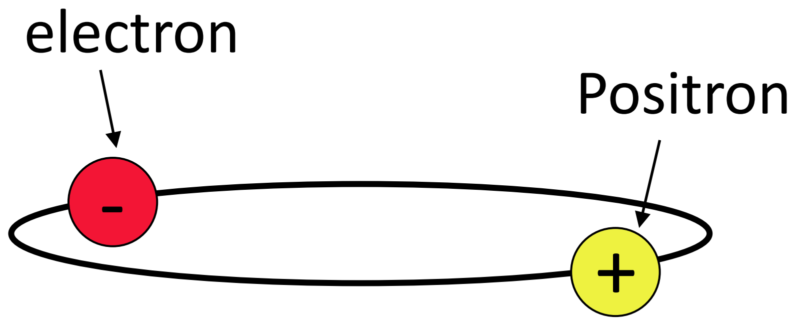
Sub-THz Spectroscopy of the Ground State Hyperfine Splitting of Positronium

T. Yamazaki[1], A. Miyazaki[1], T. Suehara[1], T. Namba[1], S. Asai[1], T. Kobayashi[1], H. Saito[2], Y. Tatematsu[3], I. Ogawa[3], T. Idehara[3]

[1]Graduate School of Science, and ICEPP, University of Tokyo
[2]Graduate School of Arts and Sciences, University of Tokyo
[3]Research Center for Development of Far-Infrared Region, University of Fukui

Positronium (Ps)

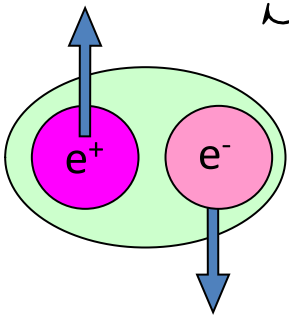


- Ps is the bound state of e^- and e^+ (e^+ is the antiparticle of e^-)
  - The lightest hydrogen-like atom
  - Unstable, particle-antiparticle system
  - Simple, good target to study bound state QED (Quantum ElectroDynamics)

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

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

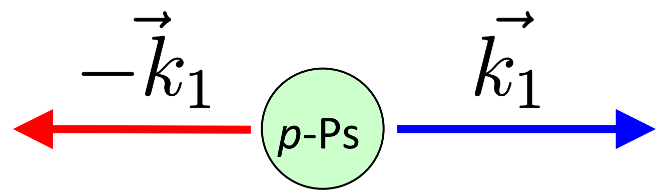
$S = 0$ Spin singlet



Short lifetime (0.125 nsec)

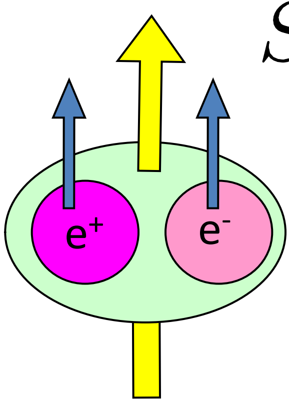
p-Ps → 2γ (, 4γ, ...)

511 keV (= electron mass) γ rays



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

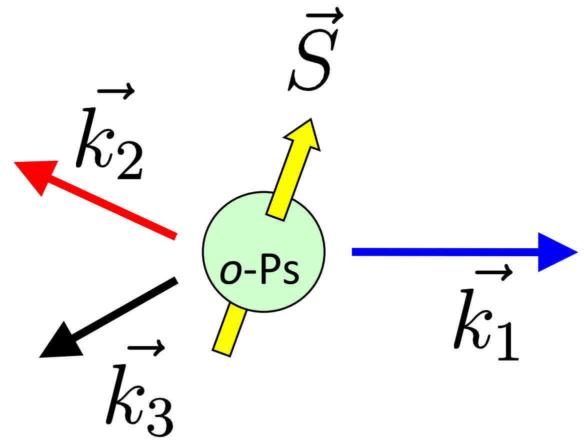
$S = 1$ Spin triplet



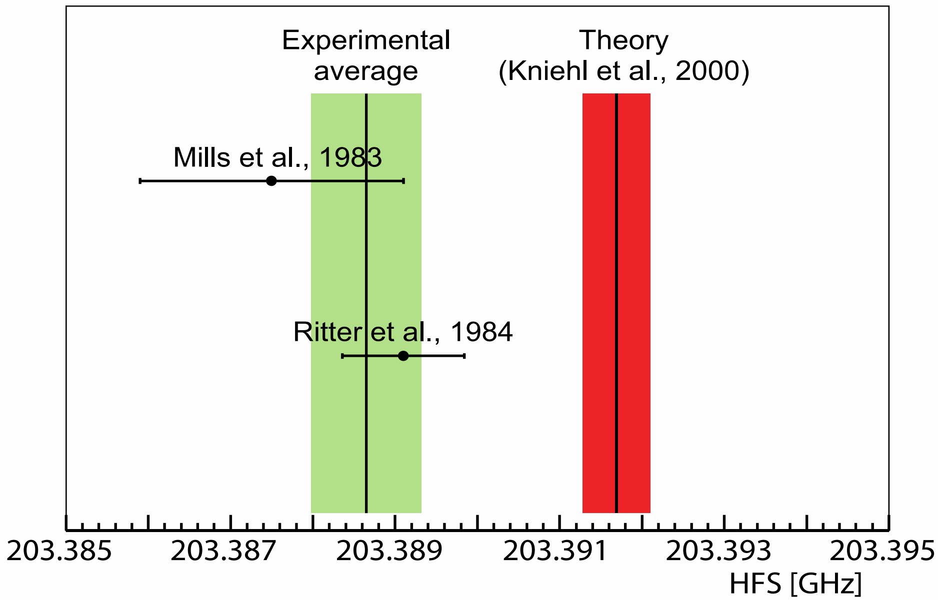
Long lifetime (142 nsec)

o-Ps → 3γ (, 5γ, ...)

Continuous energy spectrum



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



Exp.

203.388 65(67) GHz (3.3 ppm)

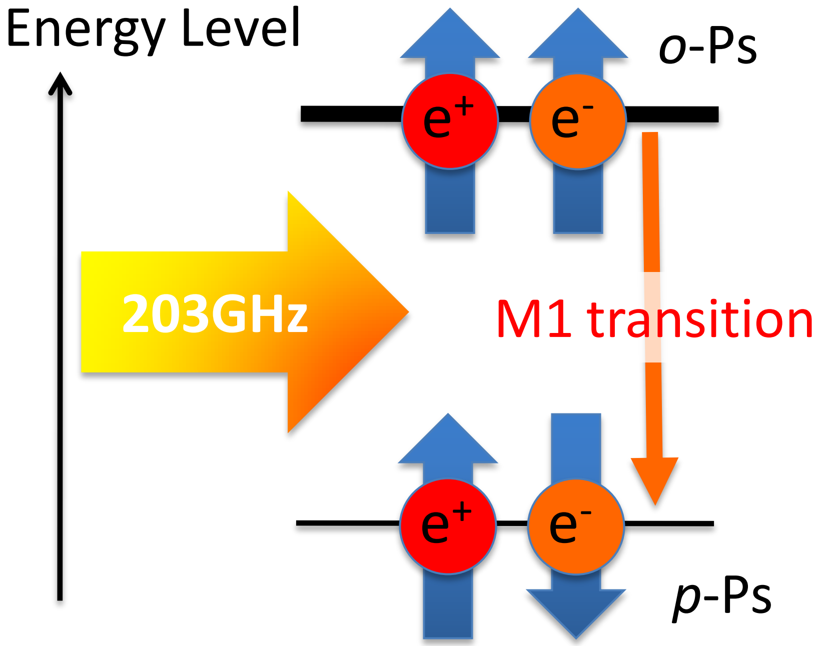
O(α^3) QED calc.

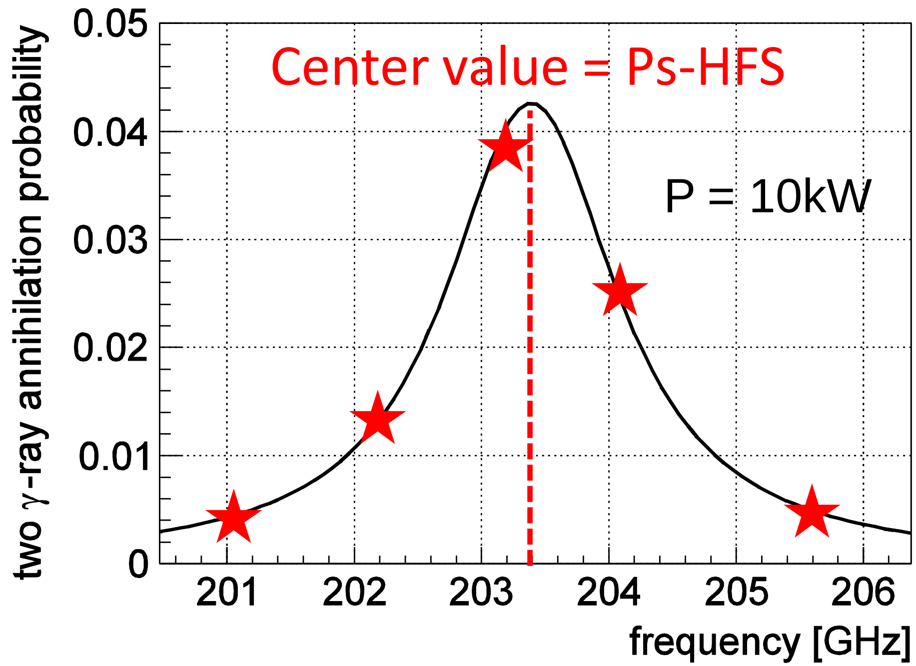
203.391 69(41) GHz (2.0 ppm)

- 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.

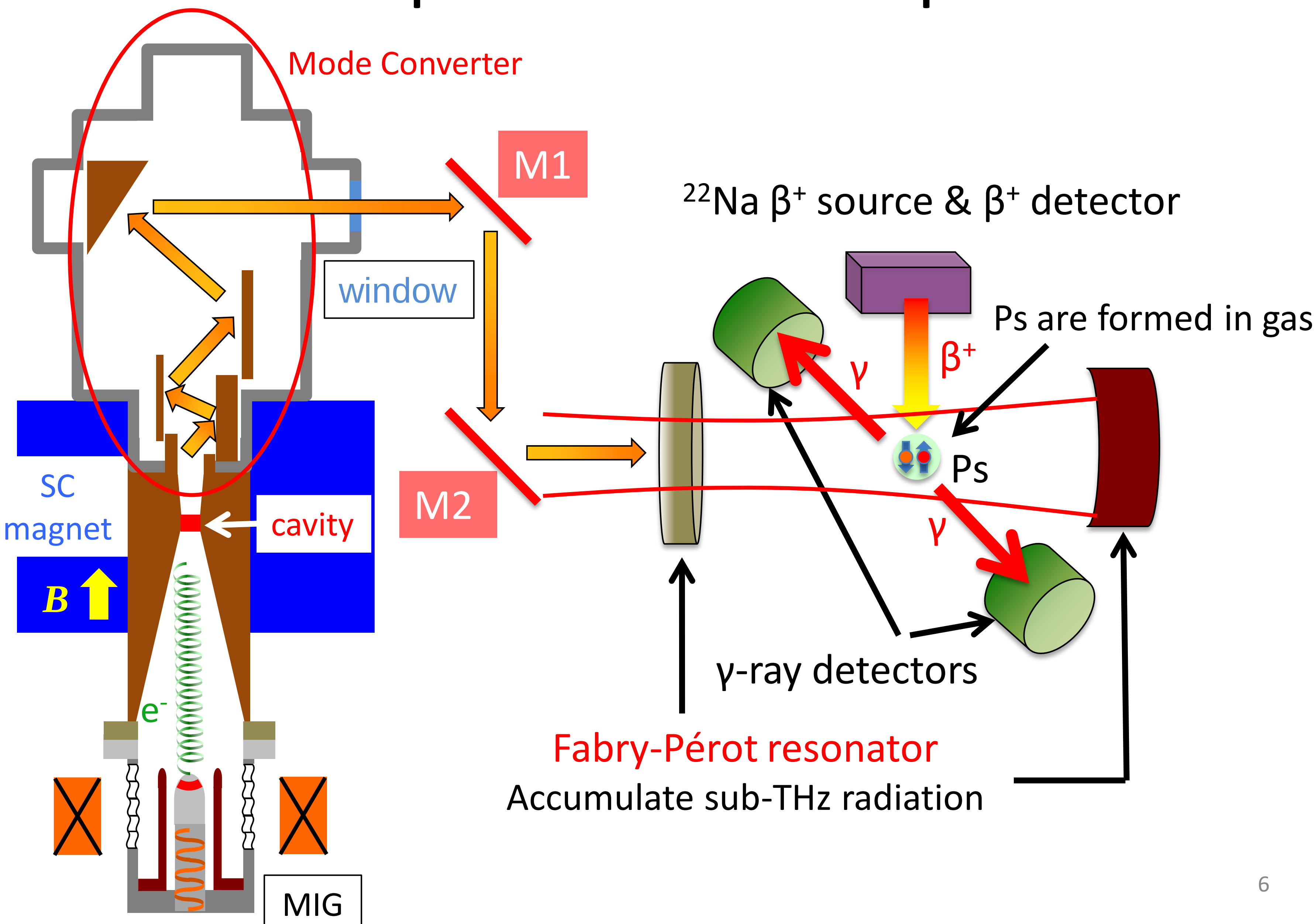
First Direct Measurement of Ps-HFS with New Sub-THz Technique





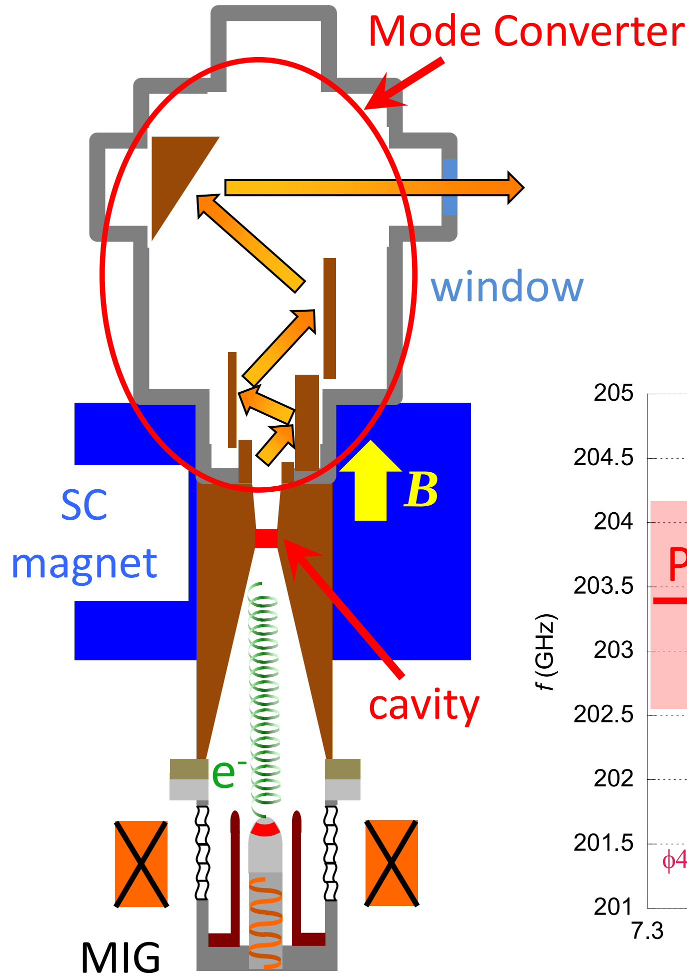
- Drive stimulated emission from *o*-Ps to *p*-Ps using 203 GHz radiation.
- Since *p*-Ps decays into 2γ promptly (125 ps), 2γ annihilation increases when Ps are exposed to 203 GHz radiation.
- The natural transition rate is 10^{14} times smaller than decay rate of *o*-Ps. High power (> 10kW) sub-THz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

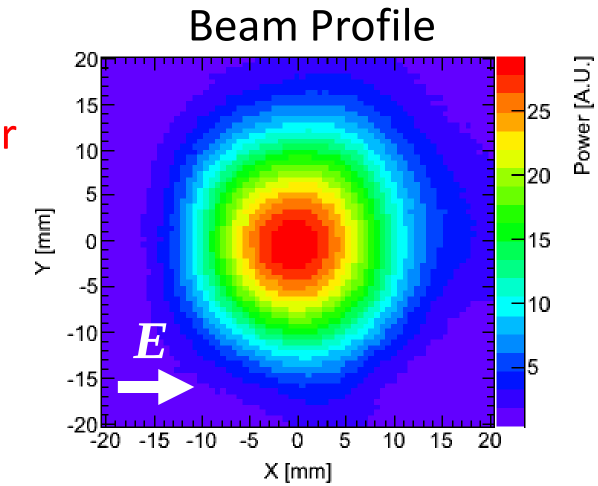
Experimental Setup

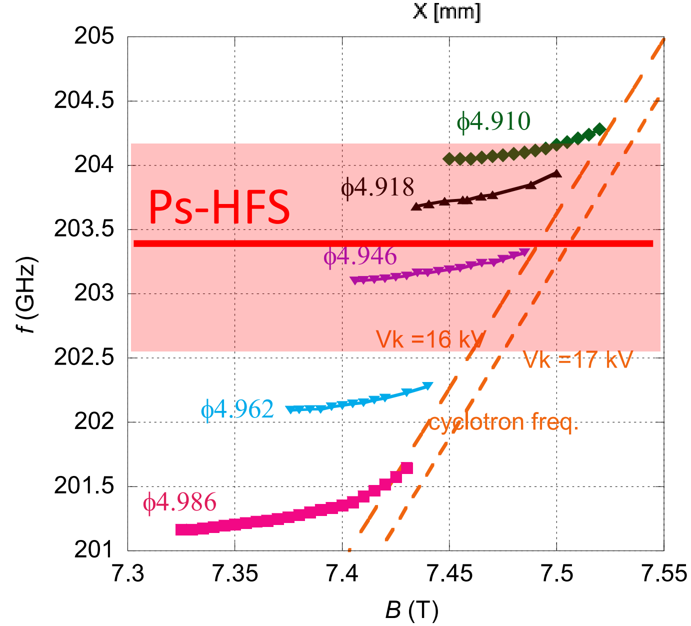


Gyrotron “FU CW GI”

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

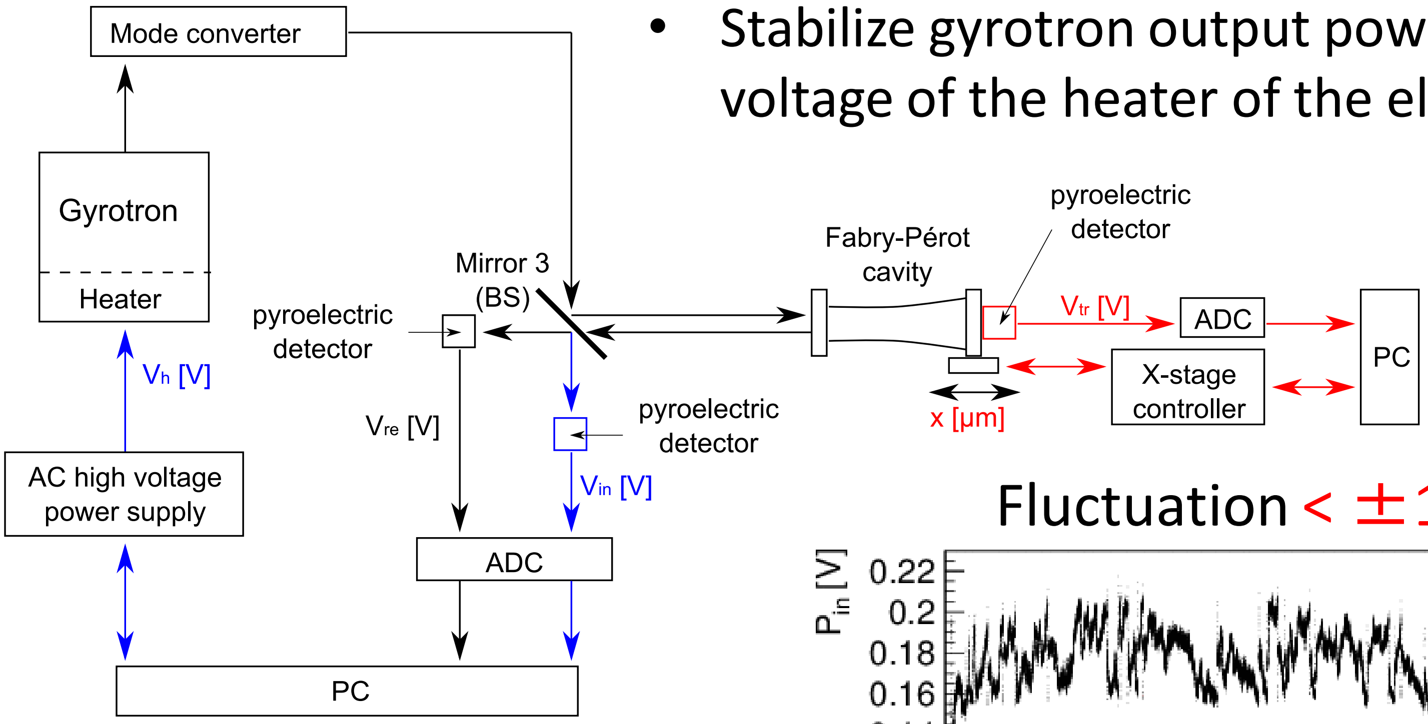




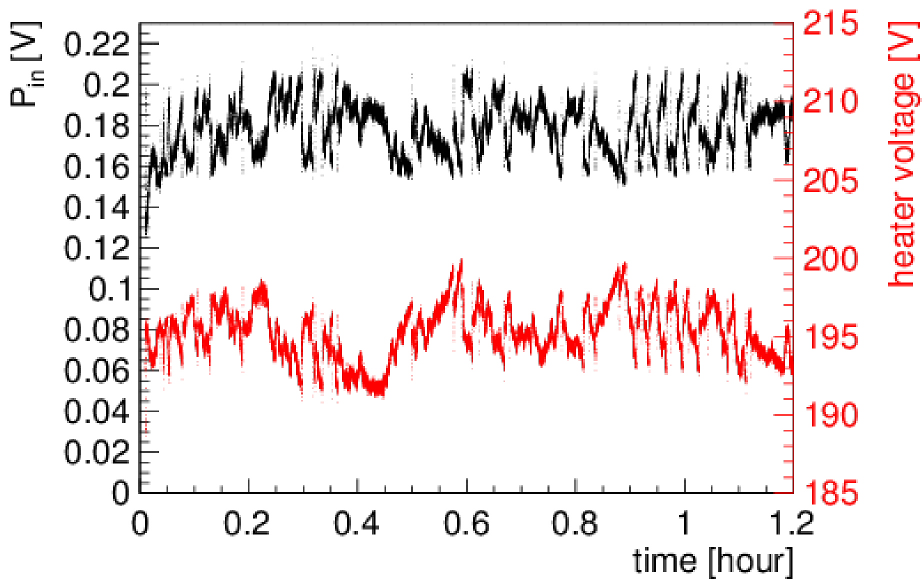


Feedback Stabilization

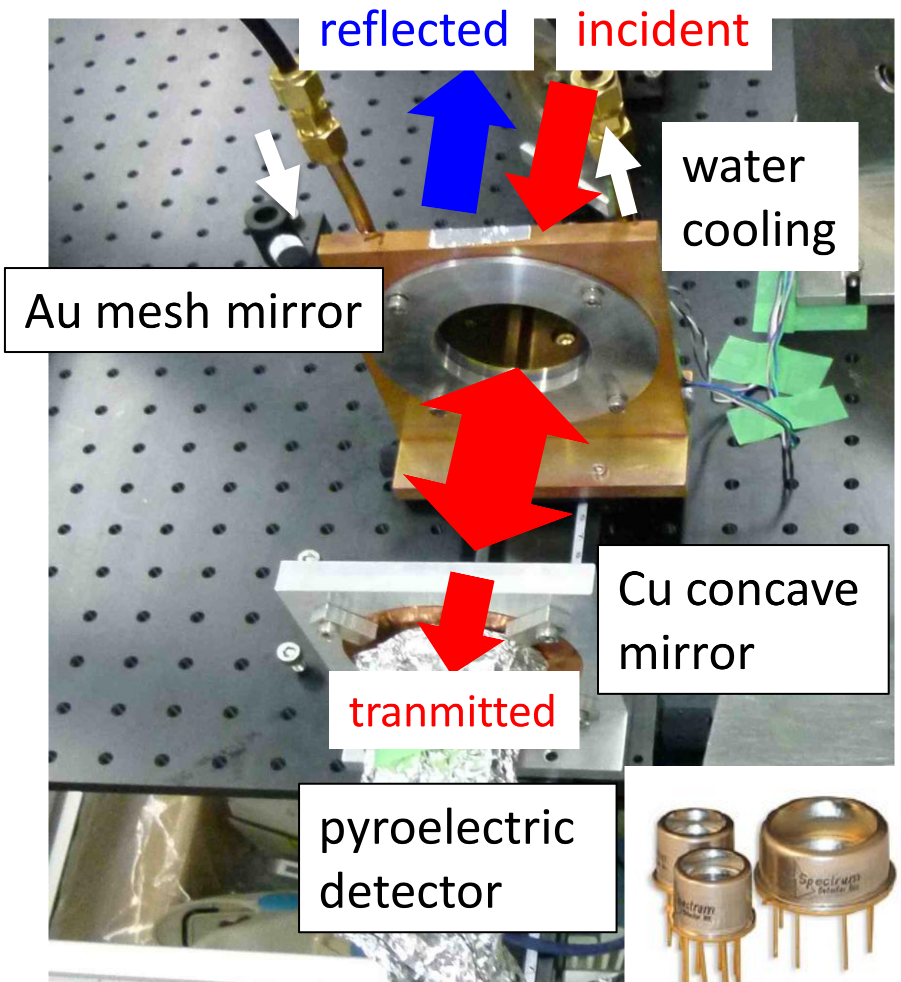
- Stabilize gyrotron output power by controlling voltage of the heater of the electron gun

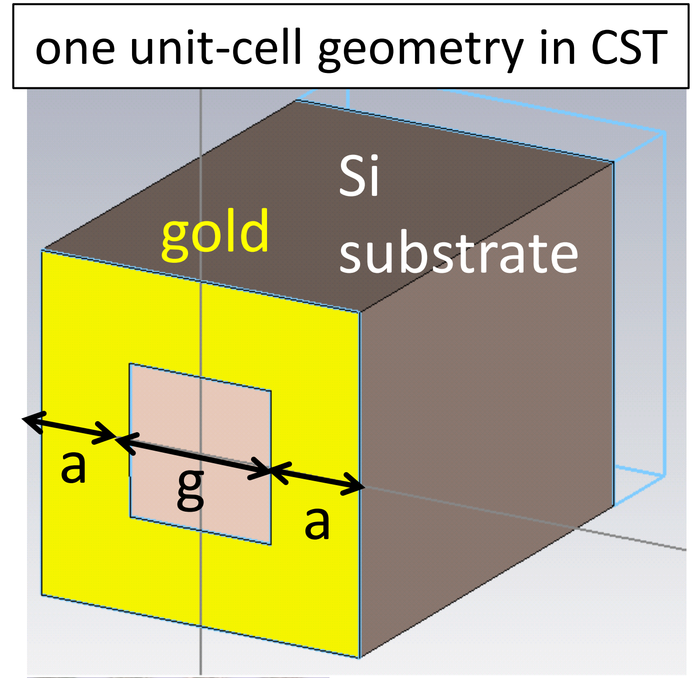


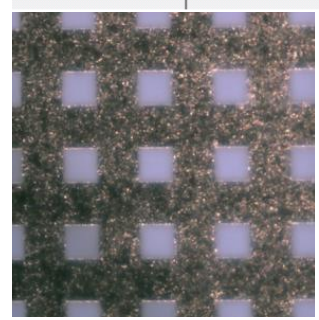
Fluctuation < ±10%



Fabry-Pérot Resonator



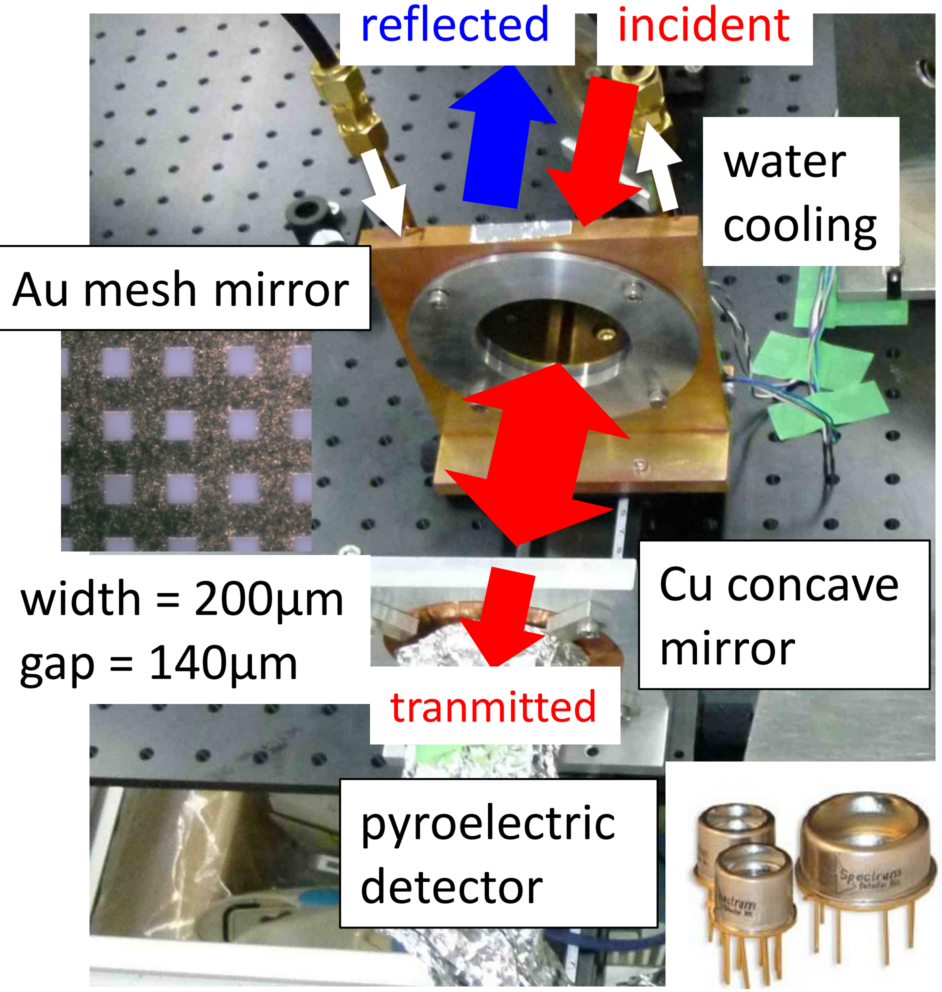


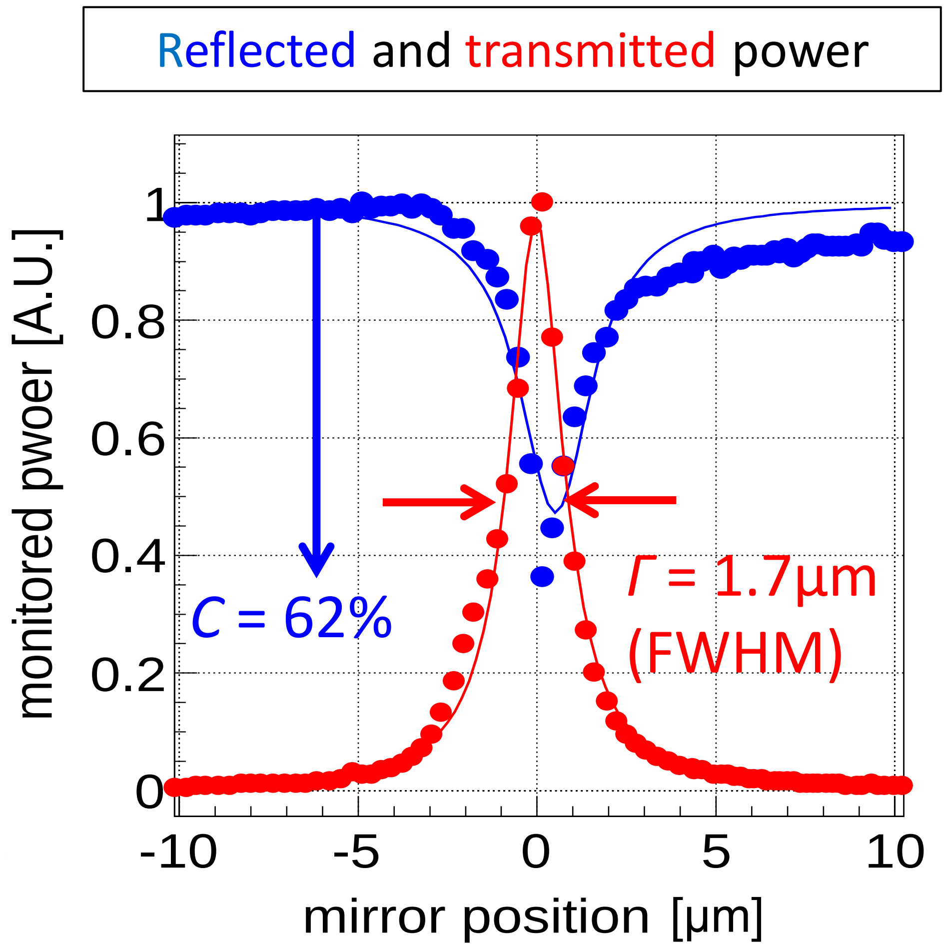


width : 2a = 200µm
gap : g = 140µm

- The mesh parameters were carefully optimized using CST MWS
  - Frequency domain analysis, periodic boundary condition
- From 201 to 205 GHz, Finesse > 400, and Coupling > 60%.

Fabry-Pérot Resonator

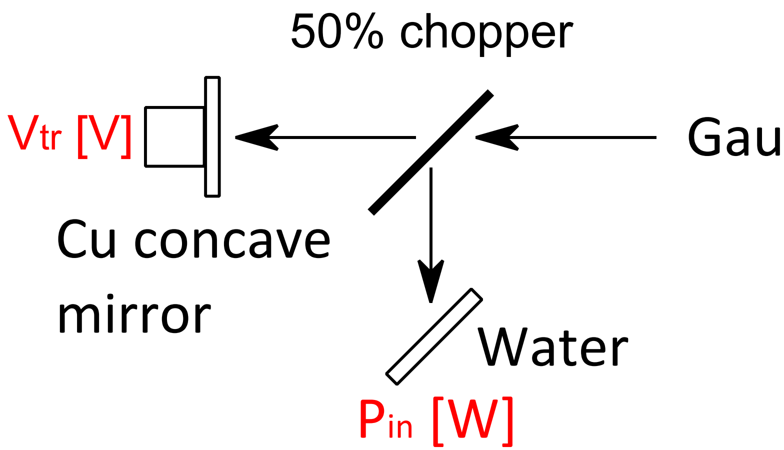




- Sharpness Γ = 1.7μm (Finesse = 430), and coupling C = 62%
  → Gain of the resonator is 85! (incident power ~ 300W)

Power Estimation

- We estimate accumulated power from transmitted power. Calibration constant from voltage of the pyroelectric detector to accumulated power is obtained as follows.



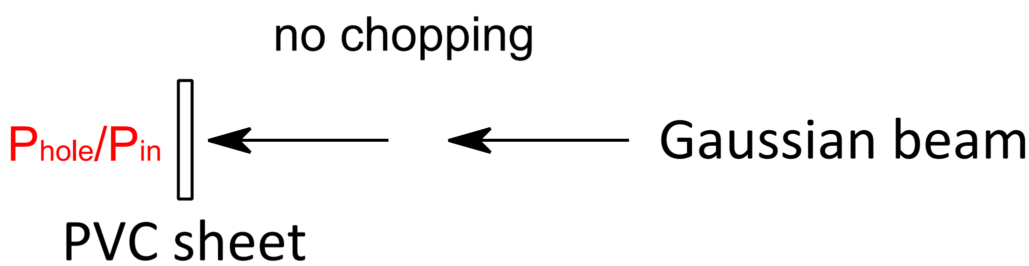
The Cu concave mirror and water are exposed to a Gaussian beam at the same time using beam chopper.

- A half of the beam is totally absorbed by water and its total power P_{in}[W] is estimated from its temperature increase.
- The other half of the beam is exposed to the Cu concave mirror and the transmitted power through ϕ0.6 hole V_{tr}[V] is measured with a pyroelectric detector.

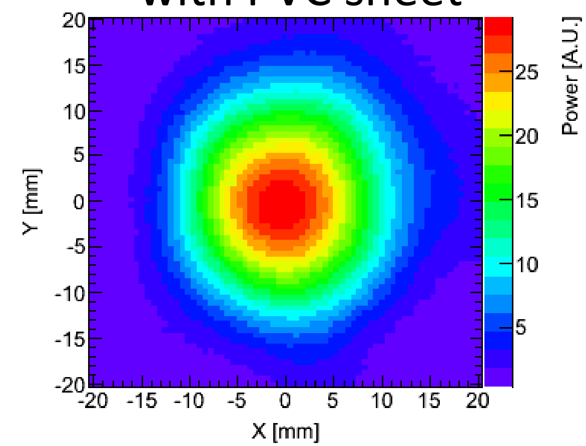
From this measurement, <u>the calibration constant for the Gaussian beam is obtained (P_{in}[W]/V_{tr}[V]),</u> but the beam shape is different from that in the Fabry-Pérot resonator.

Power Estimation

- In order to correct the difference, the beam shapes of the Gaussian beam at Cu mirror position is measured with PVC sheet. (P_{hole}/P_{in} is measured.)



Beam profile measured with PVC sheet

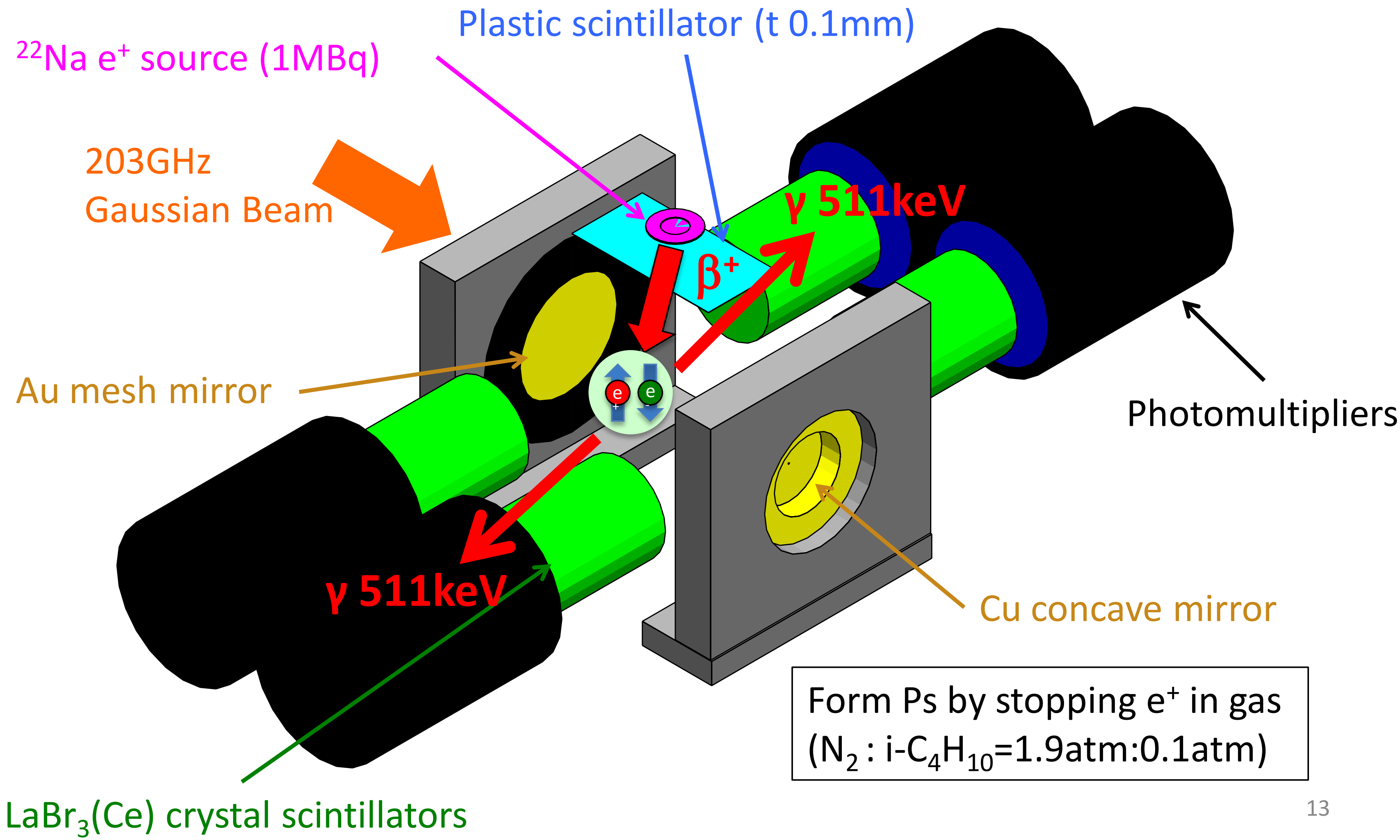


- The beam shape in the Fabry-Pérot resonator can be calculated. As a result, the calibration constant from V_{tr}[V] to P_{acc}[W] can be obtained.

- These measurements are performed every time we change gyrotron output frequency, and we monitor calibration constant during transition measurements.

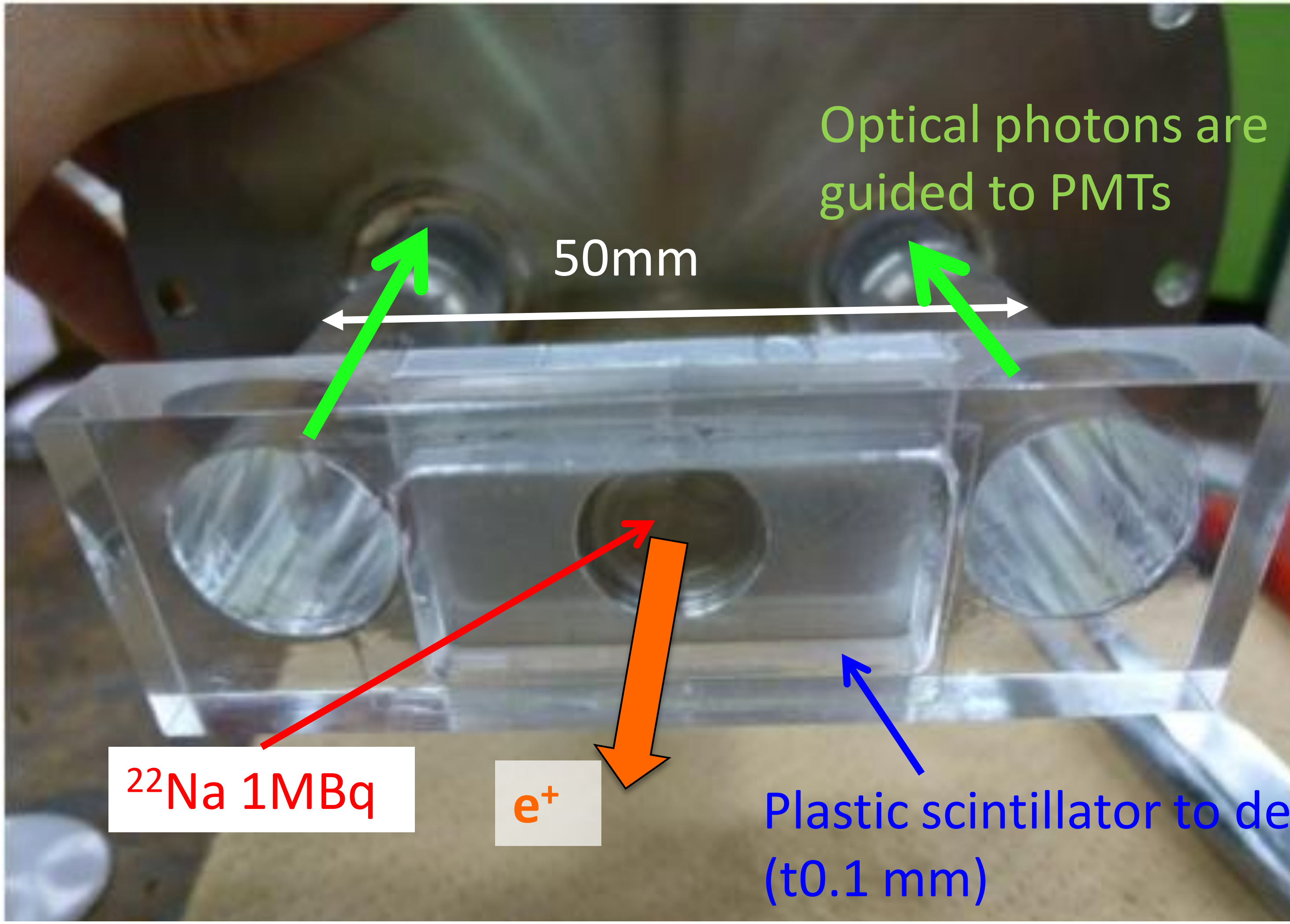
Ps Assembly and γ-ray detectors

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



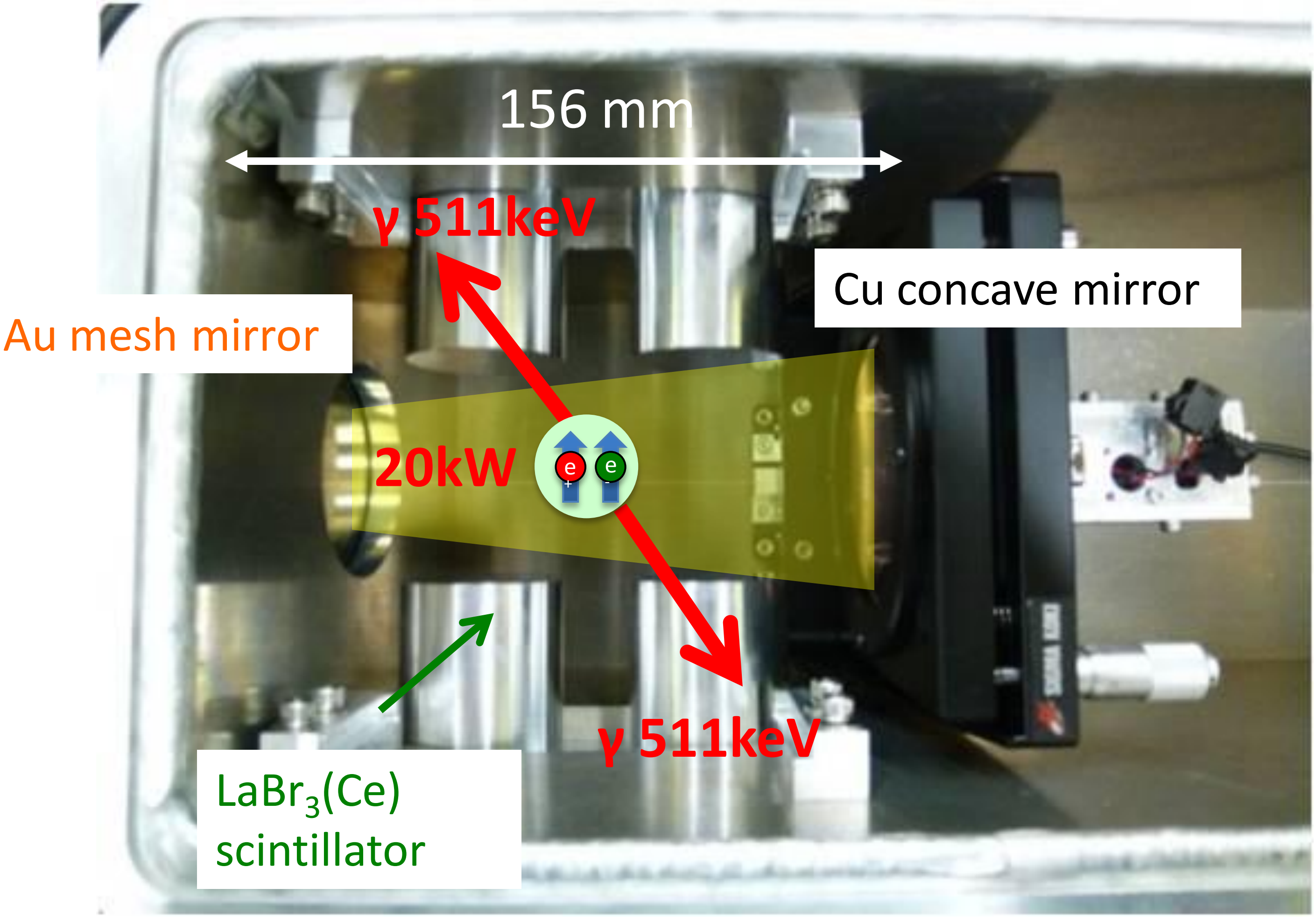
Form Ps by stopping e⁺ in gas (N_2 : i-C_4H_{10}=1.9atm:0.1atm)

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



- Optical photons are emitted when e^+ passes through a plastic scintillator, and they are measured with photomultipliers (PMTs).

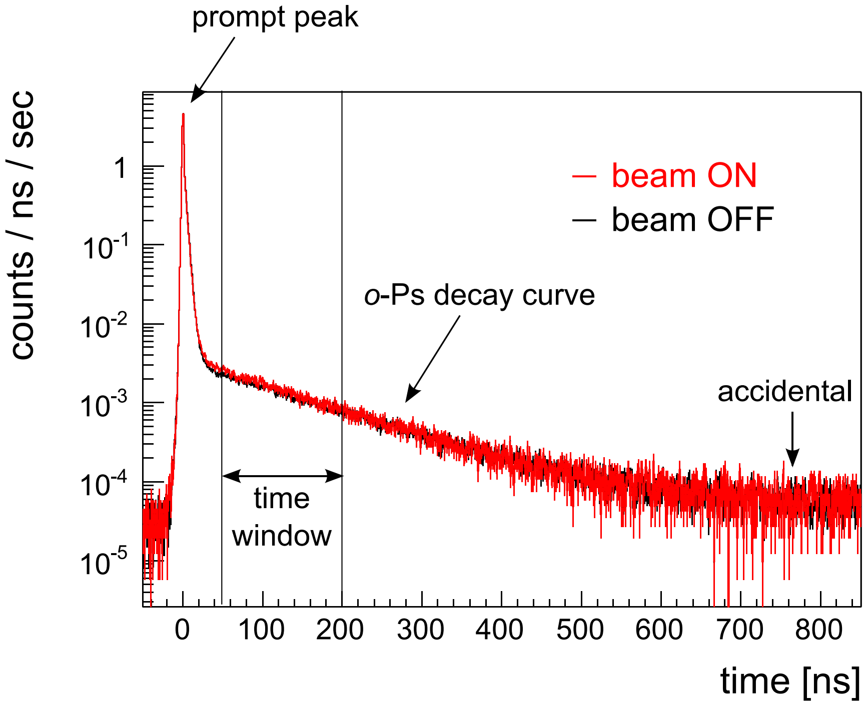
γ-ray detectors & Fabry-Pérot resonator

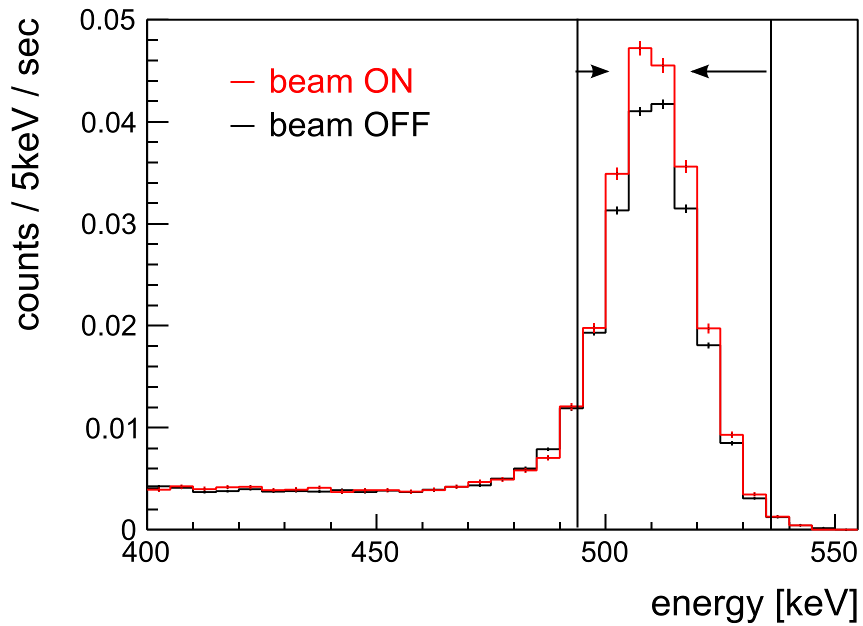


- Four γ-ray detectors are placed as near to high power radiation as possible in order to detect γ rays efficiently.

Ps-HFS transition@202.9GHz, 15kW

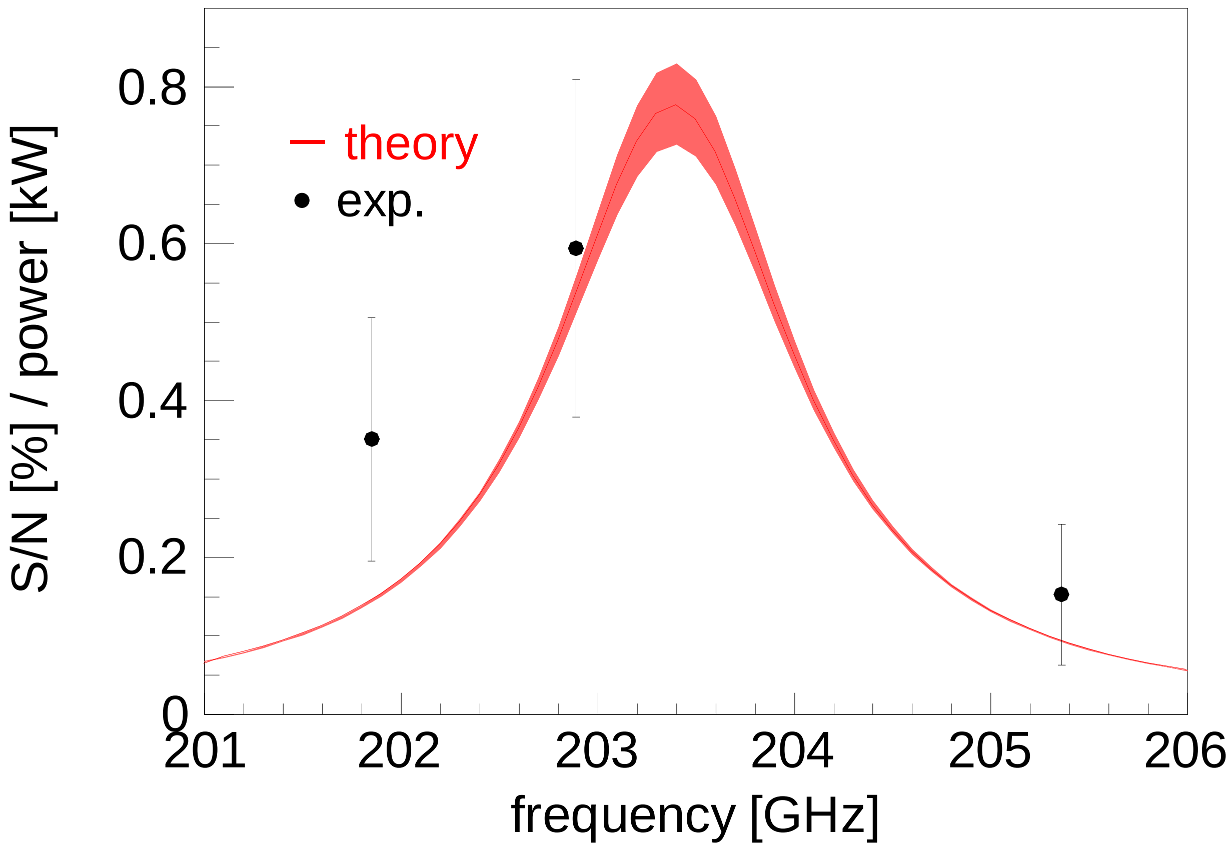
- A measurement at a frequency point takes about 3 weeks (2 weeks for preparation, 1 weeks for data acquisition)
- When Ps are exposed to 203 GHz radiation, *o*-Ps→3γ (tail at the left of 511keV peak) decrease and *o*-Ps(→*p*-Ps)→2γ (511keV peak) increase. The 511keV peak during beam OFF is due to *o*-Ps+e^-→2γ+e^-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





- S/N ＝ (ON ー OFF) / OFF ＝ 9.0±0.9 (stat.) ±1.4 (sys.)

Current Status (Preliminary)



- We have already measured transitions at 201.8 GHz, 202.9 GHz, and 205.3 GHz. The data points are consistent with the theoretical curve.
- We are going to measure at a few more points and obtain a transition curve. Then, we will be able to estimate Ps-HFS from its peak position.

Summary

- We plan to directly measure Ps-HFS (203.4 GHz) for the first time by developing new sub-THz technique.
- In order to measure transition curve of Ps-HFS, high power (>10 kW) and frequency tunability from 201 GHz to 206 GHz are necessary.
- Gyrotron “FU CW GI” is a demountable type gytoron and able to output all necessary frequency points by changing cavities with different sizes.
- A Fabry-Pérot resonator with a gold mesh mirror on high resistivity Si is able to accumulate 20 kW power without any damage on the gold mesh.

- We have already measured transitions at 201.8GHz, 202.9GHz and 205.3GHz. We are going to measure at a few more points in order to obtain a transition curve and estimate Ps-HFS from its peak position.