H·HFS
Hyperfine Structure of Antihydrogen

ERC Advanced Grant
PI: Prof. Dr. Eberhard Widmann

Hyperfine spectroscopy setup for antihydrogen and first results with a hydrogen beam

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EXA 2014

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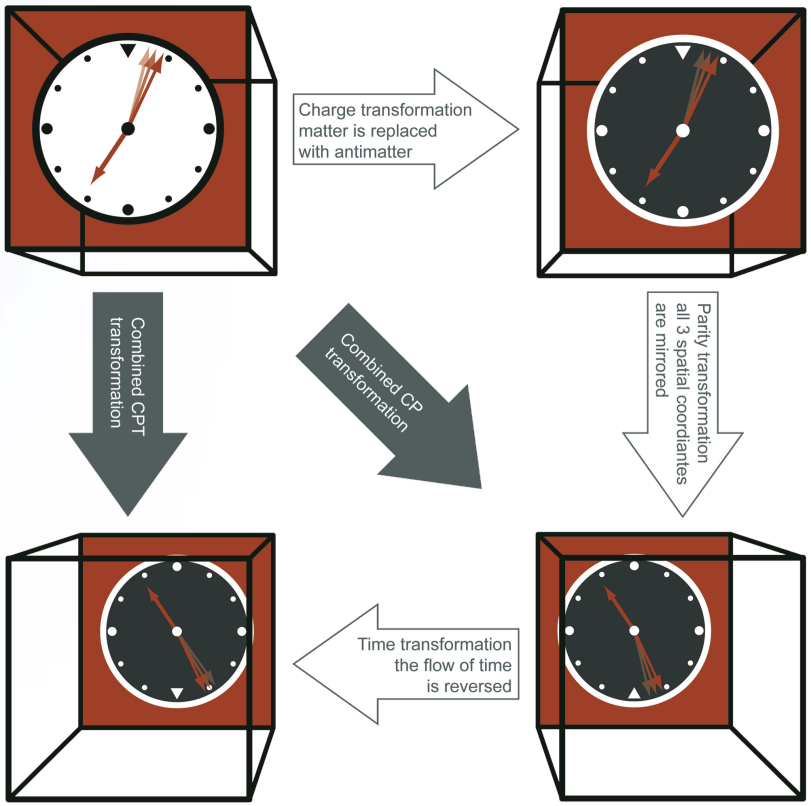
MOTIVATION

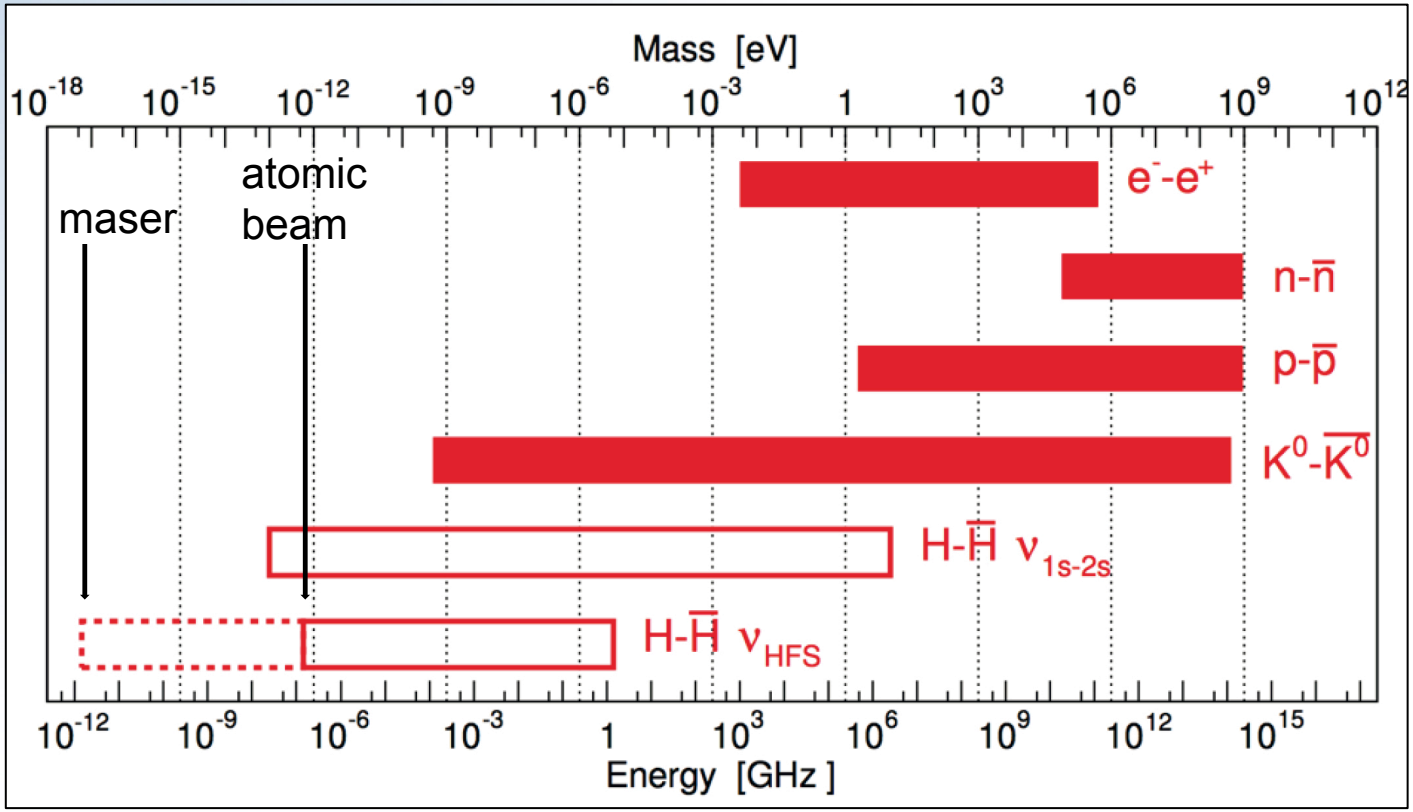
- Charge
  particle - antiparticle
- Parity
  spatial mirror
- Time reversal

- CPT symmetry
  Combined symmetry
  of charge parity and time reversal
  – same properties for particles
  and antiparticles

  No violation observed to
  date

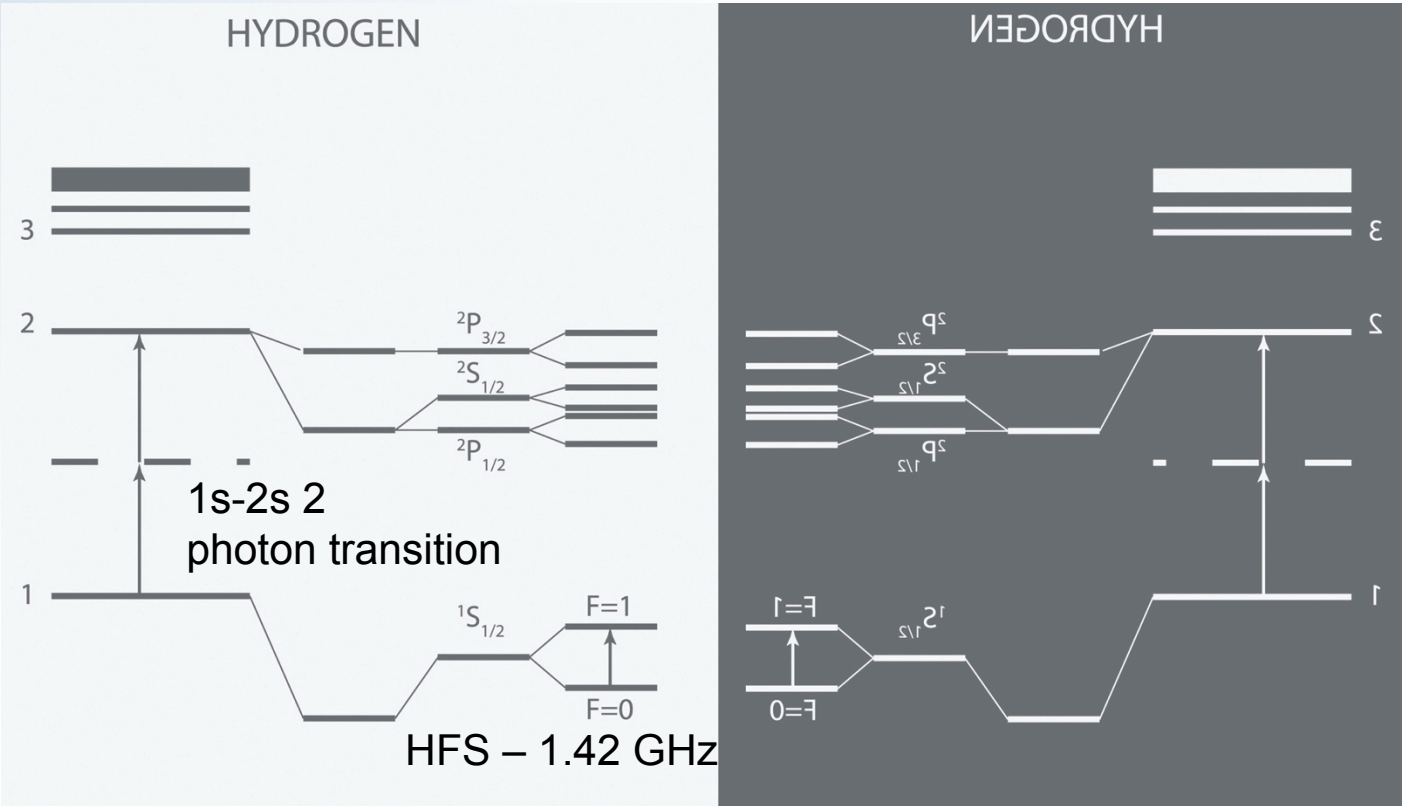


PRECISION



GS-HFS of Hydrogen / Antihydrogen offers best test of CPT on absolute scale

HYDROGEN / ANTIHYDROGEN

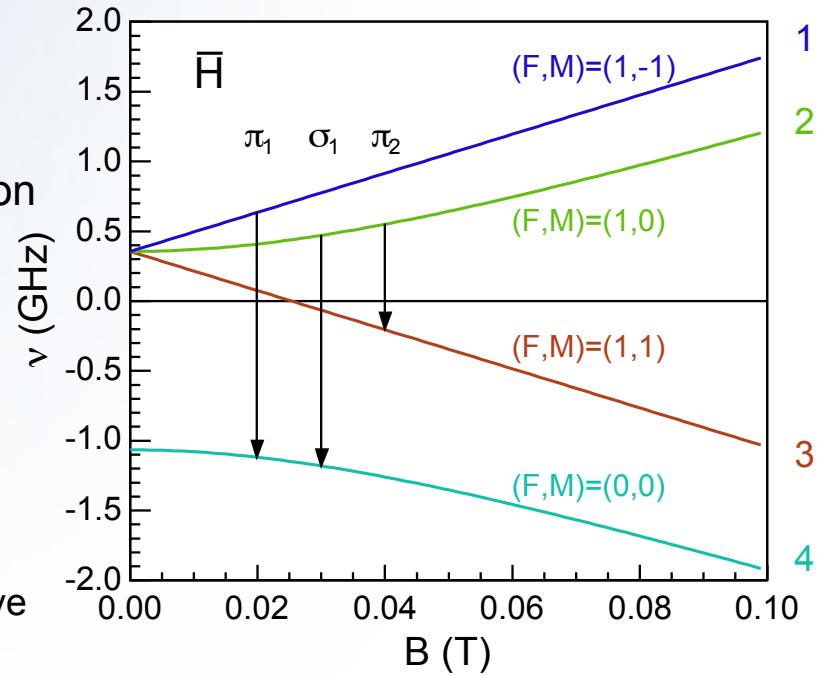


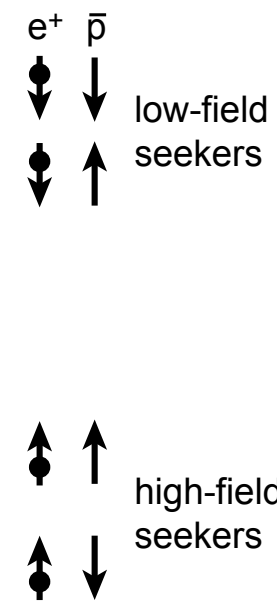
GROUNDSTATE HYPERFINE SPLITTING OF HYDROGEN

Breit-Rabi diagram

- Coupling of angular momentum of proton and electron - spin spin Interaction
- Splits into
  - Singlet state
  - Triplet state

- In an inhomogeneous magnetic field states can be classified into
  - Low field seekers – move in direction lower magn. Field
  - High field seekers – move in direction higher magn. field

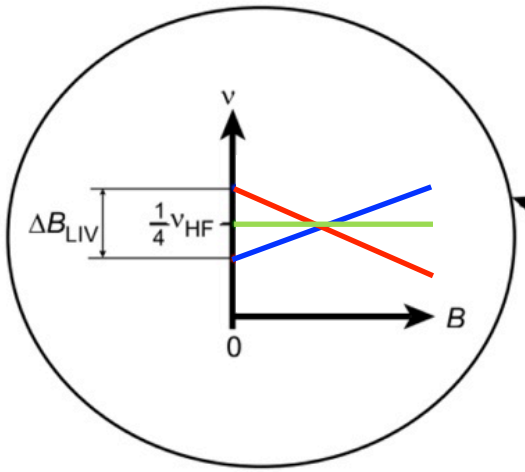


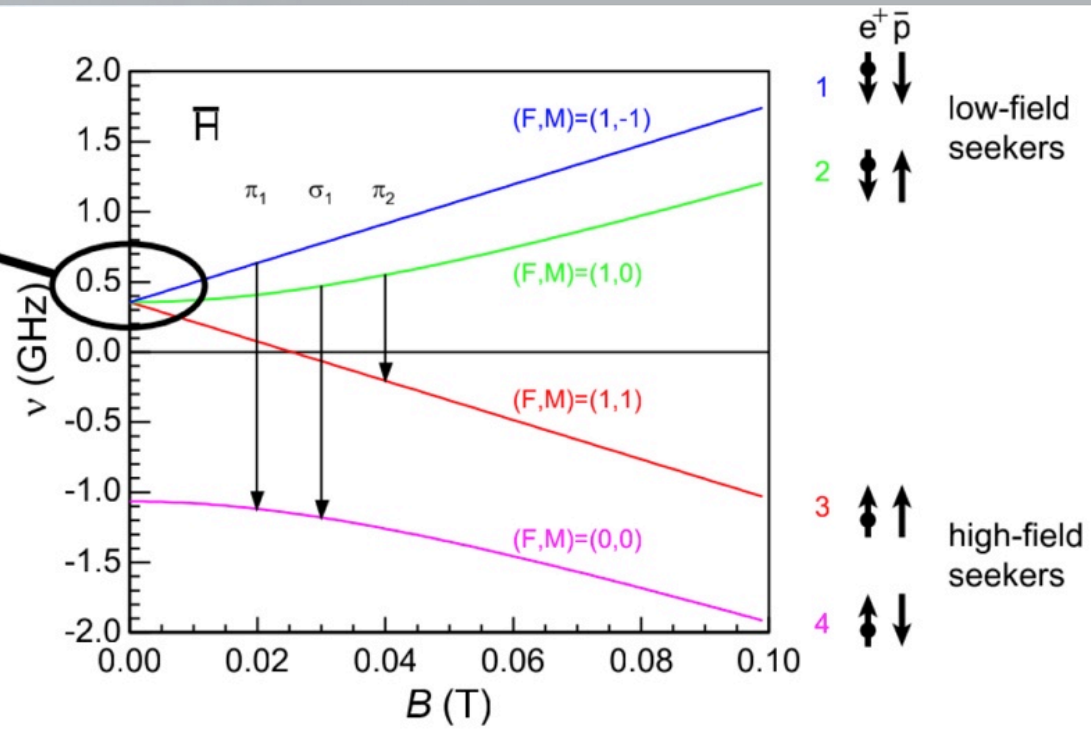


Achievable resolution:

10^{-6} for T< 100 K
100 Hbar/s in 1s state into 4π needed
eventrate 1/min

MINIMAL STANDARD MODEL EXTENSION



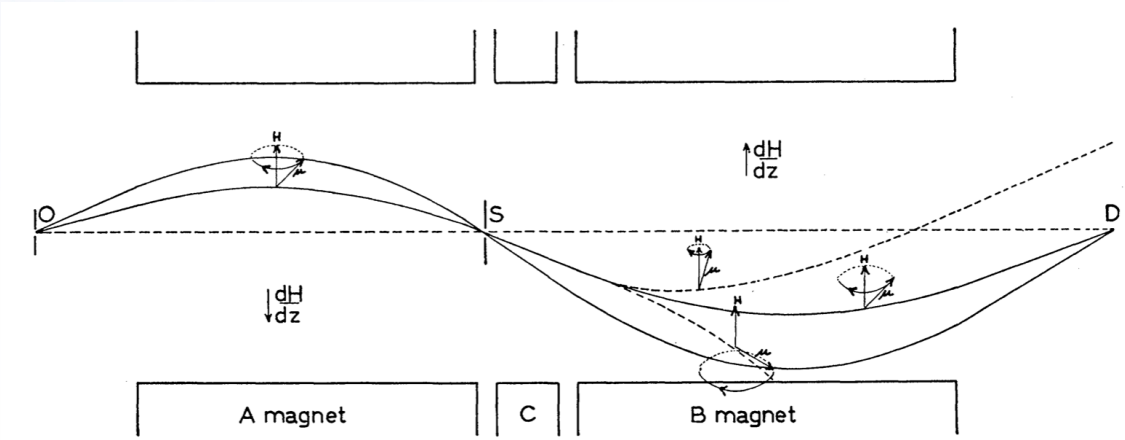


- In minimal SME HFS shows CPT violation
- 1s-2s no effect
- HFS: Splitting of triplet even in zero field

HISTORY OF HYDROGEN GS-HFS

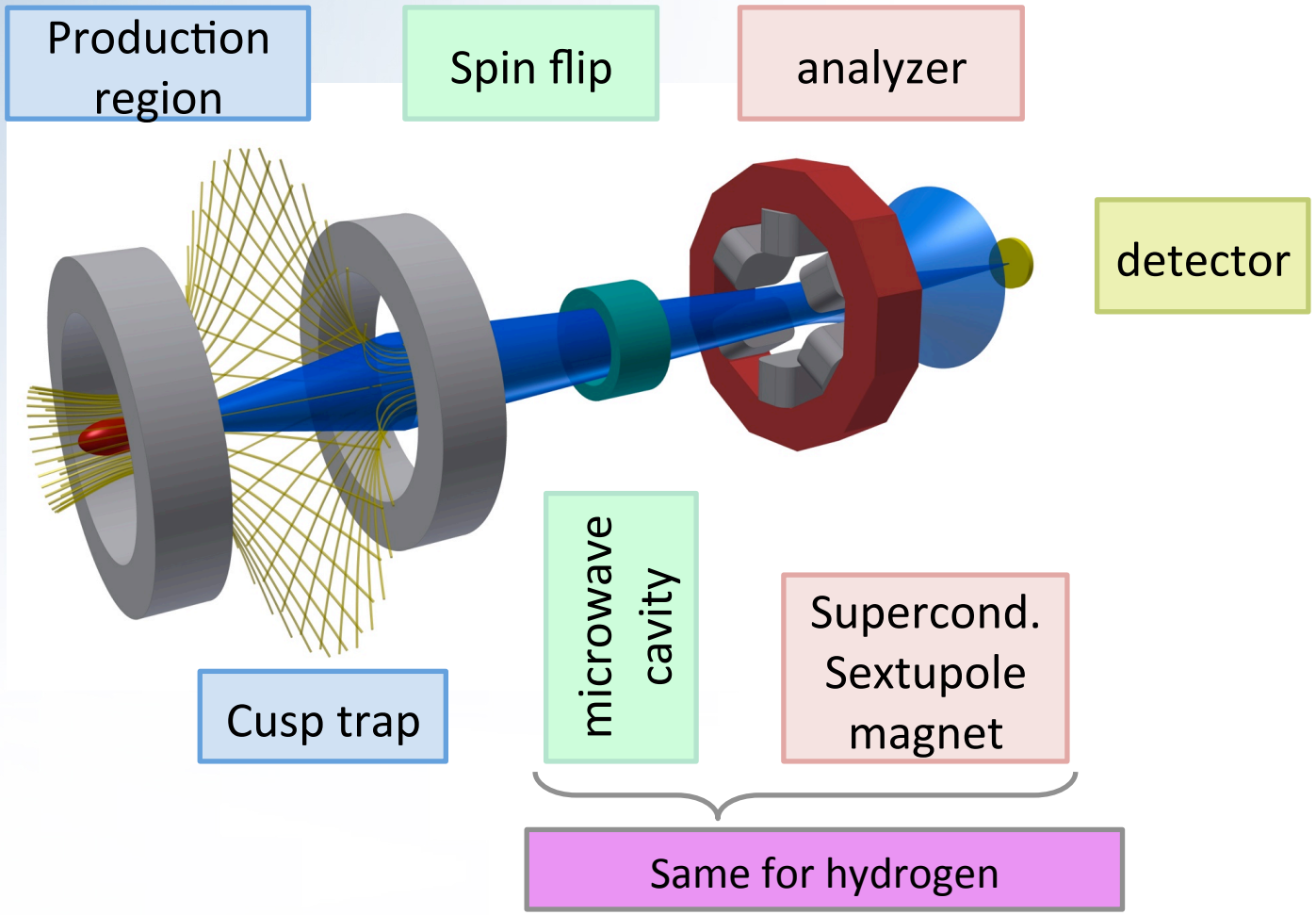
- 1936 Simple atomic beams ~5%
- 1946 Atomic beams plus microwave resonance 4×10^{-6}
- 1955 4×10^{-8}
- 1969-70 Hydrogen maser 6×10^{-13}

Not possible for antimatter



Molecular Beam Resonance Setup I.I.Rabi et al., Phys. Rev. 55, 526 (1939)

ASACUSA´S APPROACH RABI BEAM EXPERIMENT



Already reported by Dan Murtagh

DIFFERENECES H/HBAR

	Hbar	H
Beam production rate	Low ~10 per min	Very high 10^{19} per minute
Detection efficiency	Approximately 0.6	Detector $10^{-8...-9}$ + solid angle
Detection method	Annihilation products, tracking	Electron impact ionization and single ion counting
background	Cosmic radiation Supressed by tracking	Residual gas Background >> signal

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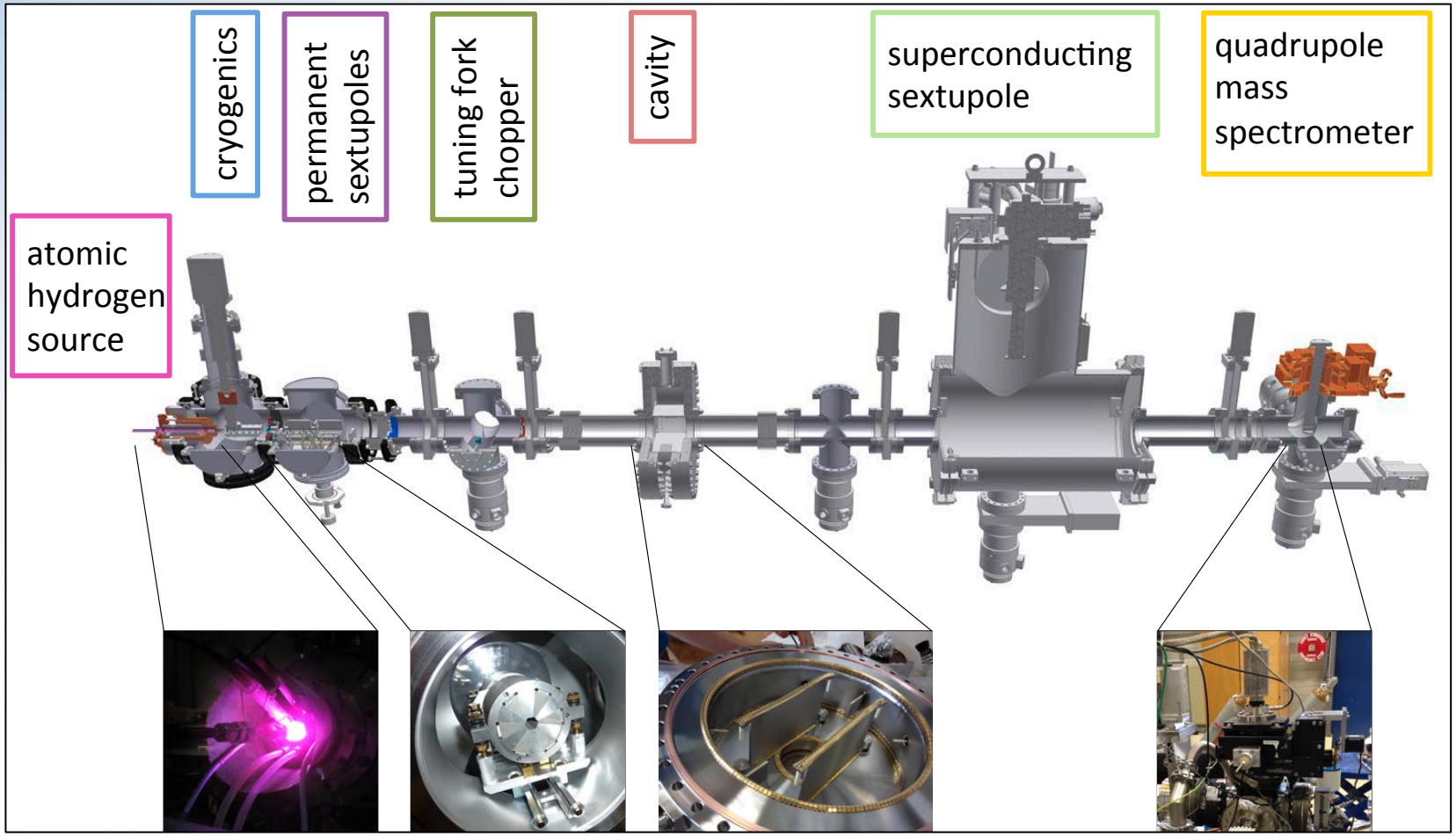
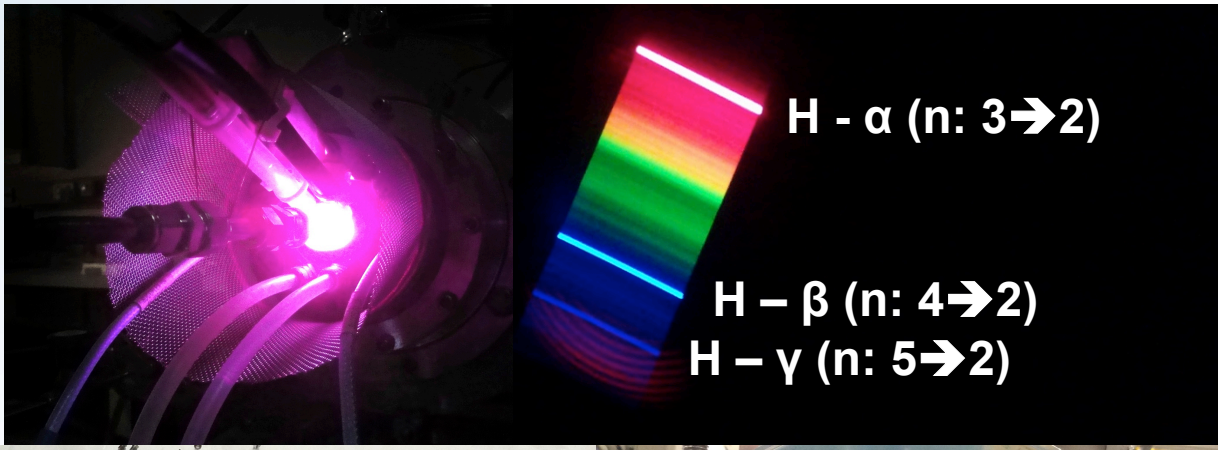
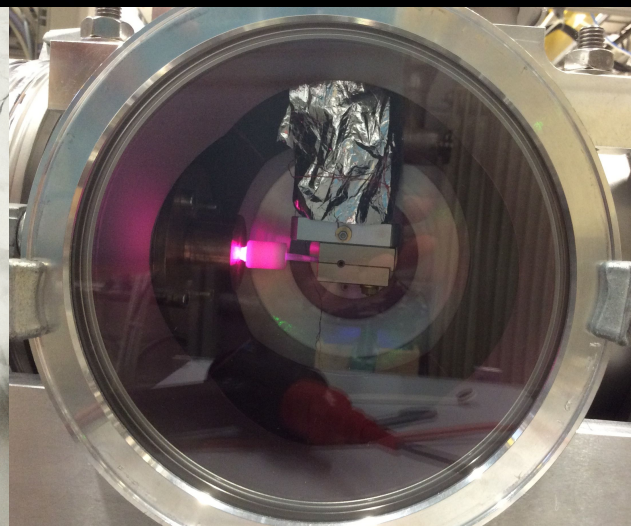
HYDROGEN BEAM LINE



ATOMIC HYDROGEN SOURCE

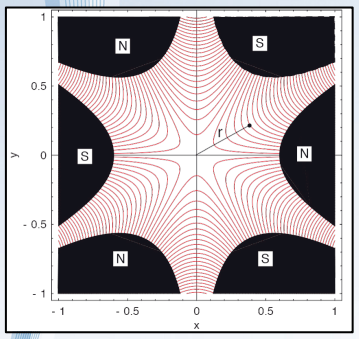
- Plasma induced by microwaves with f = 2.45 GHz
- cooled with coldhead

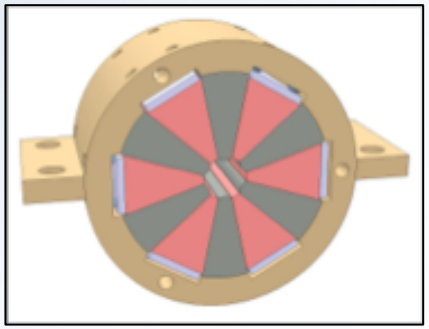




POLARIZATION
PERMANENT SEXTUPOLE MAGNETS

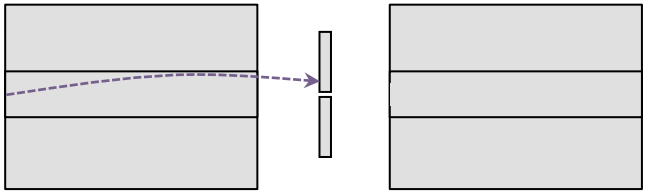
Polarization gained with a set of perm. Sextupole magnets



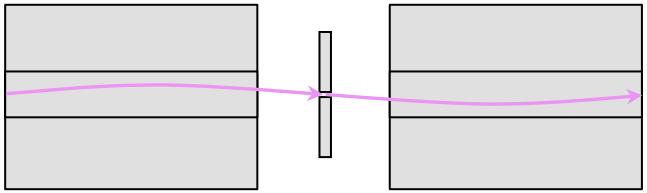


Low field seekers focused

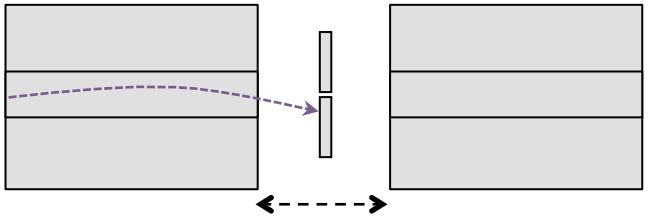
V too high



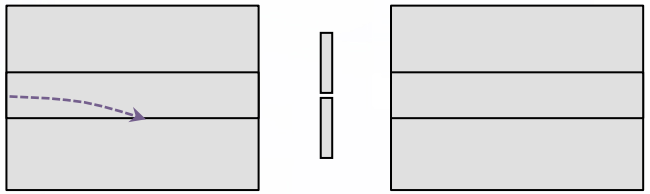
V accepted



V too low

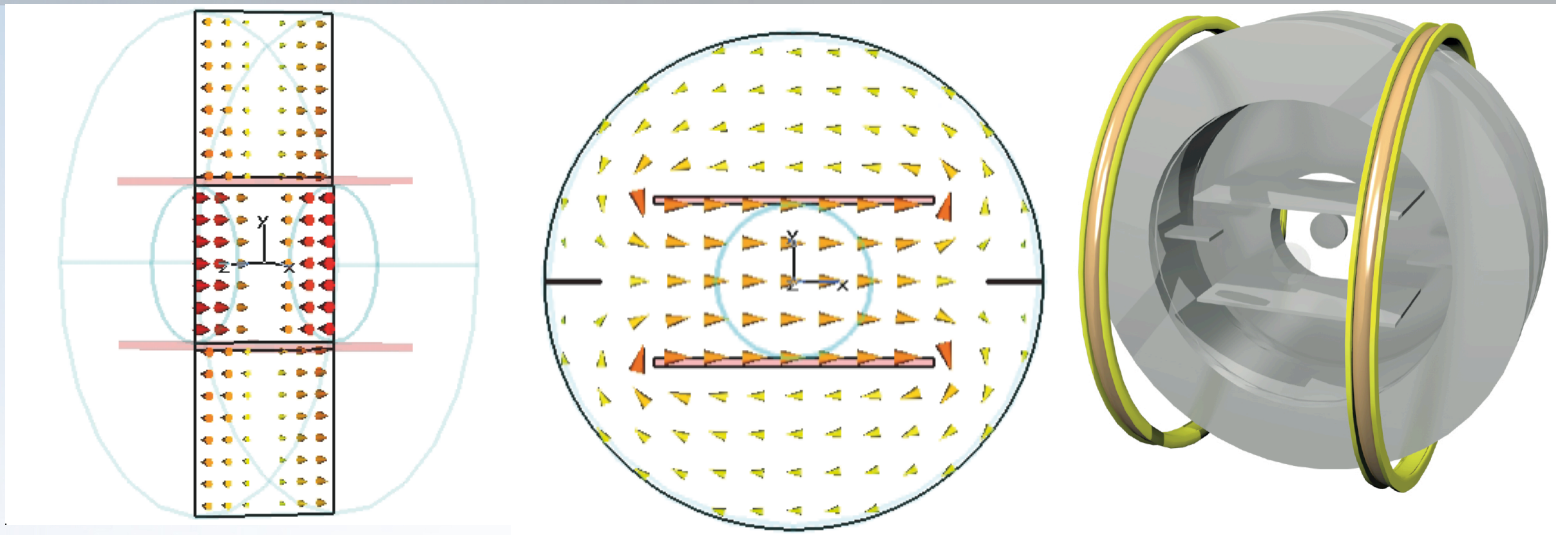


High field seekers defocused

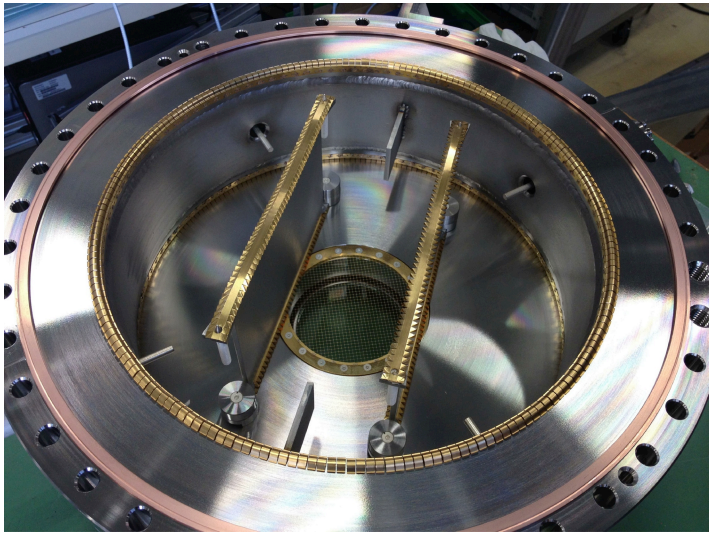


Changing the distance to each other selects velocity

CAVITY – SPIN FLIP RESONATOR



- f = 1.42 GHz, Δf = few MHz ~ mW power
- Homogenity over 10 x 10 x 10 cm^3 at λ = 21 cm
- Spin flip resonator – strip line design
- Q ~ 100



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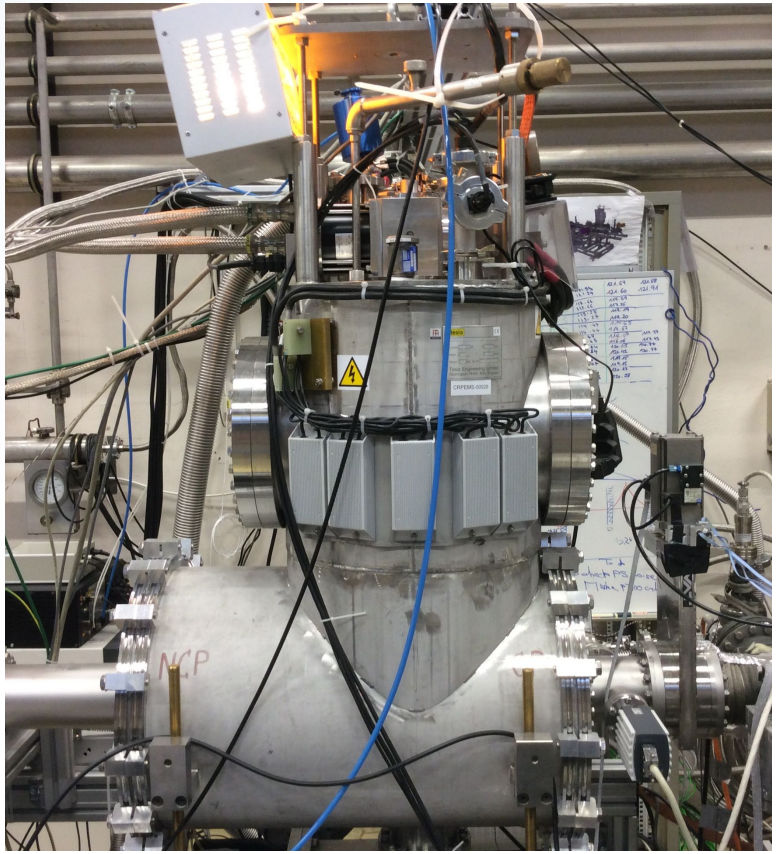
SUPERCONDUCTING MAGNET

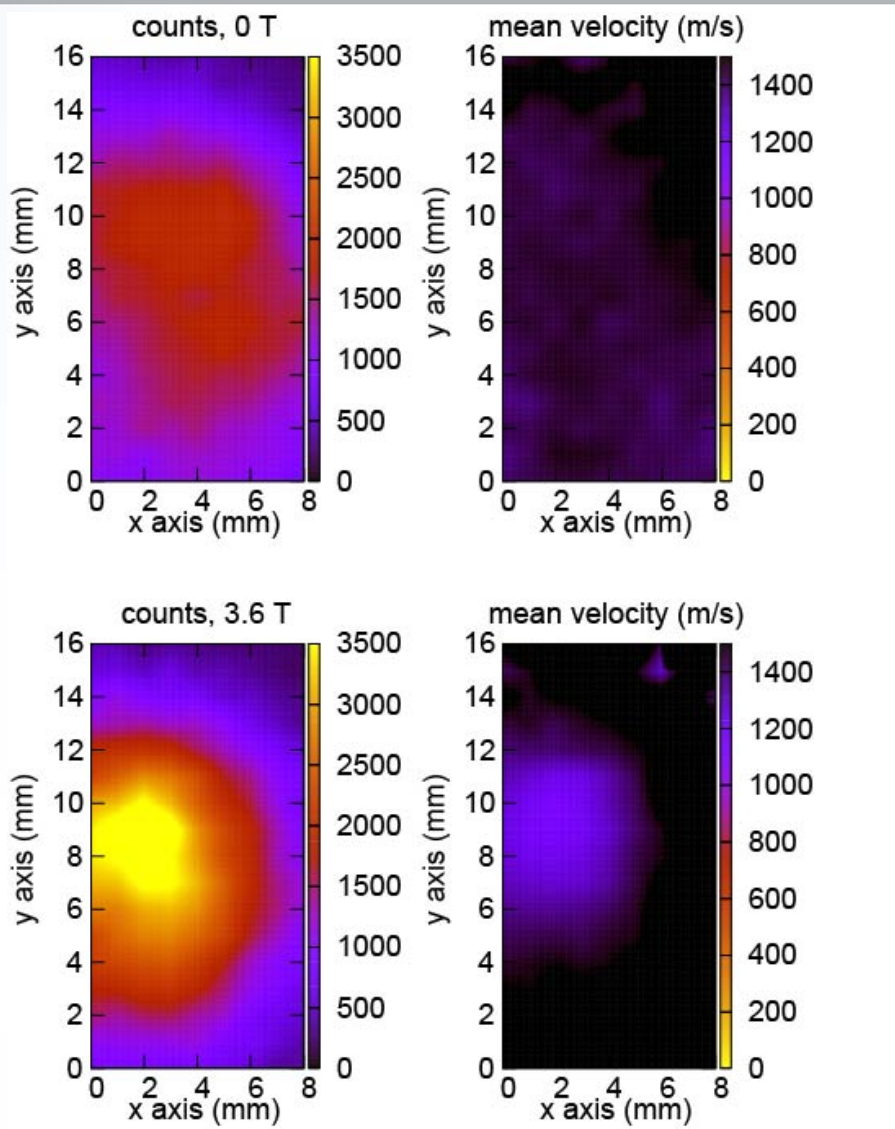
Superconducting sextupole magnet
400 A with max field strength of 3.6 T

Analyzer of the Spin state
High field seekers defocused



FOCUSING - DEFOCUSING

- when the sextupole magnet is turned off a beam with low intensity can be seen
- Sexutpole turned on beam intensity increases due to focusing
- TOF (phase) shows that slower part of the beam is focused on the detector



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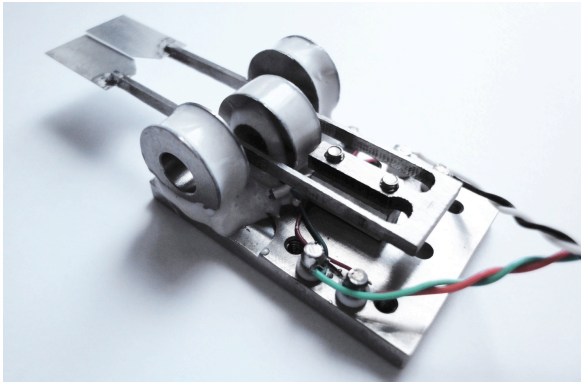
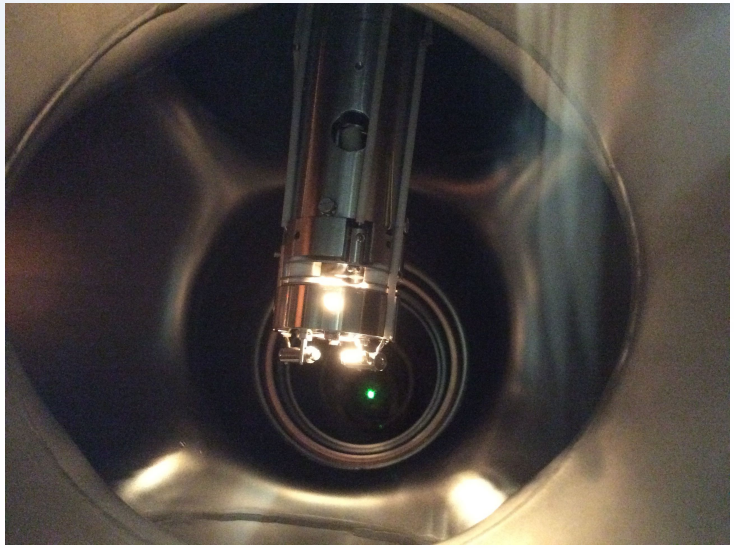
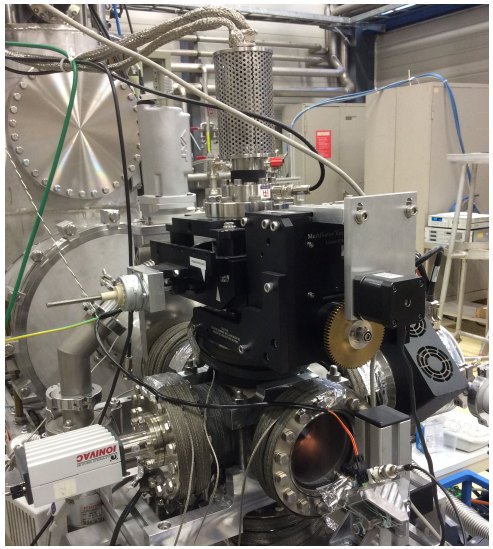
DETECTION

- QMS – crossed beam configuration – no recombination of the atoms before detection
- Single particle detection with channeltron
- Tuning fork chopper – modulation of the beam, velocity cross checks

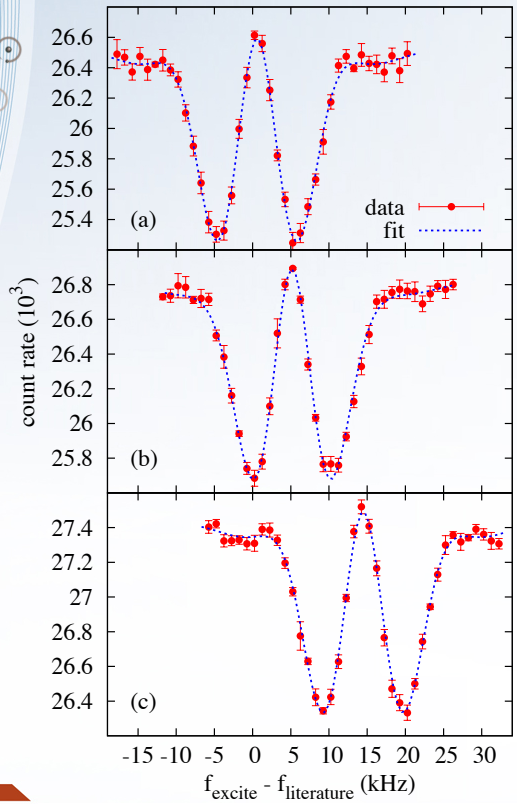






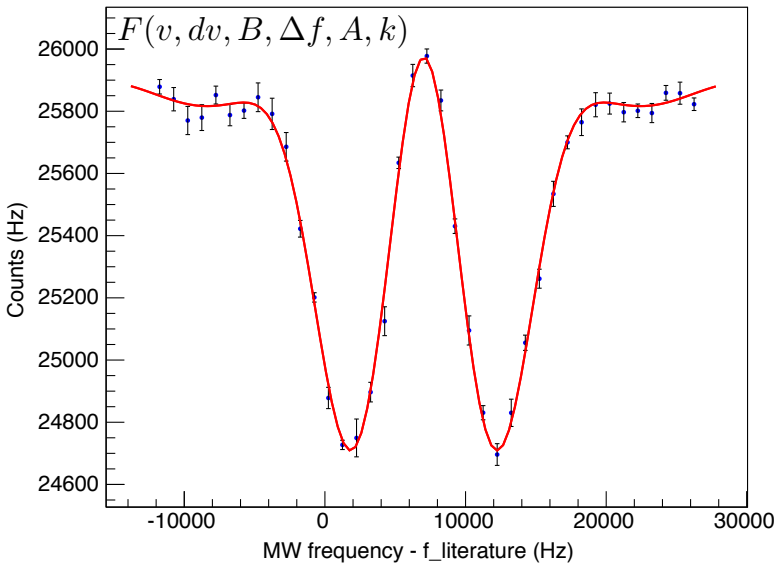
RESONANCE LINESHAPE

- σ_1 transitions
- Fit the data with numerical simulated Bloch equations data
- Get f_c, v, power



shift of resonances in magn. field
(a) 100 mA (b) 300 mA (c) 500 mA

350 mA Helmholtz coils current



Fit parameters	results
Microwave amplitude (mG)	5.93 ± 0.13
f_0 (Hz)	1420404257.6 ± 24.7
Velocity (m/s)	844.4 ± 5.5
Velocity spread (m/s)	110.6 ± 5.5
χ^2/d.o.f .	27.8/34

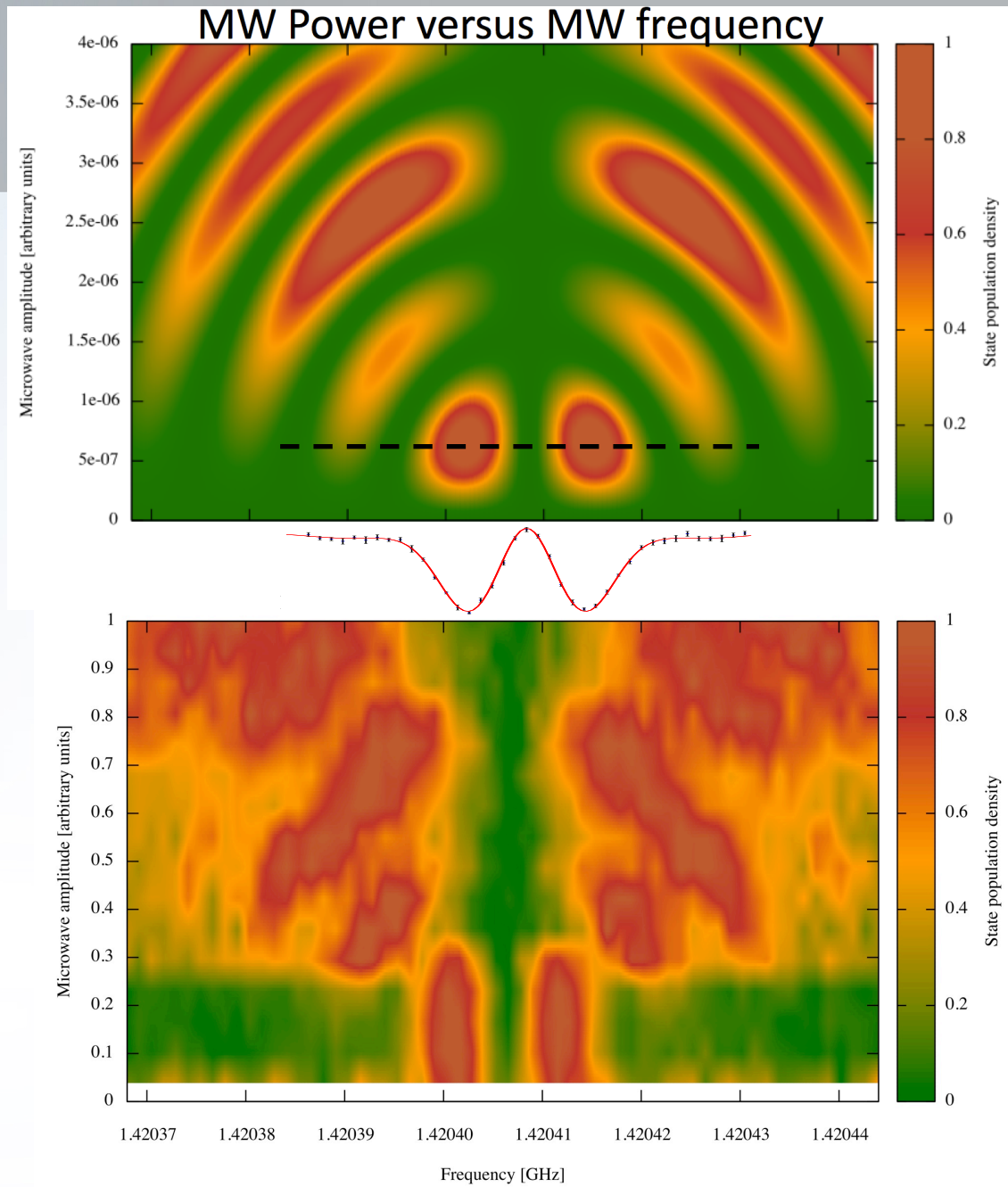
CAVITY SPECIFICATION

Simulation:

- Numerical solving the Bloch equations
- Single velocity
- No field inhomogenigty
- Theoretical lineshape – input for the spline fit

Measurements:

- Source temperature 50 K
- Finite velocity distribution



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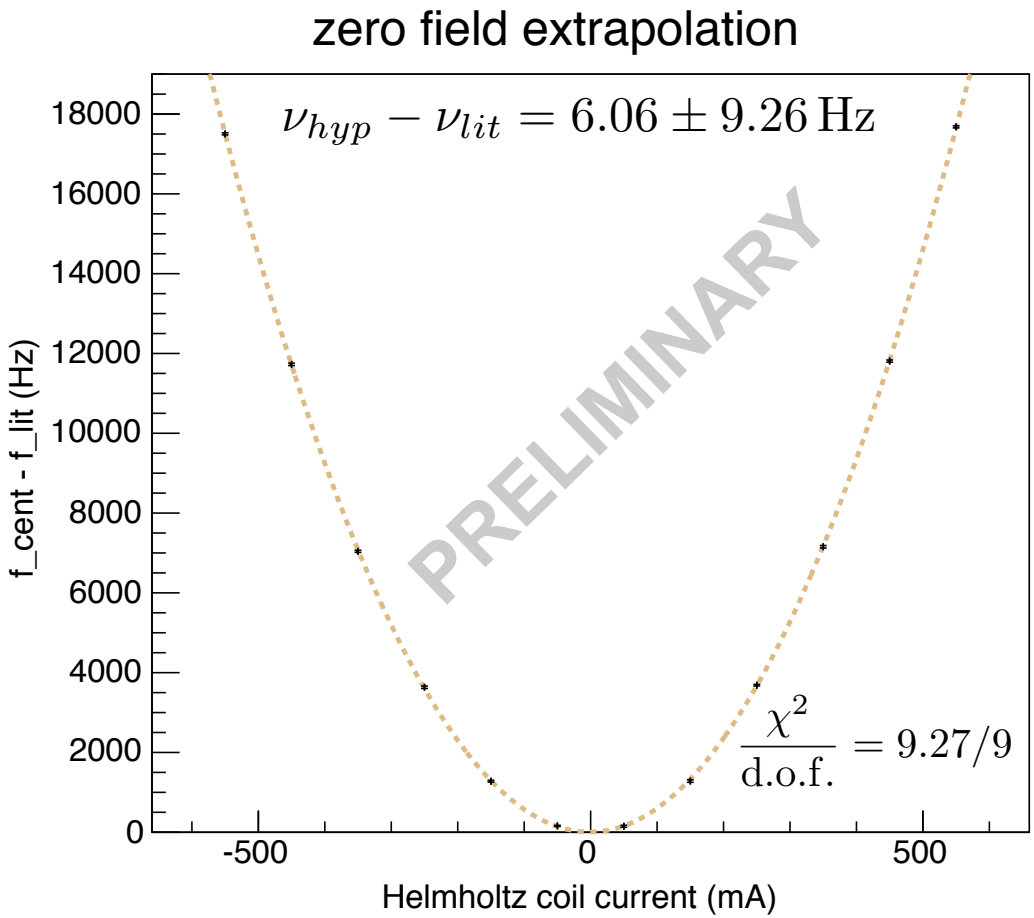
ZERO FIELD EXTRAPOLATION



- Best beam value up to date

$$\nu = 1420.40573(5)\,\mathrm{MHz}$$
$$\frac{\Delta\nu}{\nu} = 3.5 \times 10^{-8}$$

Kusch, Phys. Rev. 100, 4, (1955)

- Maser experiments

$$\nu = 1420.405751768(1)\,\mathrm{MHz}$$
$$\frac{\Delta\nu}{\nu} = 7 \times 10^{-13}$$

N.F. Ramsey et al., Quantum Electrodynamics, World Scientific, Singapore, 1990, p. 673

- This work

$$\nu = 1420.405757(9)\,\mathrm{MHz}$$
$$\frac{\Delta\nu}{\nu} = 6.5 \times 10^{-9}$$

PRELIMINARY

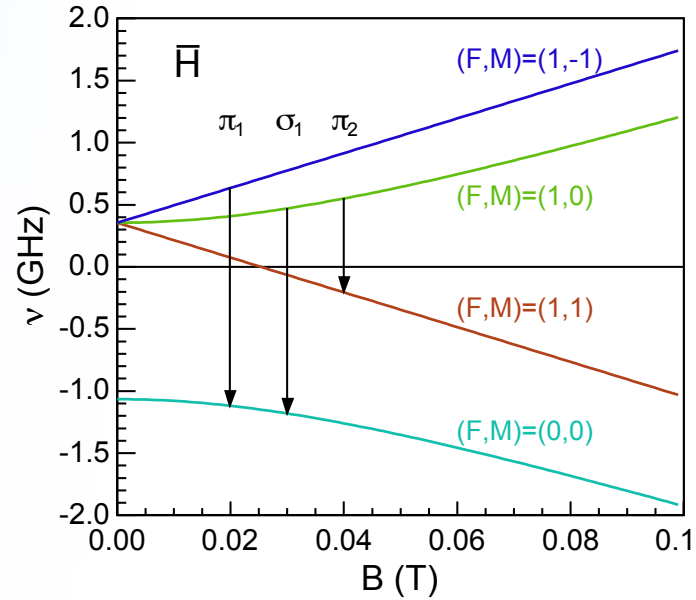
H·HFS

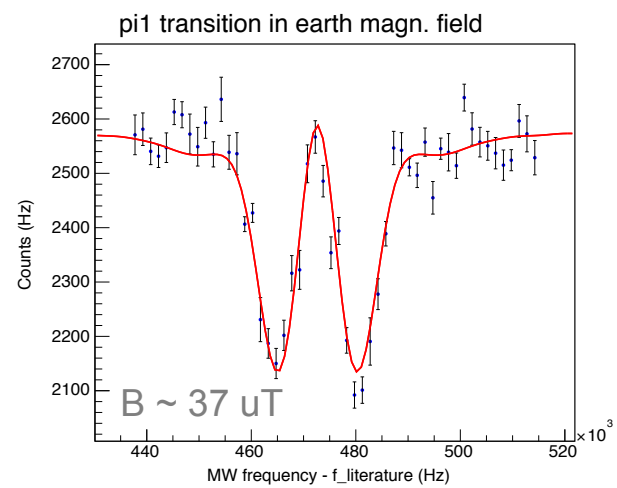
OTHER METHOD

Other method to obtain zero field HFS

- Up to now σ_1 measured at different magn. Fields and then zero field extrapolated with Breit-Rabi formula

- Measure $\pi_1 + \sigma_1$
- π_1 linear dependence on magn. Field
- σ_1 second order dependence
- Measurements depend on angle between oscillating and static magnetic field
  - for σ_1 transition B-field parallel
  - for π_1 transition B-field orthogonal





RECENT RESULTS

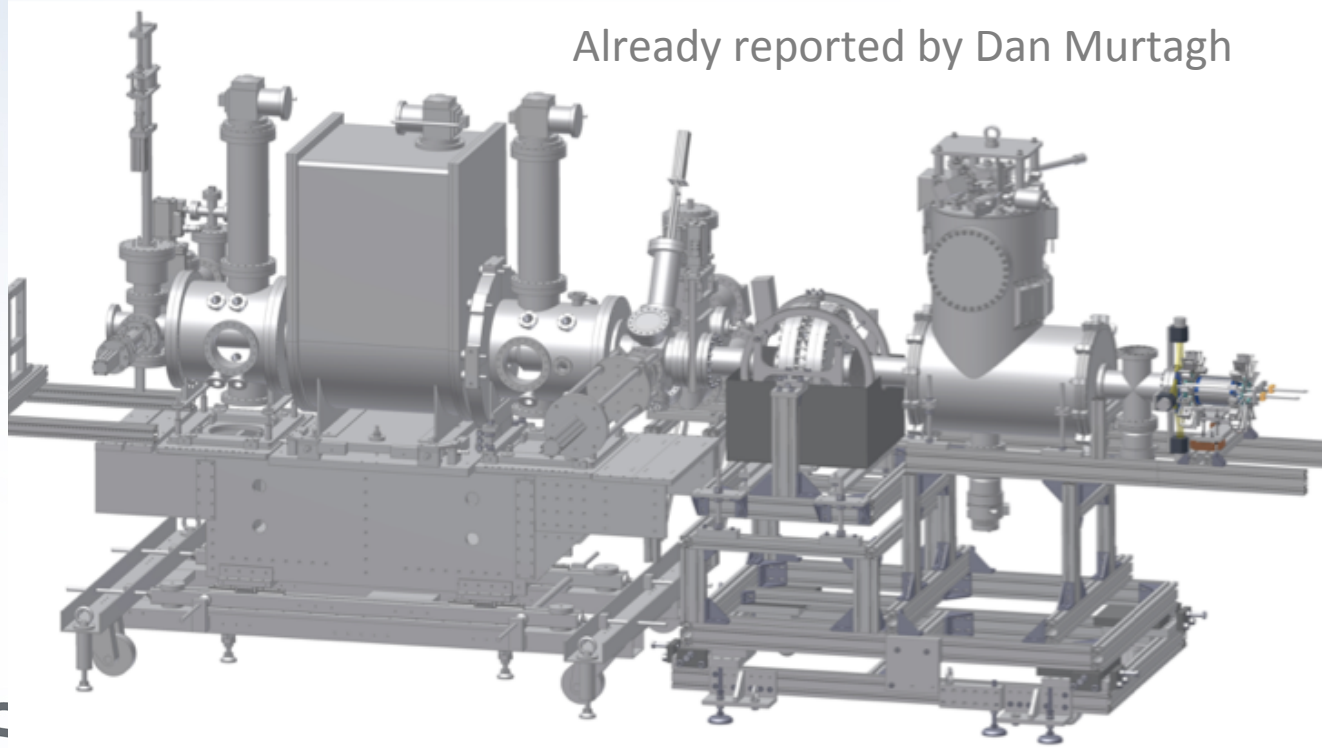
Hbar beam observed with 5σ significance

n≤43 (field ionization)

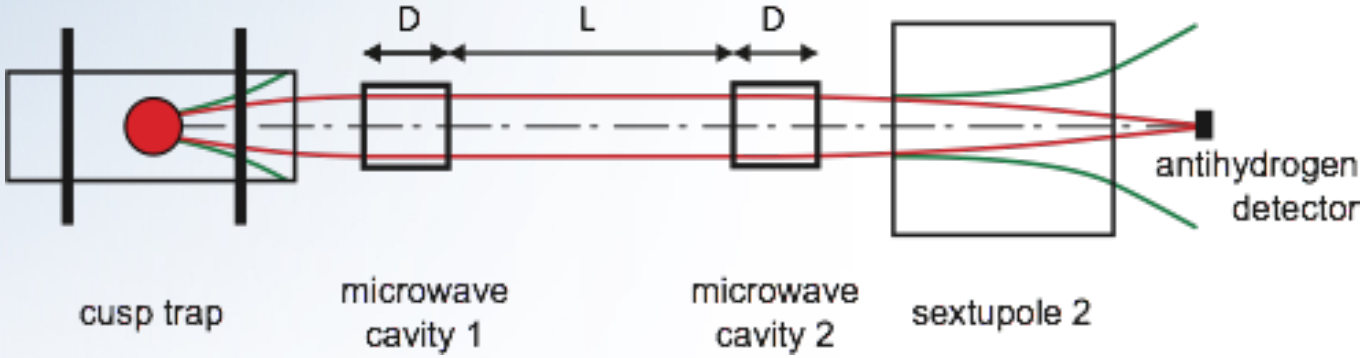
6 events / 15 min

Significant fraction in lower n

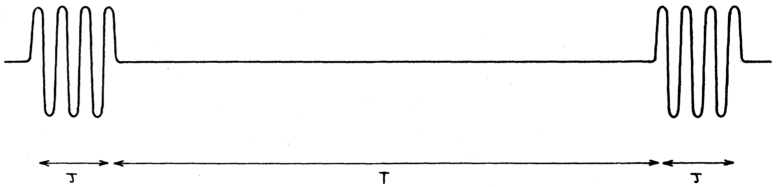
4 events / 15 min



FUTURE PLANS
SEPARATED OSCILLATORY FIELD



Linewidth reduced by D/L

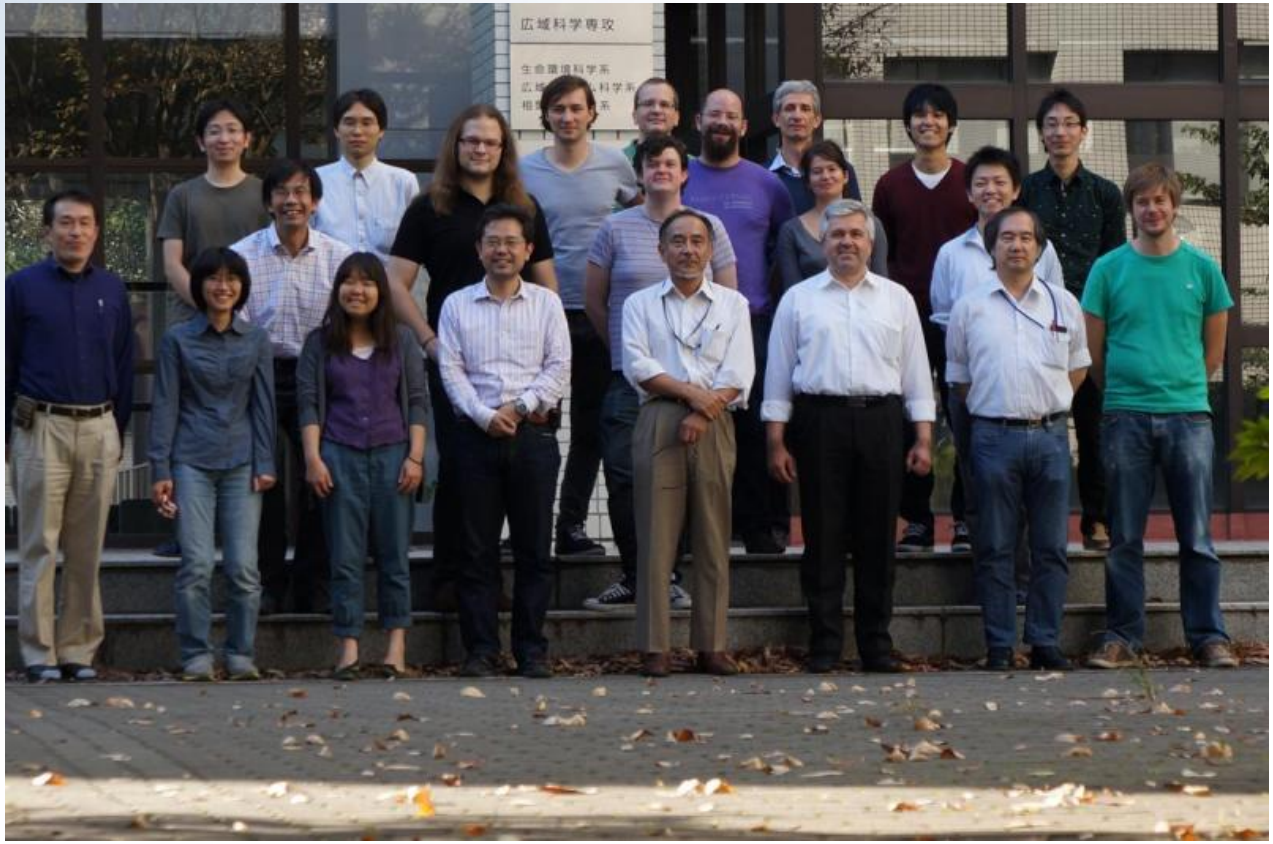


SUMMARY & CONCLUSION

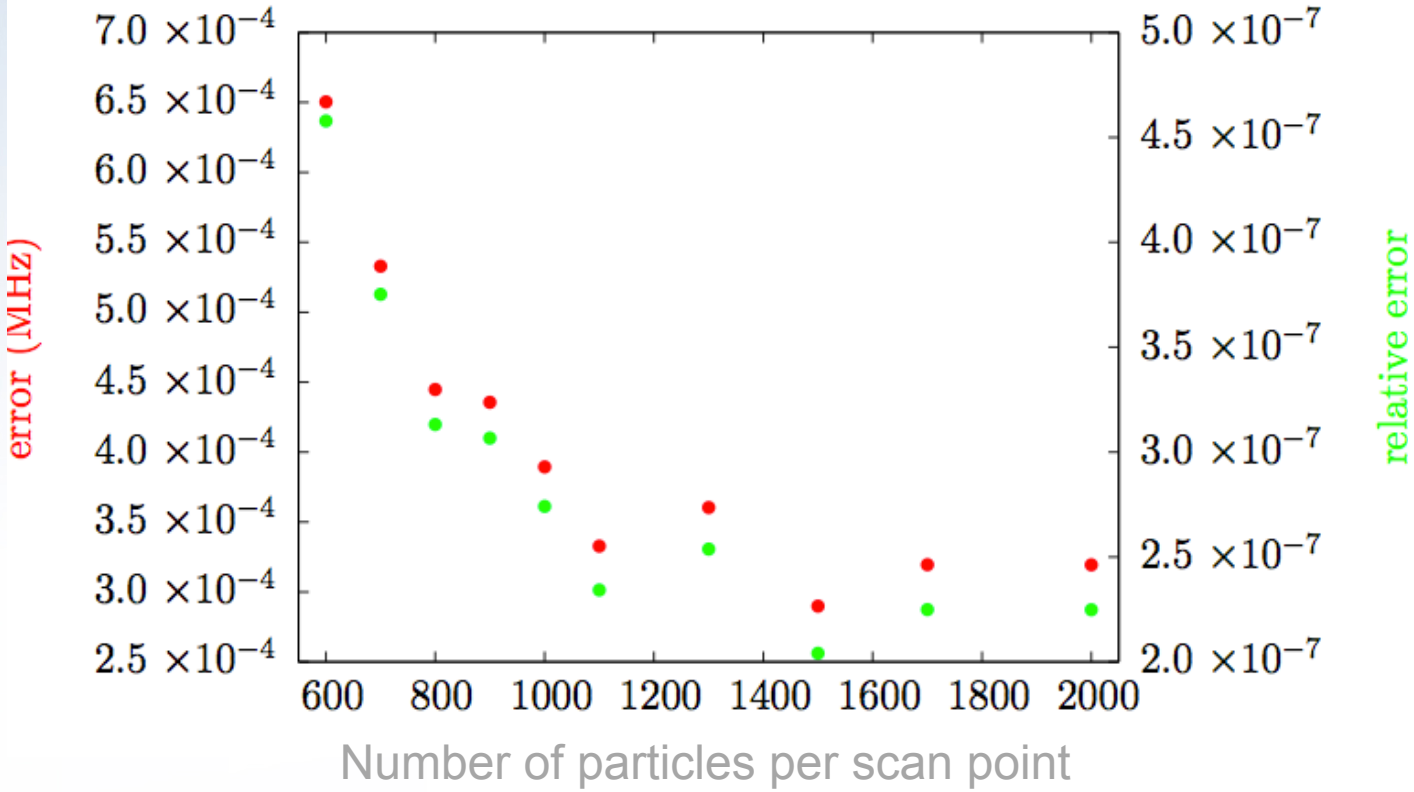
- We observed σ_1 and π_1 transitions for atomic hydrogen
- Characterization of the spin flip resonator has been done
- Showed that the sextupole magnet works and focuses atomic hydrogen
- Most precise in-beam measurement of the GS-HFS on the 10 ppb level
- Looking forward to measure zero field GS-HFS for antihydrogen

H·HFS

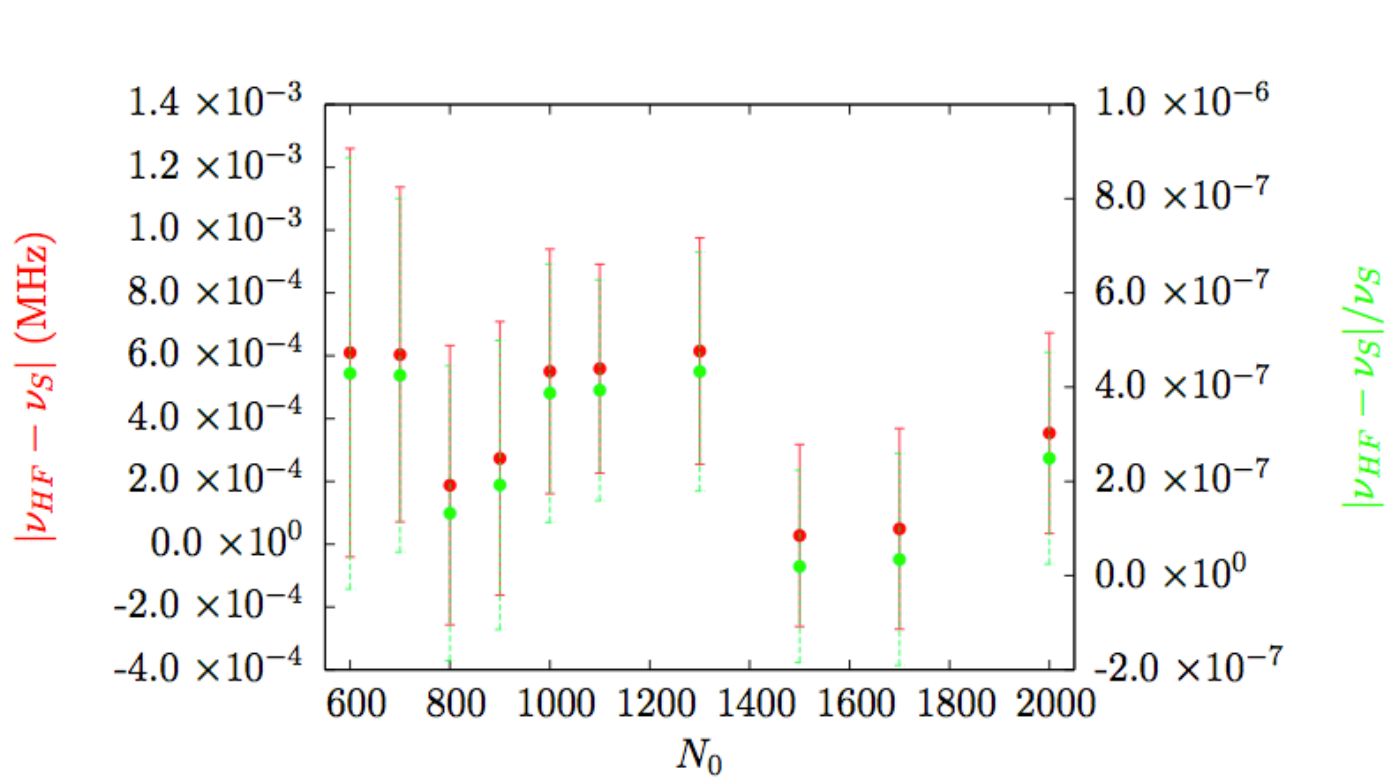
Thank you for your attention



REACHABLE ACCURACY FOR HBAR



ZERO FIELD EXTRAPOLATION



CAVITY – RESONANCE SHAPE