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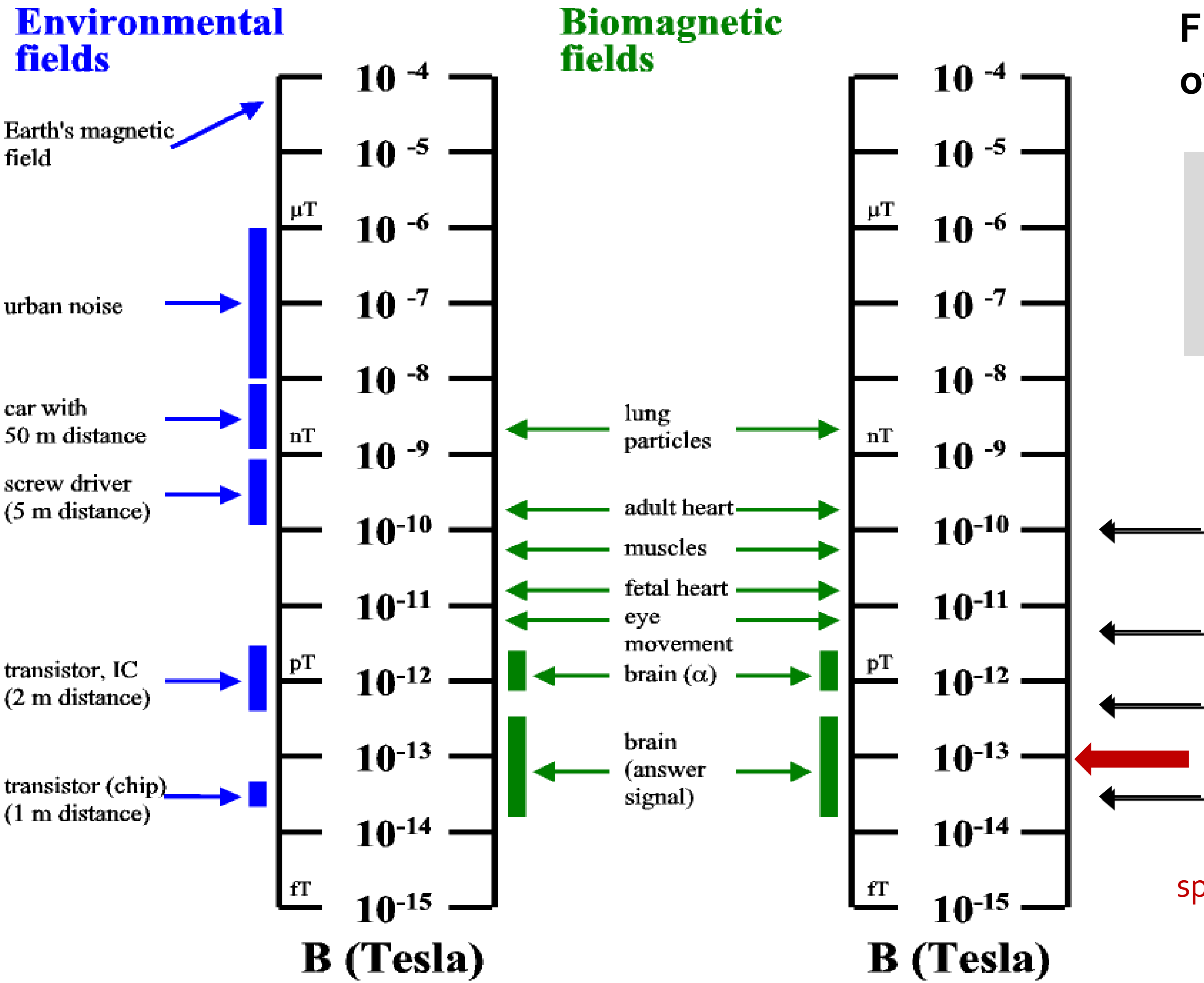
Sensitivity Analysis and Non-Linear Optimisation of Shot-Noise Limited Magnetic Field Resolution of an Optically Pumped Magnetometer

Mitglied der Leibniz-Gemeinschaft

Leibniz Institute of Photonic Technologies
WOST 2016 Presentation by Bastian Schillig

LEIBNIZ-INSTITUT für PHOTONISCHE TECHNOLOGIEN
ipht jena

Magnetic Field Strength Examples



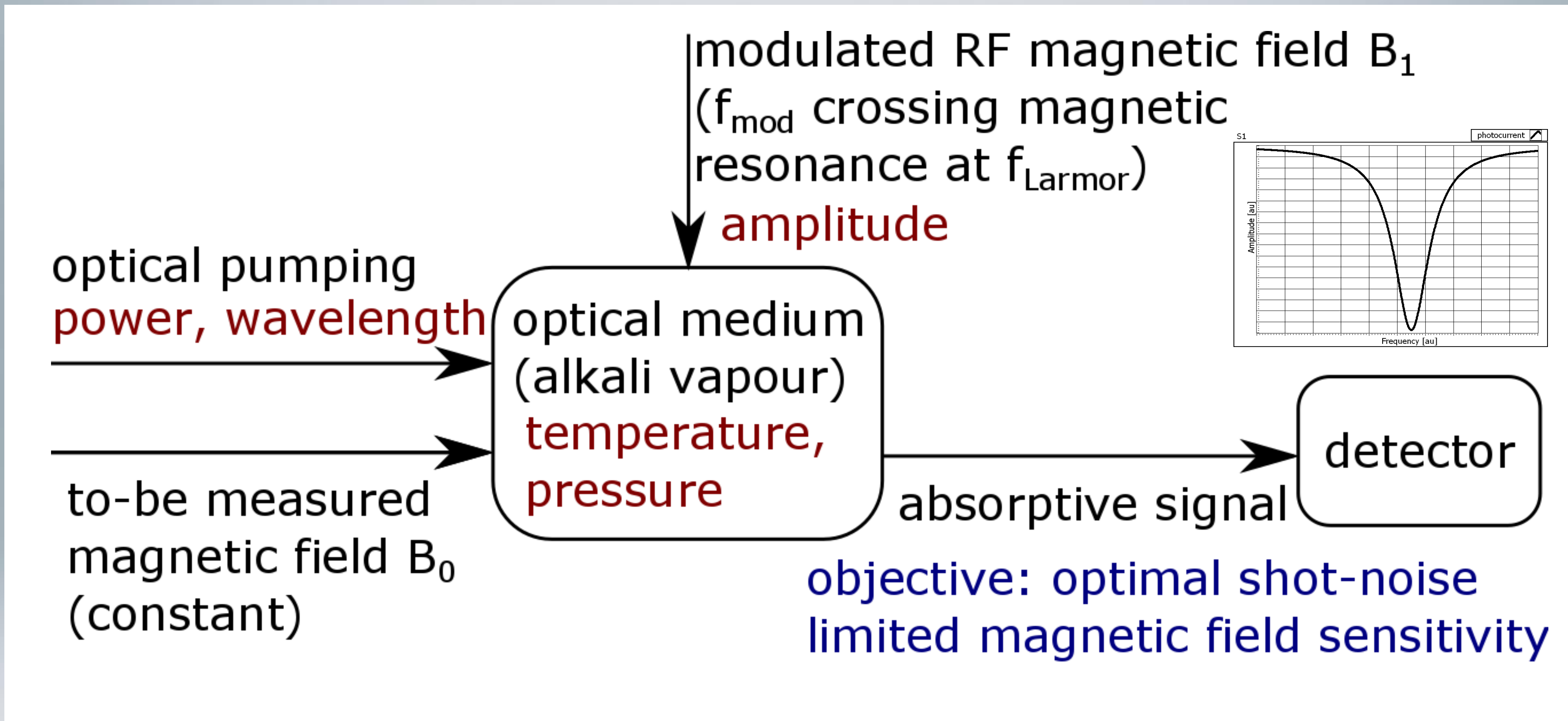
Field resolution of some sensors

Integral peak-to-peak sensor noise extrapolated in the frequency range of 0.01 Hz to 10 Hz (cresst factor = 4)

- Fluxgate (Bartington)
- Induction coil (Metronix)
- OPM (Uni Fribourg)
- OPM (IPHT)
- SQUID (IPHT)

Optimised OPM spectral resolution $B_{sn} < 10 \frac{\text{fT}}{\sqrt{\text{Hz}}}$!

Optically Pumped Magnetometer Principle



$$f_{\text{Larmor}} = \gamma \cdot B_0$$

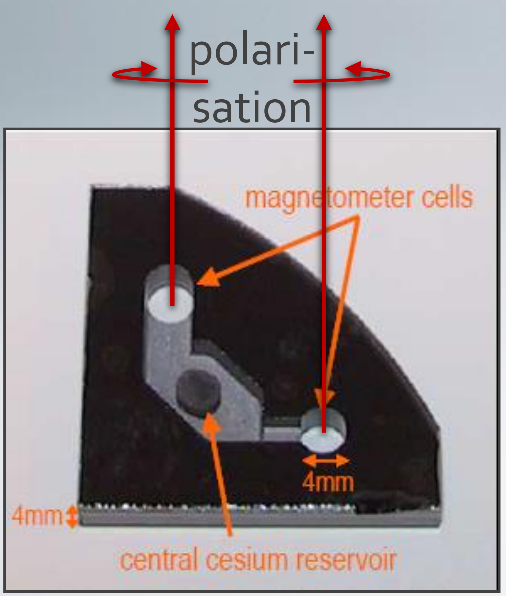
Gyromagnetic ratio γ is an atom constant

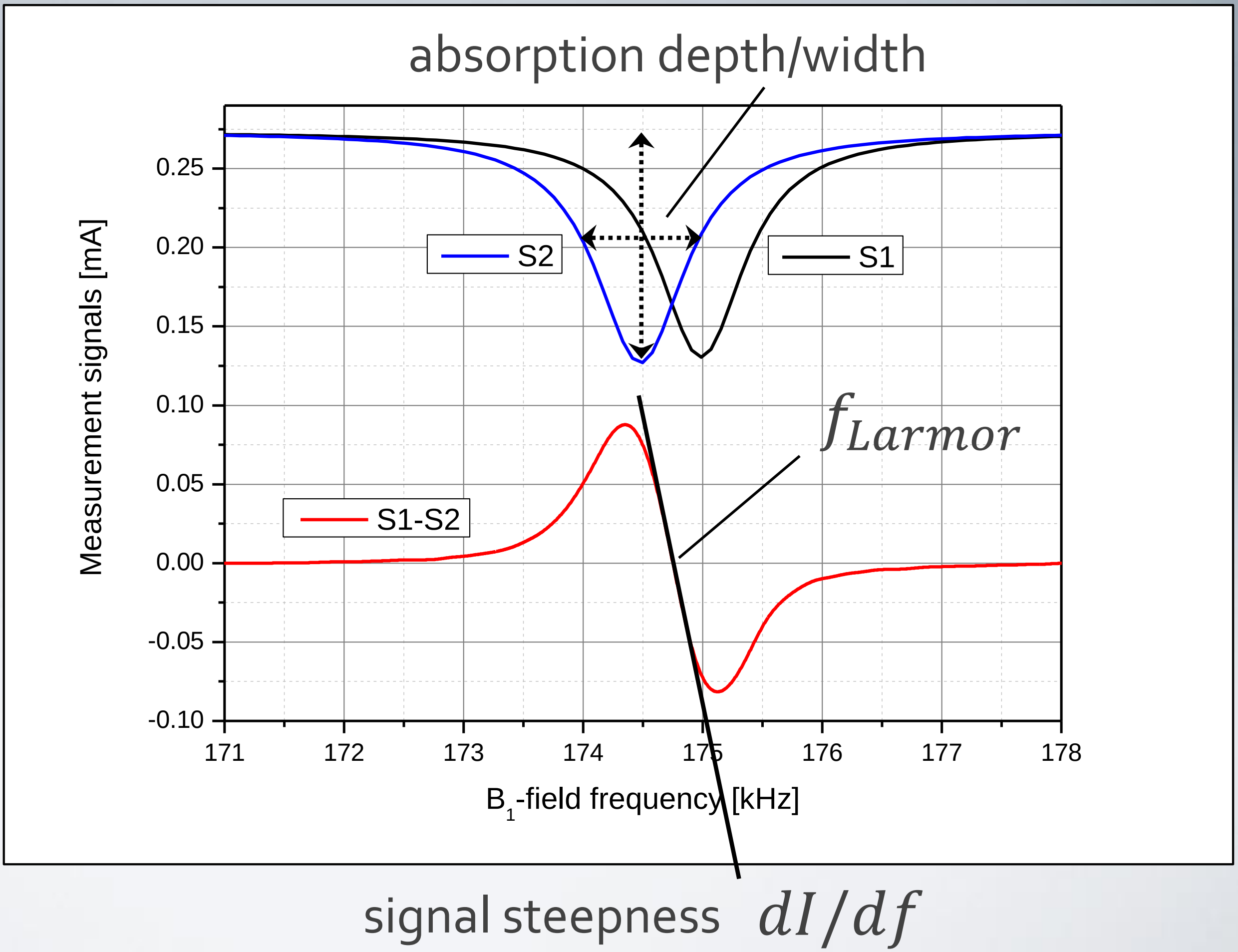
→determine f_{Larmor} at resonance frequency → know B_0

Measurement Regime

- Pumping in two equal cells
- Counter-oriented circular polarisation → peak shift
- Signal difference plot reveals Larmor frequency at zero crossing

$$B_{sn} = \frac{I_{sn}}{\gamma \cdot |dI/df|}$$



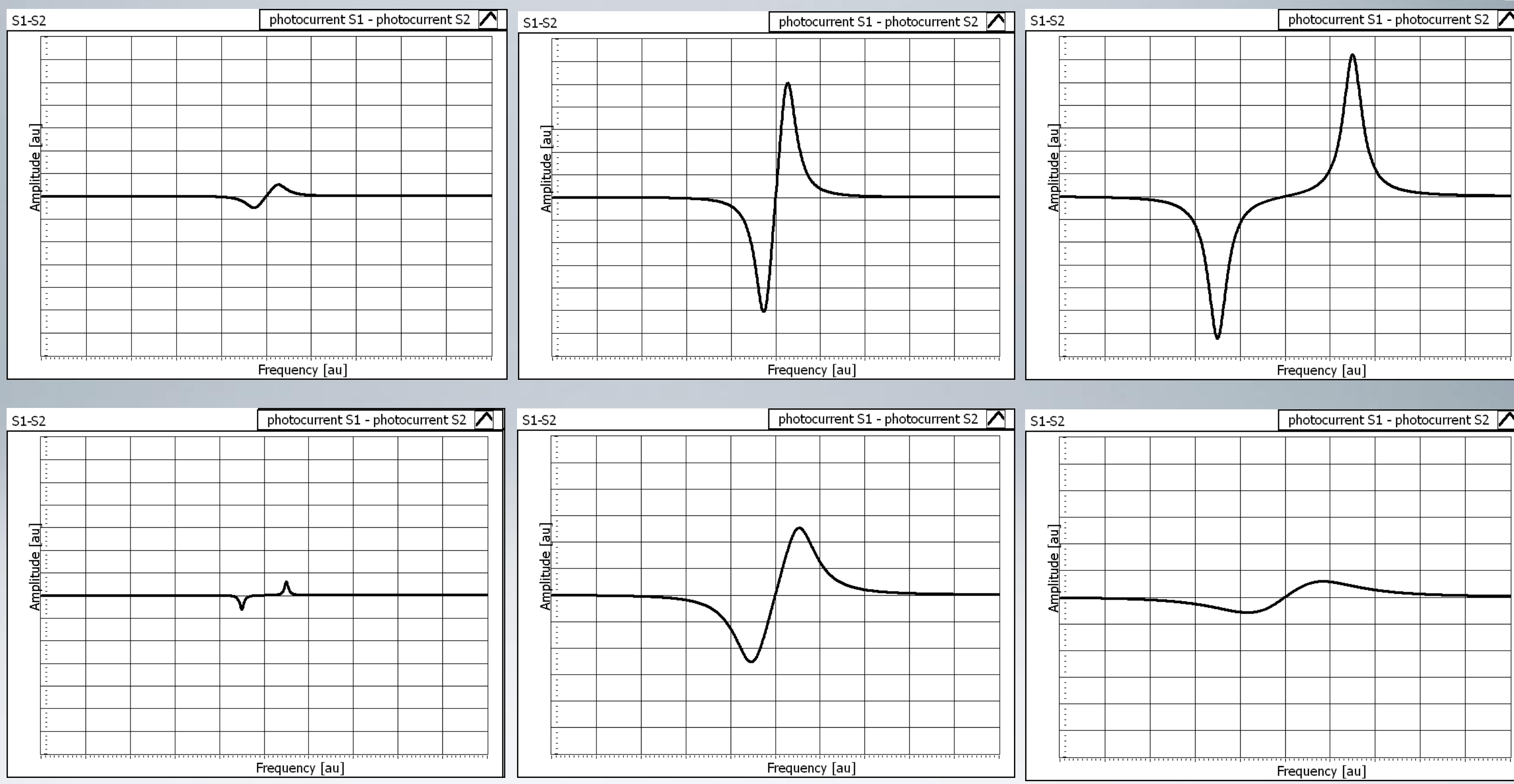


Example of two Input Parameters' Impact

low | medium | high

Pump power

B_1 amplitude



Four input parameters→ Complex interplay → **Optimisation**

Initial Situation

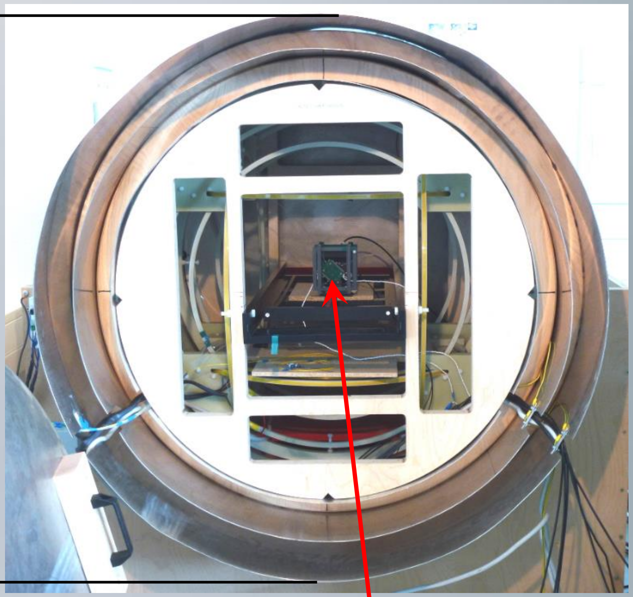
- Magnetometer characterisation setup at IPHT Jena

- Parameter range:

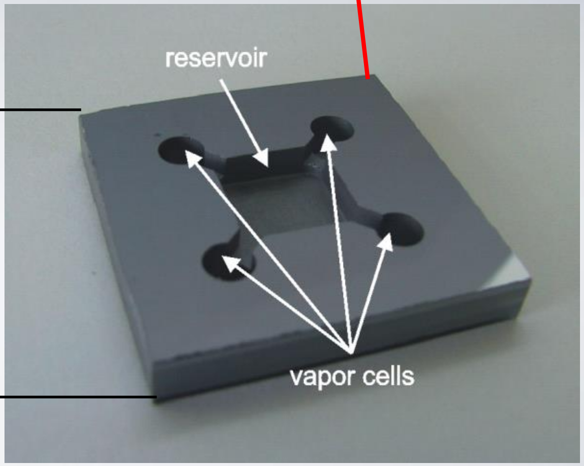
Input parameter	Range	Settling time
Laser frequency detuning voltage	± 1 V	Instant
B_1 source voltage	0.1 – 4 V	Instant
Pump laser power	0.5 – 4.5 mW	Quick (closed loop control)
Caesium cell temperature	80 – 140°C	Slow (closed loop control)
Caesium Cell pressure	110/210 mbar	Extreme (exchange alkali cell in setup)

- Time-consuming single input parameter sweeps + manual evaluation of measured data (months to characterise one cell!)

1.5 m



35 mm



Problem Approach

- Hardware → remote control by GPIB
- LabView → measuring and automated signal curve evaluation
- Integrate optiSLang → data exchange interface (batch script)
- Sensitivity analysis and optimisation on the real technical system
- Obtain system behaviour approximation model and optimal input parameter combination

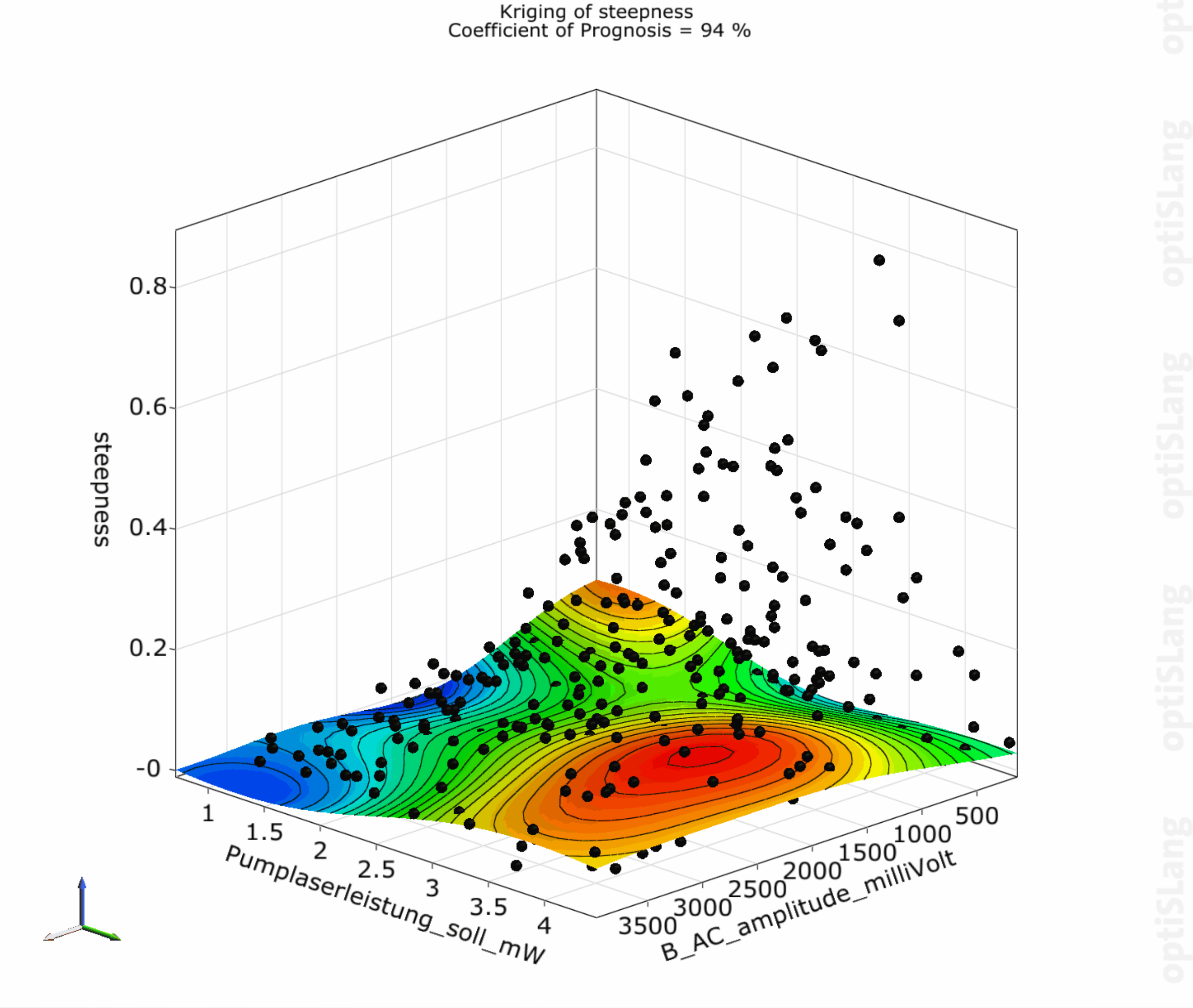
Realisation Sensitivity Analysis

- All measurements with B_0 at 50 µT (~earth magnetic field)
- Possibility of many failed designs → 10*LHS of 60 steps

  = 600 measurements
- Ordered by ascending temperature with optiSLang Excel plugin
- Measure time single data point: ~1 min

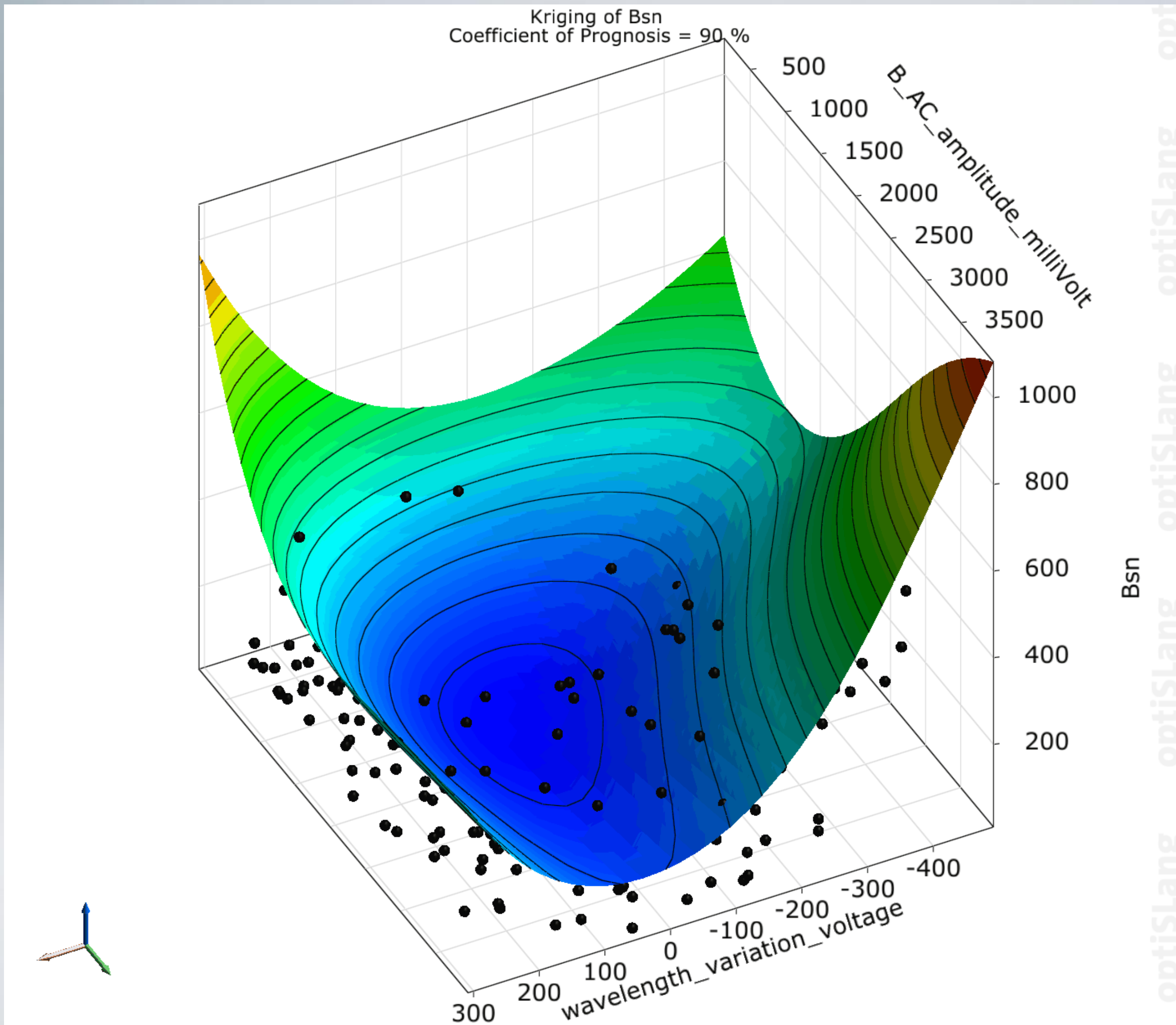
  → about ten hours measure time
- Comparison: full factorial → 60^4 measurements → over 24 years

Results Sensitivity Analysis



Signal steepness vs. pump power and B_1 RF field amplitude, sweep over temperature 80–140°C, laser wavelength constant

Results Sensitivity Analysis



B_{sn} vs. detuning voltage and B_1 RF field amplitude, sweep over temperature 80–140°C, pump power constant

Results Sensitivity Analysis – CoP Matrix

	B_AC_...iVolt	Pumpl...ll_mW	Zellen...elsius	wavel...ltage	CoP total
DC_A	Filtered!	88 %	15 %	Filtered!	99 %
DC_B	Filtered!	85 %	17 %	0 %	99 %
Differenz_DC	Filtered!	41 %	57 %	10 %	85 %
FWHM_A	59 %	4 %	11 %	32 %	93 %
FWHM_B	58 %	0 %	13 %	33 %	97 %
ResDepth_A	38 %	30 %	58 %	6 %	100 %
ResDepth_B	34 %	33 %	52 %	7 %	98 %

	B_AC_...iVolt	Pumpl...ll_mW	Zellen...elsius	wavel...ltage	CoP total
fl_A	10 %	69 %	Filtered!	15 %	90 %
fl_A_B	35 %	27 %	29 %	23 %	51 %
fl_B	6 %	77 %	Filtered!	10 %	88 %
Isn_A	Filtered!	89 %	10 %	Filtered!	99 %
Isn_B	Filtered!	81 %	15 %	0 %	99 %
steepness	41 %	43 %	53 %	22 %	98 %
Bsn	27 %	38 %	7 %	29 %	87 %

Realisation Optimisation

- Objective function is shot–noise limited magnetic field resolution

$$B_{sn} \rightarrow \min$$

- Constraints: positive signal steepness, plausible Larmor frequency ±500 Hz around expected value for B_0 = 50 µT
- Best parameter combination from sensitivity analysis as start design
- Optimisation runs by measuring on the real technical system instead of optimising on the MOP allows instant validation of results
- Pre-optimisation by ARSM with start range 0.5
- Local optimisation by Simplex with start range 0.1

Results Optimisation

Cell p = 110 mbar	Pre-Optimisation	Local Optimisation
Algorithm	ARSM	Simplex
Designs measured	220	180
Duration	ca. 7 h	ca. 4 h
B_{sn}	$8.6\,\frac{\mathrm{fT}}{\sqrt{\mathrm{Hz}}}$	$8.6\,\frac{\mathrm{fT}}{\sqrt{\mathrm{Hz}}}$
Temperature	129.8 °C	129.8 °C
Pump Power	3.3 mW	3.3 mW
B_1 Amplitude	945 mV	945 mV
Detuning Voltage	-90 mV	-90 mV

Summary and Outlook

- Automated measurement and result data evaluation
- Interaction between optiSLang, LabView process control and hardware
- Sensitivity analysis enormously saves on time when characterising cells
- Previously unknown effects discovered, subject to further investigation
- Optimal value for B_{sn} determined at 8.6 fT/sqrt(Hz)
- Easily repeat procedure with new cells
- Compatibility for further extension of functionality, even new hardware
- Sufficiently high CoP approximation models allow further optimisation runs (Pareto, EA, particle swarm…) without demand for additional measure time

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Questions, Comments, Observations

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