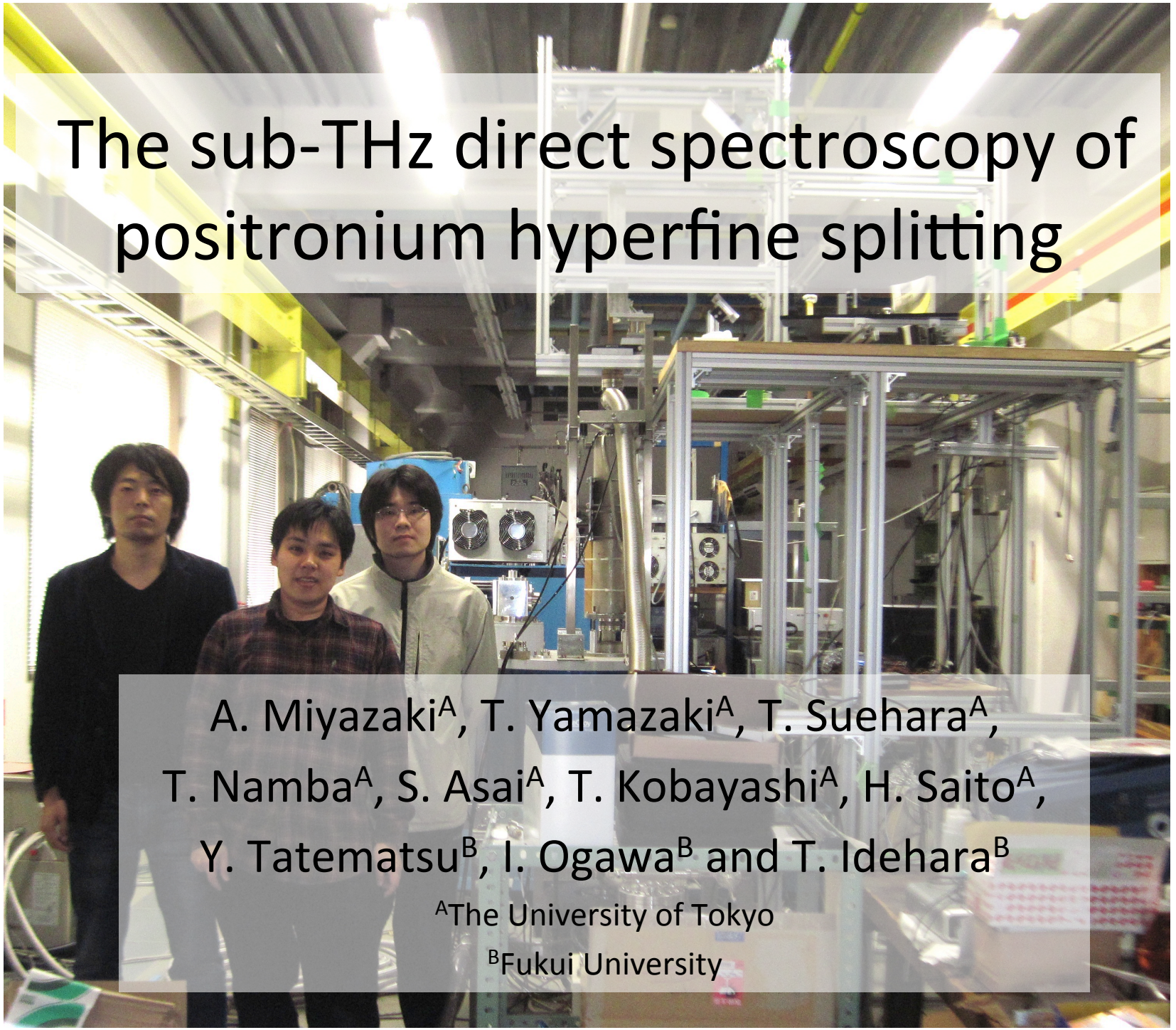

The sub-THz direct spectroscopy of positronium hyperfine splitting

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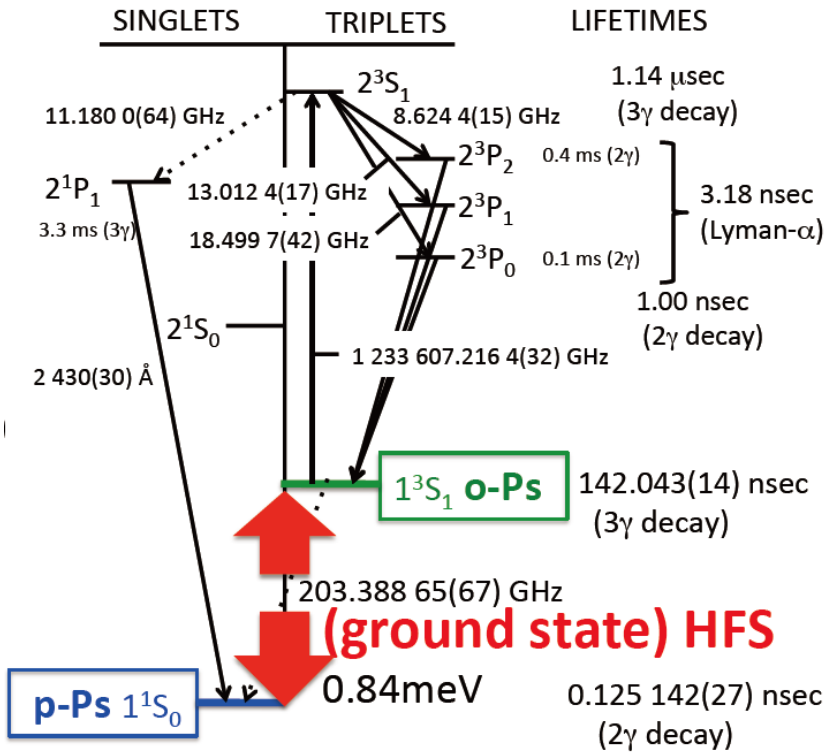
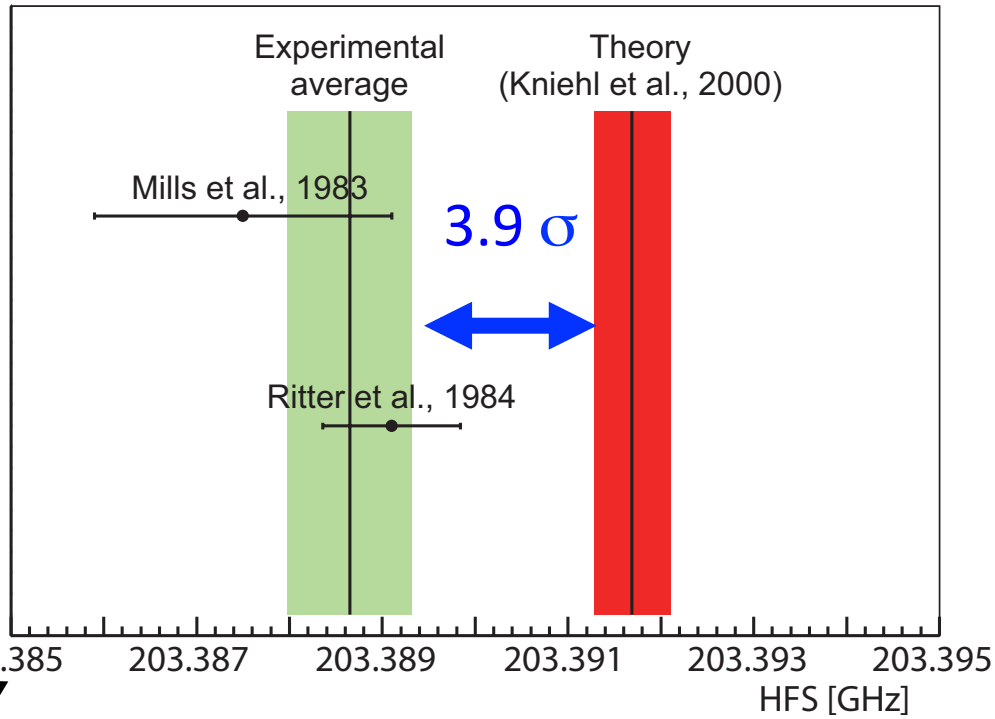
Hyperfine Splitting of Positronium(Ps-HFS)

The energy difference of o-Ps and p-Ps is called (ground-state) Ps-HFS.



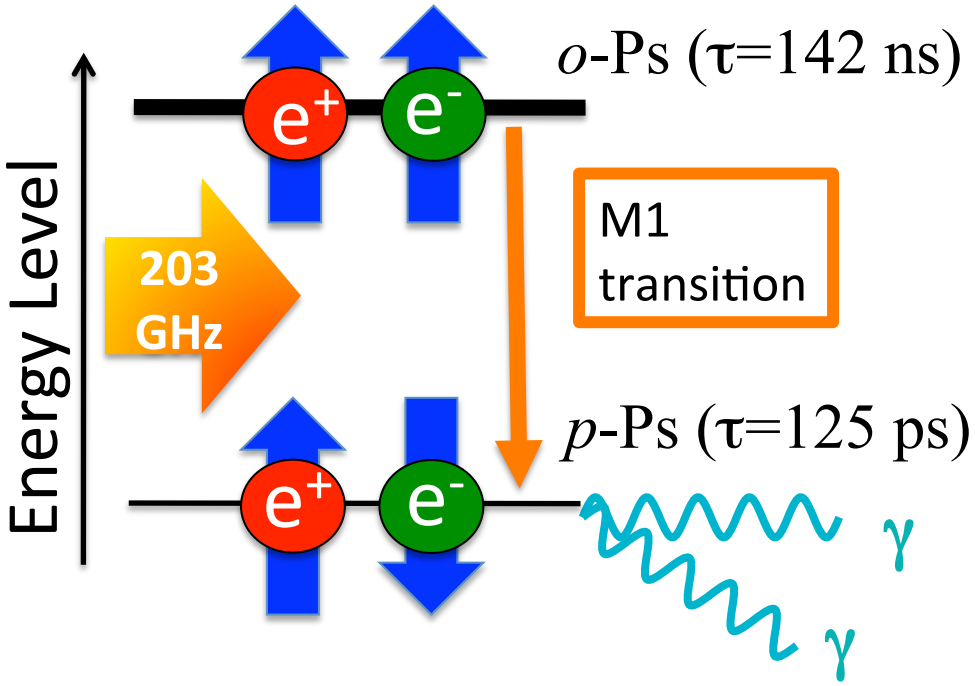
Previous measurements differs by
3.9σ (15ppm) from QED calculation

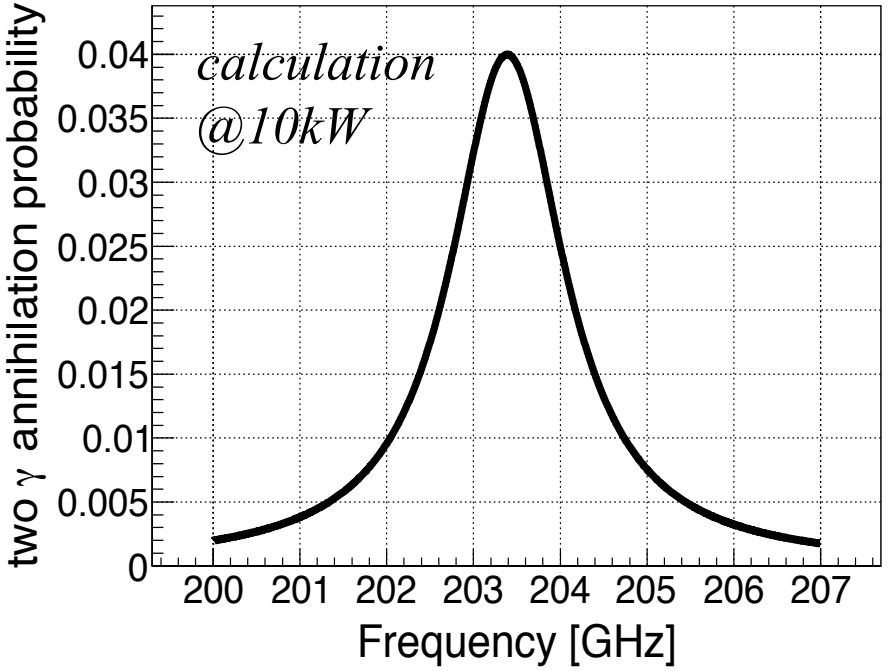


Previous experiments :
203.388 65(67) GHz (3.3 ppm)
O(α^3) QED calculation :
203.391 69(41) GHz (2.0 ppm)

Previous experiments used Zeeman effect
Unable to be free from any systematic uncertainties depending on the magnetic field.

Direct Measurements of Ps-HFS





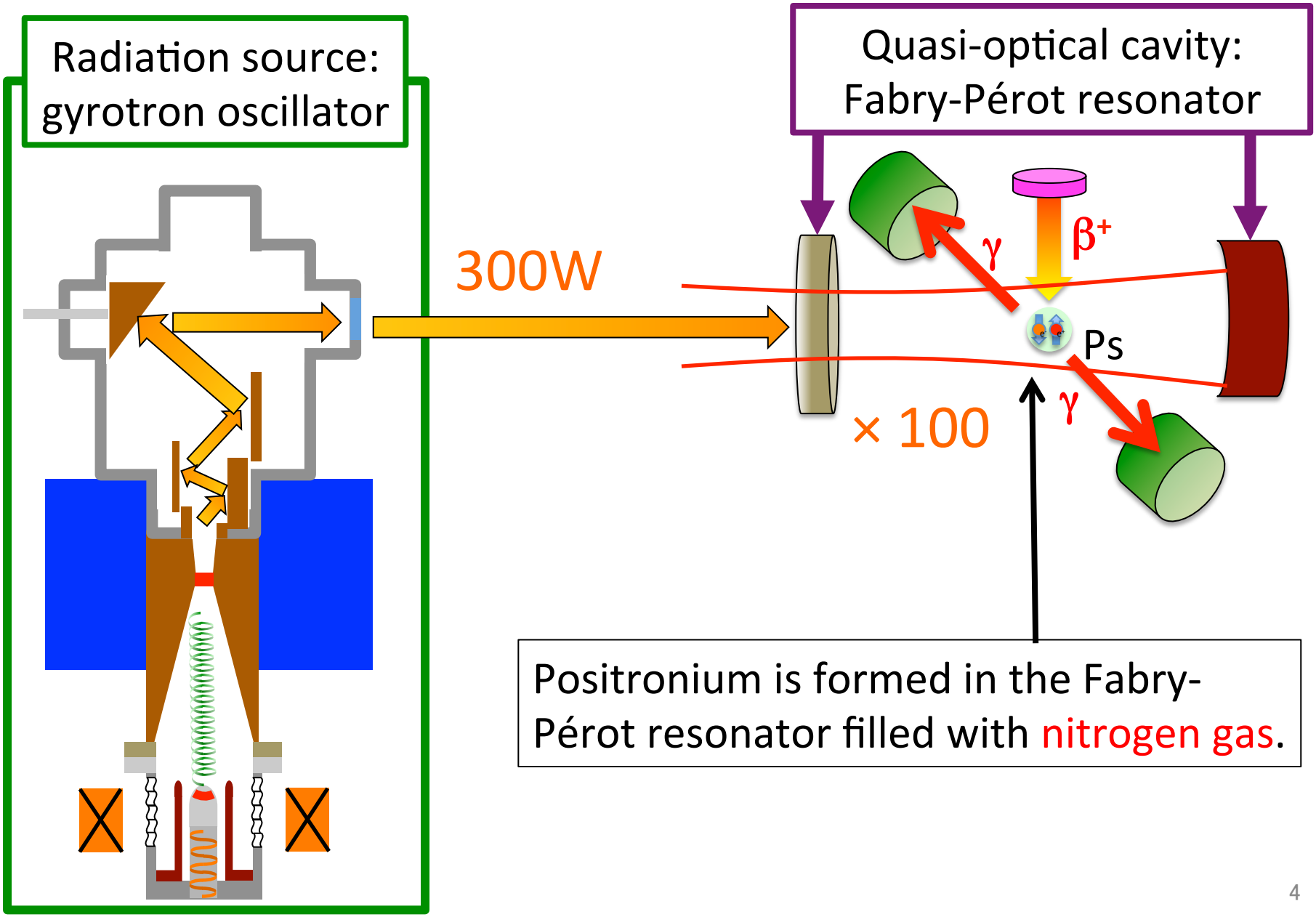
- 203GHz radiation drives transition from *o*-Ps to *p*-Ps.
- Transiting *p*-Ps promptly(125 ps) decays into 2-γ rays.

→ Increase of 2-γ annihilation indicates the direct transition.

- Since this is a magnetic dipole transition (M1), natural transition rate is extremely small ($A = 3.37 \cdot 10^{-8}\ s^{-1}$)

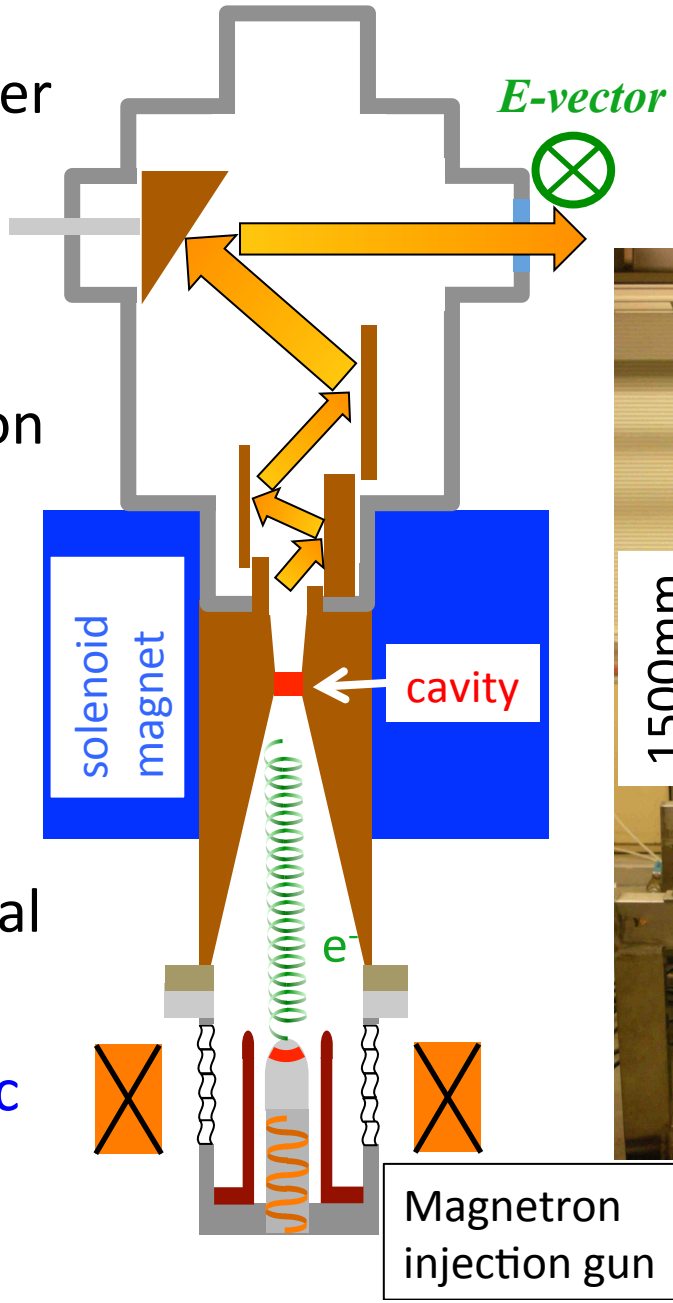
High power radiation of O (10kW) is essential to stimulate the transition.

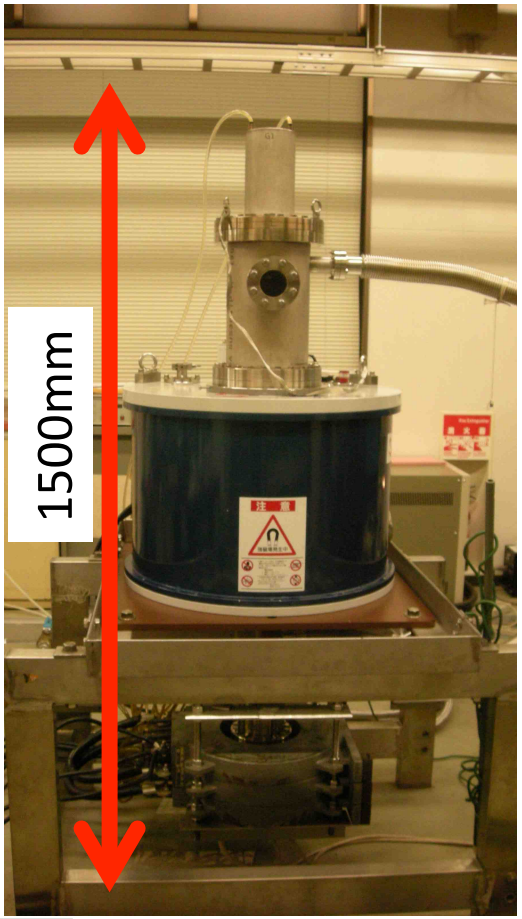
Two key devices



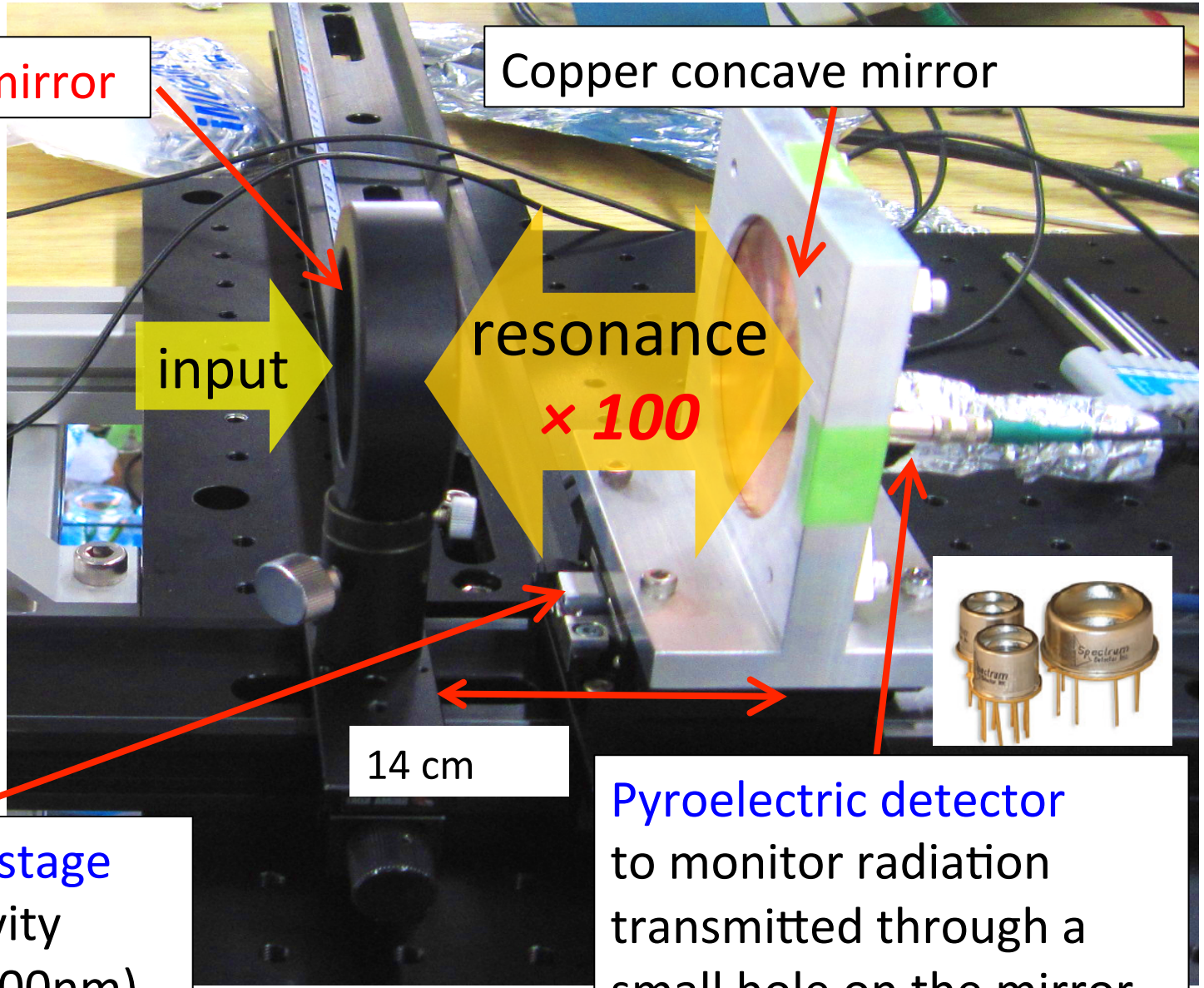
Gyrotron oscillator

- Gyrotron is a very high power terahertz-wave source developed to ignite the nuclear fusion.
- Electrons in cyclotron motion under a magnetic field (7.4T) resonates a cavity to extract terahertz-wave radiation. (cyclotron maser resonance)
- Linearly polarized gaussian beam is shaped by an internal mode converter.
- Over 100W, monochromatic (Δf=1MHz) and pulsed operation (duty ratio=30%)



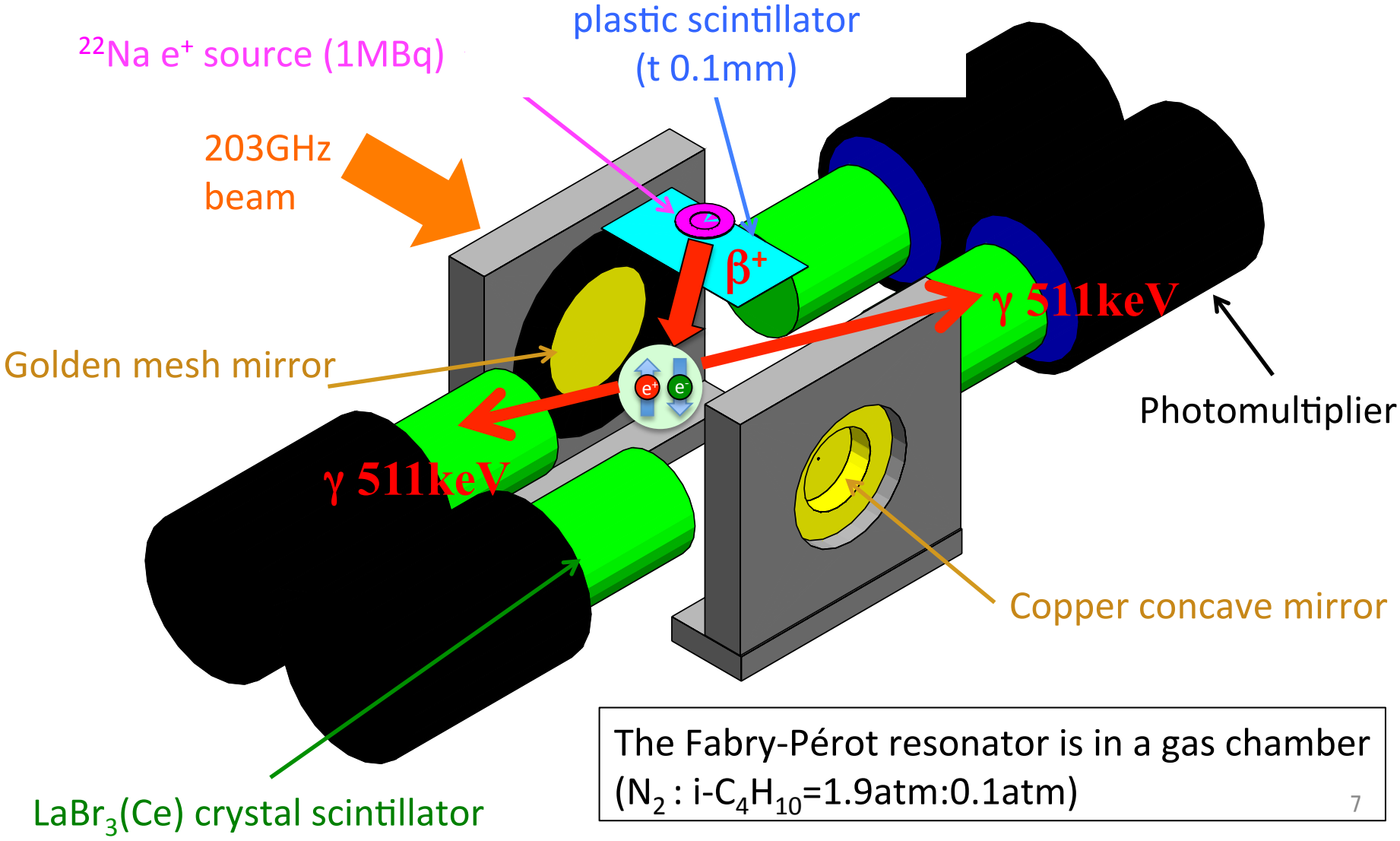


Fabry-Pérot cavity



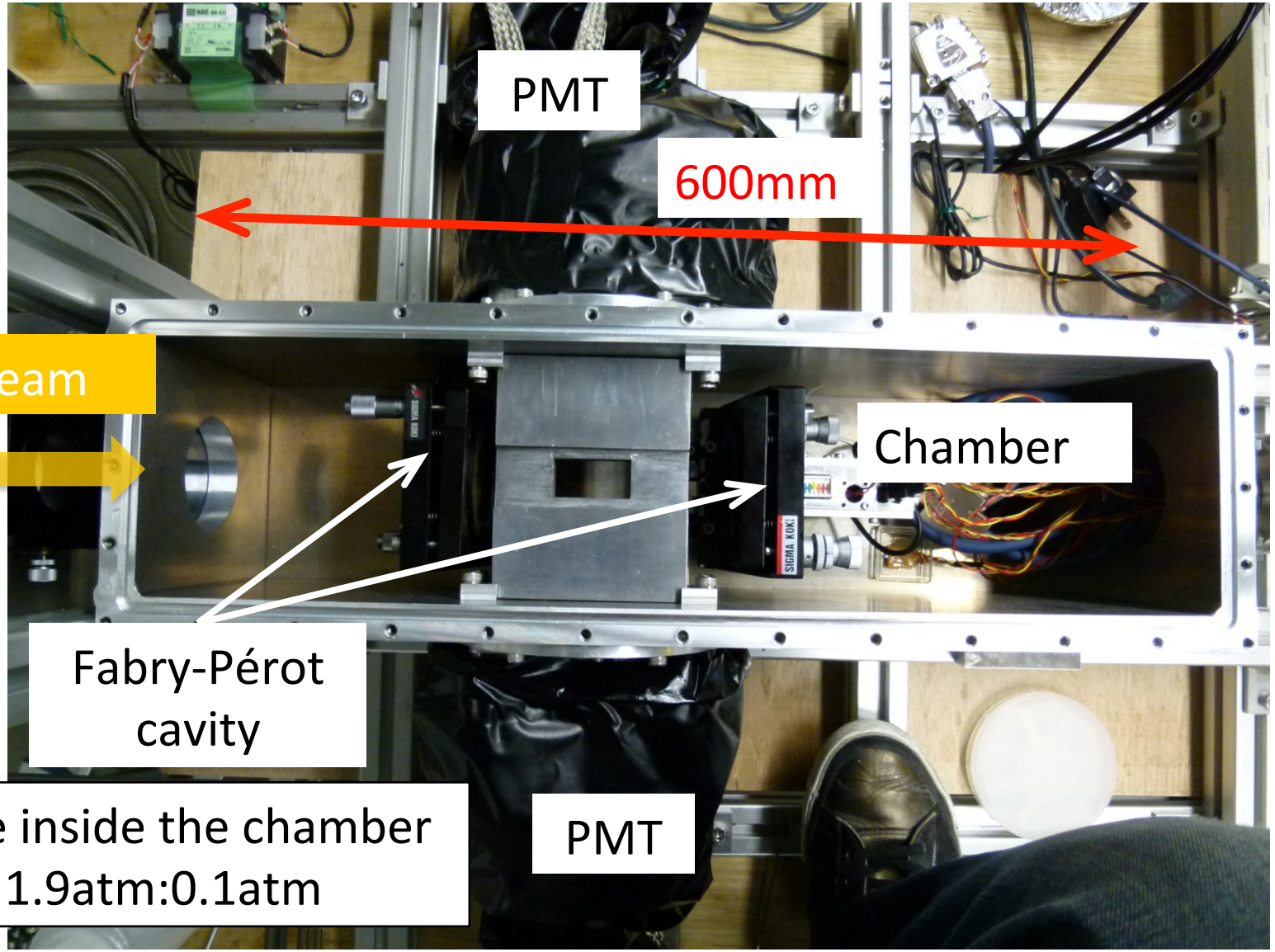
Positronium Assembly & γ-ray detectors

Positron from ^{22}Na forms o-Ps, which transits into p-Ps under 203GHz radiation.
$LaBr_3$ crystal scintillators detect decayed two γ-rays of back-to-back.



The Fabry-Pérot resonator is in a gas chamber
(N_2 : i-C_4H_{10}=1.9atm:0.1atm)

A Photograph of Ps-assembly & γ-ray detectors

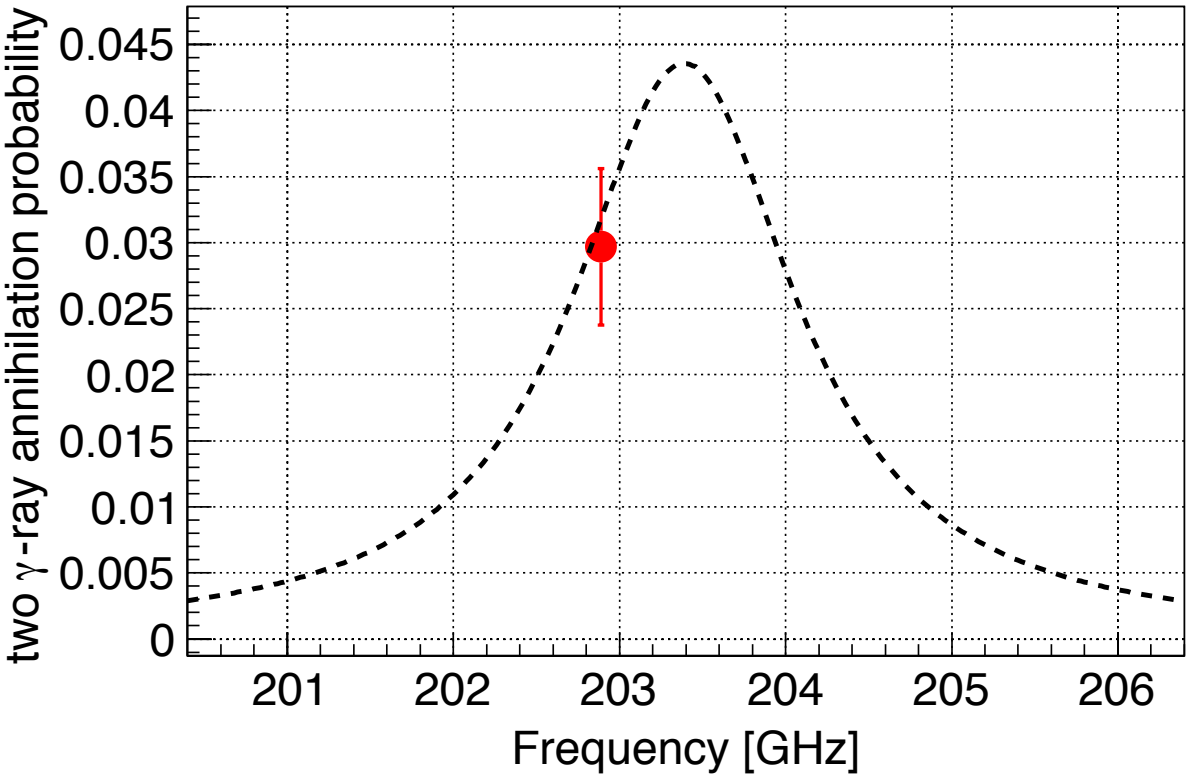


Gas mixture inside the chamber
N_2:i-C_4H_{10} = 1.9atm:0.1atm

Current result (transition @ 202.9 GHz with 10kW)

***Phys. Rev. Lett.* 108, 253401 (2012)**

We observed the direct transition at one frequency point.



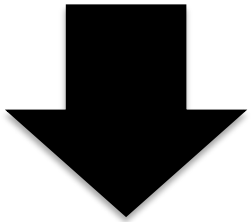
- **The direct transition is observed with significance of 5.4σ.**
- **The accuracy of the absolute power calibration of 203GHz radiation inside the Fabry-Pérot cavity is 30%.**

Next step for the Ps-HFS measurement

Problems of the current system:

i) The oscillation frequency of the gyrotron is fixed (202.9 GHz).

ii) Accumulated power in the Fabry-Pérot cavity is limited to 10 kW.

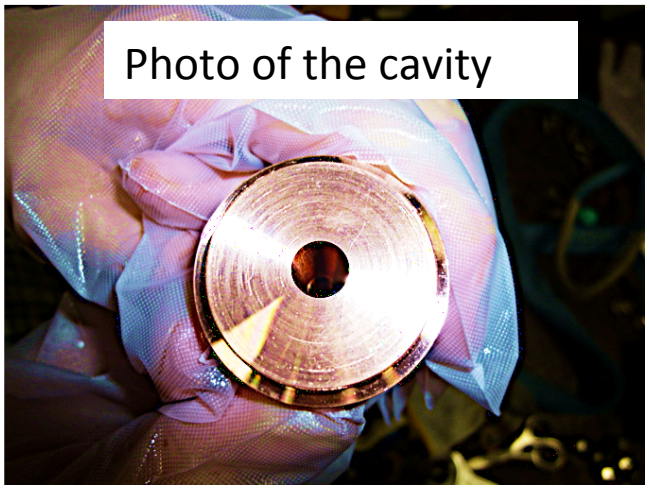


Our Solutions:

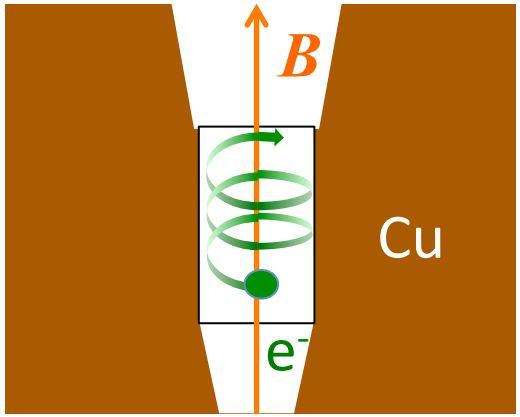
i) Replacing gyrotron cavities of different diameters to change the frequency.

ii) Developing a golden mesh mirror evaporated on silicon substrate.

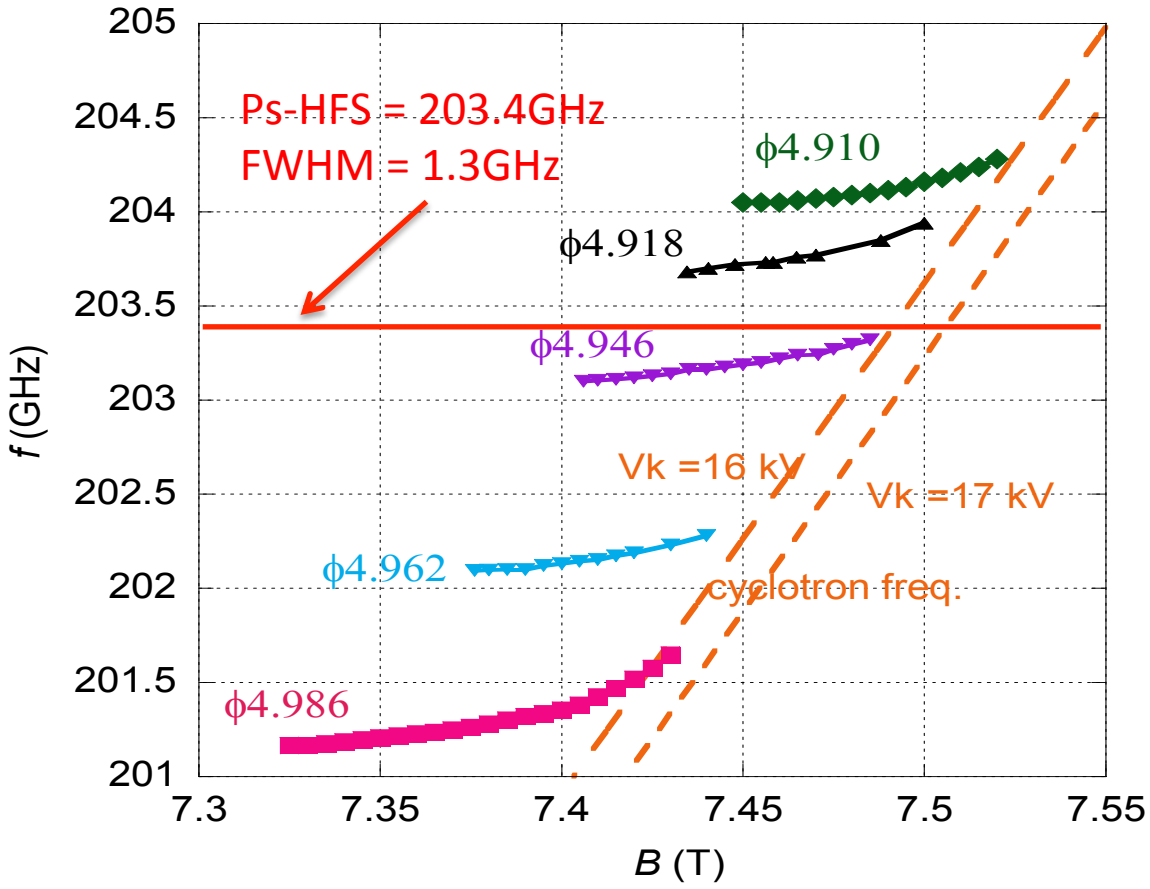
Gyrotron cavity & Frequency swept



Cross-section of the cavity

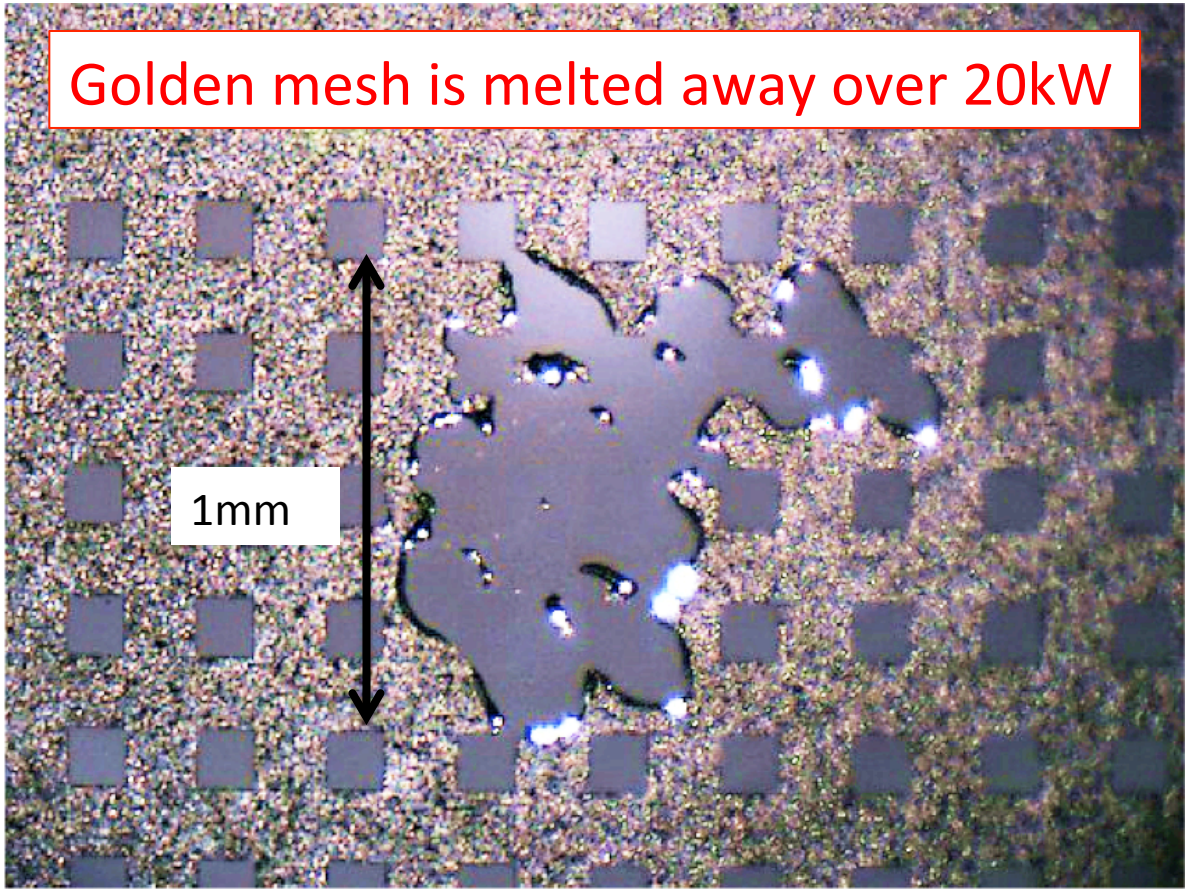


Oscillation frequency measured by heterodyne



- The cavity is waveguide-like resonator in which electron moves in cyclotron motion.
- The oscillation frequency is changed by different diameters of the cavity.
- We have already obtained all frequency points needed to measure Ps-HFS.

Power is limited by the golden mesh

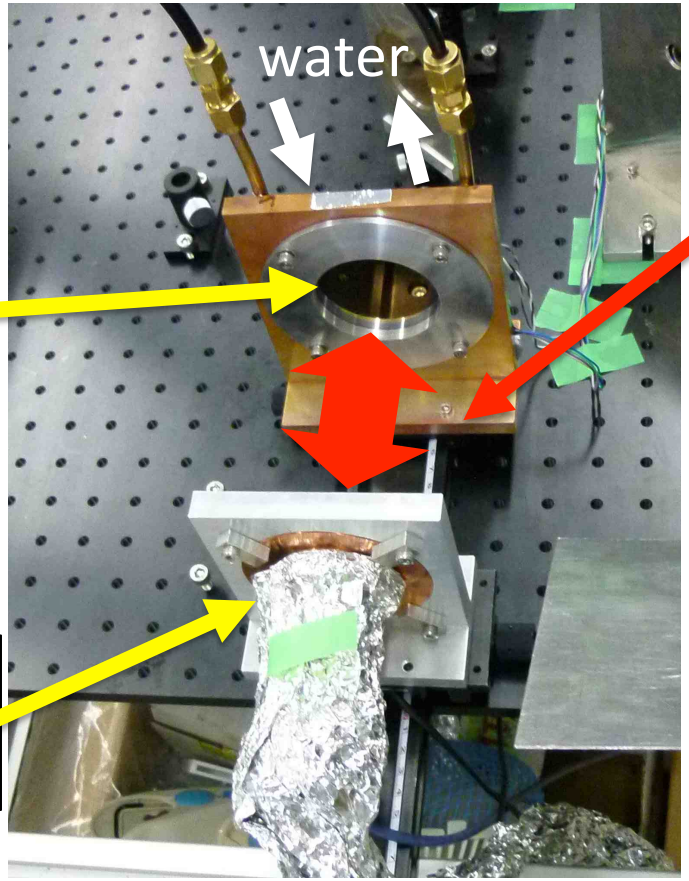


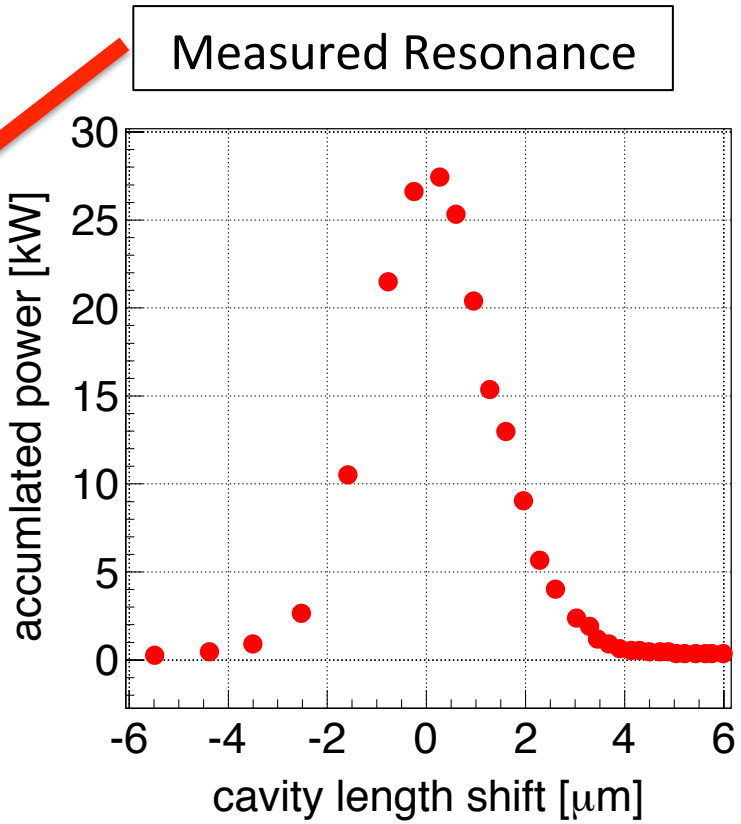
Previous golden mesh mirror was evaporated on a quartz (κ=5 $WK^{-1}m^{-1}$, very small !) substrate.

→Unable to be cooled with water

Fabry-Pérot resonator with water cooling

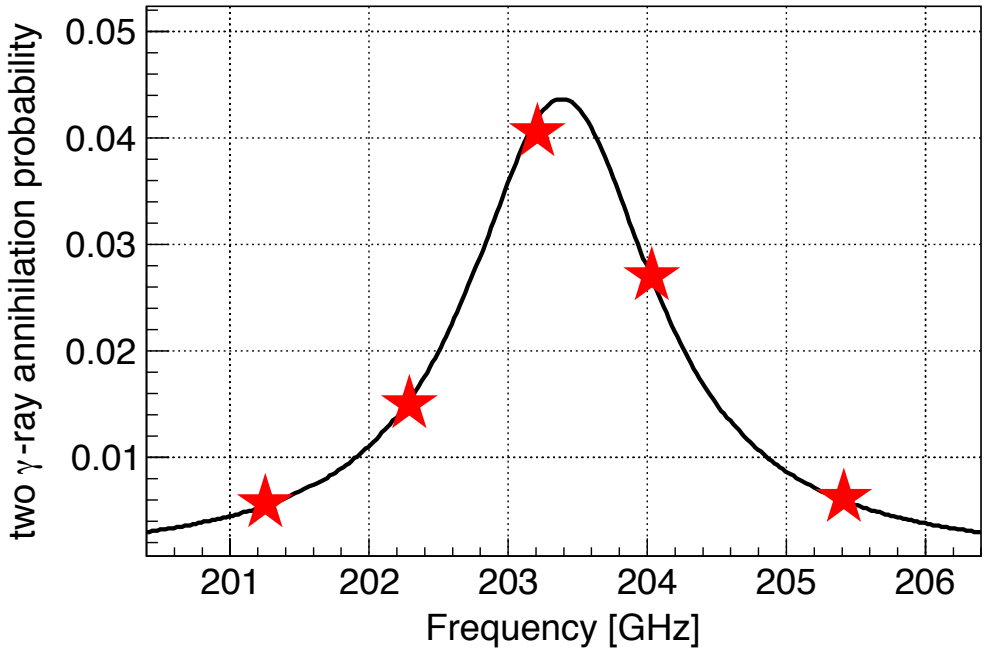
- High-resistance silicon (κ=150 $WK^{-1}m^{-1}$) is selected as a new substrate.
- The interference between silicon and the gold is carefully analyzed.





- Equivalent power of over 20 kW in the Fabry-Pérot cavity is obtained.
- Water cooling works very well.

Future prospects



- Within one year, the direct measurement of Ps-HFS will be firstly performed with accuracy of O(100) ppm.
  - The transition measurement for each one frequency point takes about one month.

- To study Ps-HFS discrepancy (15 ppm)
  - The accuracy of the relative power estimation of terahertz radiation should be less than 0.3%. (*A technological challenge in the terahertz region*)
  - Statistic should be improved using a positron beam.
  - Positronium should be formed in vacuum to eliminate the systematic errors due to gas, such as a thermalization effect of positronium.

Summary

- There is a large discrepancy about Ps-HFS between previous measurements and a QED prediction.
- We present direct measurements using sub-THz technology as a possible solution in the future.
- A direct transition from o-Ps to p-Ps is firstly observed with a gyrotron and a Fabry-Pérot resonator.
- Studies of frequency swept and higher power accumulation have been already finished.
- We will directly measure Ps-HFS value in about a year for the first time.