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

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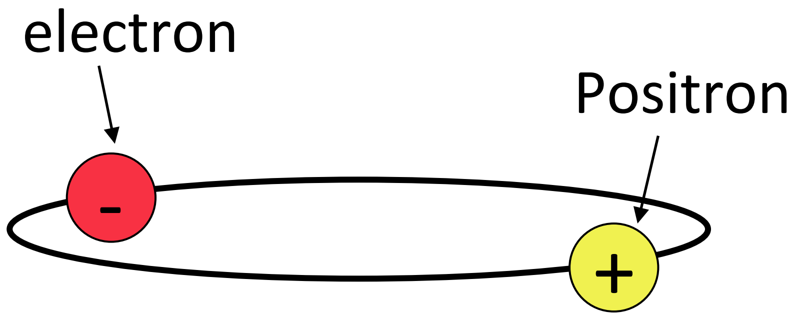
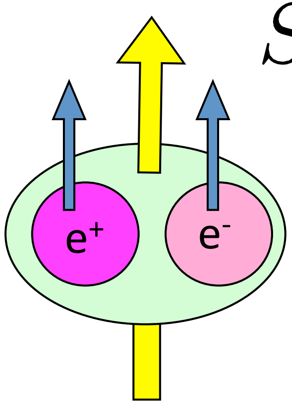
# Positronium (Ps)




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

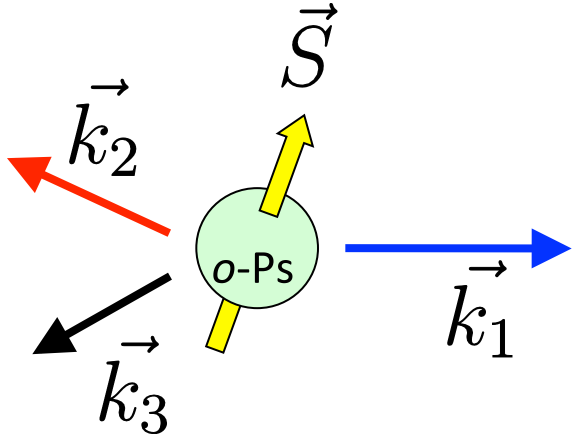
# Positronium (*o*-Ps, *p*-Ps)

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

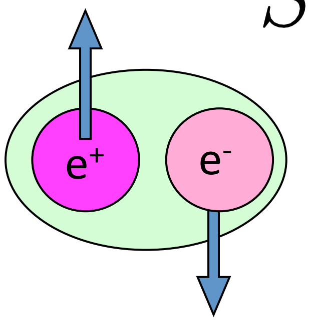



$S = 1$ Spin triplet

Long lifetime (142 nsec)
*o*-Ps → 3γ (, 5γ, …)
Continuous energy spectrum

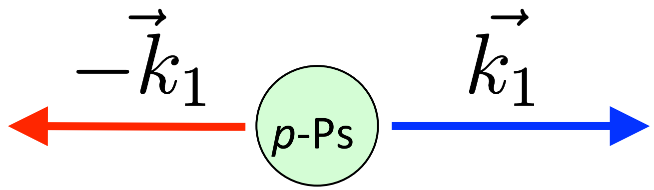



- *Para*-positronium (*p*-Ps)

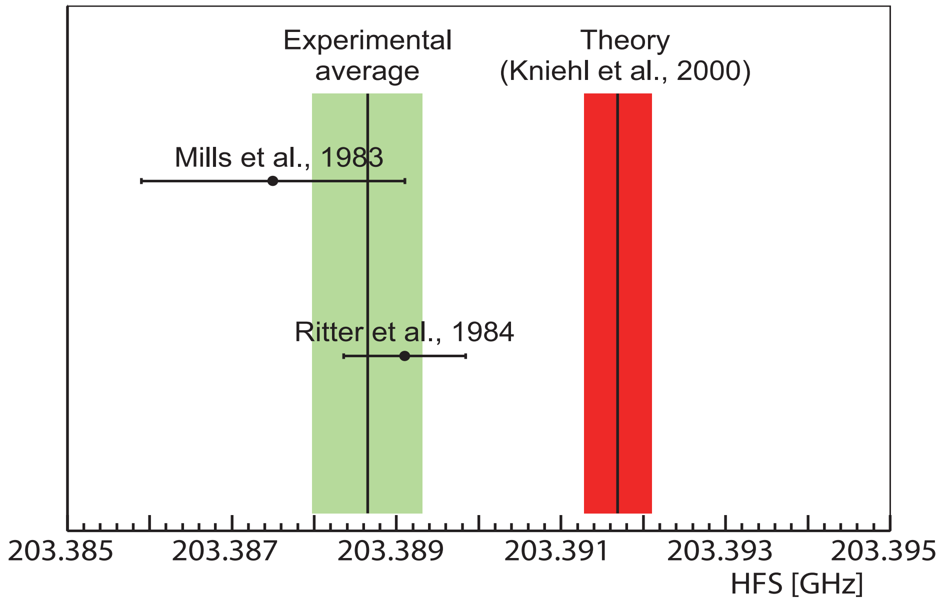



$S = 0$ Spin singlet

Short lifetime (0.125 nsec)
*p*-Ps → 2γ (, 4γ, …)
511 keV (= electron mass) gamma rays



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

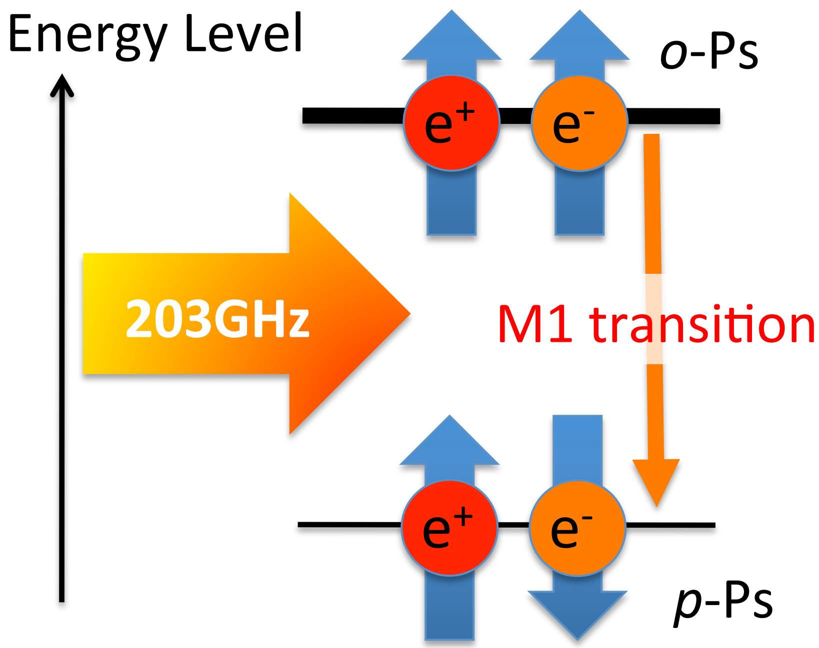


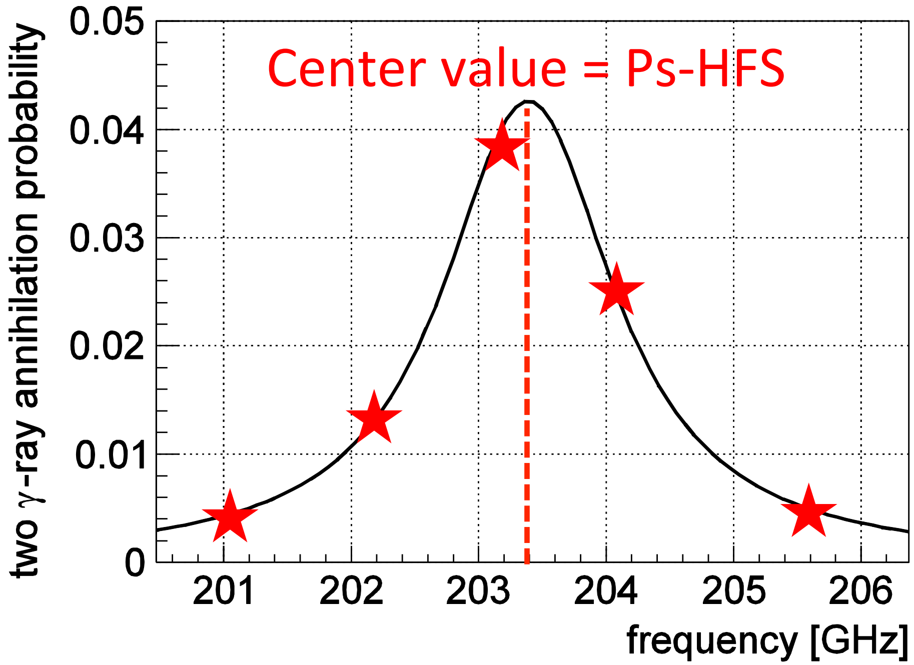

Exp.
203.388 65(67) GHz (3.3 ppm)
O($\alpha^3$) QED calc.
203.391 69(41) GHz (2.0 ppm)

- 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 using high power sub-THz (203 GHz) radiation.

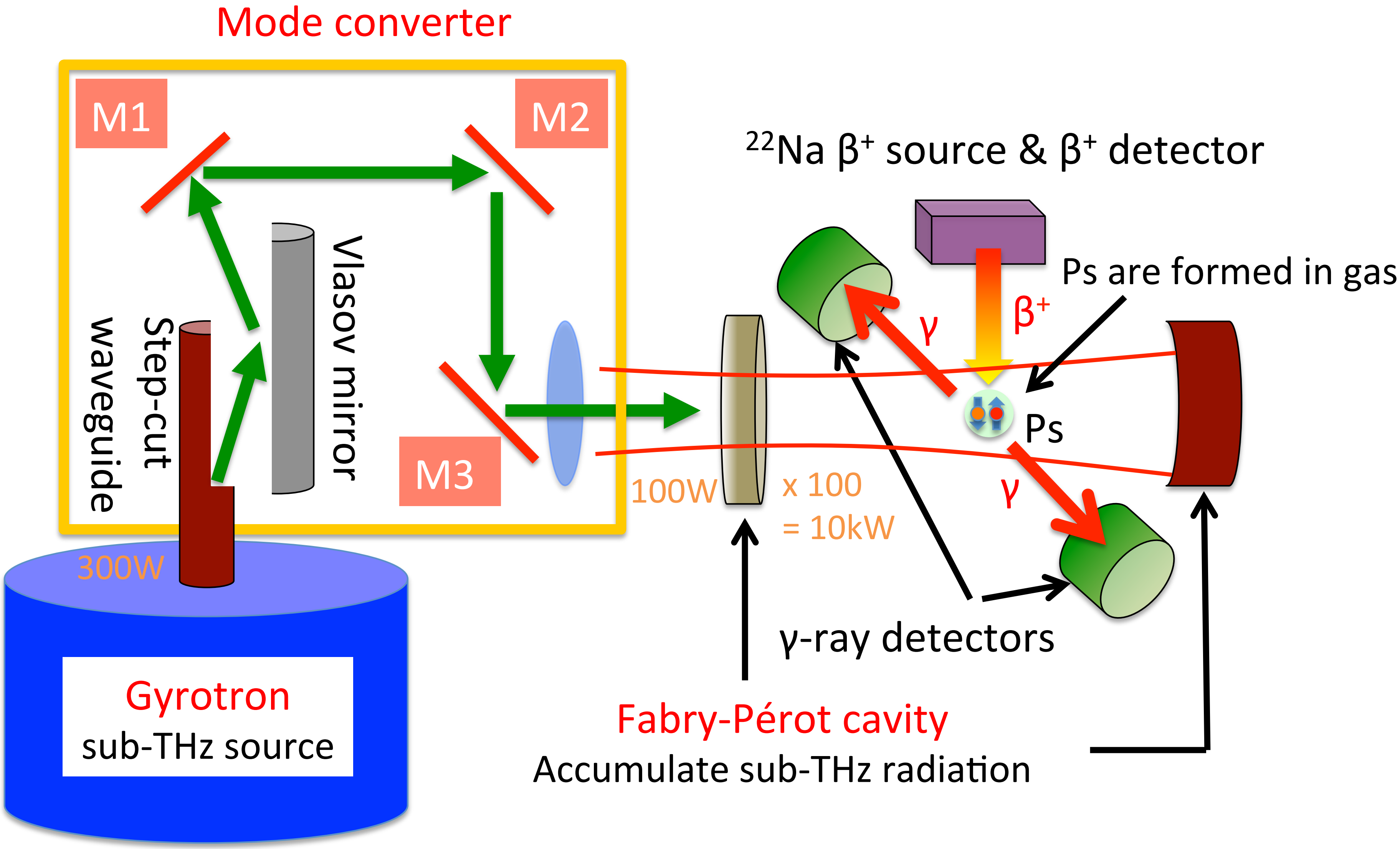
# First Direct Measurement of Ps-HFS with New Sub-THz Technique



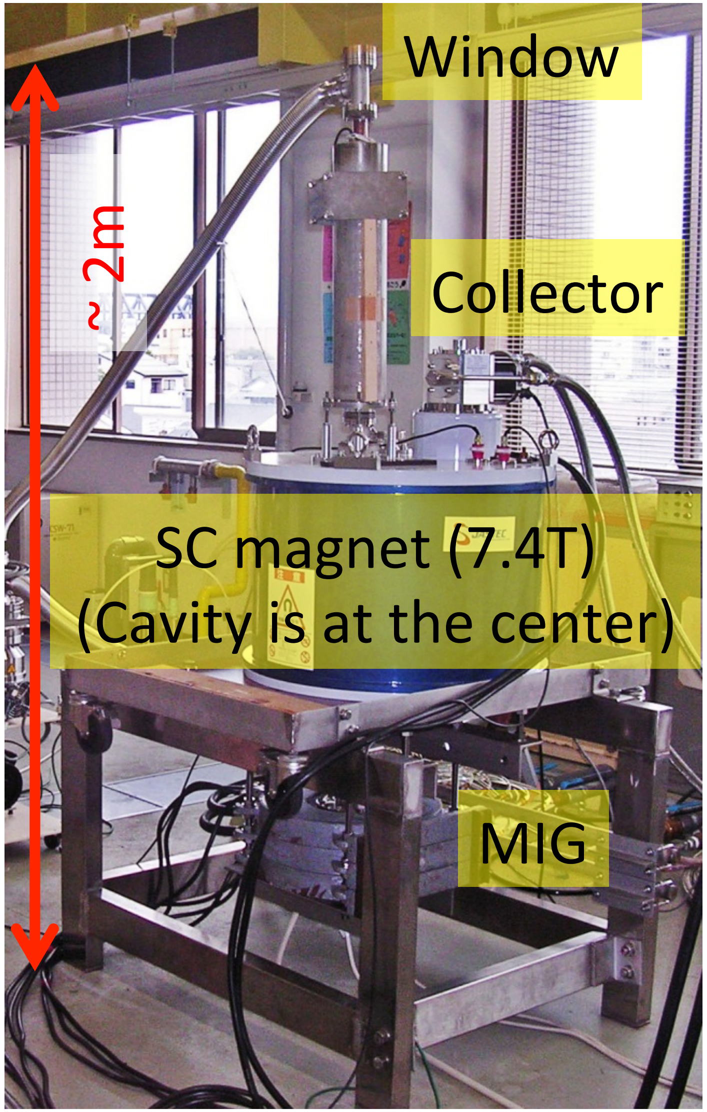

- Drive stimulated emission from *o*-Ps to *p*-Ps using 203 GHz radiation.
- Since *p*-Ps decays into 2γ promptly (125 ps), 2γ annihilation increases when Ps are exposed to 203 GHz radiation.
- The natural transition rate is $10^{14}$ times smaller than *o*-Ps decay rate. High power (> 10kW) sub-THz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

# Experimental Setup



# Key Device 1. ***Gyrotron***

@ University of Fukui



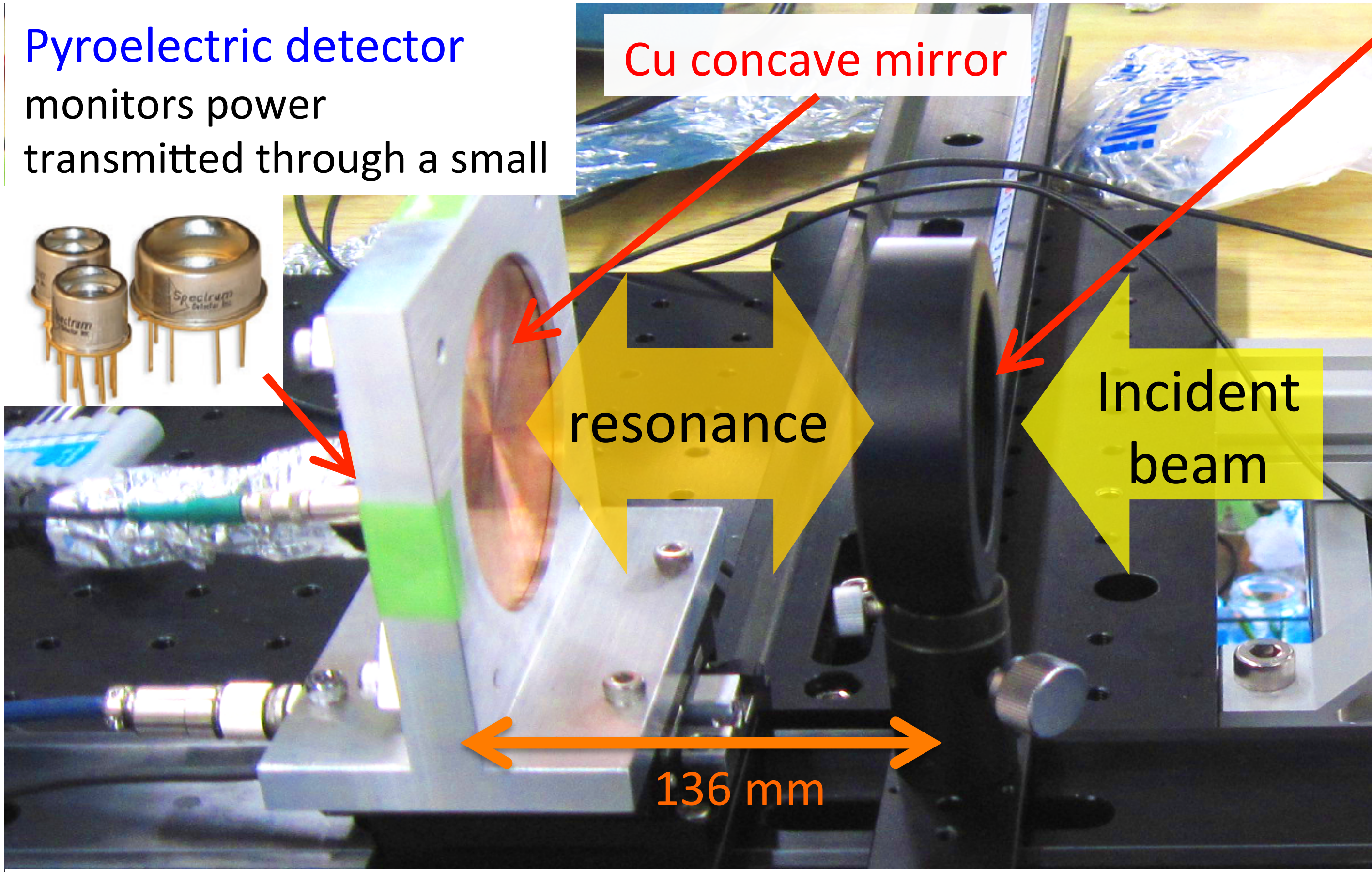

- High peak power = 300W
- Long pulse : ~10Hz, duty 30%
- Narrow bandwidth = 1MHz

→ suitable for sub-THz spectroscopy !

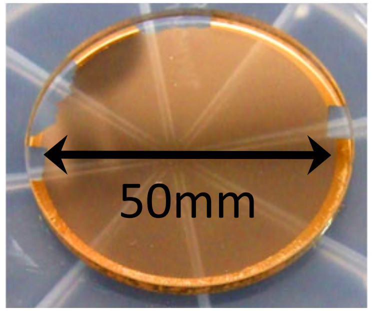
- The power fluctuation is less than 10% with feedback control of the heater voltage of the MIG (Magnetron Injection Gun).

- Acceleration voltage : $V_k$ = 18 kV
- Beam current : $I_b$ ~ 0.5 A

# Key Device 2. ***Fabry-Pérot Resonator***




Gold mesh mirror



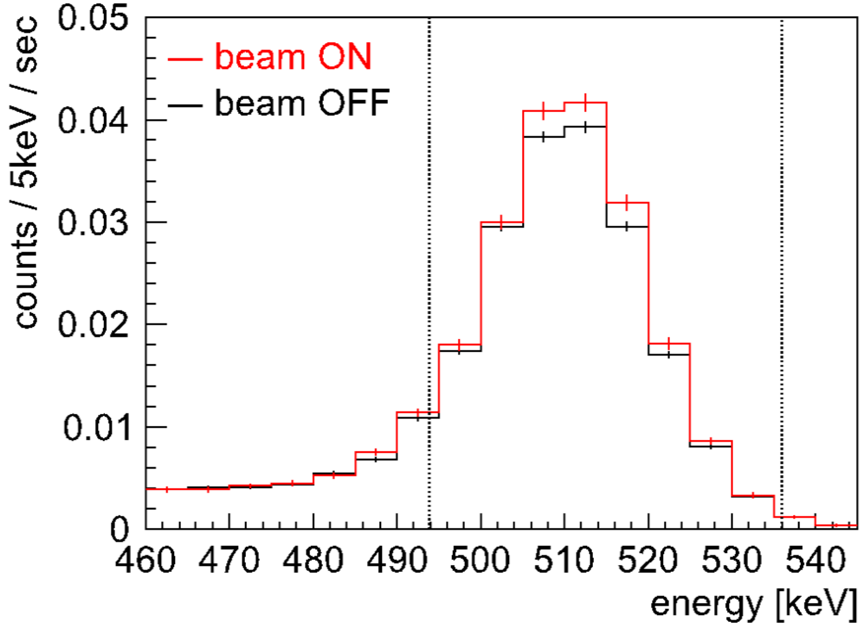

On quartz substrate
Line width = 200µm
Line separation = 160µm
Mesh thickness = 1µm

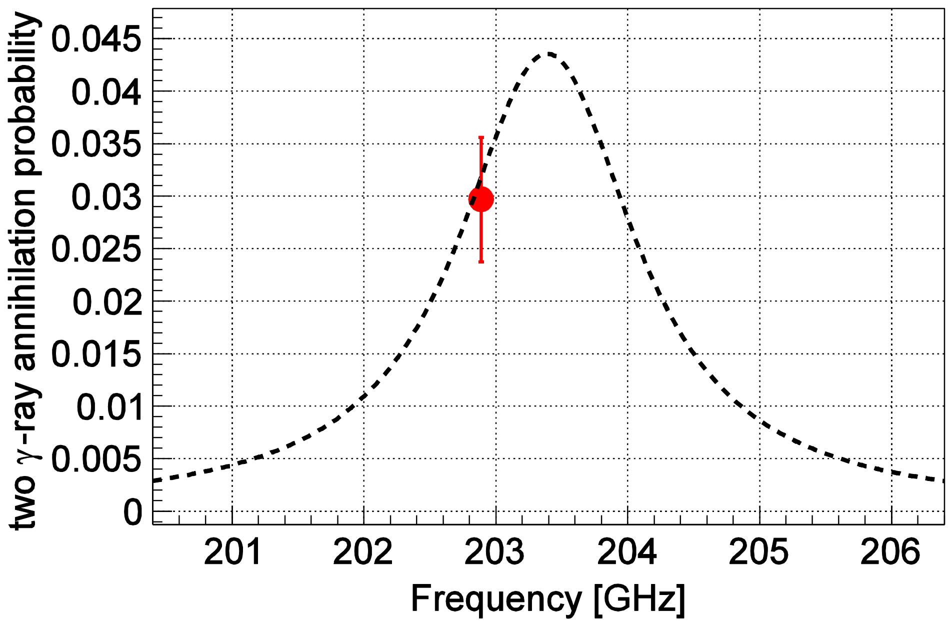
R = 99.4 %
T = 0.4 %
(Simulation)

- The incident beam resonates with FP resonator when the length between two mirrors becomes equal to the half-integer multiple of λ (= 1.5 mm).
- The accumulated power (10 kW) is about 100 times larger than the incident power (100 W).

# First Observation of the Direct Transition between Ps-HFS : *PRL 108, 253401 (2012)*

- 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).



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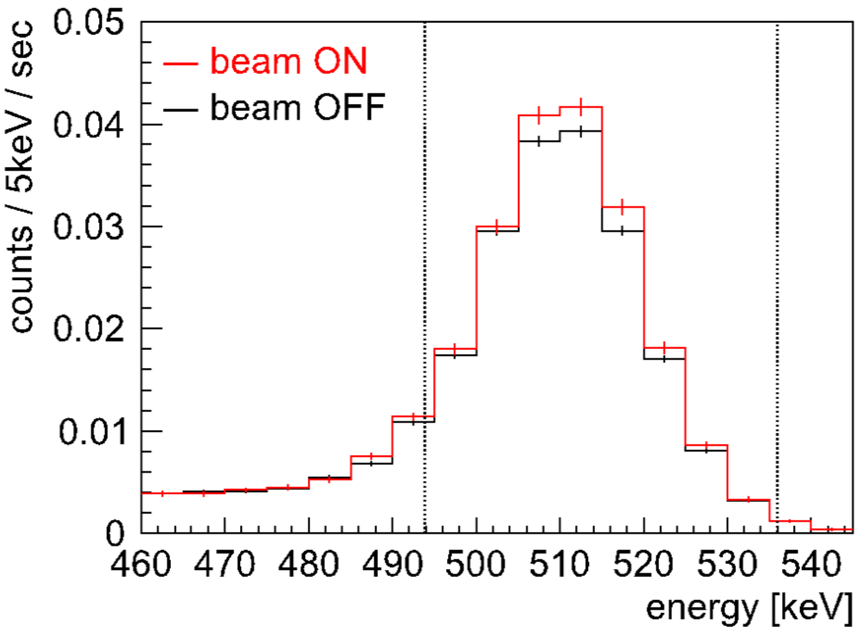
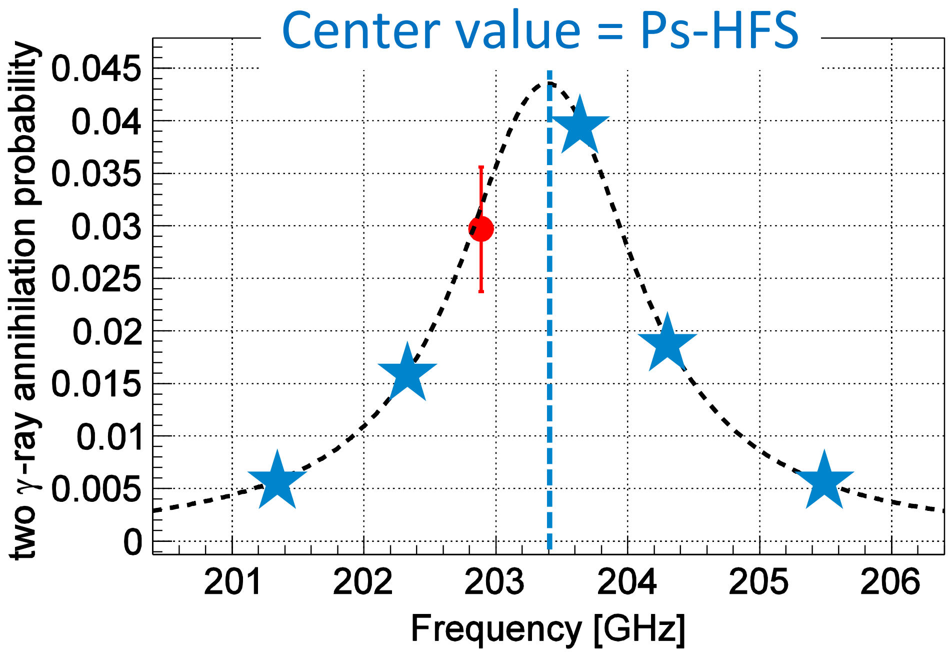


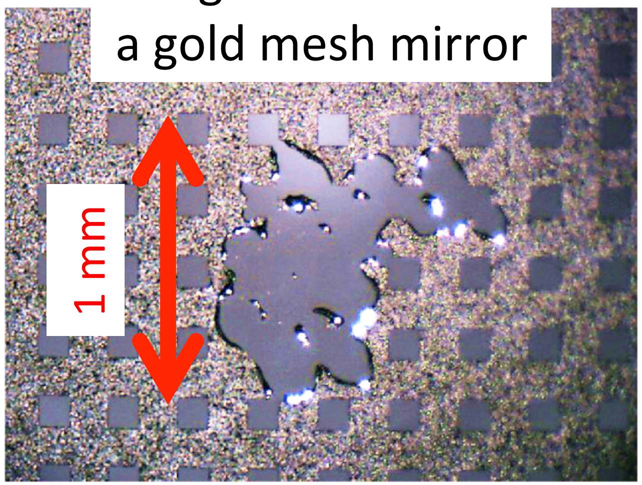

- In order to measure Ps-HFS, we have to repeat transition measurements at different frequencies.

# Upgrade for Ps-HFS Measurement

- However, there are two problems with our current optical system.

1. The oscillation frequency of the gyrotron is fixed (202.9 GHz).
   →A big problem. We cannot measure transition curve !
2. When power accumulated in a FP resonator exceeds about 15kW, the gold mesh melts away.
   →S/B ratio of the transition measurement is only 5 % at 202.9 GHz with power of 10 kW. More power is preferred for Ps-HFS measurement.

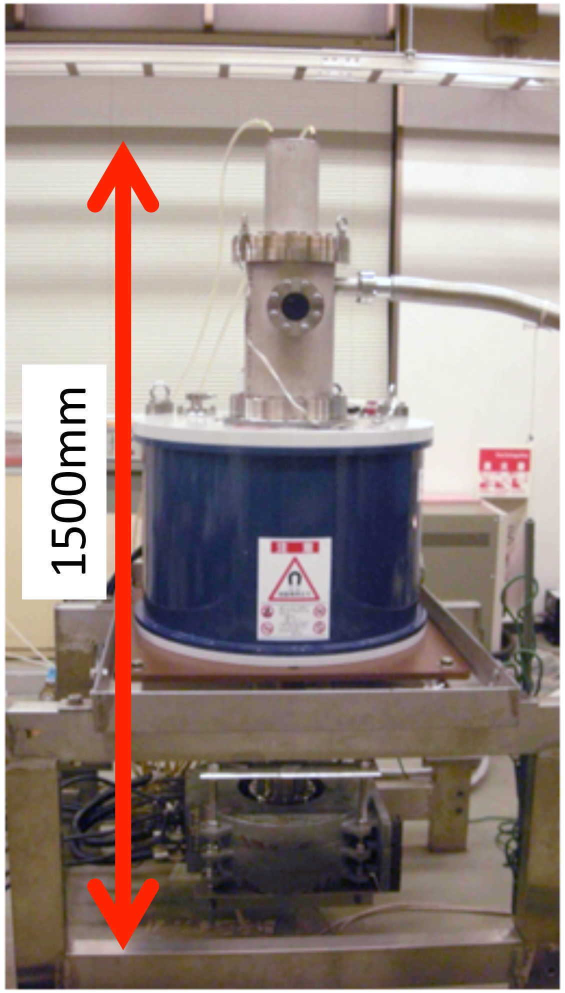
Magnified view of a gold mesh mirror

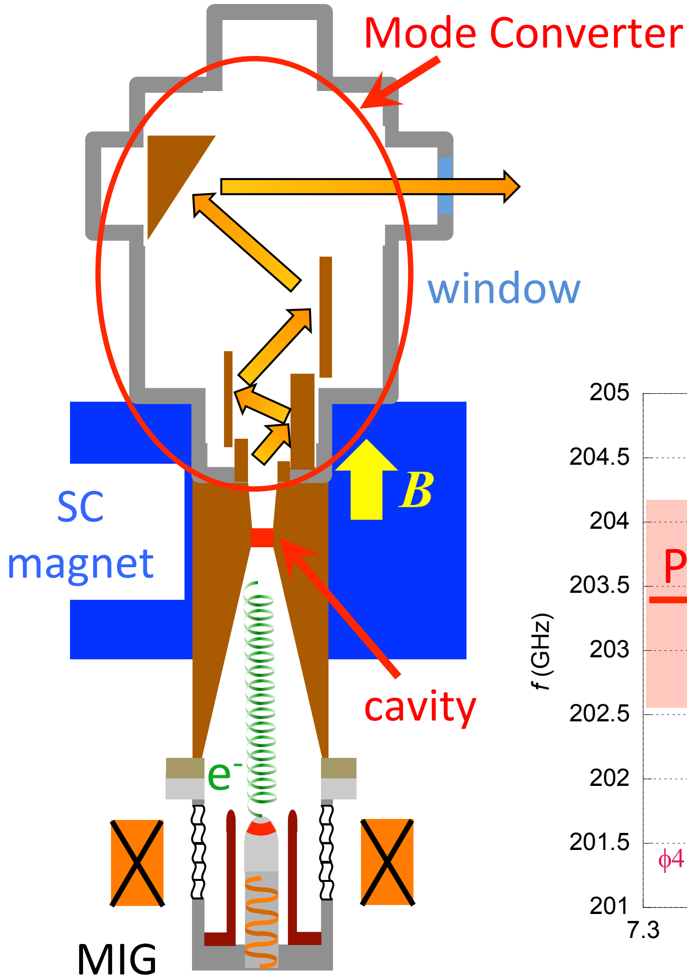



- Upgrade a gyrotron and a FP resonator to solve these problems.

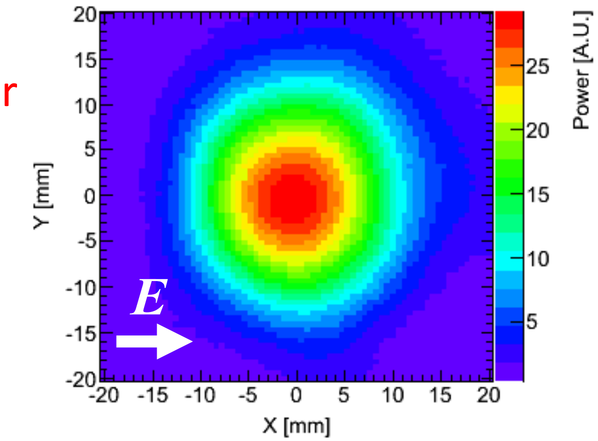
# New Gyrotron "FU CW GI"

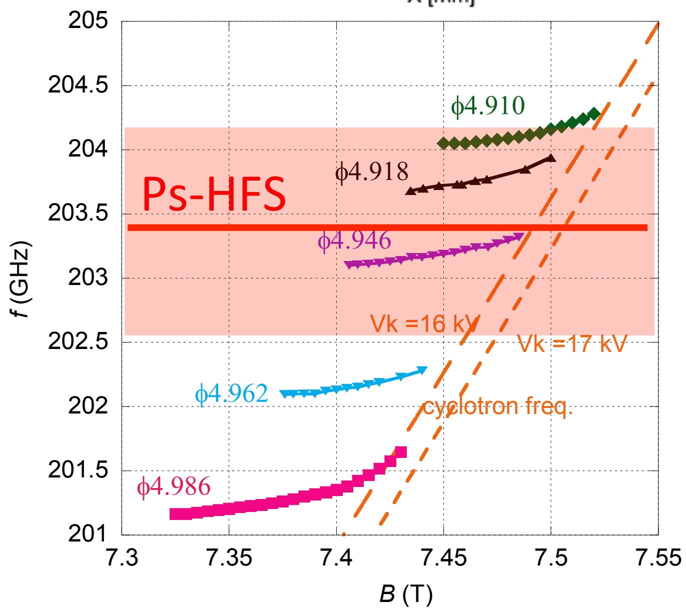
- Replacing gyrotron cavities of different sizes to change frequencies without breaking vacuum of the MIG.
- Gaussian beam power = 300 W (5Hz, duty 30%)



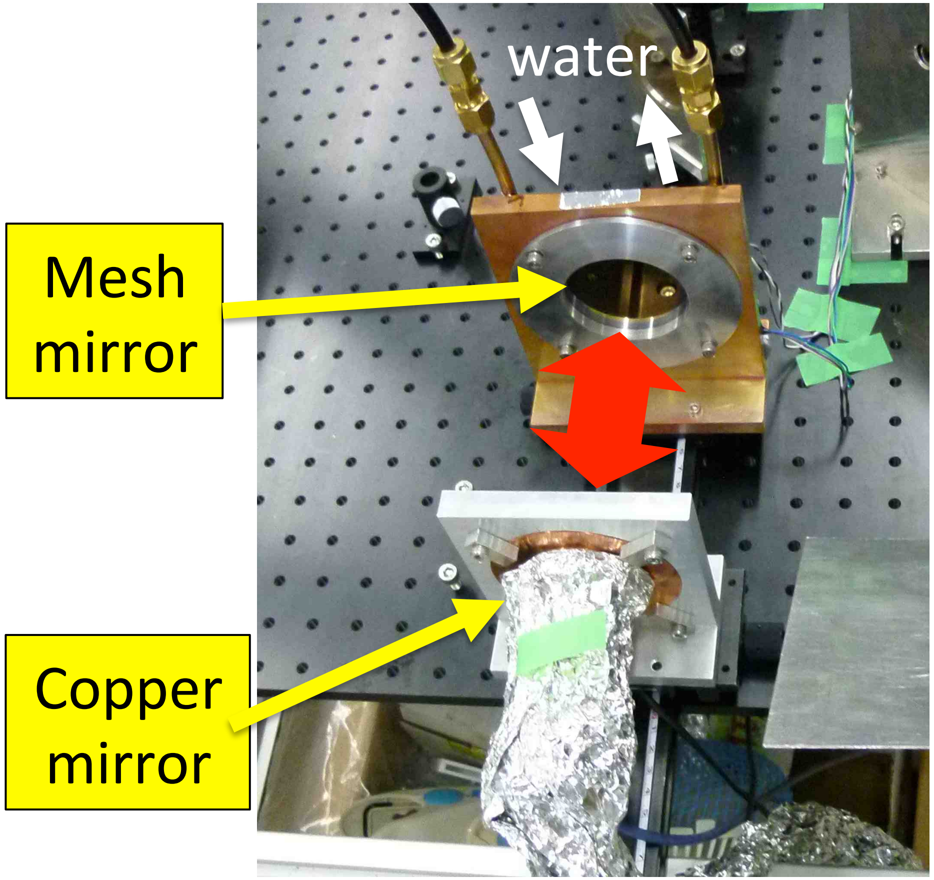

Beam Profile

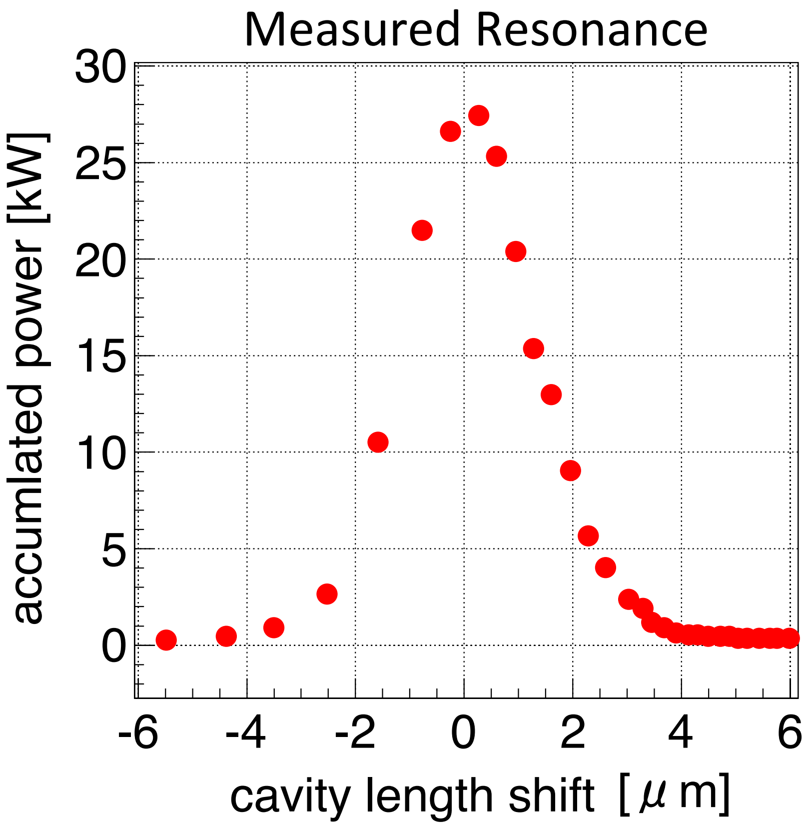


# Fabry-Pérot resonator with water cooling

- High resistivity silicon (κ=150 W/K･m) is selected as a new substrate for gold mesh instead of quarts (κ=5 W/K･m), and it is cooled with water.




- Equivalent power of about 25 kW in the Fabry-Pérot resonator is obtained without any damage on the gold mesh.

# Summary

- We plan to directly measure Ps-HFS (203.4 GHz) for the first time by developing new sub-THz technique.
- A direct transition from *o*-Ps to *p*-Ps has been already observed for the first time with a gyrotron and a Fabry-Pérot resonator.
- In order to measure transition curve of Ps-HFS, high power (>20 kW) and frequency tunability from 201 GHz to 206 GHz are necessary.
- A new demountable type gyrotron "FU CW GI" is a demountable type gytoron and able to output all necessary frequency points.
- In addition, a new Fabry-Pérot resonator with a new gold mesh on high resistivity Si is able to accumulate more power (about 25 kW) without any damage on the gold mesh.
- First direct measurement of Ps-HFS will be performed within a year.