H·HFS
Hyperfine Structure of Antihydrogen

ERC Advanced Grant
PI: Prof. Dr. Eberhard Widmann

MEASUREMENT OF HYPERFINE STRUCTURE OF ANTIHYDROGEN AT CERN

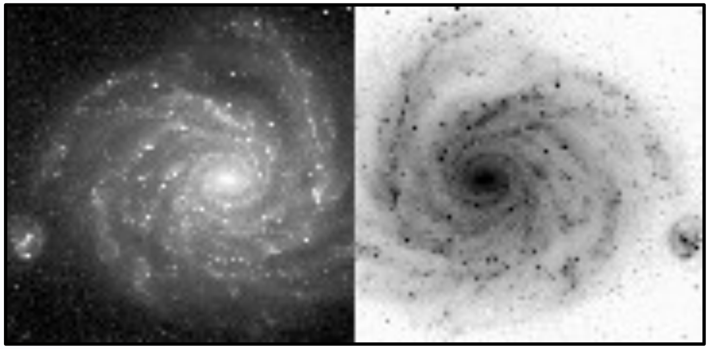
Chloé Malbrunot

on behalf of the ASACUSA collaboration

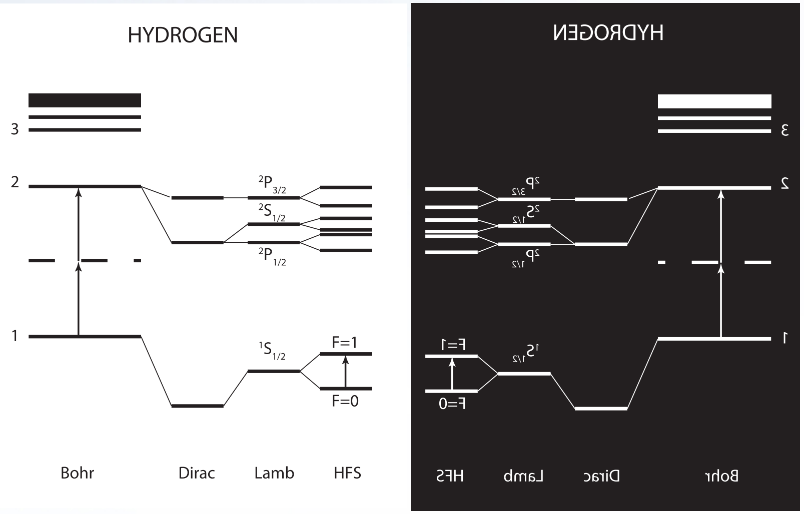
DISCRETE 2012 December 06th 2012

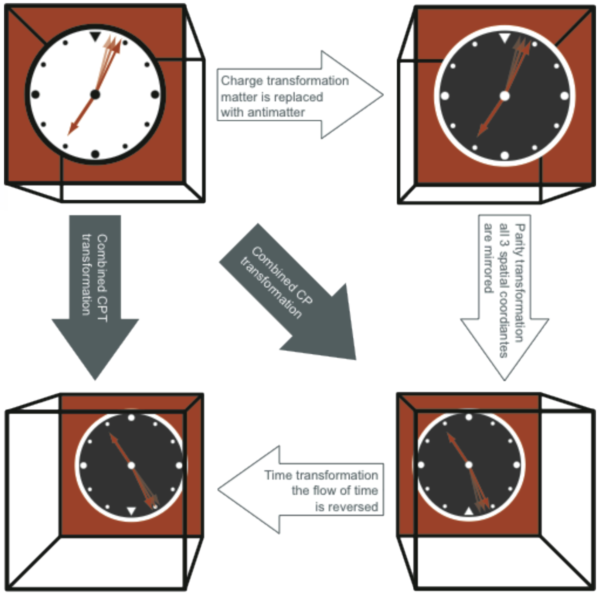
MOTIVATION

No observation of antimatter universe:
asymmetry at the cosmological scale



No violation of CPT observed to date:
symmetry at the microscopic scale





STANDARD MODEL EXTENSION

Standard Model extension (SME)

Bluhm, Kostelecky and Russel (PRL **82**)

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

$$(i\gamma^\mu D_\mu - m_e - \boxed{a^e_\mu \gamma^\mu - b^e_\mu \gamma_5 \gamma^\mu}$$

CPT and Lorentz violation

$$-\boxed{\frac{1}{2} H^e_{\mu\nu}\sigma^{\mu\nu} + i c^e_{\mu\nu}\gamma^\mu D^\nu + i d^e_{\mu\nu}\gamma_5\gamma^\mu D^\nu})\psi = 0$$

Lorentz violation

includes

- Lorentz invariance (LI) violating
- Charge-Parity-Time invariance (CPT) (& LI) violating

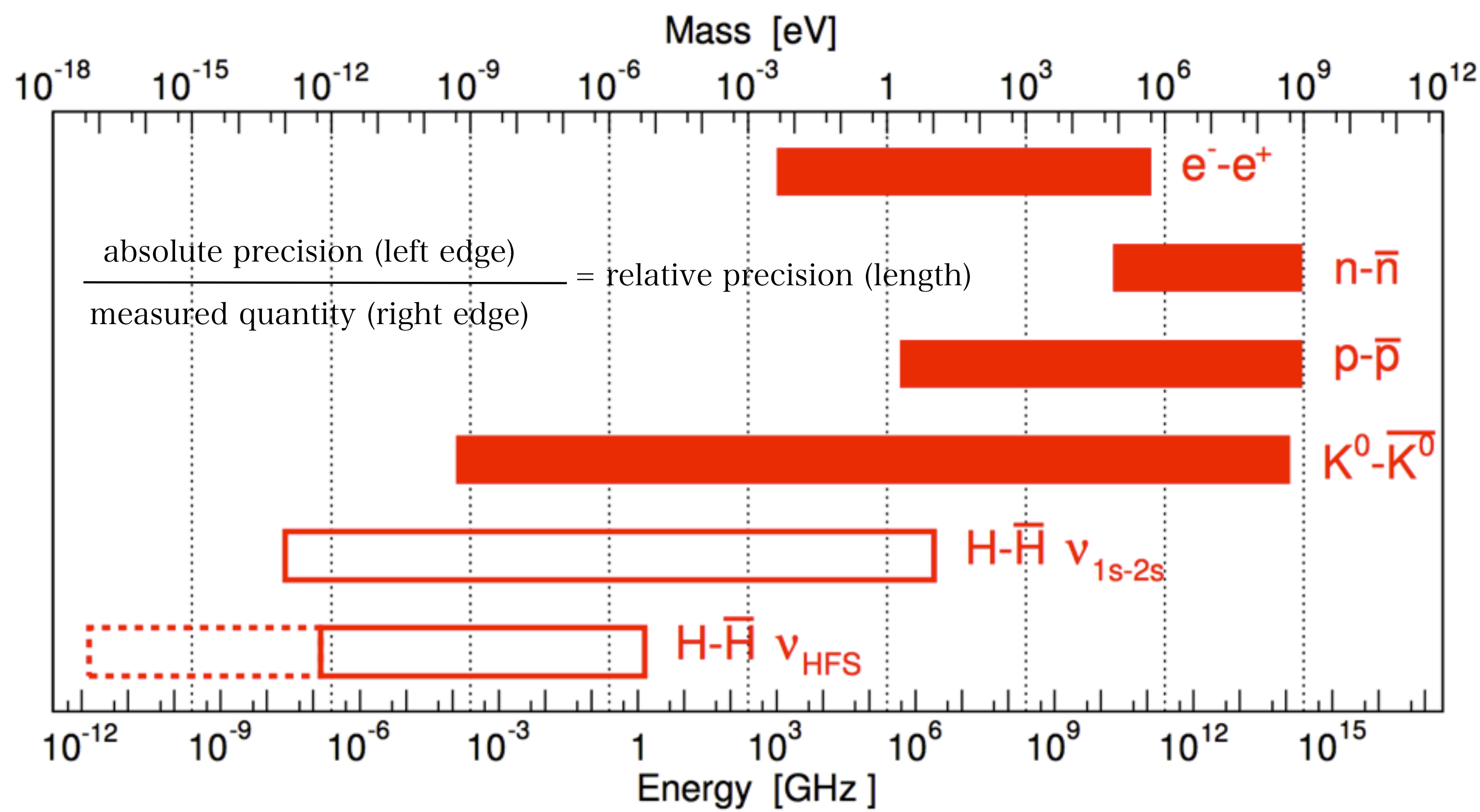
terms in the Lagrangian

Parameters a, d, and H reverse sign for antihydrogen

Parameters a and b have a dimension of **energy**

Not relative, but **absolute** precision matters

STATUS OF CPT TESTS

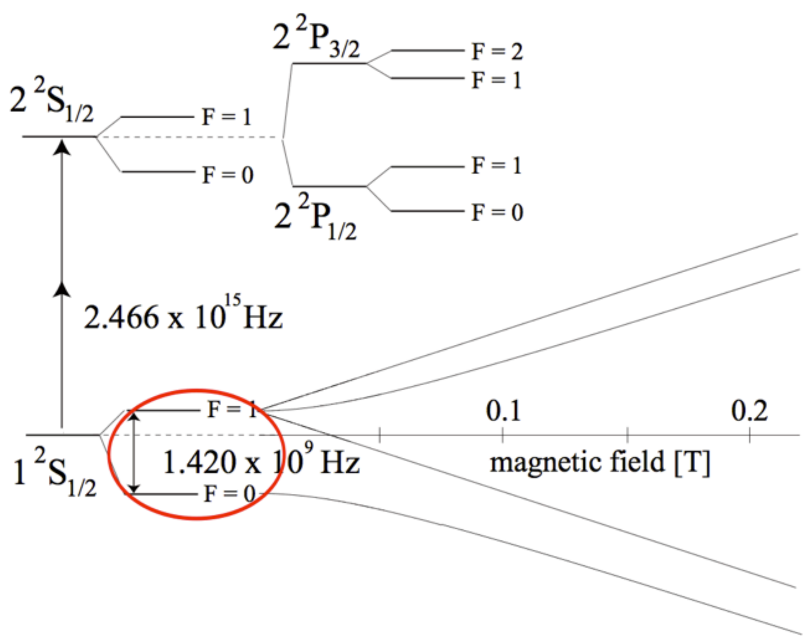


- "Best CPT test": K^0-$\bar{K}^0$ $\Delta m/m \sim 10^{-18} \Leftrightarrow 10^5$ Hz
- Relatively accuracy of 10^{-4} of $\bar{H}$ GS-HFS (~1 GHz × 10^{-4} = 10^5 Hz) can already be competitive
- CPT violation might appear in one physical system, but not in another

CPT TESTS WITH ANTIHYDROGEN

Measurements in Hydrogen:

quantity	exp. value [Hz]	δ_{exp}/ν	δ_{th}/ν
ν_{1S-2S}	2 466 061 413 187 103(46)	1.7×10^{-14}	1×10^{-11}
ν_{2S-2P}	$1\ 057\ 8450(29) \times 10^3$	2.7×10^{-6}	3.8×10^{-11}
ν_{HFS}	1 420 405 751.7667(9)	6.3×10^{-13}	$(3.5 \pm 0.9) \times 10^{-6}$



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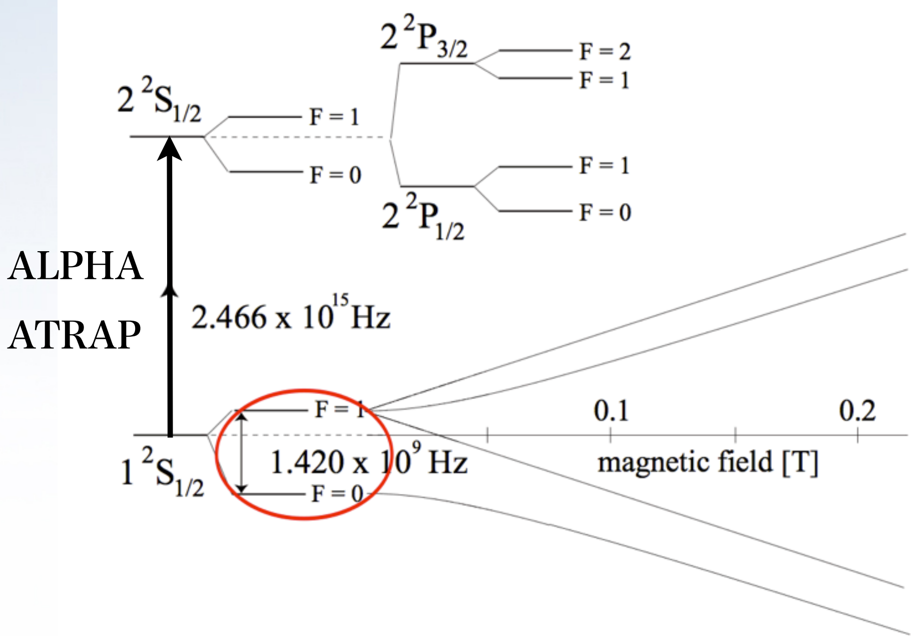

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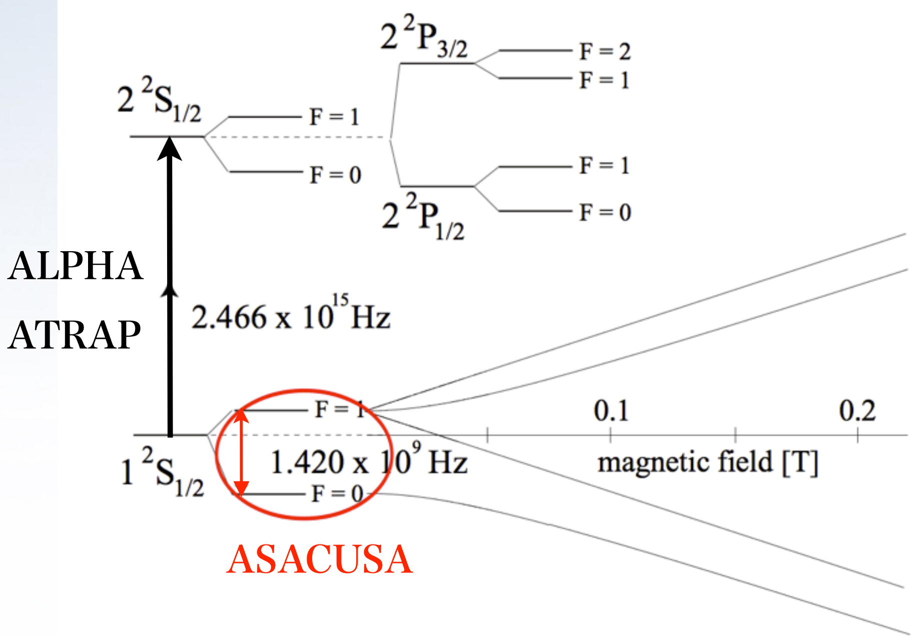

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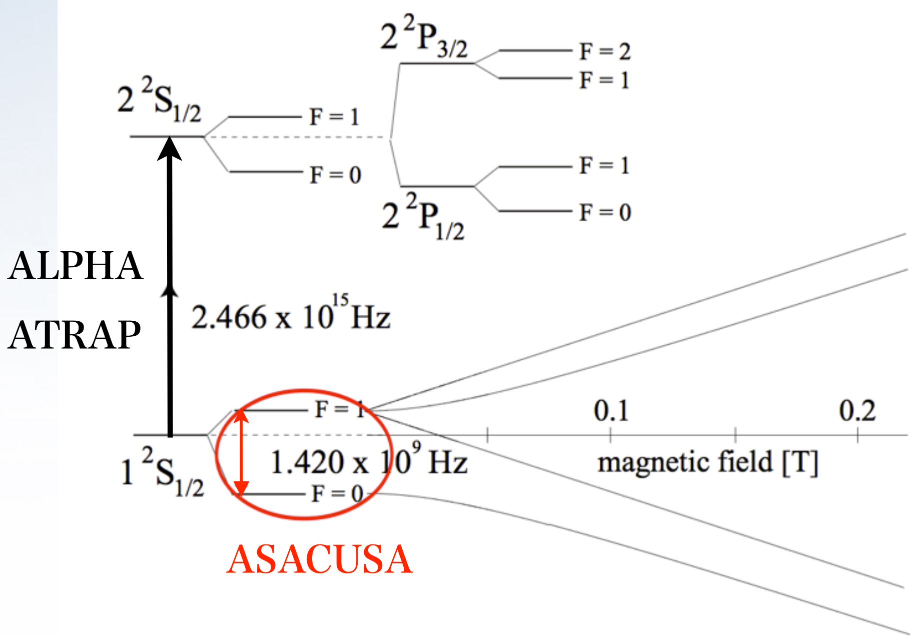

limited by knowledge of proton magnetic and electric distribution

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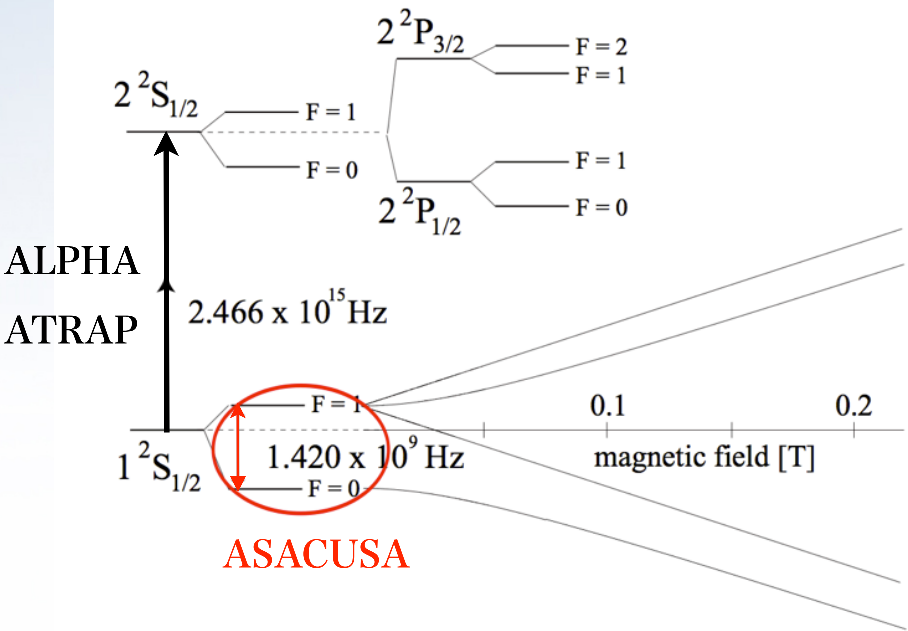
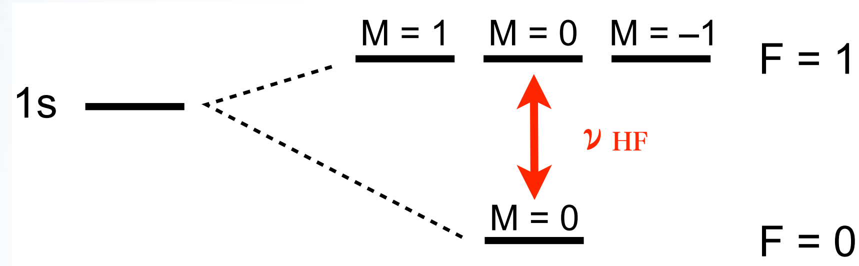


Measured CPT quantities:

quantity	value
$\Delta_{CPT}(m_e)$	$< 8 \times 10^{-9}$
$\Delta_{CPT}(m_p)$	$< 2 \times 10^{-9}$
$\Delta_{CPT}(g_e)$	$(-0.5 \pm 2.1) \times 10^{-12}$
$\Delta_{CPT}(\mu_p)$	$(-0.1 \pm 2.1) \times 10^{-3}$

THEORETICAL INTRODUCTION

- Interaction between (anti)proton and electron (positron) magnetic moments
- Results in a triplet (F = 1) and a singlet (F = 0) sublevels



- Between F = 1 and F = 0:

$$\nu_{\mathrm{HF}} = \frac{16}{3}\left(\frac{m_p}{m_p+m_e}\right)^3 \frac{m_e}{m_p}\frac{\mu_p}{\mu_N}\alpha^2 c\, R_\infty (1+\delta) \simeq 1.42\ \mathrm{GHz}$$

- ν_{HF} is appr. proportional to the (anti)proton magnetic moment $\mu_{\bar{p}}$
- δ : higher-order QED & strong interaction corrections: ~10^{-3}
- Theoretical uncertainty on δ : ~10^{-6}

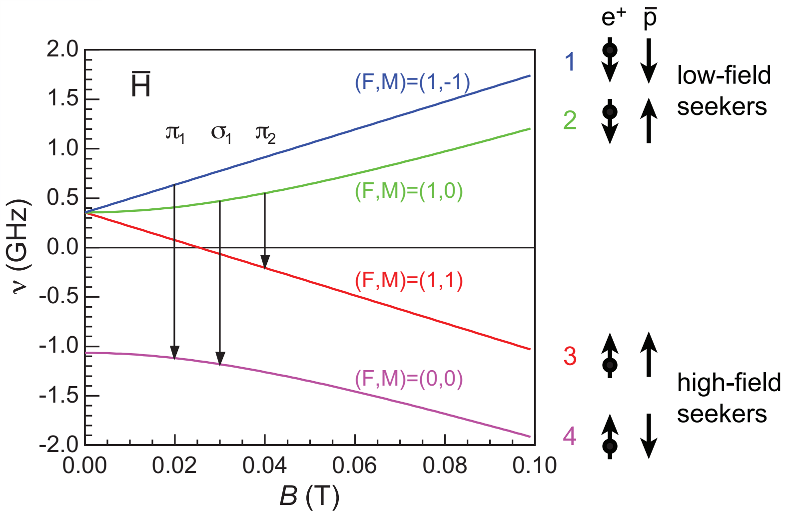
MEASUREMENT PRINCIPLE

- Highest precision for hydrogen: 10^{-12} with hydrogen maser
- But maser is not possible for antihydrogen
- 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



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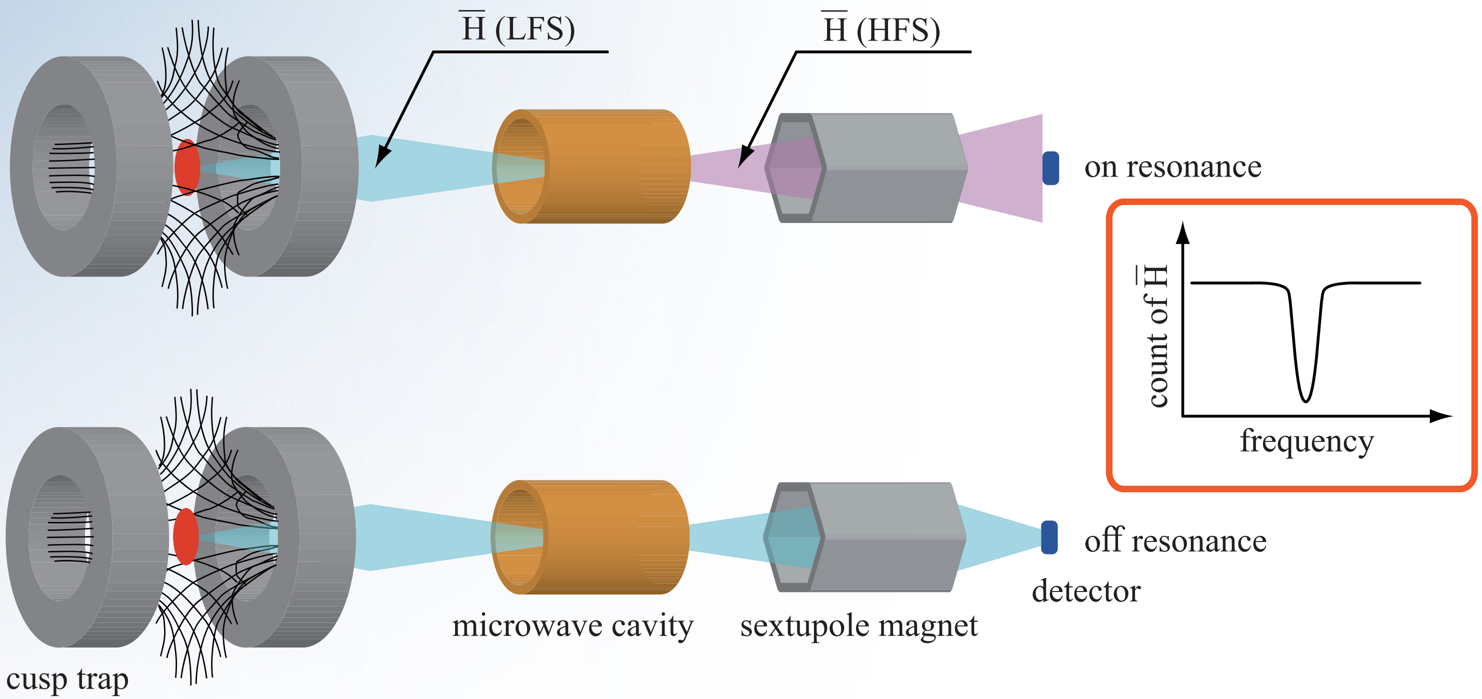


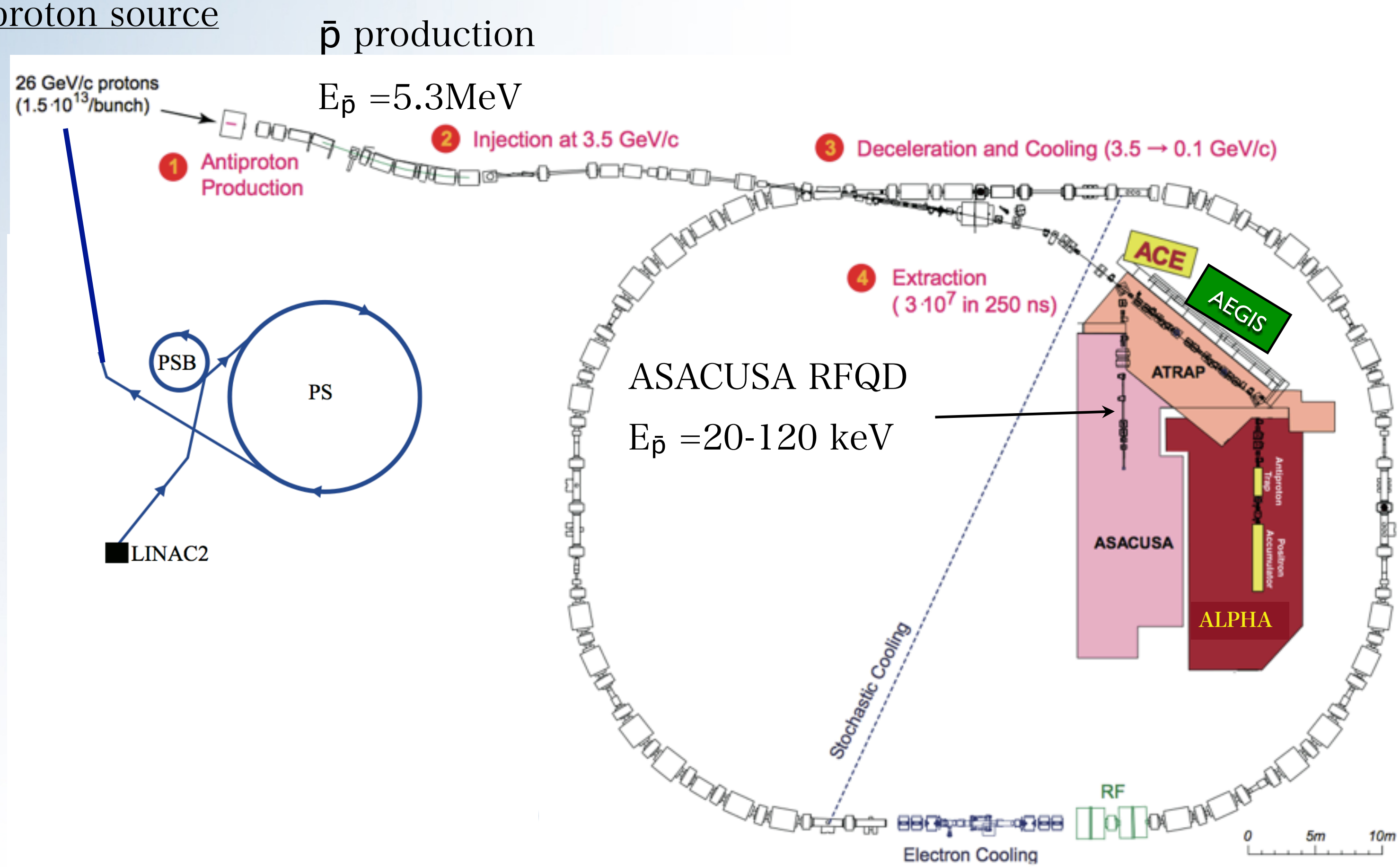
1.an inhomogeneous magnetic field → a “cusp field” selects spin state

2. a microwave cavity flips the spin

3. a sextupole magnetic field analyzes spin state

INGREDIENTS FOR $\bar{H}$

The antiproton source



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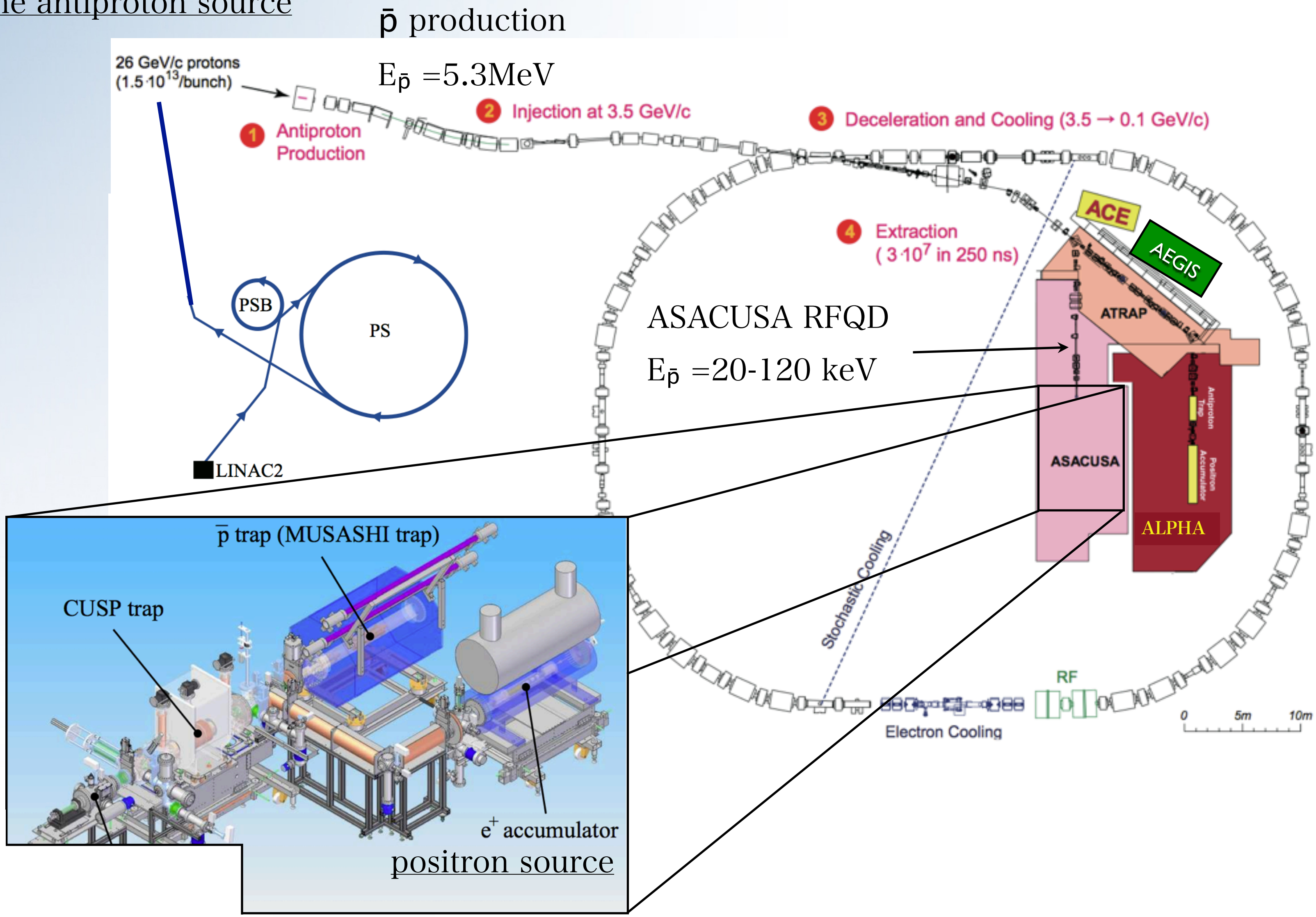
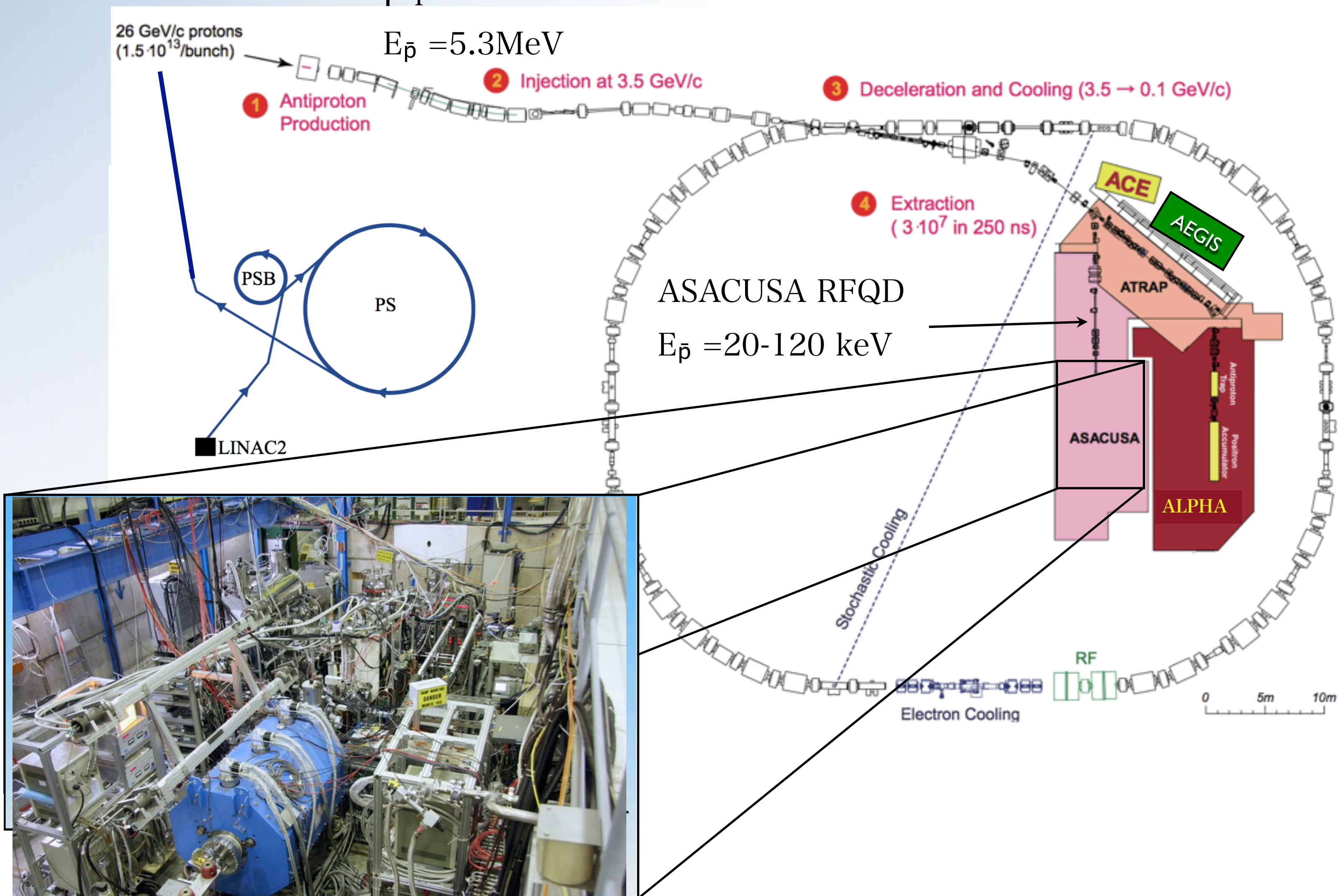


INGREDIENTS FOR $\bar{\mathrm{H}}$

The antiproton source

$\bar{p}$ production

$E_{\bar{p}}$ =5.3MeV

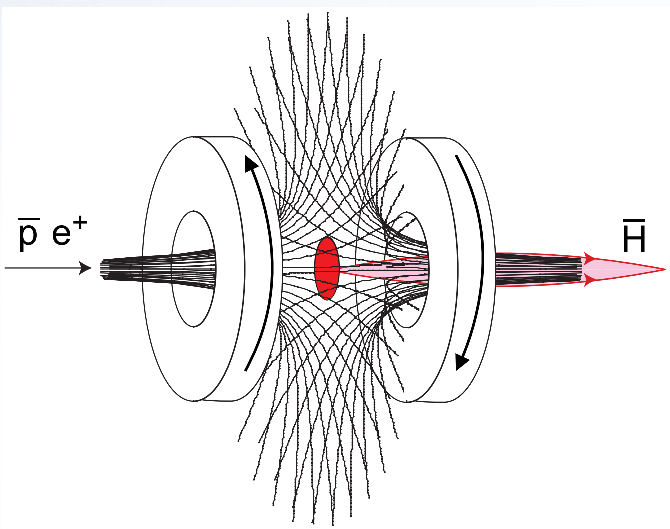


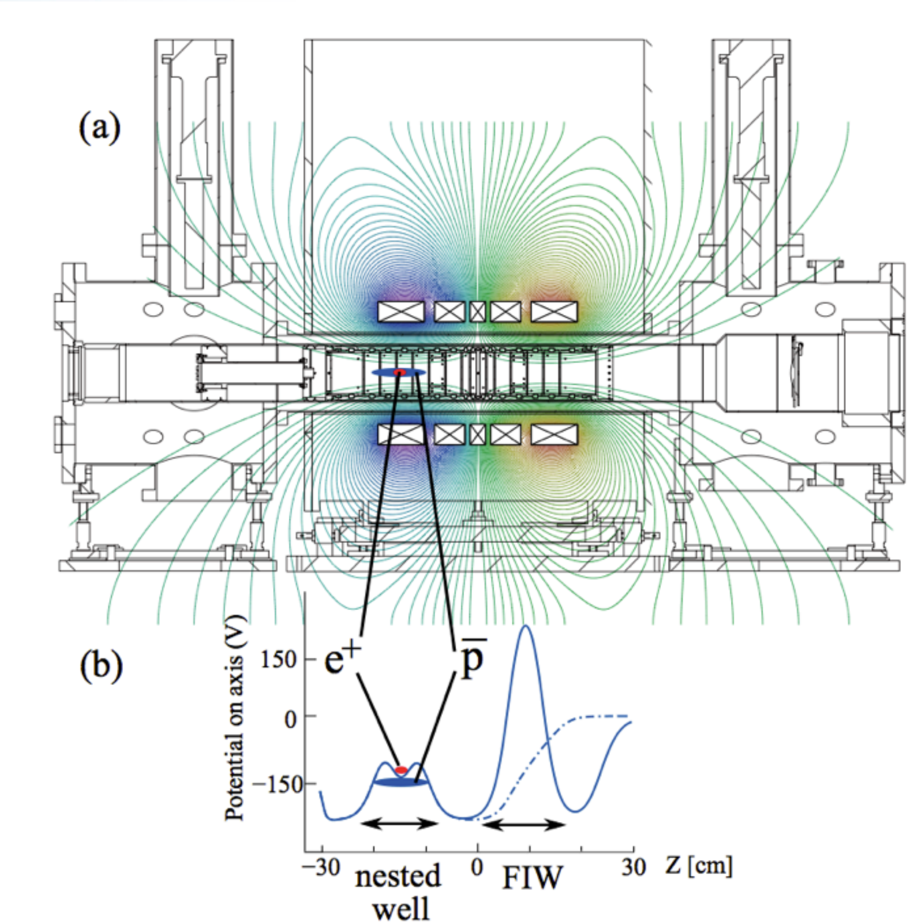
ASACUSA RFQD

$E_{\bar{p}}$ =20-120 keV

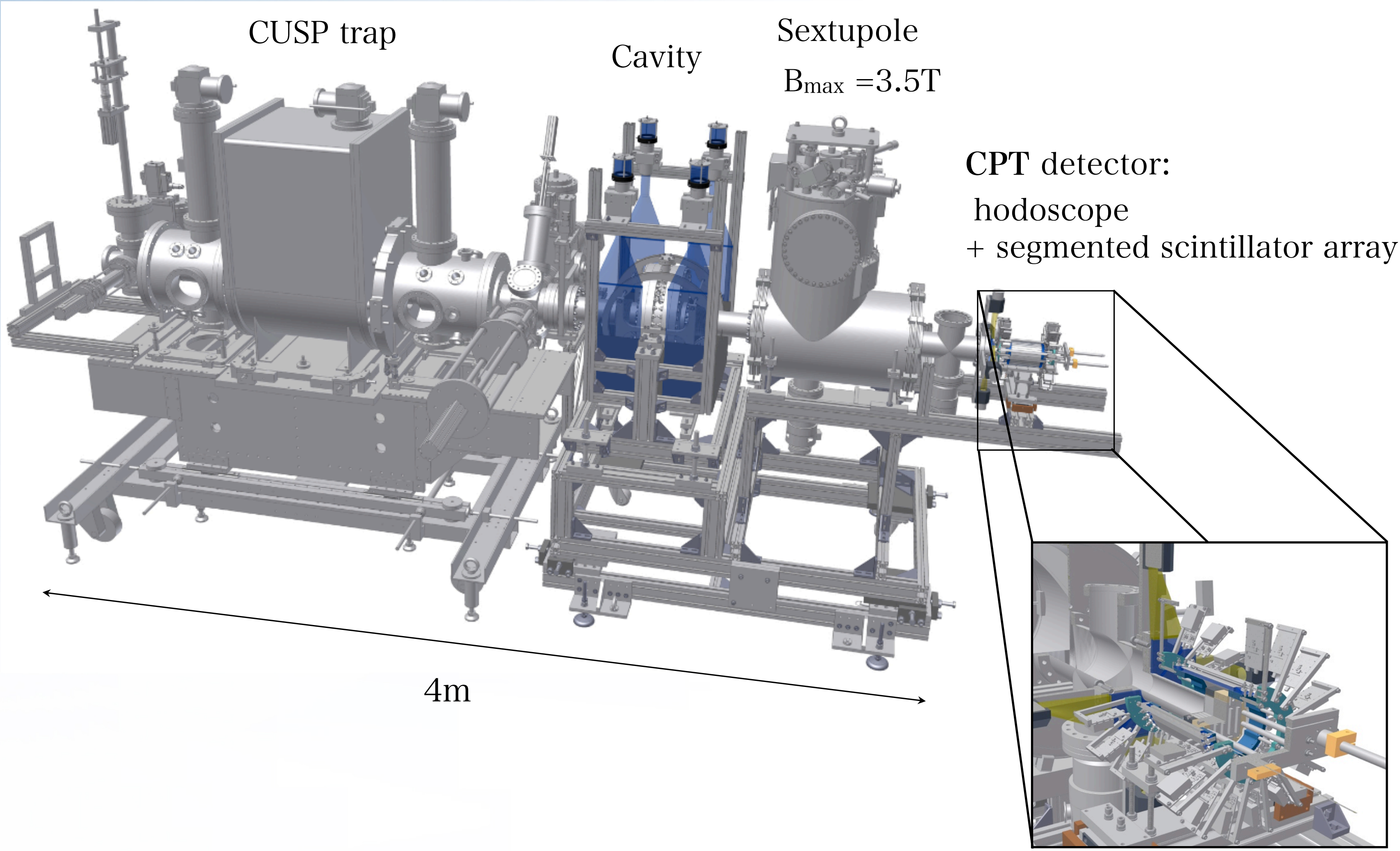
CUSP "TRAP"

- Anti-Helmholtz coil
- Multi-ring electrodes
- axially symmetric B and E
- $\bar{H}$ are formed in a nested well



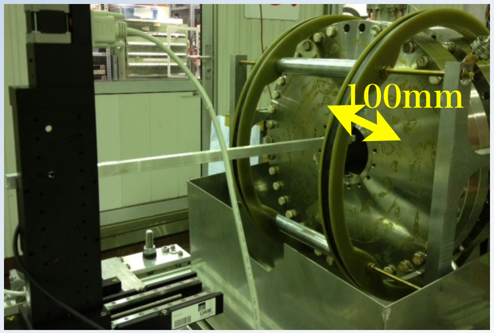


THE SETUP

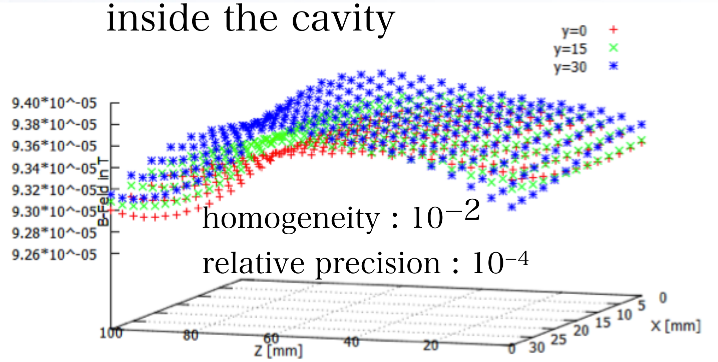

CUSP trap
Cavity
Sextupole
B_{max} =3.5T
CPT detector:
hodoscope
+ segmented scintillator array
4m

THE SETUP

Low Q microwave **cavity** surrounded by Helmholtz coils that generate an homogeneous magnetic field



3 layers of mu-metal
Highly sensitive flux gate sensors monitor field inside the cavity



homogeneity : 10^{-2}
relative precision : 10^{-4}

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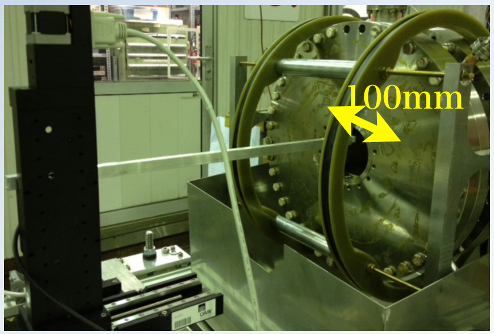

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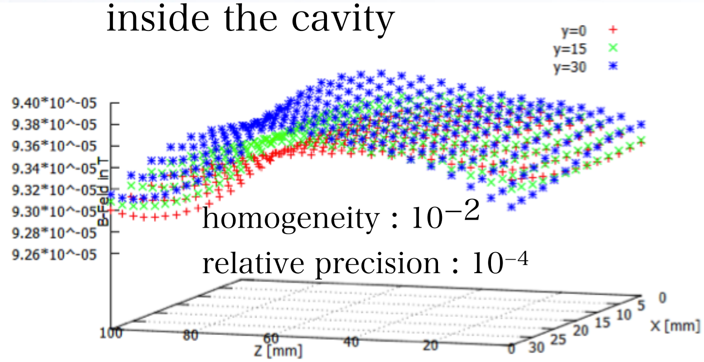

sextupole:
superconduting magnet
B_{max}=3.5T, I_{max}= 400A
effective length: 22 cm

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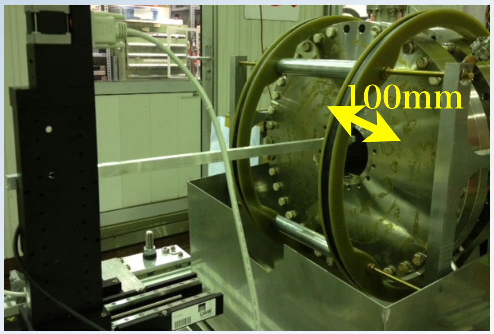


Detector: hodoscope read-out by SiPM, central detector records annihilation

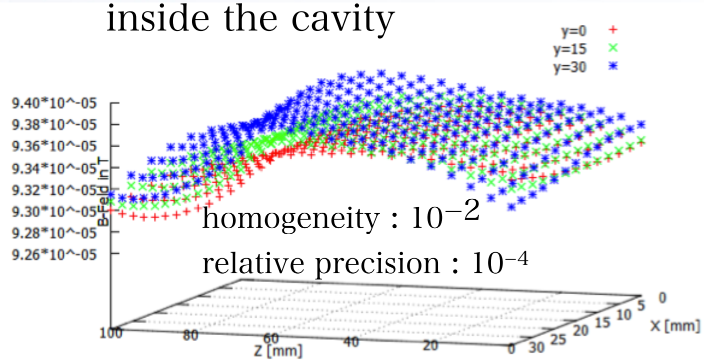
Trigger is based on a hit over threshold in the central segmented scintillator

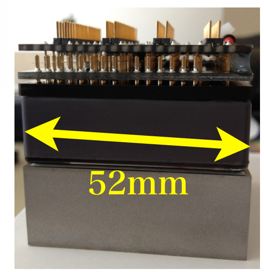
Signal filtering based on the # of hits in the hodoscope

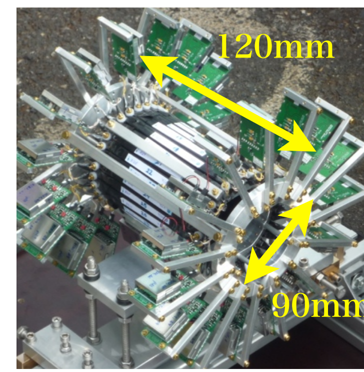
Good (5Gbs/s) timing resolution can discriminate between out-of coincidence hits in detector from background annihilations)

3 layers of mu-metal

Highly sensitive flux gate sensors monitor field inside the cavity







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superconduting magnet

B_{max}=3.5T, I_{max}= 400A

effective length: 22 cm

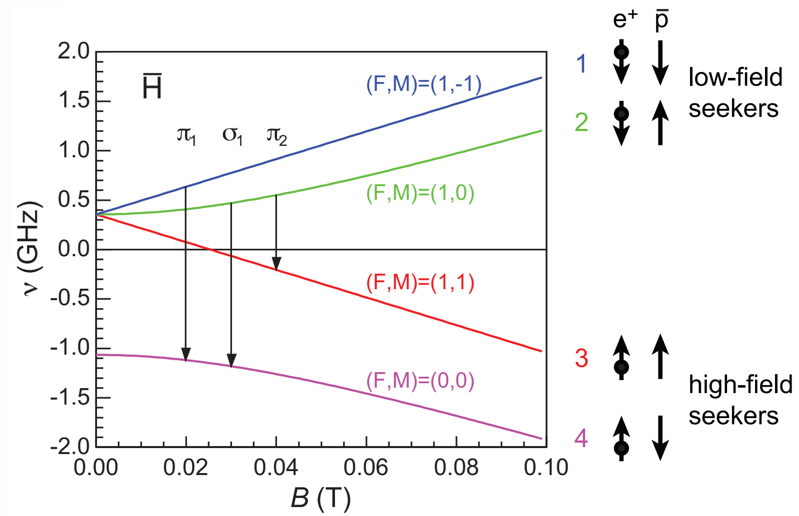
STRATEGY

Goal: determine ν_{HF} at B = 0

but we can only measure ν_{σ} & ν_{π} at B ≳ 1 G

σ_1 is quite insensitive to B and ΔB,

π_1 is very sensitive to B and ΔB

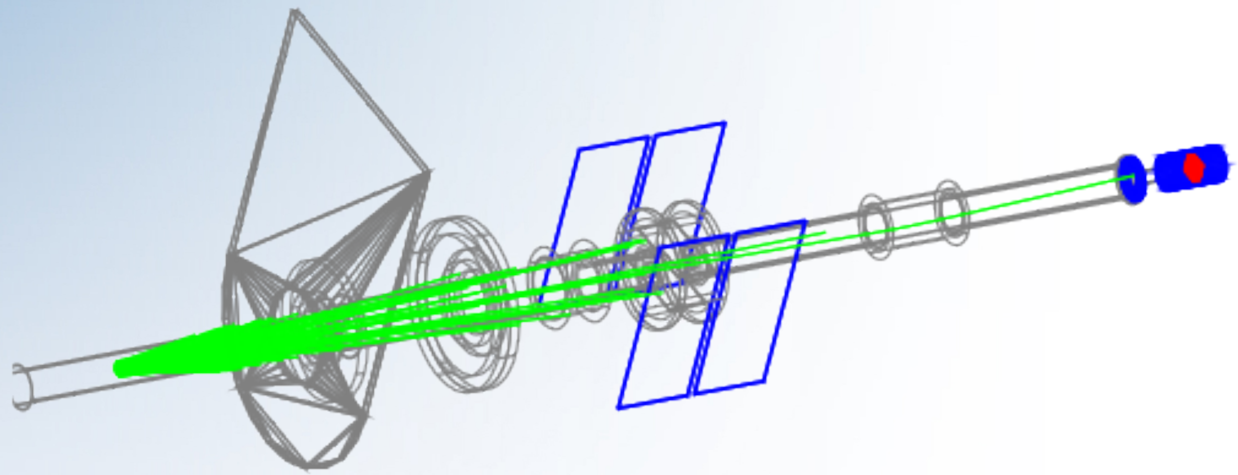


Two methods to obtain ν_{HF}

- if ΔB ≲ 0.02 G: measure ν_{σ} & ν_{π} at one B, and calculate ν_{HF}
  - Experimentally more challenging
  - But higher precision: ~10^{-7}

- if ΔB ≳ 0.1 G: measure ν_{σ} & B at several B's, and extrapolate to B = 0
  - Easier to realize
  - But lower precision: ~5×10^{-7}

SIMULATION & DATA



G4 studies:

- simulation of $\bar{H}$ trajectories in field
- background creation
- cosmics
- estimation of transition probabilities
- effect of homogeneities

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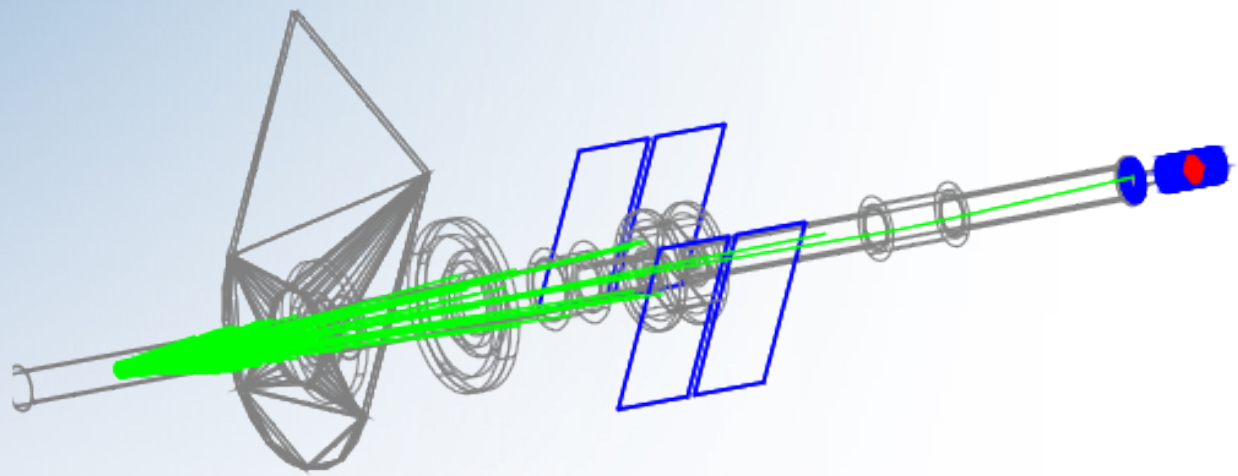

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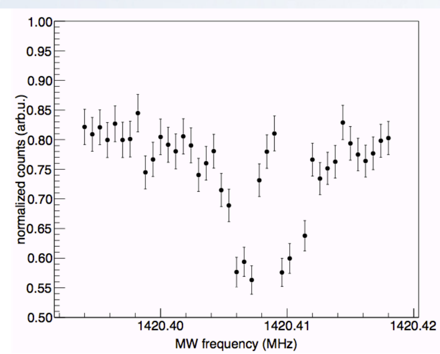
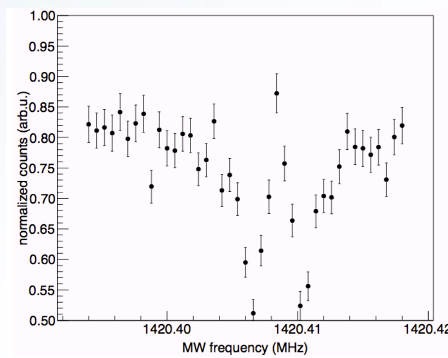


σ_1 transition, $\Delta B/B = 1\%$



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simulation done at 1G, T=5K

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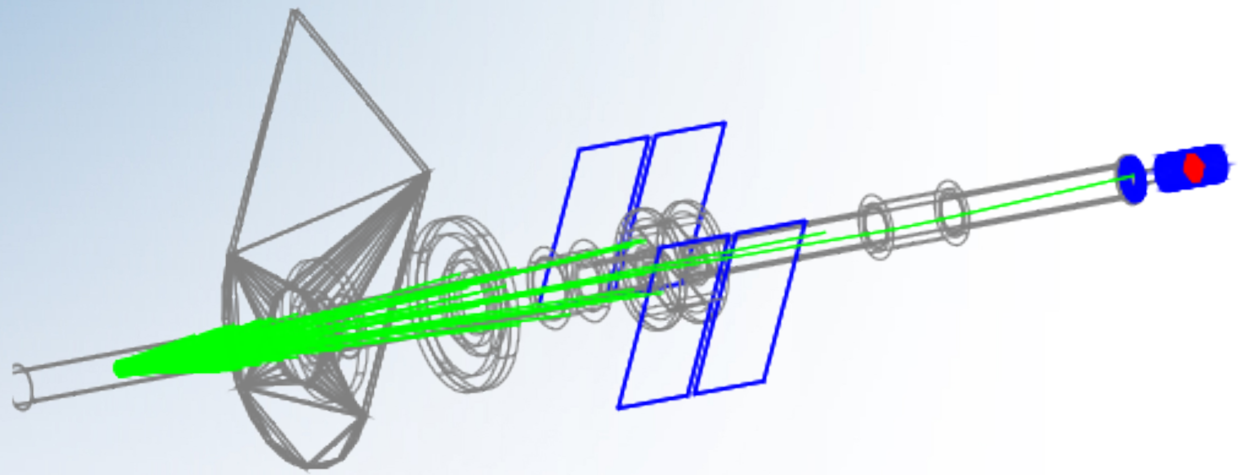

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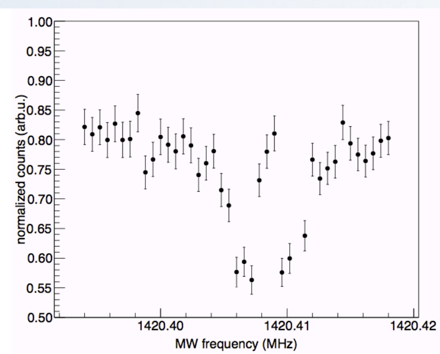

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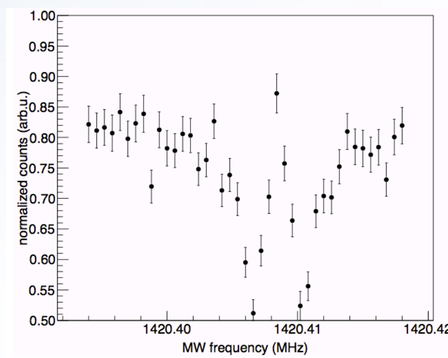

σ_1 transition, $\Delta B/B = 10\%$

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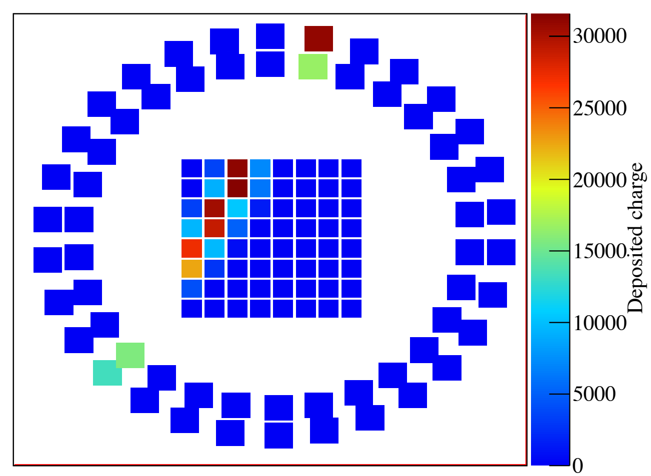
cosmic events in the CPT detector



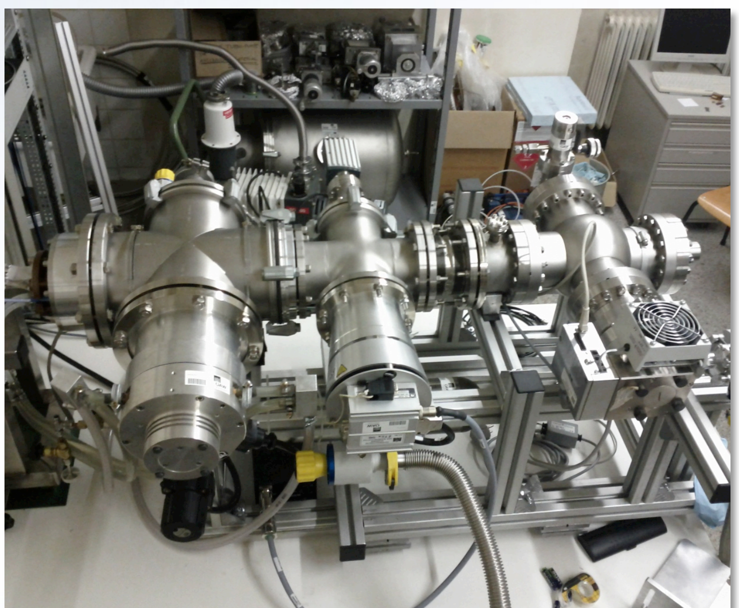
FURTHER DEVELOPMENTS

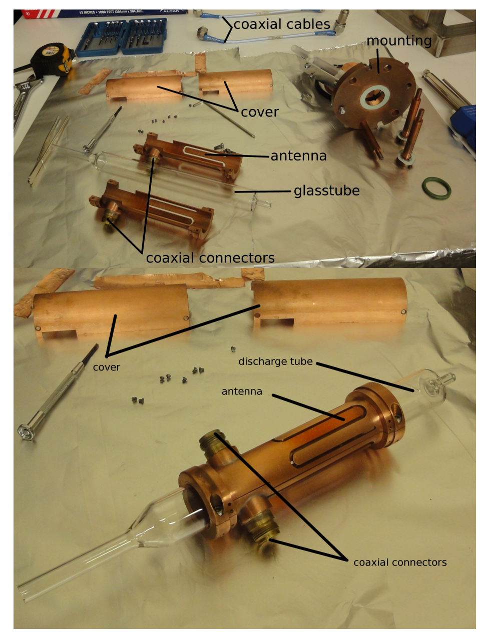
Upgrade:

- Detector (addition of calorimeter, second layer of hodoscope, new silicon boards)
- CUSP (new MRE)
- New positron source

Hydrogen beam:

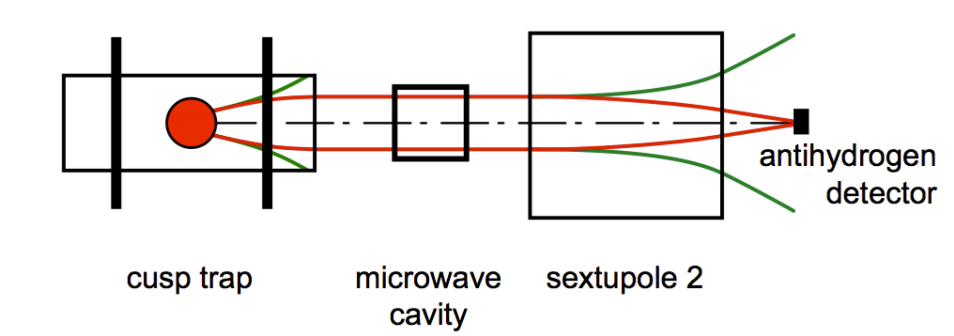
- permanent sextupoles create polarized hydrogen beam
- QMS detect GS hydrogen





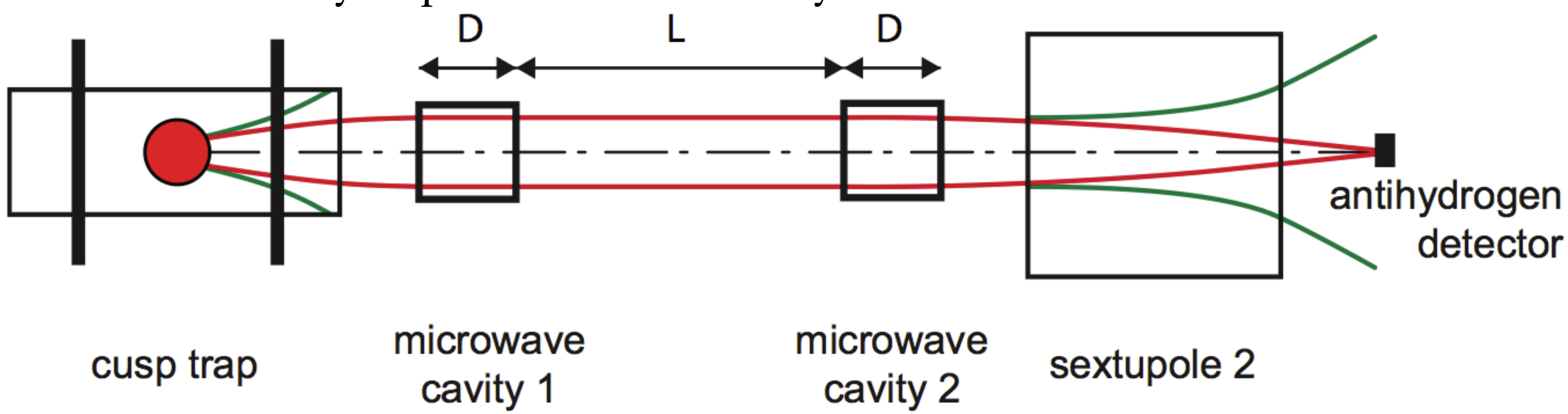
FURTHER DEVELOPMENTS

Ongoing: Rabi method



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

Phase 2: Ramsey separated oscillatory fields



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SUMMARY AND OUTLOOK

Some Highlights:

2010: first antihydrogen production in the CUSP (Y. Enomoto et al. Phys. Rev. Lett 243401, 2010). Shared 1st place with ALPHA collaboration in Physics World breakthrough

2012: Results to come…

2013/2014 : CERN shutdown. Upgrade, Hydrogen beam experiment

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- Fundamental symmetries
- Nuclear & atomic physics
- Precision spectroscopy

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Antihydrogen promises one of best CPT tests in baryon sector but high-precision experiments need Care, Particles and Time!

CERN-AD is unique in the world

More low-energy antiprotons needed

- **ELENA** upgrade at CERN (recently approved, start 2017)
- **FLAIR** at FAIR (next decade)

THE ASACUSA COLLABORATION

A tomic
S pectroscopy
A nd
C ollisions
U sing
S low
A ntiprotons

ASACUSA Scientific project

(1) Spectroscopy of $\bar{p}$He

(2) $\bar{p}$ annihilation cross-section

(3) $\bar{H}$ production and spectroscopy

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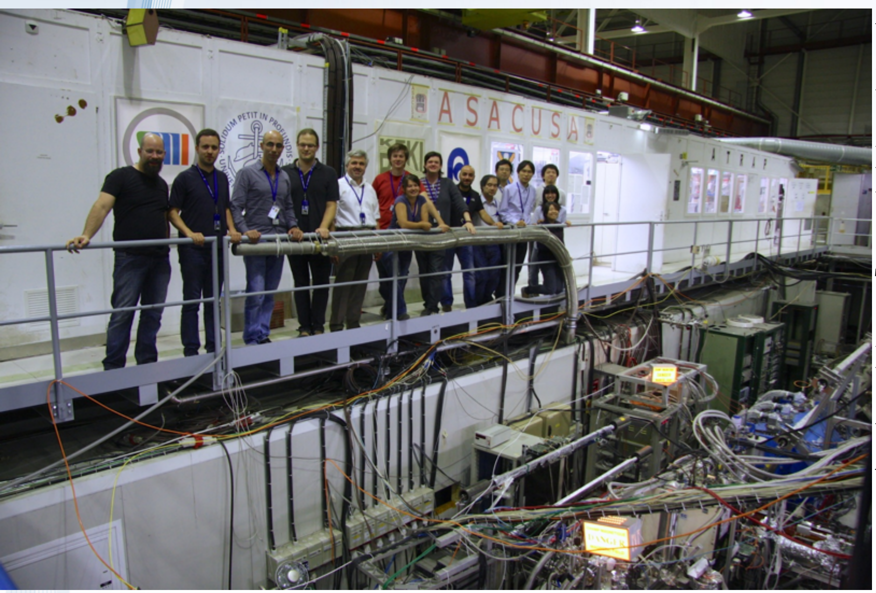
The $\bar{H}$ team

The $\bar{H}$ team



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Stefan Meyer Institut für Subatomare Physik: M. Diermaier, C. Malbrunot, O. Massiczek, C .Sauerzopf, K. Suzuki, E. Widmann, B. Wünschek, J. Zmeskal

H·HFS
Hyperfine Structure of Antihydrogen

THANK YOU VERY MUCH FOR YOUR ATTENTION!