H·HFS
Hyperfine Structure of Antihydrogen

STATUS OF THE ANTIHYDROGEN HYPERFINE STRUCTURE MEASUREMENT IN ASACUSA

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On behalf of the **ASACUSA** Collaboration

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October 13th 2015, Budapest Hungary

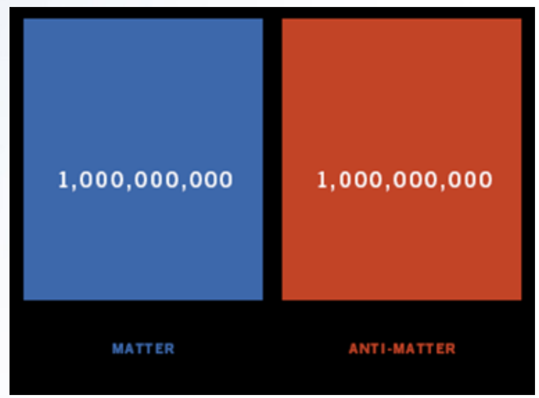
ANTIMATTER - MATTER ASYMMETRY

- No evidence of primary antimatter anywhere in the universe

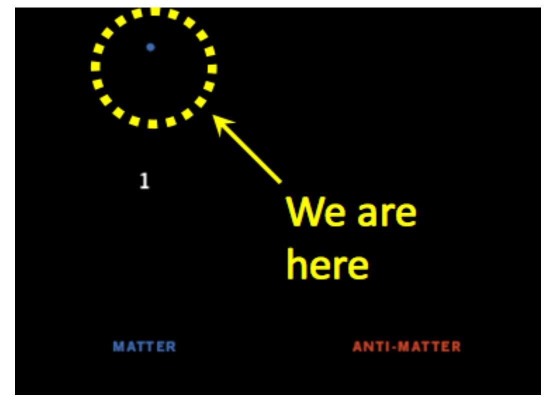
- Baryon asymmetry produced by a <u>very small deviation</u>

$$\frac{n(B) - n(\bar{b})}{n(\gamma)} < 10^{-9}$$

13.8 billions years ago :



Today :



Possible explanations :

- CP or CPT violations

A. D. Sakharov JETP Lett.-USSR 5,24 (1967).

Kostelecký et al., Lorentz and CPT tests with hydrogen, antihydrogen, and related systems, Phys.Rev. D92 (2015) 5, 056002

- Anomalous antimatter gravity: segregation of matter and antimatter in different parts of the universe

CPT SYMMETRY TEST

~~Charge conjugation~~

~~Parity transformation~~

Time reversal

CPT Theorem assumptions:

- Lorentz invariance
- Locality
- Unitarity

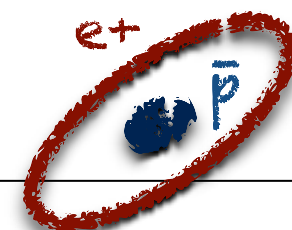
If **CPT symmetry holds**: properties of matter & antimatter particles have to be exactly equal (mass) or opposite (charge, magnetic moment). Atomic structures identical

Tests in different systems

$[m(K^0) - m(\bar{K}^0)] / m(\text{average}) < 10^{-18}$

proton ~ antiproton (compare m, q, $\vec{\mu}$)

hydrogen ~ antihydrogen (1S – 2S, HFS)



Antihydrogen:
Most simple anti-atom.
Only neutral antimatter made in large & controlled quantities so far

GROUND STATE HYPERFINE SPLITTING

$$\nu = 1.420405751768(1)\ \mathrm{GHz}$$

Essen et al., Nature 229, 110 (1971)
Hellwig et al., IEEE Trans. Instrum. Meas. IM-19, 200 (1970)

Leading term: **Fermi contact term**

has been measured to 5ppm

DiSciacca et al, Phys. Rev. Lett. 110, 13 (2013)

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

Finite electric and magnetic radius (**Zemach corrections**): ~-41ppm

access to the electric and magnetic form factors of the antiproton

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

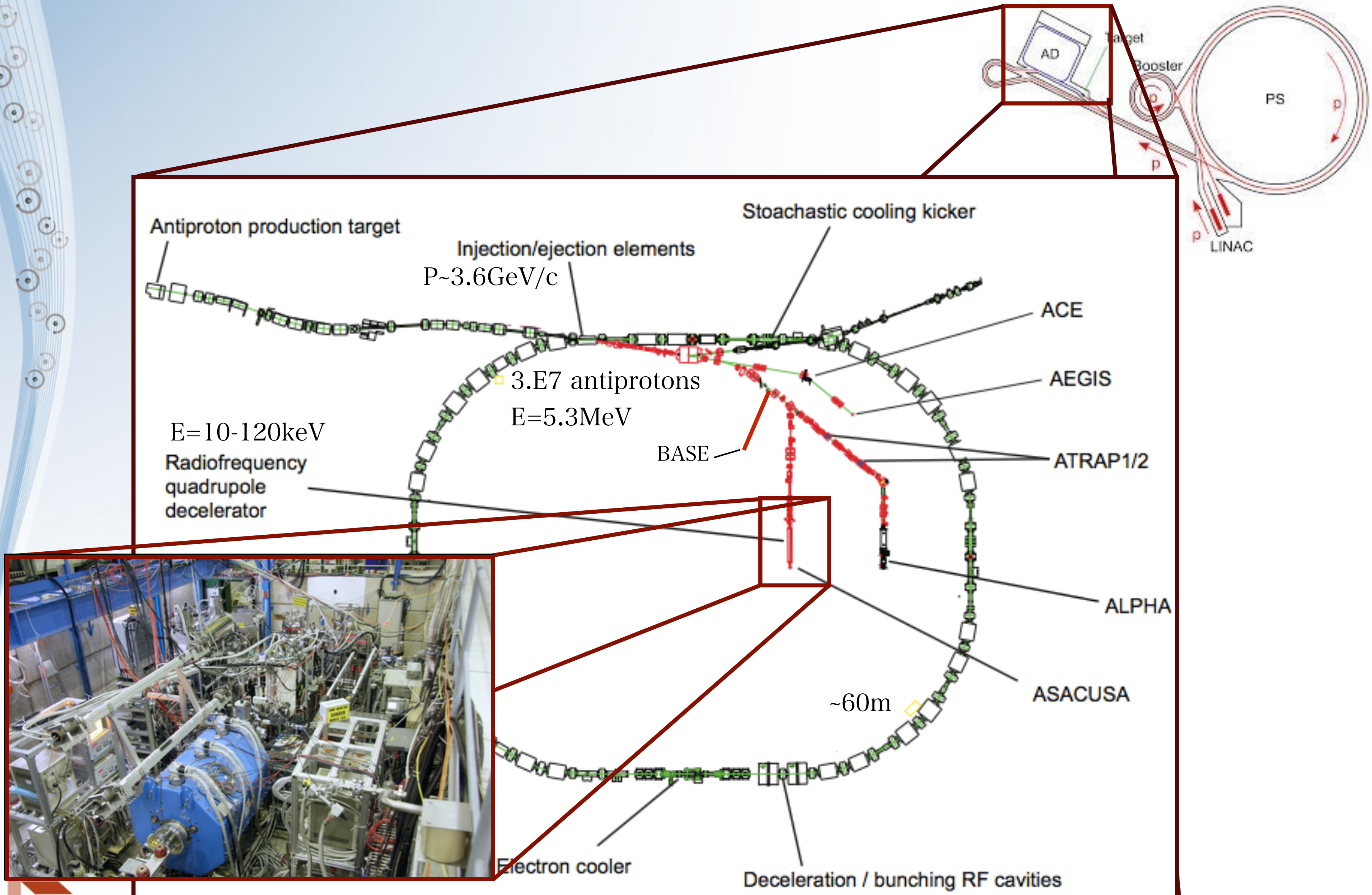
e.g Friar et al. Phys.Lett. B579 (2004)

Polarizability of p(bar) =1.88±0.64 ppm

Carlson, Nazaryan, and Griffioen PRA 78, 022517 (2008)

Remaining deviation theory-experiment: **0.86±0.78 ppm**

CERN'S ANTIPROTON DECELERATOR



20 YEARS OF $\bar{H}$ EXPERIMENTS @ CERN

1995 — First production of antihydrogen at LEAR (CERN)
Phys. Lett. B 368 (1996) 251-258

2000 — **Start up of the AD**

2002 — ATHENA and ATRAP make "cold" $\bar{H}$ at the AD
Nature **419**, 456-459
Phys. Rev. Lett. 89, 213401

2004 — First Laser-Controlled $\bar{H}$ Production by ATRAP
Phys. Rev. Lett. 93, 263401

ALPHA & ASACUSA #1 Physics World Breakthrough 2010

2010 — Synthesis of $\bar{H}$ by ASACUSA
Phys. Rev. Lett. 105, 243401 (2010)

2010 — First trapping of $\bar{H}$ by ALPHA
Nature **468**, 673 (2010)

2011 — ALPHA traps $\bar{H}$ for 1000 seconds
Nature Physics, 7, 558 (2011)

2012 — First resonant Quantum Transition on trapped $\bar{H}$ by ALPHA
Nature **483**, 439 (2012)

2013 — ALPHA "probes" antimatter gravity
Nature Communications 4, 1785 (2013)

2014 — ASACUSA creates the first "beam" of "cold" $\bar{H}$
Nature Communications. 5, 3089 (2014)

2014 — ALPHA puts limits on the charge of $\bar{H}$
Nature Communications 5, 3955 (2014)

2017 — **Start up of ELENA**

$\bar{H}$·HFS

HFS MEASUREMENT PRINCIPLE

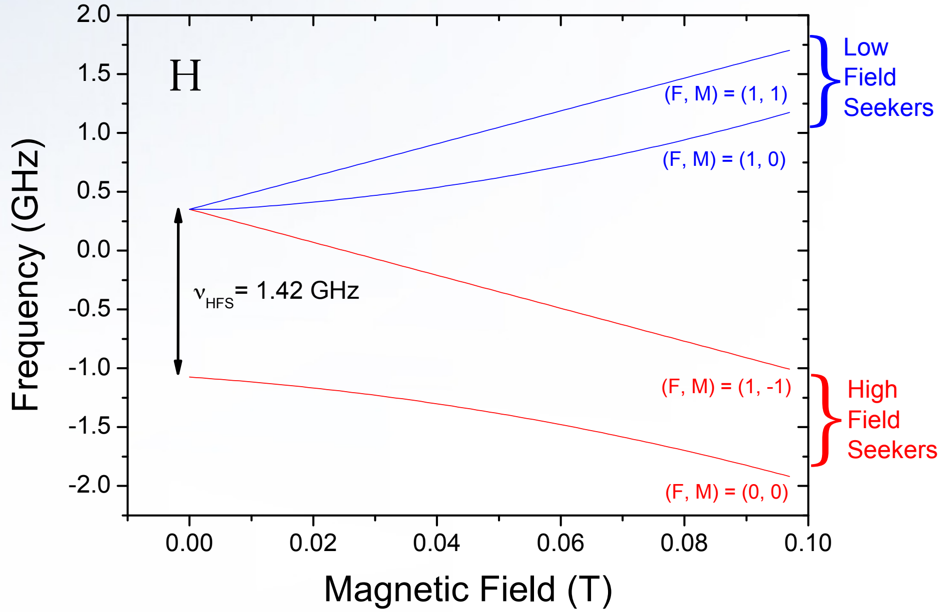
Spectroscopy with trapped antihydrogen: lower precision due to strong confining field

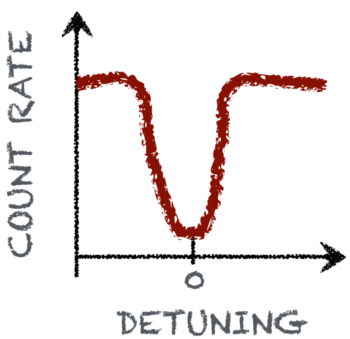
Good candidate: atomic beam with RF resonance

1) no $\bar{H}$ trapping needed → no need for ultra-cold (< 1 K) $\bar{H}$

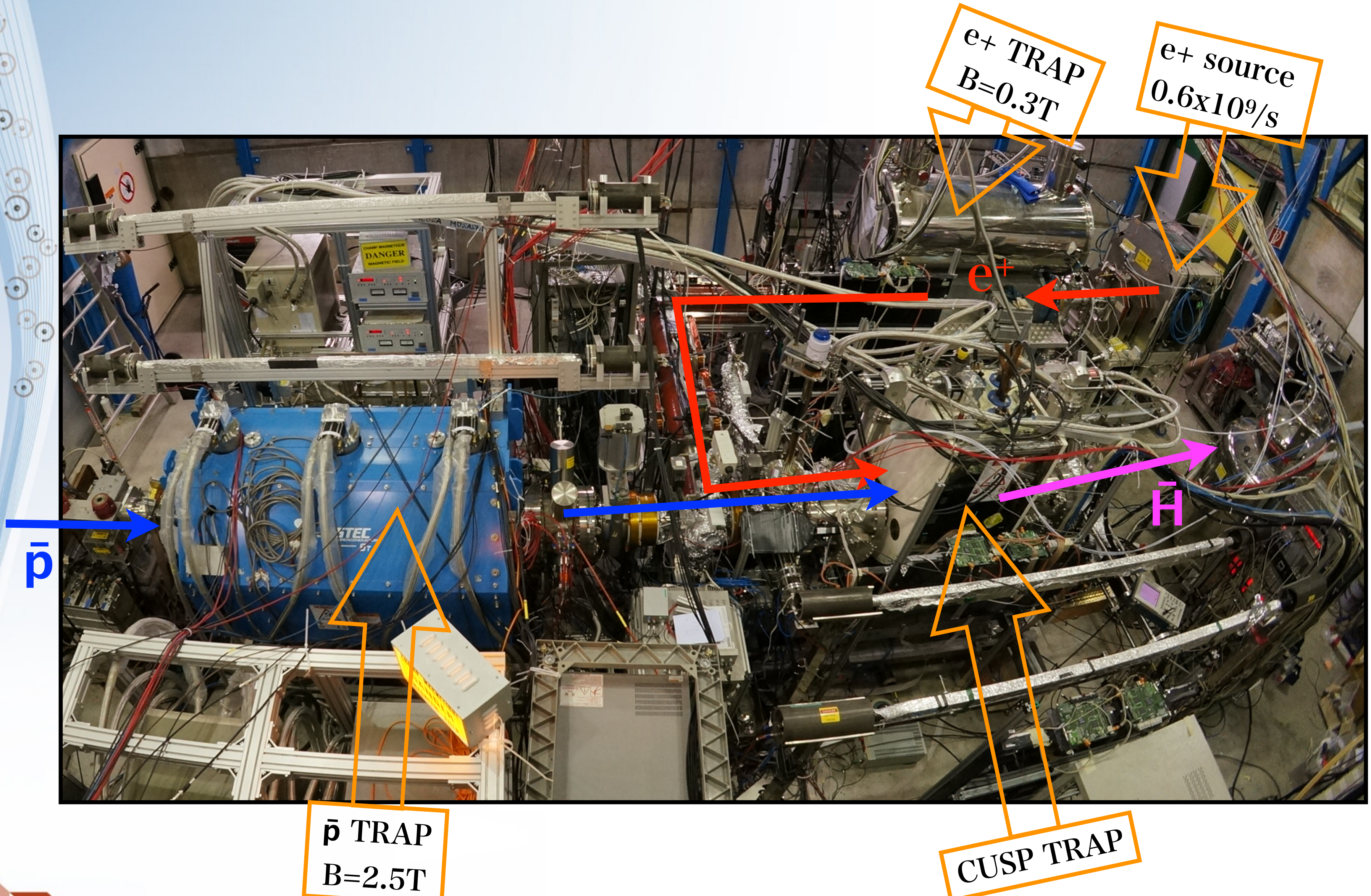
2) atomic beam method can work up to 50-100 K

3) $\bar{H}$ atoms can be guided with inhomogeneous magnetic field

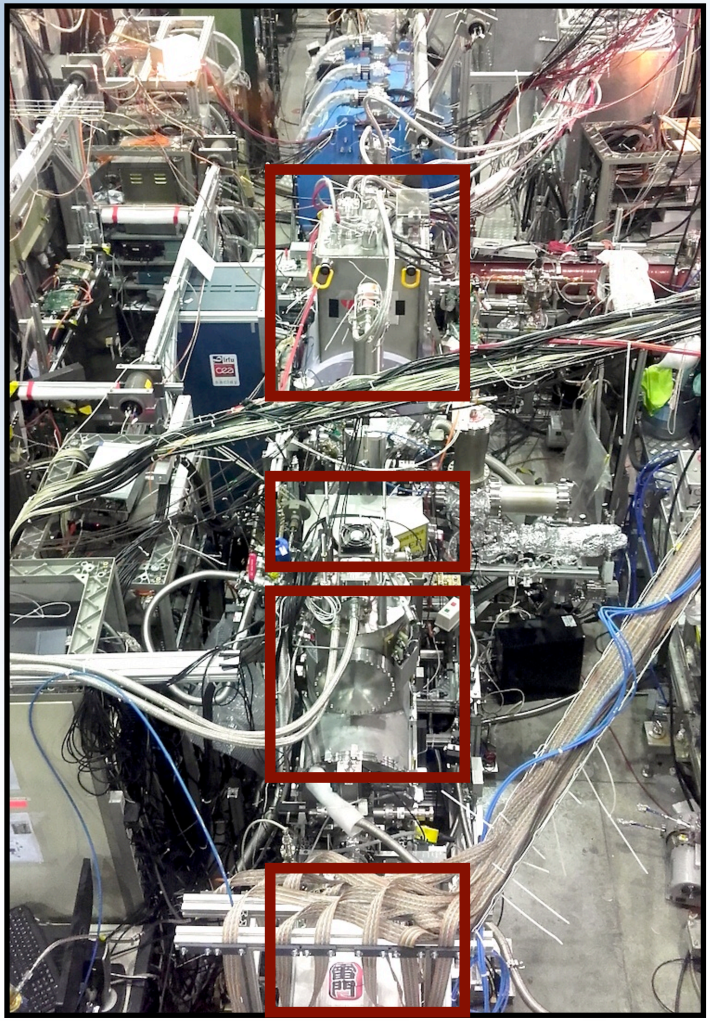


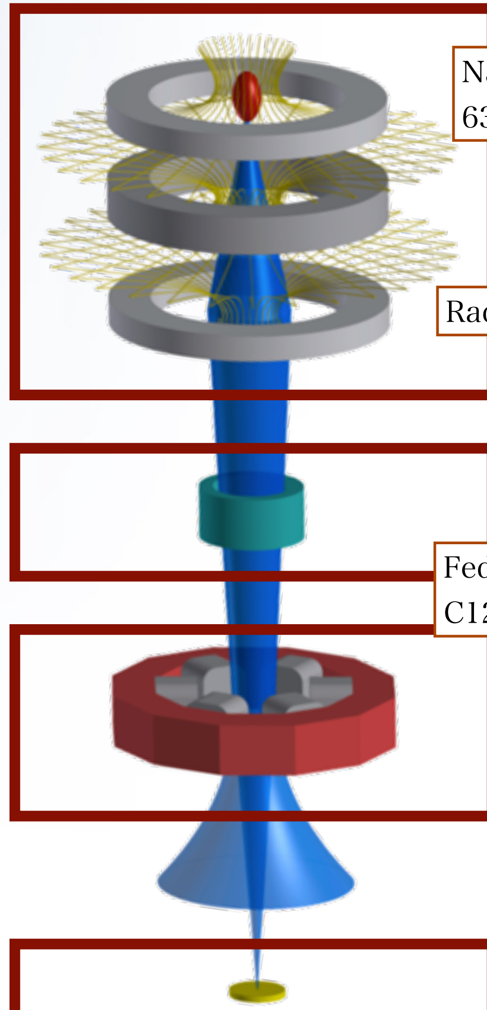


ANTIHYDROGEN PRODUCTION



ANTIHYDROGEN CHARACTERIZATION





Nagata et al., J.Phys.Conf.Series. 635 (2015) 022062

DOUBLE CUSP
&
AMT

Radics et al., RSI 86 (2015) 083304

FIELD IONIZER

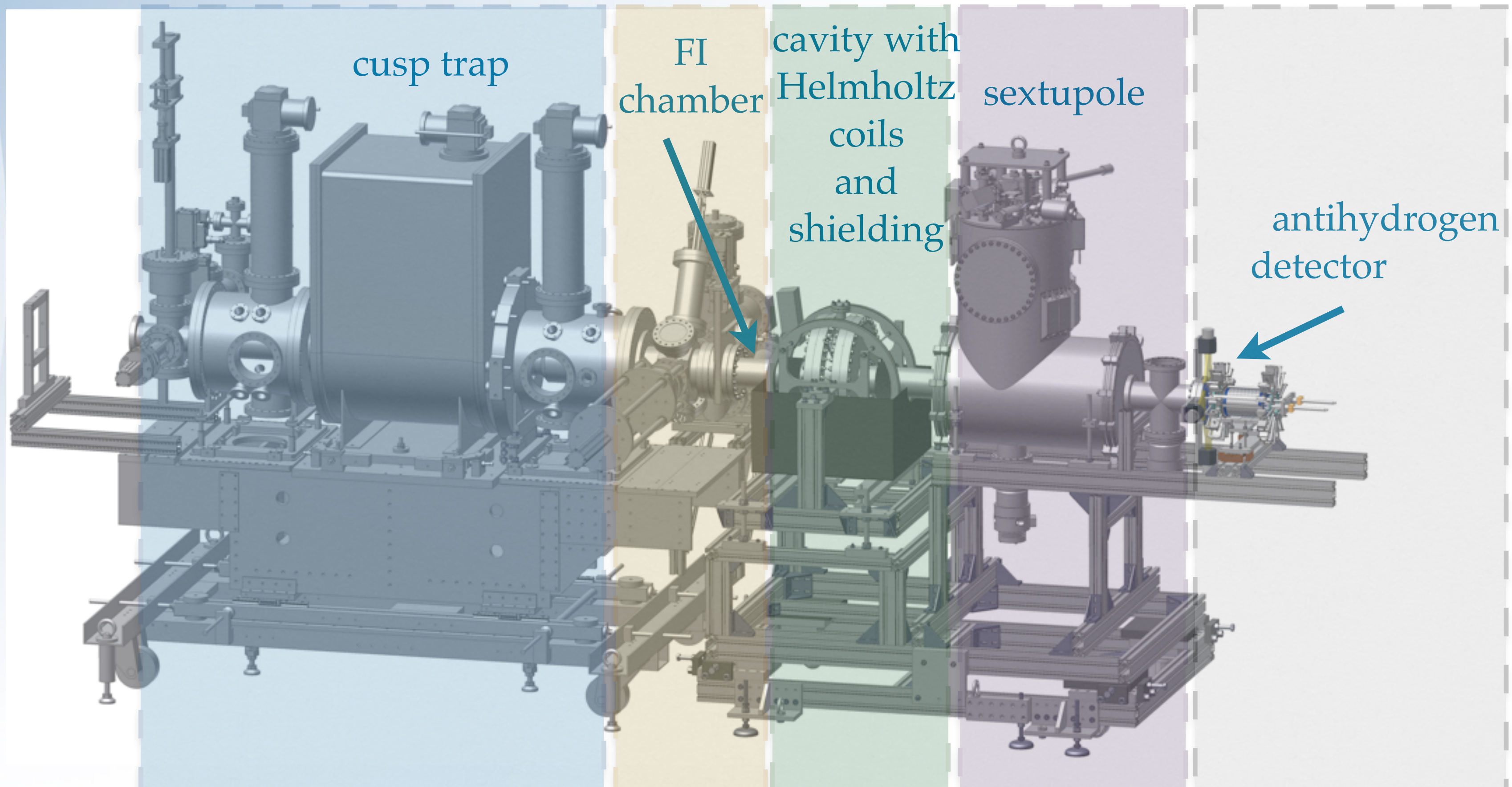
CAVITY

Federmann et al., Conf. Proc. C1205201 (2012) pp.WEPPD072

SEXTUPOLE

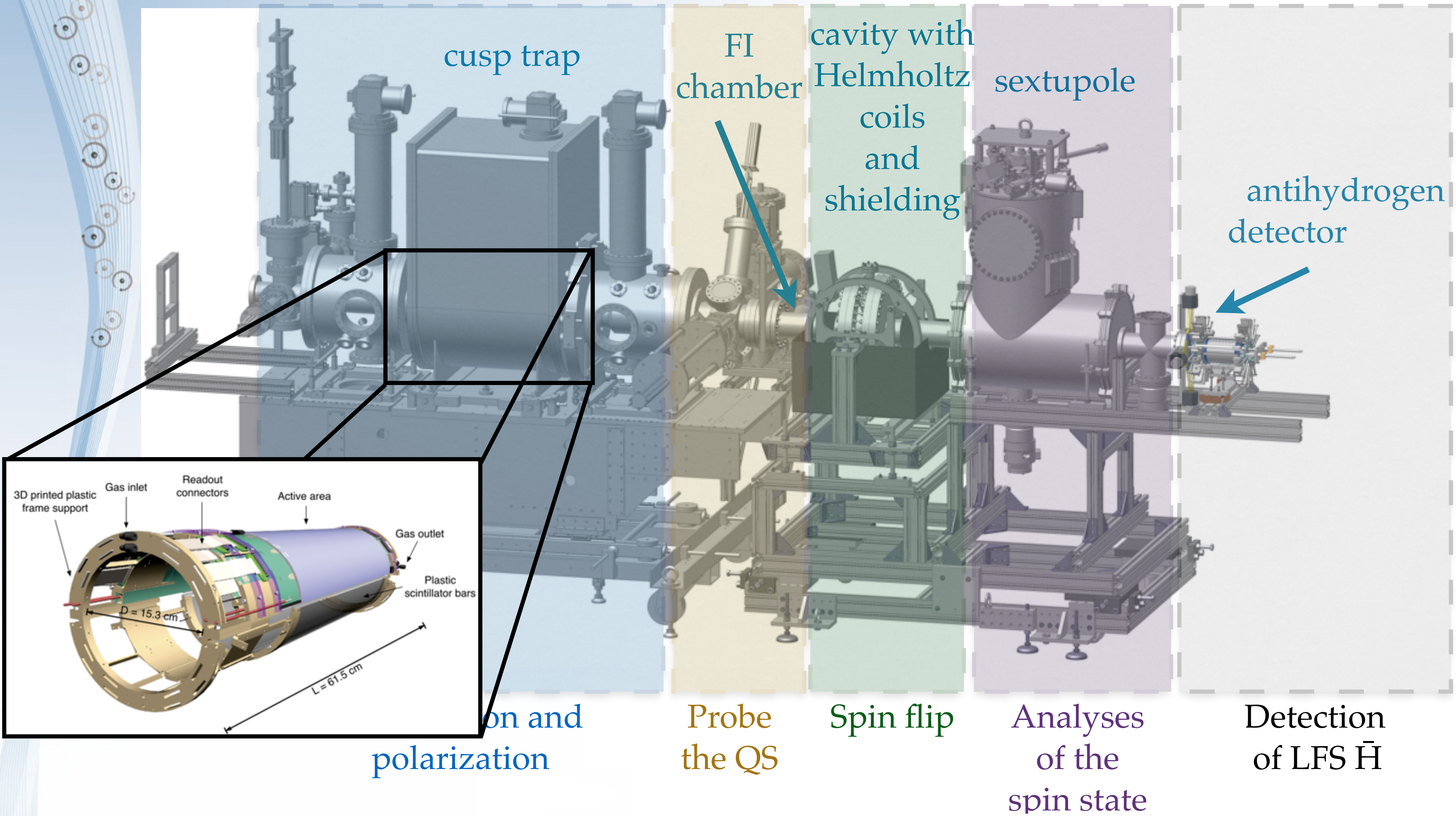
DETECTOR

FOCUS ON SPECTROMETER LINE



$\bar{H}$ formation and polarization | Probe the QS | Spin flip | Analyses of the spin state | Detection of LFS $\bar{H}$

FOCUS ON SPECTROMETER LINE



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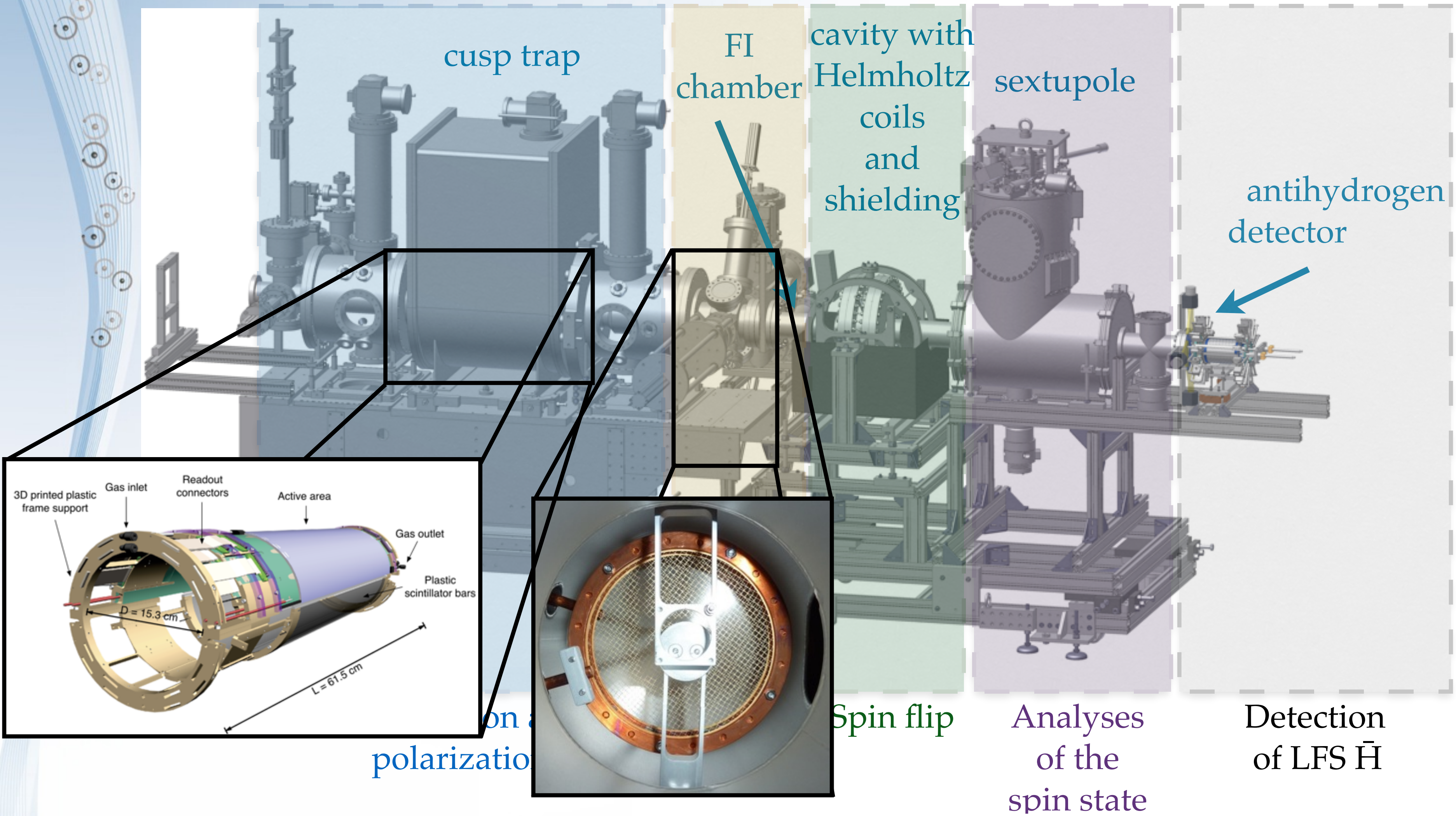

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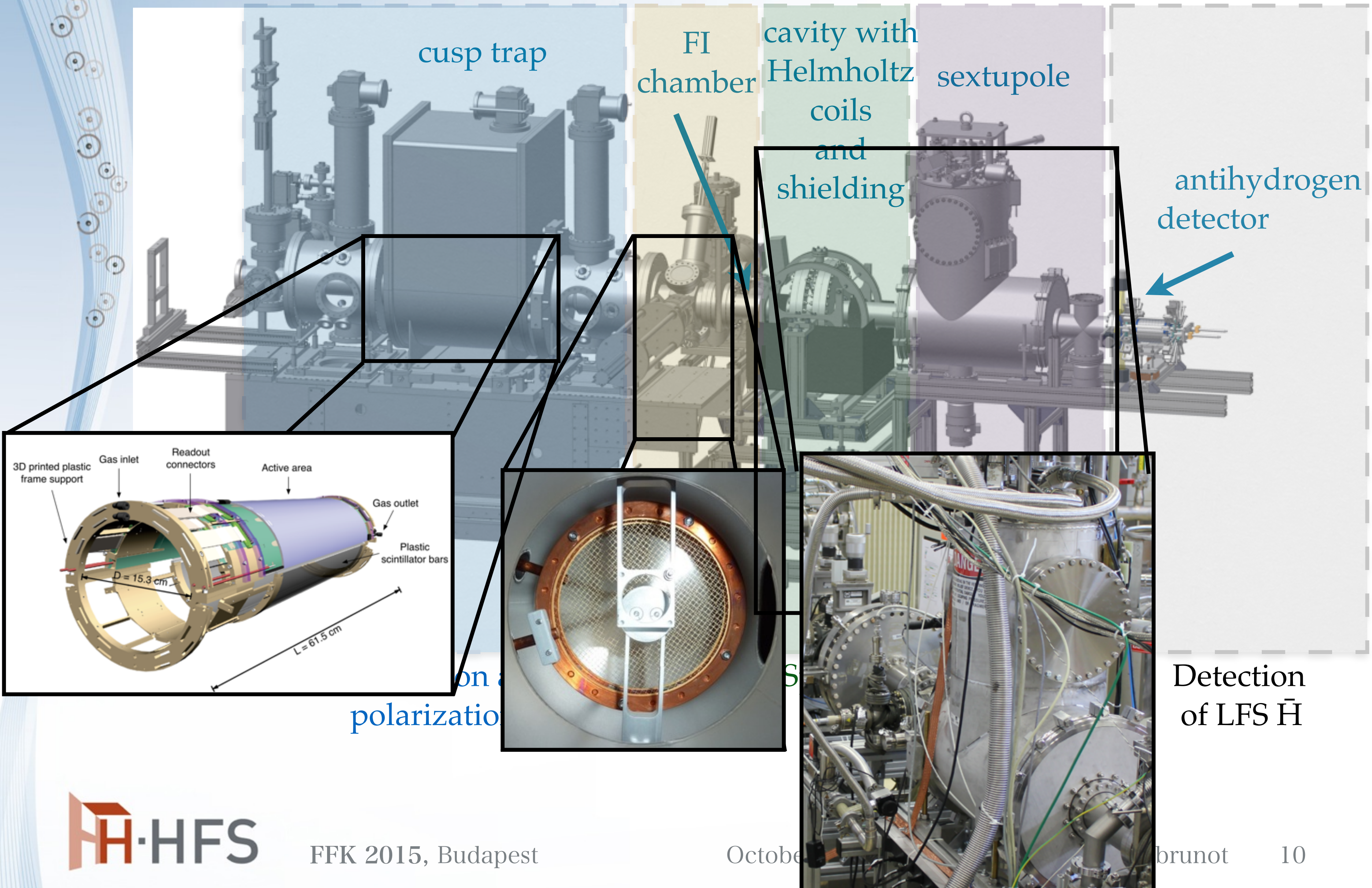

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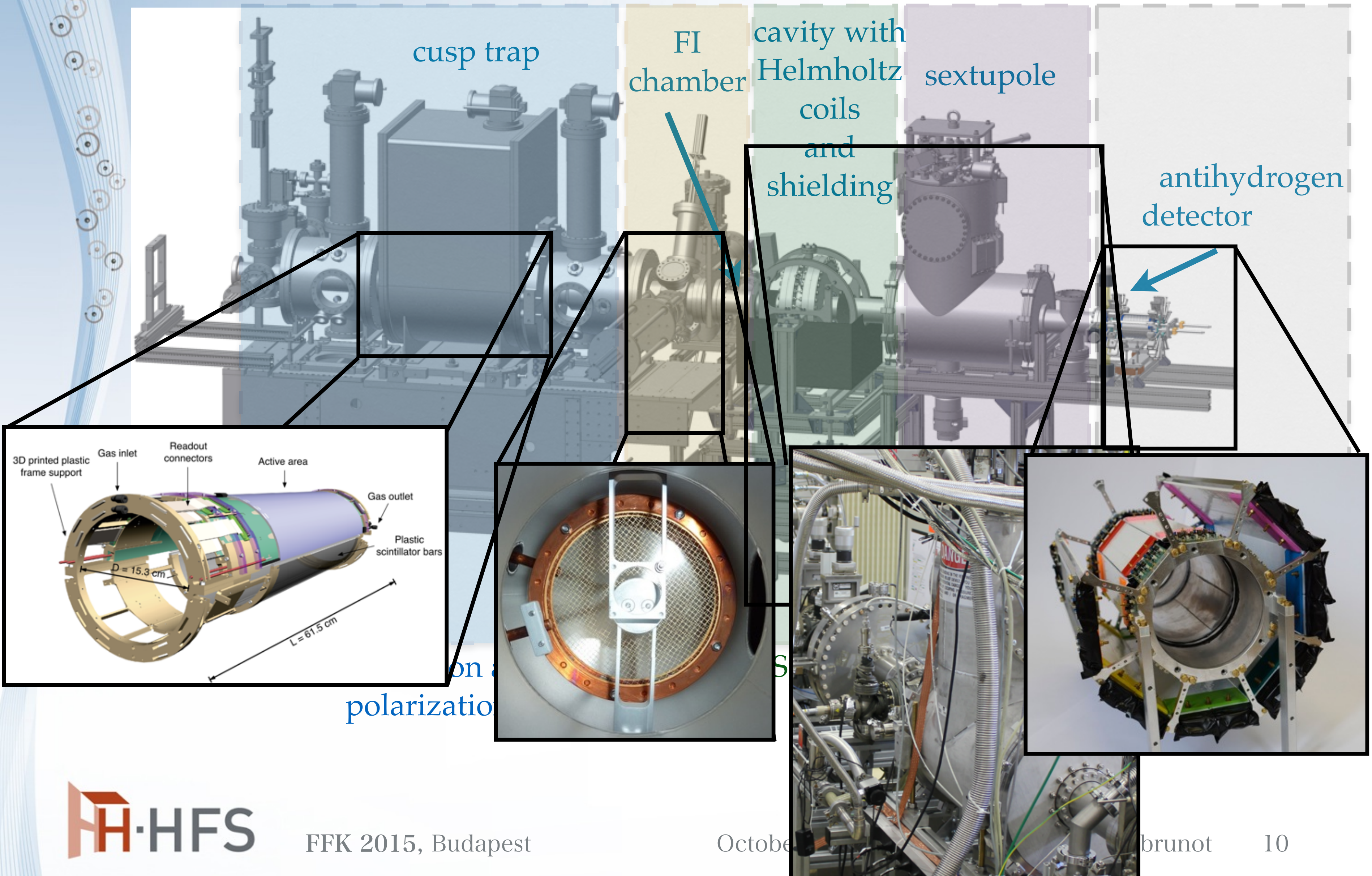
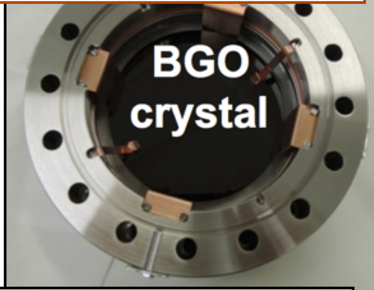


ANTIHYDROGEN DETECTORS

Annihilation: BGO crystal (position sensitive calorimeter)

read out by MchPMT array of 16x16 for position resolution

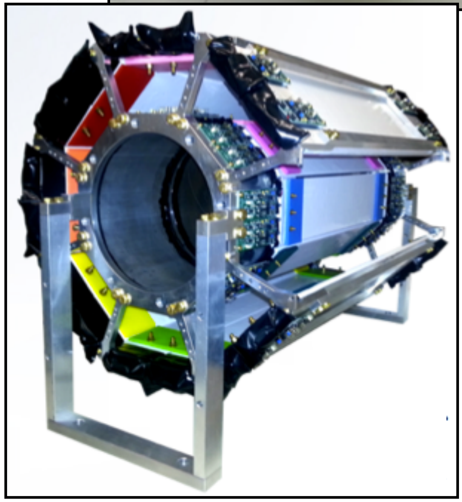
Nagata et al., J.Phys.Conf.Series. 635 (2015) 022061



Pion tracking:
- 2 layers hodoscope
- 32 (8x4) scintillator bars each
- SiPMs on each side

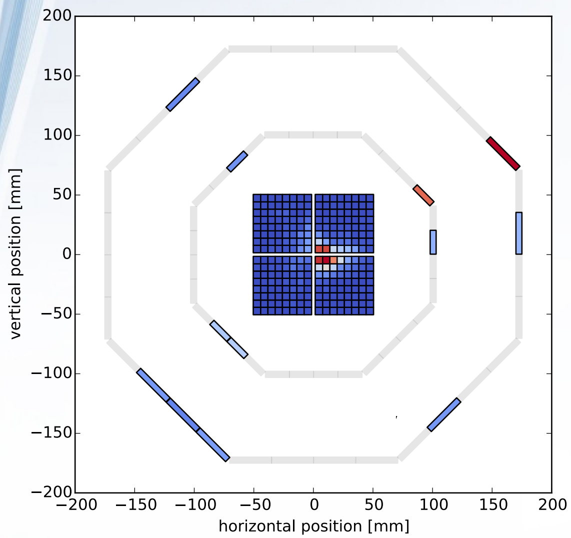
axial resol. by time difference

Cosmics suppression
- energy deposit
- trigger: triple coincidence
- fast timing (600ps FWHM)
- >60% efficiency
  < 1% false IDs

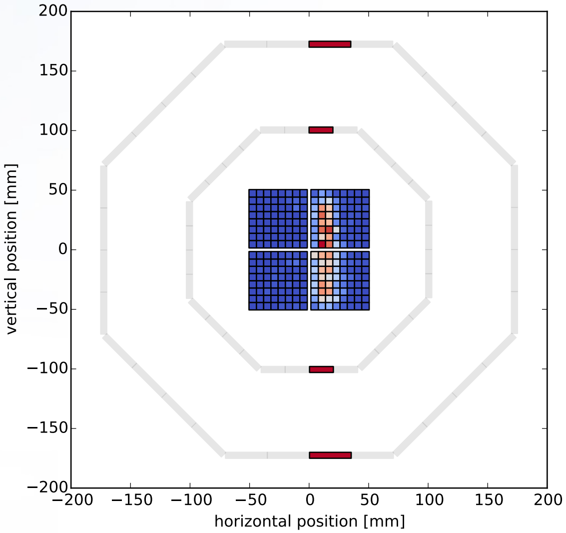


Event display

p̄ event

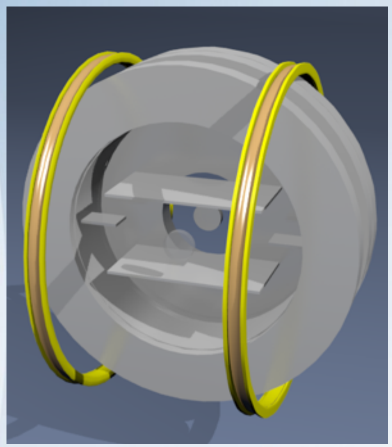


Cosmic event



Solid angle (mixing point - detector): ~0.004%

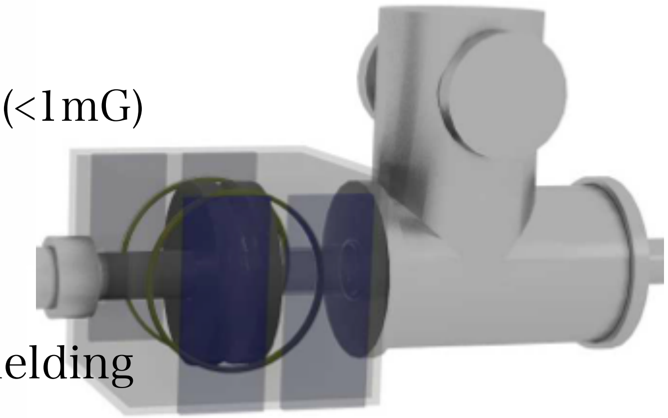
THE MICROWAVE CAVITY



Helmholtz coils 0-10G static field

high stability power supply

Field Stability <0.025% @ 4G (<1mG)



shielding

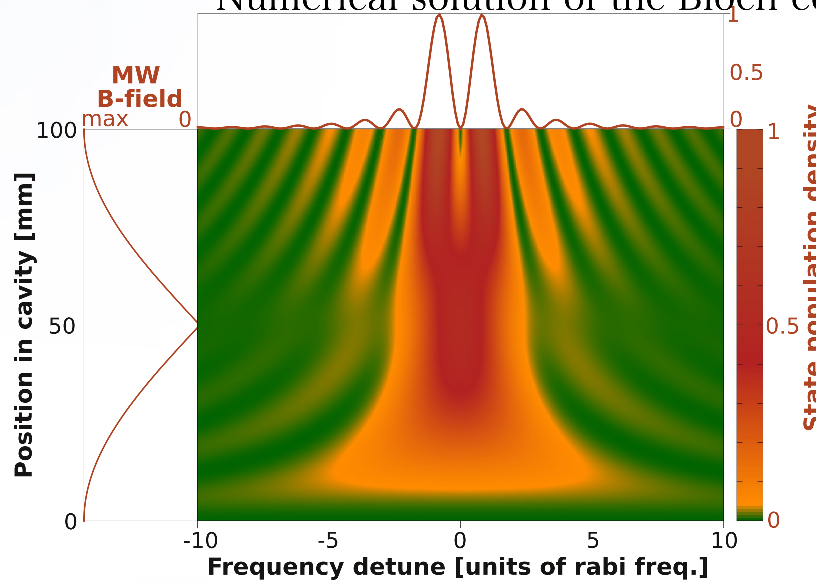
beam stopper: stop particles coming from the center of the CUSP

cavity length 10 cm

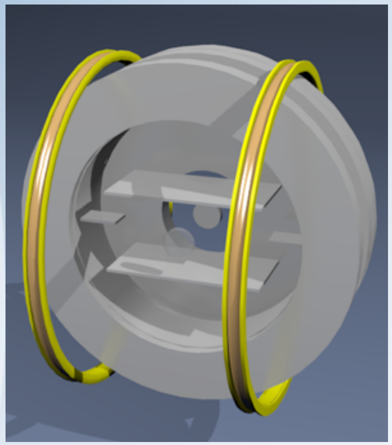
MW frequency: 1.42GHz

Q~100

Numerical solution of the Bloch equations



THE MICROWAVE CAVITY



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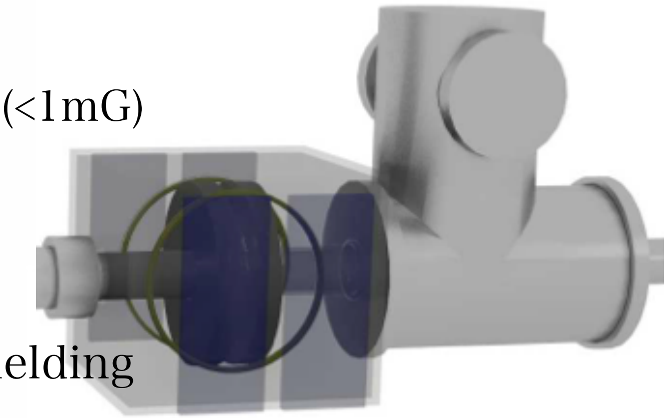

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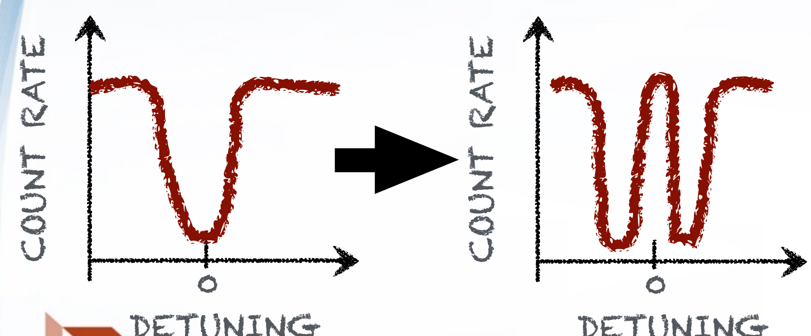

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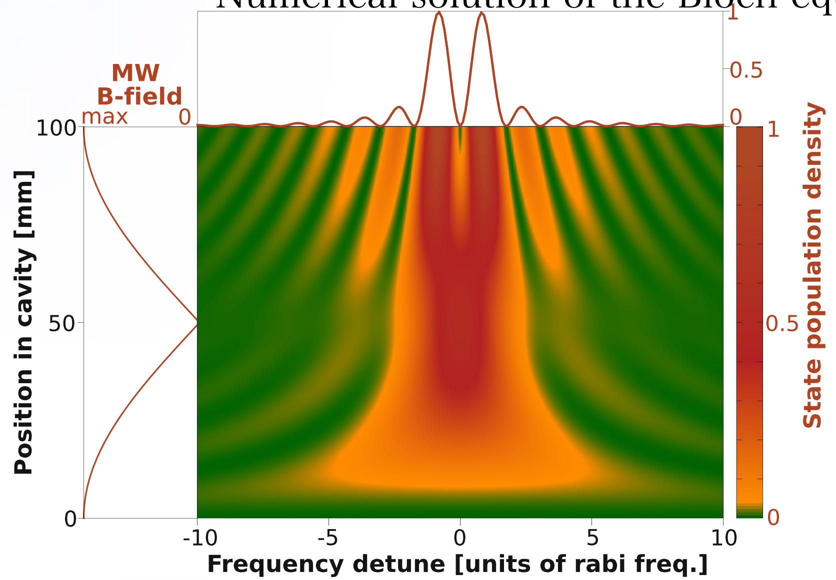

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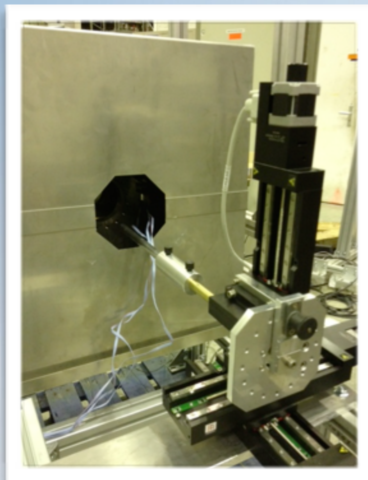
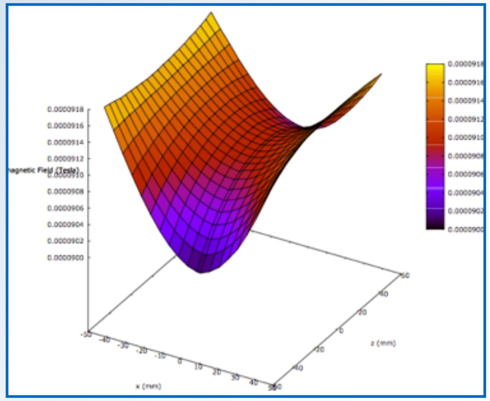
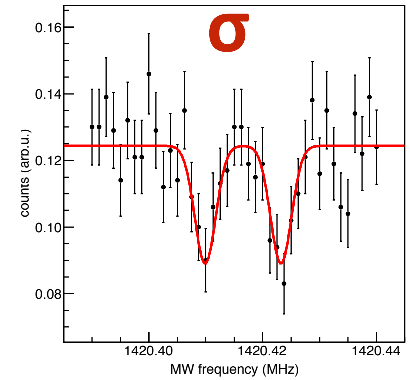


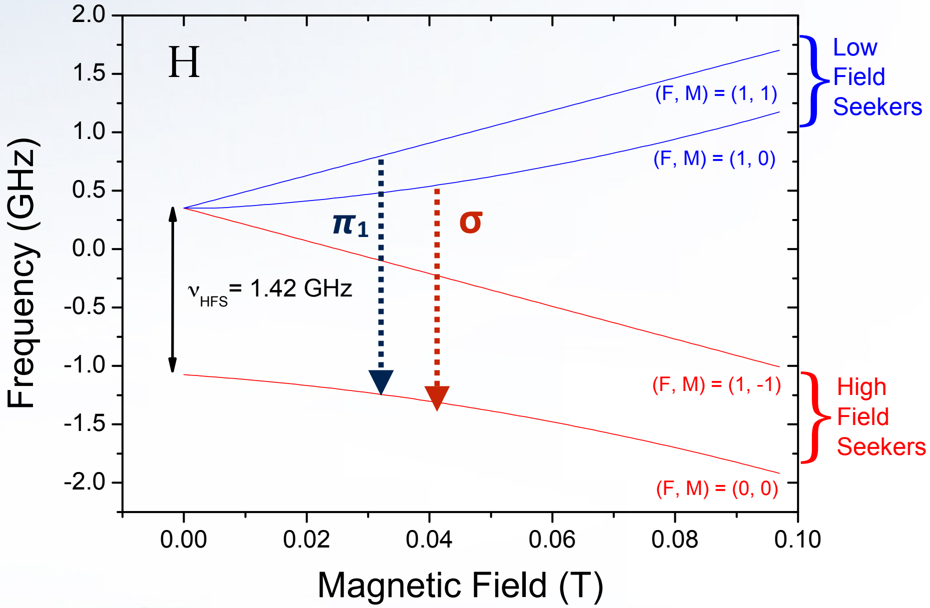


precise static field characterization

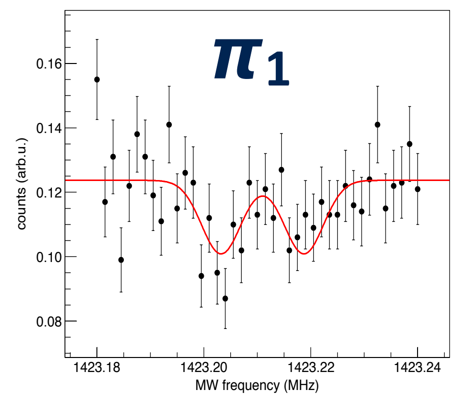
$$\frac{\Delta B}{B} = 1\%$$



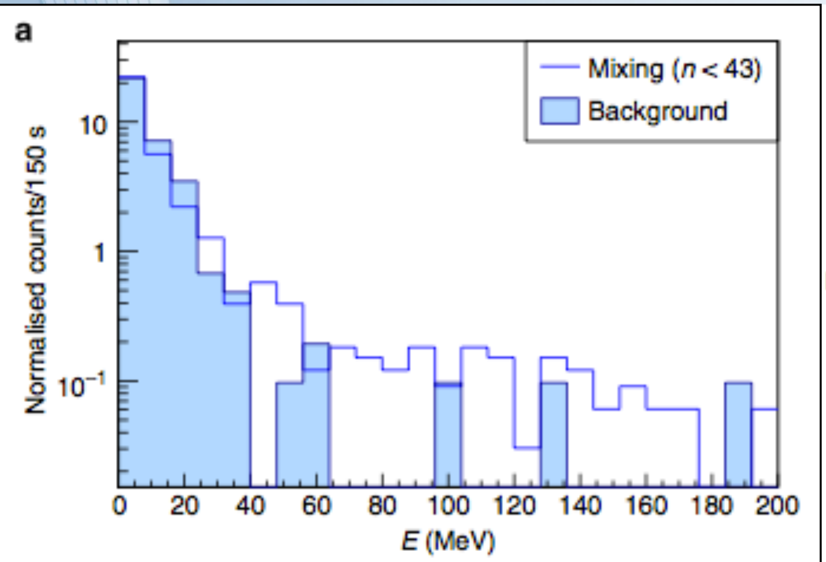
simulation done at 2G, T=50K



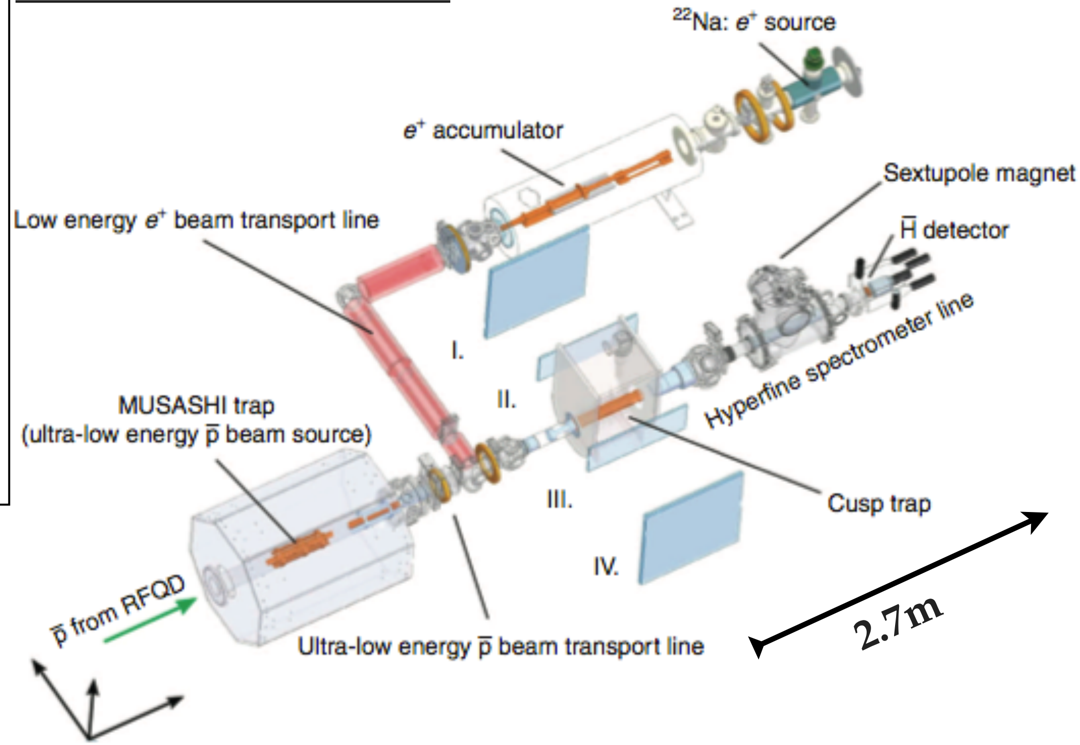
$$\frac{\Delta B}{B} = 0.1\%$$



LATEST BREAKTHROUGHS



Detection of a "Beam"



Mostly : 29 < n < 43

Kuroda et al., Nature Communications 5, 3089 (2014)

Coming next : Determine the polarization of the beam, velocity and quantum states at the cavity

==> IN PREPARATION FOR SPECTROSCOPY MEASUREMENT

Characterization of spectroscopy beamline

ANTIHYDROGEN PROPERTIES

Ultra-low temperature antihydrogen are not necessary for a beam experiments (unlike trap experiments).

BUT cold antihydrogen is better for:

1) **Polarisation intensity**

2) Cascading time: **lower n state**

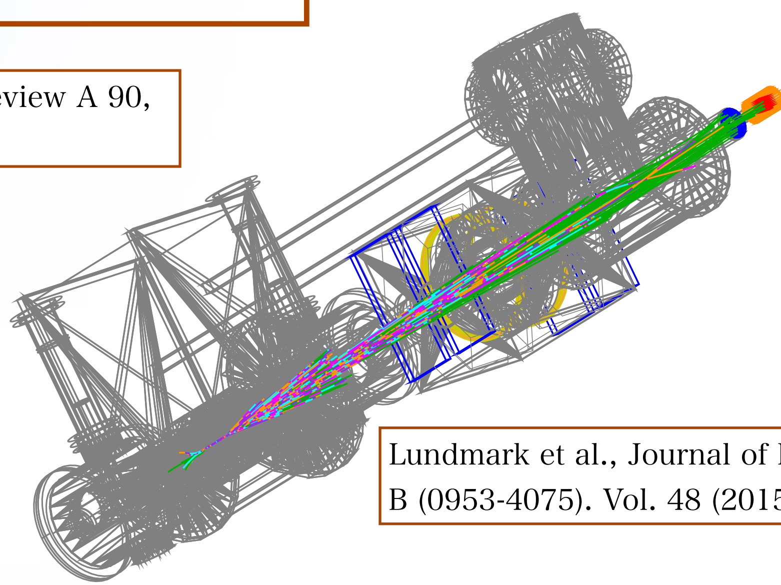
3) **Interaction time** with the microwave field in the cavity

→ SIMULATION WITH GEANT 4

Radics et al., Physical Review A 90, 032704 (2014)

Formation of antihydrogen simulated CTMC

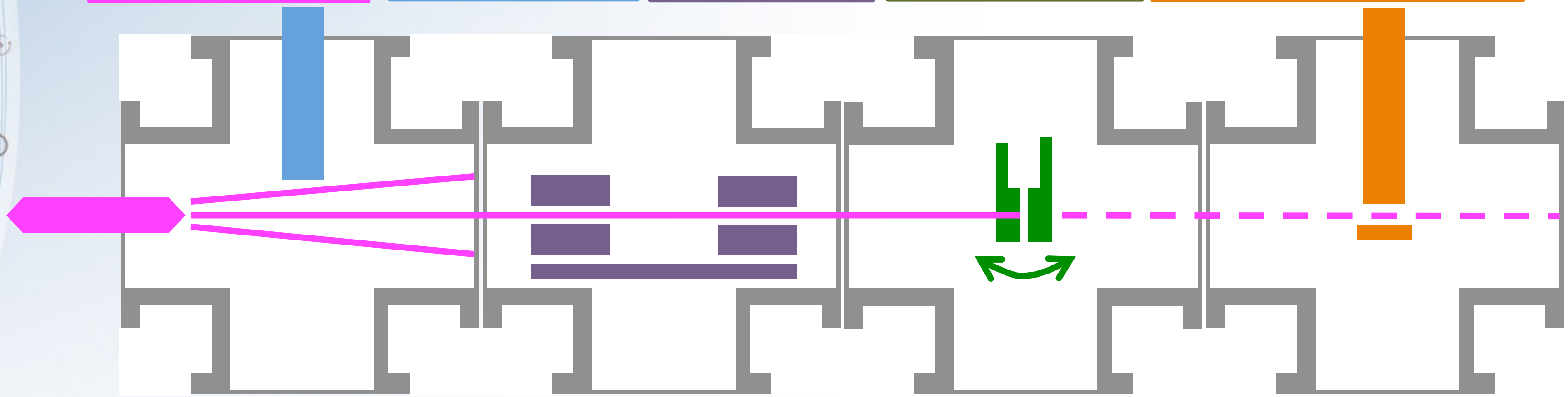
Pipeline between these simulations and Geant4

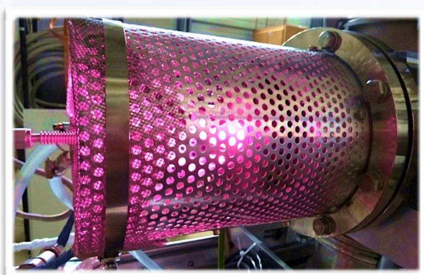


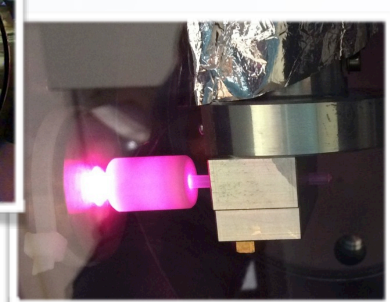
Lundmark et al., Journal of Physics B (0953-4075). Vol. 48 (2015), 18

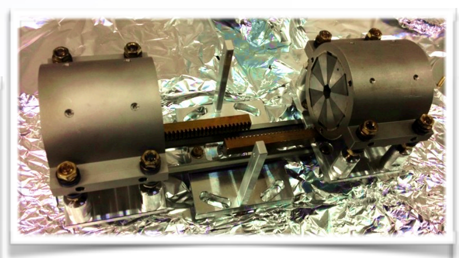
CHARACTERIZATION WITH H BEAM

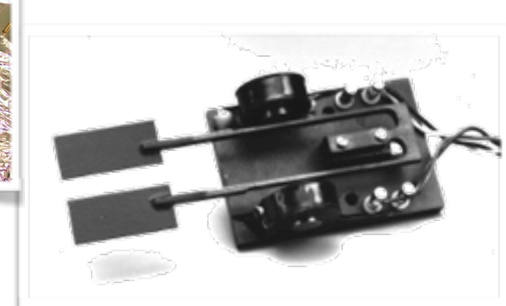
atomic H source	Cryogenic (cold head) for 50-100K beam	Sextupole for polarized beam	Fork-Chopper	Quadrup. Mass Spec.
ON → H and H_2 OFF → H_2 only			f ≈ 178 Hz 50% duty cycle	detects mass=1 H_1^+ or mass=2 H_2^+







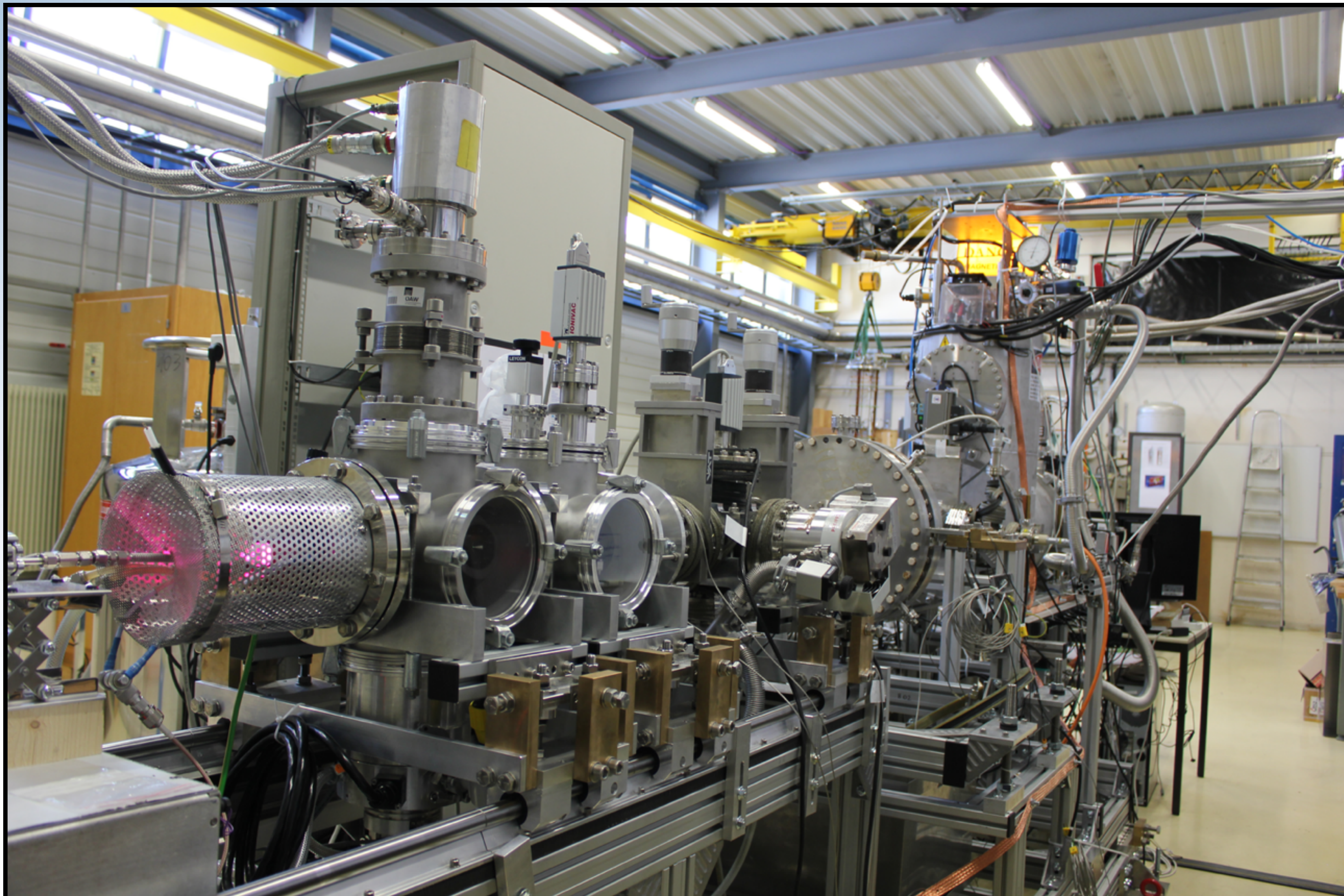




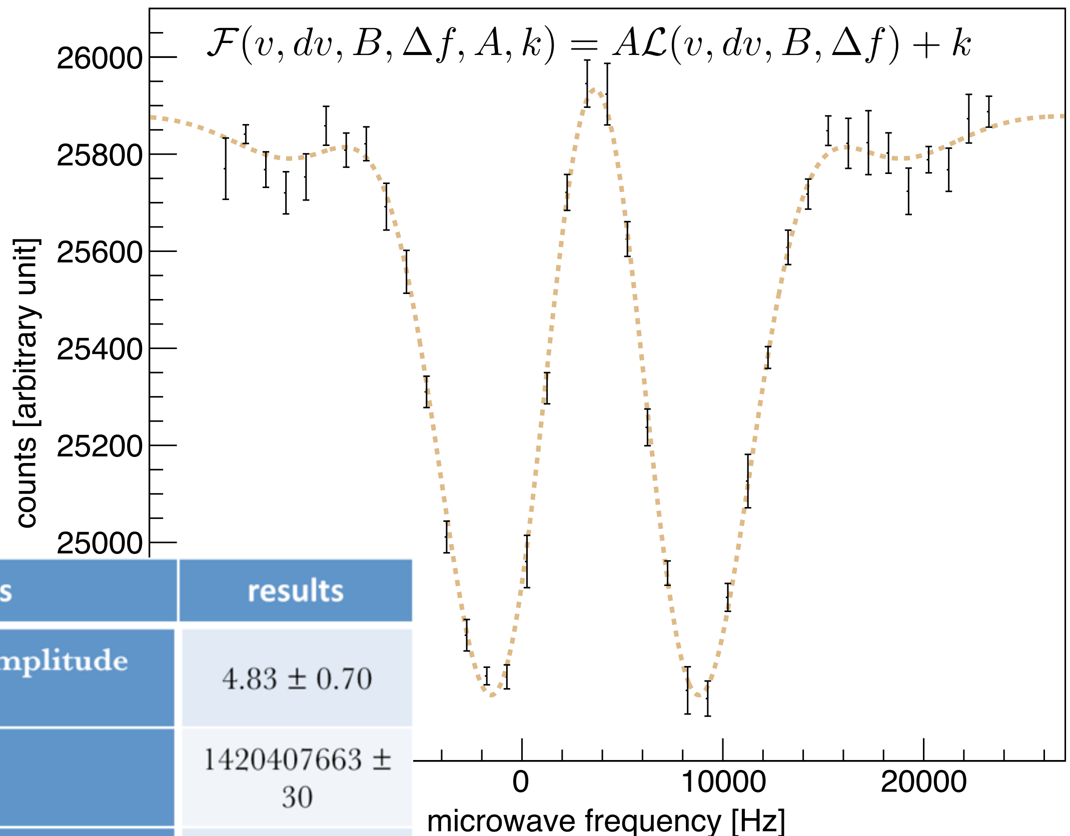
Diermaier et al.,Hyperfine Interactions (2015) Volume 233, Issue 1, pp 35-40

Malbrunot et al.,Hyperfine Interactions (2014) Volume 228, Issue 1, pp 61-66

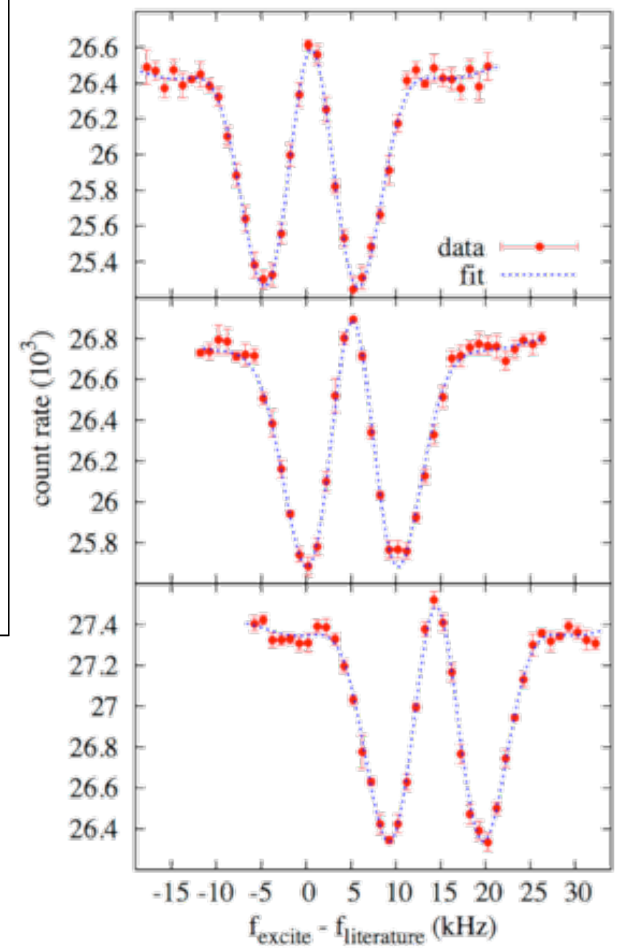
H BEAM APPARATUS



HYDROGEN MEASUREMENT

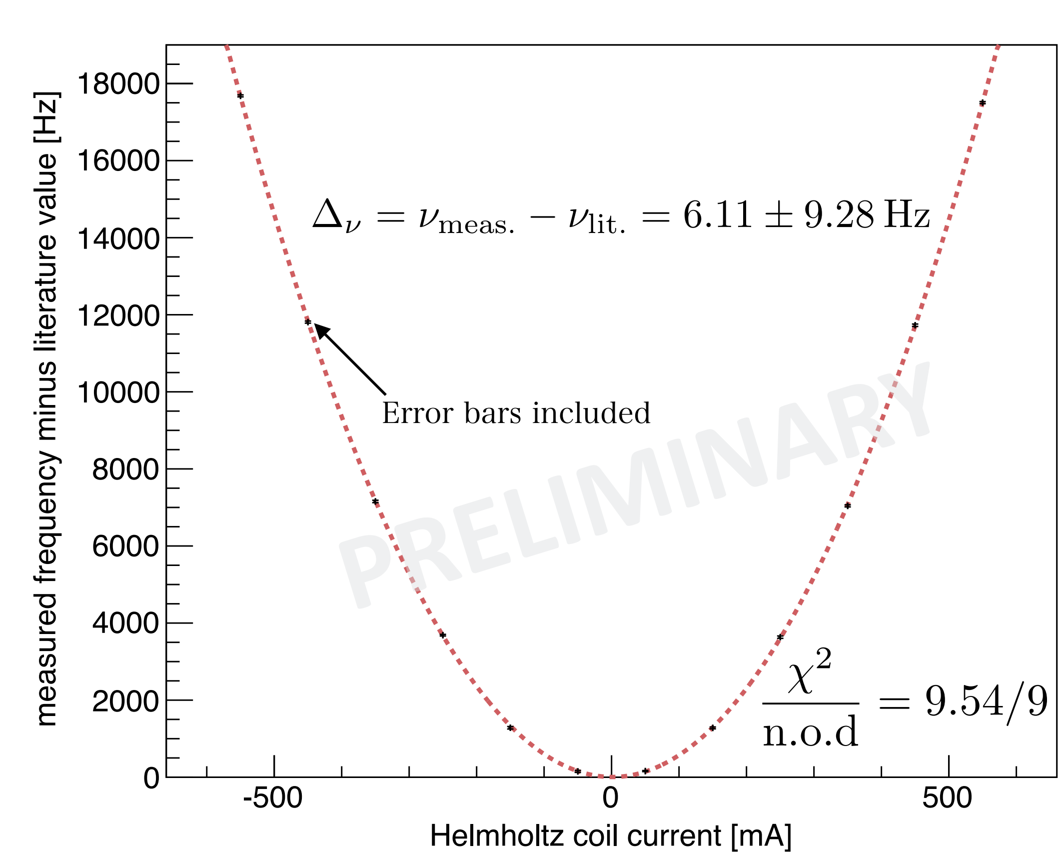


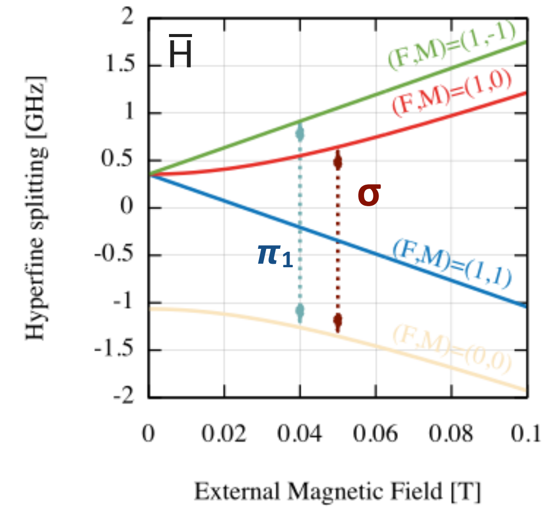
Fit parameters	results
Microwave amplitude [mG]	4.83 ± 0.70
f_0 [Hz]	1420407663 ± 30
central velocity [m/s]	835.3 ± 6.5
Velocity spread [m/s]	80 .0± 7.4
χ^2/nod	30.1/33

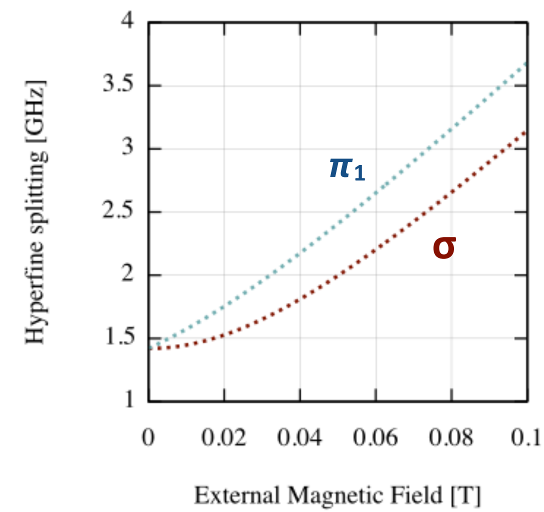


Velocity consistent with temperature of the source: 50K

HYDROGEN MEASUREMENT







B field are consistent (within 1 sigma) with flux gate readings

HYDROGEN MEASUREMENT

- Best beam measurement

$$\nu = 1420.40573(5)\ \mathrm{MHz}$$

$$\frac{\Delta\nu}{\nu} = 3.5 \times 10^{-8}$$

Kusch. Physical Review. 100, 4 (1955)

- Maser experiments

$$\nu = 1420.405751768(1)\ \mathrm{MHz}$$

$$\frac{\Delta\nu}{\nu} = 7 \times 10^{-13}$$

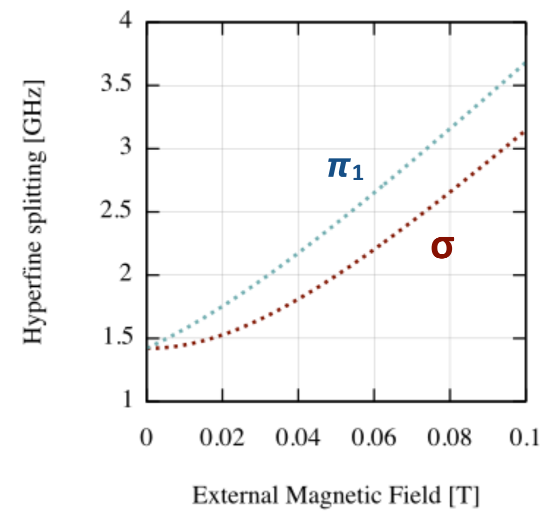
Essen et al., Nature 229, 110 (1971)
Hellwig et al., IEEE Trans. Instrum. Meas. IM-19, 200 (1970)

$$\nu = 1420.405748(3)$$

$$\frac{\Delta\nu}{\nu} \sim 2.5 \times 10^{-9}$$

PRELIMINARY

This work (to be published)



Further measurements of the π transition planned

SUMMARY AND OUTLOOK

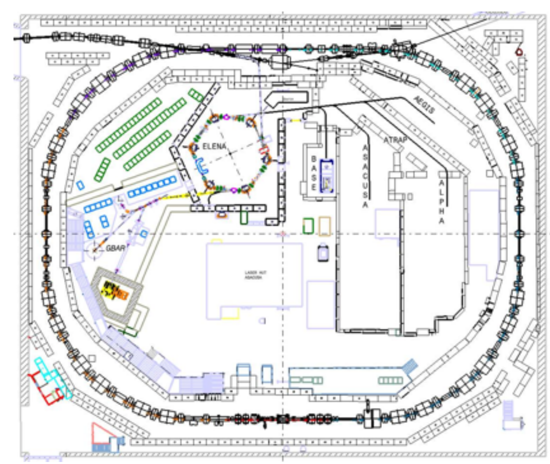
- ☑ First "beam" of $\bar{H}$ observed in field-free region
- ☑ HFS measurement of H beam ~3 ppb achieved with "identical apparatus"

- ☐ π resonance to be measured in H (simultaneous π and σ)
- ☐ Need higher yield of GS $\bar{H}$ for beam experiment
  - polarization
  - velocity measurement
  - quantum state distribution
- ☐ Extensive simulation done/ongoing

CERN-AD is unique

More low-energy antiprotons needed

ELENA upgrade at CERN: more antiprotons and more beamtime



THE ASACUSA ANTIHYDROGEN TEAM

Y. Abo, H. Breuker, A. Capon, M. Diermaier, P. Dupre, H. Higaki, Y. Higashi, S. Ishikawa, S. C. Kaga, Y. Kanai, B. Kolbinger, N. Kuroda, M. Leali, C. Malbrunot, Y. Matsuda, V. Mascagna, Y. Nagata, B. Radics, C. Sauerzopf, M. C. Simon, M. Tajima, H. A. Torii, S. Ulmer, L. Venturelli, E. Widmann, Y. Yamazaki, J. Zmeskal