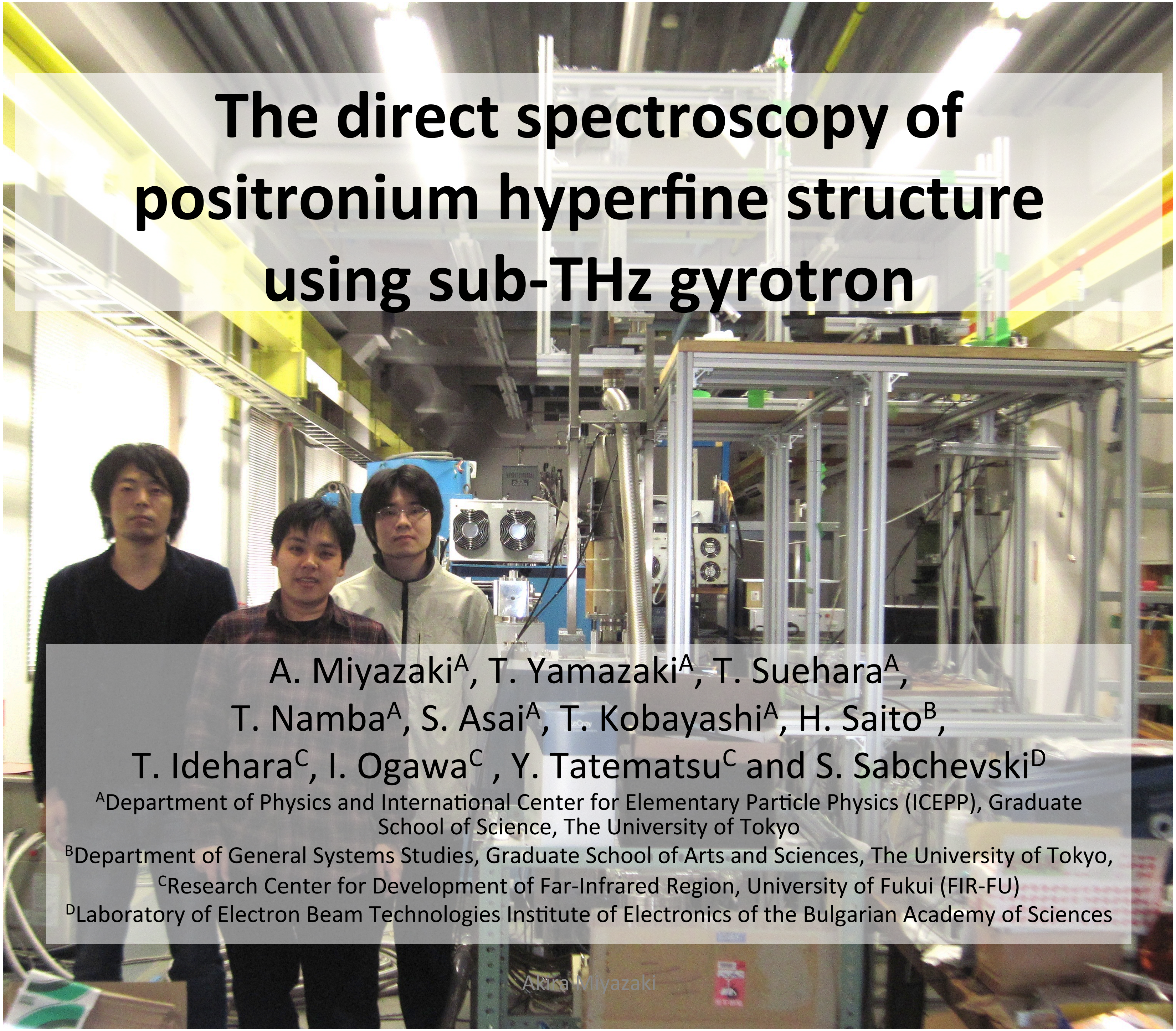
The direct spectroscopy of positronium hyperfine structure using sub-THz gyrotron



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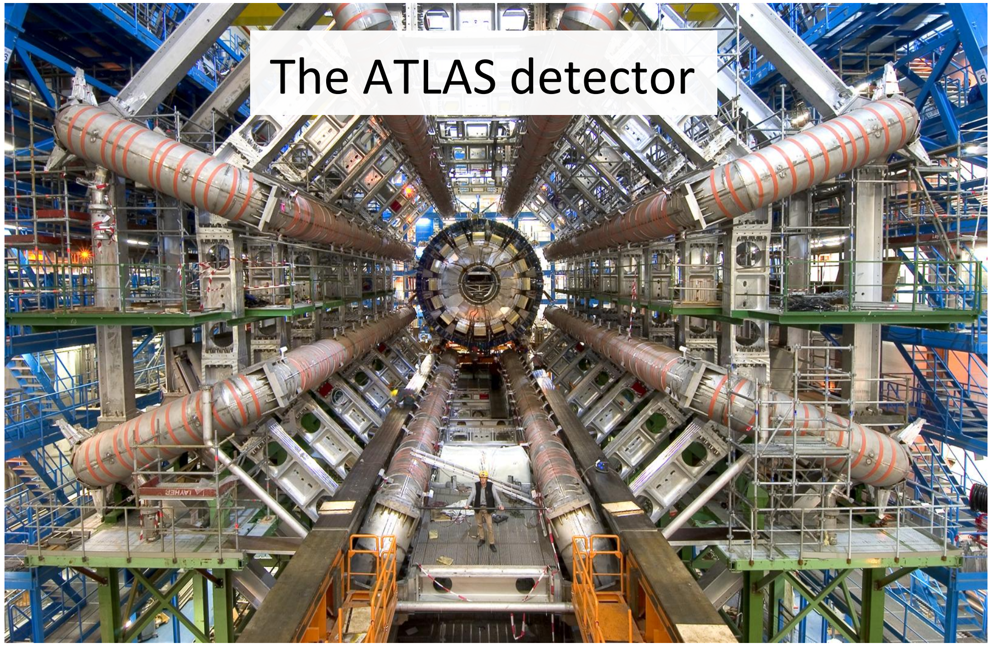
Introduction to Fundamental Physics with *New Light*

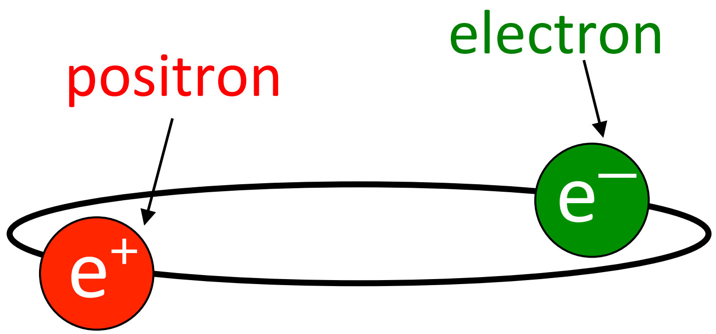


- We are experimentally studying elementary particles to understand the universe, to unify fundamental theories, or to discover new physics.
- Higgs boson was discovered by Large Hadron Collider with the ATLAS and CMS detectos in Genève this year.

- Instead of using high energy colliders, high intensity photon science is a complementary approach to study fundamental physics, such as new particles, structure of vacuum.

- *New light technology* (THz wave) has never been used for this purpose.
  → We are at the starting point of the new physics field!

Positronium (Ps)

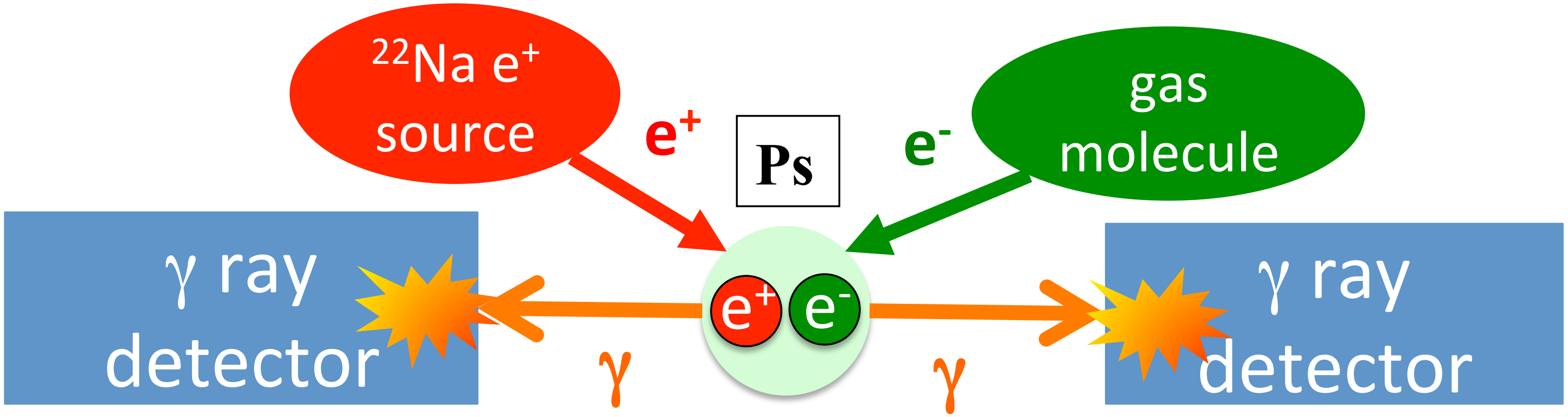


Ps is the bound state of e^- and e^+

- The lightest Hydrogen-like atom
- The simplest particle-antiparticle system
- Good target to study Quantum Electrodynamics (QED)

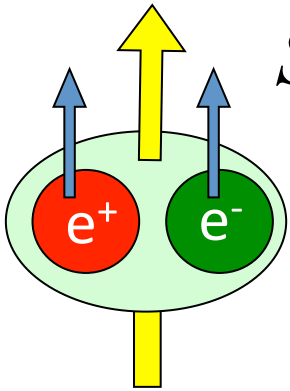
Oh…QED? Is Ps difficult to understand?

- Ps is easily formed by a positron emitted from Radioactive Isotope ^{22}Na and an electron in a material, especially a gas molecule.



- Since it is the system of particle-antiparticle, when they collide with each other Ps decays into some photons (γ rays) in finite lifetime.
- We can count the number of every single Ps with γ ray detectors.
- The number of annihilating γ rays depends on the spin.

Two spin-eigenstates of Ps



$\vec{S} = 1$ (Triplet)

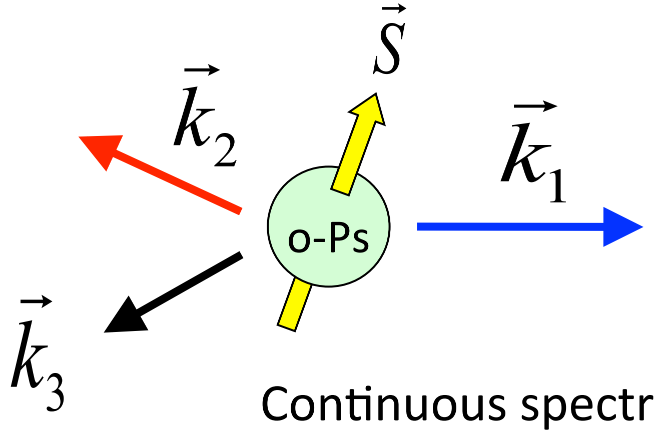
Ortho-positronium (o-Ps)

Spin=1 The same quantum number as photon

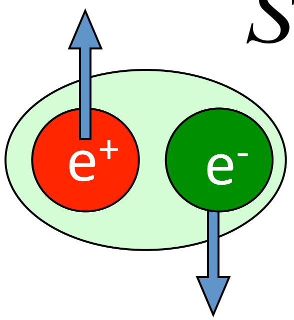
o-Ps → 3γ (, 5γ, ...)

o-Ps

Lifetime 142 ns



Continuous spectrum



$\vec{S} = 0$ (Singlet)

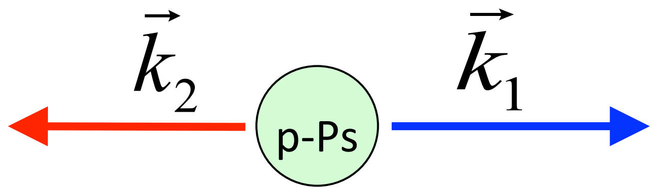
Para-positronium (p-Ps)

Spin=0 Scalar particle

p-Ps → 2γ (, 4γ, ...)

p-Ps

Lifetime 125 ps

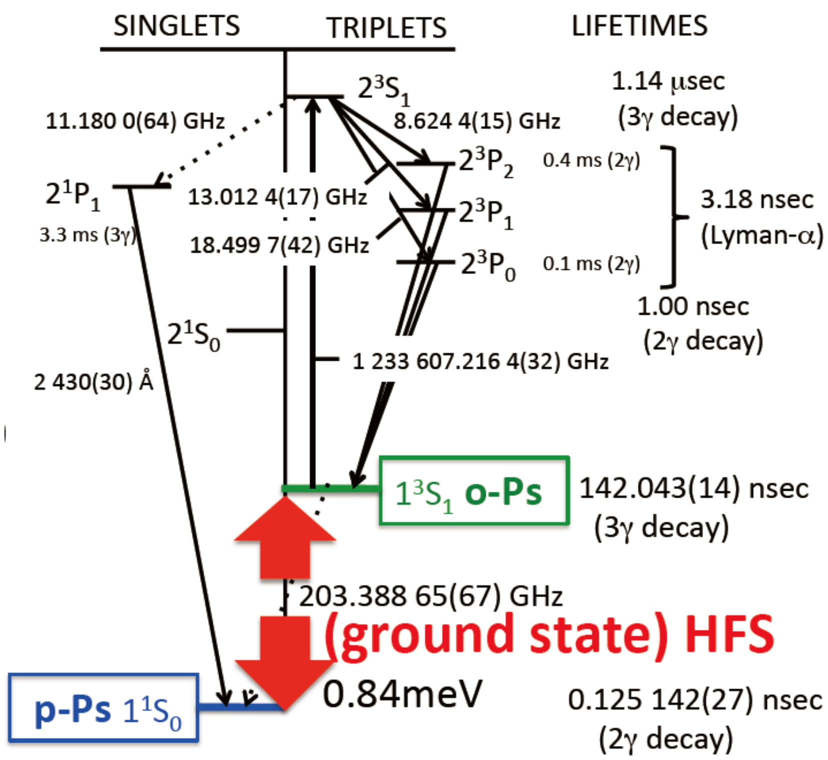


Monochromatic 511 keV

Positronium Hyperfine Splitting (Ps-HFS) & Problem

The energy difference between o-Ps and p-Ps; about 203GHz

triplet singlet



Large discrepancy of 3.9σ (15ppm) between theory and previous indirect measurements.

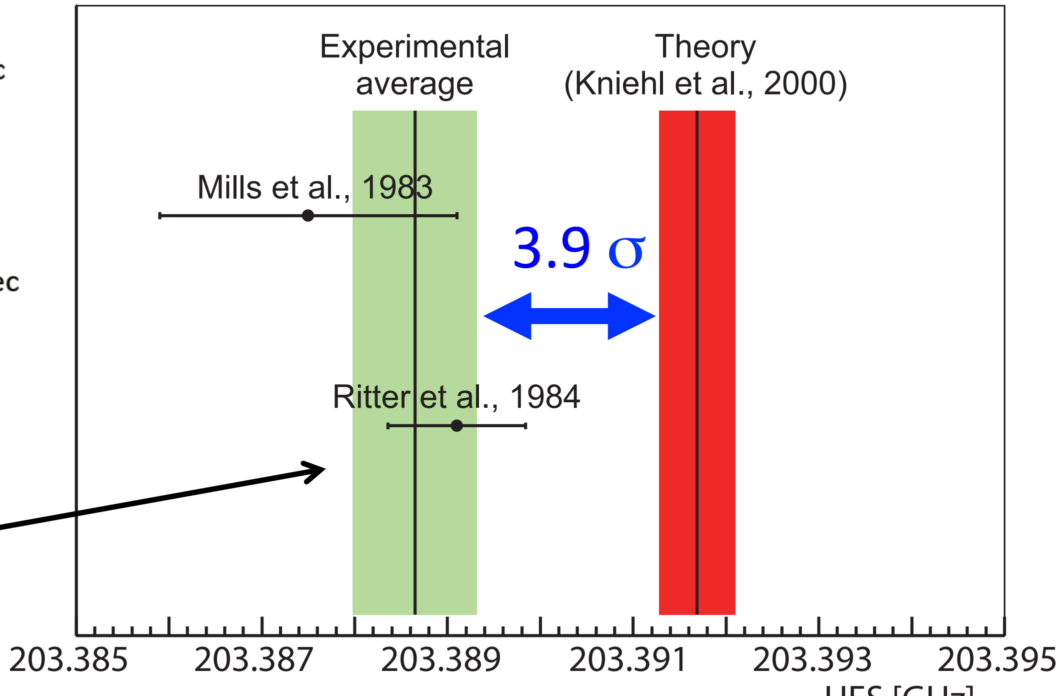
→The direct measurement is needed

Previous experiments :

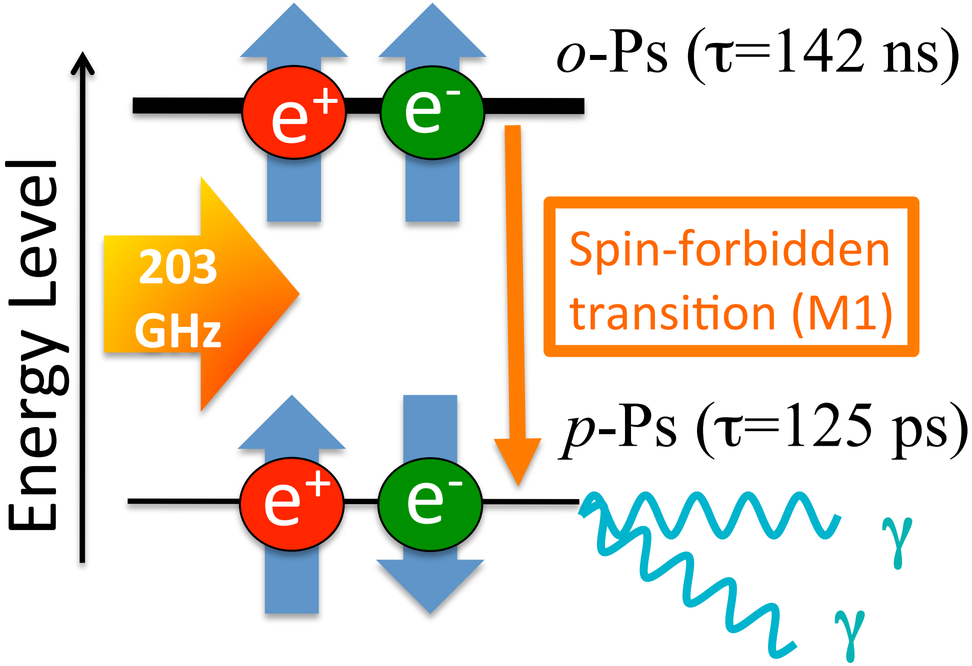
203.388 65(67) GHz (3.3 ppm)

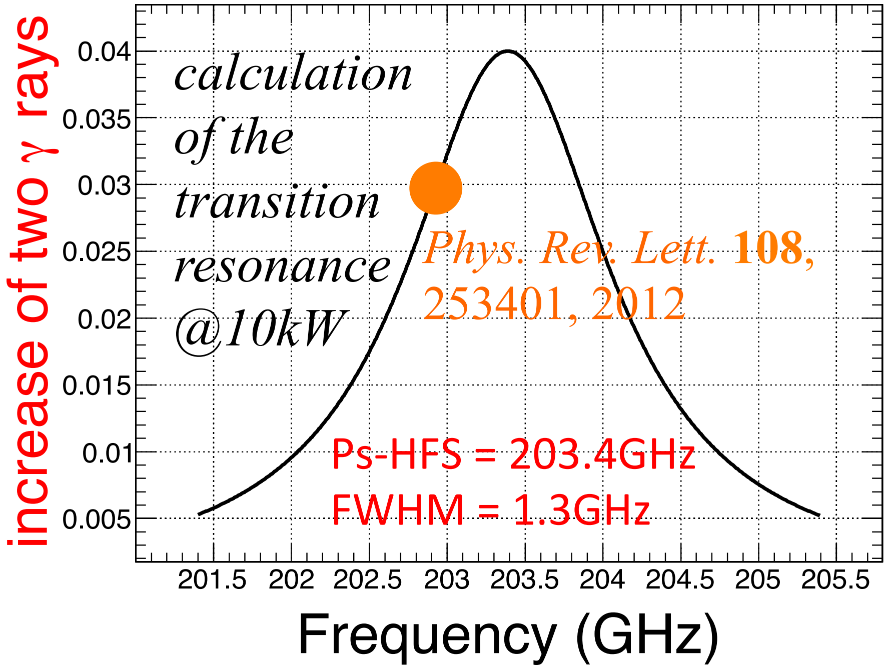
O(α^3) QED calculation :

203.391 69(41) GHz (2.0 ppm)



Direct Measurements of Ps-HFS



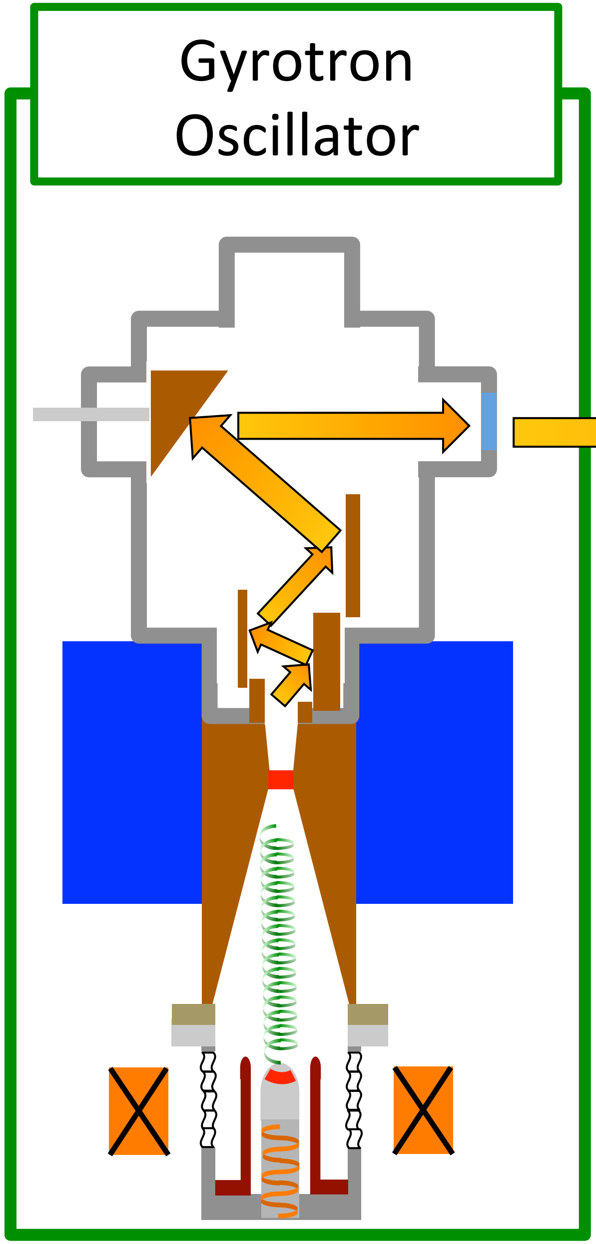


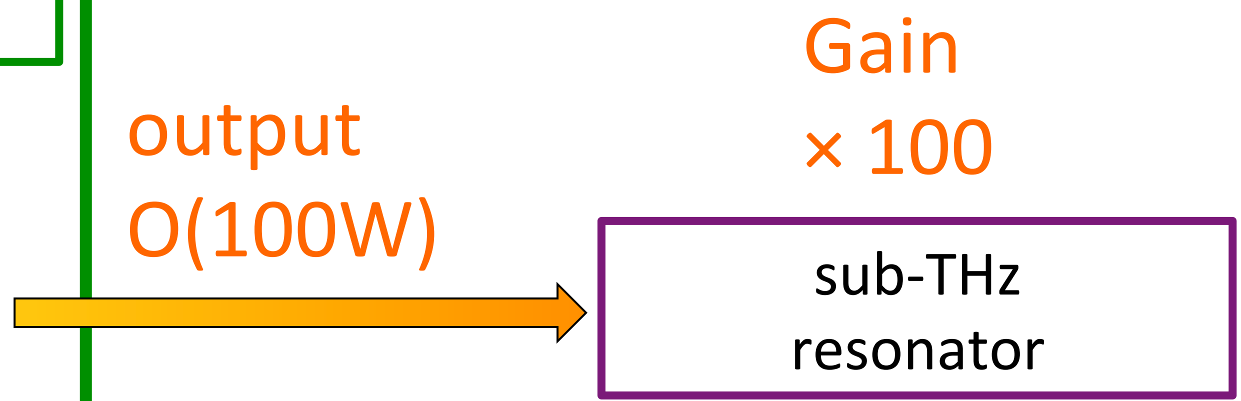
- 203GHz radiation drives the M1 transition from *o*-Ps to *p*-Ps, and the transiting *p*-Ps promptly(125 ps) decays into two γ rays.

→The transition is observed as an increase of two γ rays.

We need
- High power sub-THz radiation of O (10kW)
- Frequency tunability from 201 to 206 GHz

High power sub-THz optical system

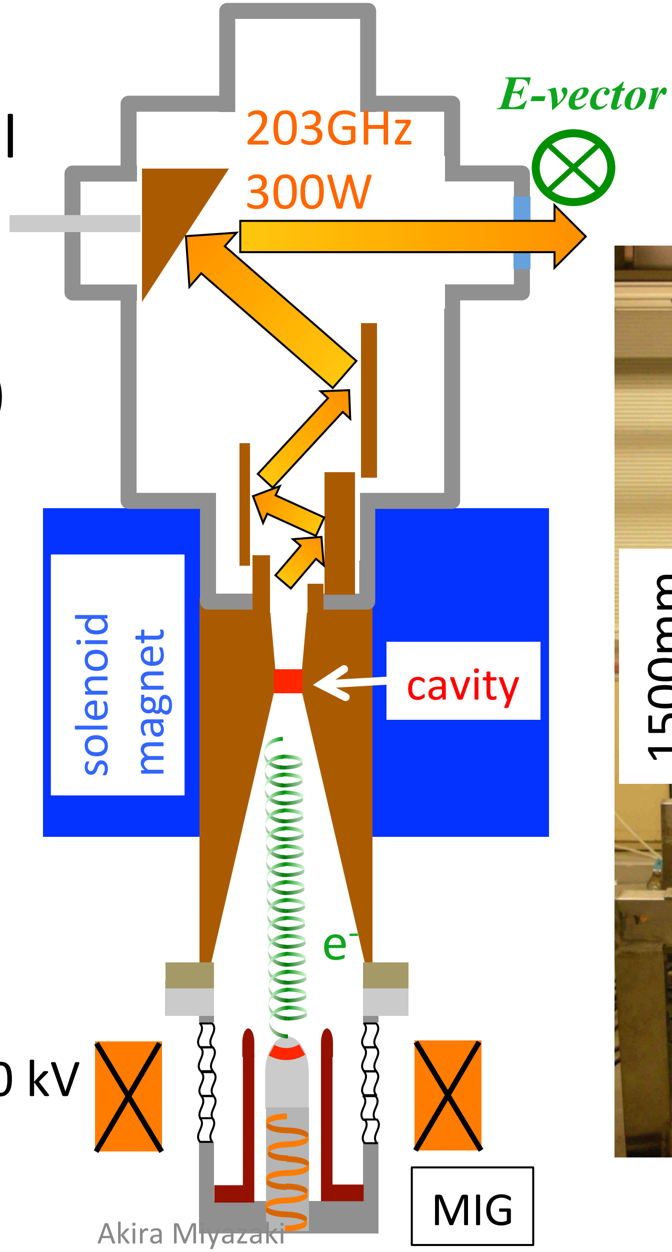




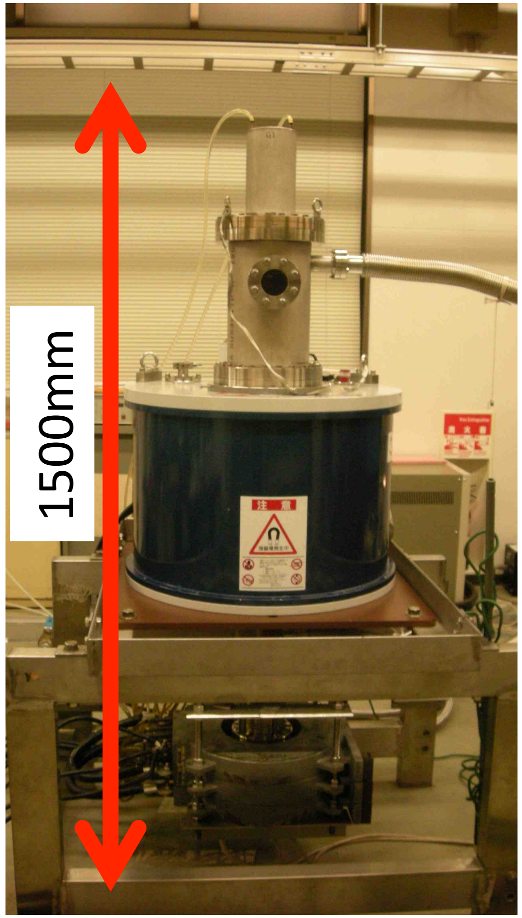
- We use gyrotron as a radiation source.
- A sub-THz resonator is needed to obtain O(10kW) equivalent power.
- *o*-Ps is formed inside the resonator and transits into *p*-Ps to decay into two γ rays.

Gyrotron oscillator

- A gyrotron with an internal Gaussian mode converter.
- Output power of 300W, monochromatic (Δf=1MHz) and pulsed operation (DR=30%, RR=5Hz)
- The frequency is changed by replacing the cavity with different diameters.

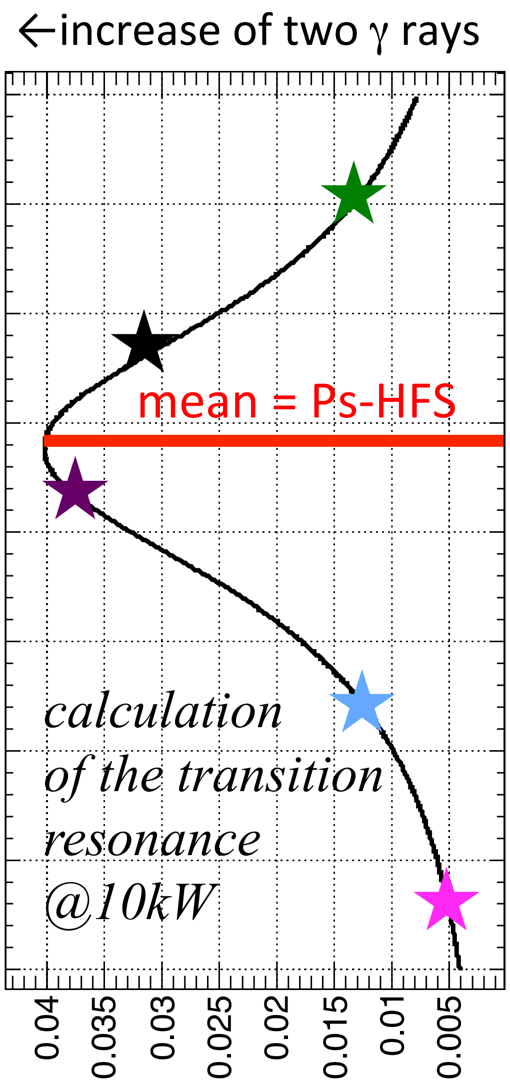


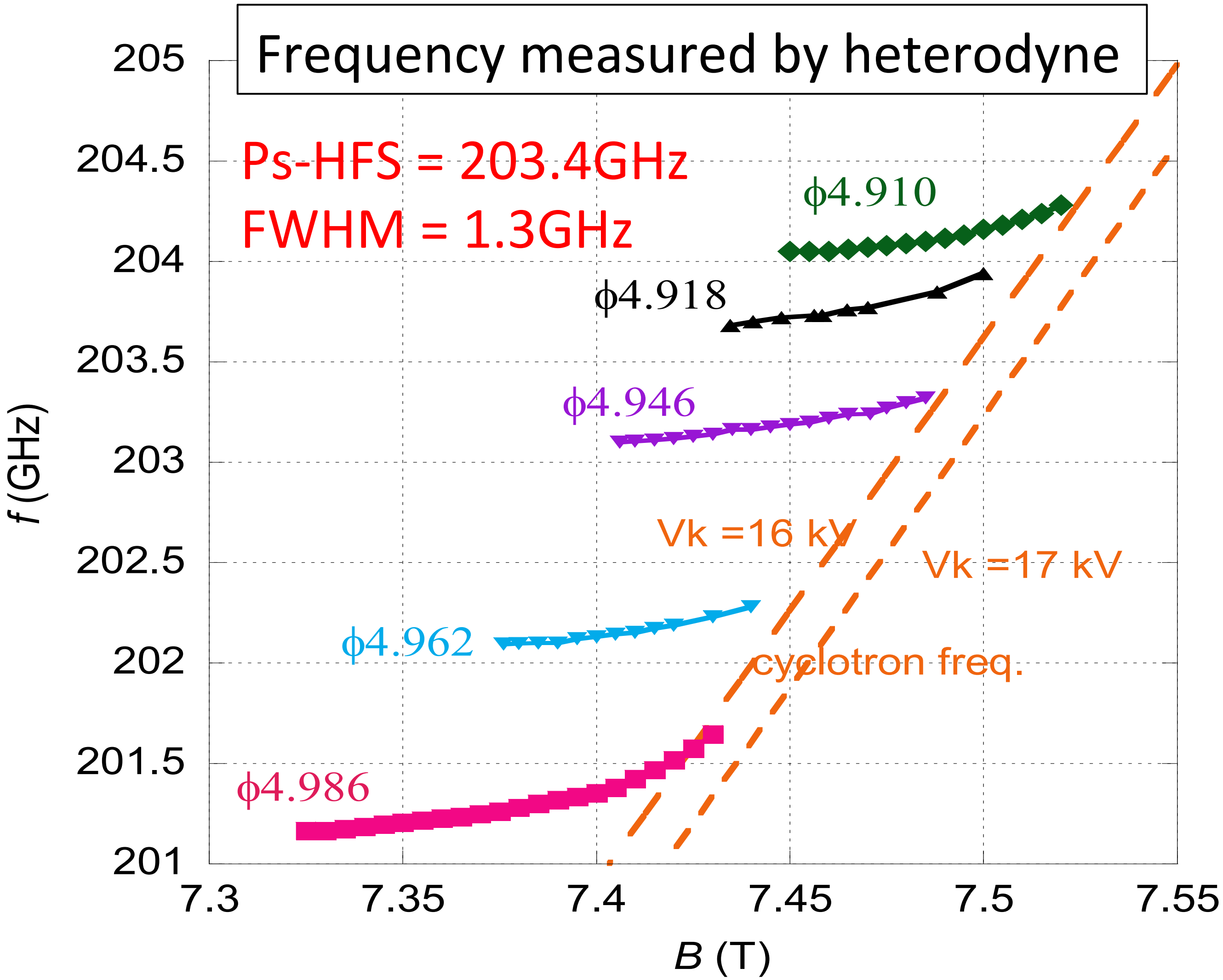
FU CW G1
@Fukui Univ.



Magnetic field B_0 ∼7.4 T
Acceleration voltage V_k = 18 kV
Modulation anode voltage V_a = 10 kV
Beam current I_b = less than 0.5 A
Cavity resonant mode = ctr-TE_{52}

Frequency change

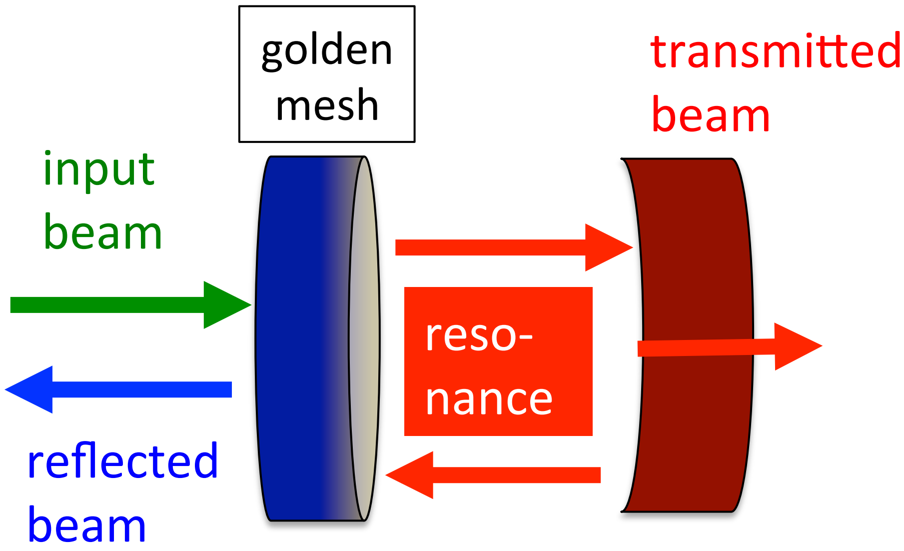




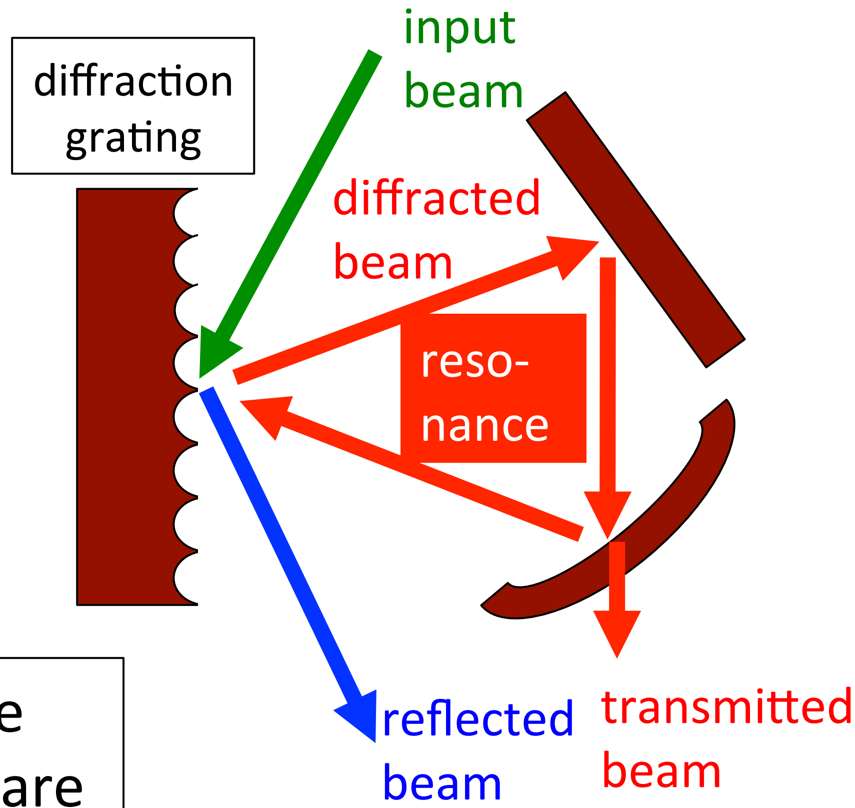
- The Ps-HFS is mean of the *Lorentzian-like* transition resonance.
- We have prepared all cavities to measure the resonance curve.

sub-THz resonator : two possibilities

1. A Fabry-Pérot resonator with a golden mesh



2. A ring resonator with a diffraction grating



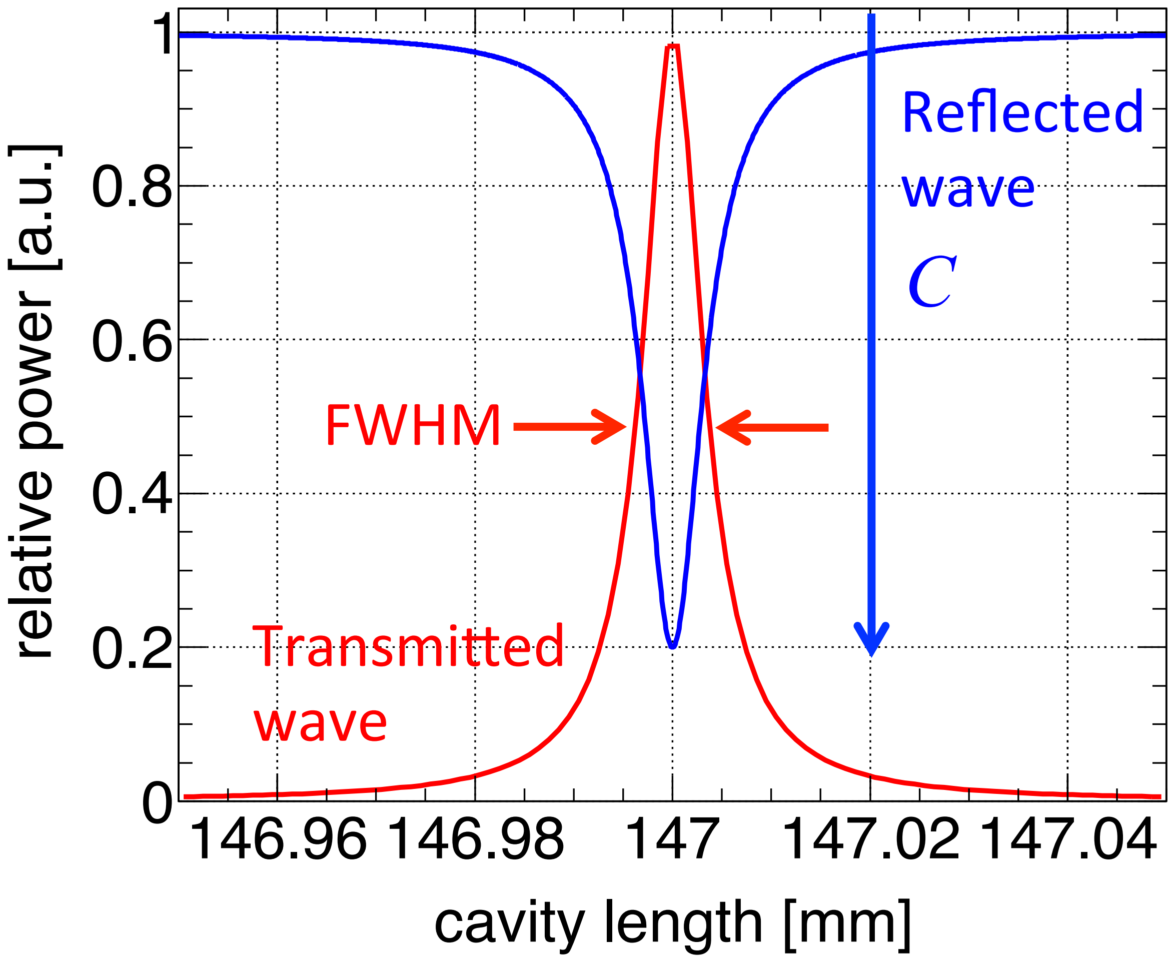
Finesse($\mathcal{F}$) and Coupling(C) will be introduced to quantitatively compare different resonators.

Finesse & Coupling

Finesse

It is corresponding to the Q-value of a RF cavity. Using Free Spectral Range (FSR), and FWHM of the resonance,

$$\mathcal{F} = \frac{\mathrm{FSR}}{\mathrm{FWHM}}$$



Coupling

The relative decrease of the reflected wave
i.e. Relative power absorption into the resonator

Equivalent Power in the resonator P_{int}

$$P_{\text{int}} \sim P_{gyrotron} \times C \times \frac{\mathcal{F}}{\pi}$$

input power from the gyrotron → $P_{gyrotron}$

how much power couples to the resonator? → C

how many times the radiation reflects in the resonator? → $\frac{\mathcal{F}}{\pi}$

So, the resonator must have…

1. High Coupling near 100%
2. High Finesse

Since P_{gyrotron} is 300W, $C>60\%$ and $\mathcal{F}>400$ mean P_{int}>20kW

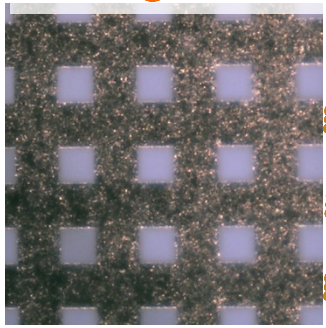
How?

- Decreasing input loss (Coupling↑)
- High reflectance (Finesse↑)

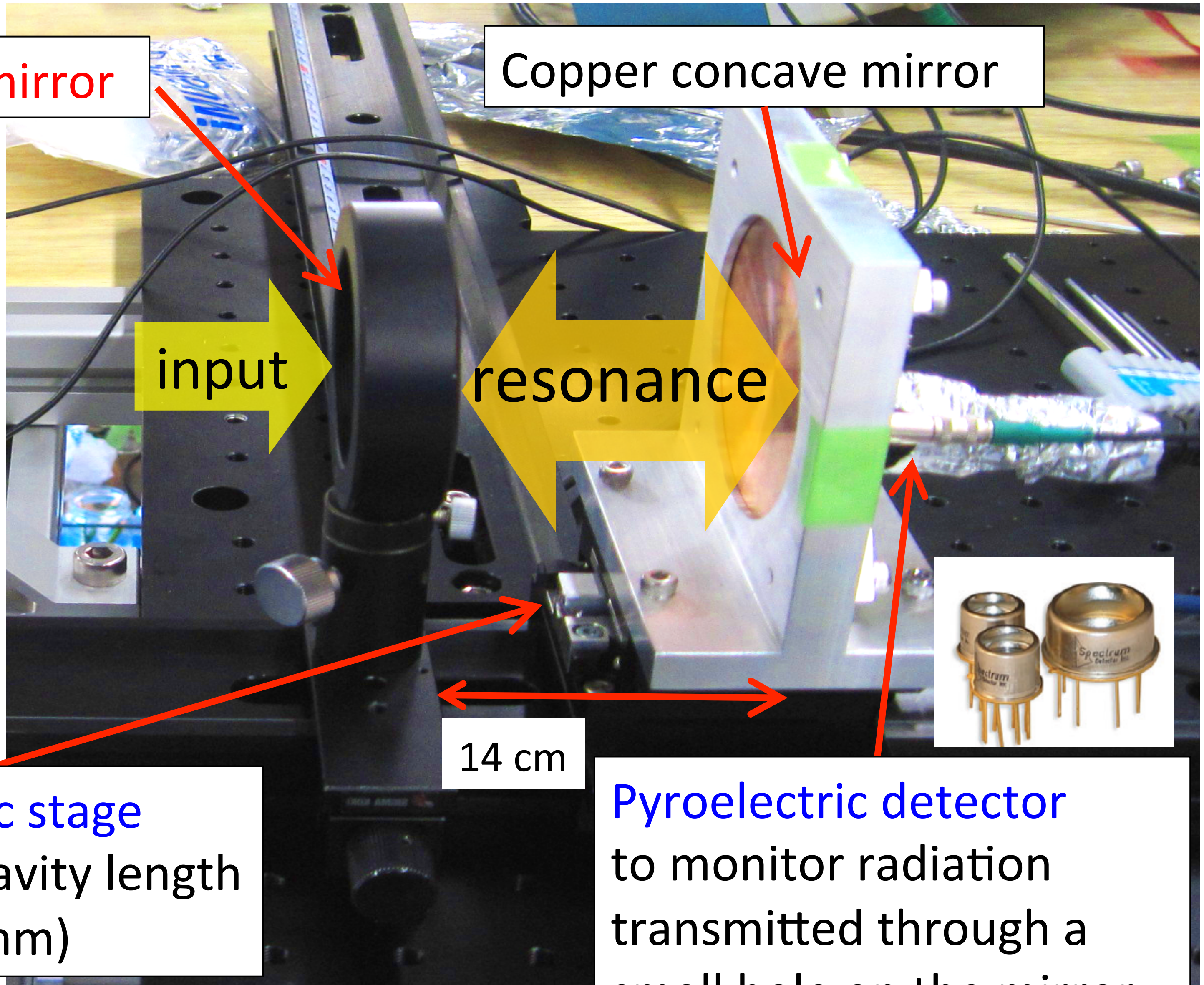
Fabry-Pérot resonator with a golden mesh (1)

Golden mesh mirror

enlarged view



thickness = 1μm
→The mesh is evaporated on a substrate.



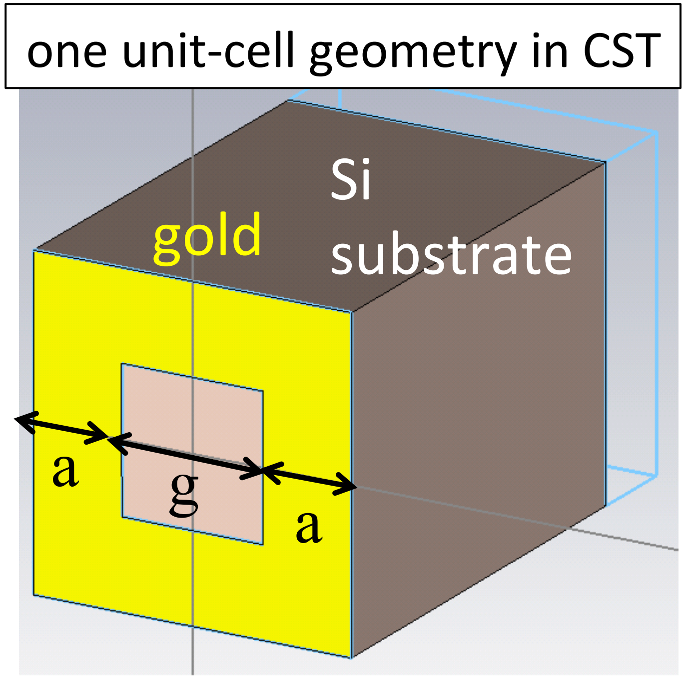
Copper concave mirror

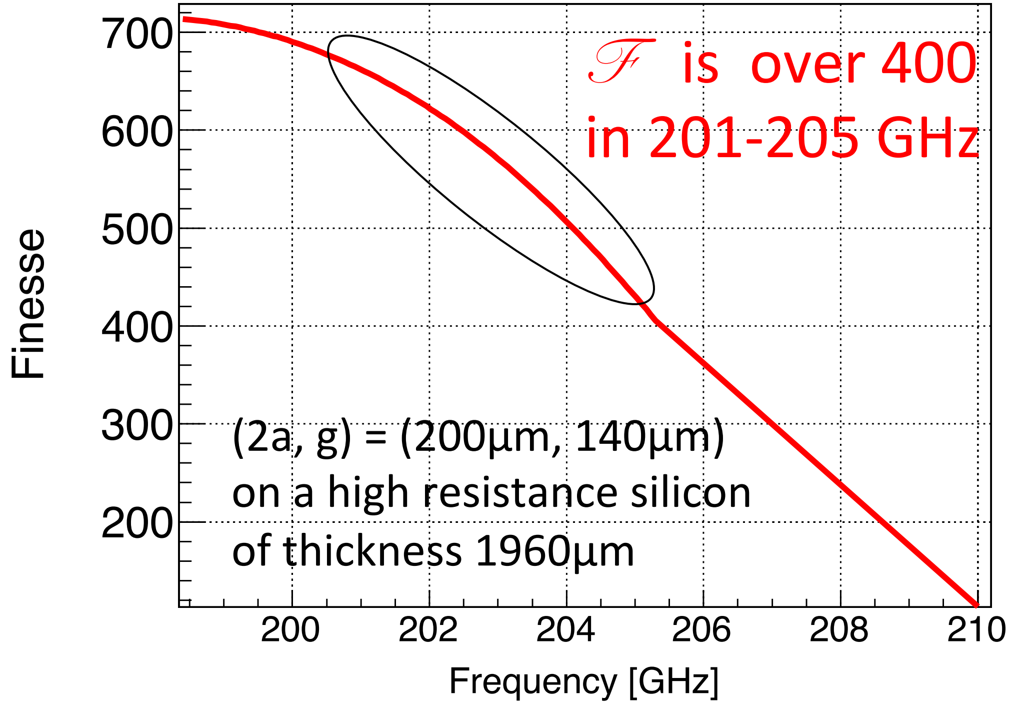
Piezoelectric stage
to control cavity length with O(100nm)

Pyroelectric detector
to monitor radiation transmitted through a small hole on the mirror

Fabry-Pérot resonator with a golden mesh (2)

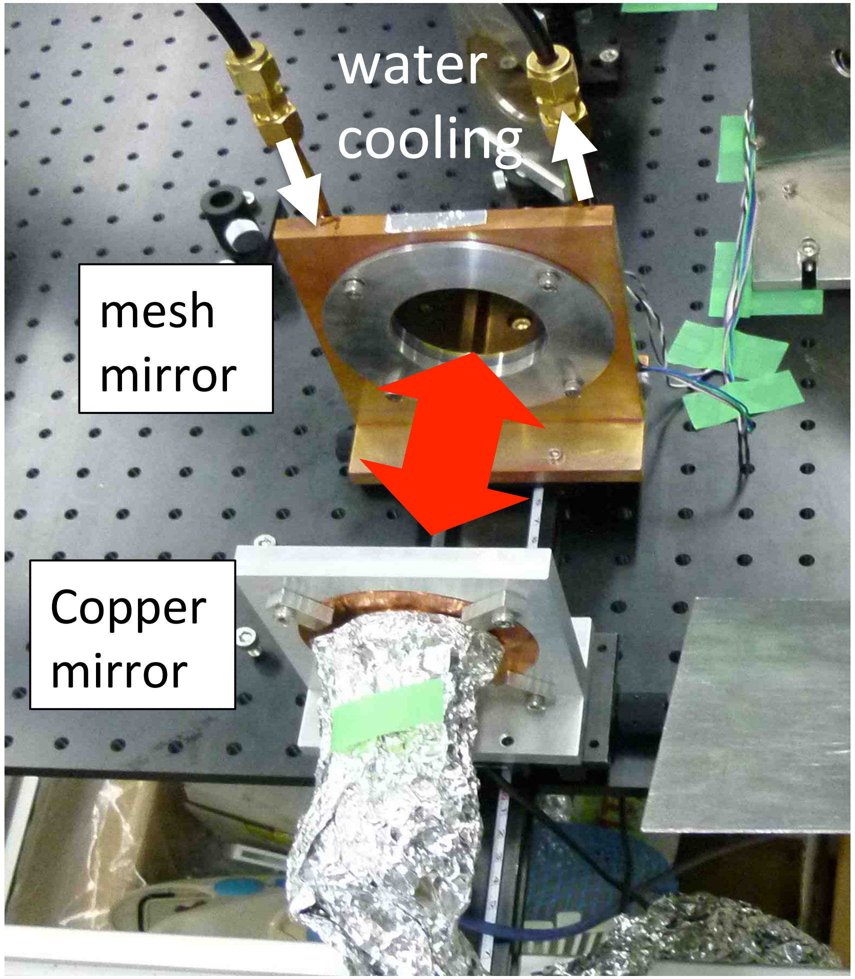
The mesh should be evaporated on silicon to be cooled by water.
→The interference between the mesh and substrate is very severe.

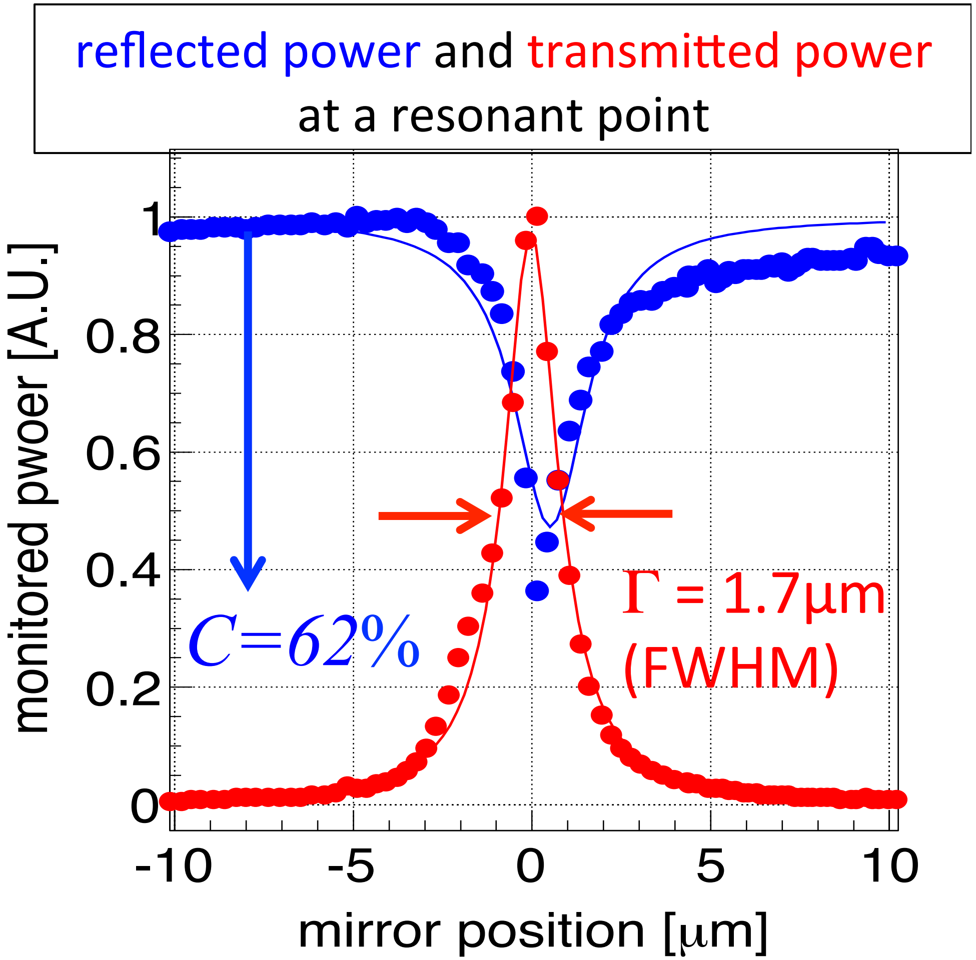




- The mesh parameters were carefully optimized using CST MW studio
  - -Frequency domain analysis, periodic boundary condition
- From 201 to 205 GHz Finesse is over 400, and Coupling is over 60%.

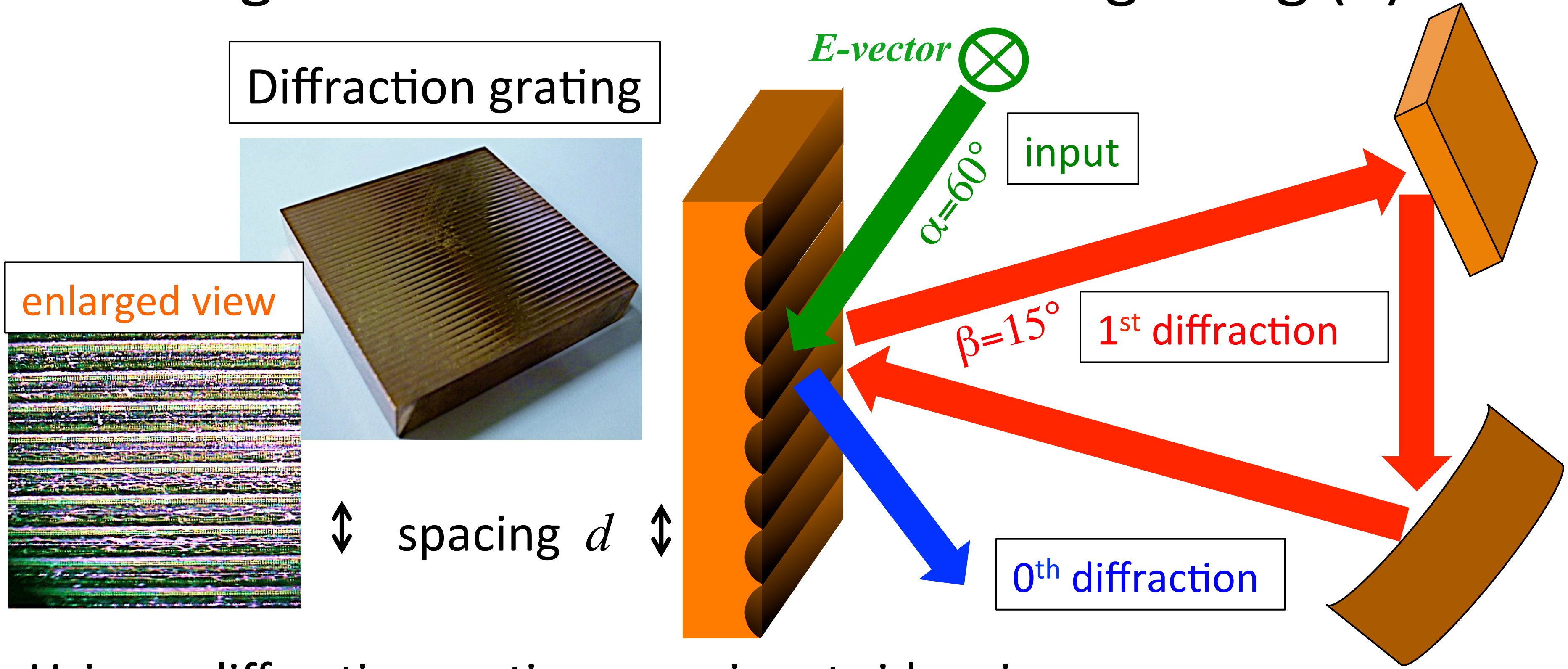
Fabry-Pérot resonator with a golden mesh (3)





- Finesse $\mathcal{F}$=430 and Coupling C=62% are observed.
- Water cooling works very well.

Ring resonator with a diffraction grating (1)



- Using a diffraction grating as an input side mirror.
- A copper grating can have high reflectance and easily be cooled.

Triangle of the ring resonator is determined by spacing *d*

$$d(\sin\alpha + \sin\beta) = m\lambda \quad (m = \pm1, \pm2, \ldots)$$ ← Coherency of grating

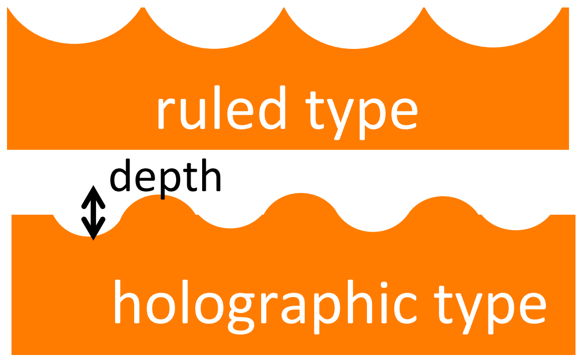
λ=1.47 mm → d=1.31mm , α=60°, β=15°

Ring resonator with a diffraction grating (2)

Diffraction Efficiency $I \propto$ Coherency term × Form factor

<u>The Form of the groove must be optimized</u>

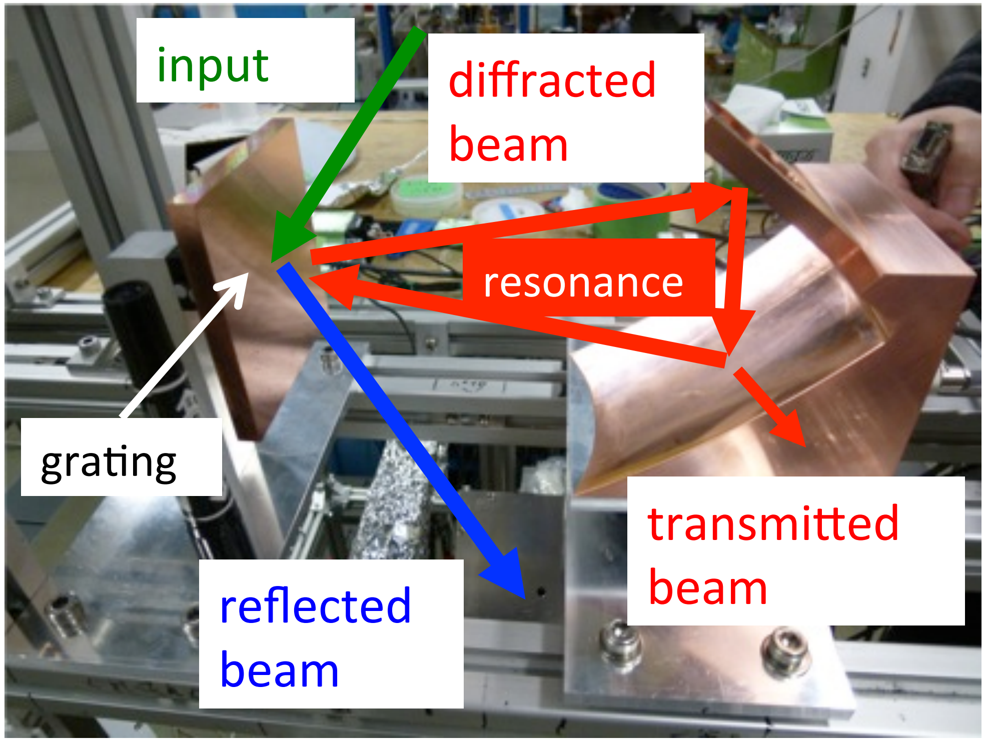
- The shape determines input loss (Coupling)
- The depth determines reflectance (Finesse)

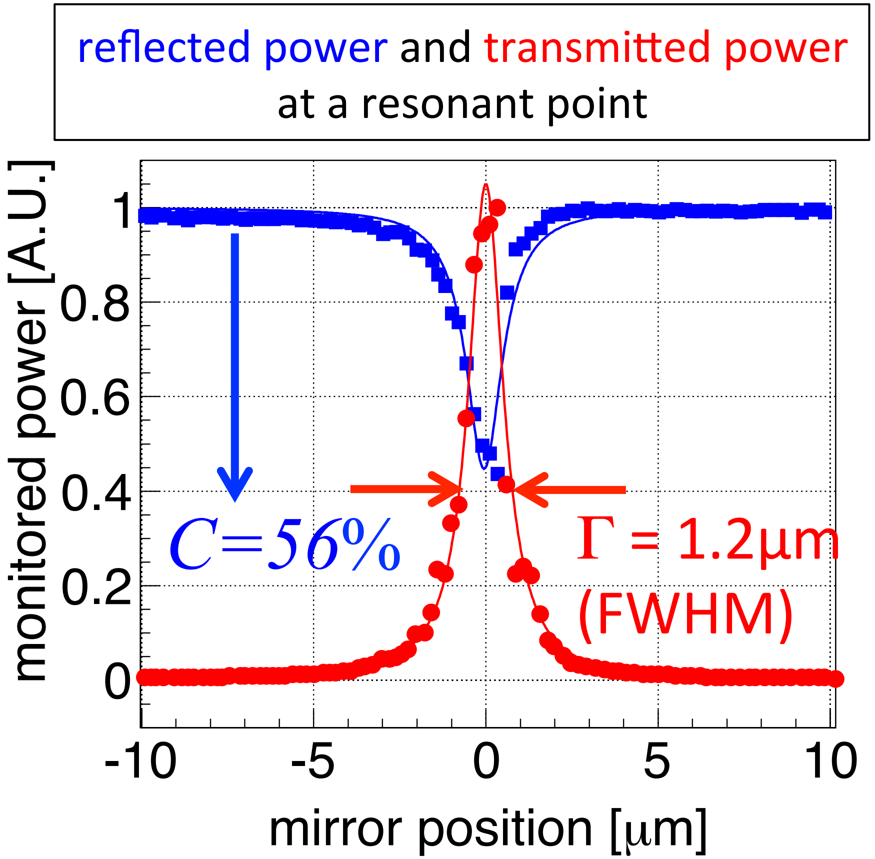


The form factor was evaluated by Gaussian beam (resonant mode) because diffraction losses of a plane wave and the beam are different.
→Conventional plane wave analysis is not proper.

★ Ruled type, depth 48μm is designed using CST and experiments.

Ring resonator with a diffraction grating (3)

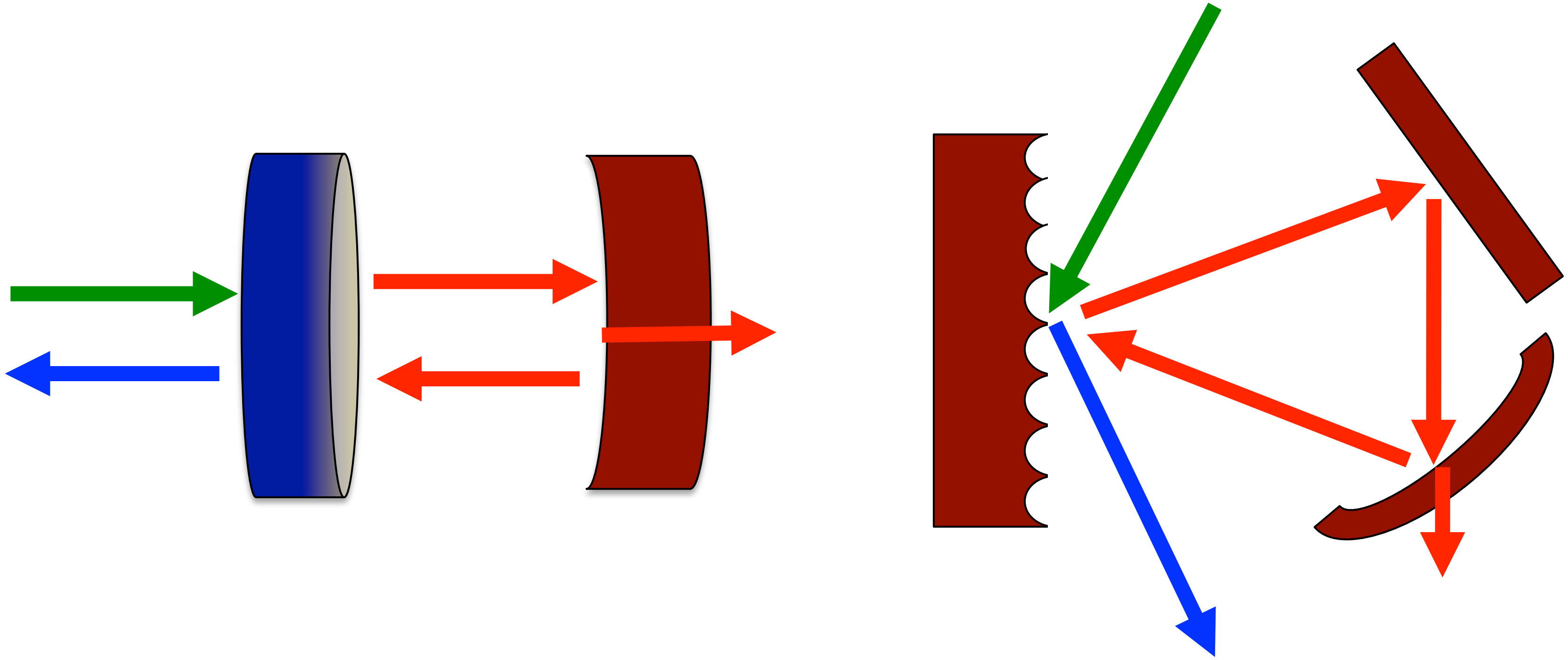




- Finesse $\mathcal{F}$=630 and Coupling C=56% is achieved
- The Fabry-Pérot resonator has $\mathcal{F}$=430, C=62%

→ *So, the ring resonator is better…*REALLY?

Which one should we select ?



- The optical path of the ring resonator is split into two ways.
  → The energy density is 1/2 of the Fabry-Pérot resonator.
- The transition probability is proportional to the energy density
  → With The Fabry-Pérot resonator we get the twice larger signal.

★We selected the Fabry-Pérot resonator.

Conclusion

- There is a large discrepancy between theoretical and experimental values of the Ps-HFS.
- We will directly measure the Ps-HFS value for the first time, using high power sub-THz system consisting of a gyrotron and a high performance resonator.
- A Fabry-Pérot resonator and a ring resonator are developed to obtain over 20 kW equivalent power, and the former is adopted from its higher energy density.
- We have already observed the direct transition at 202.9 GHz.
  (*Phys. Rev. Lett.* **108**, 253401, 2012)

Future Prospects

- We will measure the Ps-HFS direct transition at some frequency points around 203.4 GHz.
- The Ps-HFS value will be directly measured with precision of O(100ppm) within one year.