Sub-THz Spectroscopy of the Ground State Hyperfine Splitting of Positronium

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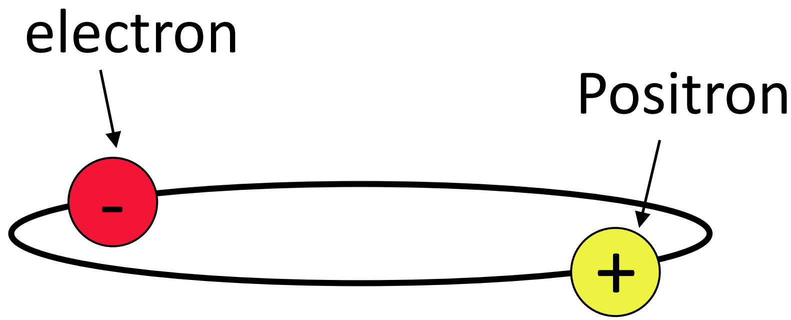
Outline

- Introduction (Ps, Ps-HFS)
- Experimental Setup
  - ✓ Quasi-optical system
  - ✓ Ps assembly & transition measurement detectors
- Analysis & Current Status
- Summary

Positronium (Ps)

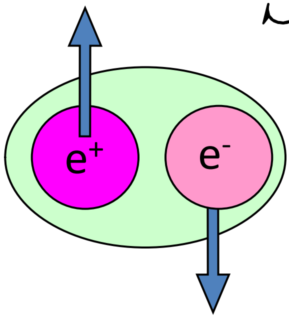


- Ps is the bound state of e^- and e^+
  - The lightest hydrogen-like atom
  - Unstable, particle-antiparticle system
  - Simple, good target to study bound state QED

Positronium (*o*-Ps, *p*-Ps)

- *Para*-positronium (*p*-Ps)

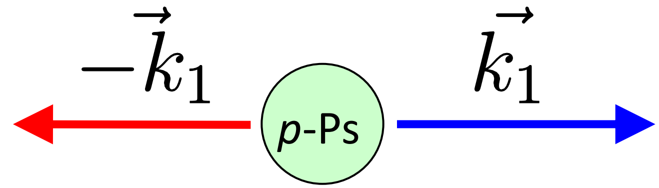
$S = 0$ Spin singlet



Short lifetime (0.125 nsec)

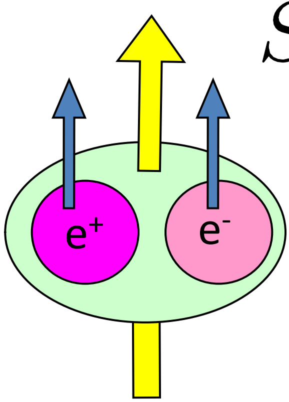
p-Ps → 2γ (, 4γ, ...)

511 keV (= electron mass) γ rays



- *Ortho*-positronium (*o*-Ps)

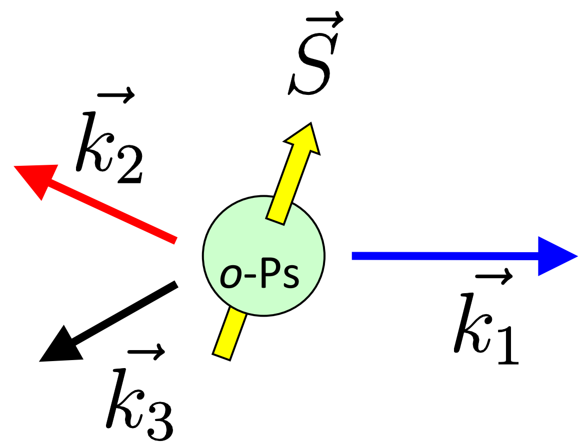
$S = 1$ Spin triplet



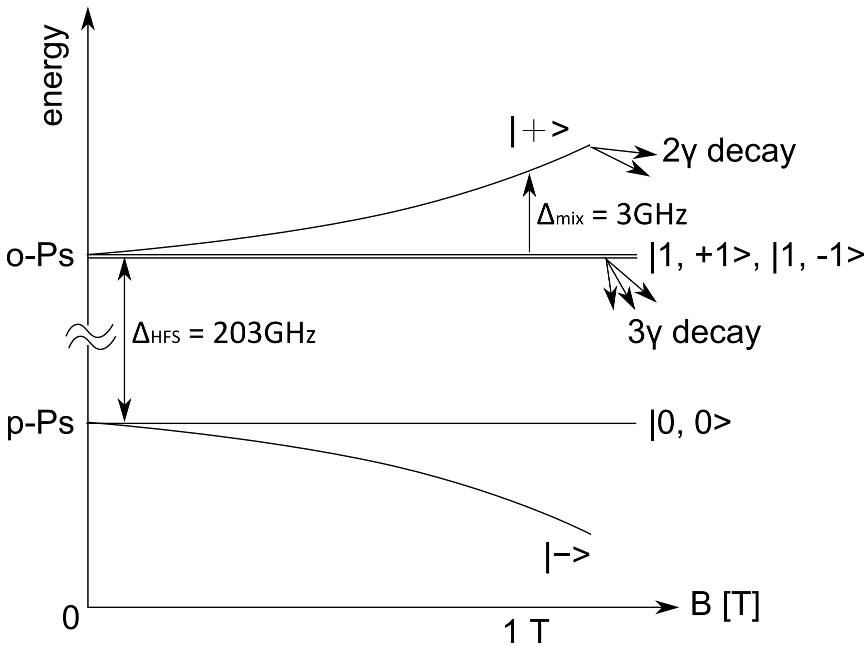
Long lifetime (142 nsec)

o-Ps → 3γ (, 5γ, ...)

Continuous energy spectrum



Ps-HFS and Previous Measurements

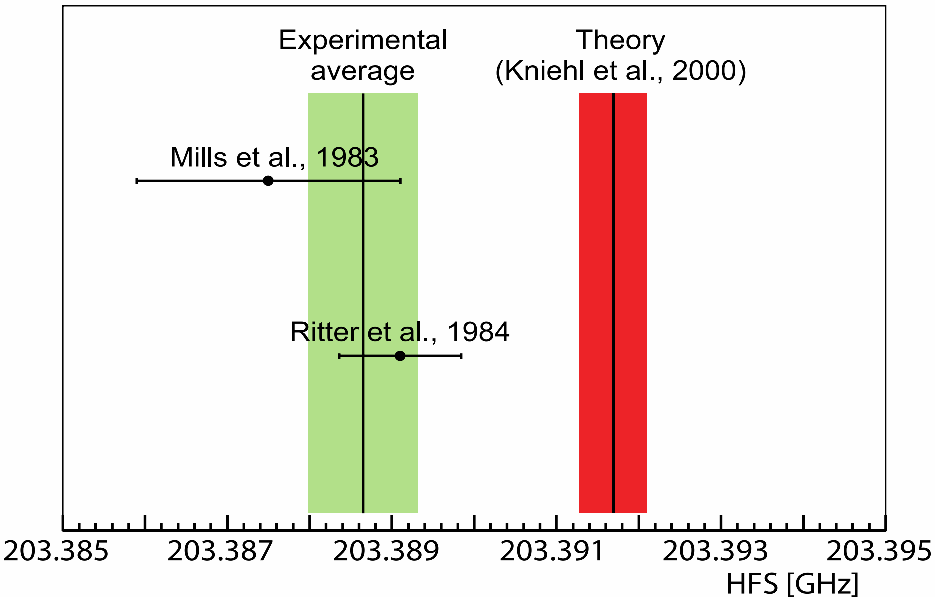


$$\Delta_{\text{mix}} = \frac{\Delta_{\text{HFS}}}{2}\left(\sqrt{1+x^2}-1\right)$$

$$x = \frac{2g'\mu_B B}{h\Delta_{\text{HFS}}}$$

- Ps-HFS is the energy difference between o-Ps and p-Ps, about 203 GHz (1.5 mm, 0.84 meV).
- Previous measurements were performed in 1970s and 1980s, when there were no high power and frequency tunable sub-THz radiation source.
- Use Zeeman splitting of about 3 GHz by a static magnetic field of about 1 T.
- It is difficult to prepare uniform magnetic field in large volume (~10cm) for Ps formation.

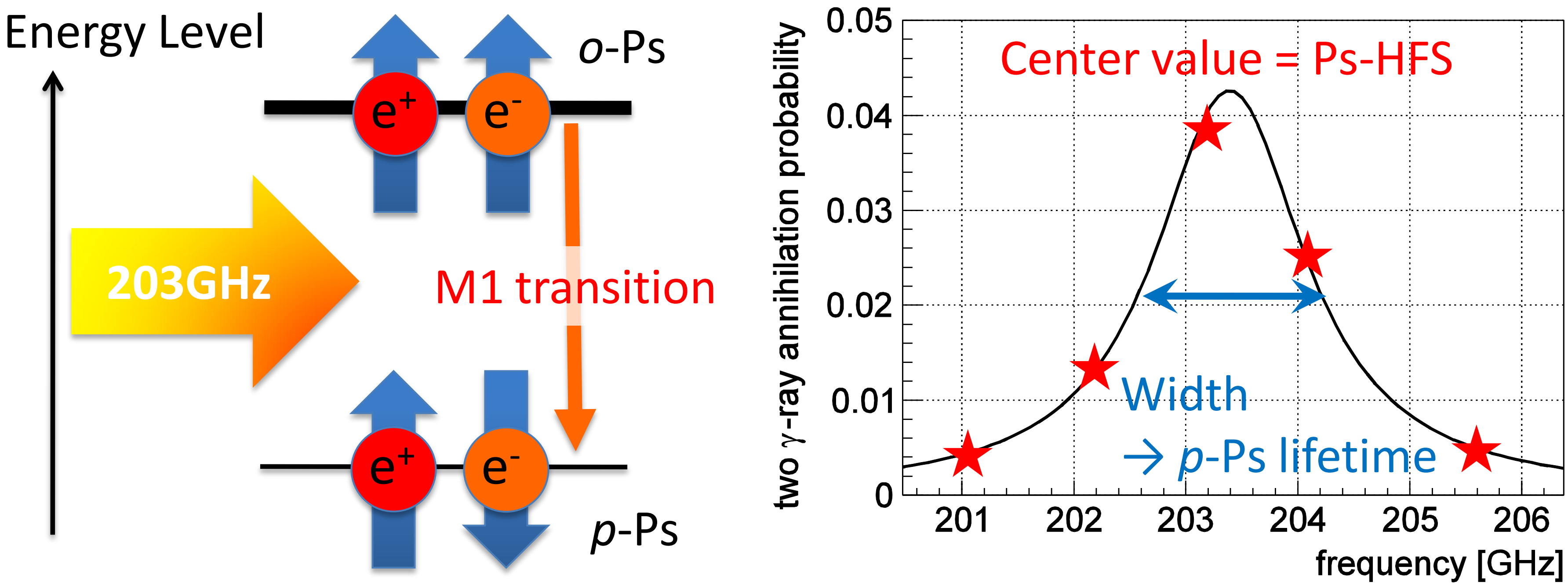
3.9σ (15ppm) discrepancy



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

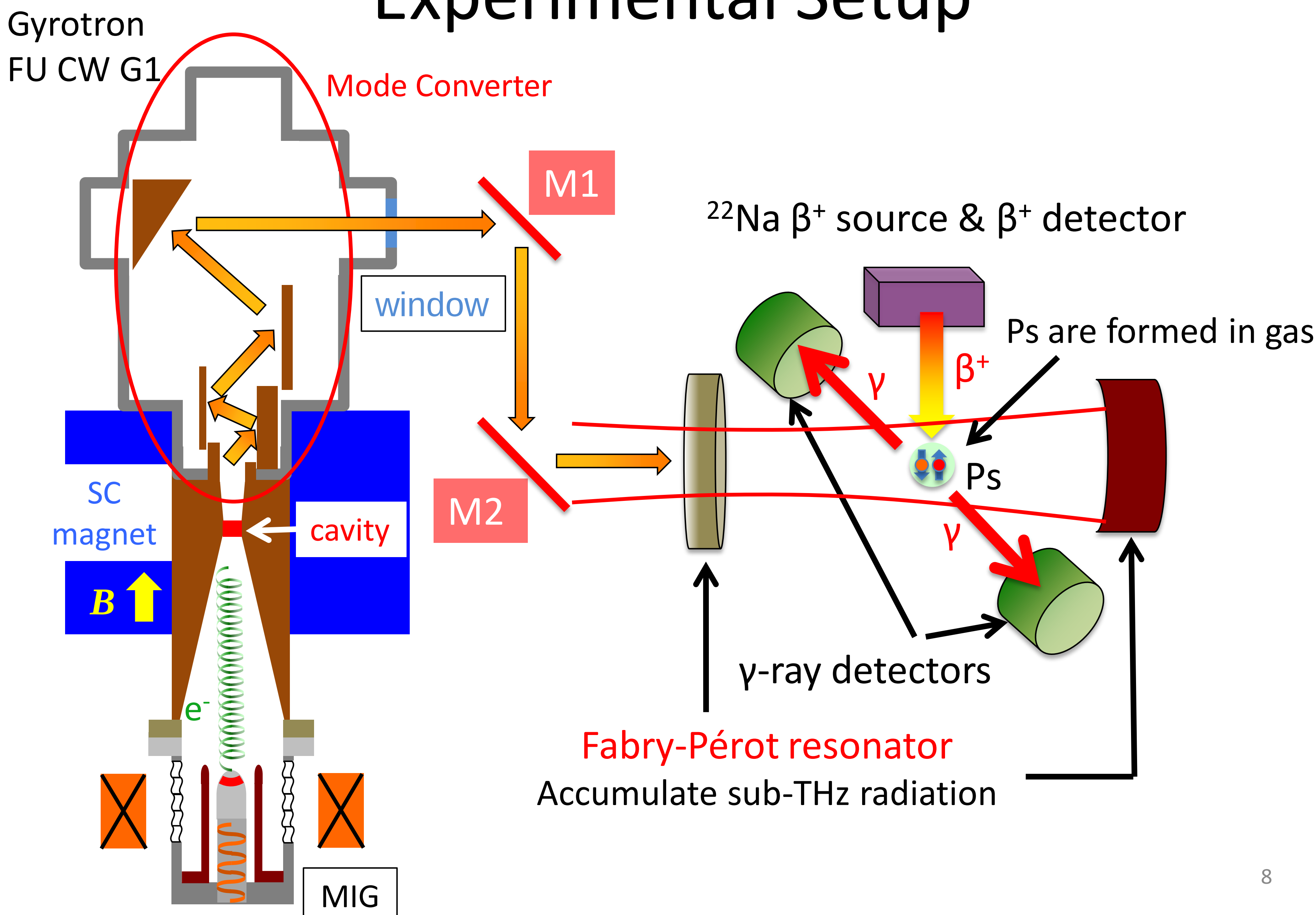
- A large (3.9 σ, 15 ppm) discrepancy between theory and previous indirect measurements.
- Possible reasons are
  - ✓ Non-uniformity of magnetic field
  - ✓ Underestimation of material (gas) effect
- We plan to “directly” measure Ps-HFS using high power sub-THz radiation.

First Direct Measurement of Ps-HFS with New Sub-THz Technique



- Drive stimulated emission from *o*-Ps to *p*-Ps using 203 GHz radiation.
- Since *p*-Ps decays into 2γ promptly (125 ps), 2γ annihilation increases when Ps are exposed to 203 GHz radiation.
- The natural transition rate is 10^{14} times smaller than decay rate of *o*-Ps. High power (> 10kW) sub-THz radiation is necessary.
- Frequency has to be changed from 201 to 206 GHz in order to measure transition curve.

Experimental Setup

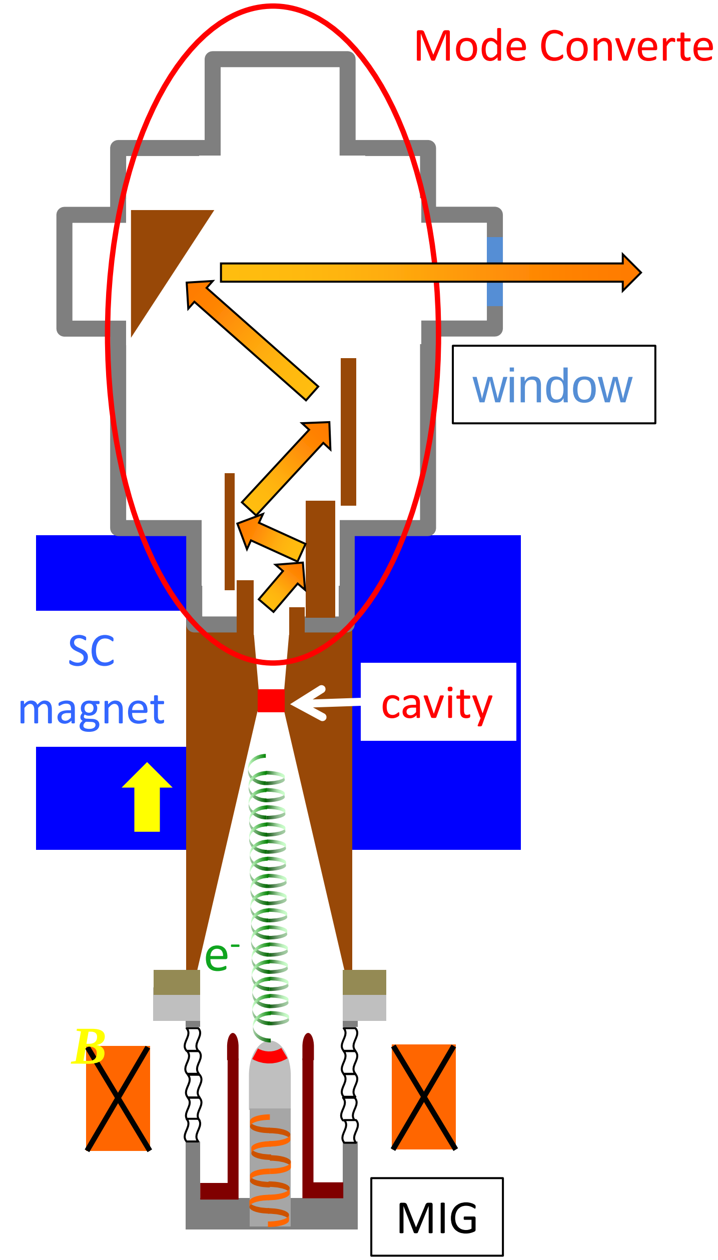


Gyrotron

- The only high power (100W – 1kW) coherent radiation source in sub-THz region, and monochromatic (<1MHz)
- Electrons emitted from an electron gun are accelerated and move in a circle in the magnetic field and go into the cavity
- When their cycrotron frequency Ω = eB/mγ matches cavity resonant frequency

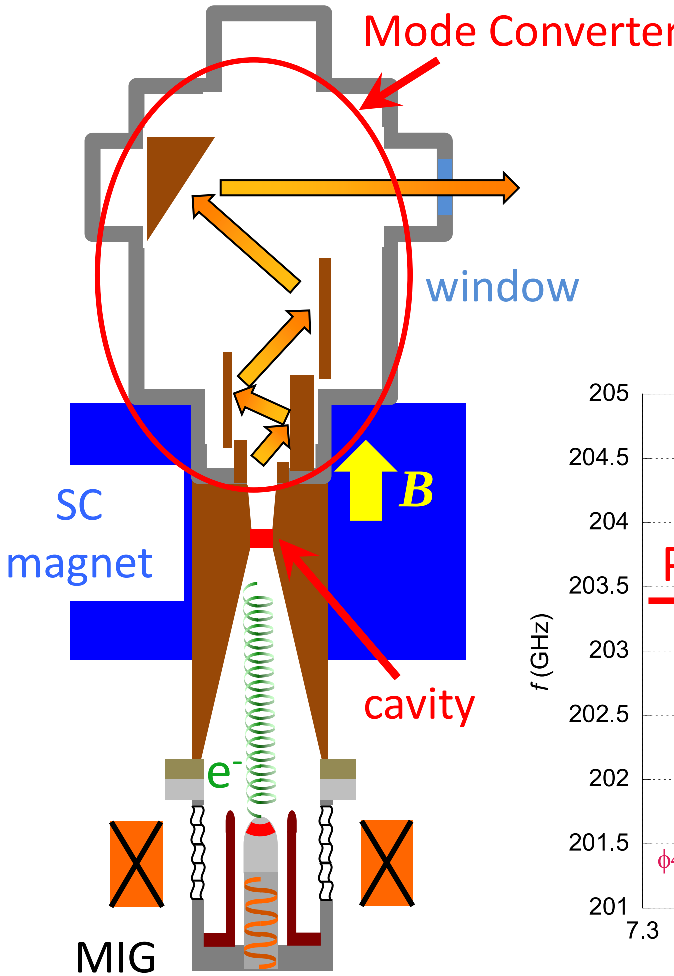
$$\omega_c = \sqrt{\left(\frac{\chi_{mn}}{R}\right)^2 + \left(\frac{l\pi}{L}\right)^2}$$

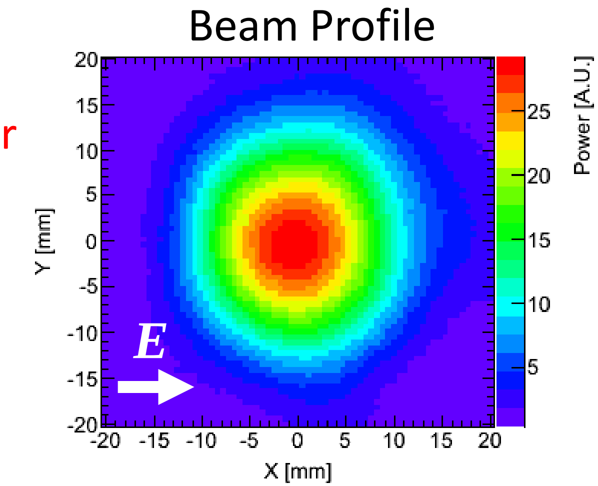
the energy of their cycrotron motion is converted to EM wave with frequency $\omega = \omega_c = \Omega$

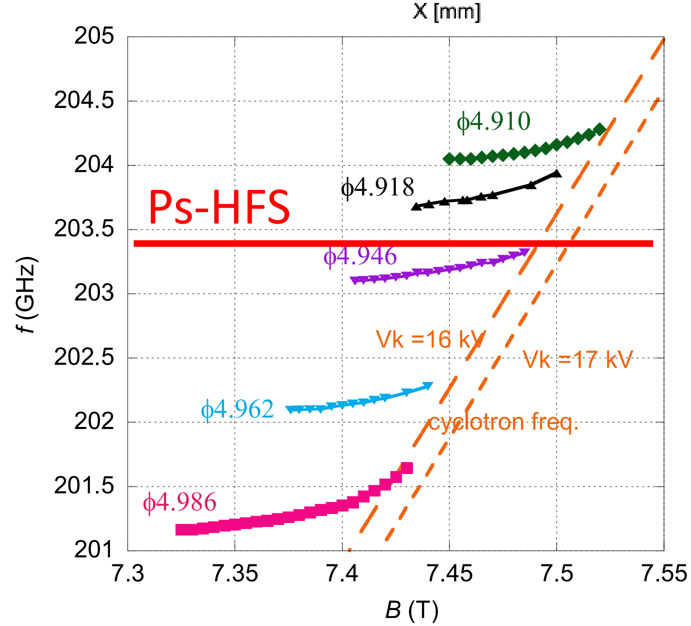


Gyrotron "FU CW GI"

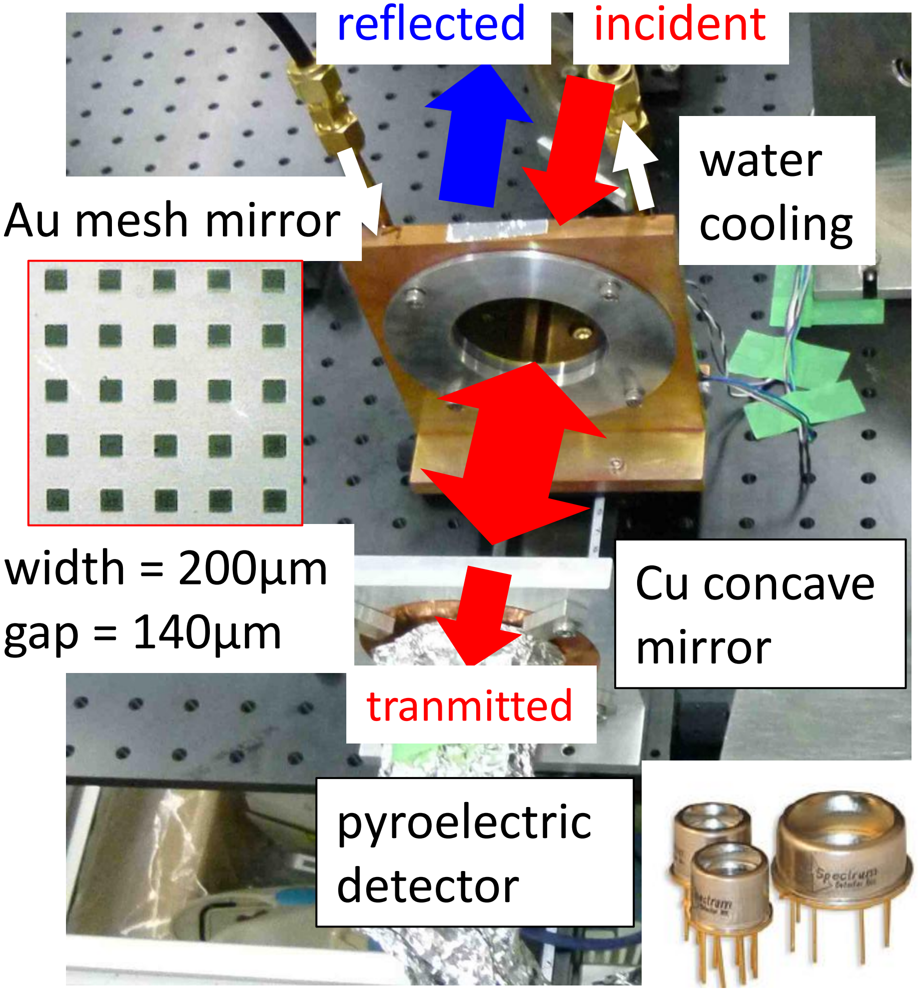
- Gaussian beam power ~ 350 W (5Hz, duty 30%)
- Replacing gyrotron cavities of different sizes to change frequency without breaking vacuum of the MIG.

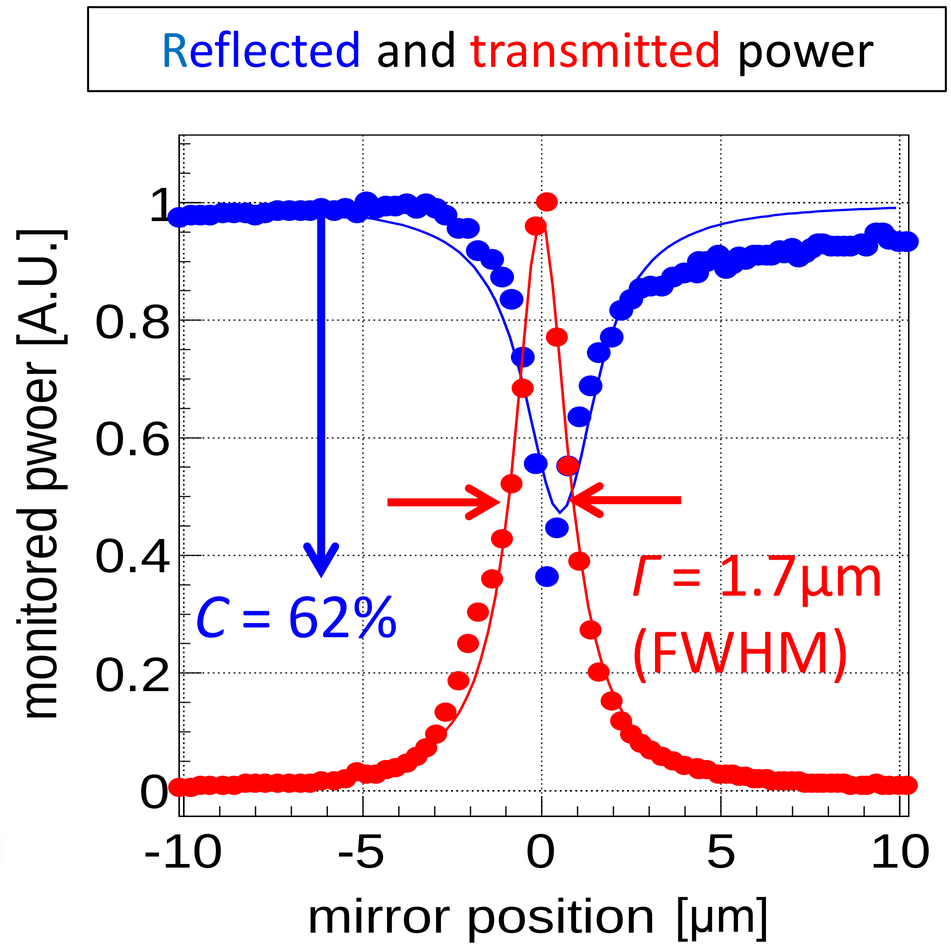






Fabry-Pérot Resonator

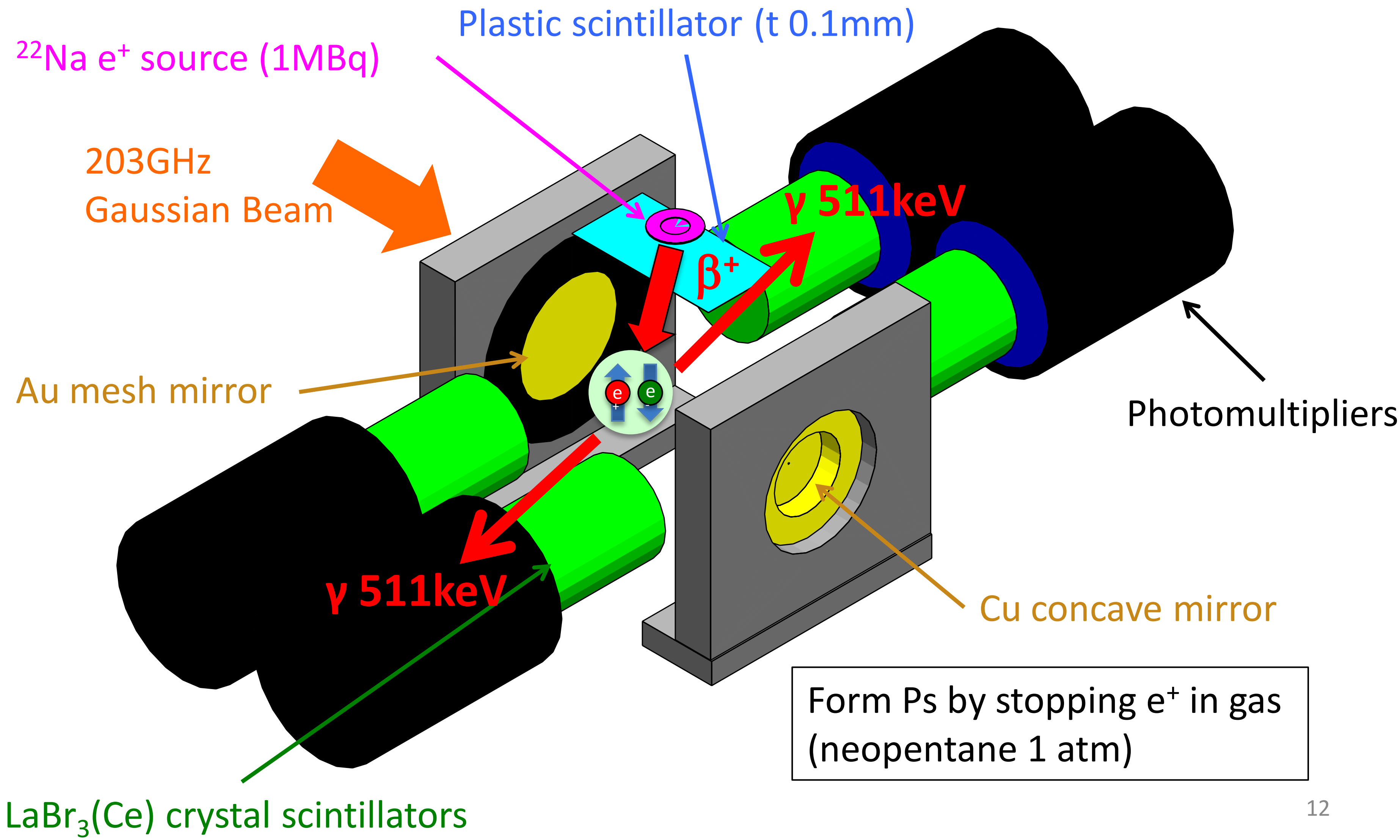




- Sharpness Γ = 1.7µm (Finesse = 430), and coupling C = 62%
  → Gain of the resonator ~ 85! (incident power ~ 350W)

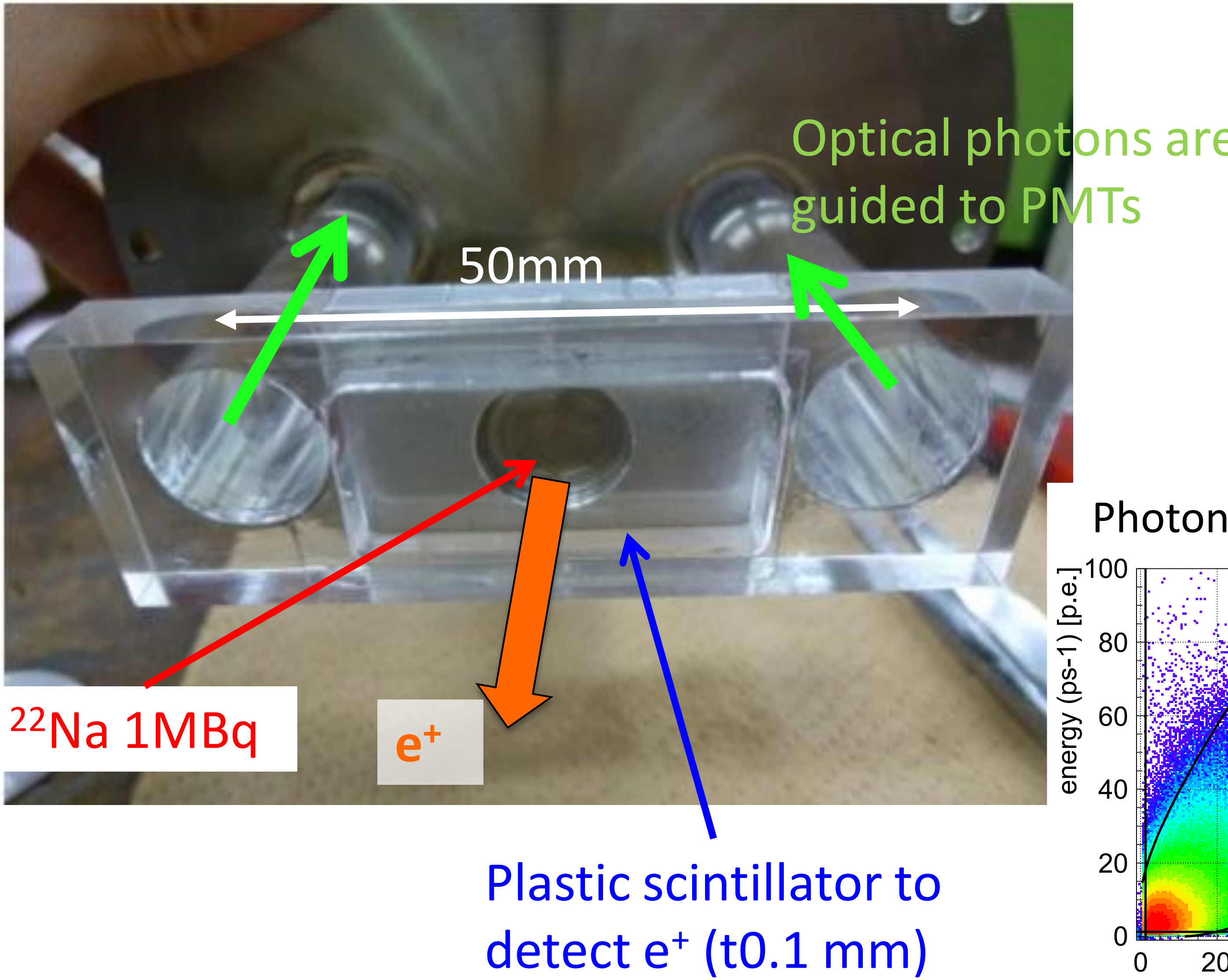
Ps Assembly and γ-ray detectors

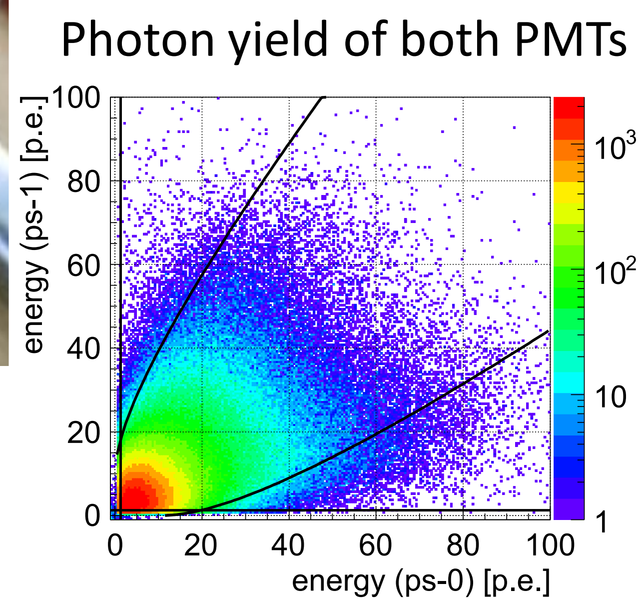
Signal = 2γ decay of *o*-Ps (monochromatic 511keV・back-to-back)



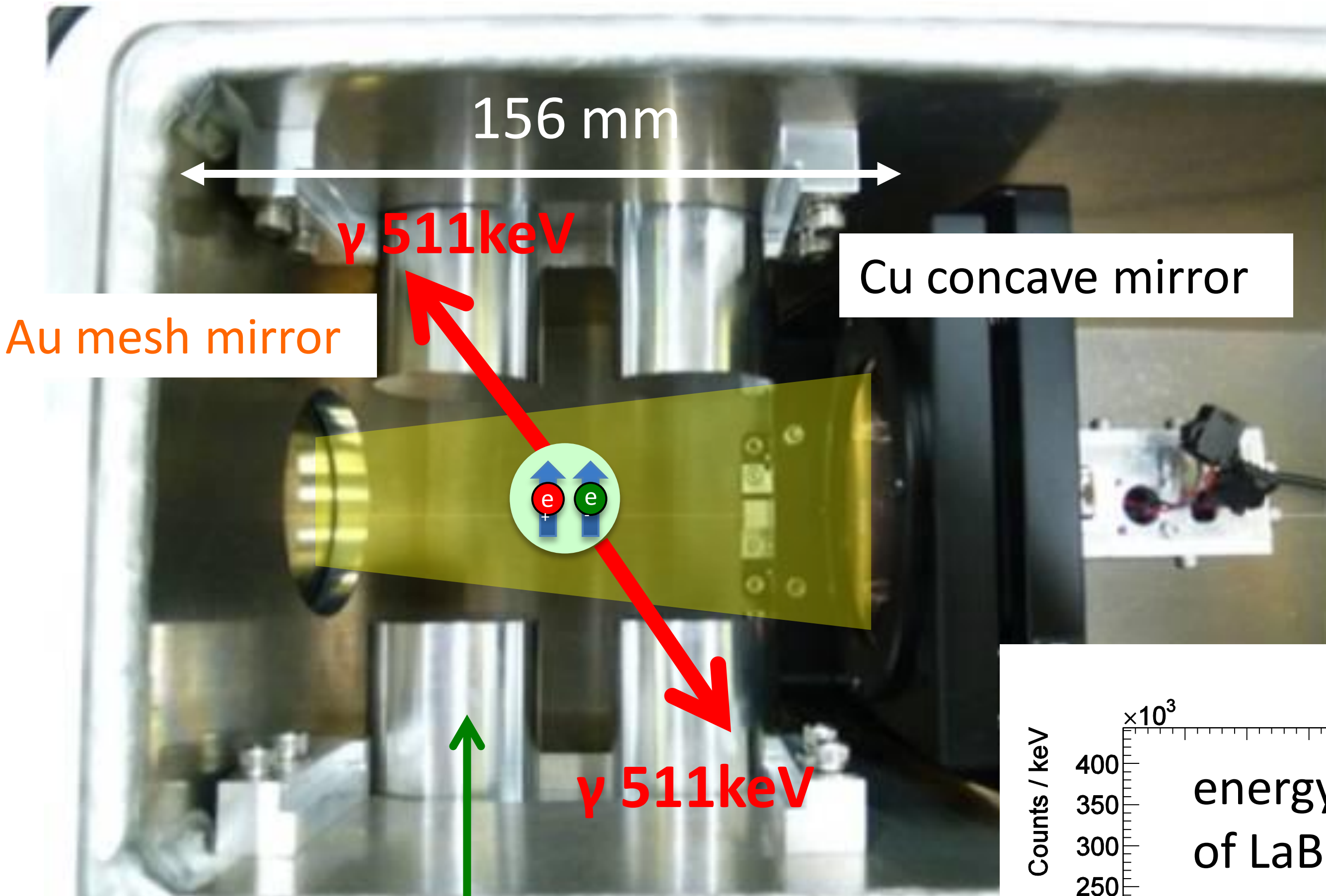
Form Ps by stopping e^+ in gas
(neopentane 1 atm)

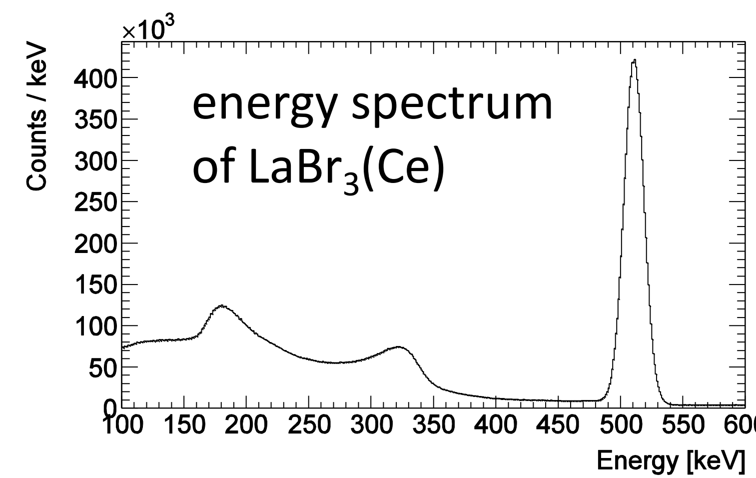
^{22}Na e^+ source and e^+ detector





γ-ray detectors & Fabry-Pérot resonator



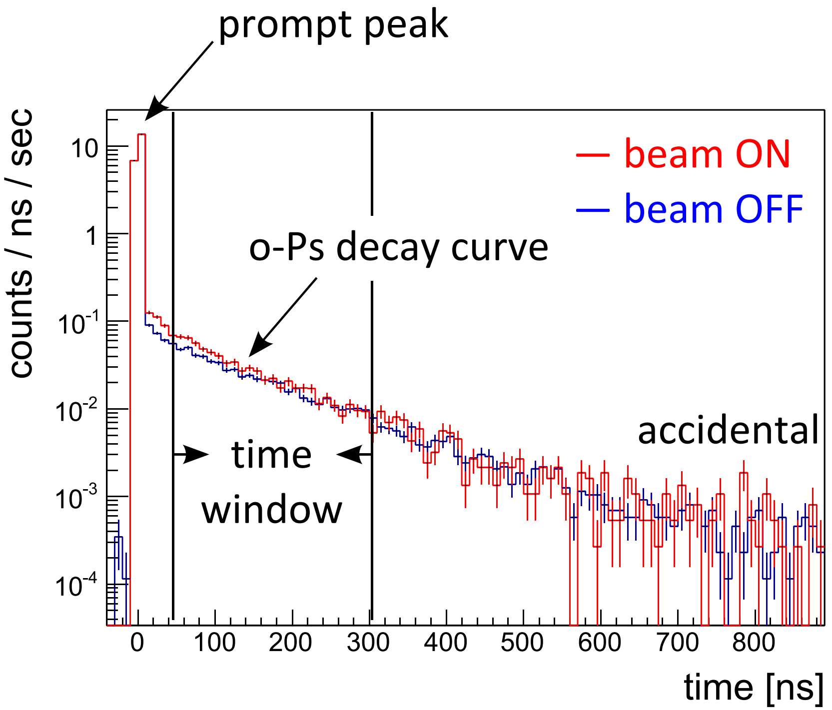


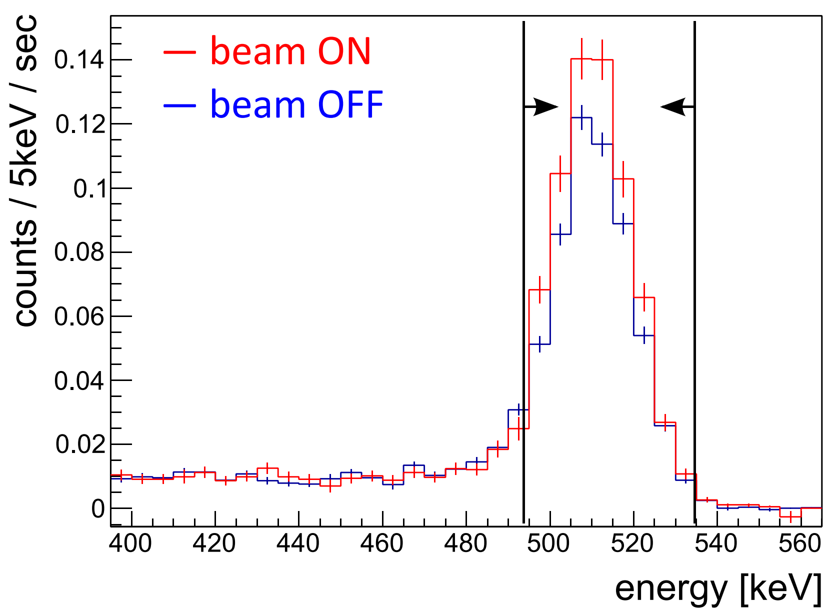
$LaBr_3(Ce)$ crystal scintillator

- energy resolution FWHM 4%@511keV
- time constant 16ns
- time resolution 200ps (FWHM) @ 511keV

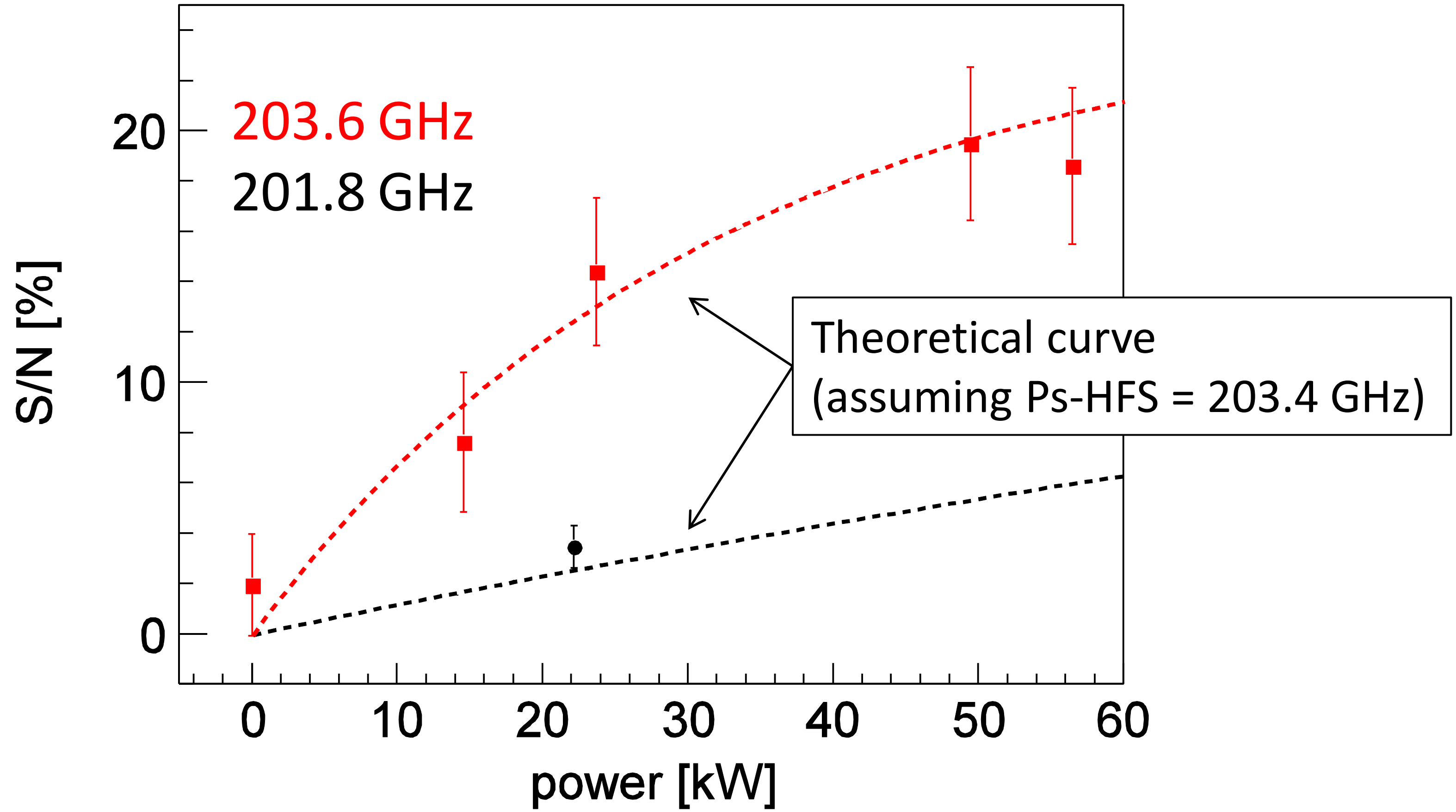
Ps-HFS transition@203.6GHz, 52kW

- A measurement at a frequency point takes about 3 weeks (2 weeks for preparation, 1 weeks for data acquisition)
- When Ps are exposed to 203 GHz radiation, *o*-Ps→3γ (tail at the left of 511keV peak) decrease and *o*-Ps(→*p*-Ps)→2γ (511keV peak) increase. The 511keV peak during beam OFF is due to *o*-Ps+e^-→2γ+e^- (pick off annihilation).





Power & Frequency Dependence of Transition



- We have already measured transitions at 201.8 GHz, 203.6 GHz. The data points are consistent with the theoretical curve.
- We are going to measure at three more freqencies to estimate Ps-HFS with an accuracy of *O*(100ppm) within this year.

Summary

- There is a 3.9σ (15 ppm) discrepancy between the measured and the theoretical value of Ps-HFS (203.4 GHz).
- All previous measurements are indirect measurement with static magnetic field. We plan to directly measure Ps-HFS for the first time by developing new sub-THz technique.
- High power (>10 kW) and frequency tunability from 201 GHz to 206 GHz are necessary, so we use a demountable type gyrotron "FU CW GI" and a high finesse Fabry-Perot resonator with a gold mesh mirror.
- We have already measure transitions at two frequencies. In order to measure Ps-HFS, we will perform three more measurements at different frequencies within this year and measure Ps-HFS and lifetime of *p*-Ps directly.
- Precision (*O*(ppm)) measurement requires
  - ✓ 0.1% accuracy of power estimation (need development of THz detector)
  - ✓ Upgrade Ps assembly to improve statistics and reduce systematics (e.g. use slow positron beam and make Ps in vacuum)