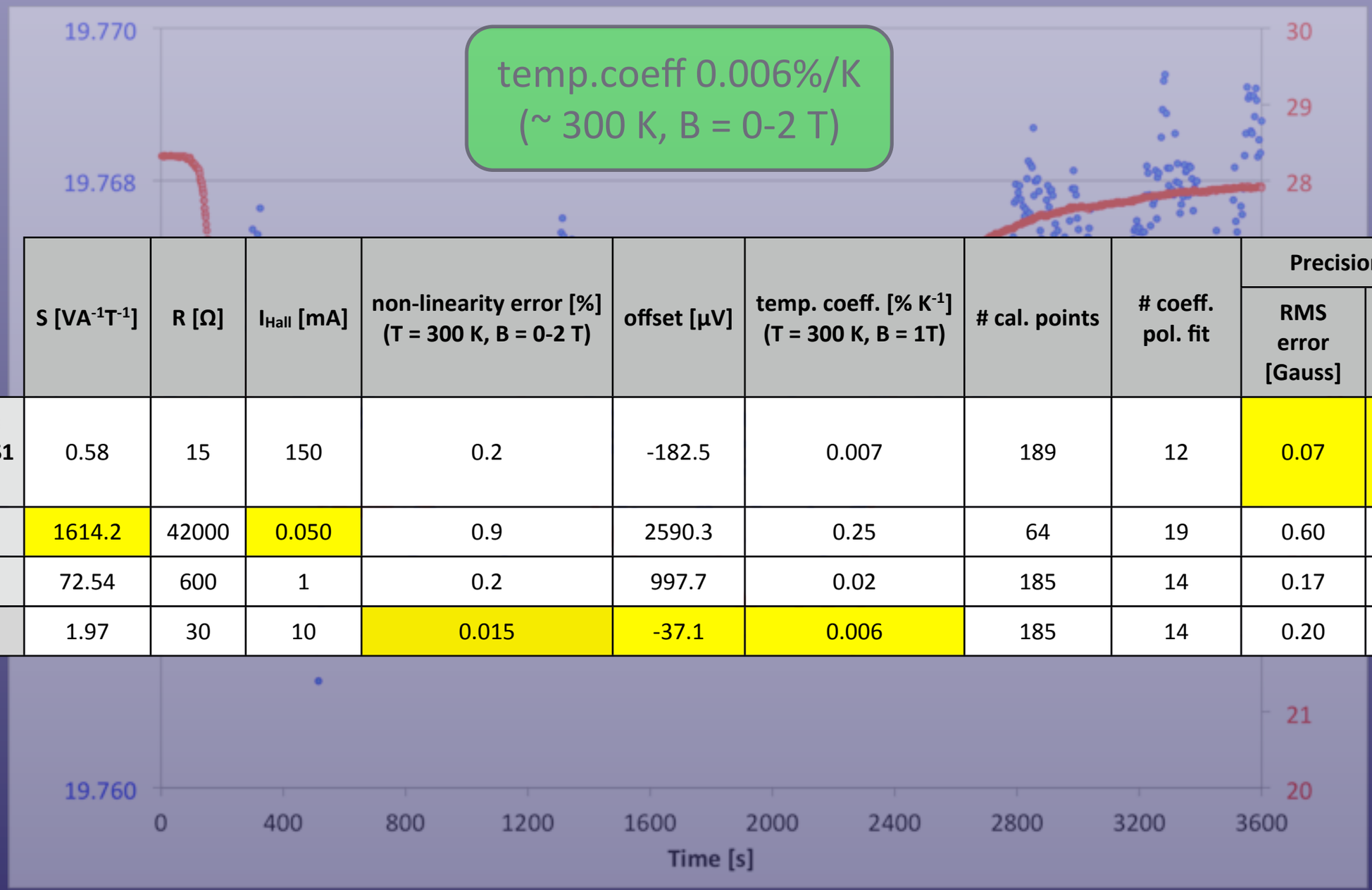
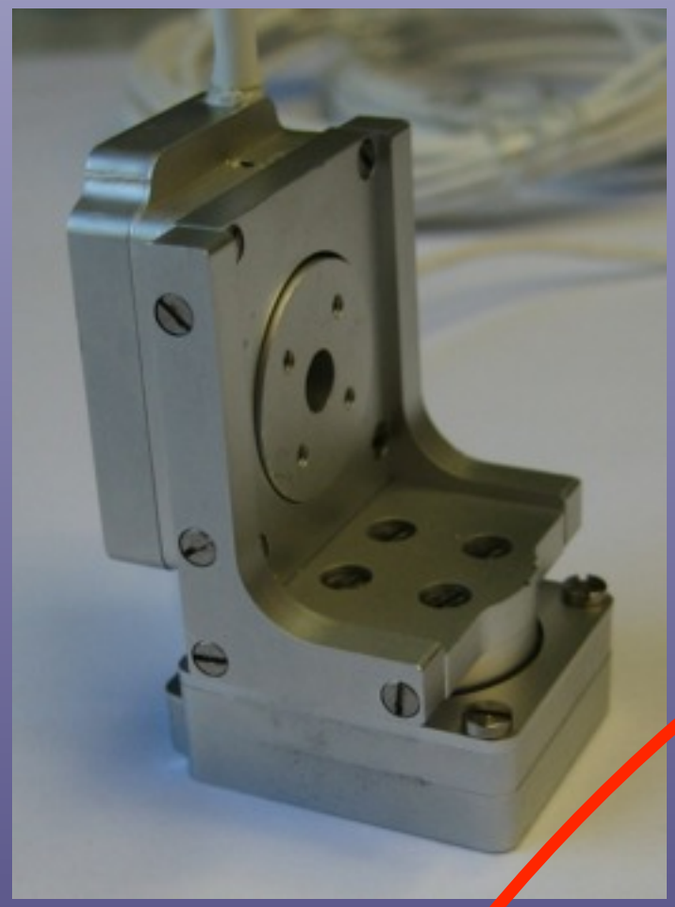
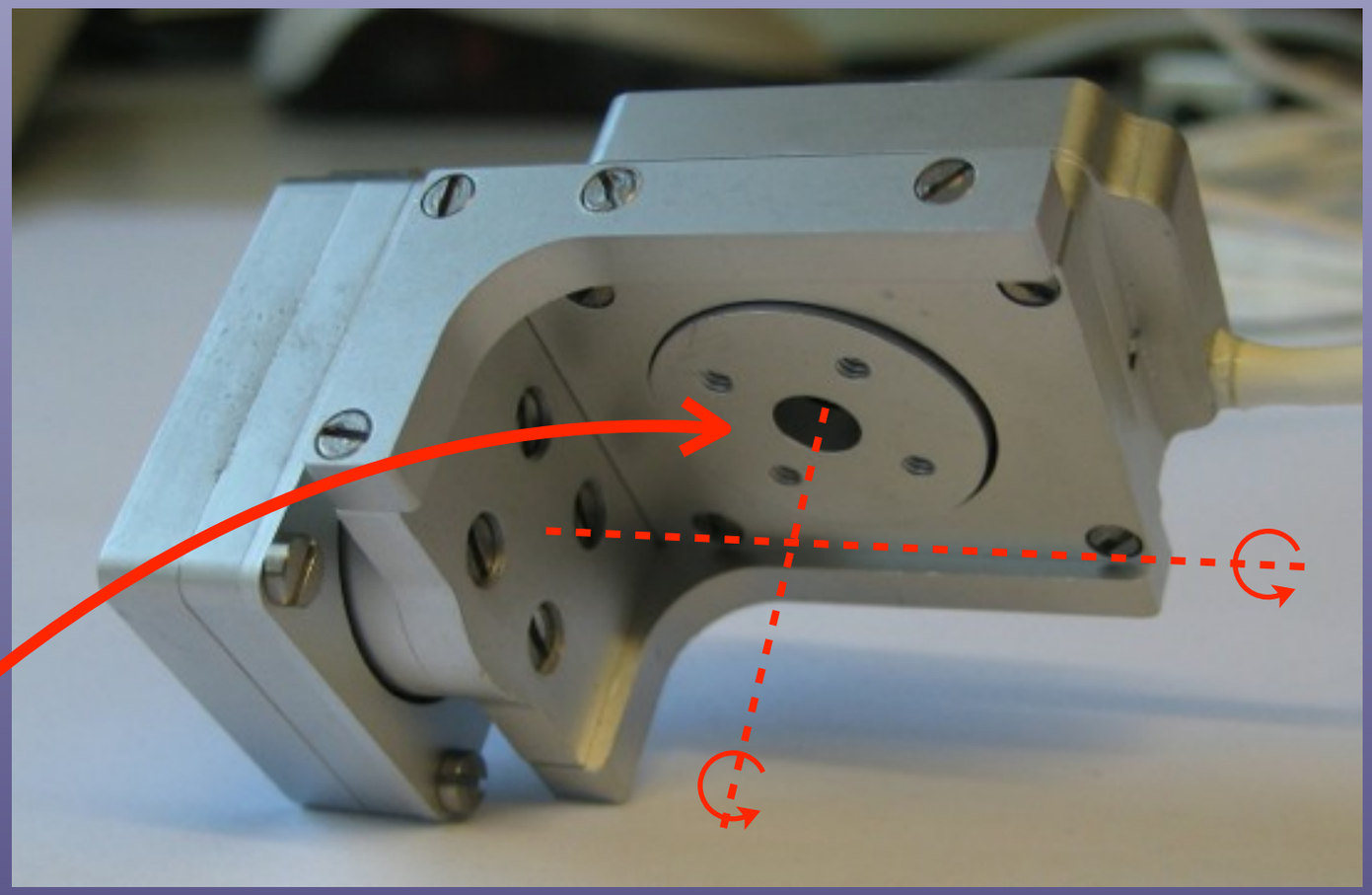
Results "HPF3"

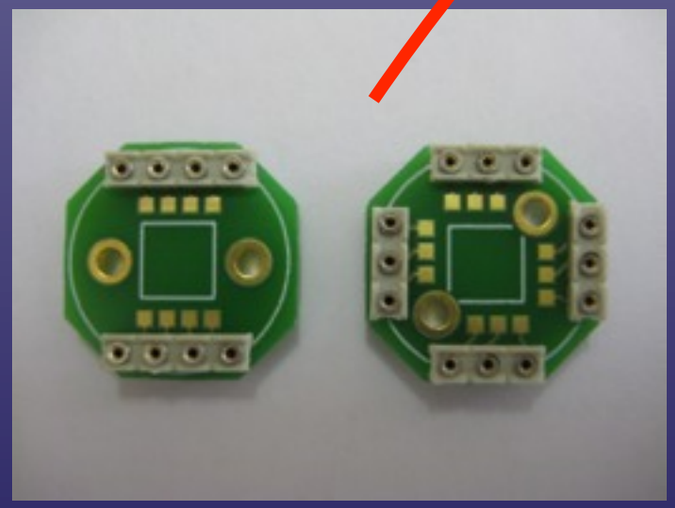


	S [$VA^{-1}T^{-1}$]	R [Ω]	I_{Hall} [mA]	non-linearity error [%] (T = 300 K, B = 0-2 T)	offset [µV]	temp. coeff. [% K^{-1}] (T = 300 K, B = 1T)	# cal. points	# coeff. pol. fit	Precision of fit	
									RMS error [Gauss]	max error [Gauss]
Siemens SBV-585 S1 #397	0.58	15	150	0.2	-182.5	0.007	189	12	0.07	0.20
HPF1	1614.2	42000	0.050	0.9	2590.3	0.25	64	19	0.60	2.16
HPF2	72.54	600	1	0.2	997.7	0.02	185	14	0.17	0.56
HPF3	1.97	30	10	0.015	-37.1	0.006	185	14	0.20	0.58

Piezo motors







SmarAct SR-2013-S-NM

- Fits into PSI calibration magnet gap (38 mm)
- HALL*cube* rotates around its centre
- Sensor resolution: 25 μrad
- Movement resolution: 3 μrad
- EPICS controlled

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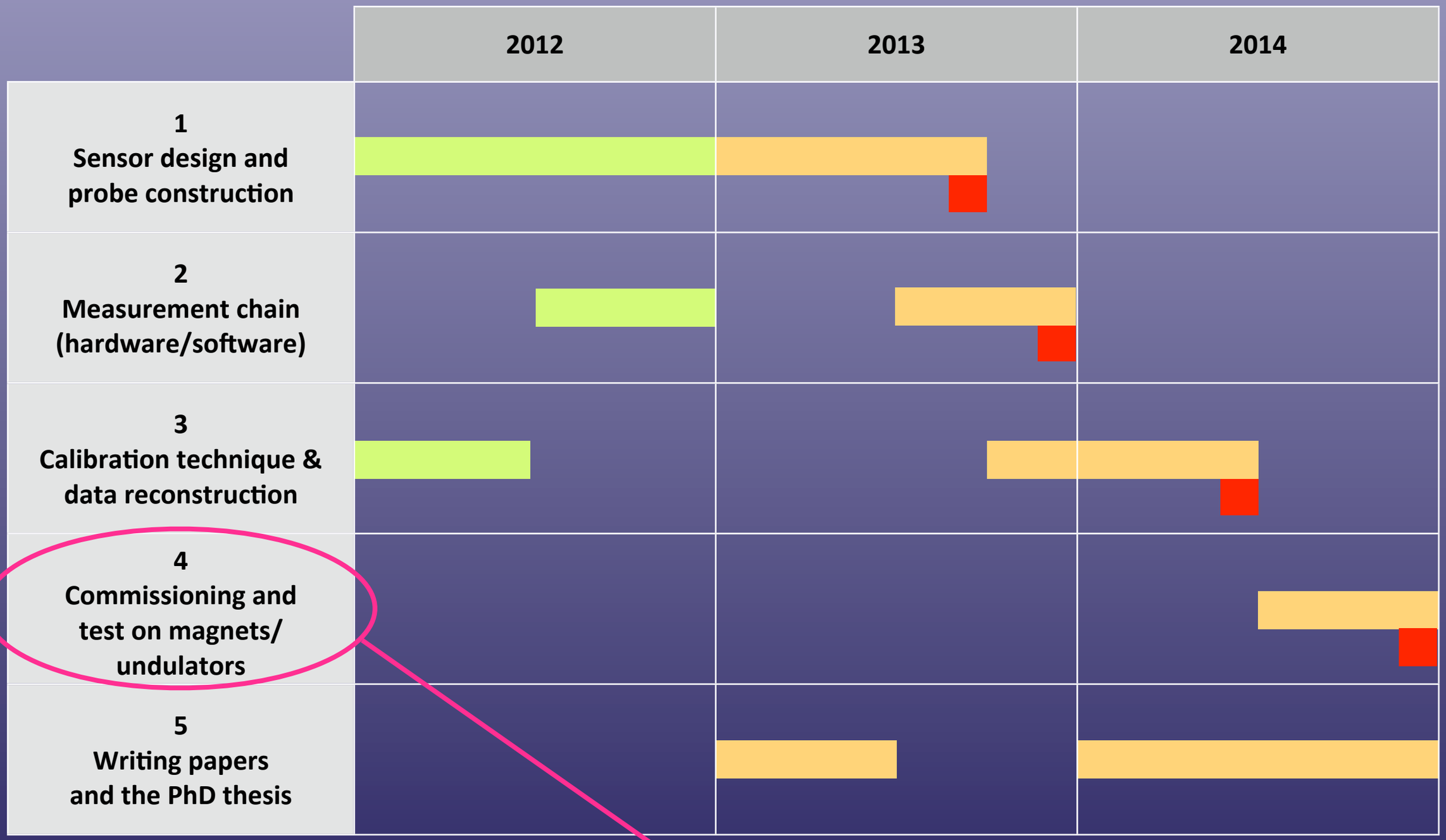
Outlook



christina.wouters@psi.ch