H·HFS
Hyperfine Structure of Antihydrogen

ERC Advanced Grant
PI: Prof. Dr. Eberhard Widmann

THE HYPERFINE STRUCTURE OF ANTIHYDROGEN

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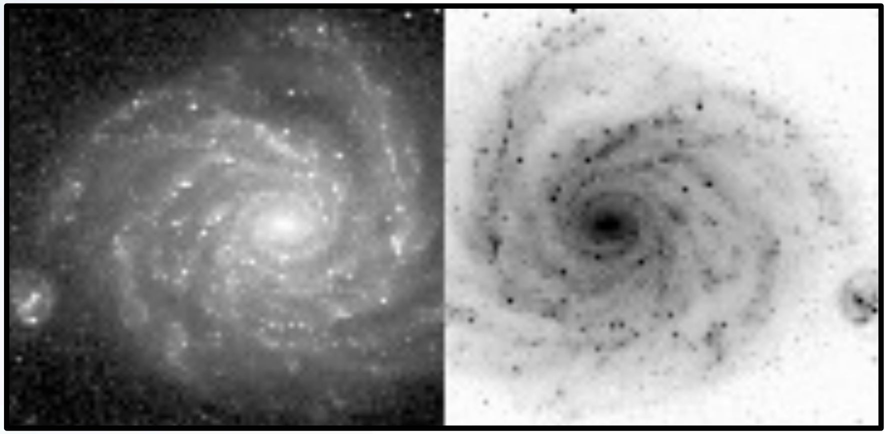
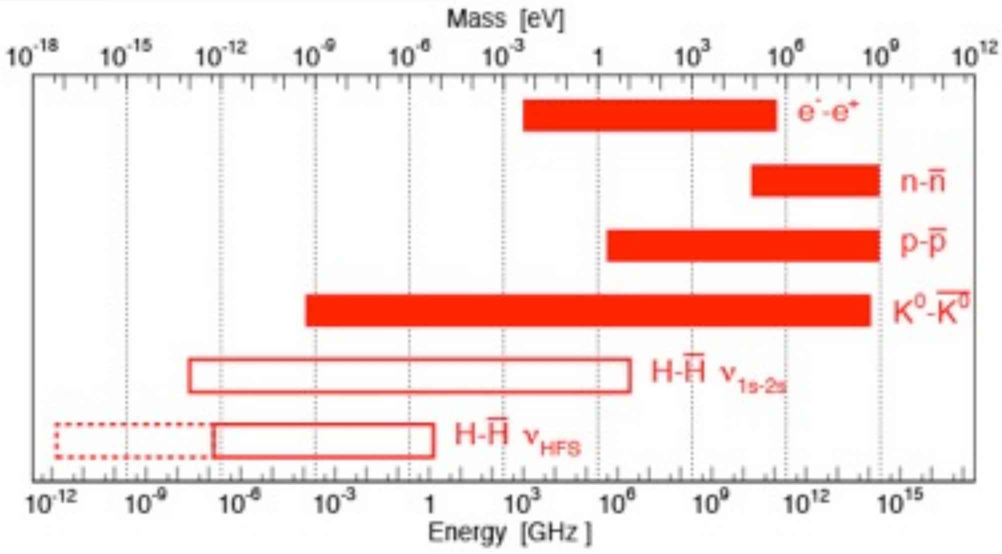
SSP 2012
GRONINGEN NL
21.6.2012

MATTER-ANTIMATTER SYMMETRY

- Cosmological scale:
  - asymmetry

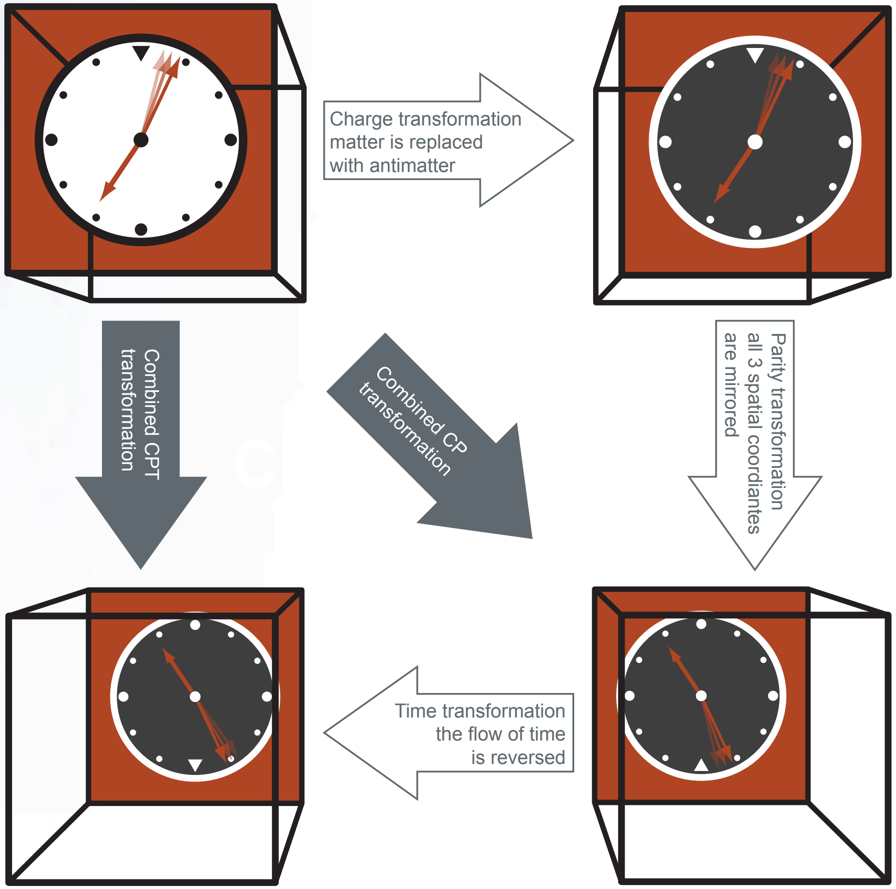


- CPT violation
  - Microscopic: symmetry?



FUNDAMENTAL SYMMETRIES C,P,T

- **C**: charge conjugation particle ↔ antiparticle
- **P**: parity: spatial mirror
- **T**: time reversal
- **CPT** theorem: consequence of
  - Lorentz-invariance
  - local interactions
  - unitarity
    - *Lüders, Pauli, Bell, Jost 1955*
- all QFT of SM obey CPT
- not necessarily true for string theory

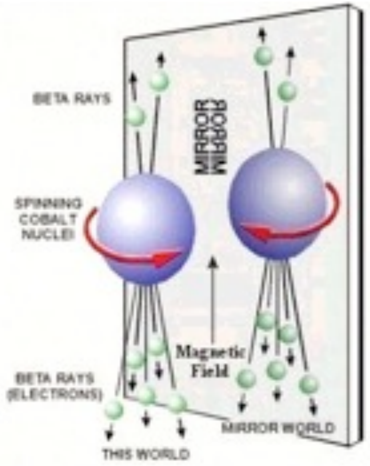


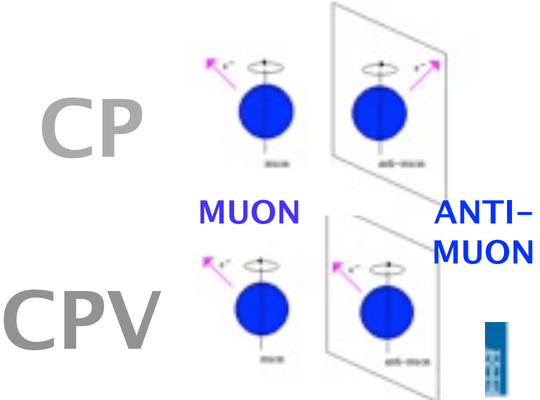
CTP → particle/anitparticle: same masses, lifetimes, g-factors, |charge|,...

VIOLATIONS OF FUNDAMENTAL SYMMETRIES

- Historically it was believed that nature would conserve symmetries of space
- Observed symmetry violations in weak interaction:

		Size of effect
Parity violation	1956 Theory: Lee & Yang 1957 ß-decay Wu et al. π -> μ -> e decay	100%
CP violation	1964 K_0 decays: Cronin & Fitch 2001 B decays: BELLE, BaBar	ε ~2.3 x 10^{-3}





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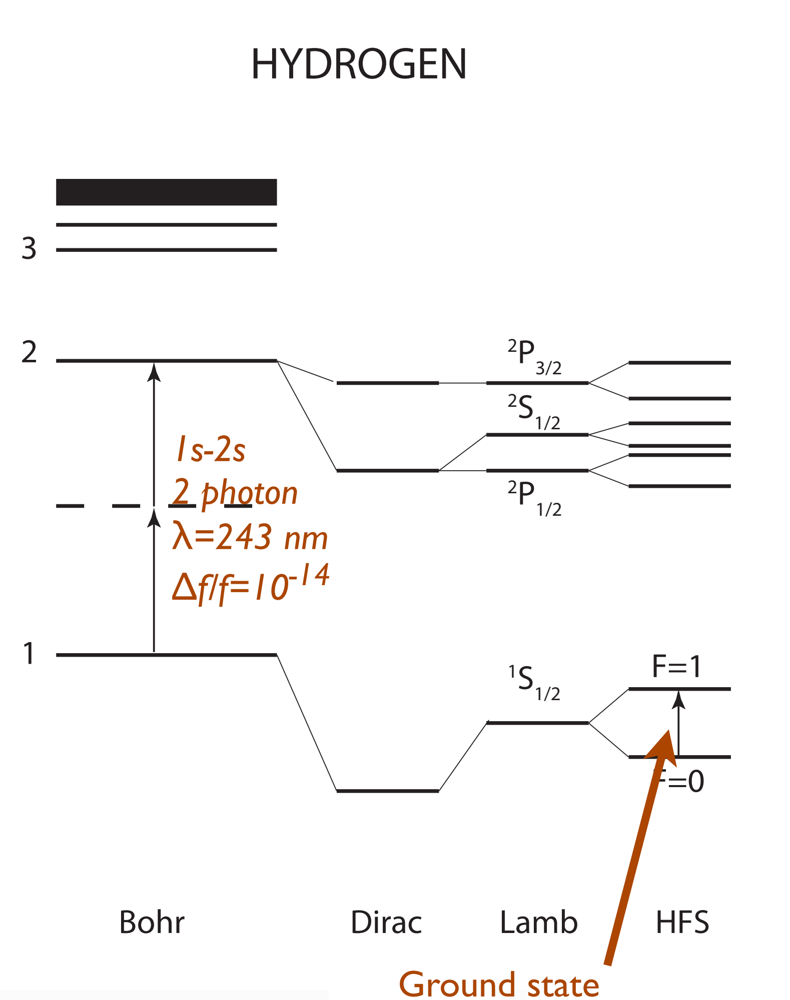
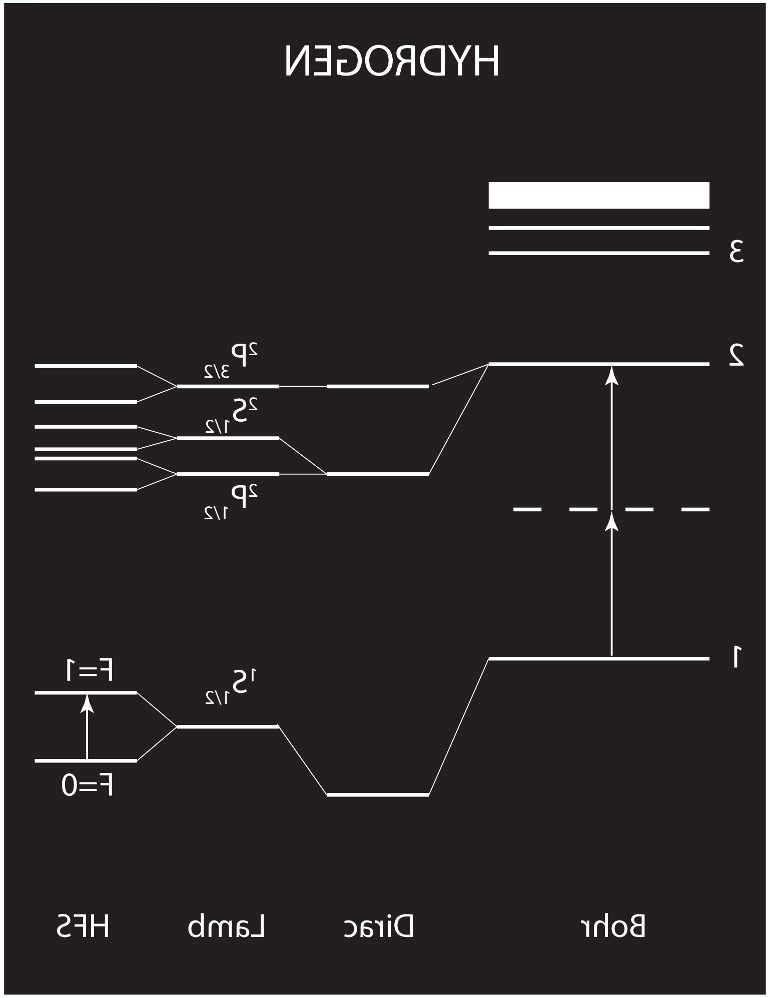
HYDROGEN AND ANTIHYDROGEN

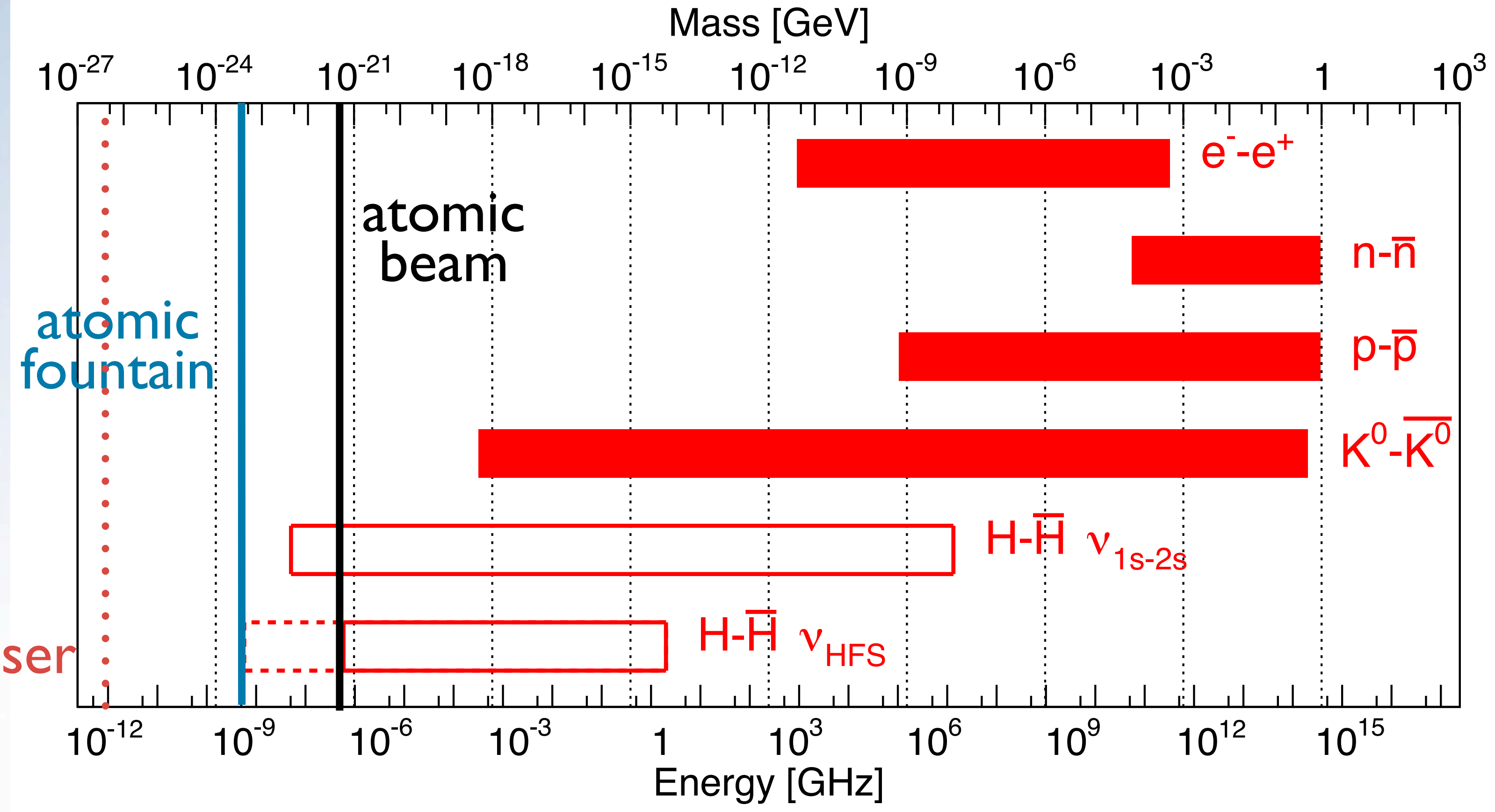


1s-2s
2 photon
λ=243 nm
$\Delta f/f=10^{-14}$



Ground state
hyperfine splitting
f = 1.4 GHz
$\Delta f/f=10^{-12}$

CPT TESTS - RELATIVE & ABSOLUTE PRECISION



- Atomic physics experiments, especially antihydrogen offer the most sensitive experimental verifications of CPT

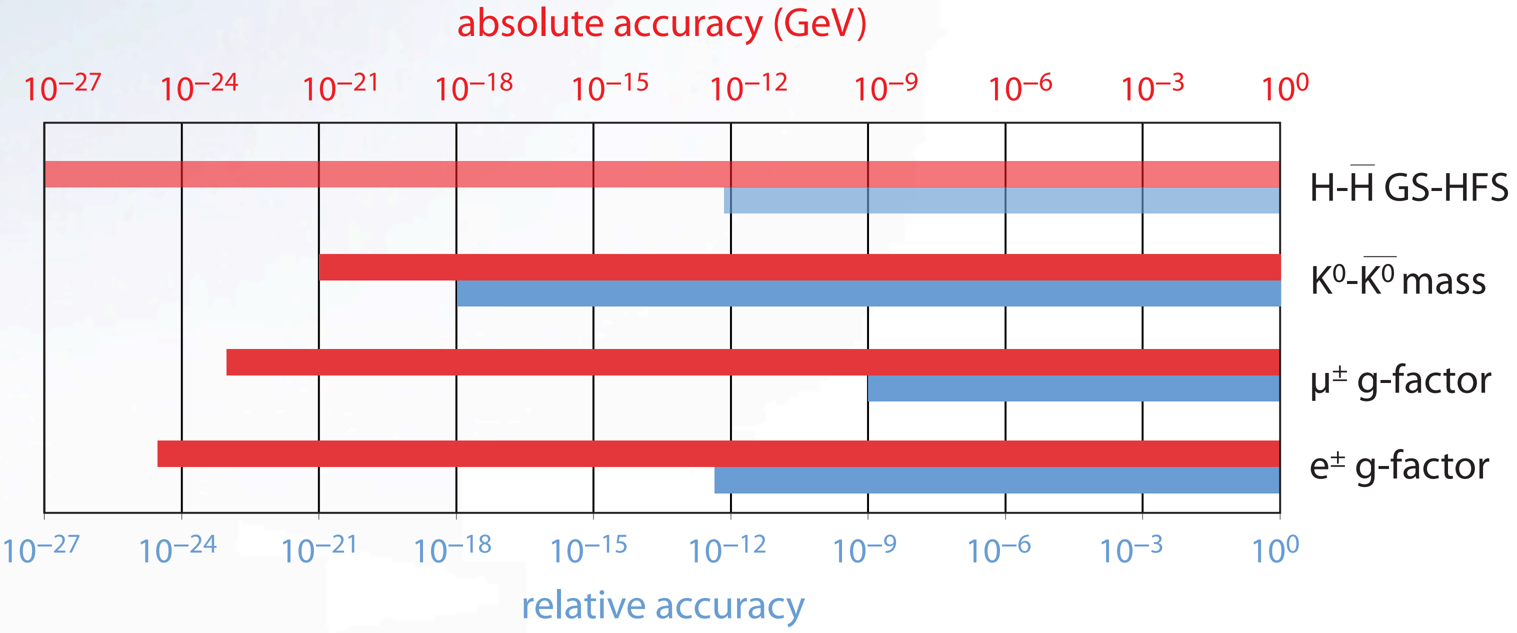
HFS AND STANDARD MODEL EXTENSION

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

CPT & Lorentz violation

Lorentz violation

D. Colladay and V.A. Kostelecky, PRD 55 (1997) 6760.



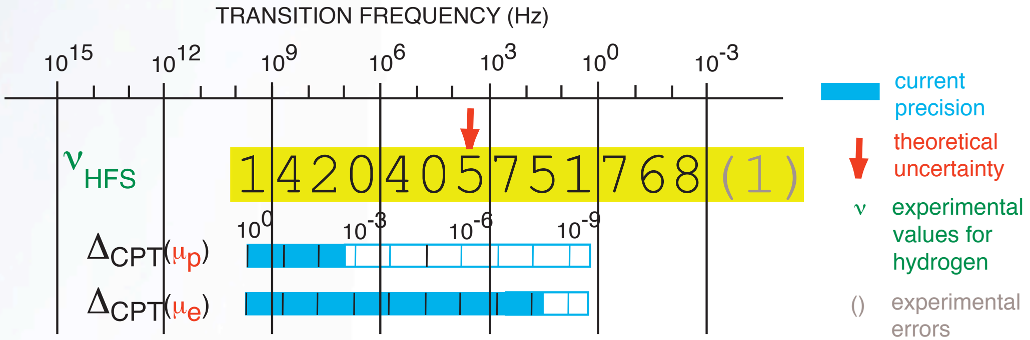
no CPT effect on 1S-2S transition

allows to compare different quantities in different sectors

GROUND-STATE HYPERFINE SPLITTING OF H$^{(\mathrm{BAR})}$

- spin-spin interaction positron - antiproton
- Leading: Fermi contact term

$$\nu_F = \frac{16}{3}\left(\frac{M_p}{M_p + m_e}\right)^3 \frac{m_e}{M_p}\frac{\boxed{\mu_p}}{\mu_N}\alpha^2 c\, Ry,$$



- magnetic moment of p$^{\mathrm{bar}}$
  - only known to 0.3%, proposals to measure in Penning trap *Gabrielse, Ulmer*
- H: deviation from Fermi contact term: ~ 32 ppm
  - finite electric & magnetic radius (Zemach corrections): 41 ppm
  - polarizability of p$^{(\mathrm{bar})}$: < 4 ppm
  - few ppm theoretical uncertainty remain

$$\Delta\nu(\mathrm{Zemach}) = \nu_{\mathrm{F}}\frac{2Z\alpha m_{\mathrm{e}}}{\pi^2}\int\frac{d^3p}{p^4}\left[\frac{G_E(p^2)G_M(p^2)}{1+\kappa} - 1\right]$$

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ASACUSA COLLABORATION @ CERN-AD

ASAKUSA KANNON TEMPLE
BY UTAGAWA HIROSHIGE (1797–1858)


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Atomic Spectroscopy And Collisions Using Slow Antiprotons

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  - Faculty of Science, Department of Physics
- RIKEN, Saitama, Japan
- SMI, Austria
- Aarhus University, Denmark
- Max-Planck-Institut für Quantenoptik, Munich, Germany
- KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
- ATOMKI Debrecen, Hungary
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- The Queen's University of Belfast, Ireland

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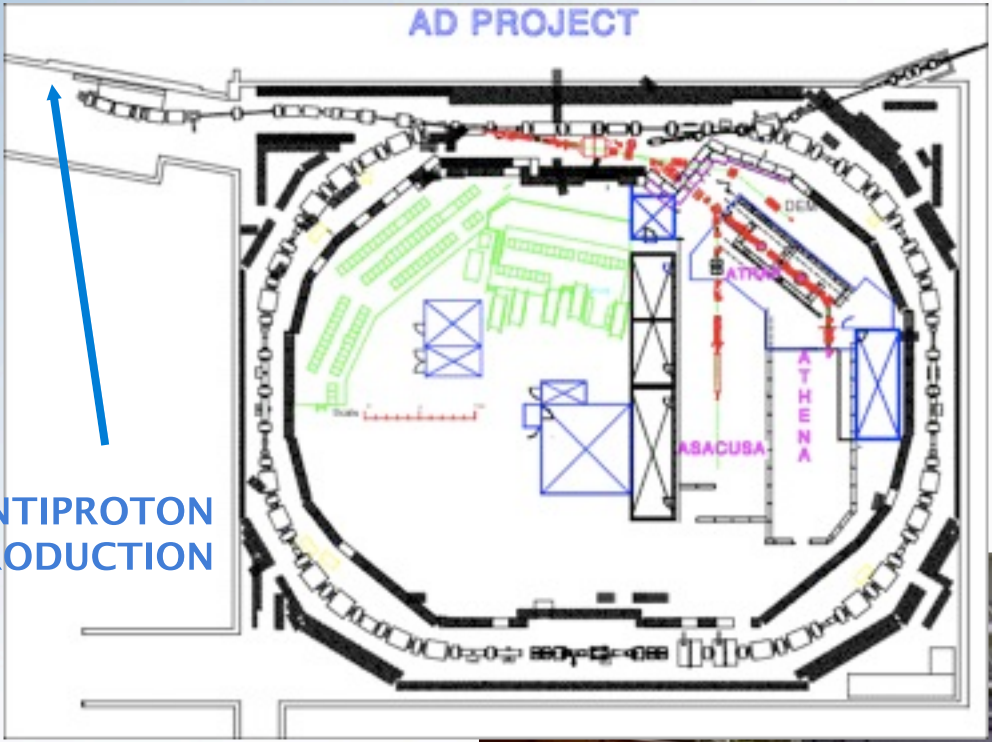
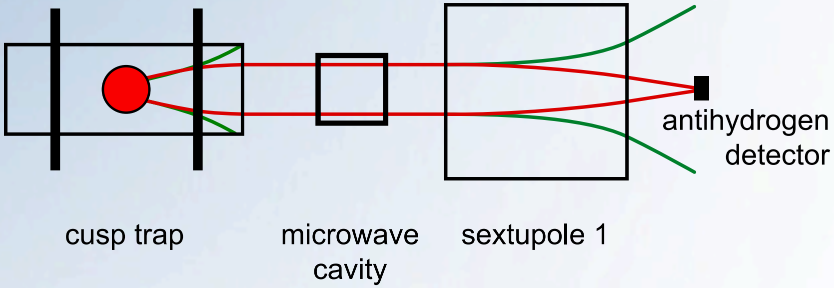
ANTIPROTON DECELERATOR @ CERN

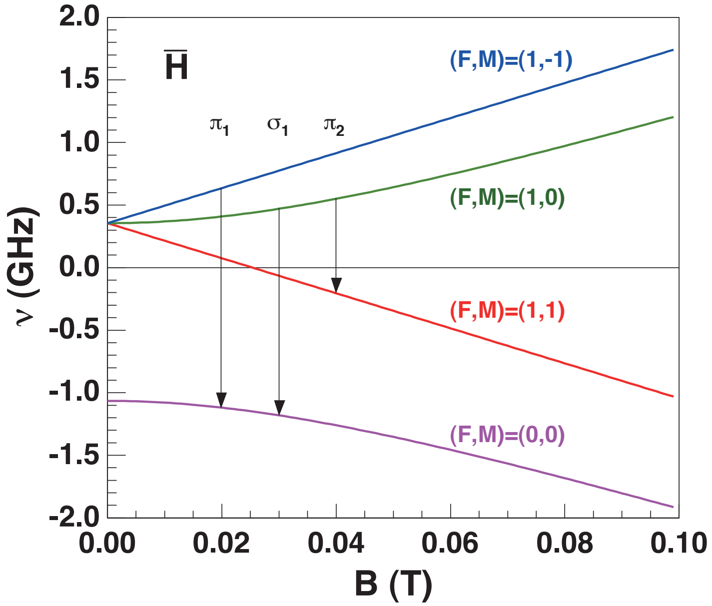


ANTIPROTON PRODUCTION

- All-in-one machine:
  - Antiproton capture
  - deceleration & cooling
  - 100 MeV/c (5.3 MeV)
- Pulsed extraction
  - 2-4 x 10^7 antiprotons per pulse of 100 ns length
  - 1 pulse / 85−120

HFS MEASUREMENT IN AN ATOMIC BEAM





- atoms evaporate - no trapping needed
- cusp trap provides polarized beam
- spin-flip by microwave
- spin analysis by sextupole magnet
- low-background high-efficiency detection of antihydrogen

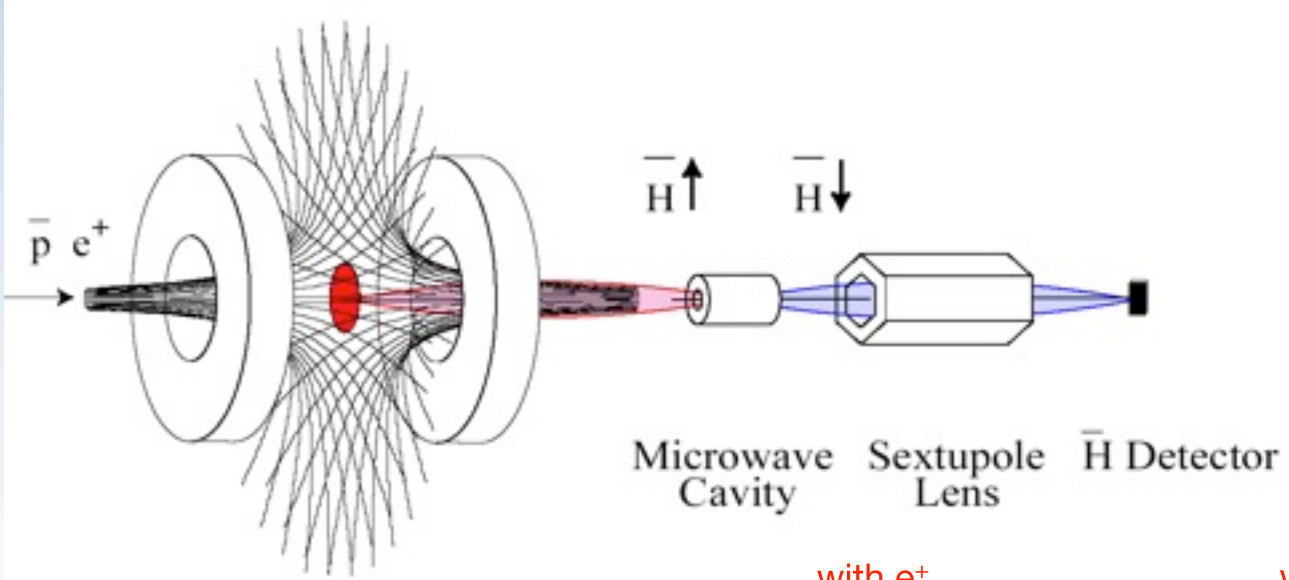
E.W. et al. ASACUSA proposal addendum CERN-SPSC 2005-002

achievable resolution

- better 10^{-6} for $T \leq 100$ K
- > 100 H^{bar}/s in 1S state into 4π needed
- event rate 1 / minute: background from cosmics, annihilations uptsreams

POLARIZED HBAR BEAM FROM “CUSP” TRAP

- First antihydrogen production in 2010
  - expectation: polarized beam

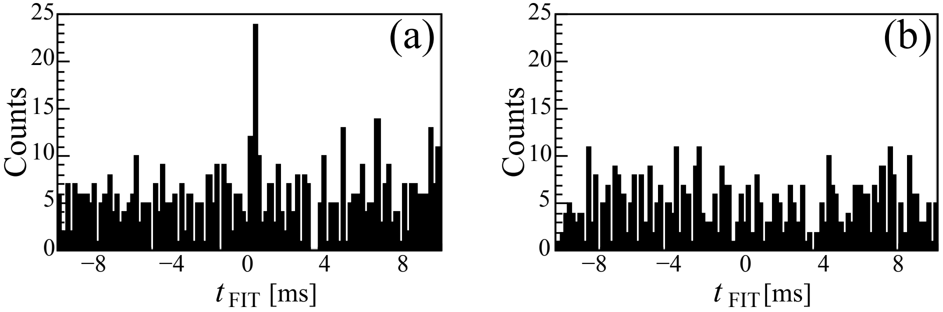


A: Mohri & Y. Yamazaki, *Europhysics Letters 63, 207 (2003).*

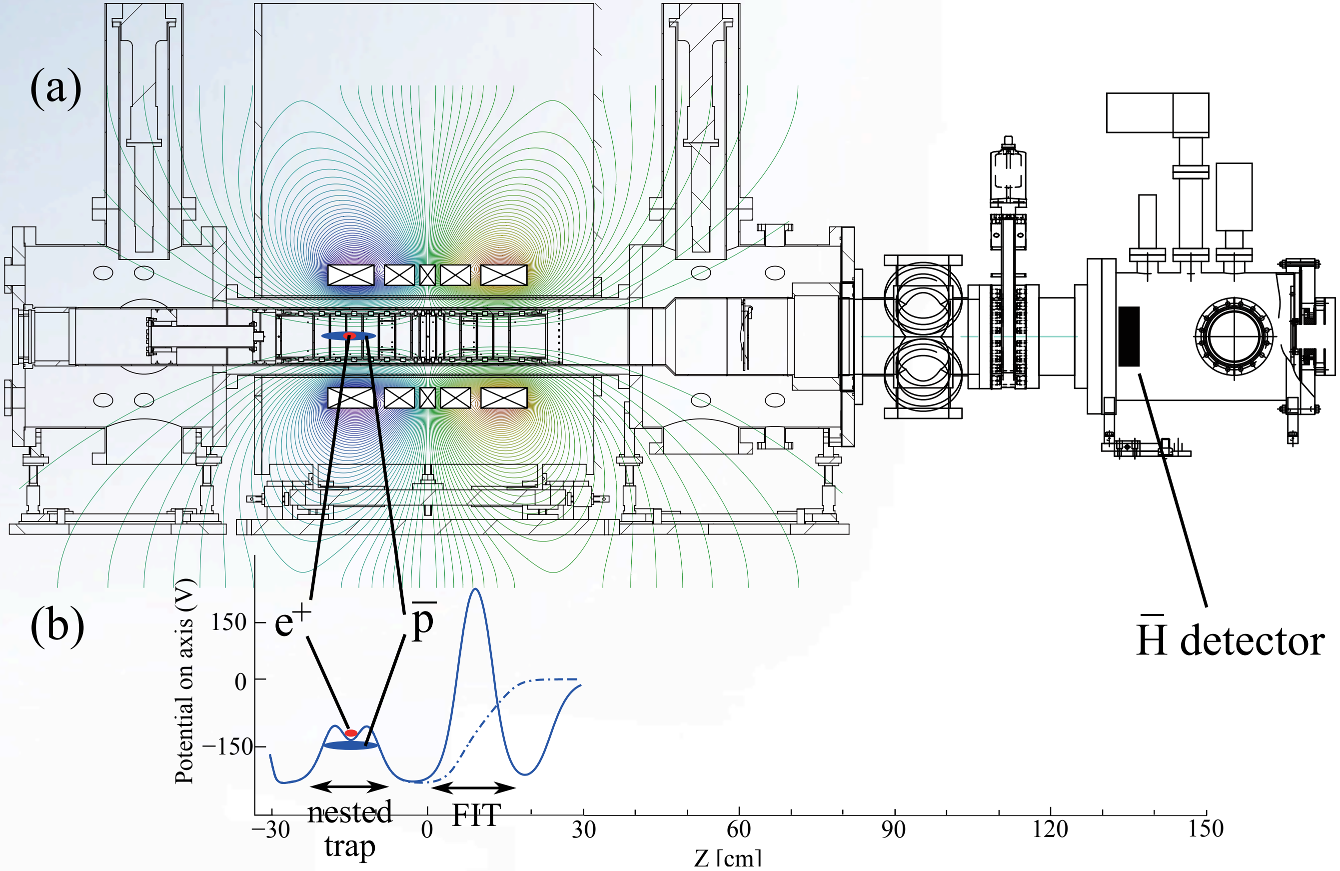
Y. Enomoto et al. *Phys. Rev. Lett 243401, 2010*

with e^+ $\bar{H}$ ↓

without e^+ no $\bar{H}$ ↓



H^{BAR} FORMATION IN CUSP TRAP



Field ionisation trap for H^{bar} detection

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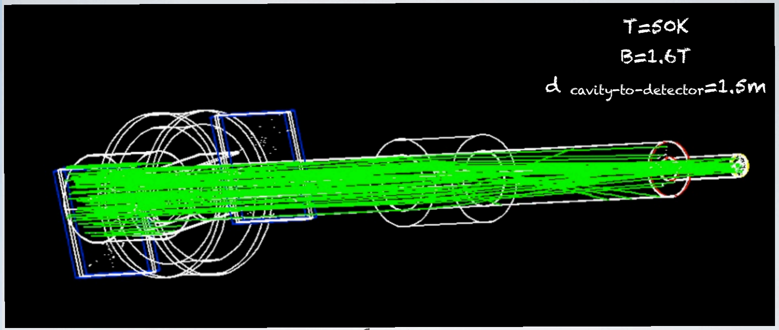
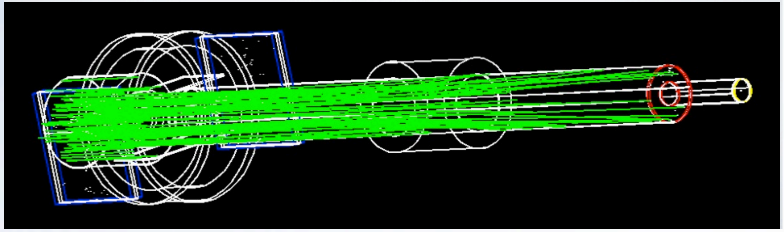
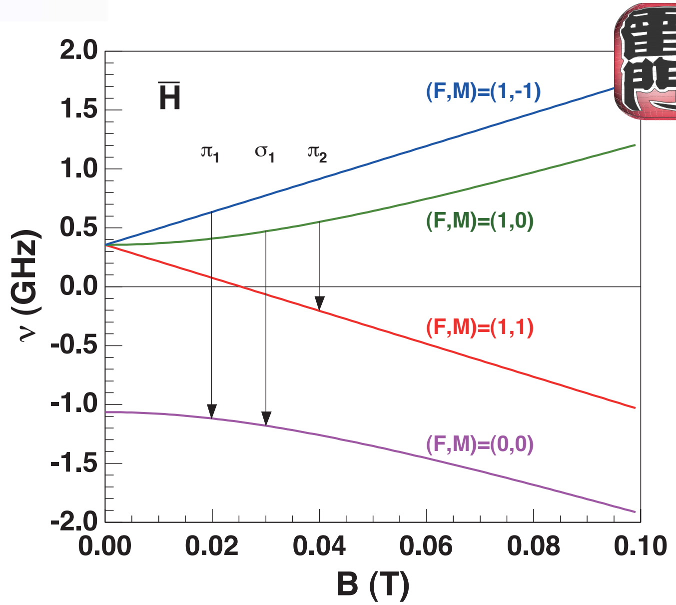
SIMULATIONS

low-field seekers



high-field seekers



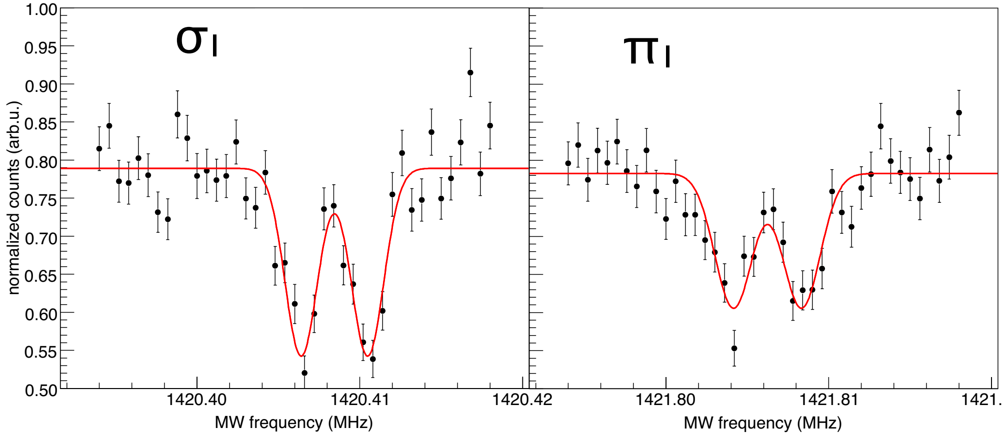


achievable precision

$<10^{-5}$: σ_1

$<10^{-6}$: σ_1 & π_1

H^{bar} rate, temp	100 Hz @ 50 K
cavity length	10 cm
most probable velocity@50K	1000 m/s
transit time	100 µs
line width	10 kHz
line width rel.	7×10^{-6}



1 week per scan

B. Juhász, & E.W.,
Hyperfine Interactions 193 (2009) 305–311

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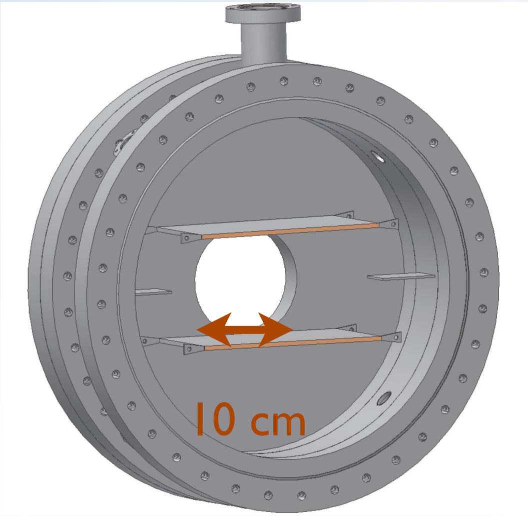
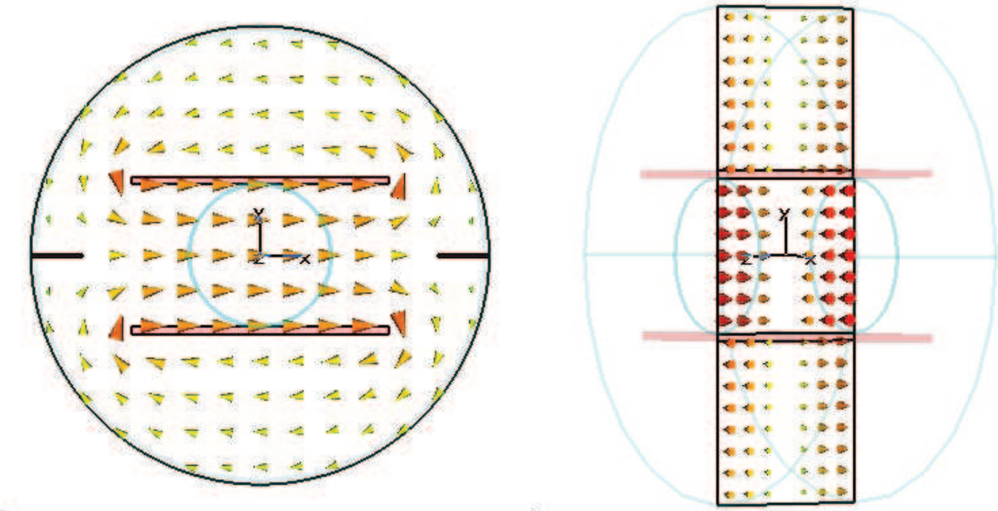
SPIN-FLIP RESONATOR

- f = 1.420 GHz, Δf = few MHz, ~ mW power
- challenge: homogeneity over $10 \times 10 \times 10\,\mathrm{cm}^3$@ λ=21cm
- solution: strip line



RF cavity

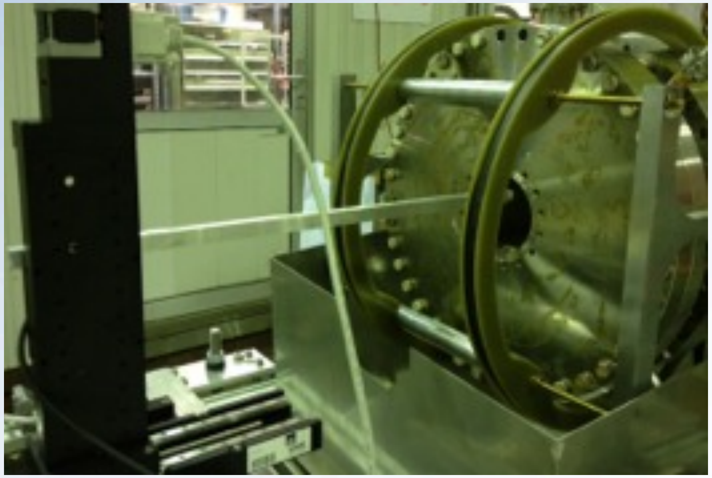


RF field pattern

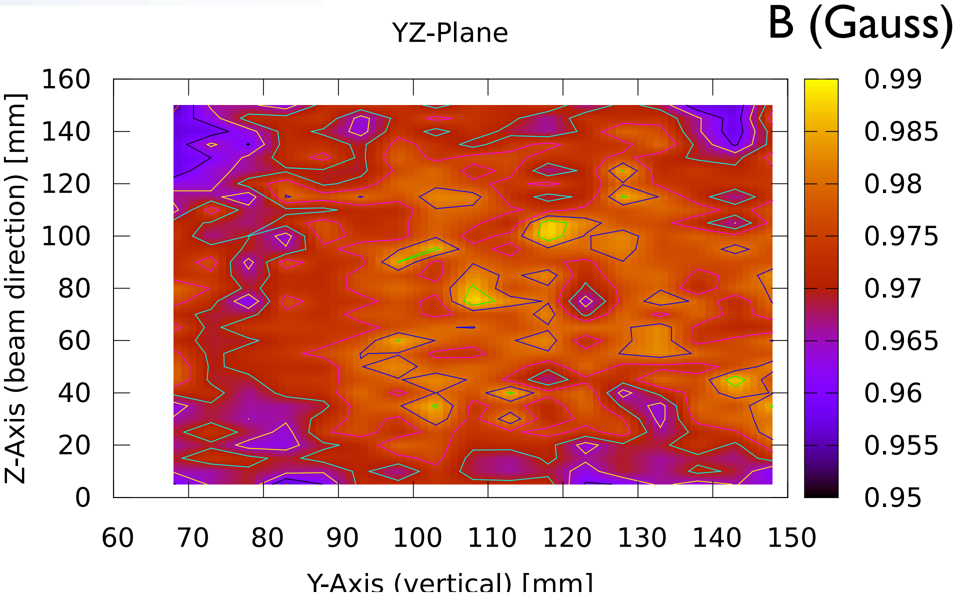
T. Kroyer., CERN-AB-Note-2008-016 (2008)

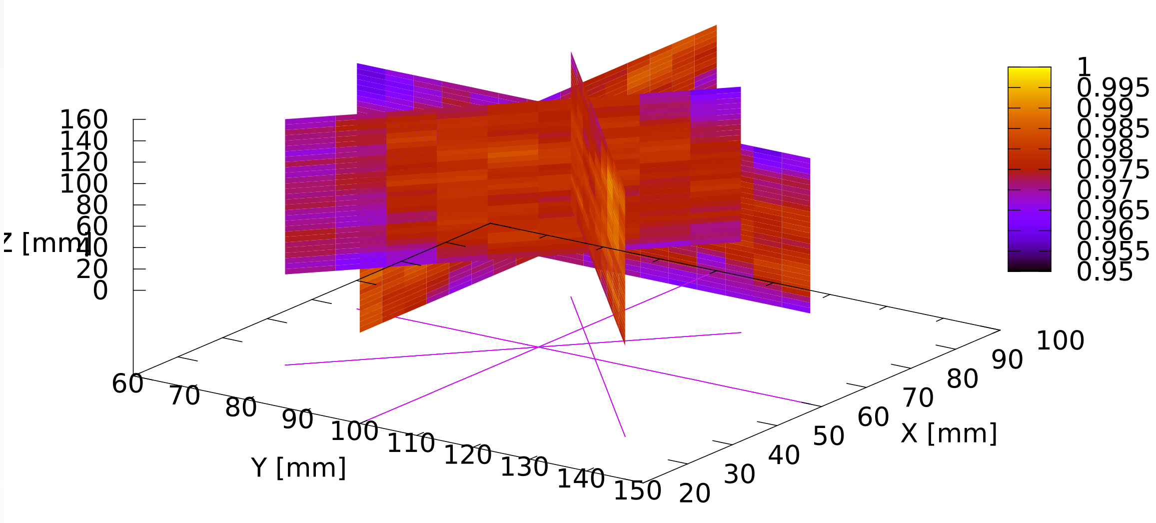
CONSTANT B-FIELD

Helmholtz coils

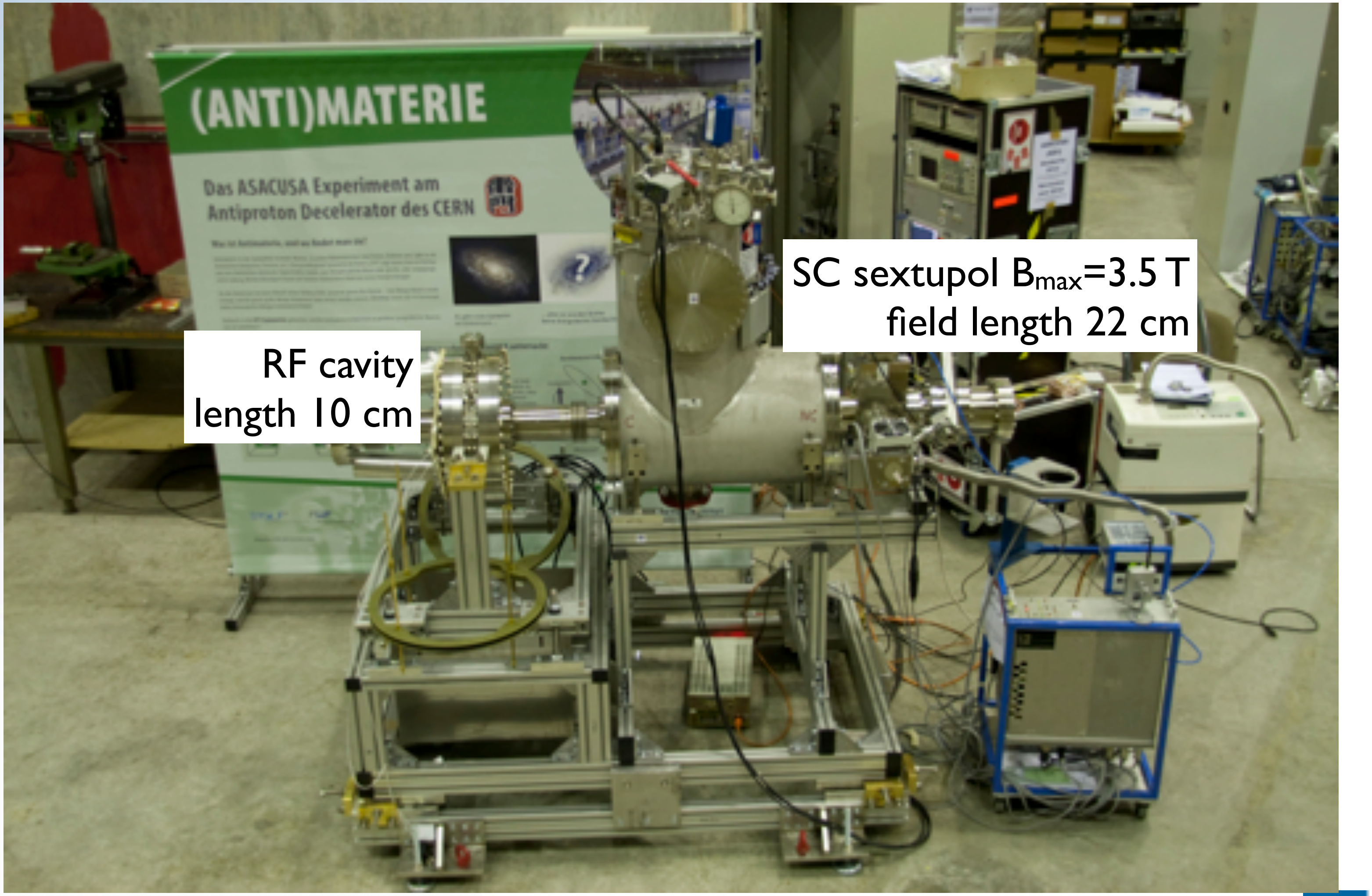


shielding





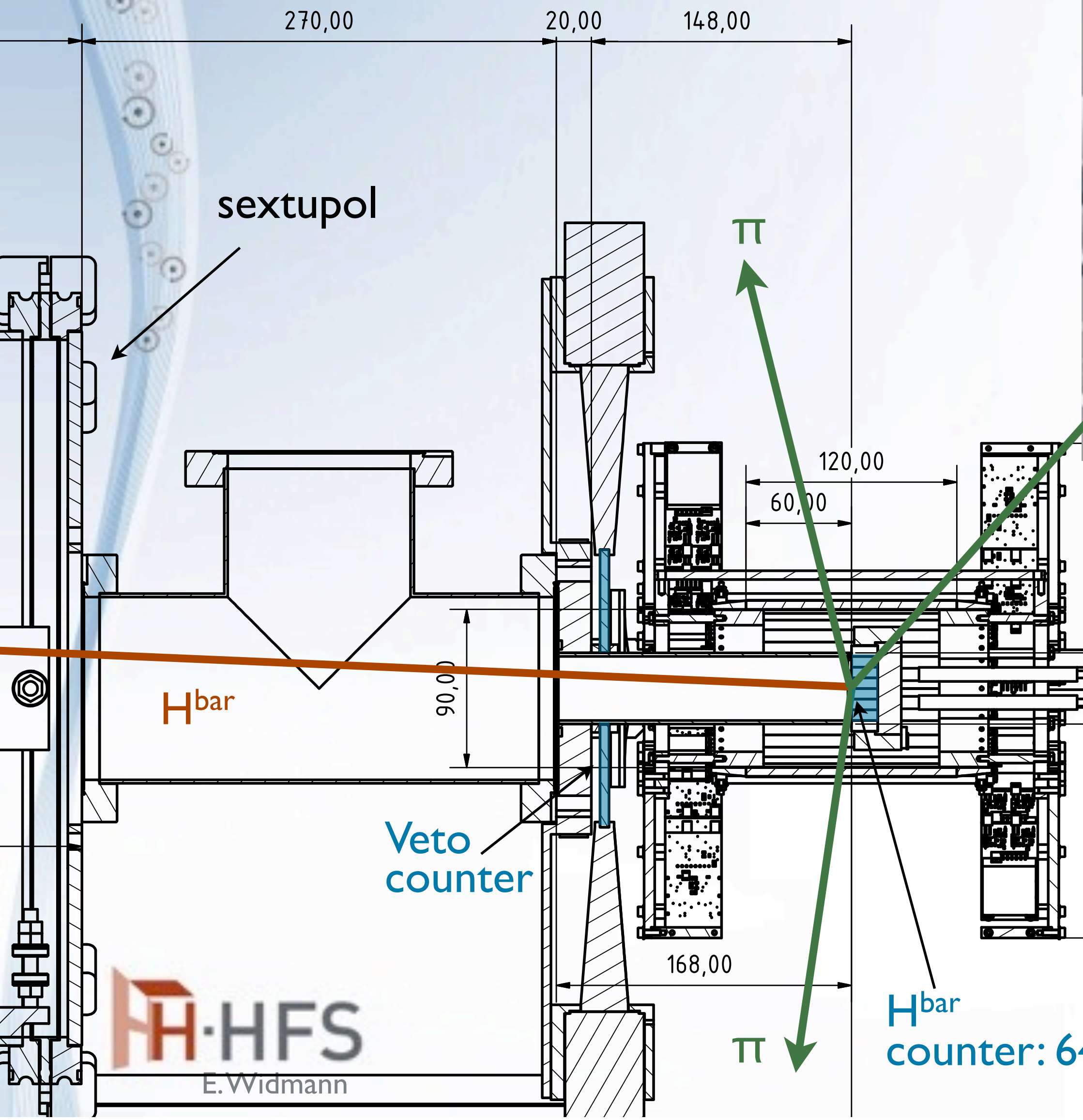
SEXTUPOLE & SPIN-FLIP RESONATOR



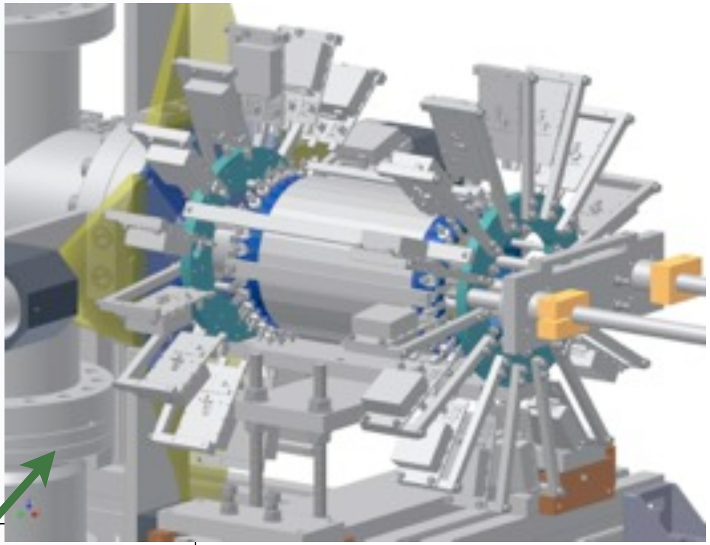
SC sextupol B_{max}=3.5 T
field length 22 cm

RF cavity
length 10 cm

SEGMENTED TRACKING DETECTOR



being prepared

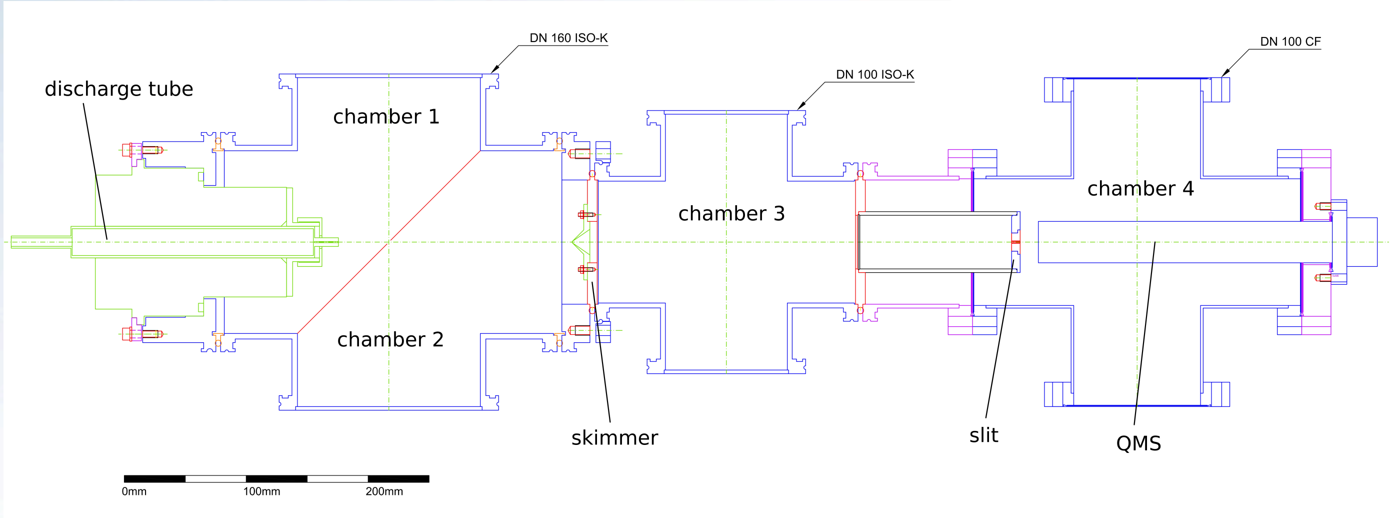


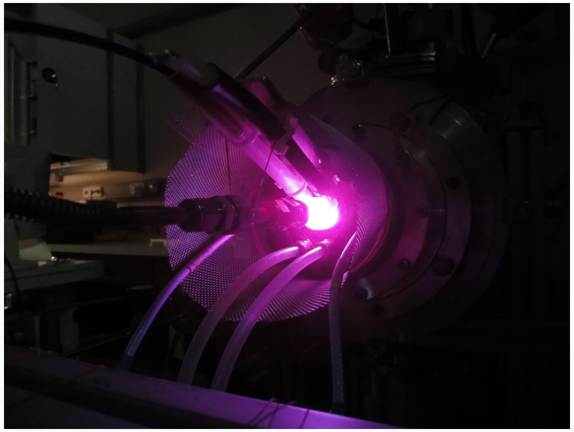
Hodoscope 8 cm diam.
30 plastic scintillators
$5 \times 10\ \mathrm{mm}^2$
length 15 cm
2x SiPM readout

$\mathrm{H}^{\mathrm{bar}}$
counter: 64 scint. + multi channel PMT

(POLARIZED) MONOATOMIC H BEAM

- test of apparatus during CERN shutdown 2013
- 1st phase: monoatomic beam (done at SMI)



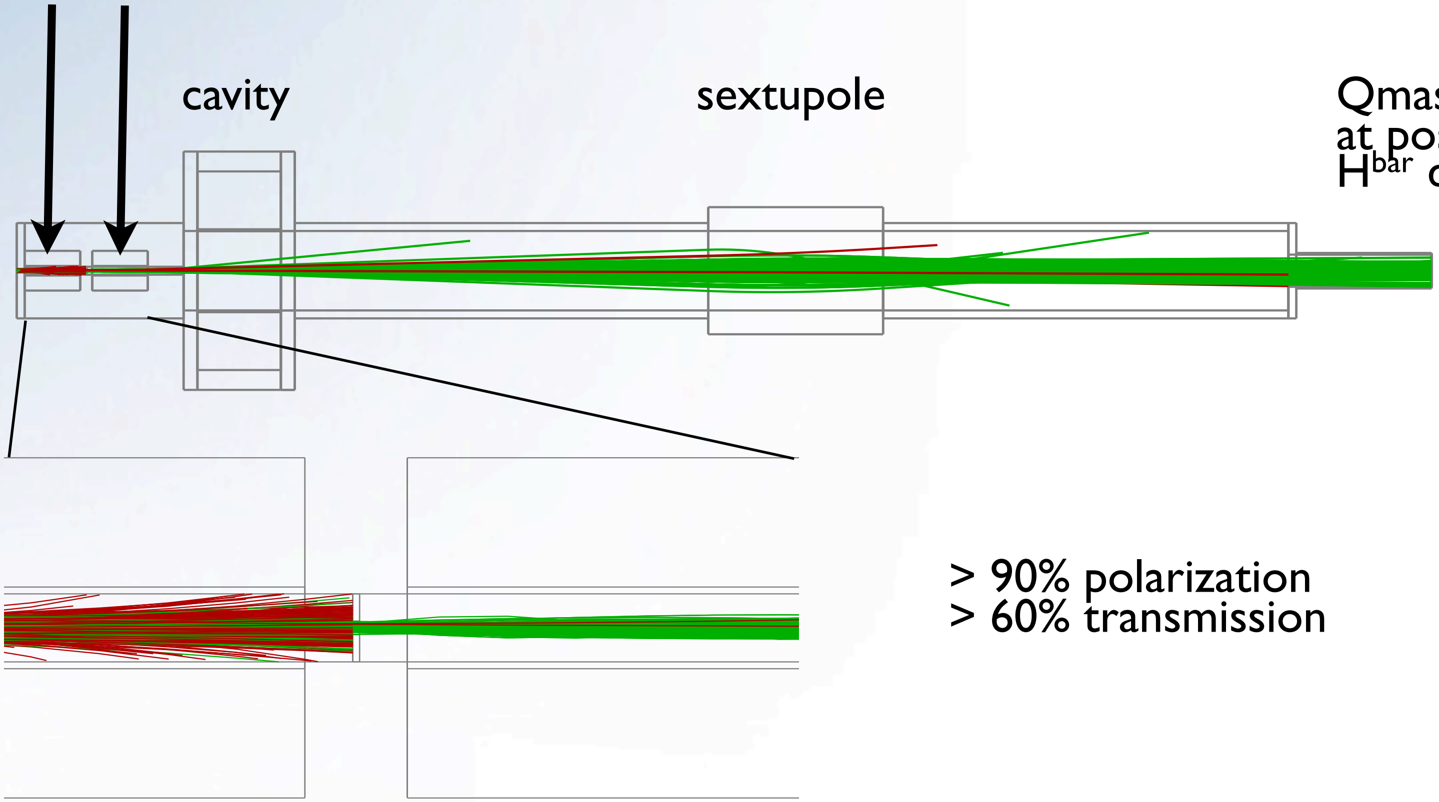


- RF discharge tube
- detection by Q-mass

M. Diermaier
Dipl. U.Wien 2012

POLARIZED MONOATOMIC H BEAM

- 2 permanent sextupoles, $B_{max}=1$ T, L=7 cm, d=1 cm



cavity

sextupole

Qmass
at position
H^{bar} detector

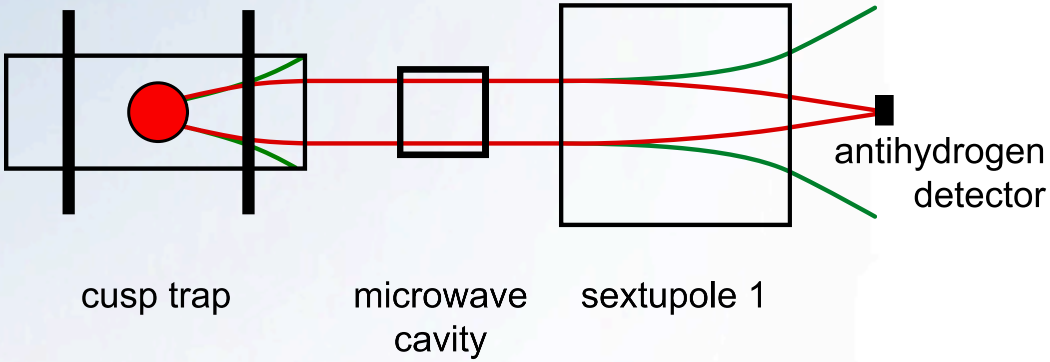
RF discharge
source

> 90% polarization
> 60% transmission

iris to block high-field seekers

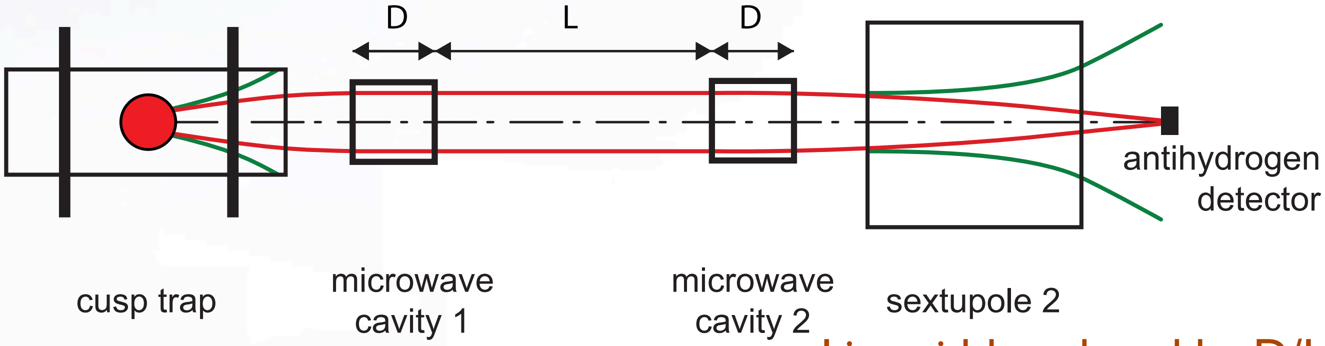
EXPERIMENTS IN AN ATOMIC BEAM

- Phase 1 (ongoing): Rabi method



$\Delta\nu/\nu \sim 10^{-7}$

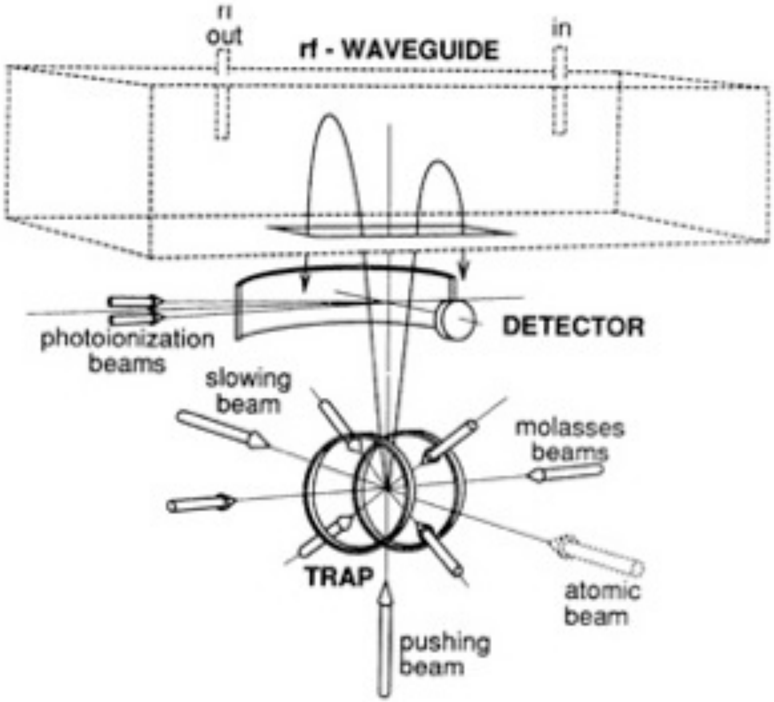
- Phase 2: Ramsey separated oscillatory fields



Linewidth reduced by D/L

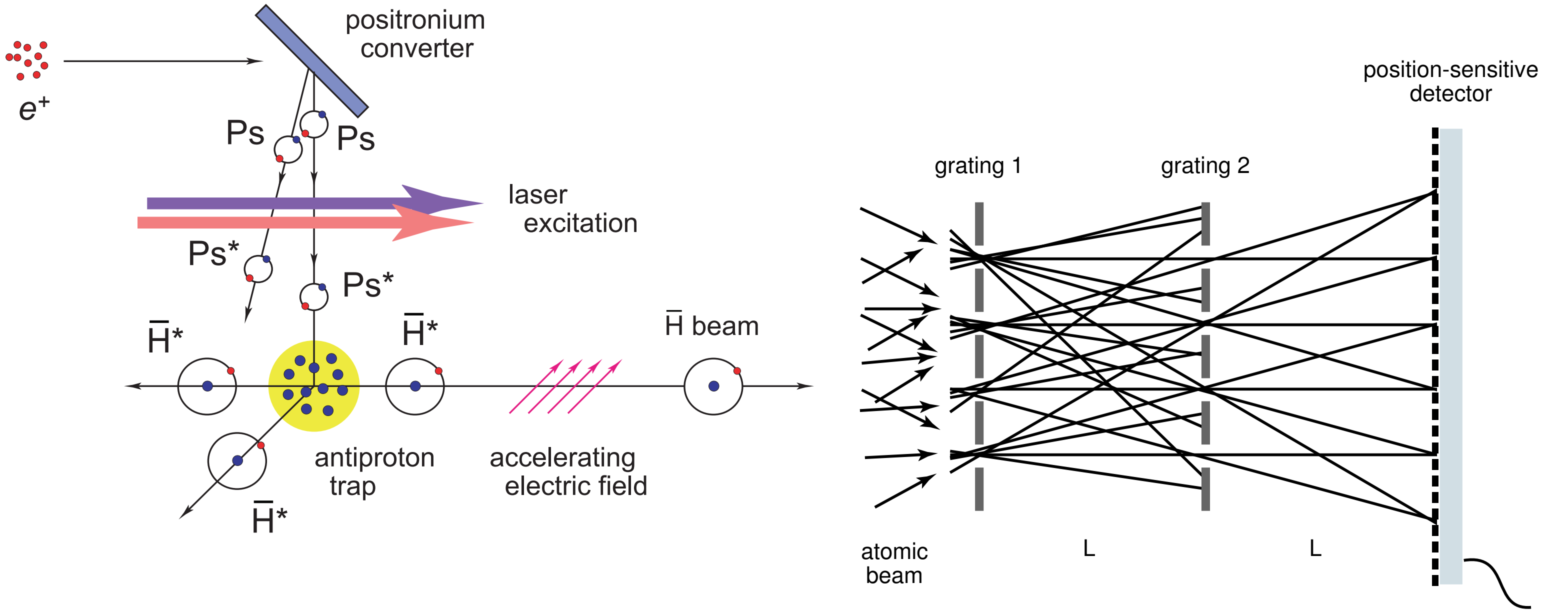
(FAR) FUTURE EXPERIMENTS

- Phase 3: trapped H$^{\mathrm{bar}}$
  - Hyperfine spectroscopy in an atomic fountain of antihydrogen
  - needs trapping and laser cooling outside of formation magnet
  - slow beam & capture in measurement trap
  - Ramsey method with d=1m
    - Δf ~3 Hz, Δf/f ~ 2×10^{-9}



M. Kasevich, E. Riis, S. Chu, R. DeVoe, PRL 63, 612–615 (1989)

AEGIS - ULTRA-LOW ENERGY BEAM



- H$^{\text{bar}}$ production at 100 mK
- primary physics goal: gravity
- opportunities for HFS measurement
  - achieve higher precision with ultra-slow beam
  - transfer H$^{\text{bar}}$ to freely accessible trap

SUMMARY

- Precise measurement of the hyperfine structure of antihydrogen promises one of the most sensitive tests of CPT symmetry
- Complementary to 1S-2S laser spectroscopy, competitive in absolute sensitivity
- Recent milestones in H^{bar} production & trapping make the field enter the era of spectroscopy
- Time scale of precision experiments is 5-10 years

ERC Advanced Grant 291242
HbarHFS
www.antimatter.at
PI EW