New Experiment for the First Direct Measurement of Positronium Hyperfine Splitting with sub-THz Light

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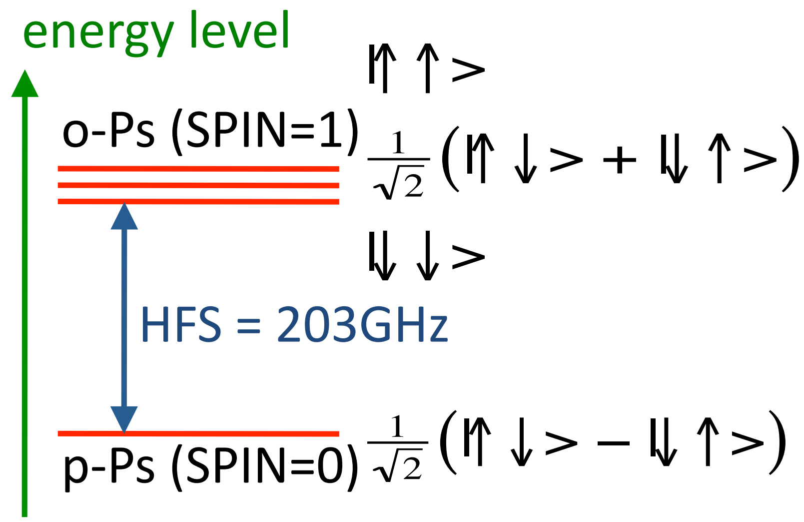
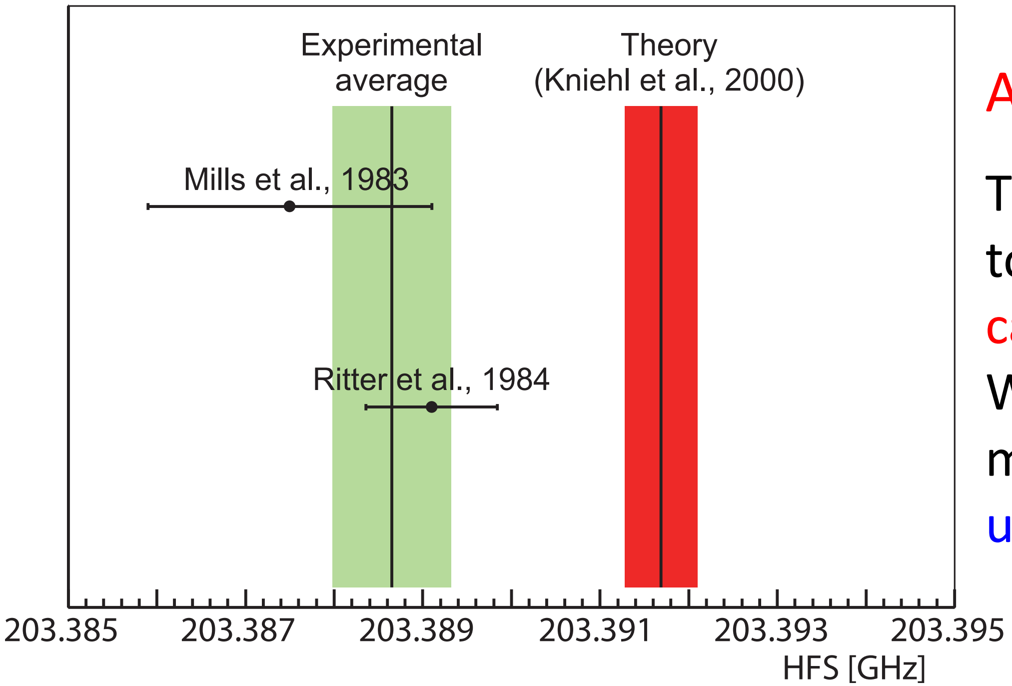
Hyperfine Splitting (HFS) of Positronium and its Problem

HFS is the energy difference between orthopositronium (o-Ps) and parapositronium (p-Ps)



The value is about 203GHz (0.84meV)

There is a large discrepancy of 3.9σ in HFS value



All previous experiments are indirect.

They applied a strong magnetic field (~1T) to cause Zeeman splitting, and indirectly calculated HFS value.
We suspect non-uniformity of this magnetic field is one of the underestimated systematic errors.

→ We have to confirm it !!

Our two approaches

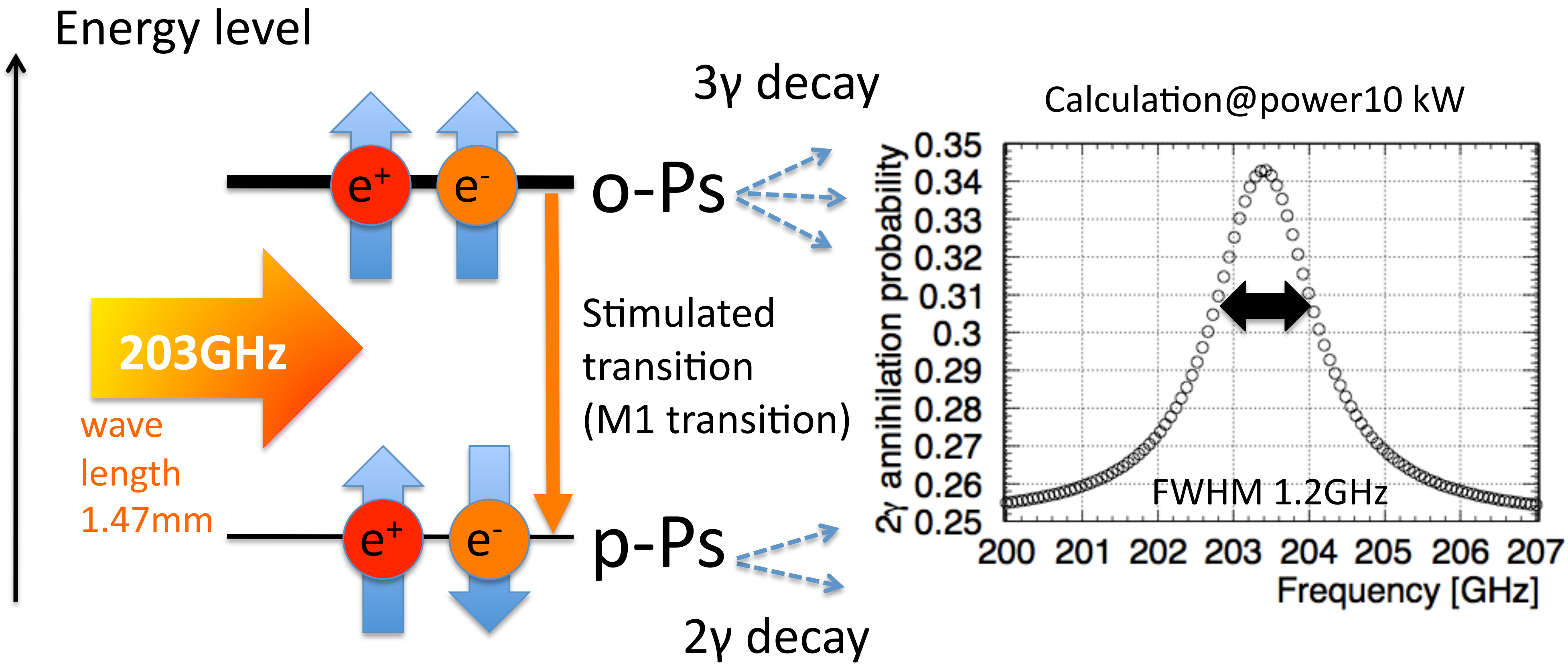
Experiment 1

- Direct observation WITHOUT magnetic field
  - This is the first trial to observe directly the HFS of positronium
  - Completely free from systematic errors of magnetic field.
  - Technology for sub-THz is still under development
    → Technologically challenging

Experiment 2

- Precise measurement WITH static magnetic field
  - Traditional approaches + new ideas
  - Next speaker will explain it in detail.

Basic idea of direct measurement



- 203 GHz light causes the transition from o-Ps into p-Ps
- p-Ps decays (lifetime 125 psec) into 2γ-rays → increase of 2γ decay ratio
- Resonance curve (mean: HFS=203.4 GHz, FWHM: $1/2\pi\tau_{p\text{-}Ps}$ =1.2 GHz)
- We can directly measure HFS value and also measure the lifetime of p-Ps as a bi-product.
- The first spectroscopy experiment in sub-THz region

Three KEY technologies

- o-Ps → p-Ps is M1 transition (seriously suppressed) : probability = 3×10^{-9} sec $^{-1}$
- Extremely small compare to o-Ps decay probability : 1/142nsec = 7×10^{6}sec^{-1}

→ High photon flux (>10kW) is crucial

This is achieved with three new devices

Required performances are listed below

100 W × 100 = 10kW

300 W

300W → 200 W

Coupling 50%

Photon Accumulation (100 times)

transportation efficiency 60%

200W → 100W

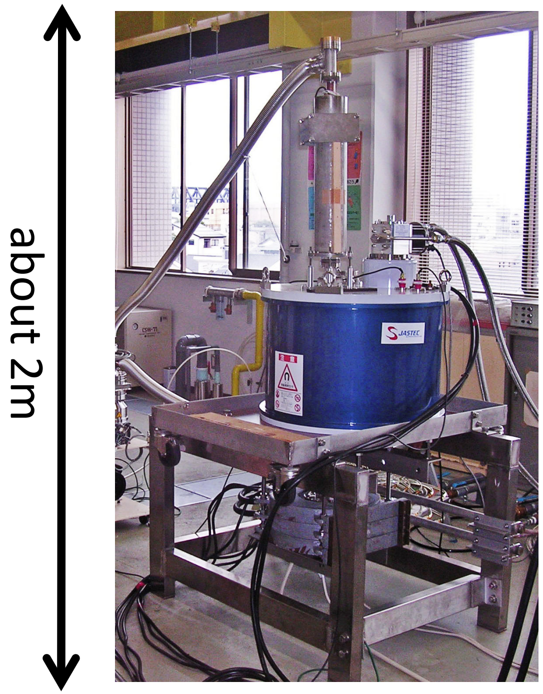
1. High power, stable and precise light source

2. Efficient transportation system

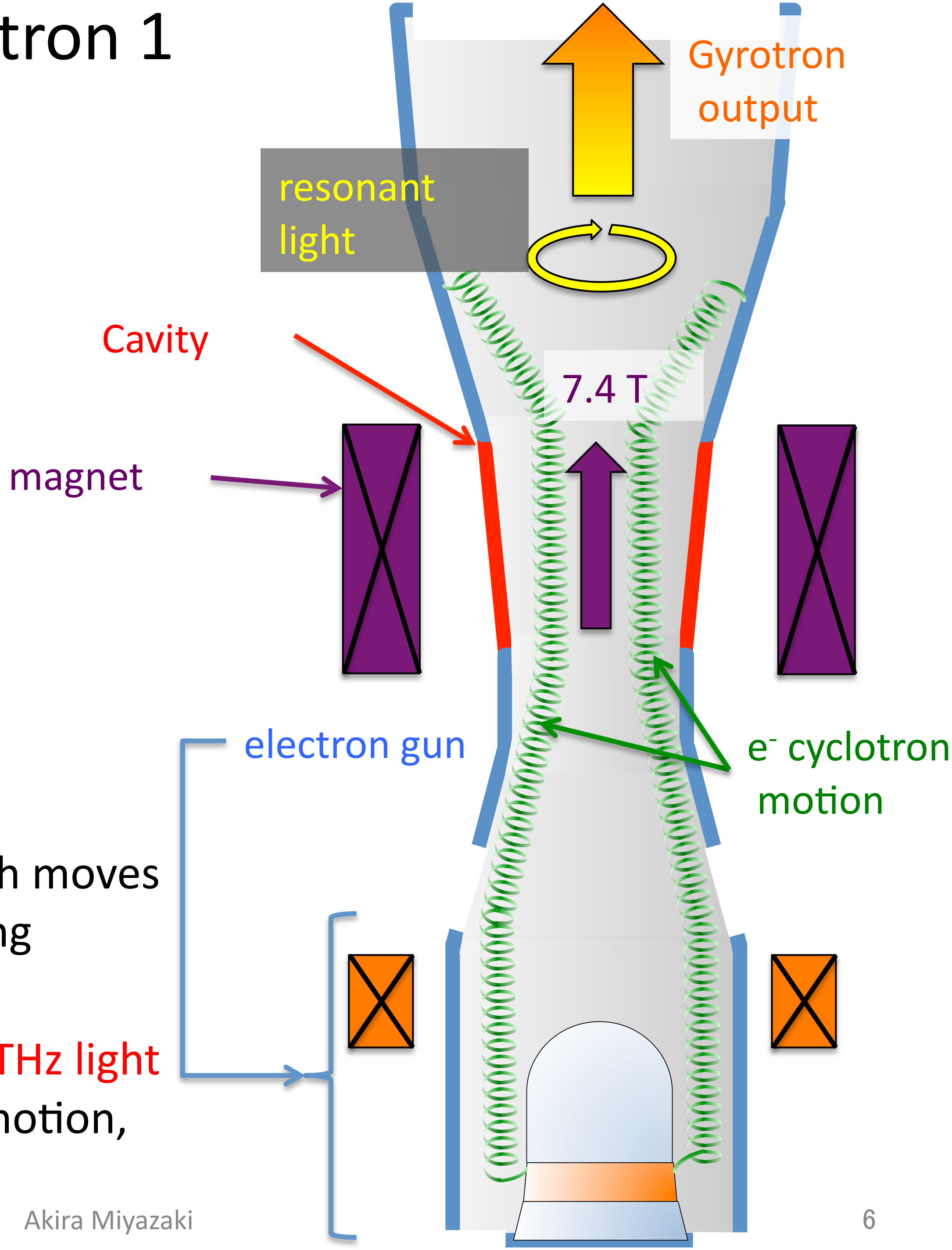
3. Fabry-Pérot Cavity (Quasi-optical cavity)

Positronium is formed and transits inside this cavity

Gyrotron 1



Gyrotron dedicated for HFS measurement
(Gyrotron FU CW V)



Mechanism

- Electron gun emits electron which moves in cyclotron motion under a strong magnetic field (7.4 T).
- Cyclotron motion resonates sub-THz light of same frequency as cyclotron motion, inside a cavity in the magnet.

Gyrotron 2 : current status

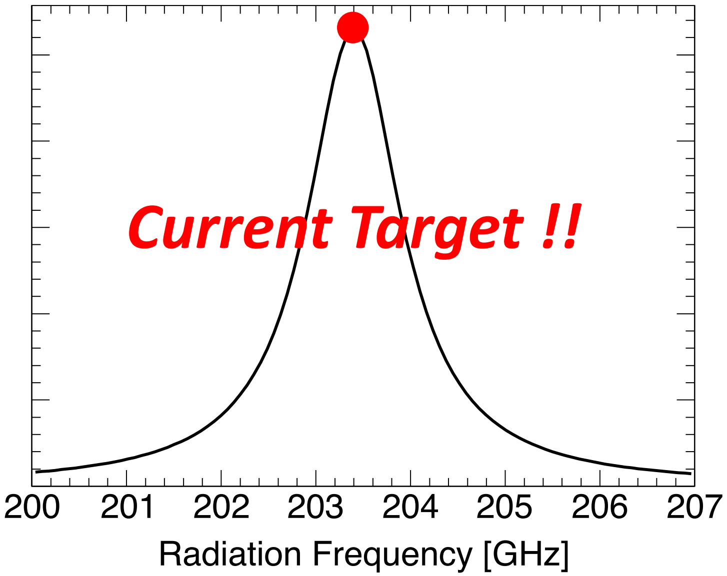
Power

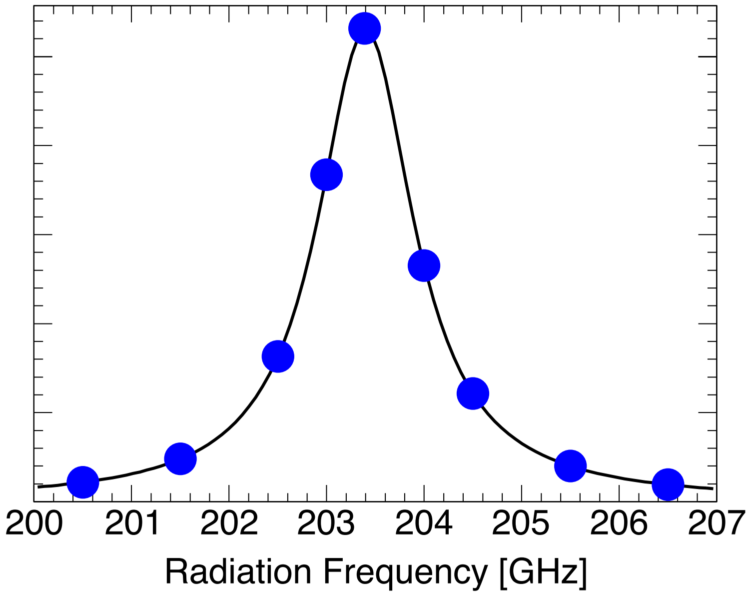
- Stable power 300W is obtained now → It is enough for our experiment

Tunability

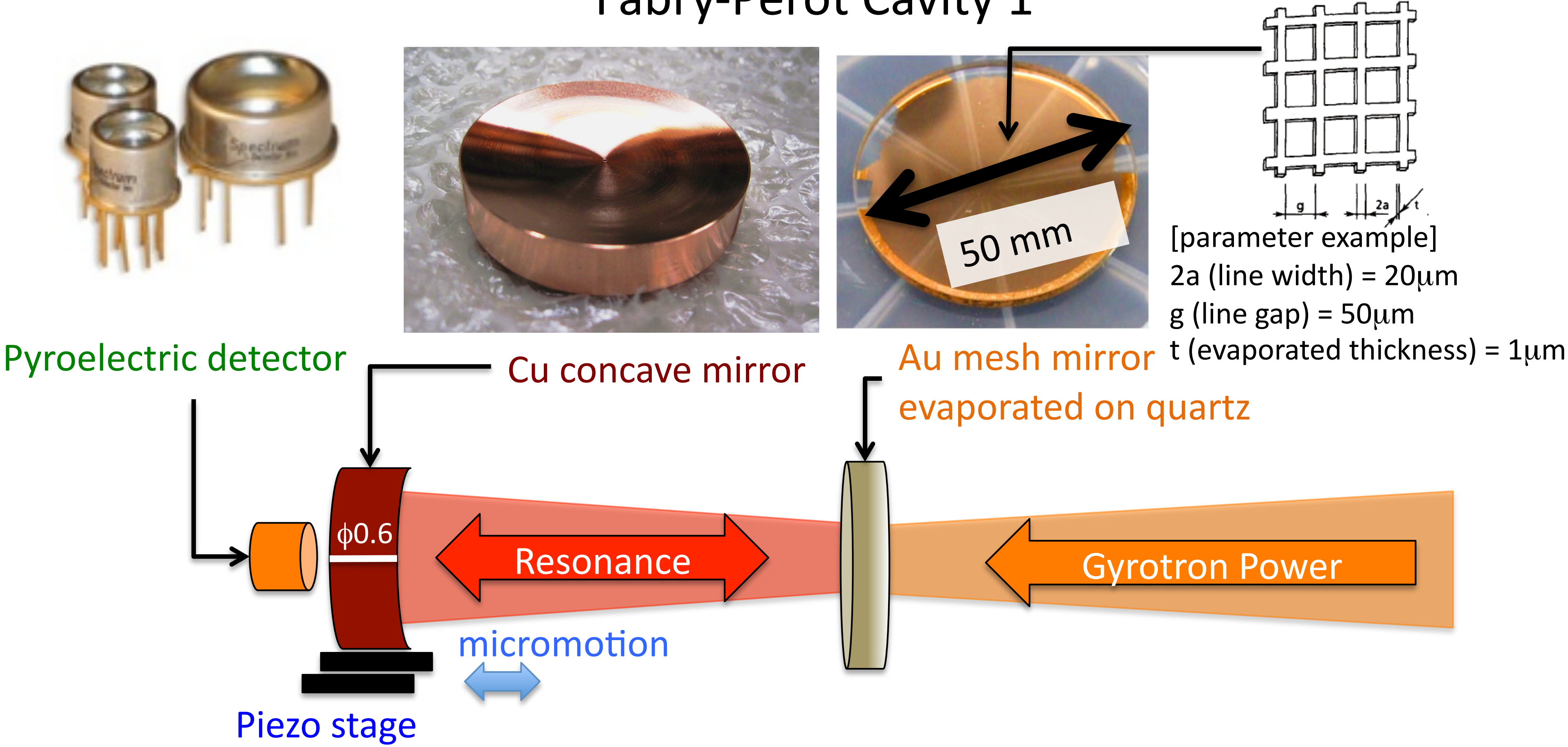
- First Step : fixed frequency
  Gyrotron is operated just on-pole to observe transition.

- Second Step : whole resonance curve
  But tunability O(1) GHz is a big trial.
  We are now developing new Gyrotron,





Fabry-Pérot Cavity 1



Components

- Efficient introduction of power : Mesh mirror (Half-mirror in sub-THz region)
- Stable resonance : Cu concave mirror (transverse stability, confocal resonance)
- Cavity length control with accuracy O(0.1μm) : Piezo stage
- Monitoring power inside cavity : Pyroelectric detector

Fabry-Pérot Cavity 2

Finesse $\mathscr{F}$

$$\boxed{\mathscr{F} = \frac{\lambda/2}{\Gamma}}$$

λ : wave length ∼ 1.4 mm

Γ : peak width [μm]

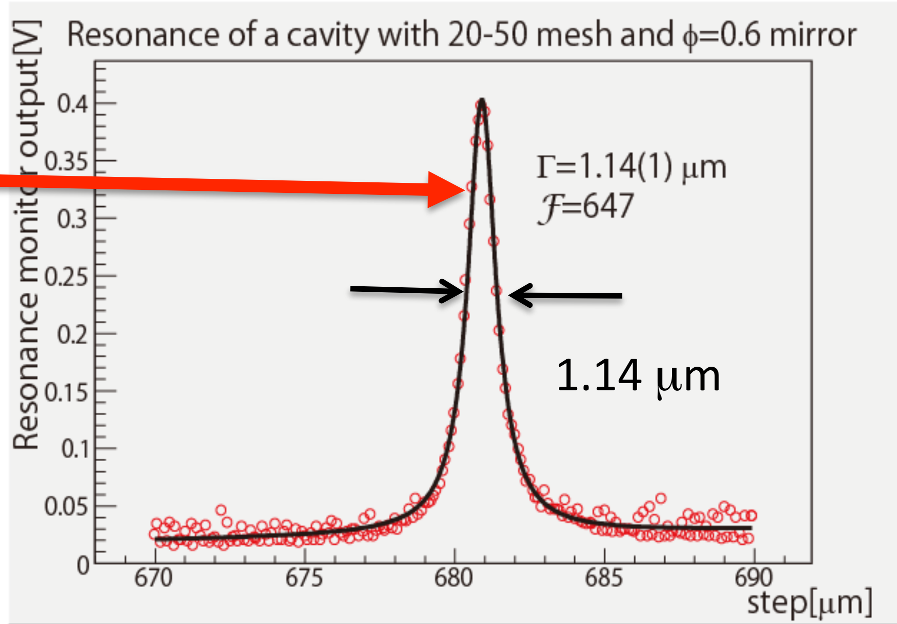
$\mathscr{F}$ ∼ 650 is achieved

- Finesse is equivalent to multiplicity factor of photon flux ×2π

  ⇒ $\mathscr{F}$ ∼ 650 → Photon flux increases

  100 times larger than input flux

The result of prototype experiment



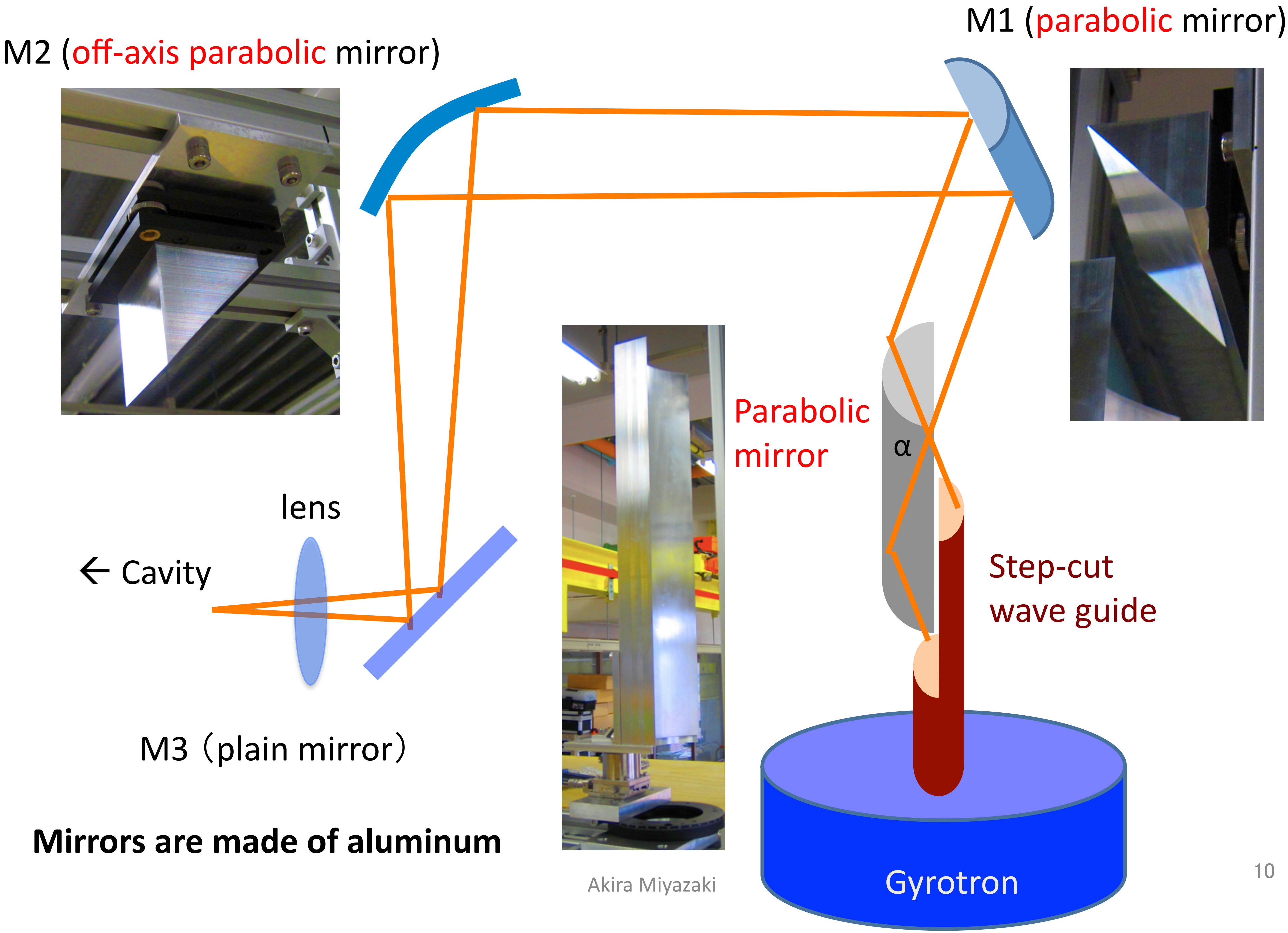
Input Coupling $\mathscr{C}$

- Efficiency of Gyrotron power introduction into the cavity
- Requirement : $\mathscr{C}$ ∼ 50% (intrinsic limit; absorption of input light by mesh)
  - Currently $\mathscr{C}$ is about 40%

    → we have chance to improve → Mode matching is necessary.

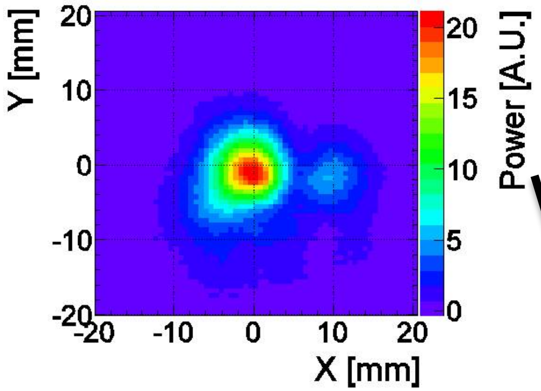
    → Coupling problem connects strongly to efficient transportation system.

Transportation System : setup



Mirrors are made of aluminum

Transportation System 2 : result of test experiment

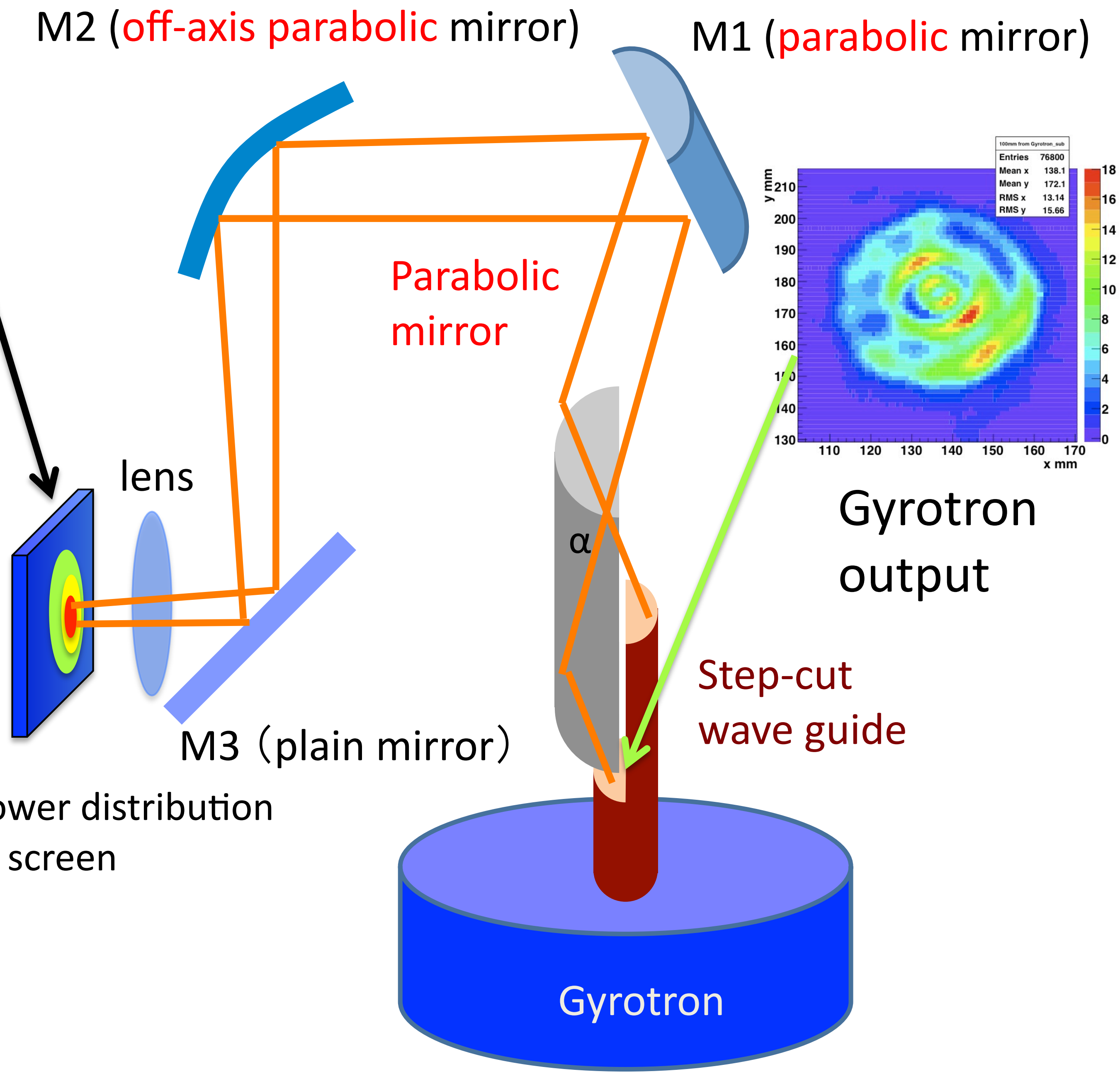


Gaussian Conversion is successful !!

- Current efficiency :30 %
  ← mode impurity

We are now optimizing mirror parameters for non-ideal Gyrotron output.

- Goal : 60 % efficiency
  → Coupling is expected to be maximum



Power estimation

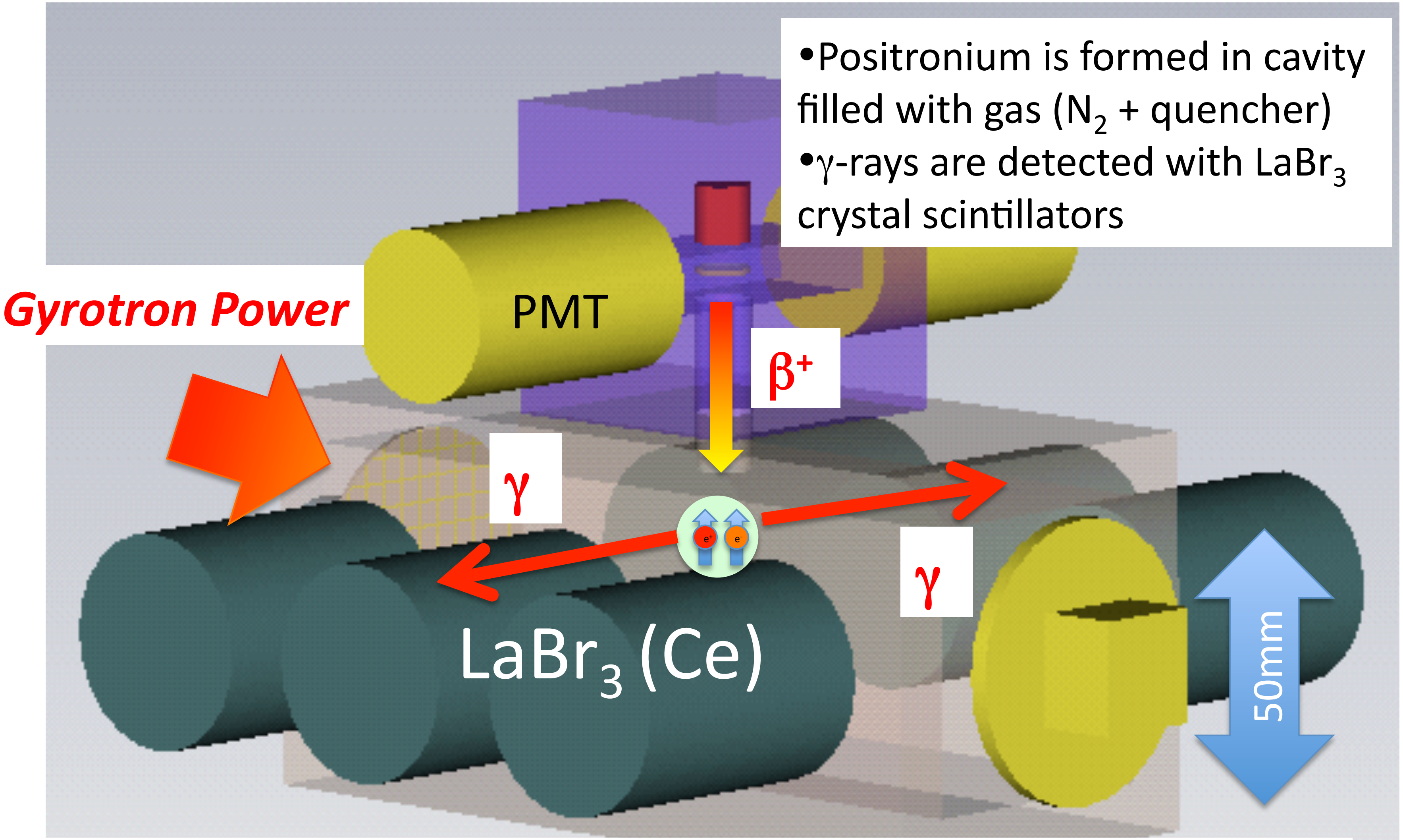
Condition	Power
stable gyrotron output achieved !	300W
transportation efficiency 60% (currently 30%)	200W
coupling 50% (currently 40%)	100W
finesse 650 achieved !	10kW

Transition probability in beam region is about 25 %

How to achieve ?

1. Lens with low absorption
2. Optimization of mirror parameters
3. Improvement of mode purity of Gyrotron output

γ-ray detection system

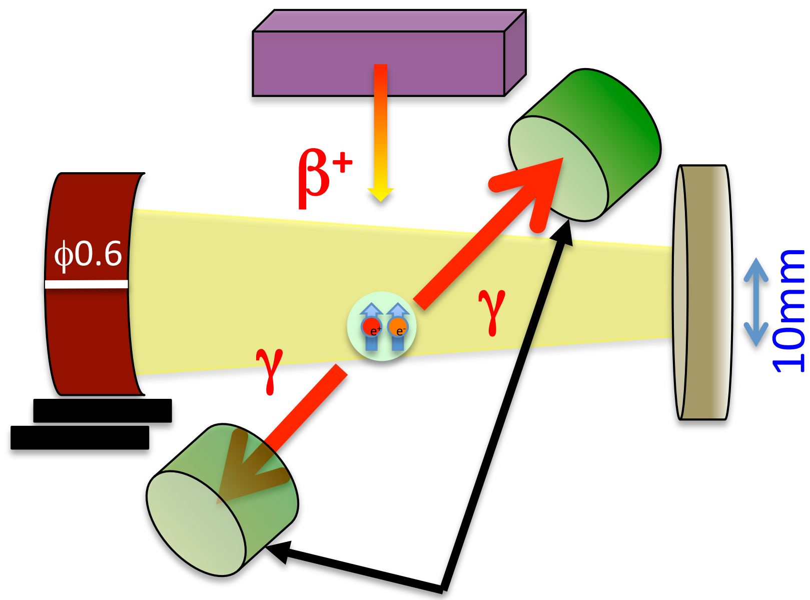


•A thin(100μm) plastic scintillator detects the timing of positron emission.

•Timing information is used to suppress the large background from prompt decay of positron and to estimate the thermalization effect.

Signal estimation

① e^+ stops in beam region	4×10^{-5}
o-Ps formation prob.	0.2×0.75
② Acceptance of $LaBr_3$ x 6 back-to-back and 511keV from beam region	8×10^{-4}
signal prob.	1×10^{-9}



- The stopping probability(①) and the efficiency of γ-rays(②) are small.
  → They can be improved with optimization of detection system (NOT YET).
- Even with current design, the detection of direct transition is feasible with rate O(1) mHz using 1MBq ^{22}Na source
- Background events can be strongly suppressed with the timing information and back-to-back selection.
  → This is achieved with $LaBr_3$ (Ce) crystal scintillator, which has extremely high energy resolution (FWHM 4% @ 511keV) and timing resolution (FWHM 200psec @ 511keV).

Current status & future plan

- There is 3.9σ discrepancy in HFS value.
- We are preparing the first observation of the direct transition WITHOUT magnetic field.
- A high power light source (Gyrotron) and a quasi-optical cavity (Fabry-Pérot cavity) are almost ready.
- A better introduction of light is nearing completion with new transportation system
- Optimization of γ-ray detection system will also finish in this summer. (not yet)
- Experiment will start from this autumn.