Precise Measurement of HFS of Positronium using Zeeman Effect

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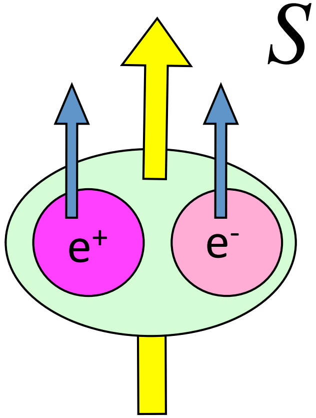
Outline

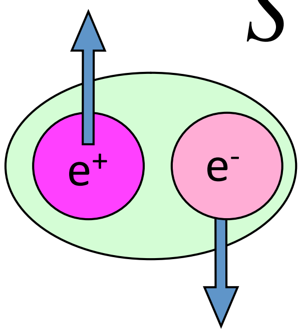
- Positronium Hyperfine Splitting (Ps-HFS)
- Our new experiment
- Results of the prototype run
- Next steps

Positronium Hyperfine Splitting (Ps-HFS)

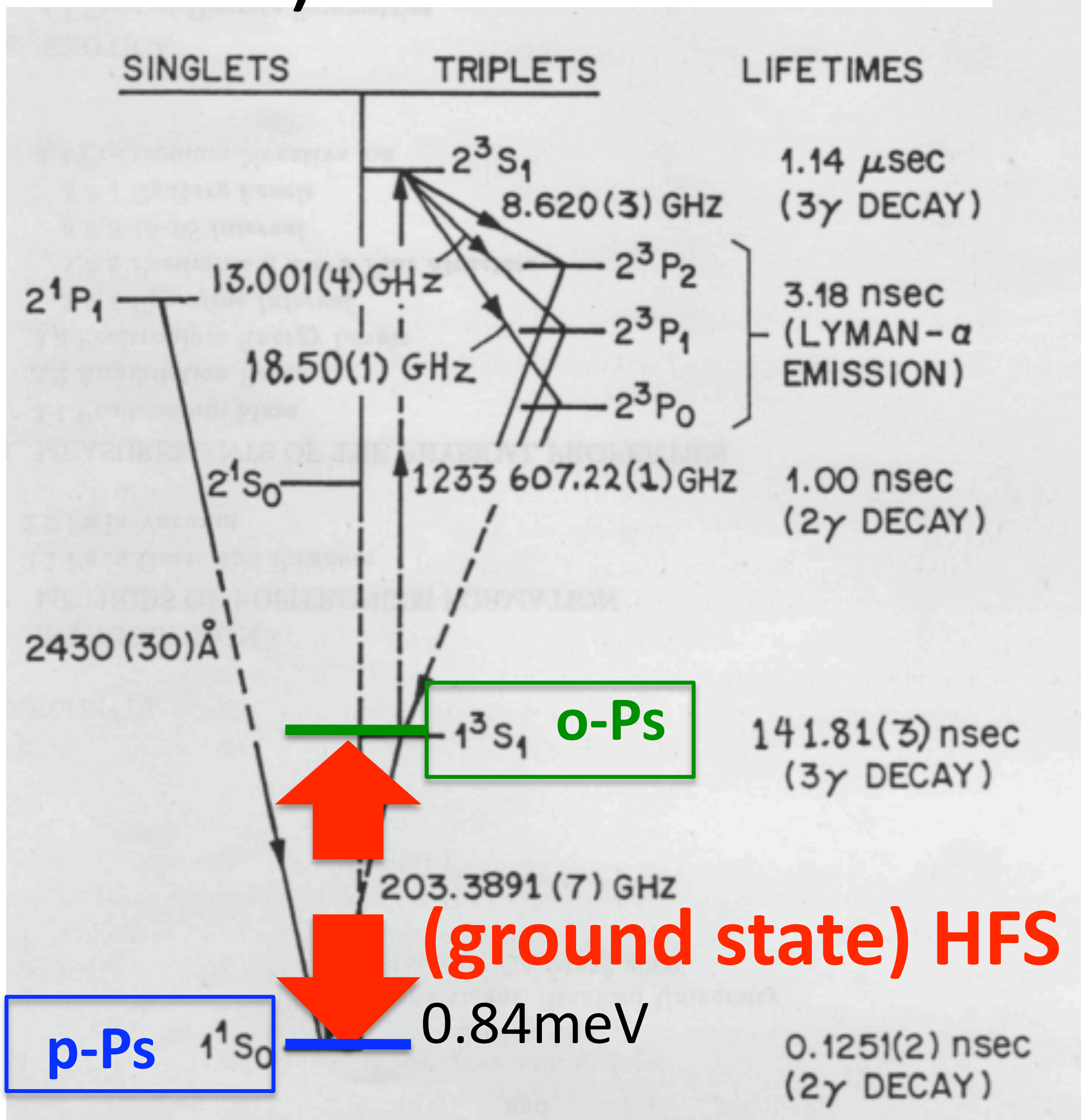
Energy difference between two spin eigenstates of the ground state Ps → Ps-HFS



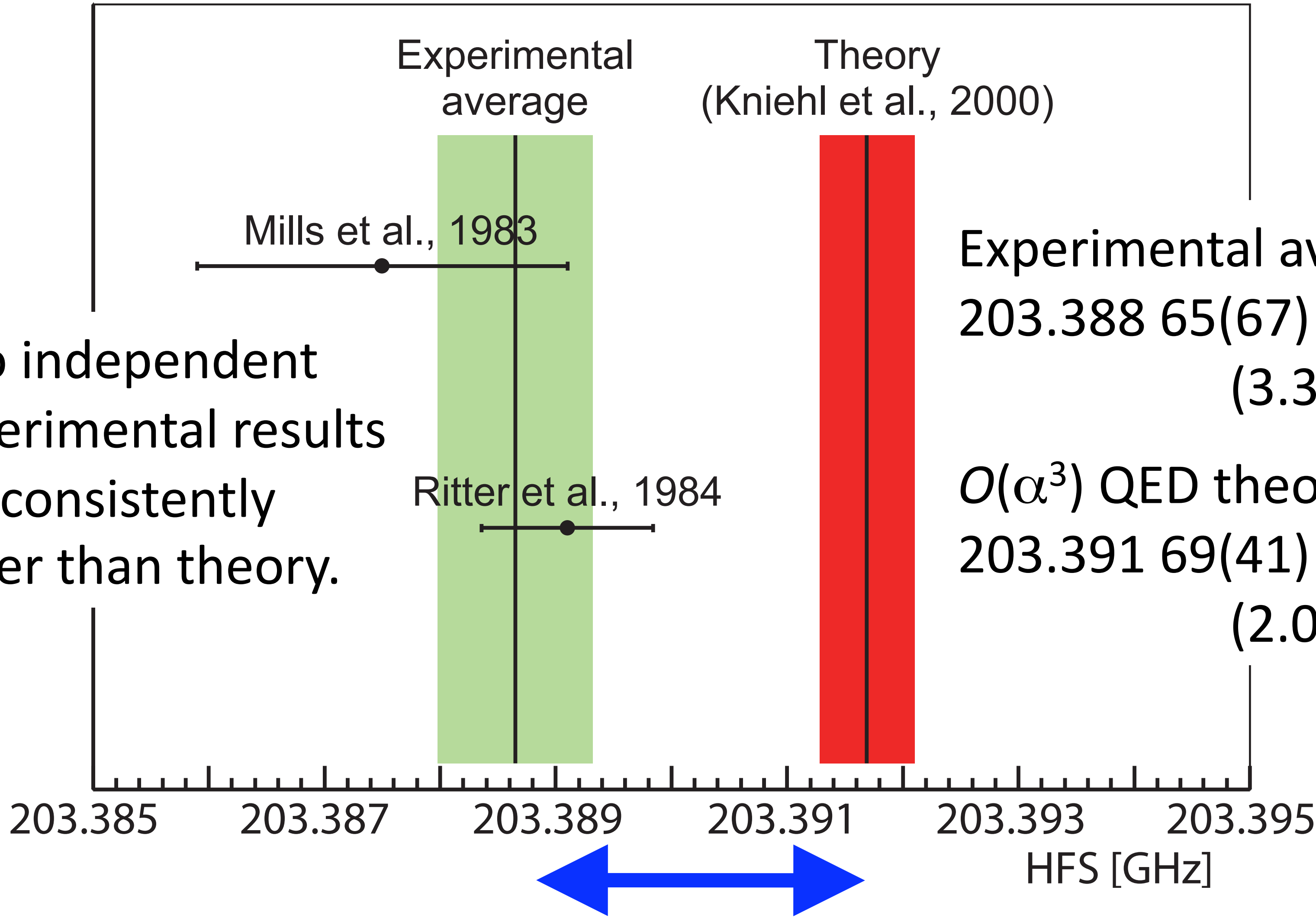
$\vec{S} = 1$ (spin triplet)
orthopositronium
(**o-Ps**, 1^3S_1)
→ 3γ (, 5γ, …)
(τ = 142 ns)



$\vec{S} = 0$ (spin singlet)
parapositronium
(**p-Ps**, 1^1S_0)
→ 2γ (, 4γ, …)
(τ = 125 ps)



Discrepancy Between Experiments and Theory



Two independent experimental results are consistently lower than theory.

Experimental average
203.388 65(67) GHz
(3.3 ppm)

$O(\alpha^3)$ QED theory
203.391 69(41) GHz
(2.0 ppm)

15 ppm (3.9 σ) discrepancy

Possible reasons for the discrepancy

- Mistakes in the theoretical calculations
  - The bound state QED is still developing. ($O(\alpha^3)$ calculation)
  - Non-relativistic QED (NRQED) might be wrong.
- Common systematic uncertainties in the previous experiments
  - Underestimation of material effects. Unthermalized o-Ps can have a significant effect especially at low material density. *cf. o-Ps lifetime puzzle (1990's)*
  - Non-uniformity of the magnetic field. It is quite difficult to get ppm level uniform field in a large Ps formation volume.
- New physics beyond the Standard Model

Experimental Technique
Indirect Measurement using Zeeman Effect

In a static magnetic field, the p-Ps state mixes with the m_z=0 substate of o-Ps.
→ Annihilate into 2 γ-rays

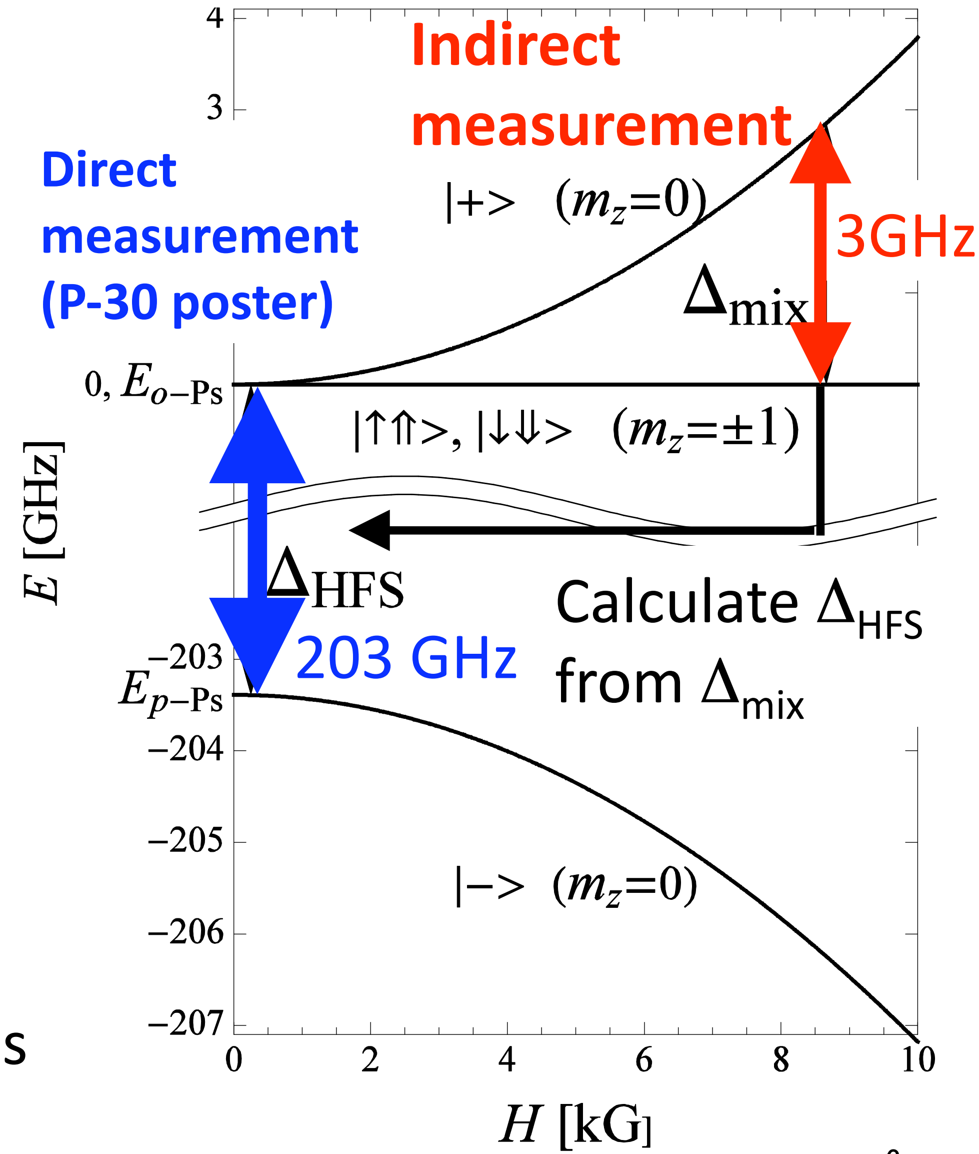
When a microwave field with a frequency of Δ_{mix} is applied, transitions between the m_z=0 and m_z=±1 substates of o-Ps are induced.

→ 2γ-ray annihilation (**511 keV monochromatic signal**) rate increases.
This increase is our experimental signal.

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

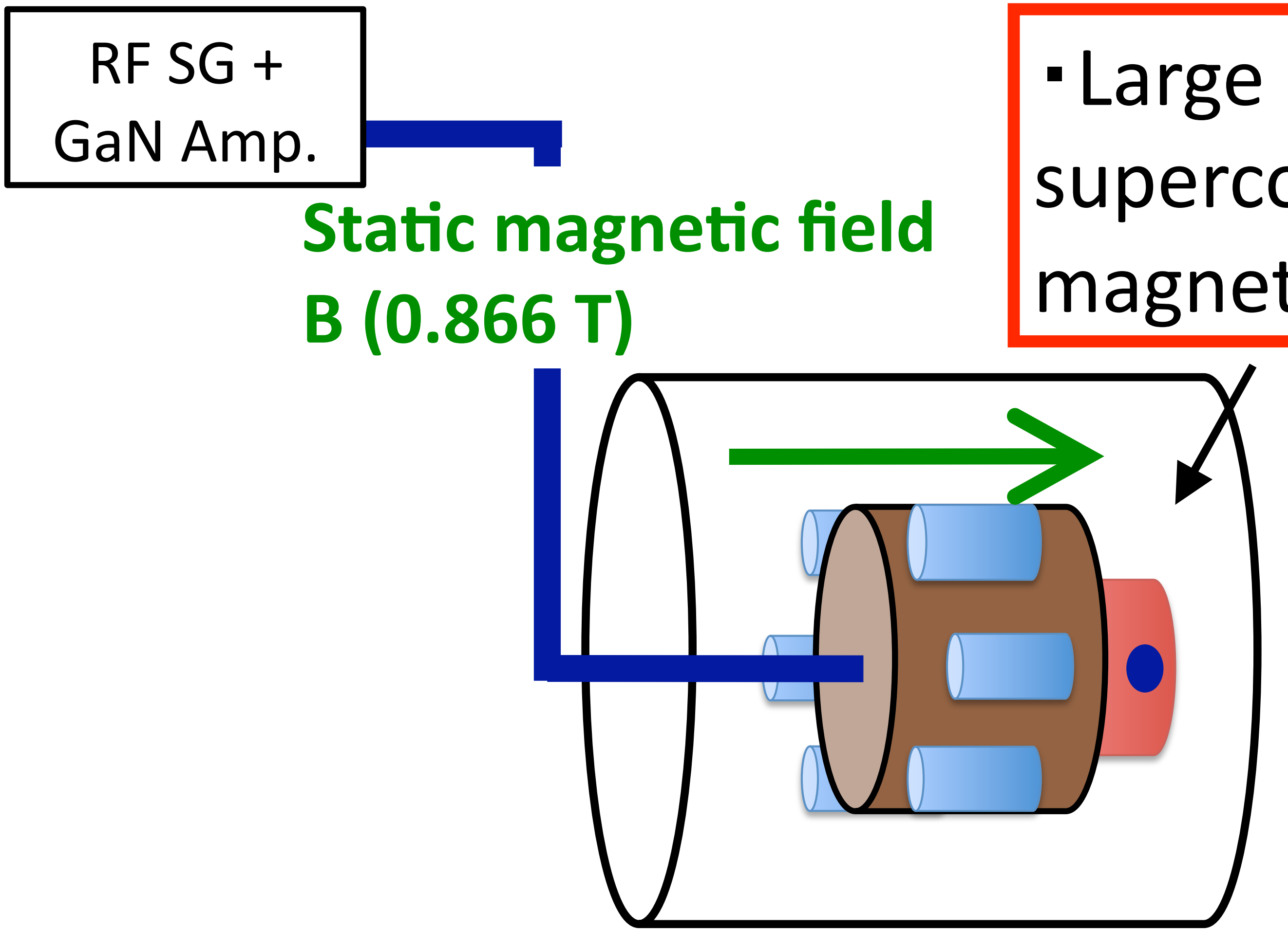
$$x = \frac{2g'\mu_B H}{\Delta_{HFS}}$$

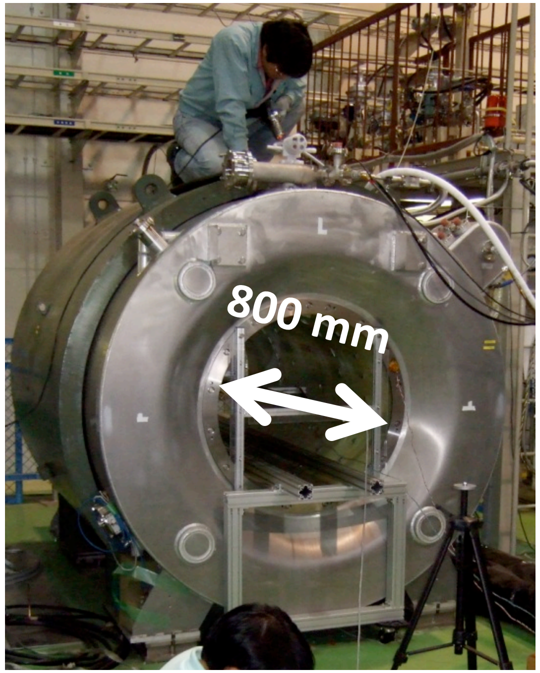
→This is the same approach as previous experiments.



Our New Experiment

To reduce the systematic uncertainties, we use the following new methods.





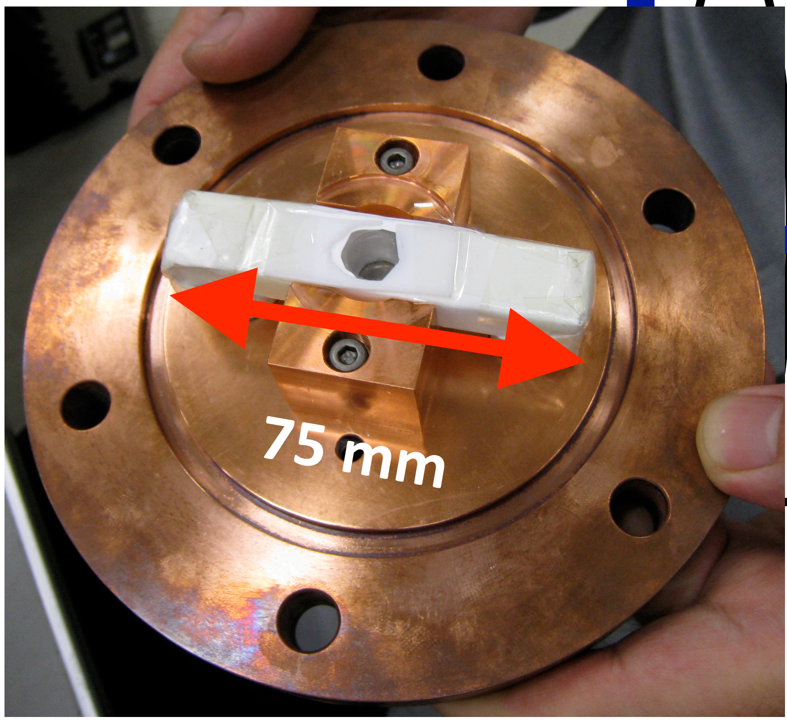
Our New Experiment

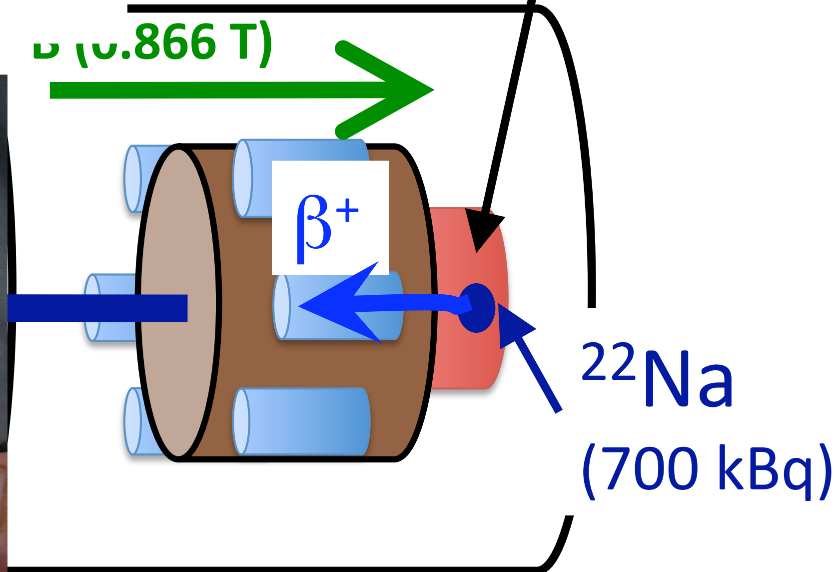
To reduce the systematic uncertainties, we use the following new methods.

- β-tagging system and timing information

(1) Prompt suppression

(2) Directly measure the Ps thermalization effect



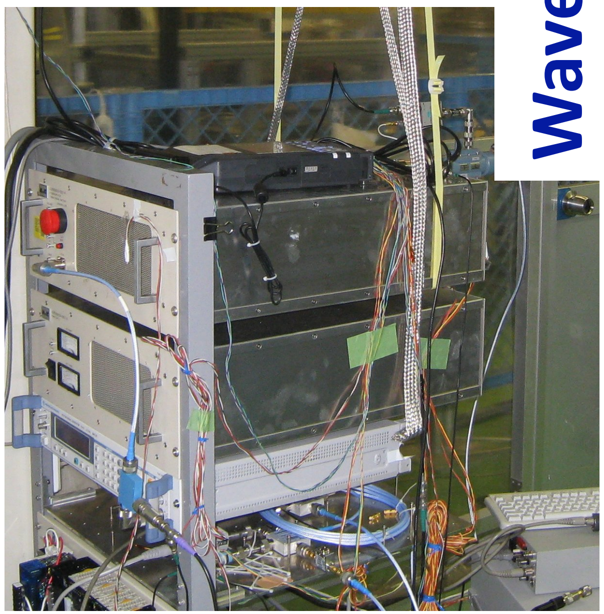


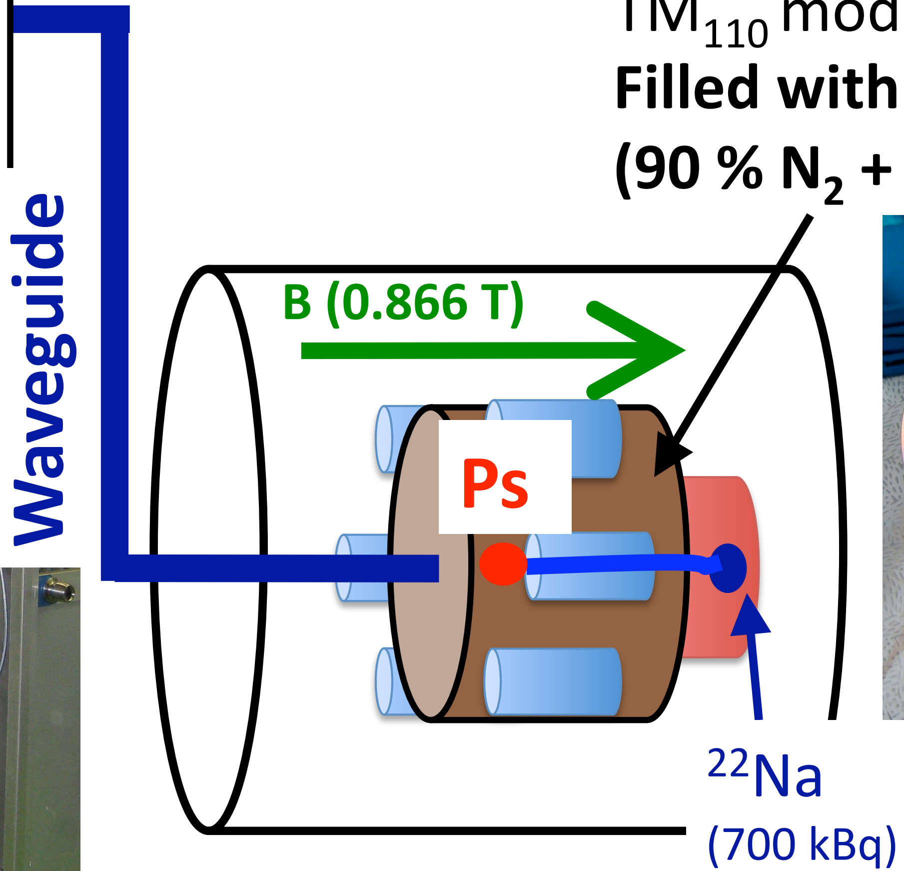
Our New Experiment

P-32 poster

To reduce the systematic uncertainties, we use the following new methods.

RF SG +
GaN Amp.
2.9 GHz
500 W CW



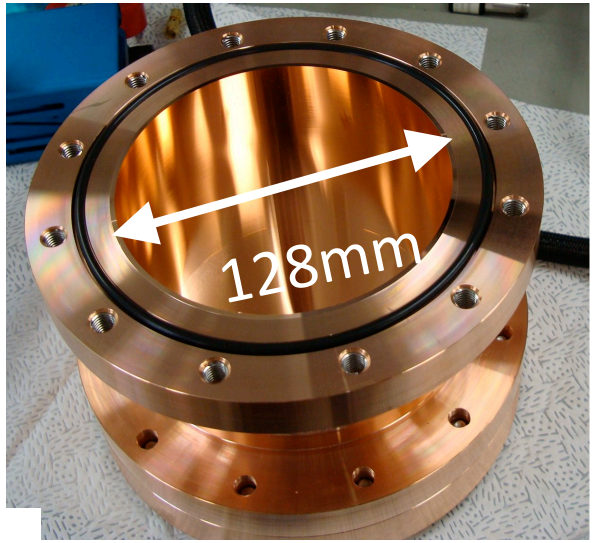


RF Cavity

TM_{110} mode, Q=14700

Filled with gas

(90 % N_2 + 10 % iso-C_4H_{10})

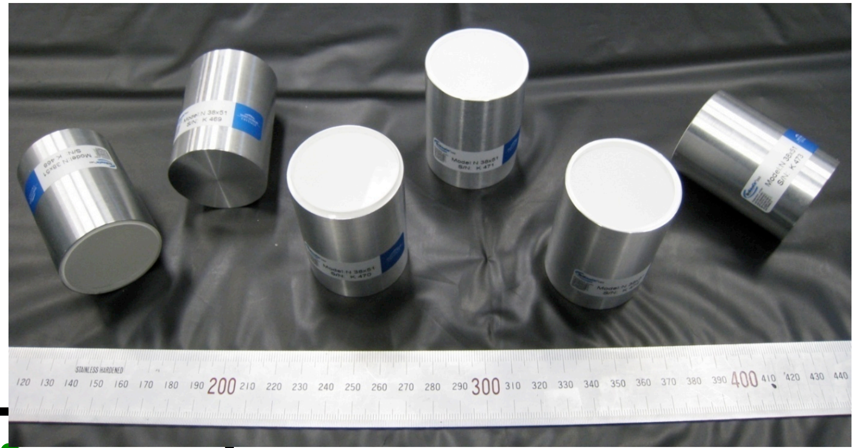


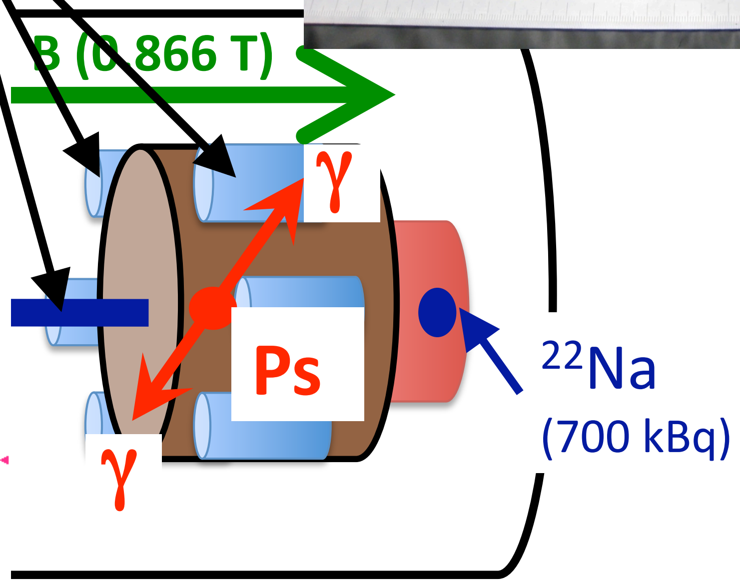
Our New Experiment

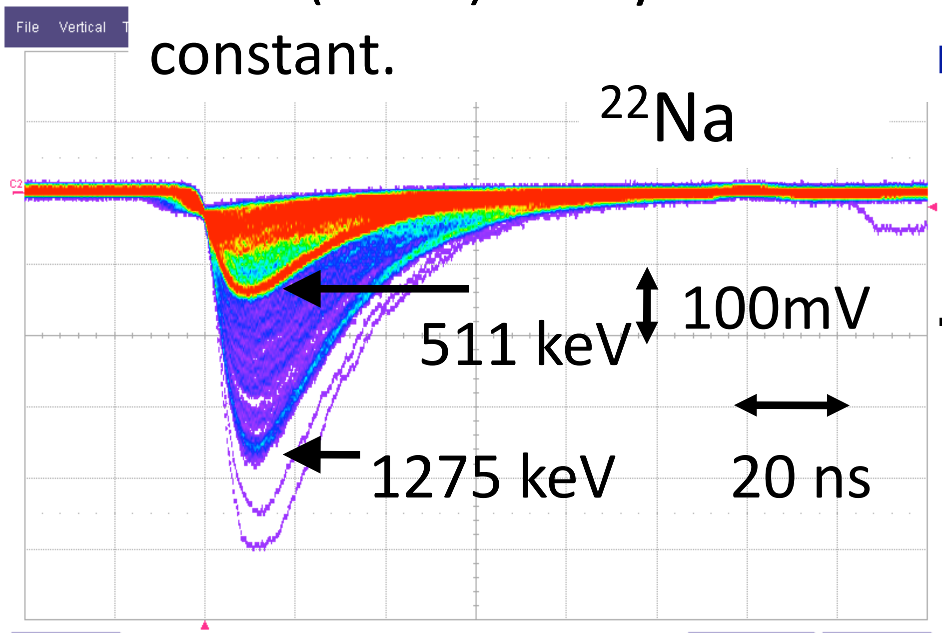
To reduce the systematic uncertainties, we use the following new methods.

- High performance γ-ray detectors

-**$LaBr_3$(Ce) scintillators** x 6
-**High energy (4%) and timing (200 ps) resolutions,** short (26 ns) decay constant.







Our New Experiment

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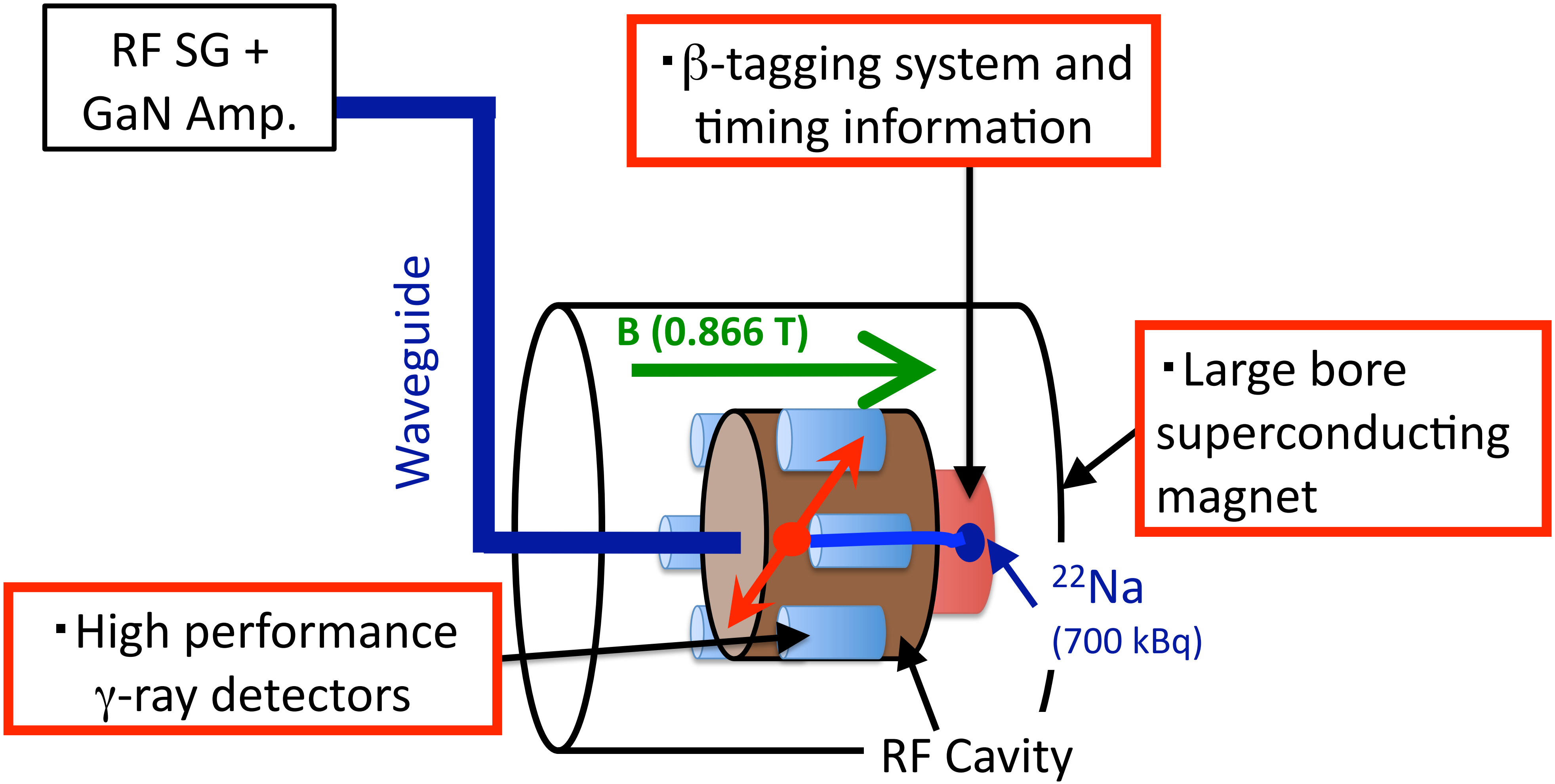
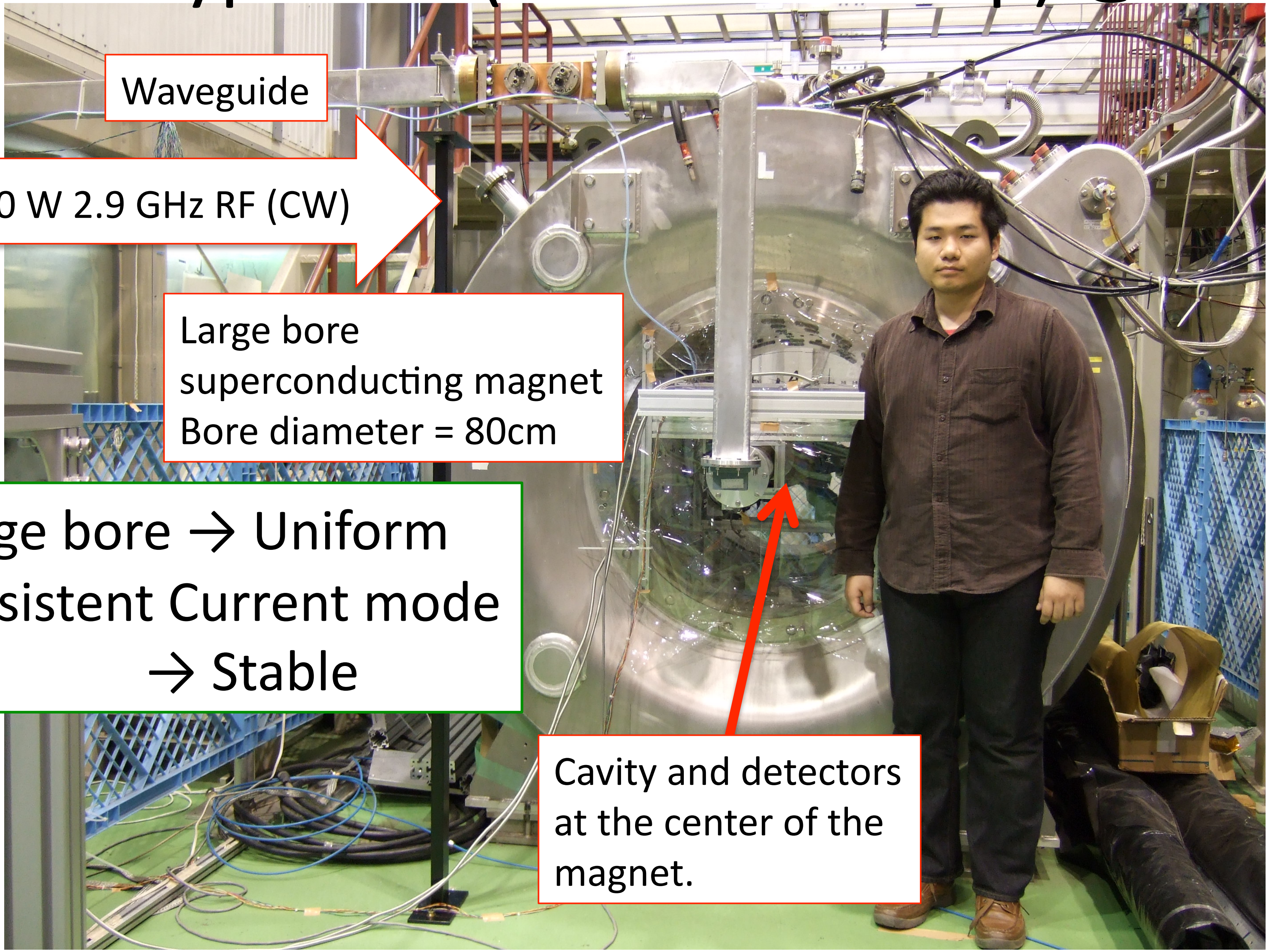
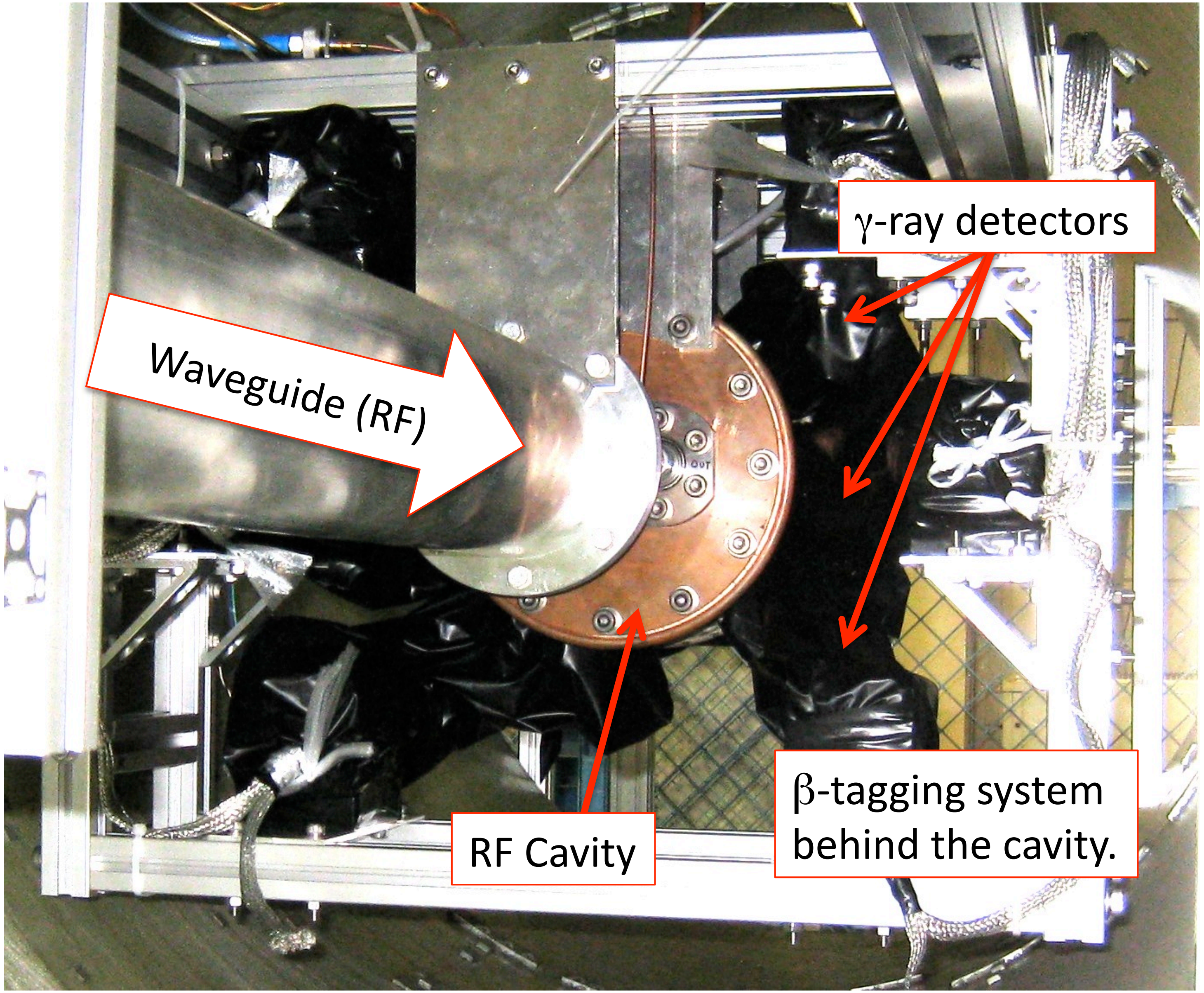


Our Experimental Setup
Prototype Run (29 Jun – 18 Sep) @KEK

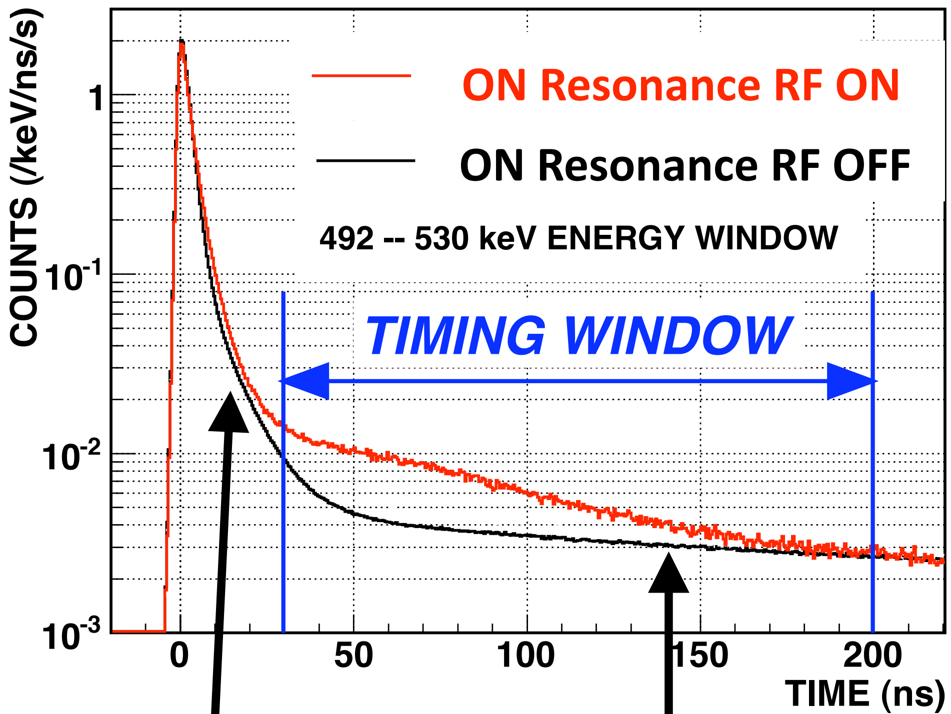


Center of the Magnet



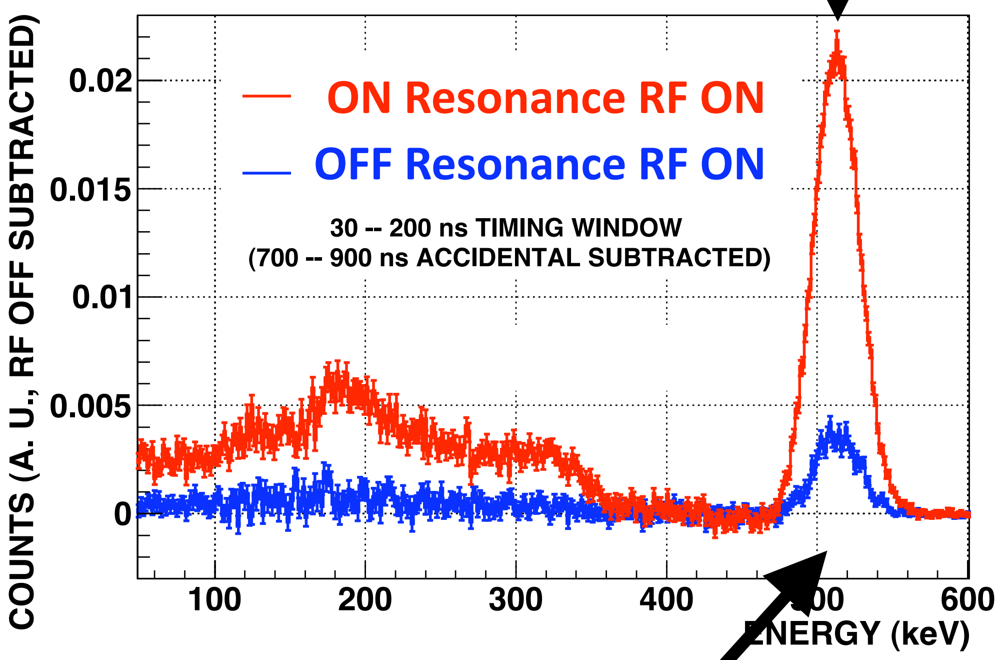
Results of the Prototype Run

Timing Spectra



Energy Spectra

511 keV



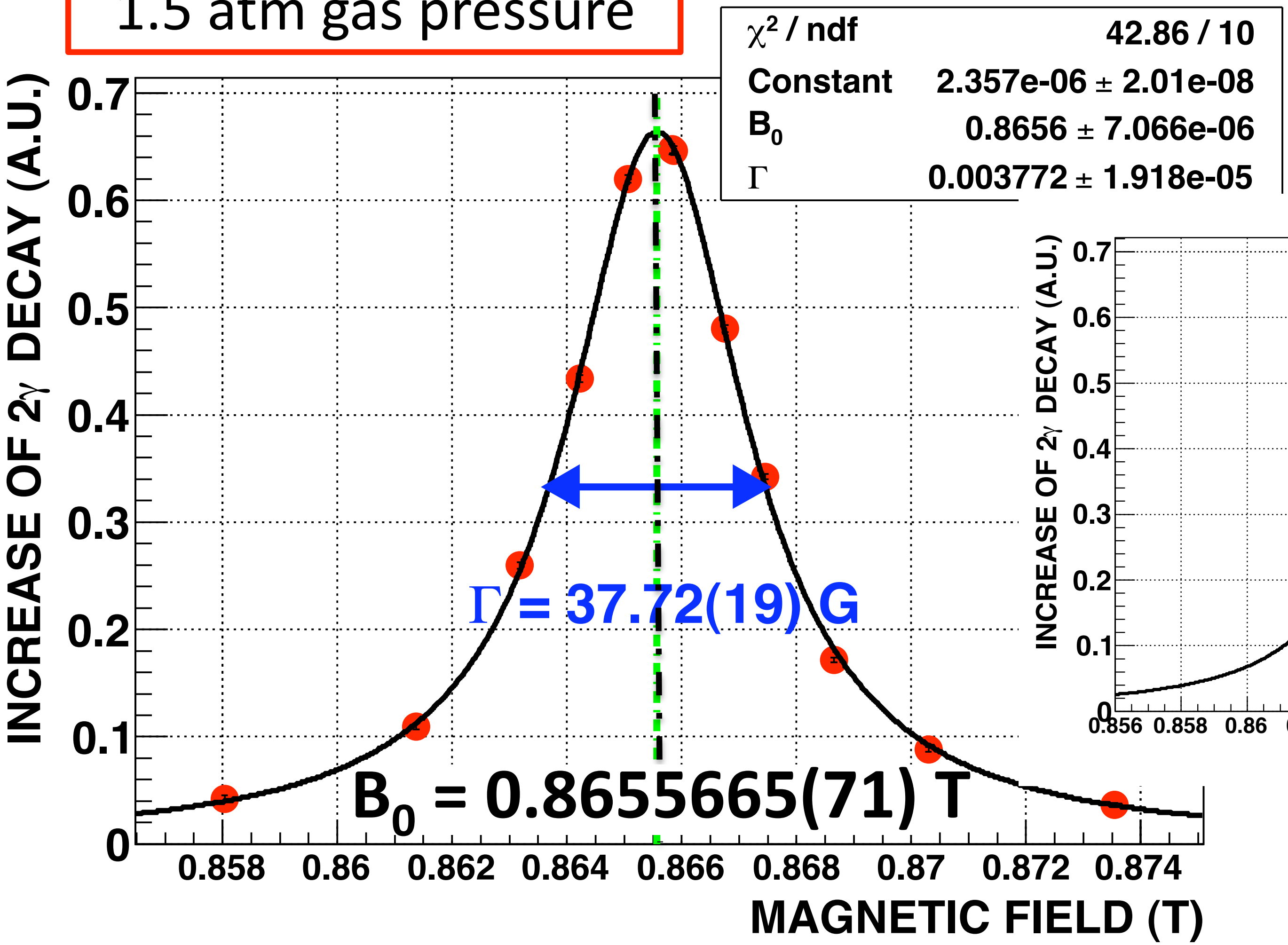
Short component ($m_z = 0$)

Long component ($m_z = \pm 1$)

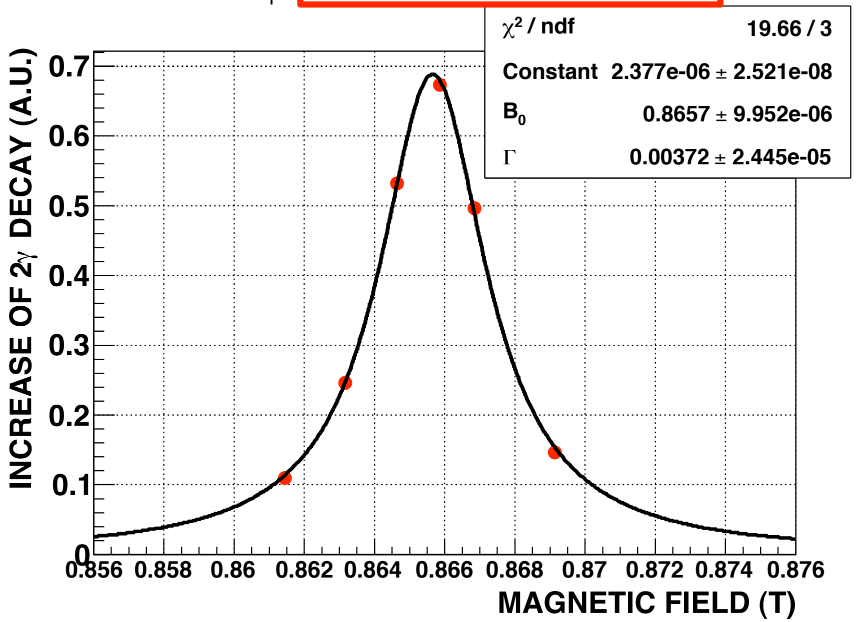
2γ decay rate increases because of the Zeeman transition.

Resonance Line

1.5 atm gas pressure



1.0 atm
gas pressure



Δ_{HFS} = 203.385 ± 0.003 GHz (14 ppm, statistical error only)

Systematic Errors

Systematic errors	(ppm)
Non-uniformity of the magnetic field	22
Analysis method	< 40
Line-shape correction	< 20
Gas pressure dependence	8
Thermalization of Ps	< 20

Systematic errors	(ppm)
RF Frequency	6
Q-value of the cavity	10
Magnetic field correction	4
Stability of the magnetic field	2
NMR measurement	2
Quadrature sum	56

Further analysis will reduce these uncertainties.

Preliminary value of Ps-HFS by 1.5 and 1.0 atm measurement is
203.385 ± 0.003 (14 ppm, stat.) ± 0.011 (56 ppm, sys.) GHz

Consistent with both of the previous experimental values and with the theoretical value.

Improvements must be made for future measurements.

Next Steps

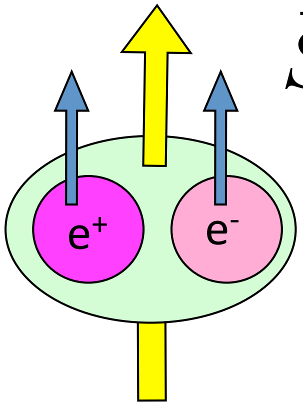
- Compensation magnets will be installed and *O*(ppm) magnetic field uniformity is expected to be achieved.
- Measurements at various pressures of gas will be performed to estimate the material effect (the Stark Effect).
- We can precisely measure the Ps thermalization effect using the timing information.
- We will begin the final run within one year.
- A measurement with a precision of *O*(ppm) is expected within a few years.

Conclusion

- There is a 3.9 σ discrepancy in the ground state Ps-HFS between the experimental results and the QED prediction.
- A new experiment to measure the Ps-HFS which reduces possible common uncertainties in previous experiments has been constructed.
- The preliminary value of Ps-HFS with an accuracy of 58 ppm has been obtained from our prototype run.
- A new result with an accuracy of *O*(ppm) will be obtained within a few years which will be an independent check of the discrepancy.

Backup

Two Spin Eigenstates of Positronium



$\vec{S}$ =1(Triplet）

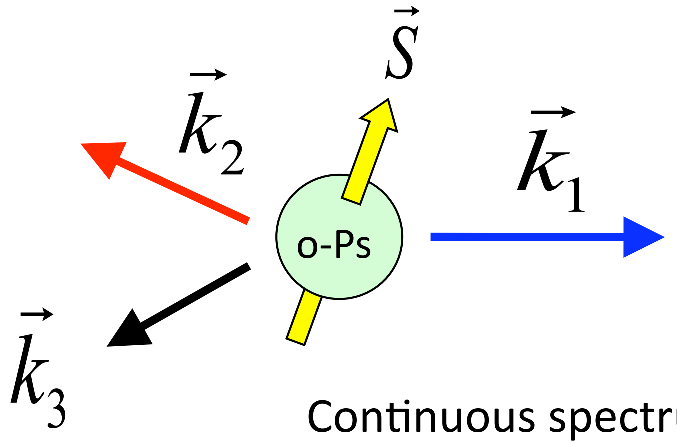
Ortho-positronium (o-Ps)

Spin=1 The same quantum number as photon

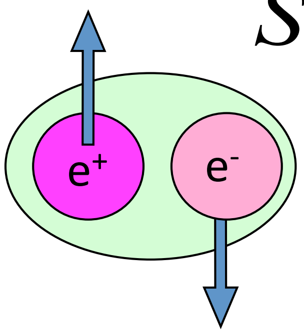
o-Ps → 3g (, 5g, ...)

o-Ps

Lifetime 142 ns



Continuous spectrum



$\vec{S}$ =0(Singlet）

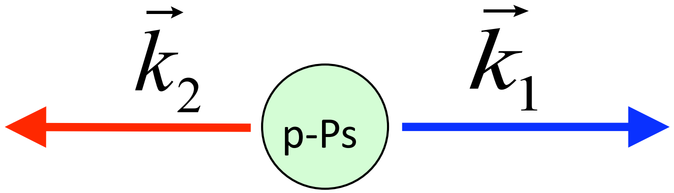
Para-positronium (p-Ps)

Spin=0 Scalar particle

p-Ps → 2g (, 4g, ...)

p-Ps

Lifetime 125 ps



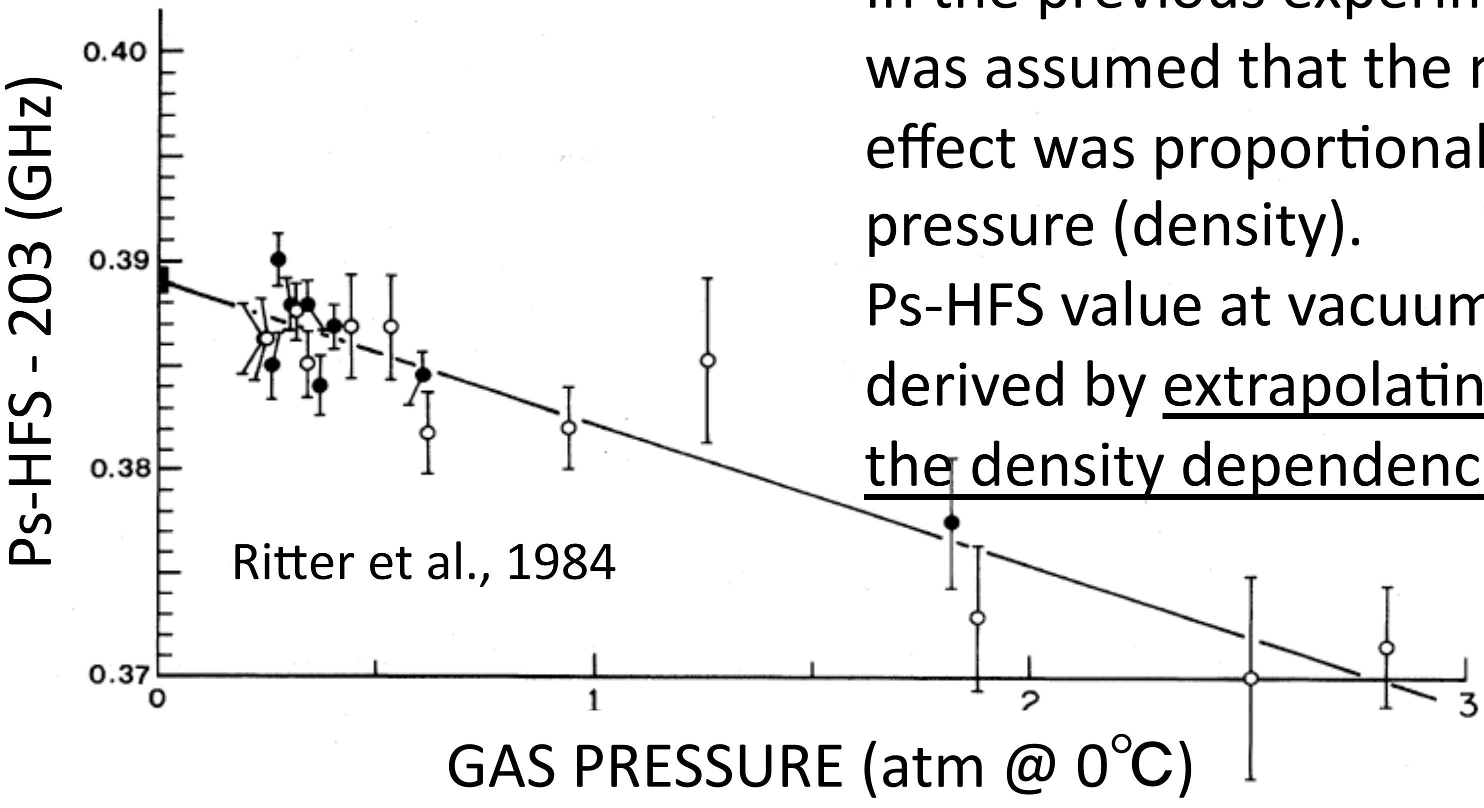
Monochromatic 511 keV

Material Effect

When a positronium collides with surrounding matters, its energy levels shift because of the electric field of the matters (the Stark effect)

This effect is proportional to the collision rate.
→It is proportional to the matter density <u>if the velocity of positronium is constant</u>.

In the previous experiments, it was assumed that the material effect was proportional to the gas pressure (density).
Ps-HFS value at vacuum was derived by <u>extrapolating linearly the density dependence</u>.

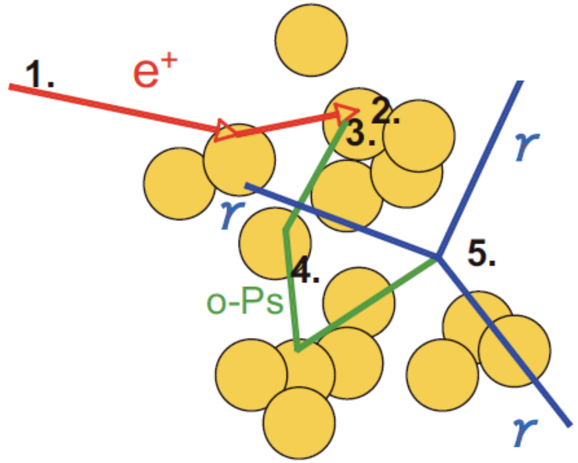


Ps Thermalization Problem

Formed o-Ps has a kinetic energy of about 1 eV.

o-Ps deposits its energy to the room temperature (1/30 eV) by collision with surrounding materials (the thermalization process).

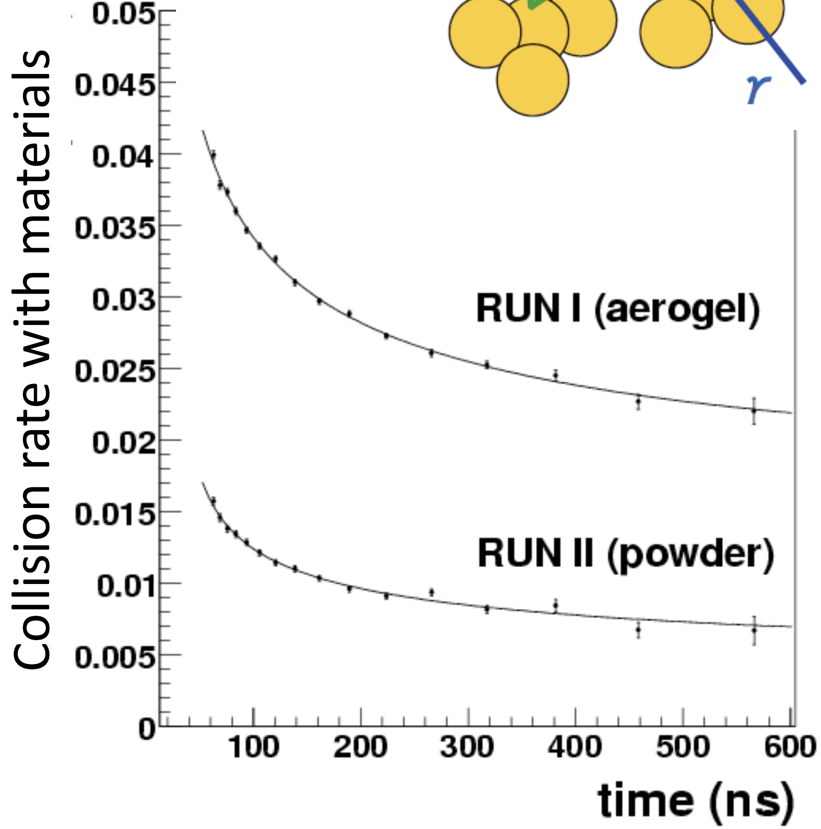
In the previous experiments, it was assumed that the thermalization occurs immediately so that the velocity of Ps is approximately constant.



But,

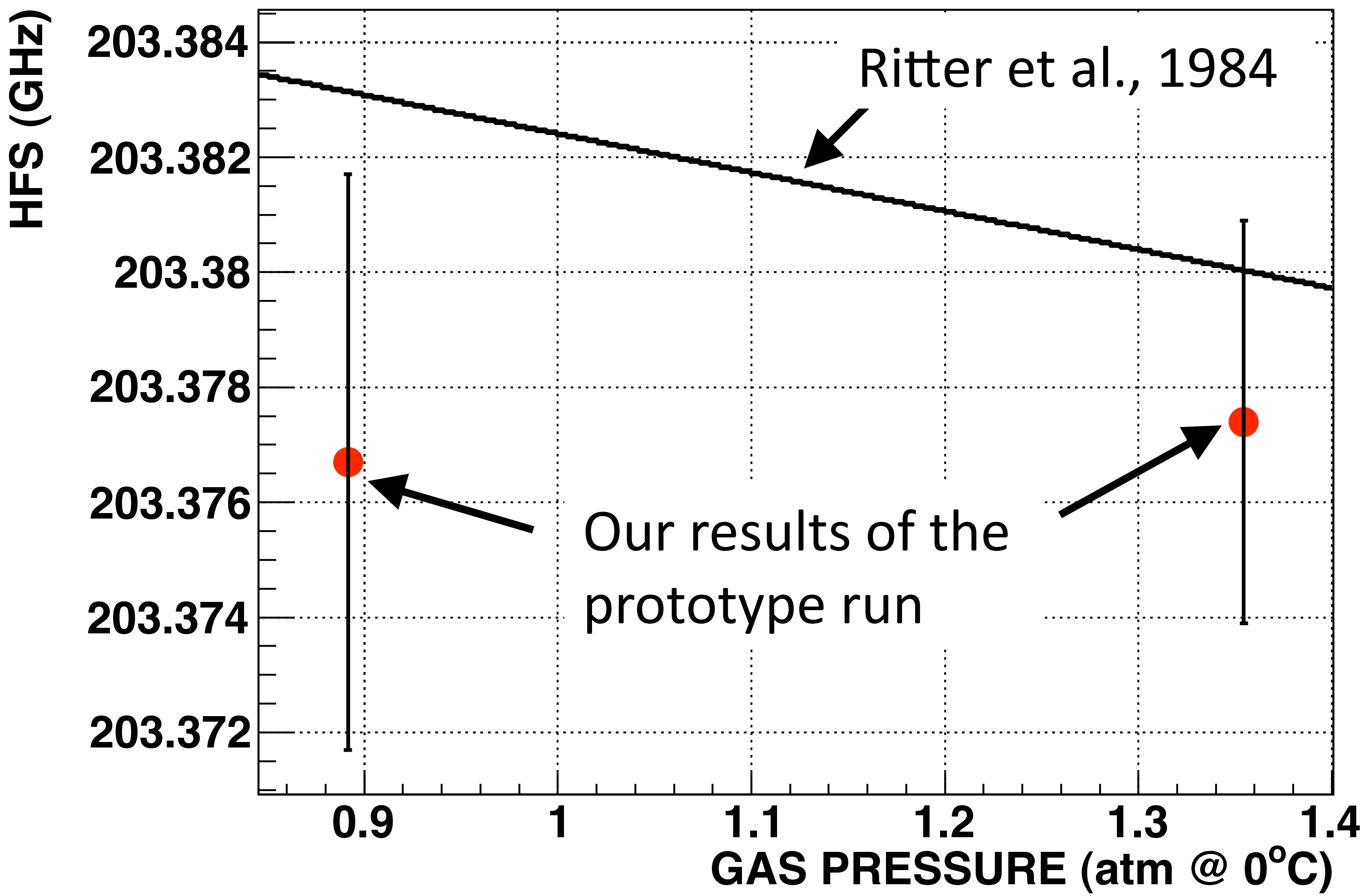
If it takes much time to thermalize, the material effect ($\propto$ collision rate) **is not proportional to material density**.

In fact, **it affects seriously** ("o-Ps lifetime puzzle" (1990's)).



→<u>Ps thermalization effect can be a serious systematic error in Ps-HFS measurement.</u>

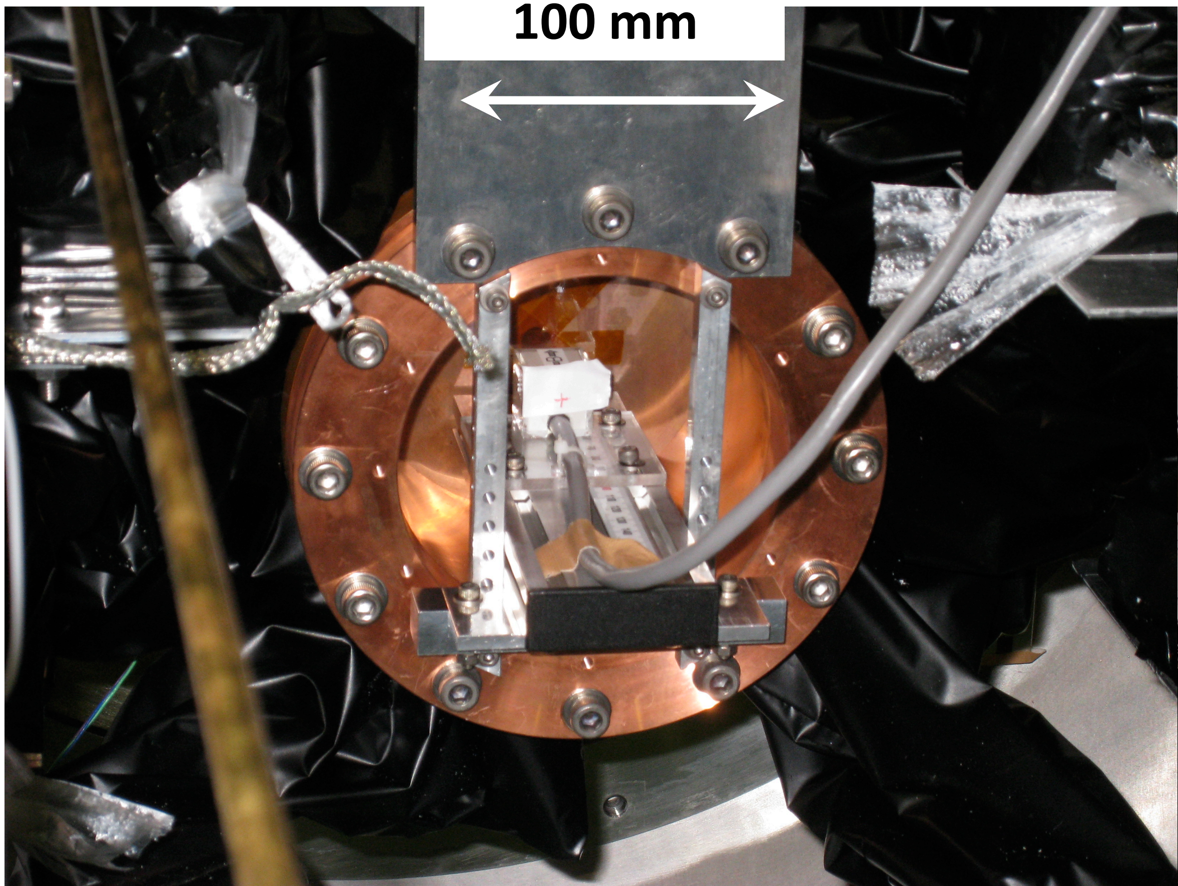
Gas Pressure Dependence



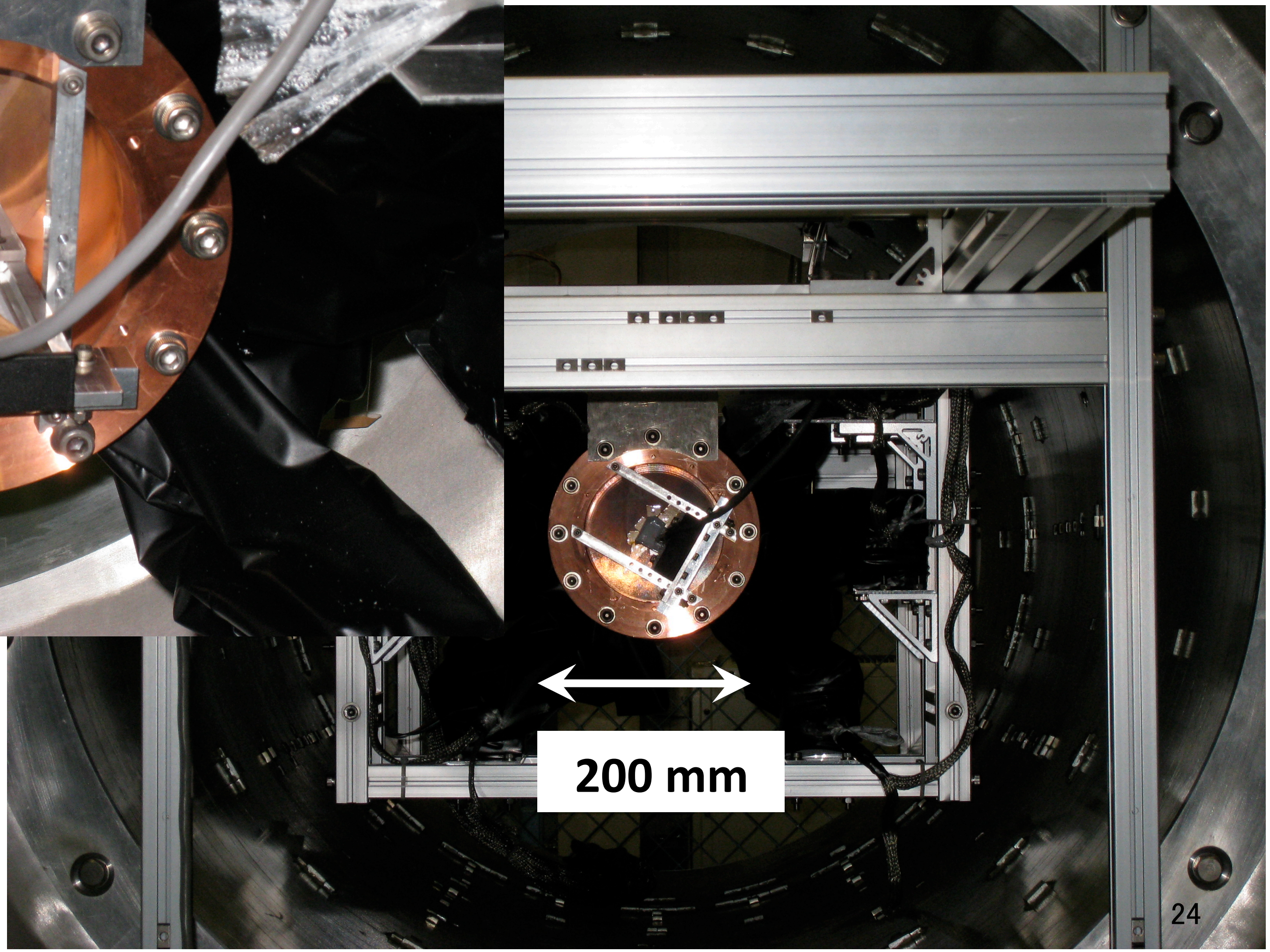
The pressure dependence is not clarified by our results of the prototype run, but it is consistent with the previous experiment.

→ Apply a correction of -33 ppm/atm (Ritter et al., 1984)

Magnetic Field Measurement

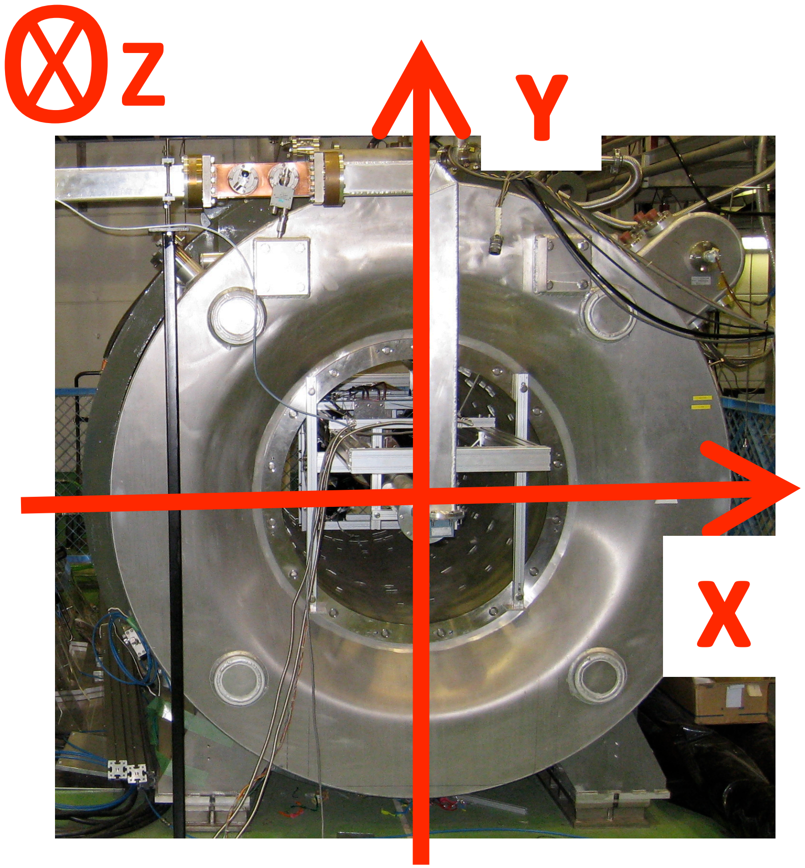


Measured the magnetic field at 310 points in the RF cavity using NMR probe.

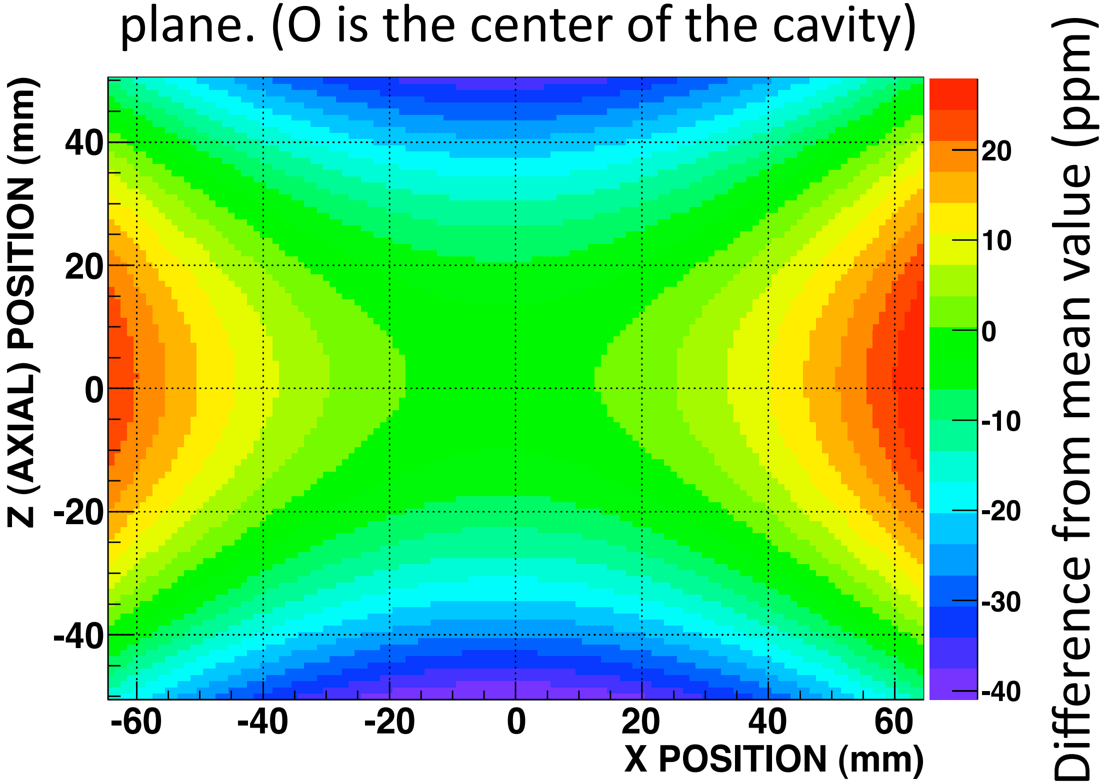


Made the map of the magnetic field.

Non-Uniformity of the Magnetic Field



Magnetic field distribution on Y=0 plane. (O is the center of the cavity)

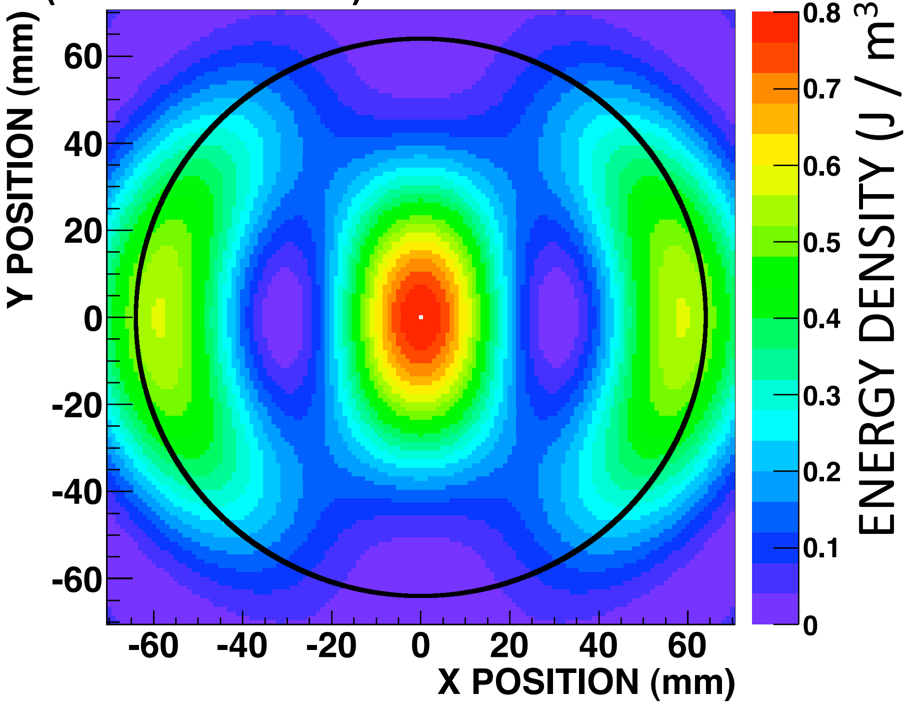


・Non-uniformity of the magnetic field is serious systematic uncertainty.

・ Non-uniformity in the RF cavity is 23 ppm (RMS).

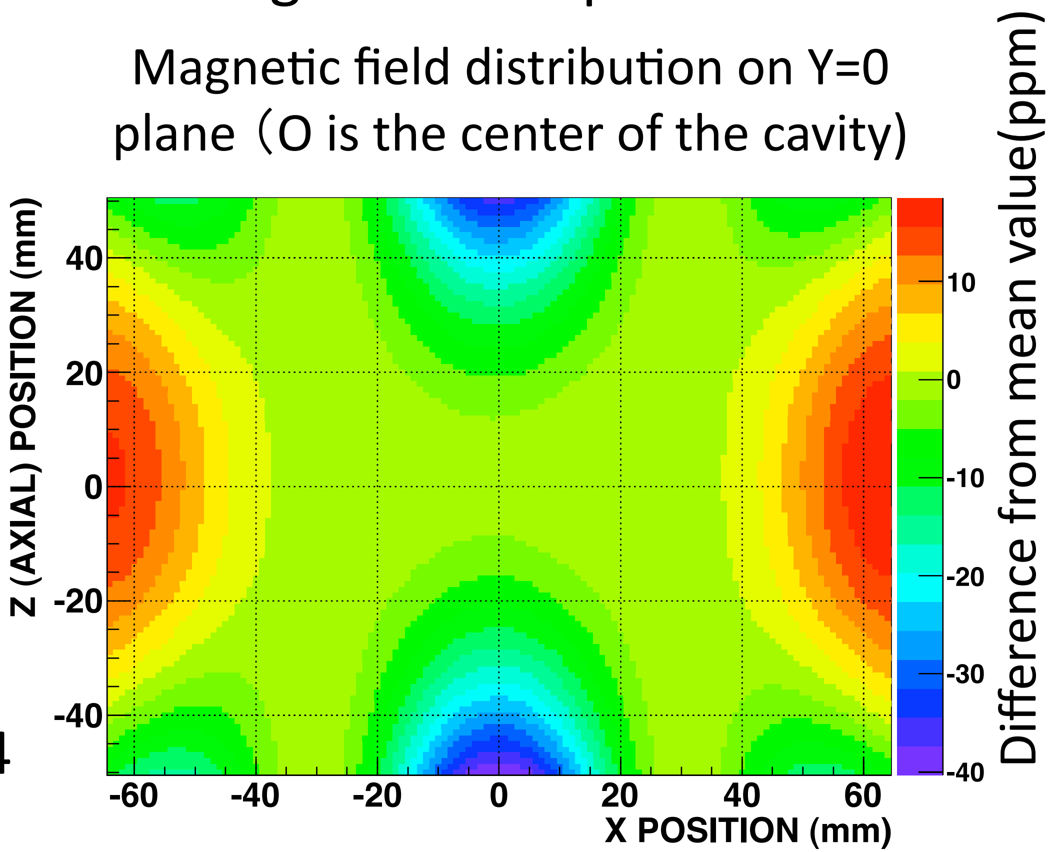
Weight 1. RF Power distribution

Energy distribution of RF magnetic field (TM110 mode)



After weighting the RF magnetic field power

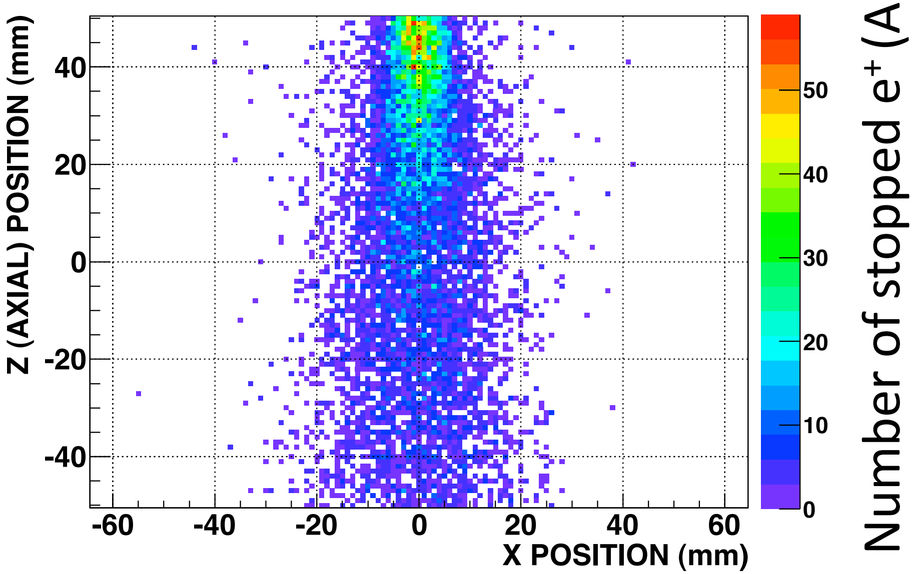
Magnetic field distribution on Y=0 plane（O is the center of the cavity)



Uniformity gets better to 14 ppm (RMS)

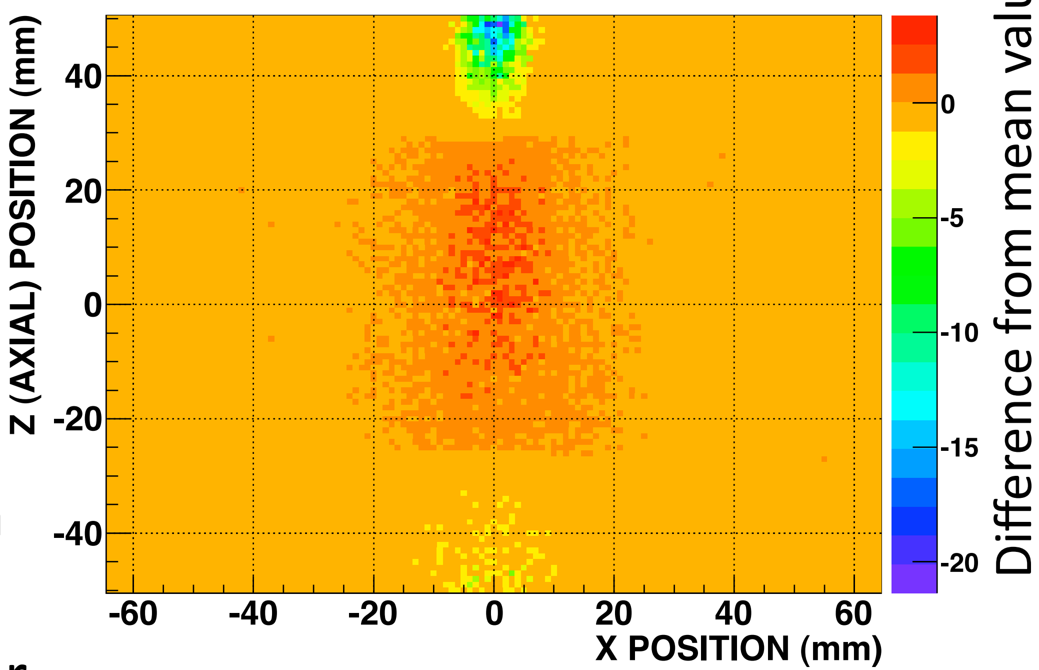
Weight 2. Positron Stop Position

e^+ stop position distribution
(Geant4 MC simulation)



After applying the RF power and e^+ stop position weight

Magnetic field distribution on Y=0 plane (O is the center of the cavity)



Uniformity gets better to 11 ppm (RMS) (22 ppm in HFS)
→This is the final systematic error.

Table of Scintillator Properties

Scintillator	Density	Refractive index	Photons per MeV	Emission Maximum	Decay Constant	Radiation Length
	g / cm^3			nm	ns	cm
NaI (Tl)	3.67	1.85	38000	415	230	2.59
CsI (Tl)	4.51	1.79	59000	565	1000	1.86
LYSO	7.25	1.81	32000	420	40	1.15
YAP (Ce)	5.55	1.93	19700	347	28	2.7
$LaBr_3$(Ce)	5.29	1.9	63000	380	25.6	1.88