Direct Measurement of the Hyperfine Structure of the Ground State Positronium using High Power Sub-THz Radiation

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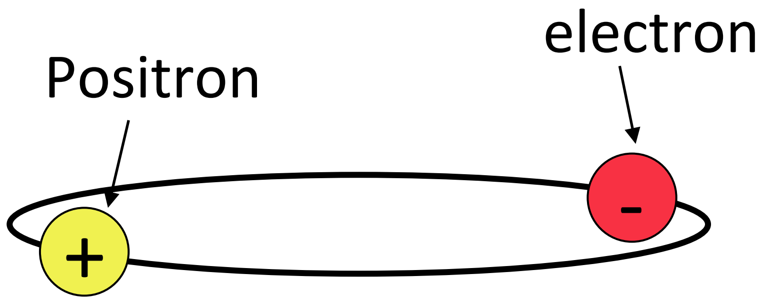
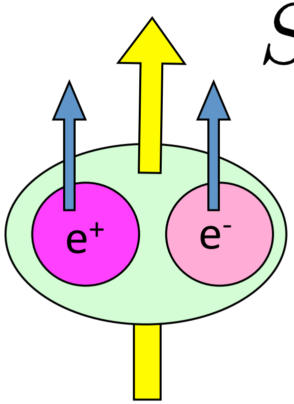
Positronium (Ps)



- Ps is the bound state of e^- and e^+
  - The lightest hydrogen-like atom
  - Particle-antiparticle system, unstable
  - Good target to study bound state QED, since it’s free from hadronic uncertainty

Positronium (o-Ps, p-Ps)

- Ortho-positronium (o-Ps)

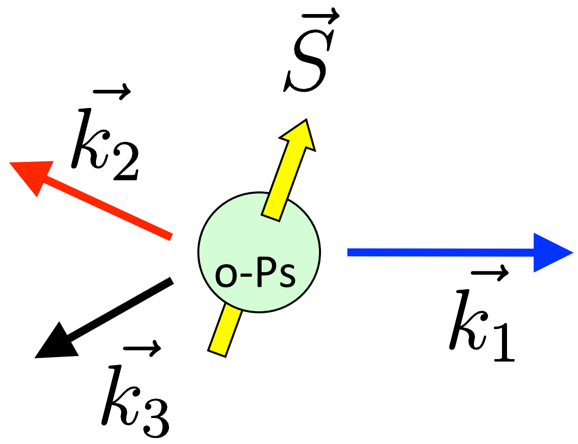


$S = 1$ Spin triplet

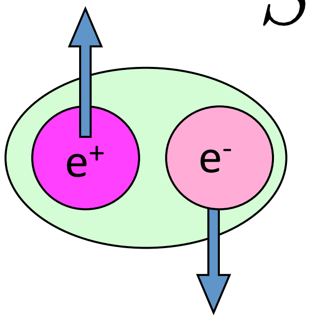
Long lifetime (142 nsec)

o-Ps → 3γ (, 5γ, …)

Continuous energy spectrum



- Para-positronium (p-Ps)

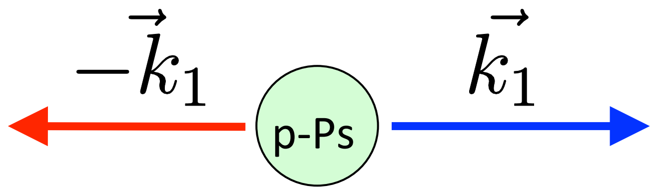


$S = 0$ Spin singlet

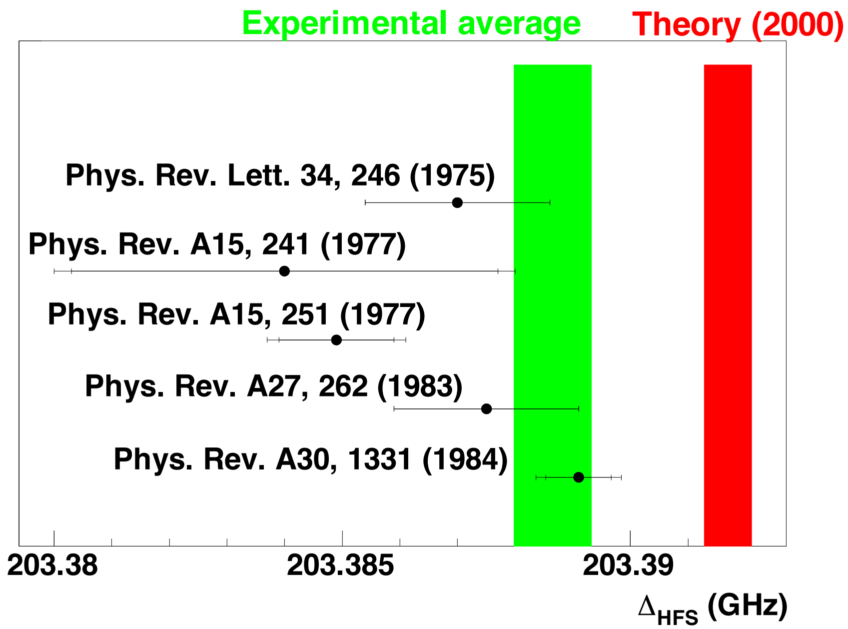
Short lifetime (0.125 nsec)

p-Ps → 2γ (, 4γ, …)

Two back-to-back 511 keV gamma rays



Hyperfine Structure of the Ground State of Positronium (Ps-HFS)

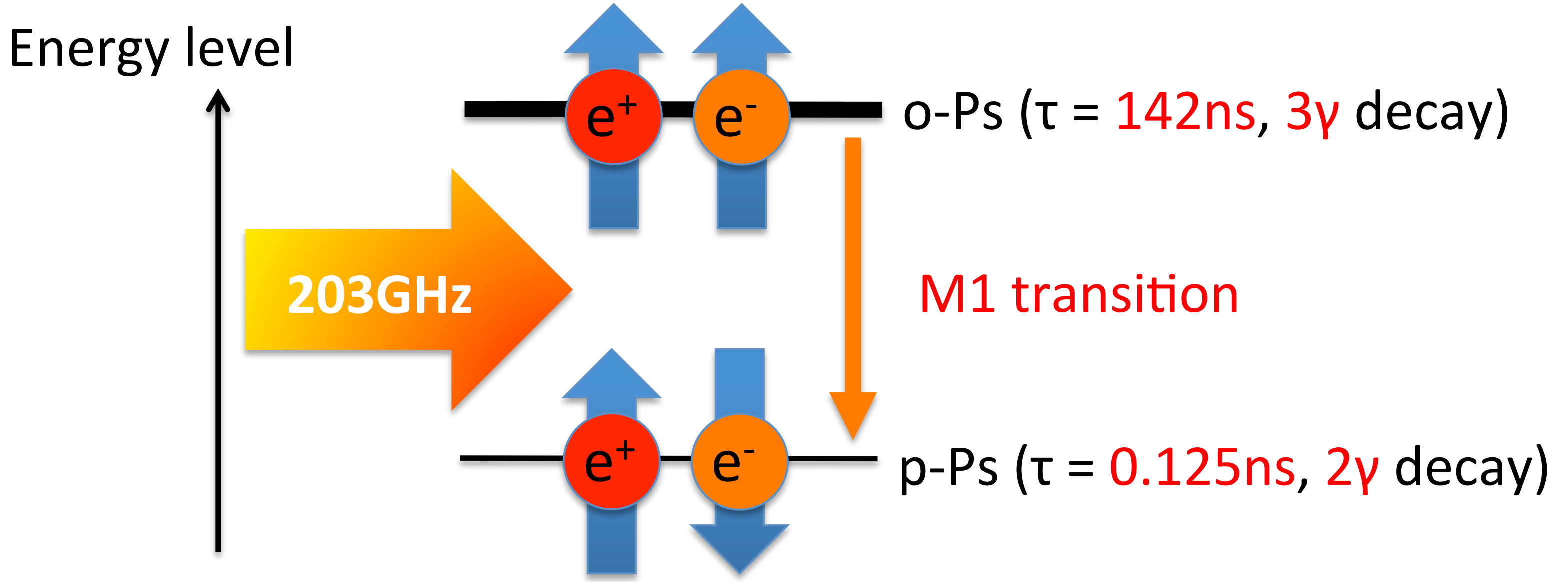


Exp.
 203.388 65(67) GHz (3.3 ppm)
$O(\alpha^3)$ QED calc.
 203.391 69(41) GHz (2.0 ppm)

- Energy difference between o-Ps and p-Ps, about 203 GHz.
- A large (3.9 σ, 15 ppm) discrepancy between the measured and the theoretical value.
- All of the previous measurements are indirect measurements using static magnetic field.

→We plan to "directly" measure Ps-HFS again. (our final goal)

Direct Measurement of Ps-HFS

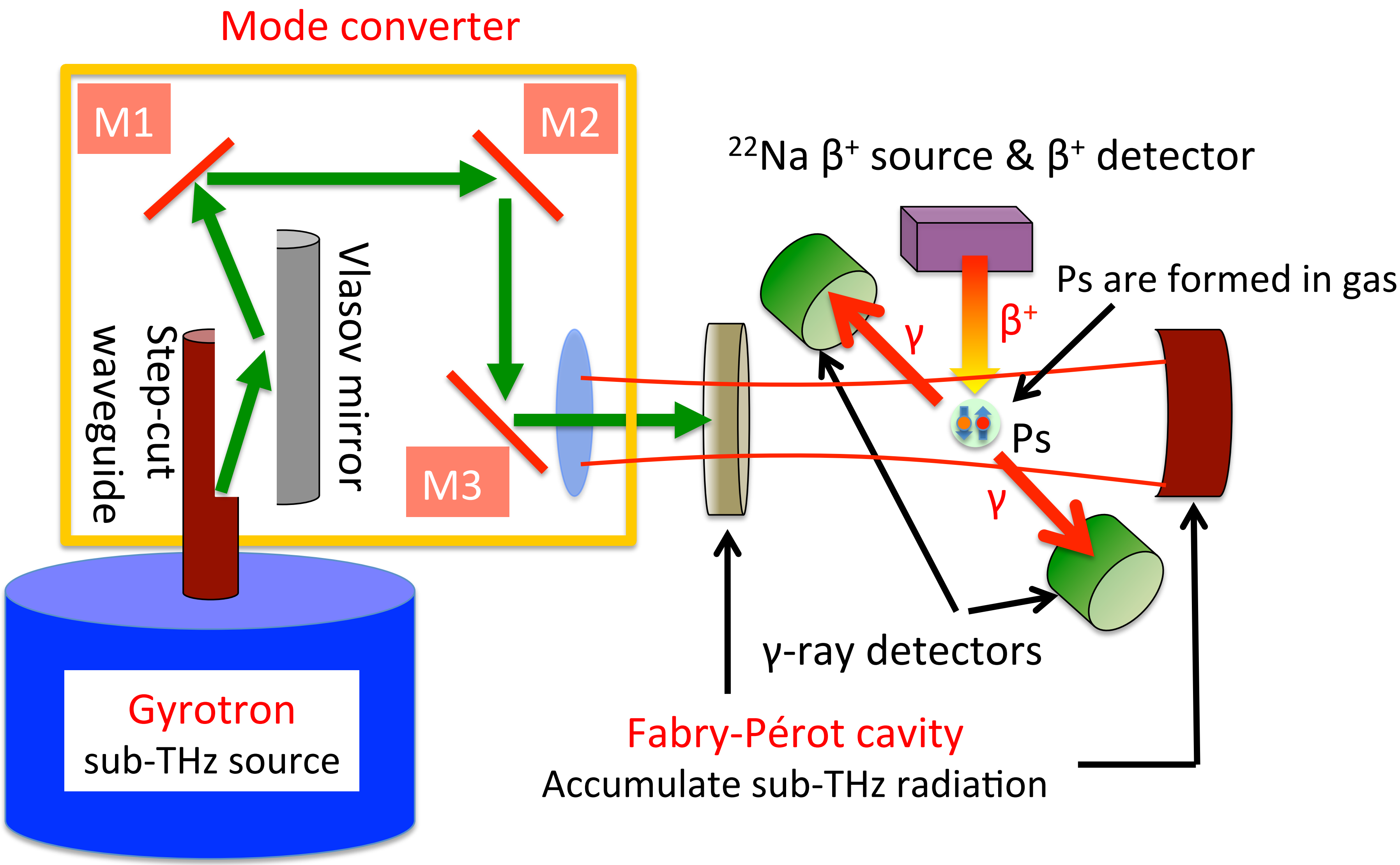


- Drive stimulated emission from o-Ps to p-Ps using 203 GHz radiation and transited p-Ps decays into 2γ promptly (125 ps).
- Transition signal has a feature that it has long lifetime of o-Ps (142 ns) and decay into two back-to-back 511 keV γ rays.
- The transition probability is extremely small ($A = 3\times10^{-8}\ s^{-1}$) since it is M1 transition. In addition, o-Ps is unstable ($\lambda = 7\times10^{6}\ s^{-1}$).

→ High power (10 kW) sub-THz radiation is necessary to cause sufficient amount of stimulated emission.

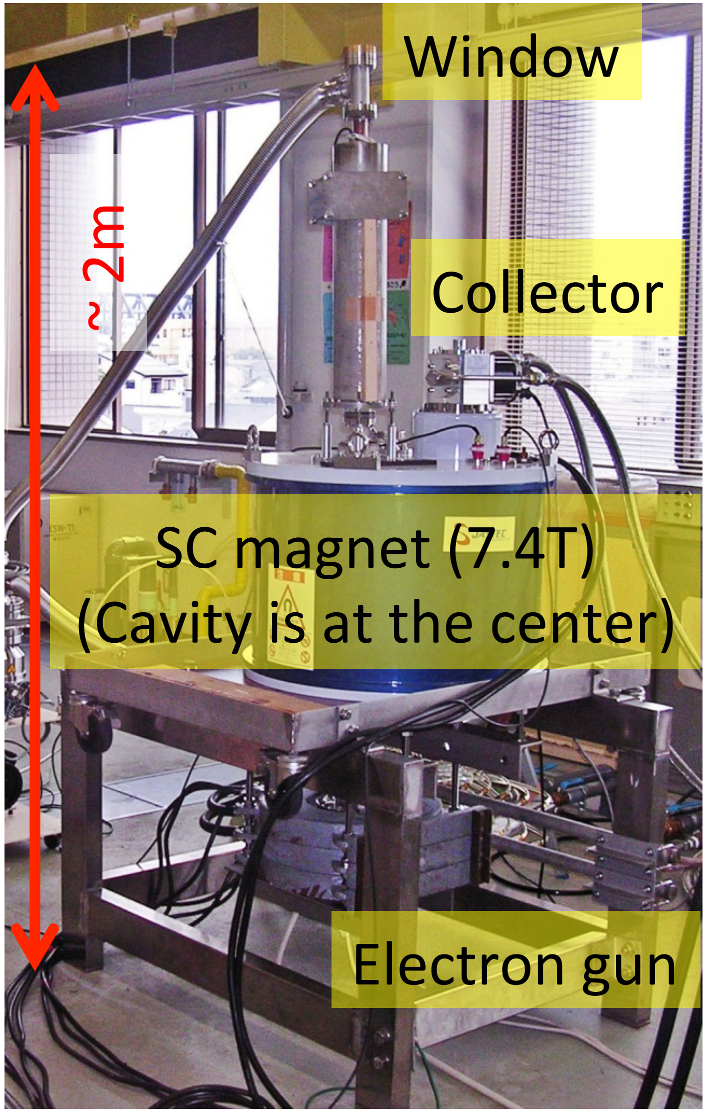
- Our 1st target is to directly measure hyperfine transition.

Experimental Setup



Gyrotron

@ University of Fukui

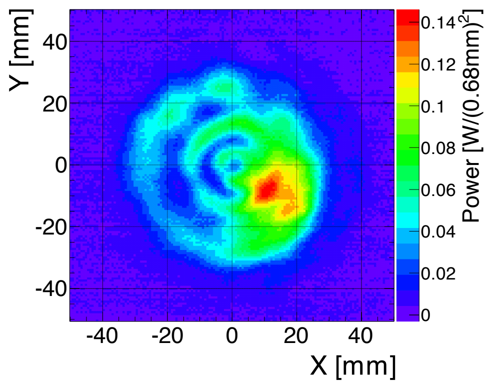


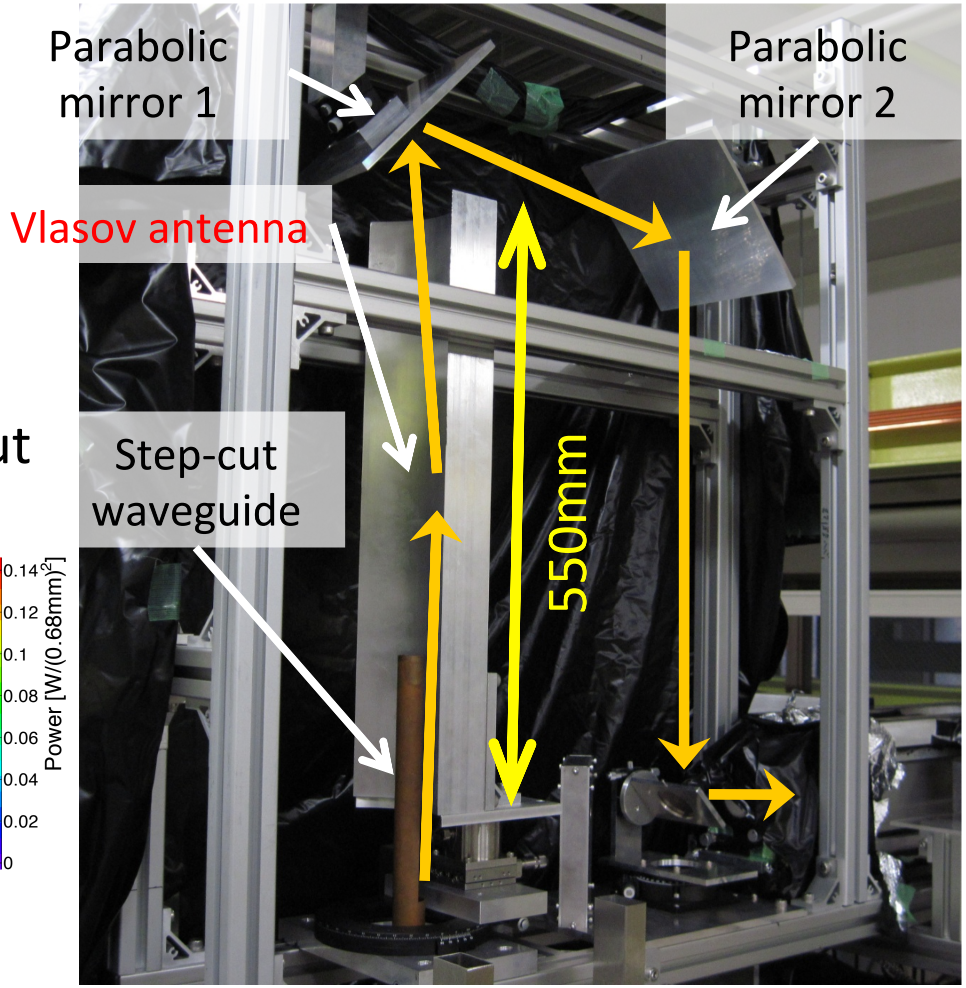
- Gyrotron FU CW V
- Use 202.89 GHz (TE_{03} mode) radiation for on-resonance measurement.
- The power is monitored with a pyroelectric detector, which is fed back to the voltage of the heater of the electron gun.
- Stable (< ±10% fluctuation) operation with peak power of 300 W (pulse length is 15 ms every 50 ms)

Mode Converter

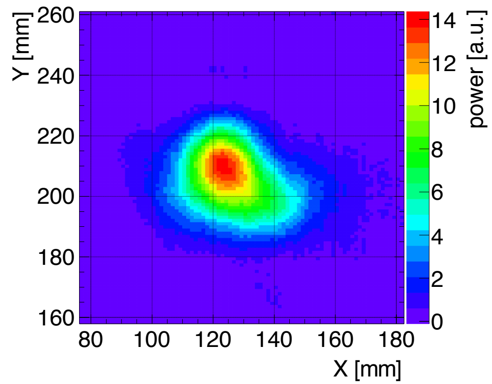
- Convert gyrotron output into a Gaussian beam with a Vlasov antenna and the following two parabolic mirrors.
- Conversion eff. = 28±2%

Gyrotron output
TE_{03} mode



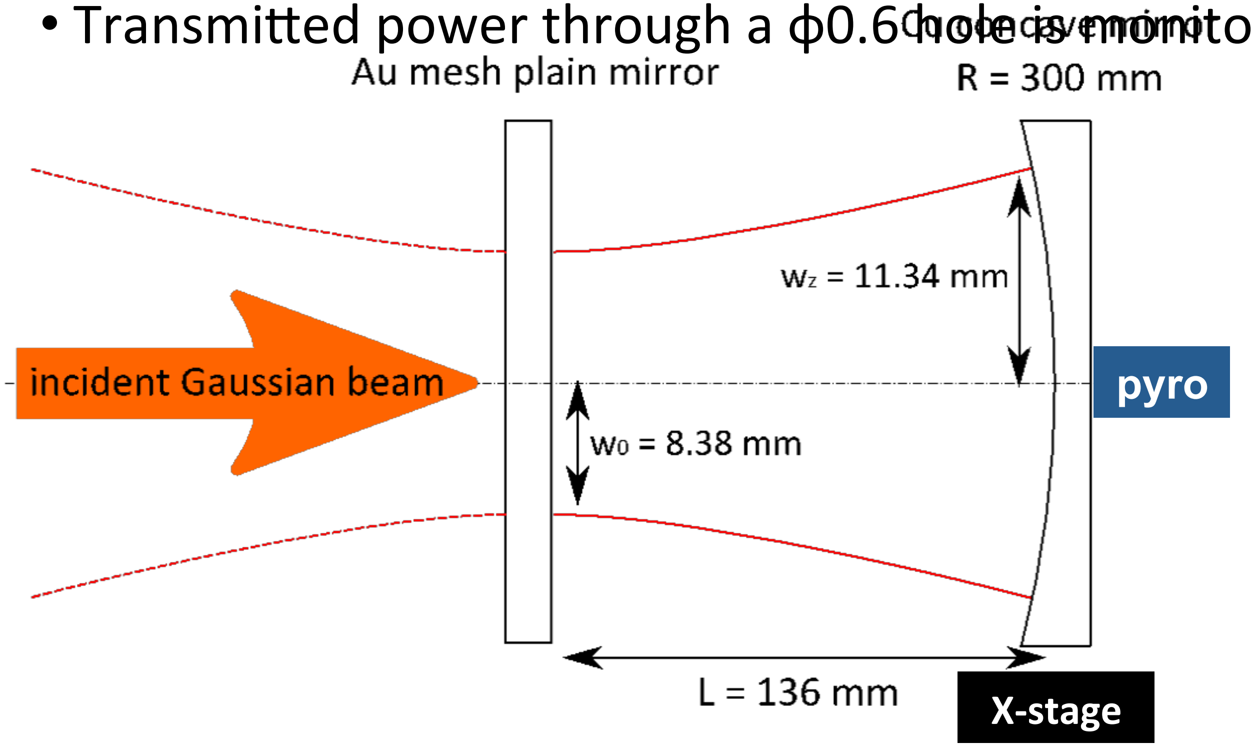


Converted beam

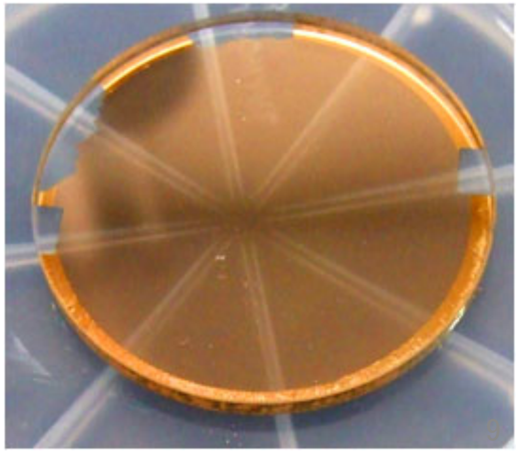


Fabry-Pérot Cavity 1/2

- The Gaussian beam resonates with the Fabry-Pérot cavity when the cavity length becomes equal to the half-integer multiple of λ (= 1.5 mm).
- The cavity length is controlled by moving the Cu concave mirror mounted on an X-axis stage (long stroke = 15 mm, high resolution = 10 nm).
- The Au mesh mirror at the input side is designed to have high reflectivity (99.4%) and reasonable transmittance (0.4%).
- Transmitted power through a ϕ0.6 hole is monitored.



ϕ50 Au mesh mirror
Line width = 200μm
Line separation = 160μm
Mesh thickness = 1μm



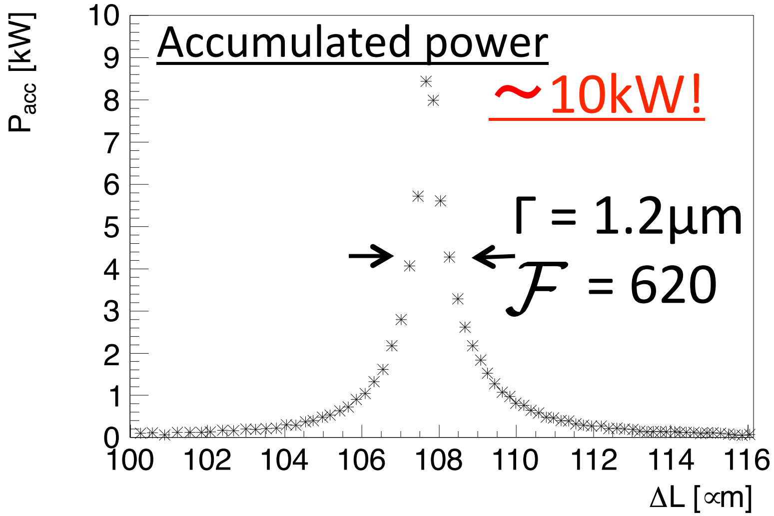
Fabry-Pérot Cavity 2/2

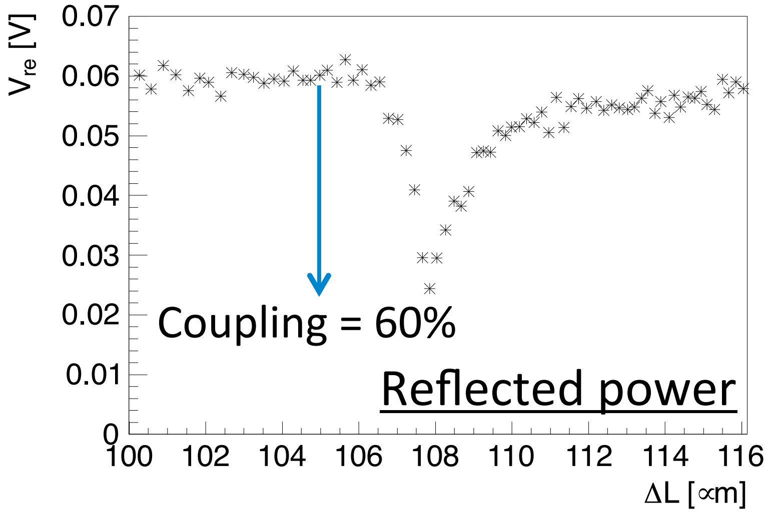
- The finesse of a Fabry-Pérot cavity is larger, the beam makes more round-trips when the beam resonates with the cavity.

$$\mathcal{F} = \frac{\pi \sqrt[4]{\rho}}{1 - \sqrt{\rho}} \approx \frac{2\pi}{1 - \rho}$$

where ρ is the round-trip reflectivity. # of round-trip is $\mathcal{F}/2\pi$

- $\mathcal{F}$ = (λ/2)/Γ, where Γ is the width (FWHM) of the resonance peak
- Accumulated power P_{acc} increases when the beam resonates with cavity. P_{acc} is estimated from the transmitted power. Reflected power P_{re} decreases by the amount equal to the beam coupled with the cavity.

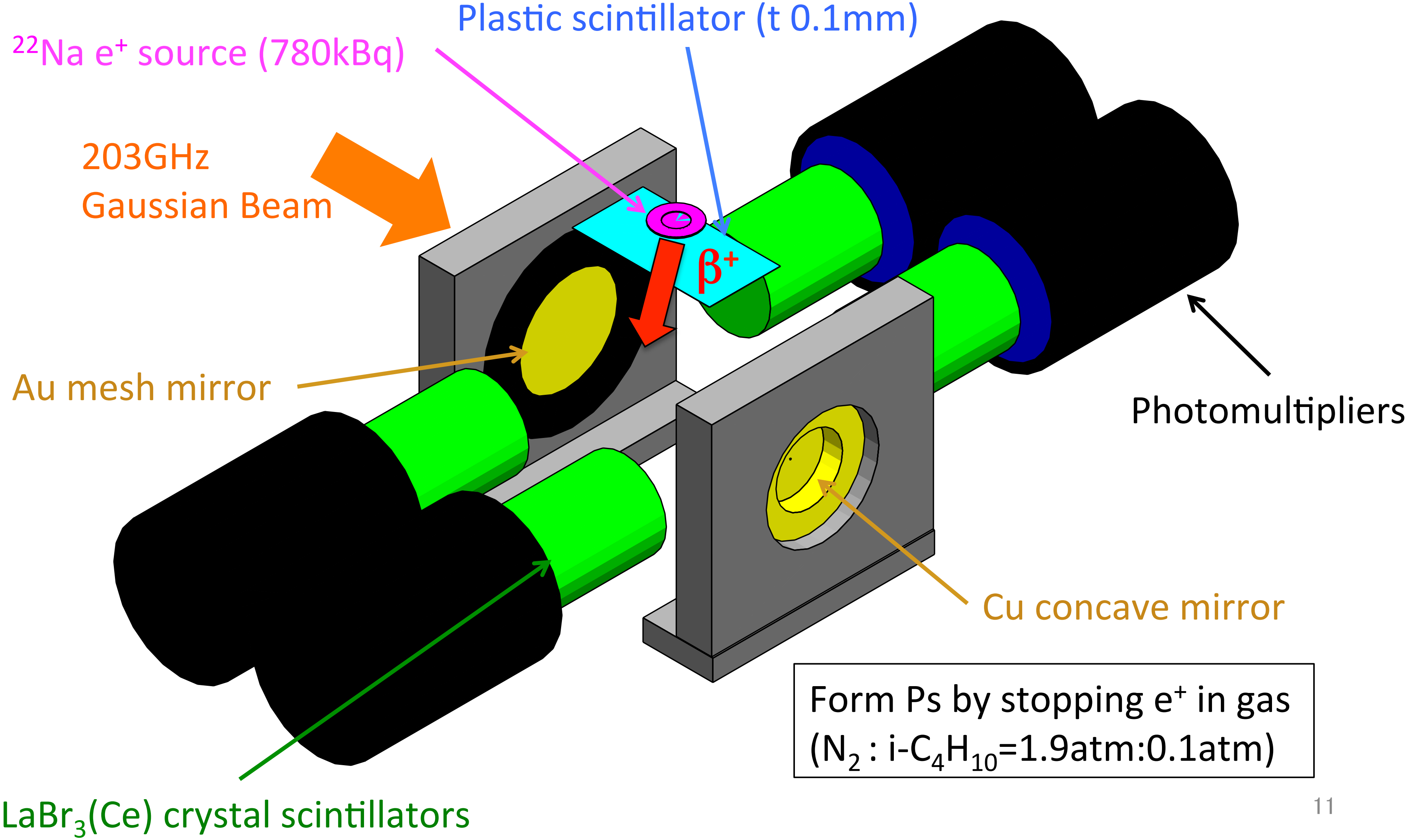




Ps Assembly and γ-ray detectors

A ^{22}Na source emits positron.

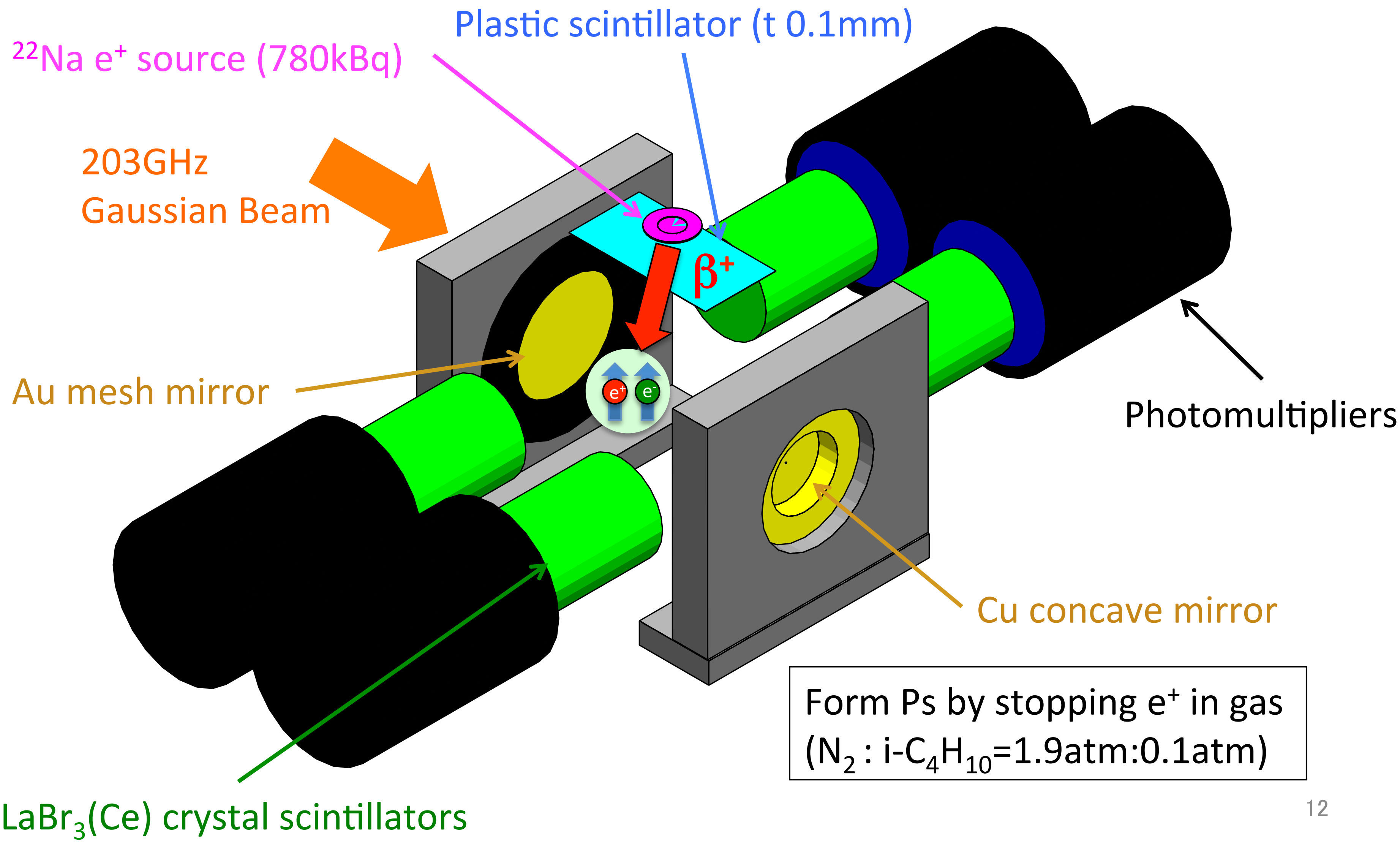
A plastic scintillator detects the emission.



Form Ps by stopping e$^+$ in gas
(N_2 : i-C_4H_{10}=1.9atm:0.1atm)

Ps Assembly and γ-ray detectors

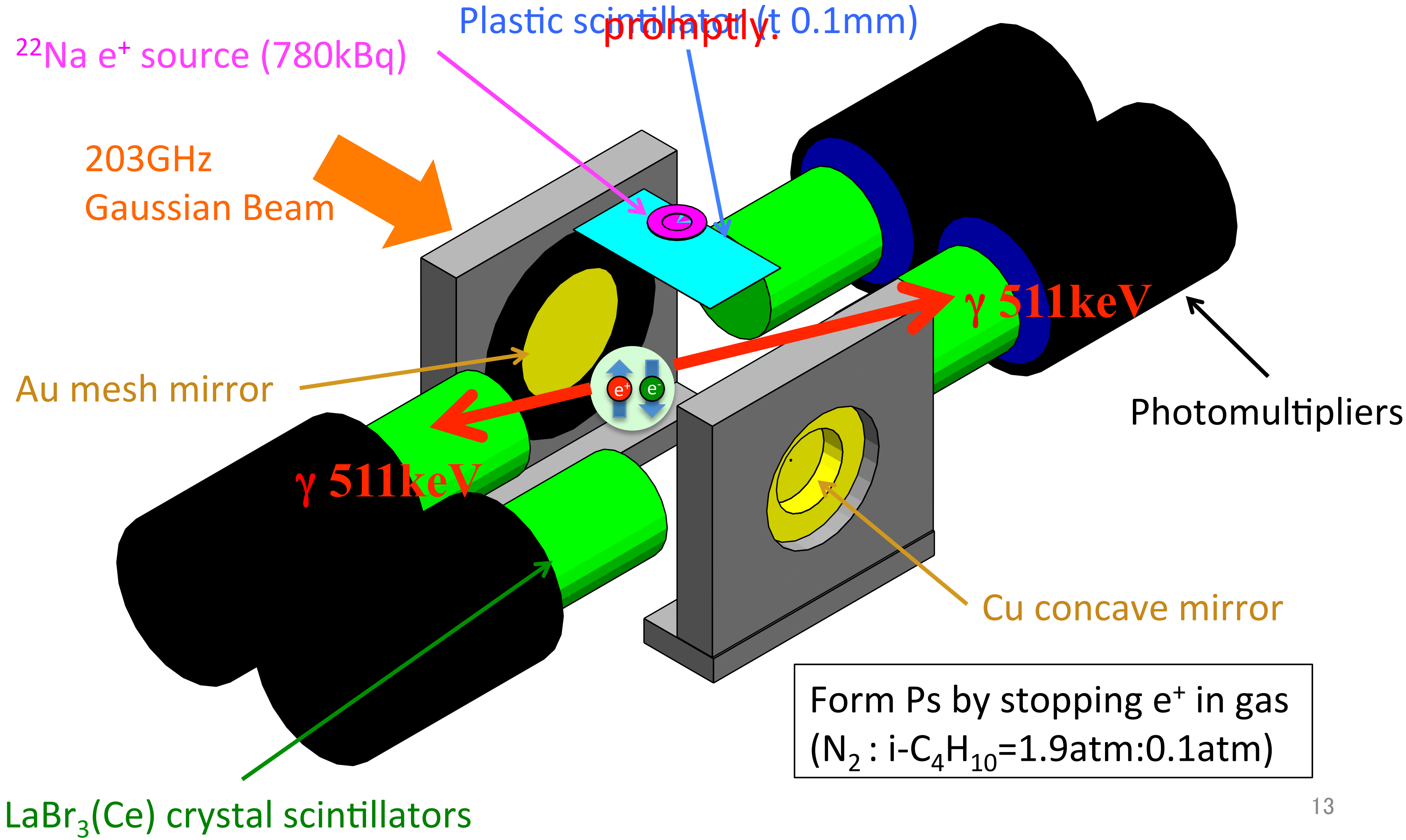
A positron forms a positronium with an electron in gas molecule



Form Ps by stopping e$^+$ in gas
(N_2 : i-C_4H_{10}=1.9atm:0.1atm)

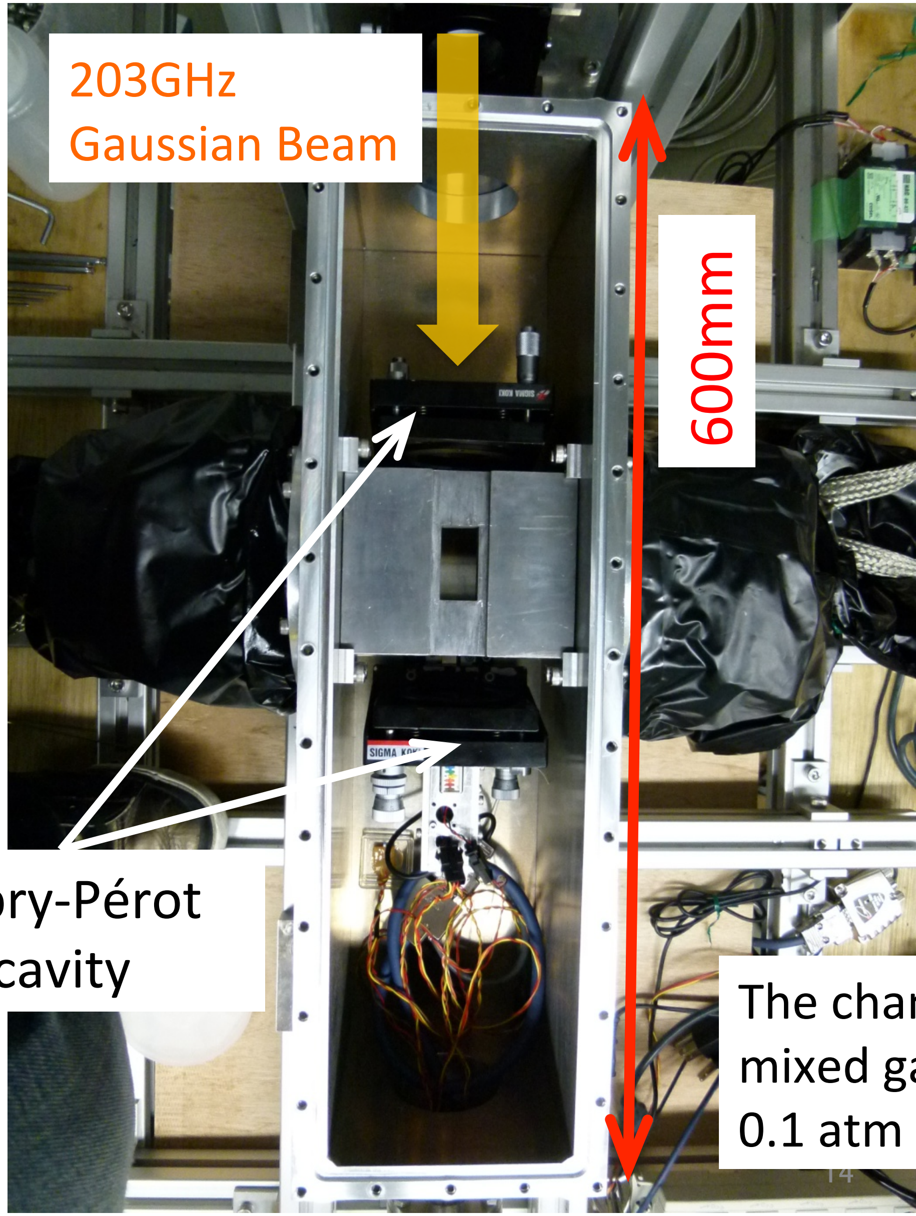
Ps Assembly and γ-ray detectors

O-Ps is exposed to high power radiation in the Fabry-Pérot cavity and transit to p-Ps. P-Ps decays into two back-to-back 511 keV γ-rays promptly.



Form Ps by stopping e^+ in gas
(N_2 : i-C_4H_{10}=1.9atm:0.1atm)

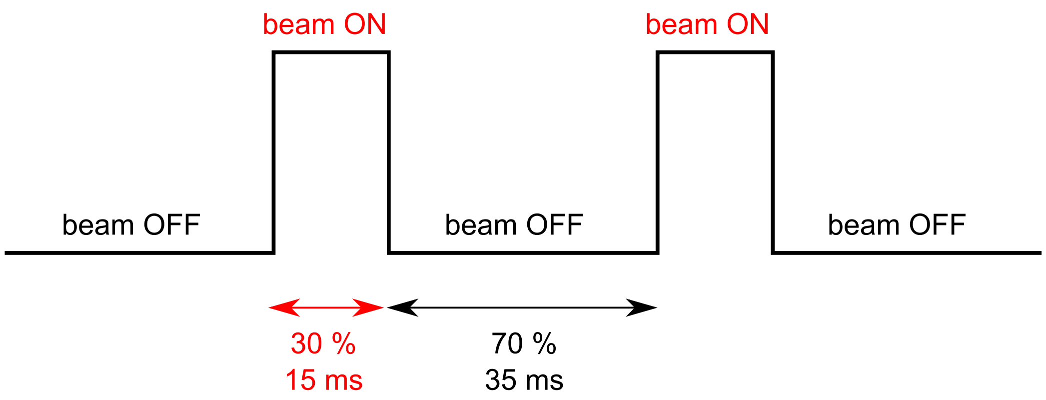
Picture of Gas Chamber



The chamber is filled with mixed gas (1.9 atm N_2 and 0.1 atm i-C_4H_{10})

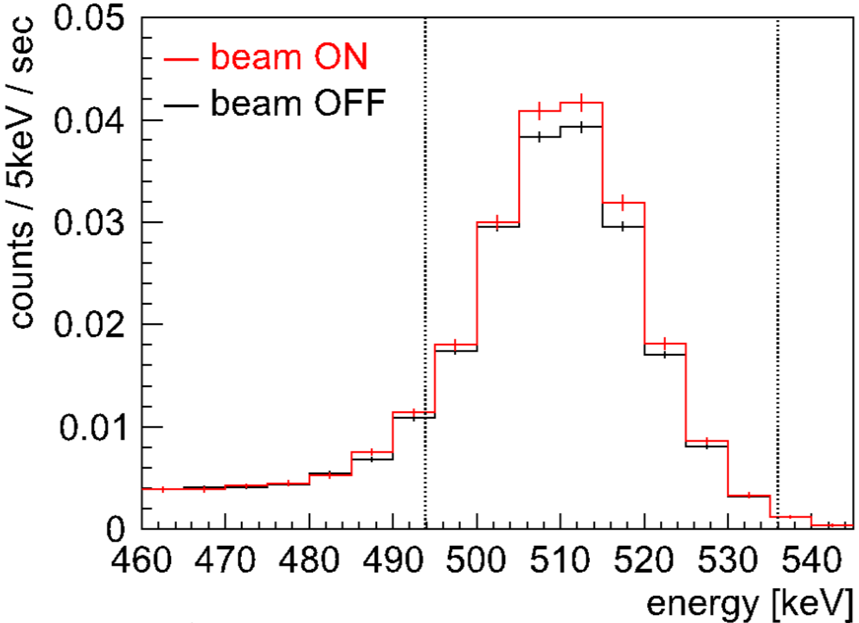
Signal and Background

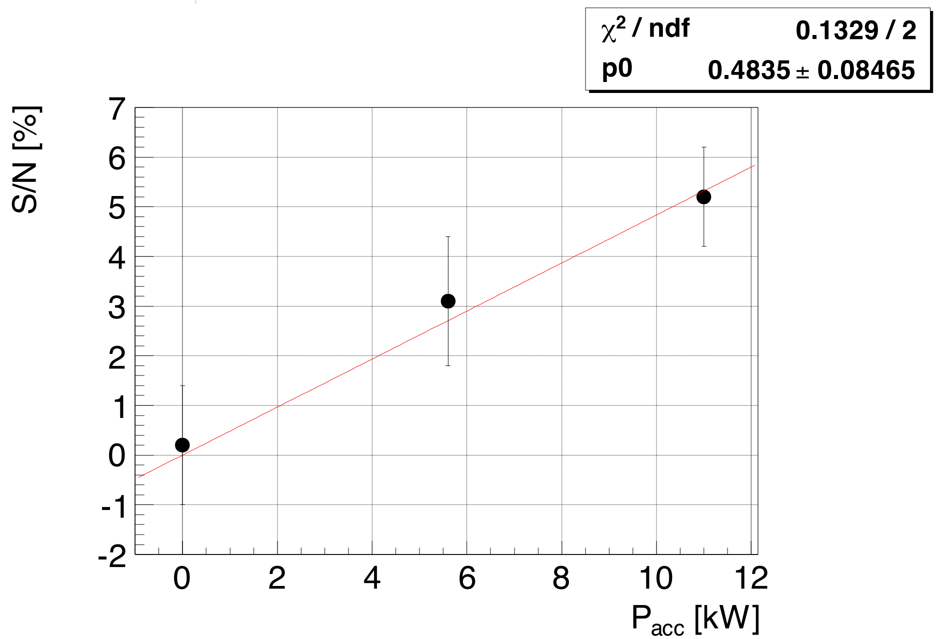
- Signal
  - ✓ o-Ps→p-Ps→2γ : long lifetime (τ = 142ns) of o-Ps & two back-to-back 511 keV γ rays
- Background
  - ✓ o-Ps→3γ : finite energy resolution of the γ-ray detectors, and 2γ is emitted in the same direction and 1γ is emitted in the opposite direction
  - ✓ o-Ps→2γ (pick-off) : e^+ annihilation with e^- in gas molecule
  - ✓ accidental overlap of the triggered e^+ and uncorrelated γ rays
- Gyrotron output is pulse output (20Hz・duty 30%). Background is estimated using events during beam OFF period.



Results

- When transition occurs during beam ON, o-Ps→3γ (tail bellow 511 keV peak) reduces and o-Ps(→p-Ps)→2γ (511keV peak) increases compared to beam OFF.



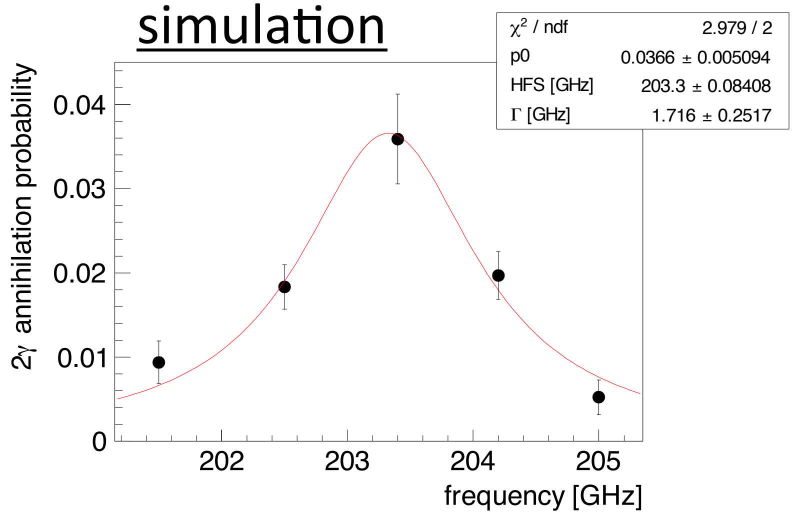


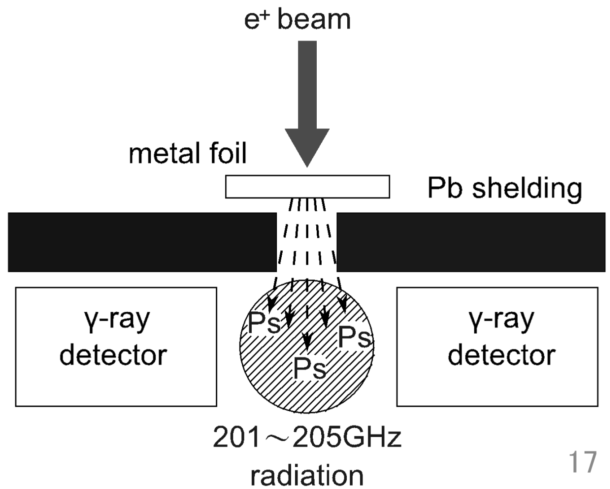
- Signal = ON − OFF = 15.1±2.7(stat.) $^{+0.5}_{-0.8}$(sys.) mHz (**5.4σ**)
- Hyperfine transition between Ps-HFS has been directly observed for the first time. The power dependence is also checked.
- The transition probability is also measured A = 3.1 $^{+1.6}_{-1.2}\times10^{-8}$ s^{-1}, which is in good agreement with the theoretical value (A = 3.37×10^{-8} s^{-1}).

Future Prospect

- First direct measurement of Ps-HFS in a year
  - ✓ Transition measurement at 5 points from 201 GHz to 205 GHz
  - ✓ New gyrotron whose cavity can be quickly replaceable (Gyrotron FU CW GI, about which was already talked by Prof. Tatematsu (7a-6))
- Final goal is precise measurement by
  - ✓ Improving power measurement
  - ✓ Using slow positron beam and a metal foil to form Ps in vacuum in order to improve S/N and statistics

simulation





Summary

- Ps-HFS (203 GHz) is a good target to study bound state QED, but there is a large discrepancy between the measured and the theoretical value.
- All of the previous measurements are indirect measurements, so we would like to directly measure Ps-HFS using high power sub-THz radiation.
- We developed a new optical system to accumulate about 10 kW power (peak energy density ε = 0.3 J/m^3) using a gyrotron, a mode converter, and a Fabry-Pérot cavity.
- The hyperfine transition of the ground state Ps has been directly observed for the first time at 5.4 σ confidence level by using high power sub-THz radiation $\rightarrow$ 1st step has been achieved!
- We plan to directly measure Ps-HFS using a new gyrotron (Gyrotron FU CW GI) with an accuracy of *O*(100 ppm) in a year by repeating transition measurement at 5 points. (2nd step)

The Other Applications…

- High power (sub-)THz radiation is useful for fundamental physics.
- Many interesting & important targets in the energy region
  - ✓ Millimeter wave spectroscopy (high power, narrow BW, long pulse/ CW operation)
  - ✓ Dark matter axion (μeV〜meV)
  - ✓ Cosmic Microwave Background (CMB, 3K black body radiation, its peak〜160GHz)
  - ✓ Neutrino absolute mass (〜meV)
  - ✓ Dark energy
- We plan to perform hidden photon (paraphoton) search. Paraphoton is a massive photon which couples with the ordinary photon.

→ Poster session ("Proposal of Hidden Photon Search using Sub-THz Gyrotron" by T. Suehara)