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ASACUSA's Ramsey spectrometer for high precision hyperfine spectroscopy

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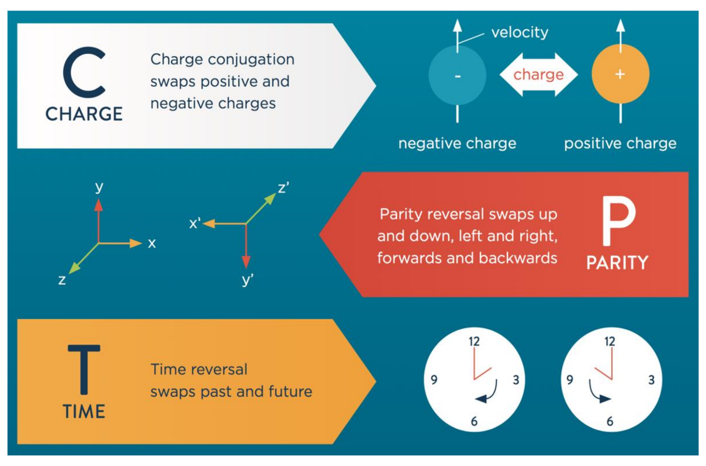
MOTIVATION: CPT SYMMETRY and HYPERFINE STRUCTURE

The Standard Model manifests the CPT symmetry to be the **most fundamental symmetry** in particle physics.



Source: http://antimattermatters.s3-website-eu-west.amazonaws.com/buildingblocks.html

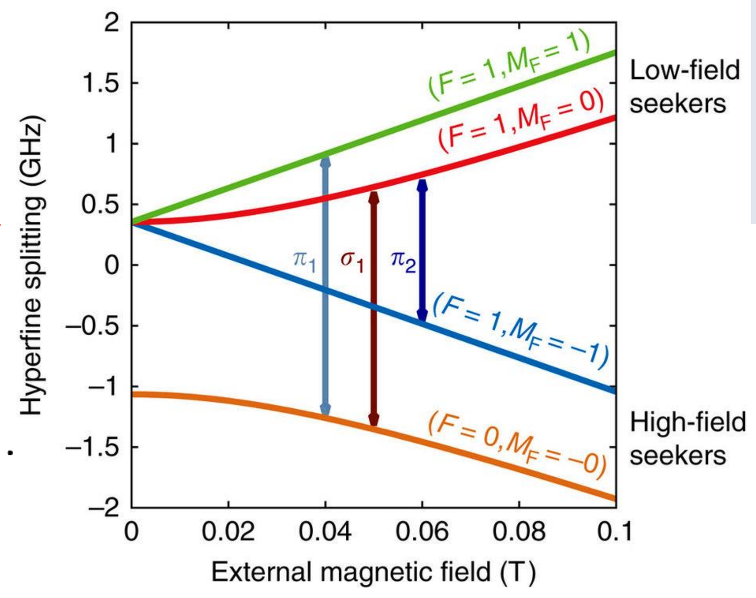
SM Dirac eqn. — CPT & LORENTZ VIOLATION

$$\left(i\gamma^\mu D_\mu - m_e - a^e_\mu\gamma^\mu - b^e_\mu\gamma_5\gamma^\mu - \frac{1}{2}H^e_{\mu\nu}\sigma^{\mu\nu} + ic^e_{\mu\nu}\gamma^\mu D^\nu + id^e_{\mu\nu}\gamma_5\gamma^\mu D^\nu\right)\psi = 0.$$

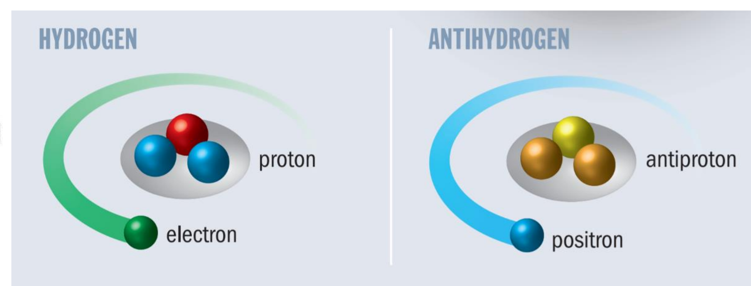
LORENTZ VIOLATION

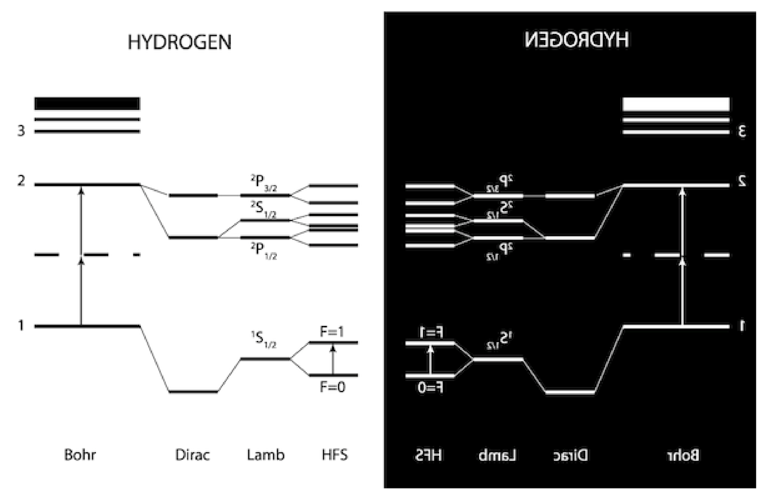
SME effect on $\overline{H}$: shift in hyperfine structure
R. Bluhm, V.A.Kostelecký & N.Russell, PRL 82, 2254-2257 (1999).

Non-minimal SME: π-transition affected by B-field direction.
Kostelecký, V. Alan., Physical Review D 92 (5), 056002, Sep. 2015.



Breit Rabi diagram of the hydrogen hyperfine structure

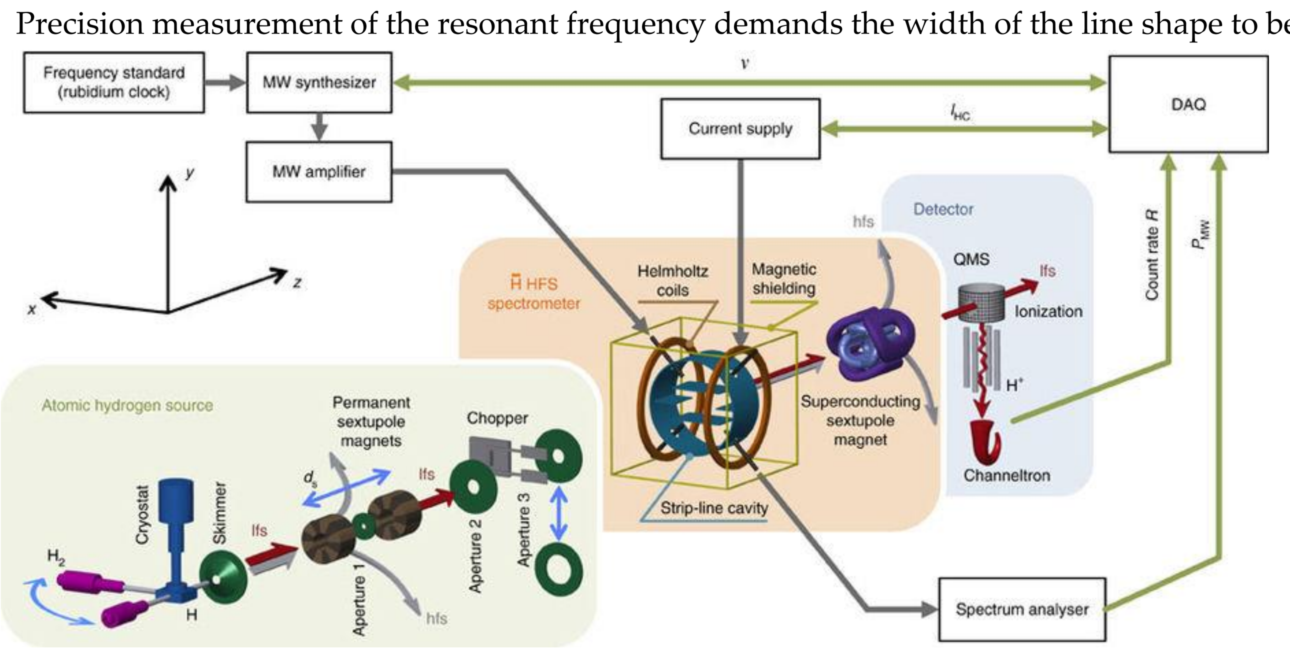




The interaction of the proton and electron spin splits up the ground state of hydrogen to four different Zeeman levels, which depends on an external magnetic field. The Standard model extension predicts the hyperfine structure to be different for hydrogen and antihydrogen.

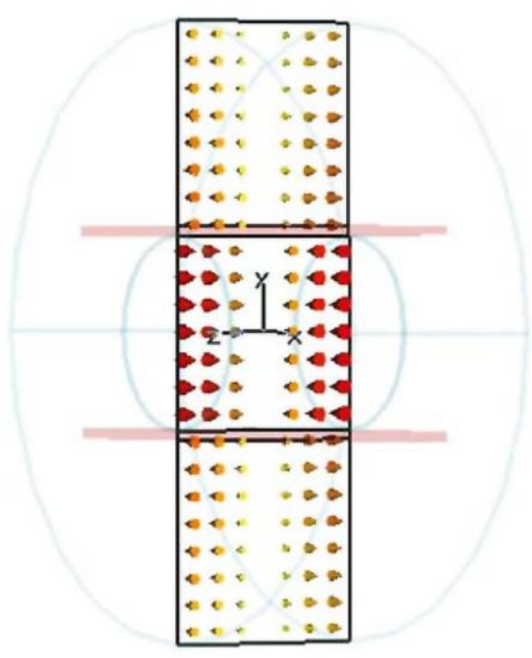
SPECTROSCOPY: RABI TO RAMSEY

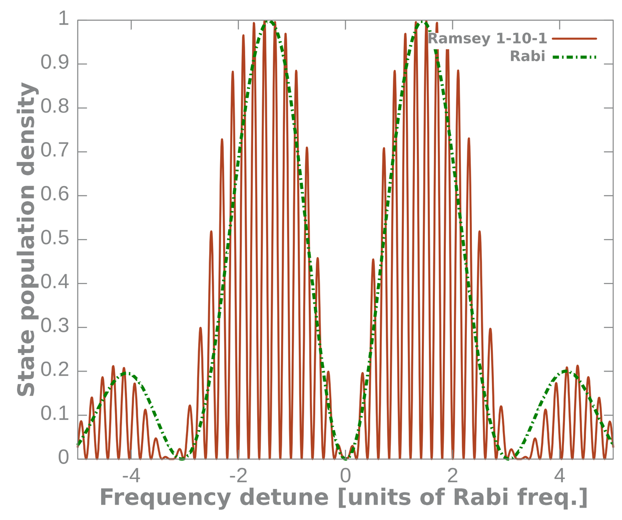
Hyperfine transitions are driven by applying an oscillating magnetic field (perturbation) in the presence of an external magnetic field. Transition probability as a function of frequency looks like a Resonance line shape. Precision measurement of the resonant frequency demands the width of the line shape to be as narrow as possible.



$$\vartheta_{HF} = 1\ 420\ 405\ 748.4\ (3.4)(1.6)Hz$$

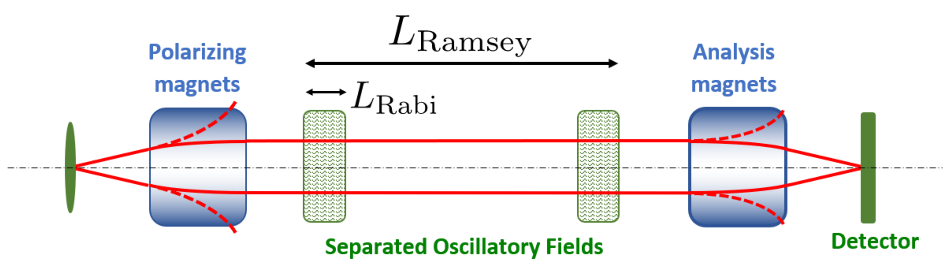
Diermaier, M. et al. In-beam measurement of the hydrogen hyperfine splitting and prospects for antihydrogen spectroscopy. Nat. Commun. 8 , 15749 (2017).





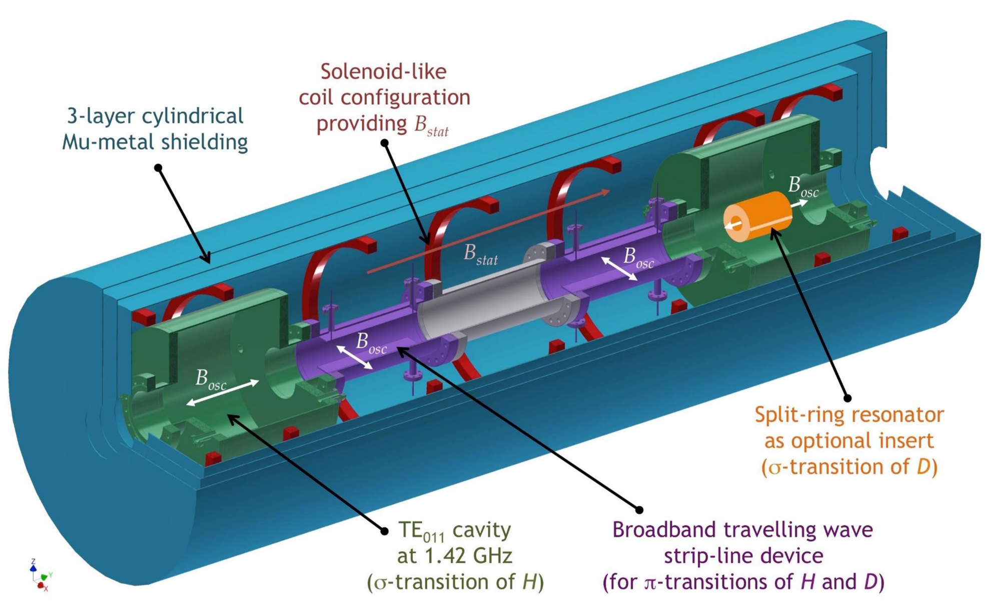
Ramsey method makes use of two separated oscillatory fields at the incident and emergent ends of the homogeneous field region.

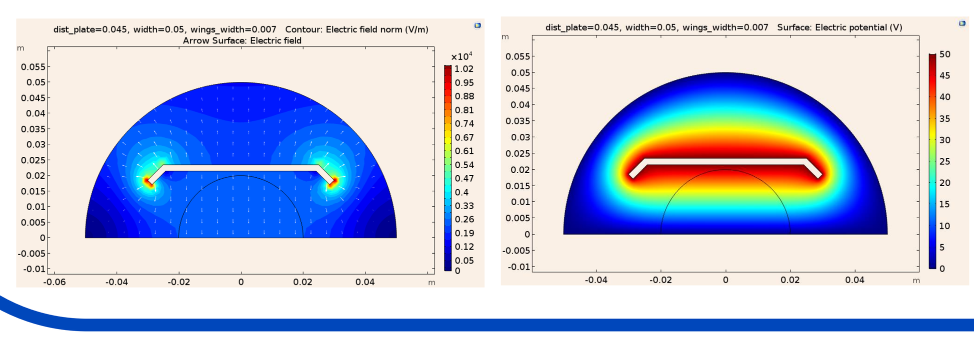
$$\delta\nu \propto \tau_{\rm int}^{-1} = \frac{v_{\rm beam}}{L_{\rm Osc.F.}}$$

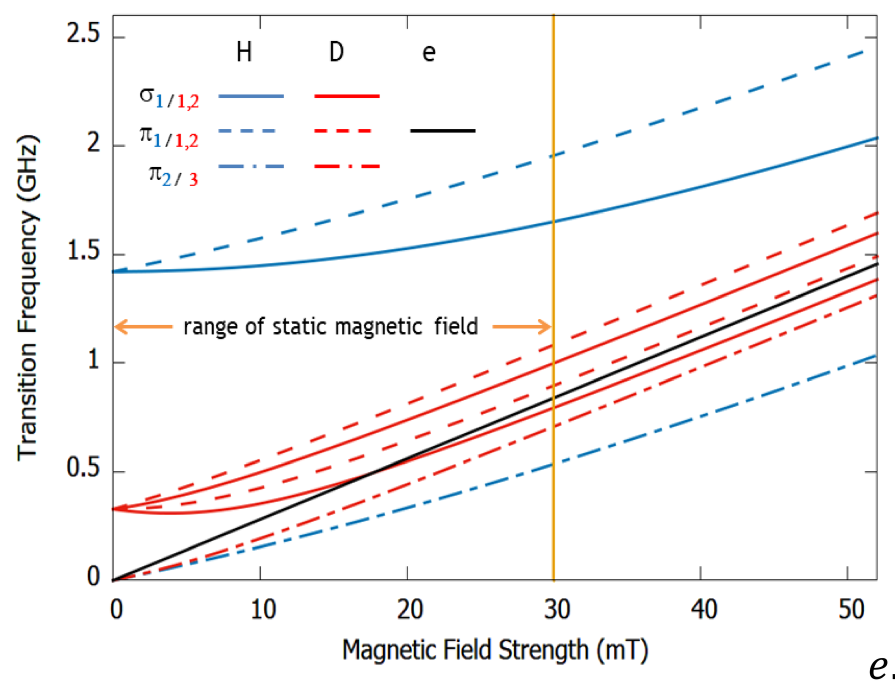


Ramsey, Norman F. A Molecular Beam Resonance Method with Separated Oscillating Fields. Phys. Rev. 78 , 695 (1950).

COMBINATION OF STANDING AND TRAVELLING WAVES



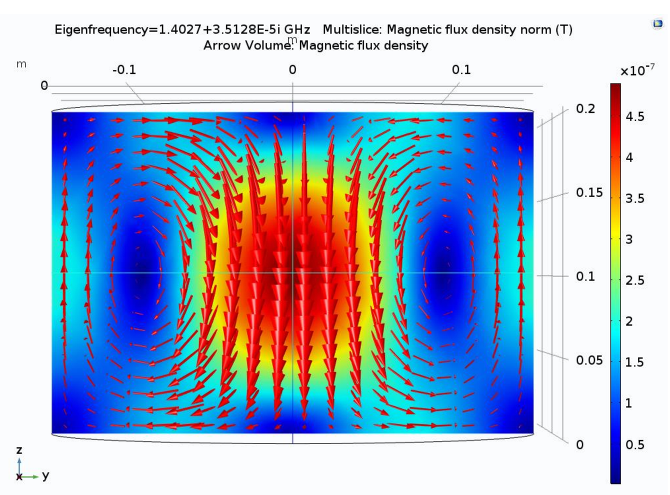


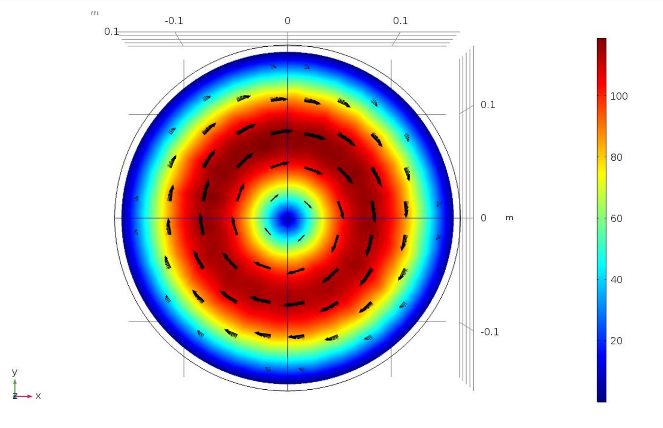


$$\omega_{ec} = \frac{e.B}{m_e}$$

- Linear dependence of electron cyclotron frequency
- Broadband striplines: both hydrogen and deuterium
- Differential mode operation of striplines
- Electrostatics study to realize a 50 Ω structure

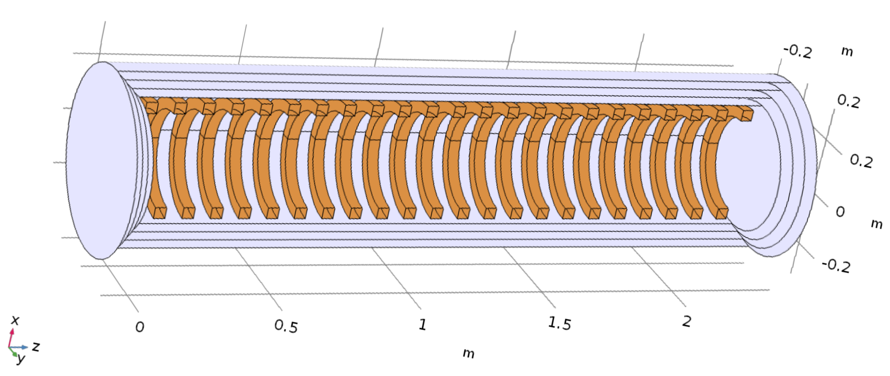
TE110 MODE CAVITY

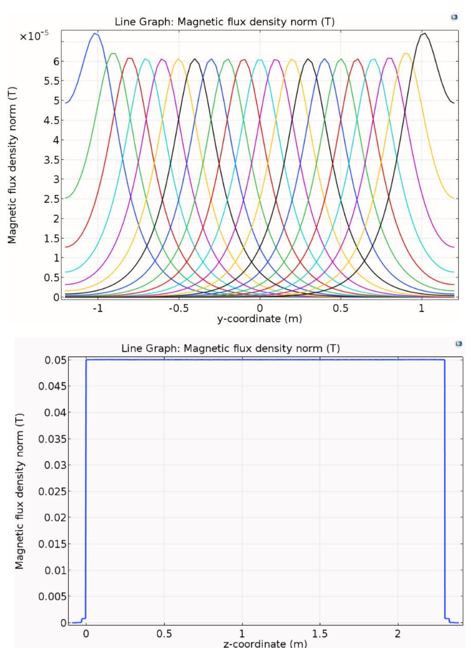


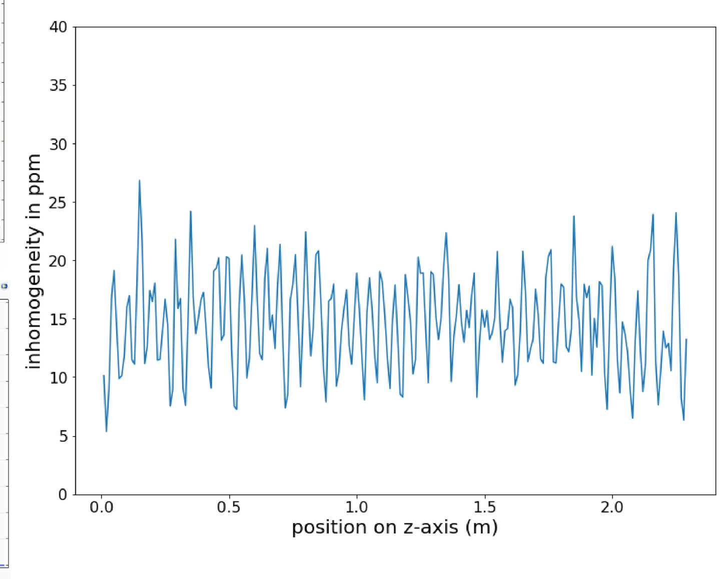


- TE-110 mode cavity at 1.42 GHz
- Magnetic field along cavity axis
- No zero crossing of the magnetic field
- Circulating electric field
- Can be used for σ-transition in hydrogen
- Geometry restricted by the frequency: for deuterium, the optionally a aplit ring resonator can be inserted

COILS FOR STATIC FIELD



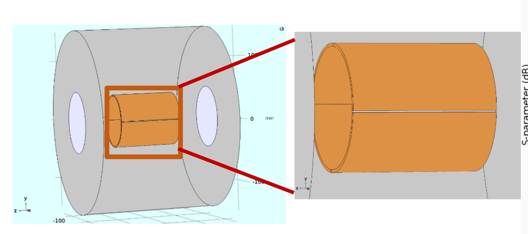


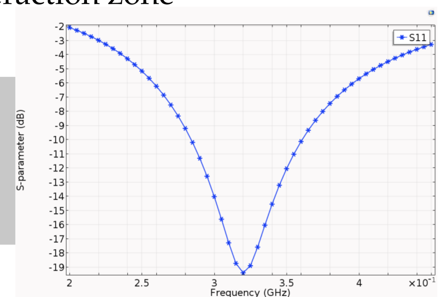


- 2D coil array simultions: each individual coil with 3 layer shielding
- Matrix inversion: optimal number of turns for each coil
- Used these numbers for simulation of coil array in 3D
- Better than 100 ppm homogeneity

OUTLOOK

- Feedthroughs and excitation of stripline
- Coils vs. solenoid: if the coils are too close to each other, with not much accessible space, solenoid is still an option
- Simulation for lineshape with counter-propagating waves
- Higher order doppler effects
- Isolation of the microwaves: we have to restrict the microwaves exactly in the interaction zone





This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 721559 and also supported by the Austrian Science Fund FWF, Doctoral Program No. W1252-N27. For the design of the stripline deveices, we acknowledge the support of Dr. Fritz Caspers. Physics of fundamental Symmetries and Interactions – PSI2019, 20 - 25 Oct. 2019, Paul Scherrer Institut, Switzerland. † http://www.cern.ch/ASACUSA.

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