Technische Universität München

Masterkolloquium

Electric Field Strength and Stability Measurement using the Linear Electro-Optic Effect in Quartz

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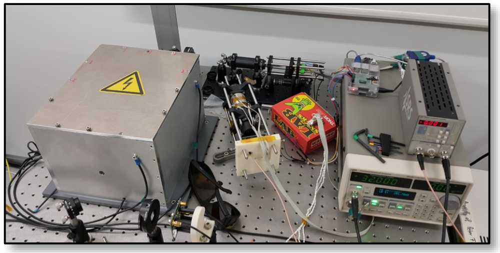
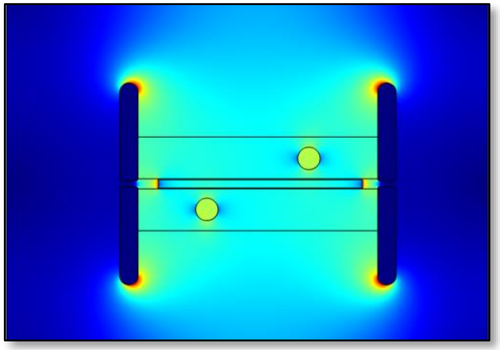
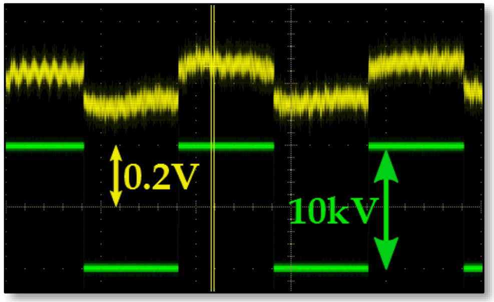
Outline

- Motivation – CP violation & nEDMs
- A bit(e) of theory
- Experimental setup
- Oscillating E-Fields
- Measuring absolute values



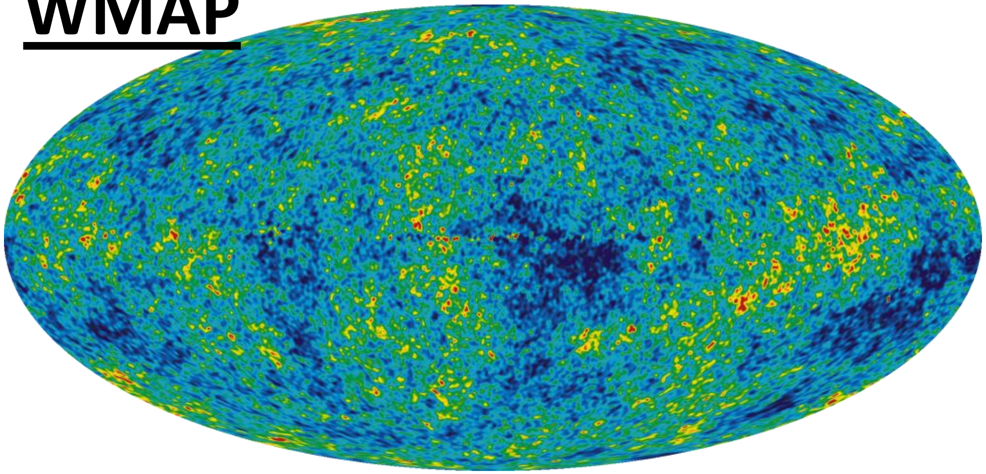




Motivation – CP violation

Matter-Antimatter asymmetry ⟷ Sakharov conditions (e.g. CP violation)

WMAP



$$\frac{n_B}{n_\gamma} \sim 6 \times 10^{-10}$$

[“Sakharov Conditions for Baryogenesis.” (Perepelitsa)]

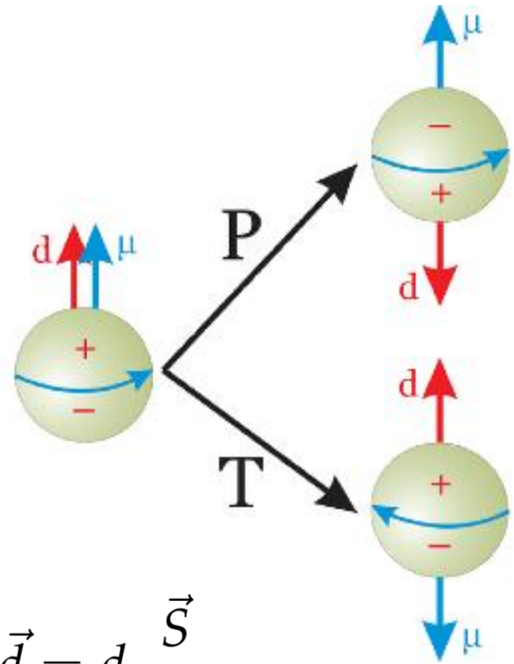
Standard Model

- CP violating complex phase in
  - CKM / PMNS matrices

$$\frac{n_B}{n_\gamma} \sim 10^{-18}$$

[Tests of fundamental physics with optical magnetometers (Kimball, Lamoreaux, Chupp)]

The neutron's electric dipole moment – a (new) probe for CP violation



$$H = -\vec{\mu}_{\mathrm{n}} \cdot \vec{B} - \vec{d}_{\mathrm{n}} \cdot \vec{E}$$

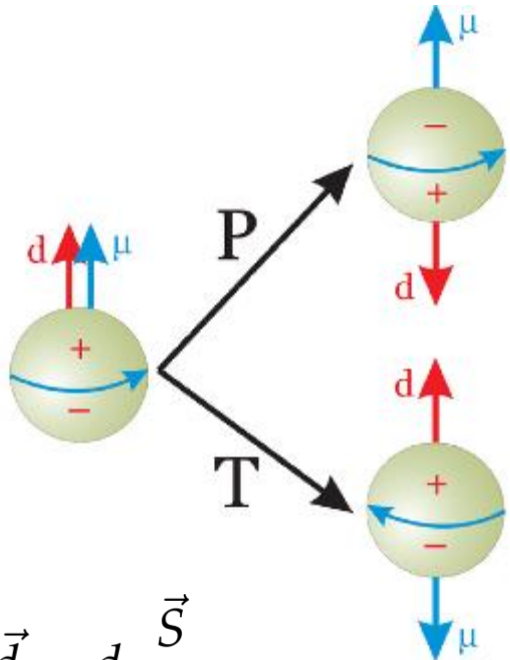
$$\vec{d} = d\,\frac{\vec{S}}{\left|\vec{S}\right|}$$

$$P(d) = -1 \qquad T(d) = +1$$

$$P(\vec{S}) = +1 \qquad T(\vec{S}) = -1$$

[Particle Physics with Neutrons I / II (P. Fierlinger)]

The neutron's electric dipole moment – a (new) probe for CP violation



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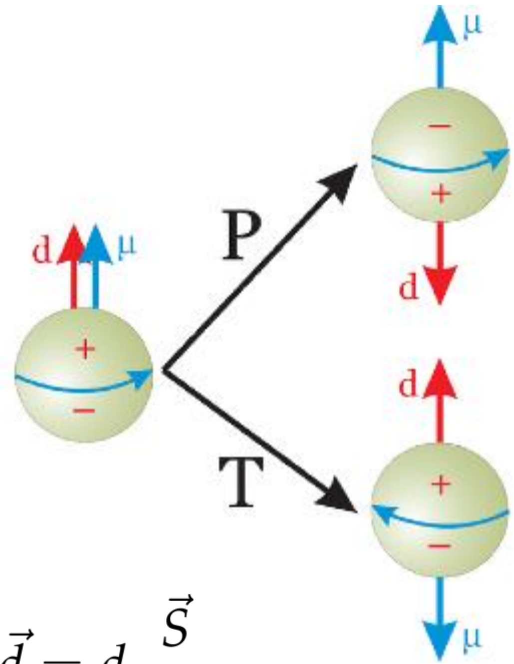
$$P(\vec{S}) = +1 \qquad T(\vec{S}) = -1$$

$$H = -\vec{\mu}_{\mathrm{n}} \cdot \vec{B} - \vec{d}_{\mathrm{n}} \cdot \vec{E}$$

$$\Rightarrow \quad \hbar\,\Delta\omega\,T = -\,2\,\mu_{\mathrm{n}}\left(B_{\uparrow\downarrow} - B_{\uparrow\uparrow}\right)T + 2\,d_{\mathrm{n}}\left(E_{\uparrow\downarrow} + E_{\uparrow\uparrow}\right)T + \hbar\,\Delta\varepsilon_{\mathrm{geo.}}$$

[Particle Physics with Neutrons I / II (P. Fierlinger)]

The neutron‘s electric dipole moment – a (new) probe for CP violation



$$H = -\vec{\mu_n} \cdot \vec{B} - \vec{d_n} \cdot \vec{E}$$

$$\hbar\,\Delta\omega\,T = -2\,\mu_n\left(B_{\uparrow\downarrow} - B_{\uparrow\uparrow}\right)T + 2\,d_n\left(E_{\uparrow\downarrow} + E_{\uparrow\uparrow}\right)T + \hbar\,\Delta\varepsilon_{geo.}$$

$$\vec{d} = d\,\frac{\vec{S}}{\left|\vec{S}\right|}$$

$$d_n = \frac{\hbar\,\Delta\phi}{4\,E\,T} + \frac{\hbar\,\Delta\omega_{geo.}}{2\,E}$$

$$P(d) = -1 \quad T(d) = +1$$

$$P(\vec{S}) = +1 \quad T(\vec{S}) = -1$$

$$\sigma_{d_n} = \frac{\hbar}{2\,\alpha\,E\,T\sqrt{N}\sqrt{M}}$$

[Particle Physics with Neutrons I / II (P. Fierlinger)]

Electric field effects

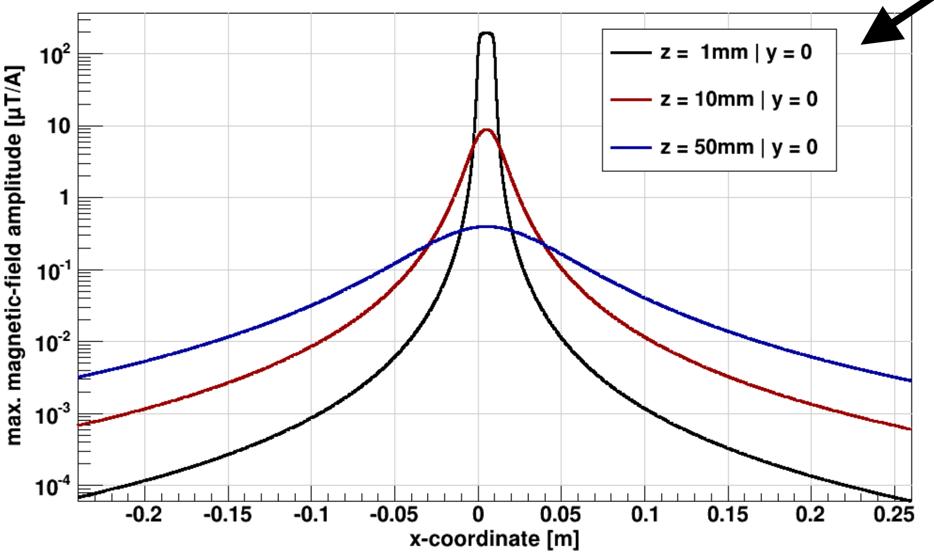
❖ Motional field

$$\vec{B}_v = \frac{1}{c^2}\,\vec{E}\times\vec{v}$$

$$\delta\omega_\mathrm{L} \propto \frac{\partial B_z}{\partial z}\,\vec{E}\times\vec{v} \sim \boxed{E}$$

[Geometric-phase-induced false electric dipole moment signals for particles in traps (Pendlebury et al.)]

=> false EDM signal!



❖ DC / AC on electrodes

- altering B_0 field

$$\delta\vec{B}\left(\vec{x},\,t\right) = \delta\vec{B}\left(\vec{x}\right)\,\sin\left(\omega_j\,t\right)$$

- changing spin polarization

$$\mu_z(t) = \mu\,\frac{2\,\alpha}{1+\alpha^2}\,\sin^2\left[\frac{1}{2}\omega_\mathrm{L}\sqrt{1+\alpha^2}\,t\right]$$

$$\alpha = \frac{\omega_x}{\omega_\mathrm{L}} = \frac{B_x}{B_0}$$

The linear electro-optic Pockels effect in quartz

[Grundlagen der Photonik (Saleh, Teich)]

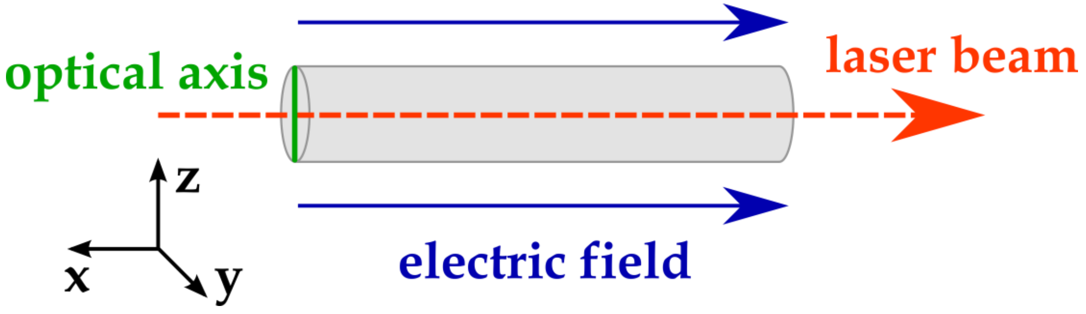
$$\sum_{i,j} \left(\eta_{ij} + r_{ijk}\, E^k + s_{ijkl}\, E^k E^l \right) x_i\, x_j = 1$$

[Handbook of Optical Materials (Marvin Weber)]

$$\boldsymbol{r}^\mathsf{T} = \begin{pmatrix} r_{11} & -r_{11} & 0 & r_{41} & 0 & 0 \\ 0 & 0 & 0 & 0 & -r_{41} & -r_{11} \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

$$n_2' = n_2 \left(1 - \frac{1}{2} r_{11}\, n_2^2\, E + \mathcal{O}\left[E^2 \right] \right)$$

$$\Delta\phi = \frac{2\pi}{\lambda_0} \Delta n\, l = \Delta\phi^{(0)} + \frac{\pi}{\lambda_0} r_{11}\, n_2^3\, E\, l$$



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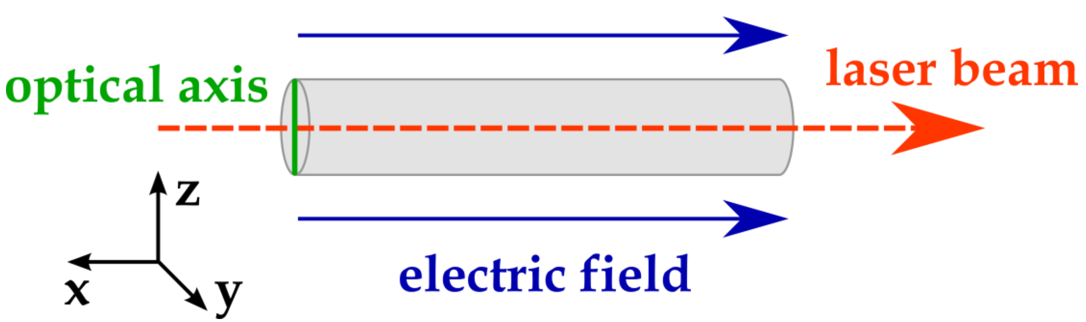
$$n_2'=n_2\left(1-\frac{1}{2}\,r_{11}\,n_2^2\,E+\mathcal{O}\left[E^2\right]\right)$$

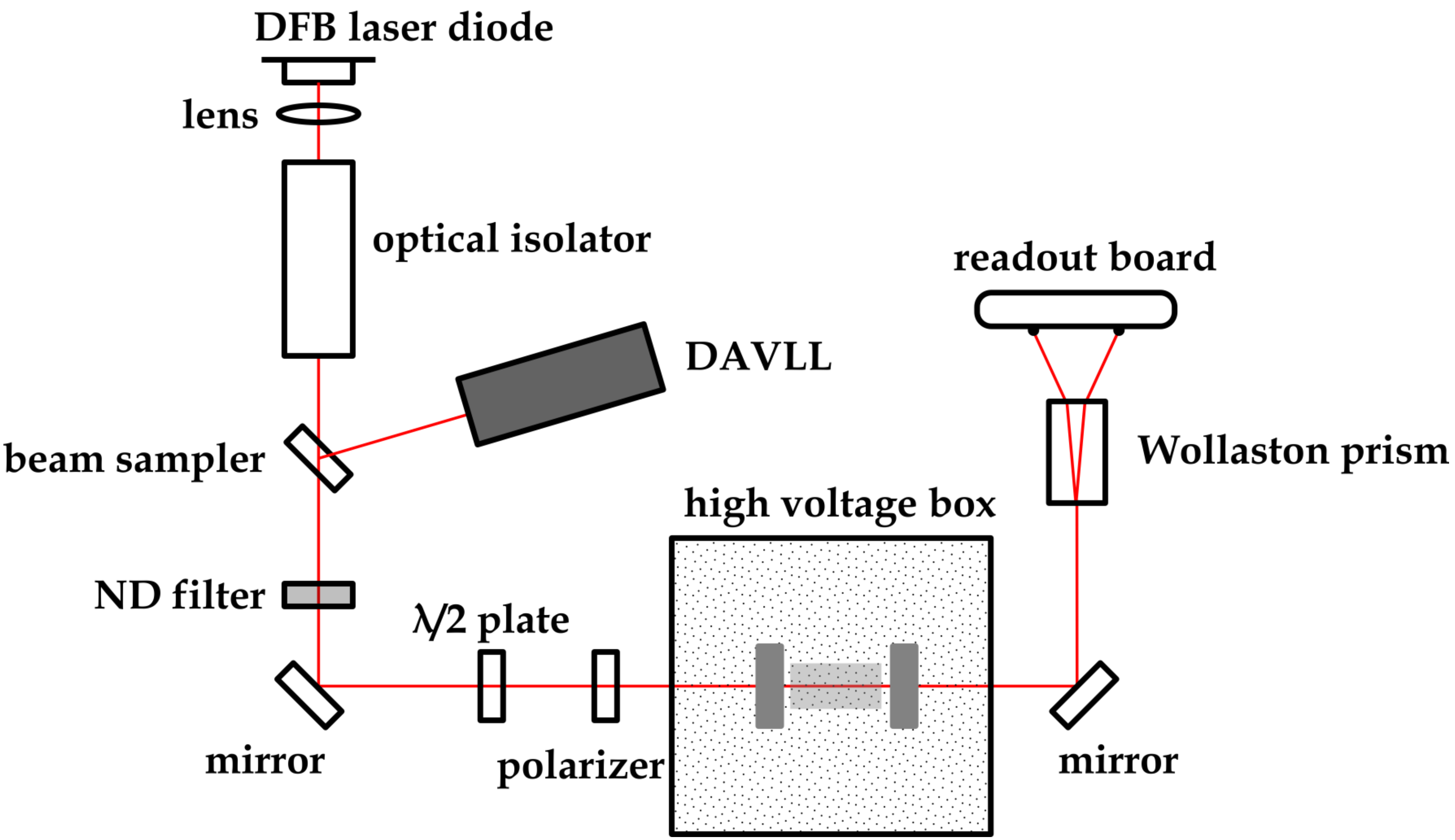
$$\Delta\phi=\frac{2\pi}{\lambda_0}\Delta n\,l=\Delta\phi^{(0)}+\frac{\pi}{\lambda_0}r_{11}\,n_2^3\,E\,l$$

$$\left|\psi_{\mathrm{fi}(\|,\perp)}\right|^2=\frac{1\pm\cos 2\vartheta\cos 2\tilde{\vartheta}}{2}\pm\frac{\sin 2\vartheta\sin 2\tilde{\vartheta}}{2}\cos\left(\phi_x-\phi_y\right)$$

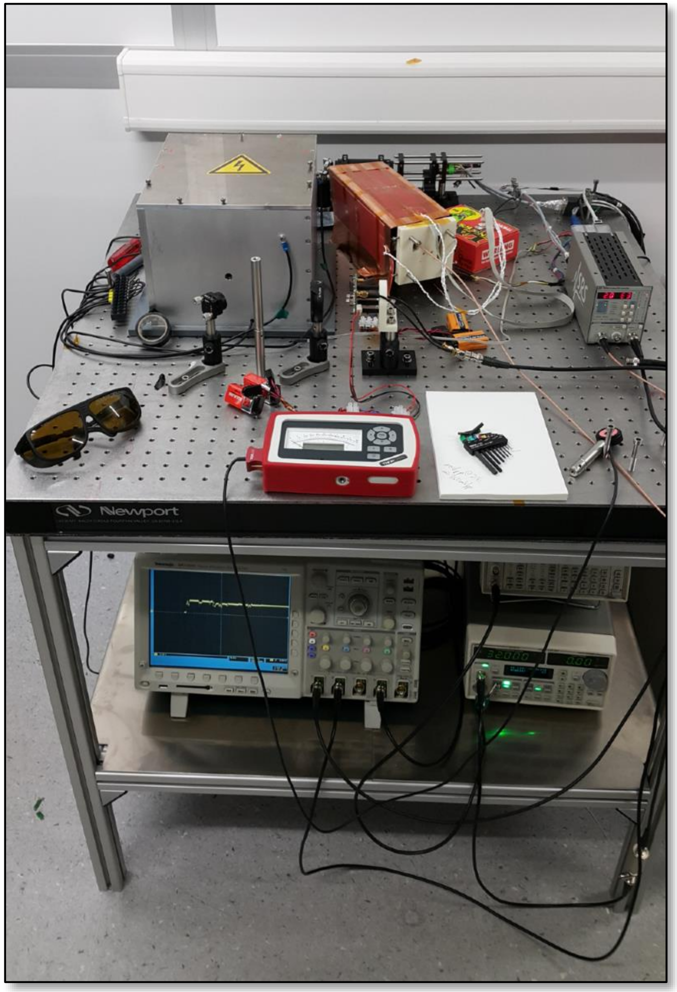
$$\left.\frac{\Delta I}{I_0}\right|_B-\left.\frac{\Delta I}{I_0}\right|_A=-\underbrace{\frac{2\,\pi\,r_{11}\,n_2^3\,l}{\lambda_0}\,s(\vartheta,\tilde{\vartheta})\,\sin\Delta\phi^{(0)}}\cdot\underbrace{\left(E_B-E_A\right)}$$

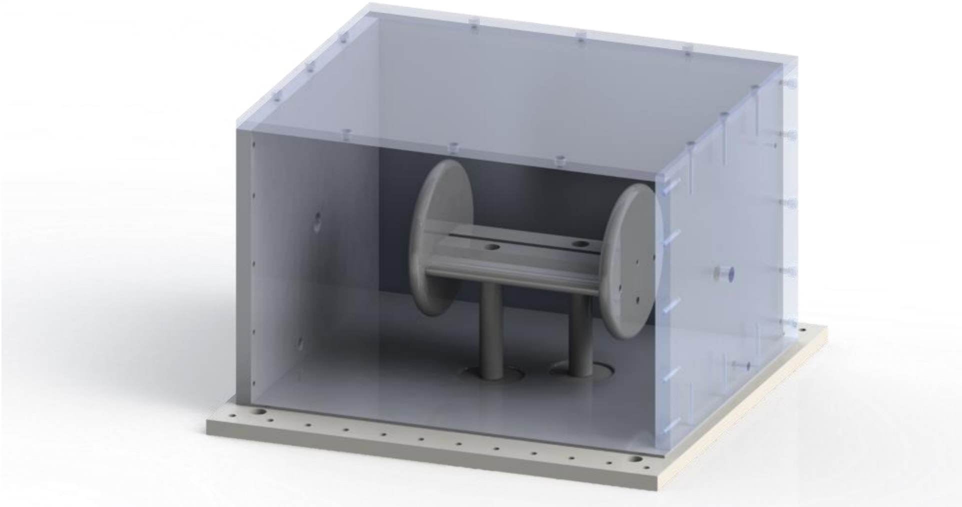


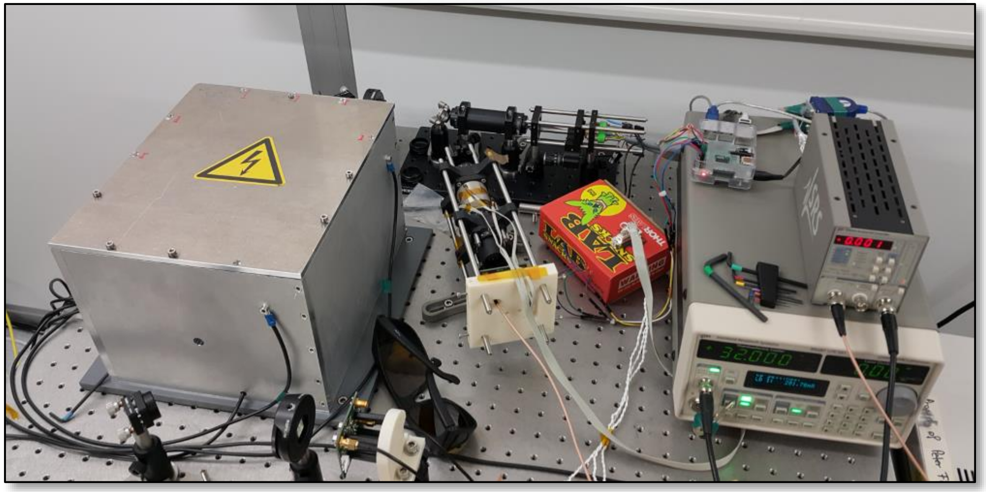
Experimental setup



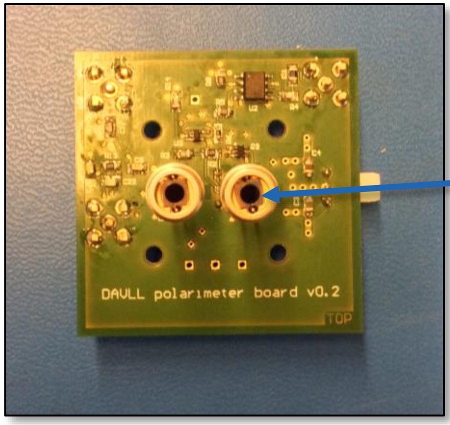
Experimental setup







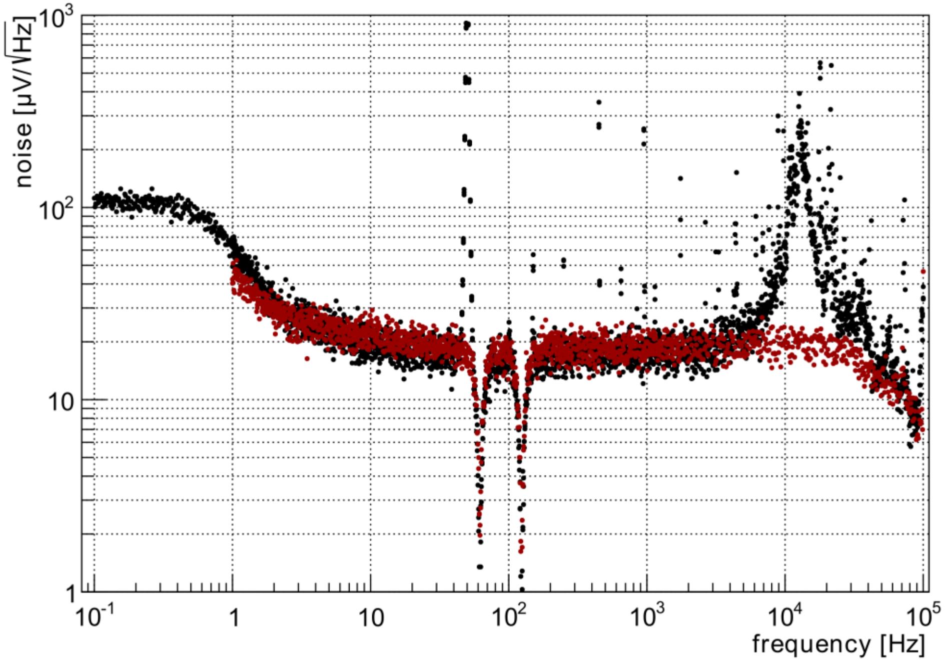
Polarimeter board and power supply



- Hamamatsu S3072
- „Large area high-speed" Si PIN diode

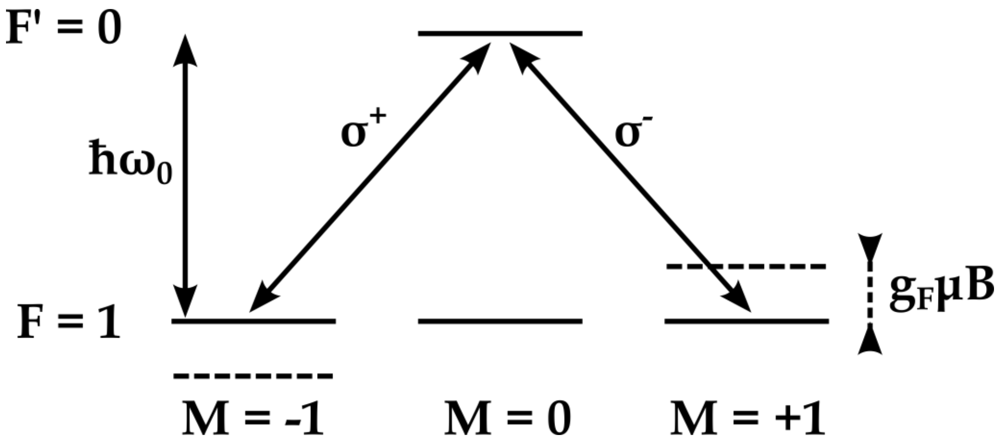
3mm diam.

- Spectral response (830nm) $U(I) = 5.6\,\mathrm{V}\,\mu\mathrm{W}^{-1} \cdot I$



- On-board single-sided / differential amplification stage(s)
  - low(er) intrinsic / pick-up noise
- Readout SMA -> BNC -> osci -> rPi
- Powered by 9V pack or battery box

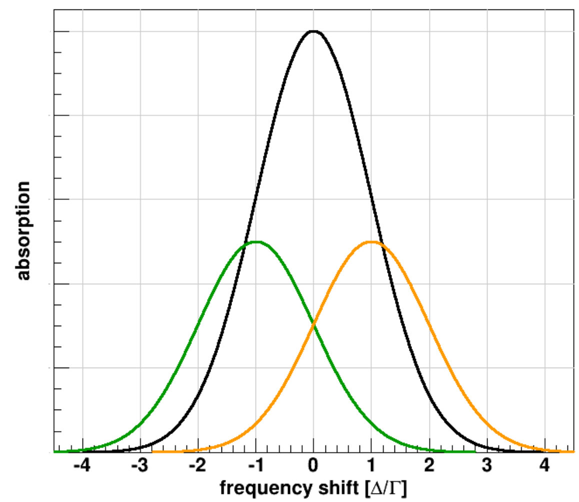
Dichroic Atomic Vapor Laser Lock (DAVLL) – principle

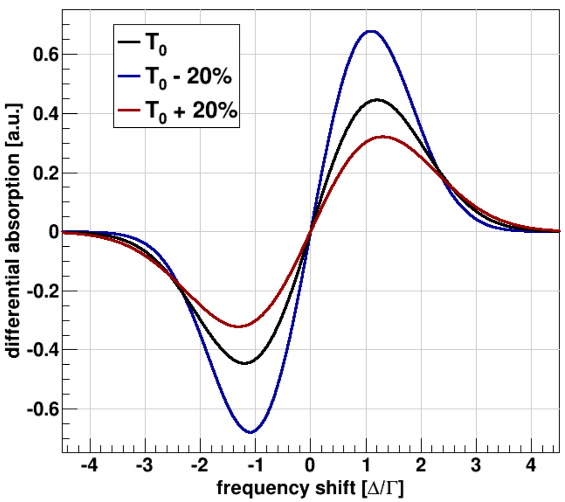


$$H_B = \frac{\mu_B}{\hbar}\left(g_S\,\vec{S} + g_L\,\vec{L} + g_I\,\vec{I}\right)\cdot\vec{B}$$
$$\equiv \frac{g_F\,\mu_B}{\hbar}\,\vec{F}\cdot\vec{B}$$

- shift: $f_{D_2}^{(\mp)} = \mp\frac{g_F\mu_B B}{\hbar}$

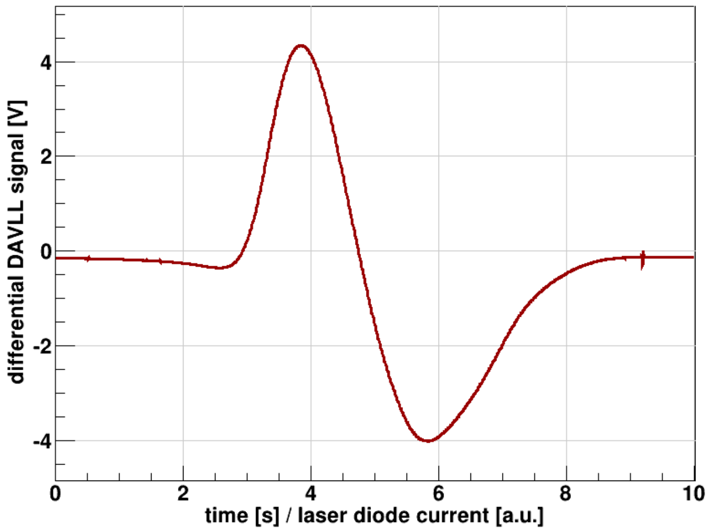
- Cs‘ D_2-line @ 852nm
- Zeeman splitting of HFS, breaking degeneracy
- Absorption resonance shift



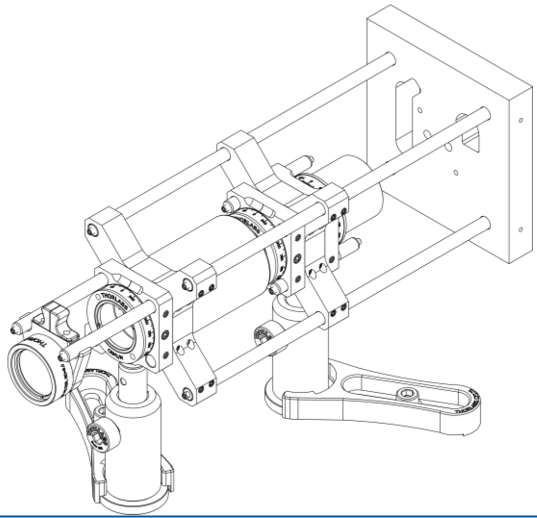


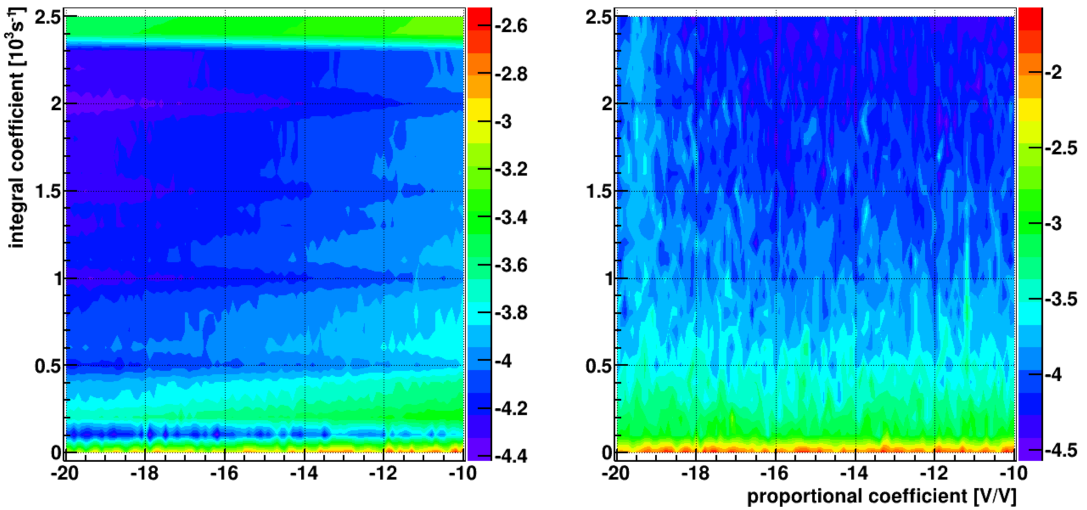
(Laser frequency stabilization using linear magneto-optics [Yashchuk, Budker, Davis])
(Cesium D Line Data [Steck])

Dichroic Atomic Vapor Laser Lock (DAVLL) – operation



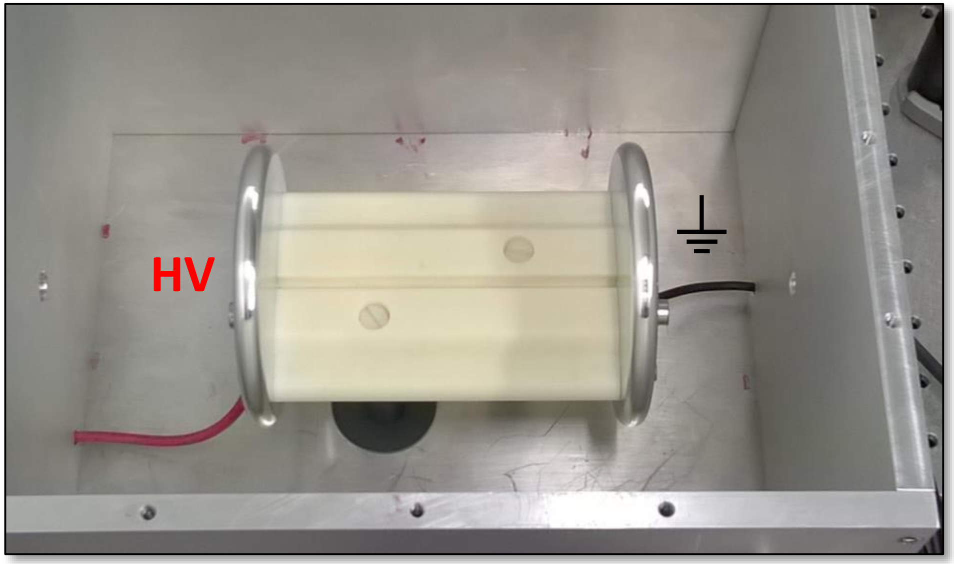
- 20mT permanent field (Mu-metal cover)
- Polarimeter board (DIFF)
- Analog PID controller (P & I channel)
  - Automated parameter tuning
- temperature stabilization (software PID)

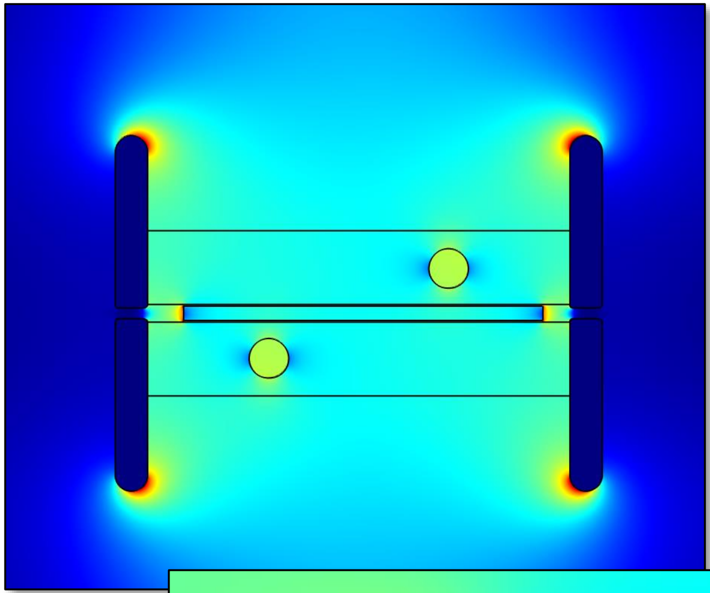


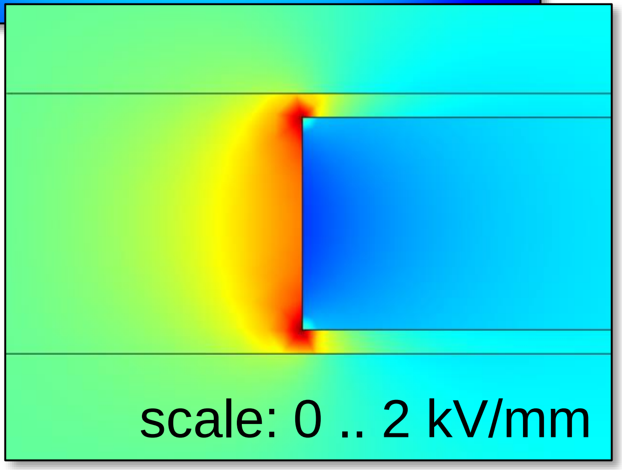


High voltage assembly

- 10kV Trek power supply
- Aluminum Faraday cage and electrodes
- COMSOL simulation to assess max. fields

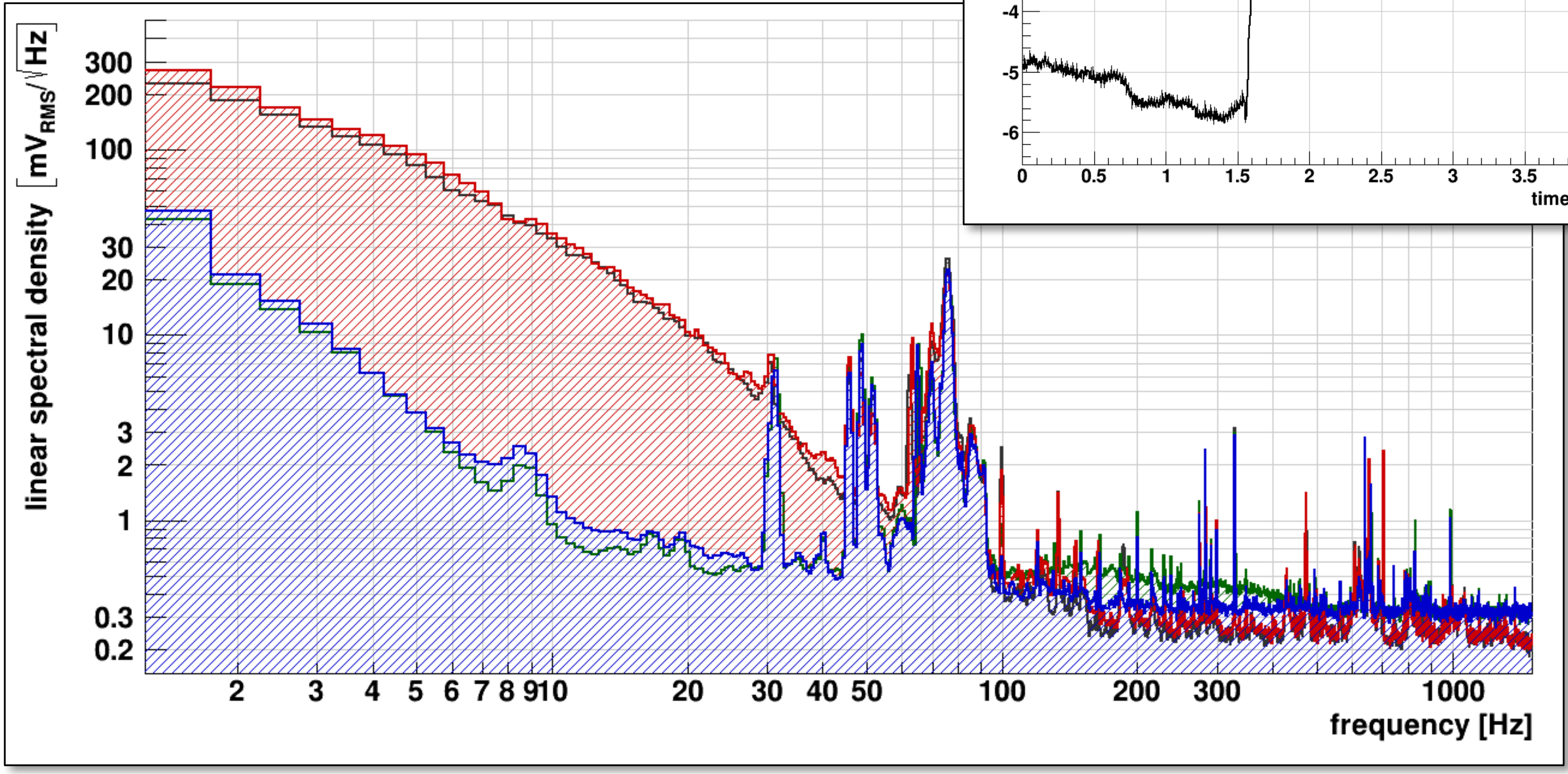


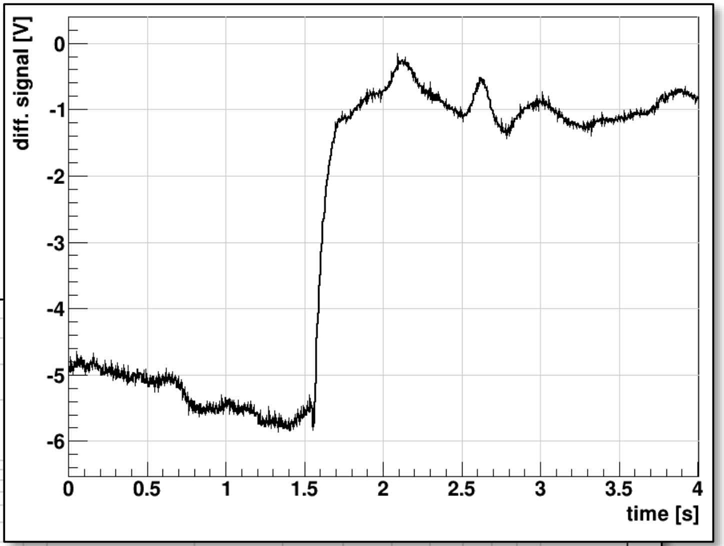




Forced HV oscillations and background

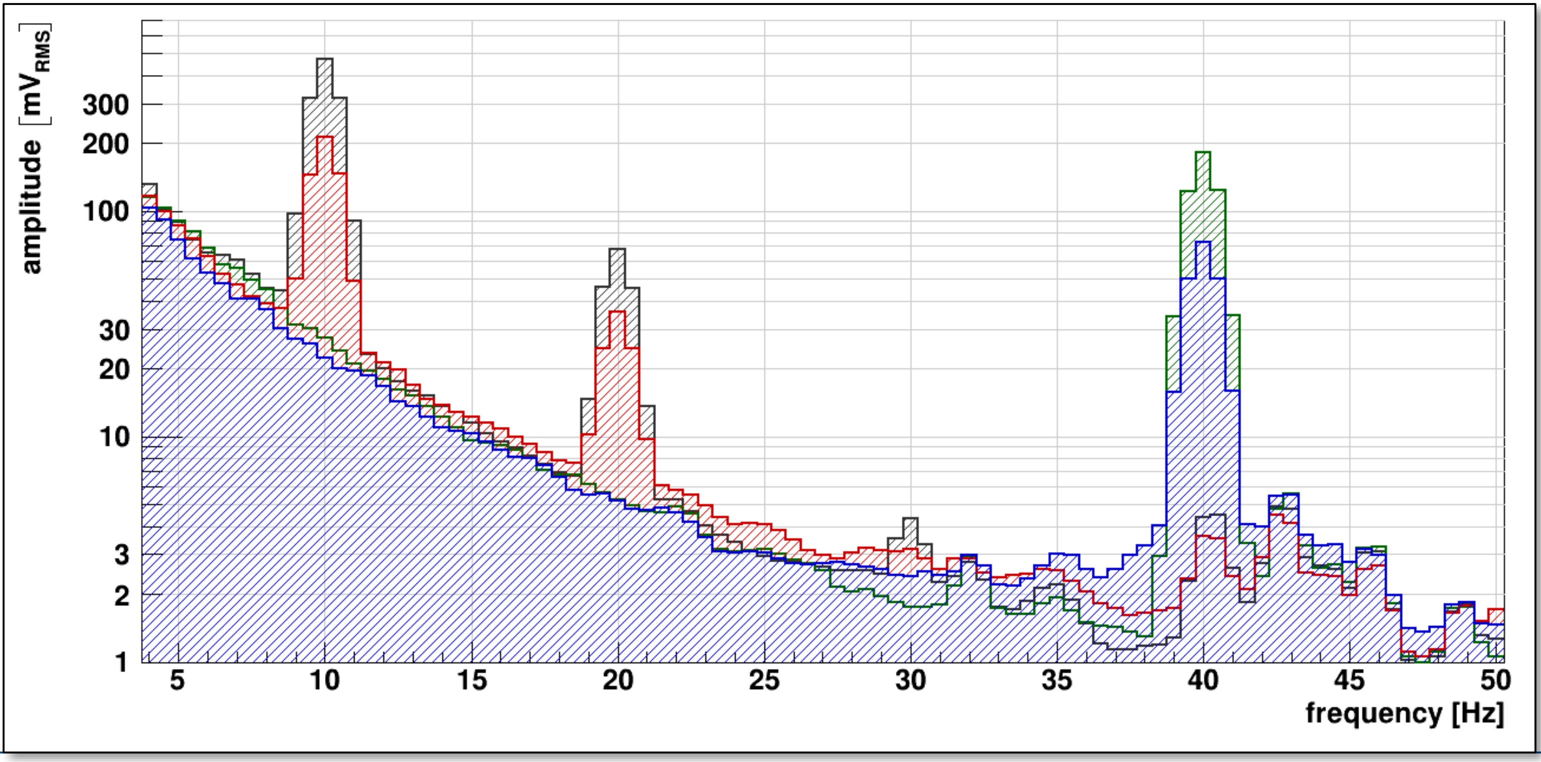
- ±10kV at ≈30Hz
- DFT for analysis





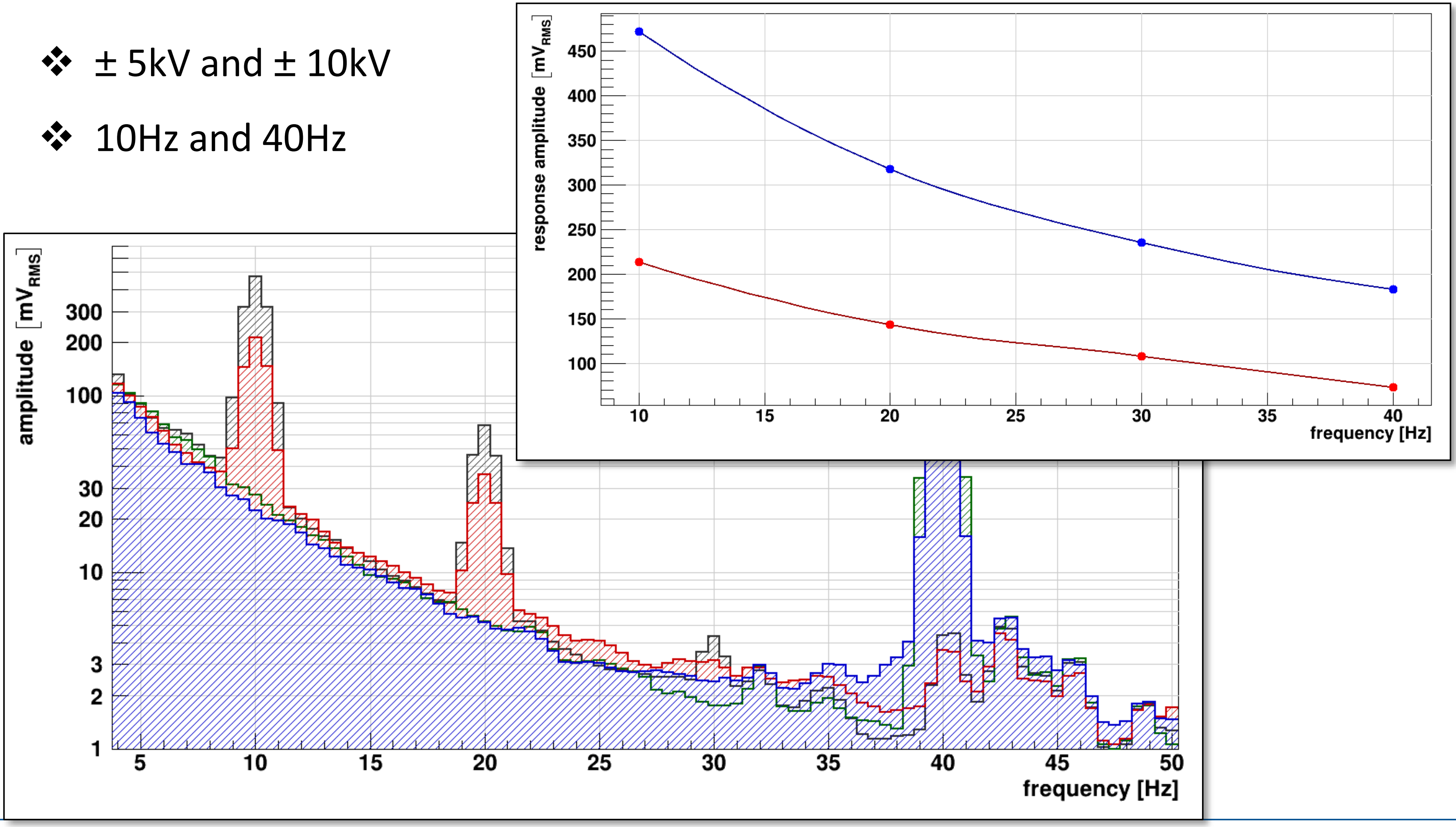
Analysis and capacitance limited amplitude

- ± 5kV and ± 10kV
- 10Hz and 40Hz



Capacitance limited amplitude

- ± 5kV and ± 10kV
- 10Hz and 40Hz



Measuring absolute field values

$$\left.\frac{\Delta I}{I_0}\right|_B - \left.\frac{\Delta I}{I_0}\right|_A = -\frac{2\,\pi\, r_{11}\, n_2^3\, l}{\lambda_0}\, s(\vartheta, \tilde{\vartheta})\, \sin \Delta\phi^{(0)} \cdot (E_B - E_A) =: \eta\, (E_B - E_A)$$

10 Hz sine (freq. domain)

- signal: 184.81 mVpp
- voltage: **18.481 kV (20kV)**

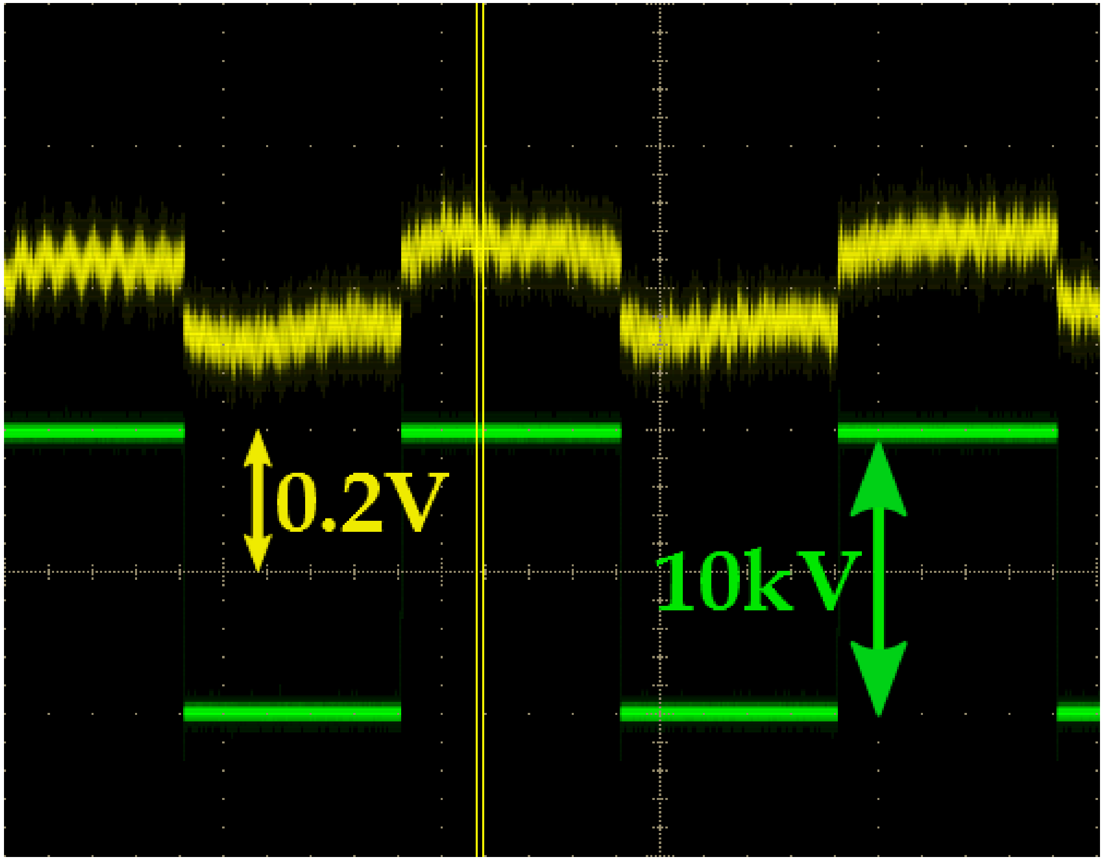
  => 7.6% error

  (capacitance limitation)

0.5 Hz step (time domain)

- signal: 99 mVpp
- voltage: **9.9kV (10kV)**

  => 1% error



Wrap-Up

New experimental setup

- active laser stabilization (DAVLL)
- $\pm$ 100 kV/m fields (parallel to beam)
- Automated readout (Raspberry Pi)

Control & data acquisition

- Oscilloscope as intermediary
- Raspberry Pi <> hardware
- Python daemons / ROOT

Measurement resolution (@ 180kV / 12cm)

- goal: 10^{-4}
- actual: 10^{-2} (time domain)
- => 2 orders of magnitude to go
  - (primarily due to external noise sources)

Data analysis

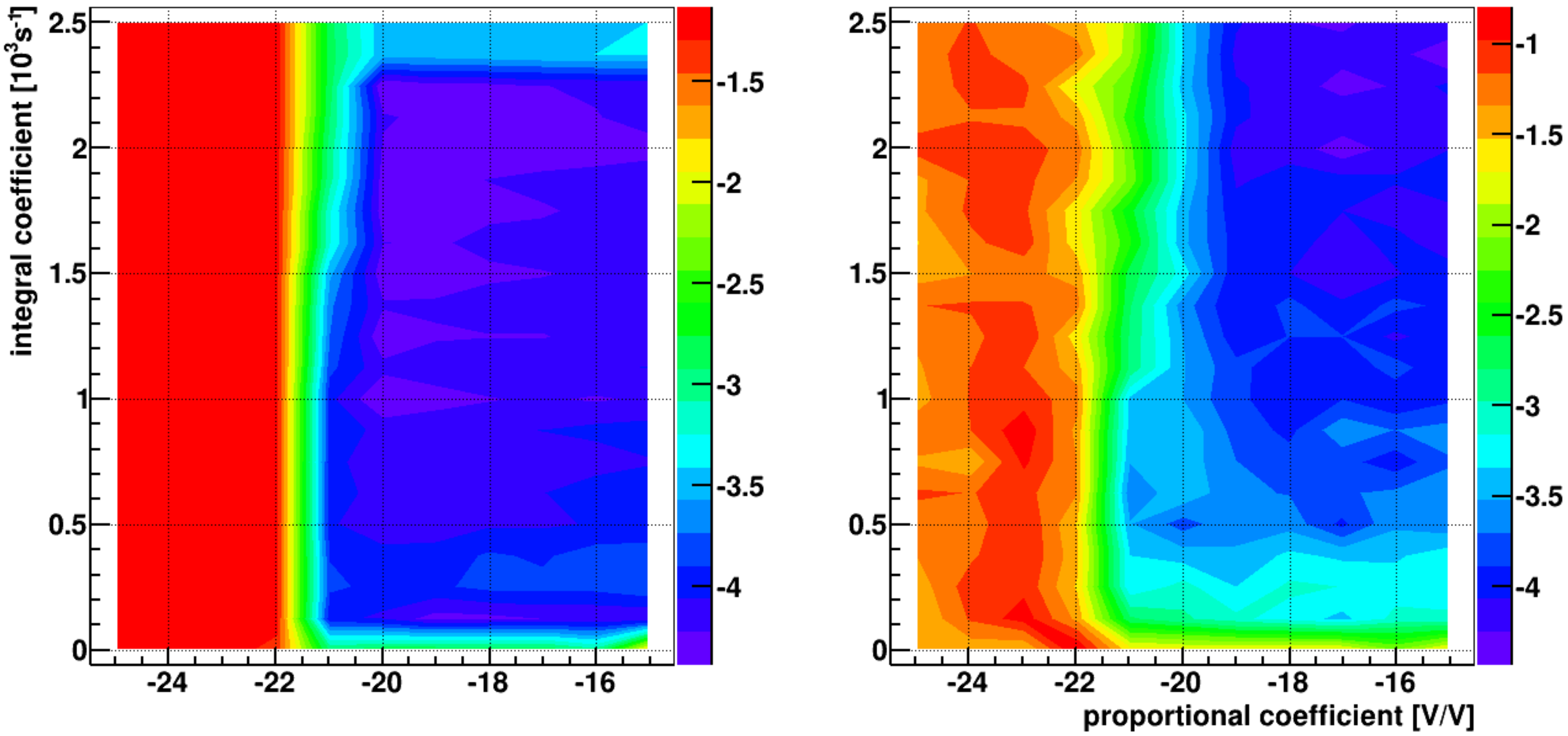
- Discrete Fourier Transform
- Software Lock-In Amplifier

200 kV high voltage supply

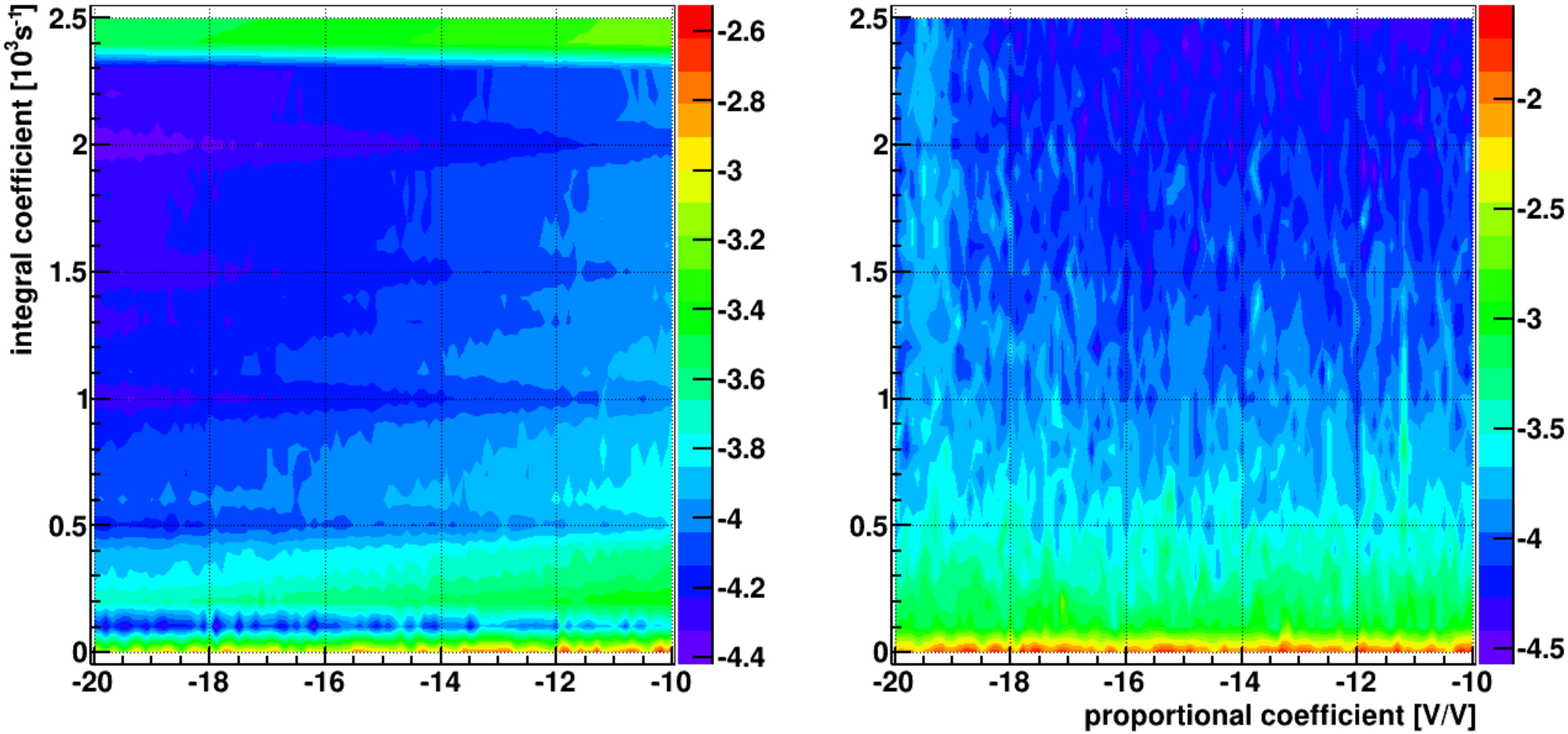
- left rotating knob
  - 0 .. 10 => -200 kV .. +200 kV
- right rotating knob
  - 1% adjustment
- connect to grid via IEC wires
  $\Rightarrow$ proper grounding necessary
- significant 50 Hz noise
  - no reduction using 20pF
  - decreasing with inc. HV!

- control via front-panel XOR remote interface
- Remote interface (serial + BNC)
  $\Rightarrow$ Possible feedback loop

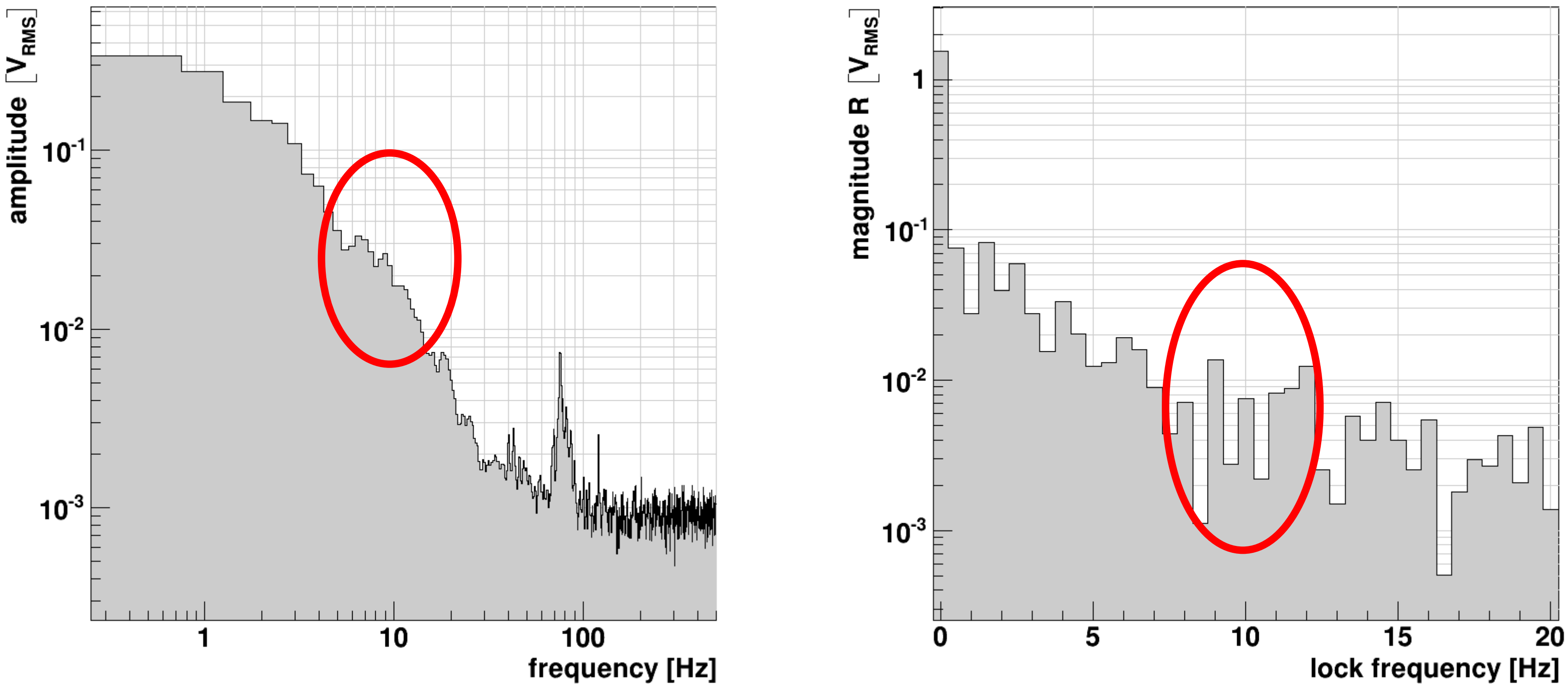
PID parameter tweaking – low I vs. big I



PID parameter tweaking – low I vs. big I

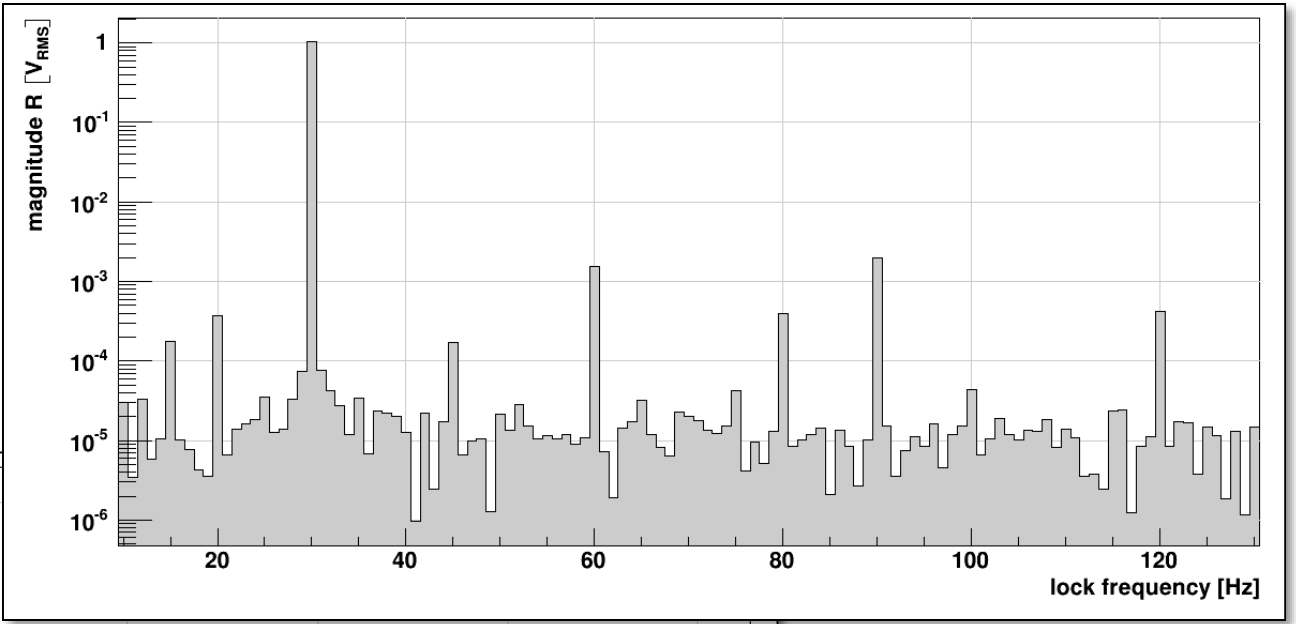


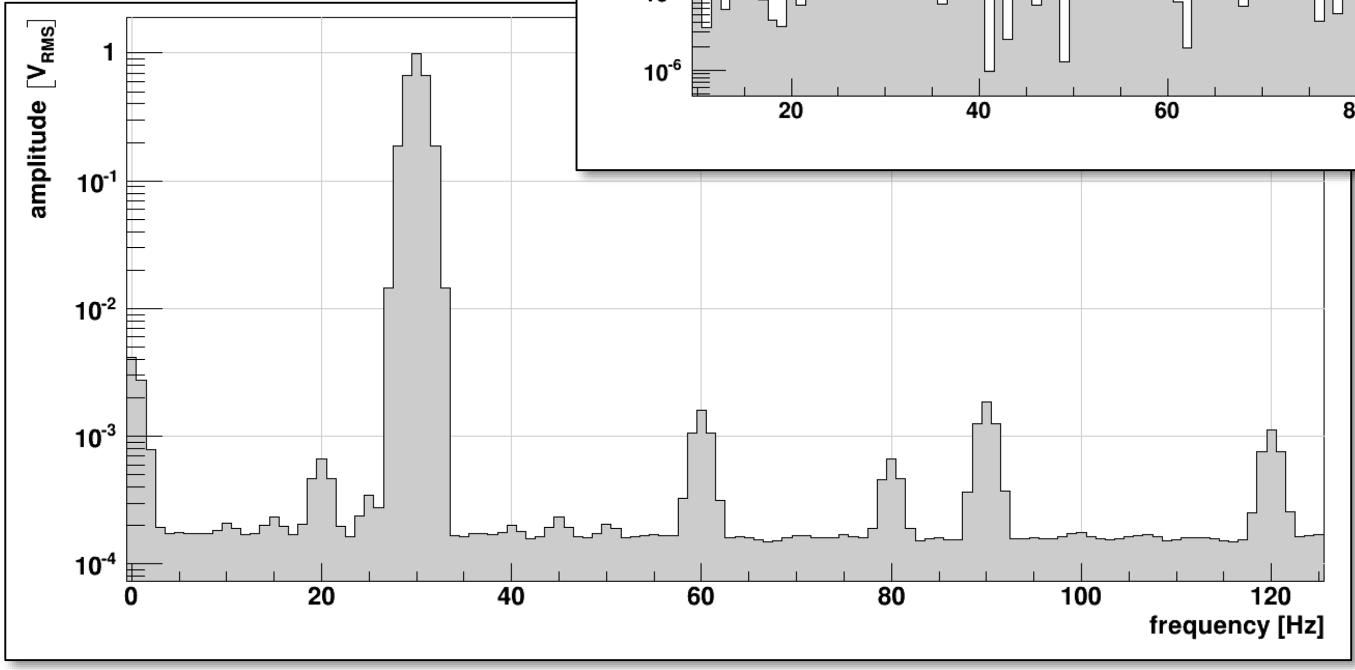
Function generator to HV transfer



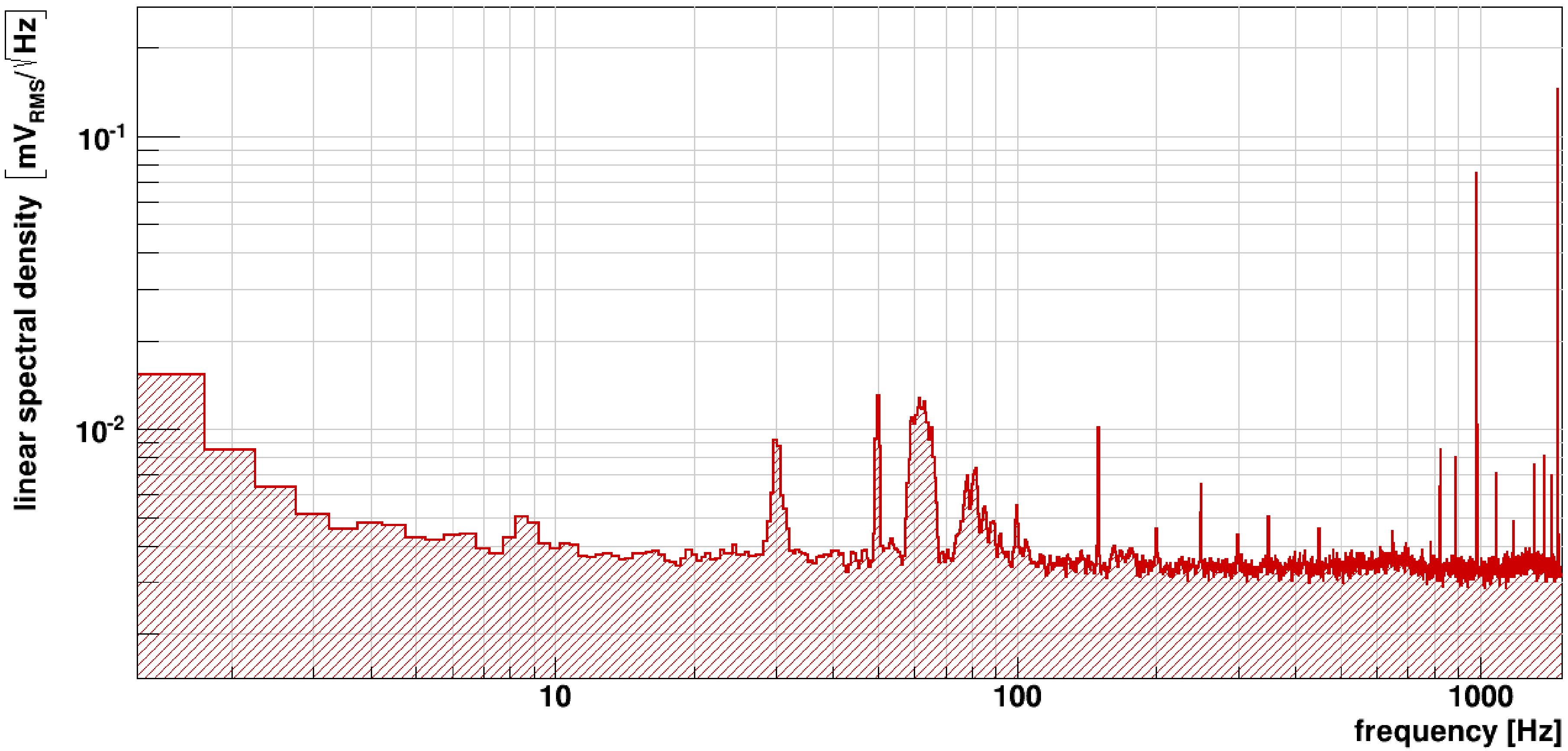
Modulation: 10 Vpp @ 10 Hz

DFT / sLI

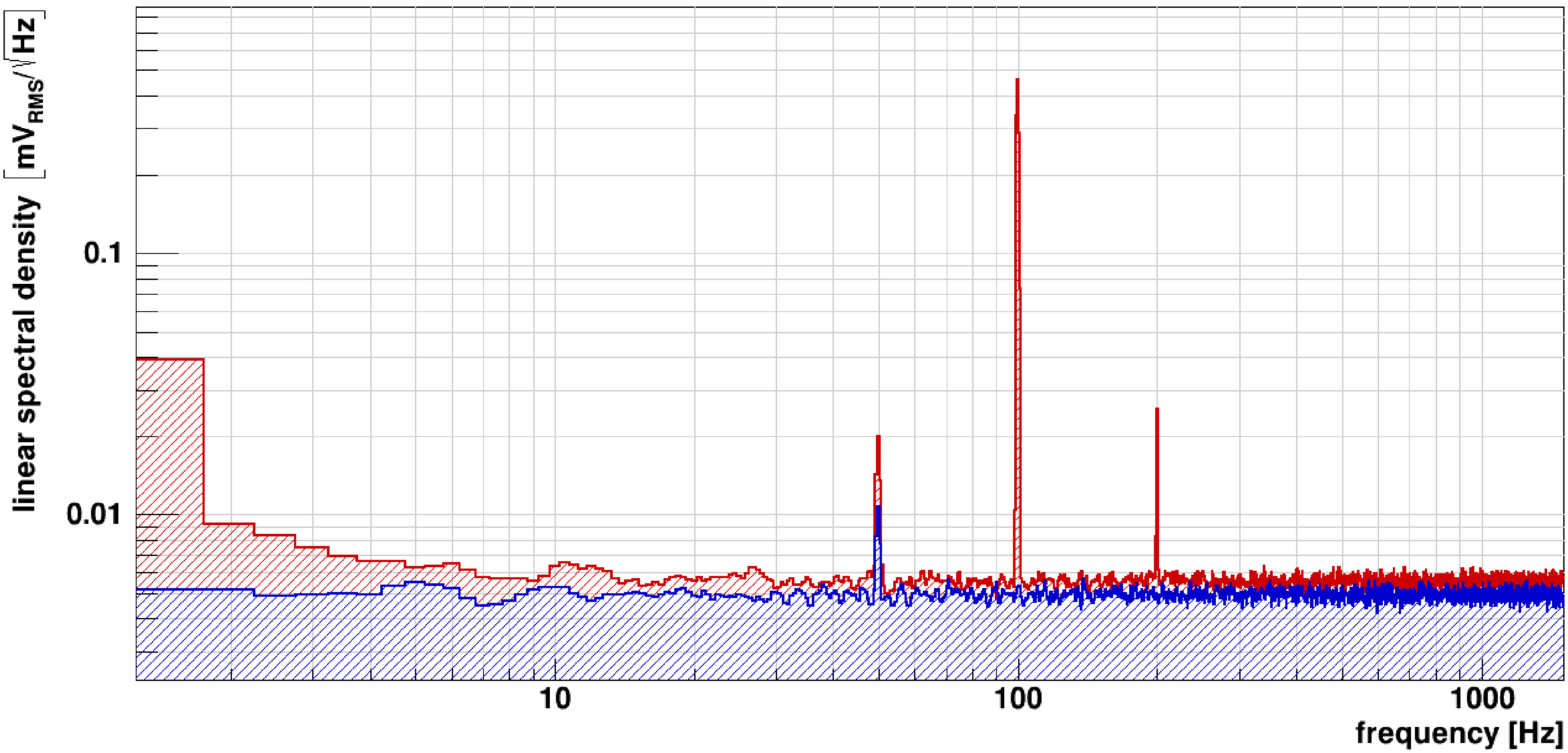

magnitude R [V_{RMS}]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
20
40
60
80
100
120
lock frequency [Hz]


amplitude [V_{RMS}]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
20
40
60
80
100
120
frequency [Hz]

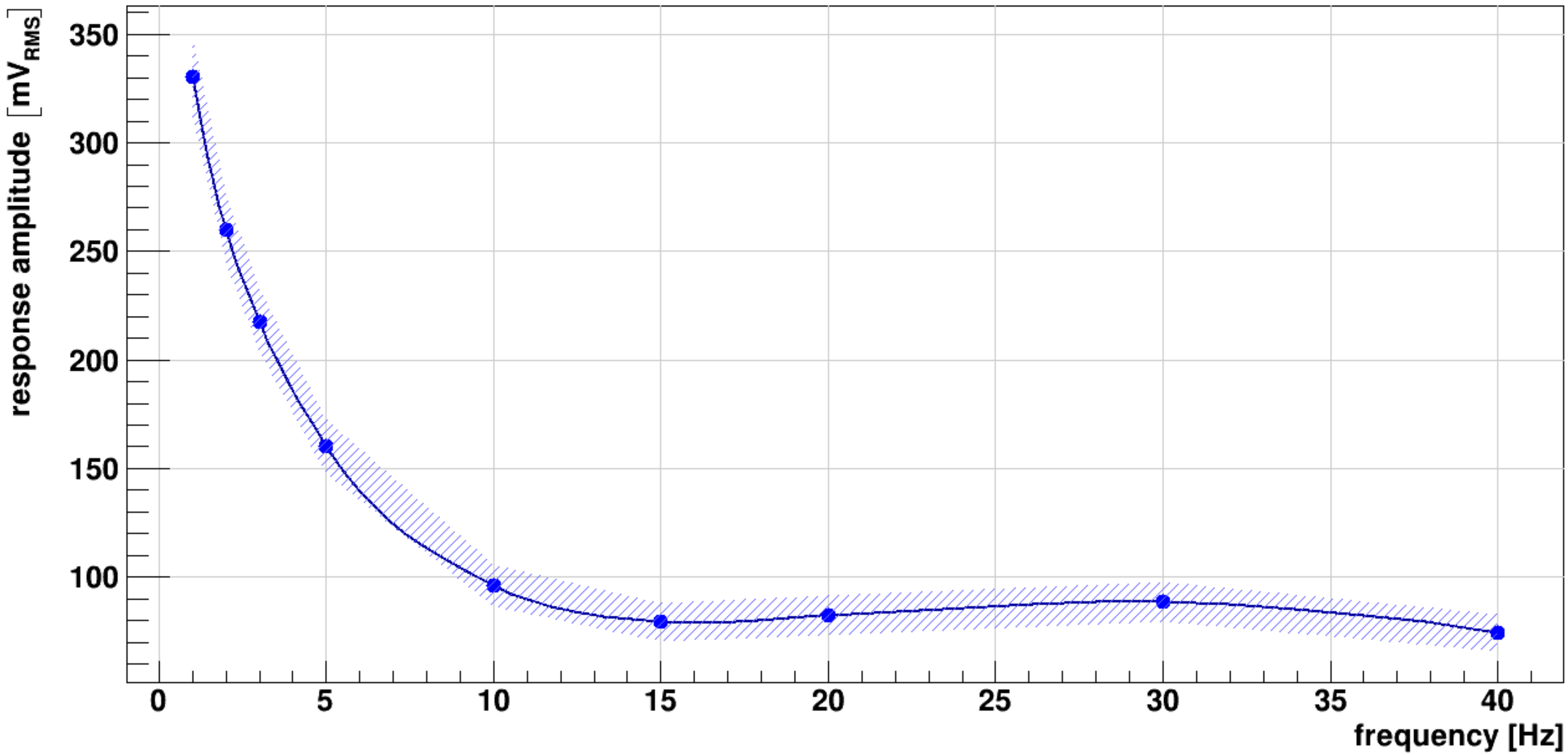
Frequency domain noise quest – DAVLL output



Frequency domain noise quest – With and without LASER



High voltage modulation amplitude – frequency dependence



Linear electro-optic effect in quartz

$$\sum_{i,j}\left(\eta_{ij}+\underline{r_{ijk}\,E^k+}\,s_{ijkl}\,E^kE^l\right)x_i\,x_j=1$$

$$\boldsymbol{r}^{\mathsf{T}}=\begin{pmatrix} r_{11} & -r_{11} & 0 & r_{41} & 0 & 0\\ 0 & 0 & 0 & 0 & -r_{41} & -r_{11}\\ 0 & 0 & 0 & 0 & 0 & 0\end{pmatrix}$$

Diagonalizing:

$$n_1'=n_1\left(1-\underline{\frac{1}{2}\,r_{11}\,n_1^2\,E}+\mathcal{O}\left[E^2\right]\right)$$

$$\Delta\phi=\frac{2\pi}{\lambda_0}\Delta n\,l=\Delta\phi^{(0)}+\frac{\pi}{\lambda_0}r_{11}\,n_2^3\,E\,l$$

$$\vec{E}=\left(E_{0x}\,\mathrm{e}^{\mathrm{i}\phi_x},E_{0y}\,\mathrm{e}^{\mathrm{i}\phi_y}\right)^{\mathsf{T}}\cdot\mathrm{e}^{\mathrm{i}\,(k\,z-\omega\,t)}$$

$$\psi_{\mathrm{in}}=\begin{pmatrix}1\\0\end{pmatrix}\qquad \mathcal{A}_{\mathrm{ret}}(\phi_x,\phi_y)=\begin{pmatrix}\mathrm{e}^{\mathrm{i}\,\phi_x} & 0\\ 0 & \mathrm{e}^{\mathrm{i}\,\phi_y}\end{pmatrix}$$

$$\psi_{\mathrm{fi}}=\boldsymbol{R}(\gamma)\,\boldsymbol{R}(\vartheta)\,\mathcal{A}_{\mathrm{ret}}\,\boldsymbol{R}^{\mathsf{T}}(\vartheta)\,\psi_{\mathrm{in}}$$

$$\psi_{\mathrm{fi}}=\begin{pmatrix}\mathrm{e}^{\mathrm{i}\,\phi_x}\,\cos\vartheta\,\cos(\vartheta+\gamma)+\mathrm{e}^{\mathrm{i}\,\phi_y}\,\sin\vartheta\,\sin(\vartheta+\gamma)\\ \mathrm{e}^{\mathrm{i}\,\phi_x}\,\cos\vartheta\,\sin(\vartheta+\gamma)-\mathrm{e}^{\mathrm{i}\,\phi_y}\,\sin\vartheta\,\cos(\vartheta+\gamma)\end{pmatrix}$$

$$\left|\psi_{\mathrm{fi}(\|,\perp)}\right|^2=\frac{1\pm\cos2\vartheta\cos2\tilde{\vartheta}}{2}\pm\frac{\sin2\vartheta\sin2\tilde{\vartheta}}{2}\cos\left(\phi_x-\phi_y\right)$$

$$\left.\frac{\Delta I}{I_0}\right|_B-\left.\frac{\Delta I}{I_0}\right|_A=-\underline{\frac{2\,\pi\,r_{11}\,n_2^3\,l}{\lambda_0}\,s(\vartheta,\tilde{\vartheta})\,\sin\Delta\phi^{(0)}}\cdot\underline{(E_B-E_A)}$$

Neutron polarization change

$$\frac{\mathrm{d}\vec{\mu}}{\mathrm{d}t} = -\gamma\,\vec{\mu} \times \vec{B} \quad \Rightarrow \quad \frac{\mathrm{d}\vec{\mu}}{\mathrm{d}t} = -\gamma \begin{pmatrix} 0 & B_z & 0 \\ -B_z & 0 & B_x \\ 0 & -B_x & 0 \end{pmatrix} \cdot \vec{\mu}$$

$$\left(\partial_t B_x = 0\right)$$

$$\vec{\mu}(t) = \frac{\mu}{1+\alpha^2} \begin{pmatrix} \alpha^2 + \cos\left[\omega_\mathrm{L}\sqrt{1+\alpha^2}\,t\right] \\ \sqrt{1+\alpha^2}\,\sin\left[\omega_\mathrm{L}\sqrt{1+\alpha^2}\,t\right] \\ 2\,\alpha\,\sin\left[\omega_\mathrm{L}\sqrt{1+\alpha^2}\,t\right] \end{pmatrix}$$

$$\vec{\mu}(t=0) = \mu\,\hat{e}_x$$

$$\alpha = \frac{\omega_x}{\omega_\mathrm{L}} = \frac{B_x}{B_z}$$

(Mathematica)