Direct Measurement of Positronium Hyperfine Splitting

- Testing Fundamental Physics with sub-THz Gyrotron-

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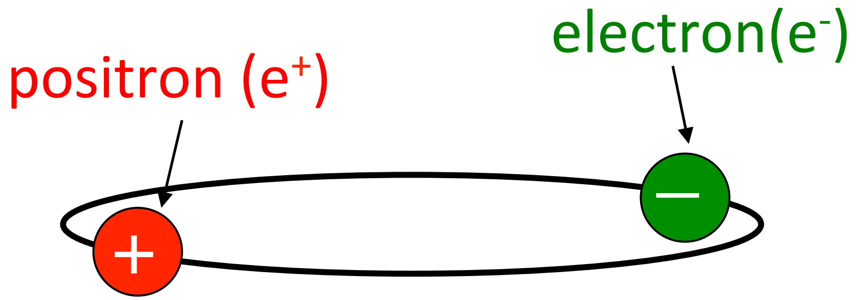
Positronium (Ps)

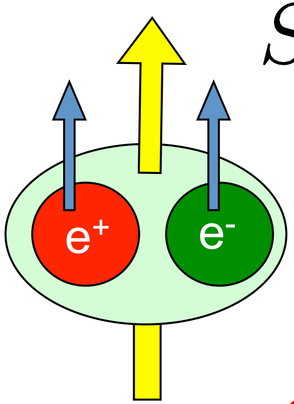


- Ps is the bound state of e^- and e^+
  - The lightest Hydrogen-like atom
  - The simplest particle-antiparticle system
  - Good target to study Quantum Electrodynamics in the bound state

Two spin eigenstates (*o*-Ps, *p*-Ps)

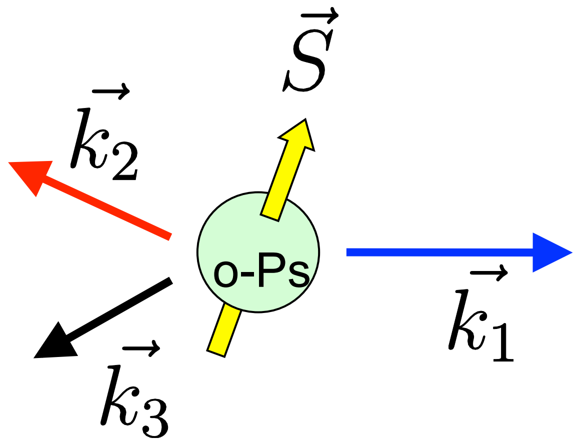
- *ortho*-positronium (*o*-Ps)

$S = 1$ spin triplet $^3S_1$



long lifetime 142ns

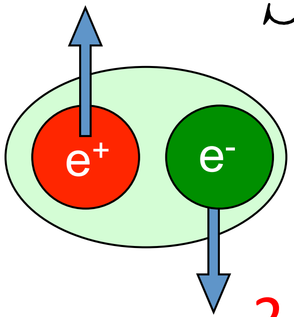
o-Ps → 3γ (, 5γ, ...)



Continuous energy spectrum & long lifetime (142ns)

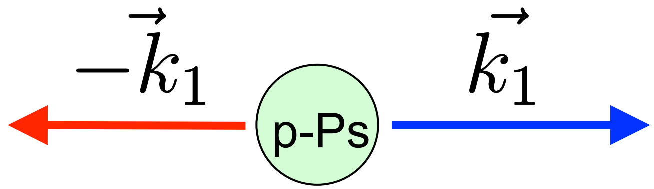
- *para*-positronium (*p*-Ps)

$S = 0$ spin singlet $^1S_0$



short lifetime 125ps

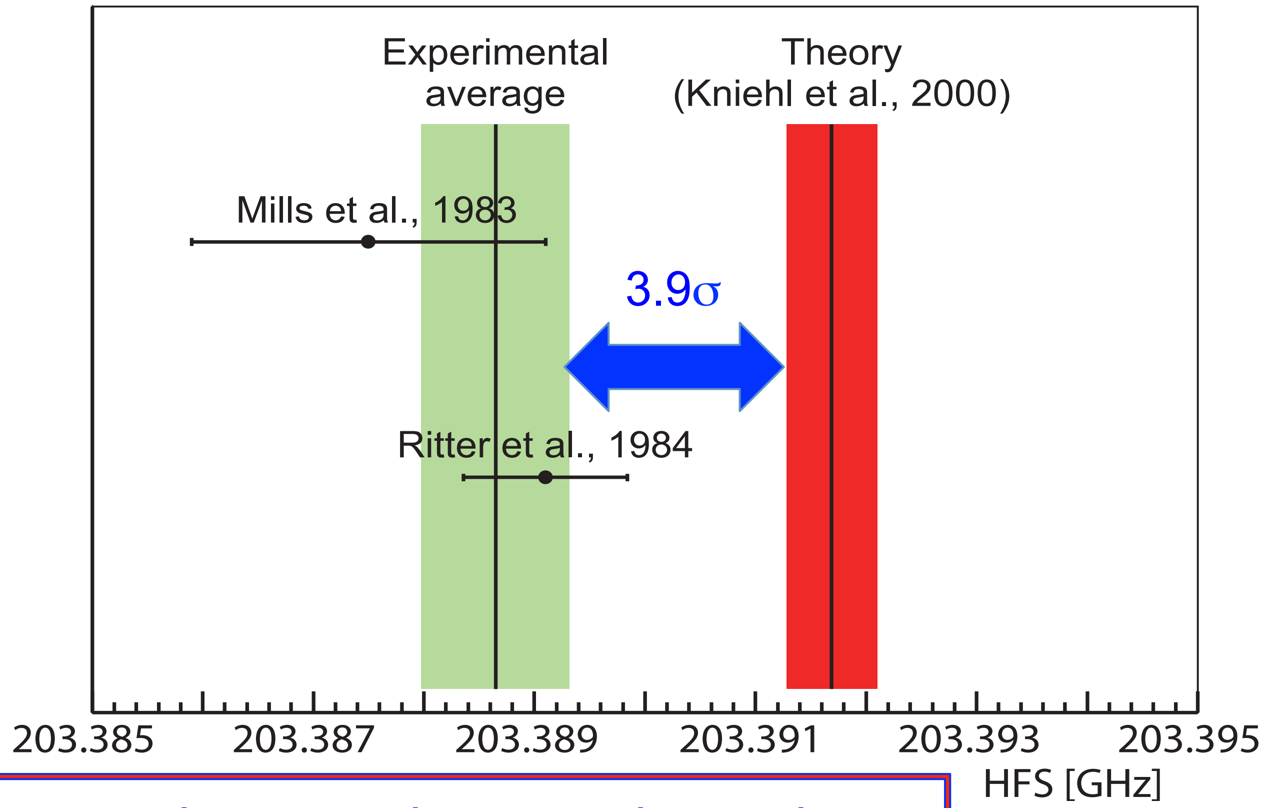
p-Ps → 2γ (, 4γ, ...)



2 back-to-back 511keV γ rays & short lifetime (125ps)

Hyperfine Splitting of Positronium (Ps-HFS)

Energy difference between *o*-Ps and *p*-Ps, about 203 GHz

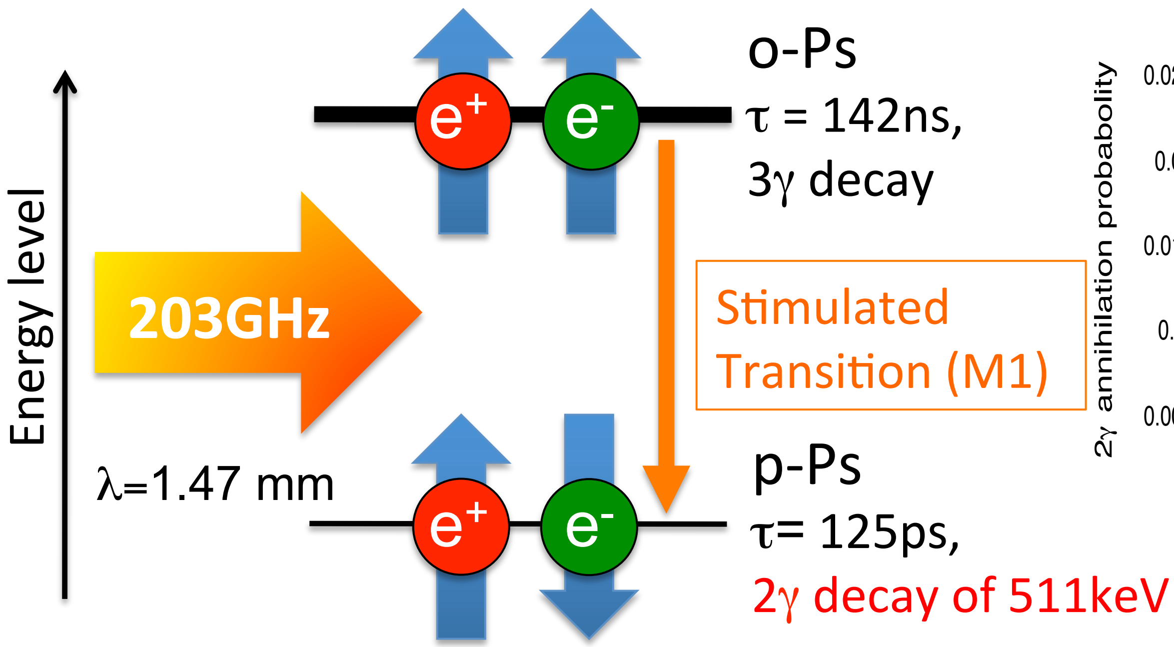


Large discrepancy between theory and experiment.

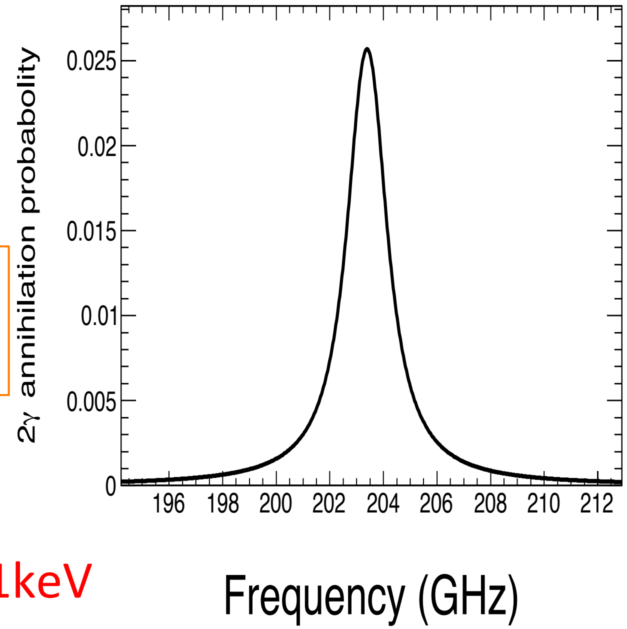
A completely different method is necessary to check this discrepancy.

In this presentation, the proposal for the new method and current status are explained.

Direct Transition

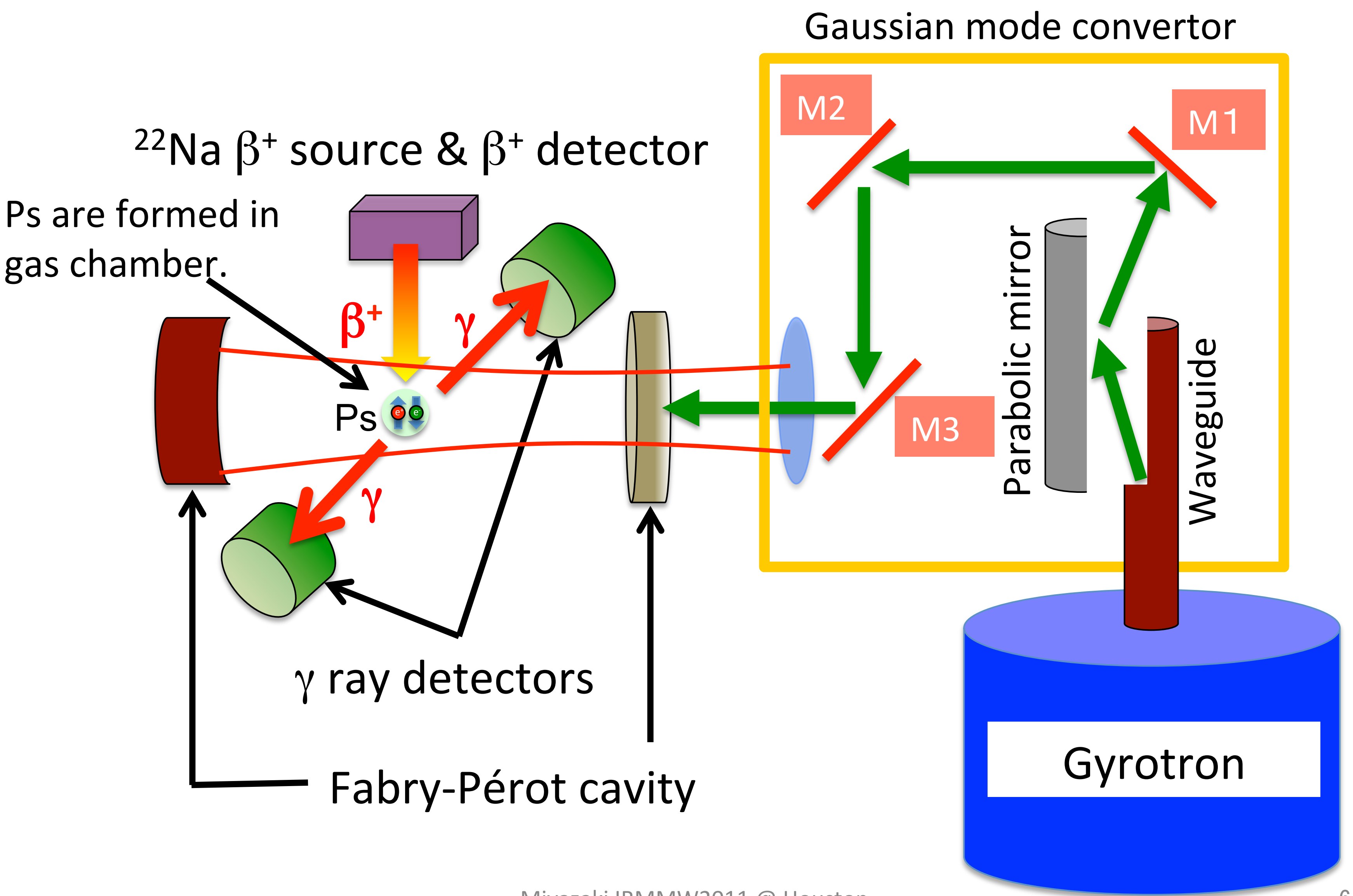


transition curve (calculation)



- <u>No one has ever observed the direct transition between these states.</u>
  - Spontaneous emission rate is extremely small (3×10^{-8} [s^{-1}])
  - High power (over 10kW) sub-THz (203GHz) radiation is necessary.
- Frequency-tunability is also necessary to measure Ps-HFS (*future plan*)
- Our first aim was to observe the direct transition

Experimental Setup



Gyrotron

We use a gyrotron (gyromonotron) dedicated to our experiment.

Stable power is 300W (duty 30%, 20Hz)

Frequency is 202.9 GHz

Cavity resonant mode is TE_{031}

The stable operation continues 170 hours with feedback control of heater voltage.

(Accumulated operation time = 3000 hours)

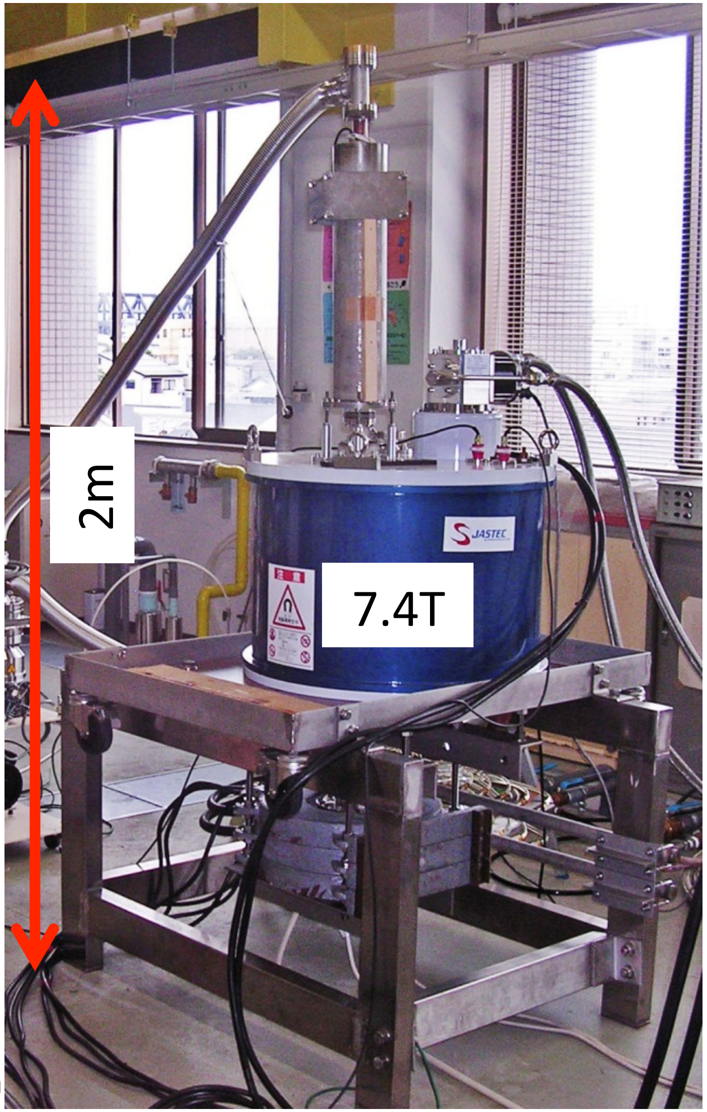
Operating main magnetic field B_0 =7.4 T

Acceleration voltage V_k = 18 kV

Modulation anode voltage V_a = 12 kV

Beam current I_b = less than 0.5 A

FU CW V @ University of Fukui



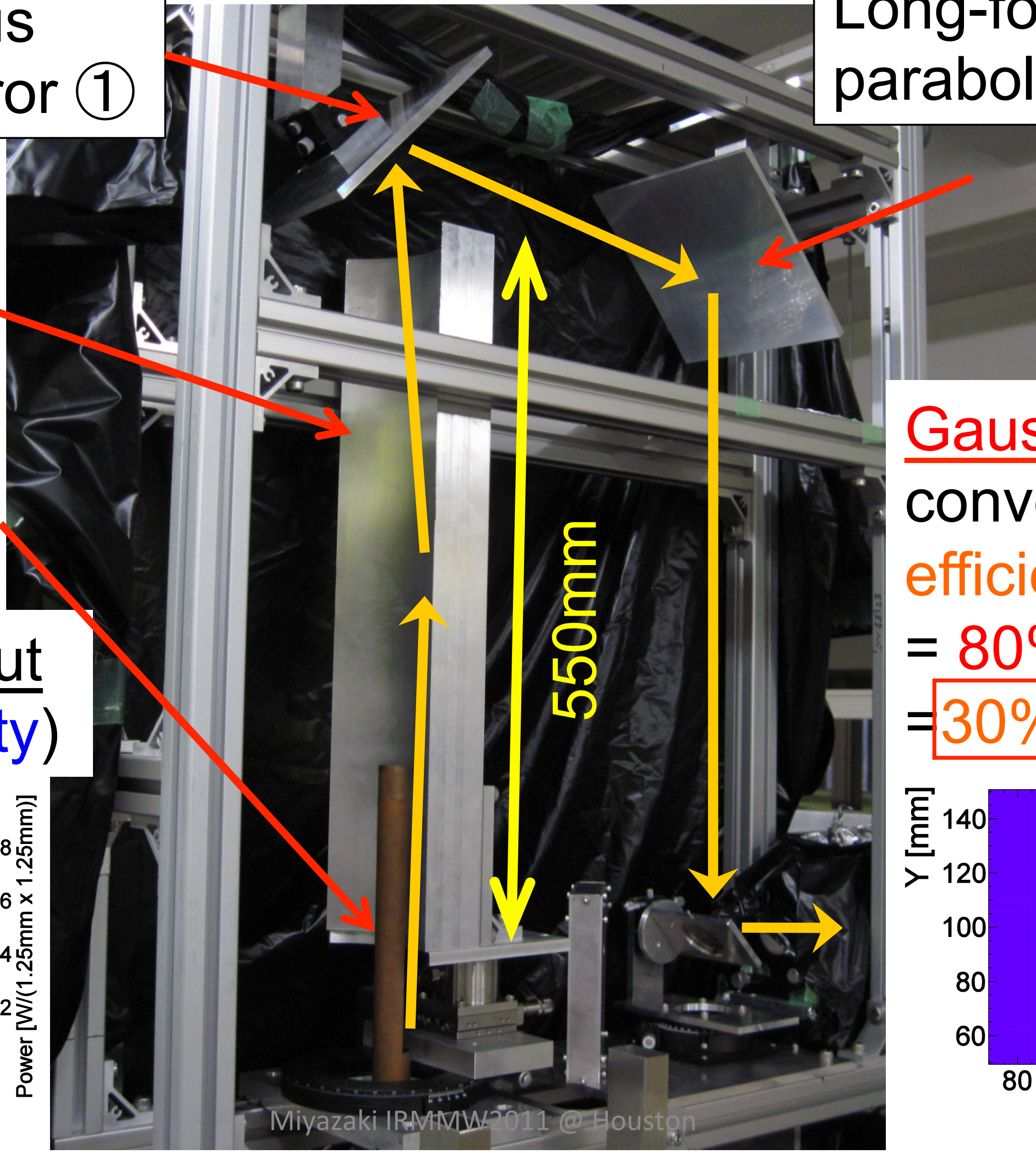
Gaussian mode converter

Long-focus parabolic mirror ①

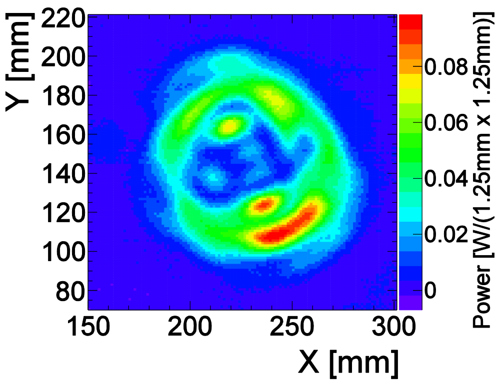
Long-focus parabolic mirror ②

Parabolic mirror
(Vlasov et al. 1972)

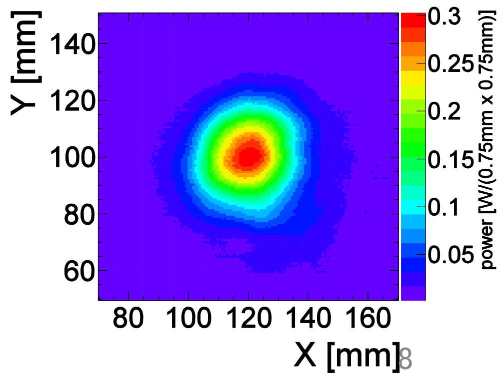
Step-cut waveguide



Gyrotron output
TE_{03} (40%purity)

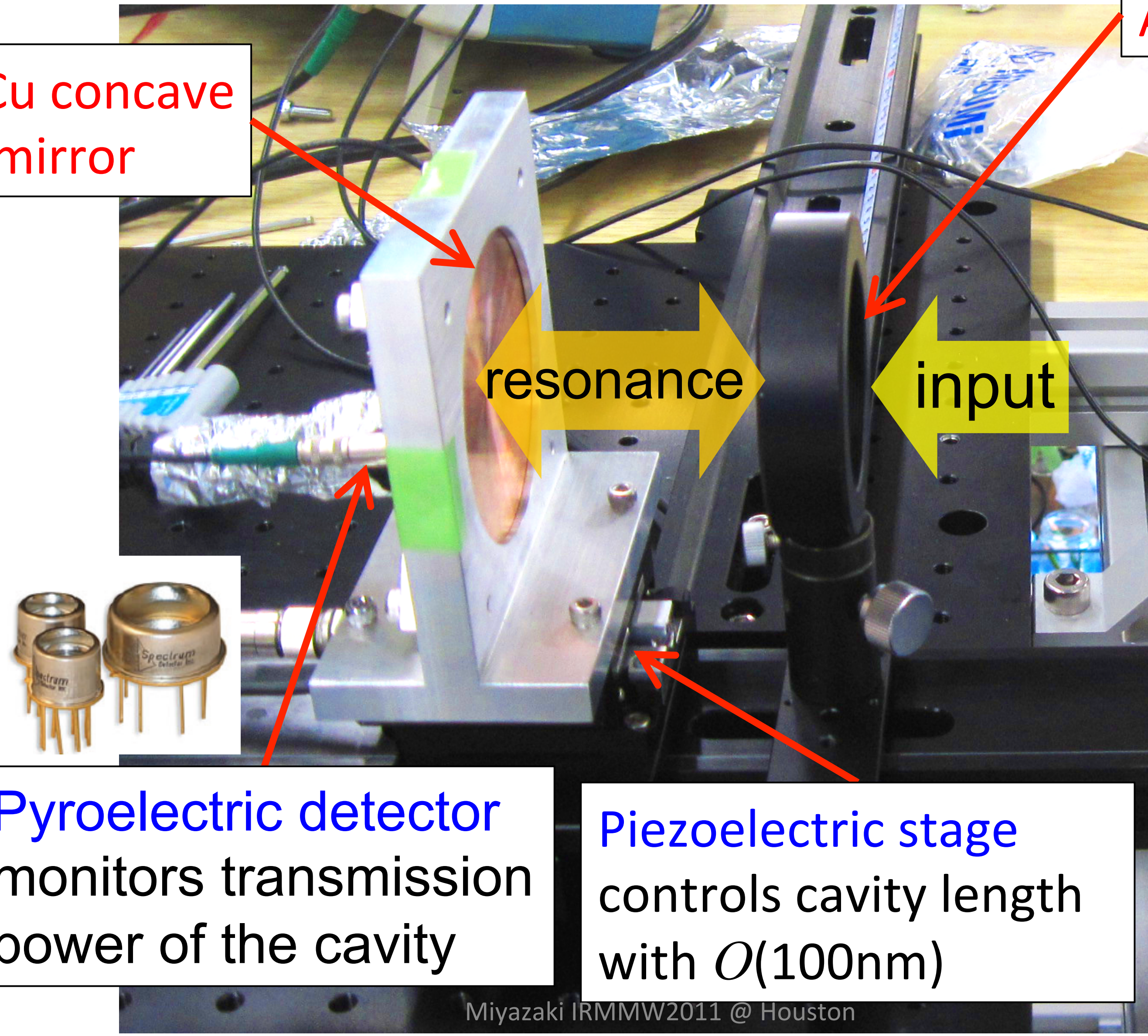


Gaussian beam conversion efficiency
= 80% • 40%
= 30%



Fabry-Pérot cavity

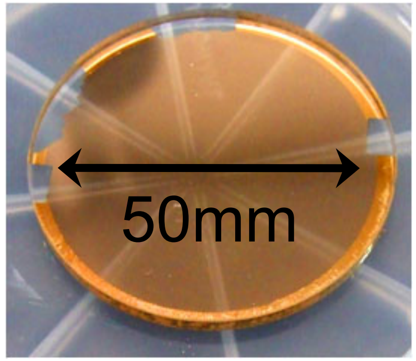
Cu concave mirror

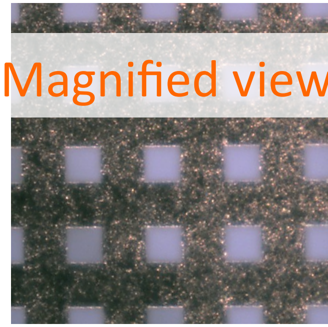


Pyroelectric detector
monitors transmission power of the cavity

Piezoelectric stage
controls cavity length with O(100nm)

Au mesh mirror

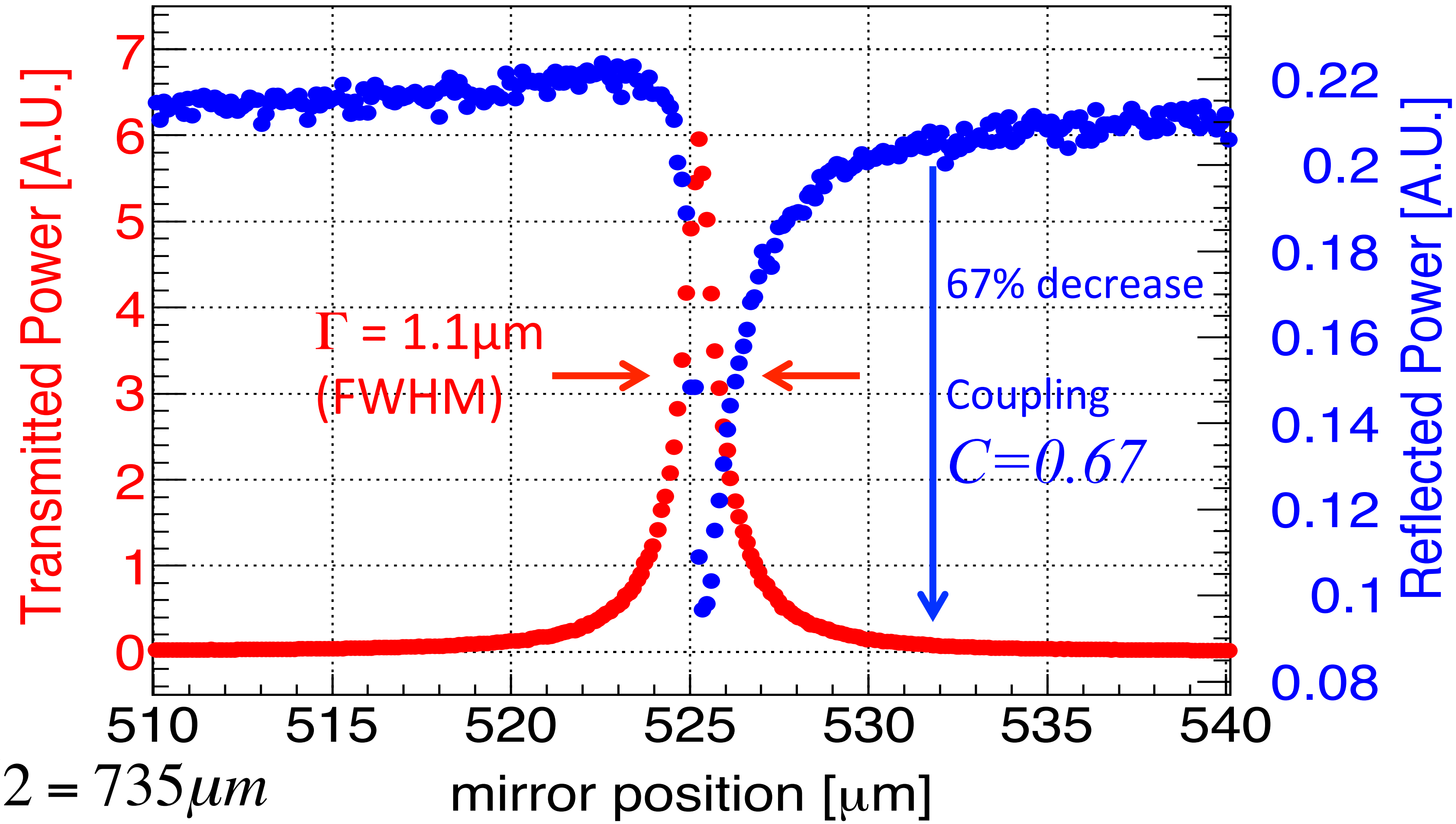




width=200 μ m,
gap=150 μ m
Thickness=1μm

R = 99.3%, T = 0.5%
(FEM simulation)

Milli-wave accumulation in the Fabry-Pérot cavity



$\lambda/2 = 735\mu m$

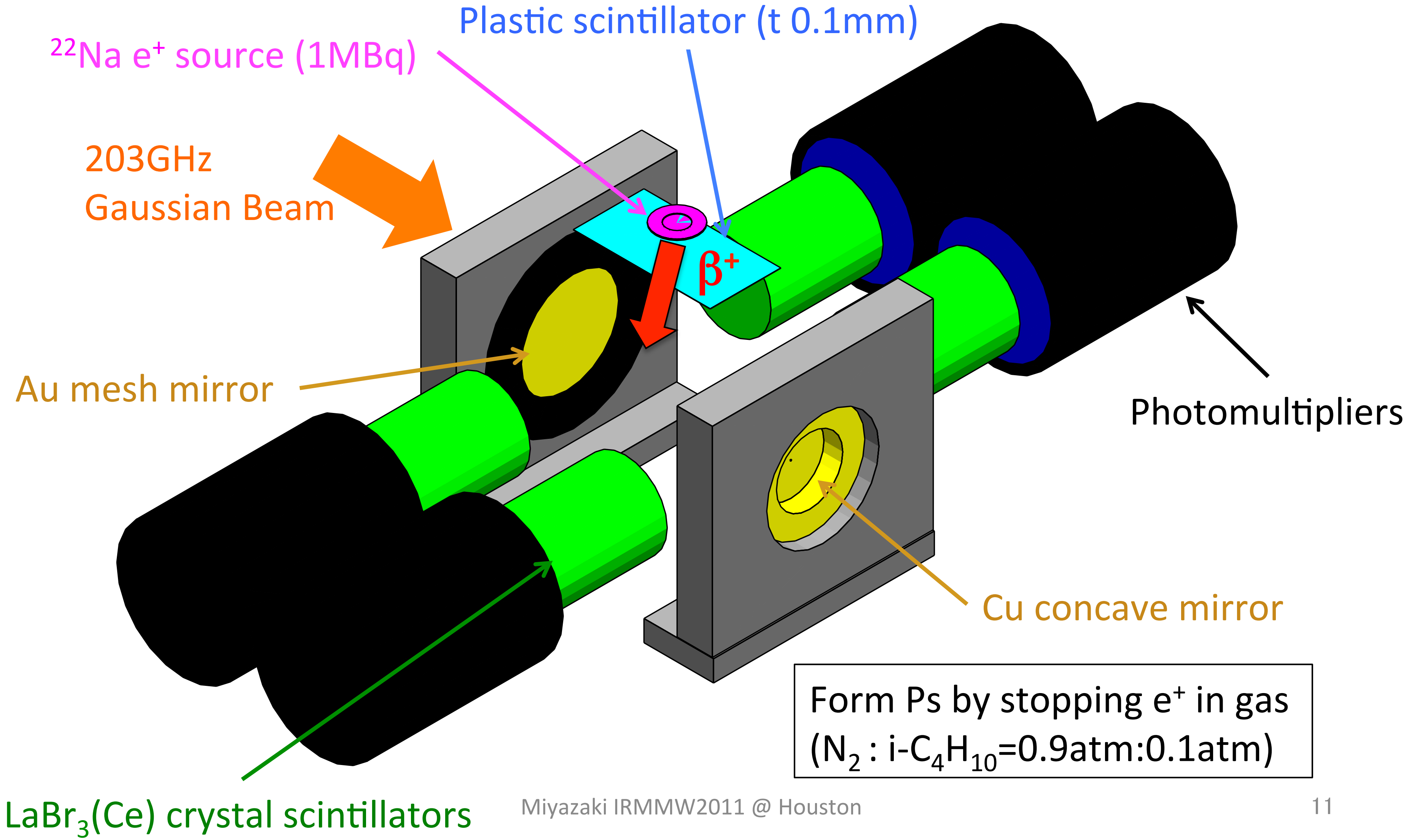
$$Gain \approx \frac{\lambda}{2\pi\Gamma} \bullet C = 140$$

Accumulated power
300W x 30% x gain140 = 12kW

Ps Assembly and γ-ray detectors

A ^{22}Na source emits positron.

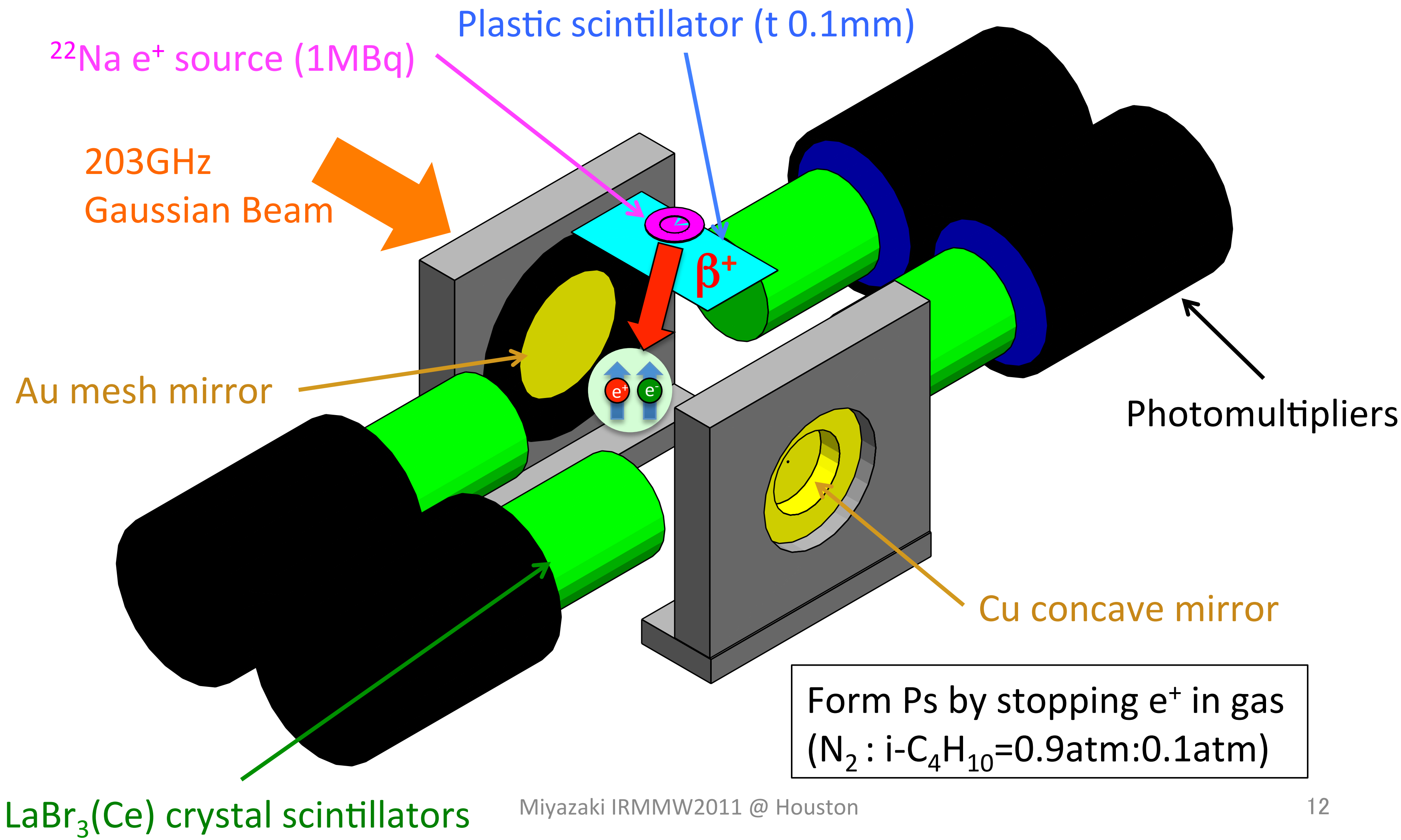
A plastic scintillator detects the emission.



Form Ps by stopping e^+ in gas
(N_2 : i-C_4H_{10}=0.9atm:0.1atm)

Ps Assembly and γ-ray detectors

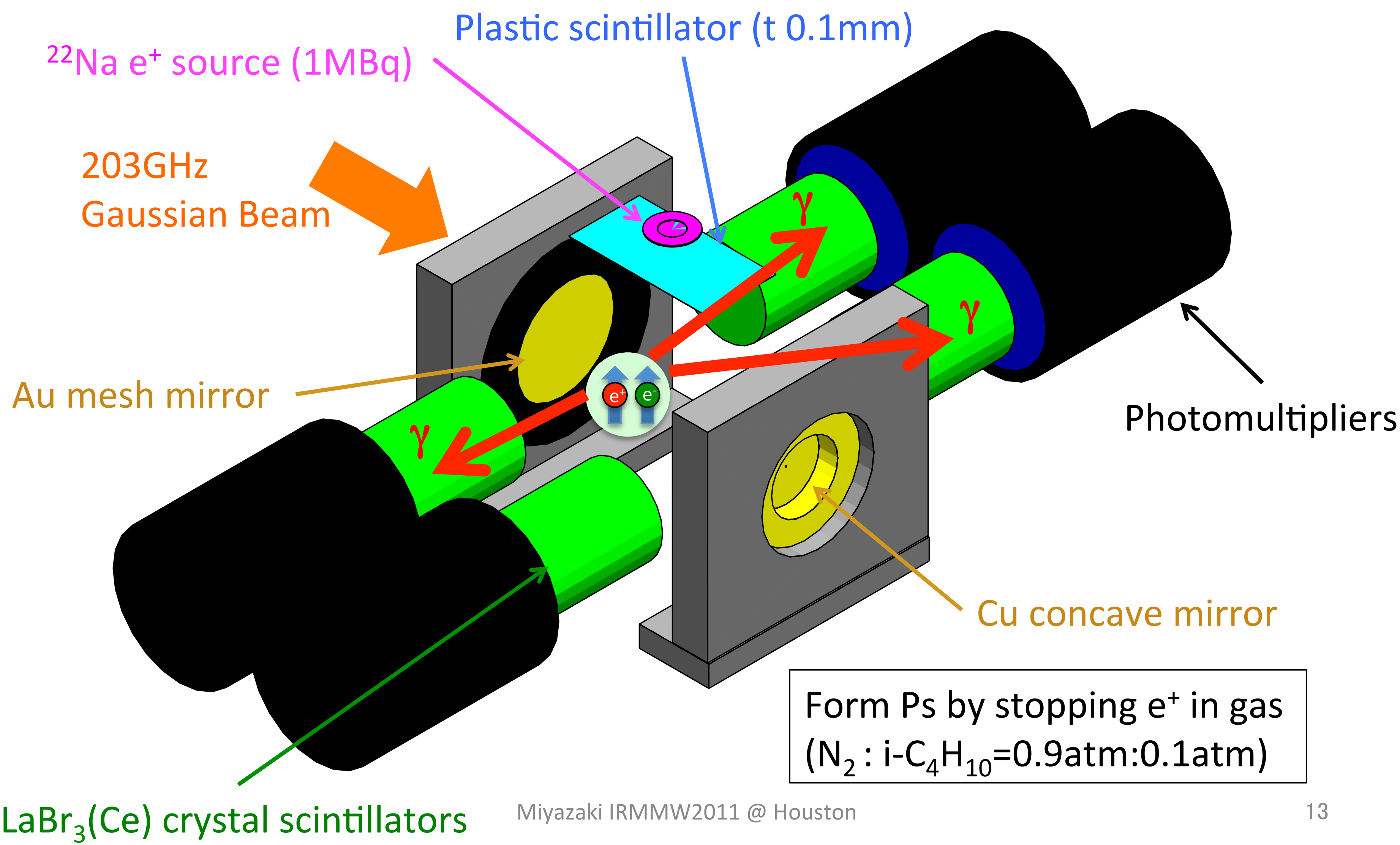
A positron forms a positronium with an electron in gas molecule



Form Ps by stopping e$^+$ in gas
(N_2 : i-C_4H_{10}=0.9atm:0.1atm)

Ps Assembly and γ-ray detectors

Non transited o-Ps decays into three γ-rays



Form Ps by stopping e^+ in gas
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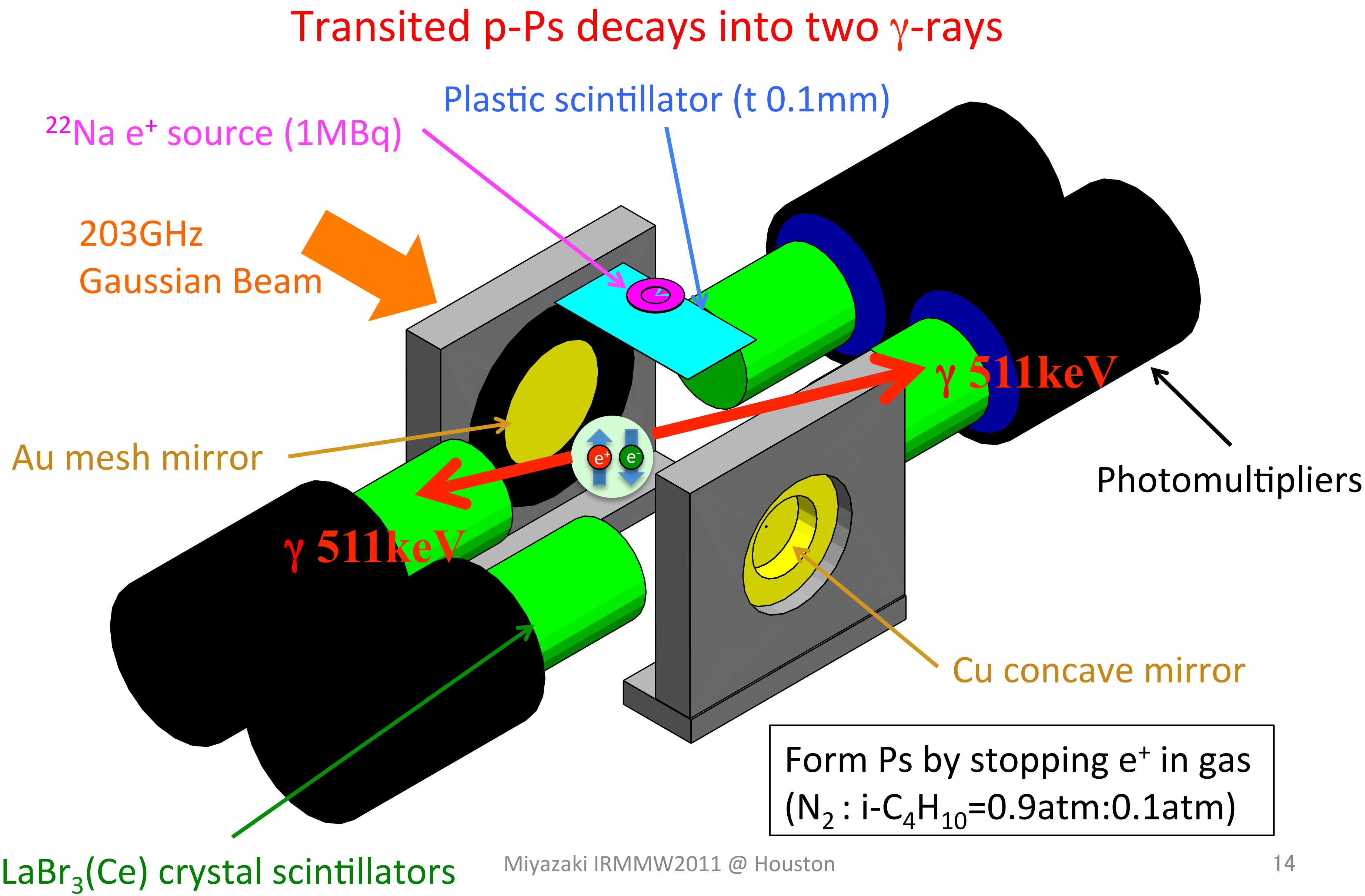
Ps Assembly and γ-ray detectors



Form Ps by stopping e^+ in gas
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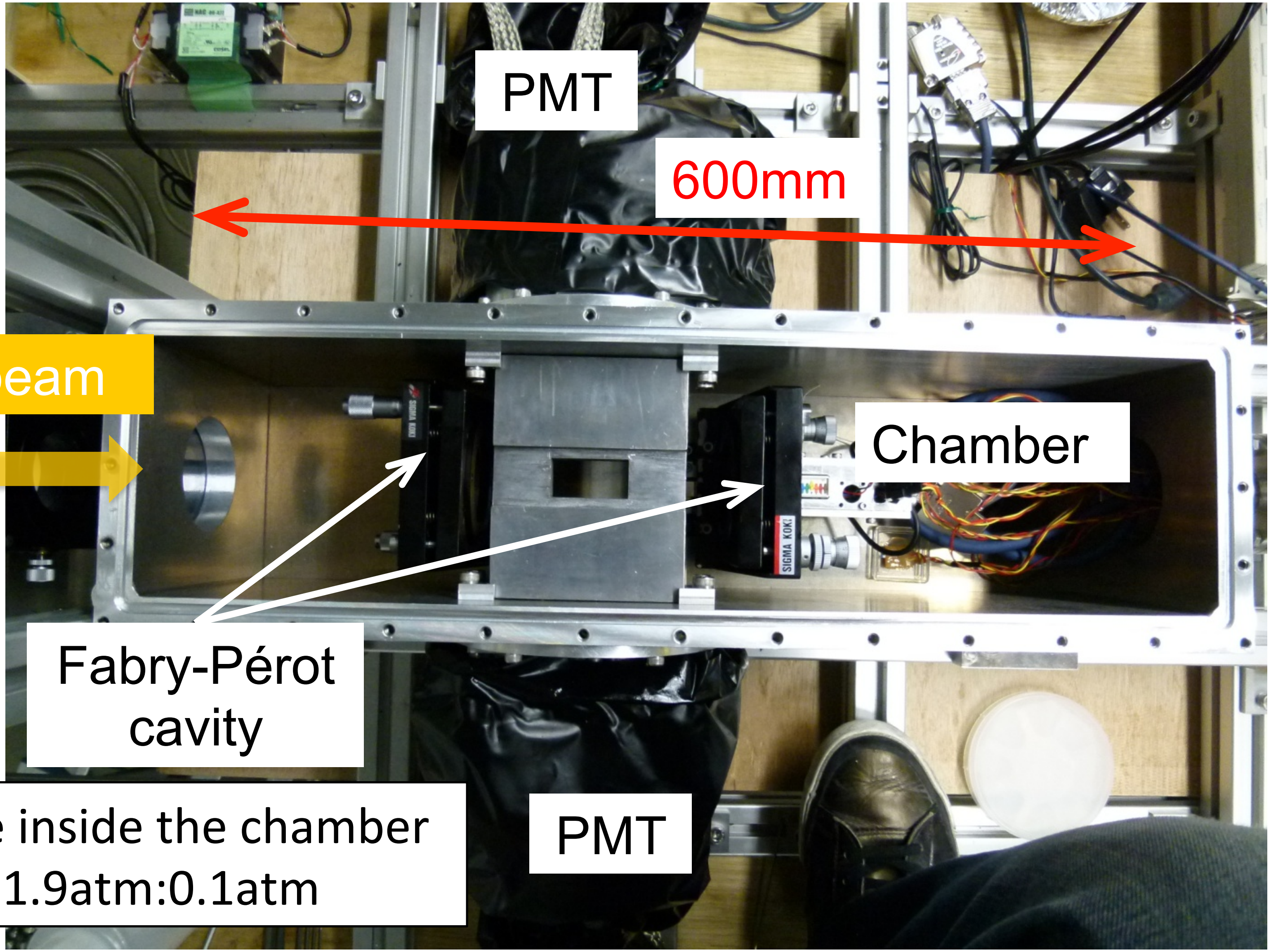
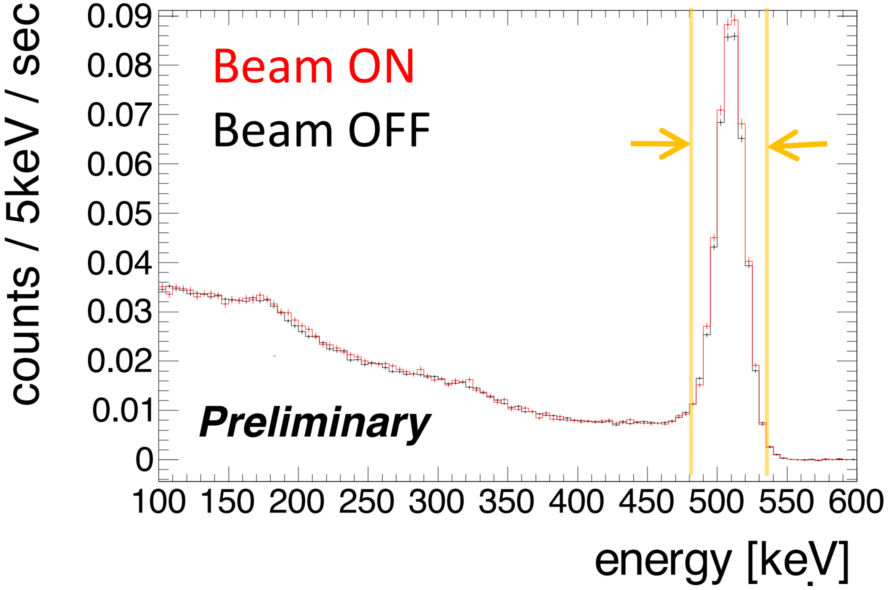
Ps-assembly & γ-ray detectors

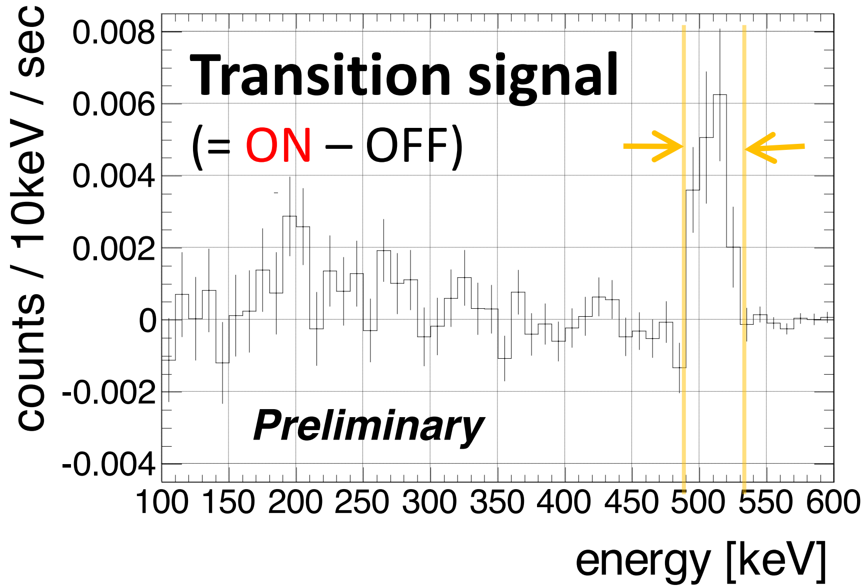


Gas mixture inside the chamber
N_2:i-C_4H_{10} = 1.9atm:0.1atm

Results

- Below figures show energy spectra on the condition of time window (50 – 250ns & pileup rejection & 511keV±2σ @ opposite $LaBr_3$(Ce)
- Beam ON events and beam OFF events were acquired alternately because we used pulse beam gyrotron (20Hz, duty 30%).





- **The first observation of direct transition between o-Ps and p-Ps is achieved**

•Signal = ON – OFF = 15.2± 3.0 (stat.) $^{+0.6}_{-0.1}$ (sys.) mHz

Future prospects

- In order to measure Ps-HFS…
  - We are developing a frequency tunable reflective gyro-BWO (N.C. Chen, et al. Appl. Phys. Lett. 96 (2010) 161591)
  - Backward-wave interaction makes gyrotron continuously tunable.
  - The frequency is tuned for several GHz by changing the magnetic field B_0.

NOT YET BEEN OPTIMIZED…

V_k=25 kV, V_a=20 kV, I_b=0.3 A, B_0=7.4-7.7 T, B_c=0.1 T

Summary

- We break ground in sub-THz spectroscopy with Gyrotron.
- Our final goal is direct measurement of Ps-HFS
- **No one had ever observed even direct transition between o-Ps and p-Ps**
- We developed new sub-THz optical system.
- Accumulated power in the cavity was around 10kW.
- The power is stabilized for over 1 week continuously with feedback control of the gyrotron.
- **First observation of the direct transition between o-Ps and p-Ps is achieved.**
- We are developing a new frequency-tunable gyrotron.