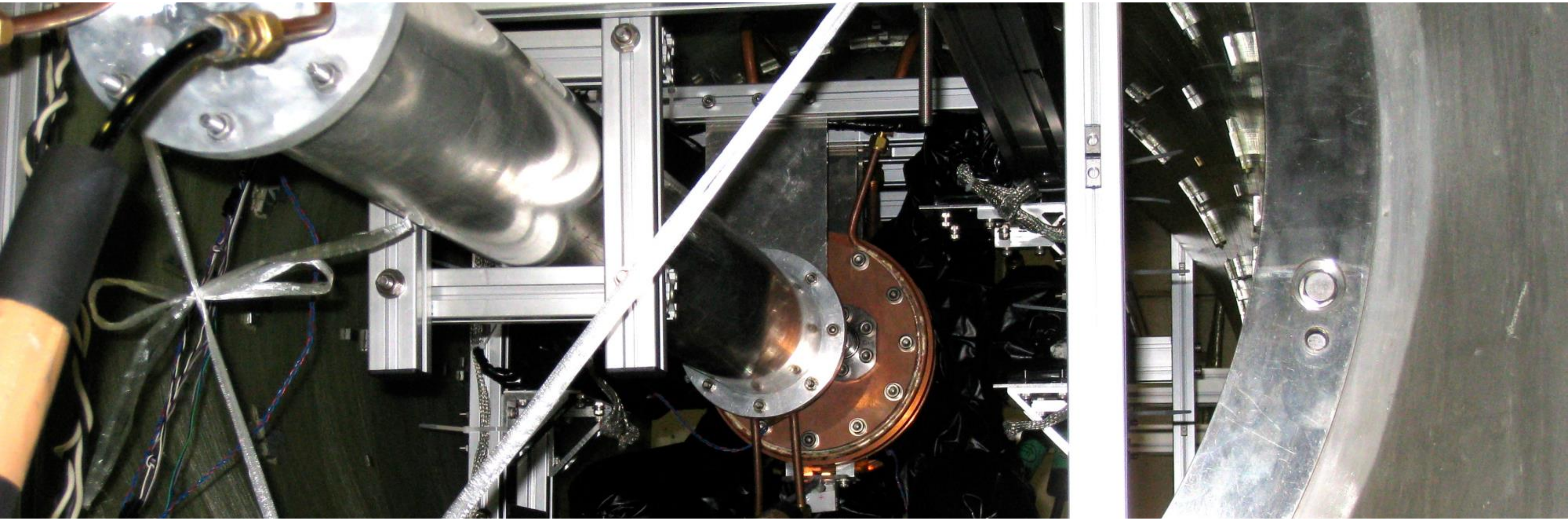
New precision measurement of hyperfine splitting of positronium



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ICPA-17

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Outline

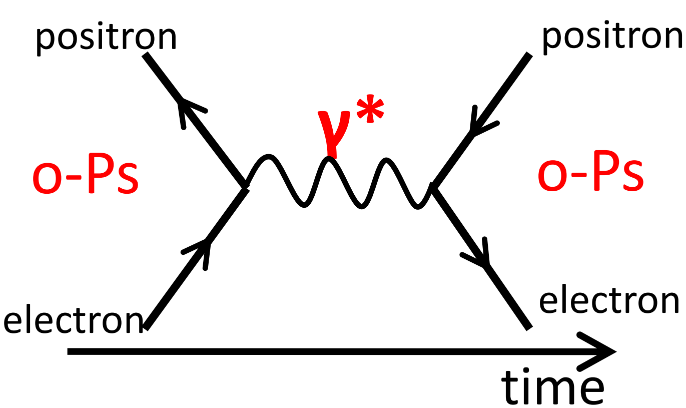
- Introduction: Positronium Hyperfine Splitting (Ps-HFS) *puzzle*
- Ps thermalization effect on Ps-HFS
- New Experiment
- Future Prospects
- Conclusion

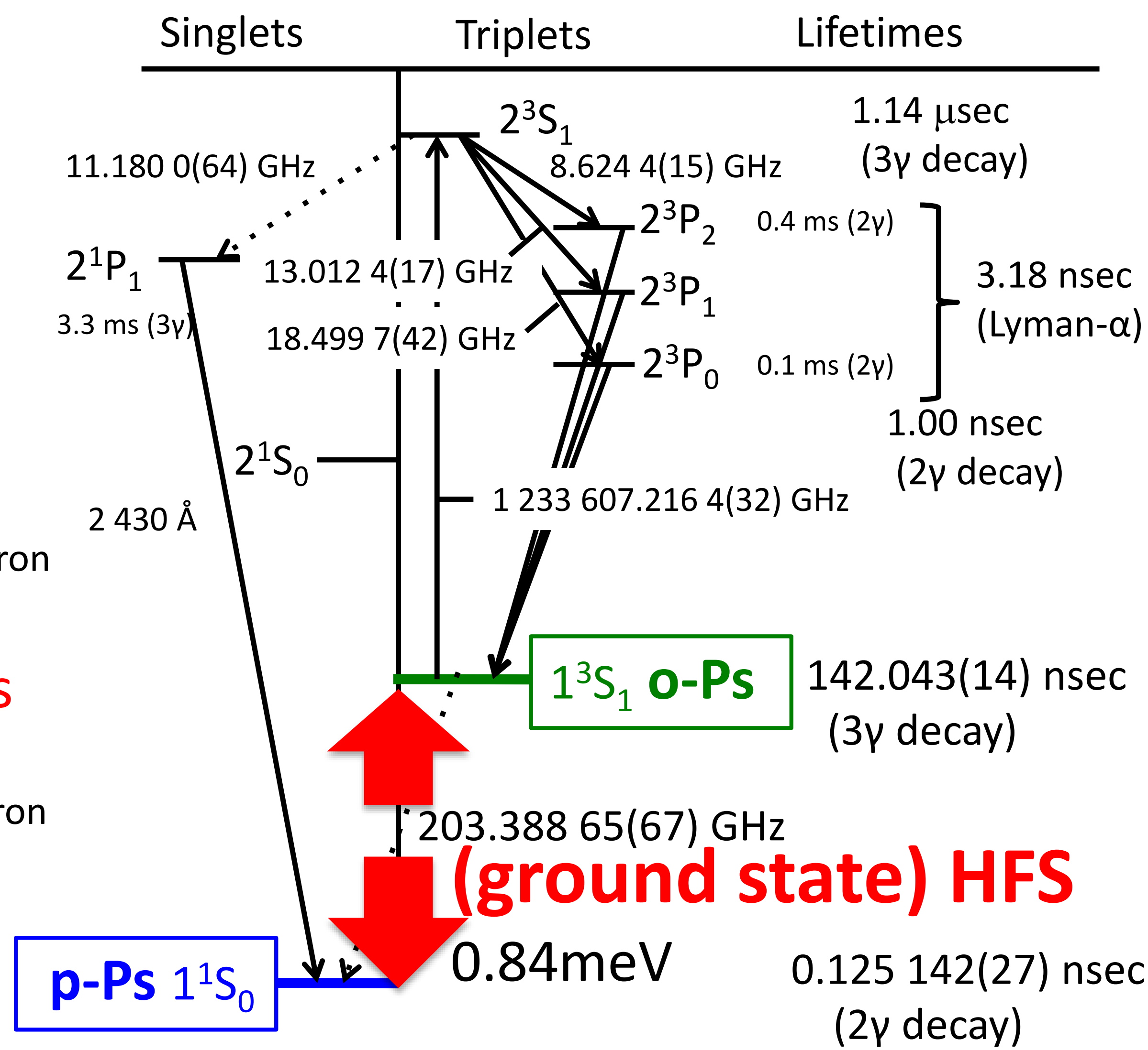
Positronium Hyperfine Splitting (Ps-HFS) and its characteristics

Energy difference between two spin eigenstates of the ground state Ps

→ Ps-HFS (203 GHz)

$$\vec{\mu} = \frac{e}{2m}\vec{\sigma}$$ spin-spin interaction





Quantum oscillation effect is also large (40%)

→ Sensitive to new physics beyond SM

History of Ps-HFS

Experiment

- First measurement by M. Deutsch and S.C. Brown (1952, 1500 ppm).
- Most precise measurements by two independent groups:
  A.P. Mills, Jr. and G.H. Bearman (1975 and 1983, 8 ppm),
  M.W. Ritter, P.O. Egan, V.W. Hughes, and K.A. Woodle (1984, 3.6 ppm).
- Our new precise measurement taking into account the Ps thermalization effect (A. Ishida *et al.*, 2014, 10 ppm).

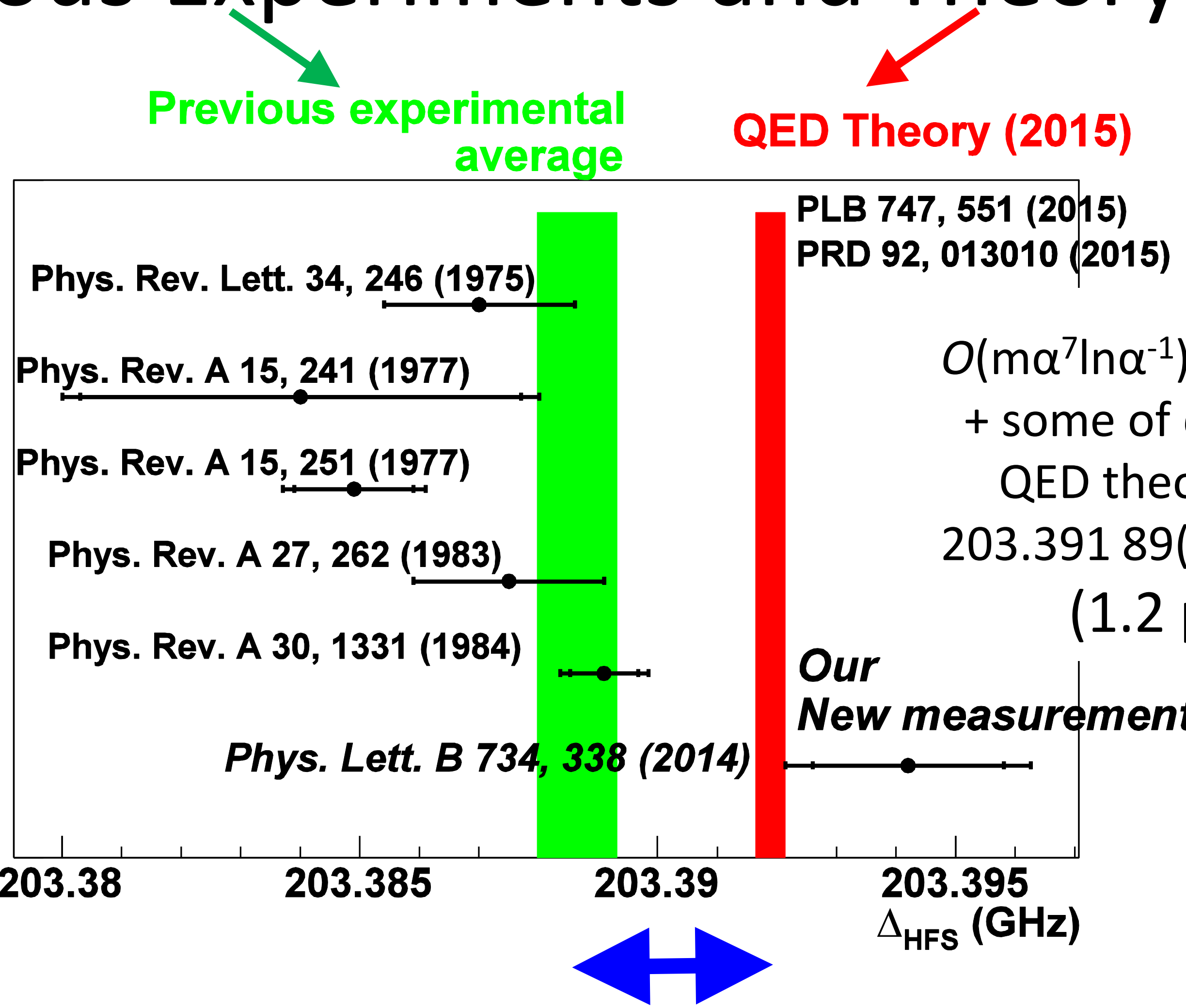
Theory

Pure
bound-state QED

$$\Delta_{\mathrm{HFS}}^{\mathrm{th}} = \frac{7}{12} m_e \alpha^4 \left\{ 1 - \frac{\alpha}{\pi}\left(\frac{32}{21} + \frac{6}{7}\ln 2\right) + \frac{5}{14}\alpha^2 \ln\frac{1}{\alpha} + \left(\frac{\alpha}{\pi}\right)^2 \left[\frac{1367}{378} - \frac{5197}{2016}\pi^2 + \left(\frac{6}{7} + \frac{221}{84}\pi^2\right)\ln 2 - \frac{159}{56}\zeta(3)\right] - \frac{3}{2}\frac{\alpha^3}{\pi}\ln^2\frac{1}{\alpha} + \left(\frac{62}{15} - \frac{68}{7}\ln 2\right)\frac{\alpha^3}{\pi}\ln\frac{1}{\alpha} + D\left(\frac{\alpha}{\pi}\right)^3 + \ldots \right\},$$

- First term calculated by J. Pirenne (1947).
- $O(m\alpha^7 \ln(1/\alpha))$ was calculated by three groups (2000).
- $O(m\alpha^7)$ non-logarithmic term calculation are ongoing since 2014, motivated by our experimental result and many other efforts.

Ps-HFS Puzzle: Discrepancy Between Previous Experiments and Theory



Previous experimental results are consistently lower than theory.

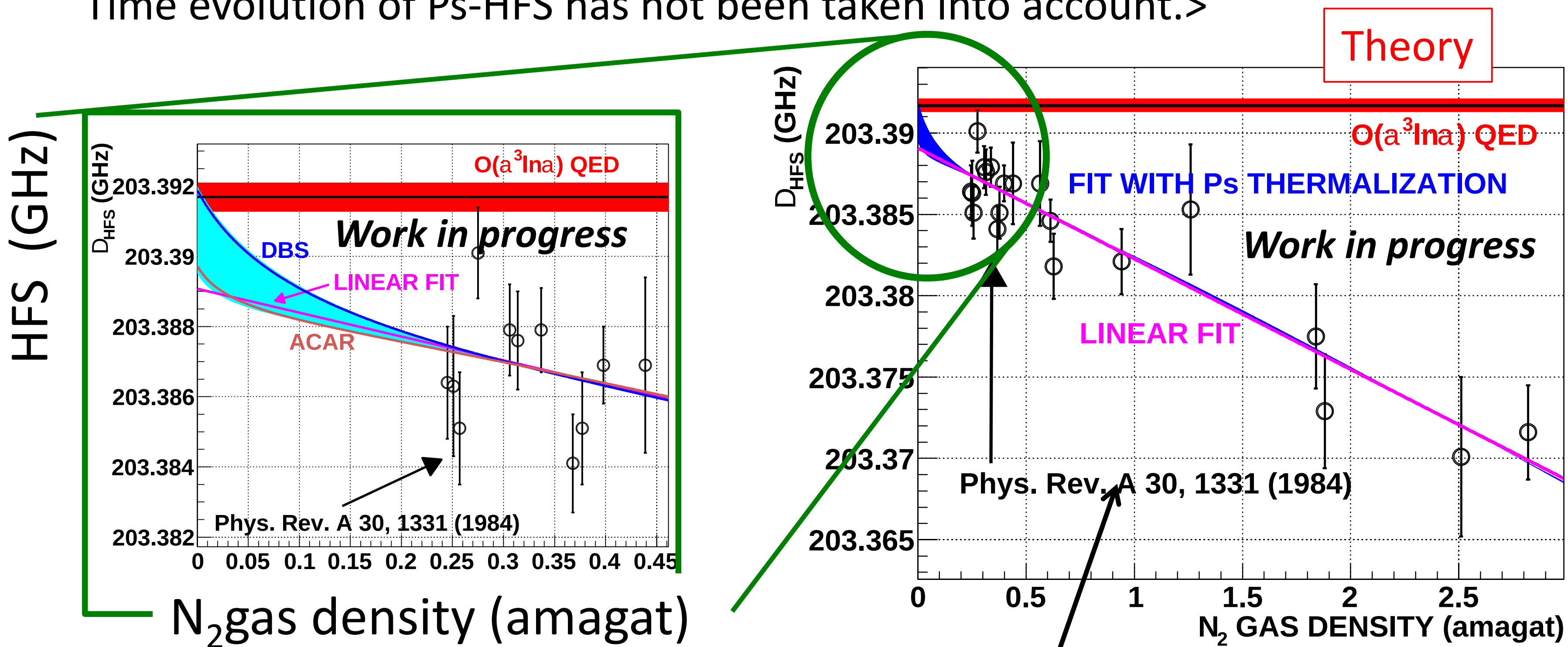
Previous experimental average 203.388 65(67) GHz (3.3 ppm)

$O(m\alpha^7 \ln\alpha^{-1})$ + some of $O(m\alpha^7)$ QED theory 203.391 89(25) GHz (1.2 ppm)

16 ppm (4.5 σ) significant discrepancy

Ps thermalization effect on Ps-HFS

<Simulation of material effect correction from density + thermaliaztion.
Time evolution of Ps-HFS has not been taken into account.>



O(10 ppm) correction in N_2 case:

- Put the experimental value close to the theory.
- Significant correction which cannot be ignored.
- Different techniques give different corrections.
  - →Main reason of large uncertainty
  - →**Measured the thermalization independently.**

(σ_m, E_0)=
DBS:(13.0×10^{-16} cm^2 , 2.07 eV)
ACAR:(37×10^{-16} cm^2 , 2.07 eV)
RF frequency = 2.32 GHz
RF magnetic field =10 Gauss
Static magnetic field = 0.78 Tesla
Experiment: Hughes et al. (1984)
Theory: Kniehl et al. (2000)

Details of Our New Experiment

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Department of General Systems Studies, The University of Tokyo

M. Yoshida, K. Tanaka, A. Yamamoto
High Energy Accelerator Research Organization (KEK)

Warm thanks to facilities and the entire members of the Cryogenics Science Center at KEK

Used new techniques to reduce the possible reasons of the puzzle

Two possible common systematic uncertainties in the previous experiments

1. Non-uniformity of the magnetic field.
2. Underestimation of material effects. Unthermalized o-Ps effect can be significant

cf. o-Ps lifetime puzzle (1990's)

New techniques were introduced to reduce these uncertainties.

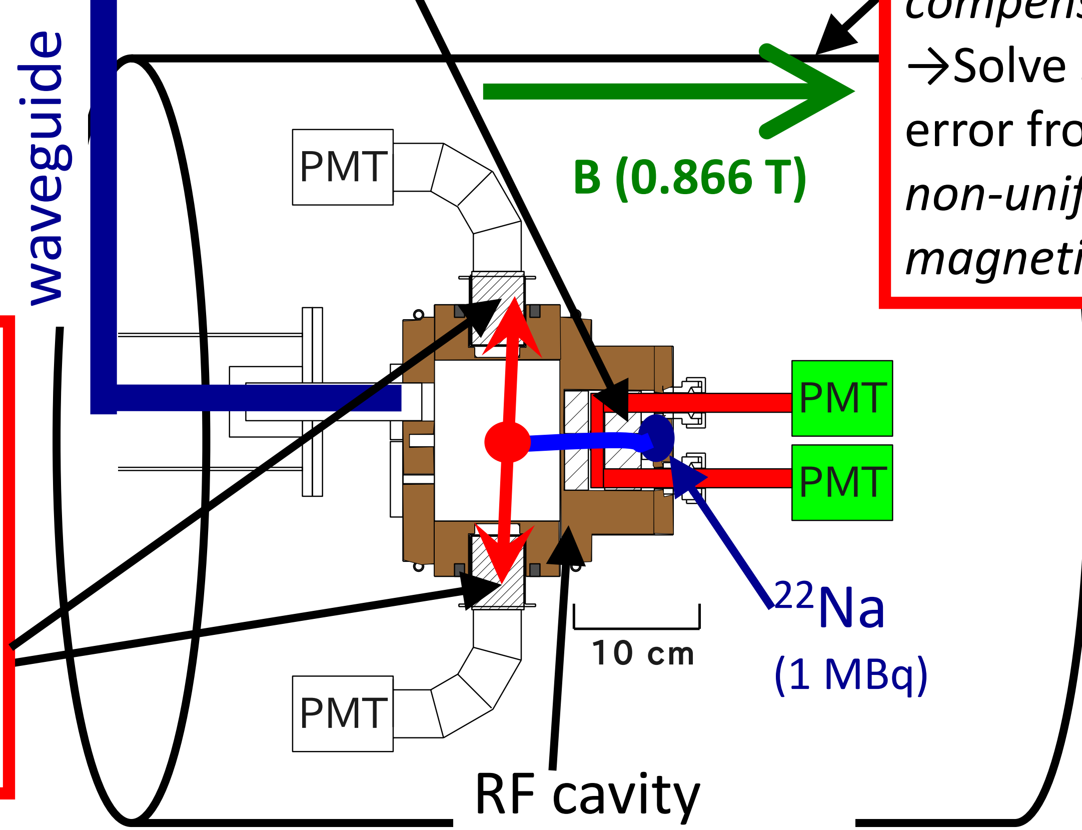
- Large-bore superconducting magnet to reduce the uncertainty 1.
- Time information (by β-tagging system and high-performance γ-ray detectors) to reduce the uncertainty 2.

Our New Experimental Setup

High power RF
(500W CW)

2 *β-tagging system*
→Solve systematic error
from *non-thermalized Ps*.

1 *Large bore superconducting magnet +*
compensation coils
→Solve systematic error from
non-uniformity of magnetic field.

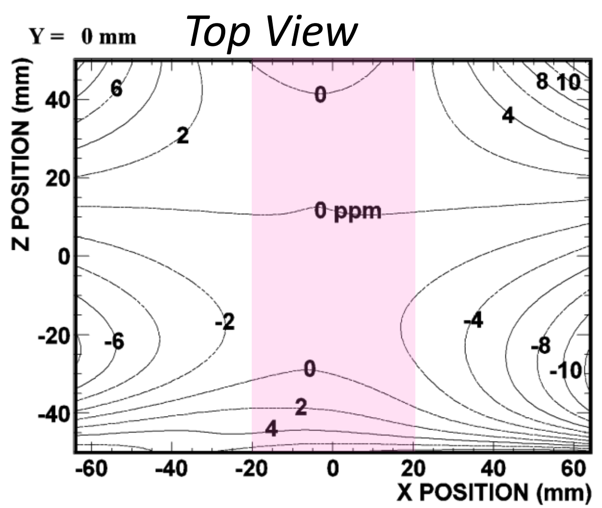


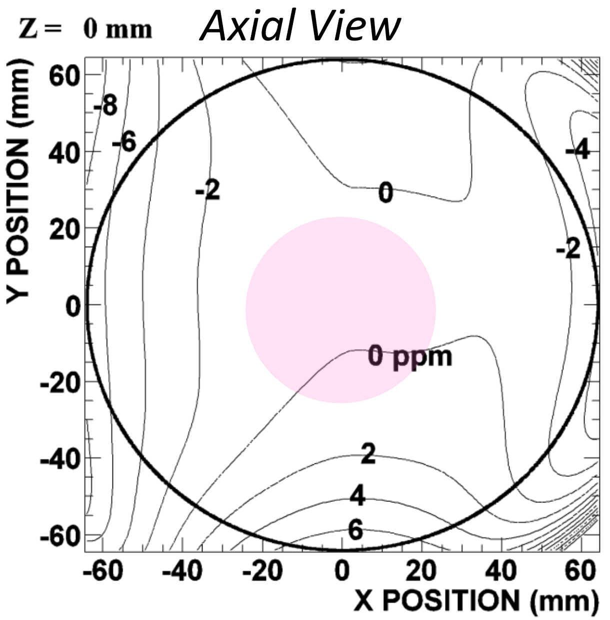
2 *High performance γ-ray detectors*
($LaBr_3$ scintillators)

→Solve systematic error from *non-thermalized Ps*.

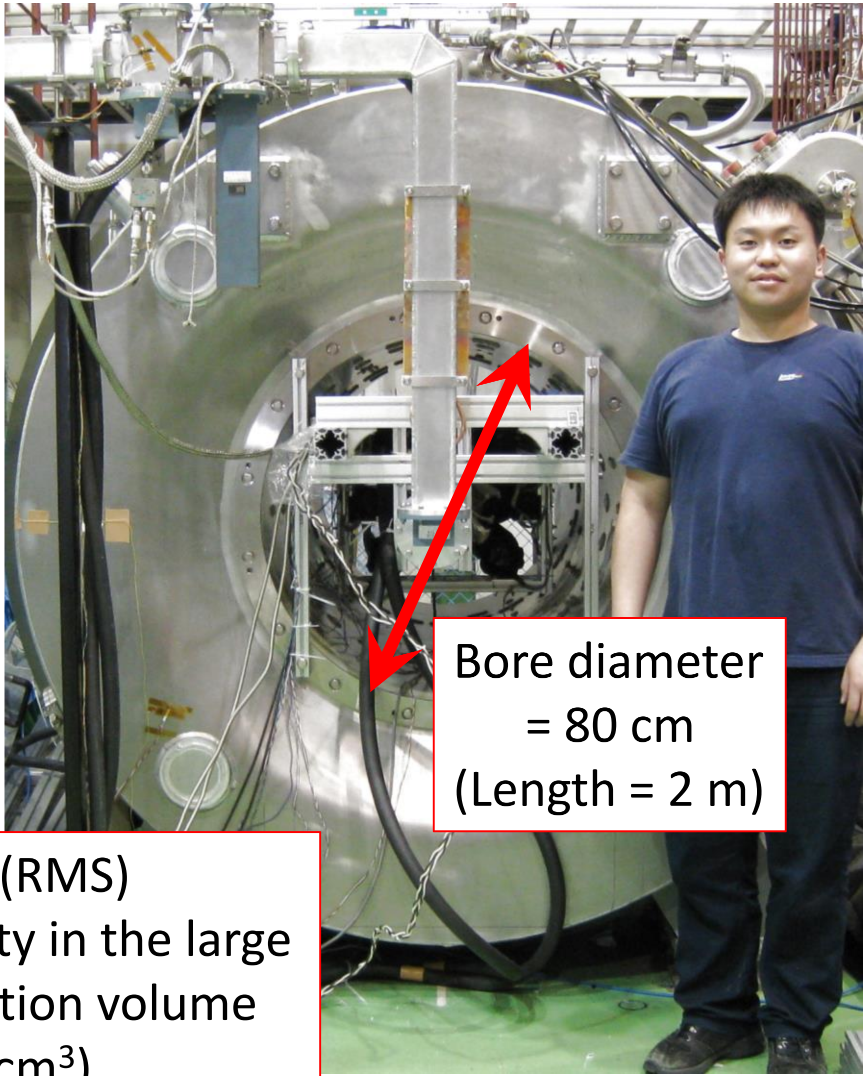
RF cavity
(Filled with
pure i-C_4H_{10})

New technique 1: Large-bore superconducting magnet





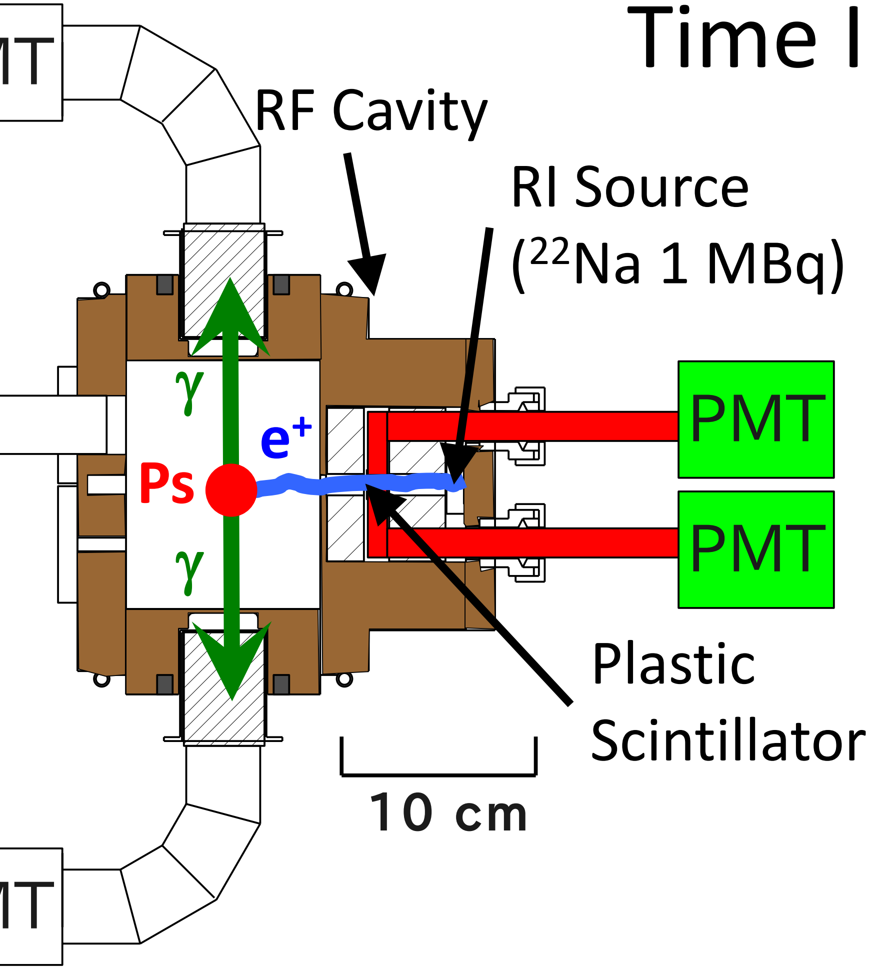
Ps formation volume



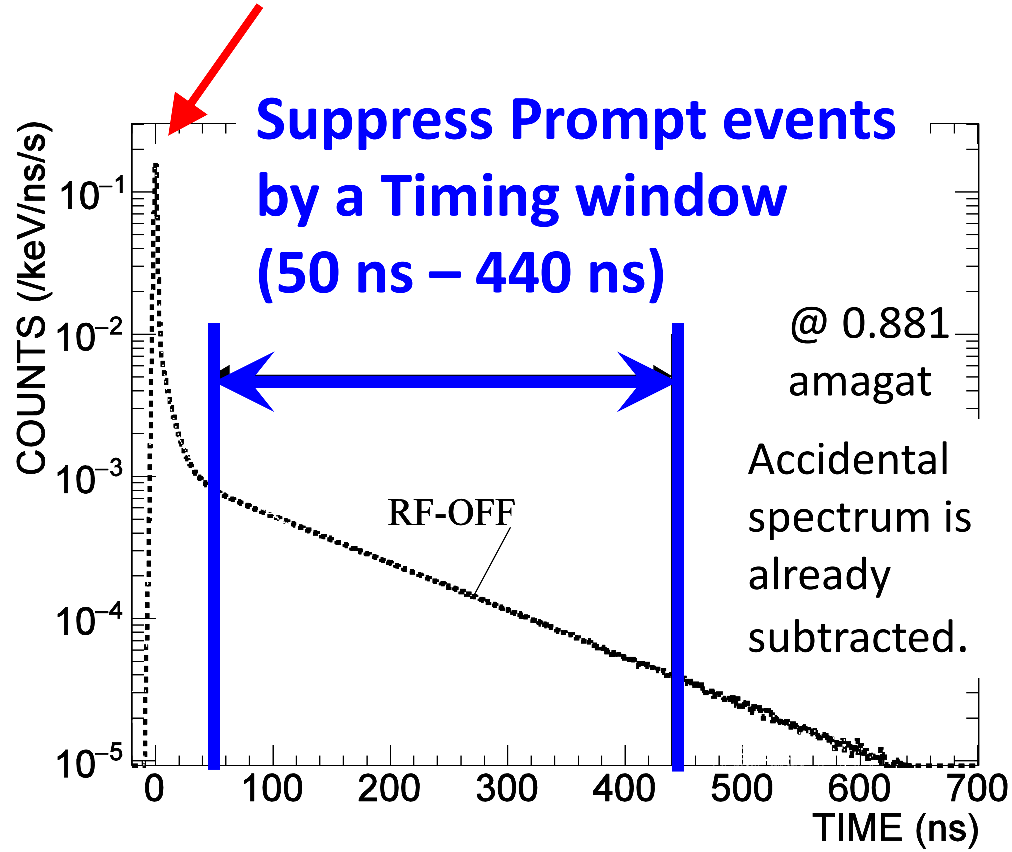
Bore diameter = 80 cm (Length = 2 m)

1.5 ppm (RMS) uniformity in the large Ps formation volume (~ 100 cm^3).

New technique 2: Time Information



- Tag e$^+$ from the ^{22}Na by thin (0.1 mm) plastic scintillator.
  → *t=0*

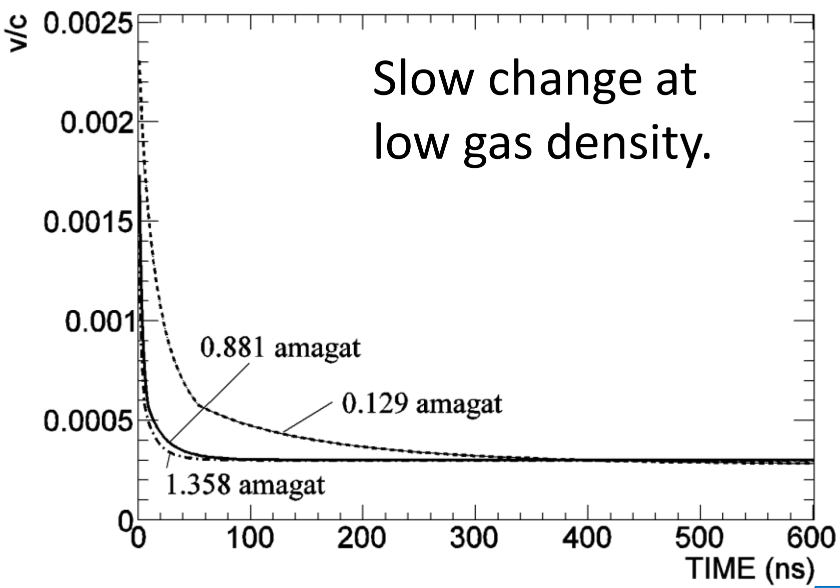


- **Treat Ps thermalization correctly**
- **20 times higher S/N**

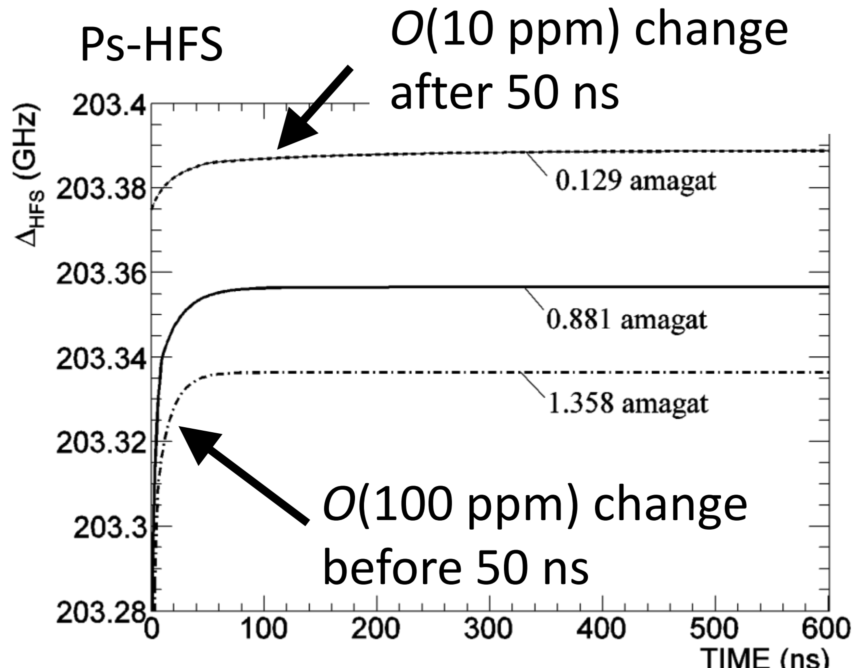
Fitting of resonance lines taking into account time evolution of Ps-HFS

- Scanned by Magnetic Field with the fixed RF frequency and power.
- 50—440 ns was divided to 11 sub timing windows.
- Simultaneous fit of all of the gas density, magnetic field strength, and (sub) timing windows.
- Time evolution of Ps velocity (thermalization) and Δ_{HFS} ($\propto nv^{3/5}$) were taken into account (Thanks to Prof. A. P. Mills, Jr. (UC Riverside) for useful discussions)

Ps velocity / c

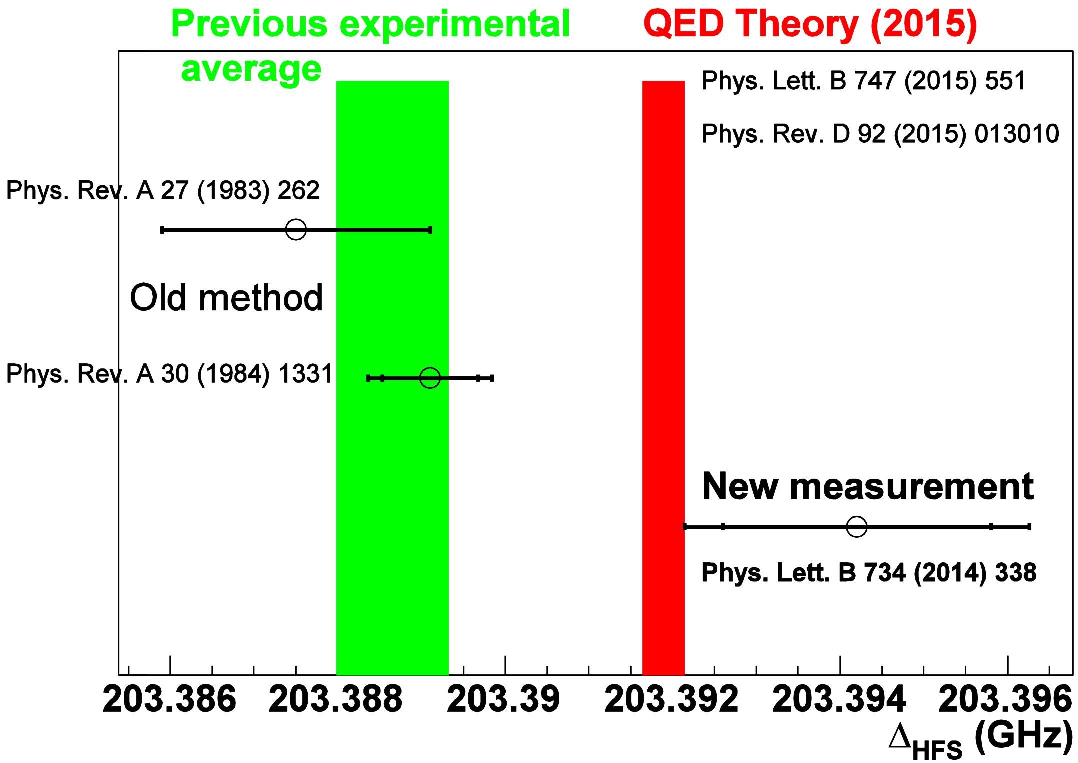


Ps-HFS



$\chi^2/ndf = 633.3 / 592$ ($p = 0.12$)

Result 1: Center value favored QED



Favors QED calculation

(Consistent with theory within **1.1σ**, disfavors previous experiments by **2.6σ**)

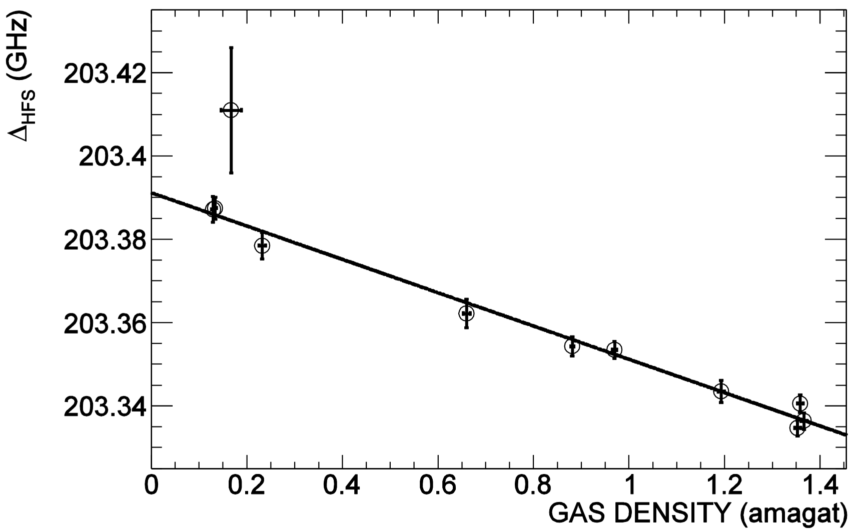
New result taking into account the Ps thermalization was obtained:

$$\Delta_{HFS} = 203.394\,2 \pm 0.001\,6 \text{ (stat., 8.0 ppm)}$$
$$\pm 0.001\,3 \text{ (sys., 6.4 ppm) GHz}$$
$$\text{(total uncertainty = 10 ppm)}$$

Main systematic errors:
Material effect (o-Ps pickoff, spatial distribution of density and temperature in the RF cavity), Magnetic field (non-uniformity)

Result 2: Ps thermalization effect = 10 ppm

Fittings of resonance lines WITHOUT
taking into account the time evolutions (Ps thermalization)
= similar method as the previous experiments



→ Gave **10 ± 2 ppm smaller** Ps-HFS value in vacuum

(χ^2/ndf=721.1/592, p=2x10^{-4})

This difference is large enough to explain the 16 ± 4 ppm discrepancy.

Ps thermalization effect is crucial for precision measurement of Ps-HFS.

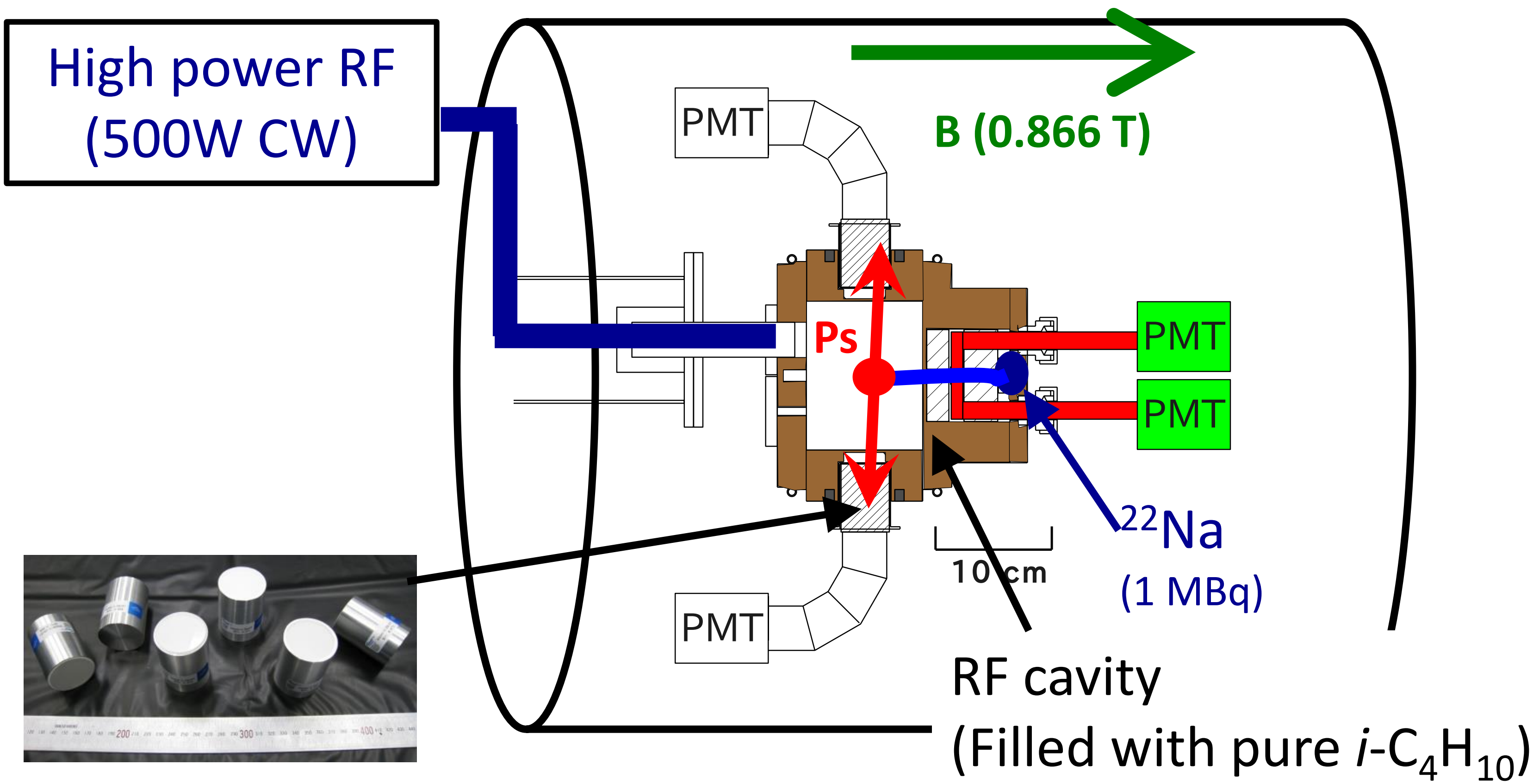
Future prospects

Measurement in vacuum using slow positron beam

(hopefully better than 1 ppm result within 4—5 years)

- High statistics (scan in vacuum instead of extrapolation, higher power RF without discharge)
- Completely free from material effect
- Short measurement period reduces systematic errors

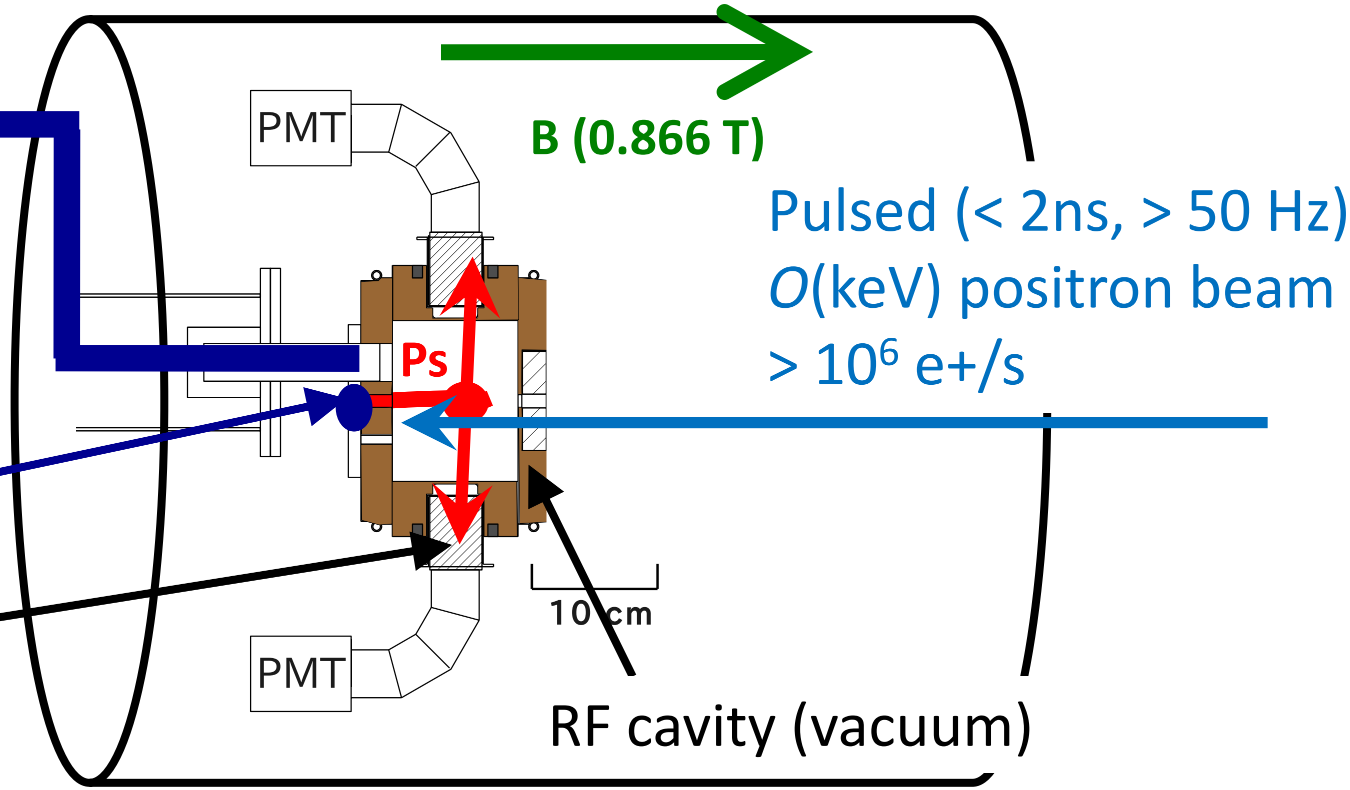
(Current Experimental Setup)

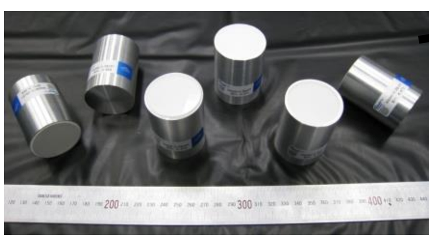


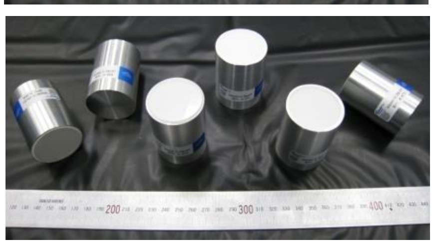
Future Experimental Setup

High power RF
(500W CW)

Ps formation in
vacuum (> 40%)
(Hot metal or
Porous Silica)







γ-ray detectors x 12
Digitization of waveforms of detector signals
(~100% separation for Δt > 8 ns (*preliminary*))
→ 1 ppm result by a few-week run

Conclusion

- *Ps-HFS puzzle:* a large 4.5 σ discrepancy of Ps-HFS between the previous experimental values and theoretical calculation.
- New precise microwave spectroscopy using the Zeeman effect was recently performed.
  - Used new techniques to reduce possible systematic uncertainties in the previous experiments (Non-thermalized Ps effect and Non-uniformity of magnetic field).
  - Δ_{HFS} = 203.3942(21) GHz (10 ppm) Favors QED calculation
  - Ps thermalization effect was found to be as large as 10 ± 2 ppm.
- Future measurements will be performed in vacuum using slow positron beam (hopefully a new result within 4—5 years).