The First Observation of Direct Transition between o-Ps and p-Ps by sub-THz Radiation

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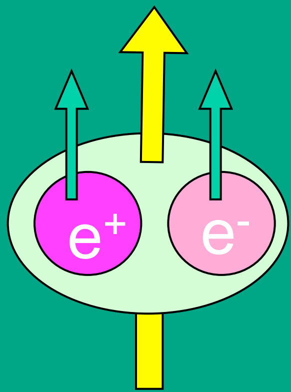
Positronium Hyperfine Splitting

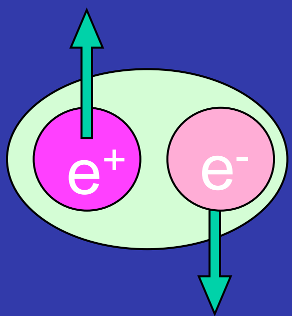
Ortho-positronium (o-Ps)



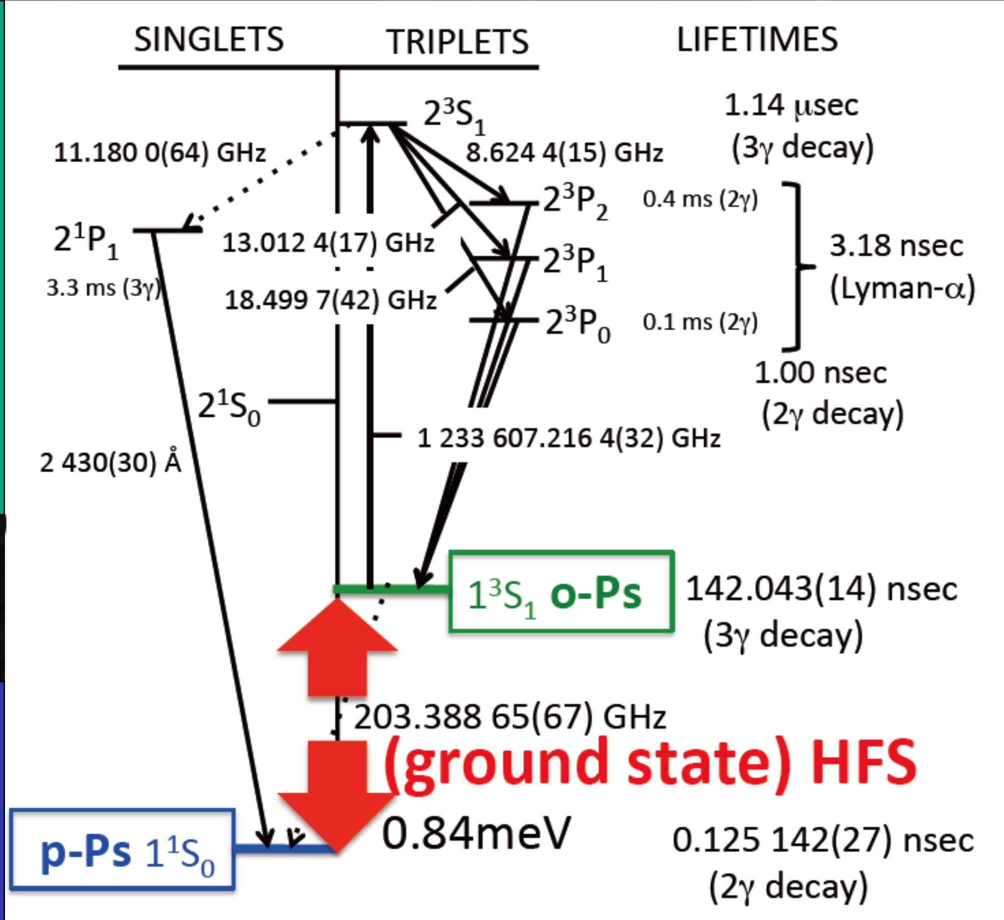
- Spin triplet
- Long life (142ns)
- 3γ decay (continuous)

HFS (203 GHz)

Para-positronium (p-Ps)

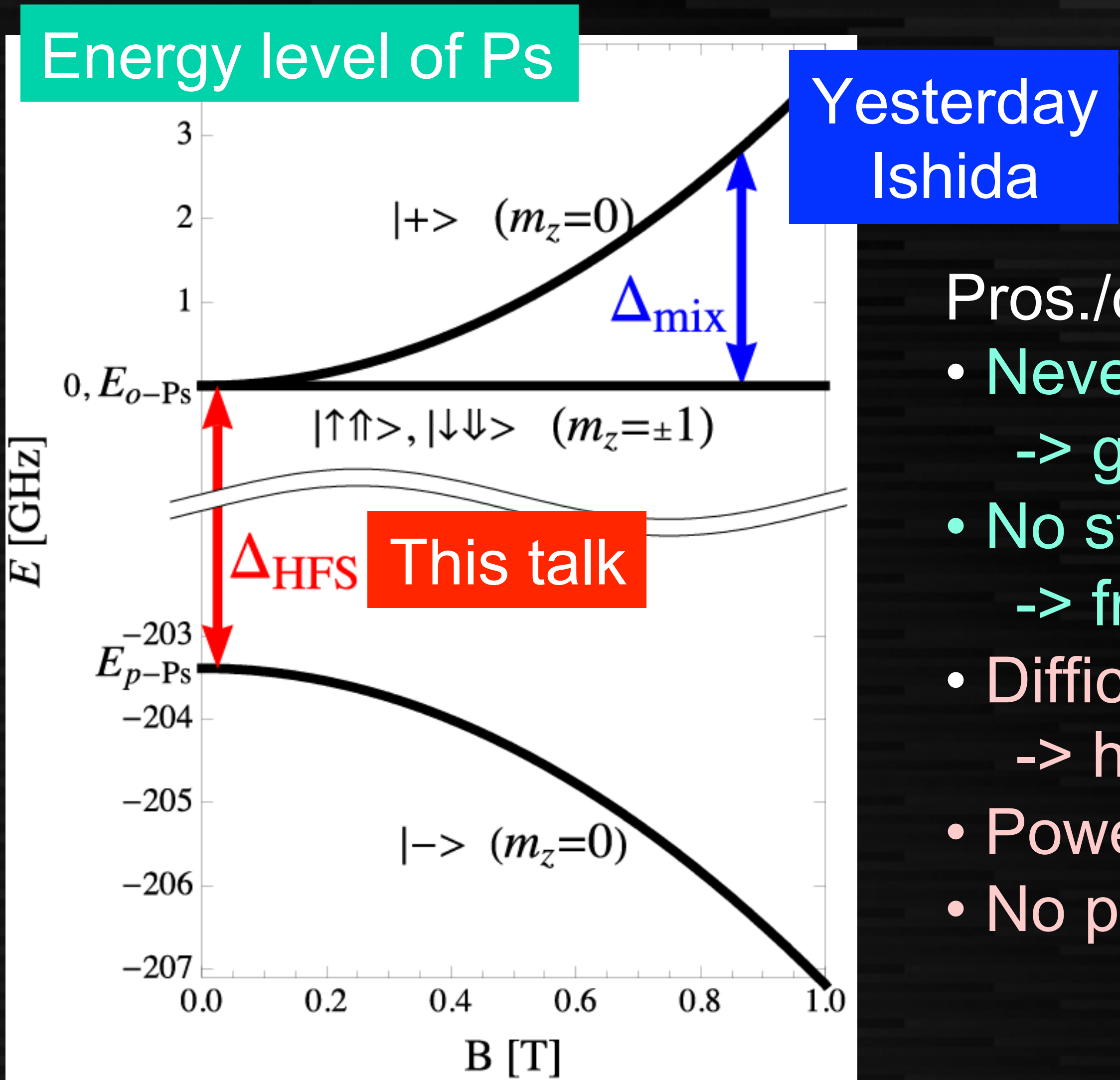


- Spin singlet
- Short life (125ps)
- 2γ decay (511keV)



3.9 σ (15 ppm) discrepancy between theory and experiment

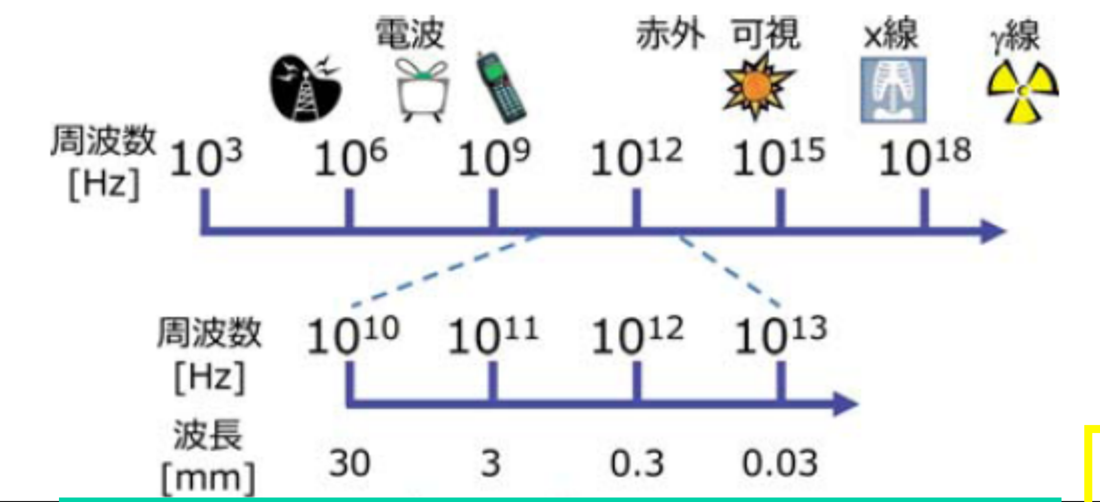
Direct vs. Indirect Transition



Pros./cons. of Direct transition

- Never seen (new technique)
  -> good for cross check
- No static magnetic field
  -> free from magnet errors
- Difficulty in radiation source
  -> high field in sub-THz
- Power measurement
- No positron trap in magnet

(Sub-)THz radiation: 0.1-10 THz



Intermediate region

- Particle-like for
  > O(1) mm vision
- Wave-like for
  < O(1) mm vision

THz gap: little existing technology

Notable progress of recent technology from both optics and microwave

New “eye” for basic science

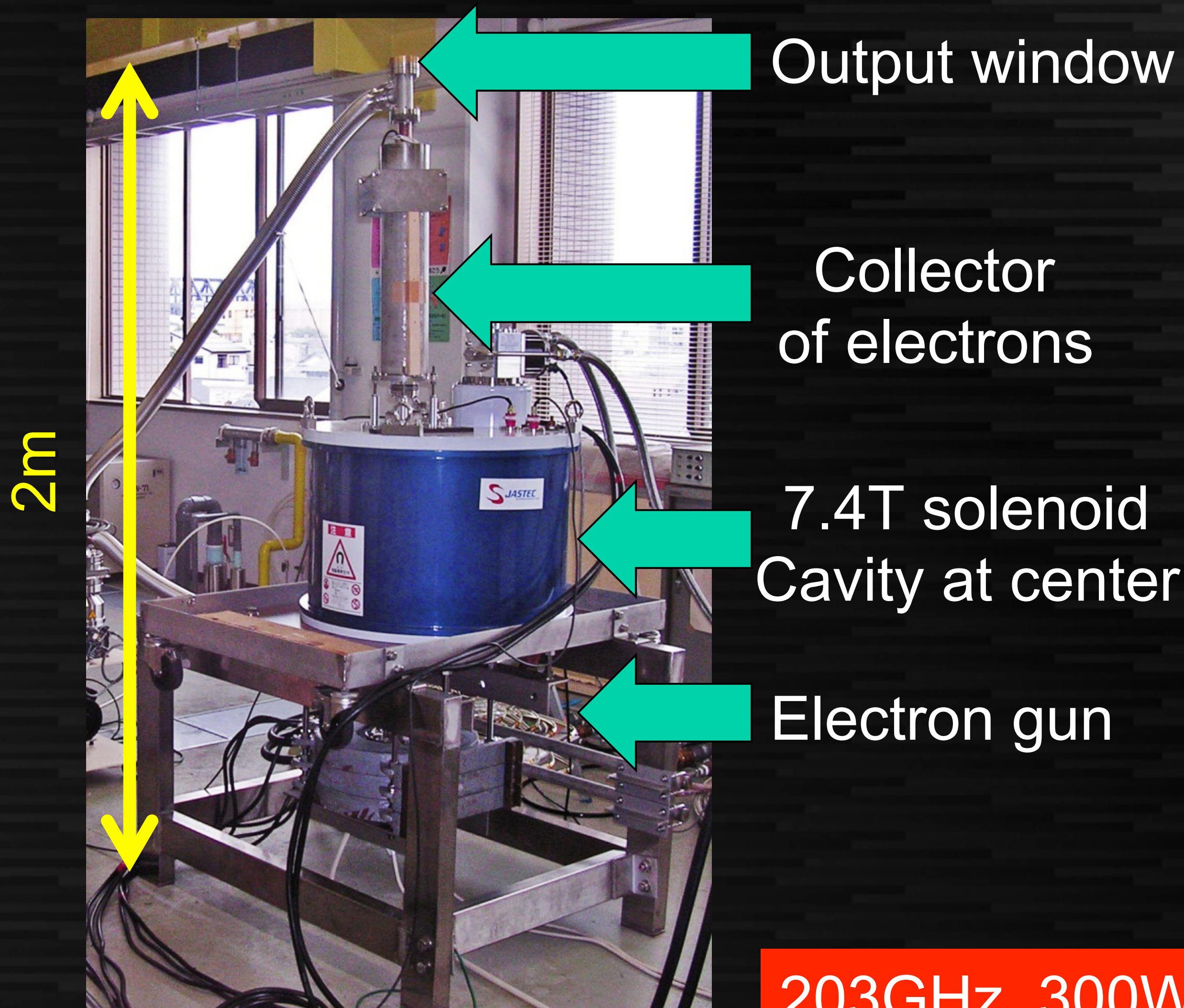
Material: THz time domain spectroscopy etc.
Astrophysics: Materials between stars/galaxies -> star formation
Cosmic microwave background etc.
Particle physics: Precise measurement of SM(this experiment)
Searching for light unknown particle etc.

Keys for the direct observation:

- Accumulation of high-power 203 GHz radiation at the positronium forming area
  1. High power sub-THz source: gyrotron
  2. Gaussian mode converter
  3. Fabry-Perot resonator
  4. Power measurement

- Optimizing the positron source, detectors and shieldings for good signal selection

1. High power sub-THz gyrotron



Gyrotron FU CW IV
@ Fukui

Gyrotron utilizes cyclotron motion of electrons to resonate a cavity inside the solenoid

[characteristics]

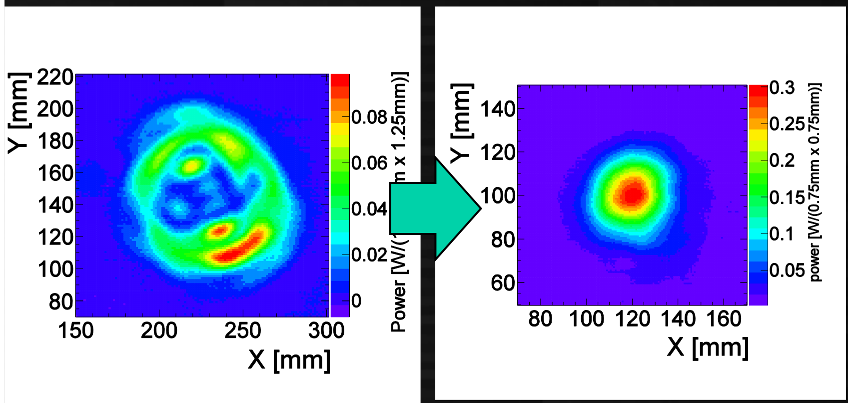
- 100 GHz – 1 THz
- High power
  (used as heaters
  for nuclear fusion)
- Continuous / pulse
- Possibly frequency
  tunable/sweep

203GHz, 300W long pulse
(15ms / 20Hz, duty 30%)
gyrotron was developed for this study

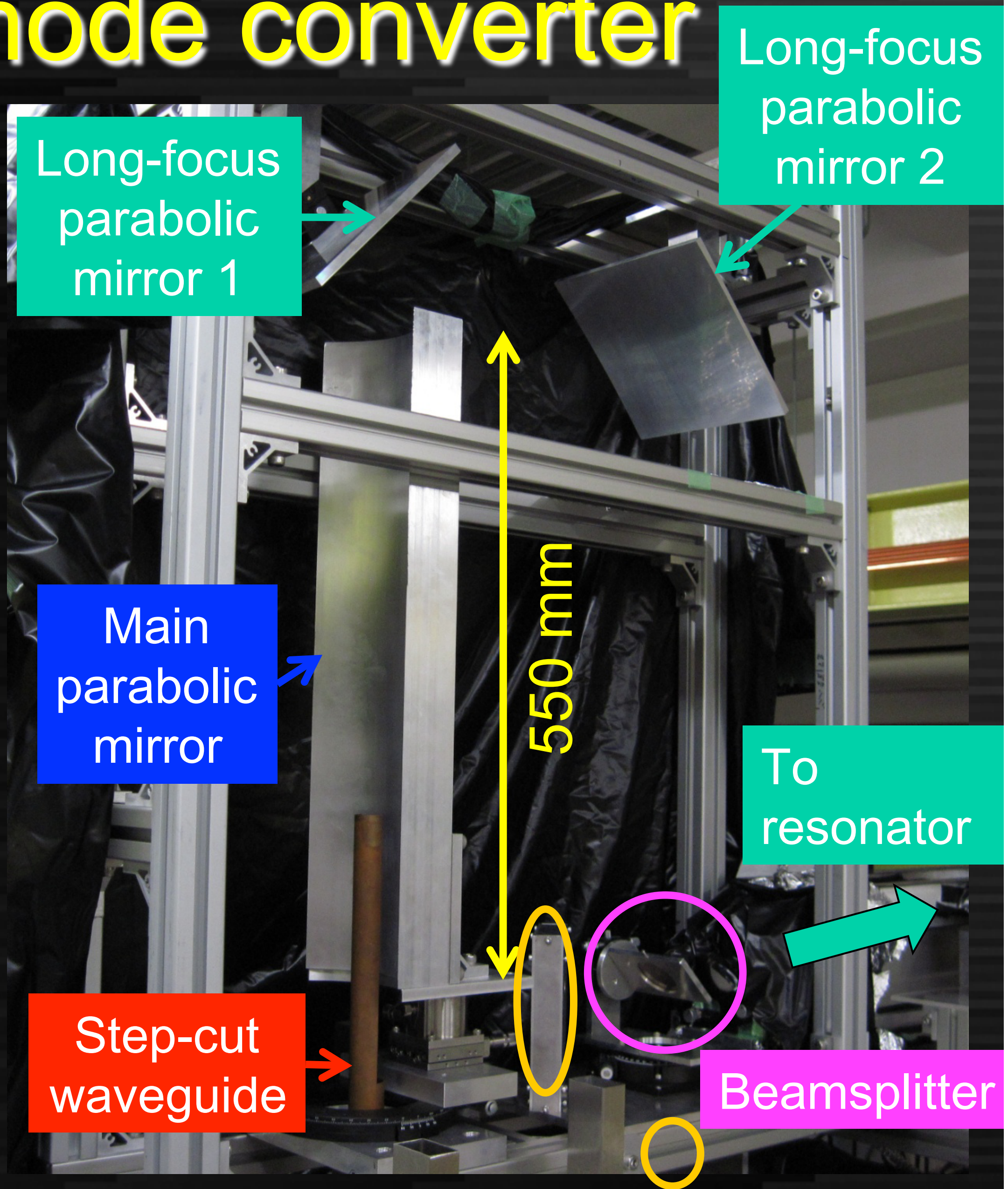
2. Gaussian mode converter

Gyrotron outputs TE_{03} waveguide mode
→ Need to convert to TEM_{00} Gaussian mode to be coupled to optical resonator

Gyrotron output (quasi-) TE_{03} | After converter TEM_{00}



Efficiency: ~30%



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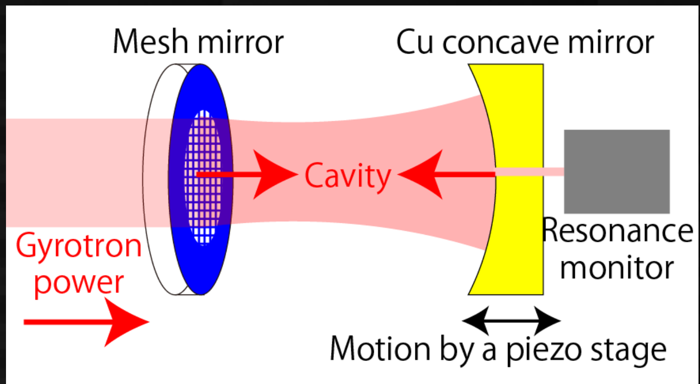
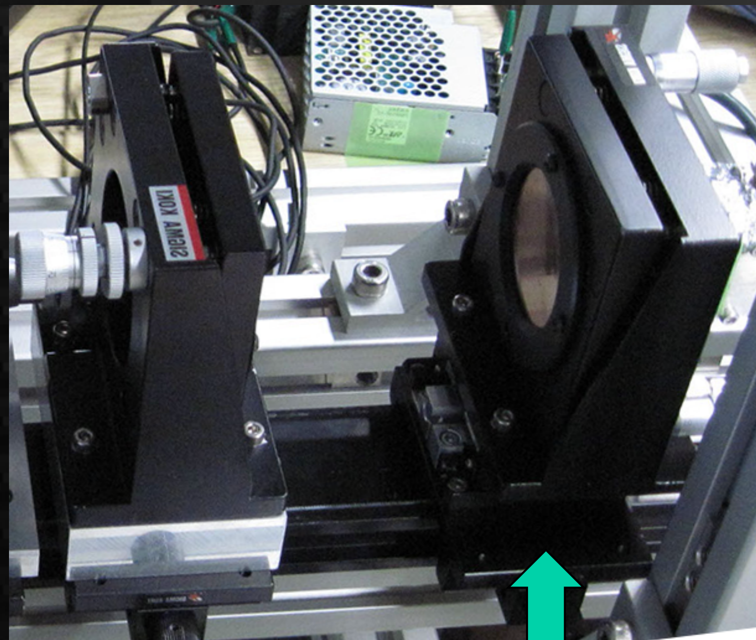
3. Fabry-Perot resonator

One-dimensional resonator(optics)

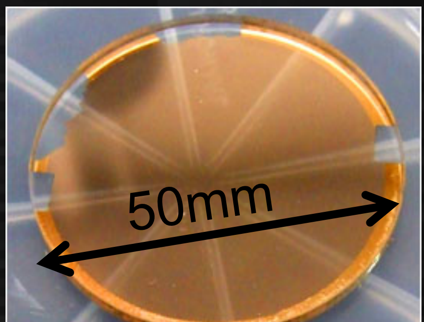
- High power density (optical focusing)
- Freely changing resonant frequency

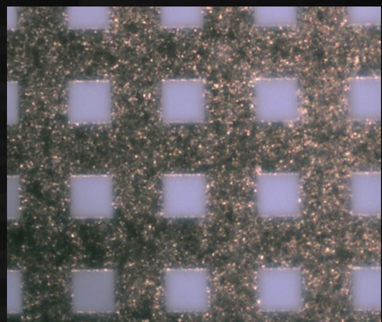




With a piezo stage, cavity length is precisely controlled (~100nm) to maintain maximum resonance

With 130 mm cavity length, ~10 kW power accumulation has been confirmed (Finesse: ~600)

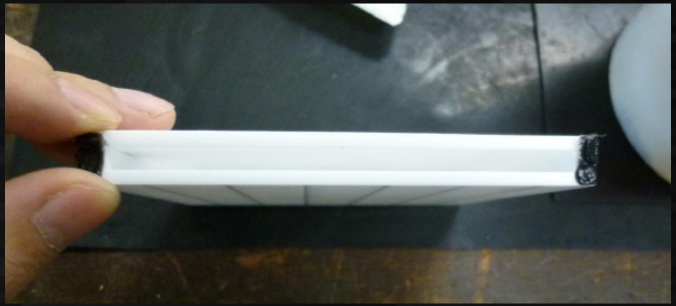




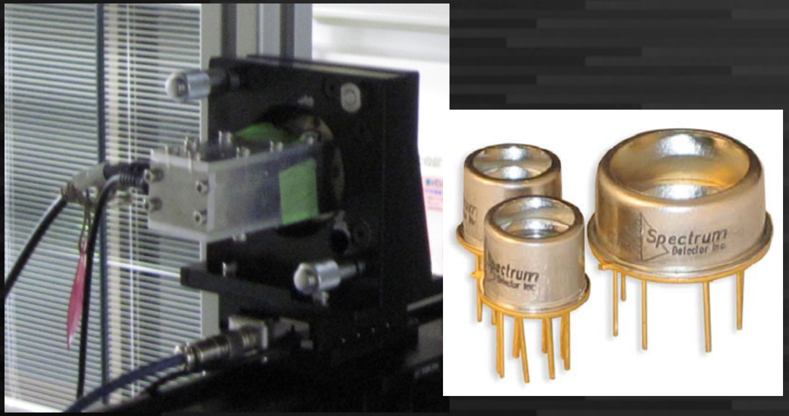
Gold thinfilm mesh (1μm thick, 200μm width, 360μm period) is depleted on the quartz
99% reflection, ~0.7% transmission

4. Power measurement

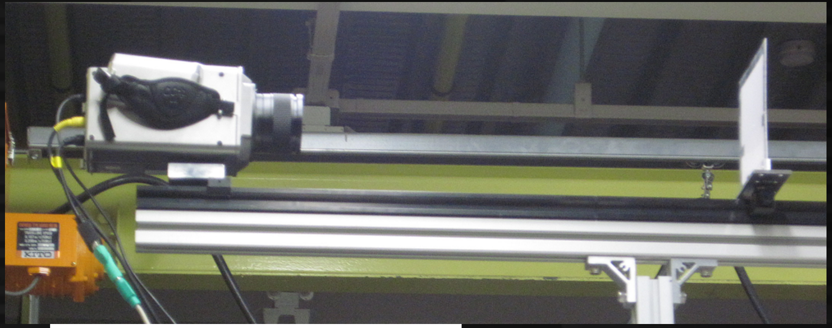
Detectors

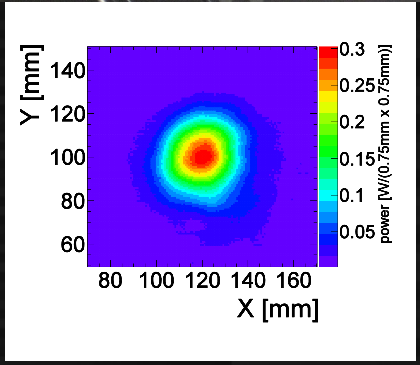


Water in a Teflon box
for absolute calibration



Cu mirror with a small hole
+ pyroelectric detector
-> power monitoring/control





PVC plate +
thermo camera
for profile/calibration

Power calibration:

Absolute power with water

↓

Power density with camera

↓

Volt / watt coefficient
in pyroelectric detector

Control of gyrotron/cavity

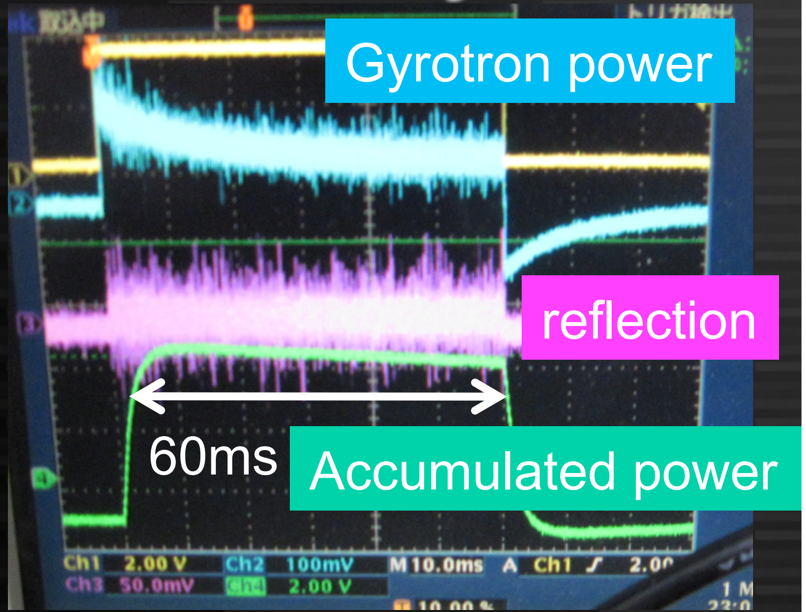
Output power of gyrotron

Fluctuate > 100% without control

Gyrotron power by pyroelectric detector

↑ Stabilize (PID control)

Temperature in electron gun of gyrotron with changing voltage to gun heater



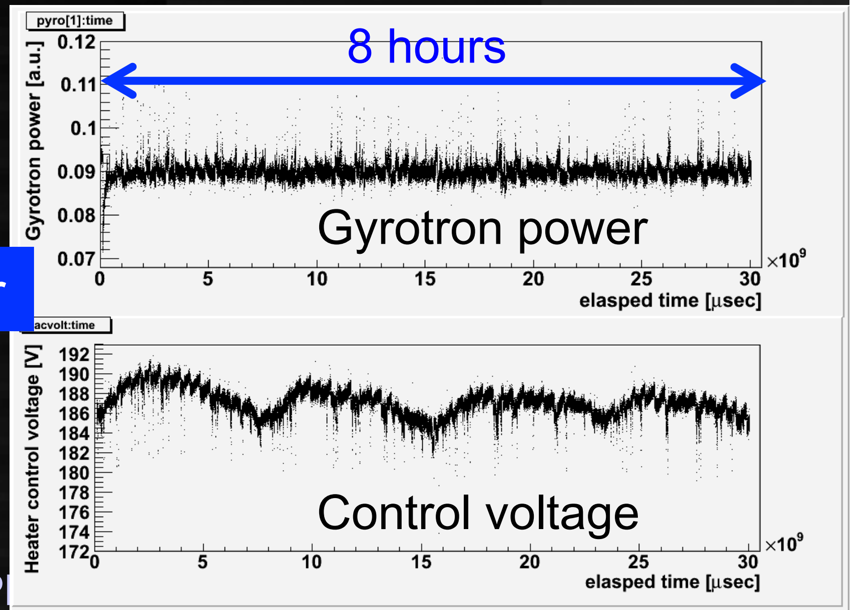
Accumulated power in cavity

Cavity length instability
-> cause off-resonance

Accumulated power by pyroelectric detector

↑ Maximize (by scanning)

Mirror position on piezoelectric stage



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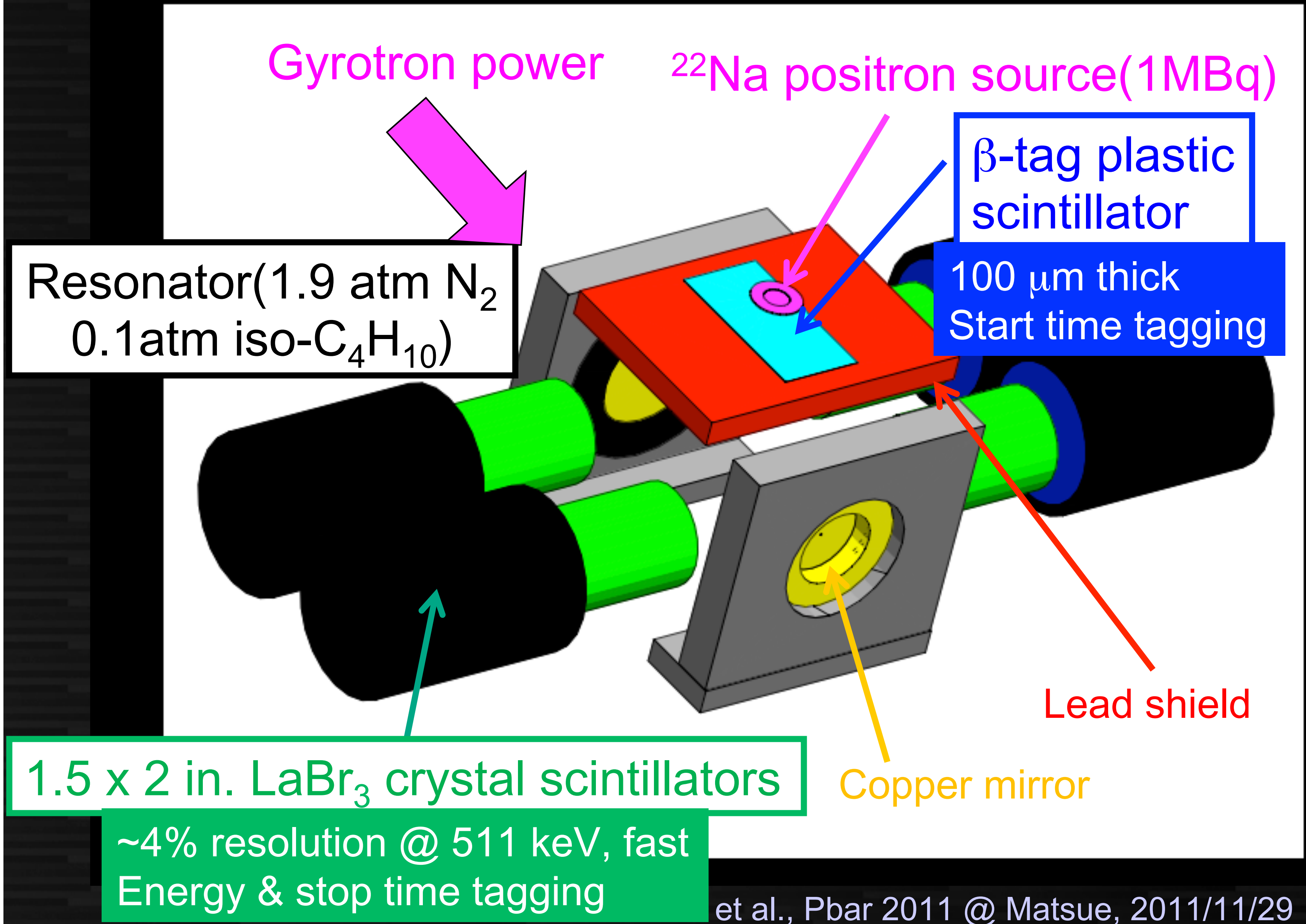
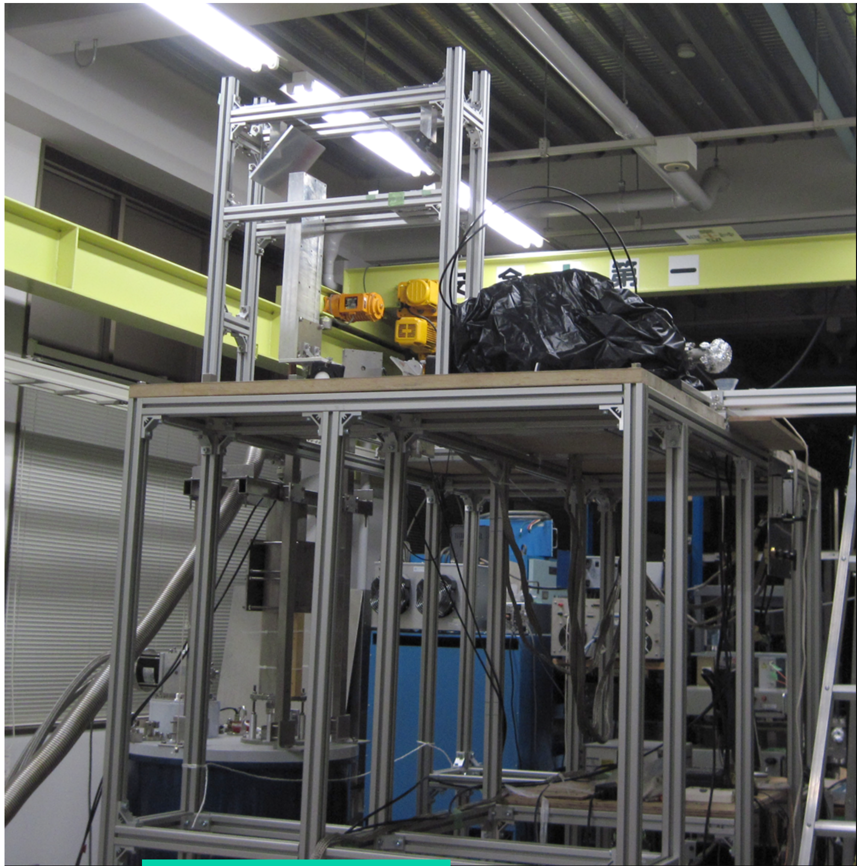
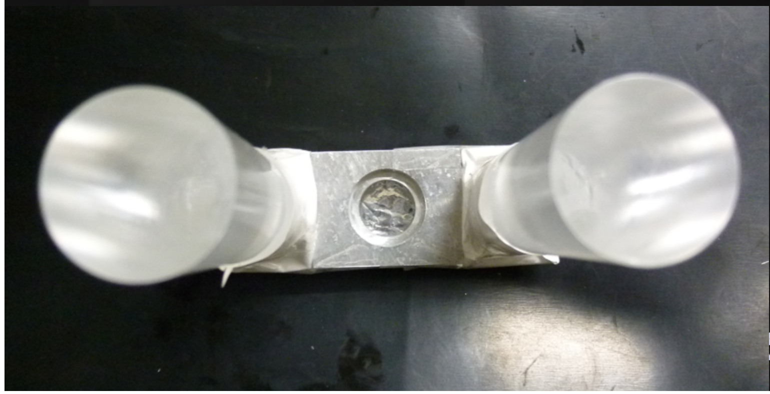
Setup of source/detector

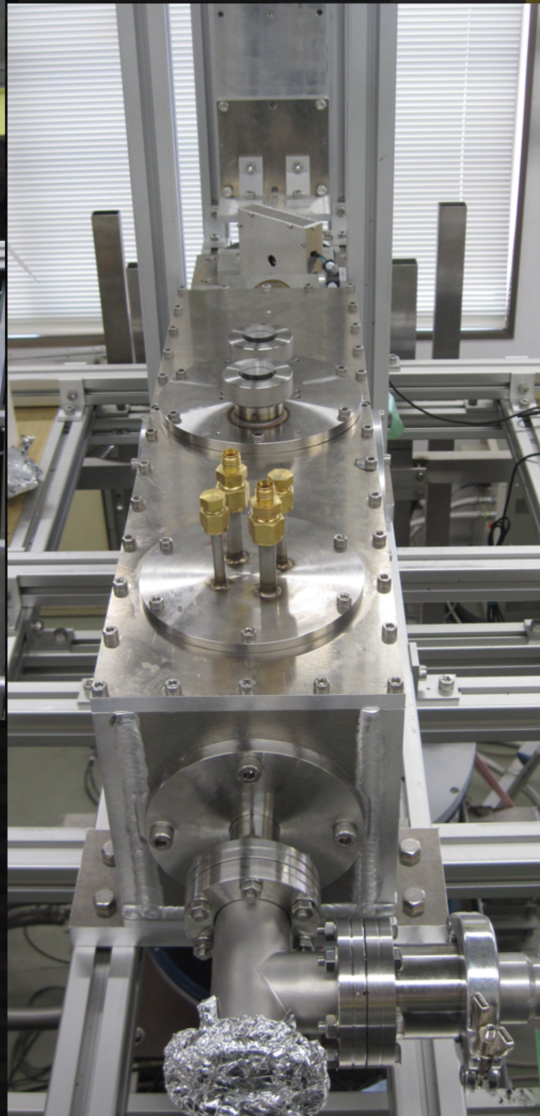


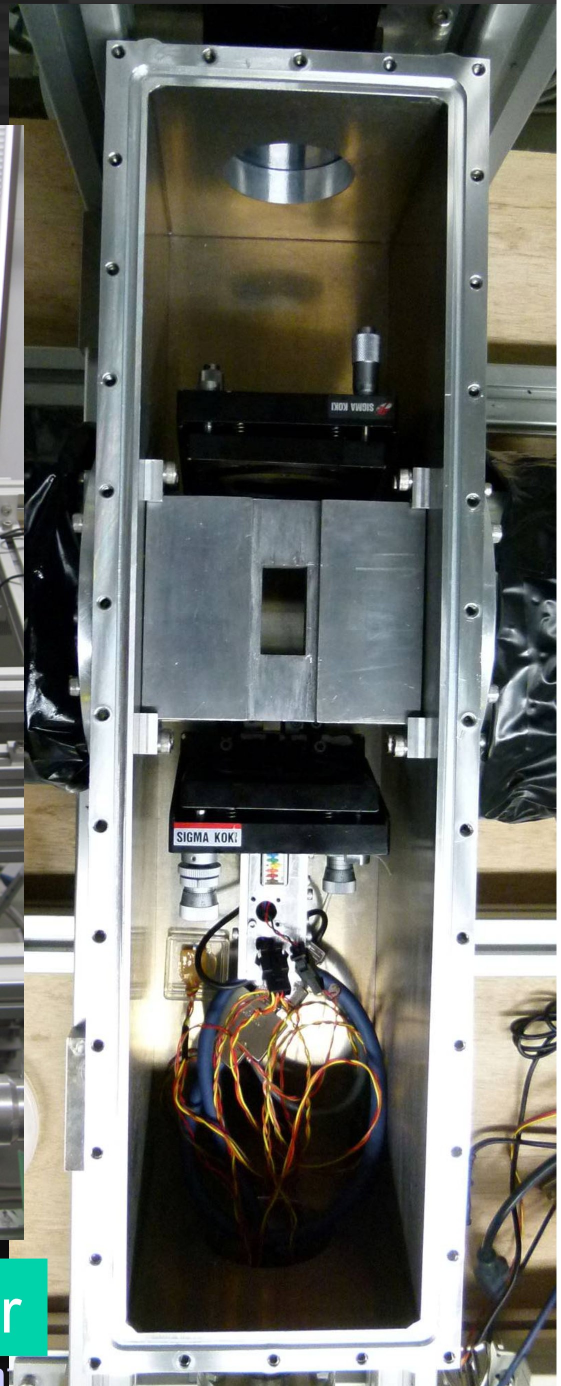


Overview

Source / holder







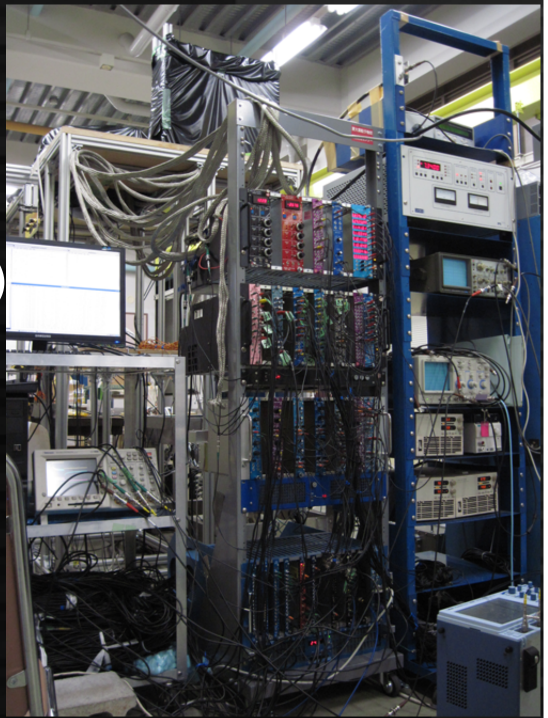
Chamber / resonator

Run / selection configuration

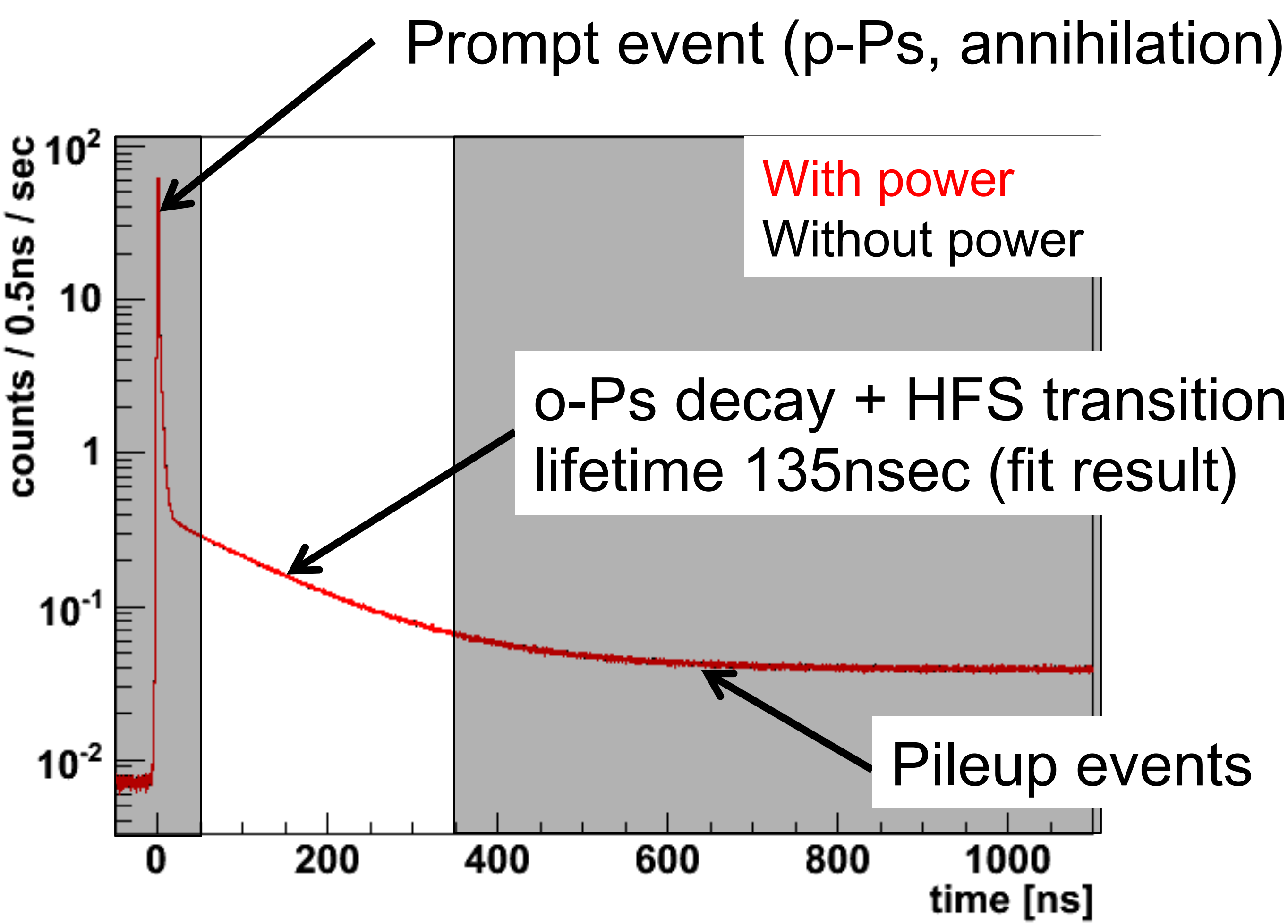
- Run configuration (accumulated power)
  - 203 GHz operation (10 kW, 5 kW, 0 kW)
    power controlled by changing cavity resonance condition
  - 140 GHz operation (3.3 kW) for off-resonance of HFS
    similar temperature rising as 10 kW / 203 GHz

  Gyrotron ON/OFF is repeated 20 Hz
  with duty=30% - ON/OFF subtraction
  performed to suppress systematic errors

- Selection strategy
  - Time between e^+ emission (by plastic scintillator)
    and γ detection (by LaBr3 scintillators)
  - Back-to-back emission of photons
    (opposite $LaBr_3$ hits required)
  - Energy selection (around 511 keV)
  - Pileup rejection (see later slide)



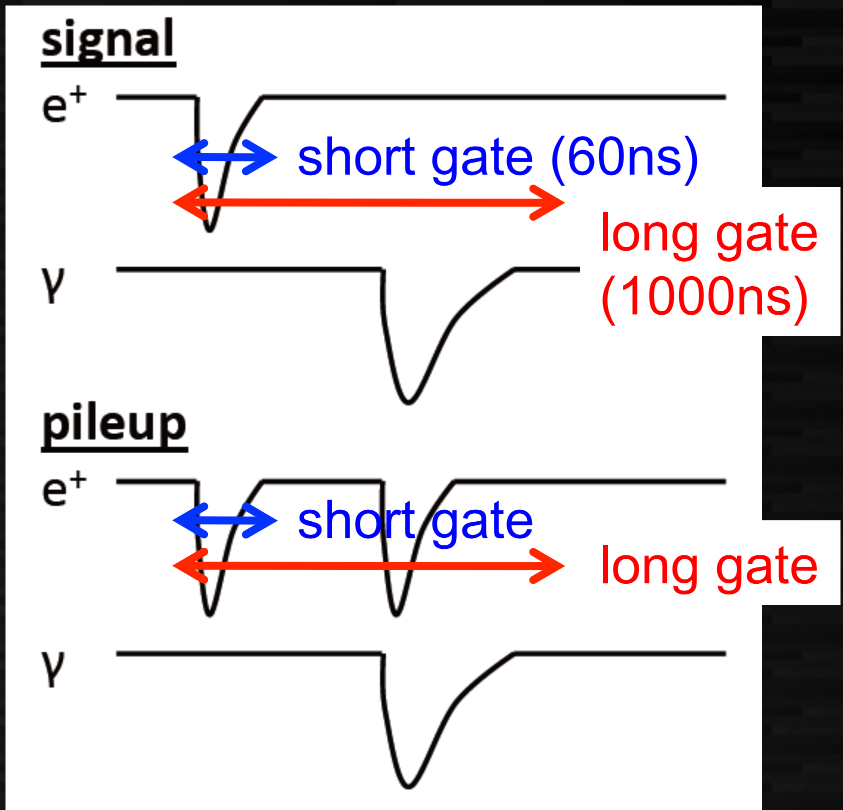
Timing selection



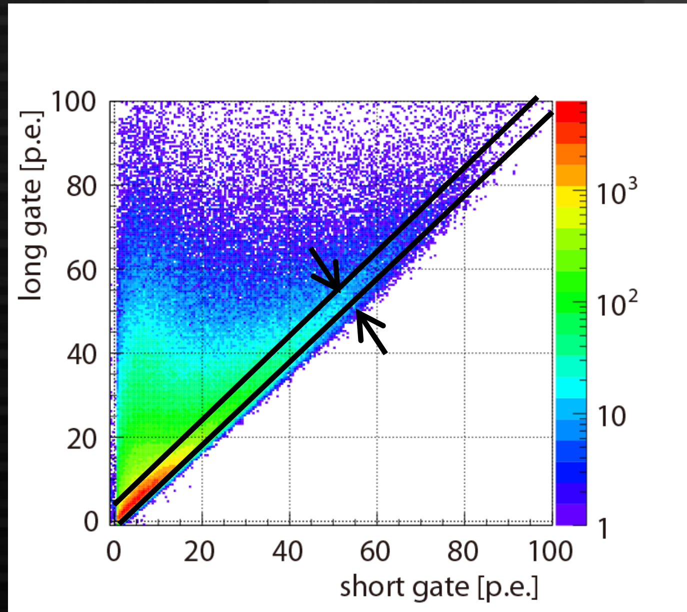
No difference seen between power on/off events

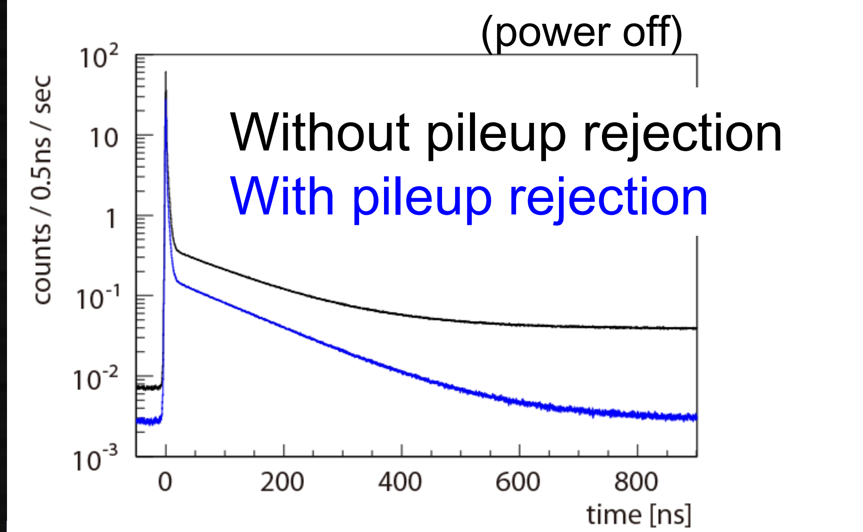
Pileup rejection

The most significant bkg.: pileup



Cutting pileup events
by comparing QDC value
with short/long gate





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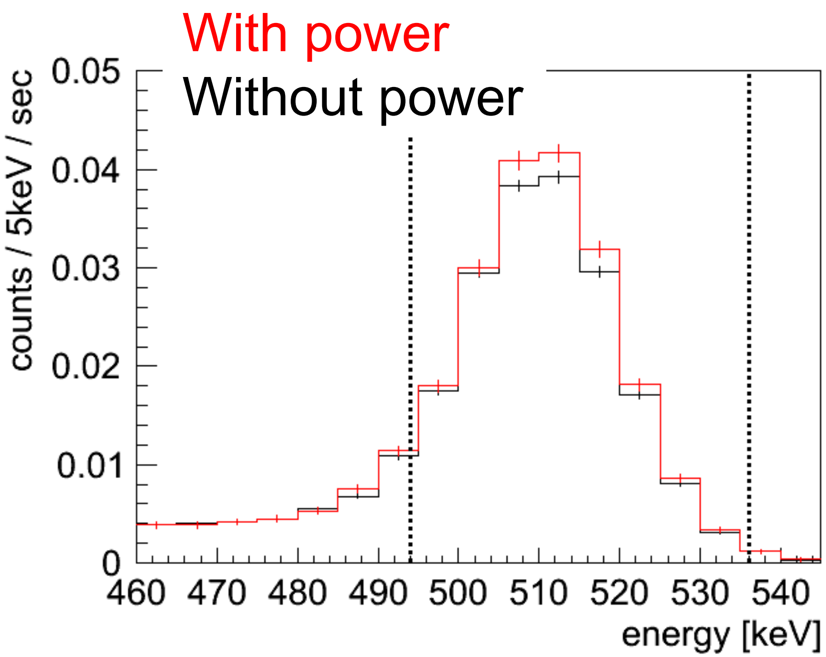
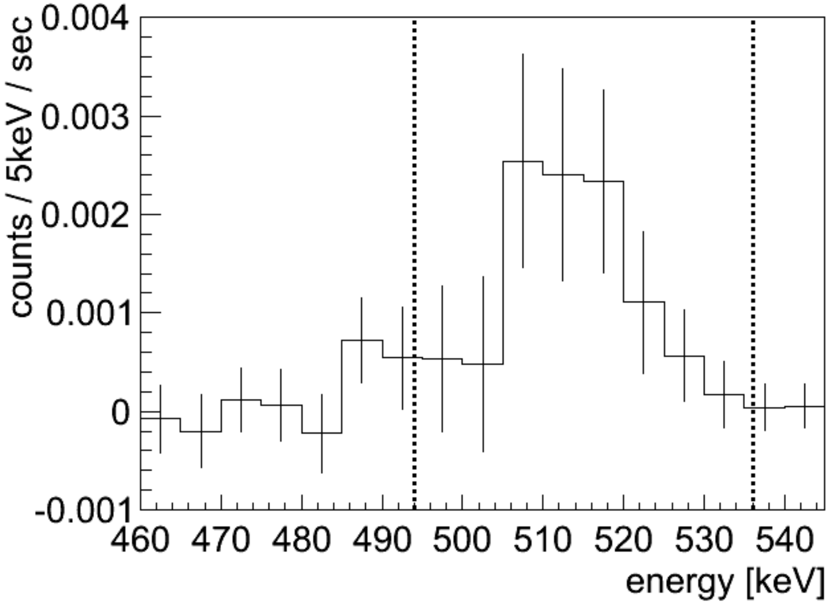
Energy cut & result



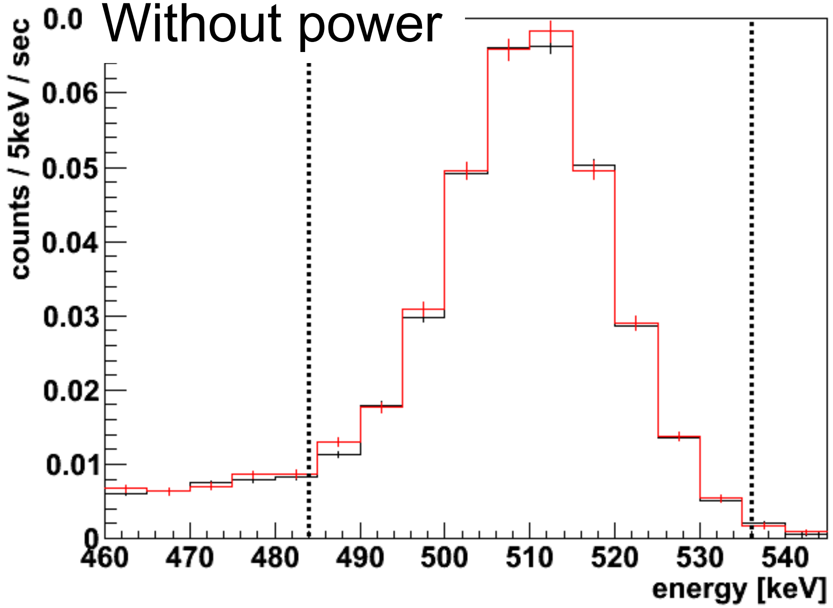
Power on – power off



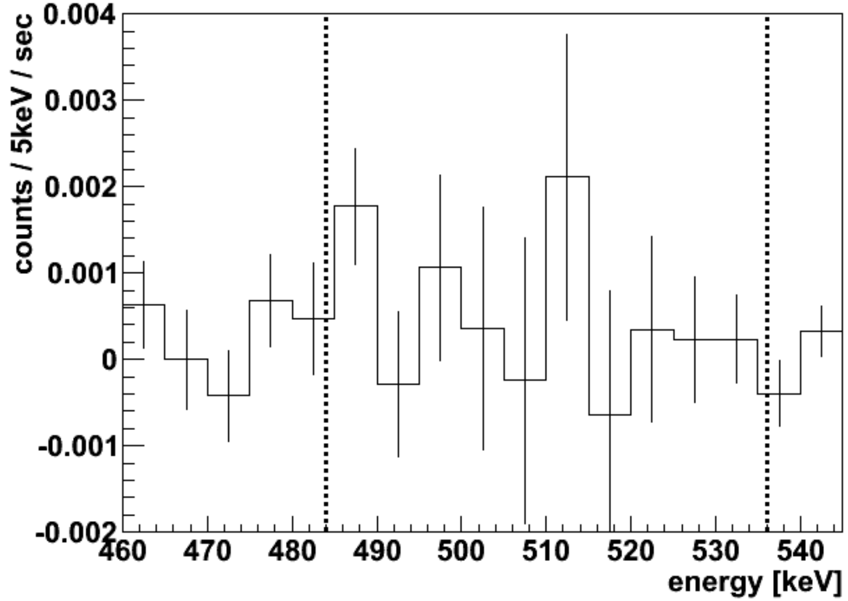
With energy window of 494-536 keV,
transition rate of 15.1 ± 2.7 mHz (stat. error only)
is obtained.

The first direct transition observation!

Result with 140 GHz radiation



Power on – power off



Transition signal is not seen in 140 GHz result.
(3.3 ± 3.6 mHz (stat. only))

Cut flow & systematic errors

	ON [Hz]	OFF [Hz]	ON − OFF [Hz]	(ON−OFF)/OFF (%)
No cut	948.55(11)	948.59(7)	−0.04	−0.004
Offline trigger	457.44(8)	457.47(5)	0.03	0.007
Timing cut	67.933(29)	67.797(19)	0.136	0.20
Pileup rejection	29.116(19)	29.079(13)	0.037	0.13
Energy cut	0.3037(23)	0.2886(15)	0.0151(27)	5.23

Systematic errors with respect to OFF rate:

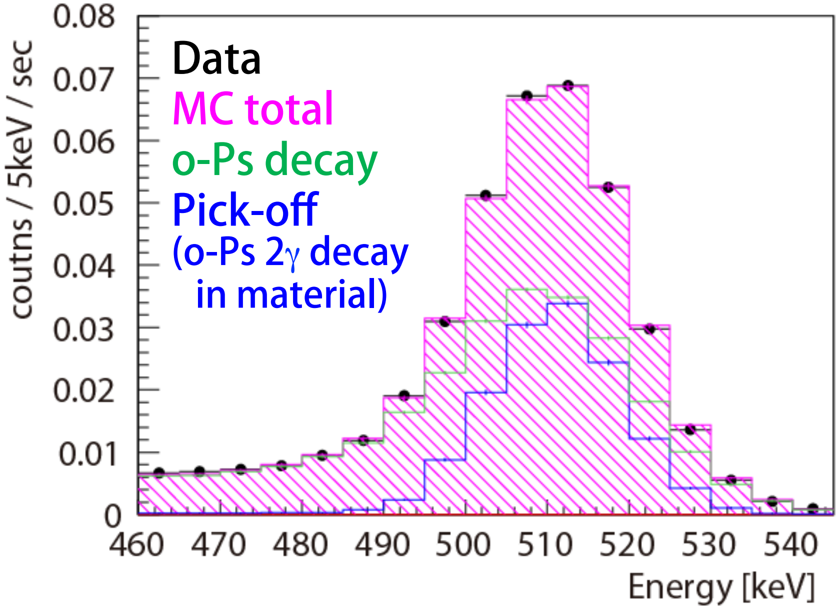
- Energy scale / resolution: -0.08%
- Ps formation probability: -0.27%
- Pileup rejection efficiency: +0.17%
- Background normalization: ±0.13%

Total: +0.17% / -0.29% -> +0.5 / -0.8 mHz

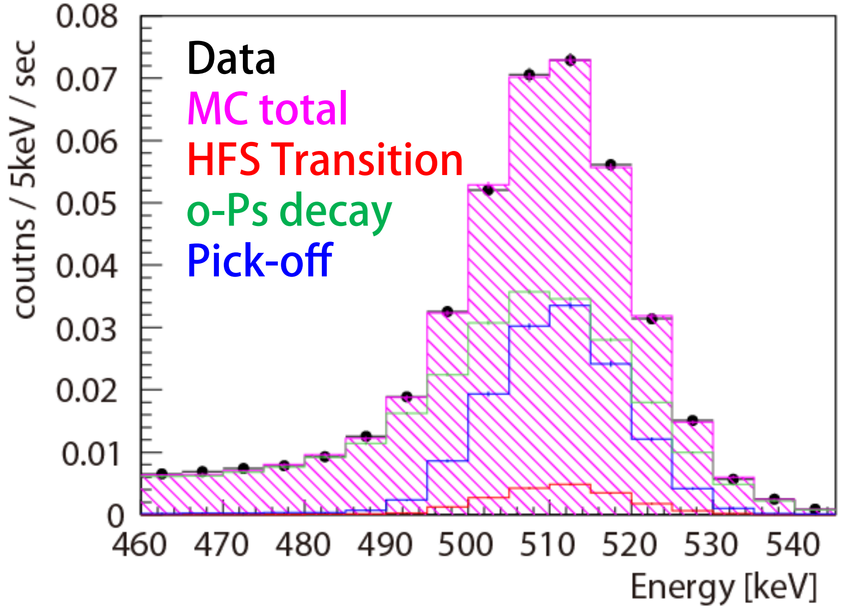
Transition rate: 15.1 ± 2.7(stat.) +0.5/-0.8(syst.) mHz

Comparing to MC

Power off

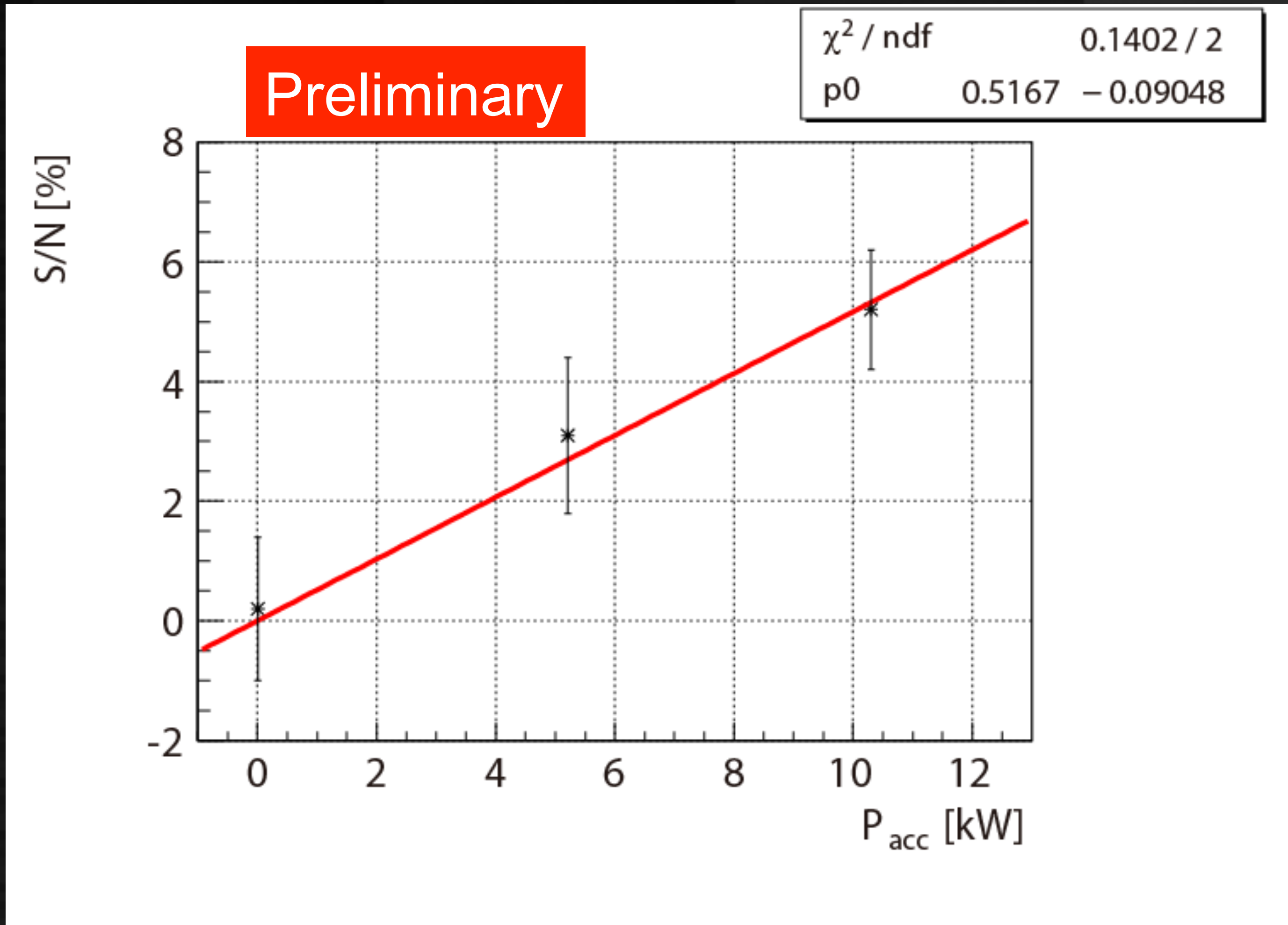


Power on



- Good agreement between Data & fitted MC (Fitting parameter: transition rate & pick-off rate)
- Transition rate is consistent to QED calculation

Dependence on input power

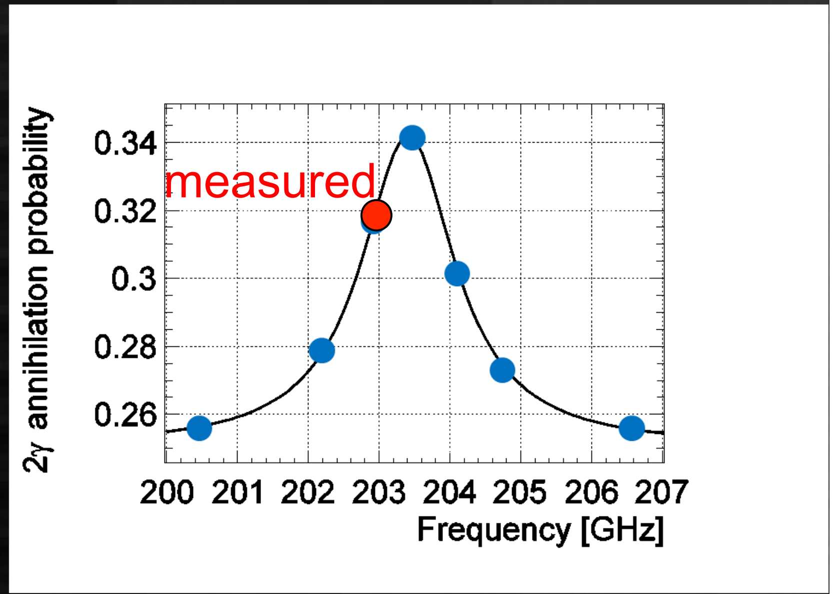


Transition ratio is confirmed to be proportional to the input power.

Toward the HFS measurement

- Need to measure transition in multiple frequencies to obtain resonance curve

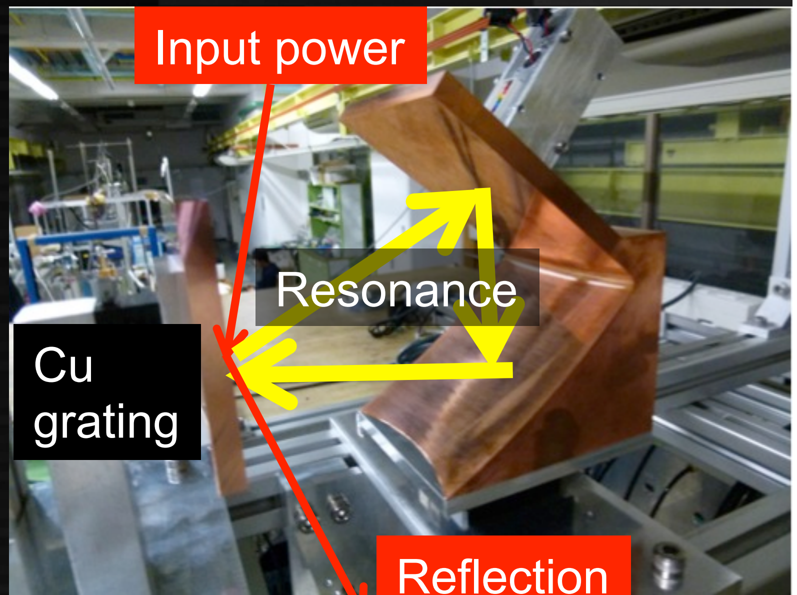
Gyrotron with replaceable cavity (now fabricating / testing)



- Avoid damage by heat at higher operation power

Replace the Fabry-Perot cavity with a mesh to a ring cavity with a grating

Finesse ~ 1000 achieved, coupling optimizing



We plan to measure HFS O(100ppm) in 1.5 years

Summary

- The first direct transition of positronium hyperfine splitting has been observed.
- The transition rate is consistent with QED calculation.
- The first direct measurement of positronium hyperfine splitting value will be performed with O(100ppm) in 1.5 years.

Thank you for your attention.