Low Radioactivity Techniques Workshop [LRT 2017]
May 23rd – 27th 2017, Seoul, Korea

Development of CANDLES Low Background HPGe Detector and Half-life Measurement of ^{180m}Ta

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for the **CANDLES** Collaboration

CANDLES

Contents

HPGe Detector System of CANDLES

- Construction and Development
- Detector Performance

CANDLES

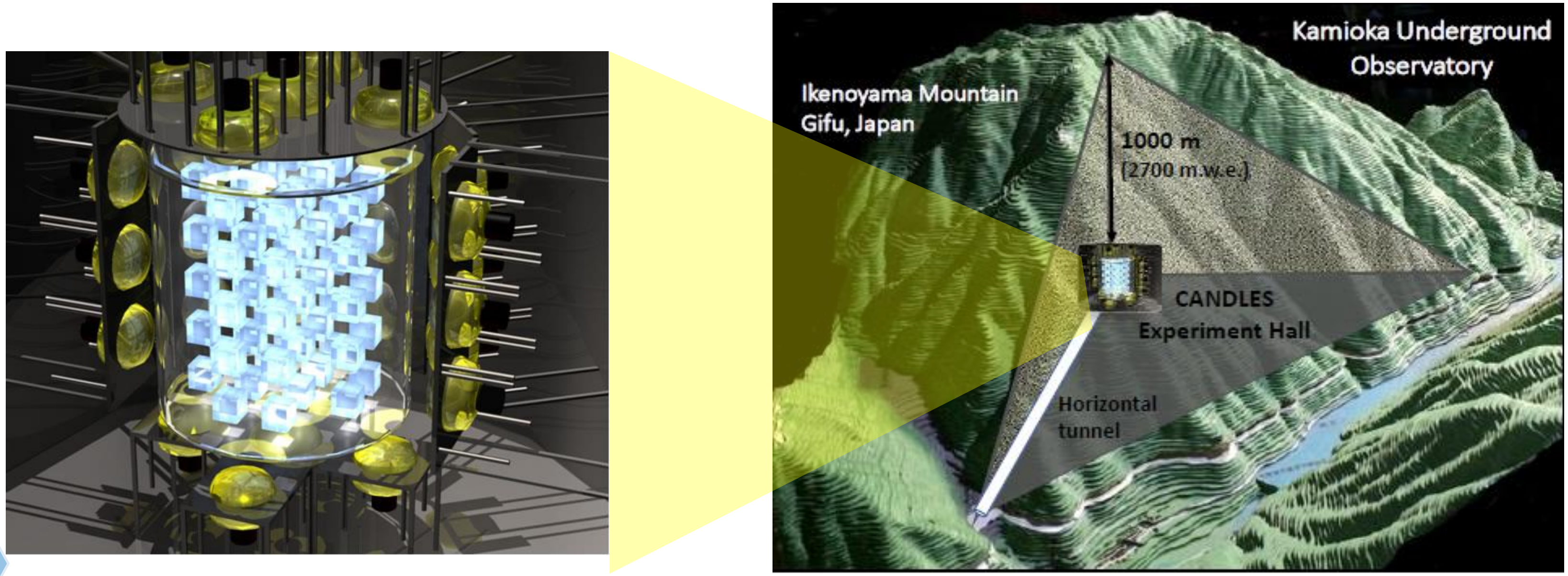
- Neutrinoless double beta decay experiment using ^{48}Ca isotope
- Location: Kamioka Underground Observatory (2700 m.w.e.)

[Muon flux is 5 order magnitude lower than ground]

- Rare event -> ultra-low background condition is very essential

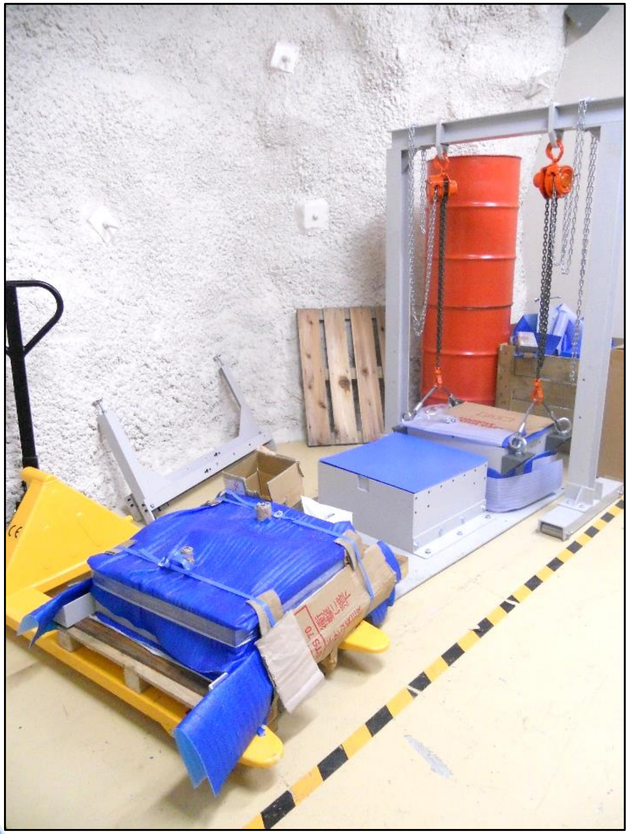
[Session 6: "Performance of Upgraded Shielding System in CANDLES"
by Dr Nakajima Kyohei]

- An ultra-low background HPGe detector system was installed in the same experimental hall for support of CANDLES.

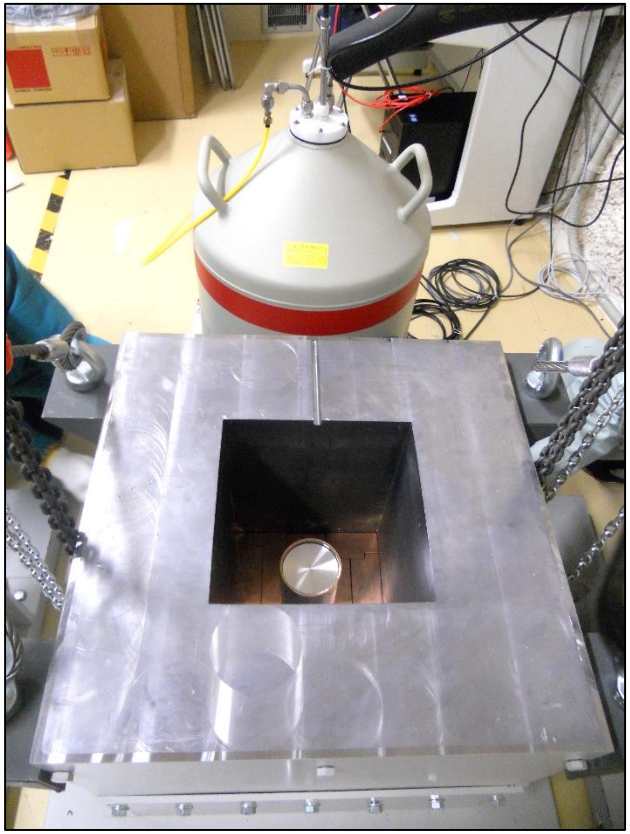


Construction Works

- Assembly of detector and shields (year 2013)
- Shields [150 mm Hermetic Pb + 50 mm OFHC Cu + Inner Cu (if need)]



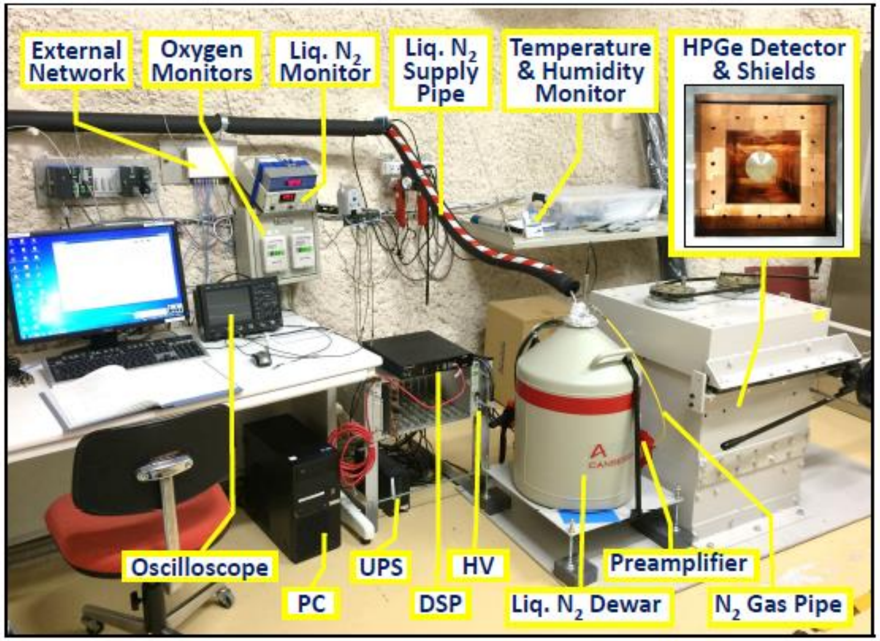
Construction site [Back Experimental Room of CANDLES]

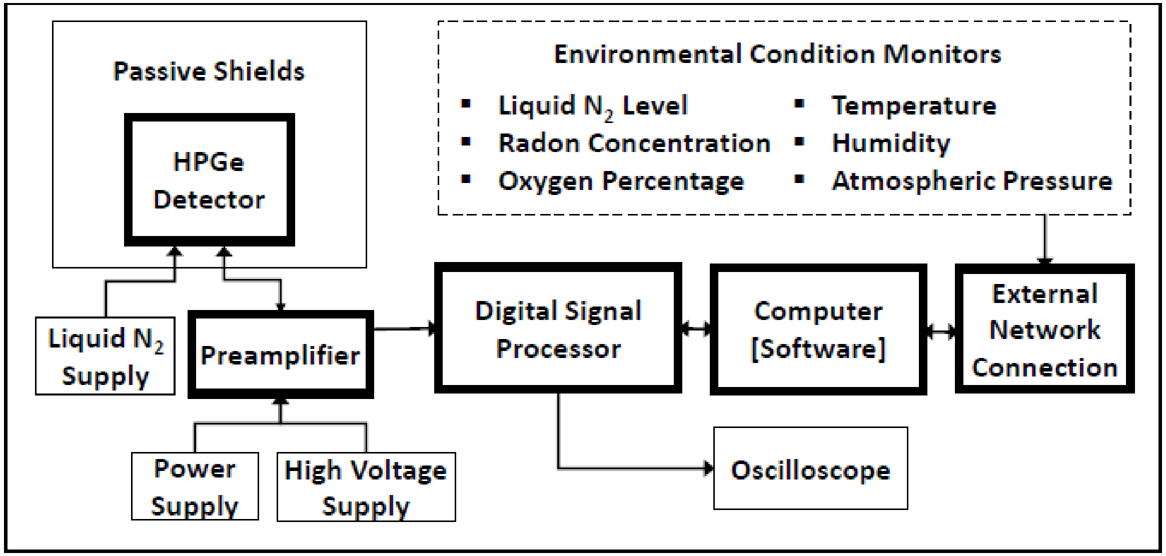


Hermetic lead shield HPGe detector & Dewar

Zig-zag shape copper blocks

Completed HPGe Detector System





Data taking was started from year 2013

- **Material Screening of CANDLES**
- **Tantalum Phase I & II**
- **Others**

Performance of Passive Shields

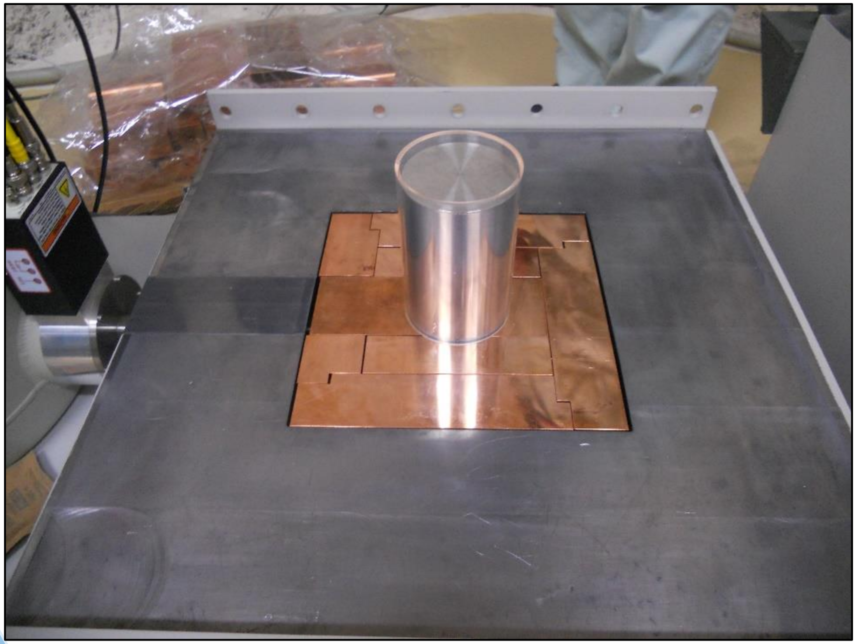
HPGe detector:

crystal size Φ65mm, relative efficiency = 50%, FWHM ~1.9 keV at 1.3 MeV]

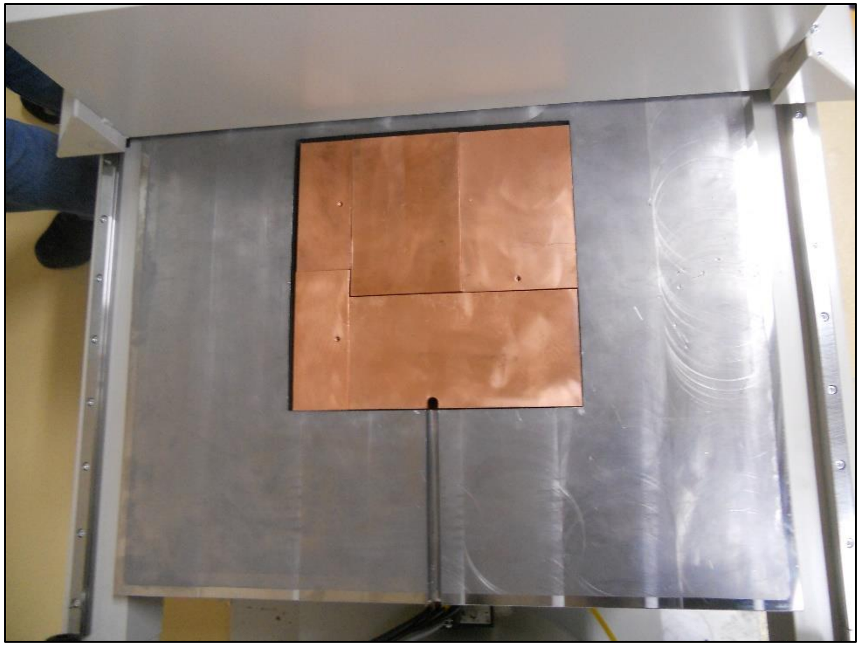
Full Shields:

9 mm Fe + 150 mm Pb + 50 mm Cu + inner Cu around detector

- Continuous nitrogen gas flow



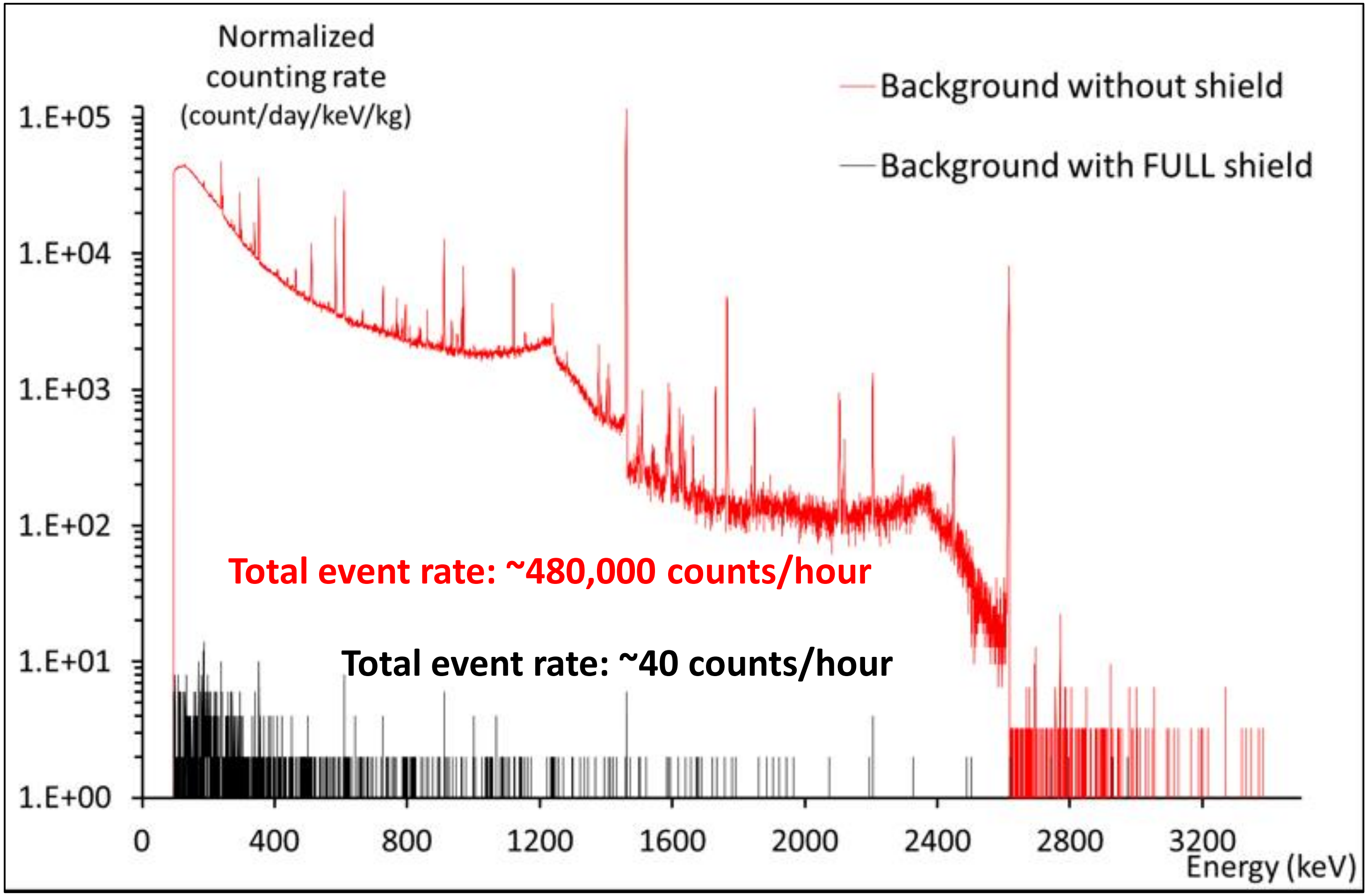
Without full shields



Full shields + Boil-off nitrogen gas flow

Comparison of Background Spectrum [1 day]

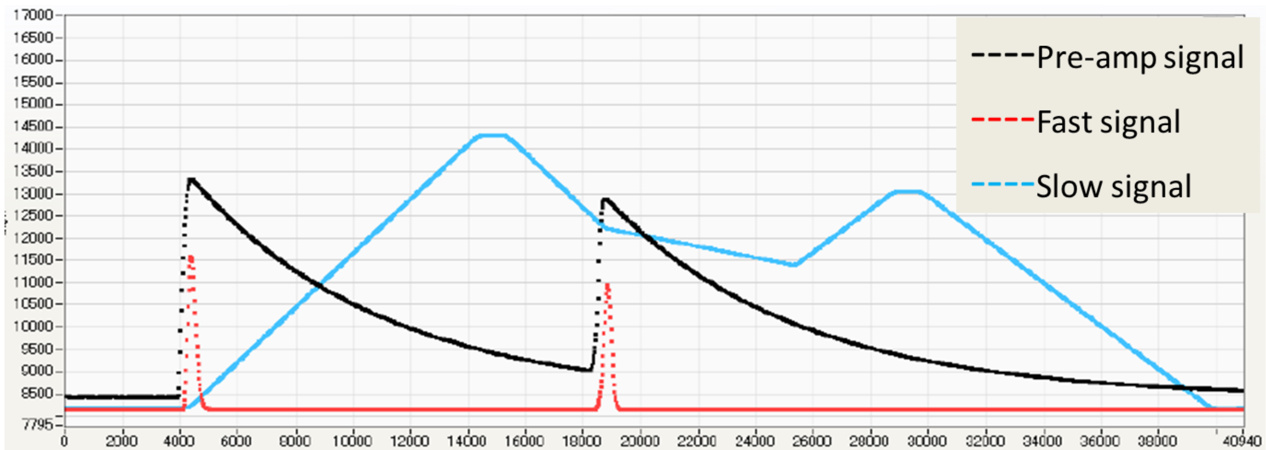
- With hermetic shields, background level has reduced 4 orders of magnitude.



Data taking of HPGe detector

- Digital Signal Processor (DSP) was used.
- Fast signal is the timing filter, Slow signal is the energy filter (trapezoidal filter).

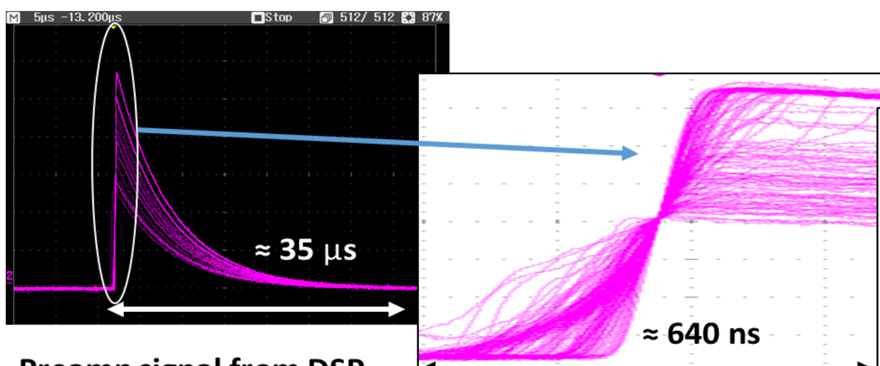
Pulse Height (a.u.)



Time (ns)

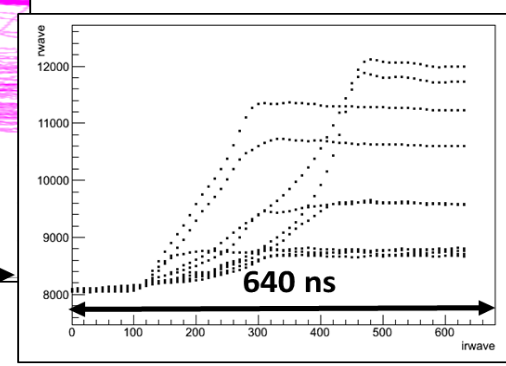
Event Format:

- Time
- Channel (Energy)
- Pulse shape at rising part (640 ns)



Preamp signal from DSP [Oscilloscope] Co-60

Rise Wave from DSP [Oscilloscope]



Digitized Rise Wave of DSP [Offline analysis]

Half-life Measurement of ^{180m}Ta

- Introduction of ^{180m}Ta Decay
- Tantalum Phase I & Phase II

Motivation to study ^{180m}Ta Decay

- ^{180m}Ta is **the longest natural isotope that exist in excited state.**
  - Long-lived isomeric state $J_\pi = 9^-$ & short-lived ground state $J_\pi = 1^+$
- Half-life of ^{180m}Ta **has never been determined.**
- Lower limit of half life

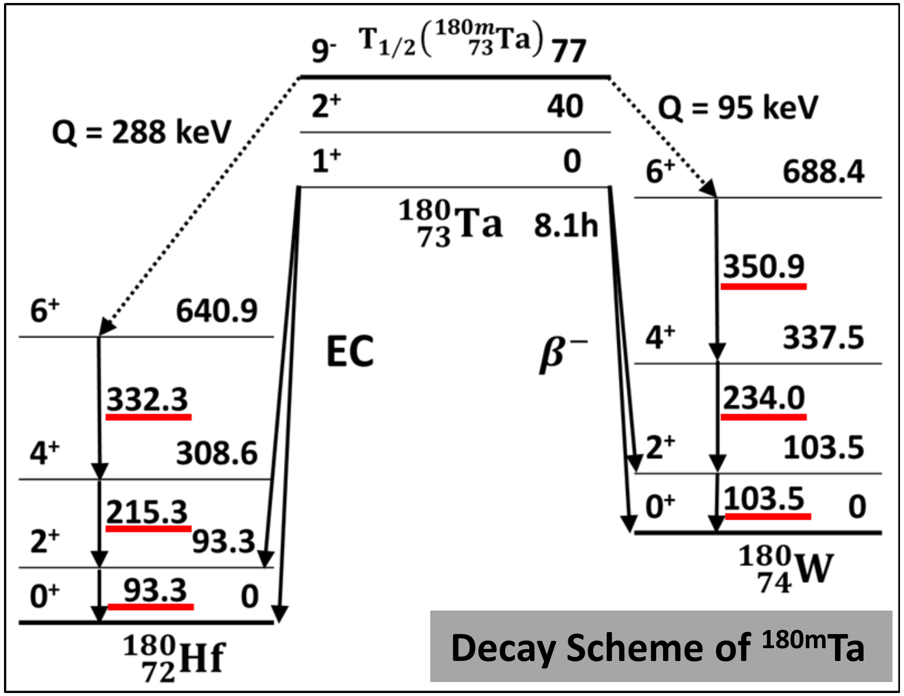
  4.5 × 10^{16} years [PRC, Lehnert 2017]

- ^{180m}Ta is predicted to decay in 3 ways:
  1) Isomeric transition to ^{180}Ta [$>10^{27}$ yrs]
  2) Beta decay to ^{180}W
  3) Electron capture to ^{180}Hf

Observe events produced by γ decays

$6^+ \rightarrow 4^+$, $4^+ \rightarrow 2^+$, $2^+ \rightarrow 0^+$

- ROI is 90 – 360 keV
- Backgrounds at low energy region



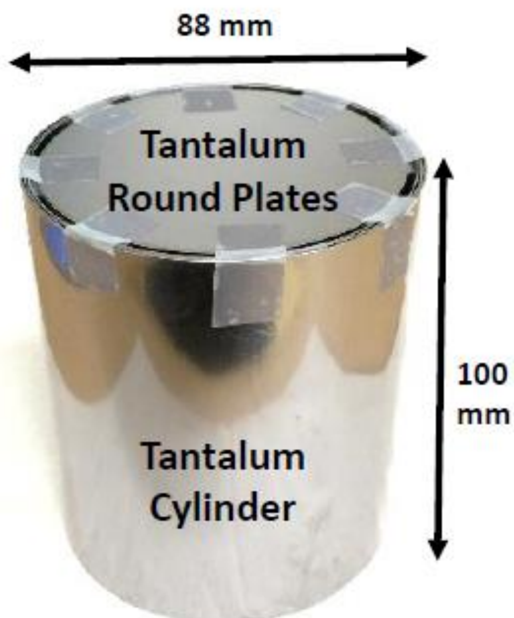
Decay Scheme of ^{180m}Ta

Challenge: To obtain the world most stringent half-life limit for ^{180m}Ta.

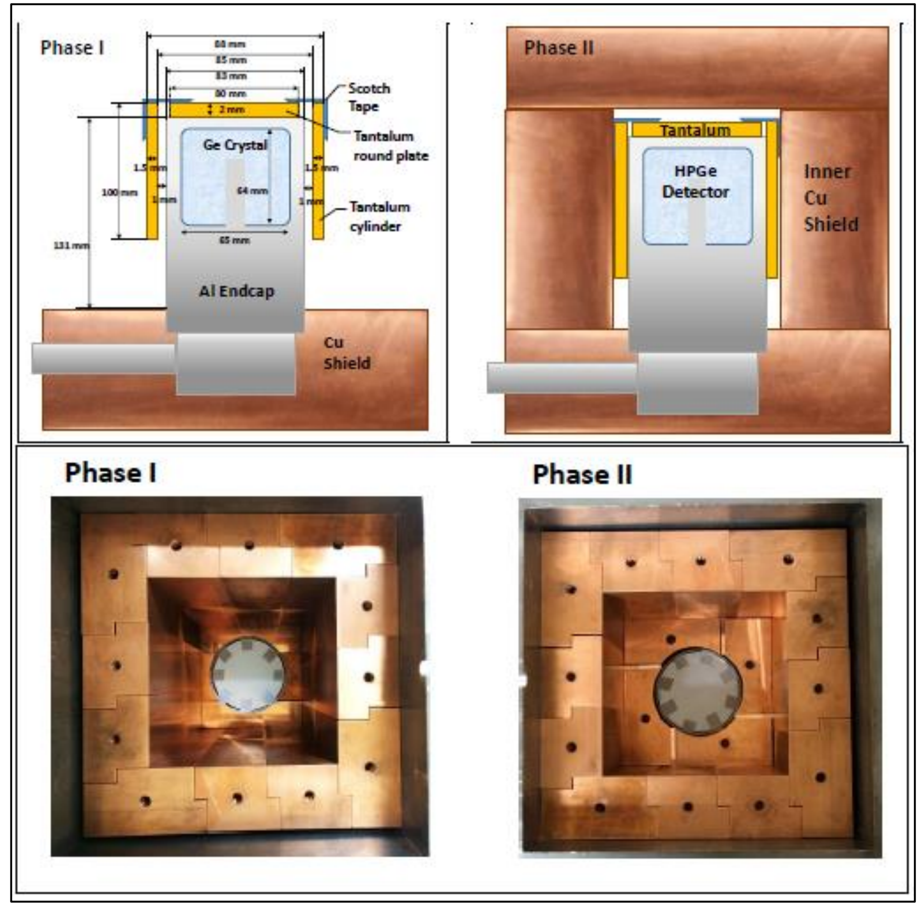
Tantalum Phase I & Phase II Measurements

- Tantalum cylinder sample was inserted for long-term measurement.

Tantalum	Phase I	Phase II
Total mass (g)	863.0 ± 0.1	848.8 ± 0.1



Tantalum Cylinder Sample



Tantalum Sample Configuration
[Phase II with Inner Cu Shield]

Tantalum Physics Runs

- After pre-analysis process [energy calibration by background peaks, bad run cut, noise rejection, etc.], two phases of tantalum physics runs were obtained.

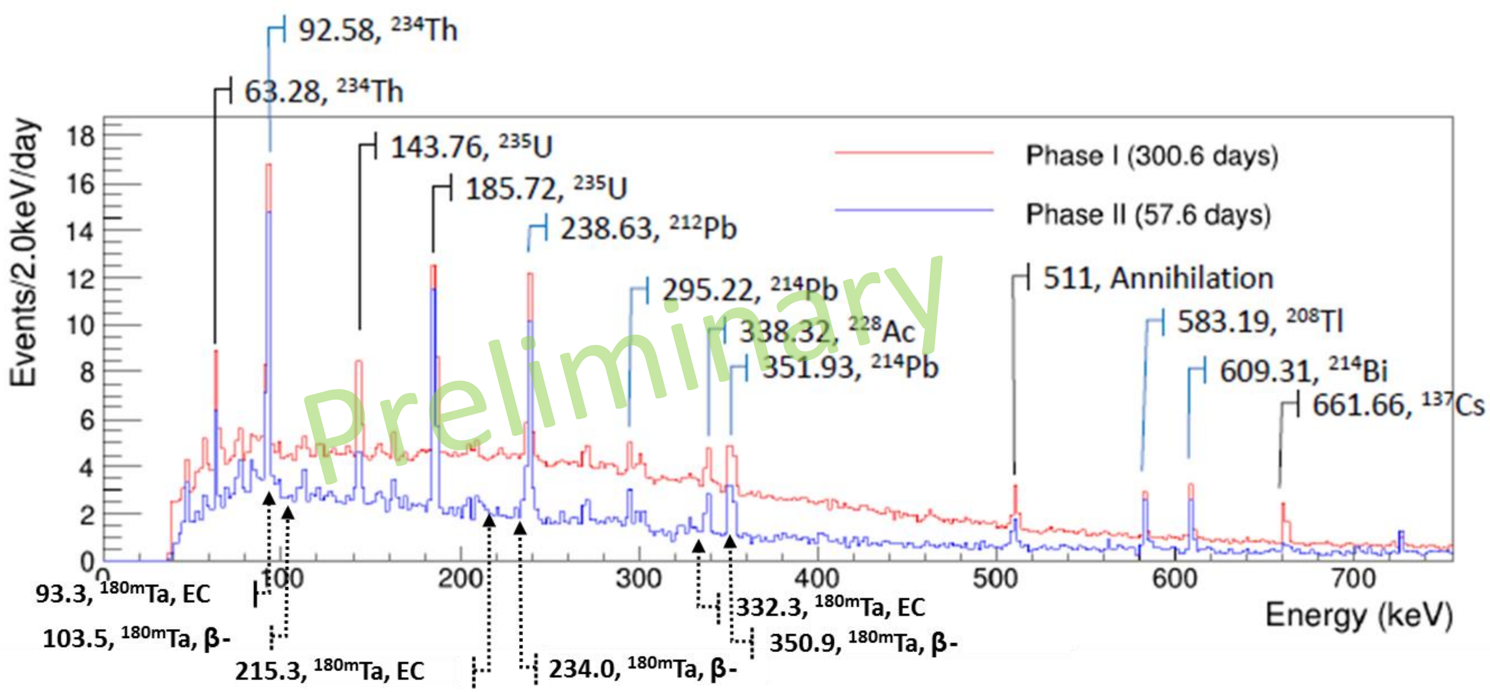
Subject	Phase I	Phase II	Total
Physics Runs	237	32	269
Live time (days)	300.6	57.6	358.2

Phase 1:
~50 events/hour

Phase 2:
~27 events/hour

Event rate reduction:
- 46 %

Energy range:
40 keV – 1540 keV



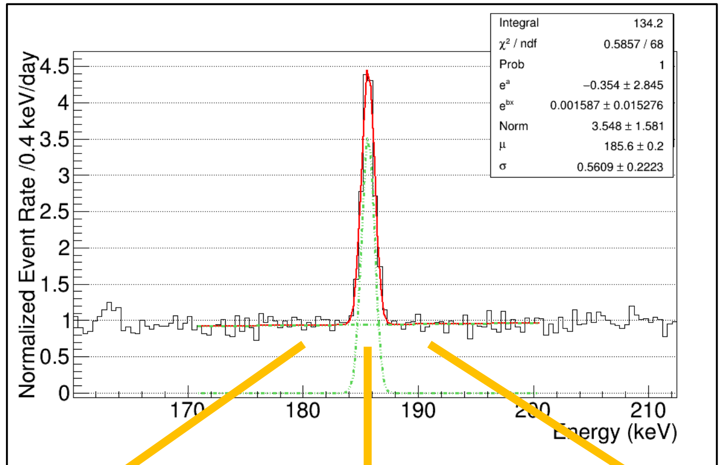
Data Analysis & Result

- Pulse Shape Discrimination
- Monte Carlo Simulation
- Half-life limit of ^{180m}Ta

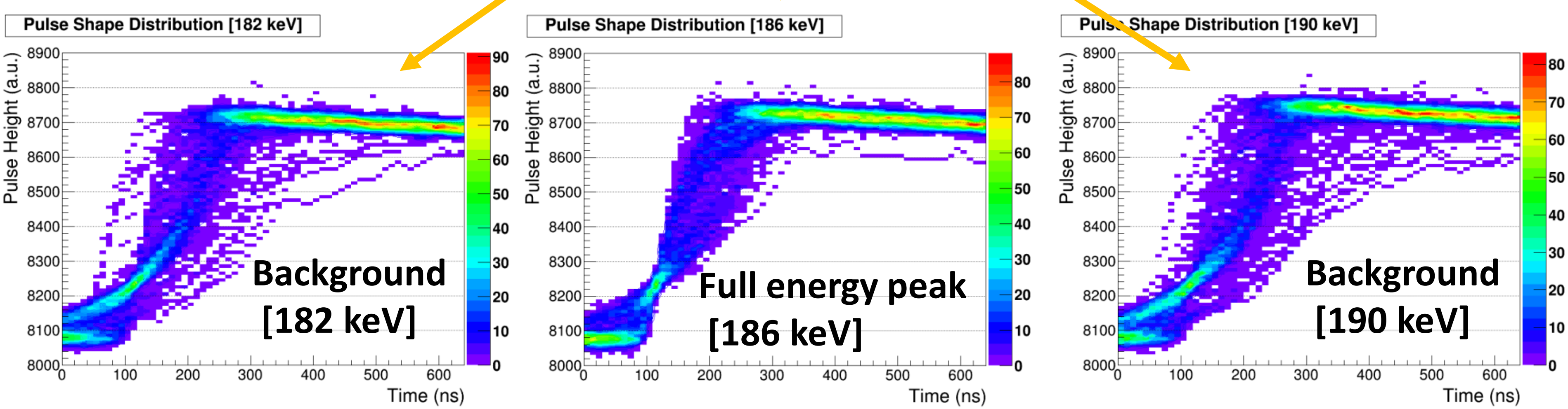
Background Reduction by Pulse Shape Discrimination (PSD)

- Different pulse shape distribution at low energy region
- Photopeak (mostly surface) vs background (uniformly distributed) regions

Example: 186 keV
±1 keV
limit 250 events



Pulse Shape Distribution at Rising Part:



PSD method

Current Pulse Amplitude Method

Current Pulse, $I = \frac{dQ}{dT}$

dQ = charge integral (pulse height)

dT = time window

A = maximum amplitude

Procedure:

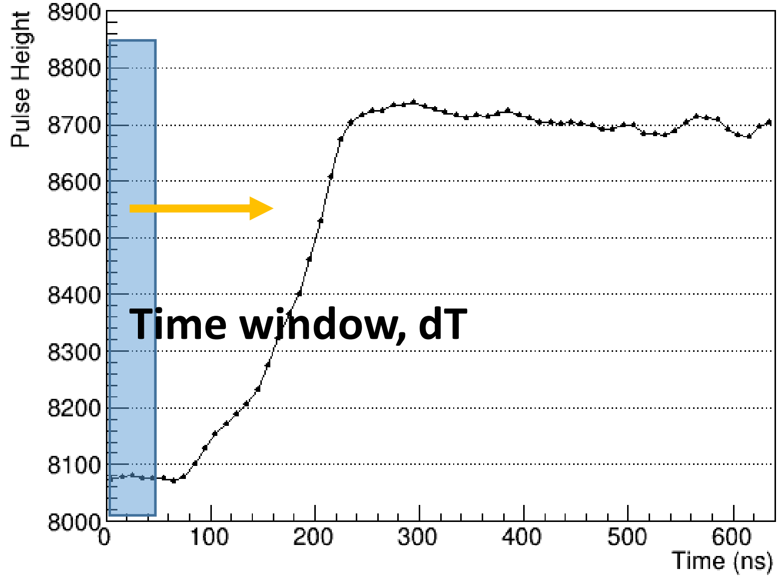
i. Plot pulse shape event-by-event

ii. Plot current pulse

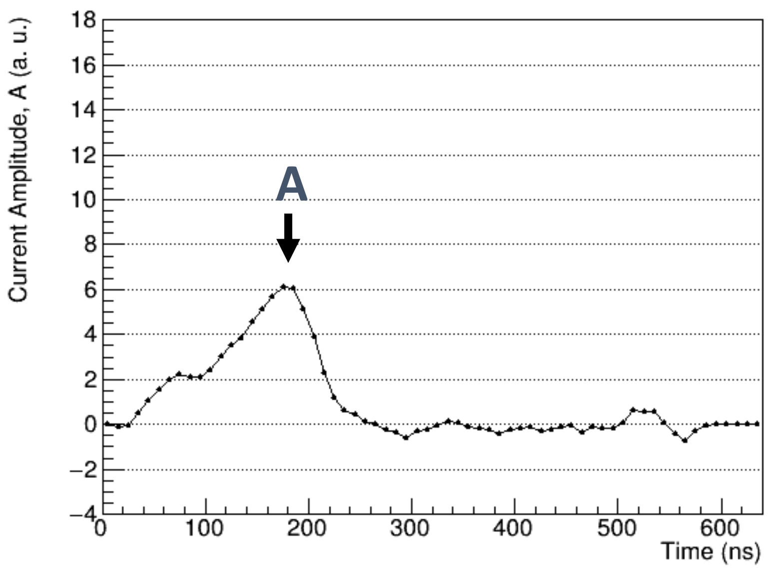
iii. Find the maximum amplitude

iv. Plot maximum amplitude distribution

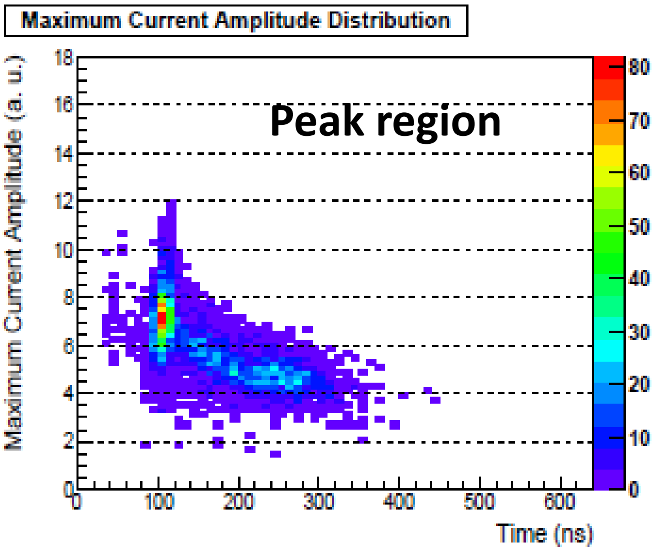
Pulse Shape of Single Event

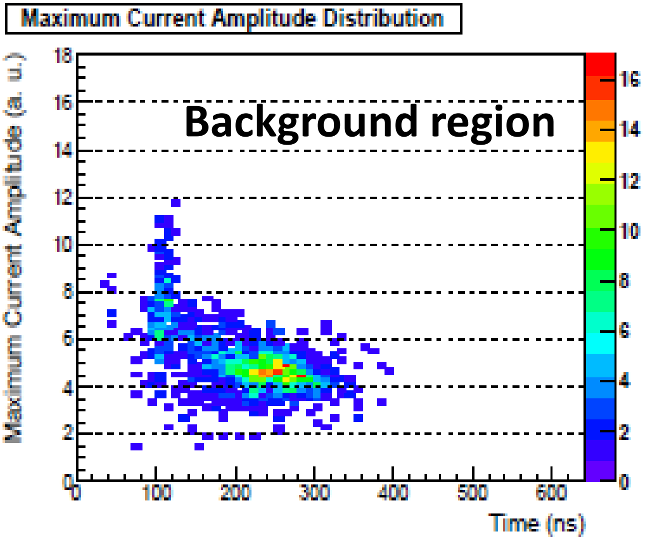


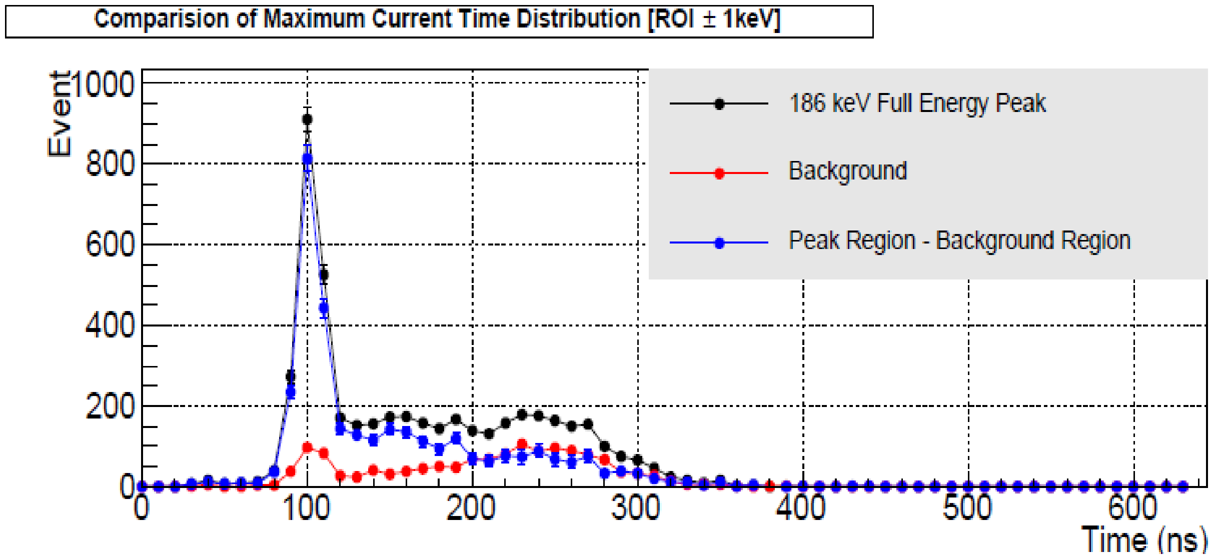
Current Pulse

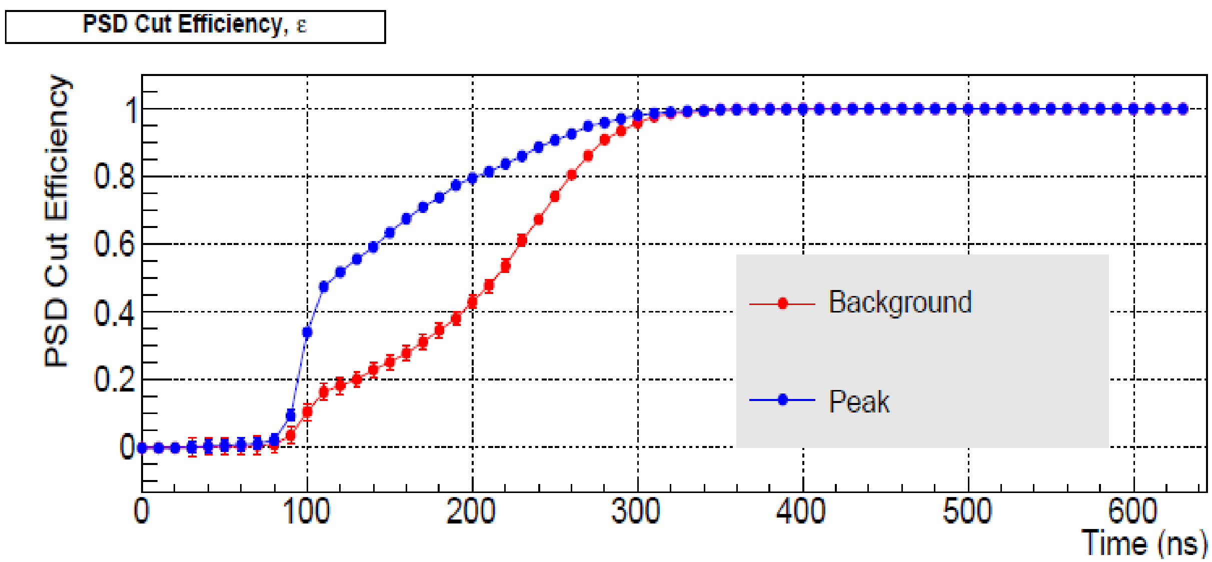


Distribution of Maximum Current Amplitude [186 keV]





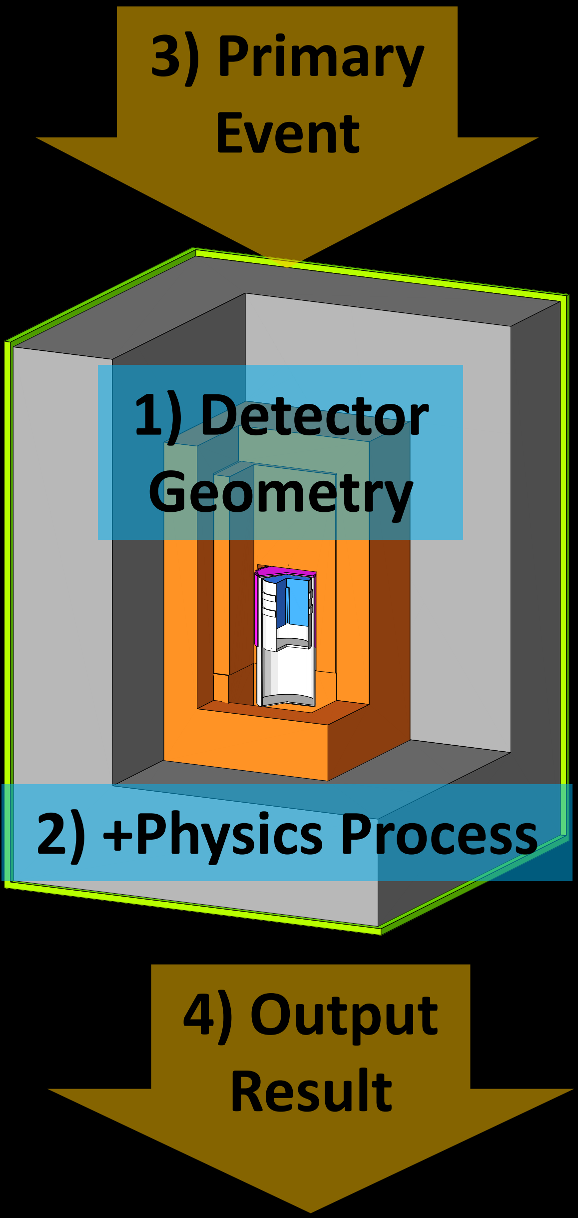




Monte Carlo Simulation

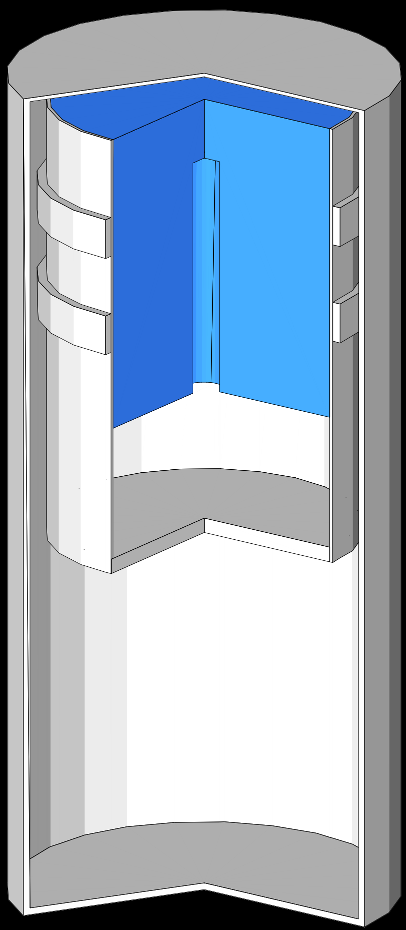
To obtain detection efficiency, GEANT4 simulation was used.

1) Define geometrical setup
   - Material, volume
2) Define physics involved
   - Particle, physics process, attenuation of γ-ray
3) How an event starts
   - Primary event generation
4) Extract useful information
   - Visualization, physics output (energy, position, trajectory)

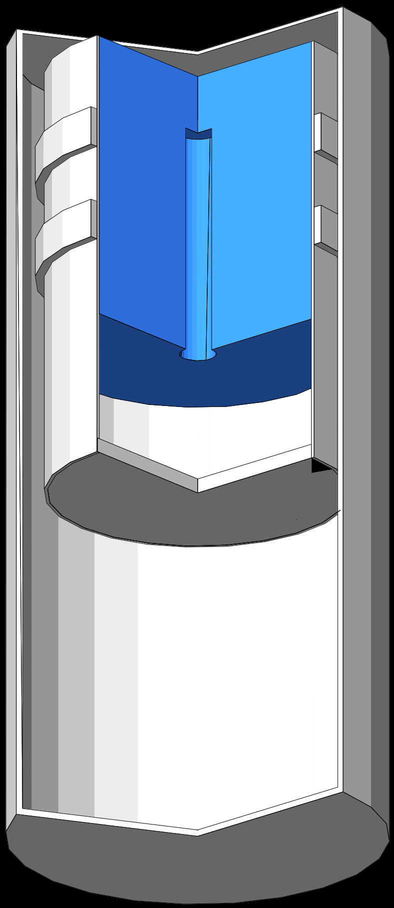


HPGe Detector

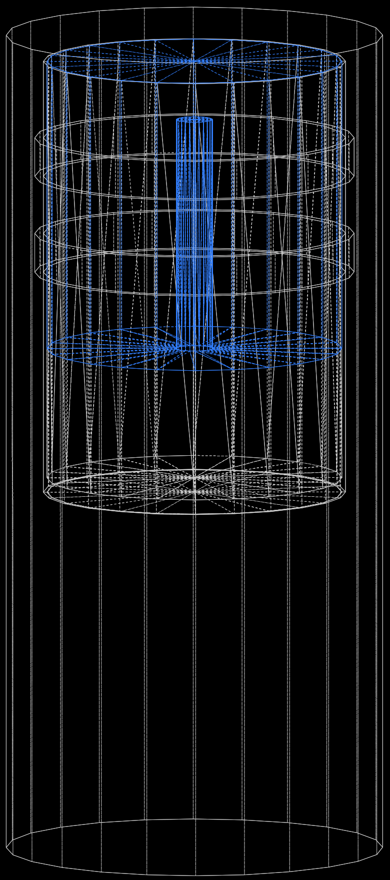
- Assembly of Ge crystal, inner structure and Al endcap



Cross Section
View from top



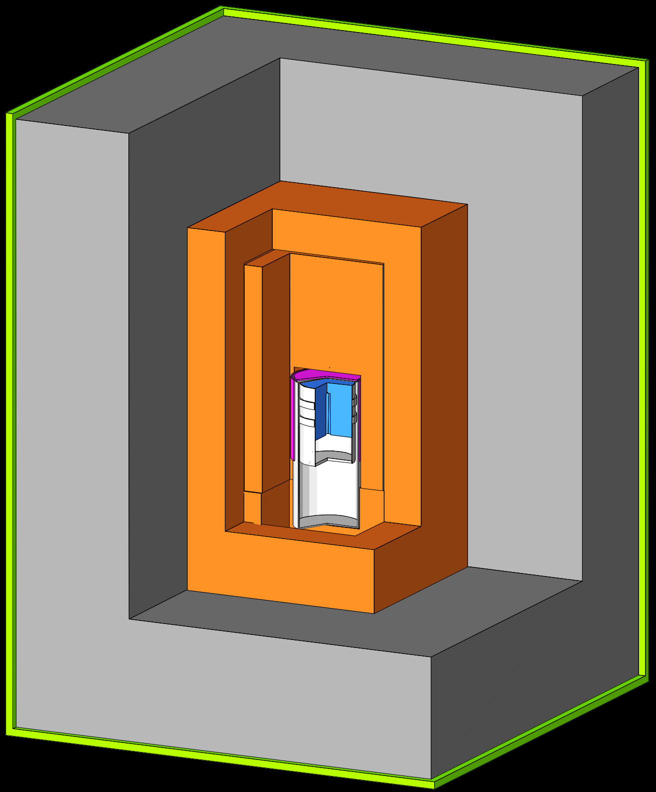
Cross Section
View from bottom



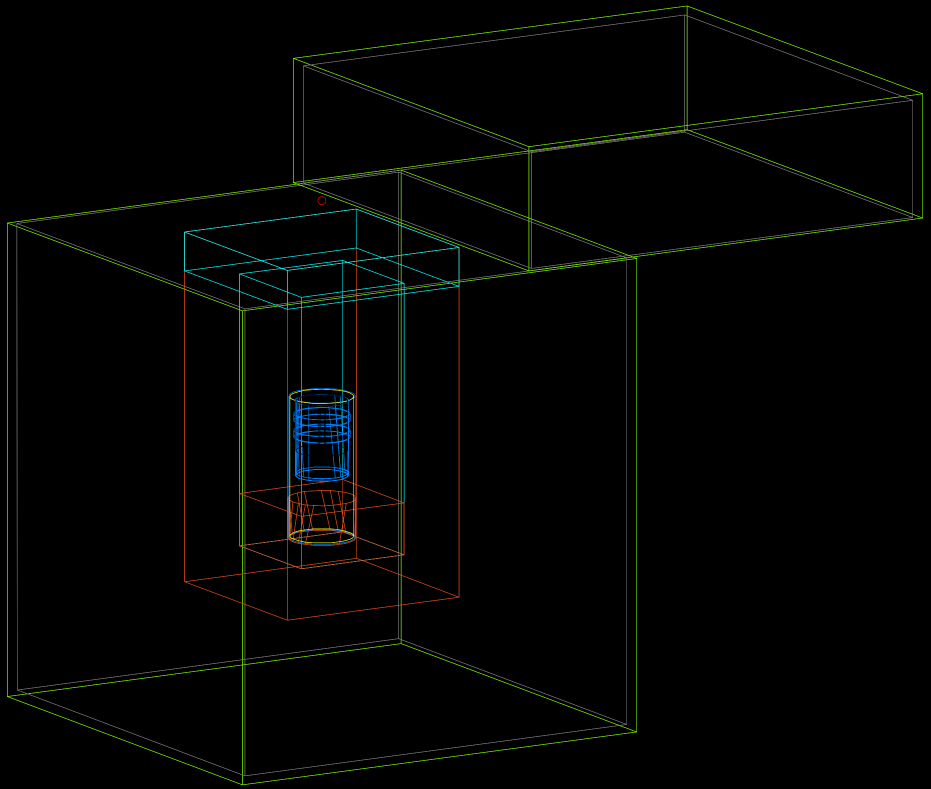
Detailed line graphic

Full Assembly Geometry

- Illustration was presented with cross sectional view.



Tantalum Phase II
Physics Run

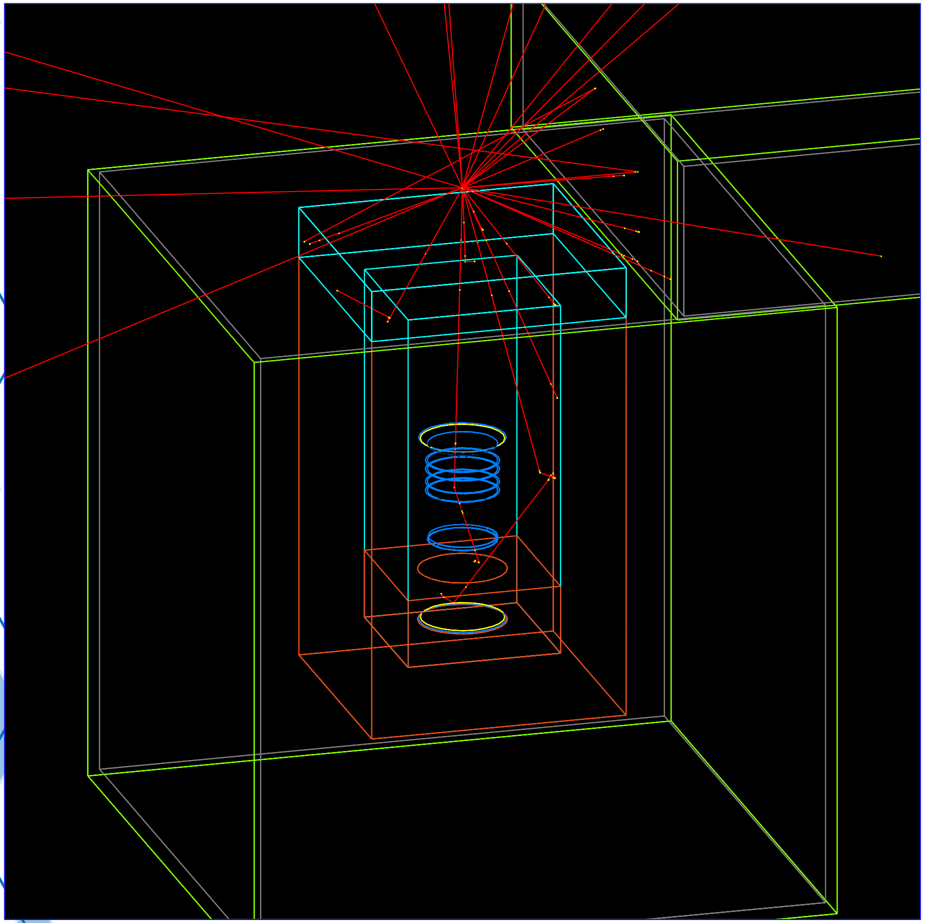


Calibration Run
[Top shield opened]

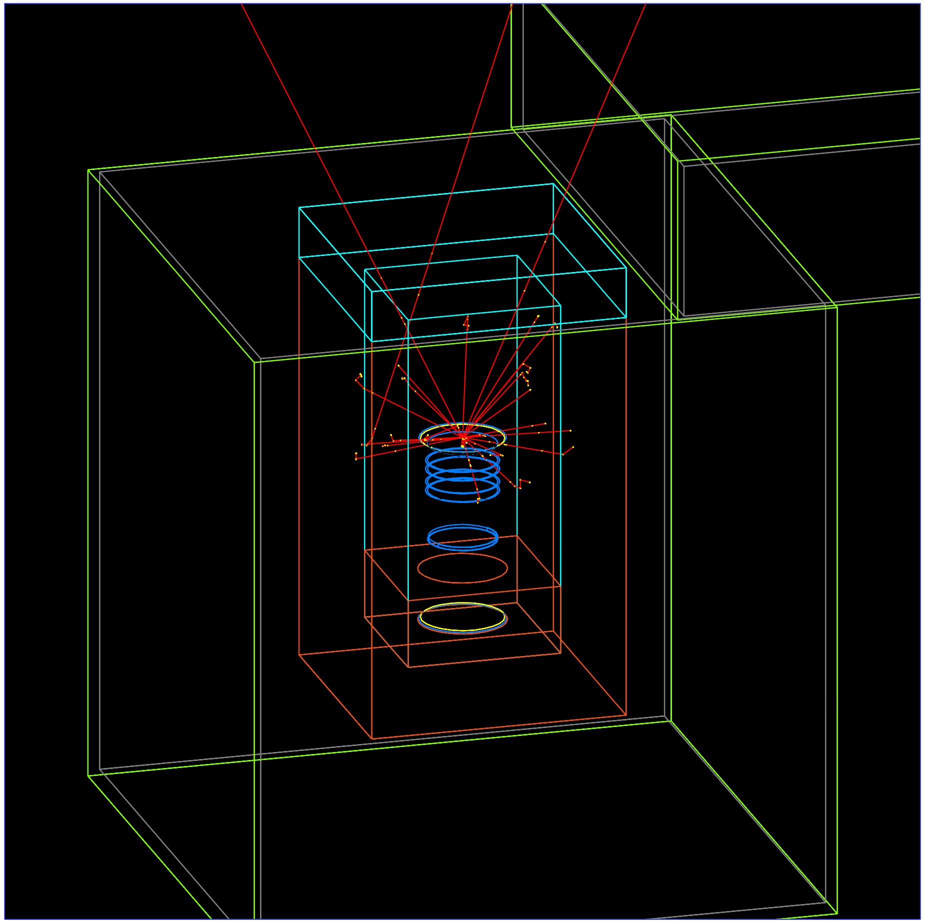
Trajectory of gamma-ray

- The path of gamma-rays travel within detector system can be observed.

γ –ray path   e- ionization path



Gamma point source
Distance from endcap = 250 mm
Solid angle = 0.016 π

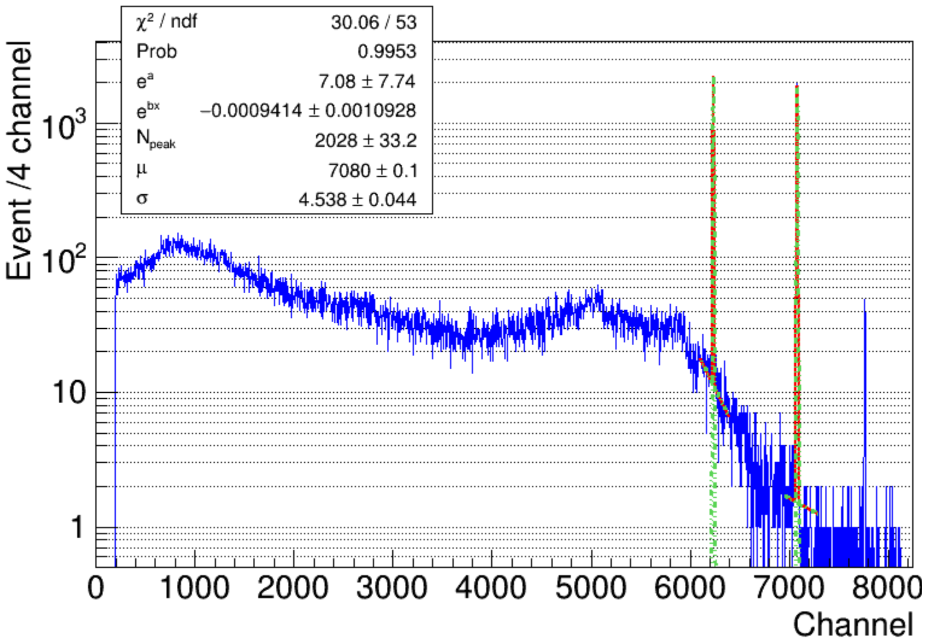


Gamma point source
Distance from endcap = 5 mm
Solid angle = 1.359 π

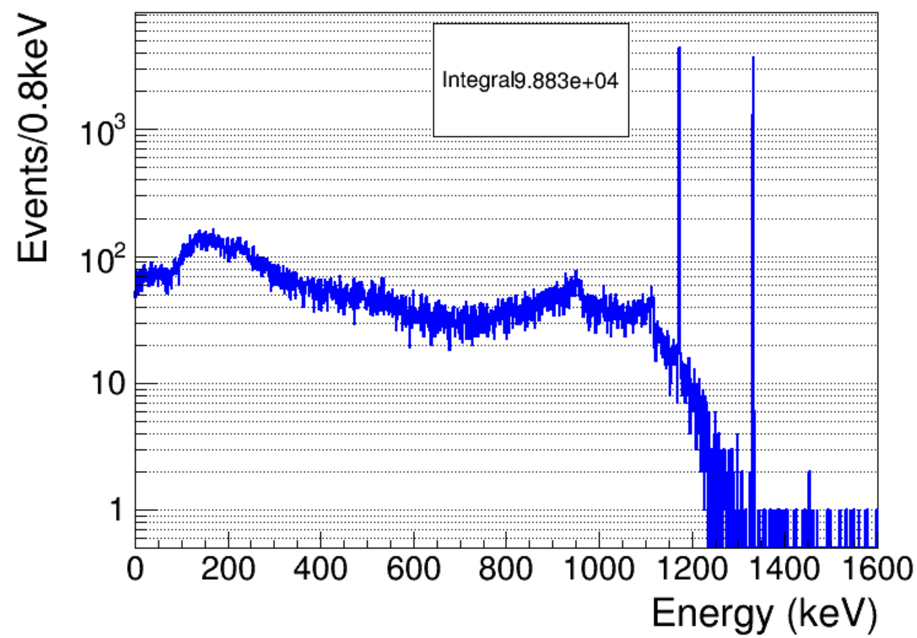
Comparison of Simulation and Experiment Data

The simulated spectrum shape **agree very well with the actual experiment data**.

- Prove that geometry of surrounding shielding was well simulated.



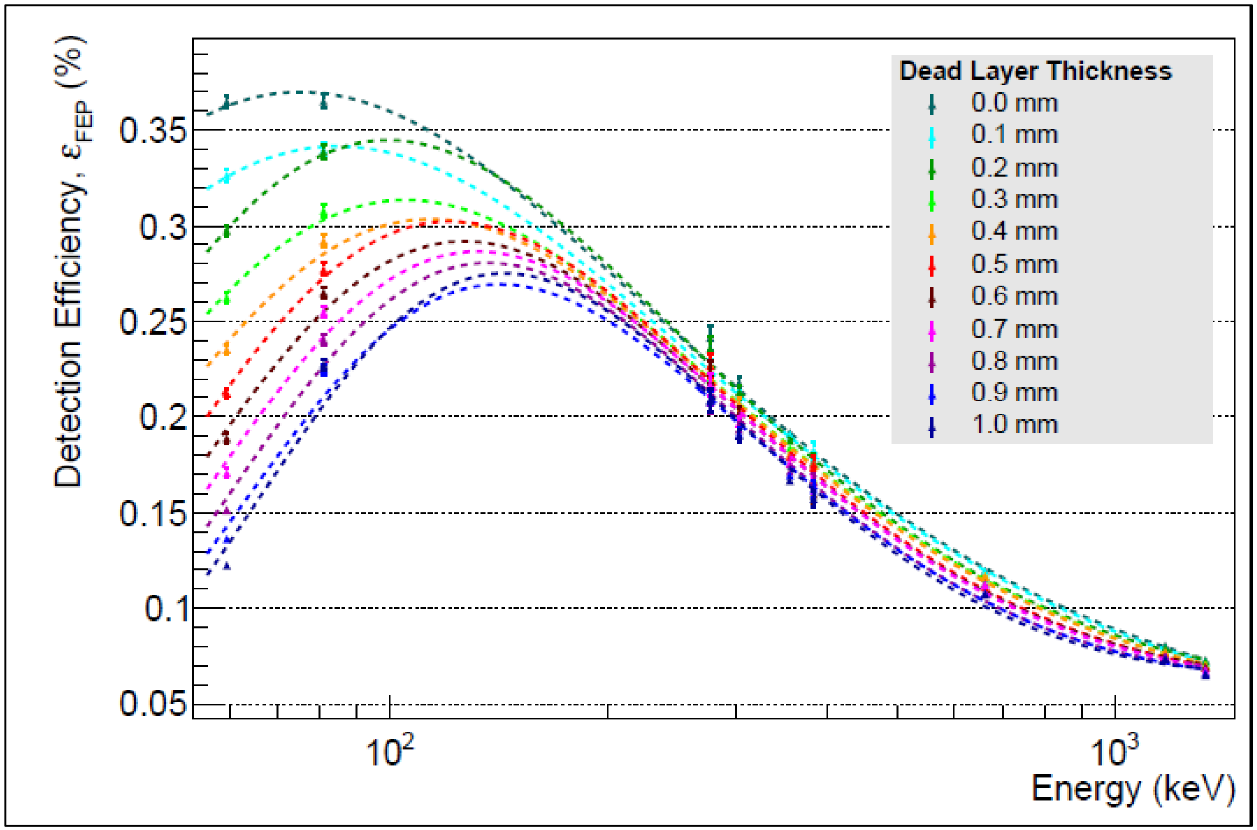
Experiment data [Co-60]

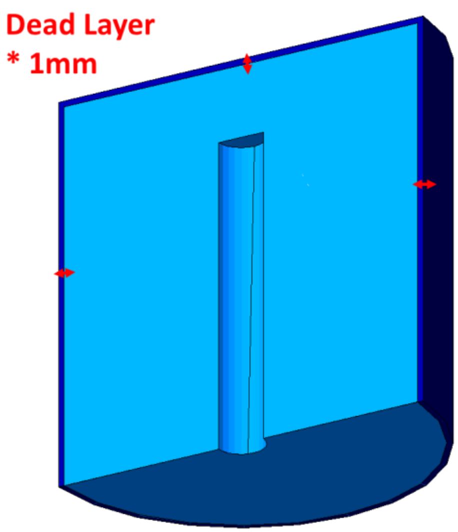


Simulation spectrum [Co-60]

Dead Layer Adjustment

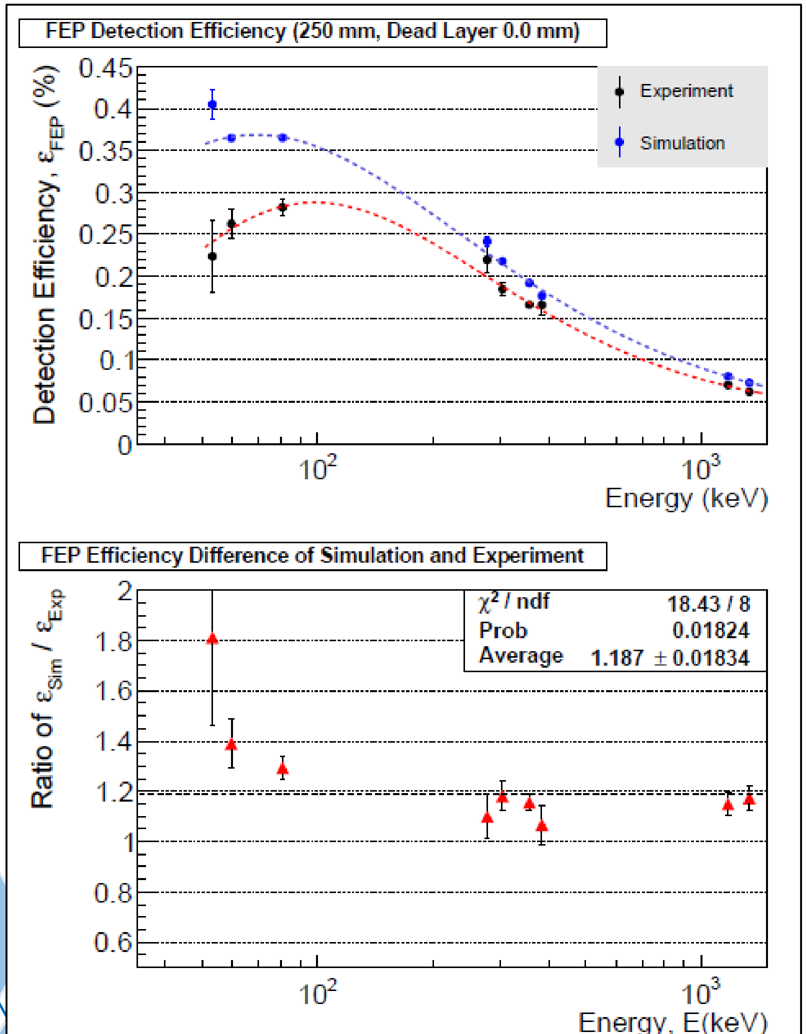
- Several fine tuning of the simulation were done.
- For example, adjustment of surface dead layer of germanium crystal.



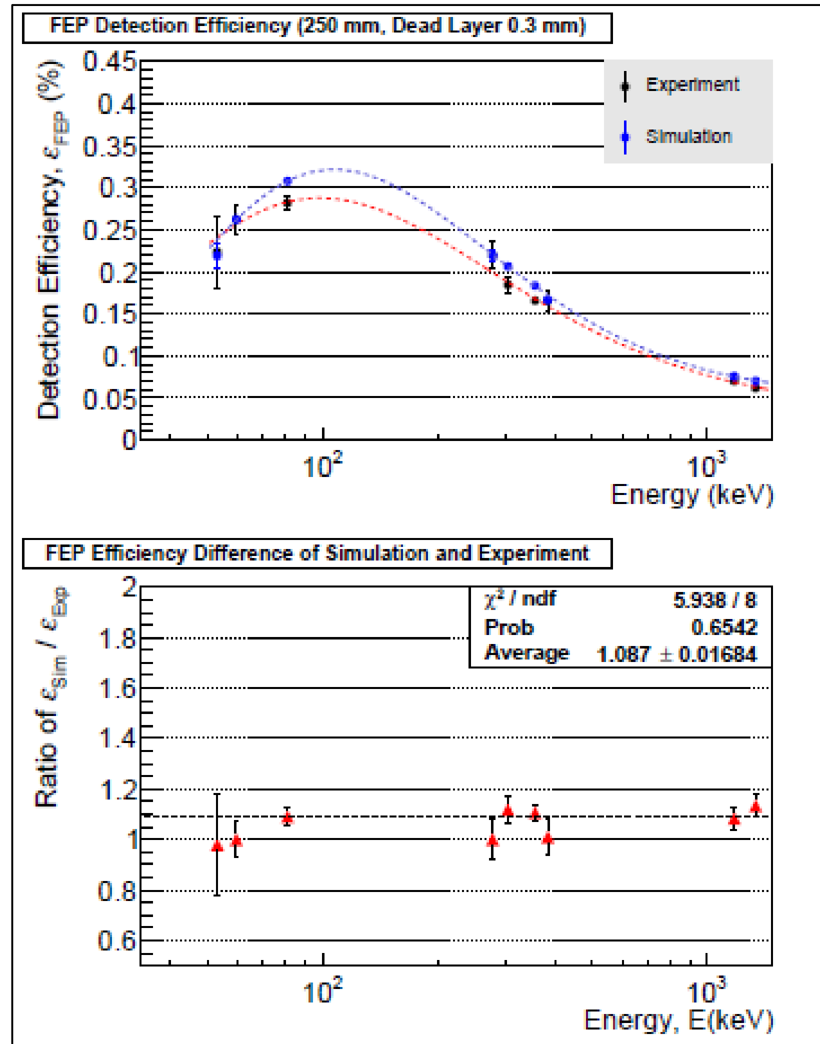


Verification of Simulation

Dead layer = 0.0 mm
Simulation is 18.7 % higher than experiment.
-> Not good.



Dead layer = 0.3 mm (best fit)
Simulation agreed well with experiment.
Systematic uncertainty = 8.7 %



Half-life limit of ^{180m}Ta

- The most stringent half-life limit has been obtained

Decay Branch	ROI (keV)	I_γ (%)	ε_{Det}(%) Phase I	ε_{Det}(%) Phase II	$T_{1/2}$ limit (yrs) Phase I	$T_{1/2}$ limit (yrs) Phase II	$T_{1/2}$ limit (yrs) Phase I + II
EC	93.3	17.5	0.69	0.69	1.21×10^{16}	5.59×10^{15}	1.33×10^{16}
	215.3	81.5	4.11	4.11	1.29×10^{17}	8.19×10^{16}	1.47×10^{17}
	332.3	94.4	4.73	4.81	1.72×10^{17}	1.30×10^{17}	1.99×10^{17}
β-	103.5	22.5	0.92	0.93	4.15×10^{16}	1.96×10^{16}	4.58×10^{16}
	234.0	84.4	4.32	4.42	1.44×10^{17}	9.81×10^{16}	1.66×10^{17}
	350.9	94.8	4.74	4.78	1.45×10^{17}	7.71×10^{16}	1.62×10^{17}

$$T_{1/2}^{EC} > 1.99 \times 10^{17} yrs$$

$$logft = 25.0$$

$$T_{1/2}^{\beta-} > 1.66 \times 10^{17} yrs$$

$$logft = 23.6$$

$$T_{1/2}^{Total} > 9.03 \times 10^{16} yrs$$

Achievement:

The world most stringent half-life limit for ^{180m}Ta is obtained.

Latest published value = 4.5×10^{16} yrs
[Factor of 2 higher than Lehnert 2017]

Summary

- HPGe detector system at CANDLES Experimental Hall was completed and started for data taking since year 2013.
  - CANDLES Material Screening, Tantalum Half-life Measurement, etc.

- New simulation model and PSD method were developed for the HPGe detector.

- With Tantalum Phase I & Phase II results (livetime of 358.2 days), the world most stringent half-life limit for ^{180m}Ta is achieved.

~Thank you~
Q & A

Kamioka, Japan@Winter2017