H·HFS
Hyperfine Structure of Antihydrogen

ERC Advanced Grant
PI: Prof. Dr. Eberhard Widmann

THE HYPERFINE STRUCTURE OF ANTIHYDROGEN

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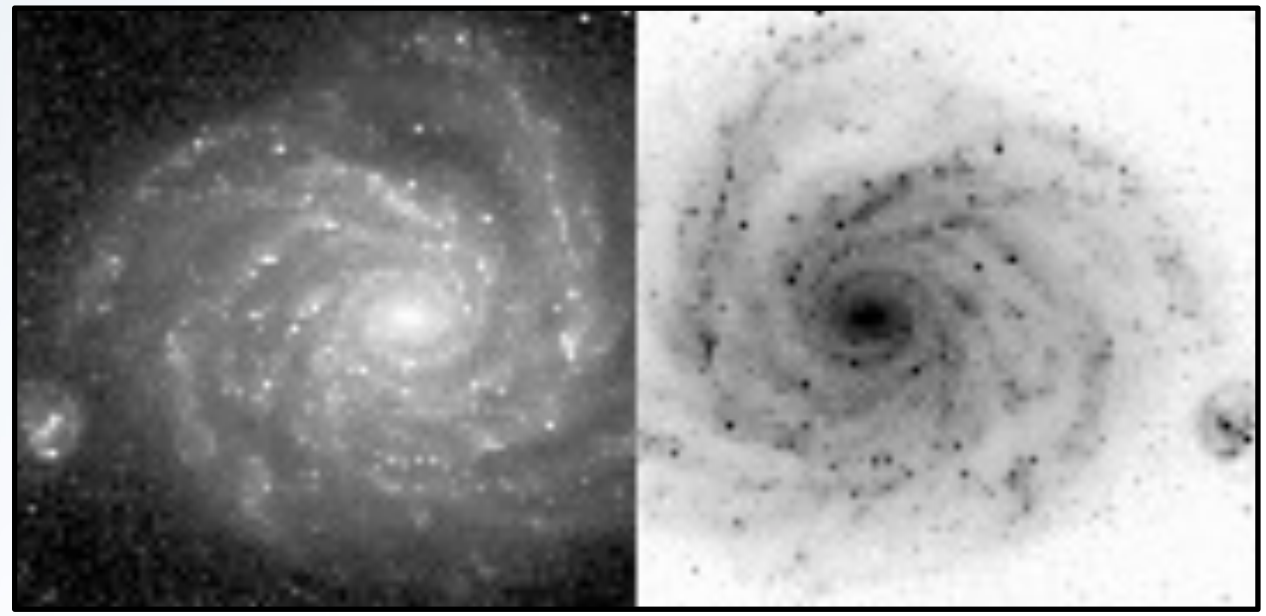
SMI erc ÖAW Austrian Academy of Sciences

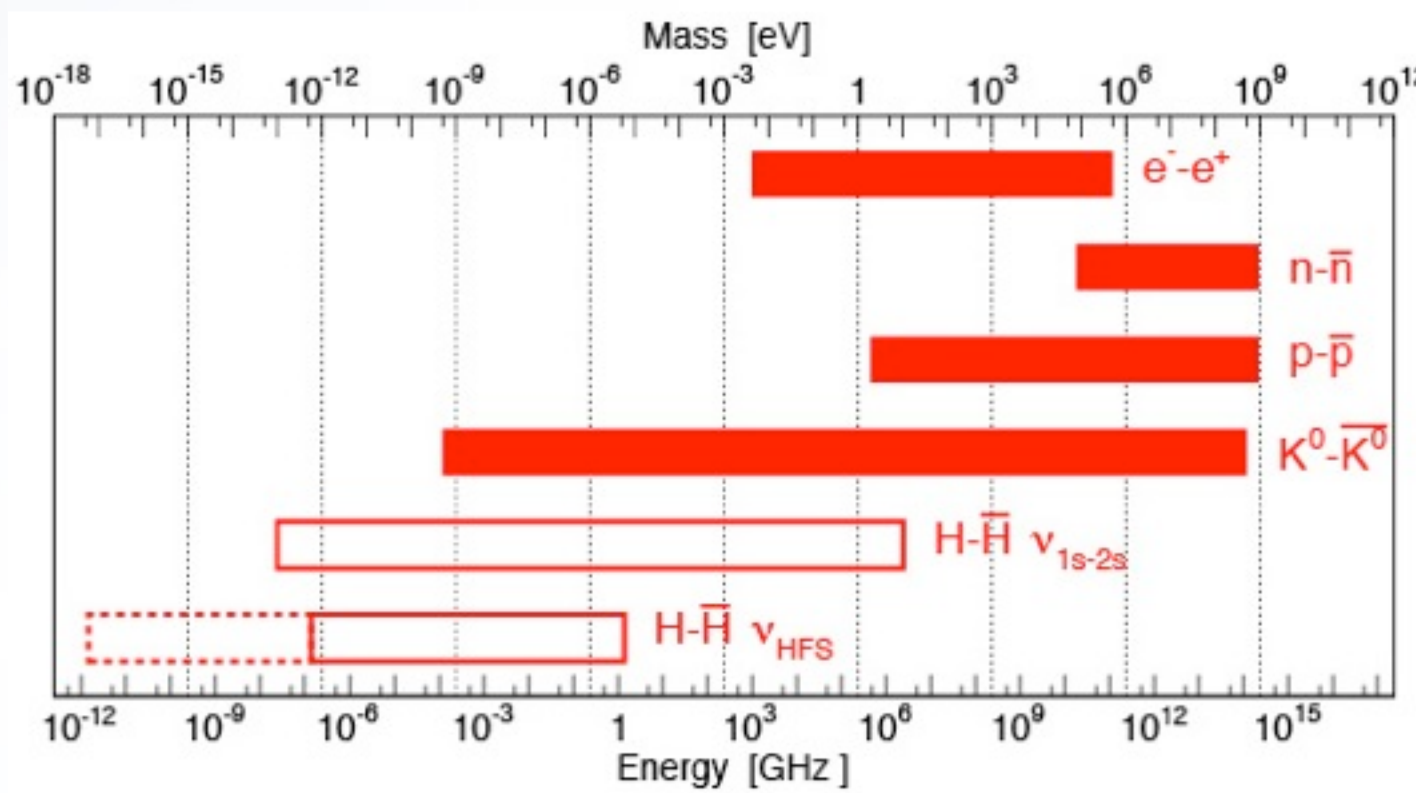
LEAP2013
UPPSALA
13.6.2013

Matter-antimatter symmetry

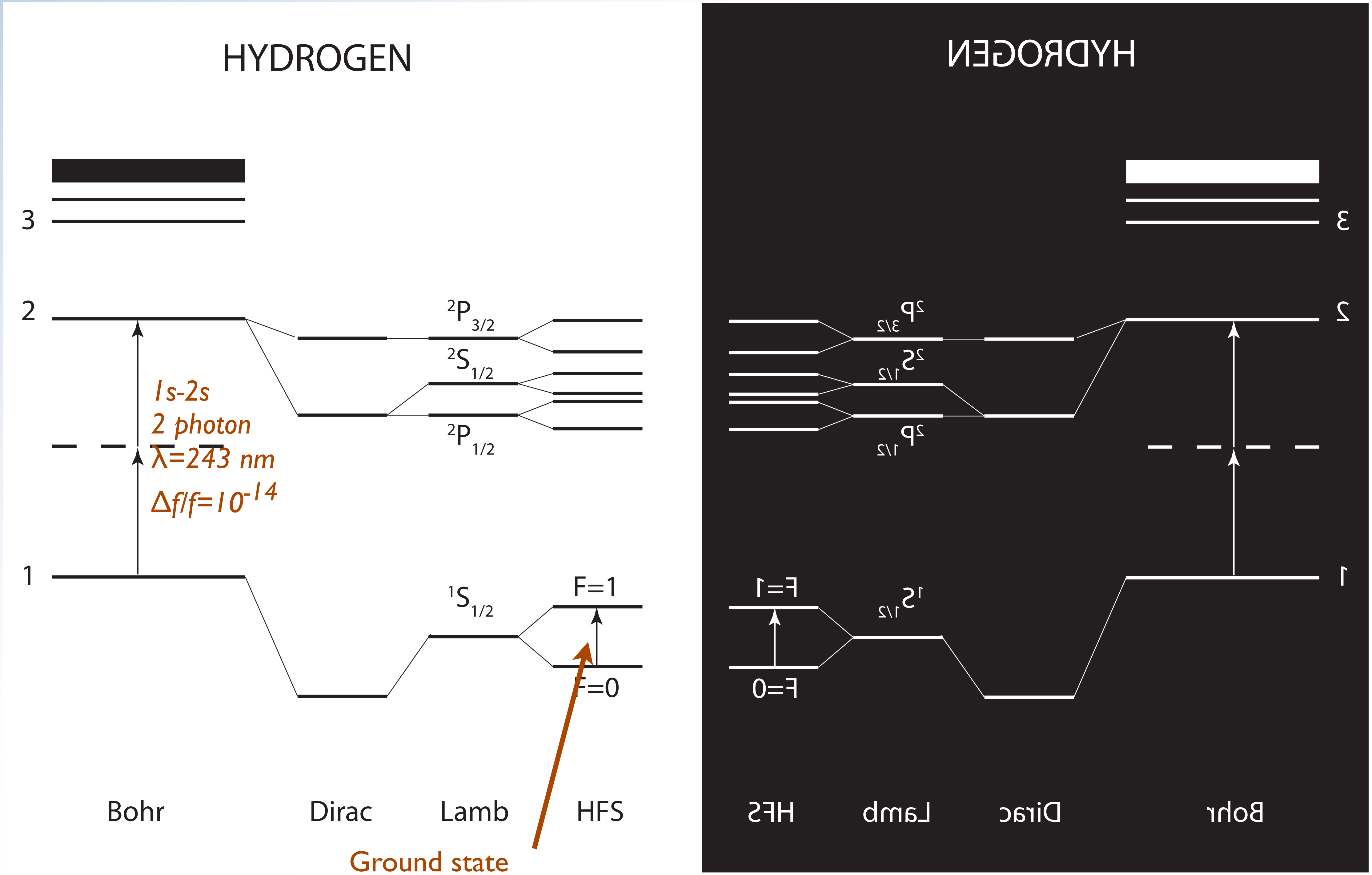
- Cosmological scale:
  - asymmetry



- CPT violation
  - Microscopic: symmetry?

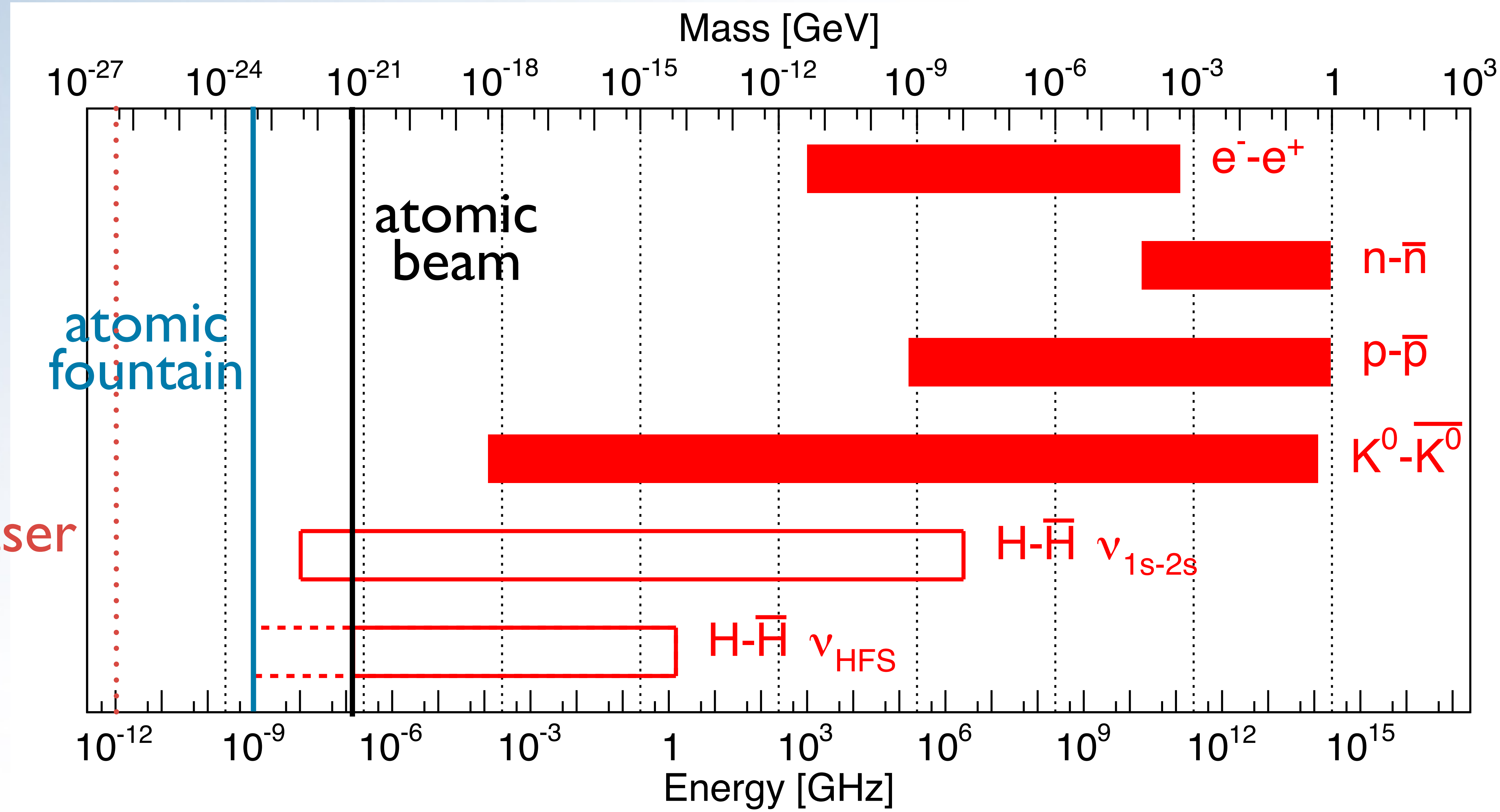


HYDROGEN AND ANTIHYDROGEN



Ground state
hyperfine splitting
f = 1.4 GHz
Δf/f=10^{-12}

CPT TESTS - RELATIVE & ABSOLUTE PRECISION



- ATOMIC PHYSICS EXPERIMENTS, ESPECIALLY ANTIHYDROGEN OFFER THE MOST SENSITIVE EXPERIMENTAL VERIFICATIONS OF CPT

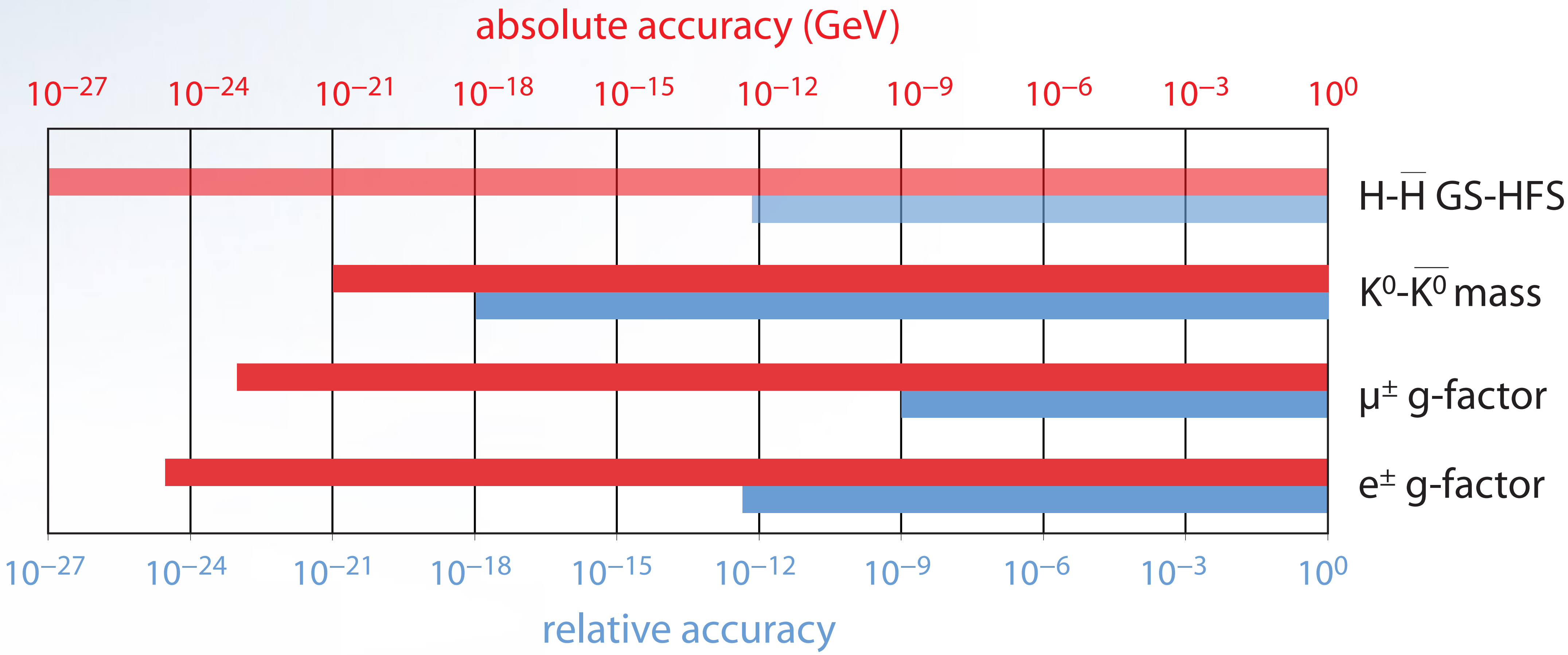
HFS and Standard Model

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

CPT & Lorentz violation

Lorentz violation

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



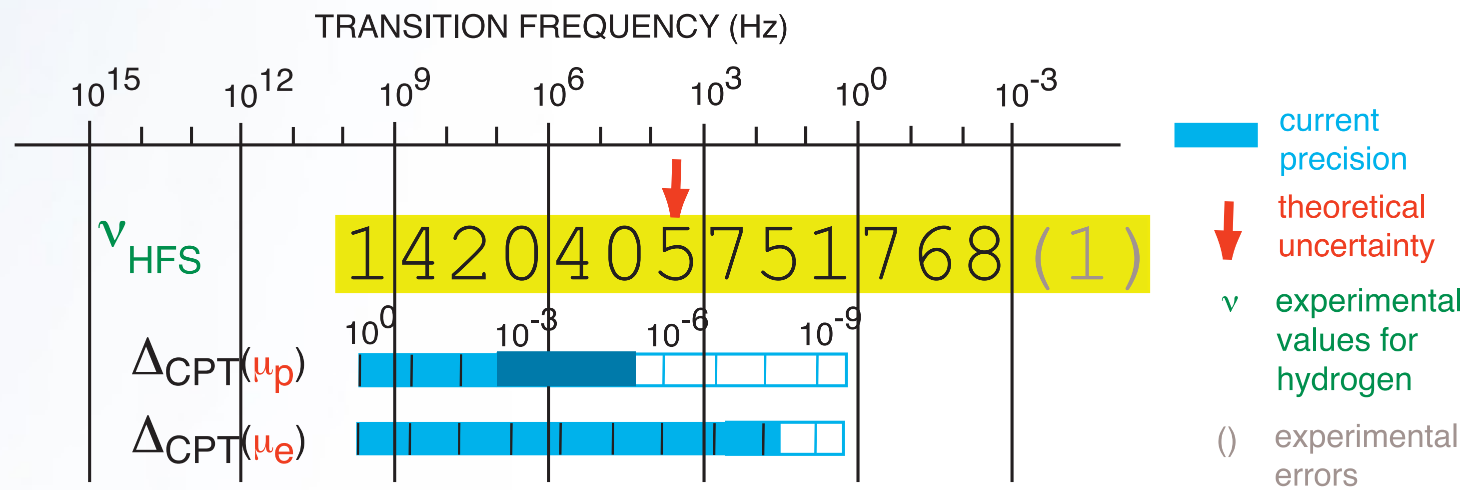
no CPT effect on 1S-2S transition

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

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



- magnetic moment of $\bar{p}$
  - previously known to 0.3%, 2012 Gabrielse Penning trap 5 ppm arXiv:1301.6310
- 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

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

ASACUSA COLLABORATION @ CERN-AD

ASAKUSA KANNON TEMPLE
BY UTAGAWA HIROSHIGE (1797–1858)

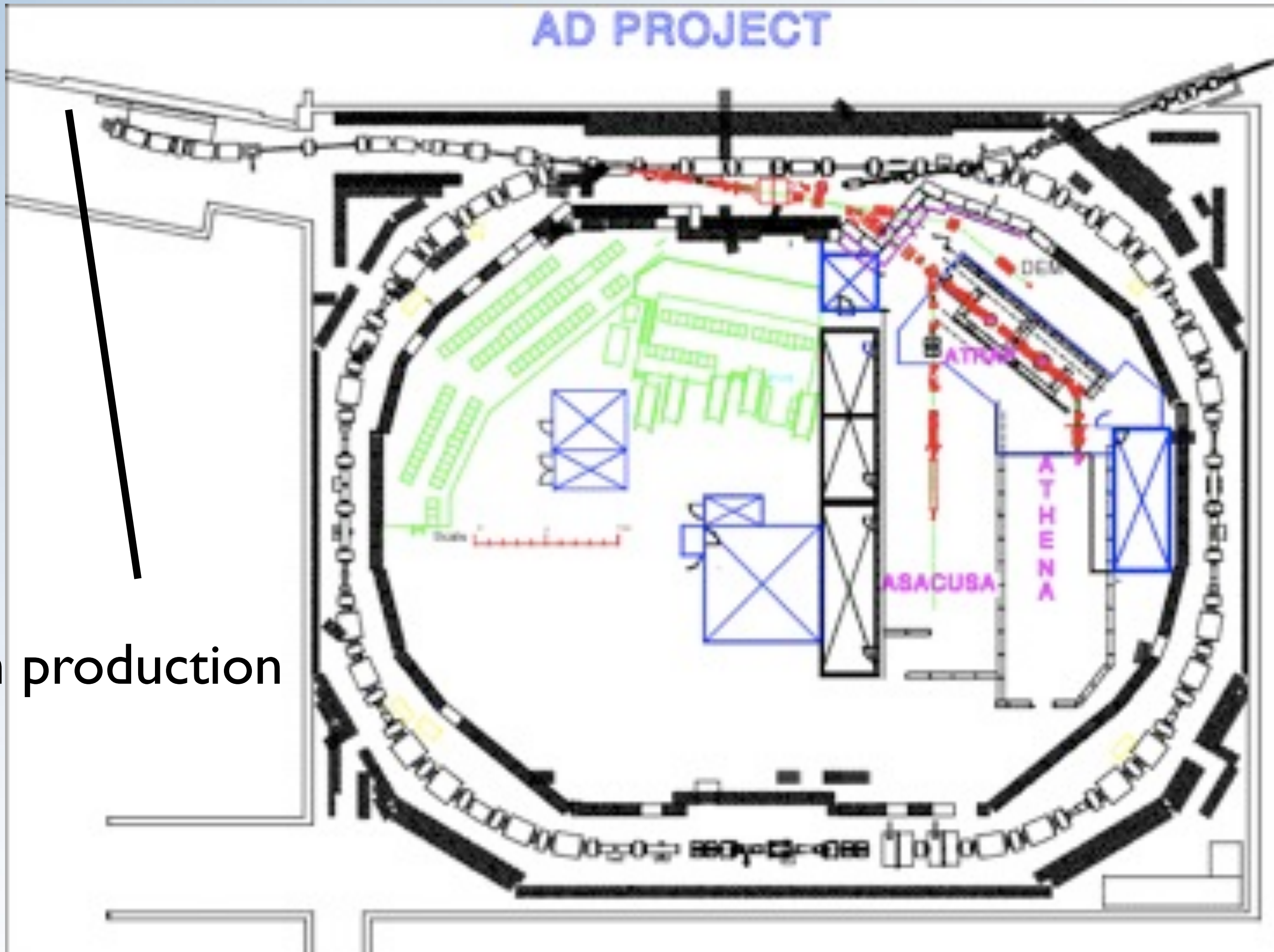
Atomic **S**pectroscopy **A**nd **C**ollisions
Using **S**low **A**ntiprotons

SPOKESPERSON: R.S. HAYANO, UNIVERSITY OF TOKYO

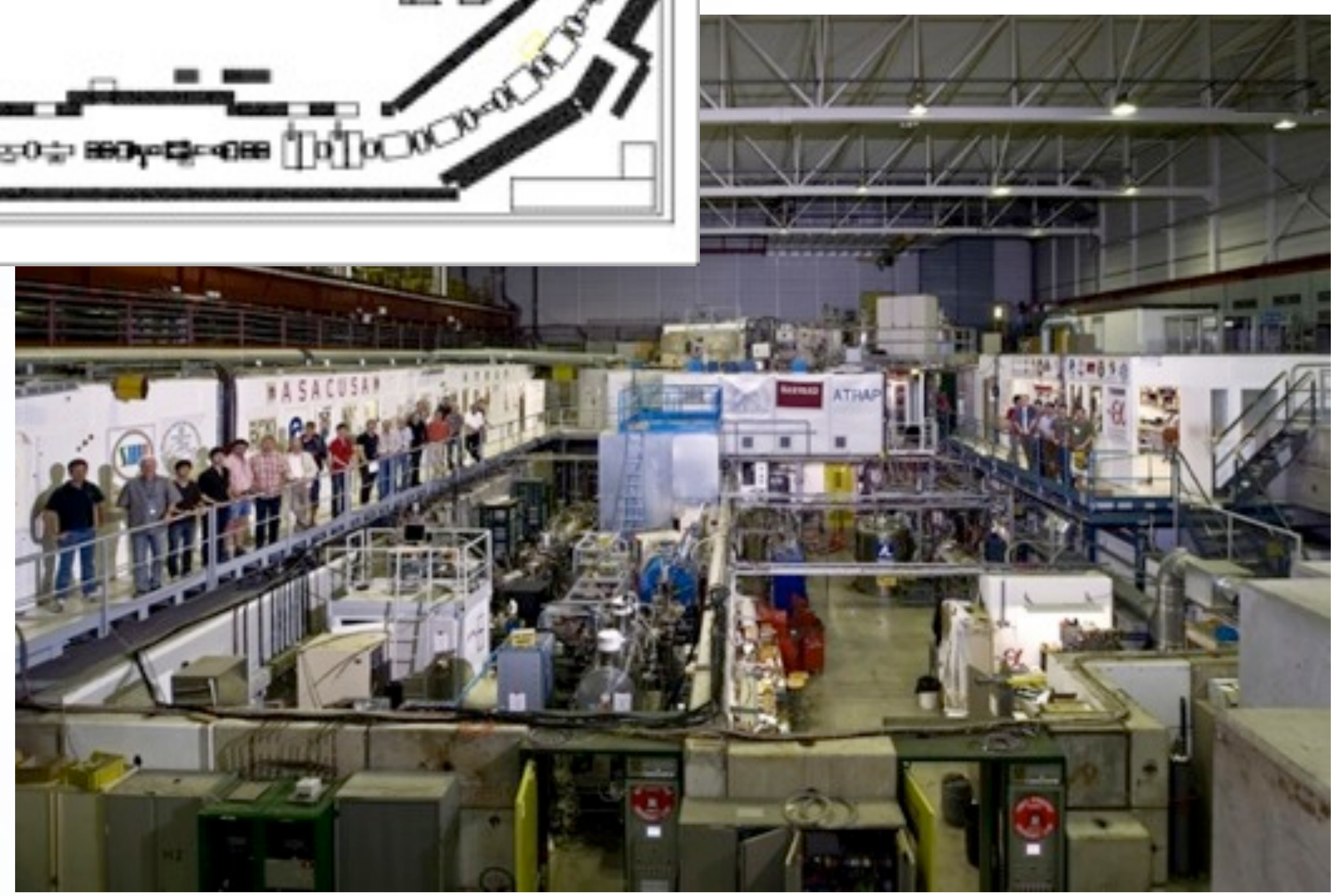
- University of Tokyo, Japan
  - INSTITUTE OF PHYSICS
  - FACULTY OF SCIENCE, DEPARTMENT OF PHYSICS
- RIKEN, Saitama, Japan
- SMI, Austria
- Aarhus University, Denmark
- Max-Planck-Institut für Quantenoptik, Munich, Germany
- KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
- ATOMKI Debrecen, Hungary
- Brescia University & INFN, Italy
- University of Wales, Swansea, UK
- The Queen's University of Belfast, Ireland

~ 44 MEMBERS

Antiproton Decelerator @ CERN



Antiproton production



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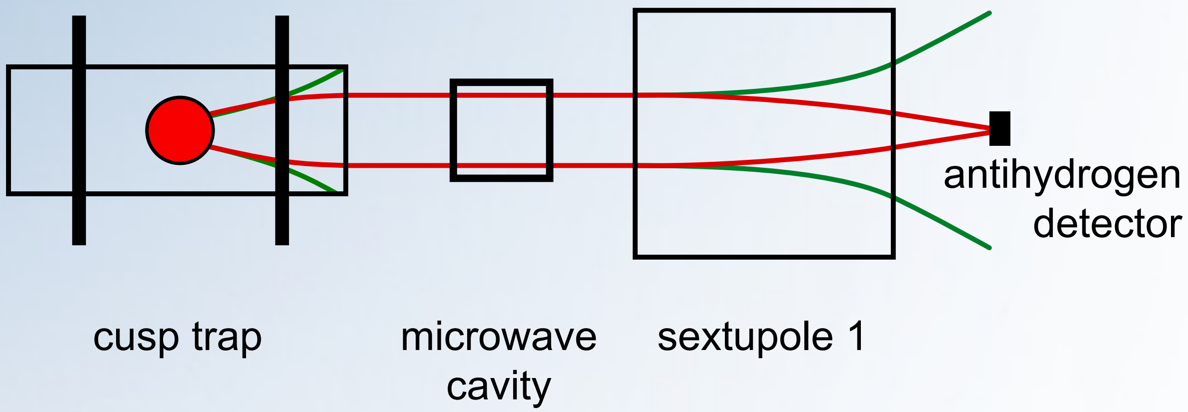
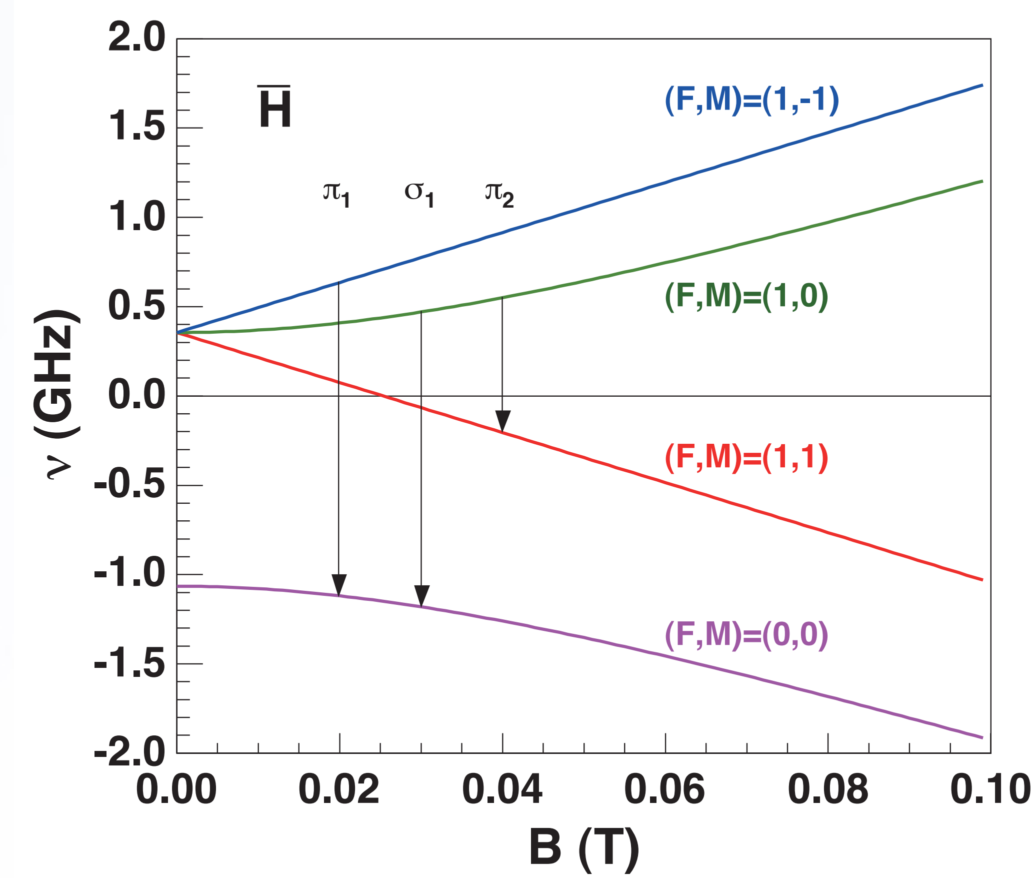
HFS MEASUREMENT IN AN ATOMIC BEAM



- 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

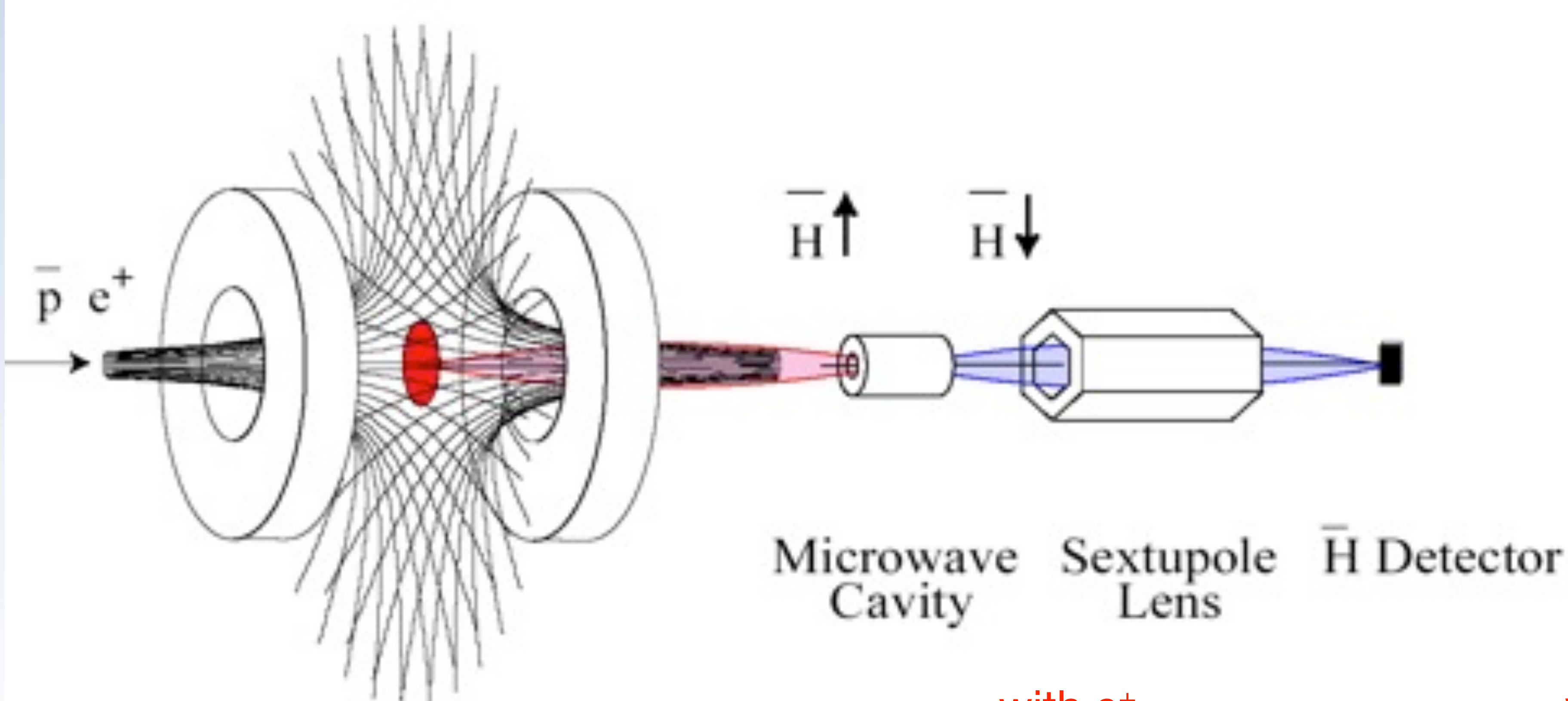


achievable resolution

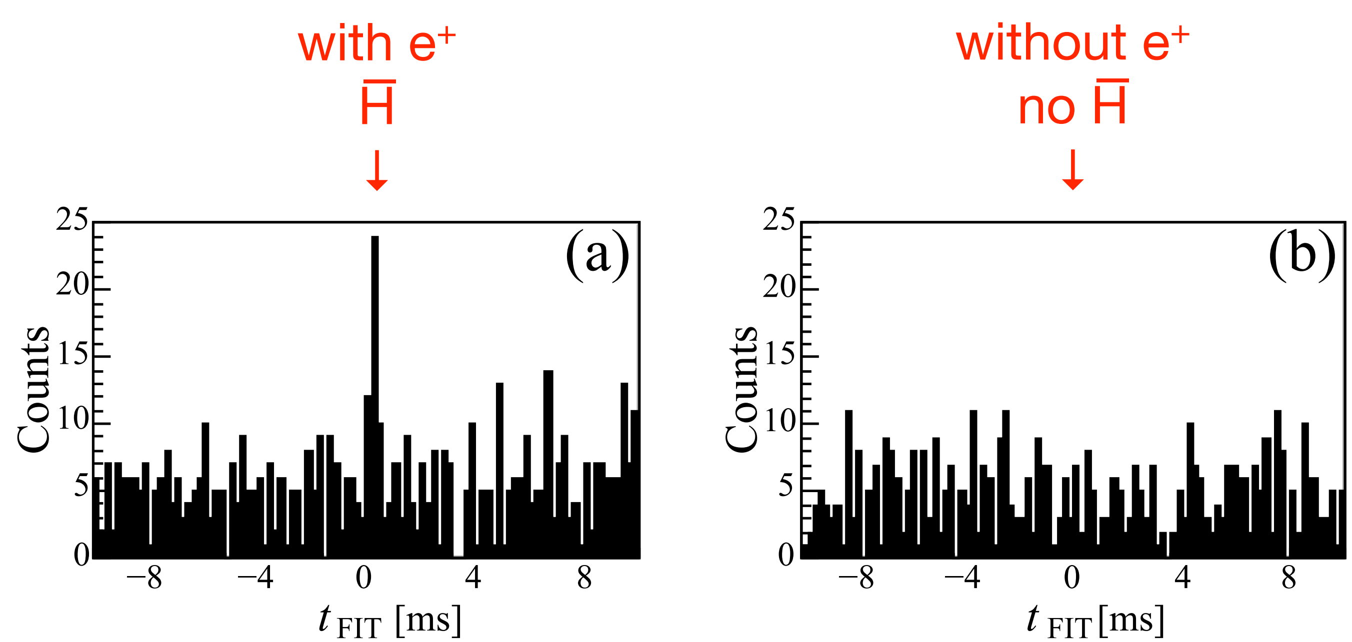
- better 10^{-6} for $T \leq 100$ K
- > 100 H^{bar}/s in 1S state into 4π needed
- event rate 1 / minute: background from cosmics, annihilations uptsreams

POLARIZED $\overline{H}$ 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

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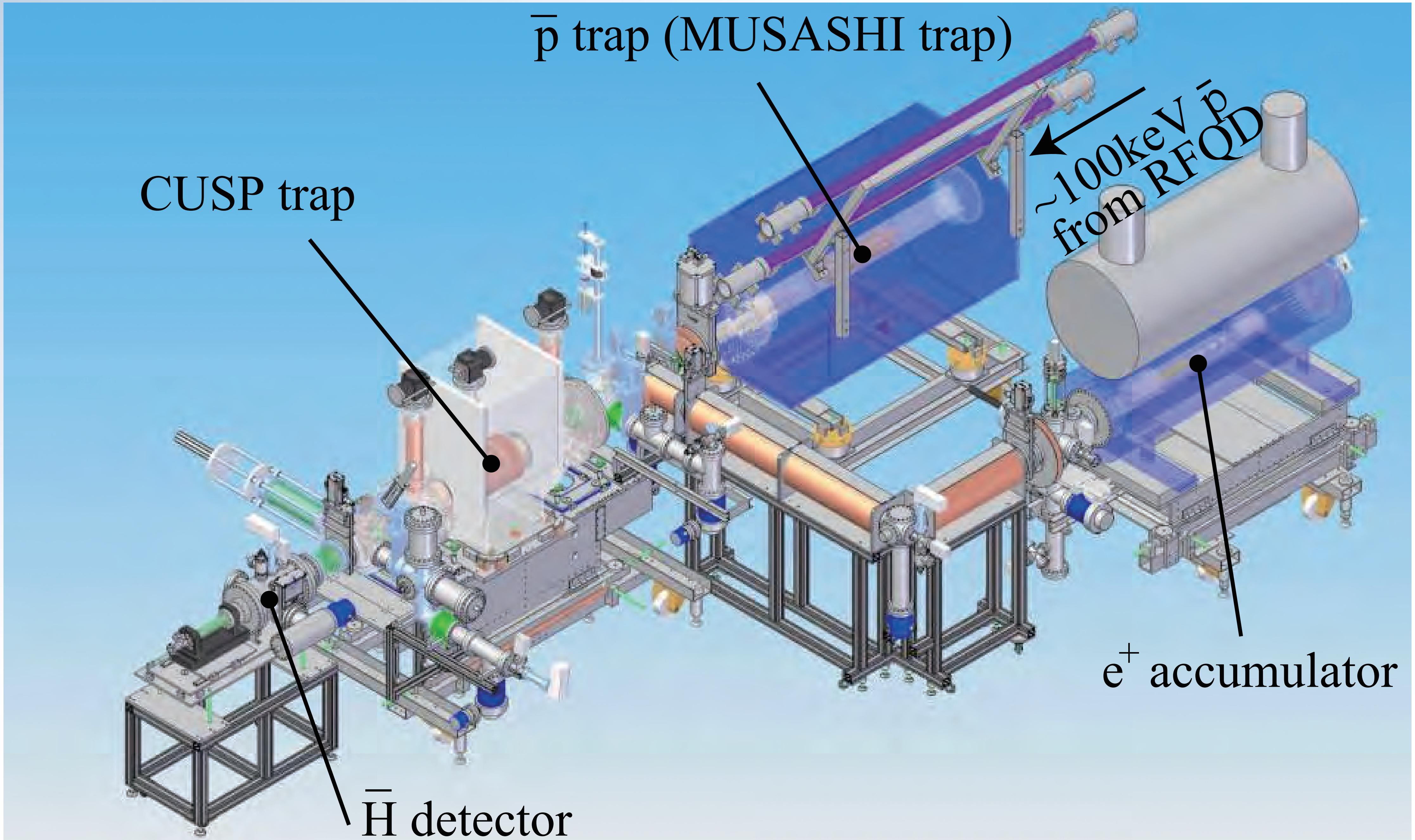
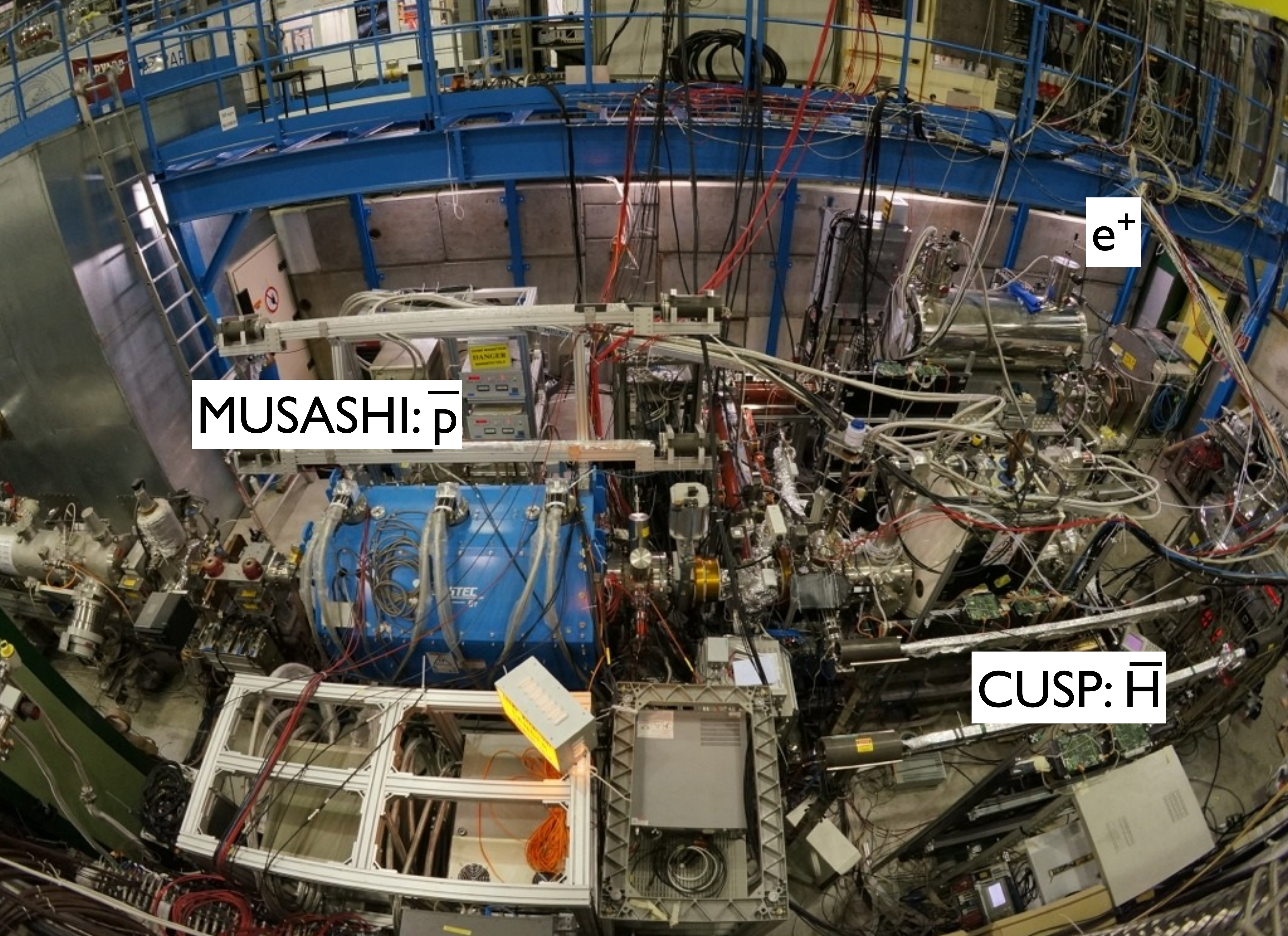
$\overline{H}$ PRODUCTION SETUP





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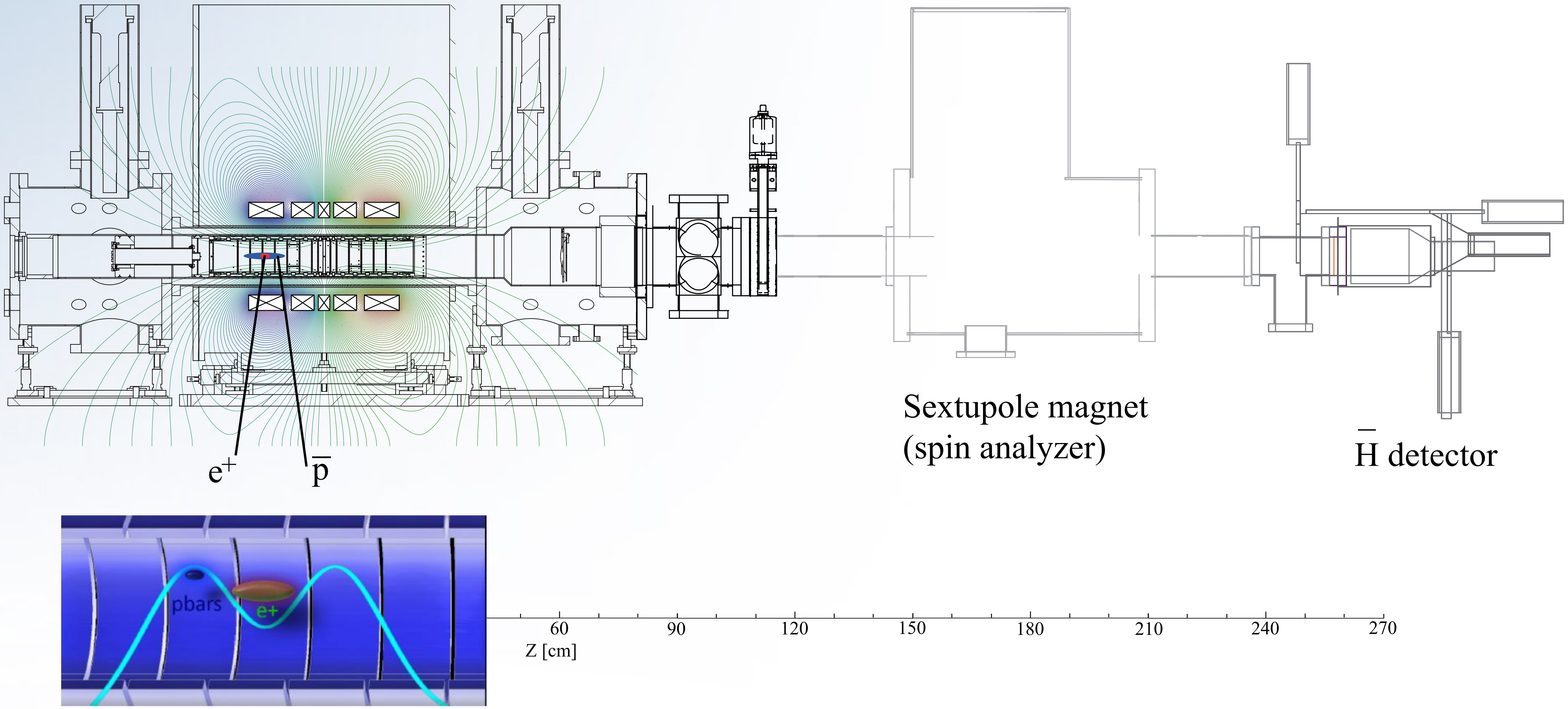
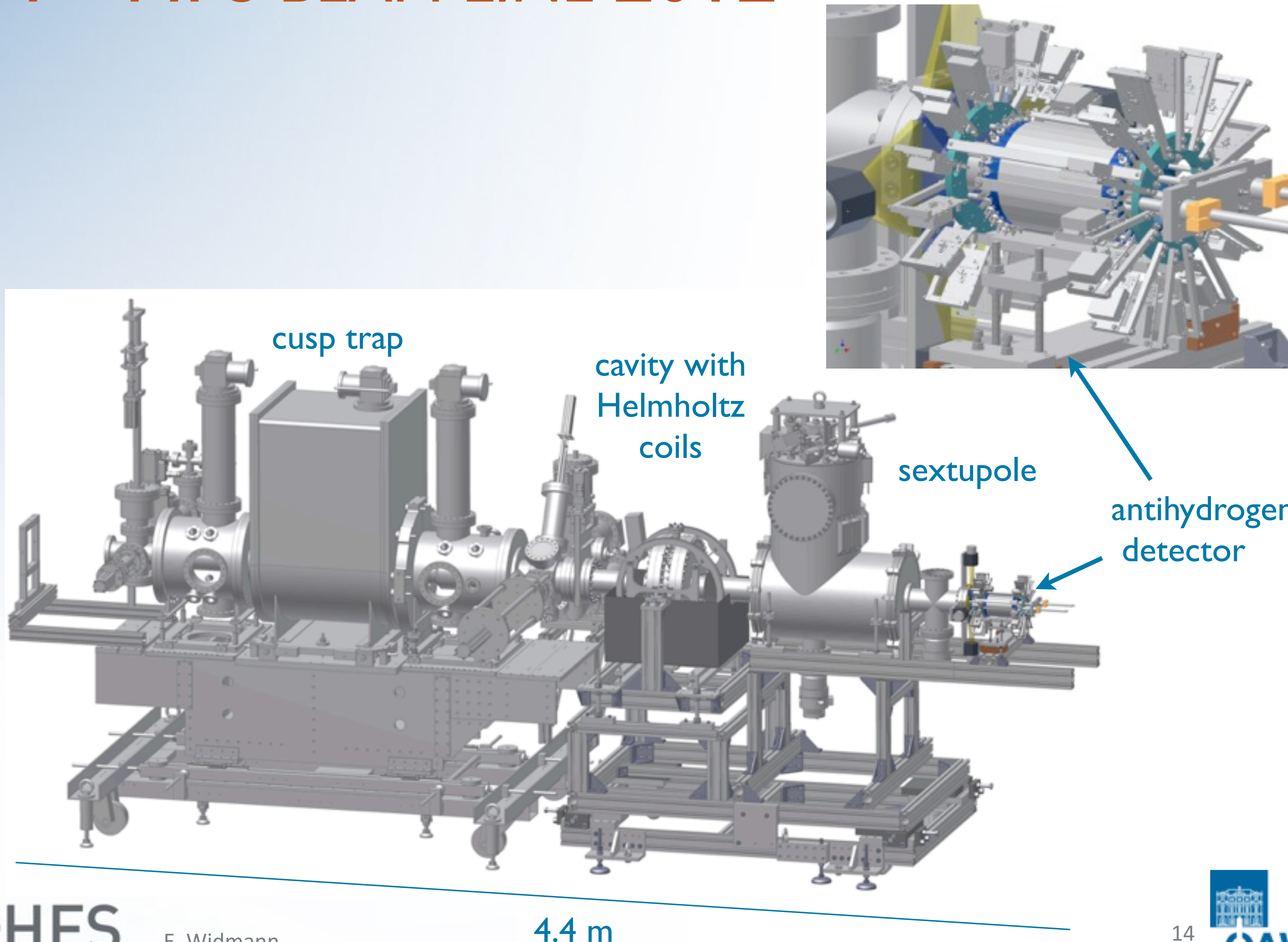
$\overline{H}$ FORMATION IN CUSP TRAP



Nested Penning traps

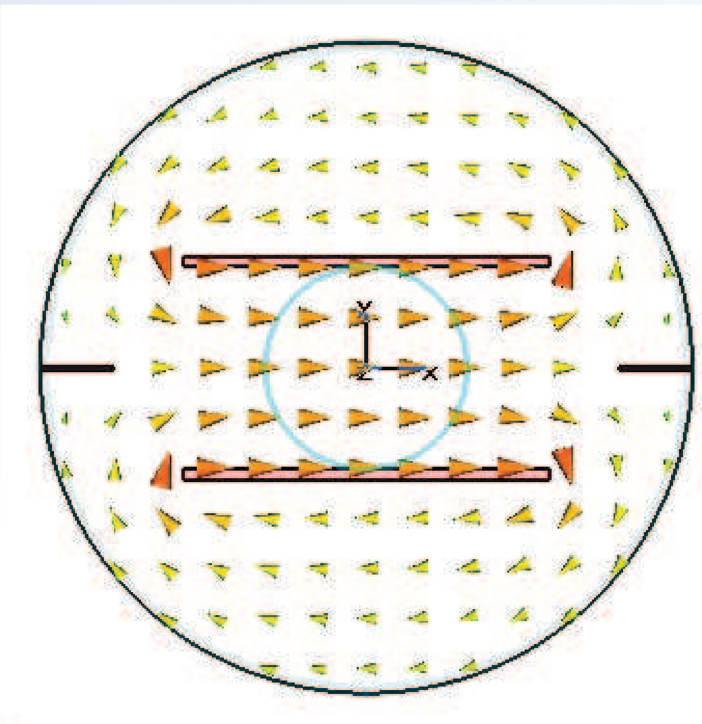
Results of 2012 run to come...

HBARHFS BEAM LINE 2012



SPIN-FLIP RESONATOR

- f = 1.420 GHz, Δf = few MHz, ~ mW power
- challenge: homogeneity over 10x10x10cm^3@ λ=21cm
- solution: strip line

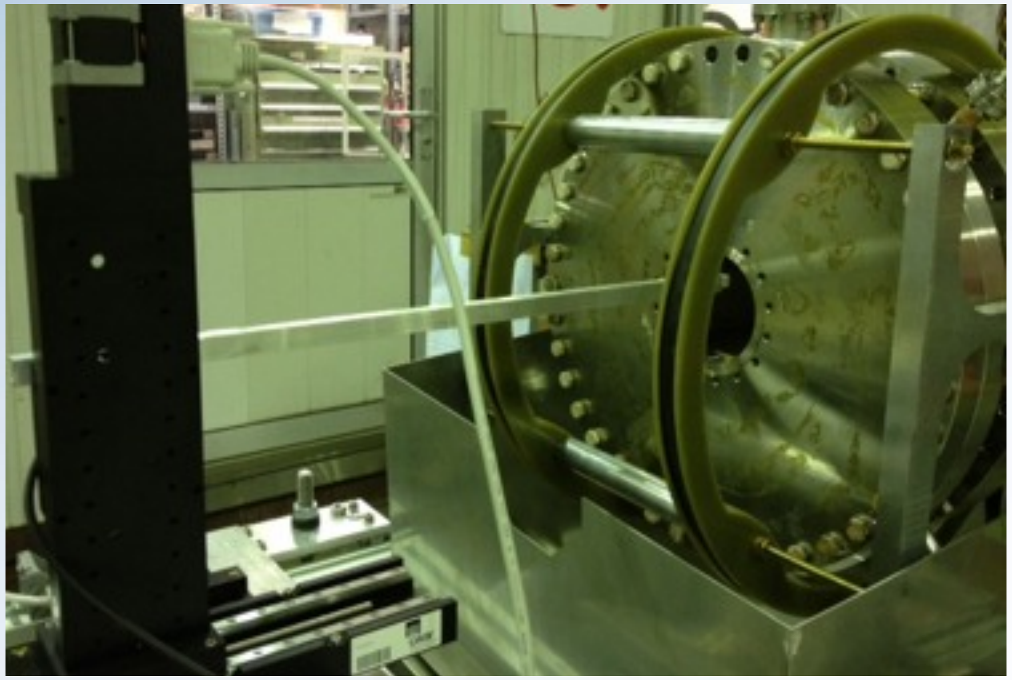


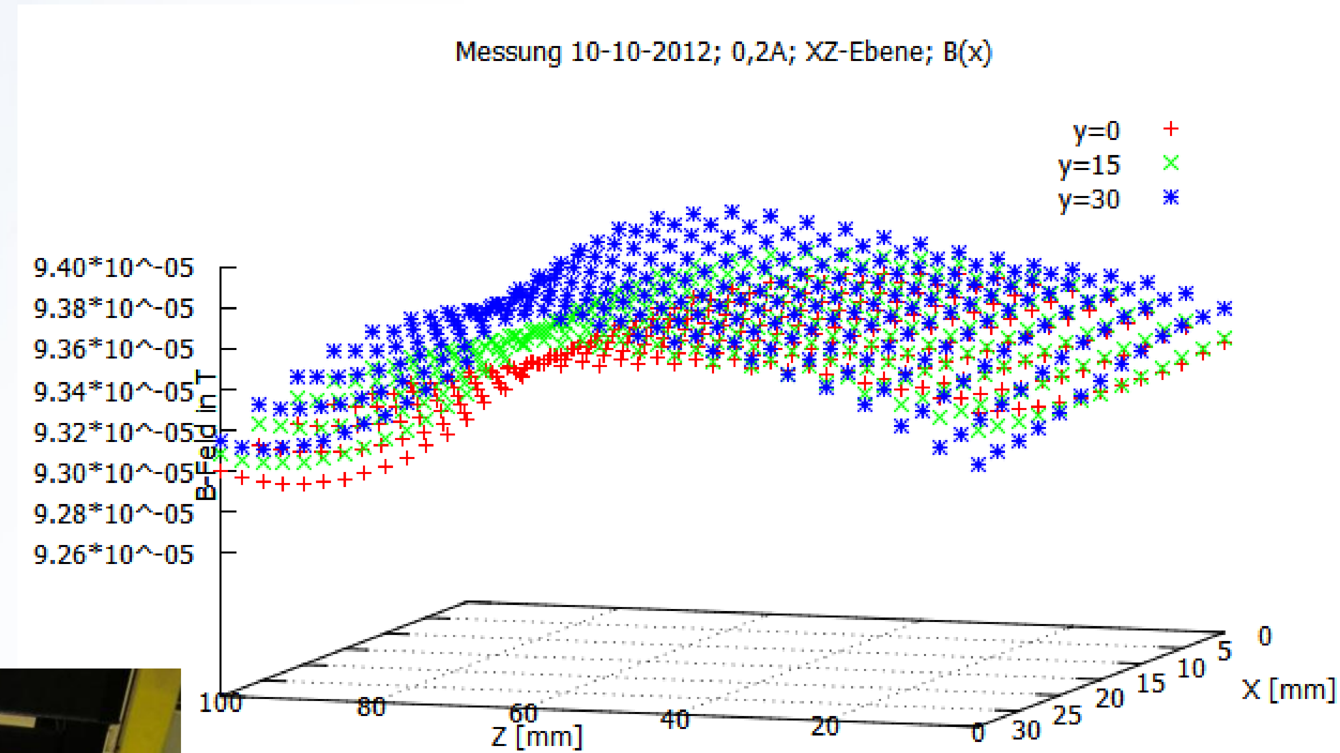
strip line

RF cavity

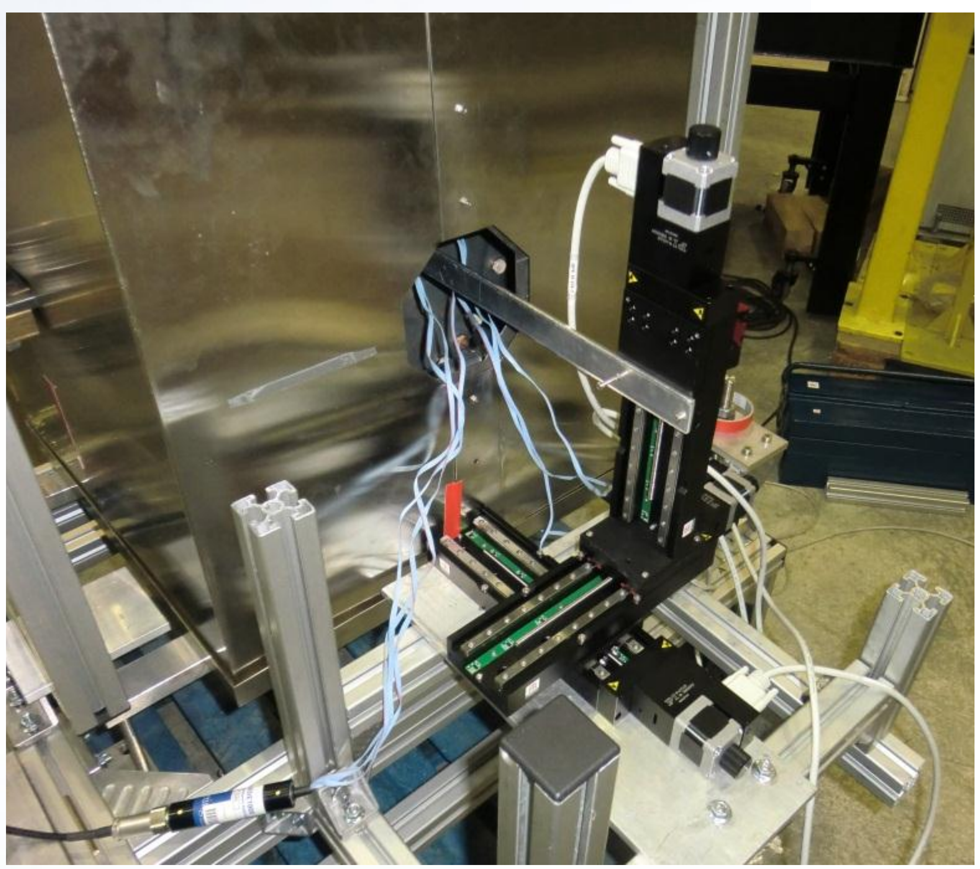
CONSTANT B-FIELD

Helmholtz coils



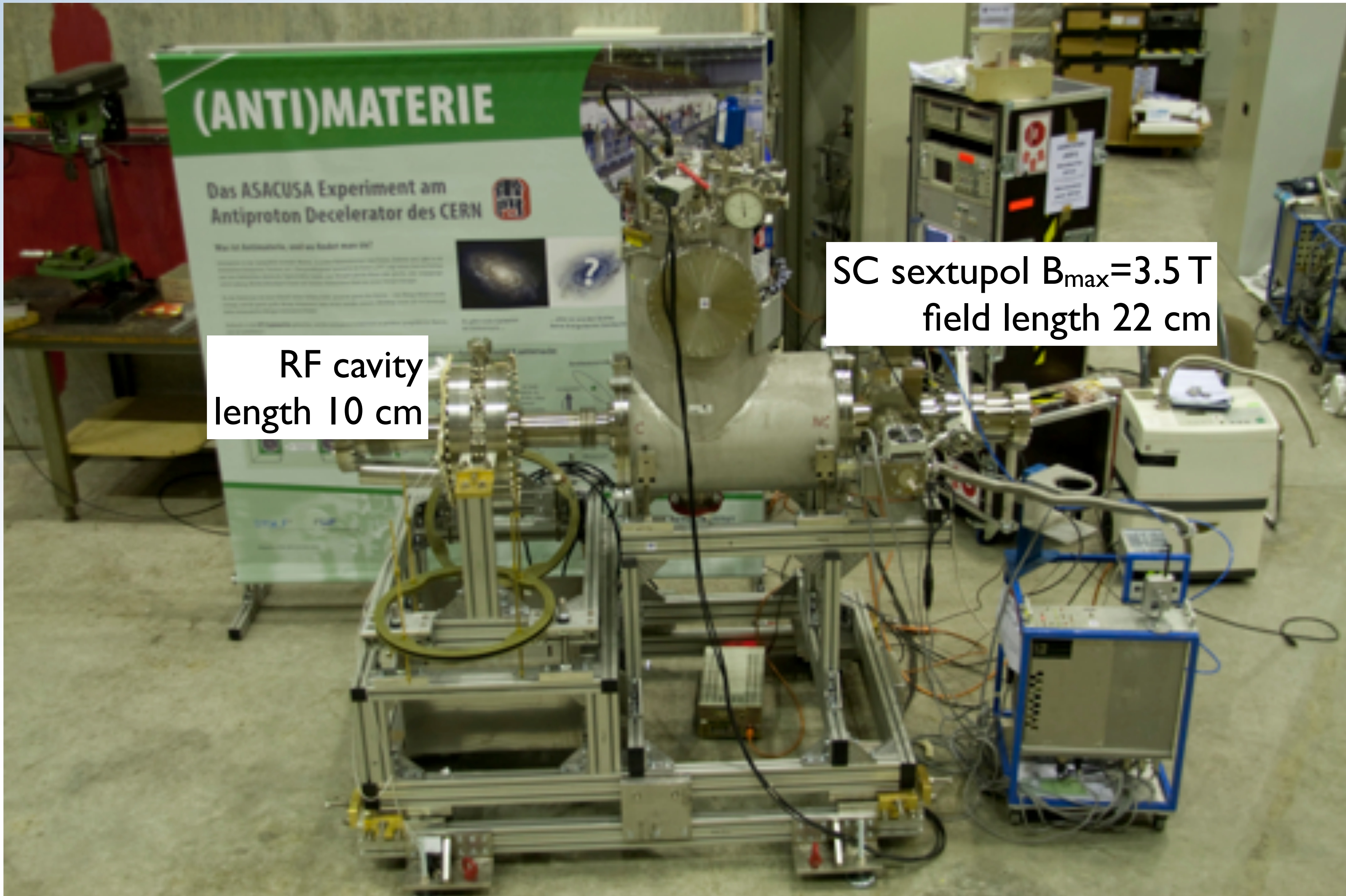


Fluxgate sensors

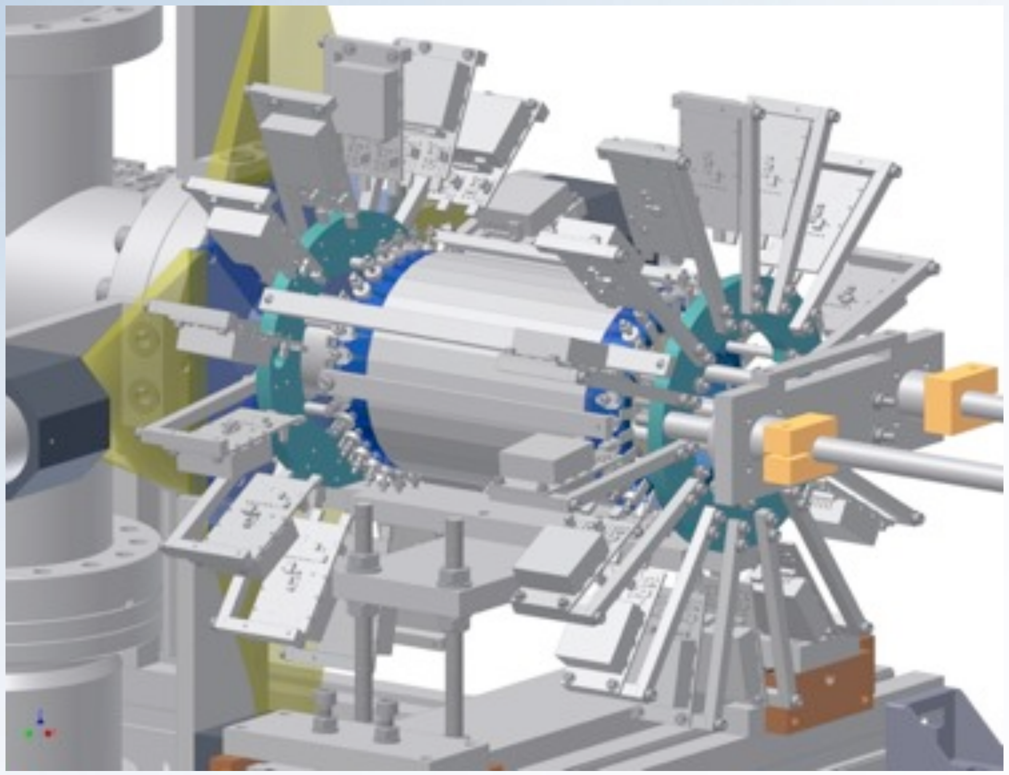


magnetic shielding

SEXTUPOLE & SPIN-FLIP RESONATOR

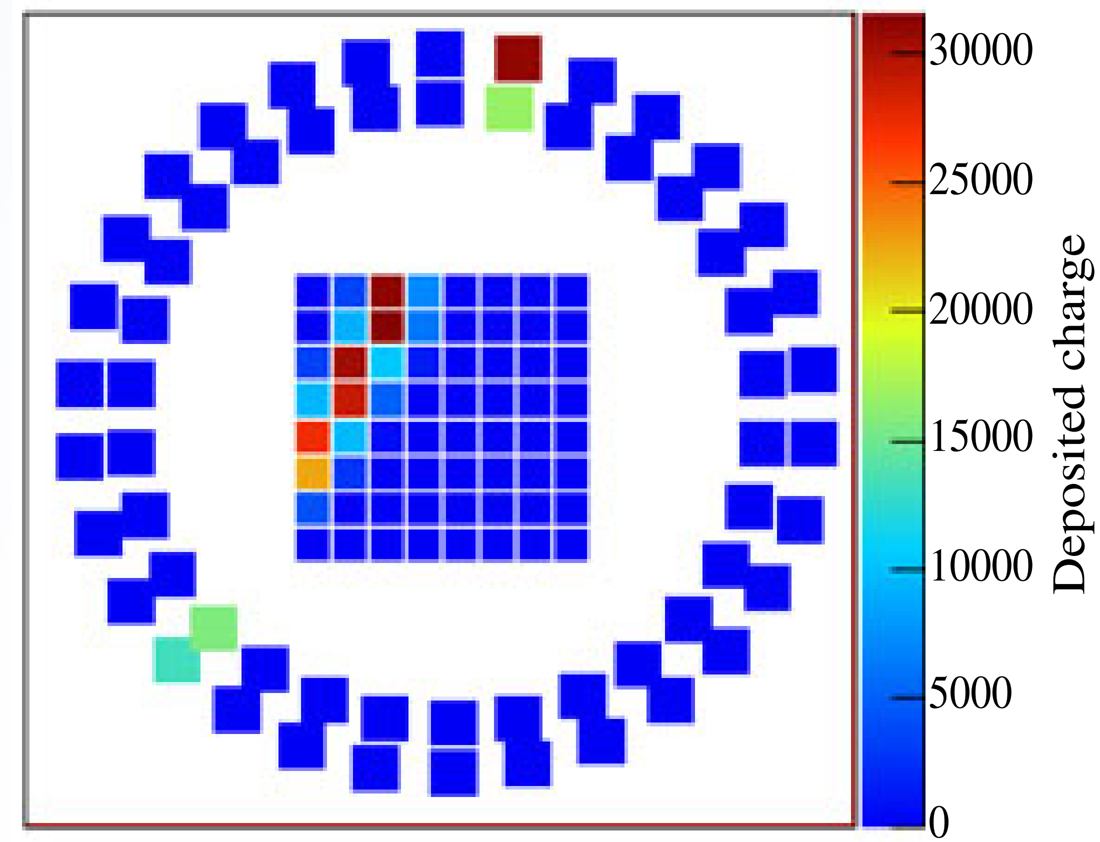


SEGMENTED TRACKING DETECTOR



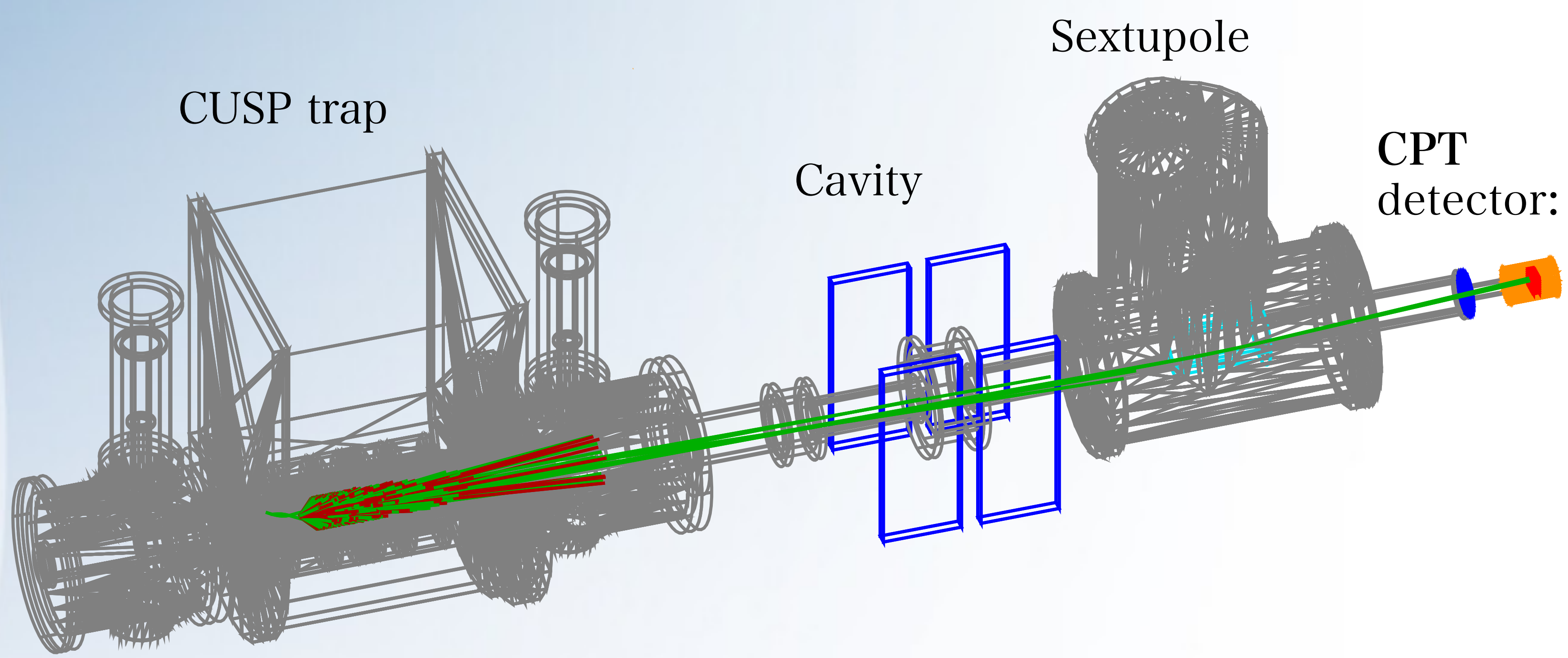
Hodoscope 8 cm diam.
30 plastic scintillators
- 5×10 mm^2
- length 15 cm

2x SiPM readout



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

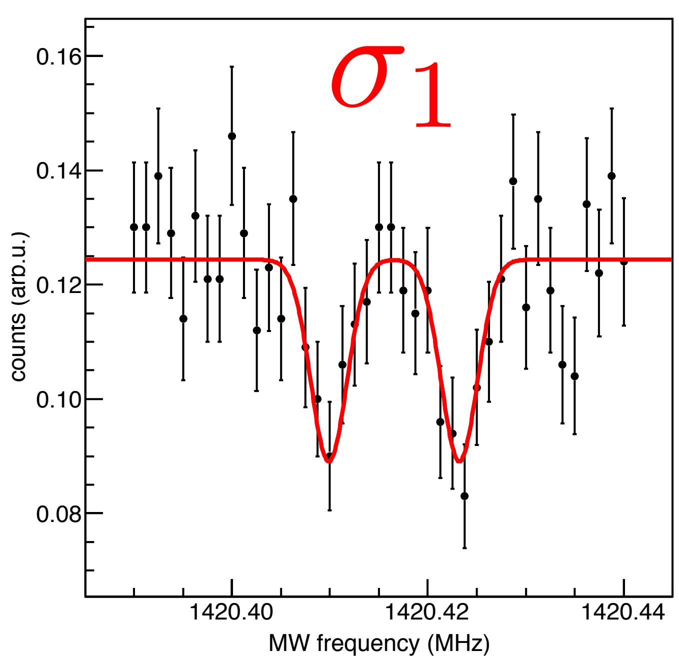
SIMULATION & DATA



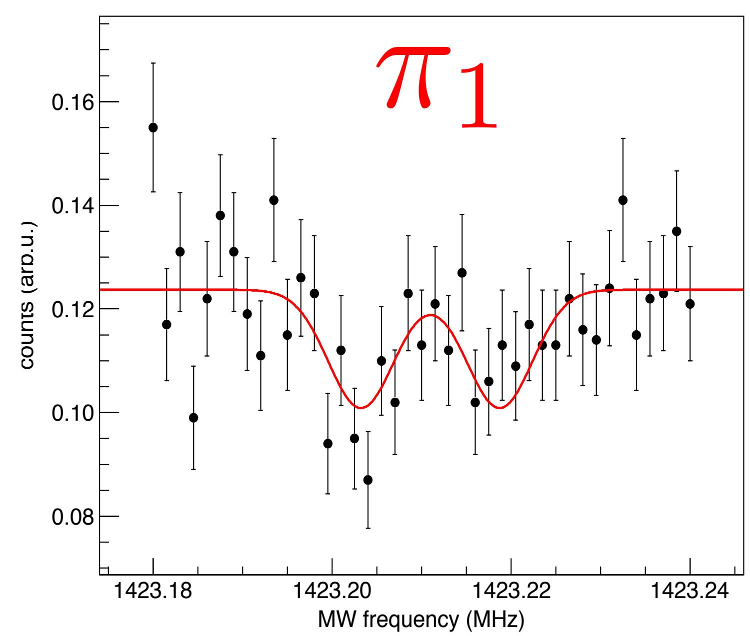
G4 studies:

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

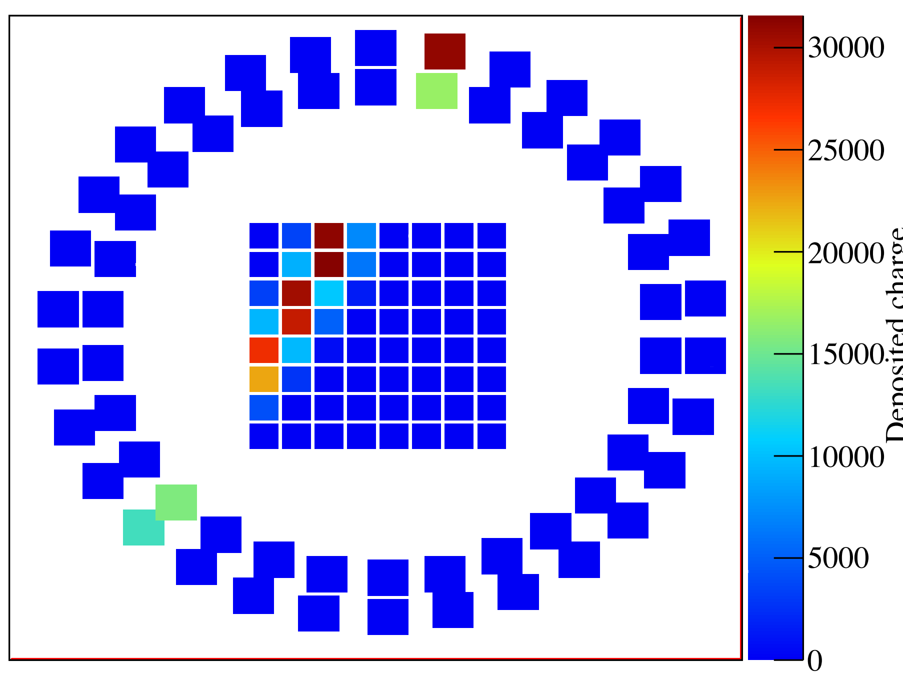
$$\frac{\Delta B}{B} = 1\%$$



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



simulation done at 2G, T=50K

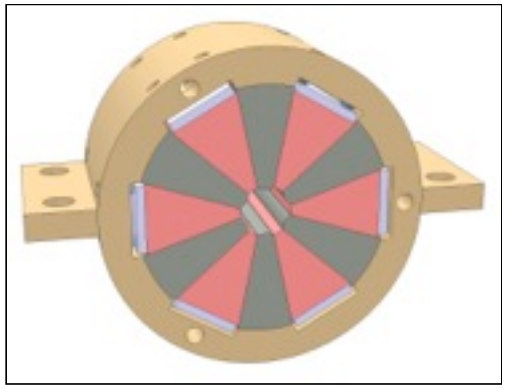


cosmic events in the CPT detector (2012)

SETUP TESTING DURING LS1

Hydrogen beam:

- Source of atomic hydrogen (microwave discharge)
- Permanent sextupoles create polarized hydrogen beam
- QMS detect GS hydrogen
- Choppers connected to a lock-in amplifier for noise reduction

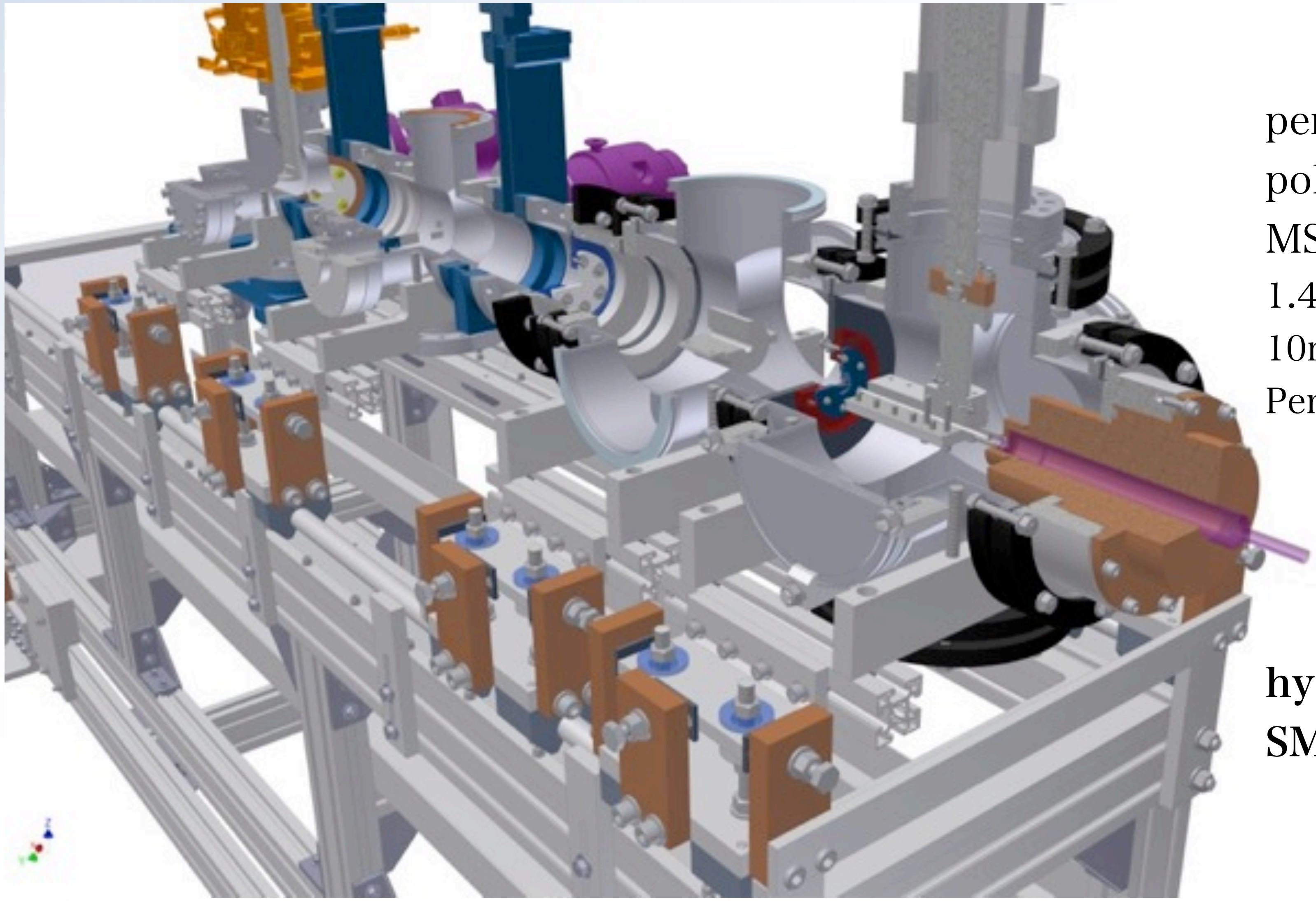


permanent sextupole for initial polarization developed at CERN by TE-MSC-MNC

1.4T integrated field

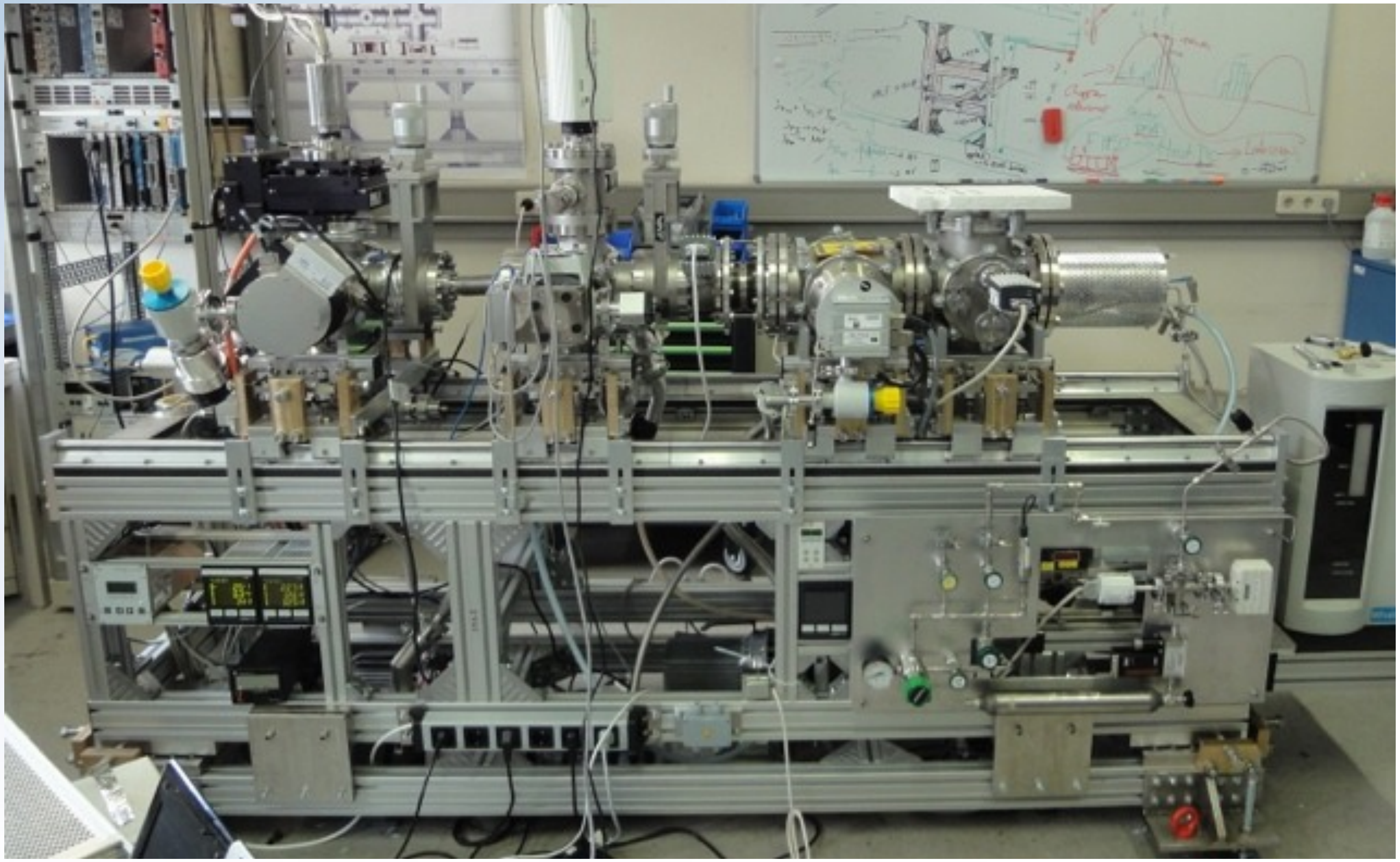
10mm inner diameter

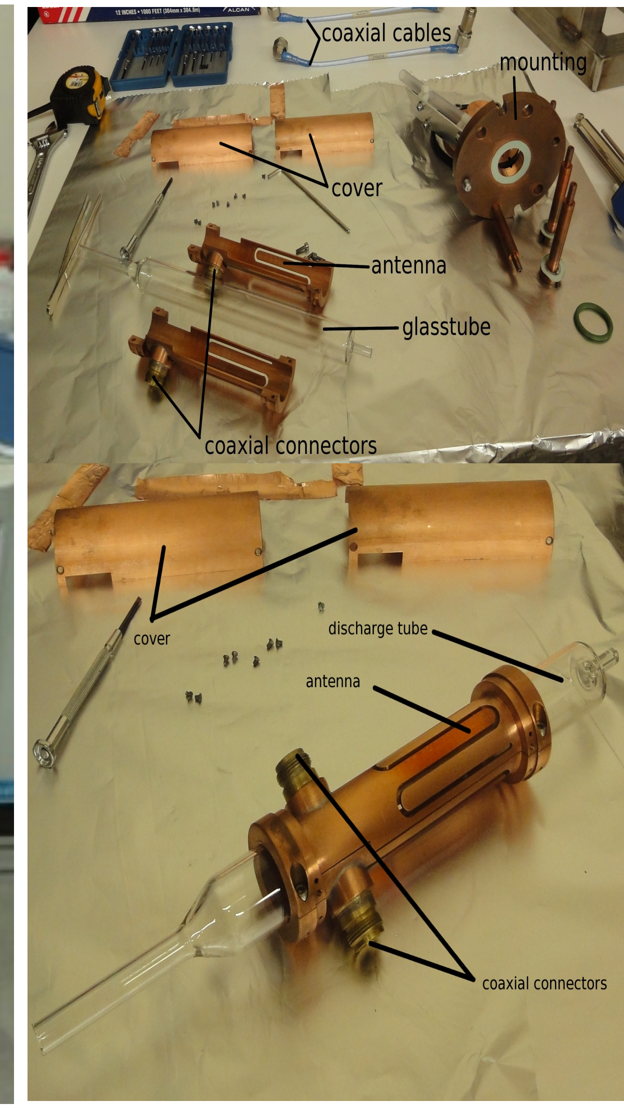
Permendur/permanent magnet



hydrogen beamline developed at SMI

HYDROGEN BEAMLINE

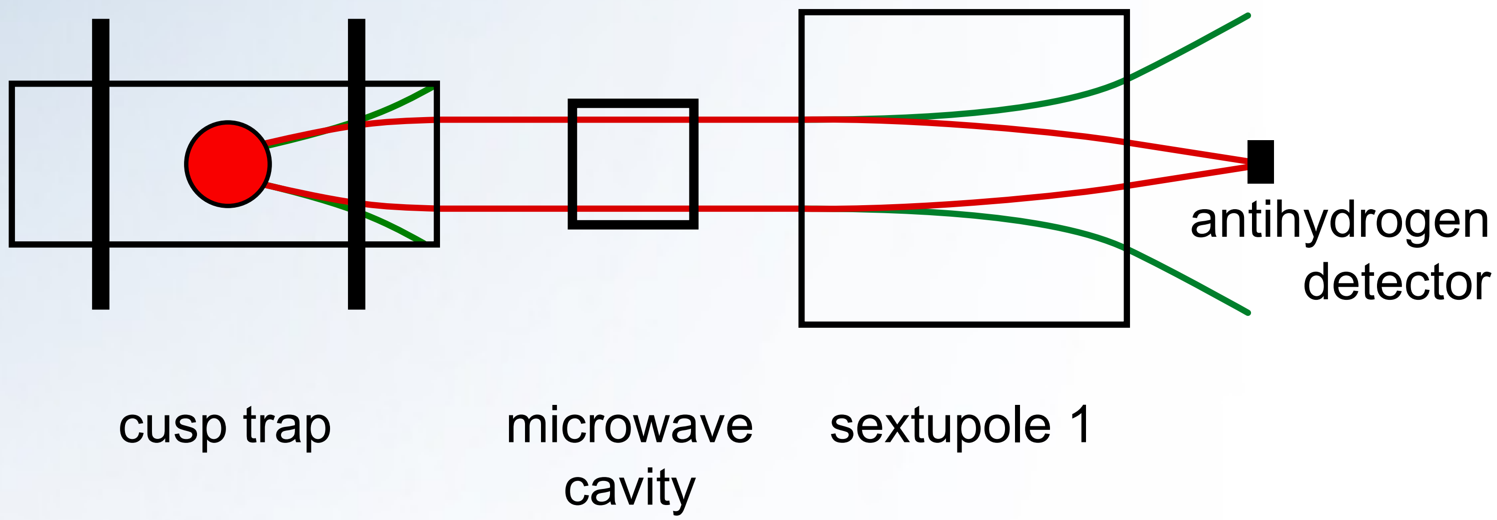




Setup will be transported to CERN in July 2013 to be coupled to the **cavity** and **superconducting sextupole**

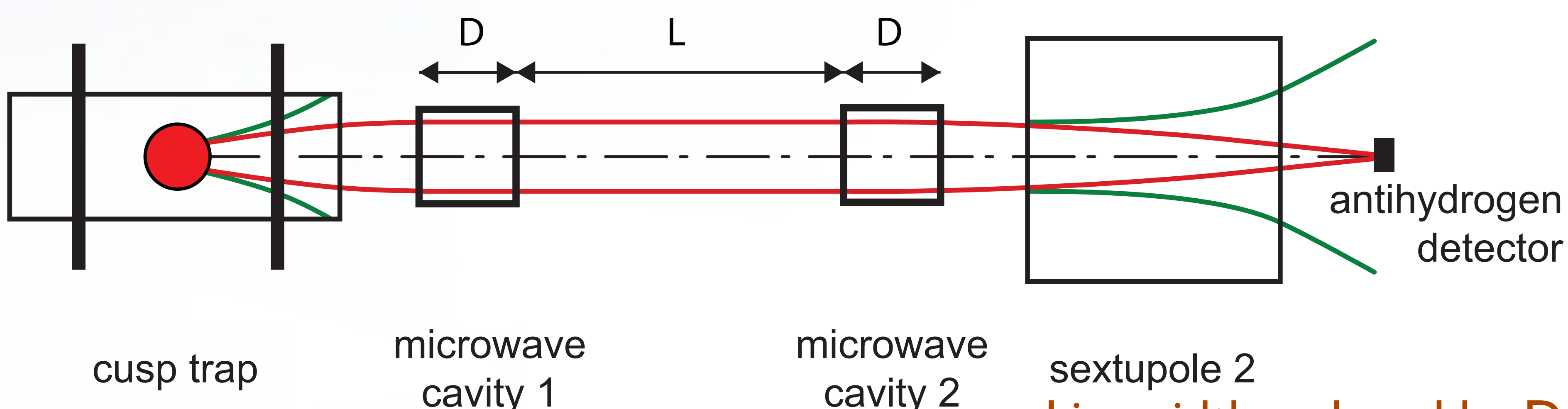
EXPERIMENTS IN AN ATOMIC BEAM

- Phase 1 (ongoing): Rabi method



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

- Phase 2: Ramsey separated oscillatory fields

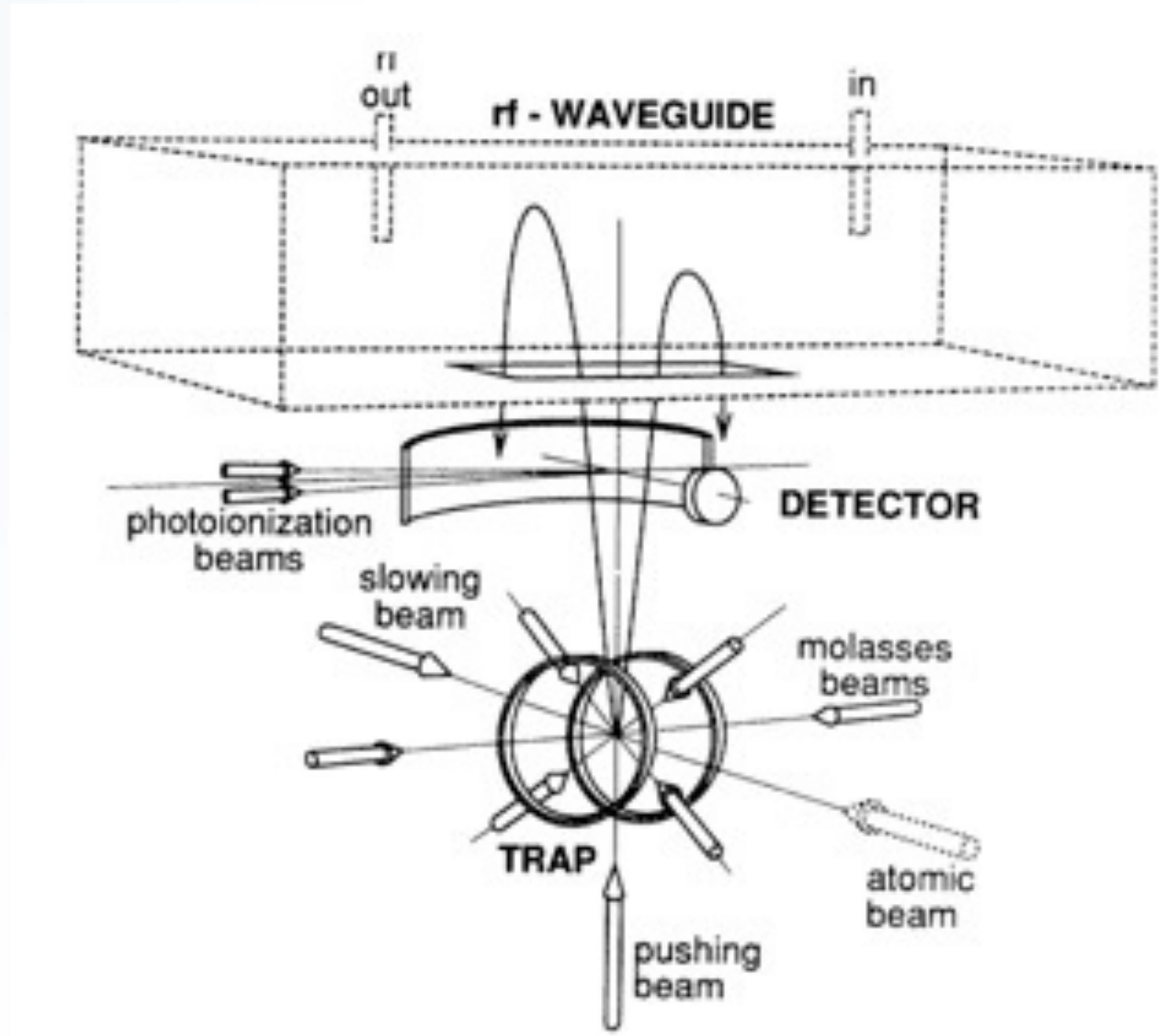


Linewidth reduced by D/L

(FAR) FUTURE EXPERIMENTS

• PHASE 3: TRAPPED $\bar{H}$

- 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 ~ 2x10^{-9}



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

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 $\bar{H}$ 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

THE ASACUSA COLLABORATION

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

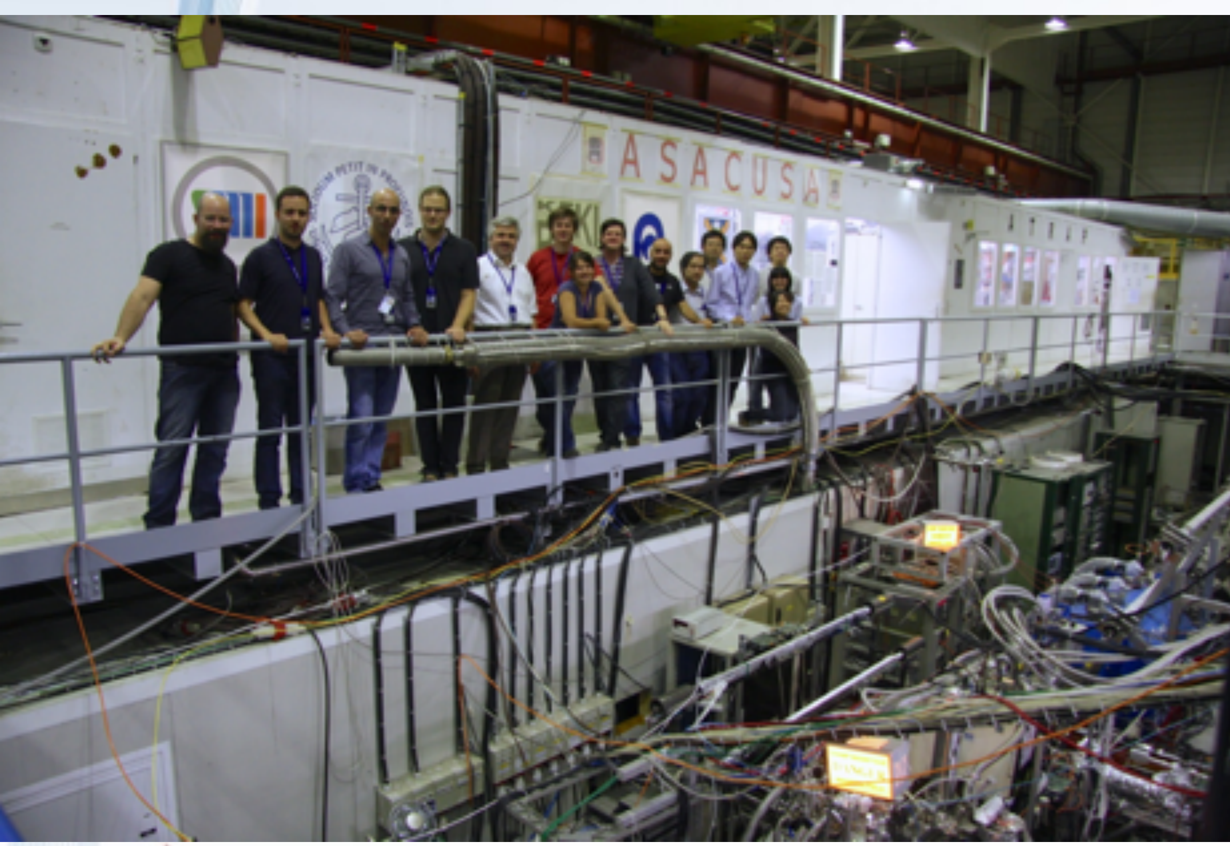
ASACUSA Scientific project

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

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

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

The $\bar{H}$ team



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Stefan Meyer Institut für Subatomare Physik: P. Caradonna, M. Diermaier, S. Friedreich, C. Malbrunot, O. Massiczek, C .Sauerzopf, K. Suzuki, E. Widmann, M. Wolf, J. Zmeskal