Direct measurement of the Hyperfine Structure of Ground -State Positronium

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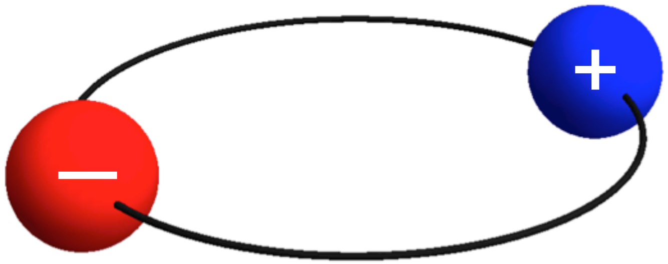
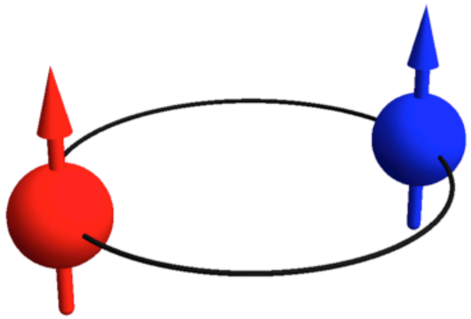
Positronium (Ps)



- Ps is the bound state of electron (e^-) & positron (e^+)
  - Particle-antiparticle system
  - Only two lepton system
  - The lightest hydrogen-like atom
  - Good target to study bound state Quantum ElectroDynamics (QED)

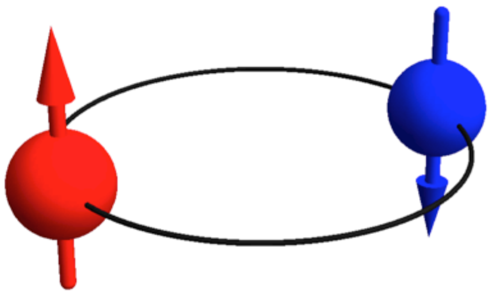
Two ground states of Ps



Ortho-Positronium (o-Ps)

- Spin triplet state (S=1)
- Long lifetime (142ns)
- Decays to odd gammas (3γ, (5γ, …))

Continuous γ-ray spectrum



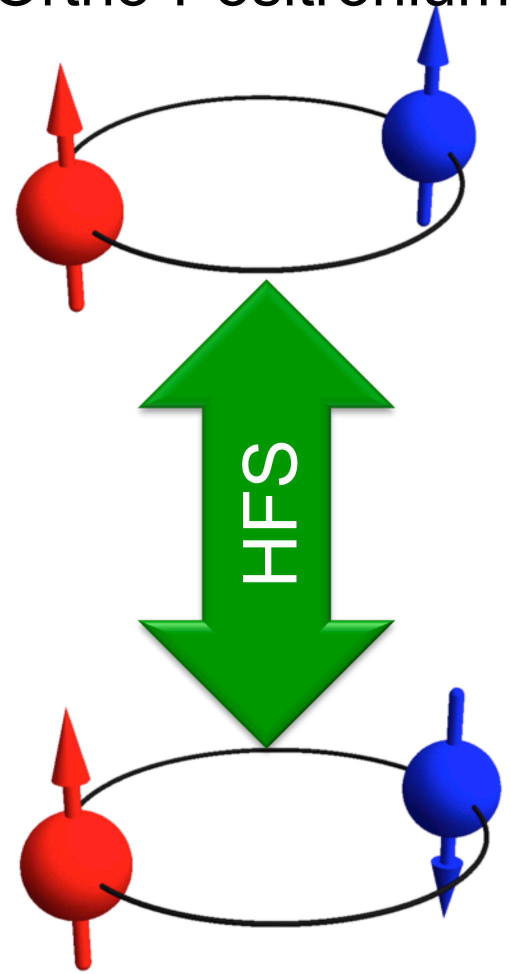
Para-Positronium (o-Ps)

- Spin singlet state (S=0)
- Short lifetime (125ps)
- Decays to even gammas (2γ, (4γ, …))

511keV monochromatic γ-rays

Positronium Hyperfine Splitting (Ps-HFS)

Ortho-Positronium (o-Ps)



Para-Positronium (p-Ps)

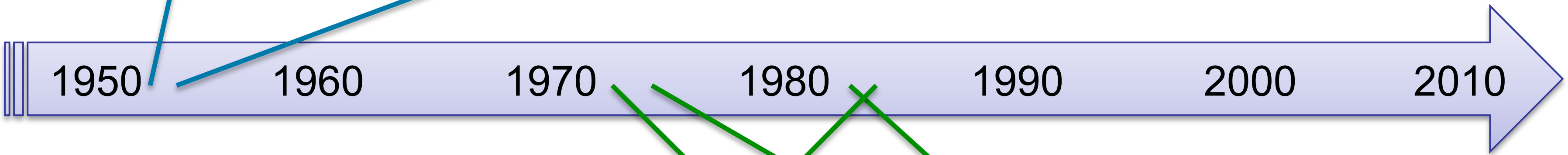
Energy level difference between two states
=Ps Hyperfine Splitting (Ps-HFS)

- 203GHz (=0.84meV), large value!
  (cf. Hydrogen 1.4GHz)
- Origin of Ps-HFS:
  - Spin-spin interaction
  - Virtual photon oscillation

Ps HFS history

1951: Discovery of Ps
(M. Deutsch)

1952: First measurement of Ps HFS
(M. Deutsch)
203.2(3)GHz

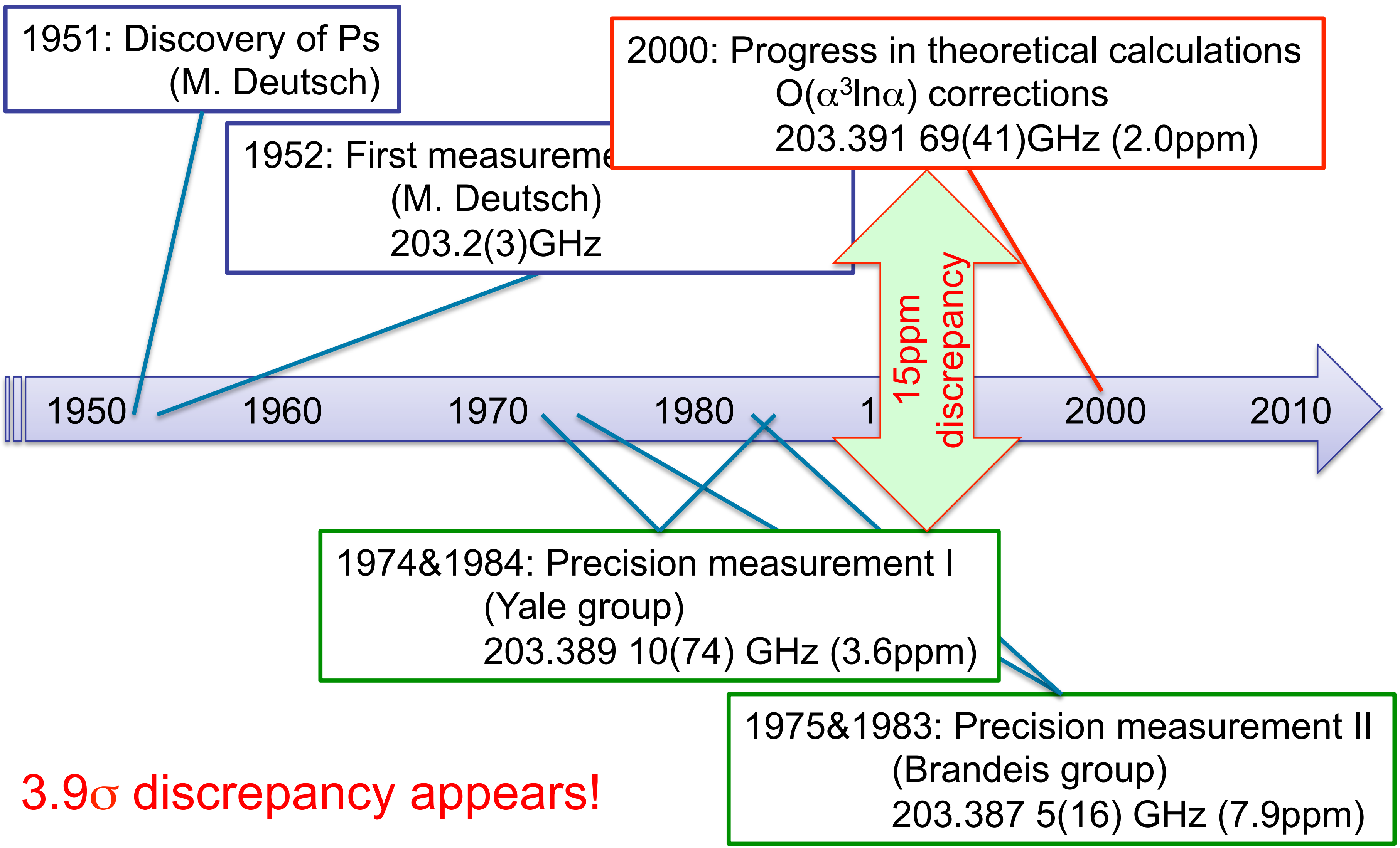


1974&1984: Precision measurement I
(Yale group)
203.389 10(74) GHz (3.6ppm)

1975&1983: Precision measurement II
(Brandeis group)
203.387 5(16) GHz (7.9ppm)

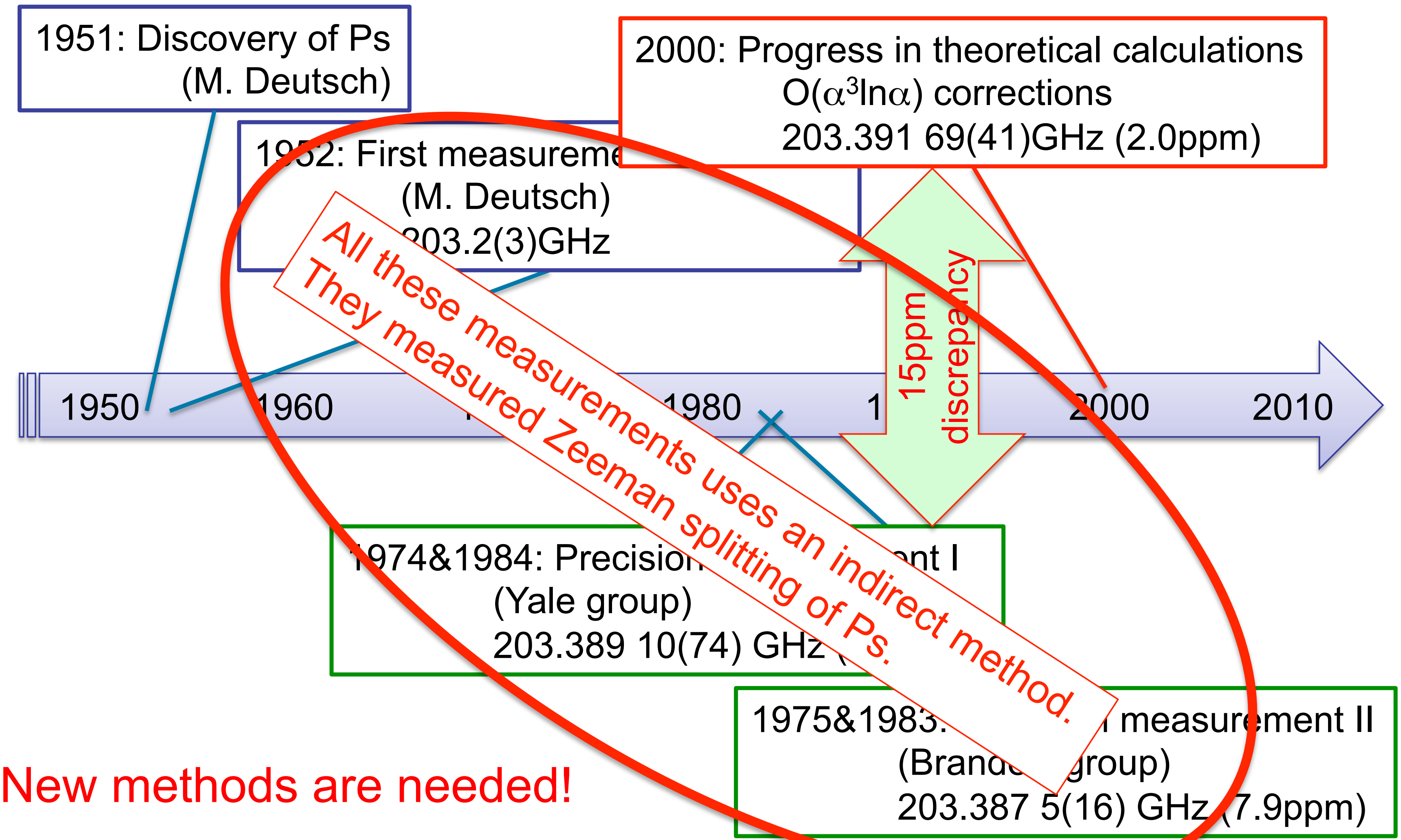
Improved measurements in 70's & 80's
by two groups (ppm level!)

Ps HFS history



3.9σ discrepancy appears!

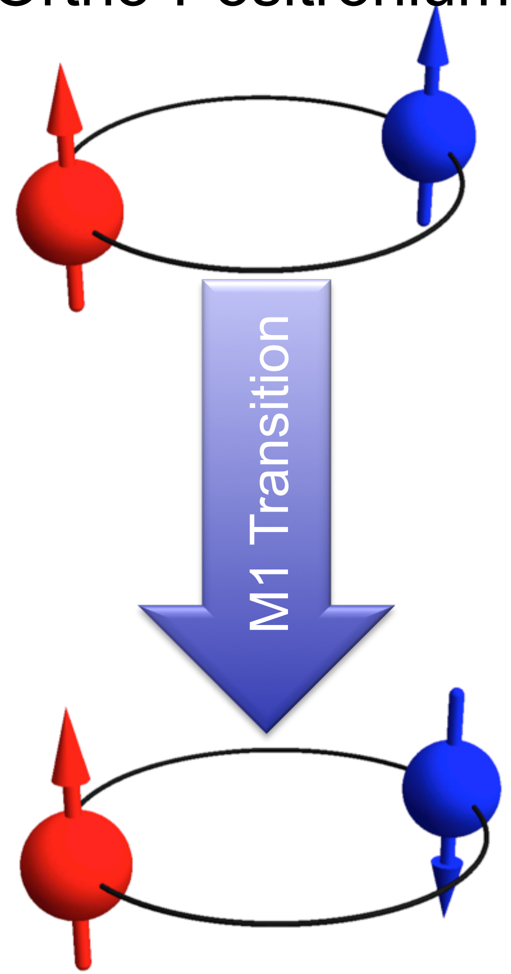
Ps HFS history



New methods are needed!

Our method: Direct measurement of Ps-HFS

Ortho-Positronium (o-Ps)



Para-Positronium (p-Ps)

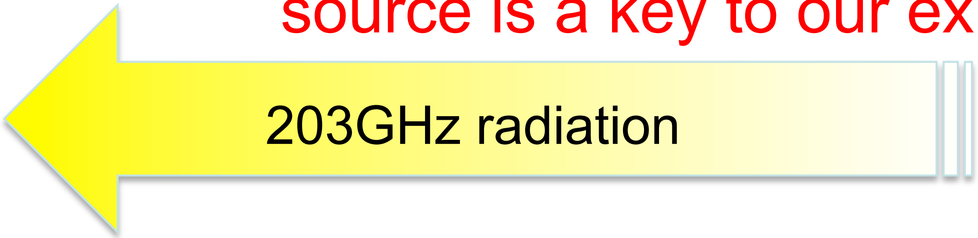
- o-Ps➔p-Ps: M1 transition (suppressed)
- Natural transition rate=$3.37\times10^{-8}\ s^{-1}$

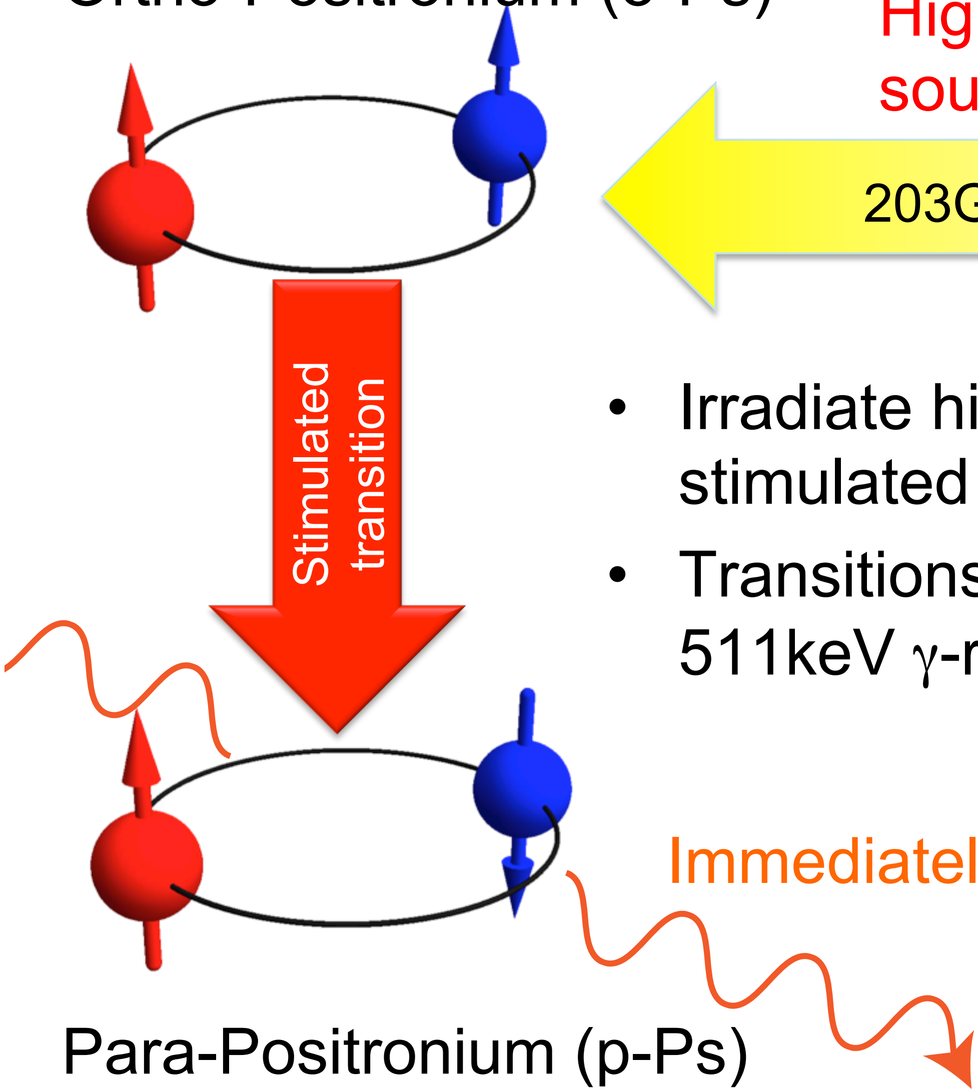
☹ Extremely small compared with o-Ps decay rate ($7.04\times10^{6}\ s^{-1}$)

Our method: Direct measurement of Ps-HFS

Ortho-Positronium (o-Ps)

High power millimeter wave source is a key to our experiment!



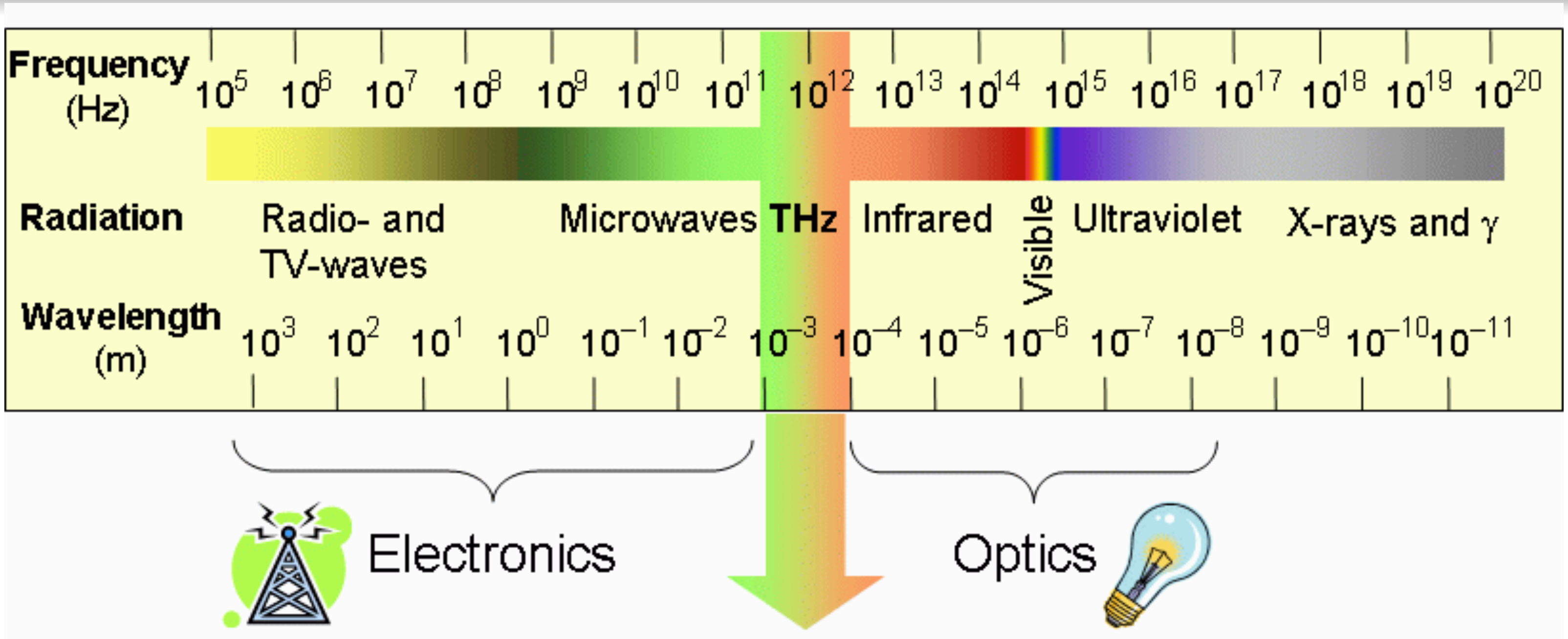


- Irradiate high power 203GHz light to make stimulated transitions from o-Ps to p-Ps
- Transitions are detected by increase of 511keV γ-rays

Immediately decays to two 511keV γ-rays.

Para-Positronium (p-Ps)

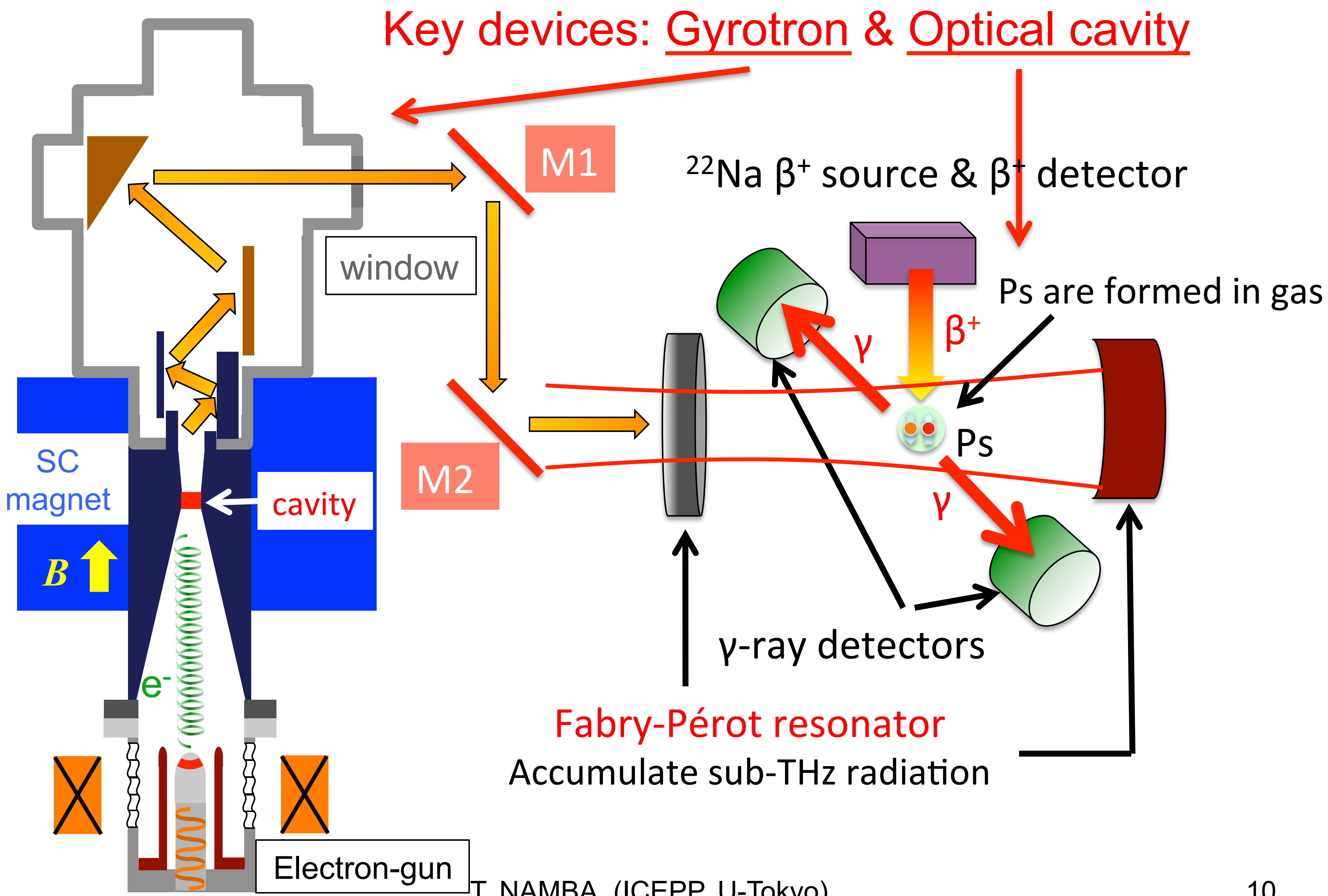
Millimeter ~ sub-millimeter:
a frequency range with rich scientific potential



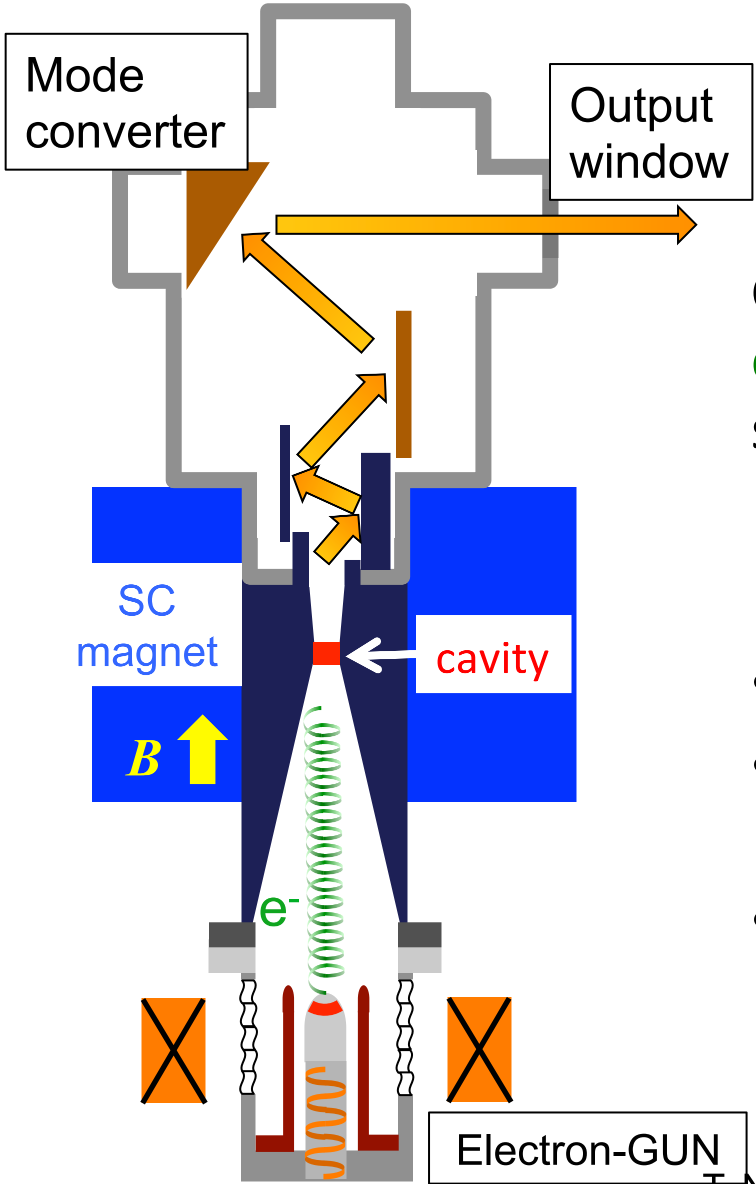
200GHz ~ 1.5mm ~ 0.8meV

- Intermediate region
  - Particle-like for O(>10THz) region
  - Wave-like for O(<100GHz) region
- THz gap: little existing technology
  - Challenging, but can be a new `eye' for basic science

Experimental setup



Gyrotron: Strong millimeter wave source

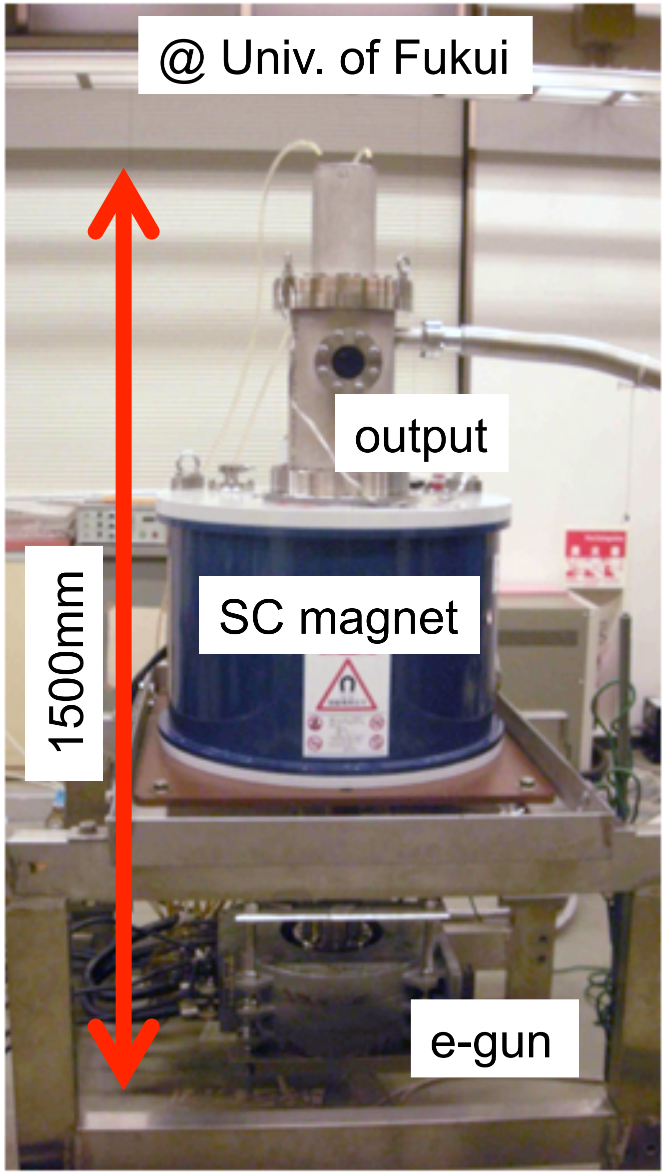


Gyrotron utilizes cyclotron motion of electrons to resonate a cavity inside the solenoid

[Characteristics]

- 10GHz-1THz
- High power (used as heaters for nuclear fusion)
- Continuous/pulse mode operation

Gyrotron: FU-CW-GI



- FU-CW-GI: Dedicated to our experiment
- Gaussian beam power = 300W (5Hz, duty 30%)
- Δf=1MHz
- Output power is stabilized by a feedback system (<±10%)

Gyrotron improvement: FU-CW-V → FU-CW-GI

FU-CW-V

First gyrotron for Ps-HFS measurement

- Fix frequency (202.9GHz)
- TE_{03} mode output (needs external mode converter)

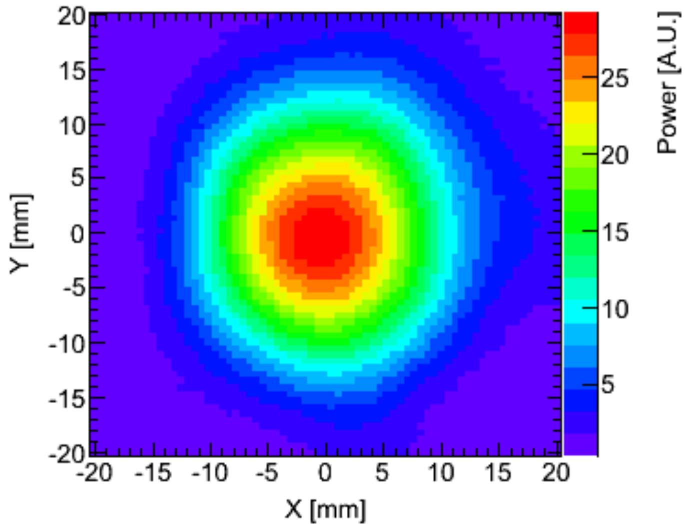
FU-CW-GI

Second gyrotron

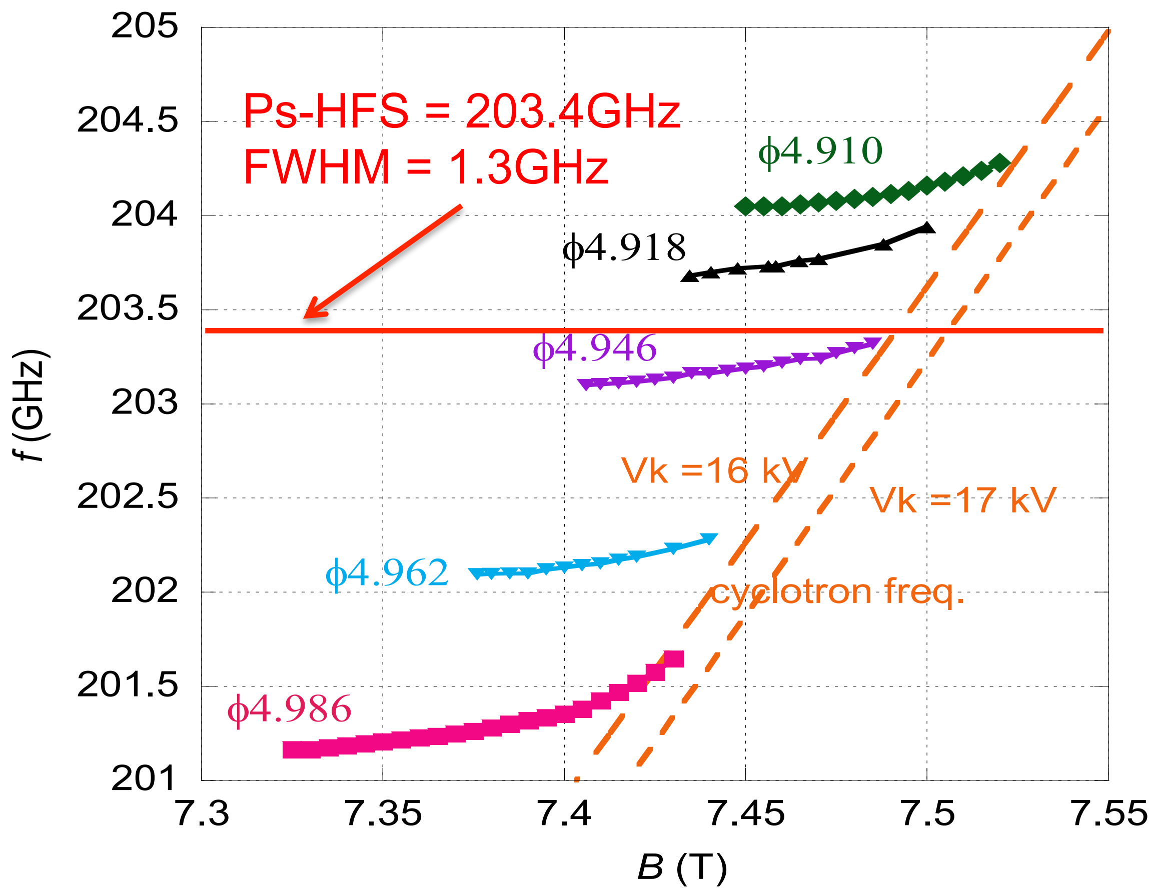
- Output frequency is tunable by replacing cavities
- Gauss mode output with an internal mode converter

FU-CW-GI (Improved characteristics)

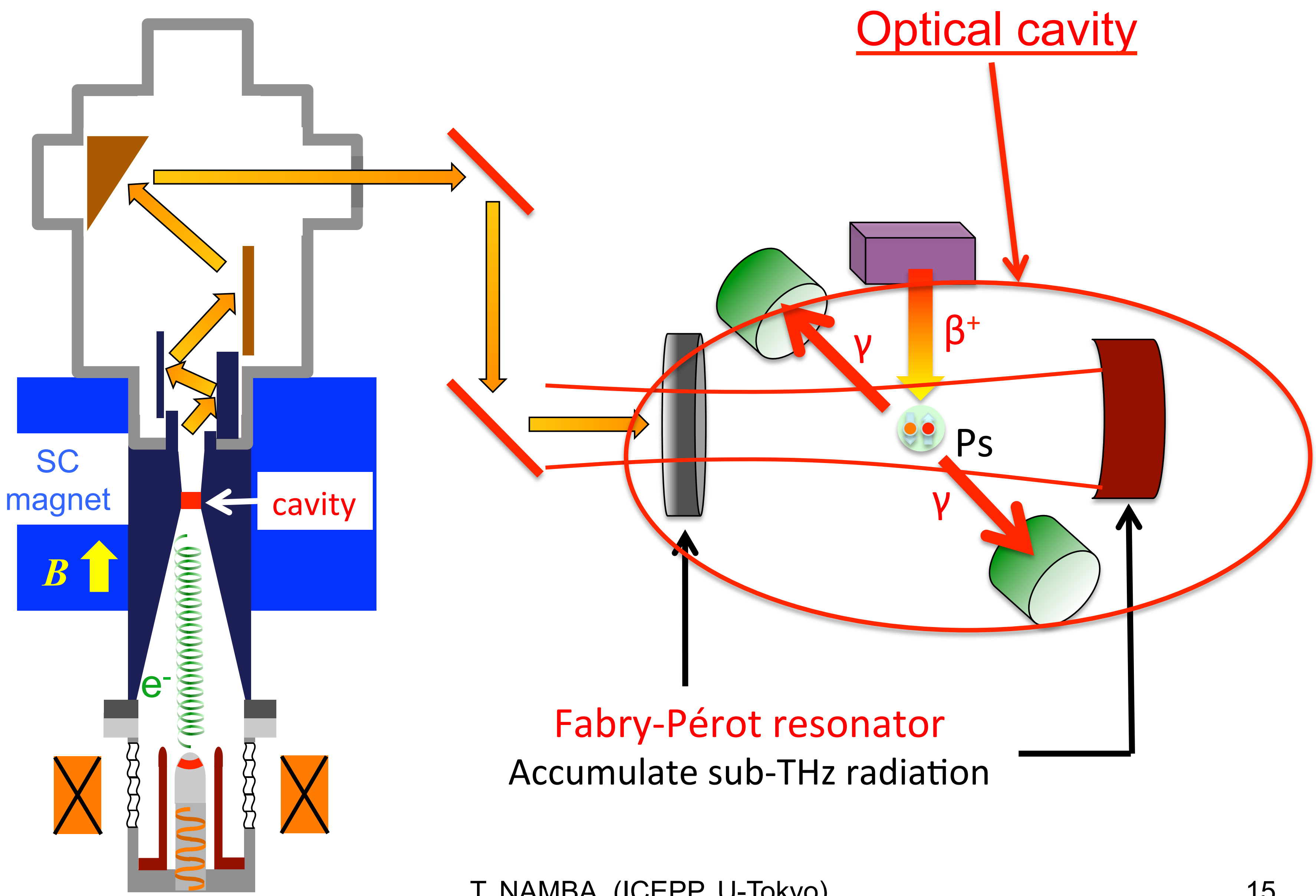
Beam output profile



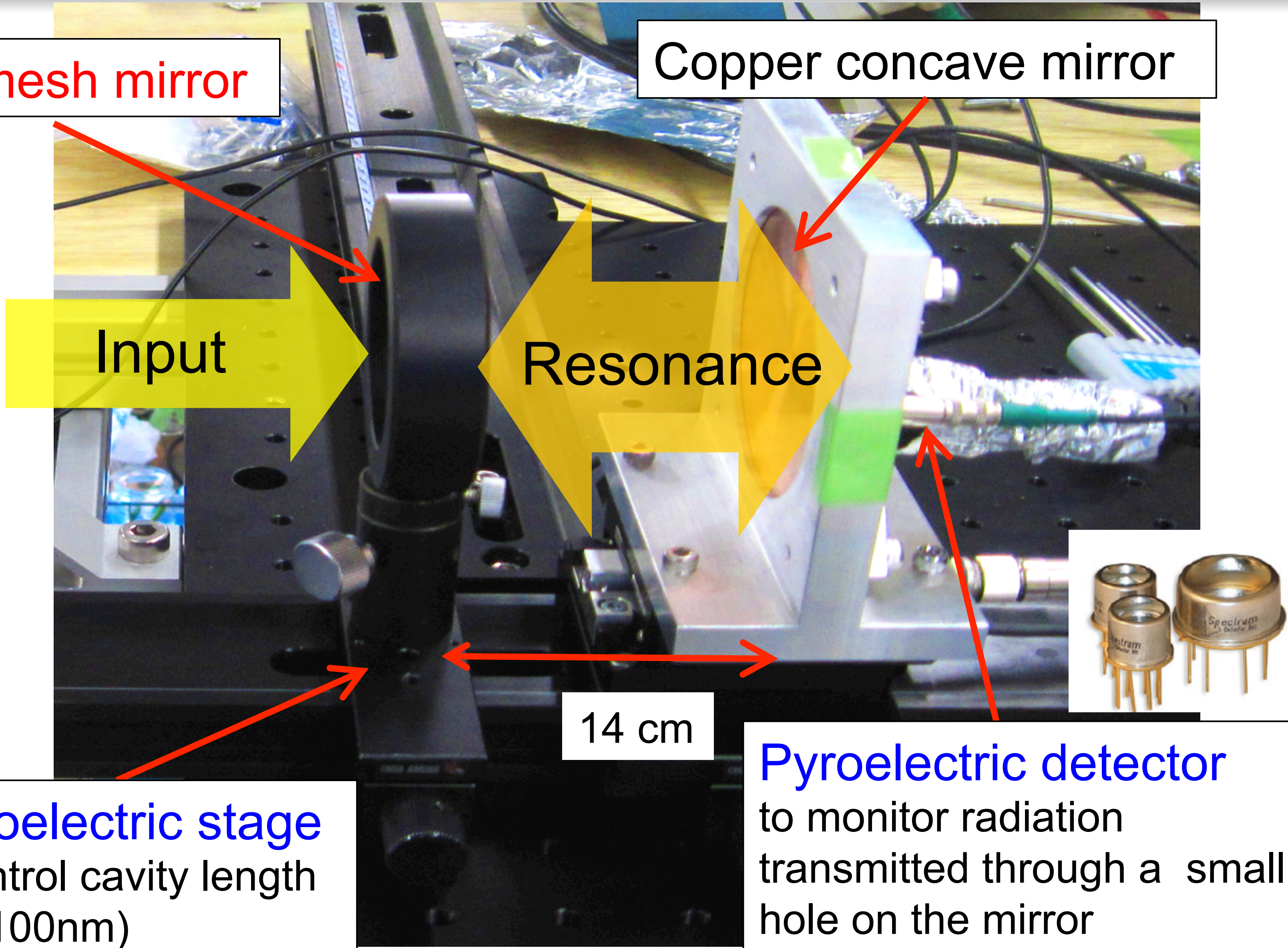
Oscillation frequency measured by heterodyne



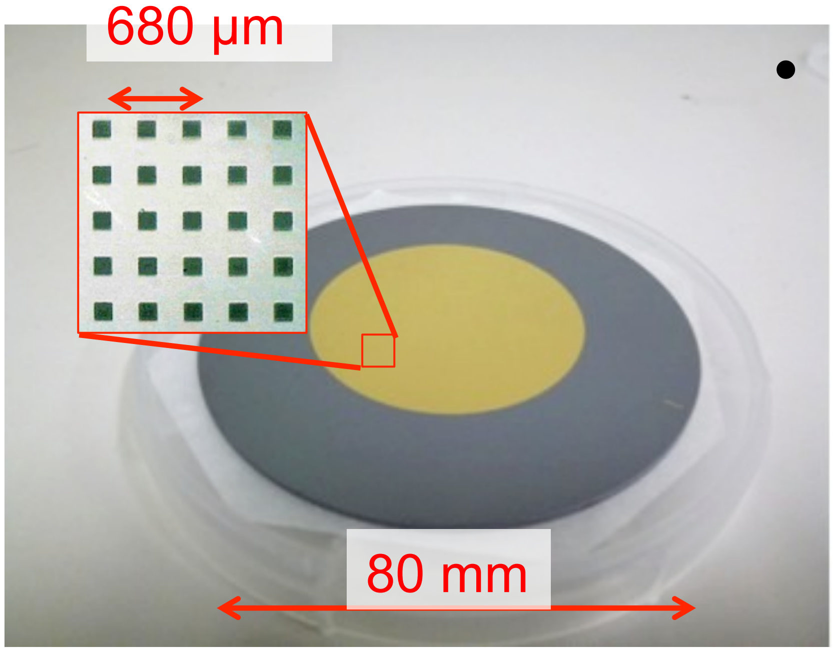
Experimental setup



Fabry-Pérot cavity: accumulating millimeter wave with two mirrors



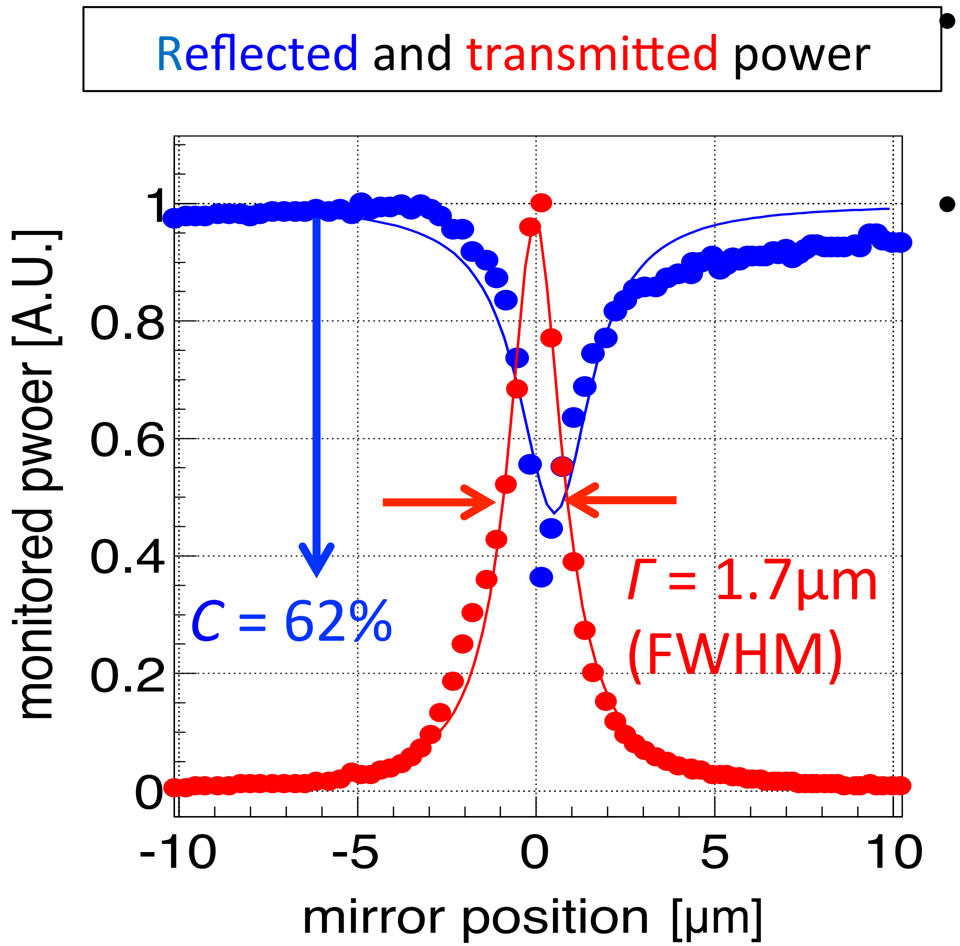
Gold mesh mirror for the input side



- An input mirror of the cavity is required to have
  - high reflectivity
  - reasonable coupling

- A mesh mirror is developed
  - Sub-millimeter size gold mesh is evaporated on silicon plate
  - Reflectivity: 99.15%, Transparency: 0.53% (Simulated by CST MICROWAVE STUDIO)

Cavity performance



- From reflected power:
  Coupling=62%
- From transmitted power:
  Finesse=430
  (means ×136 accumulation)

Gain of the cavity is 85!

Mirror improvement

- Base material of the mesh mirror is changed

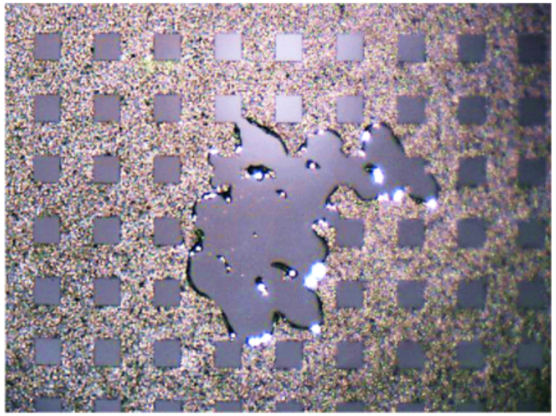
  Quartz base ➔ High resistivity silicon base

Thermal conductivity
5W/Km

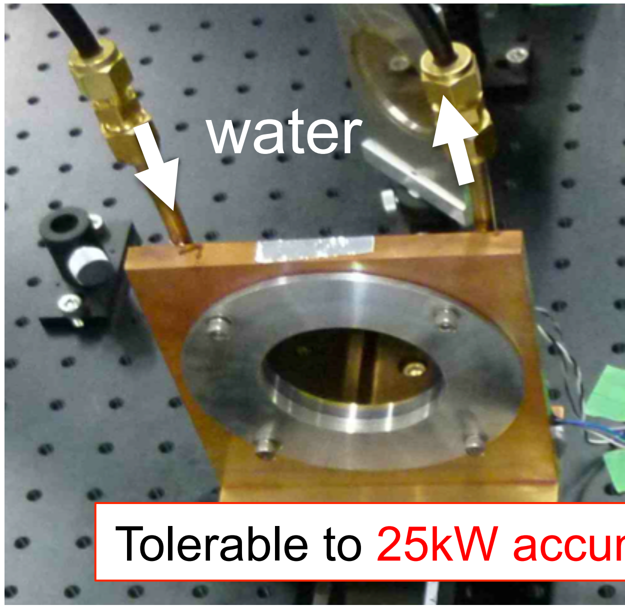
Thermal conductivity
148W/Km

The mesh is melted down
by high heat load (>10kW accumulation)

Can be cooled down by water
at the mirror holder

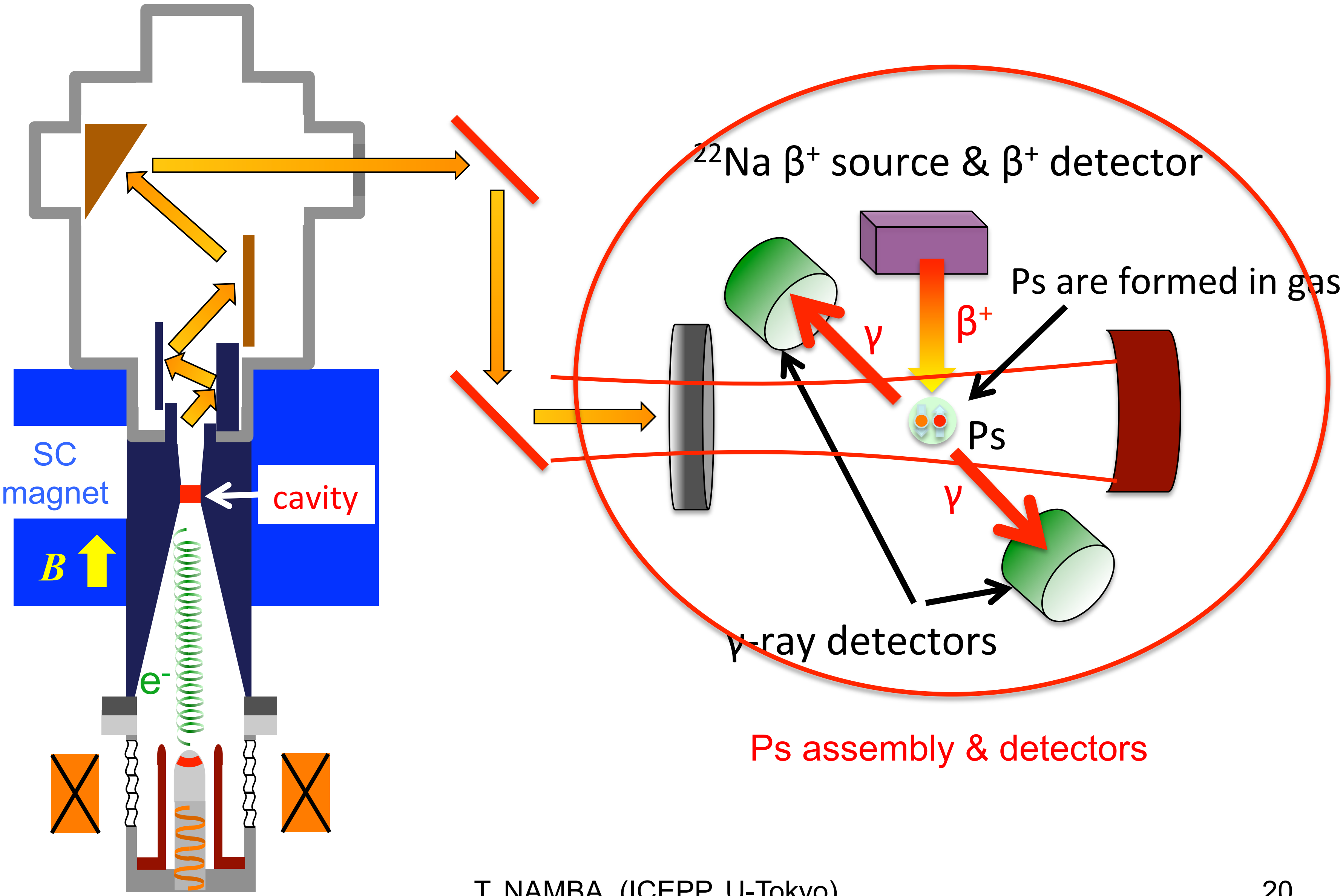


(Magnified view)



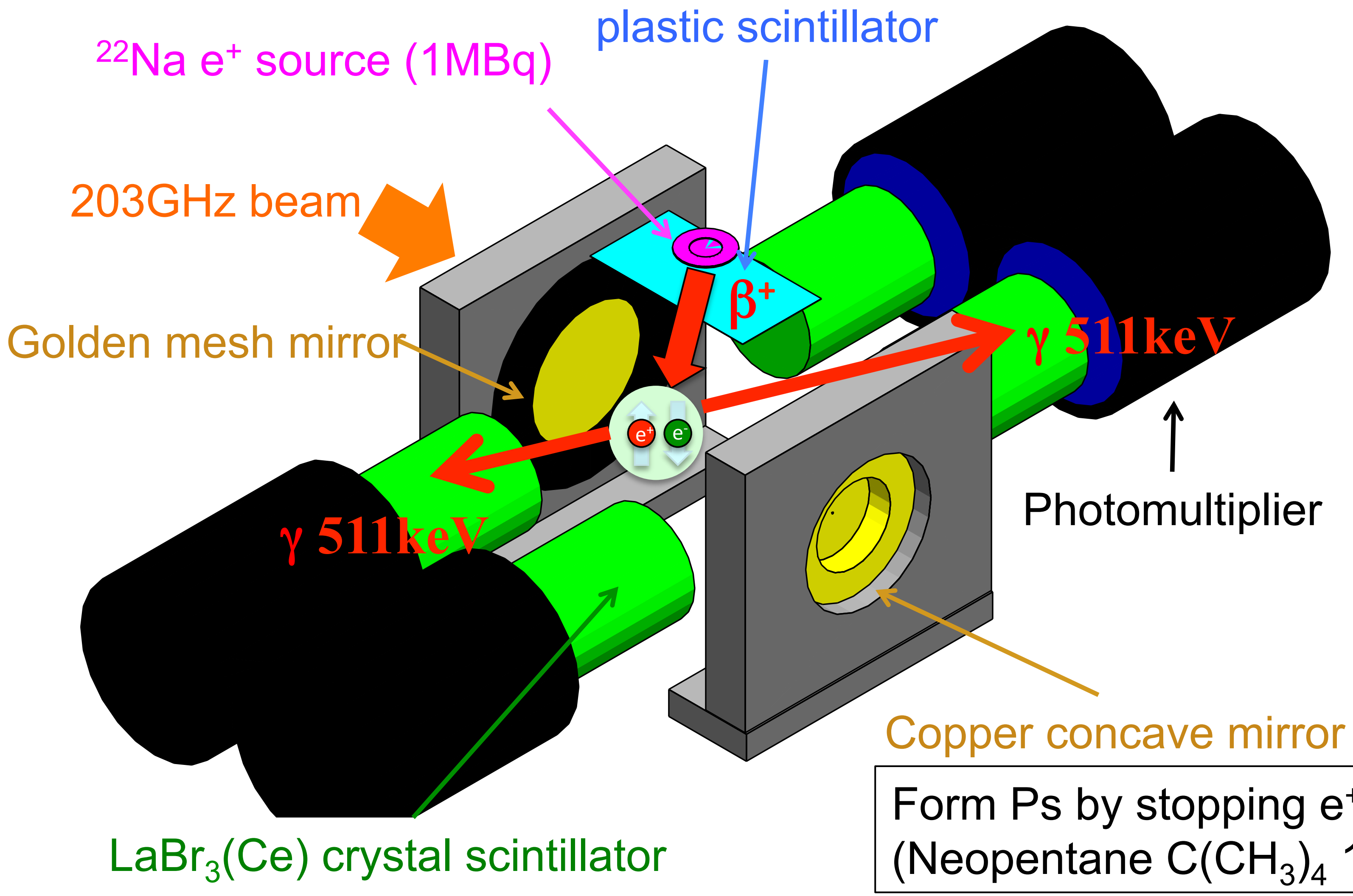
Tolerable to 25kW accumulation

Experimental setup



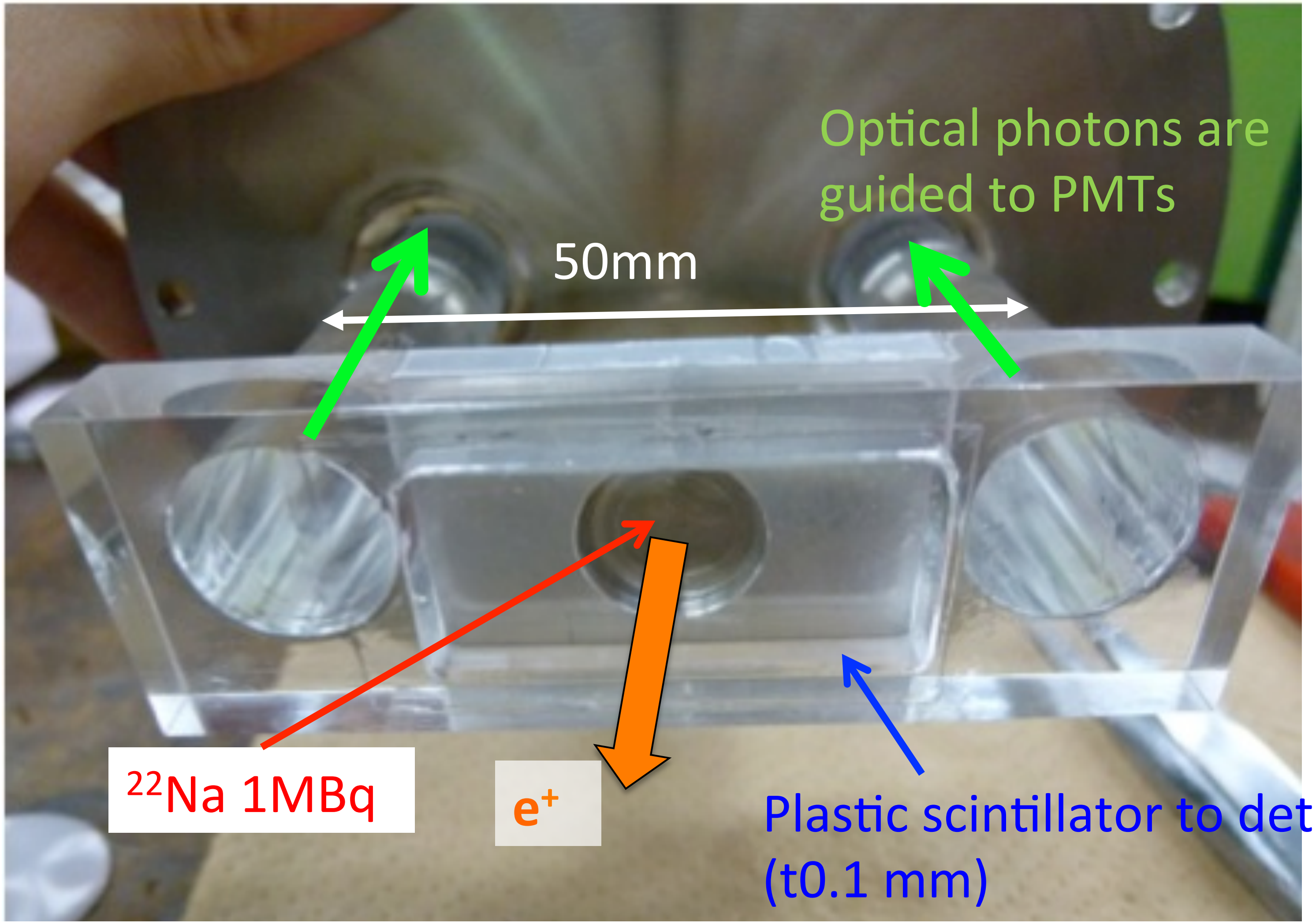
Positronium assembly & γ-ray detectors

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



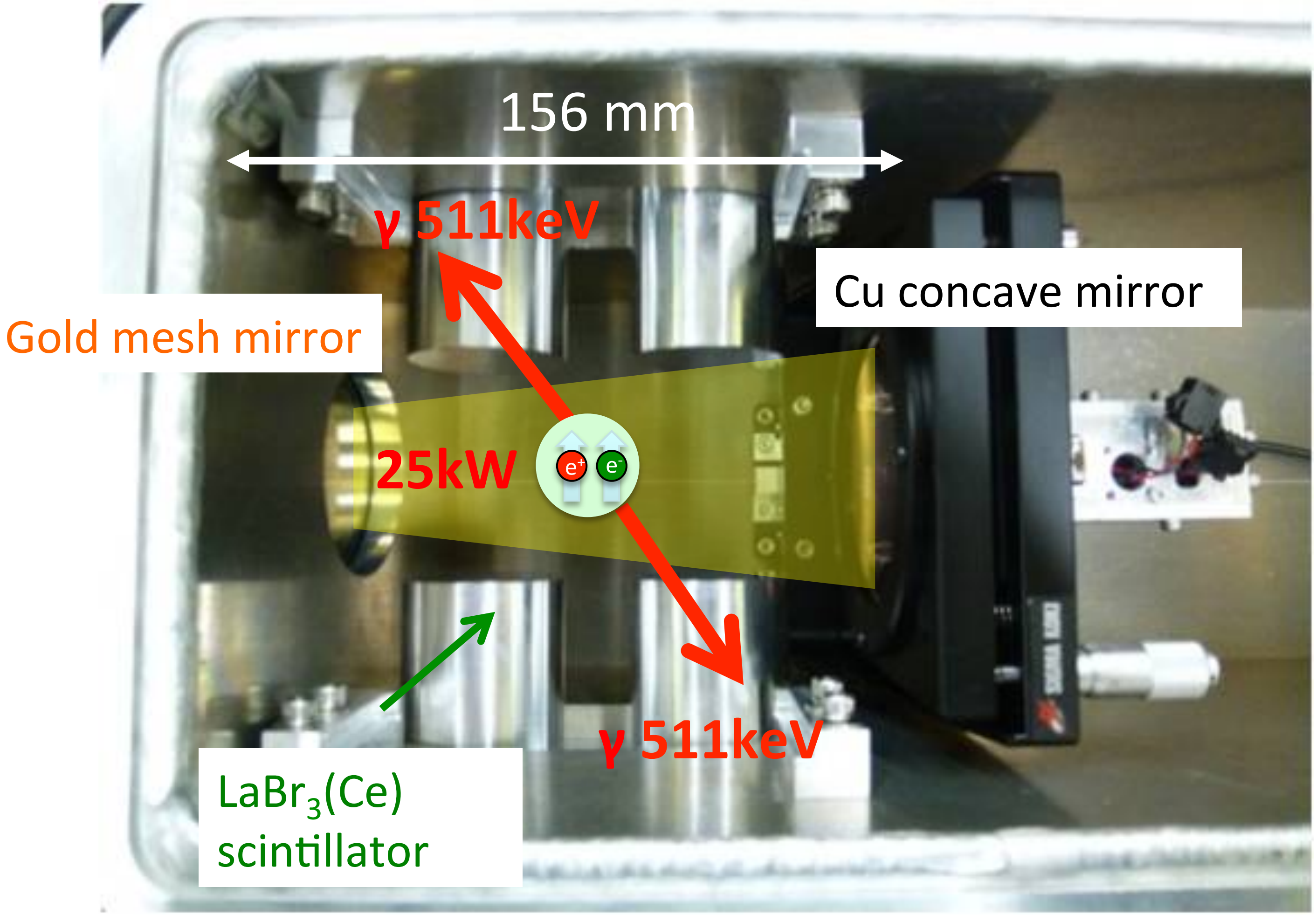
Form Ps by stopping e^{+} in gas (Neopentane $C(CH_3)_4$ 1atm)

^{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 cavity

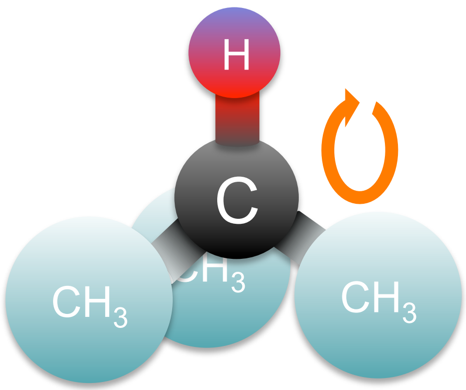


- Four γ-ray detectors are placed as near to high power radiation as possible in order to detect γ rays efficiently.

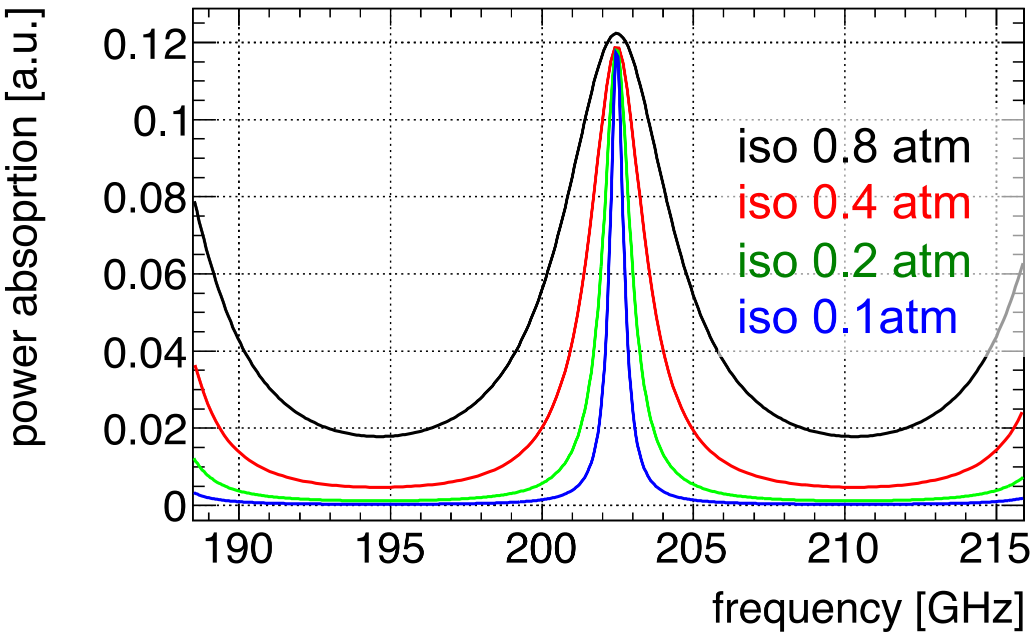
Improvement on the assembly: Cavity gas

Cavity is filled with gas for positron stopping & Ps formation

Previous setup: isobutane 0.1atm + N_2 1.9atm



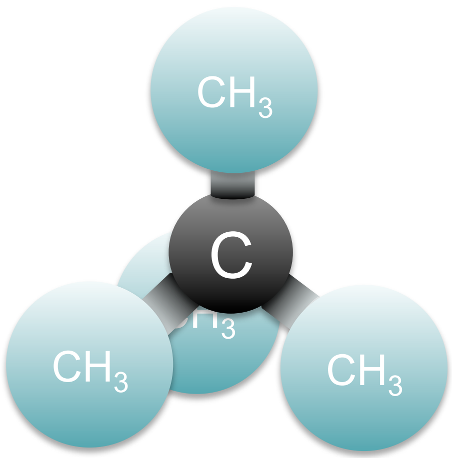
Rotation motion of isobutane makes an absorption peak around 203GHz



Improvement on the assembly: Cavity gas

Cavity is filled with gas for positron stopping & Ps formation

New setup: neopentane 1.0atm



Symmetric shape!

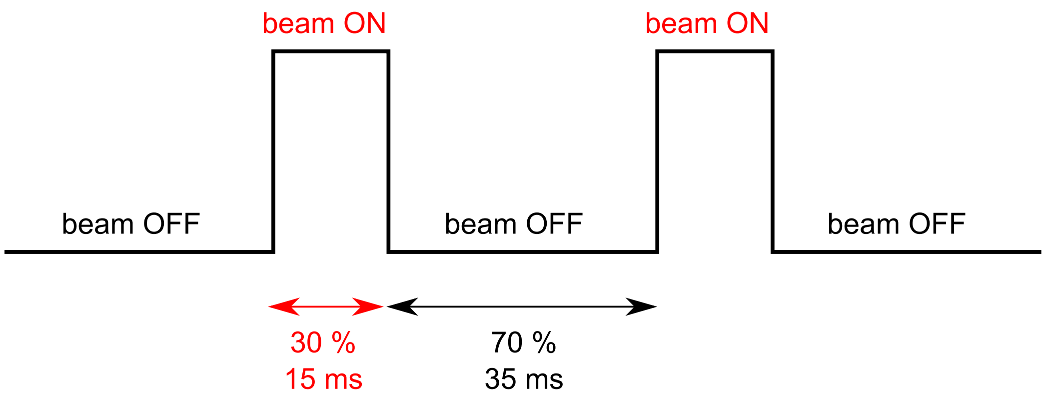
- No absorption around 200GHz region
- Ps creation rate is similar to the previous gas
- A little bit expensive (~$10/g)

Data analysis
(Based on the first observation of Ps-HFS transition @ 202.9GHz)

ID	frequency	power	duration	live time (ON)	live time (OFF)	trigger rate
I	203 GHz	11.0 kW	4.3 days	7.0×10^4 sec	1.6×10^5 sec	949 Hz
II	140 GHz	3.3 kW	3.3 days	4.3×10^4 sec	1.0×10^5 sec	949 Hz
III	203 GHz	0.0 kW	2.4 days	4.1×10^4 sec	9.6×10^4 sec	936 Hz
IV	203 GHz	5.6 kW	2.8 days	3.8×10^4 sec	8.9×10^4 sec	932 Hz

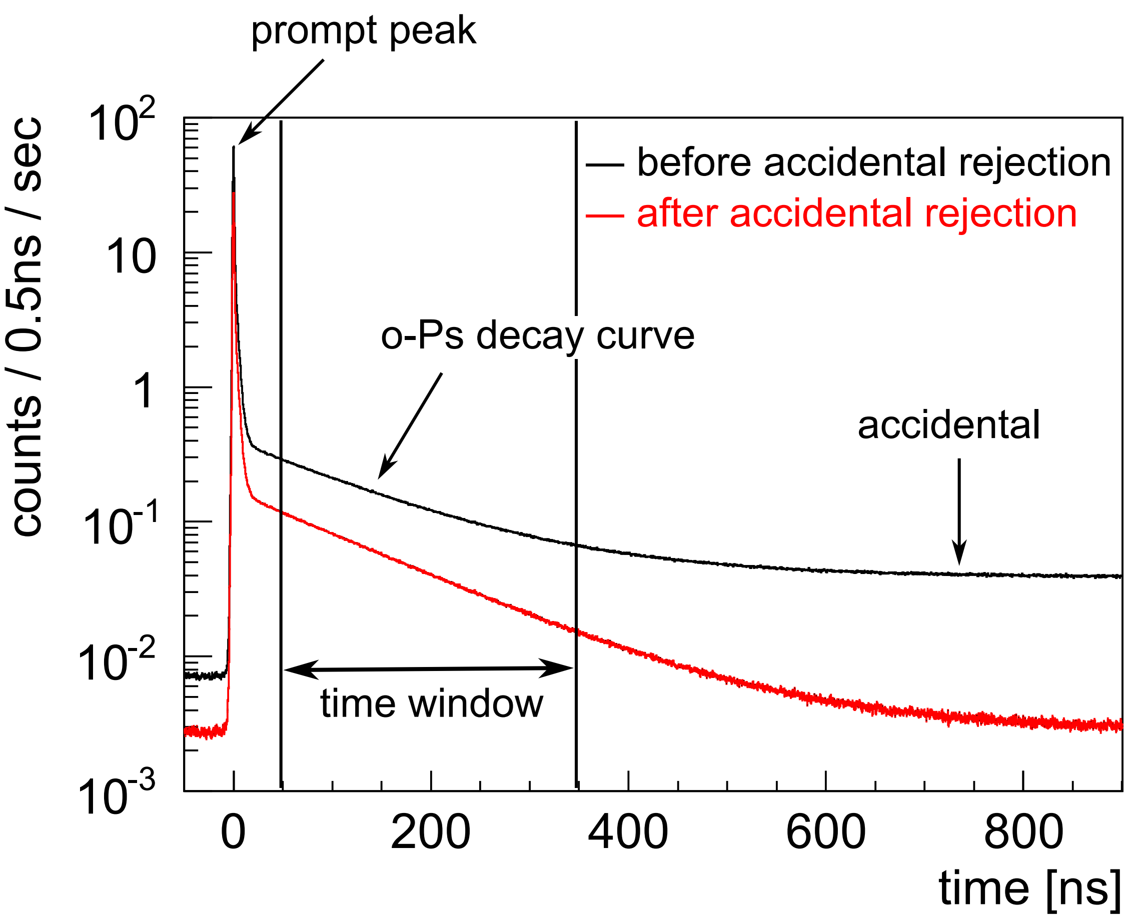
Direct observation of Ps-HFS transition

- Signal
  - ✓ o-Ps→p-Ps→2γ : long lifetime (τ = 142ns) of o-Ps & two back-to-back 511 keV γ rays
- Background
  - ✓ o-Ps→3γ : contamination of 3γ events due to the detector resolution
  - ✓ o-Ps→2γ (pick-off) : e^+ annihilation with e^- in gas molecule
  - ✓ accidental overlap of the triggered e^+ and uncorrelated γ rays
- Gyrotron output is pulse output (20Hz･duty 30%). Background is estimated using events during beam OFF period.



Event selection I (Delayed Coincidence)

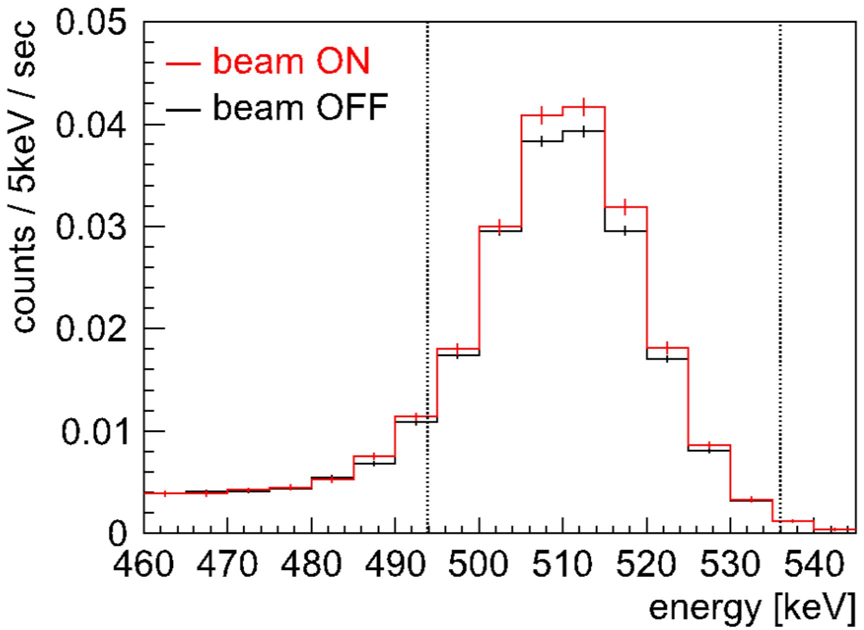
- Timing difference between the positron tag and the γ-ray detector signal
- Signals are enhanced by delayed coincidence



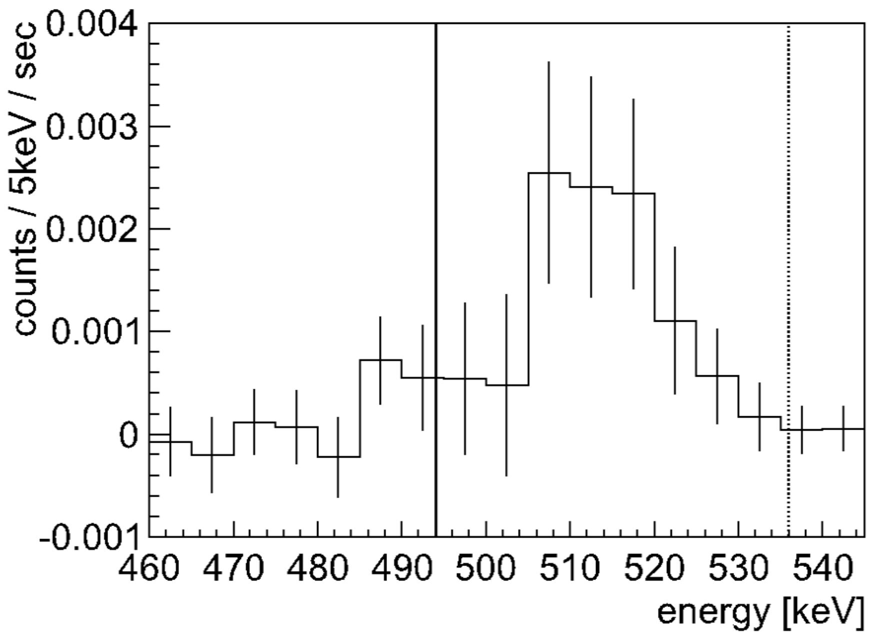
Event selection II (Back-to-back 511keV cut)

Events are selected by γ-ray detector's energy (496~531keV) and hit position (back-to-back)

Energy spectrum
(require 511keV for opposite side)



Transition signal (= ON – OFF)

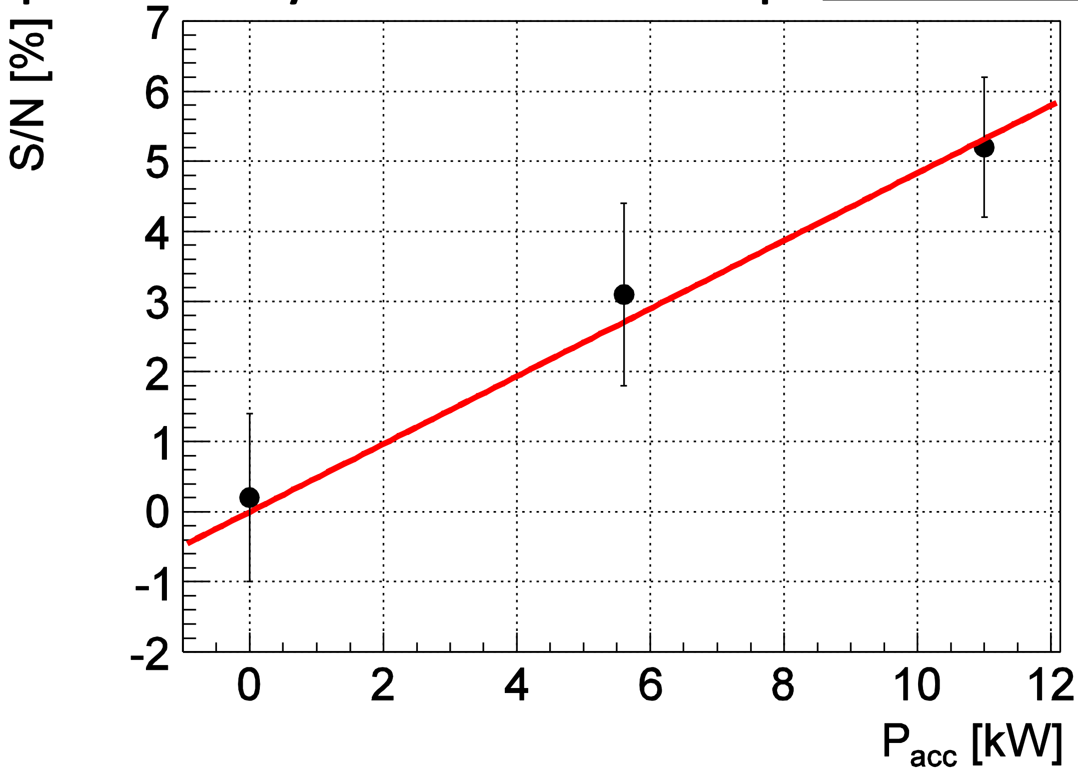


- Signal = ON − OFF = 15.1±2.7(stat.)$^{+0.5}_{-0.8}$ (sys.) mHz (**5.4σ**)
- First observation of Ps-HFS direct transition

Power dependence and transition probability

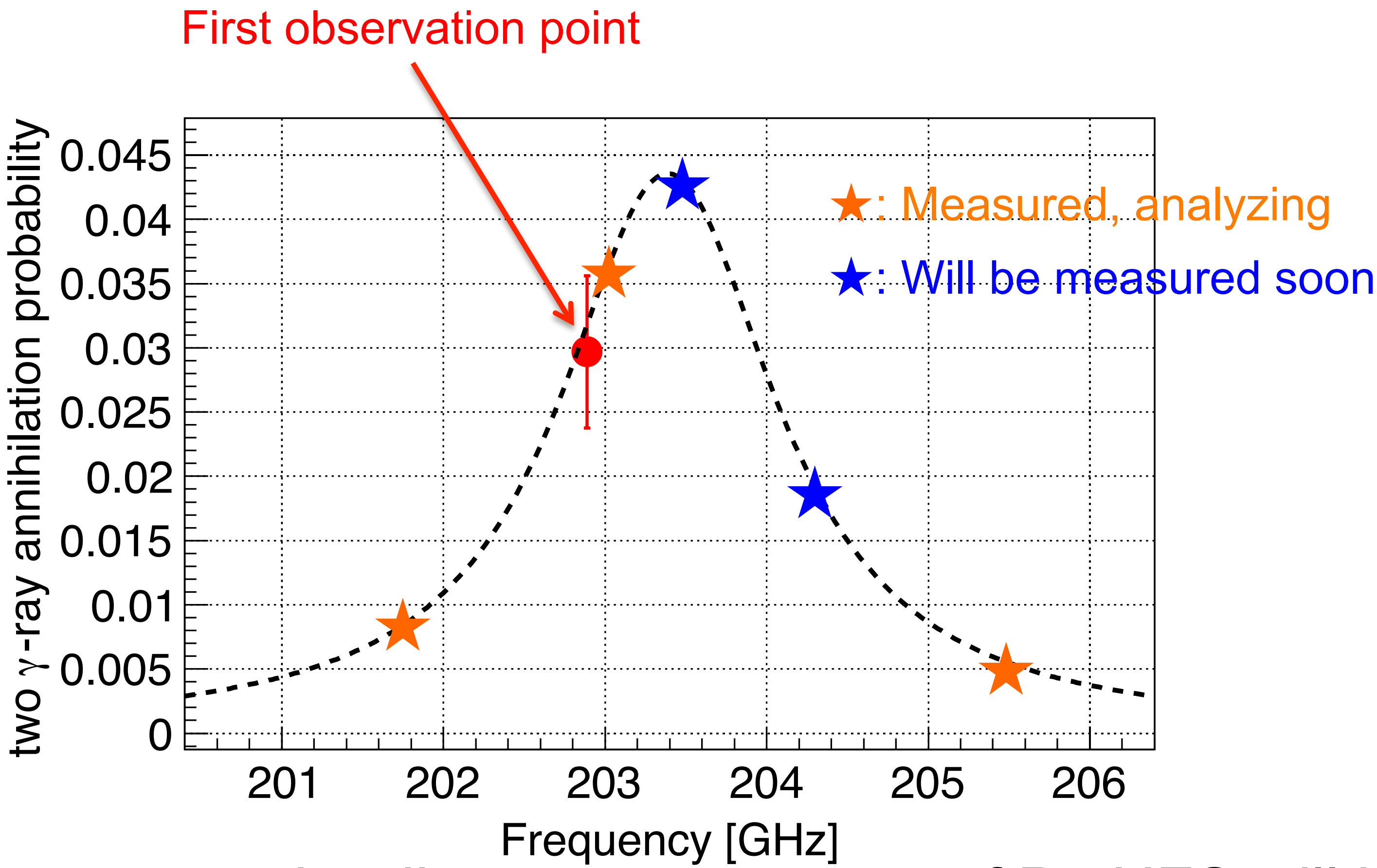
The events depends on the millimeter-wave power.

Dependency on millimeter power is confirmed



Obtained transition rate $A = 3.1^{+1.6}_{-1.2} \times 10^{-8}$ [s^{-1}] is consistent with the theoretical value 3.37×10^{-8} [s^{-1}]

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.

Summary

- Direct measurement of Ps HFS (203.4GHz) is interesting, because
  - New method to measure HFS can be a way to solve PS-HFS discrepancy
  - Millimeter wave can be a new eye for basic science
- A direct transition from o-Ps to p-Ps is firstly observed with a gyrotron and a Fabry-Pérot cavity
- We will directly measure Ps-HFS value in about a year for the first time