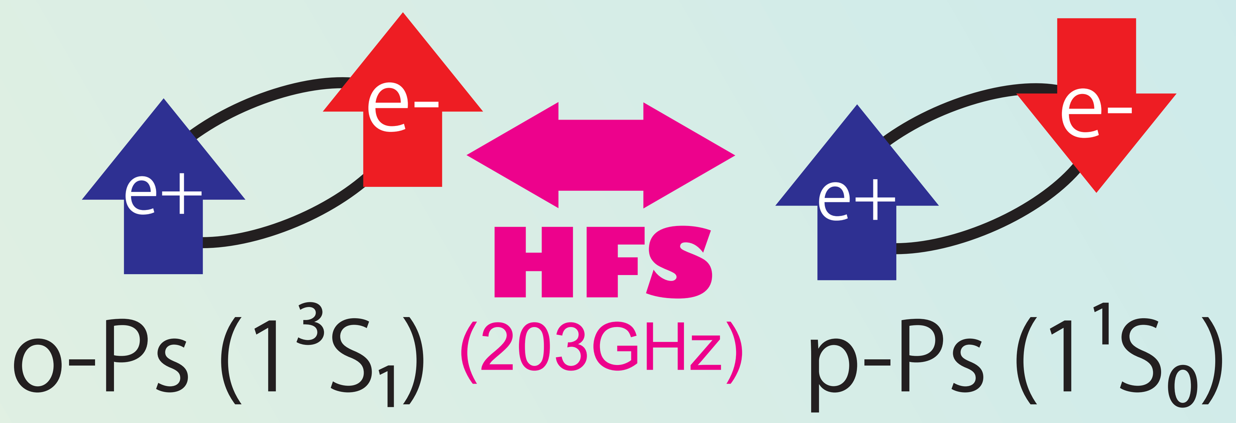
Detection of the Direct Hyperfine Transition of Positronium Atoms using sub-THz High-power Radiation



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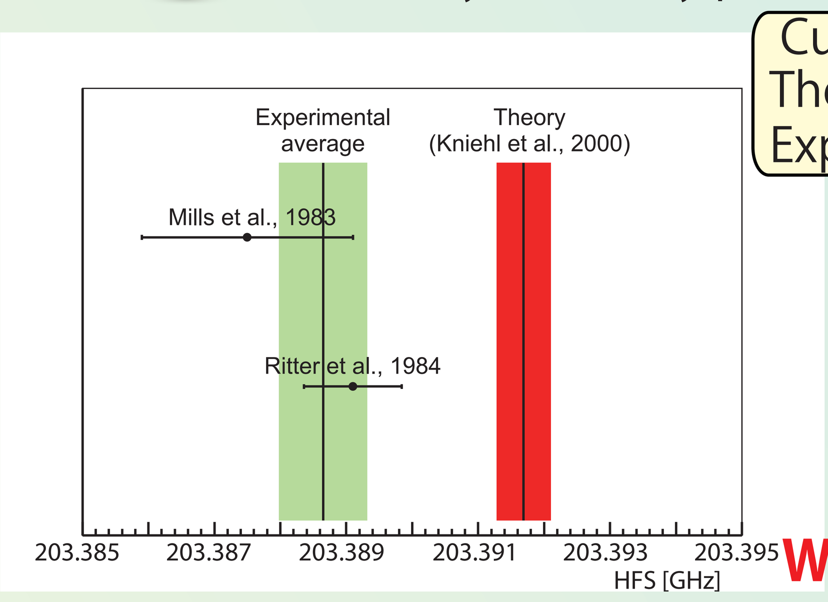
The HFS Problem in Positronium

Positronium HFS is an ideal target for precise measurements probing new physics.

- Frequency measurement: very precise measurement possible
- Pure QED system: very precise theoretical calculation possible

Current best numbers:
Theory: 203.3**9169 (41)** GHz (2.0 ppm)
Experiment: 203.3**8865 (67)** GHz (3.3 ppm)



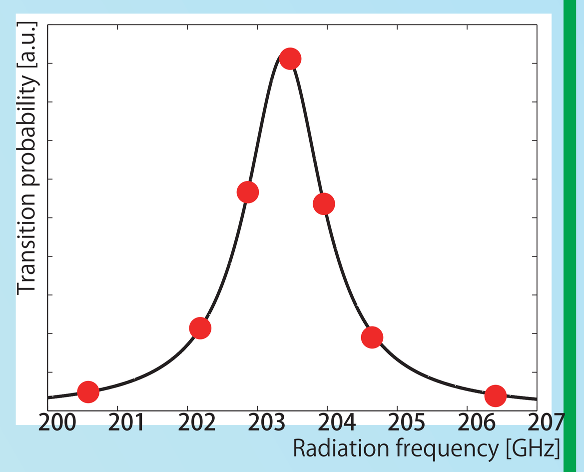
Theory vs. Experiment on Ps-HFS

3.9 σ Discrepancy between calculation and measurement was found!

We will investigate the discrepancy by a new experiment!

Requirements for Measuring the HFS

Simple (but new) method: just apply 203 GHz on positronium

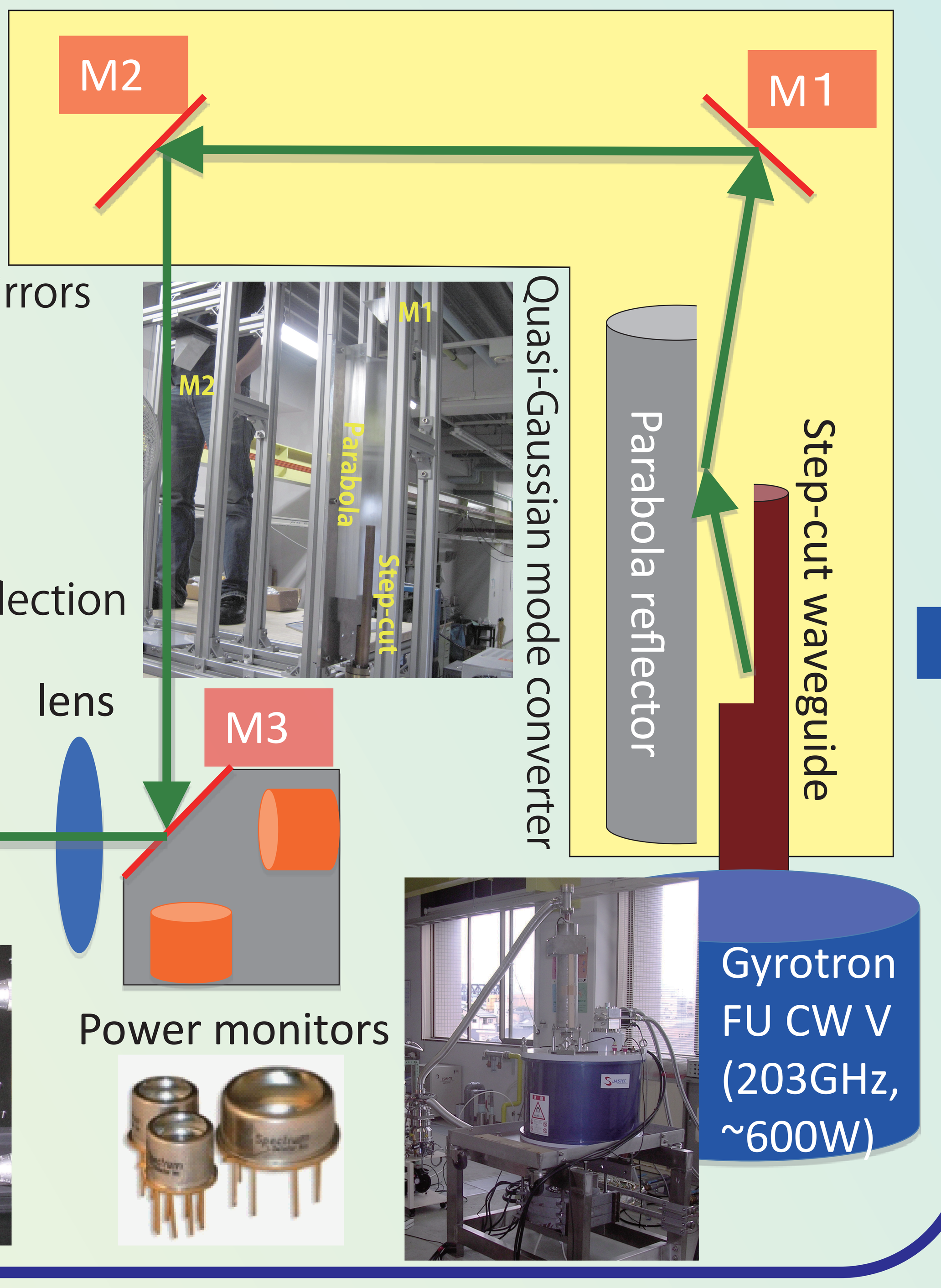


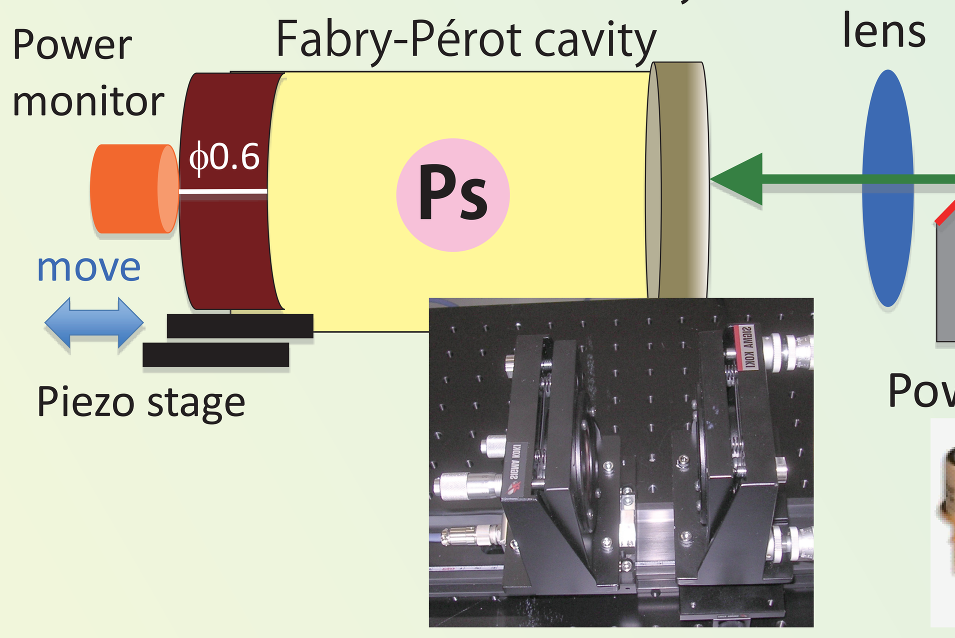
- Requirements:
  - High power radiation around 203GHz to cause rare o-Ps to p-Ps transition (M1 transition: $\tau \sim 3 \times 10^8$ sec)
  - Tunable frequency up to several GHz to obtain Breit-Wigner resonance shape
  - Good separation of o-Ps decay and e^+ annihilation background from HFS signal
- To fulfill these requirements, we use
  - **High-power 203 GHz gyrotron**
  - **High-finesse Fabry-Pérot cavity**
  - **High-resolution energy and timing detectors**

Optical Design

Optical elements:

- **Gaussian converter**
  Convert gyrotron output (TE03) into quasi-Gaussian mode: Step-cut waveguide + parabola mirrors
- **Fabry-Pérot cavity**
  Accumulate 203 GHz photons at the positronium target
- **Power monitors**
  Pyroelectric monitors for input, reflection and transmission of the cavity





Optimization of the Cavity

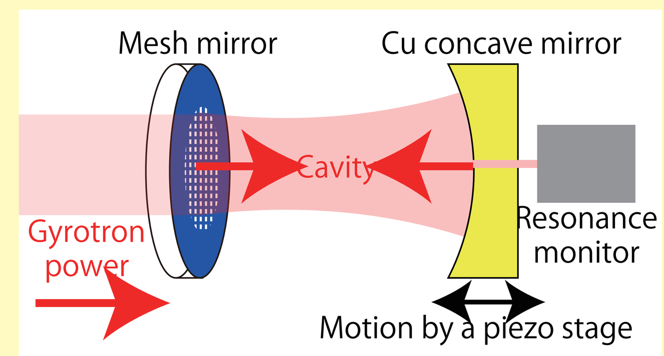
Two parameters to maximize power density:

1. Finesse describes **resonance power (multiplicity)** of the cavity

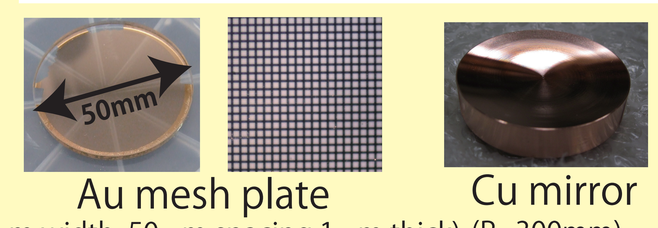
$$\mathcal{F} = \frac{\delta\nu}{\Gamma} \sim \frac{2\pi}{1-\rho}$$

δν: spectral width (λ/2 for our cavity)
Γ: FWHM of resonance (measurable)
ρ: round-trip reflection

Target: $\mathcal{F} > 628$ (> 99% reflection)



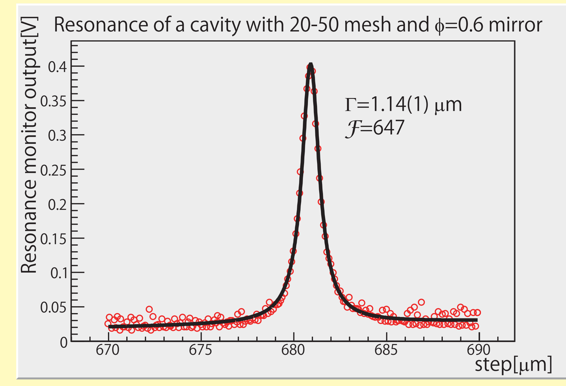
- High-reflection mirrors
  (Mesh: >99.2%, Cu: >99.8%)
  Mesh parameters are optimized by EM field simulation



Au mesh plate (20 μm width, 50 μm spacing, 1 μm thick)
Cu mirror (R=300mm)

- Suppress diffraction loss
  by the concave mirror
  (beam size: < 15mm)

Finesse can be measured by monitoring resonance width Γ:
it shows **$\mathcal{F}$ > 630 is already obtained.**

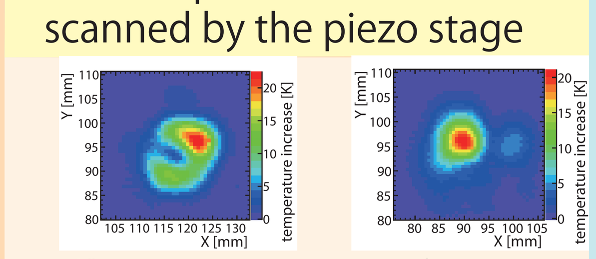


Power output at the resonance scanned by the piezo stage

2. Coupling determines fraction of power introduced to the cavity

Target: > 50% coupling (< 50% input loss)

- Transverse mode matching between input and inner field
  - Quasi-TEM00 (Gaussian) mode converter
  - Fine tuning of input beam (beam size, dispersion angle and beam position) at the mesh

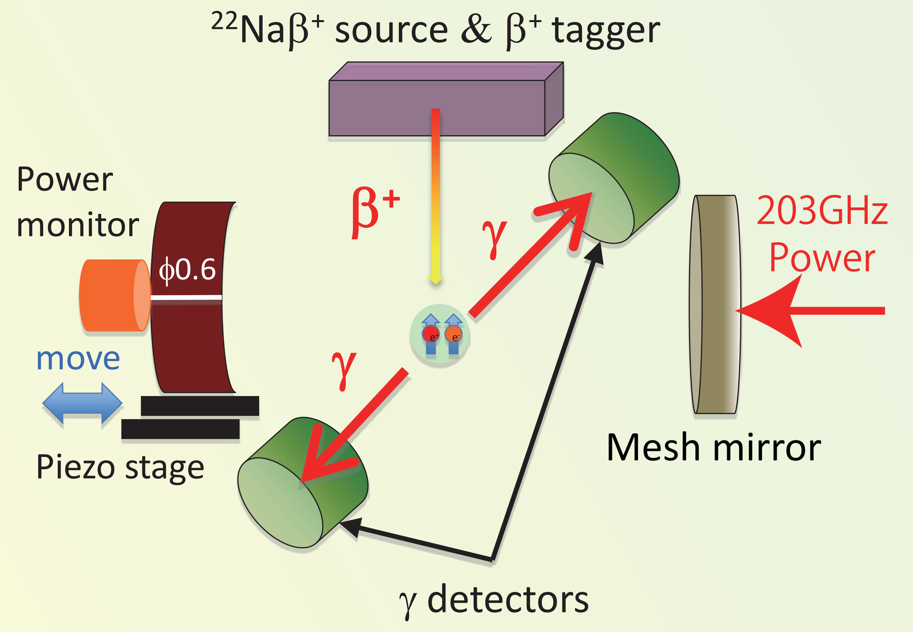


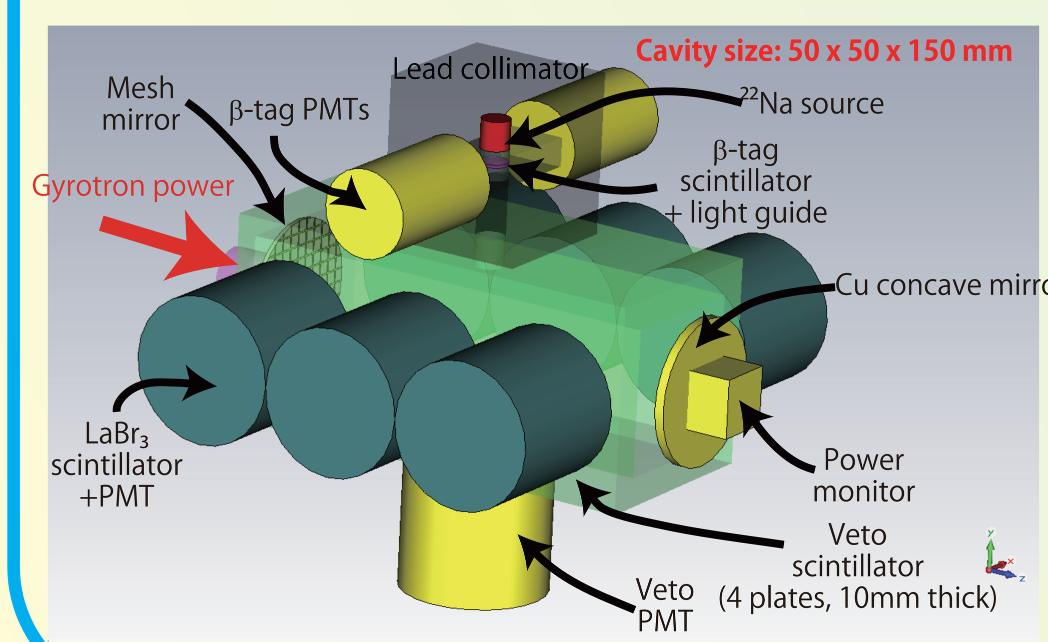
beam profile at the mesh

- Low reflection/absorption loss before the cavity
  low-loss, low-reflection material of the lens and mesh substrate
- High transmission at the mesh
  optimizing mesh parameters

Coupling can be measured by monitoring output and reflection power:
final optimization is now ongoing.

Source & Detectors





Positronium formation

- ^{22}Na β$^+$ source emits positrons (545 keV max, ~1 MHz)
- Positrons scatterd with gas (isobutan) and decelerated to several eV
- Some of the decelerated positrons take an electron from gas at the cavity and form positronium (Ps)
- 1/4 of the Ps are **p-Ps**, decaying **immediately** to **2γ (just 511 keV)**, other 3/4 are **o-Ps**, decaying to **3γ (< 511 keV)** with **140 ns lifetime**

HFS transition & detection

- Emission time of positron is recorded by the β-tag scintillator
- HFS transition occurs on the o-Ps, which creates **p-Ps** in o-Ps lifetime
- Emitted photons are captured by $LaBr_3$ scintillators, which record energy and timing of the photons
- Counting **delayed 2γ (511 keV)** events, which indicate HFS transition

Summary and Plan

- **A new direct method of Ps-HFS measurement is under development.**
- **A 203 GHz high power gyrotron with a Fabry-Pérot cavity is utilized to obtain high photon density.**
- **After the final optimization of the coupling, the first observation of direct HFS transition is aimed at this summer, leading to precise HFS measurements.**