H·HFS
Hyperfine Structure of Antihydrogen

TOWARDS THE MEASUREMENT OF THE HYPERFINE STRUCTURE OF ANTIHYDROGEN AT CERN

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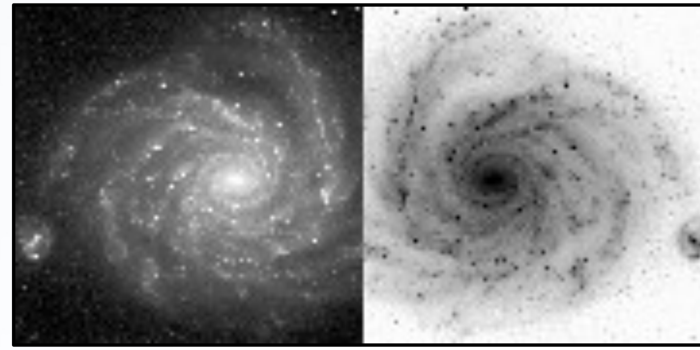
On behalf of the **ASACUSA** Collaboration

PANIC
August 25th 2014

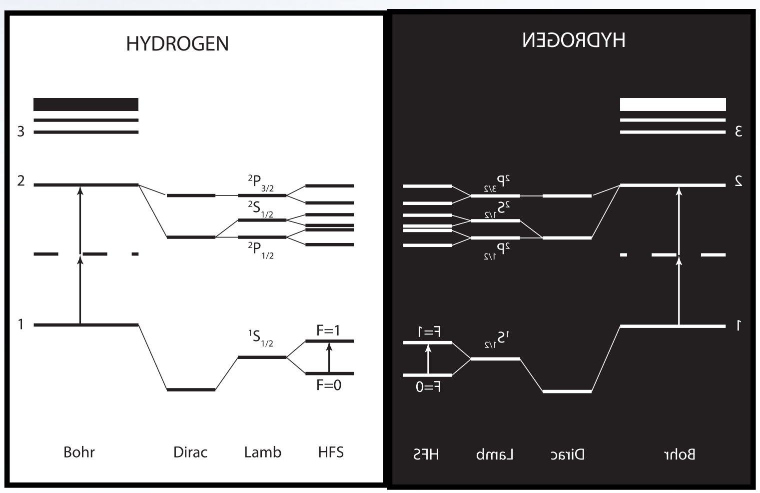
MOTIVATIONS

No observation of antimatter universe:
asymmetry at the cosmological scale

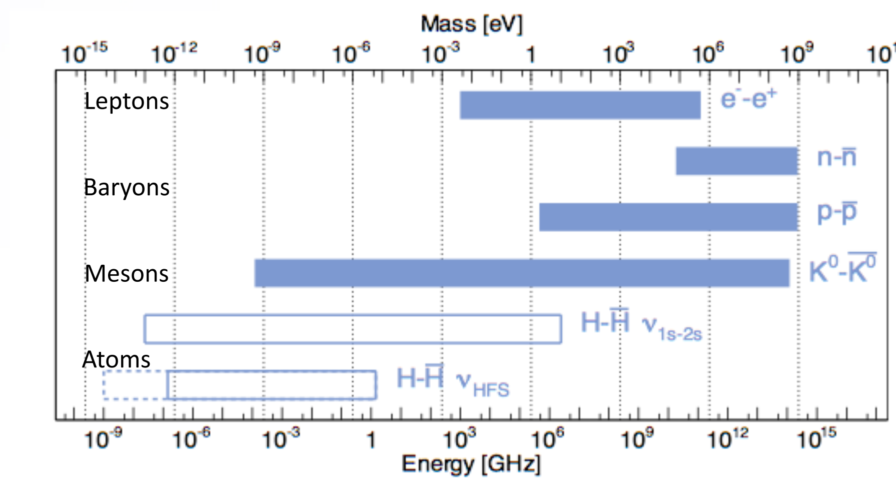


CPT Theorem

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



High absolute precision (potential high sensitivity: Standard Model Extension)



GROUND STATE HYPERFINE SPLITTING

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

S. G. Karshenboim, Precision Physics of Simple Atomic Systems, pages 142–162, Springer, Berlin, Heidelberg, 2003, hep-ph/0305205.

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

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

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**

MEASUREMENT PRINCIPLE

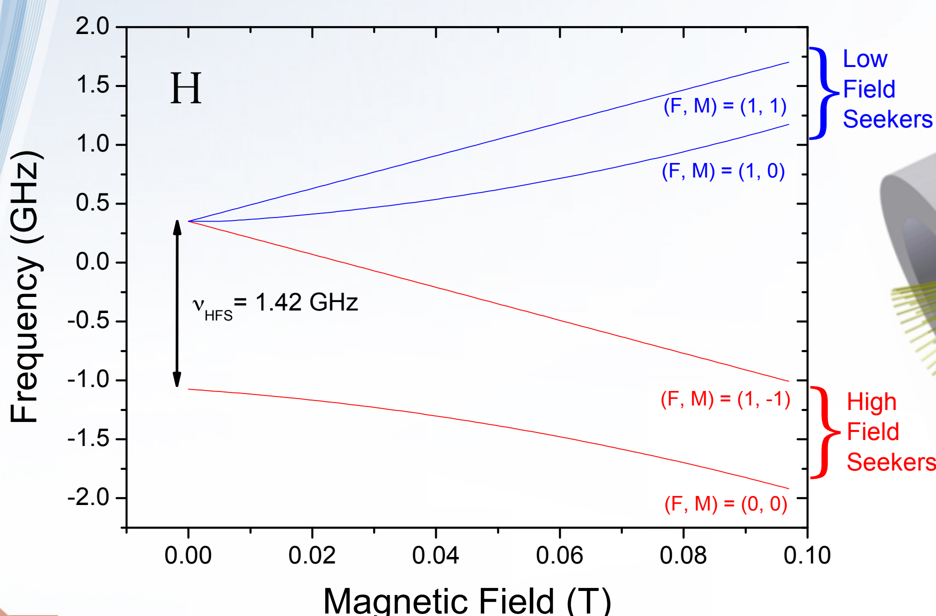
Spectroscopy with trapped antihydrogen: lower precision due to strong confining field

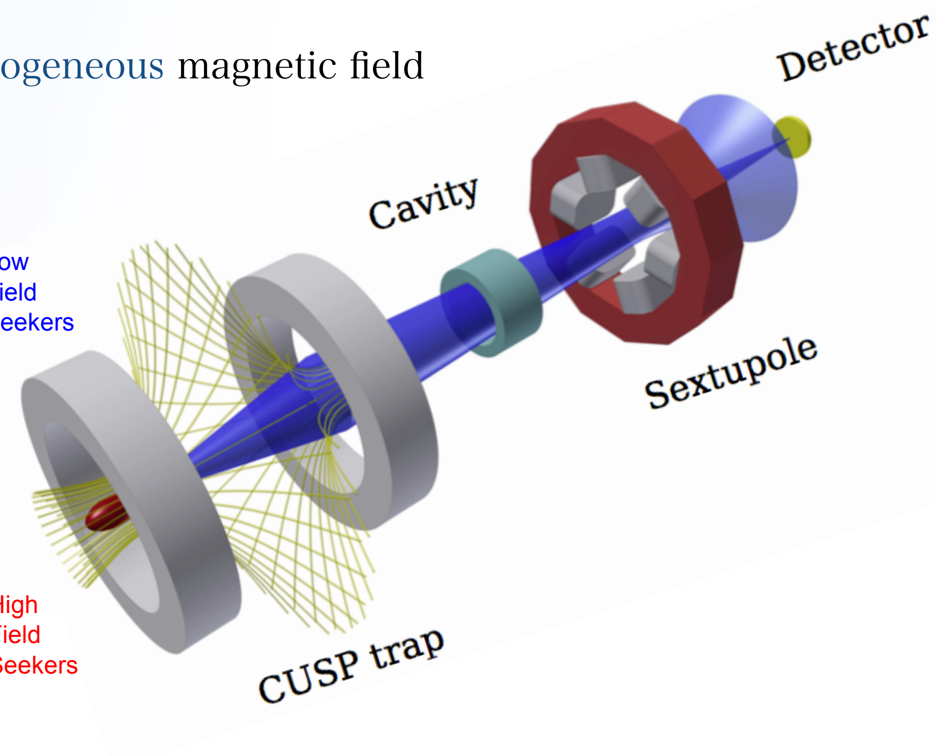
Good candidate: atomic beam with RF resonance

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

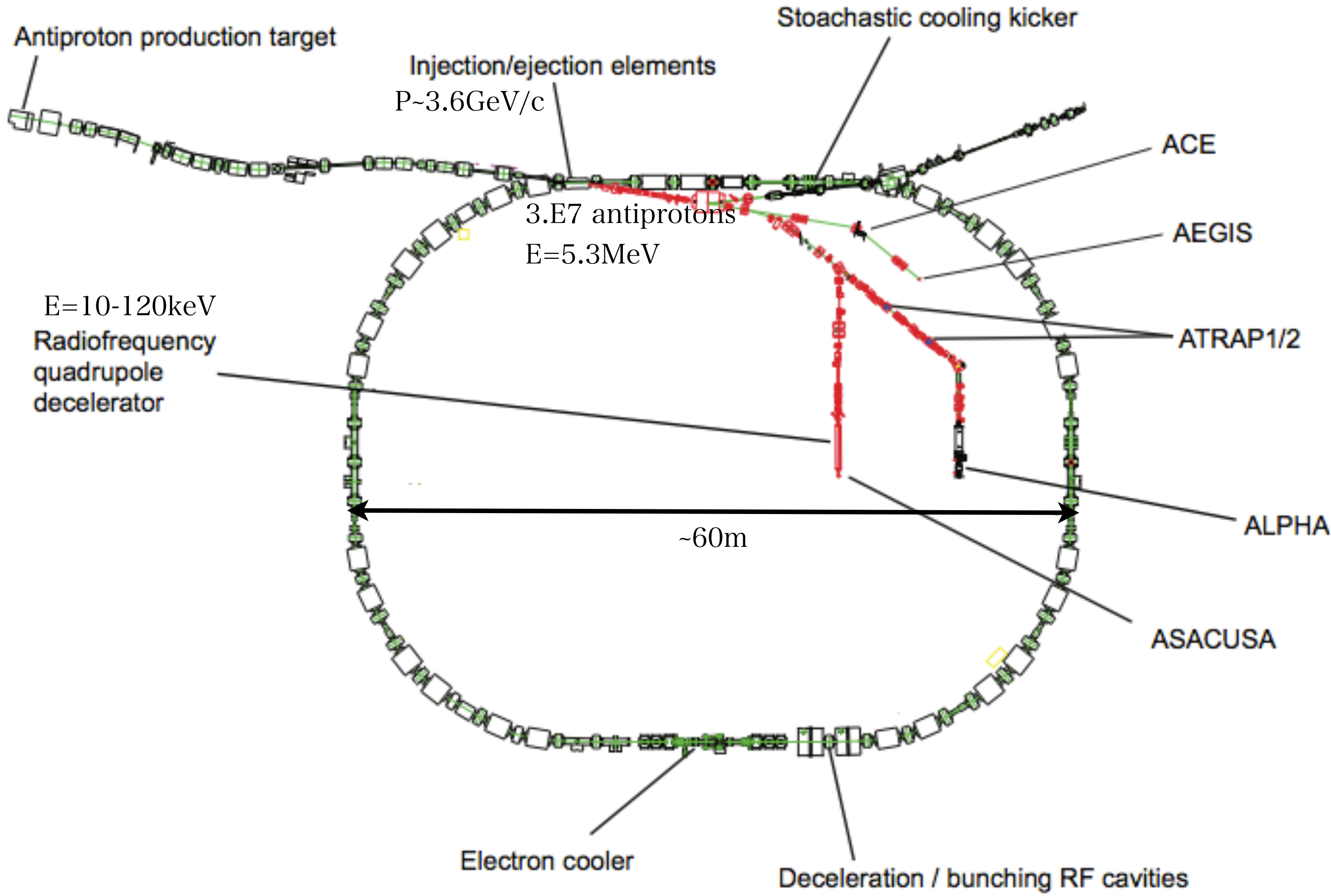
2) atomic beam method can work up to 50-100 K

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





CERN'S ANTIPROTON DECELERATOR



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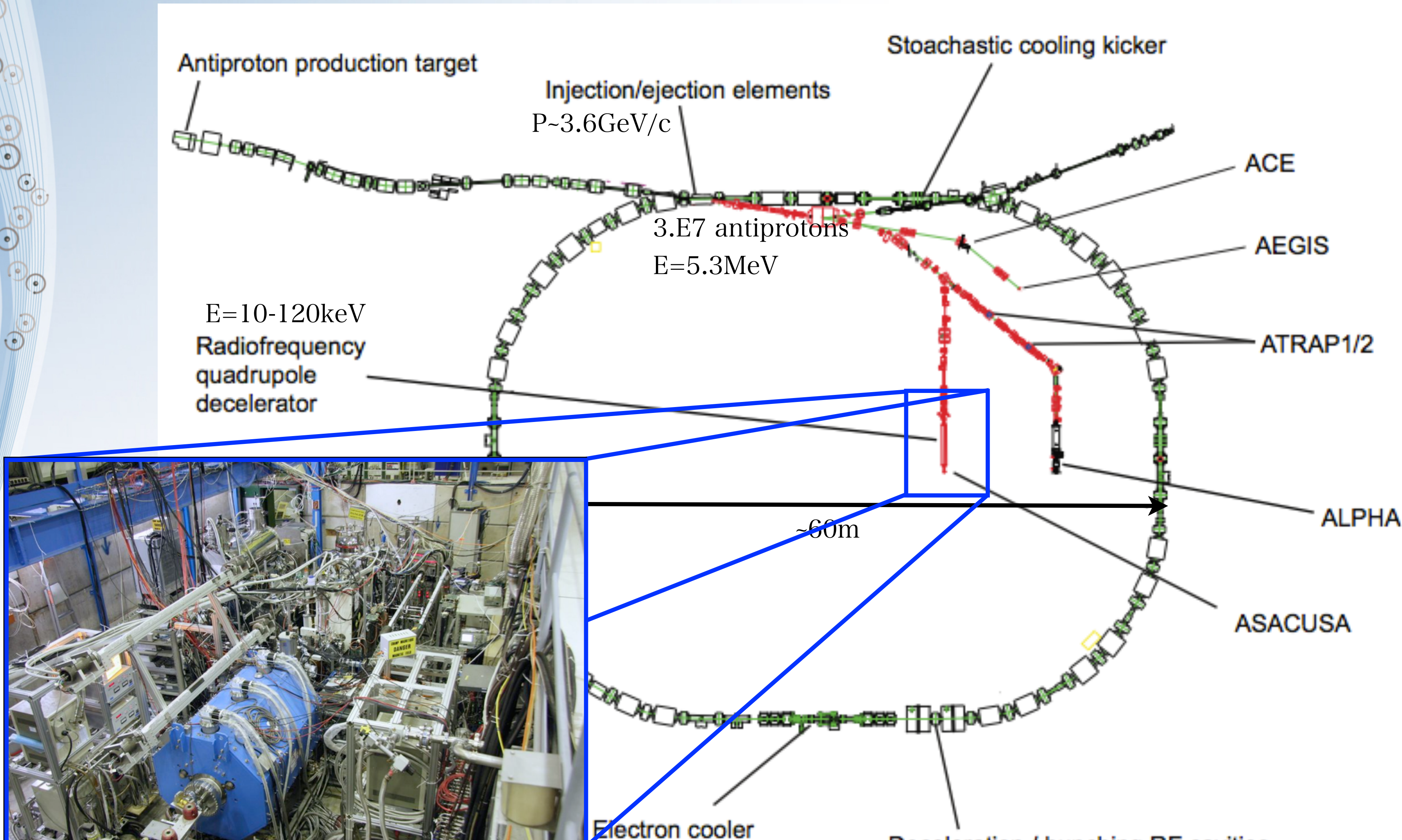
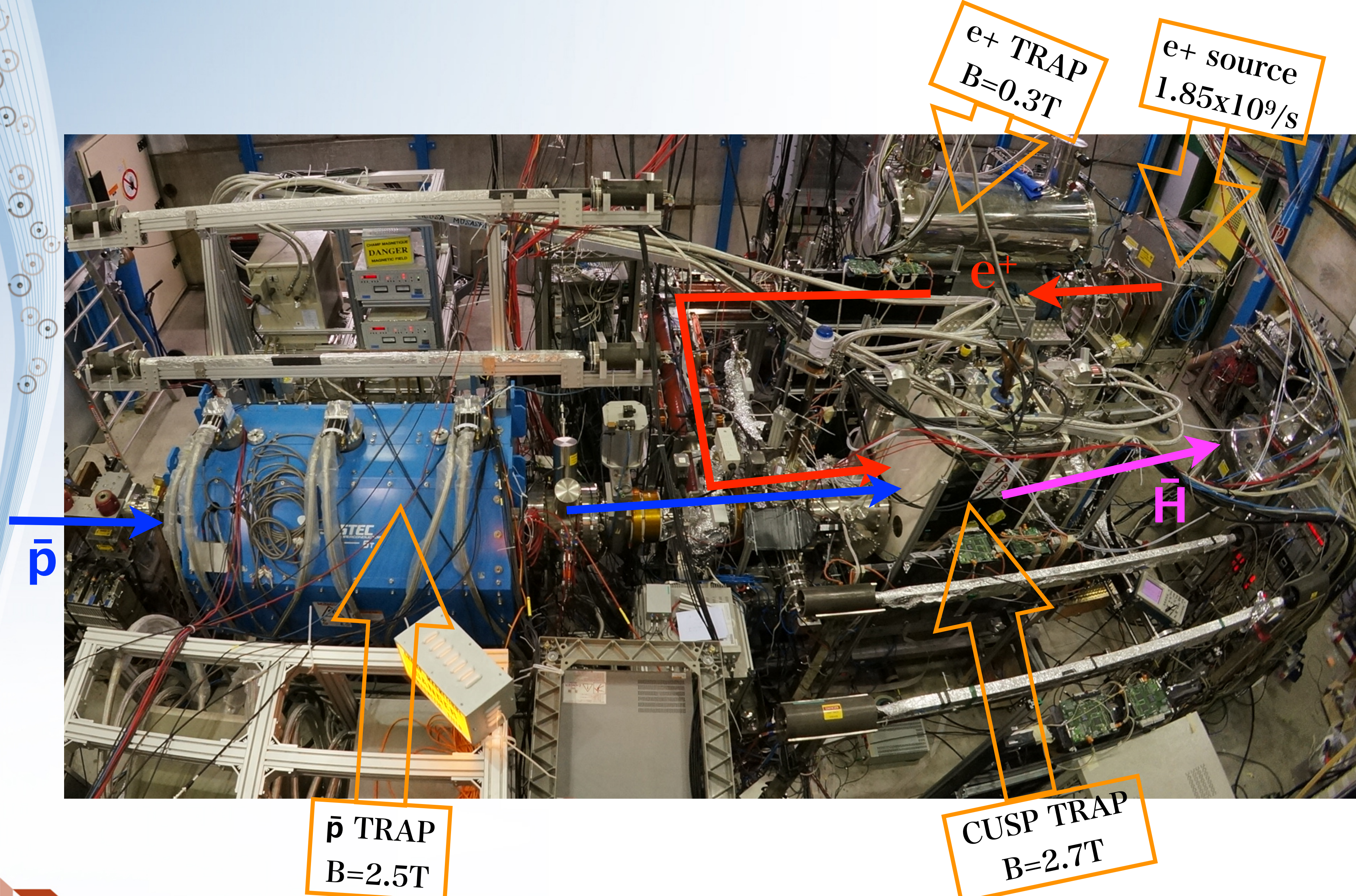


ANTIHYDROGEN PRODUCTION



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**

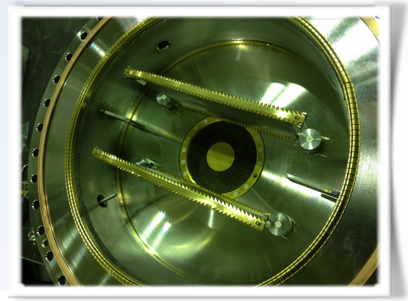
3) **Interaction time** with the microwave field in the cavity

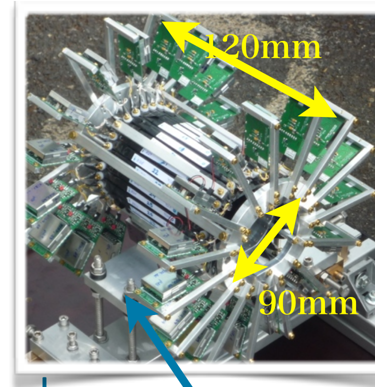
→ **SIMULATION WITH GEANT 4**

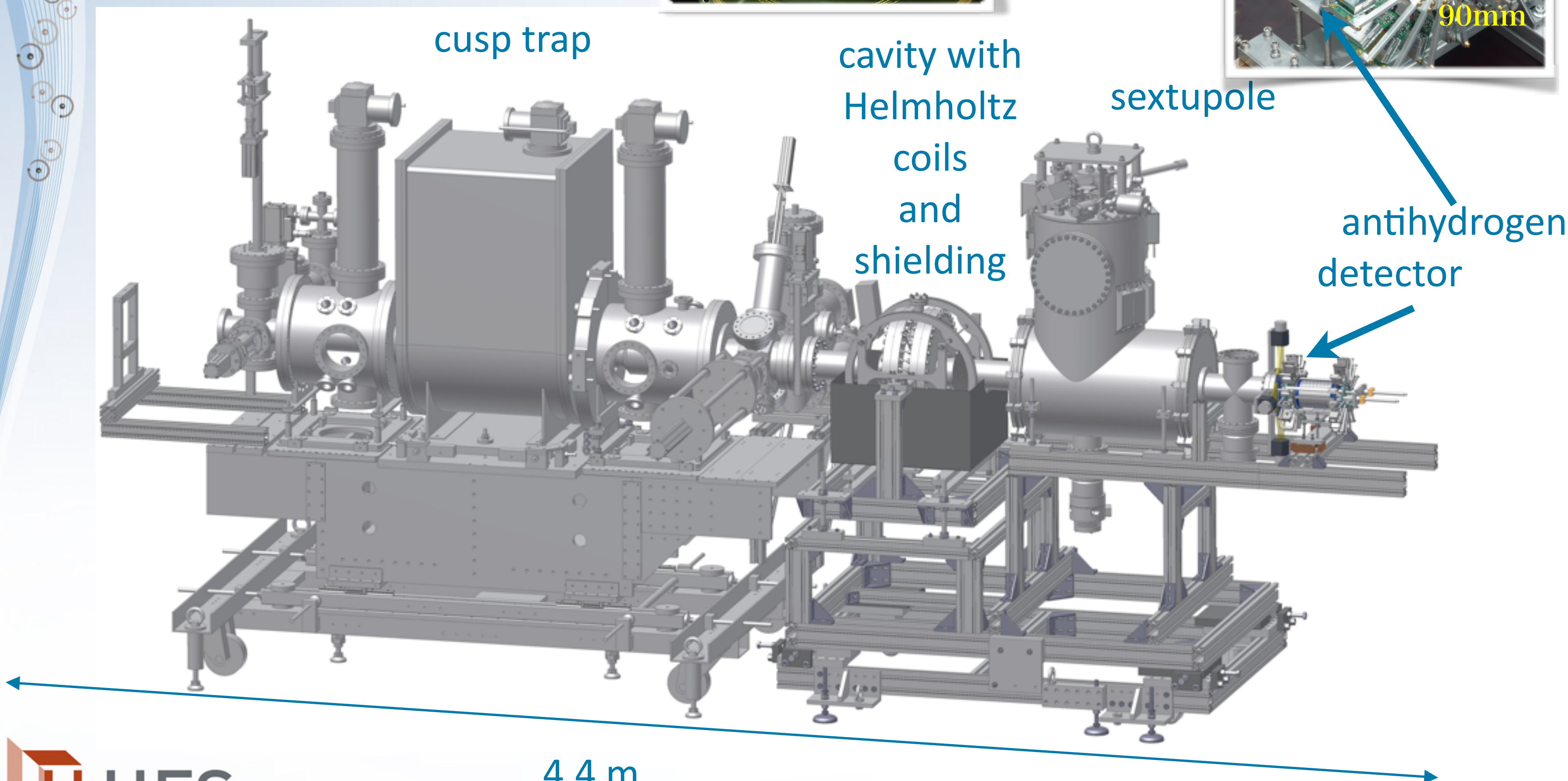
Behaviour of antiproton and positron plasmas simulated using **SIMBUCA**
Formation of antihydrogen simulated CTMC

Pipeline between these simulations and Geant4

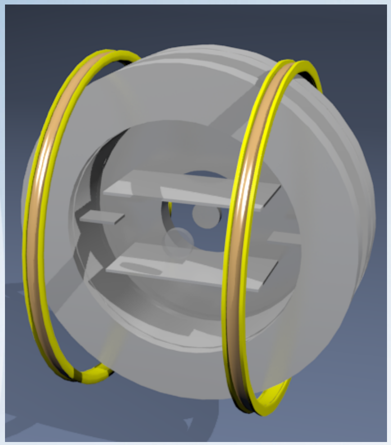
THE SPECTROMETER LINE (2012)







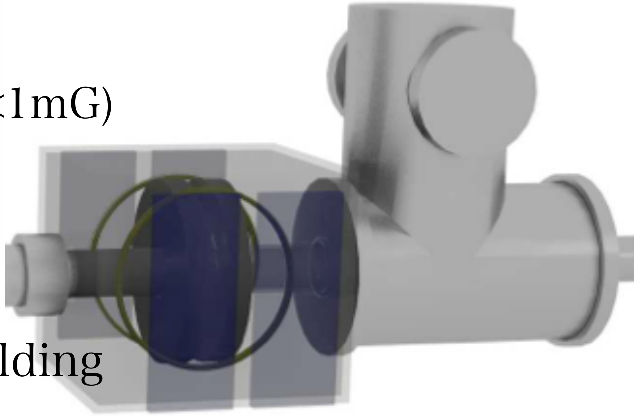
THE MICROWAVE CAVITY



Helmholtz coils 0-10G static field

high stability power supply

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



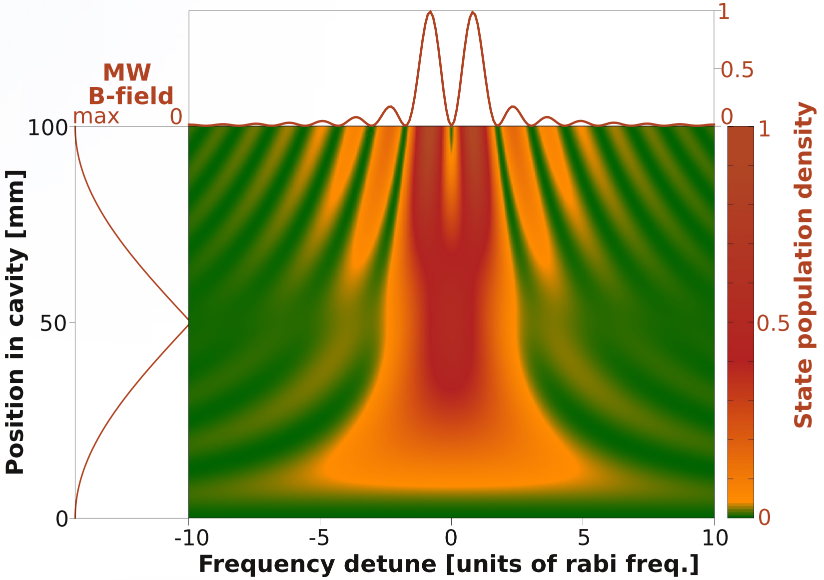
shielding

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

cavity length 10 cm

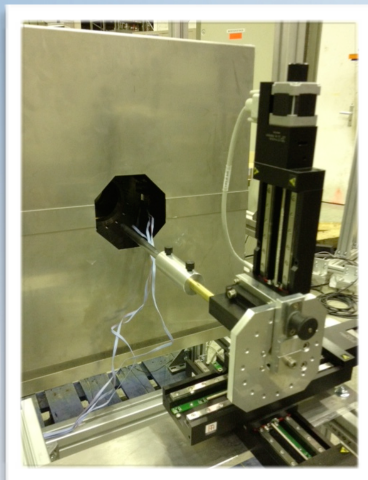
MW frequency: 1.42GHz

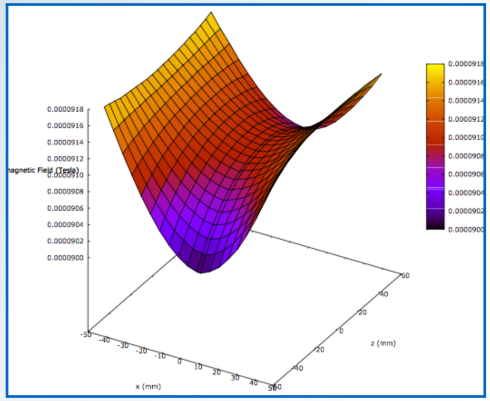
Q~100



Numerical solving of the Bloch equations

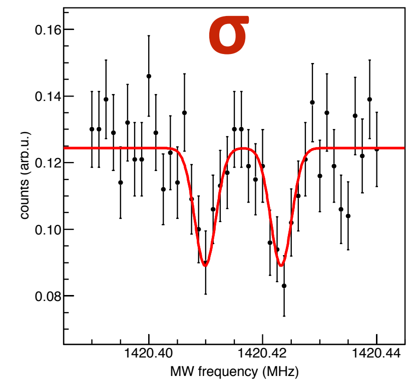
THE MICROWAVE CAVITY



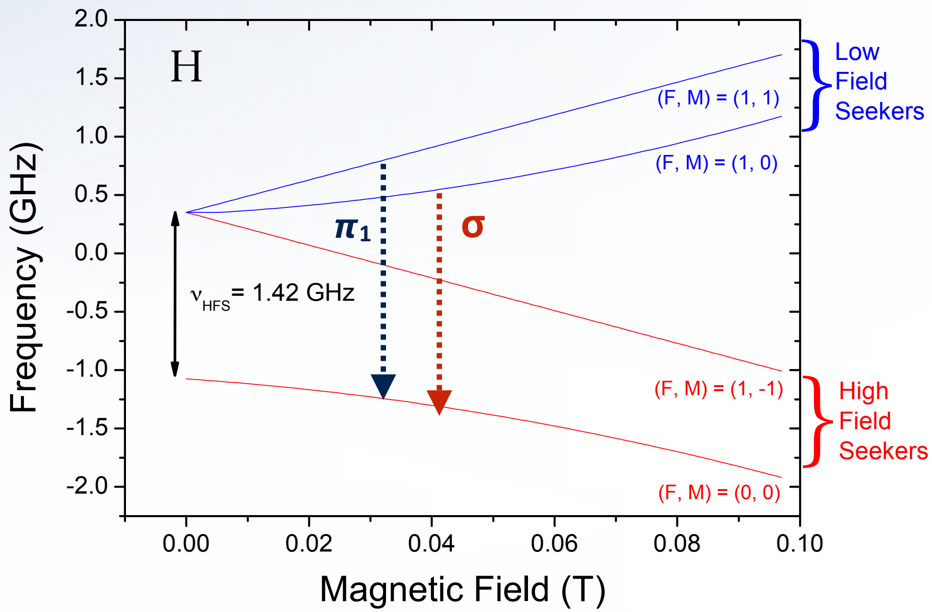


precise static field characterization

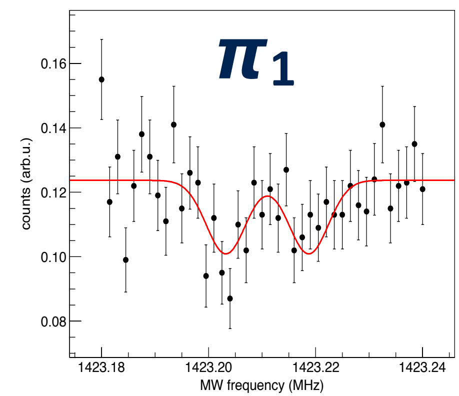
$$\frac{\Delta B}{B} = 1\%$$



simulation done at 2G, T=50K



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

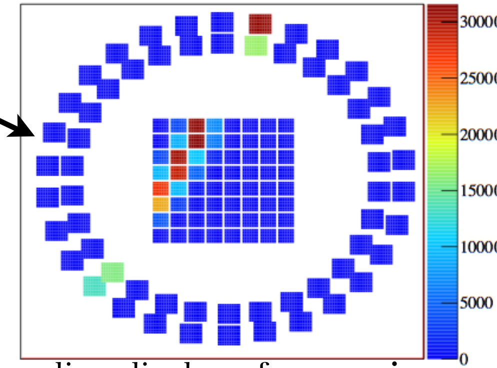


DETECTOR IMPROVEMENTS

Detector:

- combination of calorimeter (distinction between $\bar{H}$ and $\bar{H}$ annihilation products) and tracking detector
- addition of a 2nd layer of hodoscope (vertex reconstruction)

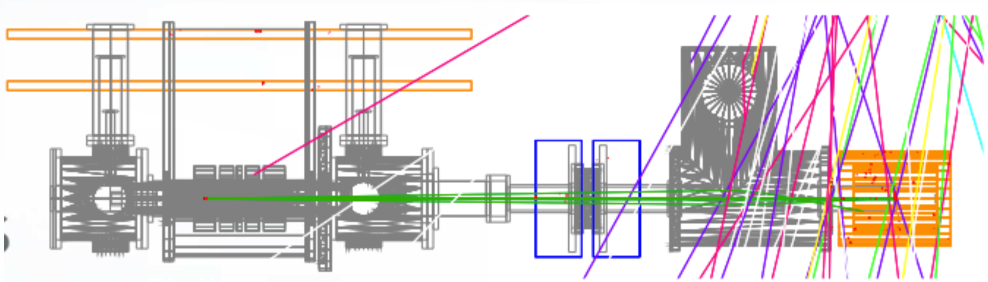
1 layer of hodoscope.
Read out on both side



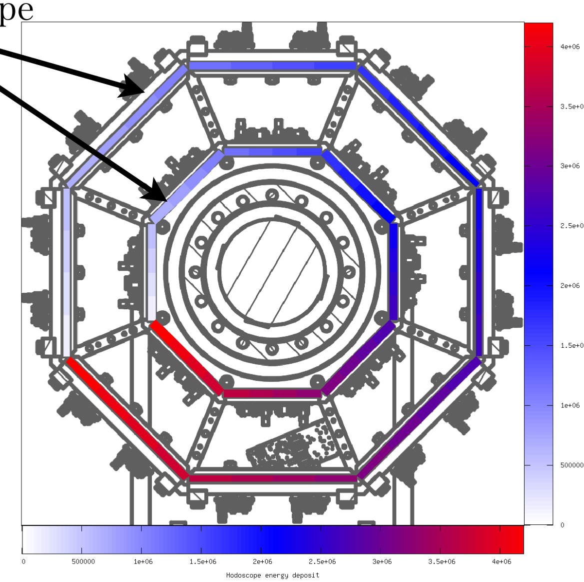
online display of a **cosmic** events in the detector (2012)

SIMULATION:
cosmics simulated with CRY 1.7 in G4

Assuming 2012 experimental conditions, S/N ratio of ~10
~50% detection efficiency



2 layers of hodoscope



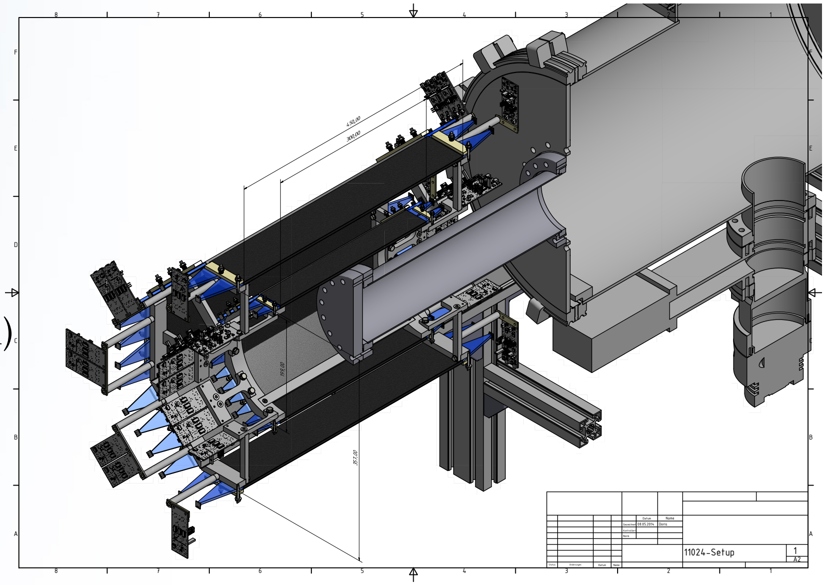
online display with simulated $\bar{H}$ annihilation

SILICON PM DEVELOPMENTS

Read-out:

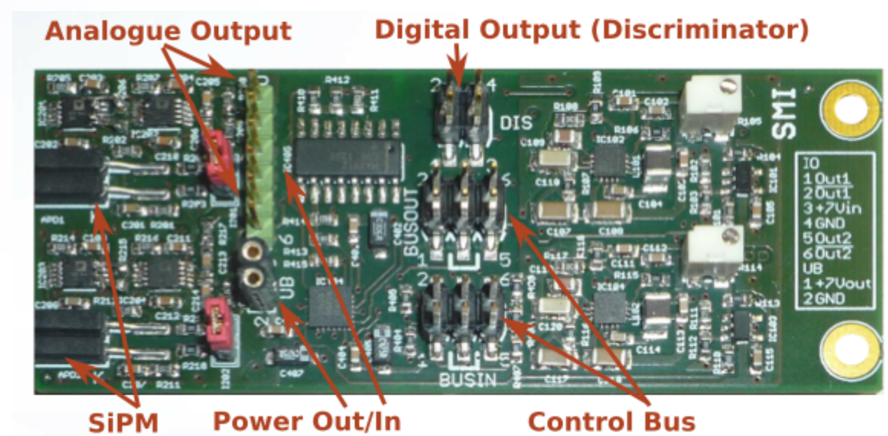
Faster read-out, improvement of the SiPM read-out electronics

- computer controlled gain
- each channel self triggering (e.g for calibration)
- computer controlled trigger threshold for each SiPM channel
- differential digital and analogue signal transmission

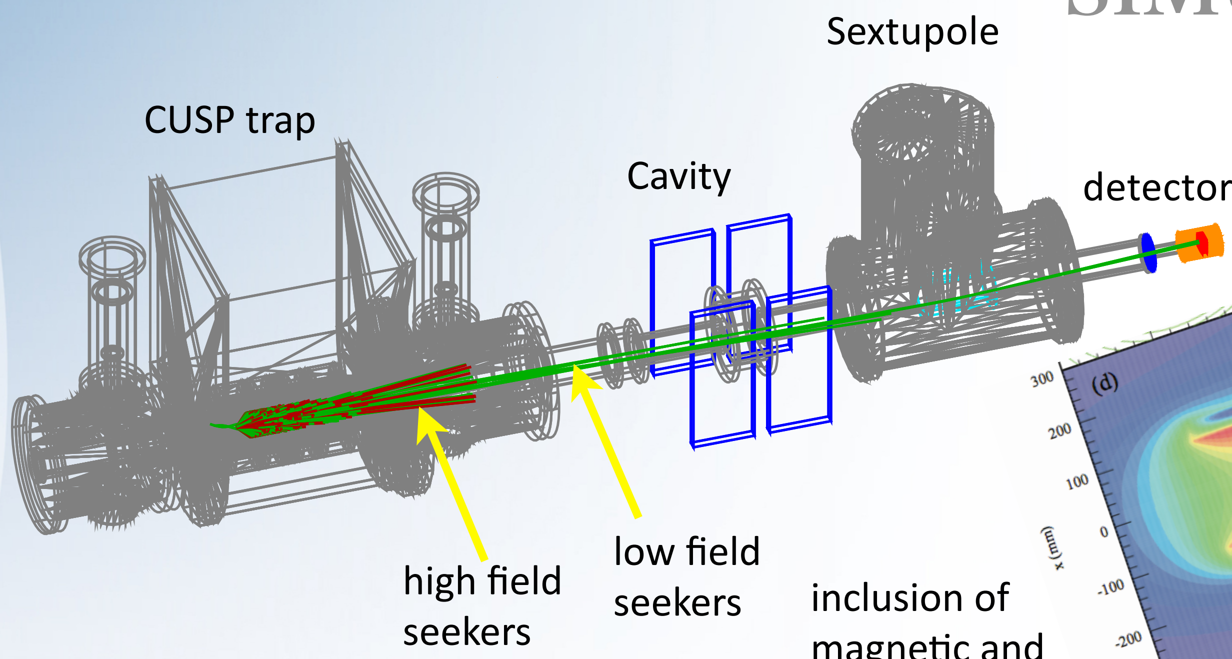


Timing resolution including scintillator response ~600ps FWHM

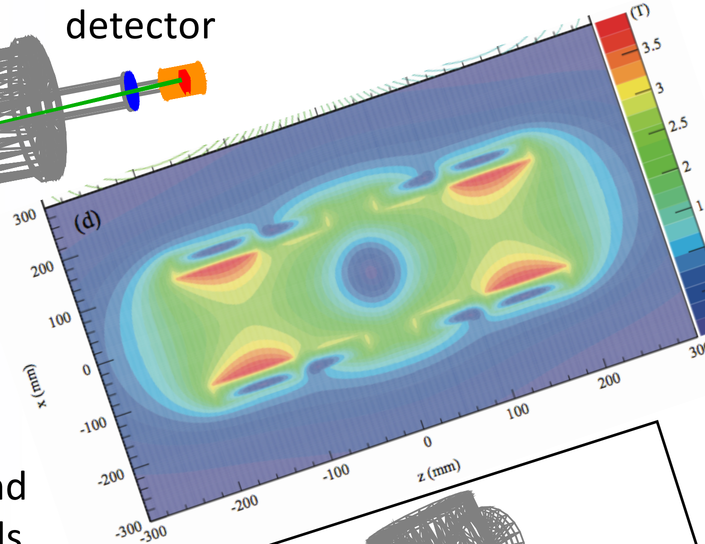
Further S/N enhancement using timing cut

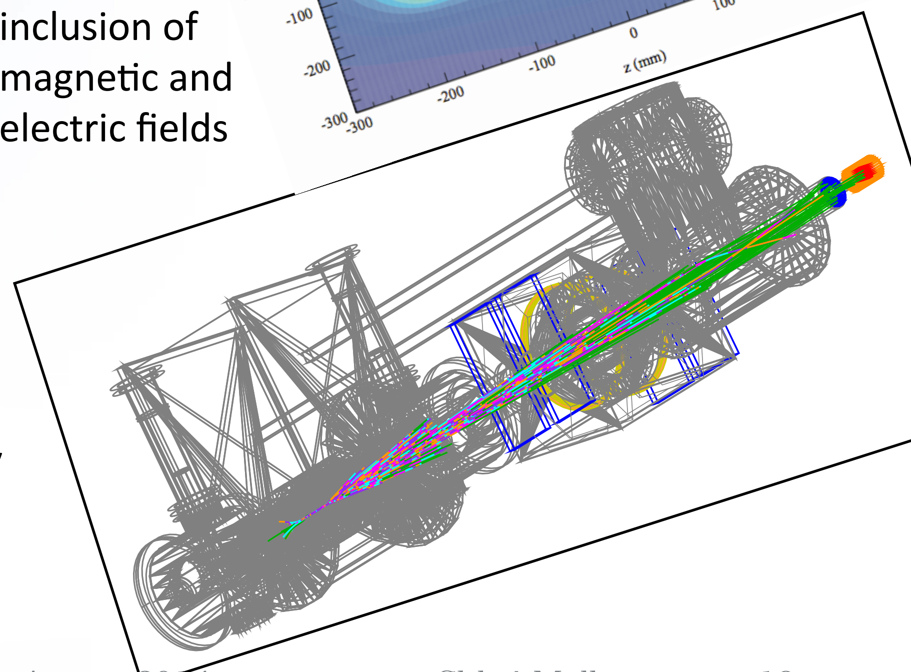


SIMULATION



inclusion of magnetic and electric fields

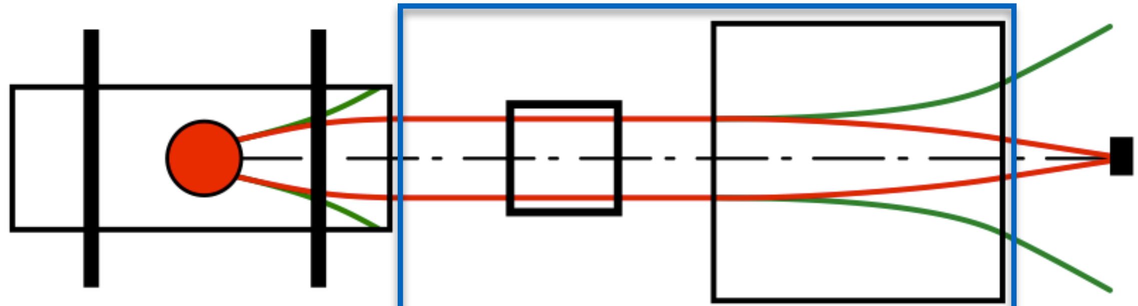




G4 studies:

- simulation of $\bar{H}$ trajectories in field (tracking neutral particle)
- inclusion of radiative decay
- background simulation
- cosmics
- estimation of transition probabilities in cavity
- effect of inhomogeneities of static field
- benchmarking of physics lists

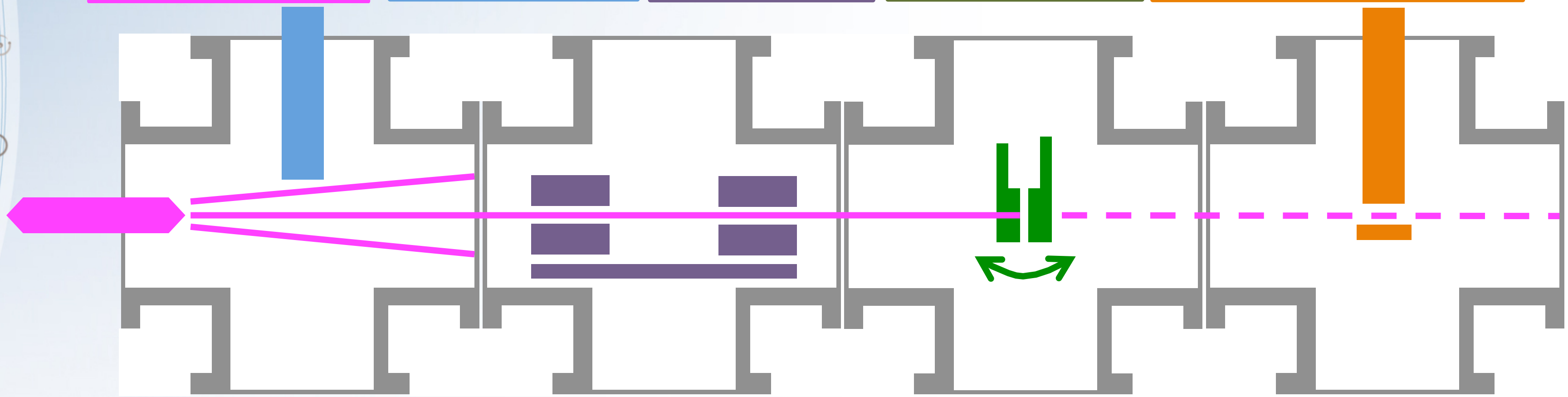
TEST SETUP WITH HYDROGEN BEAM (LS1)

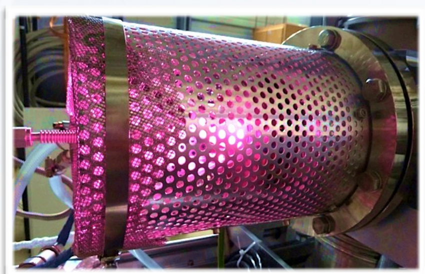


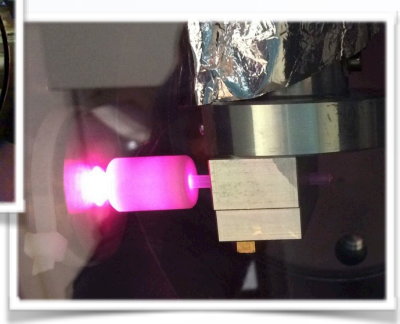
	H̄ beam	H beam
Beam rate at production (4π)	small (≈10^3/minute)	high (≈10^{19}/minute)
Quantum state	broad distribution	GS
Detection efficiency	detector 0.4 to 0.6 solide angle (≈10^{-4})	detector (≈10^{-8}) solide angle (≈10^{-6})
Detection method	Energy deposit, tracking	ionization and single ion counting
Background	cosmics, upstream annihilation	residual gas background>>signal (LIA)

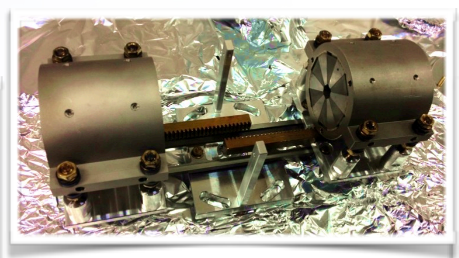
TEST SETUP WITH HYDROGEN BEAM (LS1)

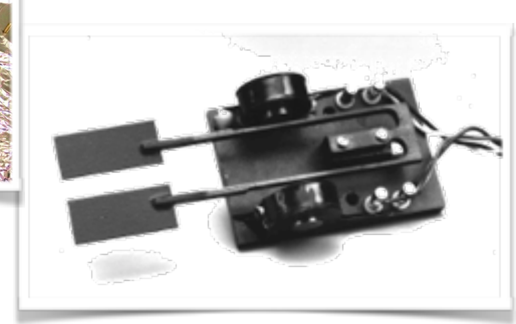
atomic H source	Cryogenic (cold head) for 50-100K beam	Sextupole	Fork-Chopper	Quadrup. Mass Spec.
ON → H and H_2 OFF → H_2 only		for polarized beam	f ≈ 178 Hz 50% duty cycle	detects mass=1 H_1^+ or mass=2 H_2^+











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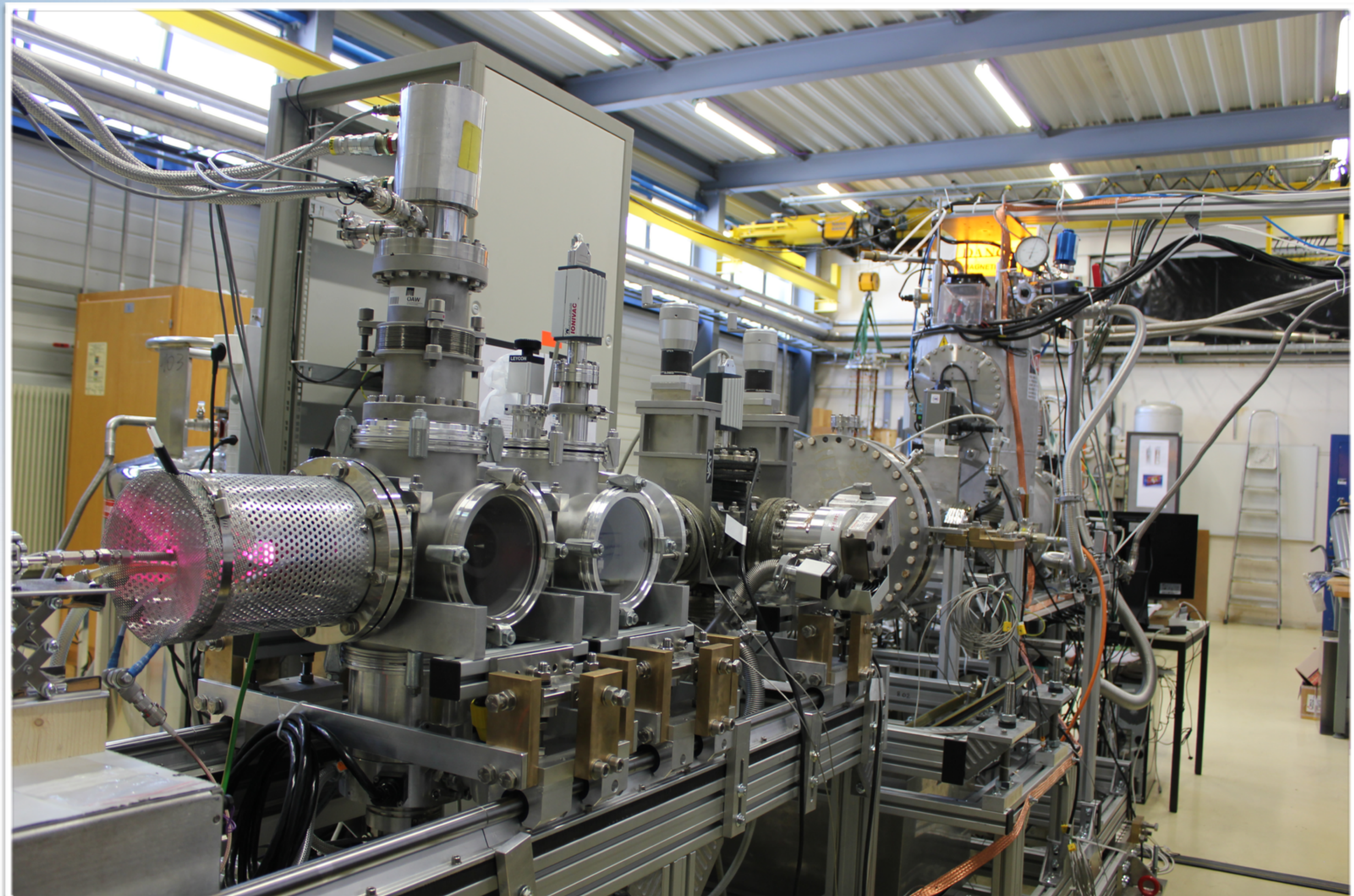
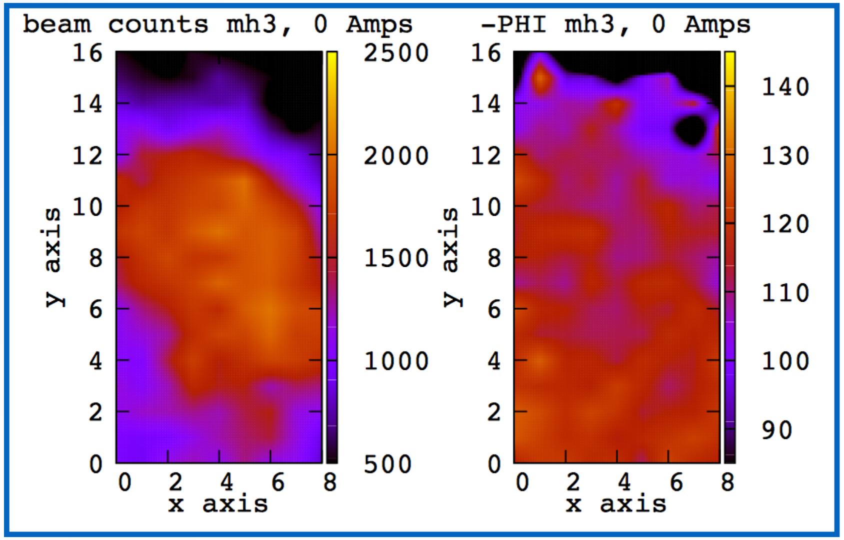
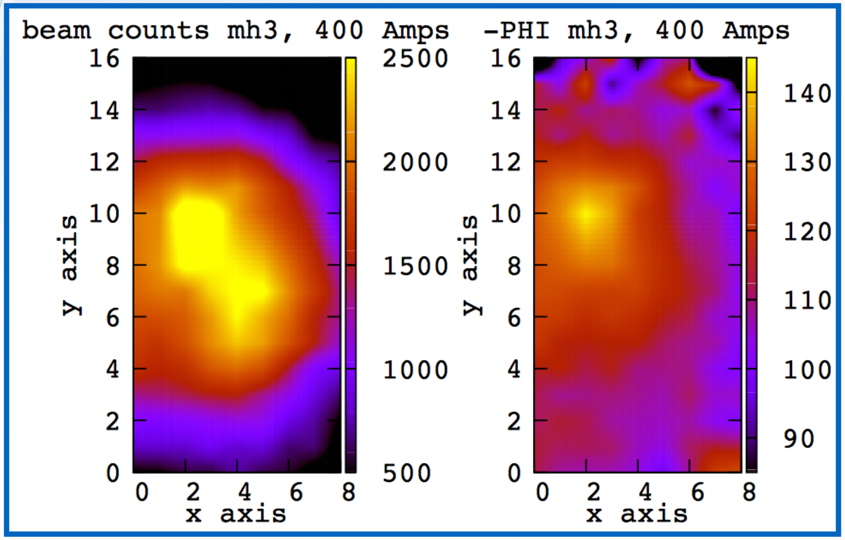


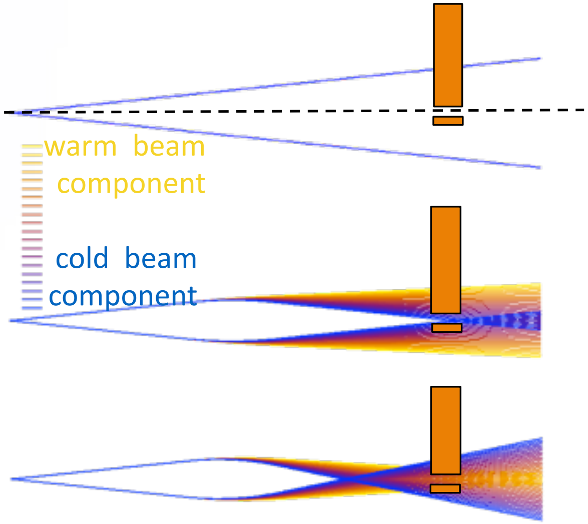
HYDROGEN BEAMTEST

Polarized beam:

focusing effect of cold atoms
Phase can be compared to a laser beam
Estimation of the temperature of the beam

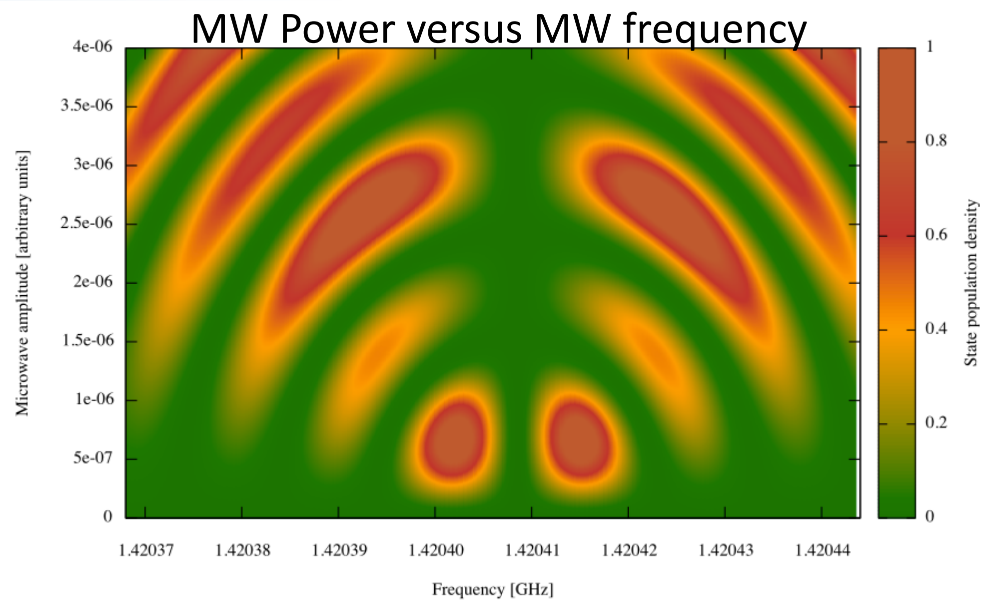




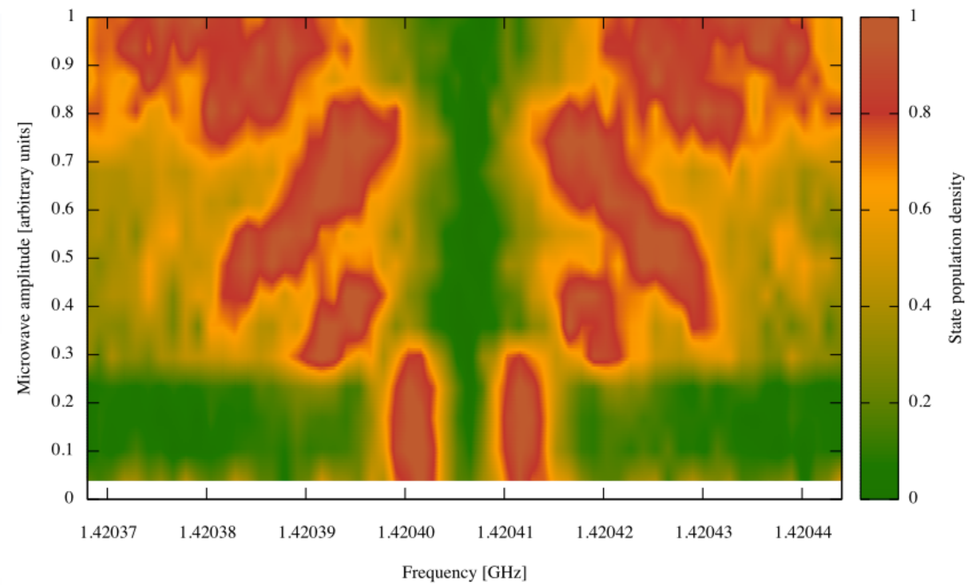


HYDROGEN BEAMTEST

Simulation:
- Numerical solving of optical Bloch equ.
- Single velocity
- No field inhomogeneity
- Theoretical lineshape: input for the spline fit

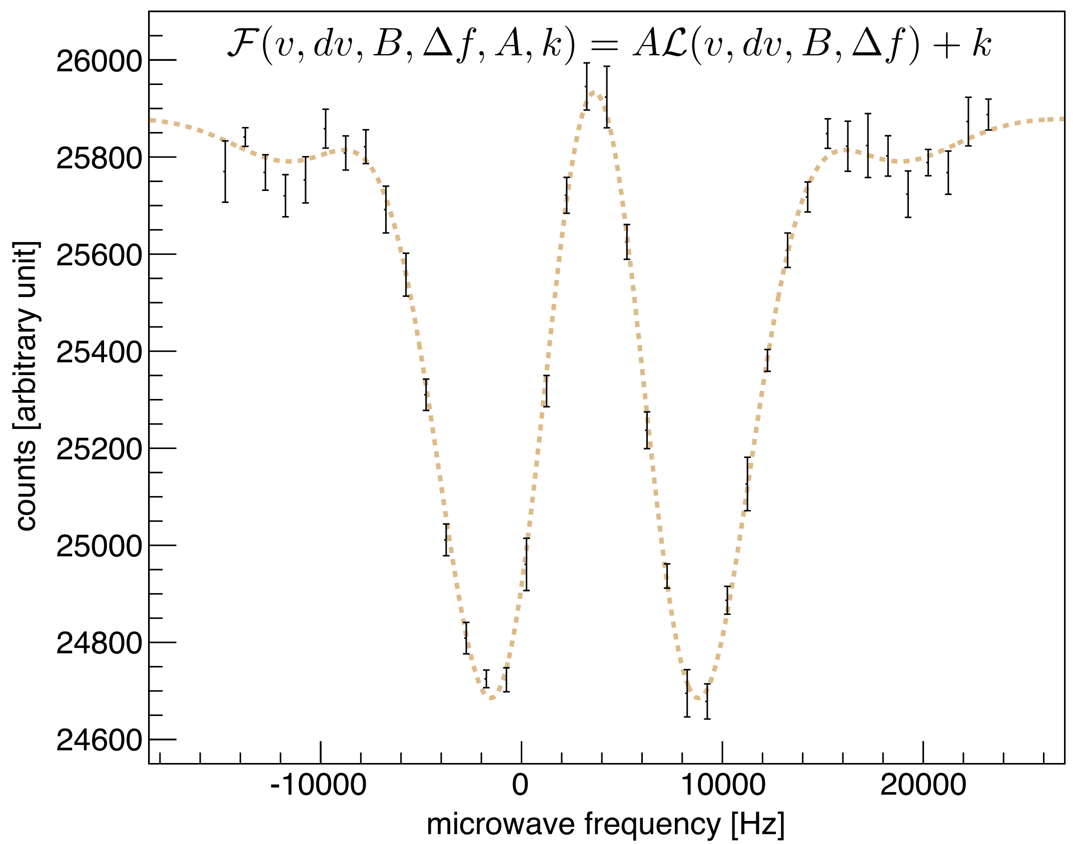


Measurements:
- Source temperature at 50K
- Finite velocity distribution



HYDROGEN BEAMTEST

Illustration of a measurement and spline fit

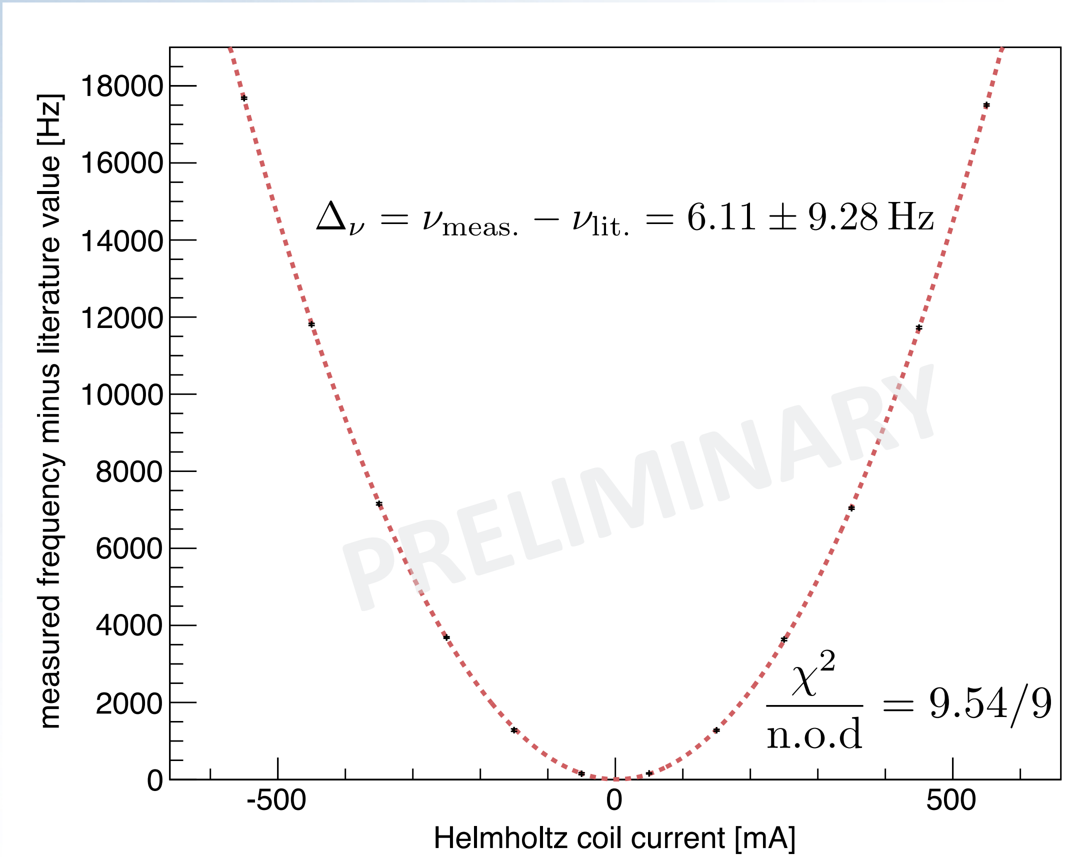


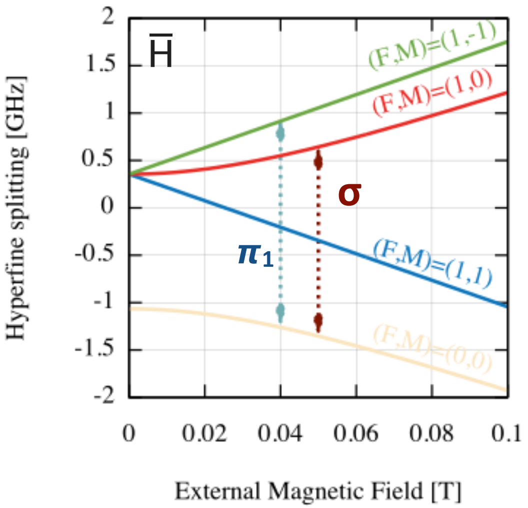
Fit parameters	results
Microwave amplitude [mG]	4.83 ± 0.70
f_0 [Hz]	1420407663 ± 30
central velocity [m/s]	835.3 ± 6.5
Velocity spread [m/s]	80 .0± 7.4
χ^2/nod	30.1/33

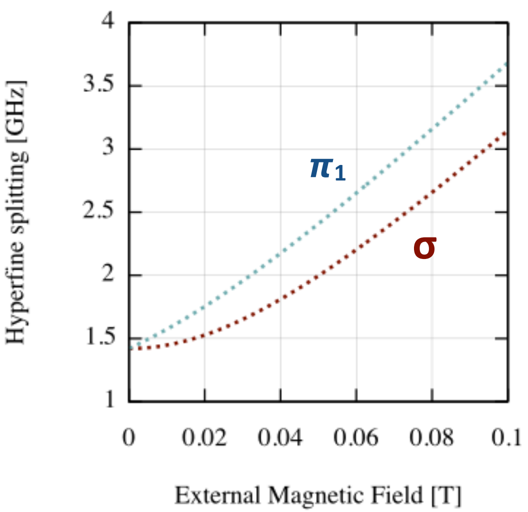
Velocity consistent with temperature of the source: 50K

HYDROGEN BEAMTEST

Fitting the theoretical curve to the data
Helmholtz coil currents: external B field is a fit parameter





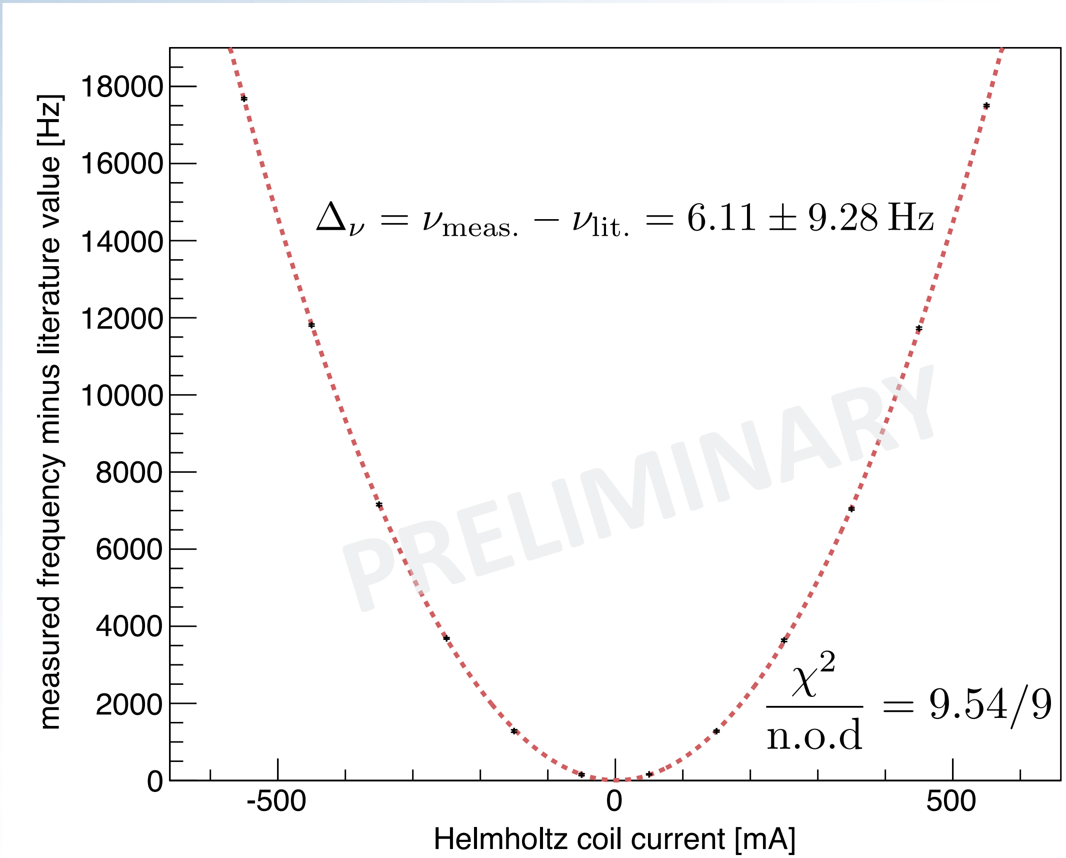


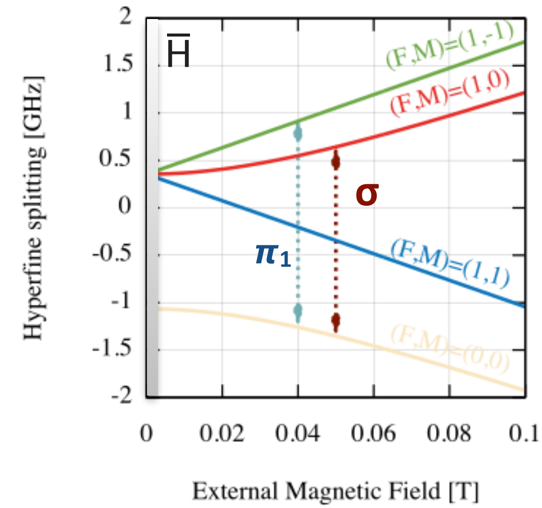
Error bars included
B field are consistent (within 1 sigma) with flux gate readings

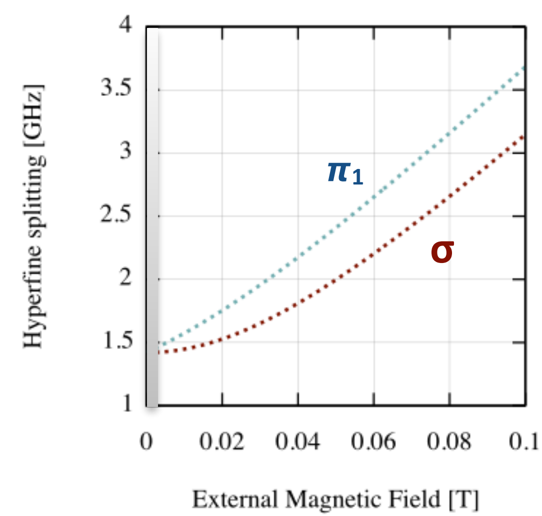
HYDROGEN BEAMTEST

Fitting the theoretical curve to the data

Helmholtz coil currents: external B field is a fit parameter







Error bars included

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

HYDROGEN BEAMTEST

- Best beam measurement

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

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

Kusch. Physical Review. 100, 4 (1955)

$$\nu = 1420.405757(9)\ \mathrm{MHz}$$

$$\frac{\Delta\nu}{\nu} = 6.5 \times 10^{-9}$$

PRELIMINARY

This work

- Maser experiments

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

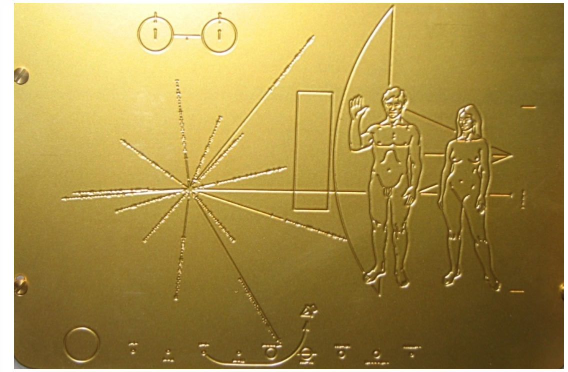
$$\frac{\Delta\nu}{\nu} = 7 \times 10^{-13}$$

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

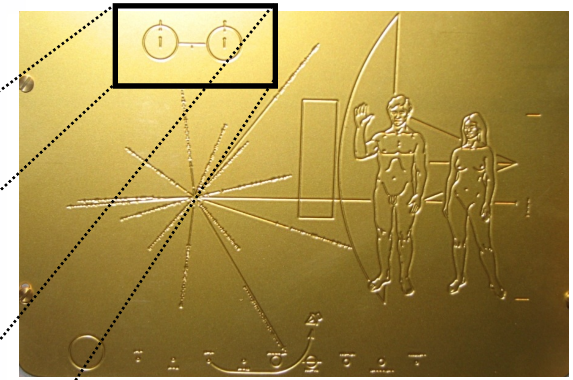
Observation of π transition in Earth magnetic field
Further measurements with π planned

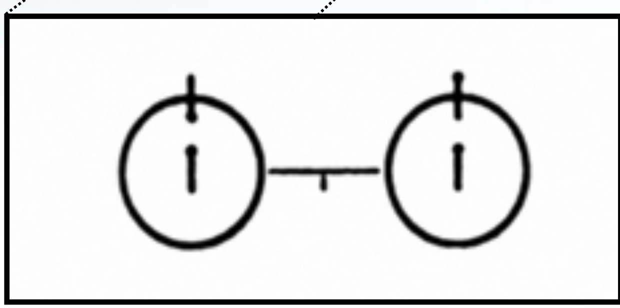
SUMMARY AND OUTLOOK

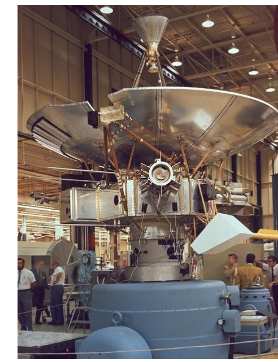
- Construction of a antihydrogen **detector** ongoing. Ready for 2014 beamtime
- Extensive **Monte Carlo** simulation done/ongoing
- Full **spectroscopy beamline** is ready for the beamtime
- Precise **σ Resonance** (ppb) measured in Hydrogen
  - Majorana spin flip is not affecting the signal
  - Resonance width is small
  - ***π*** resonance to be measured
- **Systematics study** being finalized
- ppm precision measurement of $\nu_{\bar{H}}$ in sight
  - "cold" beam
  - Ground state at the cavity
  - Factor ≈10 more statistics



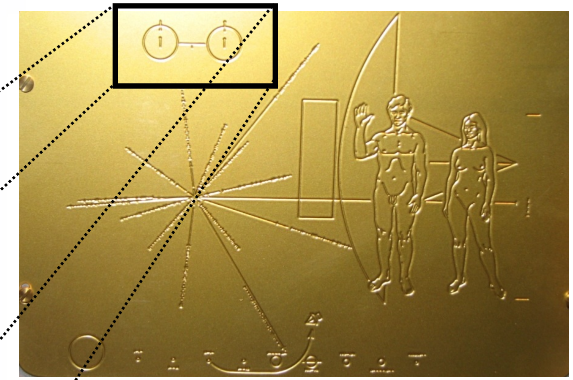
Pioneer 10 (1973)



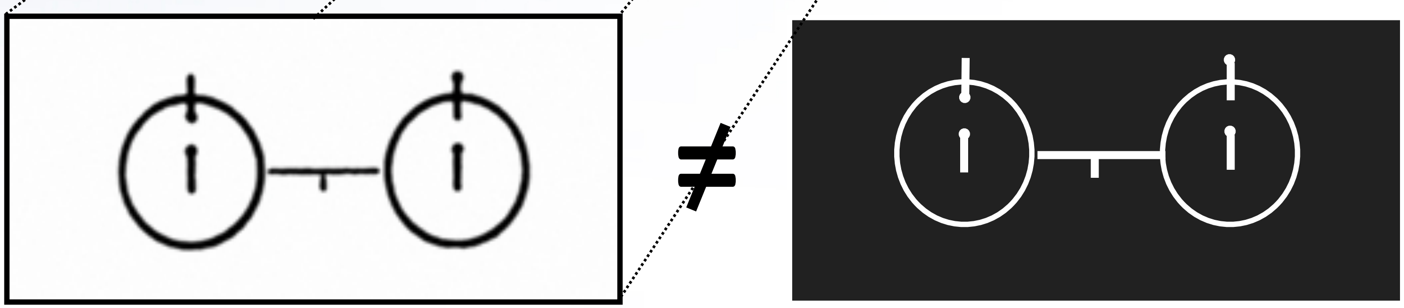




Pioneer 10 (1973)



Pioneer 10 (1973)



ACKNOWLEDGEMENTS

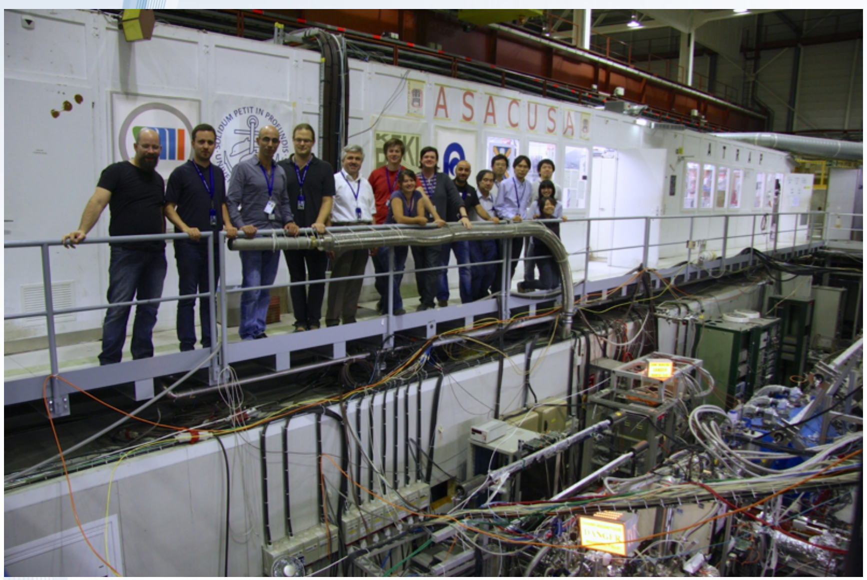
A tomic
S pectroscopy
A nd
C ollisions
U sing
S low
A ntiprotons

ASACUSA Scientific project

(1) Spectroscopy of p̄He

(2) p̄ annihilation cross-section

(3) H̄ production and spectroscopy



The H̄ team

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Tokyo University of Science: K. Michishio, Y. Nagashima

Hiroshima University: H. Higaki, S. Sakurai

Univerita di Brescia: M. Leali, E. Lodi-Rizzini, V. Mascagna, L. Venturelli, N. Zurlo

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THANK YOU FOR YOUR ATTENTION