First Direct Measurement of Hyperfine Splitting of Positronium using sub-THz light

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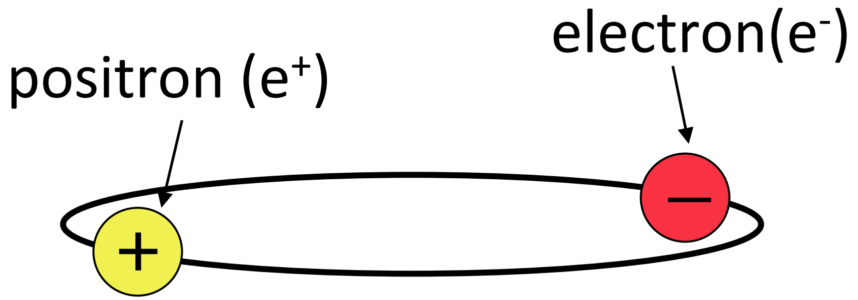
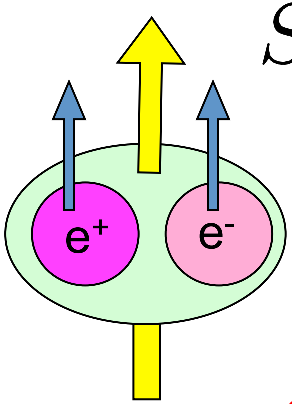
Positronium (Ps)



- Ps is the bound state of e^- and e^+
  - The lightest Hydrogen-like atom
  - exotic atom, particle-antiparticle system
  - good target to study bound state QED because it's free from hadronic uncertainty

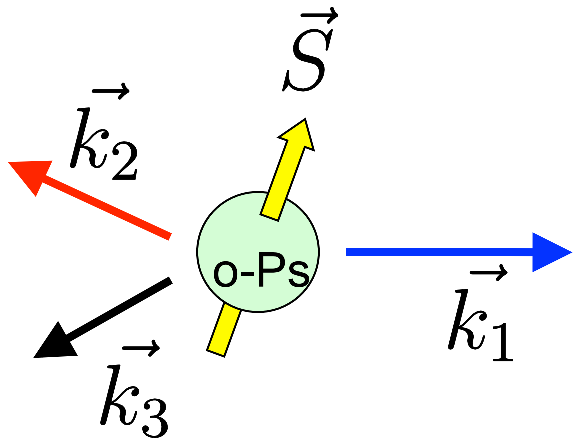
Positronium (o-Ps, p-Ps)

- ortho-positronium (o-Ps)



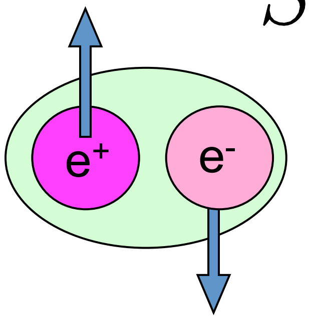
$S = 1$ spin triplet

long lifetime 142nsec
o-Ps → 3γ (, 5γ, …)



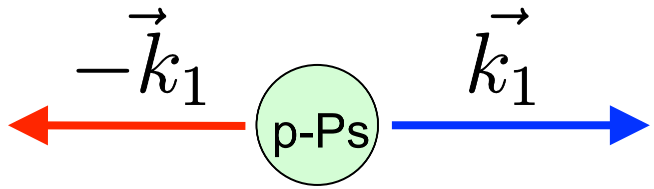
Continuous energy spectrum & long lifetime (142ns)

- para-positronium (p-Ps)



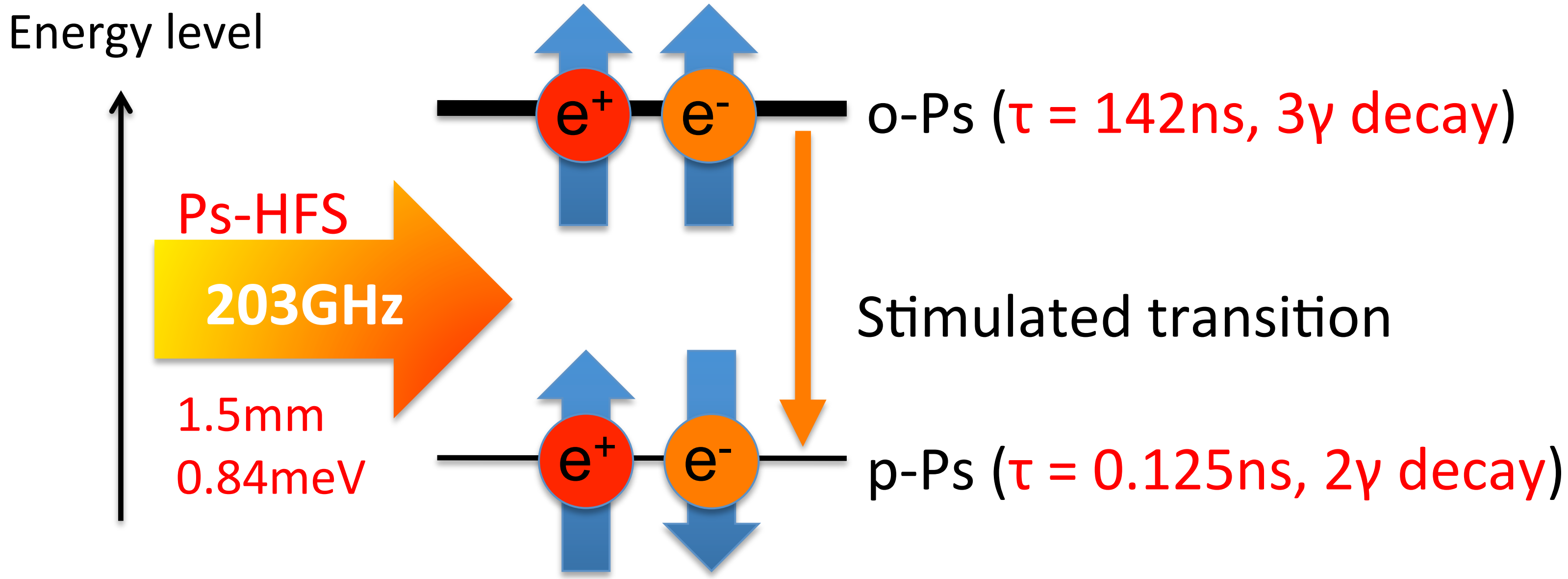
$S = 0$ spin singlet

short lifetime 0.125nsec
p-Ps → 2γ (, 4γ, …)



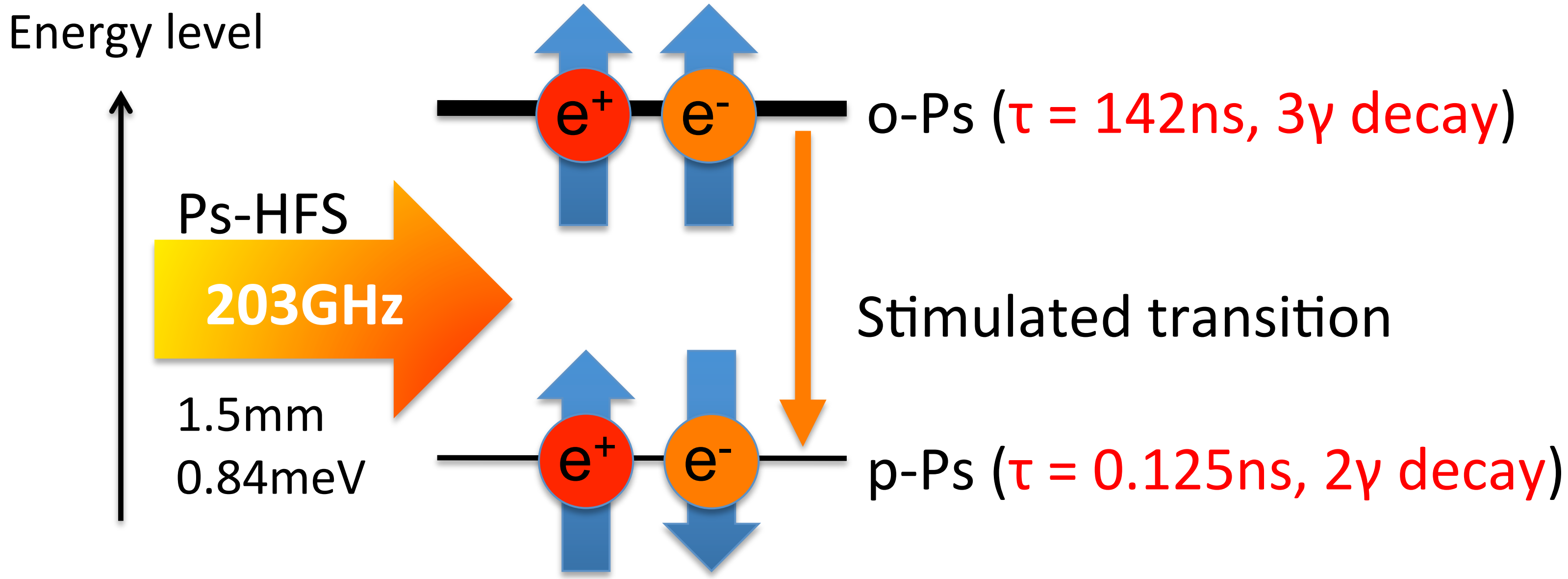
2 back-to-back 511keV γ rays & short lifetime (0.125ns)

Ps-HFS, Direct Transition



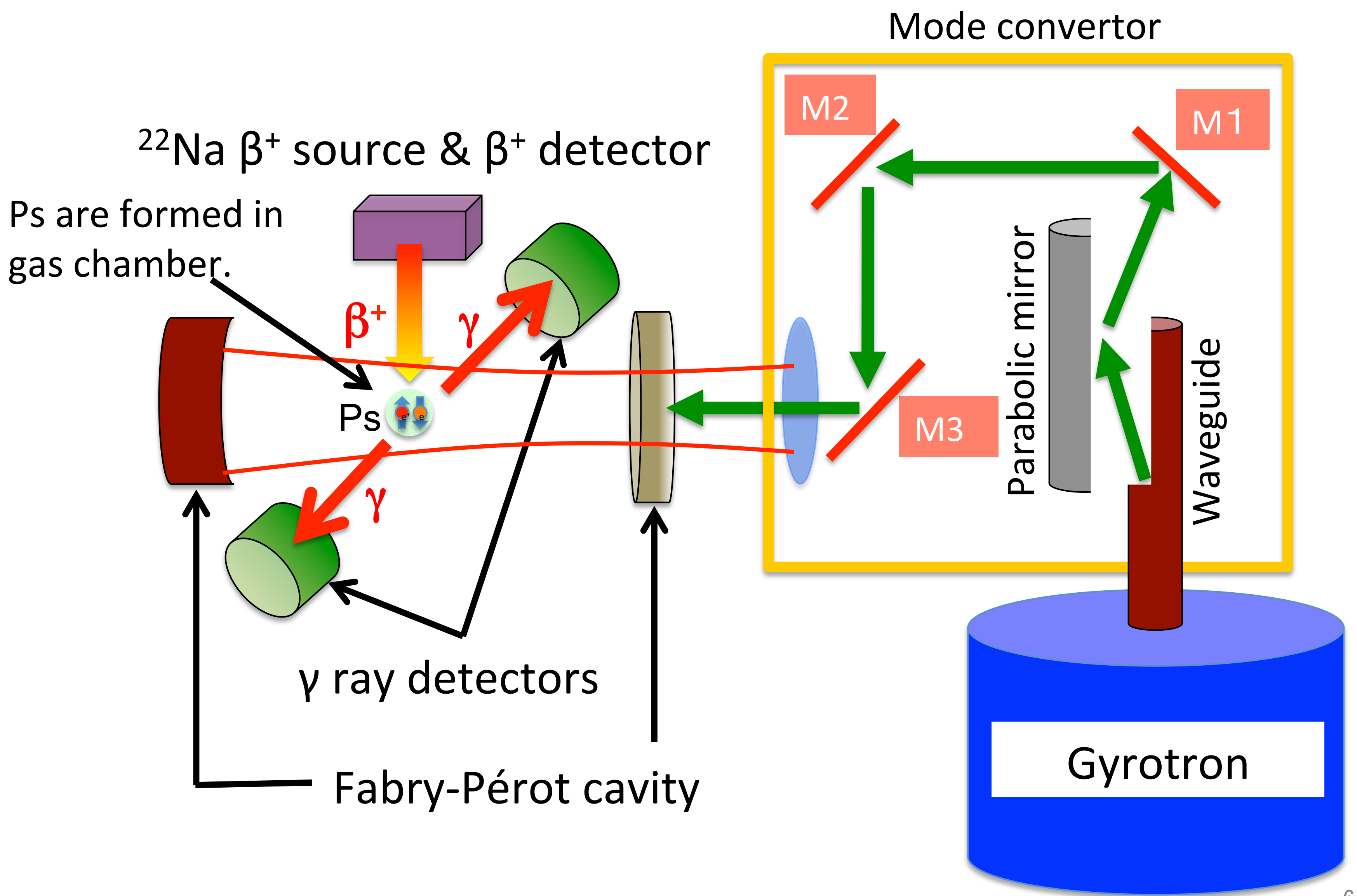
- Ps-HFS is energy difference between ground state p-Ps and o-Ps
- <u>No one has ever observed direct transition between these states</u>
- Spontaneous emission probability (3×10^{-8} [s^{-1}]) is smaller than o-Ps decay probability (7×10^{6} [s^{-1}]) by 14 orders of magnitude
- High power (over 10kW) sub-THz (203GHz) radiation is necessary to drive enough stimulated transition
- Frequency-tunability is also necessary to measure Ps-HFS

How to Detect Transition



- Transitions between o-Ps and p-Ps result in increase of 2γ decay rate because lifetime of p-Ps (τ = 0.125ns, 2γ decay) is shorter than that of o-Ps (τ = 142ns, 3γ decay) by 3 orders of magnitude
- Our "signal" is 2γ decay from p-Ps which is created via transition from o-Ps, which have a distinctive feature of 2 back-to-back γ rays with long lifetime (τ = 142ns)

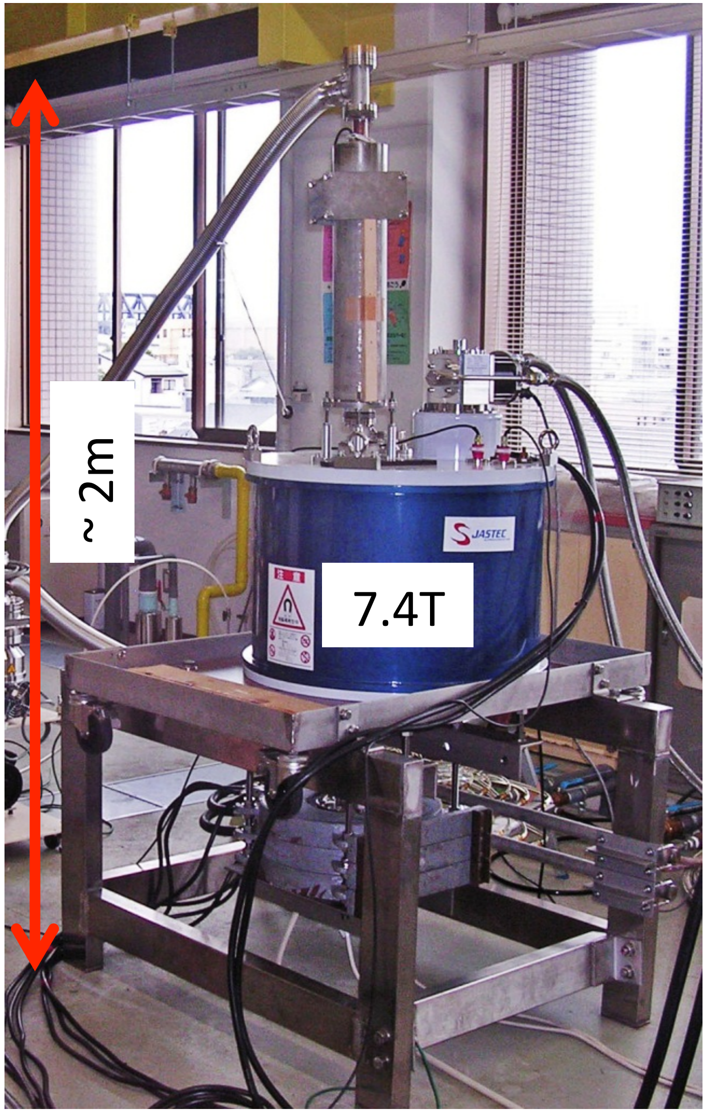
Experimental Setup



Gyrotron

- electron cyclotron maser
- tune magnetic field (~7.4T) such that the electron cyclotron frequency is slightly smaller than the cavity resonant frequency, then the energy of the cyclotron motion is converted to the energy of EM wave in the cavity
- the only high power (100W – 1kW) coherent radiation source in sub-THz region
- Currently we use a monochromatic gyrotron dedicated to our experiment, whose peak power is 300W (5Hz pulse output, duty 30%, 202.9 GHz)

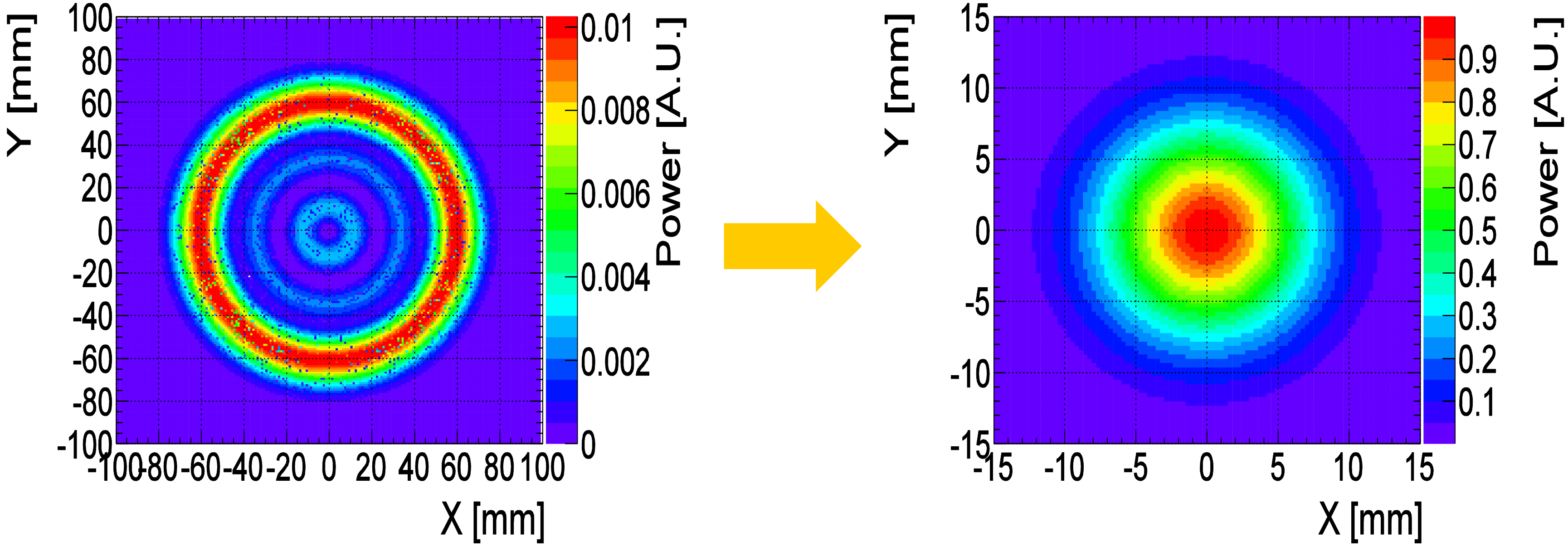
Gyrotron @ University of Fukui



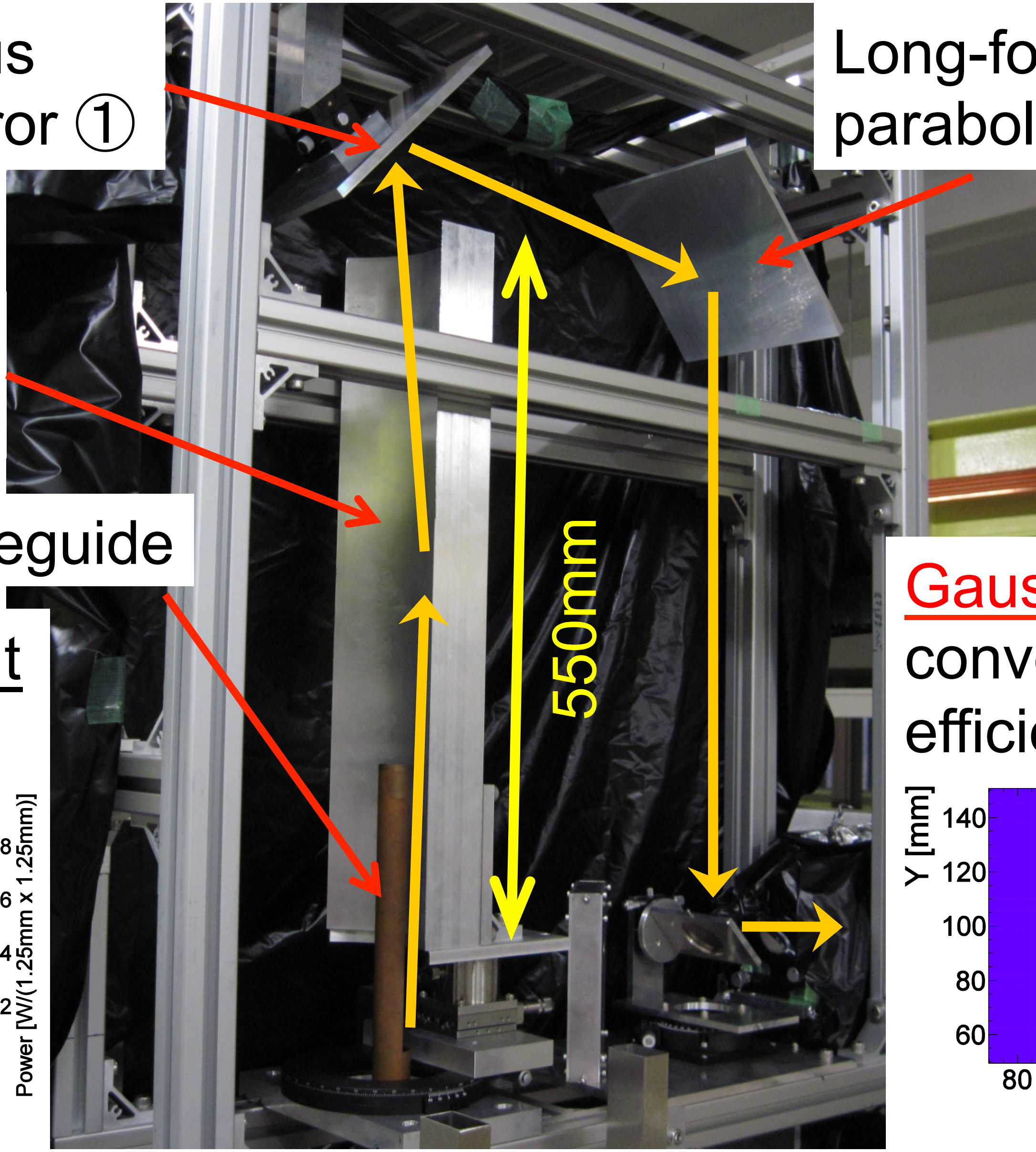
Mode Conversion

- Gyrotron output = TE_{03} waveguide mode
- Fabry-Pérot cavity mode = Gaussian beam (= TEM_{00})
- have to convert gyrotron output to Gaussian beam in order to couple the sub-THz radiation with the Fabry-Pérot cavity

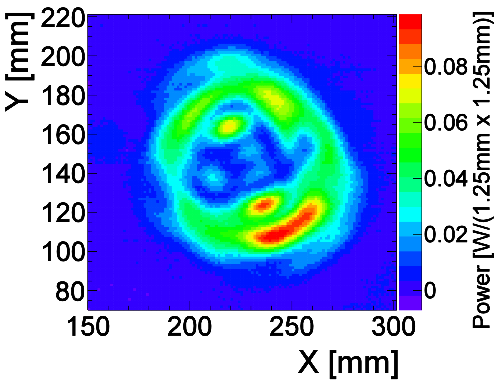
TE_{03} (far-field, <u>calculation</u>) Gaussian beam (<u>calculation</u>)



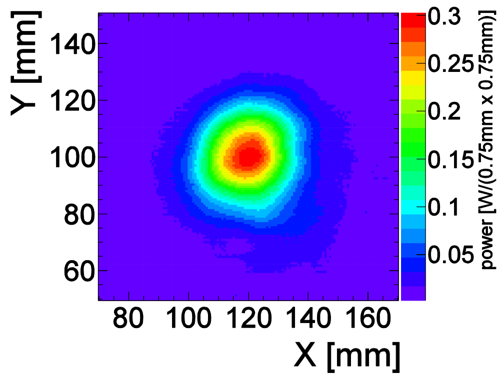
Mode Converter



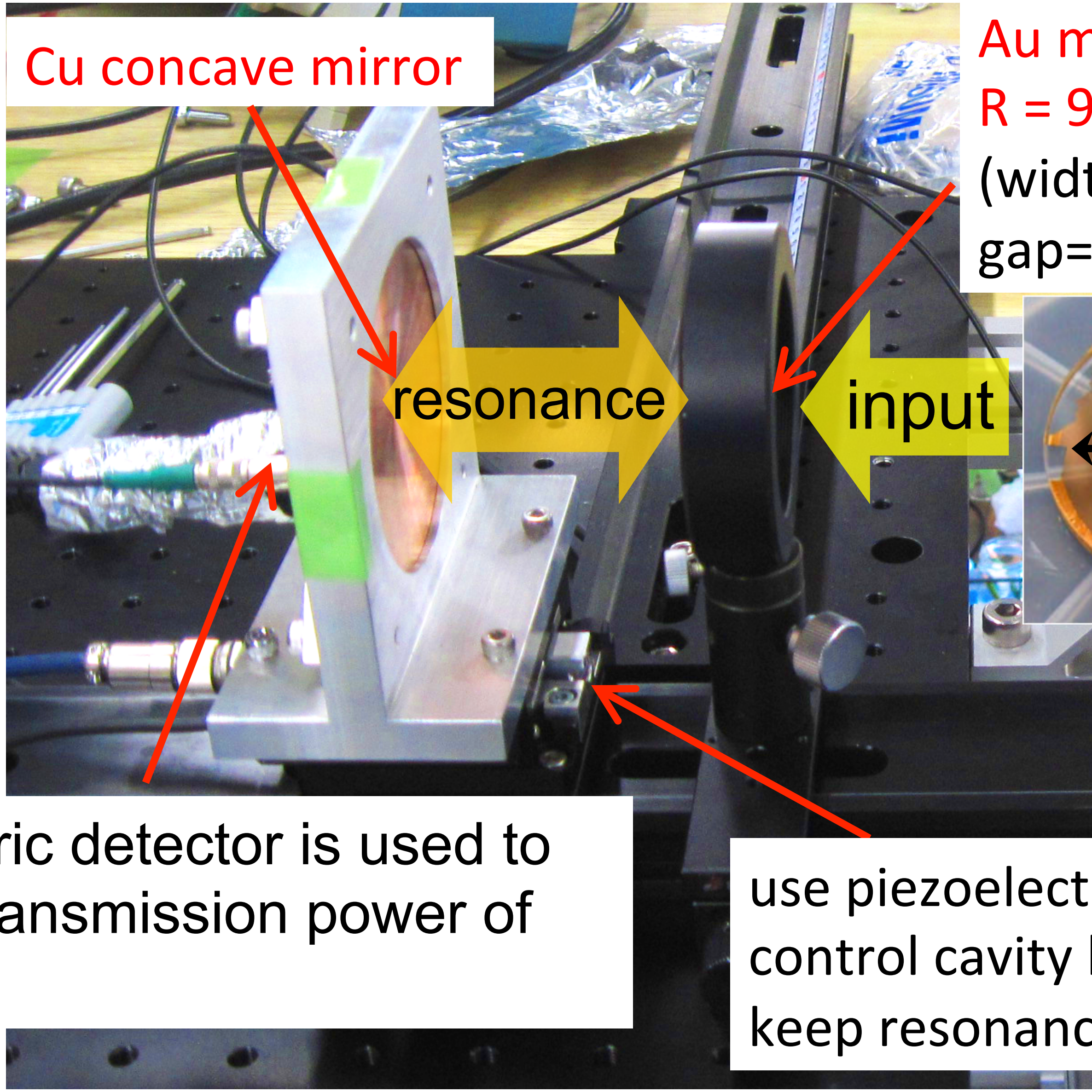
Gyrotron output
TE_{03}



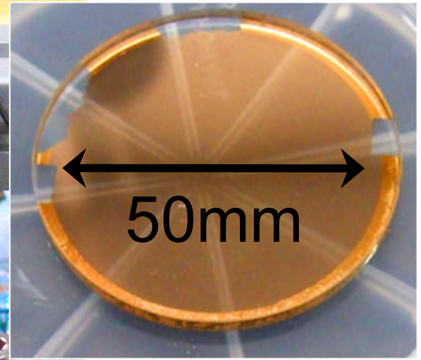
Gaussian beam
conversion
efficiency = 30%



Fabry-Pérot resonant cavity



Au mesh mirror
R = 99.3%, T = 0.5%
(width=200μm,
gap=150μm)



Pyroelectric detector is used to monitor transmission power of the cavity

use piezoelectric stage to control cavity length and keep resonance

Fabry-Pérot resonant cavity

- Coupling of the input beam to the cavity can be estimated from decrease of the reflection power

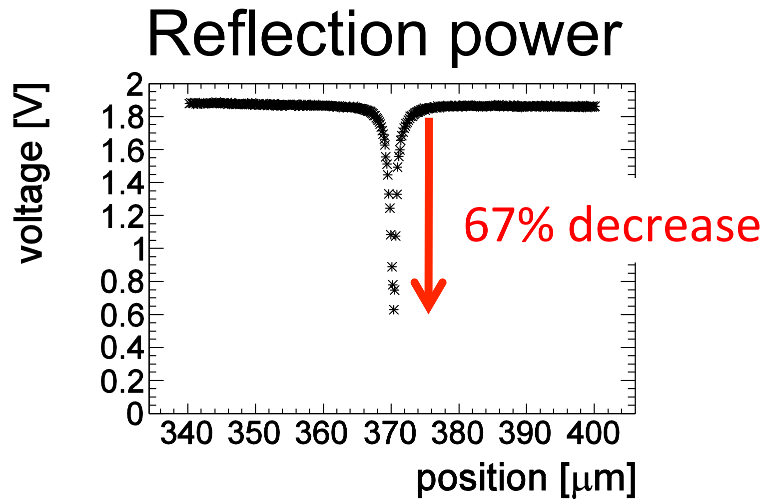
$$C = 0.67$$

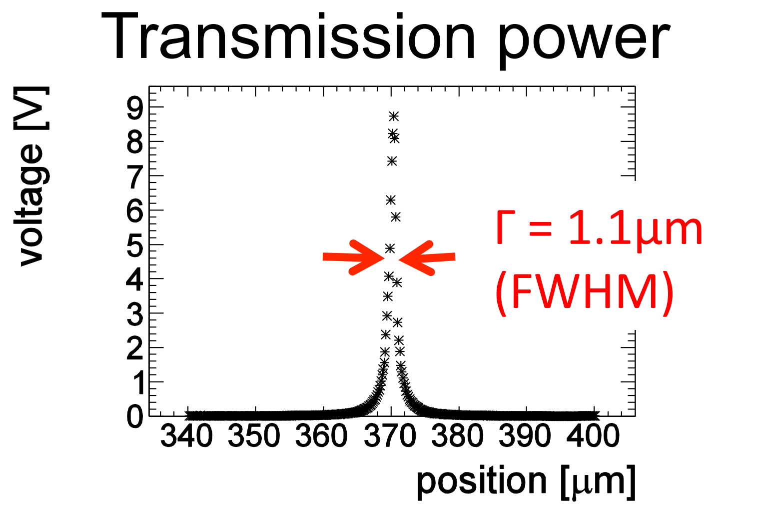
- The number of round-trips inside the cavity is inversely proportional to the sharpness of the resonance

$$N = \frac{1}{2\pi} \cdot \frac{\lambda/2}{\Gamma} = 100$$

- Approximate cavity gain is

$$G = C \cdot 2N = 140$$

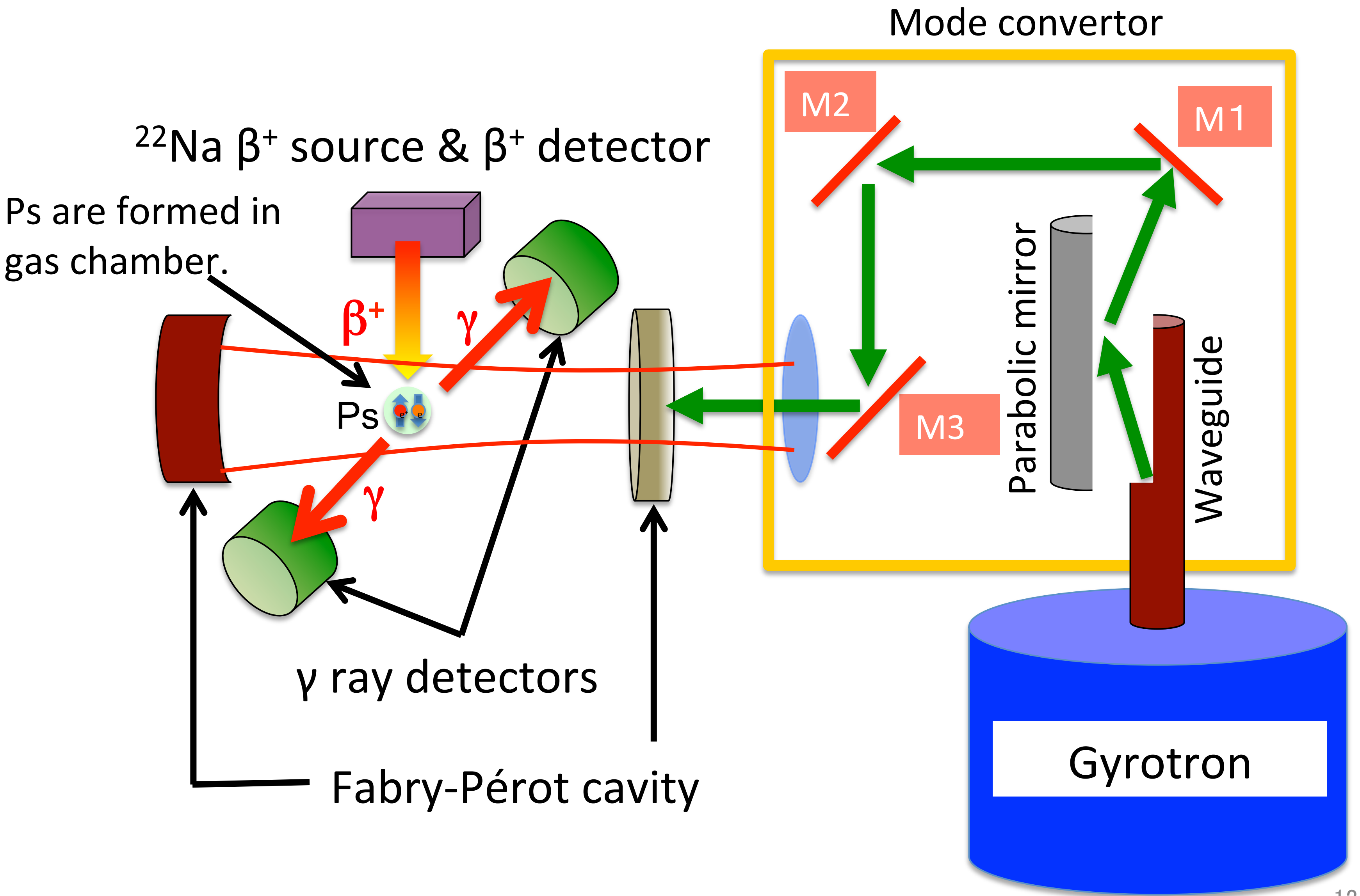




- Power accumulated in the Fabry-Pérot cavity is

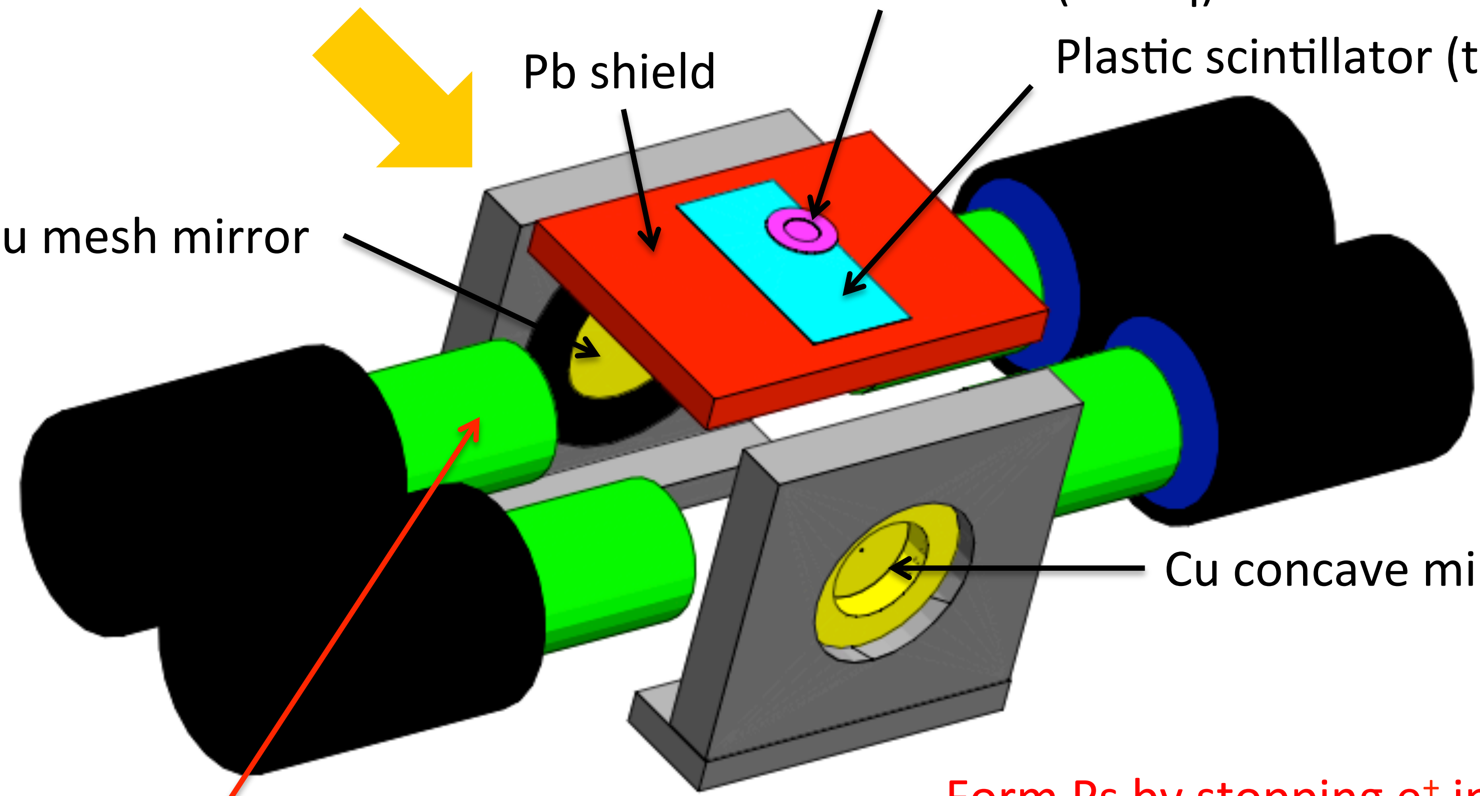
$$P_{\text{acc}} = P_{\text{gyro}} \cdot \epsilon_{\text{conv}} \cdot G = 300 \ [\text{W}] \cdot 0.3 \cdot 140 = 14 \ [\text{kW}]$$

Experimental Setup



Ps Assembly and γ-ray detectors

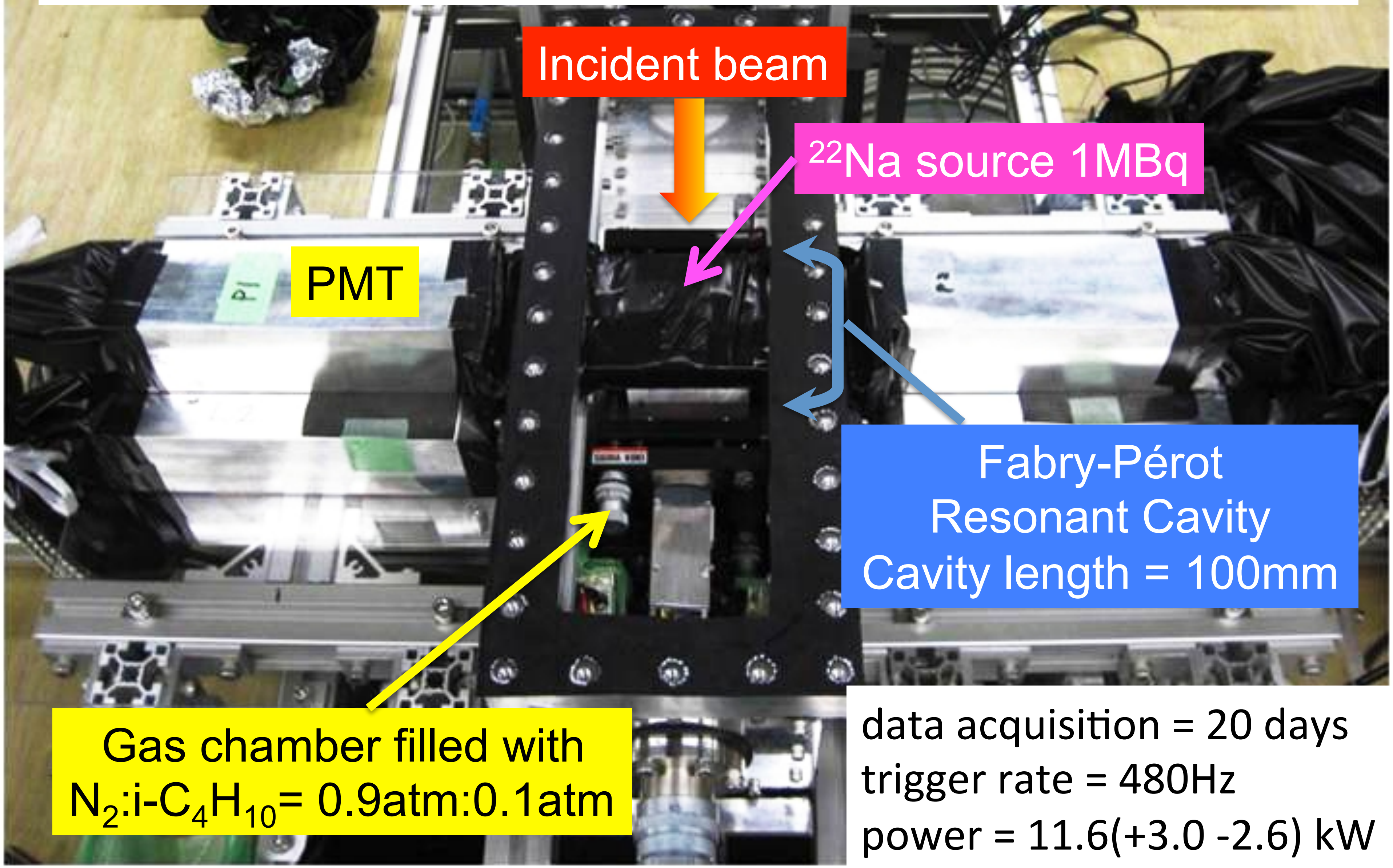
signal = 2 back-to-back 511keV γ rays with long lifetime (τ = 142ns)



LaBr$_3$(Ce) crystal scintillator
- energy resolution FWHM 4%@511keV
- time constant 16ns
- time resolution 200ps (FWHM) @ 511keV

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

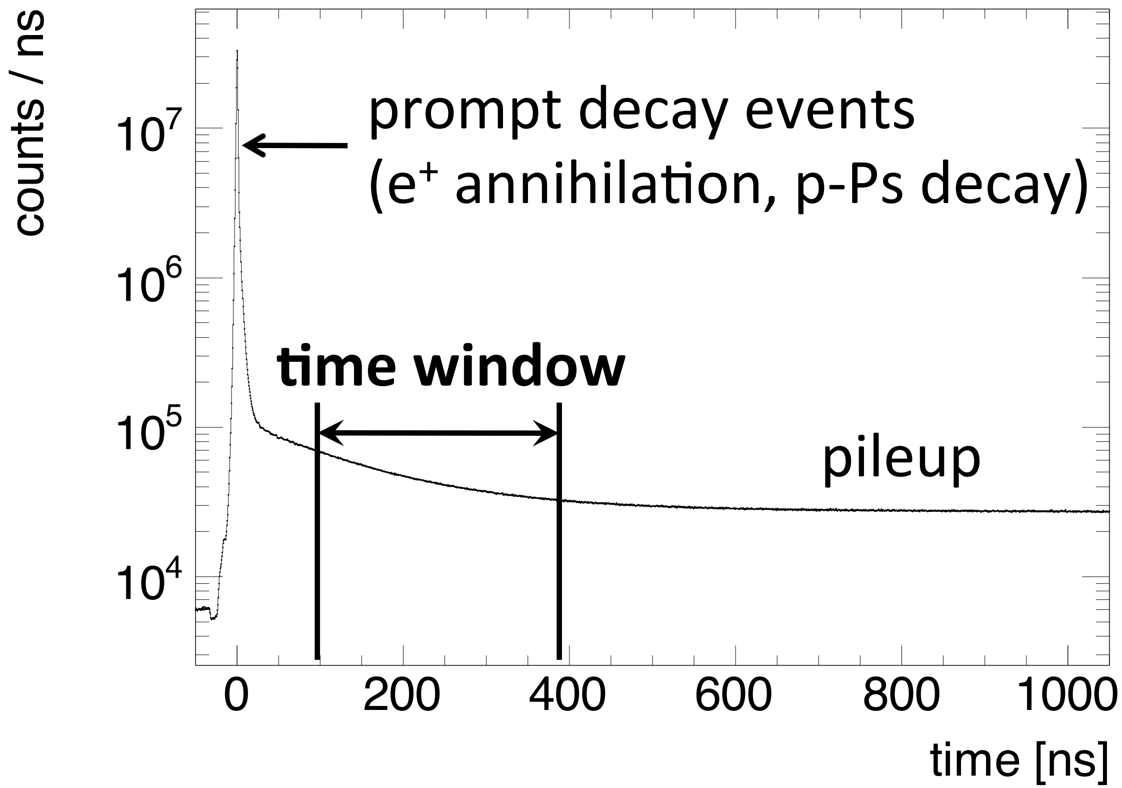
Ps assembly and γ-ray detectors



data acquisition = 20 days
trigger rate = 480Hz
power = 11.6(+3.0 -2.6) kW

Time Window

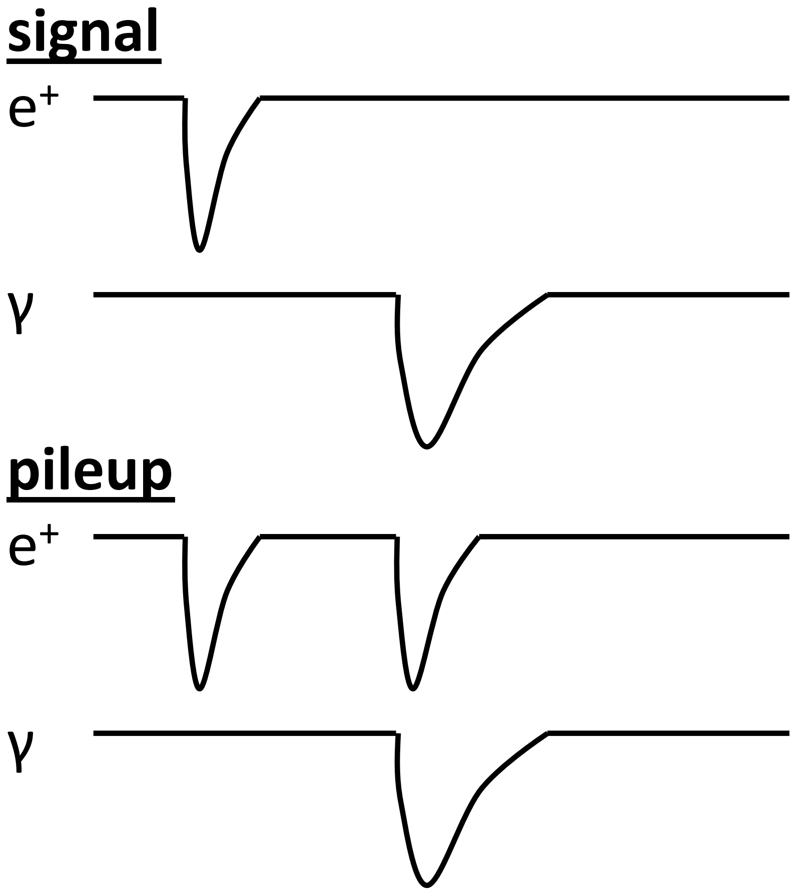
- Time difference between e^+ emission and γ-ray hits means lifetime of Ps.



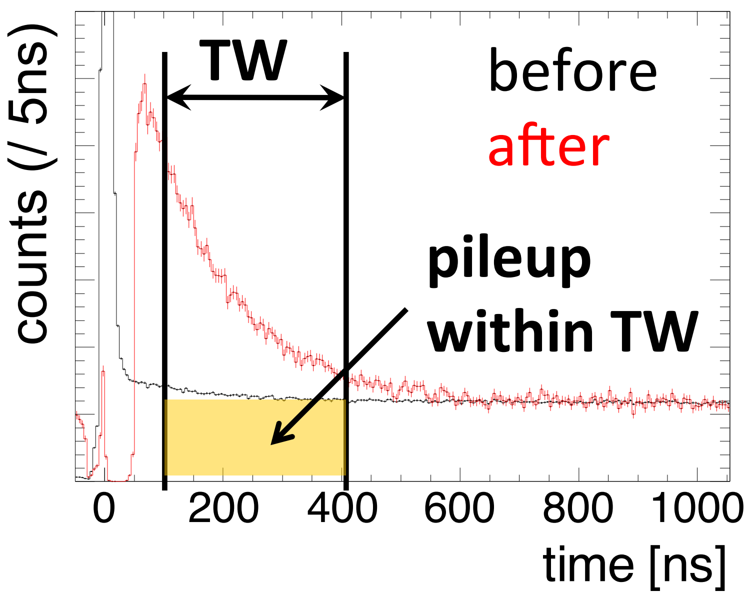
- Set time window to select long lifetime events (transition signal, o-Ps decay) and improve S/N

Pileup rejection

- Pileup is most serious background of our experiment.
- If another e^+ hit coincides with γ ray hit, the event is vetoed. This veto reduces pileup and increase S/N by a factor of 10.

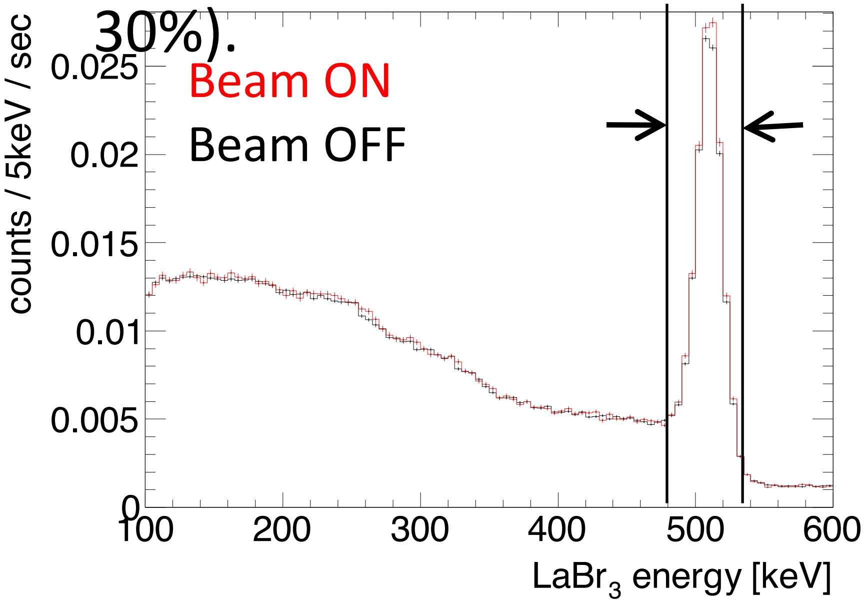


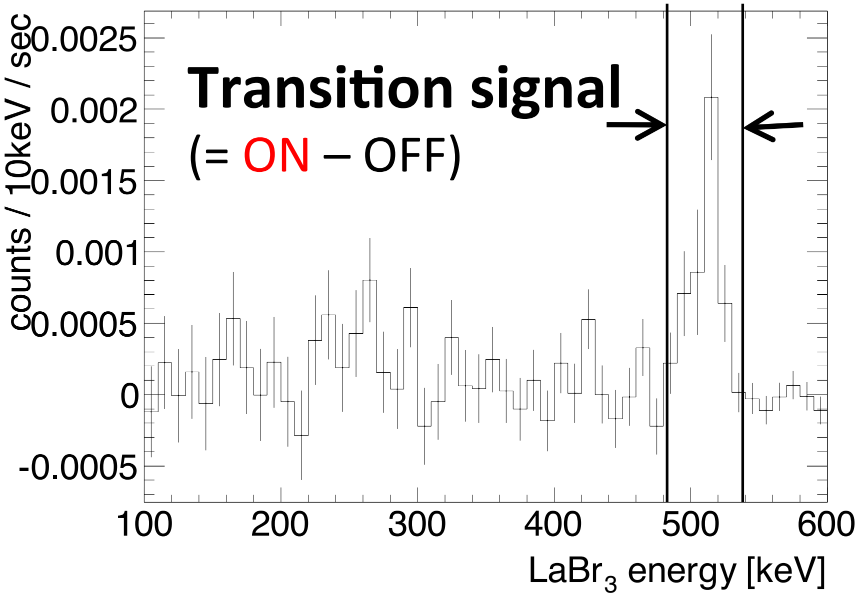
Time spectra on the condition of 2 back-to-back 511keV γ rays
Normalized by the number of pileups



Results

- Final selection is “2 back-to-back 511keV γ rays”. Below figures are energy spectra on the condition of time window (100 – 400ns & pileup rejection & 511keV±2σ @ opposite $LaBr_3$(Ce)
- Beam ON events and beam OFF events were acquired alternately because we used pulse beam gyrotron (5Hz, duty 30%).





- **First observation of direct transition between o-Ps and p-Ps with a significance of 5σ !**
- Signal = ON – OFF = 3.99±0.71(stat.)±0.35(sys.) mHz

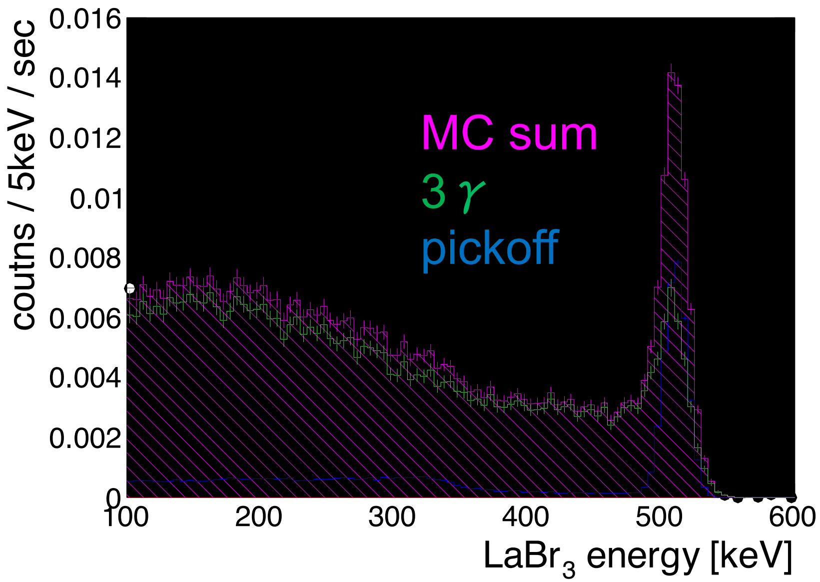
Systematic Errors

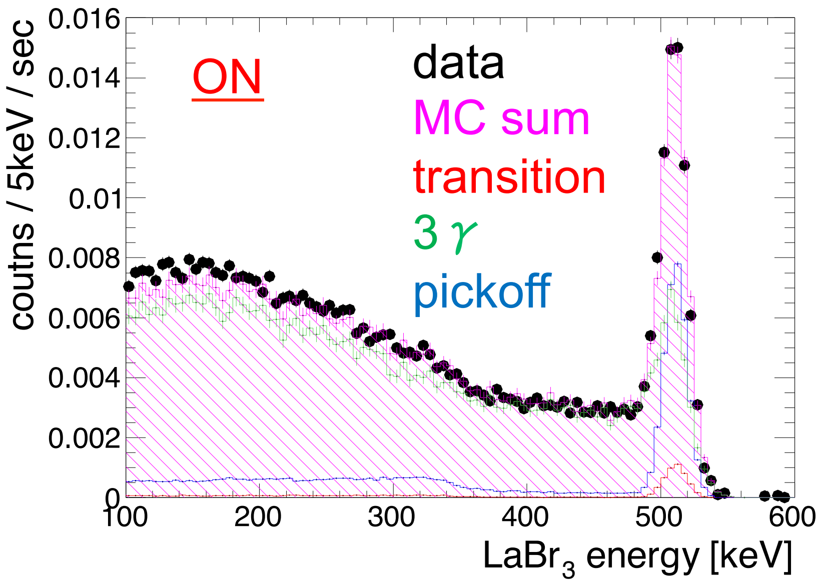
Source	Systematic error
$LaBr_3$ energy resolution (< 1% difference between ON and OFF)	3.0%
origin of the time spectrum (0.01ns difference between ON and OFF)	0.3%
e^+ tag rate (0.25% difference between ON and OFF)	7.7%
normalization (< 0.1% difference between ON and OFF)	3.1%
Quadrature sum	8.8%

Einstein A Coefficient of Ps

- Fit data spectra (remaining pileup events are subtracted) with MC spectra to estimate Einstein A Coefficient of Ps

- χ^2 / NDF = 1.12 (fitting range : 200keV – 550keV)





- **Estimated Einstein A coefficient of Ps is 3.9 (+1.8 -1.7) x 10^{-8} [s^{-1}]**, which is consistent with theoretical value (3.37 x 10^{-8} [s^{-1}]). The error is mainly due to the error of the average accumulated power during DAQ (11.6 +3.0 -2.6 [kW]).

Summary

- Our final goal is direct measurement of Ps-HFS
- **No one had ever observed even direct transition between o-Ps and p-Ps** because its transition probability is very small and high power sub-THz radiation is necessary to drive enough transitions.
- We developed new sub-THz optical system. Accumulated power in the cavity was over 10kW.
- **First observation of the direct transition between o-Ps and p-Ps**
- **Estimated Einstein A coefficient of Ps = 3.9 (+1.8 -1.7)$\times 10^{-8}$ [s^{-1}]**

Future Plan

- In order to measure Ps-HFS
  - Develop frequency tunable gyrotron
  - Upgrade Ps assembly & γ-ray detection system to improve statistics and S/N
  - use slow positron beam