A novel ^{139}La-GPS scintillator for β-implantation detectors in decay spectroscopy at fragmentation facilities

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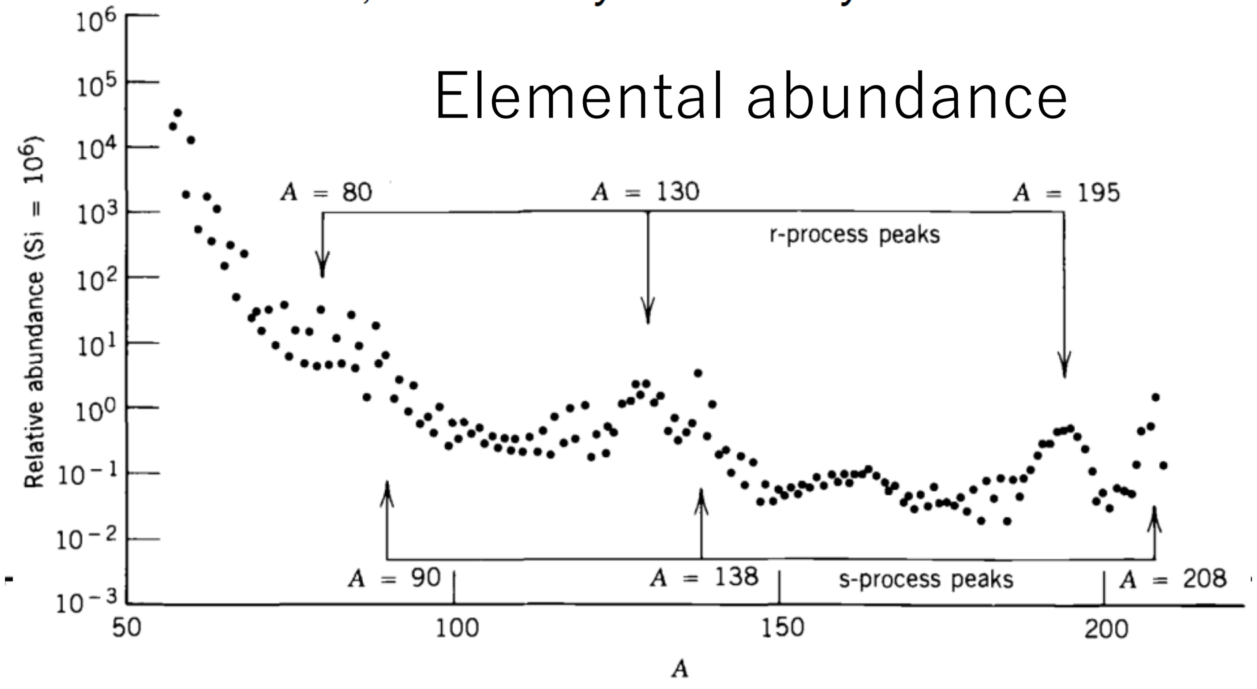
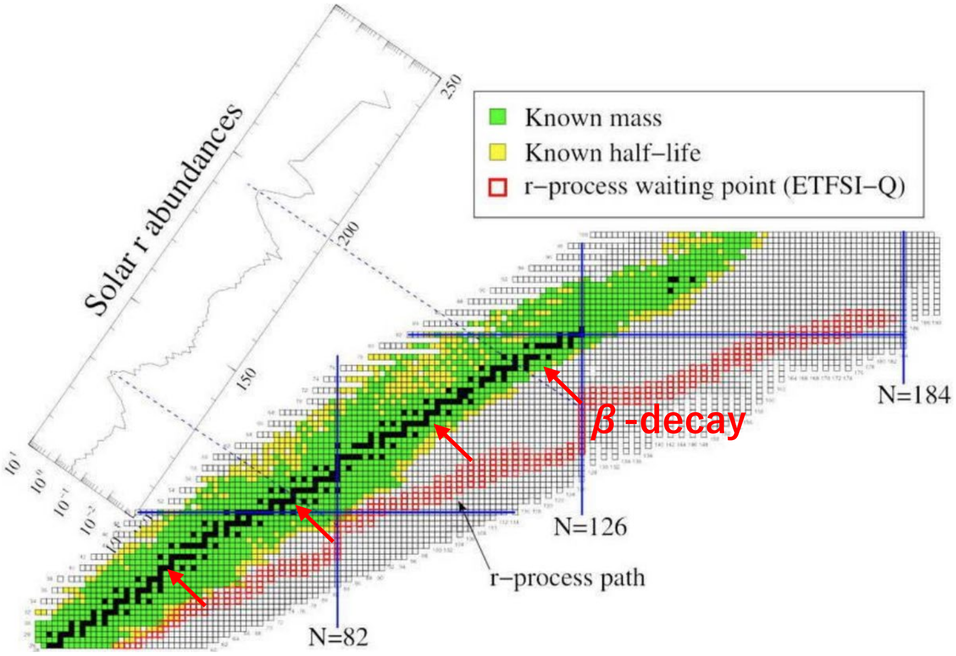
科研費 KAKENHI 22K14053、24K00655

r(rapid neutron capture) process

K. Krane, Introductory Nuclear Physics

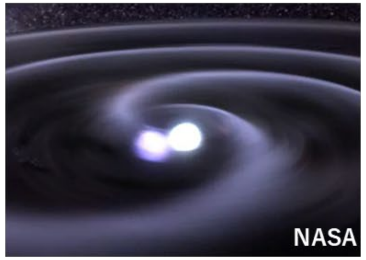




- Primary source of elements heavier than iron
- β -decay data of neutron-rich nuclei are essential for the r-process simulations

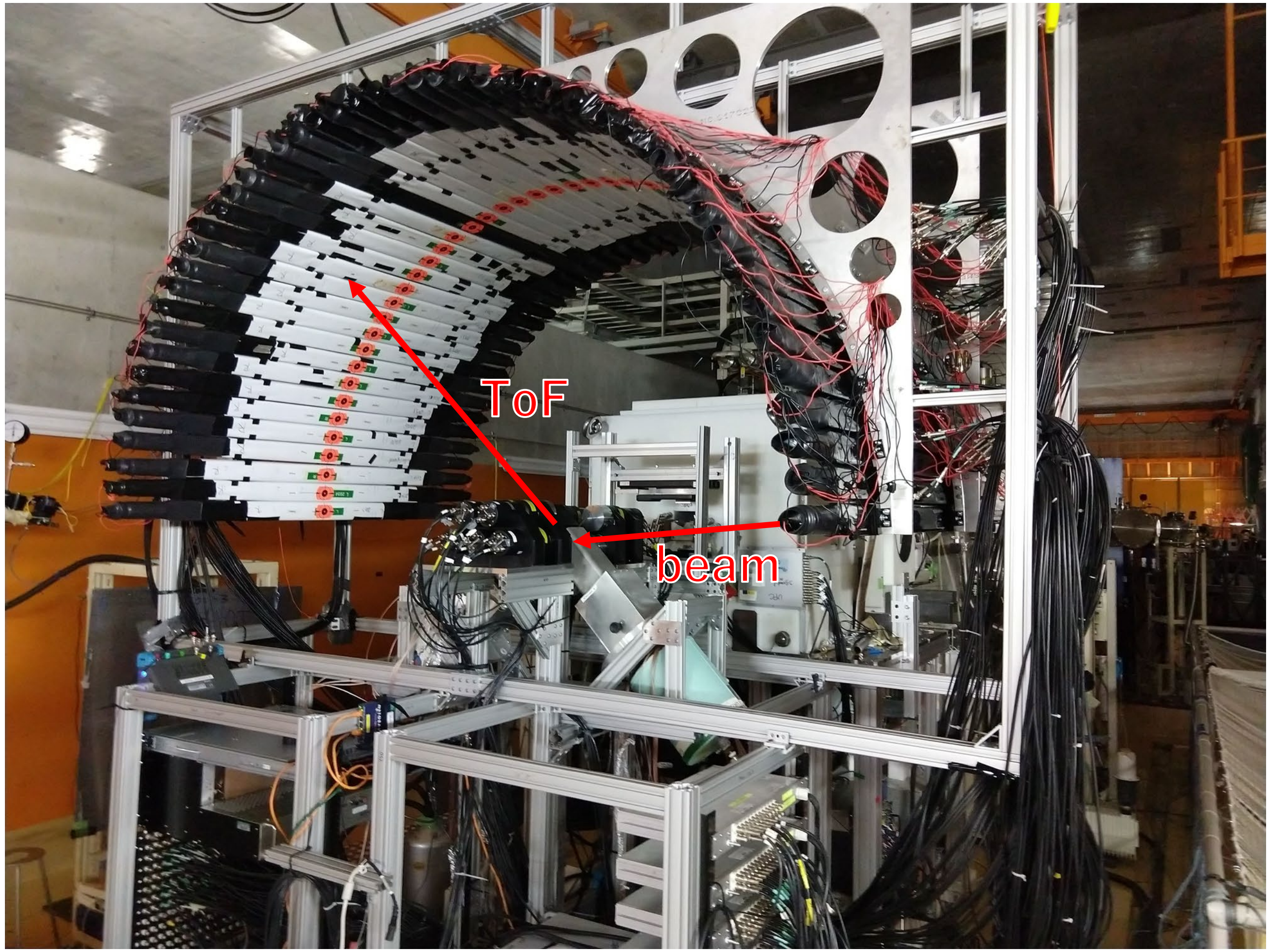
Core Collapse Supernovae

Neutron Star Merger

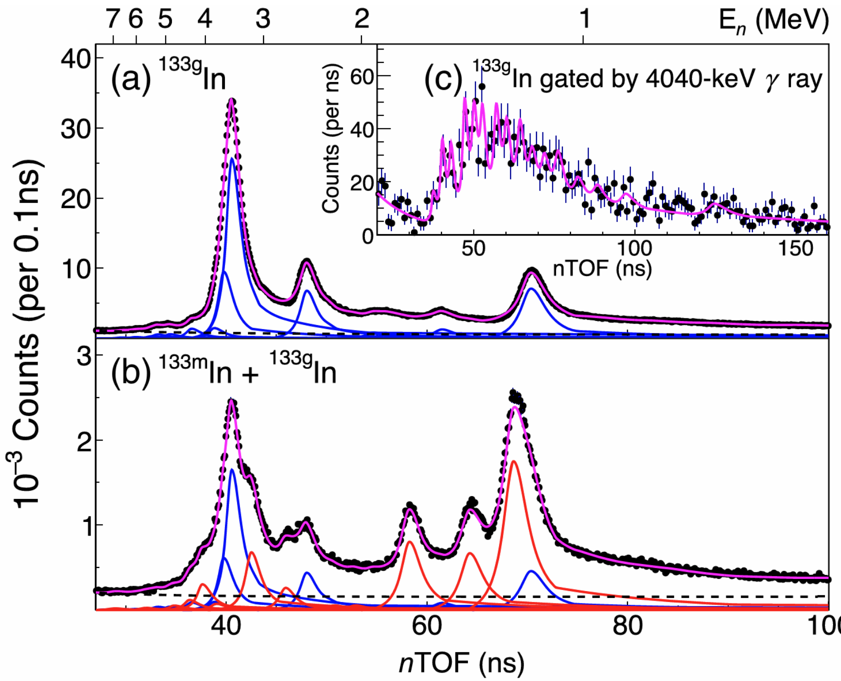


Beta-delayed Neutron ToF measurements

VANDLE *W.A. Peters et al. (2016)*



- Neutron spectroscopy is a powerful tool to study neutron-rich nuclei



Z.Y.Xu et al., Phys. Rev. Lett. 131 022501 (2023)

- Requires fast β detector for the start timing of nToF

Types of RI beam facilities

- Spontaneous fission (^{252}Cf)
  - CARIBU ANL, ILL Grenoble, …
- Spallation (p beam on UCx target)
  - TRIUMF Canada, ISOLDE CERN, …

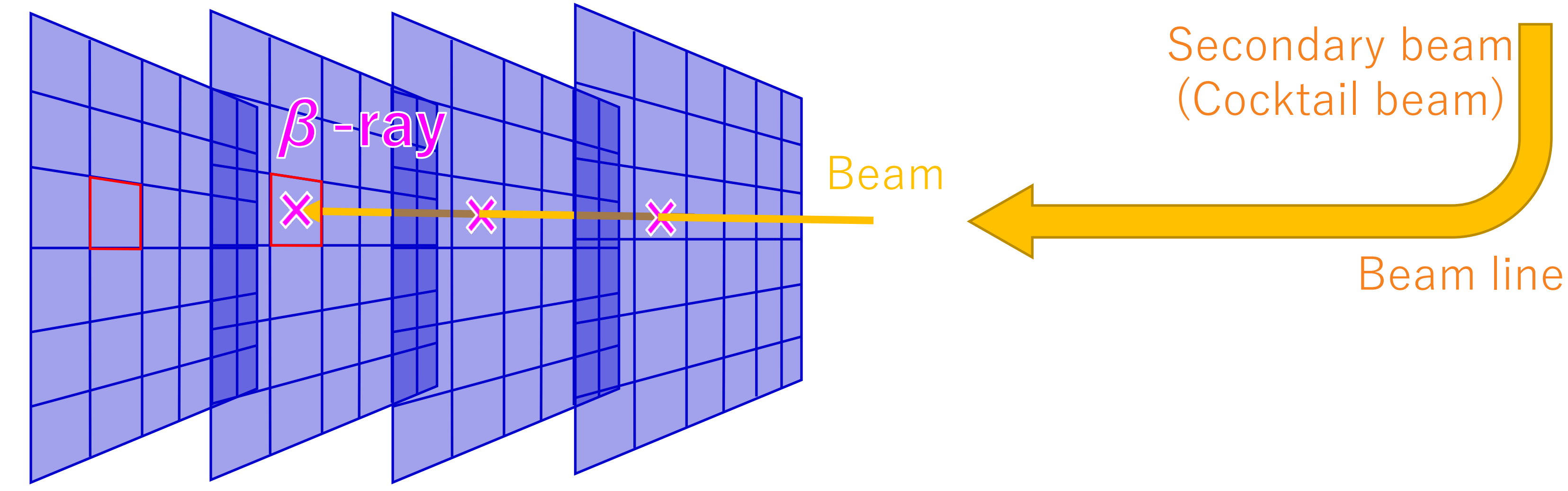
} Ion source
-> pure and slow beam

- Fragmentation/In-flight fission (^{238}U beam on Be target)
  - RIBF RIKEN, FRIB MSU, …

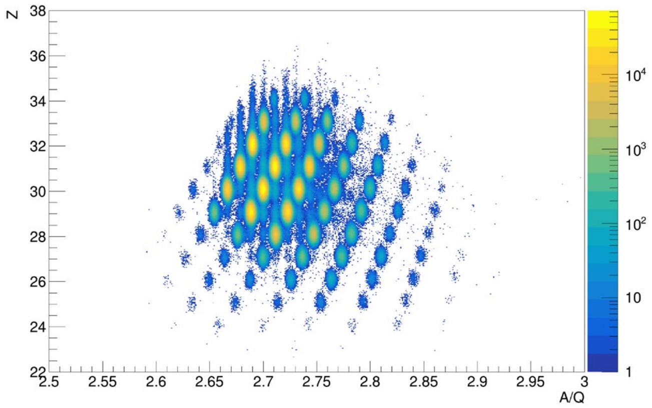
-> fast cocktail beam

β-decay experiments at a fragmentation facility

Implant detector (Stack of DSSSD)



PID



x-y position of an implant
x-y position of β-ray emission

} Correlate β with PID

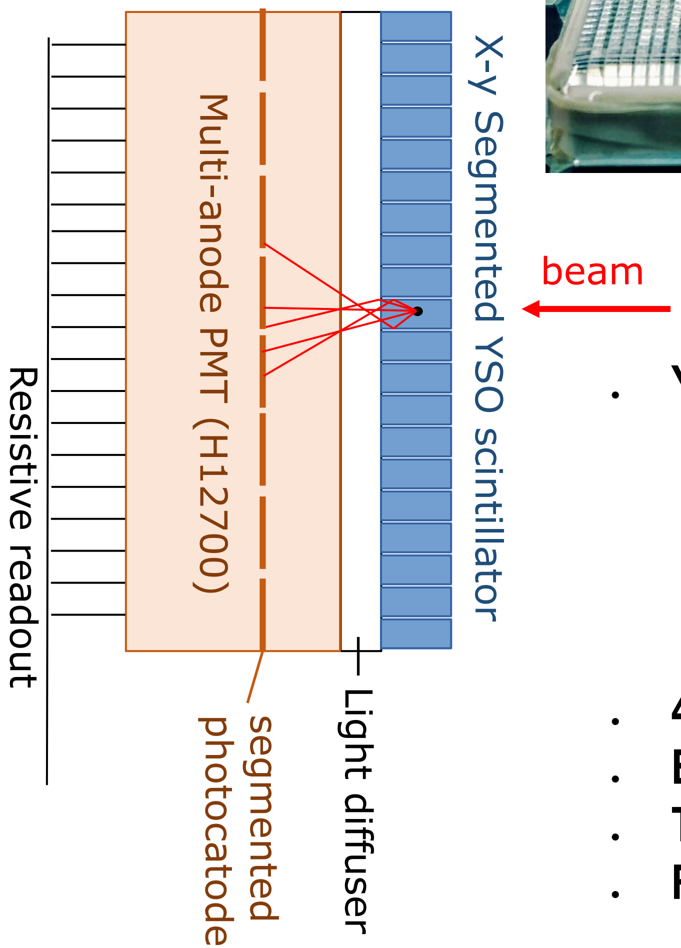
Implant detector requires

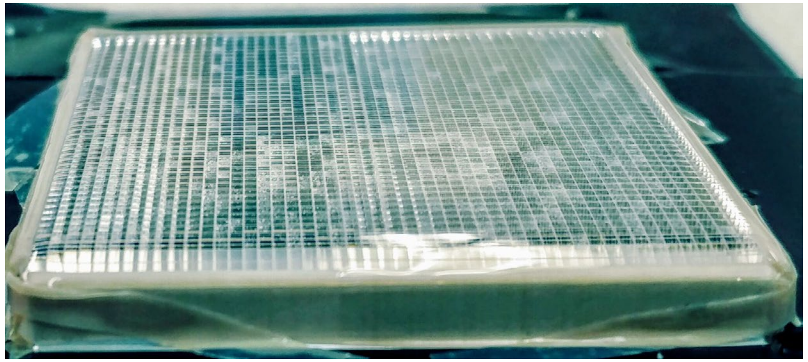
- Good position resolution for both ions and beta
- Implantation rate per pixel << $1/T_{1/2}$ of interest

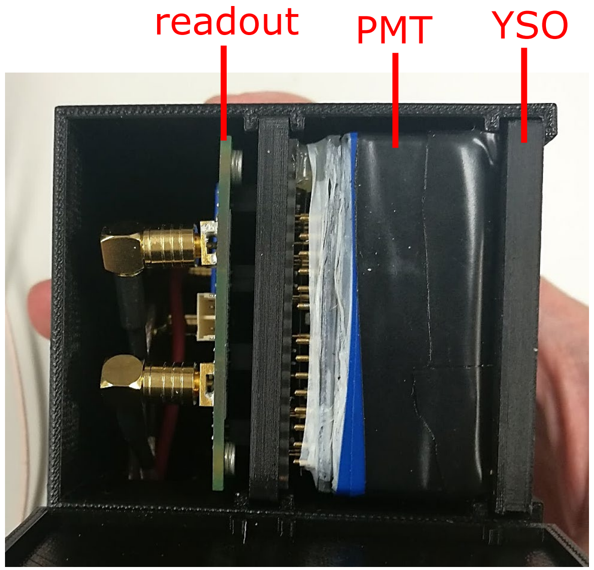
DSSSD is too slow for nToF measurements

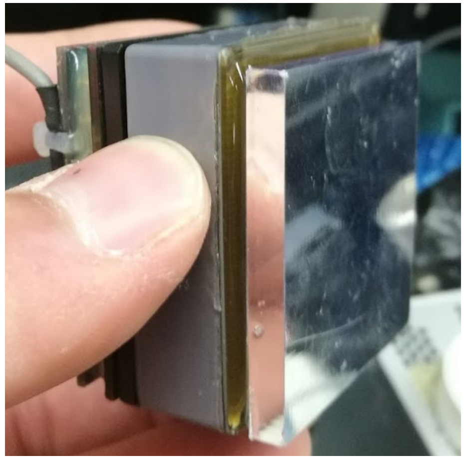
Segmented YSO detector

R.Yokoyama et al. NIM A 937, 93-97(2019)









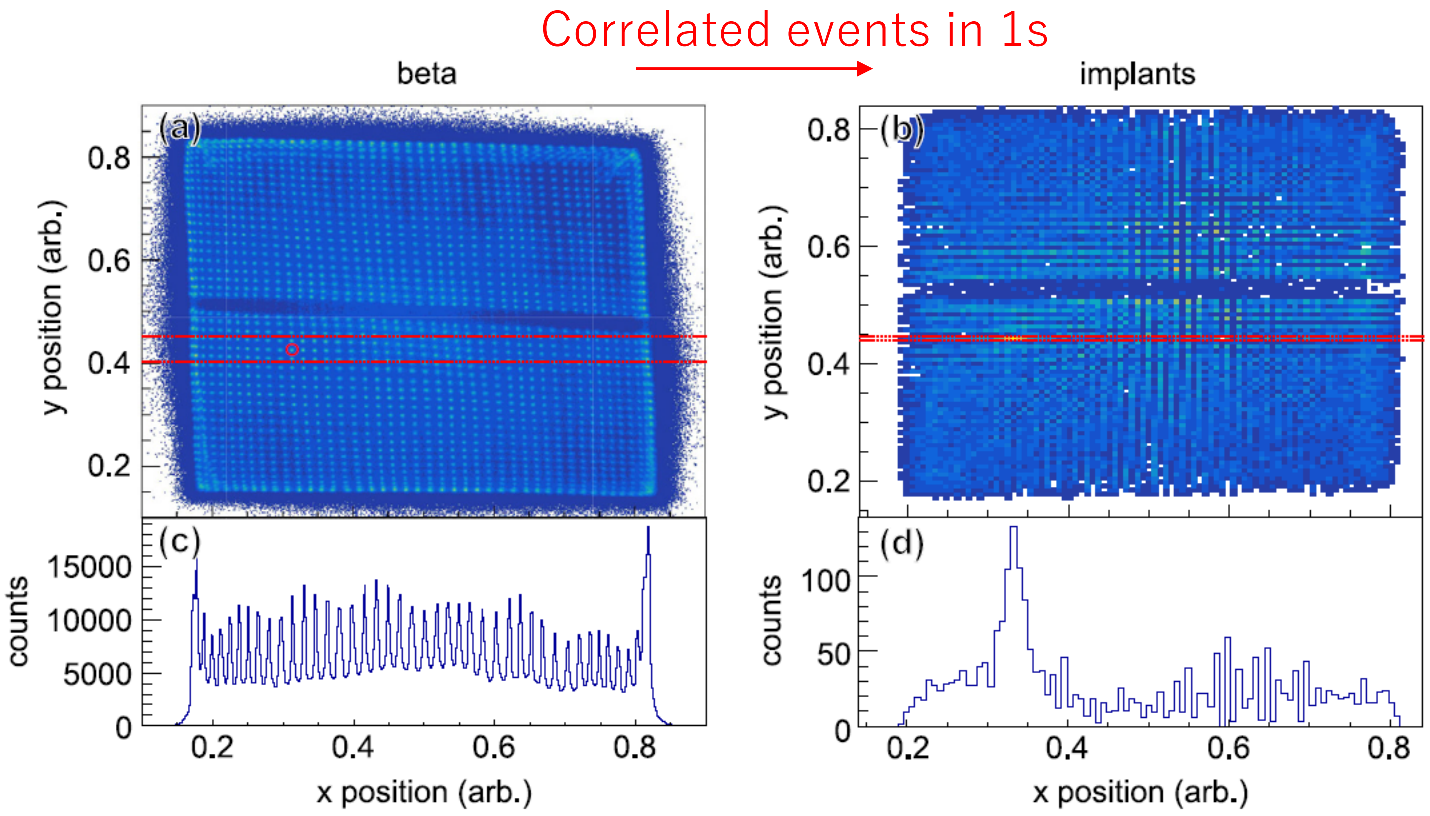
- YSO (Yttrium Orthosilicate, Y_2SiO_5) crystal
  - Effective atomic number: Z~39
  - Density: ~4.5 g/cm^3
  - Wavelength: 420 nm
  - Decay time: ~70 ns
- 48 x 48 segments
- Each segment: 1 x 1 mm
- Thickness: 5 mm
- Reflective material: ESR

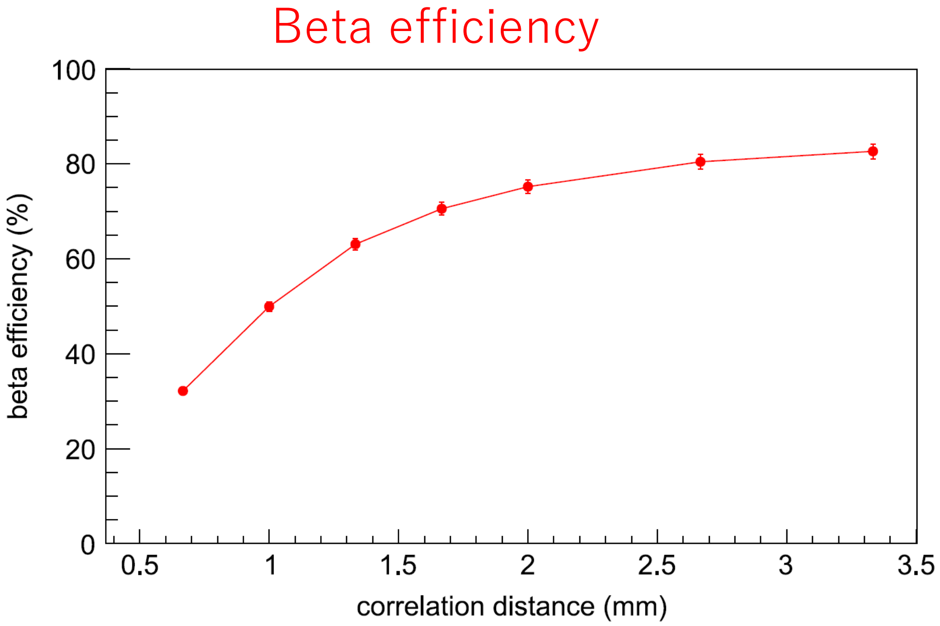
Compared to DSSSDs

- Fast response time (~500 ps)
- Hard to radiation damage
- High stopping power
  - High beta efficiency
  - Good position correlation
- Can be thick
- Simple and compact
- More γ absorption
- ~10% energy resolution for ions

^{78}Ni region with YSO

R.Yokoyama et al. NIM A 937, 93-97(2019)

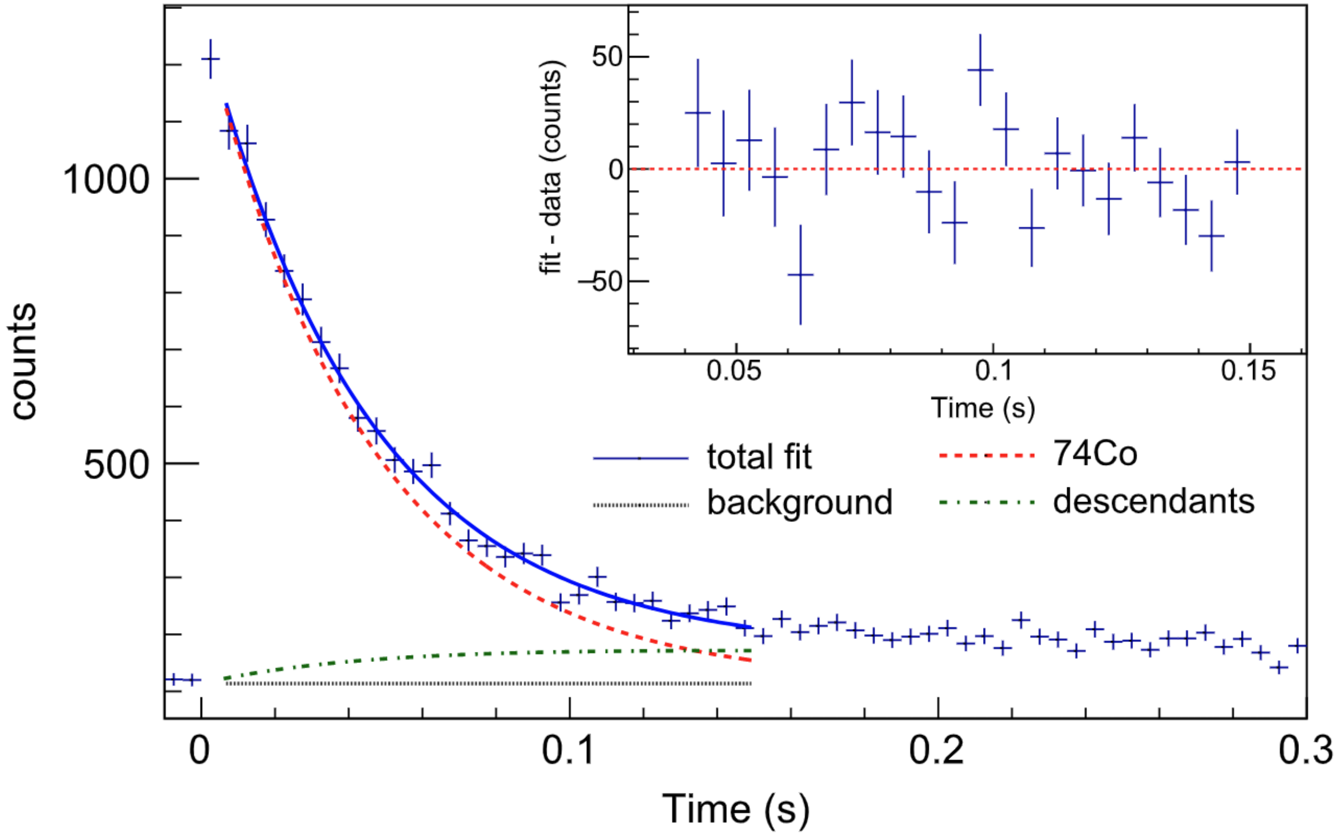




- Clear position correlation between beta and implant events
- Beta efficiency is as high as 80% at 3mm correlation radius (^{74}Co).

74Co decay curve

R.Yokoyama et al. NIM A 937, 93-97(2019)

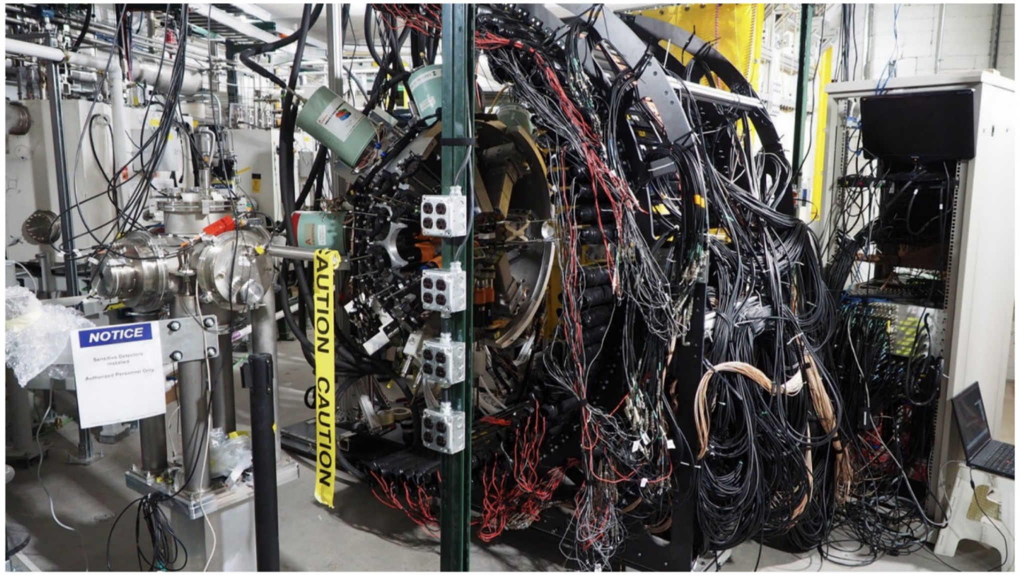


T1/2 = 30.8(6) ms

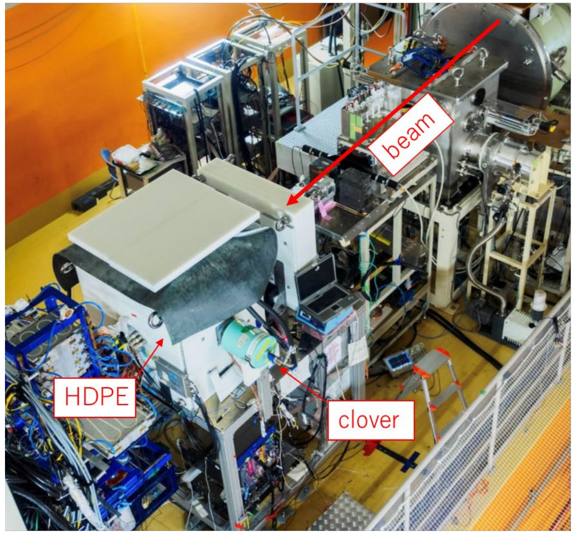
Clean measurements up to ~100cps total implantation rate

Success of YSO detector

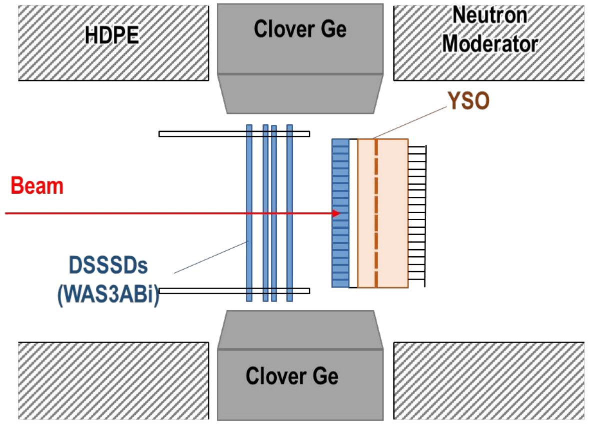
with FRIB Decay Station



with BRIKEN



- Setup inside the HDPE moderator

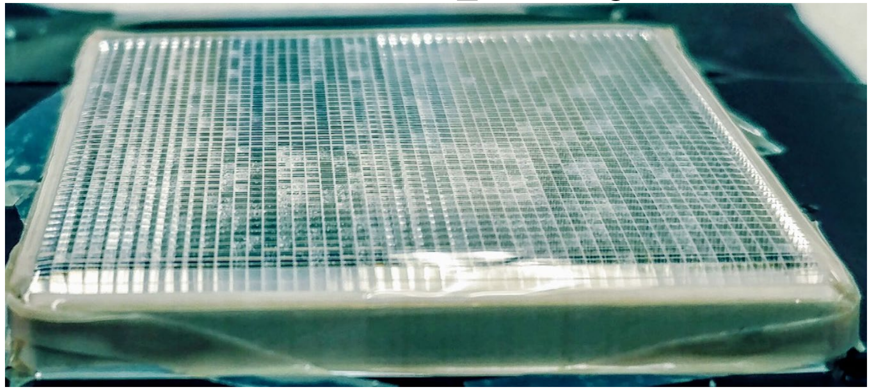


- Shared implantation between the conventional DSSDs and new YSO detector

[11] R. Yokoyama et al., Phys. Rev. C 100, 031302 (2019)
[12] R. Yokoyama et al., Phys. Rev. C 108, 064307 (2023)
[13] R. S. Lubna et al., Phys. Rev. C 108, 014329 (2023)
[14] T. J. Gray et al., Phys. Rev. Lett. 130, 242501(2023)
[15] M. Madurga et al., Phys. Rev. C 109, L061301 (2024)
[16] I. Cox et al., Phys.Rev. Lett. 132, 152503 (2024)
[17] S. Neupane et al., Phys. Rev. C 110, 034323 (2024)

New scintillator material for a β-implant detector

YSO (Y_2SiO_5:Ce)

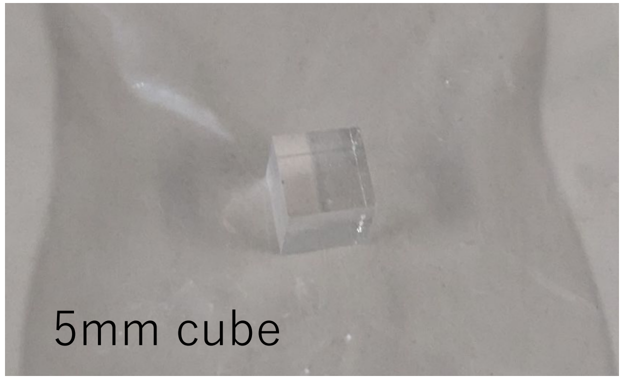


Zeff ~ 39, ρ ~4.5g/cm3

2MeV β range: ~2.7mm

La-GPS ($(Gd,La)_2Si_2O_7$:Ce)

A. Suzuki et al., Applied Physics Express 5 (10) (2012) 102601
S. Kurosawa et al., Nucl. Instrum. and Meth. A 744 (2014) 30–34
S. Kurosawa et al., IEEE TNS 65 (8) (2018) 2136–2139



Zeff ~ 51,
ρ ~5.2g/cm^3

2MeV β range: ~1.8mm

Heavier material
→Shorter β range
→Smaller β-implant correlation radius
→Lower accidental background

La-GPS characteristics

Waveform

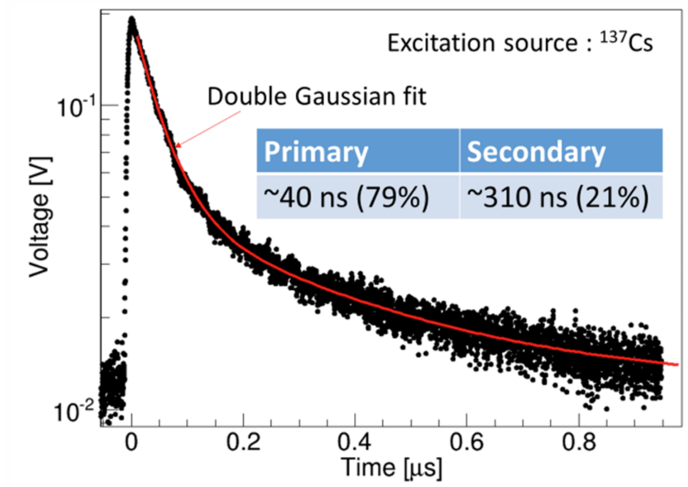


Fig. 6 Decay curve of Ce:La-GPS irradiated with gamma rays from a ^{137}Cs source.

Energy resolution

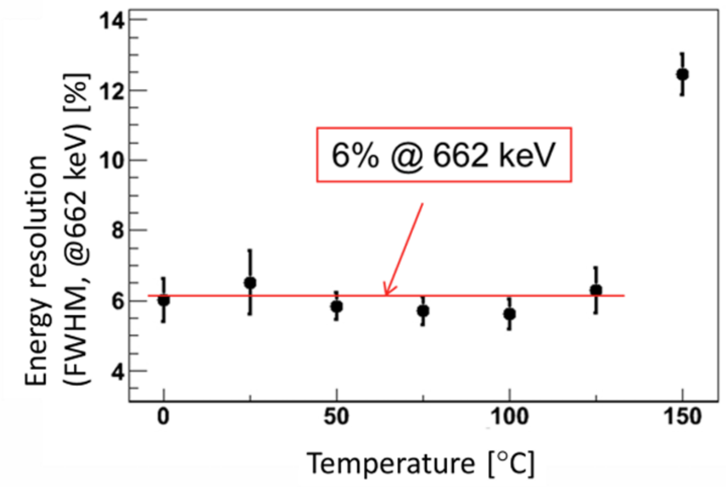
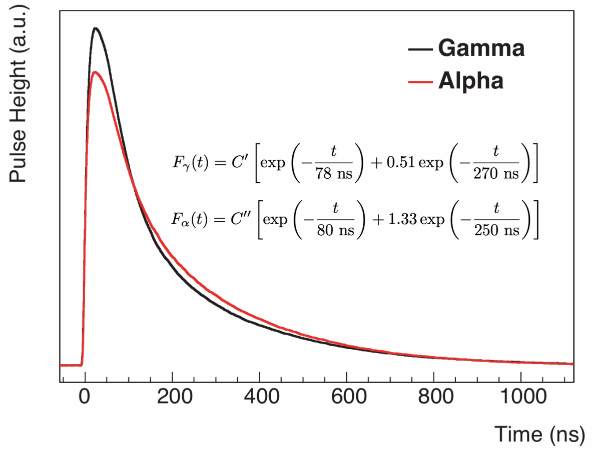
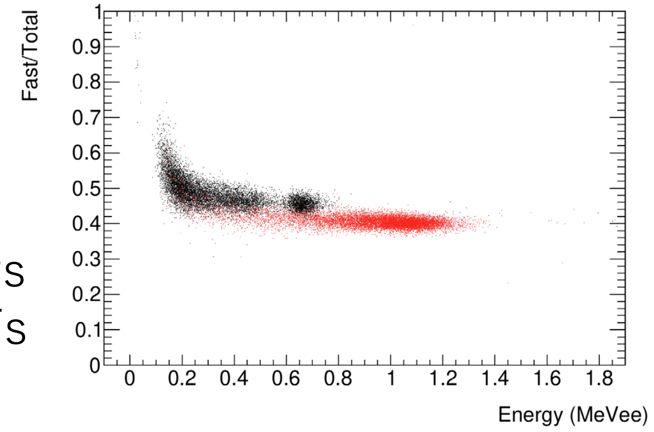


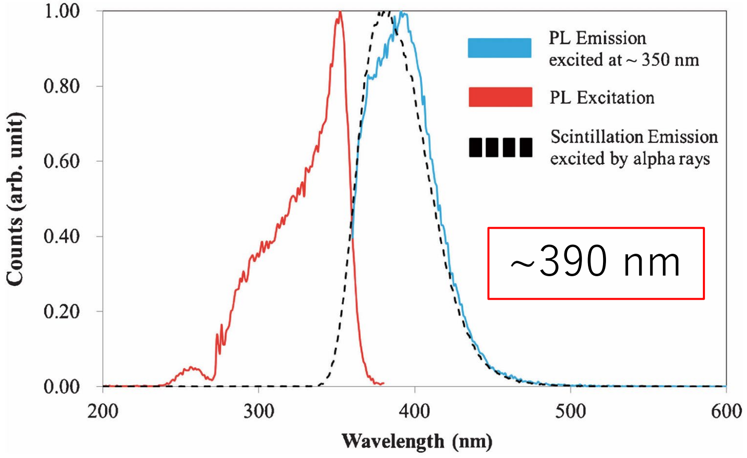
Fig. 9 Temperature dependence of energy resolution (FWHM, 662 keV) for Ce:La-GPS.

Pulse-shape discrimination capability





Emission wavelength



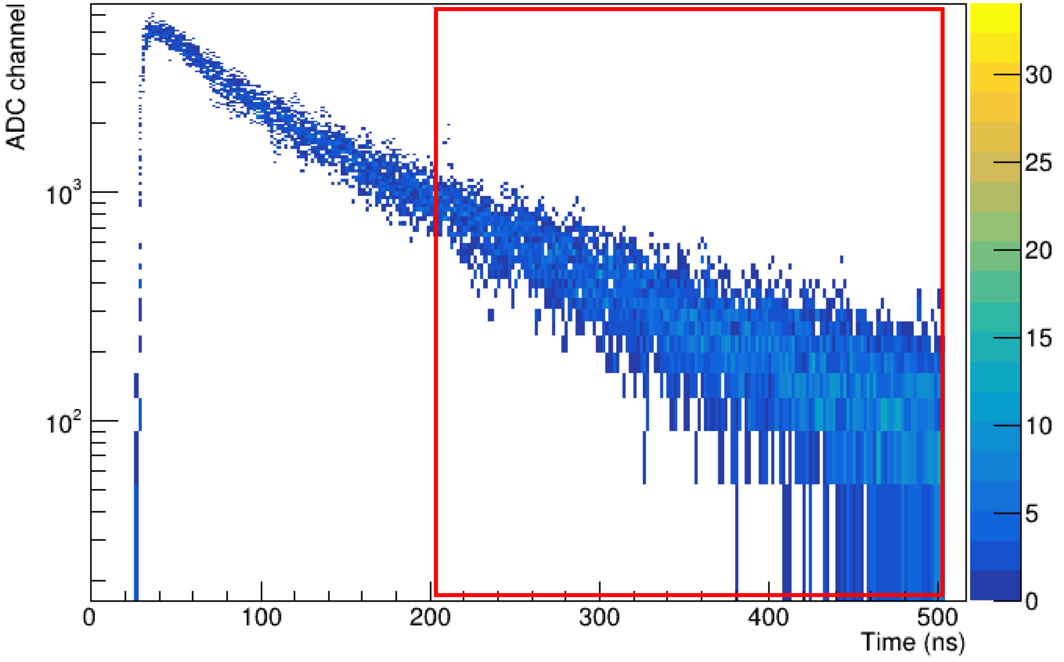
- High light output as halide scintillators (~36k photons/MeV)
- Fast time response as oxide scintillators
- Short wavelength that matches to PMTs unlike GAGG

S. Kurosawa et al.,日本結晶成長学会誌 Vol. 43, No. 1, 47-53 (2016)
K. Mizukoshi et al., Journal of Instrumentation 14, P06037 (2019)

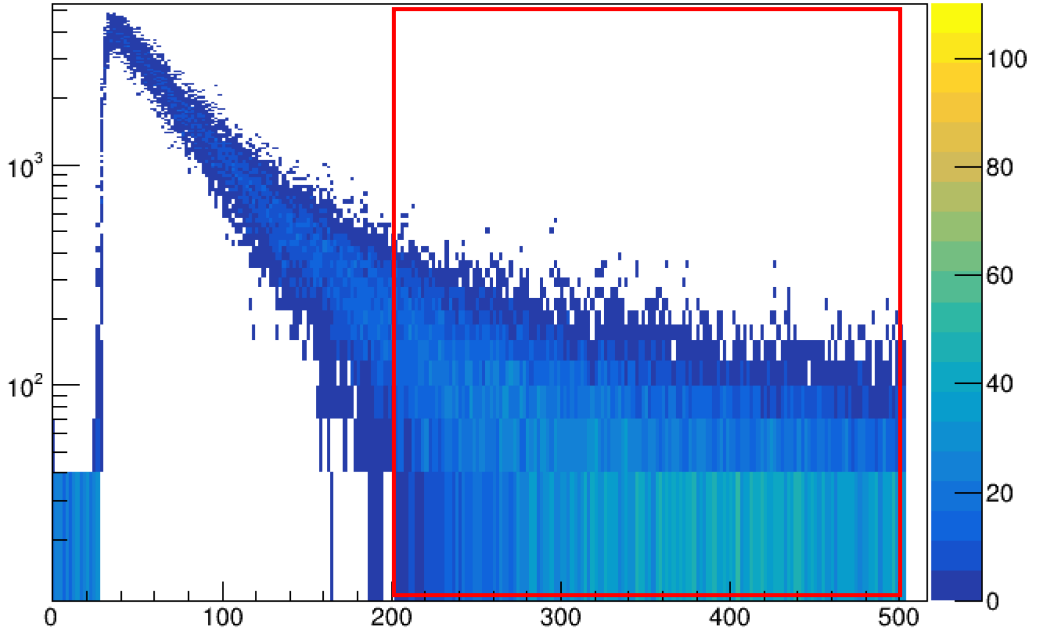
Adjusting the amount of Ce doping

With 137Cs source, gated on the 662-keV peak

Conventional La-GPS:Ce waveform



High-Ce La-GPS:Ce waveform

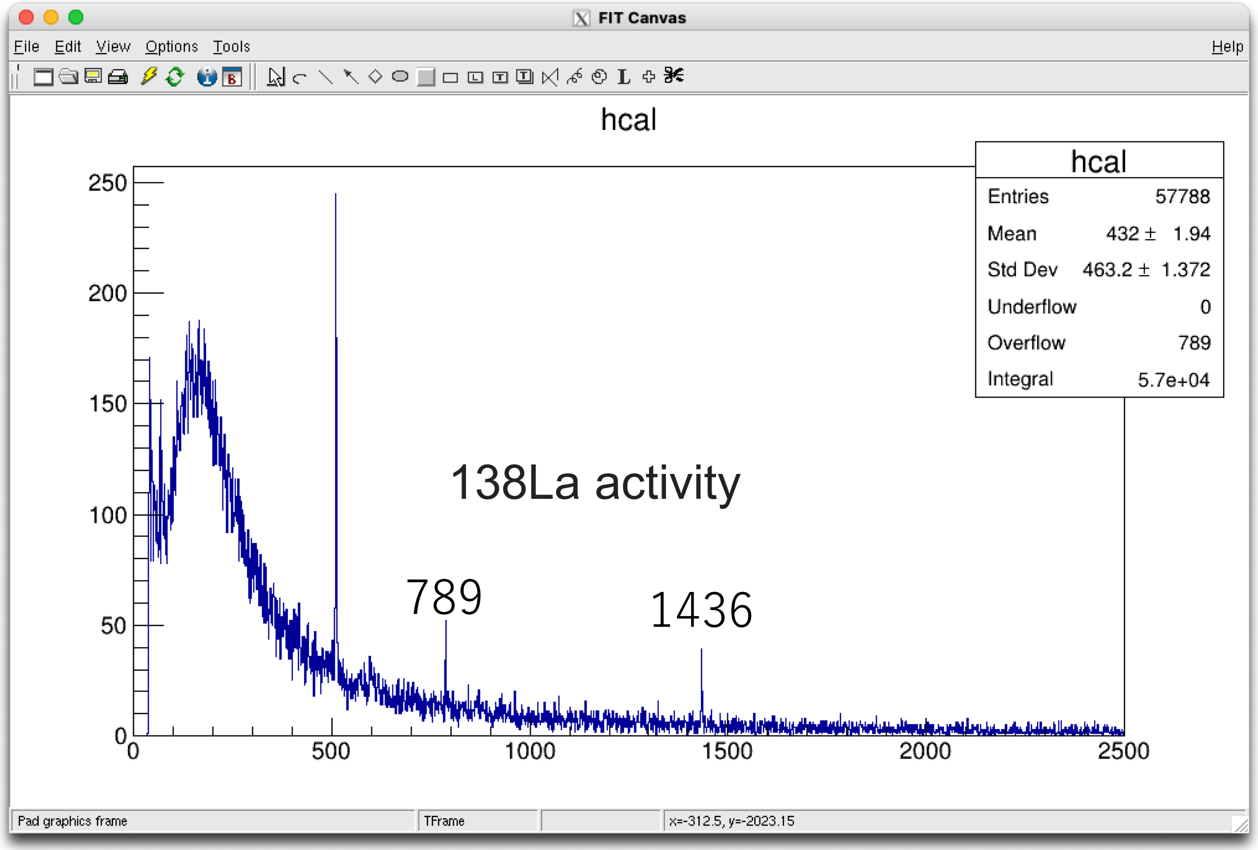


- GPS can be grown with heavy Ce doping up to 10 mol %
- We grew new crystal with higher Ce doping
- Light yield reduced to ~70%, lower yield in crystal growth
- Long decay component almost disappeared

S. Kawamura et al., IEEE Nuclear Science Symp. Conf. Rec., 2006, p. 1160.

Gamma measurement with Niikura setup

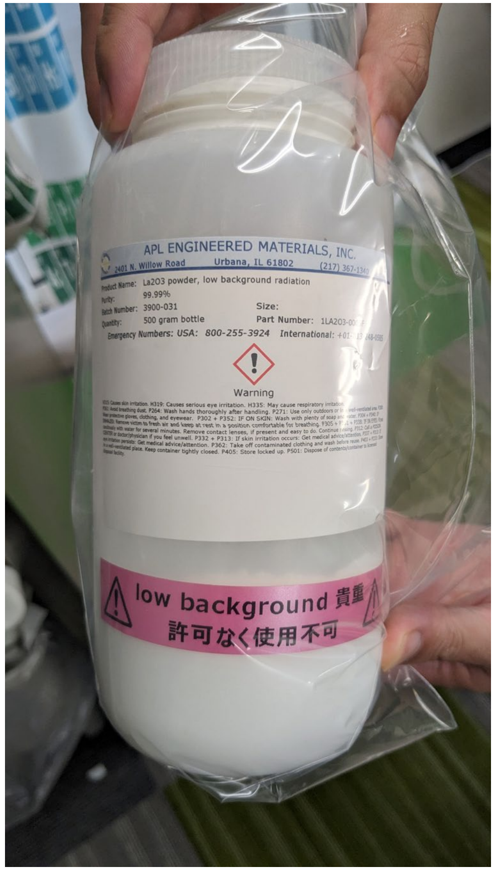
Natural-La-GPS 5-mm cube



~5 Bq for a 5-mm cube
~250 Bq for the 50 x 50 x 2.5 mm array

Ultra-low background HPGe setup by University of Tokyo

2023/8/21 Tohoku



139-enriched

La_2O_3

~350kJPY/500g

(70k for natural La)

~10% of total cost

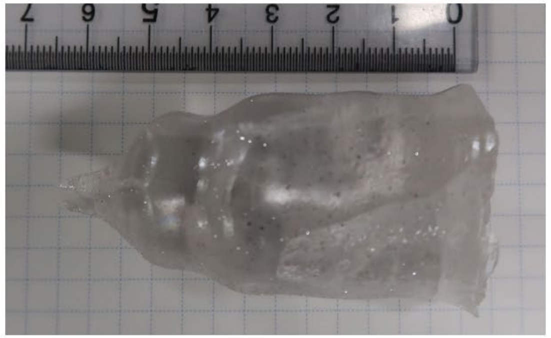
Heat and compress materials in an iridium pod

La-GPS crystal growth

Seed crystal

2.5” rod

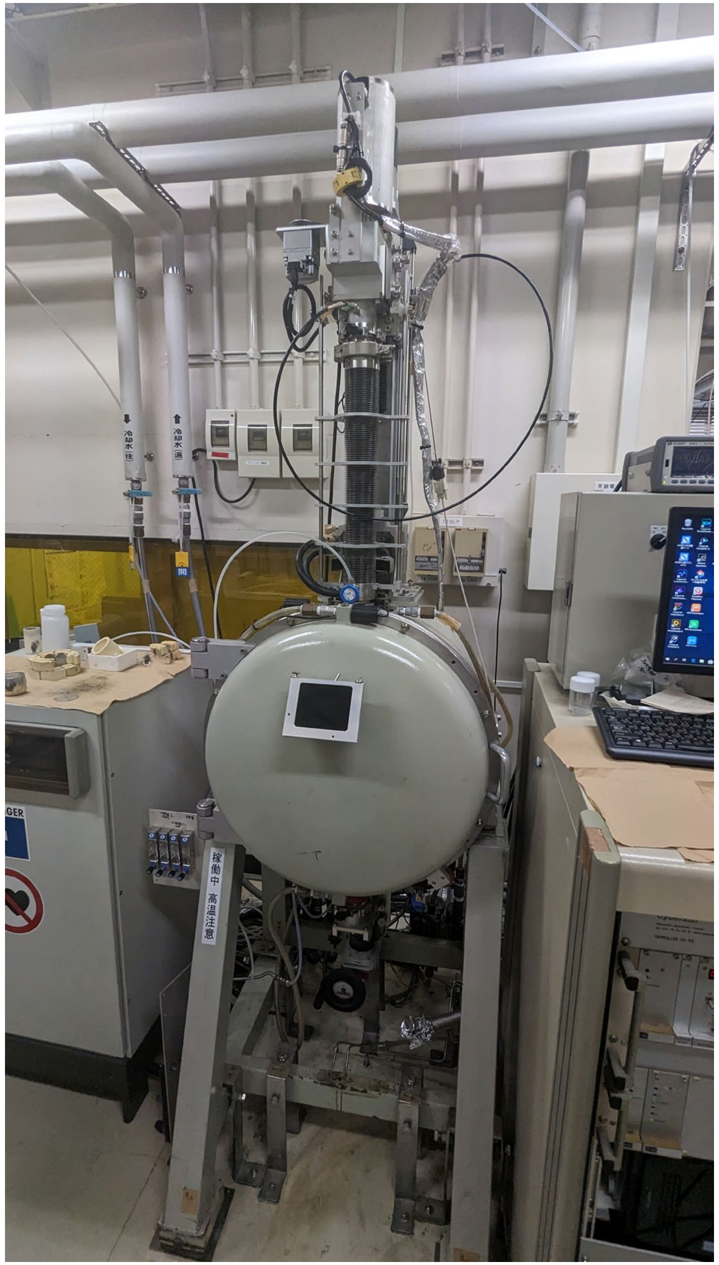
1st batch



2nd batch

3rd batch

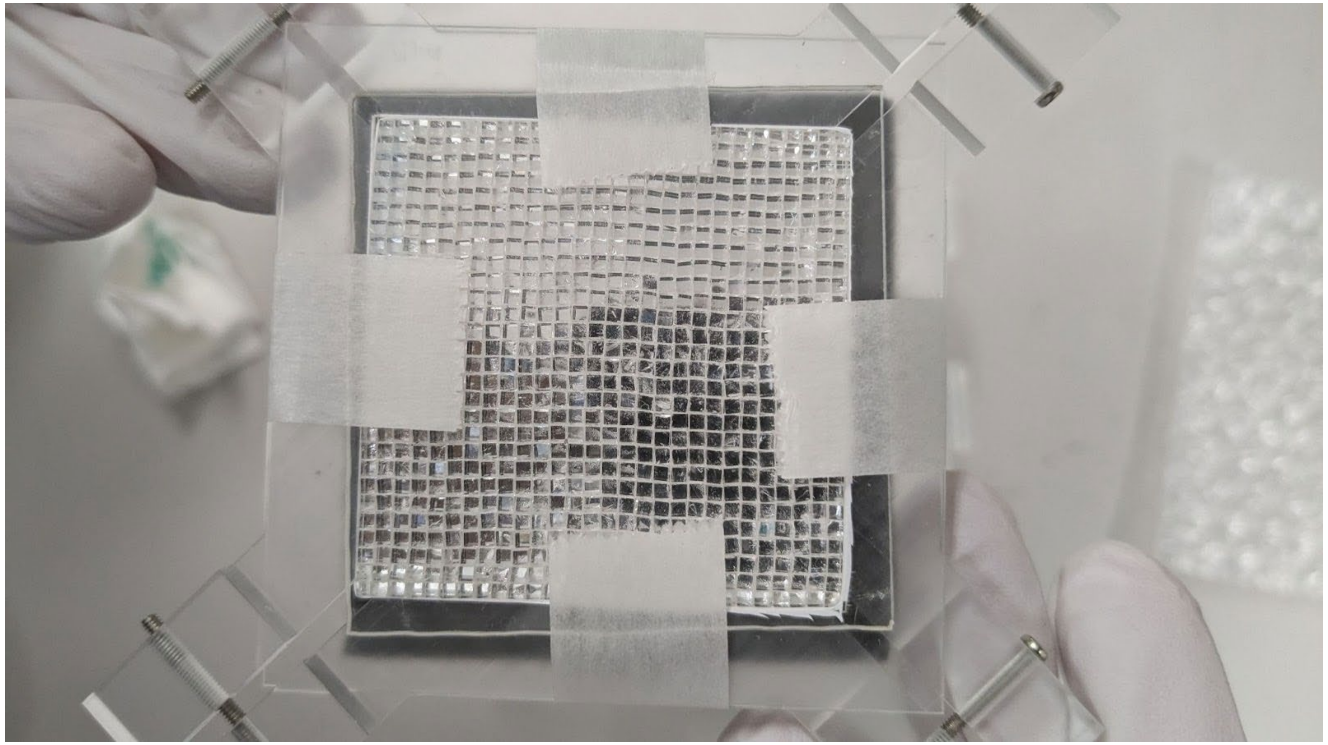
Heating chamber for Czochralski method

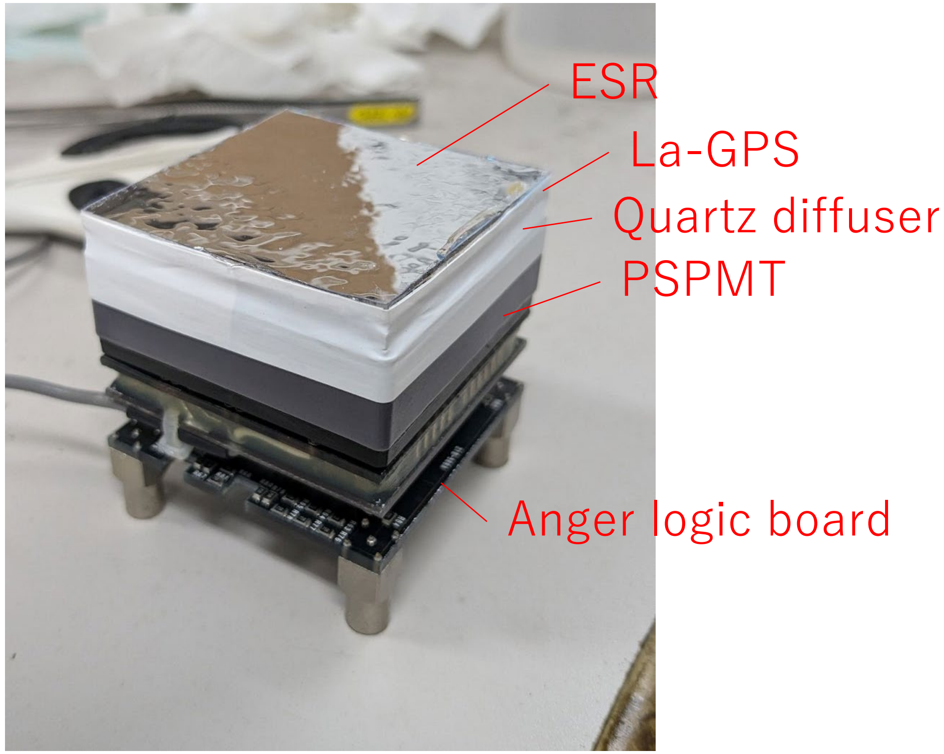


Making pixels

Cut into
1.5 mm x 1.5 mm x 2.5 mm pixels

La-GPS Array

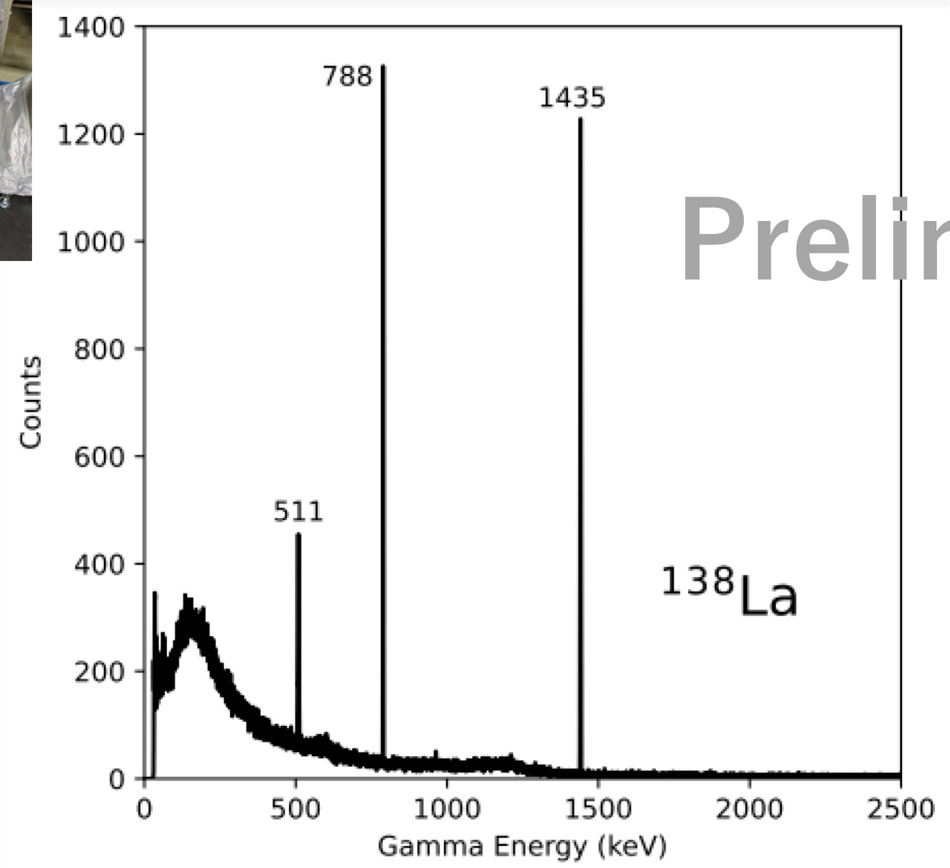




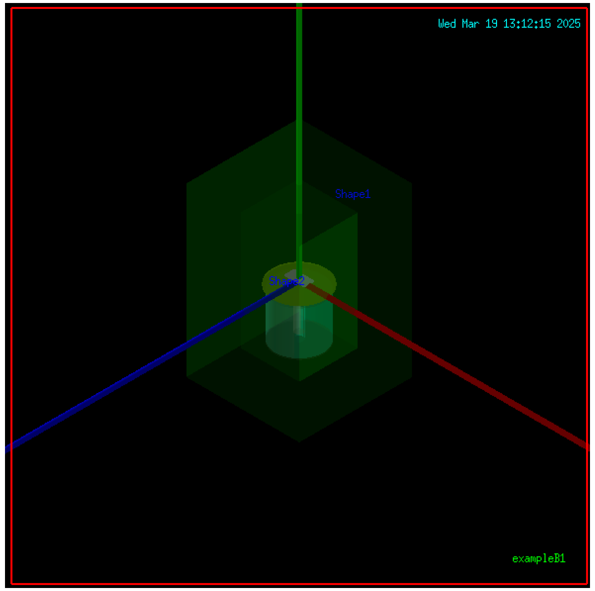
32 x 32 1.5mm x 1.5mmx2.5mm pixels
→Half the thickness of YSO

139La-GPS activity measurement

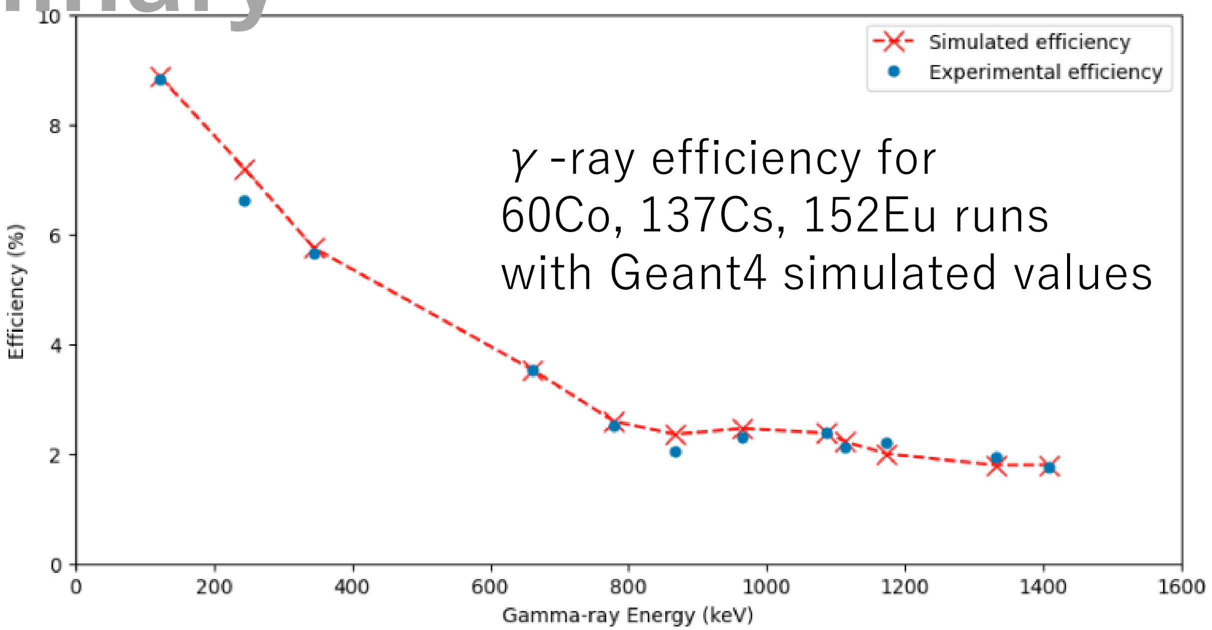
by Yasmin Anuar



Geant4 simulation
with Cascade γ emissions



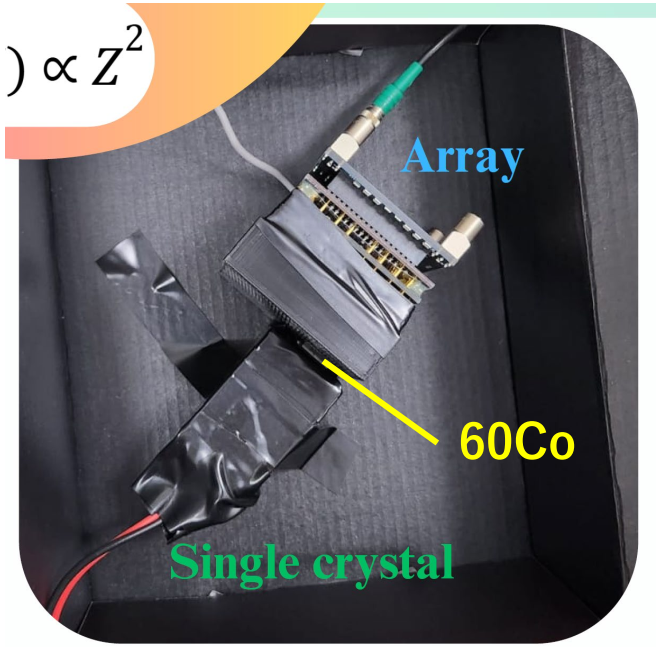
Preliminary

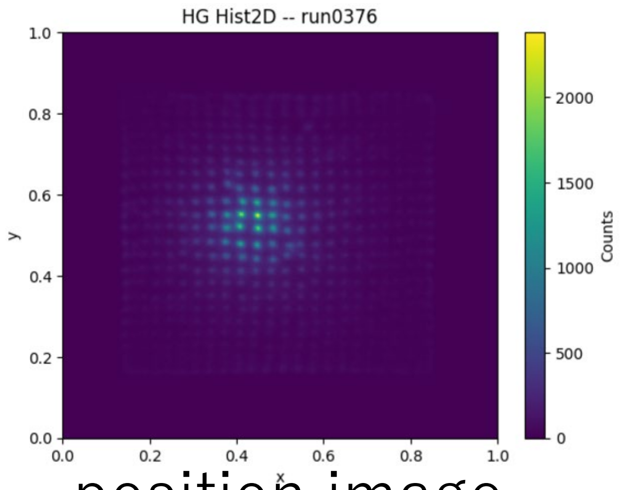


γ-ray efficiency for
60Co, 137Cs, 152Eu runs
with Geant4 simulated values

~2Bq for the entire array

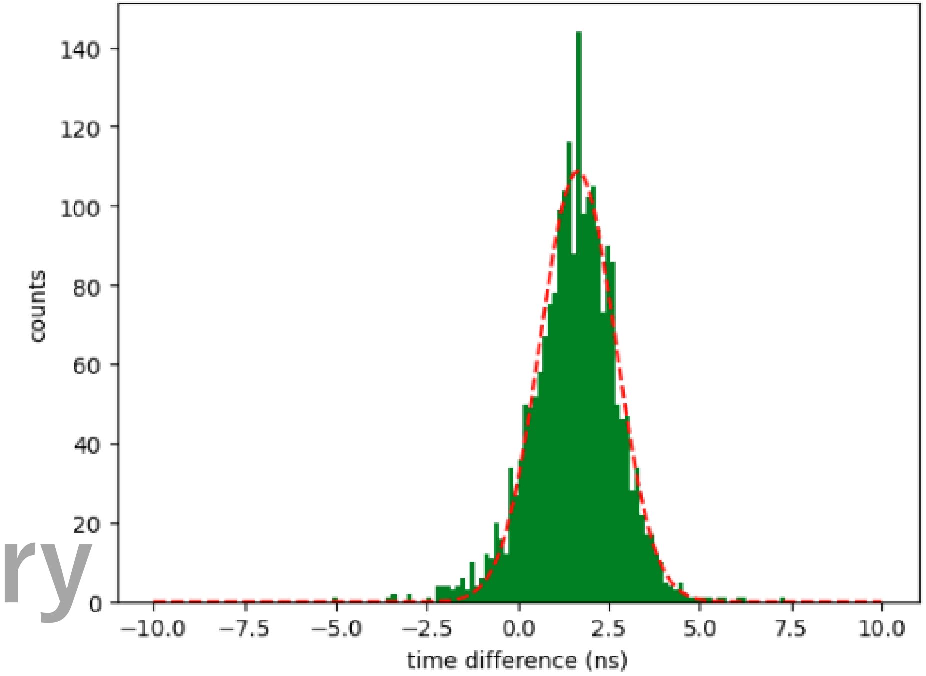
Time resolution measurement by Yasmin Anuar

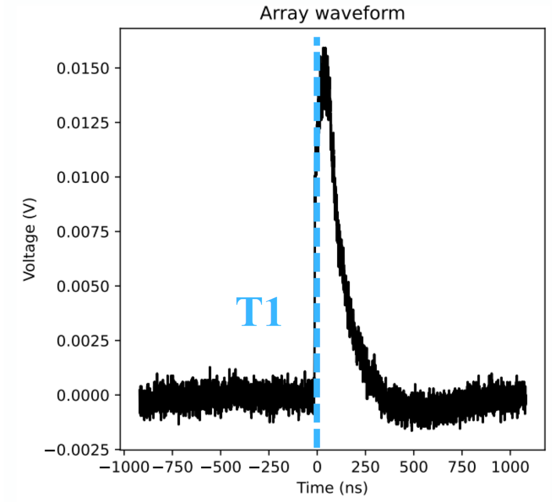


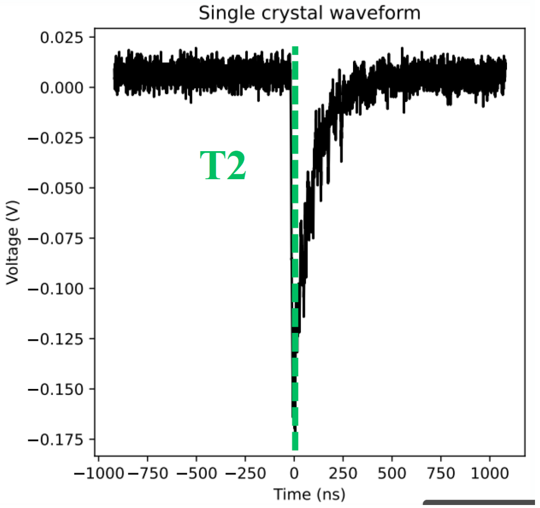


position image

Preliminary





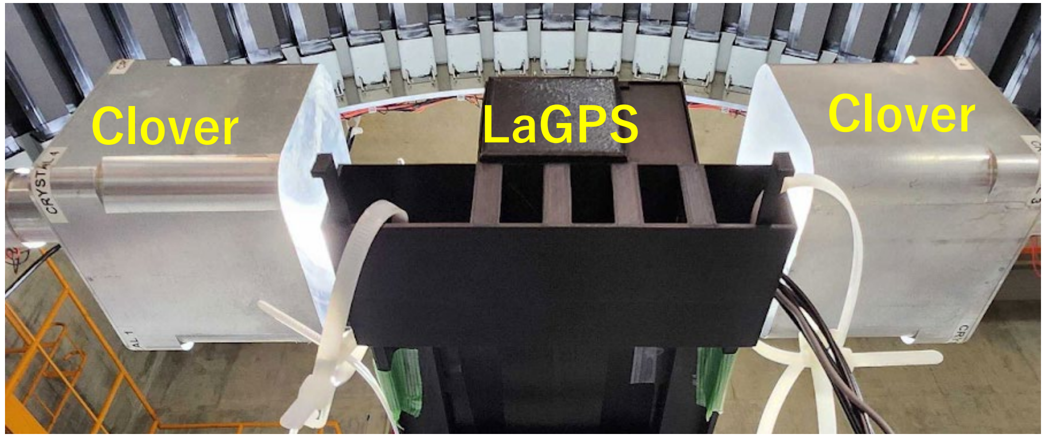


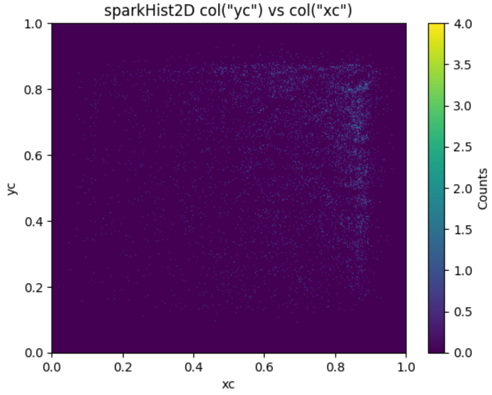
$\frac{1}{\sqrt{2}}\sigma_{\Delta T}$~730 ps

(~650 ps for YSO)

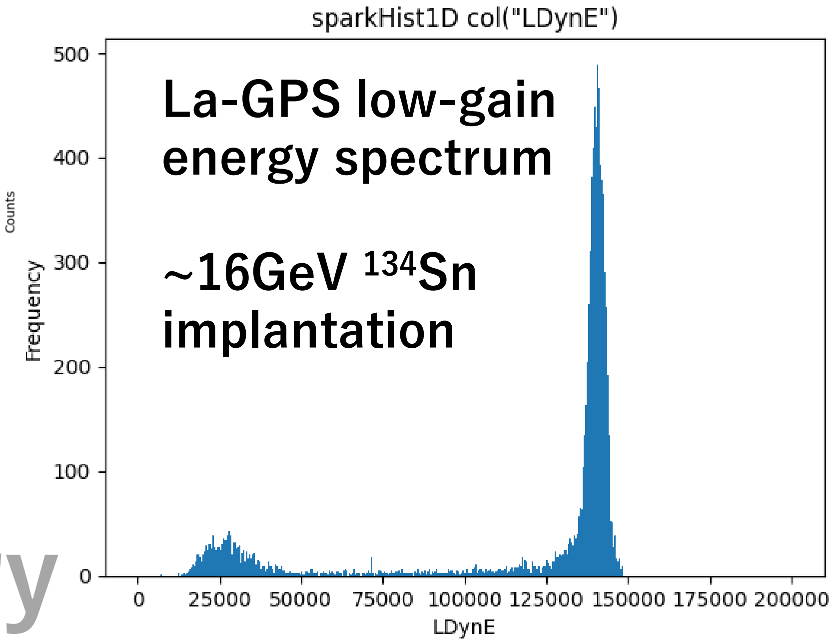
M. Singh et al., Nucl. Instrum. and Meth. A 1073, 170239 (2025)

Heavy ion implantation test at RIBF by Yasmin Anuar



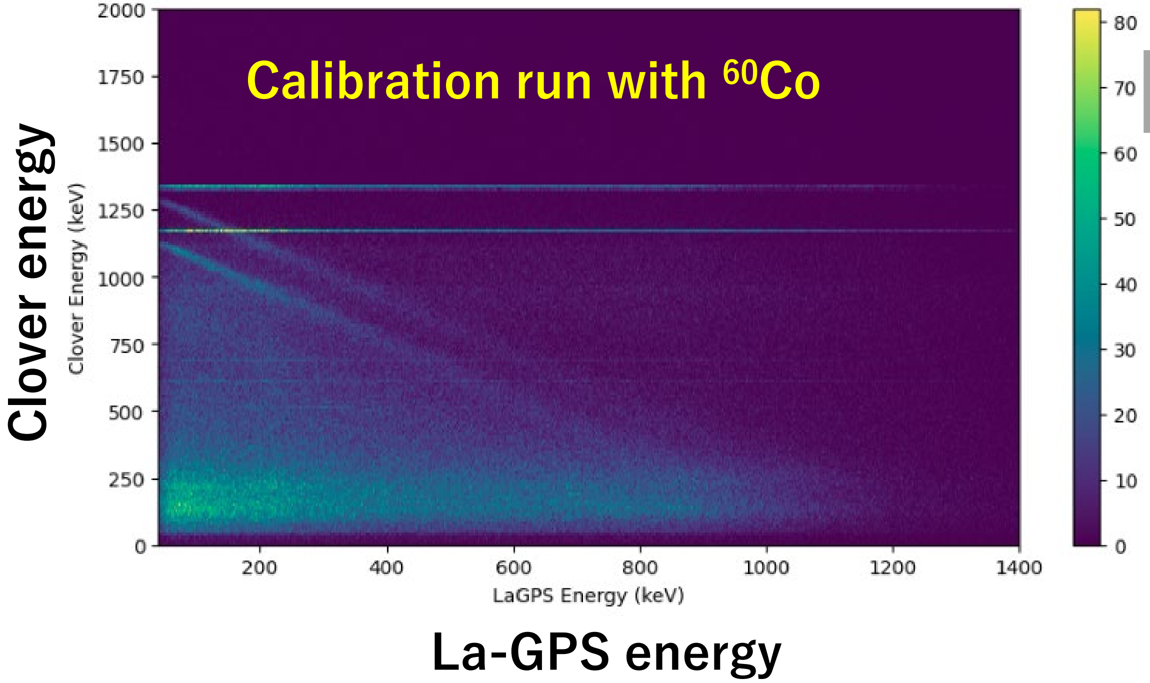


low-gain image



keVee

Preliminary



~120 Quenching factor

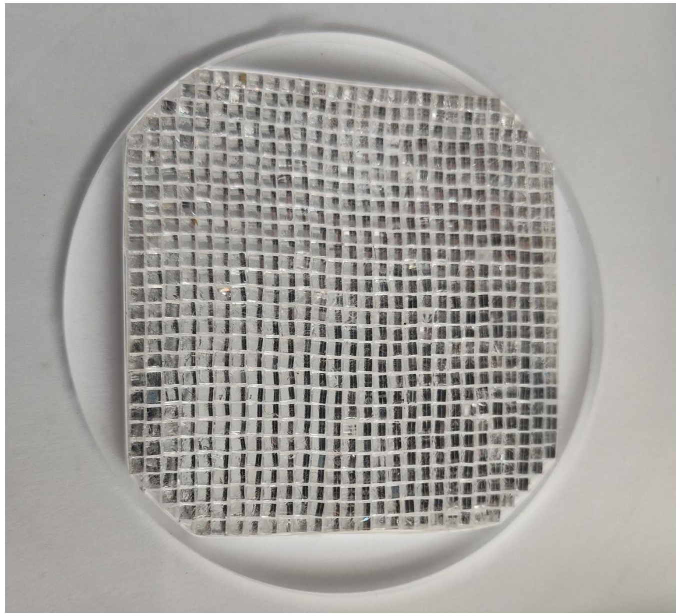
Amplitude is ~120 times smaller than electrons with same kinetic energy

(~40 for ^{78}Ni region with YSO)

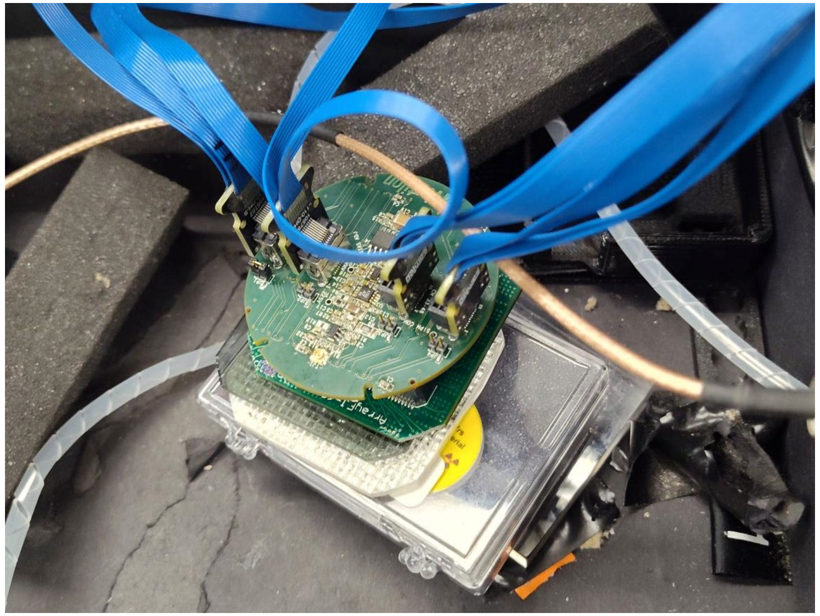
M. Singh et al., Nucl. Instrum. and Meth. A 1073, 170239 (2025)

La-GPS array for MTAS at FRIB Decay Station

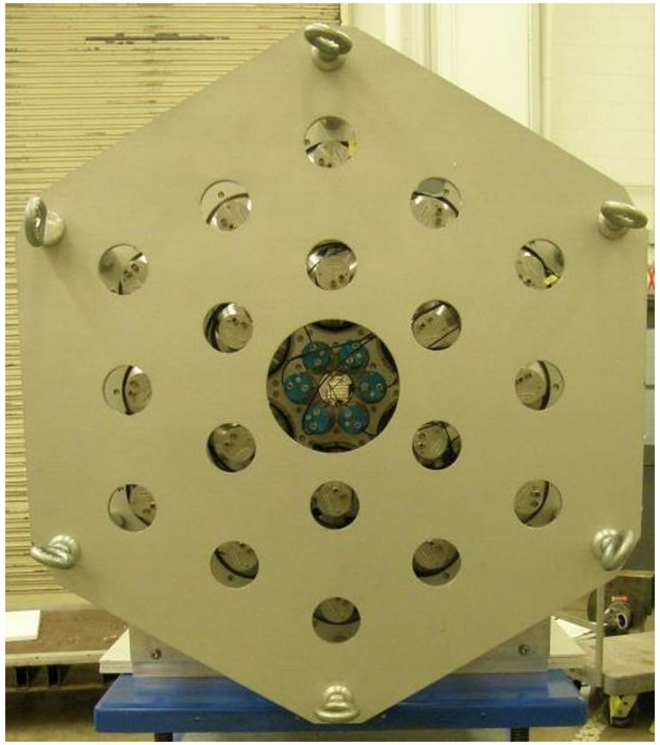
La-GPS array that fits
to the 25” duct



Read out with a SiPM array



Modular Total Absorption Spectrometer



Preparation in progress for runs in April and May 2025

Summary

- β-implant detector for a fragmentation facility requires good position resolution.
- Scintillator based detector is needed for nToF measurements that require good time resolution of β-ray detection.
- Heavier scintillator material stops β-ray in shorter range resulting in good position resolution.
- La-GPS is a good candidate for the β-implant detector.
  Zeff ~ 51, ρ ~5.2g/cm^3, Wavelength ~390nm, Eres ~6%, Decay ~40ns
- A 139-enriched La-GPS array was developed to reduce internal activity from ^{138}La.
- Performances were tested: ~2Bq internal activity, ~730ps time resolution, ~120 quenching factor for ^{134}Sn
- MTAS array will be tested at FRIB soon