Probing the Energy Structure of Positronium with a 203 GHz Fabry-Perot Cavity

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HFS Measurement

Hyperfine splitting of Positronium (Ps-HFS: 203 GHz)
energy difference between o-Ps (1^3S_1) and p-Ps(1^1S_0)

Direct observation of Ps-HFS is difficult.

< O(10) GHz: RF technology (Klystron etc.)
> O(10) THz: Infrared laser (ex. CO2 laser: 28.3 THz)
No traditional high power source around THz region.

We plan to observe direct Ps-HFS transition with
- **203 GHz gyrotron**
- **High-Finesse Fabry-Perot cavity.**

Motivation: HFS puzzle

Inconsistency of HFS value between theory and experiment
Theory: 203.3**9169 (41)** GHz (Kniehl et al, 2000)
Experiment: 203.3**8865 (67)** GHz (Ritter et al., 1984)
3.9σ discrepancy!

Systematic error?
All previous measurements are indirect with static B-field.
Uncertainty (incl. non-uniformity) of B-field can affect the result (quadratic dependence of HFS on B-field).

Direct observation may solve the puzzle!

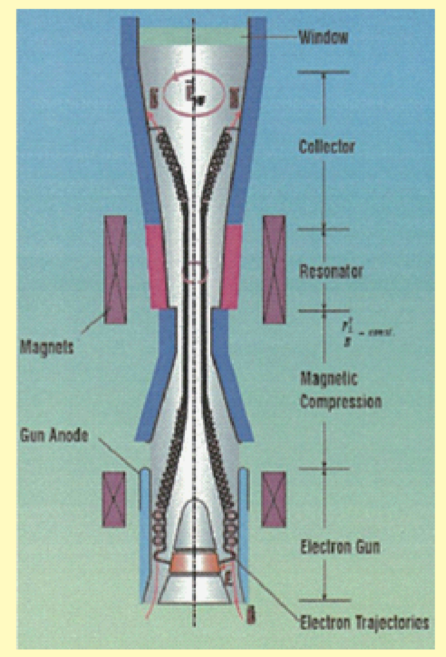
203 GHz Gyrotron

Gyrotron is a novel high power radiation source for THz region.

Radiation power up to ~kW (ours: 200W)
Narrow line width (10 kHz level)
Moderate frequency tuning (~ GHz)

Good for the HFS observation!

Gyrotron FU CW V developed in Fukui Univ. dedicated for the HFS study.



Schematic of gyrotrons. It utilizes cyclotron motion of electrons to cause resonance at the center cavity.

Fabry-Perot Cavity

HFS transition is a rare process (τ ~3×10^8 sec)

High density of 203 GHz photon is needed to observe HFS transition.

Photon accumulation by a cavity resonator is essential! (Target: 100x multiplication).

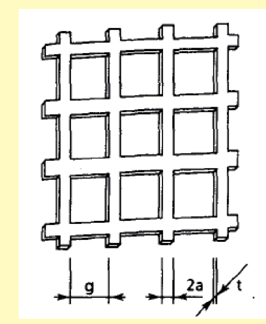
Fabry-Perot cavity: an optical resonator with two face-to-face mirrors.

Two important characteristics of the cavity:

Finesse (resonator quality)
- Corresponding to the **multiplication factor of the photon accumulation** at the resonance.
- **Measured by resonance width** Γ.
- Condition of high finesse cavity:
  - High reflectivity at two mirrors
    - Small ohmic loss
    - Small external coupling
  - Small diffraction loss

Input coupling
- If the coupling is not appropriate, large part of the power is lost by reflection or diffraction.
- **Estimated by reflection** at the resonance (critical coupling: R=0) **or measuring absolute power** at the output resonance monitor.
- Condition of proper input coupling:
  - Matched coupling strength to Finesse of the cavity.
  - Small transmission loss
  - Field shape at the input similar to the cavity mode

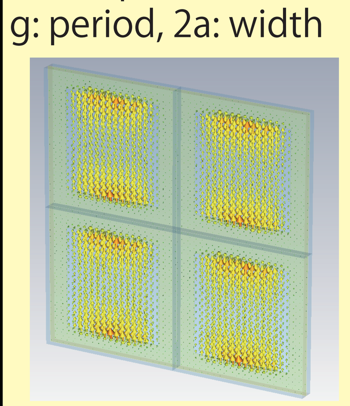
Optimization of the mesh parameters by EM simulations



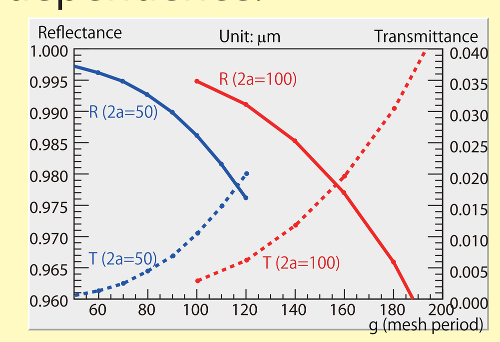
Mesh parameters: g: period, 2a: width

Reflectivity and transmission loss depend much on mesh parameters.

We used an EM simulator (CST MWstudio) to estimate this dependence.

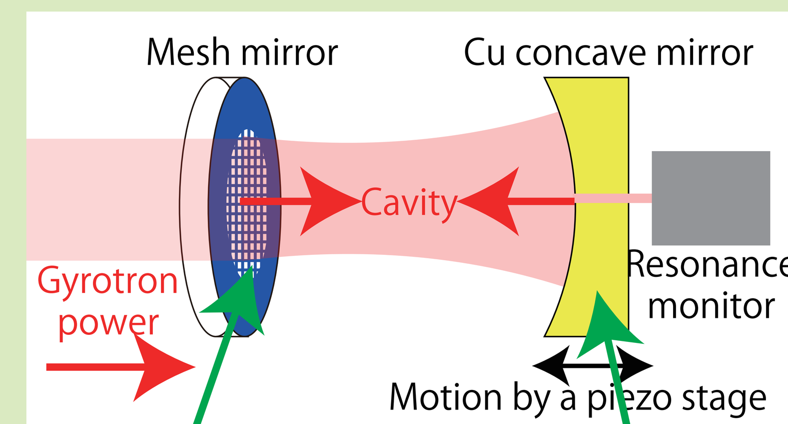


Field view of the EM simulator



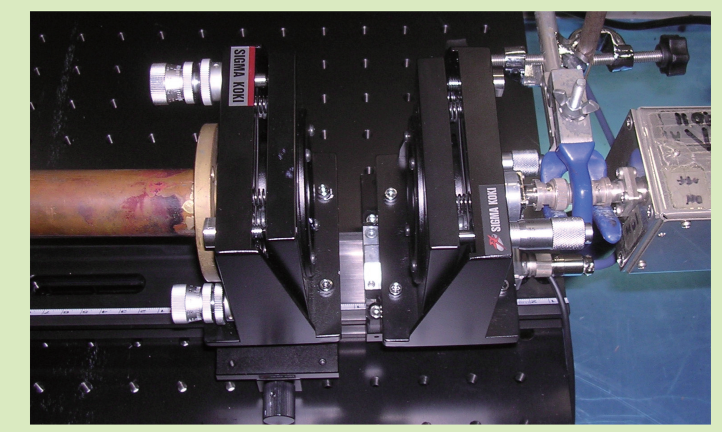
Simulated results of reflection and transmission
Good agreements to measurements are seen in relatively low-reflection meshes.

We use a **metal-mesh mirror** for the input mirror and a **Cu concave mirror** for the opposite side.



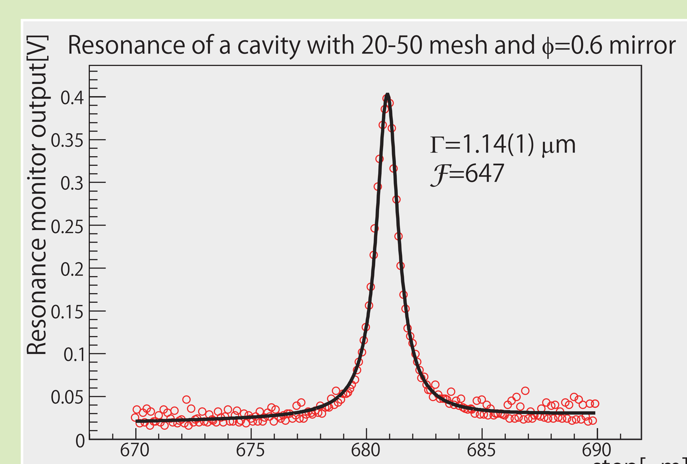
Metal mesh mirror:
Low transmisson loss
High reflectivity

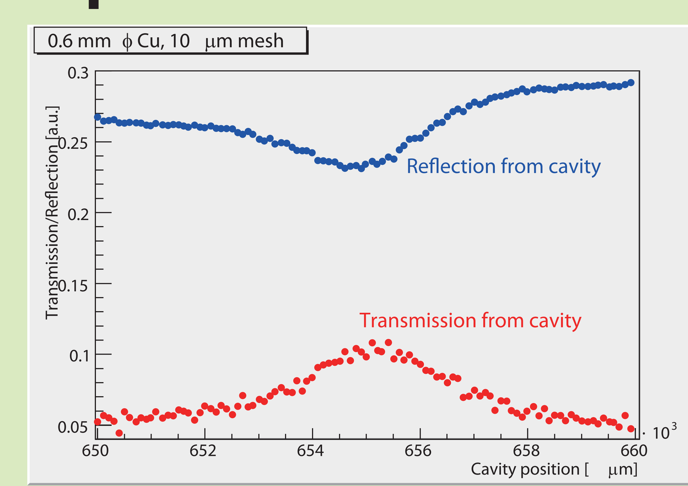
Cu concave mirror:
Reduce diffraction loss
High reflectivity



Setup for the cavity test. (Geometry is almost the same as the left drawing).

Resonance scan has been performed to obtain cavity parameters

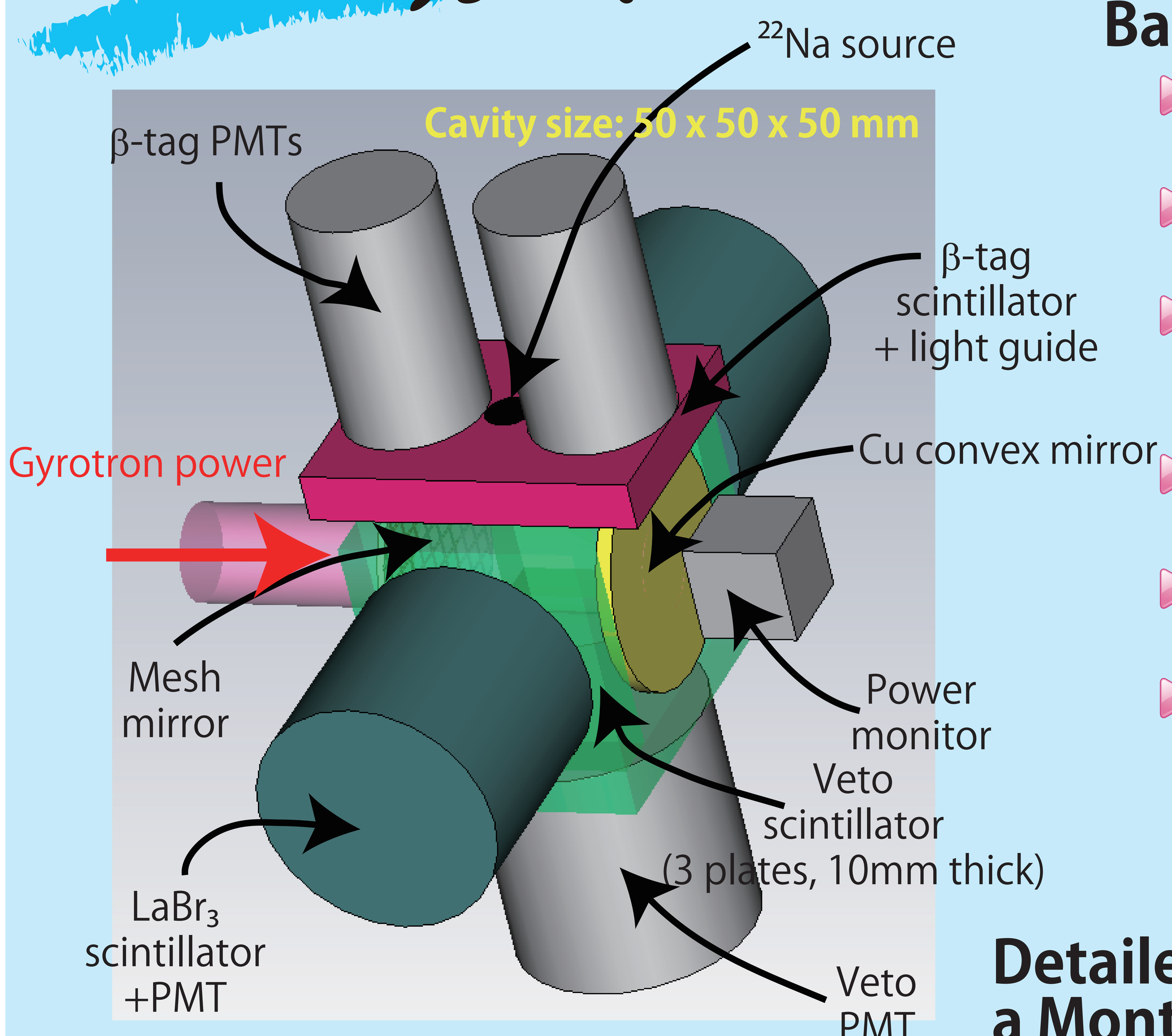


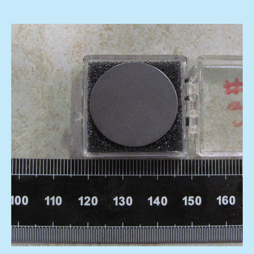


ℱ > 630 is obtained.
Round-trip reflectivity > 99% - OK.

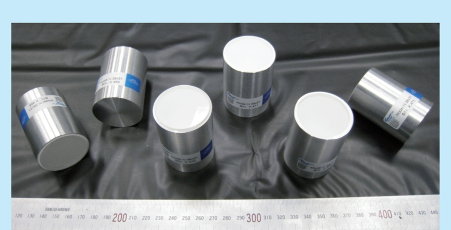
Now performing detailed optimization of the cavity.
Increase input coupling.
less ohmic/diffraction loss.

Detector System





^{22}Na source (1MBq, 9.52 mm active dia. Ti-coated (12.7μm))

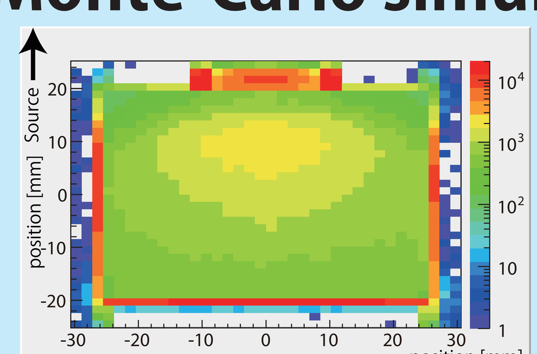


LaBr$_3$ crystals (2 inch)

Basic ideas

- ^{22}Na positron source (1MBq) at 25 mm from the center of the cavity.
- Timing of the positron emission is tagged by a plastic scintillator (100 μm thick).
- Positrons stop and form positroniums by scattering with N_2 gas in the cavity (isobutane is added to reduce slow positrons).
- Part of positrons which do not stop in the cavity are vetoed by surrounded veto plastic scintillators.
- Positronium decays in the cavity (τ=138ns), emitting photons (3γ: o-Ps, 2γ: p-Ps with HFS transition).
- Emitted photons are observed by LaBr$_3$ crystal scintillators (~3% energy resolution, fast rise time).
  - Separate 2γ (511 keV, monchromatic) and 3γ (< 511 keV, continuum) events by energy.
  - Separate prompt events by the timing difference.

Detailed optimization is ongoing with a Monte-Carlo simulation package (Geant4)



S/N is not good, but observation is possible in the current geometry if target performance of the cavity and the gyrotron are acchieved.

A simulation result of the positron stopping position in 1 atm N_2.

Summary & Plan

- **A new direct method of Ps-HFS measurement is under development.**
- **A high power 203 GHz gyrotron and a Fabry-Perot cavity are utilized to obtain high radiation density.**
- **The first observation of direct HFS transition will be in this fall, leading to precise HFS measurements to investigate the HFS puzzle.**
- **THz light is a rapidly developing field. We are searching other applications for the fundamental physics.**