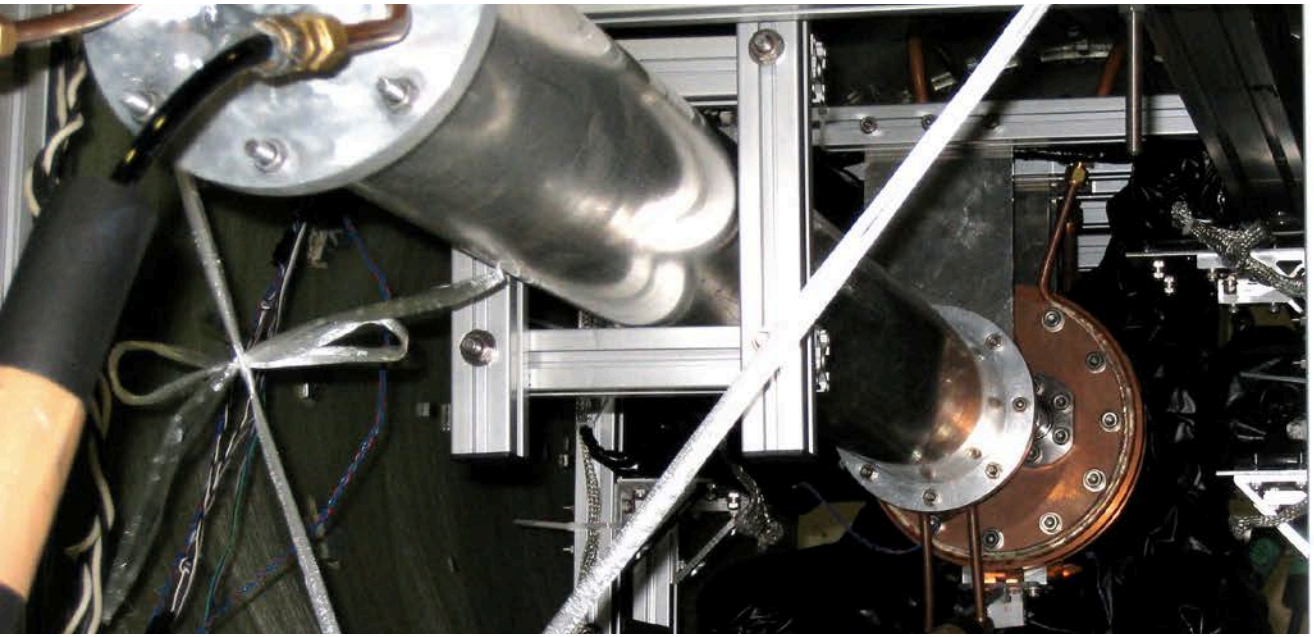
New Precision Measurement of the Hyperfine Splitting of Positronium



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DESY Physics Seminar

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

Outline

- Positronium Hyperfine Splitting (Ps-HFS)
- Material effect and Ps thermalization
- Our New Experiment
- Analysis and Results
- Prospects & conclusion

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New precision measurement of hyperfine splitting of positronium

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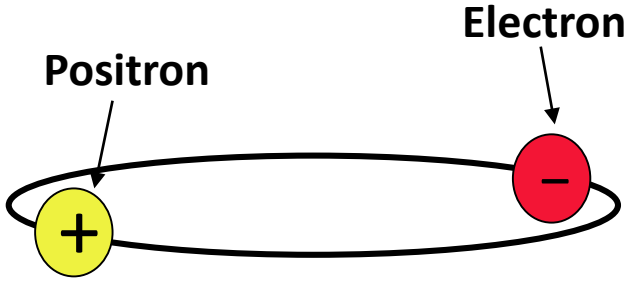
Positronium (Ps)

Bound state of an electron (e^-)

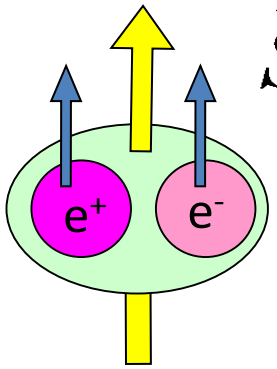
and a positron (e^+)



Lightest and Exotic Atom

- Lightest hydrogen-like atom (mass = 1.022 MeV)
- Pure leptonic system. Free from uncertainties of hadronic interactions.
  -> Ideal system for precision test of bound-state Quantum ElectroDynamics (QED).
- Particle-antiparticle system
  -> Sensitive to physics beyond standard model.
- The lowest energy e^+ e^- “collider”

Positronium (Ps)



$\vec{S}$ = 1 (Triplet)

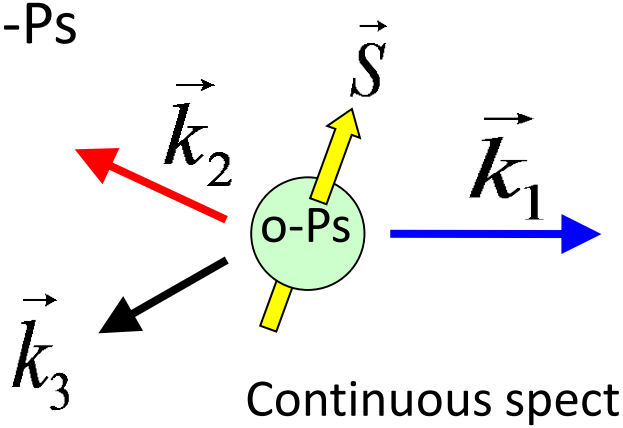
Ortho-positronium (o-Ps)

Spin=1 The same quantum number as photon

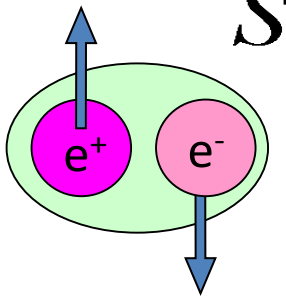
o-Ps → 3γ (, 5γ, …)

o-Ps

Lifetime 142 ns



Continuous spectrum



$\vec{S}$ = 0 (Singlet)

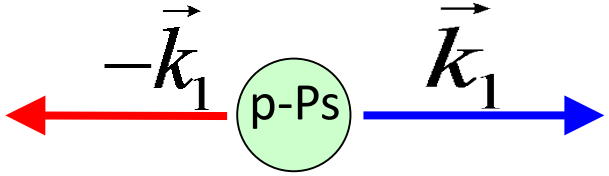
Para-positronium (p-Ps)

Spin=0 pseudo-scalar

p-Ps → 2γ (, 4γ, …)

p-Ps

Lifetime 125 ps



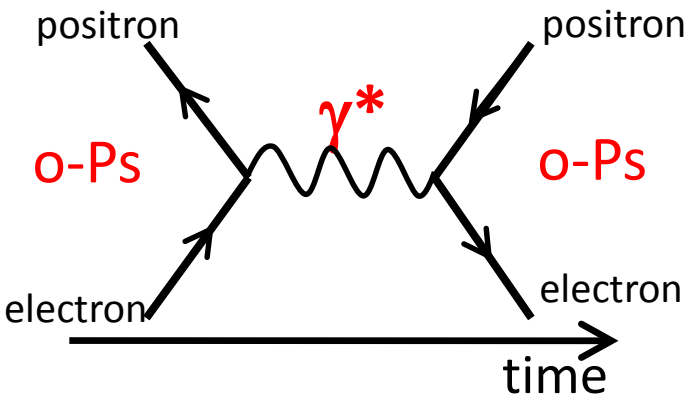
Monochromatic 511 keV

Positronium Hyperfine Splitting (Ps-HFS)

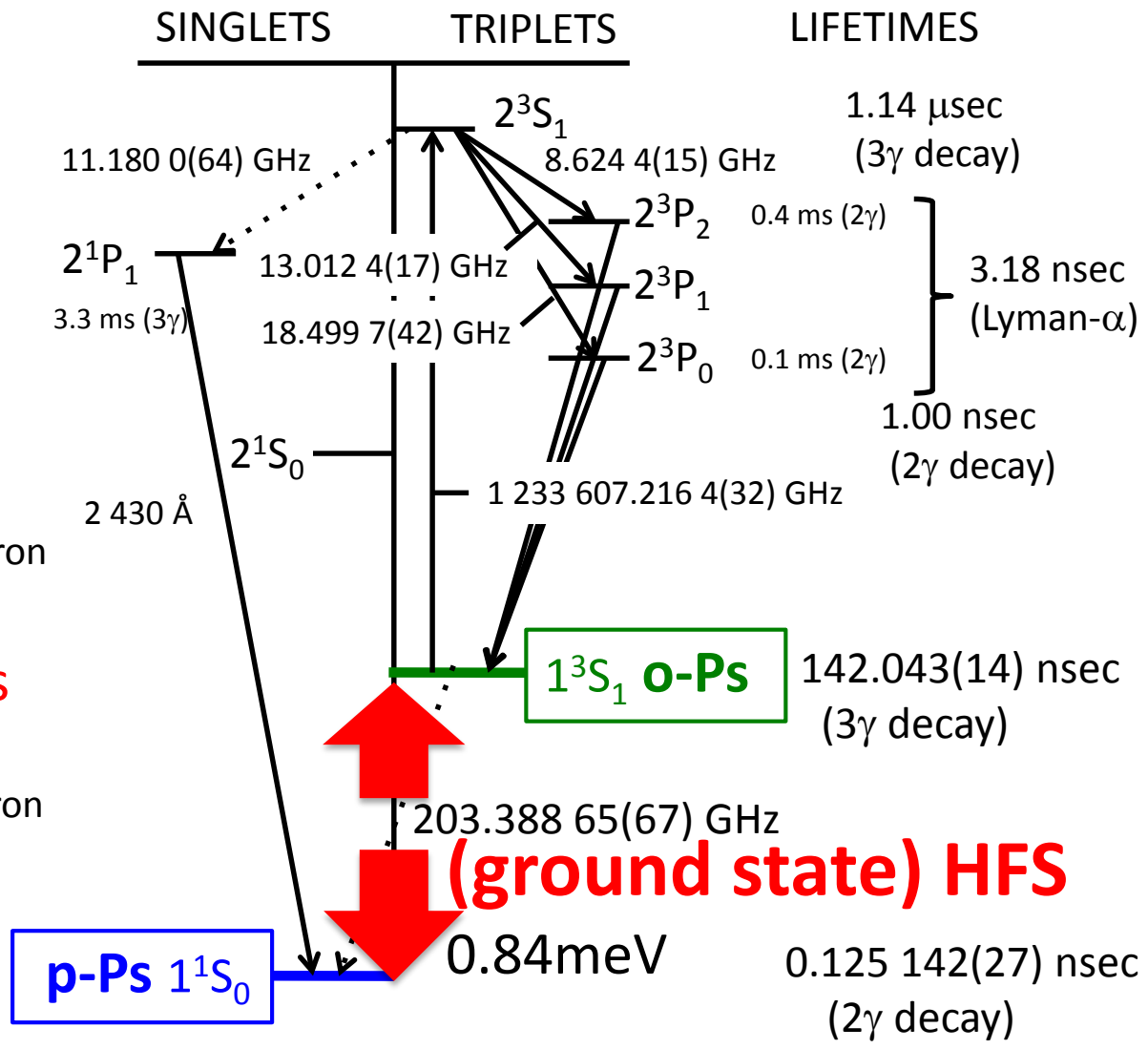
Energy difference between two spin eigenstates of the ground state Ps

→ Ps-HFS (203 GHz)

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

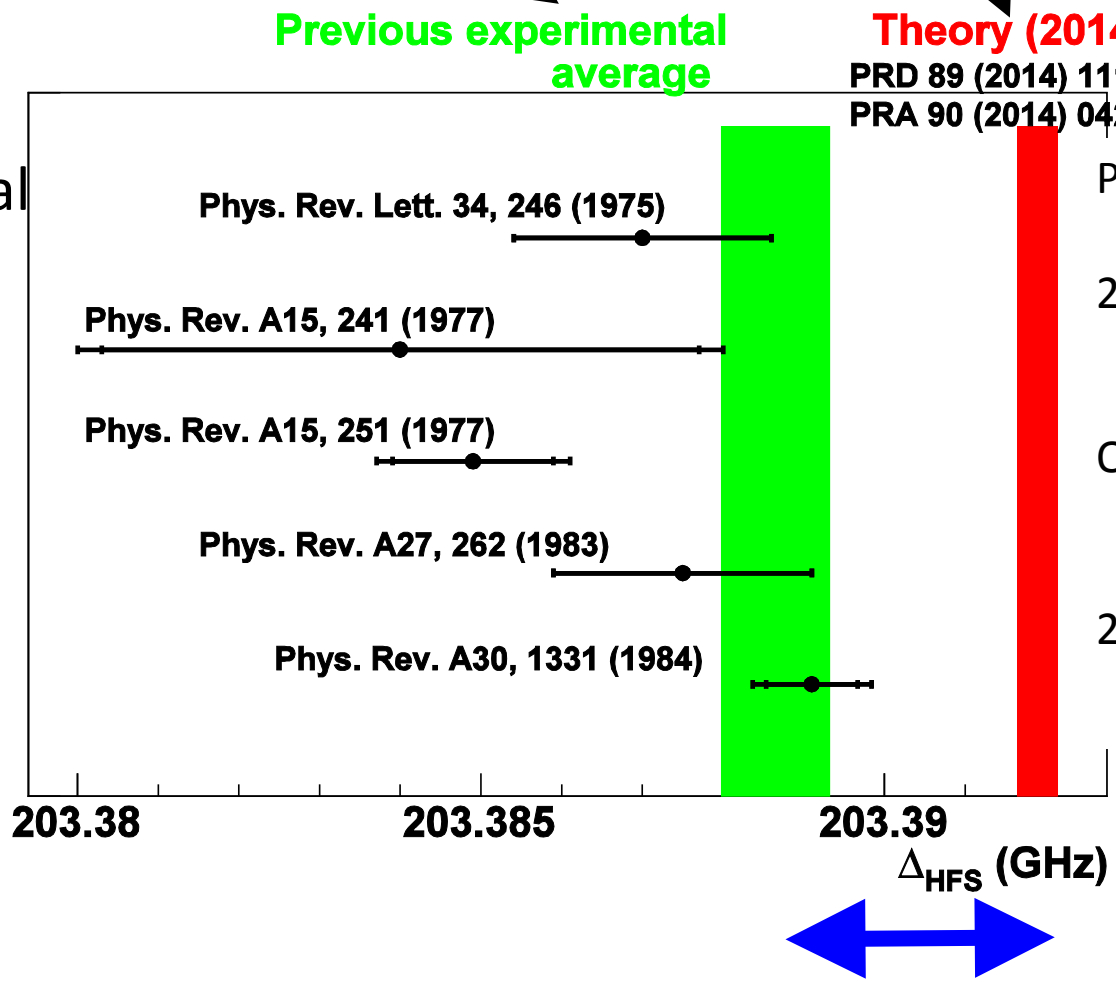


Quantum oscillation effect is also large (40%)



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)

$O(\alpha^3 \ln \alpha^{-1})$
+ some of $O(\alpha^3)$
QED theory
203.391 90(25) GHz
(1.2 ppm)

16 ppm (4.5 σ) significant discrepancy

Possible reasons for the discrepancy

- Common systematic uncertainties in the previous experiments
  1. Non-uniformity of the magnetic field.
  2. Underestimation of material effects. Unthermalized o-Ps can have a significant effect especially at low material density. *cf. o-Ps lifetime puzzle (1990's)*

We introduced new methods to reduce these systematic errors.

- Need new development on calculation of bound-state QED or New physics beyond the Standard Model.

- Positronium Hyperfine Splitting (Ps-HFS)
- Material effect and Ps thermalization
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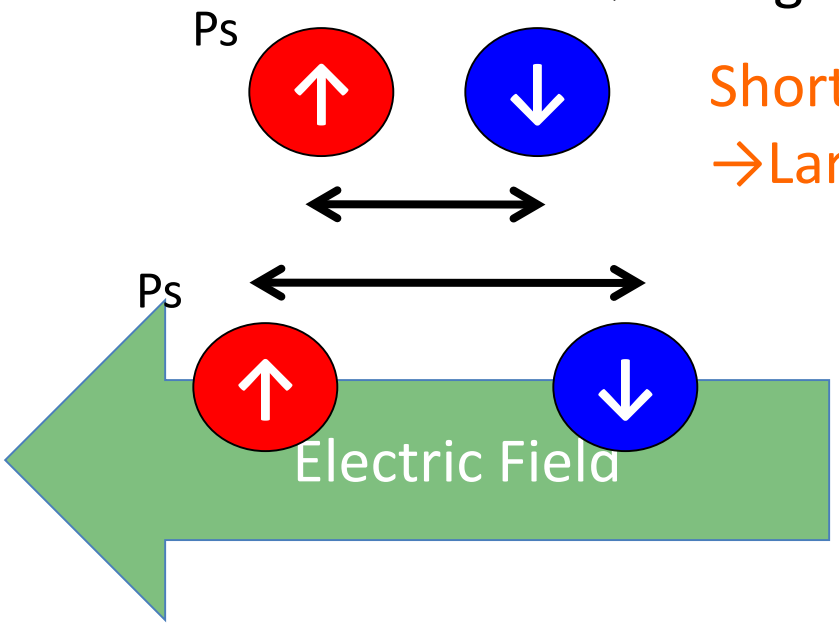
Material Effect on Ps-HFS

- Need material (in this case gas molecules) so that positron can get electron and form Ps.
- Ps-HFS
  = Spin-spin interaction + quantum oscillation
  →Depends the distance between e^- and e^+.
- Materials make electric field around Ps
  →Change the distance of the electron and the positron
  →Change HFS（The Stark Effect）



Short distance
→Large HFS

Long distance
→Difficult to interact
→Small HFS

Estimation of Material Effect in previous experiments

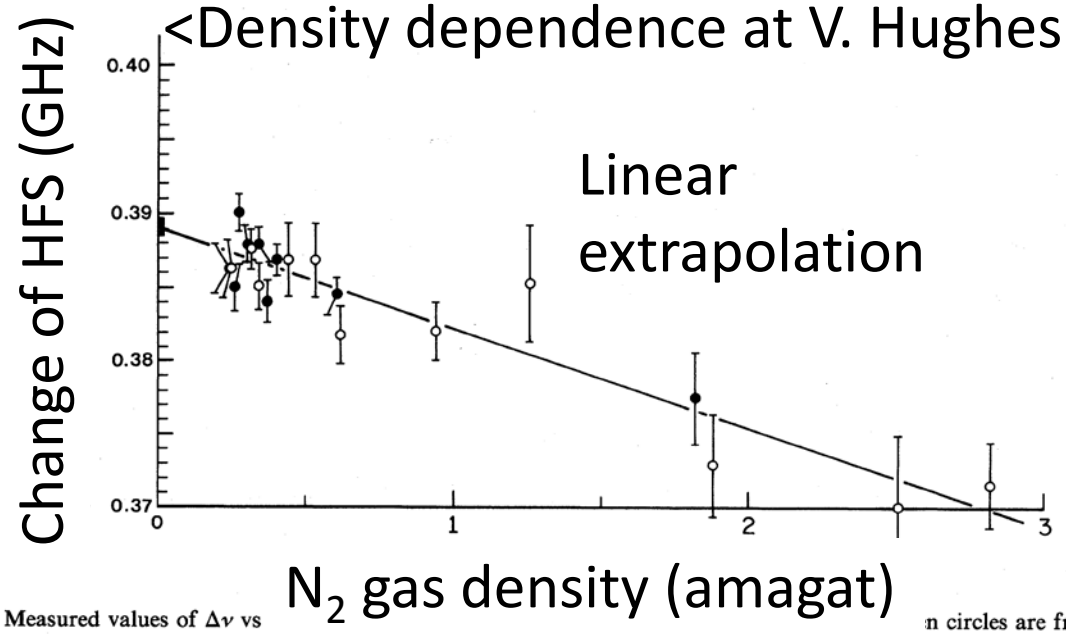
- Need material (in this case gas molecules) so that positron can get electron and form Ps → Ps feels electric field of material

Strength of the Stark Effect
∝ ~ Collision rate with surrounding molecules
∝ (Density of surrounding molecules) x (Ps velocity v) $^{3/5}$

→If the Ps velocity is constant (under assumption that Ps is well thermalized), the material effect is proportional to gas density.

→The Previous experiments

<Density dependence at V. Hughes *et al.*>



Phys. Rev. A
1984 **30** 1331
Ritter, Egan, Hughes et al.

FIG. 7. Measured values of $\Delta\nu$ vs ... n circles are from Ps IV and the closed circles are from the present work. The straight line is the best fit described in Eq. (14).

Evolution of Ps velocity

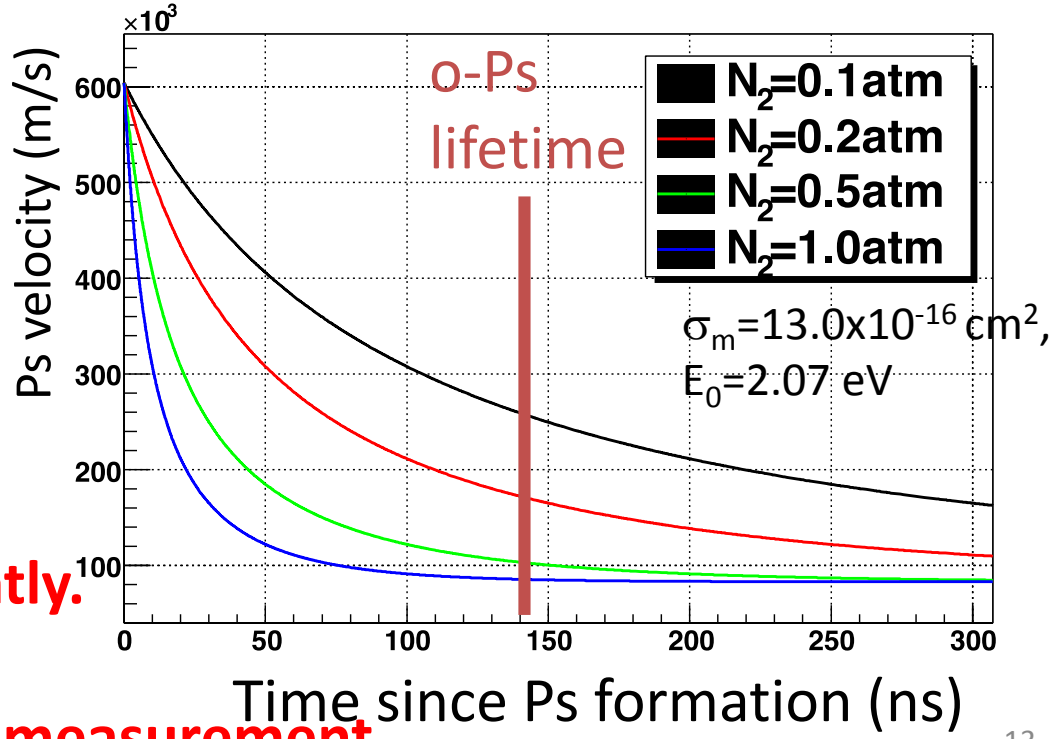
Strength of the Stark Effect
$\propto$ ~ Collision rate with surrounding molecules
$\propto$(Density of molecules) x $(\text{Ps velocity } v(t))^{3/5}$

Ps loses its kinetic energy and gets room temperature = Thermalization

It takes longer time to thermalize in lower density
→ Linear extrapolation could be a large O(10ppm) systematic uncertainty

→We also measured Ps thermalization independently. Used obtained result for analysis of our new Ps-HFS measurement.

< Simulation of time evolution of Ps velocity in N_2 gas >

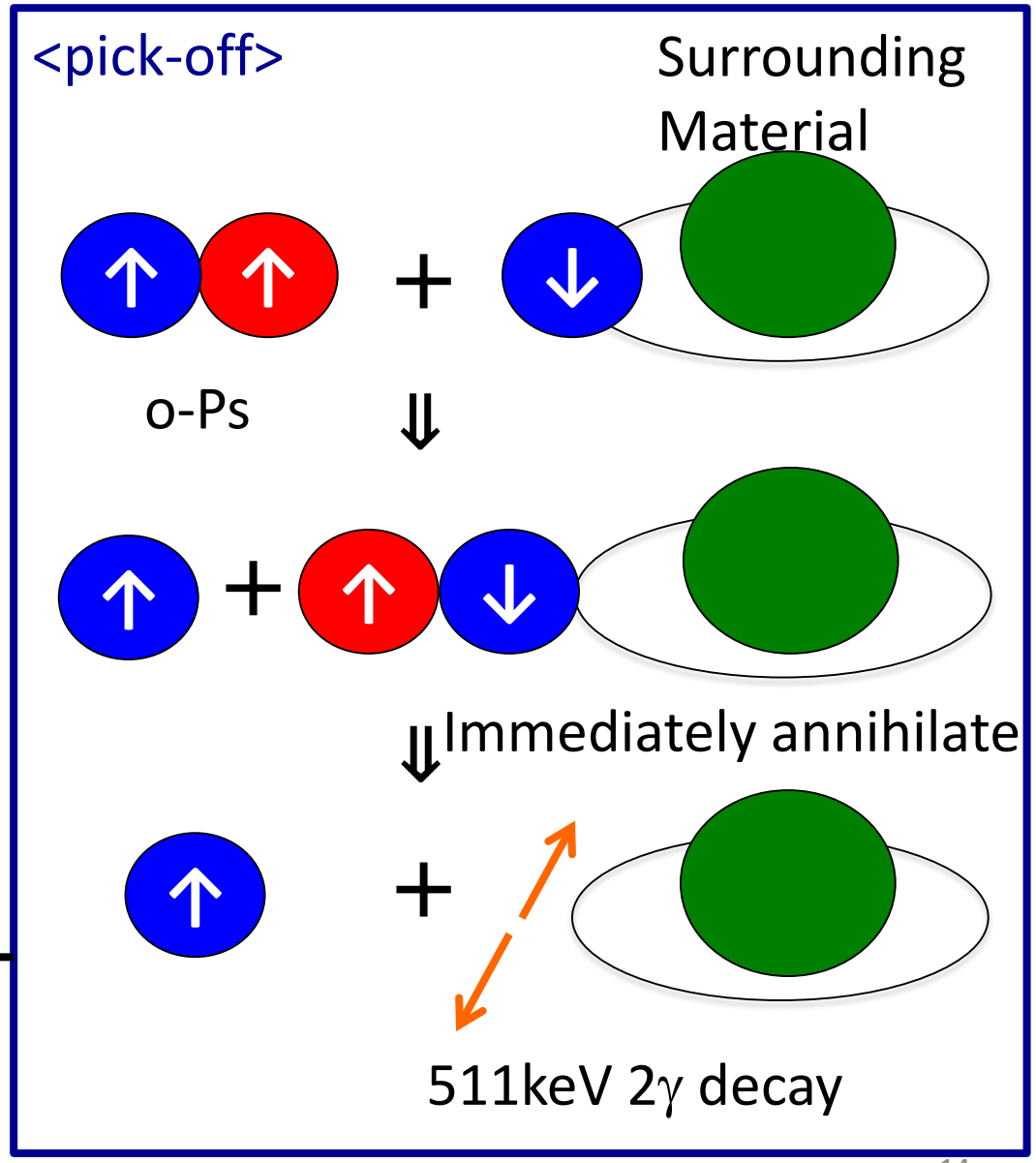


How to measure the Ps velocity v(t) ?

- Use pick-off of o-Ps

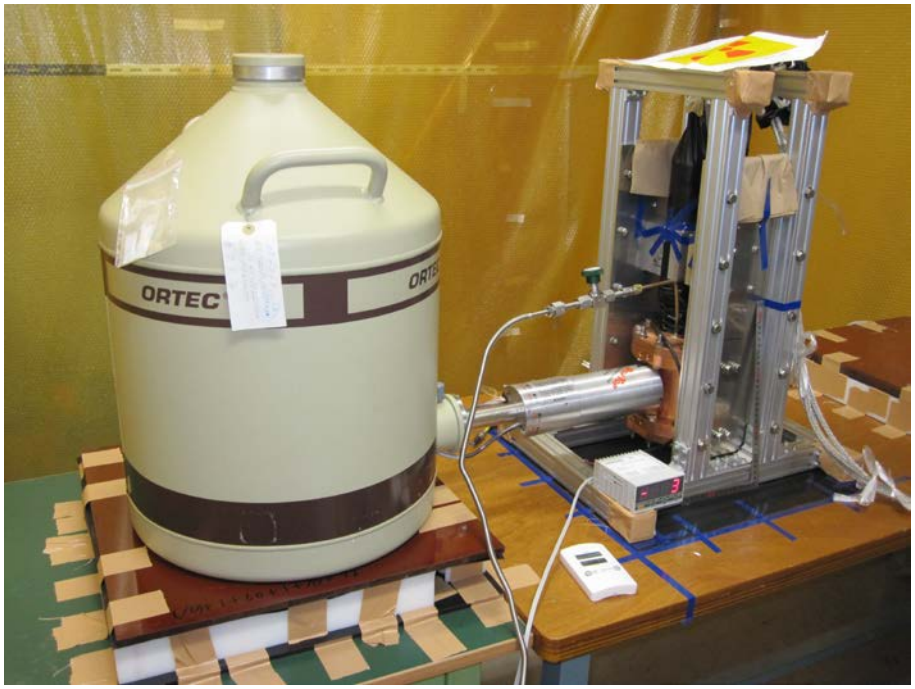
- pick-off(t)
  = pick-off cross section
  x density of material
  x o-Ps amount (t)
  x $v(t)^{0.6}$

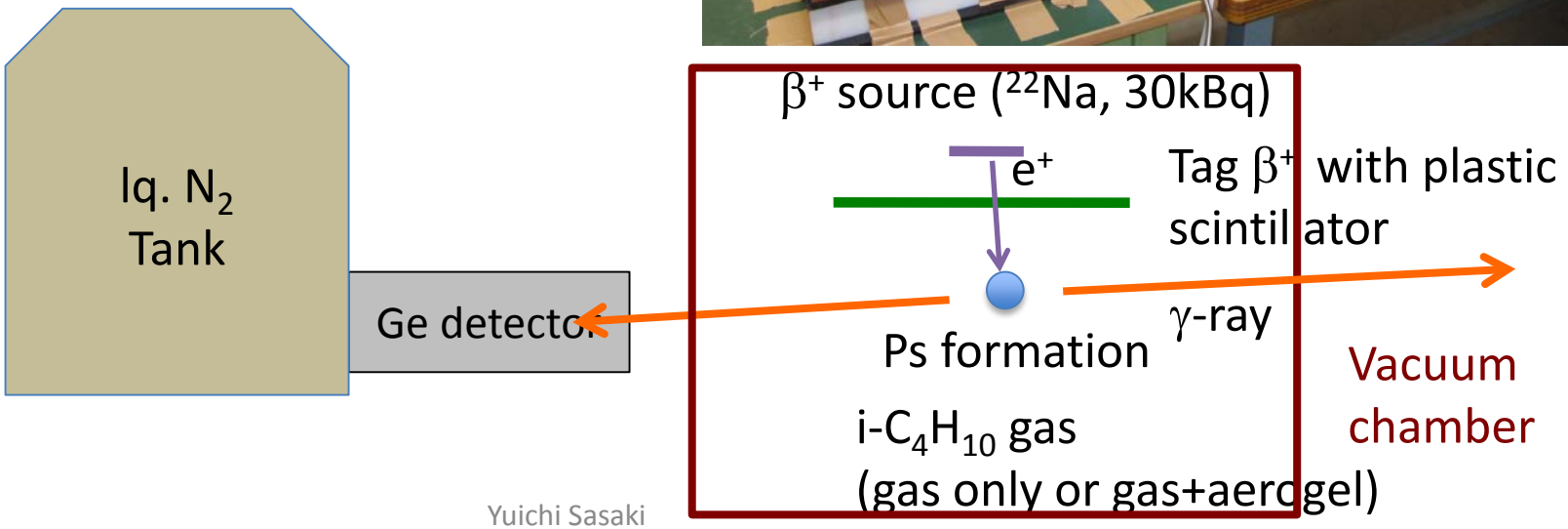
$$v(t)^{0.6} \propto \frac{\textbf{pick-off (2}\gamma\textbf{ decay)}}{\textbf{o-Ps (3}\gamma\textbf{ decay)}}$$



Measurement of Ps Thermalization Experimental Setup (Overall)

- Timing; START by Plastic Scintillator & STOP by Ge detector
- Stop e^+ in the gas and form Ps
- Source is inside the vacuum chamber.
- Change thermalization condition by changing the gas pressures.





Estimate amounts of o-Ps and pick-off

1, Make energy spectrum at each timing window

2, o-Ps is normalized at continuous region (480—500 keV).

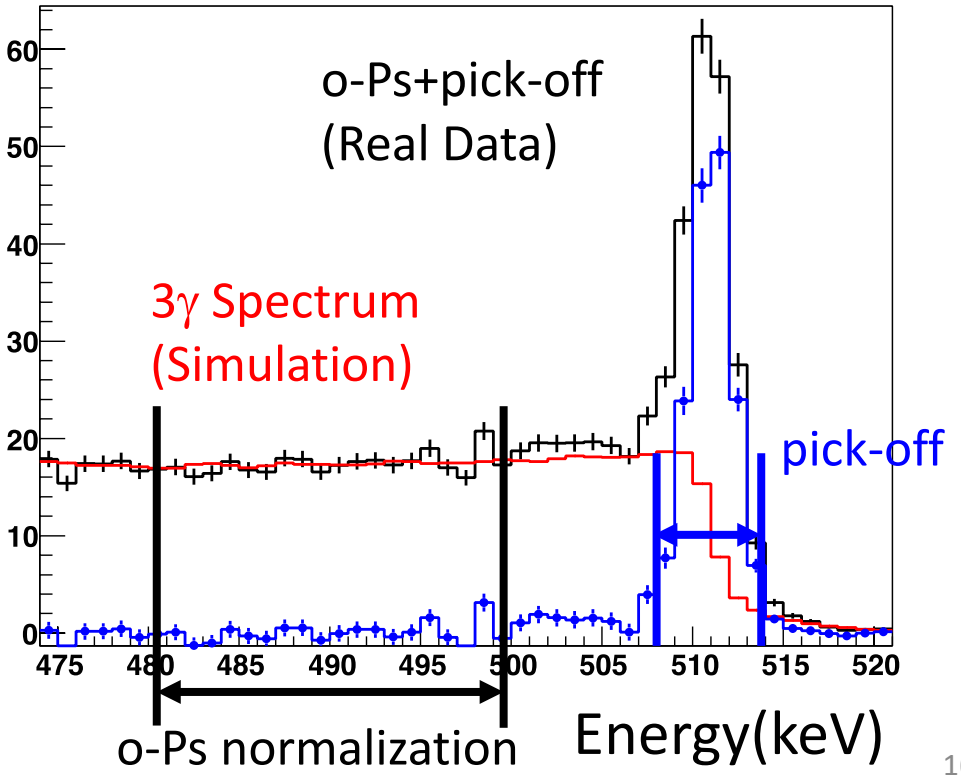
3, 511 ± 3 keV is taken as pick-off

4, Efficiencies of o-Ps, pickoff, and pileup are estimated by MC simulation.

Isobutane only / Isobutane + aerogel measurement.

Change gas pressure, measure 2g/3g at various gas pressures

$$v(t)^{0.6} \propto \frac{\text{pick-off (2}\gamma\text{ decay)}}{\text{o-Ps (3}\gamma\text{ decay)}}$$



Analysis of thermalization measurement

- Use timing window of 40—800 ns in order to avoid prompt peak. Use the following equation for fitting.

Parameter to fit : σ_m: Momentum-transfer cross section

Aerogel term

$$\frac{d}{dt}E_{av}(t) = -\sqrt{2m_{Ps}E_{av}(t)}\left(E_{av}(t) - \frac{3}{2}k_BT\right)\left(\frac{8}{3}\sqrt{\frac{2}{3\pi}}\frac{2\sigma_m n}{M} + \alpha\left(\frac{E_{av}(t)}{k_BT}\right)^{\beta}\right)$$

from J. Phys. B **31** (1998) 329 Y. Nagashima, et al.

m_{Ps} : Ps mass
n : gas density
M : mass of molecule

- Thermalization of Ps before 40 ns, where kinetic energy is high (>0.15 eV), has been already measured by Doppler Broadening Spectroscopy (DBS) method to be $\sigma_m = 146 \pm 11$ Å^2, $E_0 = 3.1\ ^{+1.0}_{-0.7}$ eV (initial kinetic energy)

DBS: Phys. Rev. A **67**, 022504 (2003)

- Isobutane has a rovibrational level at 0.17 eV. Value of σ_m can be different above (DBS) and below (pick-off) this level. → Fit with fixed initial condition of DBS result, but change σ_m at 0.17 eV.

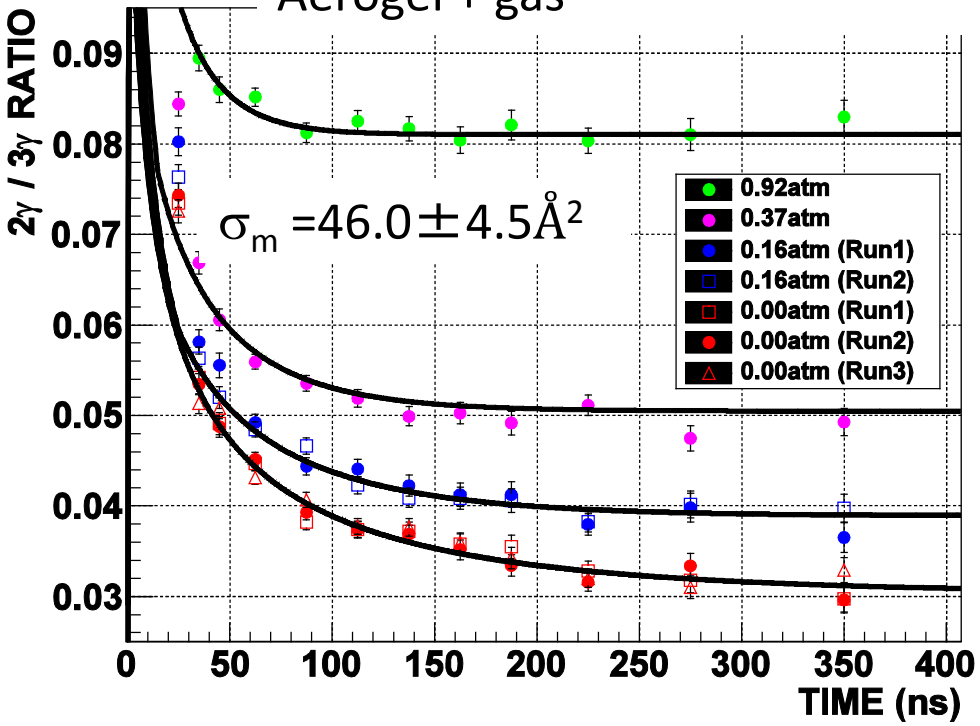
2γ/3γ fitting

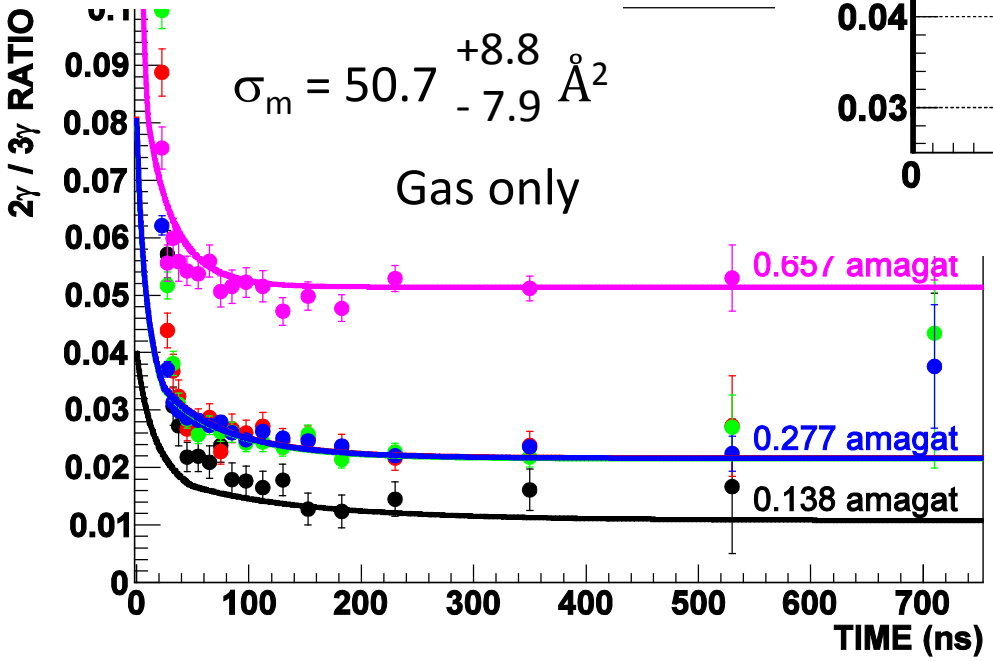
Velocity dependence of pickoff rate in isobutane gas

$\propto v^{0.6}$ (= $E^{0.3}$)

Simultaneous fit of all gas densities

Aerogel + gas





Consistent results from gas-only measurement and with aerogel measurement.

mean $\sigma_m = 47.2 \pm 3.9$ Å²

systematic error 5.4 Å

$\rightarrow \sigma_m = 47.2 \pm 6.7$ Å²

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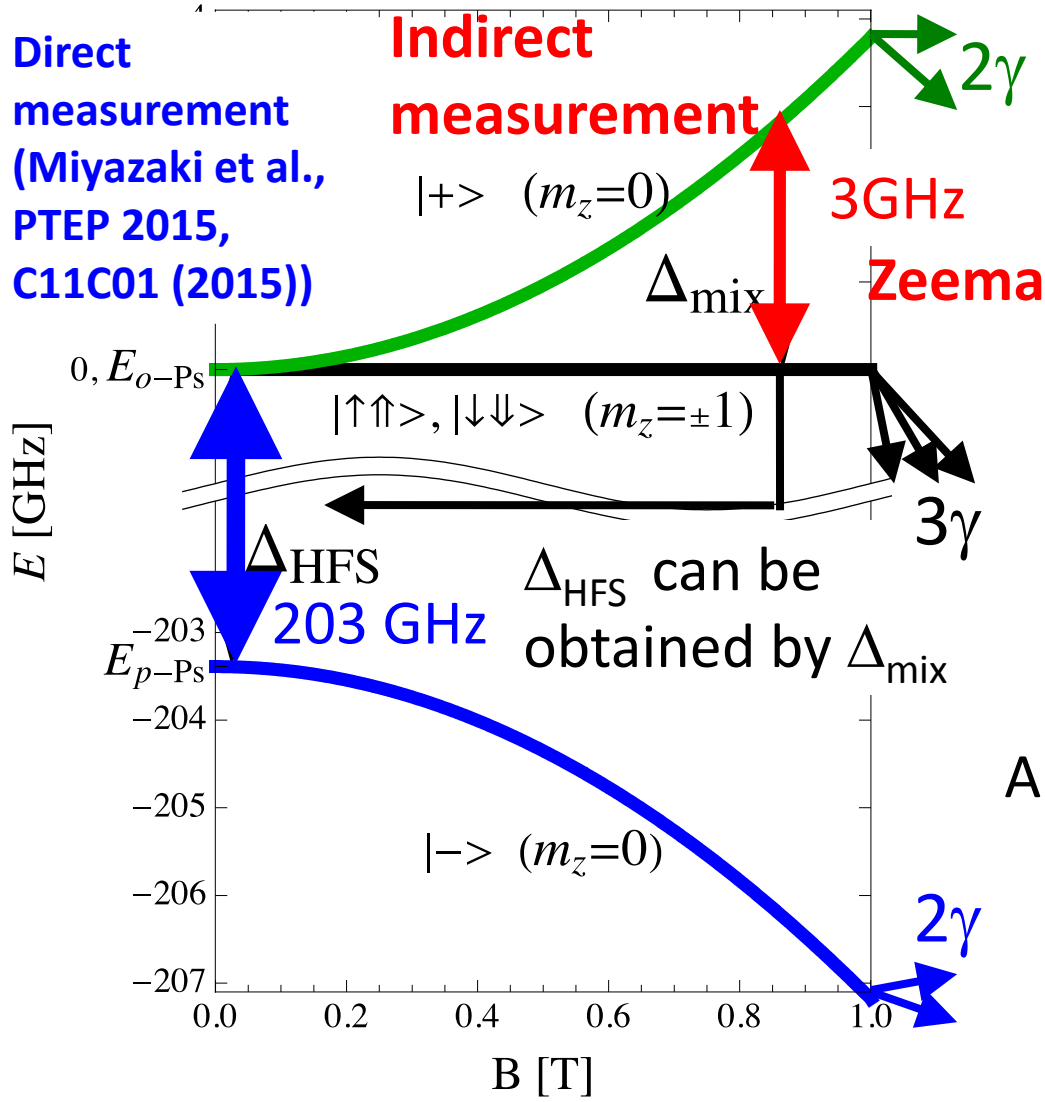
Experimental Technique
Indirect Measurement using Zeeman Effect

Direct measurement (Miyazaki et al., PTEP 2015, C11C01 (2015))



In a static magnetic field, the **p-Ps** state mixes with the **m_z=0 state of o-Ps** (Zeeman effect).

→ 2γ-ray annihilation (**511 keV monochromatic signal**) rate increases.

This increase is our experimental signal.

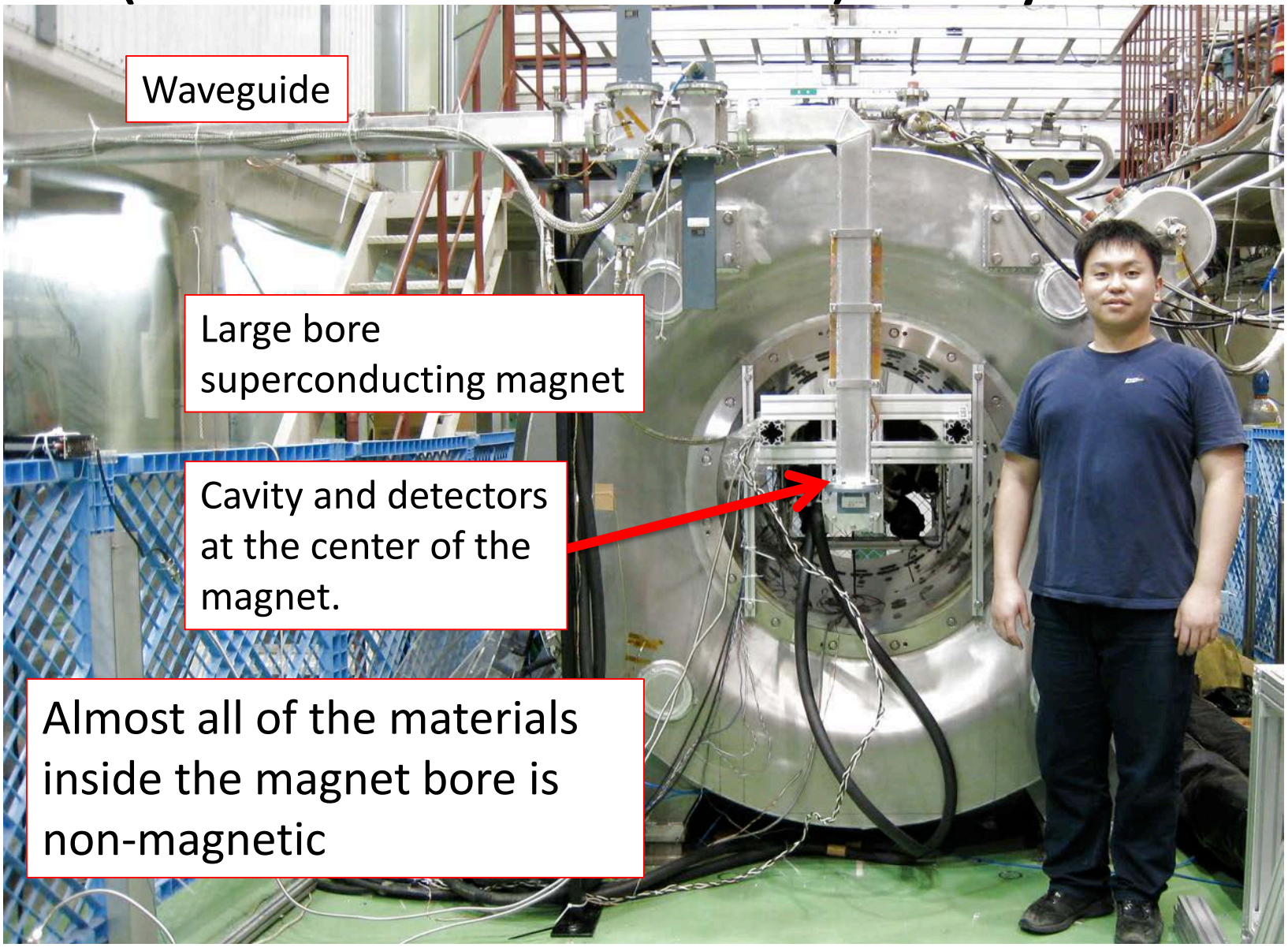
Approximately,

$$\Delta_{mix} \approx \frac{1}{2}\Delta_{HFS}\left(\sqrt{1+4x^2}-1\right),$$

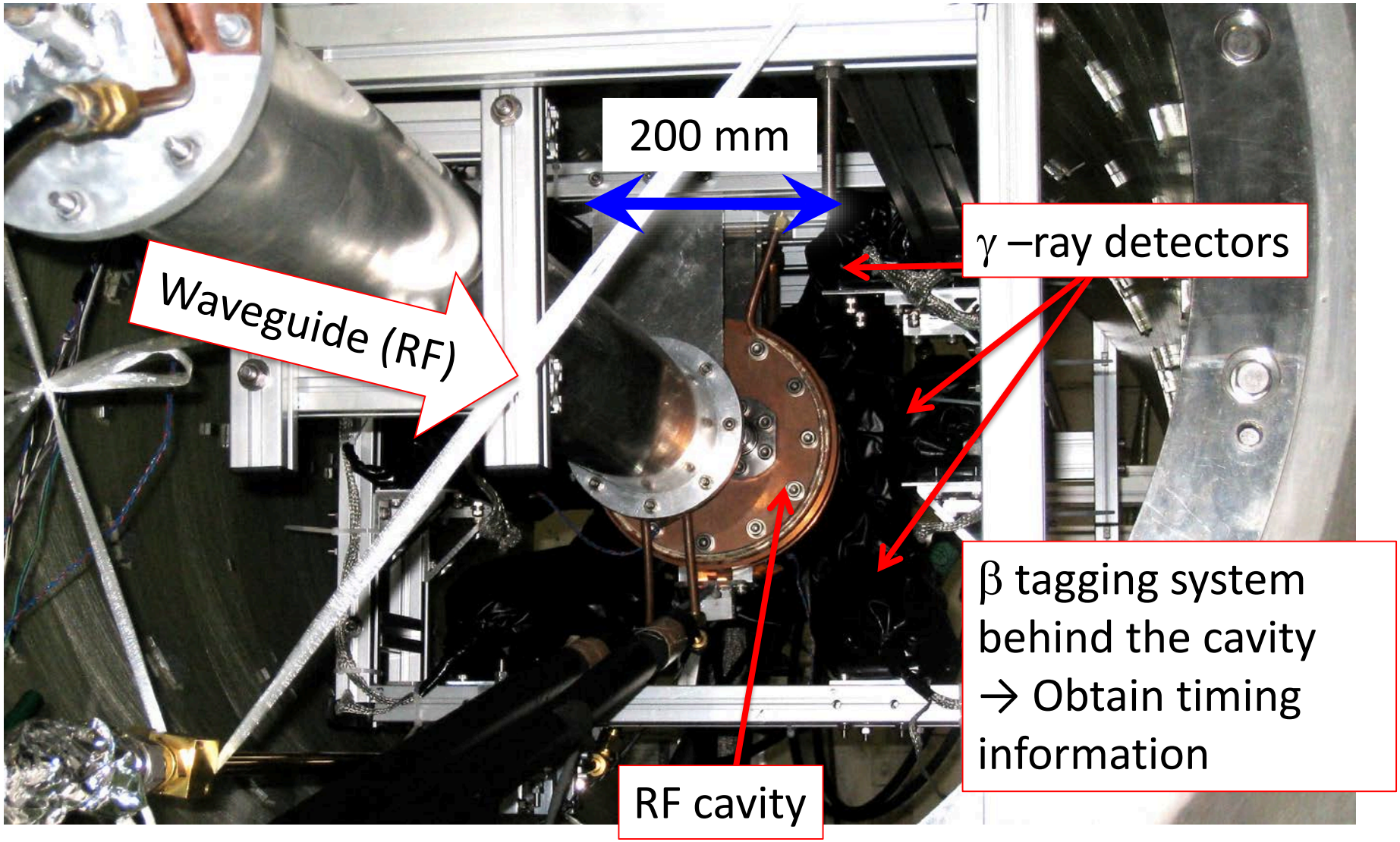
$$x = \frac{g'\mu_B B}{h\Delta_{HFS}}.$$

This is not precise enough, so we solve time evolution of density matrix.

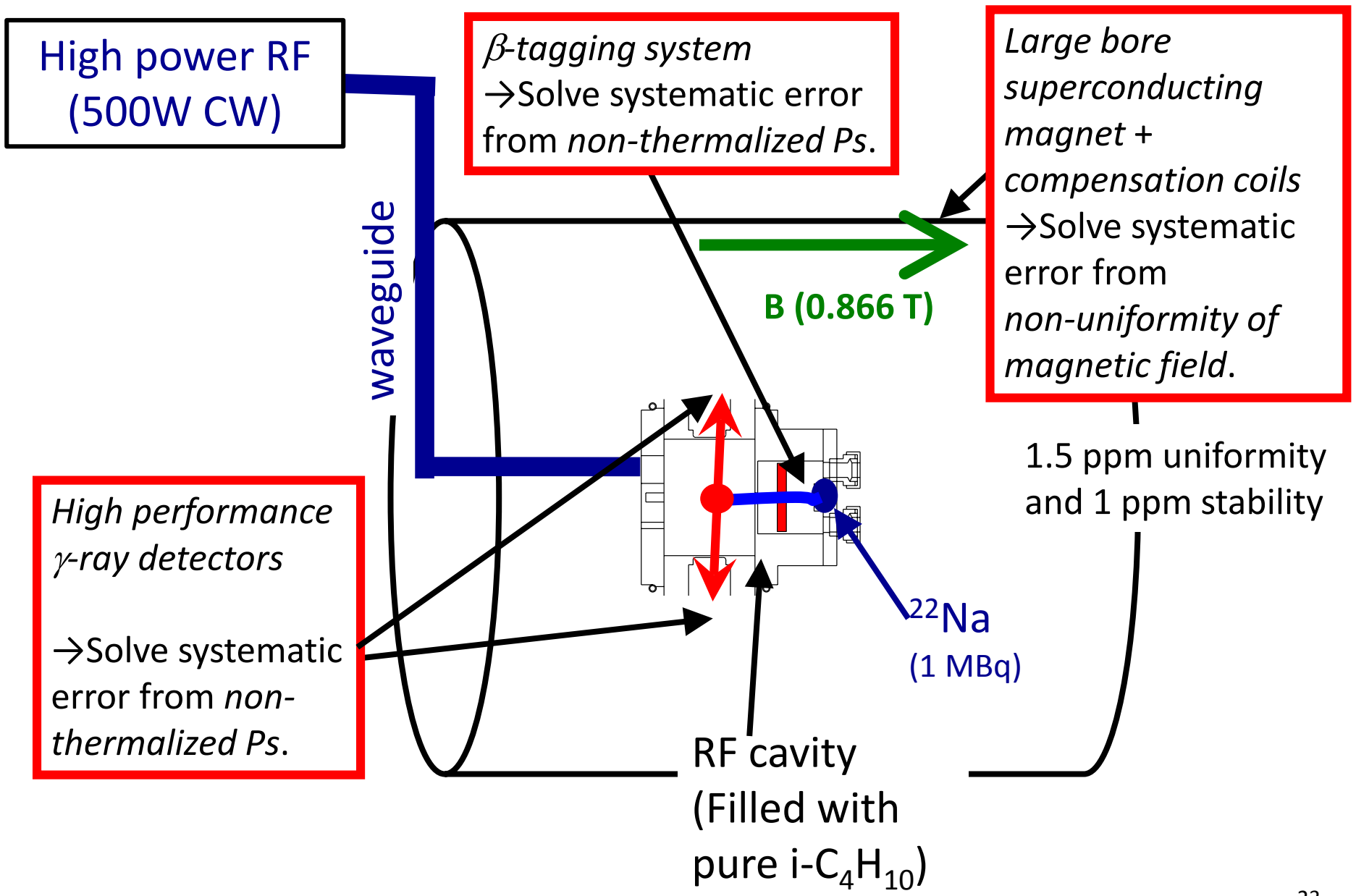
Measurement @ KEK CSC (Jul 2010 – Mar 2013) ~3 years



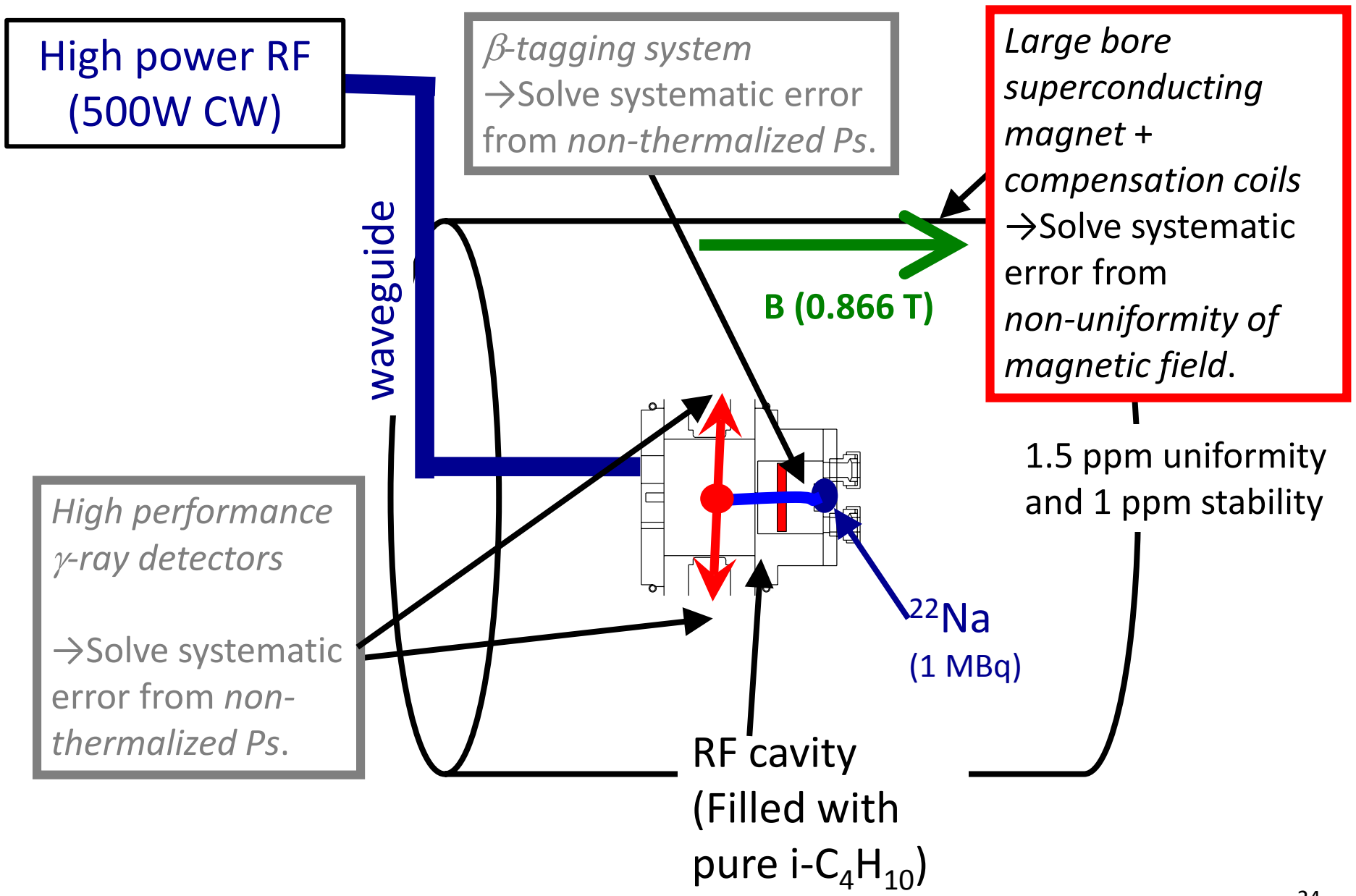
Center of the magnet



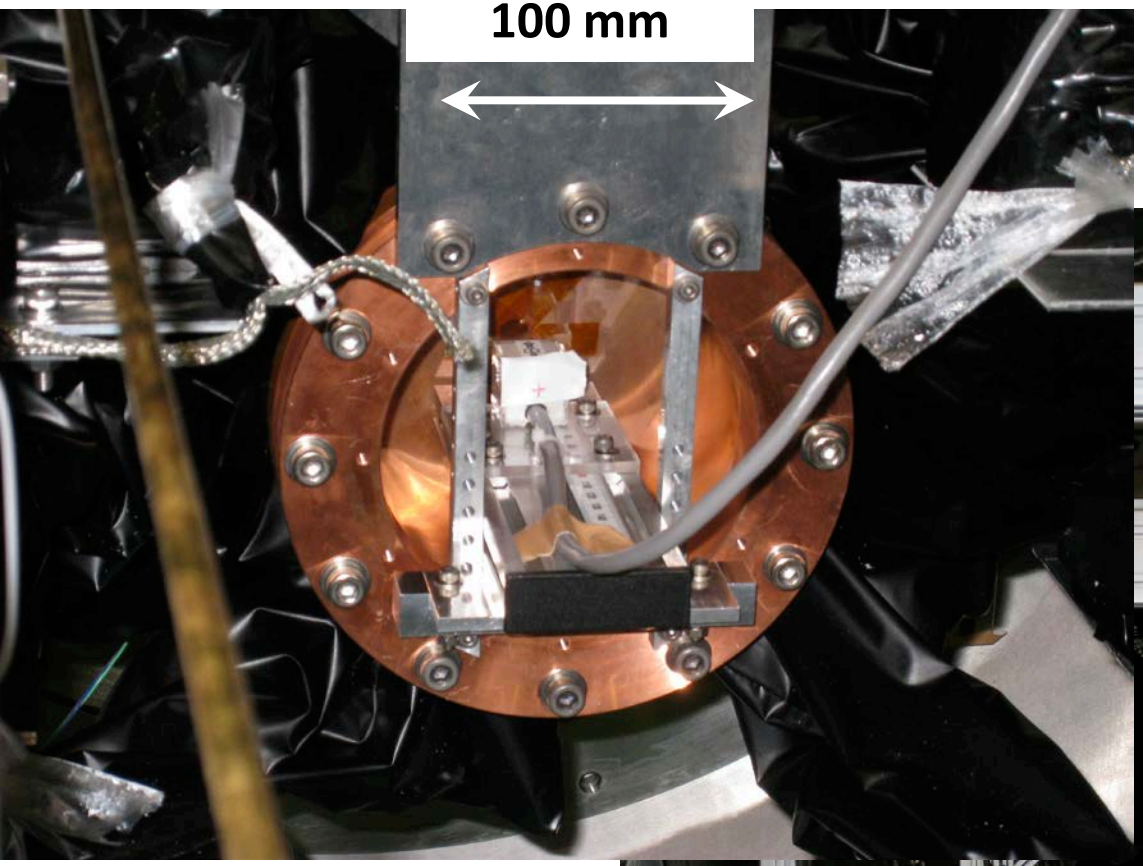
Our new Experiment



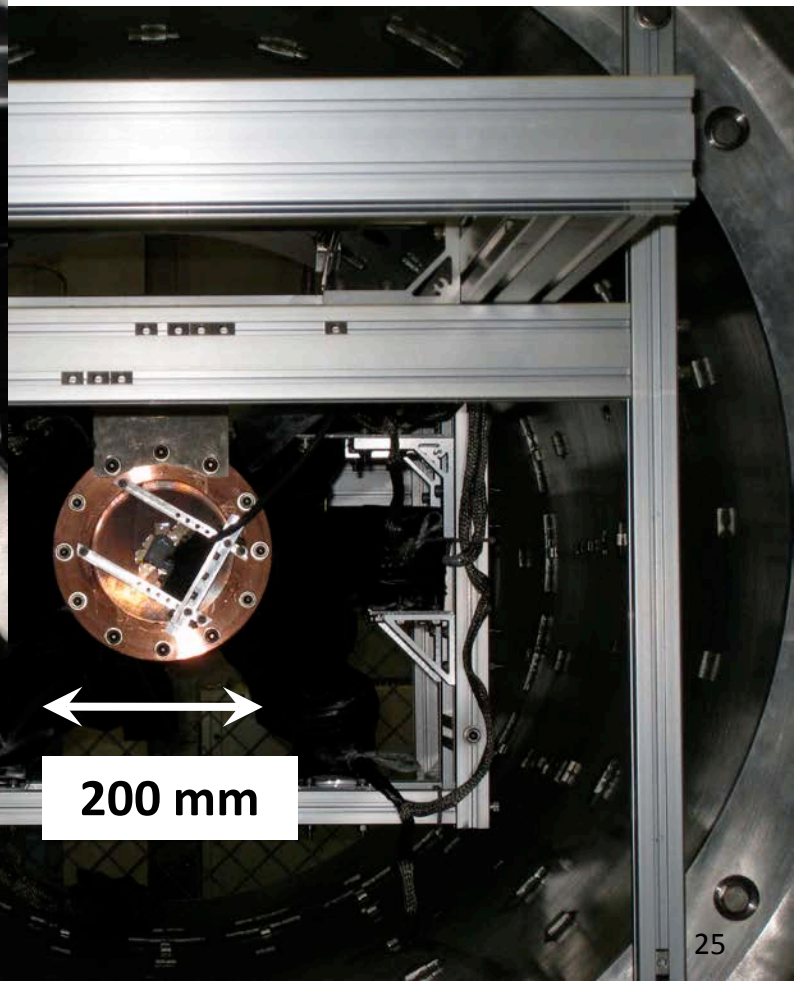
Our new Experiment



Magnetic Field



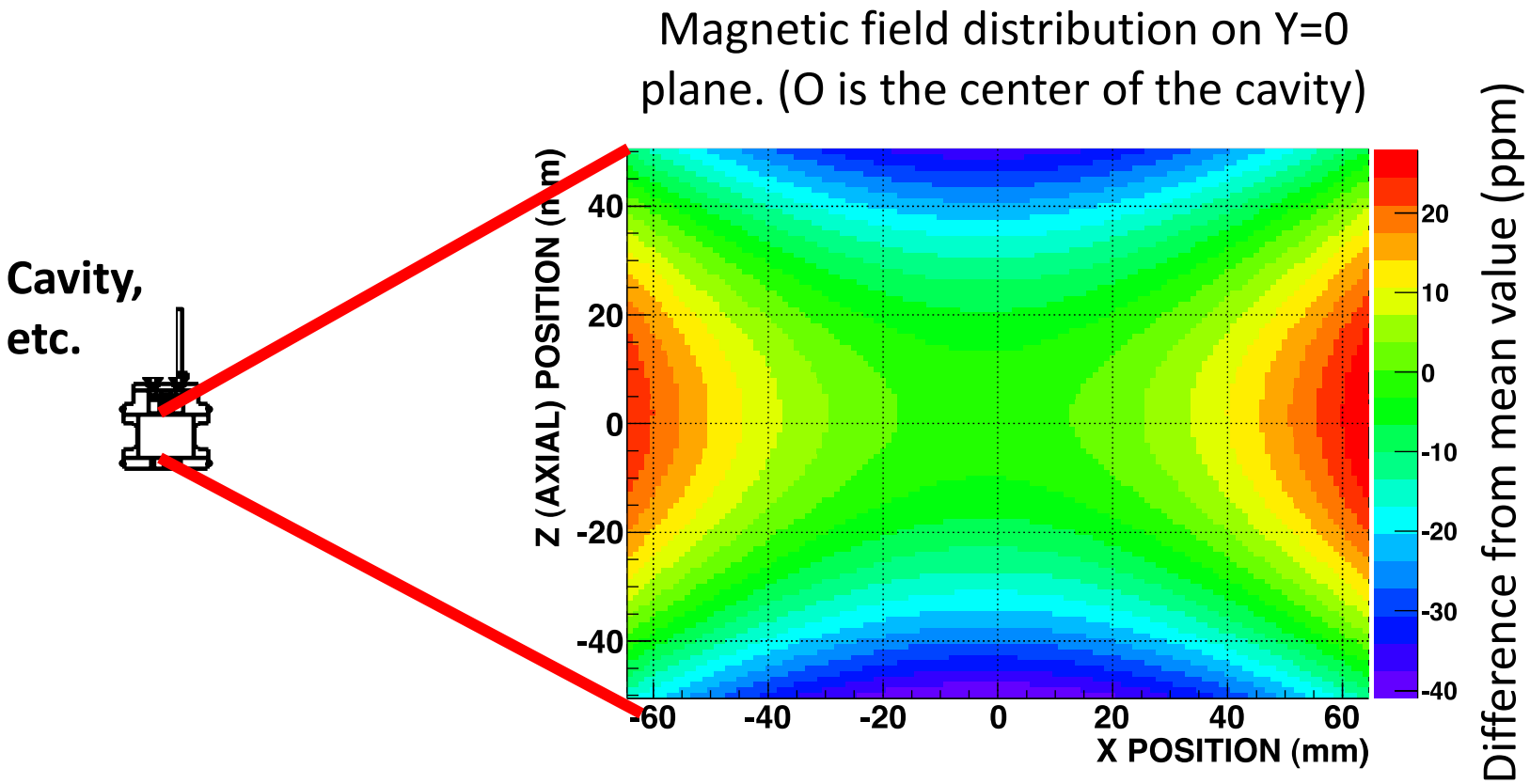
Measured the magnetic field at 310 points in the RF cavity using NMR probe.



Made the map of the magnetic field.

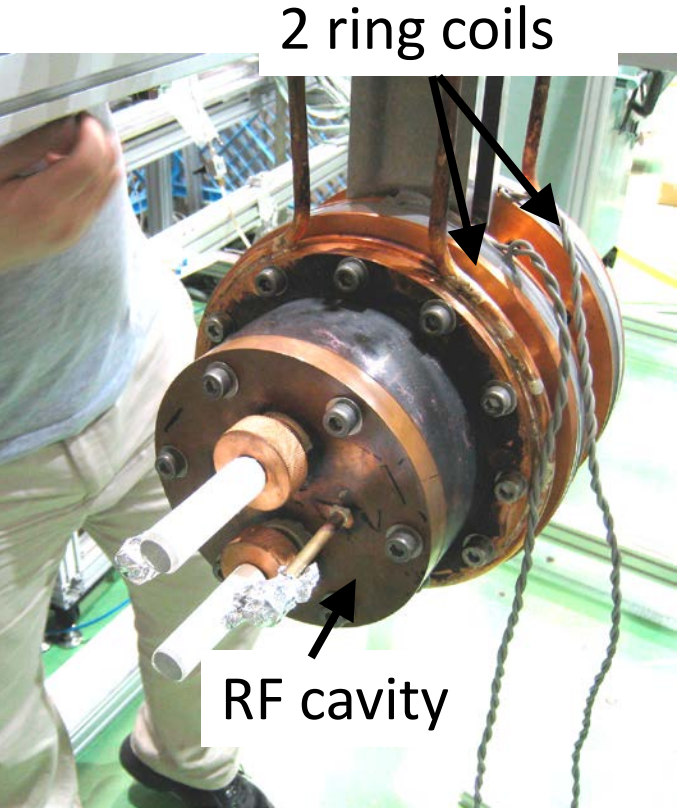
Uniformity of the Magnetic Field

Top view

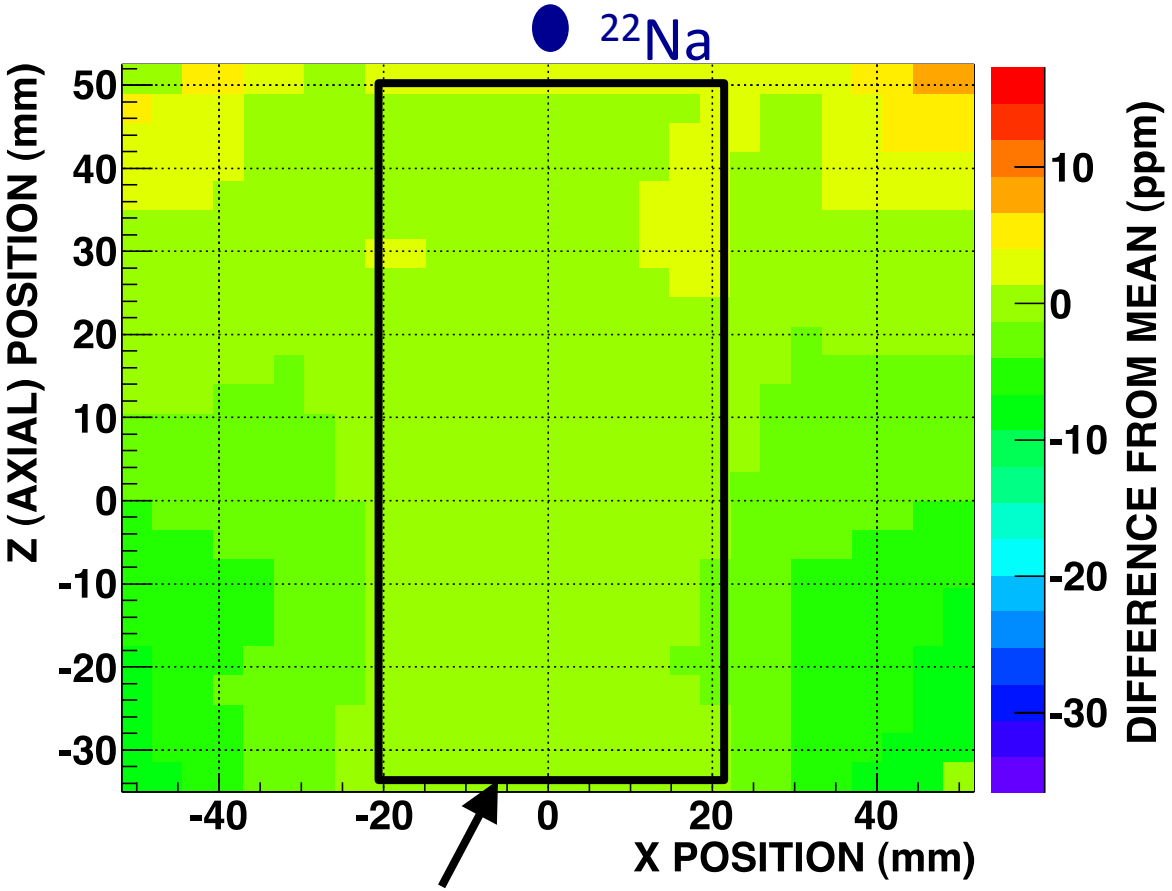


- Non-uniformity in the Ps formation volume is 10 ppm (RMS) without any compensation coil.
- Effects of PMT (strongly magnetic) and jigs are also big. Compensation coil was made to get O(ppm) homogeneity including these materials.

Compensation Magnet



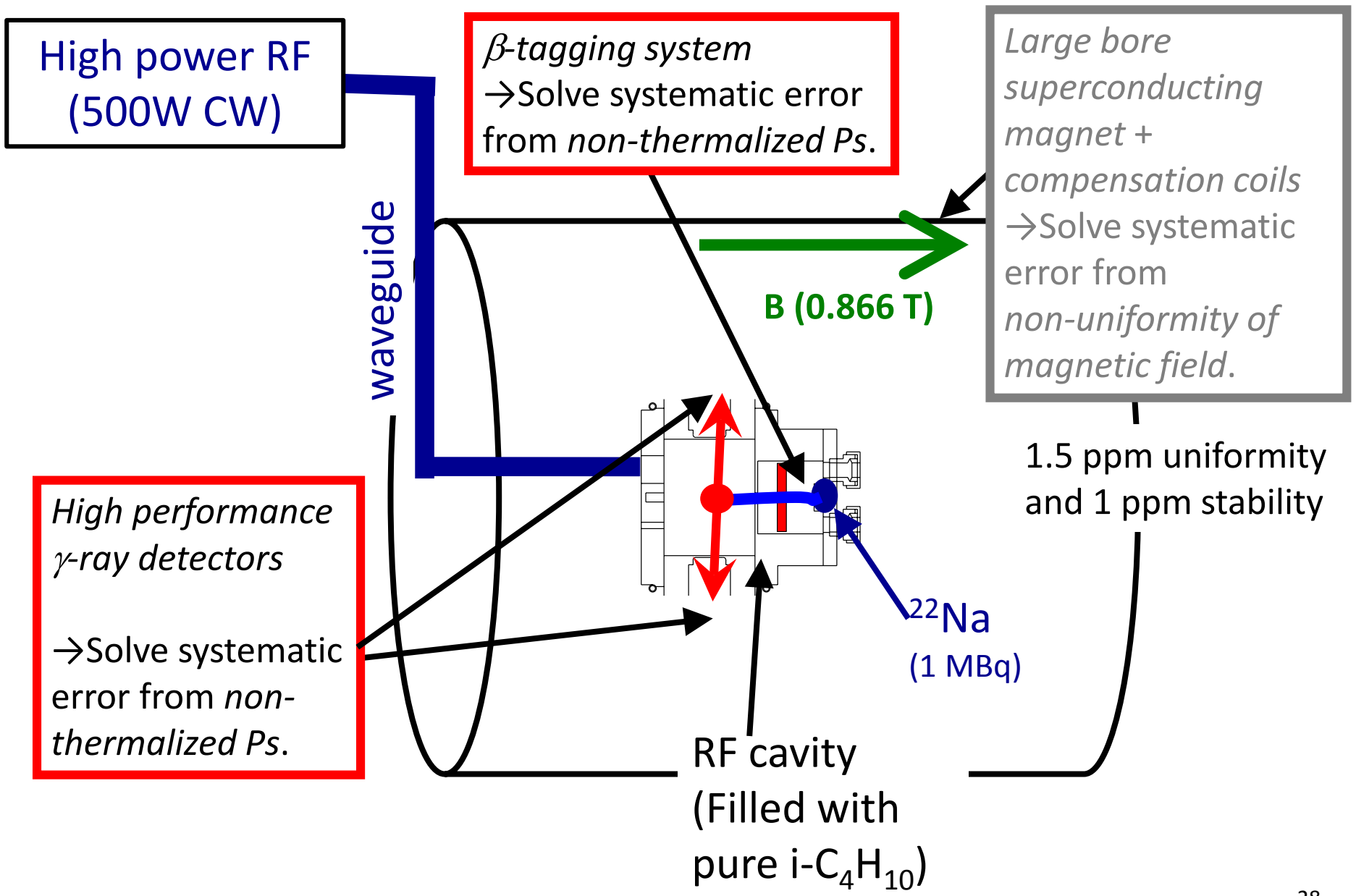
Magnetic Field distribution (Horizontal)
(O is the center of the cavity)



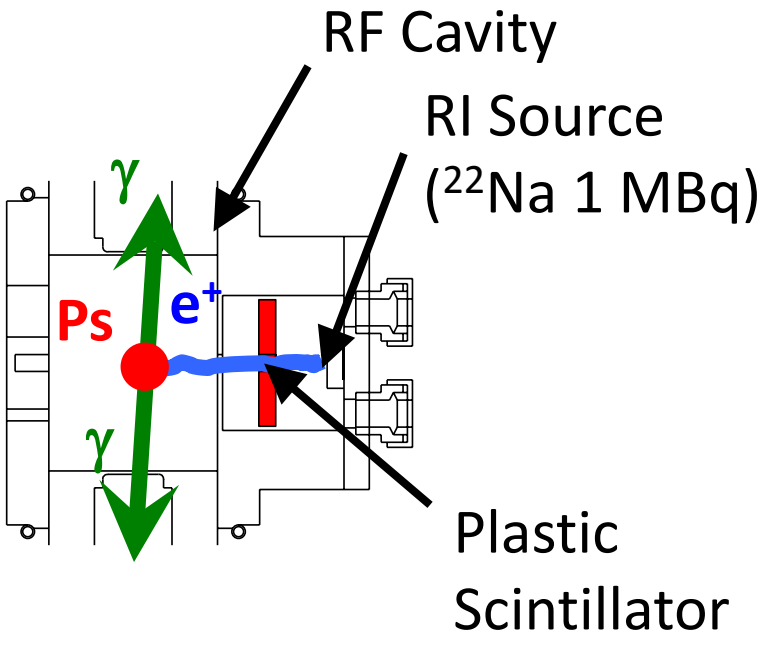
- 2 ring-coils are rolled on the cavity flange.
- They make the opposite field and reduce the gradient.

1.5 ppm (RMS) uniformity in the Ps formation volume (10.4 ppm w/o coils)
→3.0 ppm systematic errors ($\Delta_{\mathrm{HFS}} \propto B^2$).

Our new Experiment

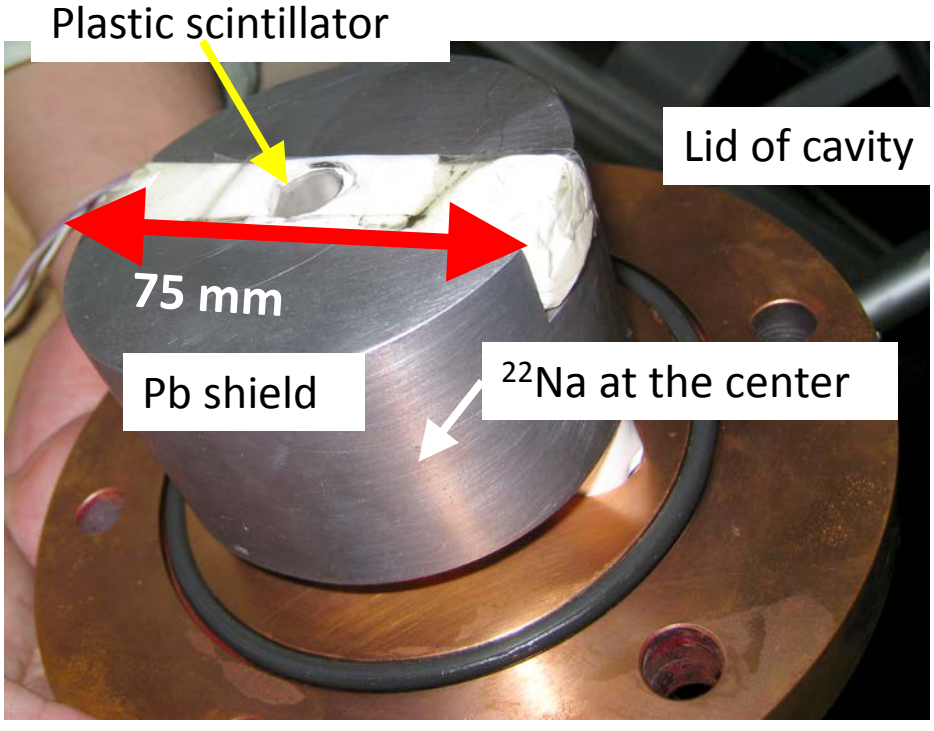


β-tagging system

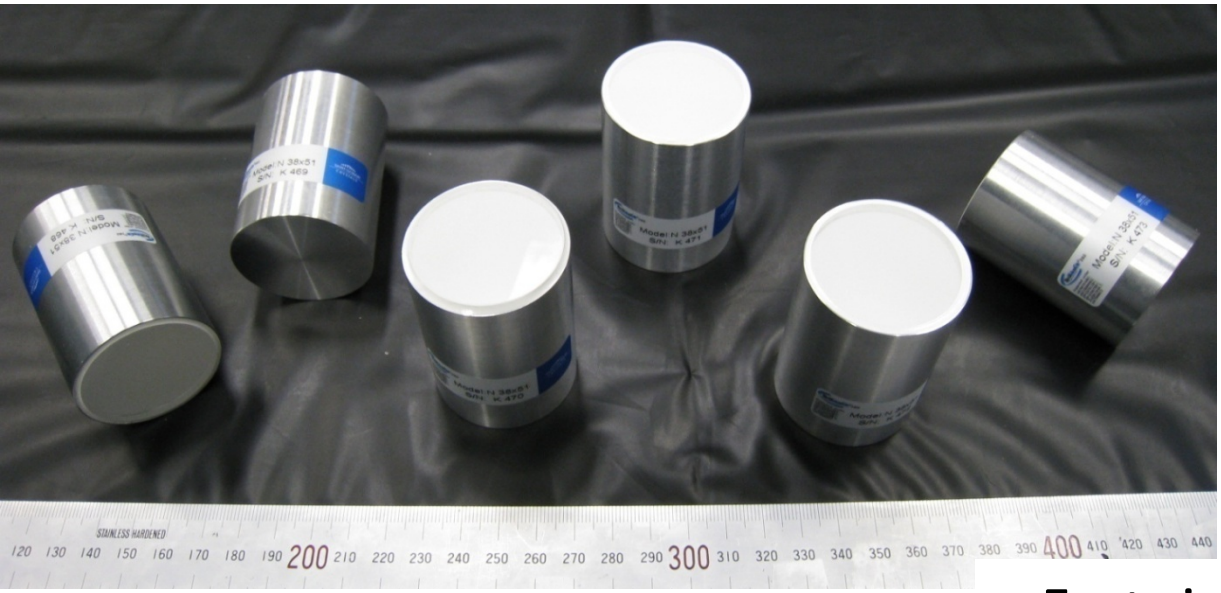


- Tag e^+ from the ^{22}Na by thin (0.1 mm) plastic scintillator.
  → *t=0*

- DAQ Trigger is made by coincidence of e^+ tag signal and γ-ray detection.
- Time difference of these signals is Ps life time of each event.

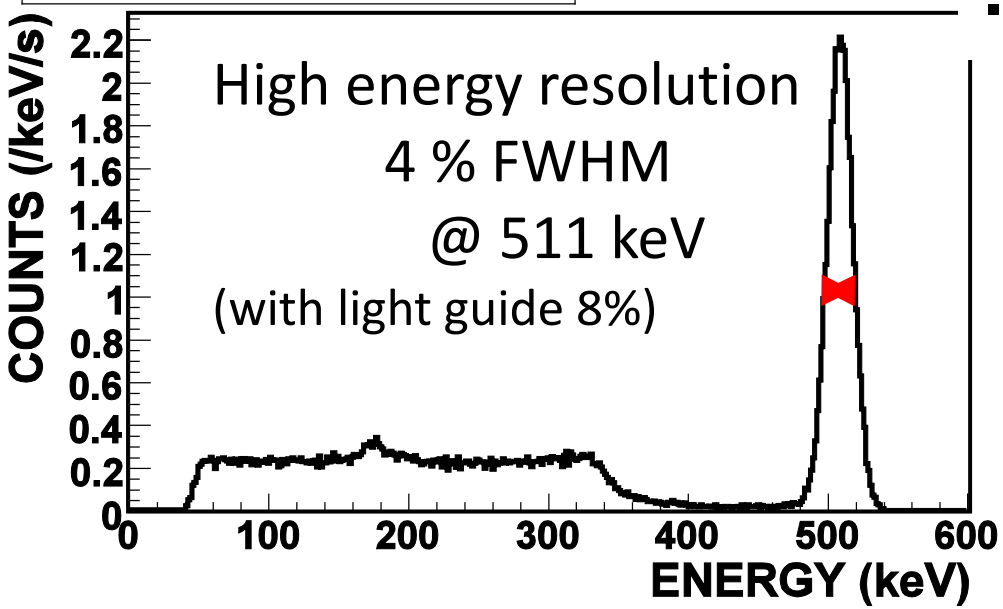


γ-ray detectors ~$LaBr_3$~



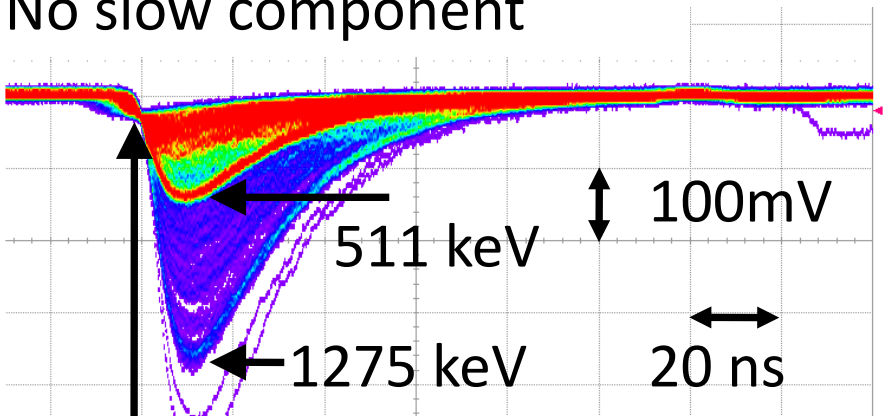
$LaBr_3$(Ce) scintillator x 6
（38.1 mm in diam., 50.8 mm long)

Guide scintillation light by UVT (Ultra-Violet Transmitting) light guides.
Detect photons by Fine-mesh PMTs in the magnetic field.



- Fast rising
- No slow component

^{22}Na



High timing resolution
200 ps FWHM @ 511 keV

Treat Ps thermalization correctly by introducing a completely new concept (Timing Information)

- Underestimation of Ps thermalization effect could be a large systematic error of O(10ppm).
- Obtain timing information, which was not considered in the previous experiments.

→ Reduce the effect from non-thermalized o-Ps.

Analysis can treat Ps thermalization correctly by measuring the time evolution precisely.

The first precision measurement of Ps-HFS using timing information

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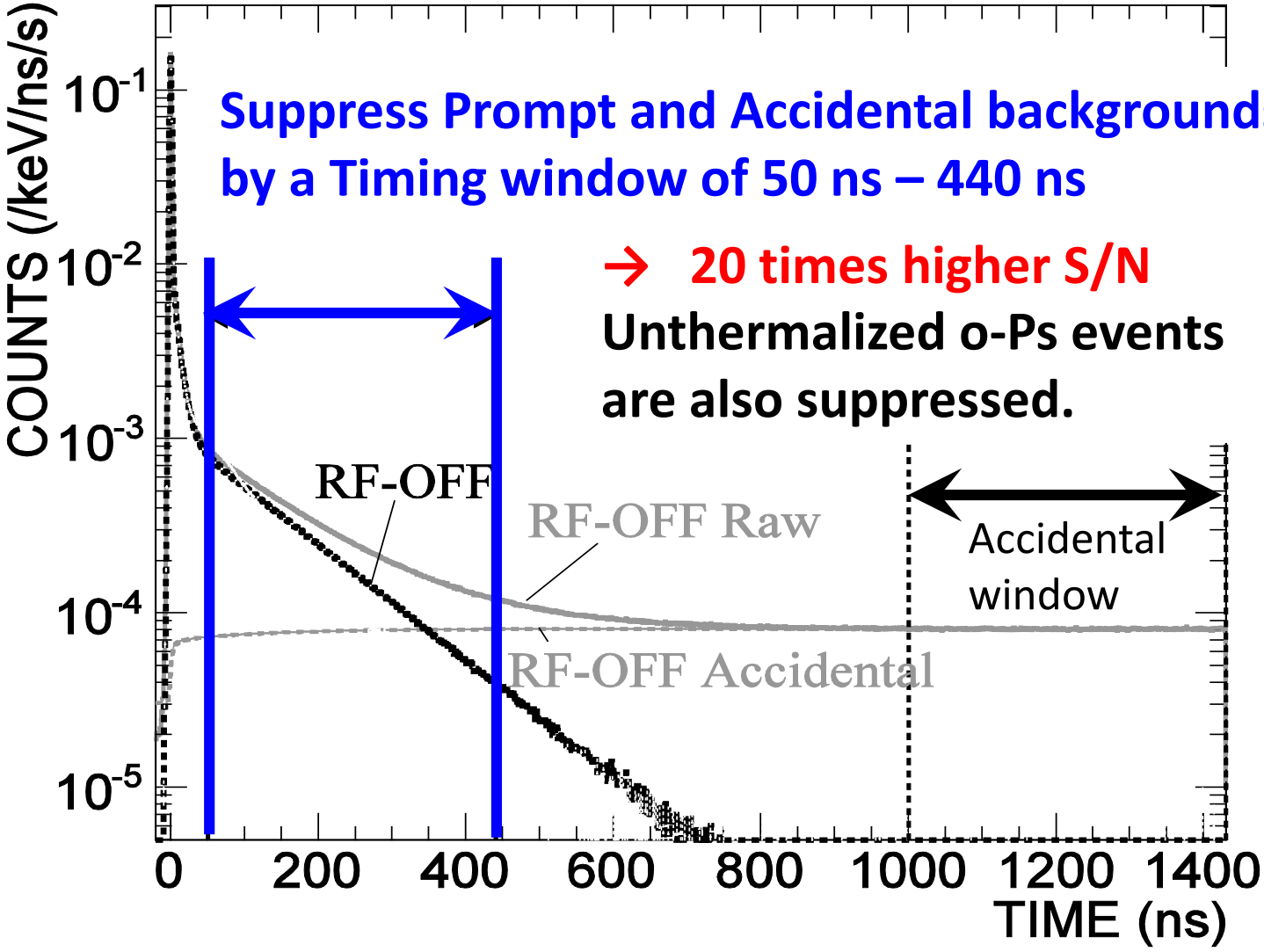
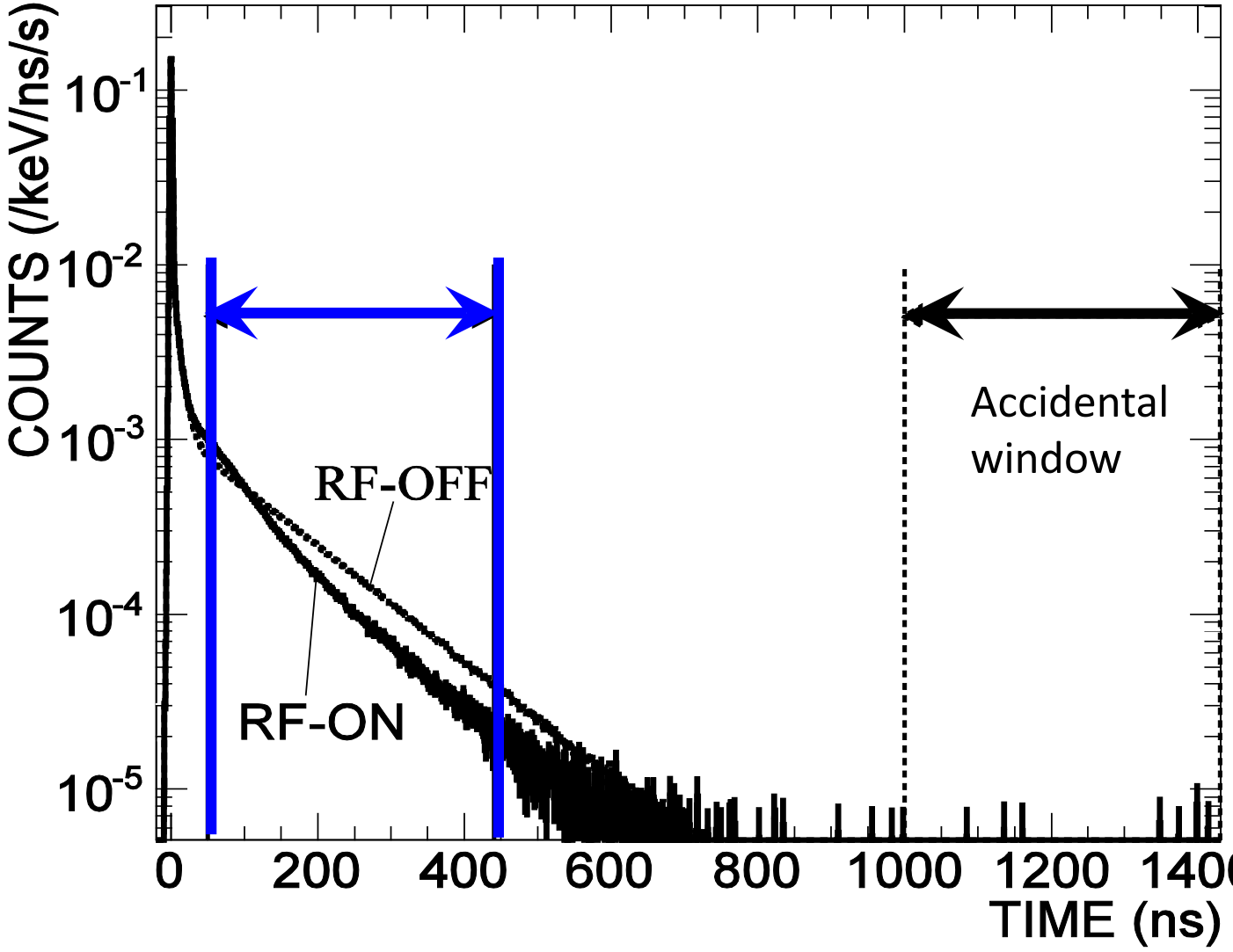
Timing spectra (RF-OFF)



@ 0.881 amagat

Timing spectra (RF-ON/OFF)



@ 0.881 amagat

Lifetime is clearly shortened by RF due to the Zeeman transition.

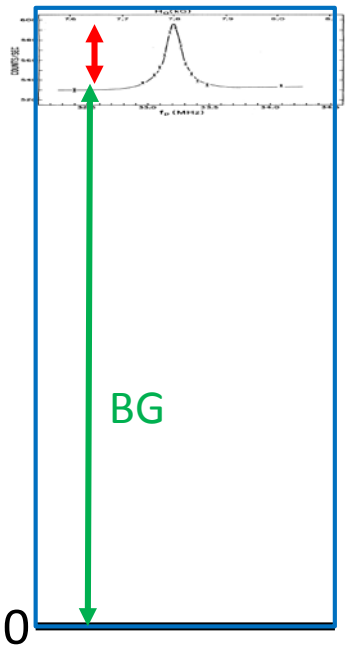
Energy spectra

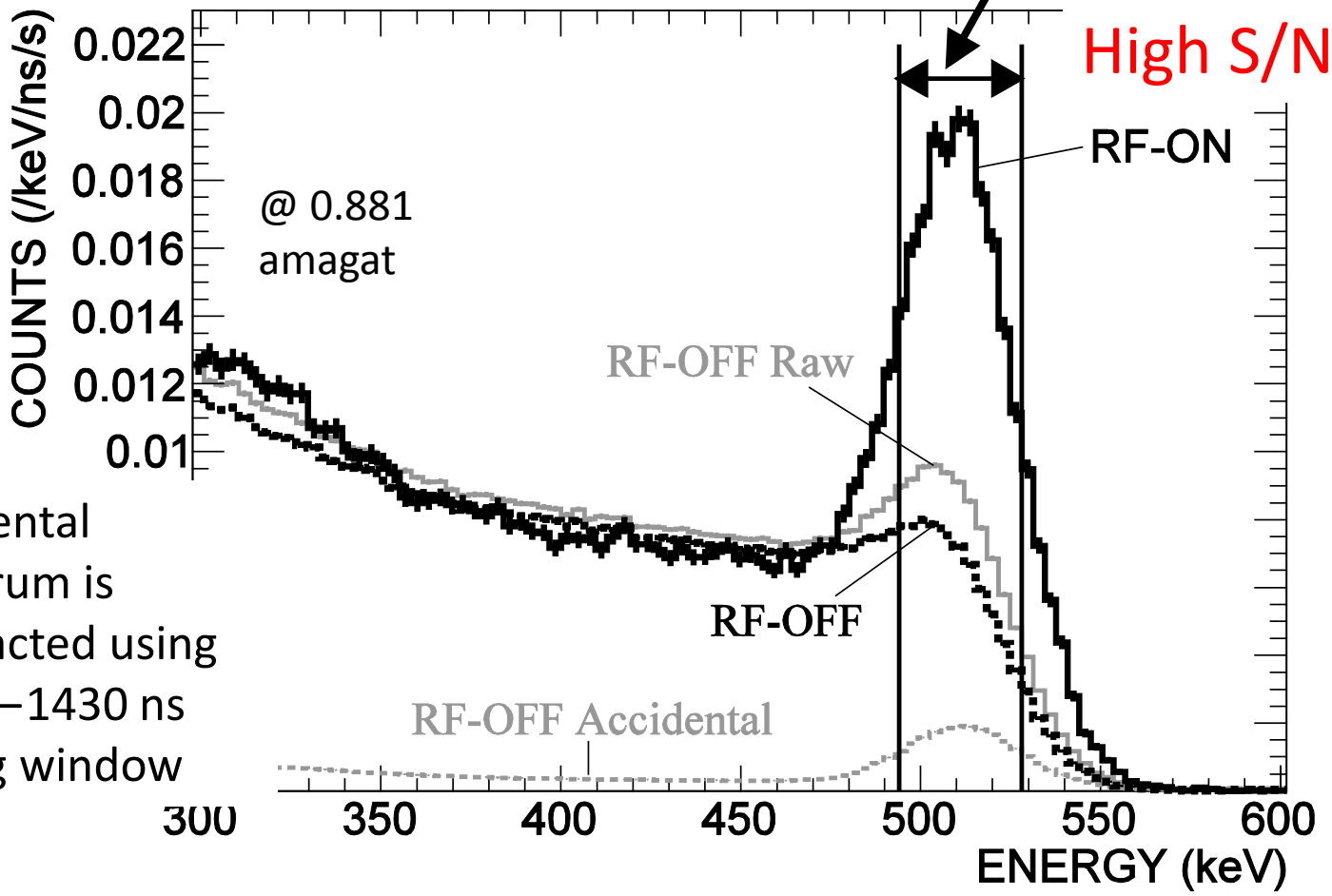
timing window 50 – 60 ns

511 keV ± 1σ

High S/N

cf. S/N of previous experiment



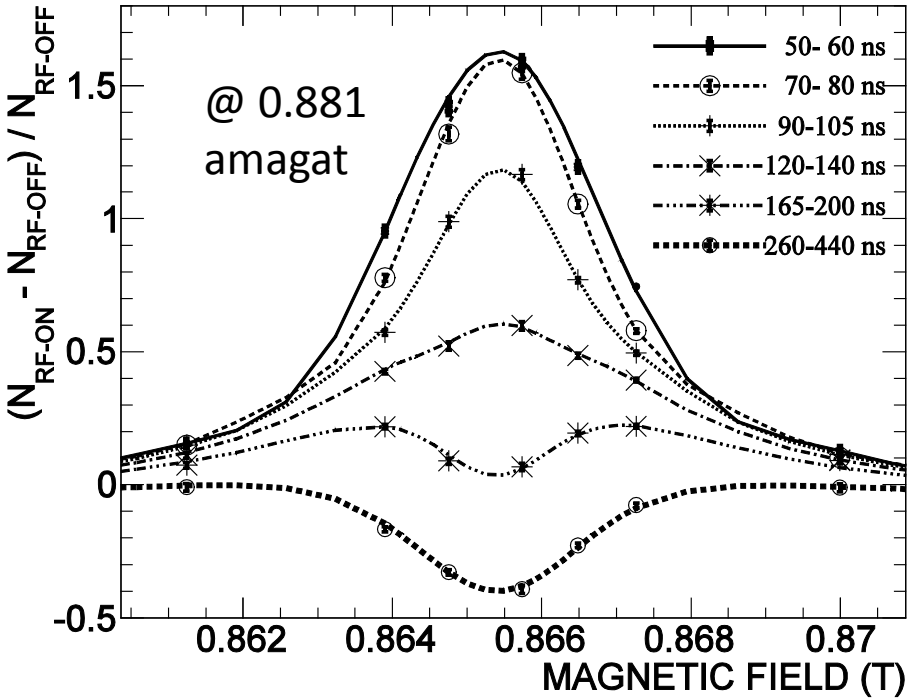


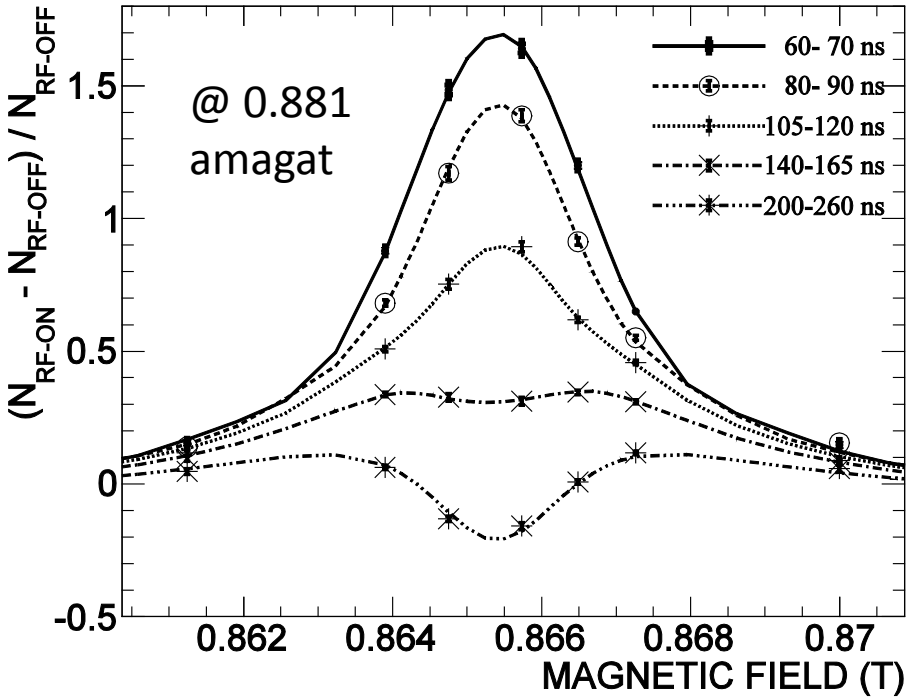
Accidental spectrum is subtracted using 1000—1430 ns timing window

2γ decay rate increases because of the Zeeman transition. Calculate (RF-ON — RF-OFF) / RF-OFF of count rates in the 511 keV ± 1σ energy window.

Resonance line

- Scanned by Magnetic Field with the fixed RF frequency and power.
- 50—440 ns is divided to 11 sub timing windows.
- Simultaneous fit of all of the gas density, magnetic field strength, and (sub) timing windows.
- Time evolution of Δ_{HFS} and pick-off rate ($\propto nv^{3/5}$) is taken into account.

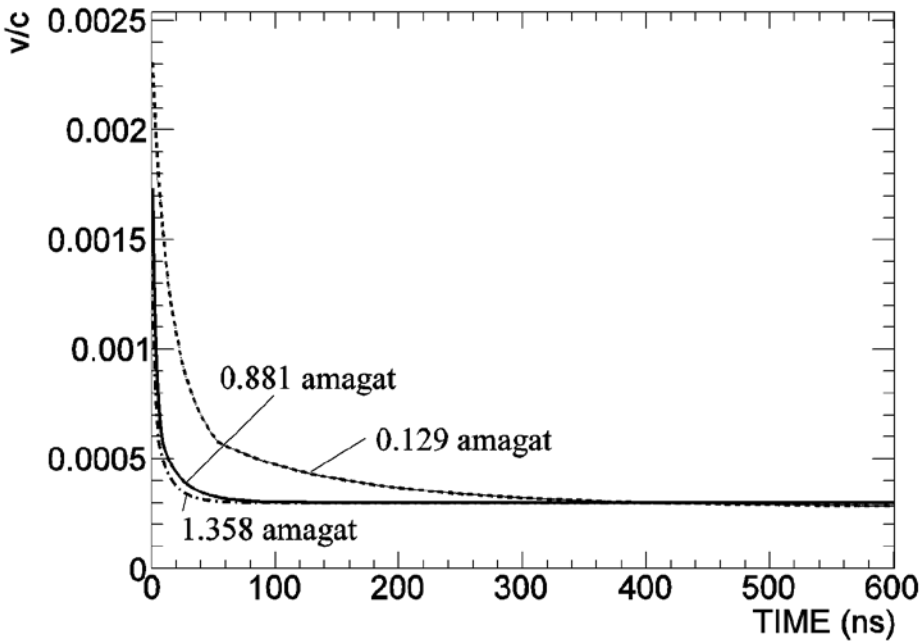




Δ_{HFS} = 203.394 2(16) GHz (8.0 ppm) χ^2/ndf = 633.3 / 592 (p = 0.12)

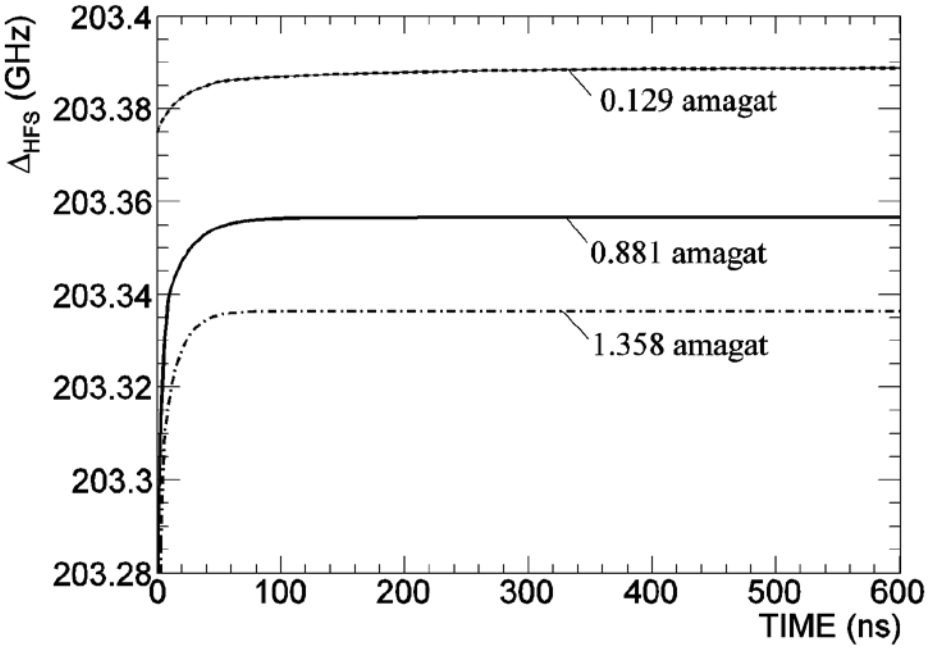
Time evolution of some parameters (fitting results)

Ps velocity / c



- Slow change at low gas density.
- Kinks are due to change of σ_m from DBS value to our pick-off value.

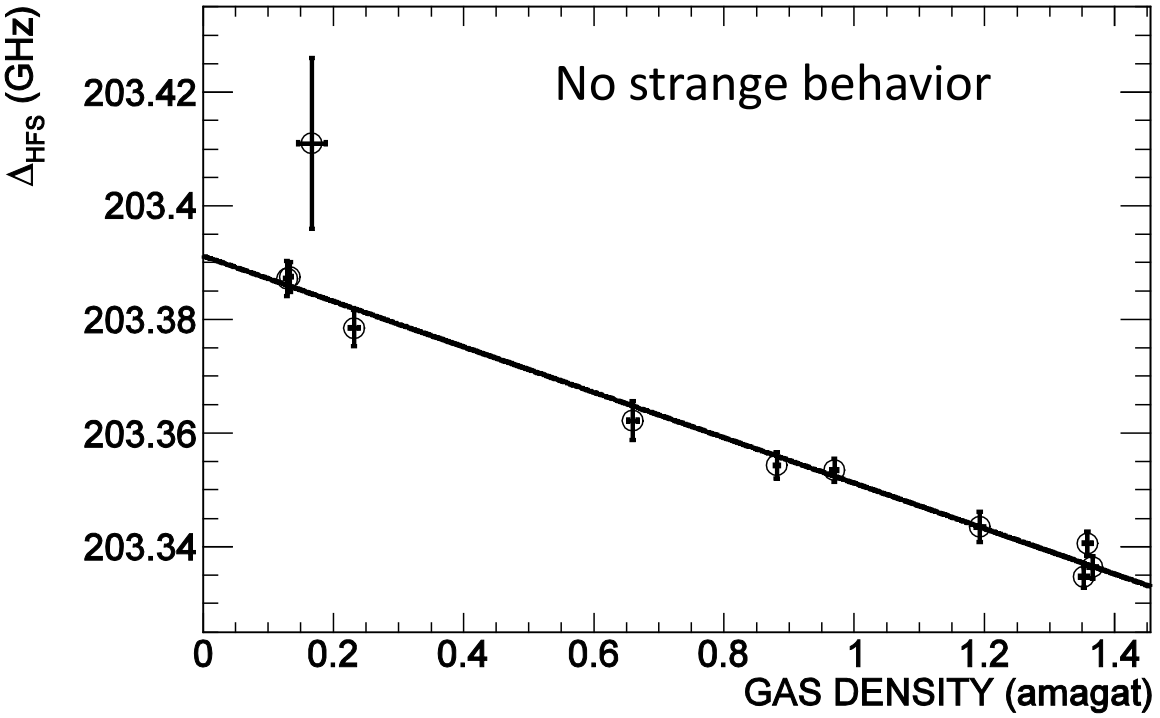
Ps-HFS



- O(100 ppm) change in 0—50 ns TW.
- O(10 ppm) slow change at low gas density.

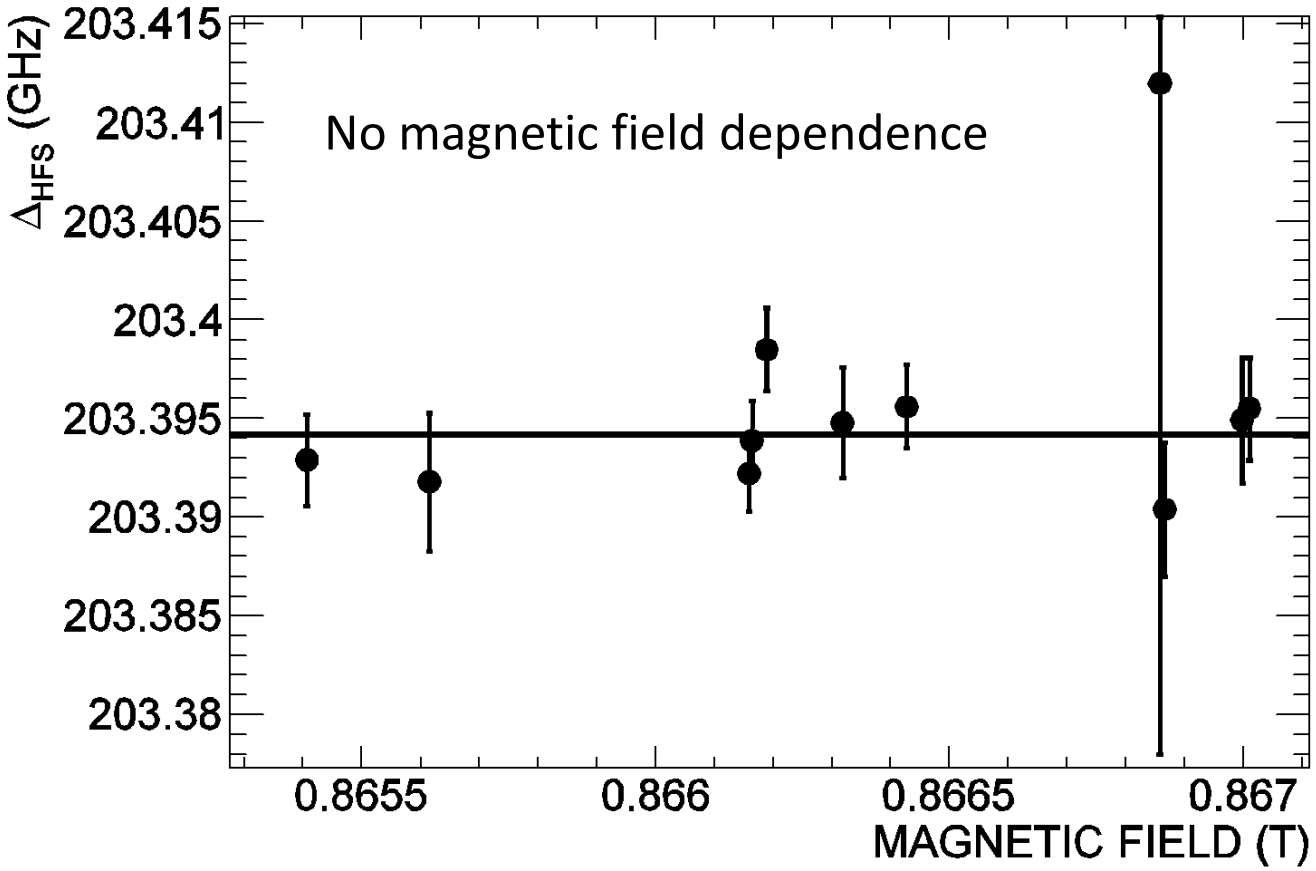
Quality check: gas-density dependence of Ps-HFS

Completely separate analysis which determine Δ_{HFS} value at each gas density has been performed to provide additional insight into the complete experimental data set and confirm their quality, although this method cannot take into account the time evolution of Ps-HFS.



Magnetic field dependence

Checked magnetic field (center value of the resonance) dependence. The material-effect parameter C ("slope" in density dependence plot) was fixed in this check.



Systematic errors (Main ones)

	Source	ppm in Δ_{HFS}
Material Effect	o-Ps pick-off rate	3.5
	Gas density measurement	1.0
	Spatial distribution of density and temperature of gas in the RF cavity	2.5
	Thermalization of Ps	1.9
Magnetic Field	Non-uniformity	3.0
	Offset and reproducibility	1.0
	NMR measurement	1.0
RF	RF power	1.2
	Q_L value of RF cavity	1.2
	RF frequency	1.0
Analysis	Choice of timing window	1.8
	Quadrature sum	6.4

Combined with 8.0 ppm stat. err., Δ_{HFS} = 203.394 2(21) GHz (10 ppm).

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Magnetic Field	Non-uniformity ($\Delta_{HFS} \propto B^2$)	3.0
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Analysis	Choice of timing window	1.8
	Quadrature sum	6.4

Combined with 8.0 ppm stat. err., Δ_{HFS} = 203.394 2(21) GHz (10 ppm).

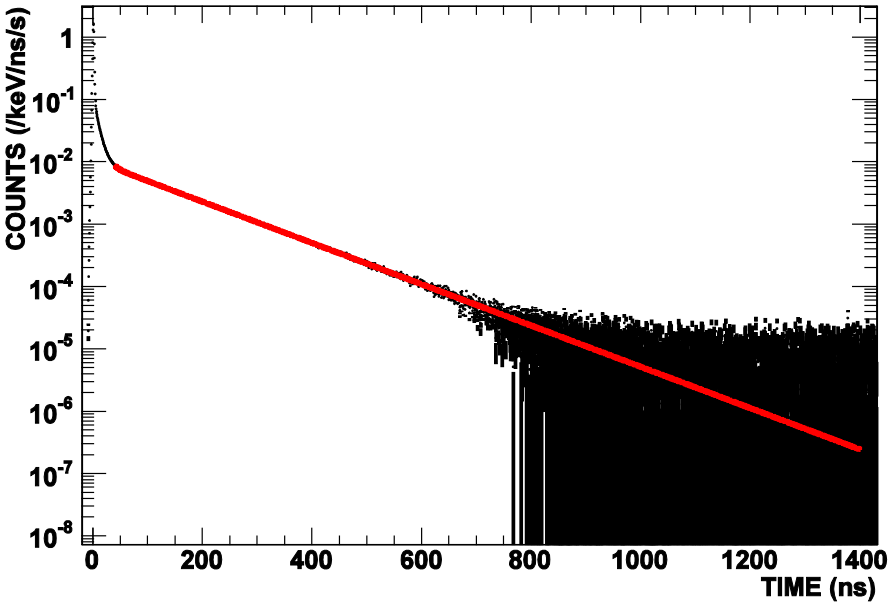
Systematic error (o-Ps pick-off rate)

We obtain HFS by fitting the data with theoretical transition line shape. This calculation needs o-Ps pick-off rate ($\Gamma_{pick}(t)$) as an input parameter. Obtain this rate by fitting the RF-OFF time spectra by the following function which includes Ps thermalization.

$$N(t) = N_0 \exp\left[-\Gamma_{\text{o-Ps}} \int_0^t \left(1 + \frac{\Gamma_{\text{pick}}(t')}{\Gamma_{\text{o-Ps}}}\right) dt'\right] + N_1 \exp\left[-\Gamma_{|+\rangle} \int_0^t \left(1 + \frac{\Gamma_{\text{pick}}(t')}{\Gamma_{|+\rangle}}\right) dt'\right]$$

$$\Gamma_{\text{pick}}(n,t) = \Gamma_{\text{pick}}(n,\infty) \times \left[\frac{v(t)}{v(\infty)}\right]^{0.6}$$

Obtain this value



Error of $\Gamma_{pick}(n,\infty)$ in this fit corresponds to 3.5 ppm of Ps-HFS error.

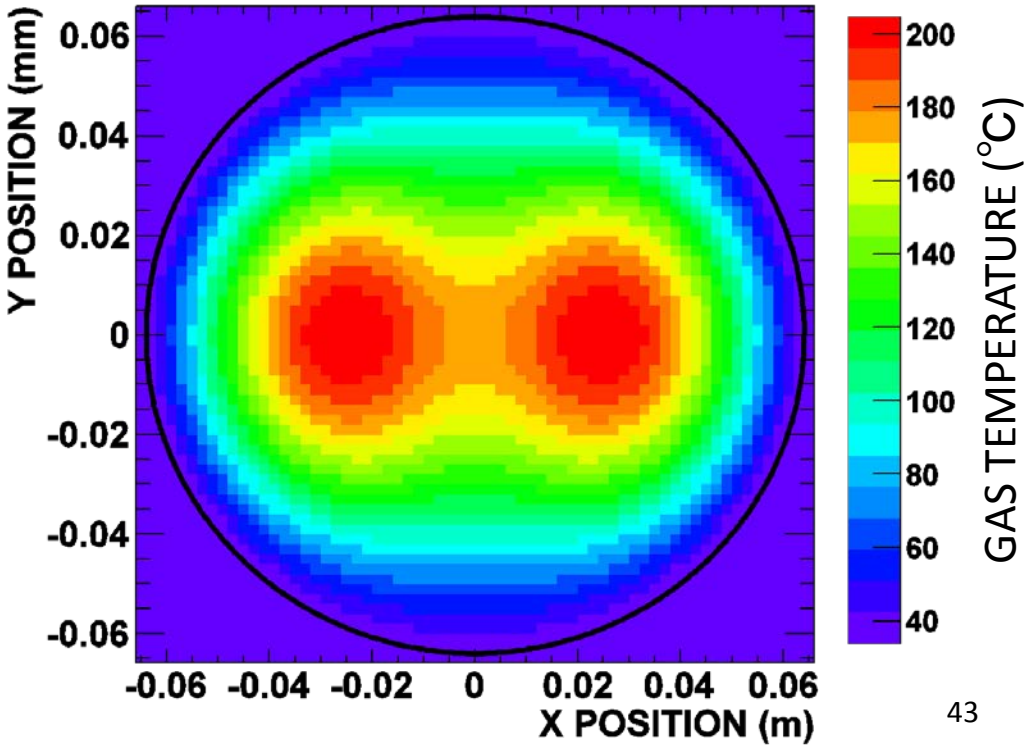
Systematic error

(Spatial distribution of density and temperature of gas in the RF cavity)

- i-C_4H_{10} slightly absorbs microwaves
  -> heated up -> high temperature (low density)
- This temperature (density) distribution in the RF cavity depends on the position in the RF cavity (RF power distribution)
  -> Ps feels different gas density depending on position

- Distributions with an *extreme* condition of no gas convection are calculated.
- Assumed absorbed RF $\propto$ energy density of E-field of TM_{110}

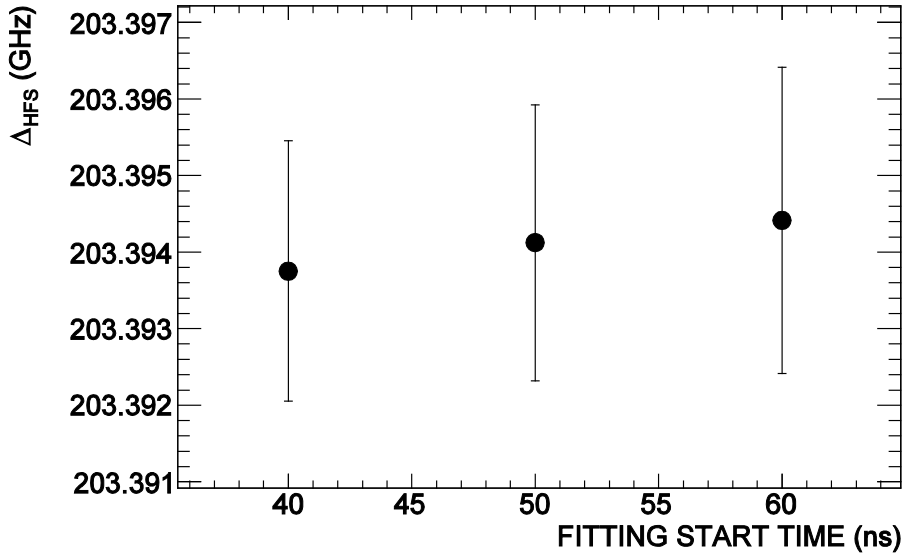
≈170 K range distribution
-> shifts Δ_{HFS} by +2.5ppm.

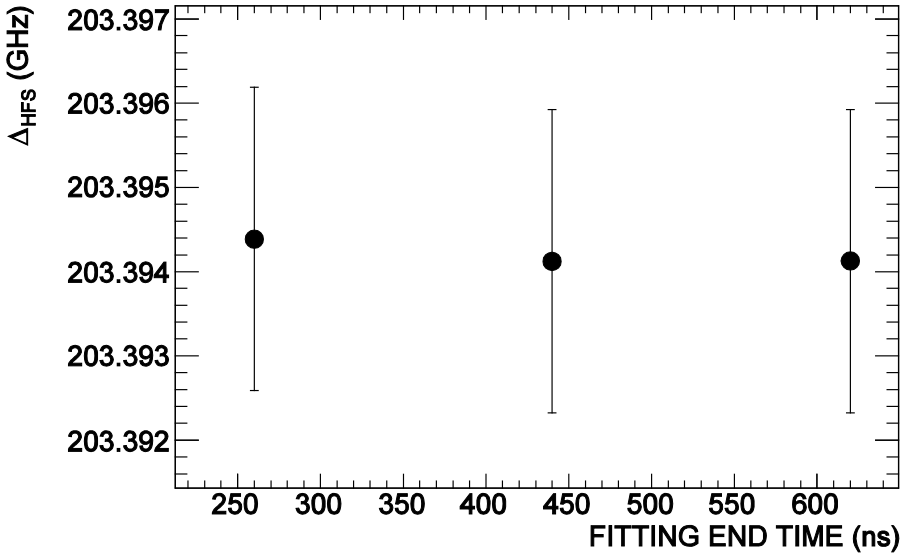


Systematic error (choice of timing window)

Timing window of 50—440 ns

1. Ending time of 440 ns is fixed, compared starting time 40 ns, 60 ns
2. Starting time of 50 ns is fixed, compared ending time 260 ns, 620 ns





In both cases, no systematic dependence was observed.

1.8 ppm shift at the maximum → systematic error.

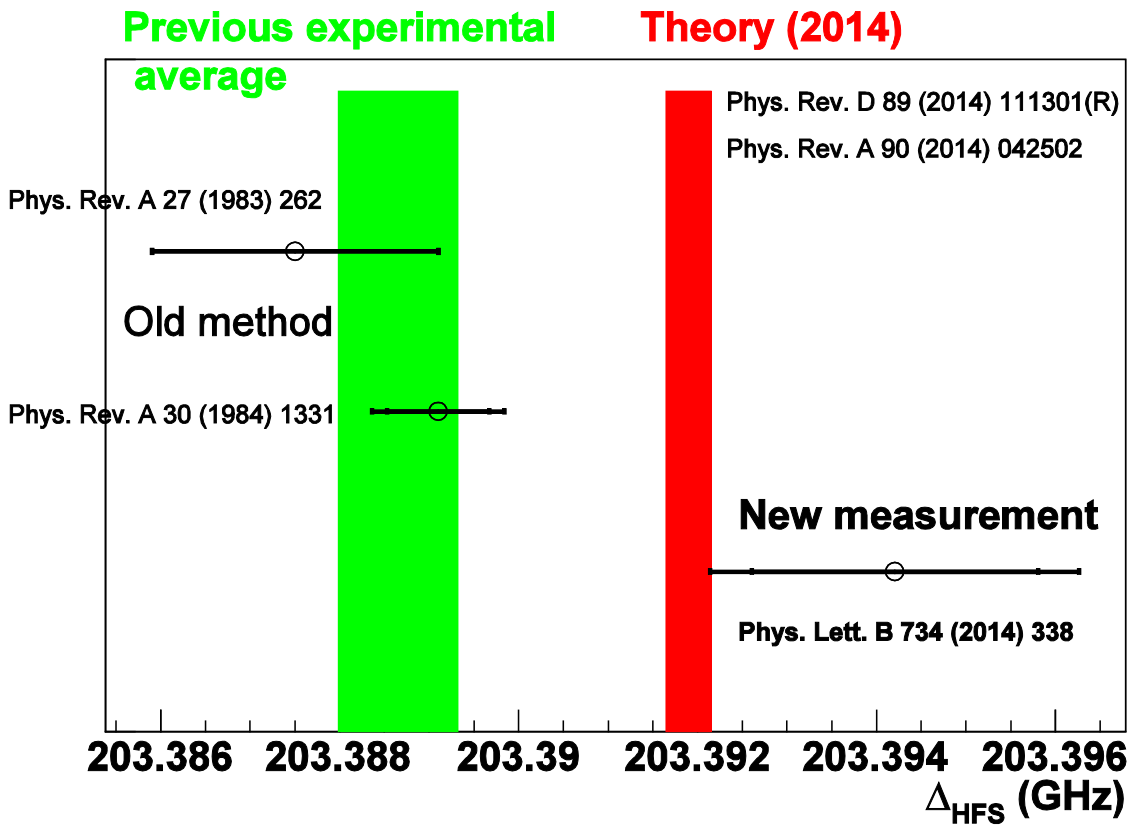
Estimation of non-thermalized o-Ps effect

- In order to evaluate the non-thermalized o-Ps effect on Ps-HFS, fitting without taking into account the time evolution of Δ_{HFS} and pick-off rate was performed. (well-thermalized assumption)
- Other procedures were the same (used 50 – 440 ns timing window)
- Result was:

  203.392 2(16) GHz (χ^2/ndf=721.1/592, p=2x10^{-4})

  (*cf.* with time evolution 203.394 2(16) GHz, (χ^2/ndf=633.3/592, p=0.12))
- This value is lower than the fit with time evolution by as large as 10 ± 2 ppm. This is comparable to the discrepancy of previous experimental results and theory (16 ppm).
- This effect might be larger if no timing window is applied, since Ps-HFS is dramatically changing in the timing window of 0—50 ns because of the rapid change of Ps velocity.
- It strongly suggests that the reason of the discrepancy in Δ_{HFS} is the effect of non-thermalized Ps.

Result



Favors QED calculation

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

Our new result taking into account the Ps thermalization is:

Δ_{HFS} = 203.394 2 ± 0.001 6 (stat., 8.0 ppm)
± 0.001 3 (sys., 6.4 ppm) GHz

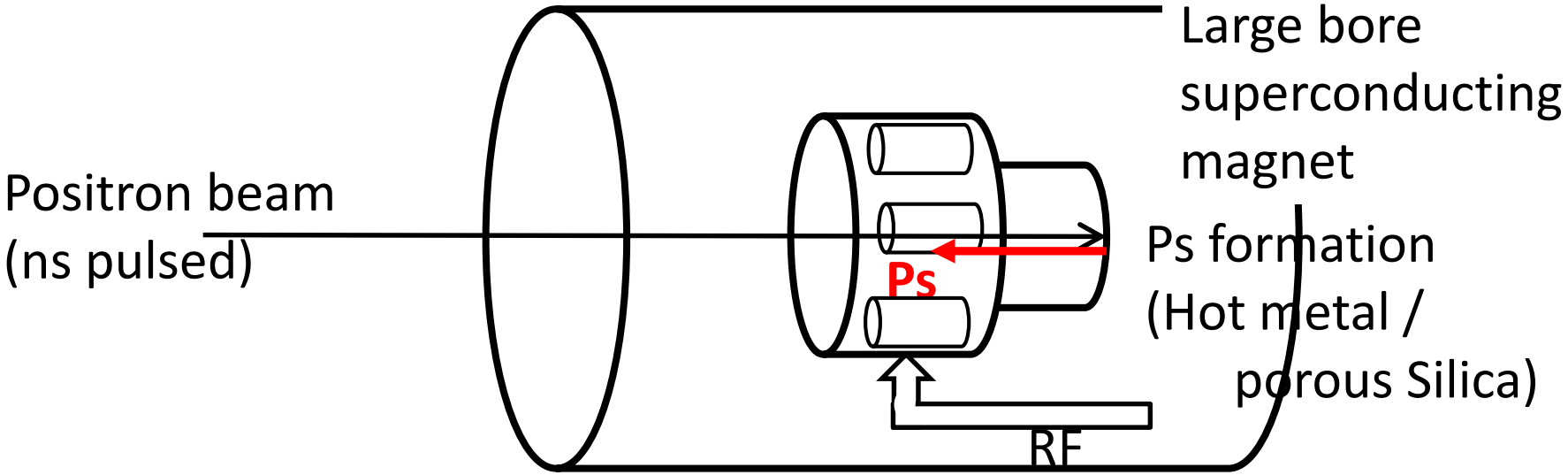
- Positronium Hyperfine Splitting (Ps-HFS)
- Material effect and Ps thermalization
- Our New Experiment
- Analysis and Results
- Prospects & conclusion

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



Other methods

- A. Miyazaki *et al.*, Prog. Theor. Exp. Phys. **2015**, C11C01 (2015).

  Direct measurement without static magnetic field (540 ppm).

  It is mentioned that it can be improved to < 10 ppm in future.

- D. B. Cassidy *et al.*, Phys. Rev. Lett. **109**, 073401 (2012).

  Saturation absorption spectroscopy between Zeeman-shifted 1S and 2P levels (2%).

  It is mentioned that it can be improved to ~ ppm in future.

- Y. Sasaki *et al.*, Phys. Lett. B **697**, 121 (2011).

  Quantum oscillation between Zeeman shifted levels (200 ppm)

  It is mentioned that it can be improved to 15 ppm in future.

Conclusion

There is a large 4.5 σ discrepancy of Ps-HFS between the previous experimental values and theoretical calculation. We performed a new precise measurement which obtains time information.

- It reduced possible systematic uncertainties in the previous experiments (Non-thermalized Ps effect and Non-uniformity of magnetic field).
- Ps thermalization function was measured to treat material effect correctly. Time evolution of Δ_{HFS} and pick-off rate due to Ps thermalization was taken into account.
- **Non-thermalized Ps effect turned out to be as large as 10 ± 2 ppm.** The result taking into account the Ps thermalization effect correctly was Δ_{HFS} = 203.394 2 ± 0.001 6 (stat., 8 ppm) ± 0.001 3 (syst., 6.4 ppm) GHz, which is **consistent with QED calculation** within 1.1σ, whereas it disfavors the previous measurements by 2.6σ.
- **Our new result shows that the Ps thermalization effect is crucial for the measurement.**