In-beam measurements of the hydrogen hyperfine splitting to constrain SME coefficients

Lilian Nowak, September 2021

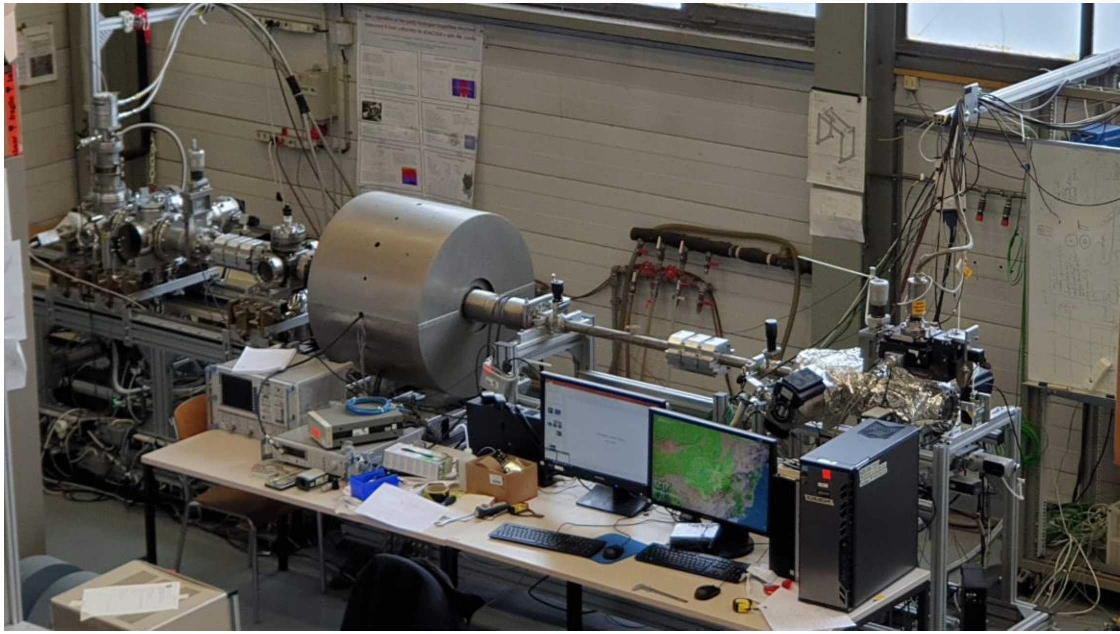
Abstract

The ASACUSA-CUSP experiment located at CERN's antiproton decelerator aims at measuring the ground state hyperfine splitting of antihydrogen ($\bar{\mathrm{H}}$) using a beam technique to test CPT symmetry. For this purpose, a beam of cold (~50K) hydrogen was developed to characterize the antihydrogen spectroscopy apparatus [1]. Beyond serving as a testbench for the $\bar{\mathrm{H}}$ experiment, the hydrogen beamline offers on its own a variety of possible measurements especially in the context of the Standard Model Extension (SME). The SME is an effective field theory that allows CPT and Lorentz symmetries to be broken [2]. A precise measurement of the hydrogen ground state hyperfine splitting was realized already in 2017 using the extrapolation of a single hyperfine transition (σ_1) reaching a relative precision of 2.7 ppb [3]. Since then several additions to the setup were made allowing the precise measurement of the π_1 transition which provides sensitivities to some SME coefficients [4, 5]. A new measurement campaign on hydrogen started in 2021 and focuses on π_1 precision measurements with swapping external magnetic fields using the σ_1 transition as a reference to constrain SME coefficients. The status and results of these measurements will be presented and an overview on the underlying theory and the experimental setup will be given.

[1] Malbrunot C, et al. 2019 A hydrogen beam to characterize the Asacusa antihydrogen hyperfine spectrometer. Nucl. Instrum. Methods A 935: 110-120.
[2] D. Colladay and A. V. Kostelecký 1998 Lorentz-violating extension of the standardmodel. Phys. Rev. D, 58:116002.
[3] Diermaier M, et al. 2017 In-beam measurement of the hydrogen hyperfine splitting and prospects for antihydrogen spectroscopy. Nat. Commun. 8, 15749.
[4] Malbrunot C, et al. 2018 The ASACUSA antihydrogen and hydrogen program: results and prospects, Phil. Trans. R. Soc. A 376: 2116.
[5] Kostelecký A. V. and Vargas A. J. Lorentz and CPT tests with hydrogen, antihydrogen, and related systems. Phys. Rev., D92(5):056002, 2015.

Overview

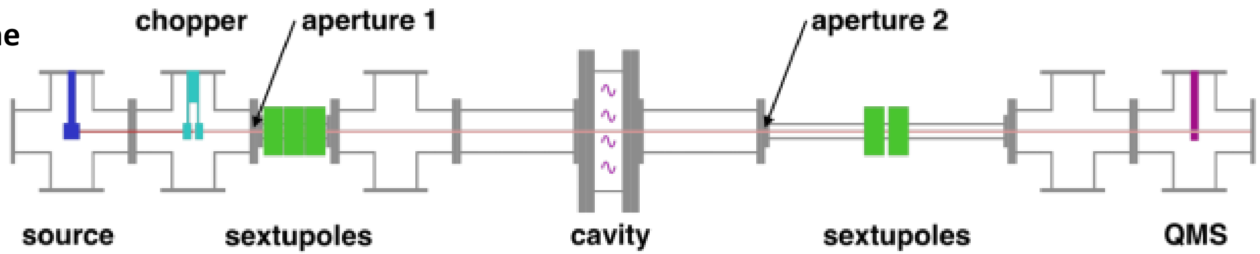
- Hydrogen beamline (overview)
- Strip-line Cavity
- Detection System
- SME
- Hydrogenbeam – Timeline
- Fitting routine
- B-field estimation
- First results/data analysis
- Status and Outlook

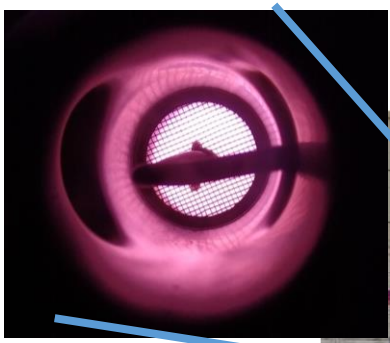


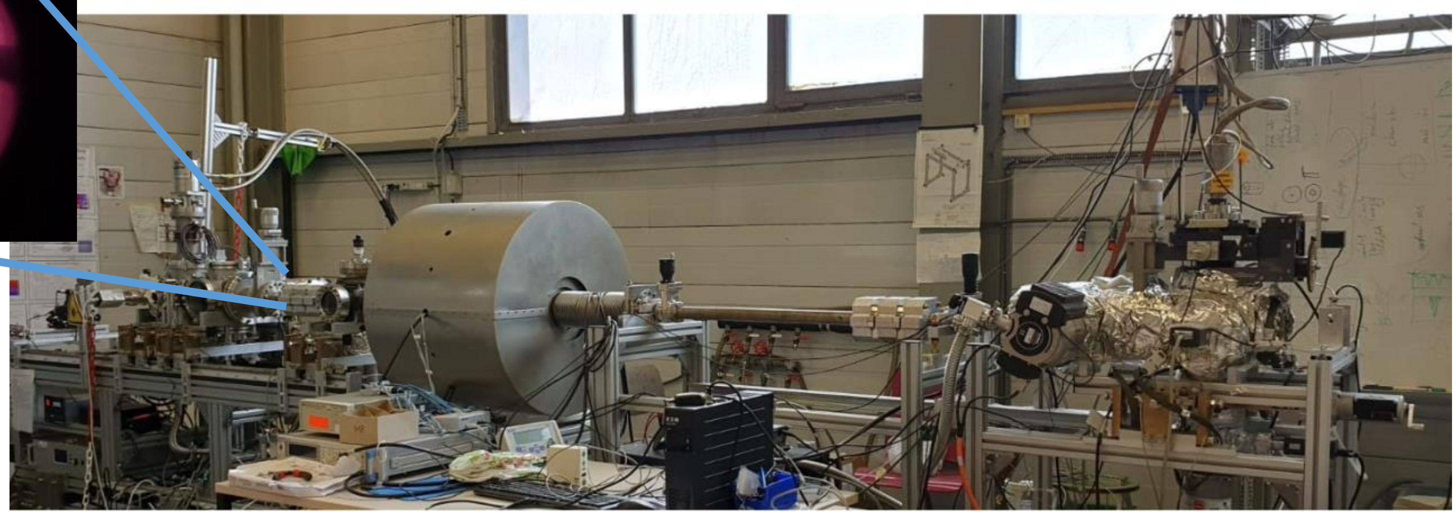
Hydrogen Beamline

- ➢ The hydrogen beamline offers a variety of possible measurements in hydrogen especially in the context of the Standard Model Extension (SME) [1]
- ➢ SME: effective field theory that allows CPT and Lorentz symmetry to be broken, by adding all possible Lorentz-violating terms to the SM Lagrangian

Schematic sketch of the hydrogen beamline:

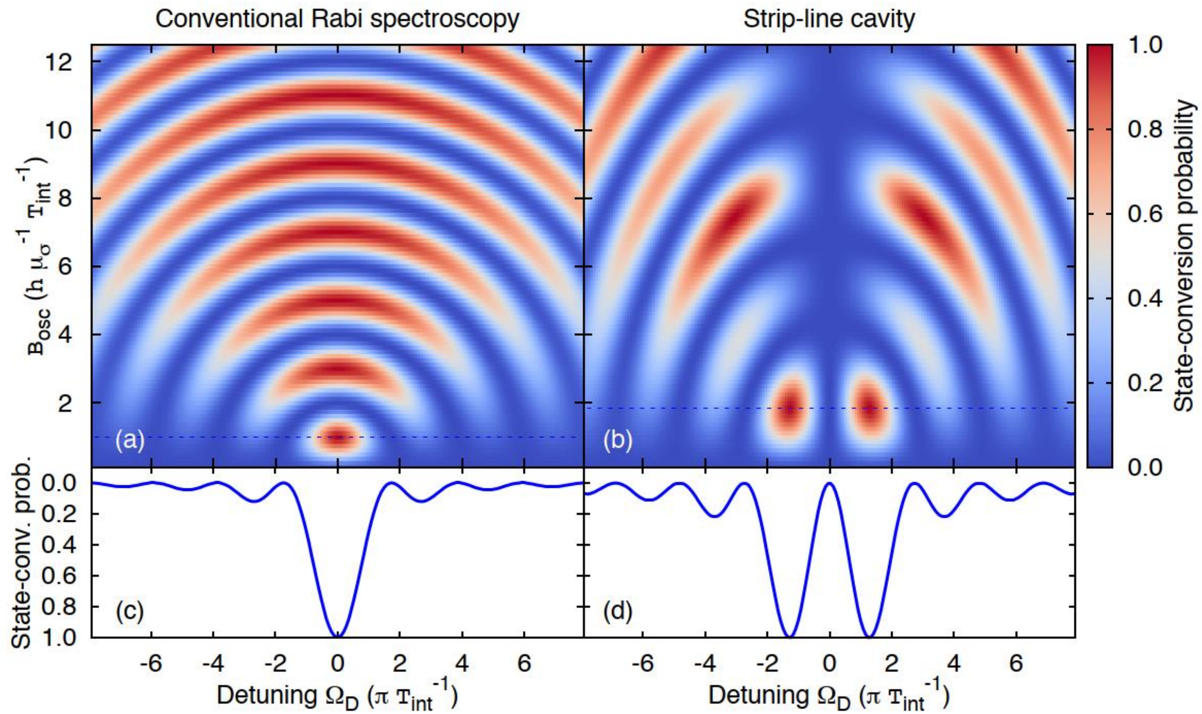




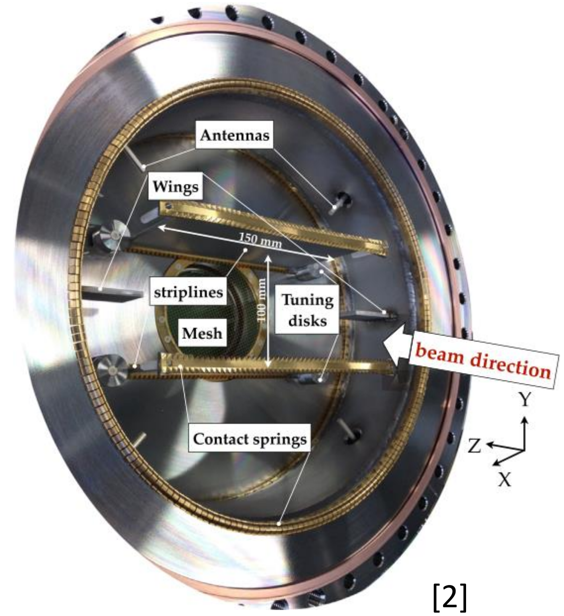


[1] D. Colladay and A. V. Kostelecký. Lorentz-violating extension of the standardmodel. Phys. Rev. D, 58:116002, 1998.

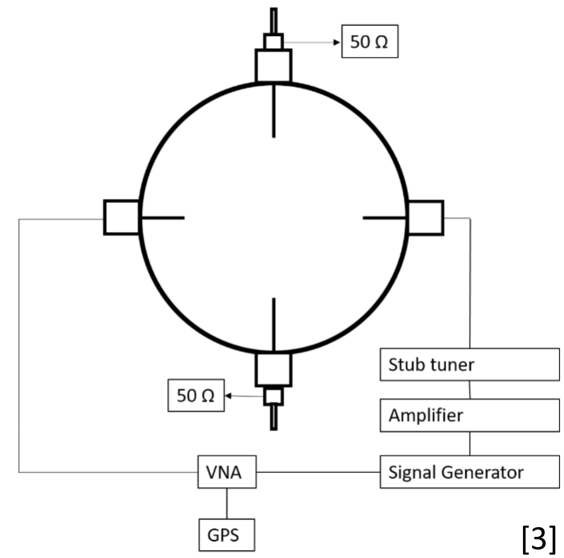
Strip-line Cavity



Spin flip probability conversion for conventional Rabi spectroscopy and the Strip-line cavity. (a) and (b) show the transition as a function of the oscillating magnetic field and the frequency detune. (c) and (d) show the transition as a function of the detune frequency for a constant oscillating magnetic field at the first conversion maximum, taken from [1]



[2]

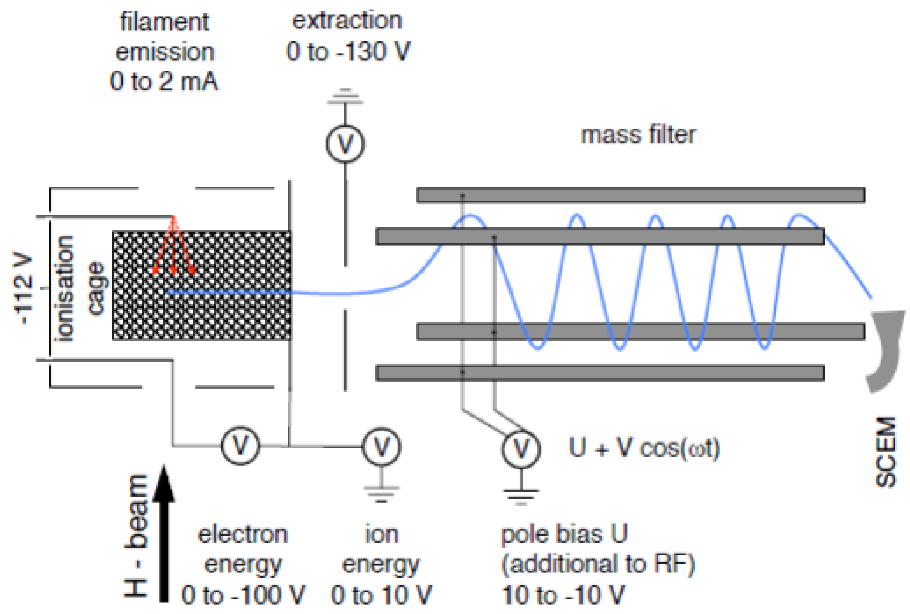


[3]

[1] Diermaier M, et al. 2017 In-beam measurement of the hydrogen hyperfine splitting and prospects for antihydrogen spectroscopy. Nat. Commun. 8, 15749.
[2] Malbrunot C, et al. 2019 A hydrogen beam to characterize the Asacusa antihydrogen hyperfine spectrometer. Nucl. Instrum. Methods A 935: 110-120.
[3] S. Argueda Cuendis. Measuring the hydrogen ground state hyperfine splitting through the π1 and σ1 transitions. Master's thesis, University of Vienna, 2017.

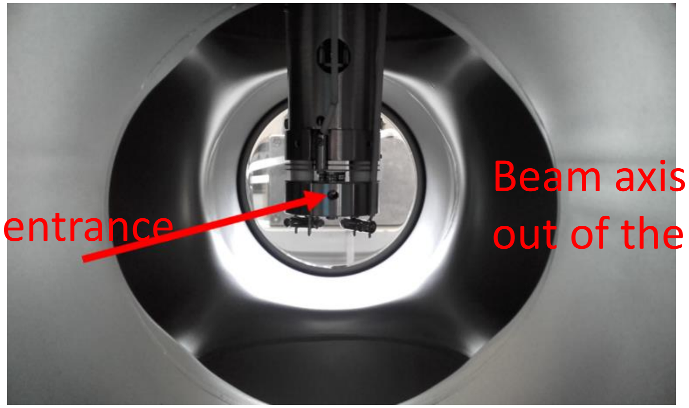
Detection System

Schematic representation of the detector apparatus, taken from [1]:



- Quadrupole mass spectrometer is mounted perpendicular to the beam axis
- The hydrogen atoms enter the QMS apparatus through a 3 mm diameter
- hydrogen atoms and residual gas get ionized by collisions with electrons emitted from a filament
- The ions are accelerated towards the oscillating quadrupole field of the spectrometer

QMS entrance

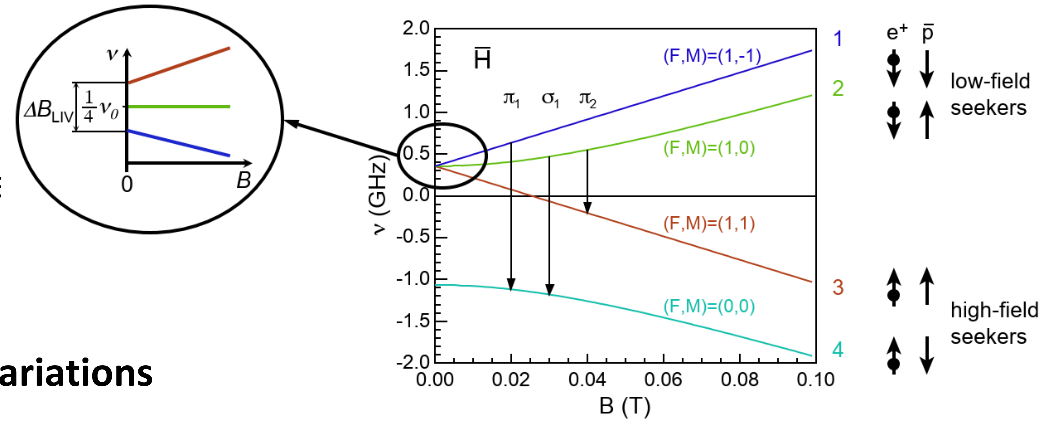


Beam axis is pointing out of the picture

[1] MKS Instrument. Quadrupole mass spectrometer theory - ion source, mass filter, detector, control unit. https://link.springer.com/article/10.1007%2FBF01392963.

Testing SME coefficients via Hydrogen's GS HFS

Constraints on SME coefficients through the **comparison of the zero-field frequency** obtained using an extrapolation method on the π1 transition and the combination of the π1 and σ1 transitions at the same B-field



Breit–Rabi diagram: shows the energy levels in ground-state hydrogen as a function of an external magnetic field, taken from [1]

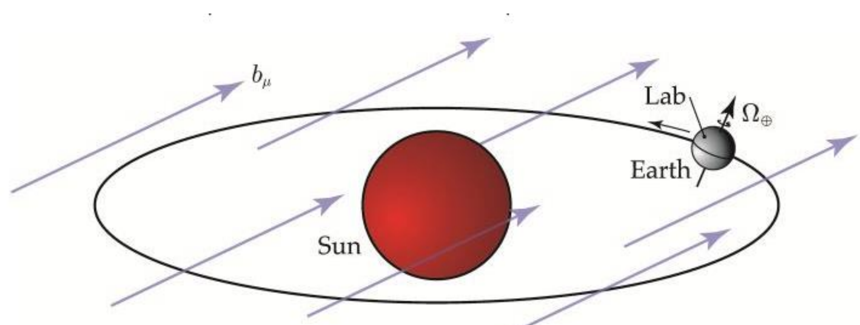
Constraints on SME by measuring **sidereal variations of the hyperfine splitting**:

→ These could be caused by the change of the magnetic field orientation (due to the rotation of the Earth) with respect to the Lorentz violating background field

→ In total a total of 24 × 3 = 72 independent SME coefficients in the Sun-centred frame!

→ Sidereal measurements of the hyperfine transition using a maser reached an absolute precision of mHz [1], which led to the constraint of 48 of the coefficients

→ **the remaining 24 unconstrained coefficients can be probed by changing the field orientation in the laboratory frame**

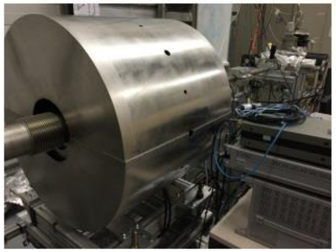


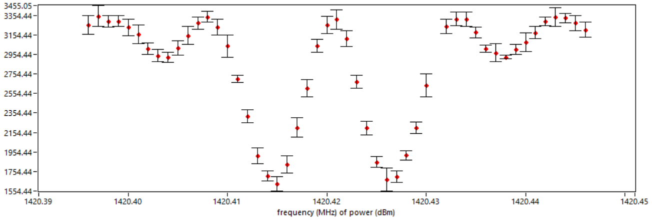
The presence of Lorentz violation would appear as an effective field felt by the atoms. Within (the minimal) SME this field acts as a cosmically (constant and) fixed background field

[1] M. A. Humphrey, D. F. Phillips, E. M. Mattison, R. F. C. Vessot, R. E. Stoner, and R. L. Walsworth, Phys. Rev. A 68, 063807 (2003).

Measurements and Timeline

2017-2018	2019 - 2020	May 20	Sep 20	Dec 21
• σ transition at high precision (not sensitive to SME) [1] • Improvement of B-fields homogeneity • π1 transition at high precision (sensitive to SME) [2]	• Recommission-ing work • Beam search and optimization • Upgrade of experimental control • Improving data-acquisition and logging	• σ and π1 at opposite B-fields: May measurement campaign completed • Data analysis • Improvement of precision		• σ and π1 at opposite B-fields (high currents) • σ and π1 at low B-field (four level system)





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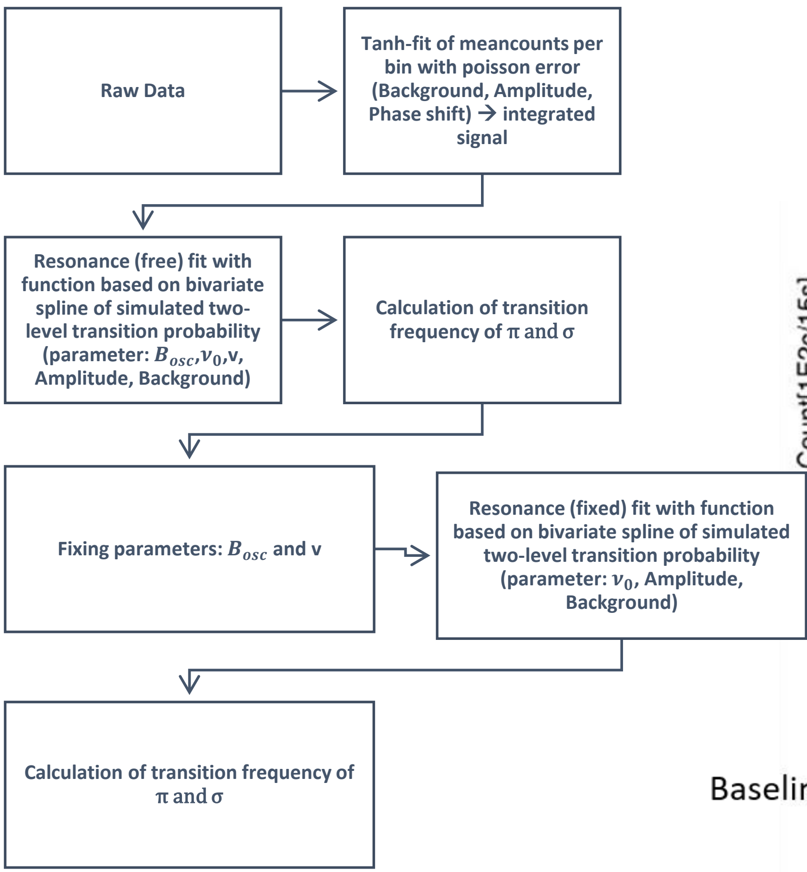
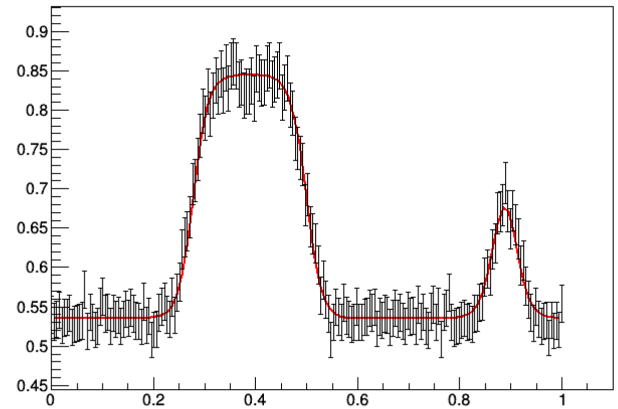
Fitting routine

Schematic overview of the data evaluation (Python/Root based):

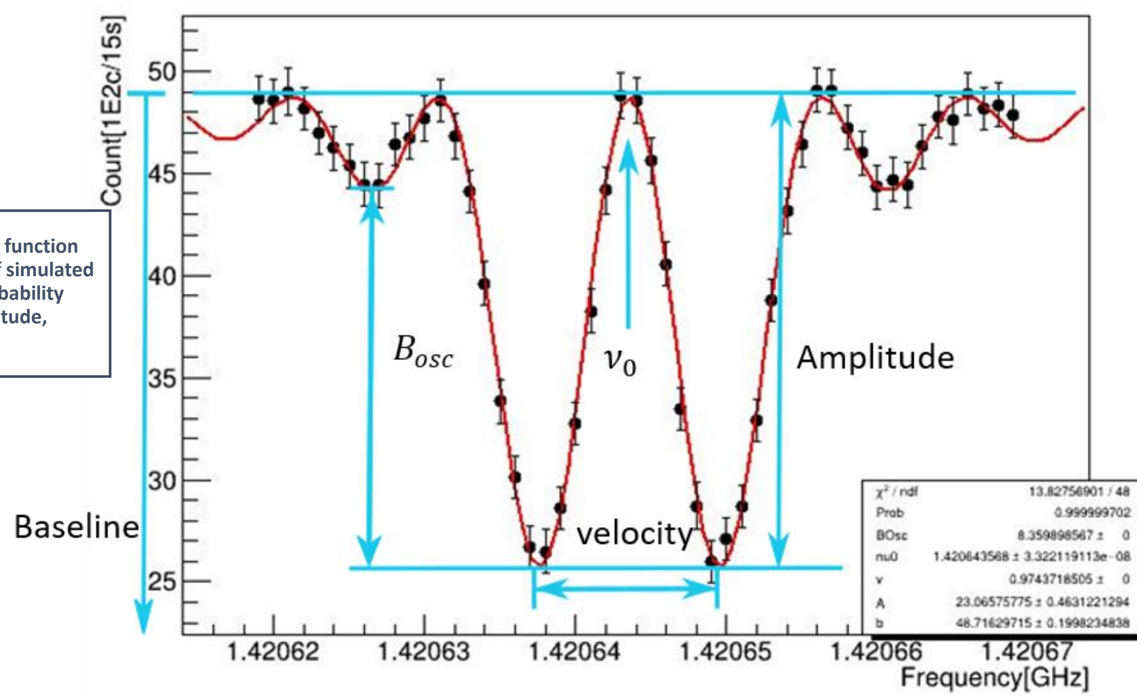


Typical (raw data) meancounts-fit:



Note: a chopper (with fixed frequency) is used to modulate the beam for background/signal separation via Lock-in Amplifier

Typical resonance fit:



B-field estimation: we are using B_σ as a reference

$\mu_\pm = |g_e|\mu_B \pm g_p \mu_N$

σ - transition

- $\nu_\sigma = \sqrt{{\nu_0}^2 + \left(\frac{\mu_- B}{h}\right)^2}$

$\rightarrow B_\sigma = \sqrt{\nu_\sigma^2 - \nu_0^2} * \frac{h}{\mu_-}$

$\rightarrow \Delta B_\sigma = \frac{dB_\sigma}{d\nu_\sigma} * \Delta\nu_\sigma$

π - transition

- $\nu_\pi = \frac{1}{2}(\nu_0 + \frac{\mu_+ B}{h} + \sqrt{{\nu_0}^2 + \left(\frac{\mu_- B}{h}\right)^2})$

$\rightarrow \nu_\pi^{exp} = \frac{1}{2}(\nu_0 + \frac{\mu_+ B_\sigma}{h} + \sqrt{{\nu_0}^2 + \left(\frac{\mu_- B_\sigma}{h}\right)^2})$

$\rightarrow \Delta\nu_\pi^{exp} = \frac{d\nu_\pi^{exp}}{dB_\sigma} * \Delta B_\sigma$

B-field dependencies:

$\frac{\partial\nu_\sigma}{\partial B} = \frac{\mu_-^2 B}{h^2 \nu_\sigma(B)} \approx B * 555 \frac{GHz}{T^2}$
$or\ 5.55\ kHz/Gauss^2$

$\frac{\partial\nu_\pi}{\partial B} = \frac{1}{2}\left(\frac{\mu_+}{h} + \frac{\partial\nu_\sigma}{\partial B}\right) \approx 14 \frac{GHz}{T}\ or\ 5.55 \frac{kHz}{Gauss}$

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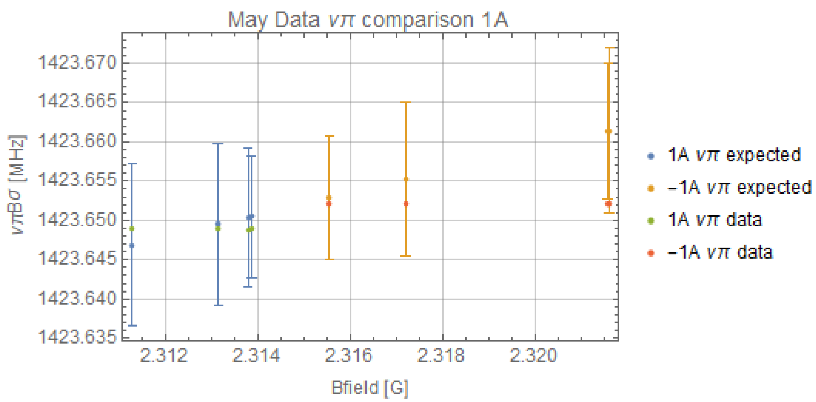
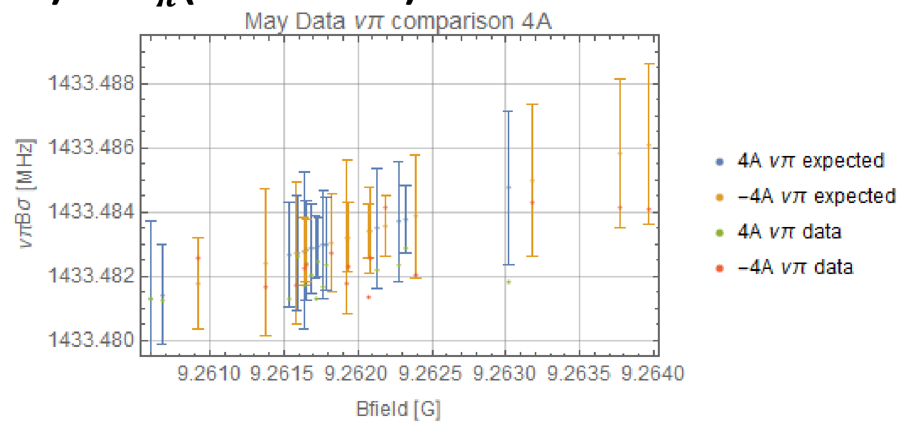
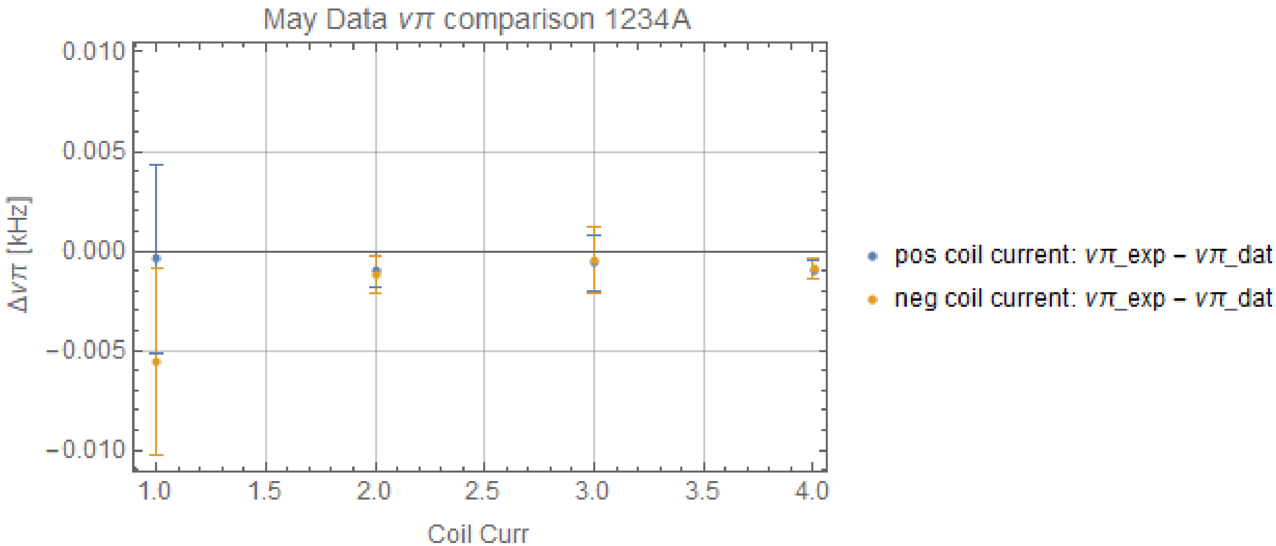
First results/Data Analysis (May Measurement Campaign)

Example: ν_π (expected value) vs ν_π(data value)





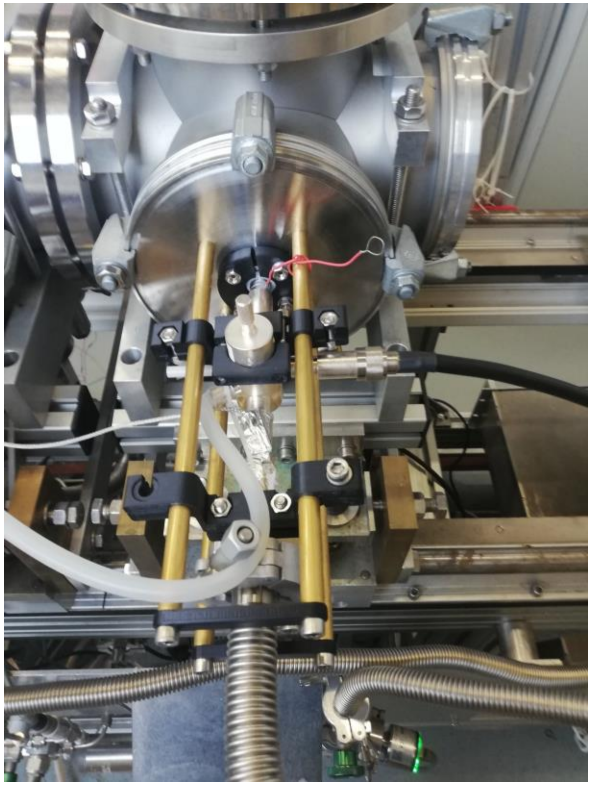
Averaged ν_π (expected value) $-\nu_\pi$(data value)



Is a systematic error responsible for the sub-zero shift?

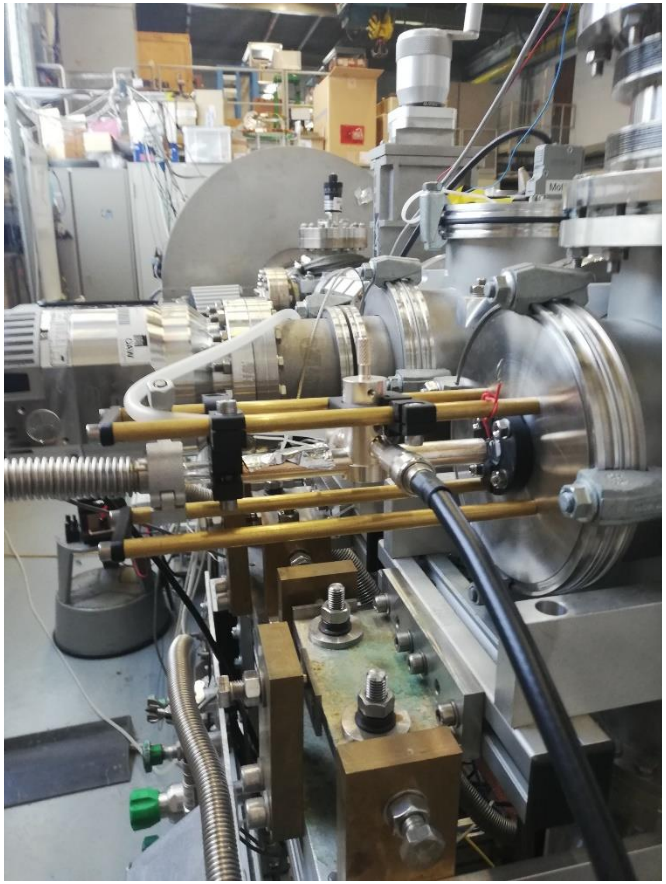
Status and Outlook

- Data taking (below 10 Gauss) is still ongoing
  → After switching to a new plasma source we see a factor 3 improvement in rate!
- B-field extraction is our biggest limiting factor
  → Longer measurement times for σ transitions
- High current measurement campaign?
- Low B-field measurement campaign? (four level system)

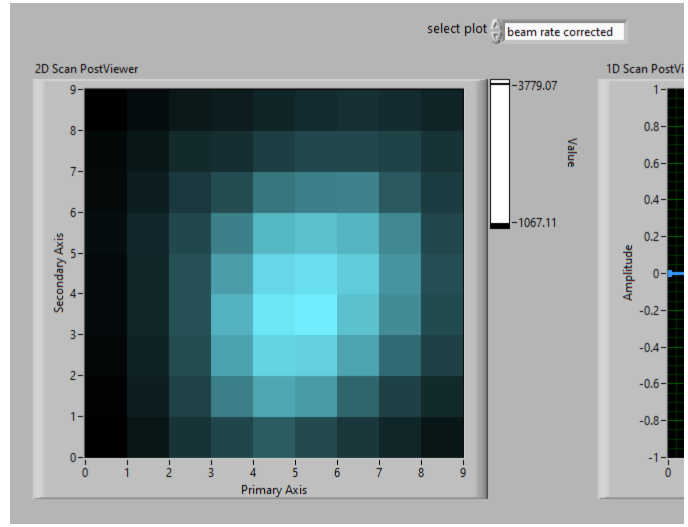


Thank You For Your Attention!

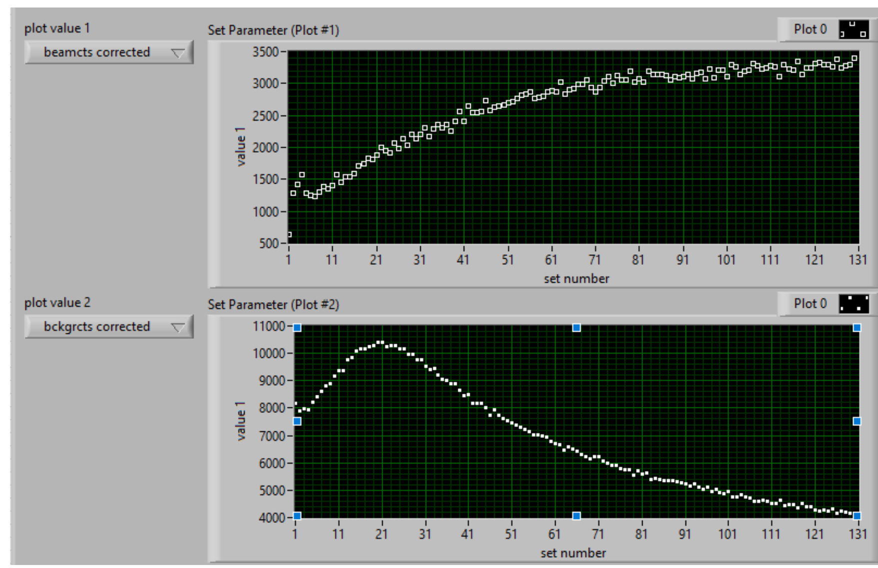
McCarroll Cavity



2D measurement of the beam-profile



Rate improvement after implementation of McCarroll cavity



SME - formulas

- SME – coefficients:

$$\mathcal{K}_{\mathcal{W}_{k10}}^{Lab} = \mathcal{K}_{\mathcal{W}_{k10}}^{Sun}\cos(\theta) - \sqrt{2}\,\mathfrak{Re}\left(\mathcal{K}_{\mathcal{W}_{k11}}^{Sun}\right)\sin(\theta)\cos\left(\omega_{\oplus}T_{\oplus}\right) + \sqrt{2}\,\mathfrak{Im}\left(\mathcal{K}_{\mathcal{W}_{k11}}^{Sun}\right)\sin(\theta)\sin\left(\omega_{\oplus}T_{\oplus}\right)$$

- $\omega_{\oplus} = \frac{2\pi}{23\,h\,56\,min}$: earth’s rotation frequency
- $T_{\oplus}$: sidereal time
- θ: angle between the applied magnetic field and the earth’s rotational axis

→ The hyperfine splitting is sensitive to a linear combination of the 4 $\mathcal{K}_{\mathcal{W}_{k10}}^{Lab}$ coefficients.

- Shift of a hyperfine transition in the laboratory frame:

$$2\pi\delta\nu(\Delta M_F) = \frac{\Delta M_F}{2\sqrt{3\pi}}\sum_{q=0}^{2}\alpha {m_r}^{2q}(1+4\delta_{q2}) \times \sum_{\mathcal{W}}\left[-g_{\mathcal{W}(2q)10}^{0B} + H_{\mathcal{W}(2q)10}^{0B} - 2g_{\mathcal{W}(2q)10}^{1B} + H_{\mathcal{W}(2q)10}^{1B}\right]$$