National Institutes of Natural Sciences
Institute for Molecular Science

The workshop on photonuclear science in 2025
10 August 2025

Gamma-ray-induced positron annihilation spectroscopy at UVSOR

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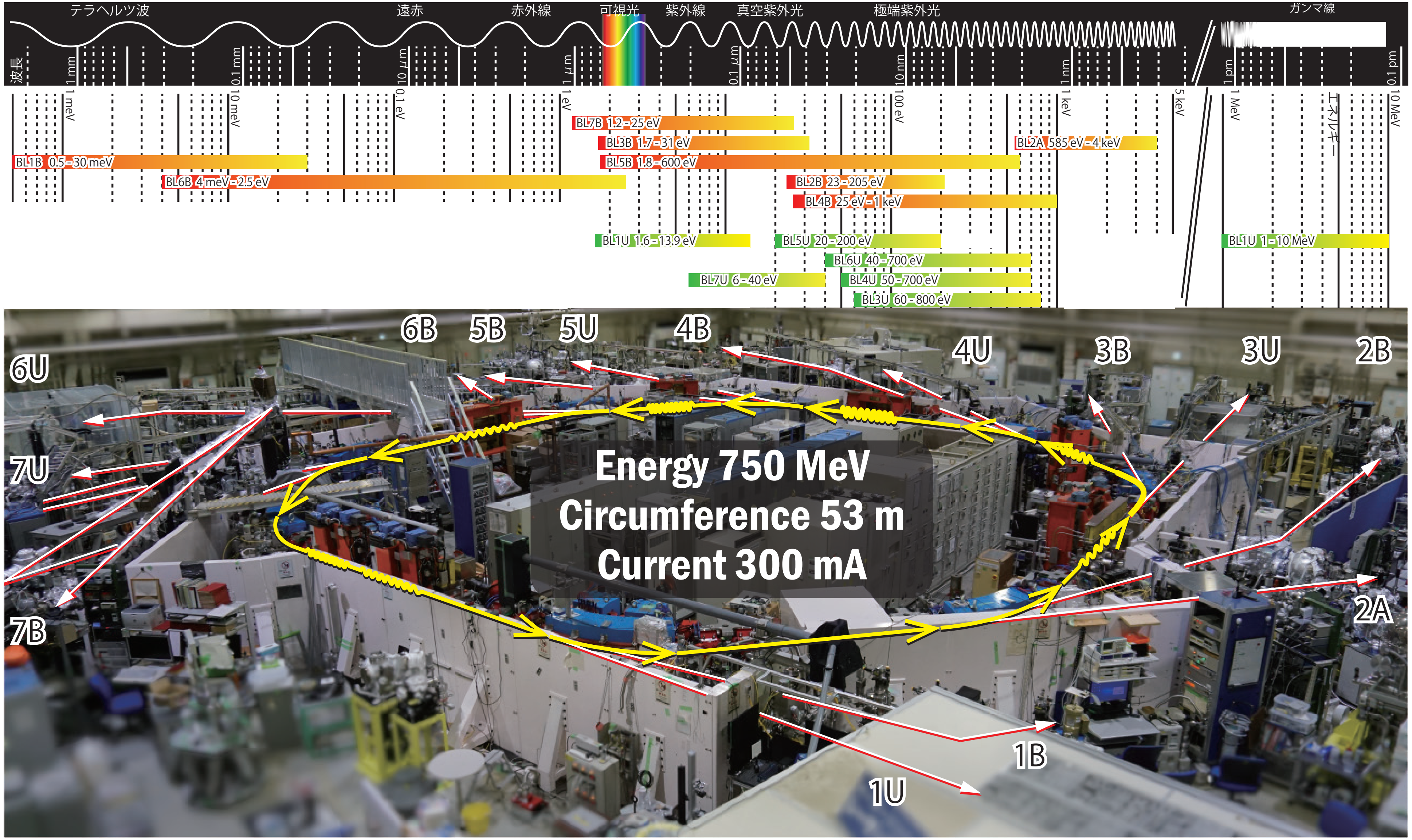
UVSOR synchrotron facility, Okazaki, Japan



Gamma-ray sources at UVSOR

The electron beam energy is fixed at 750 MeV.
Collimator: ϕ 1, 2, 3, 5, 8, 12 mm

1 6.6 MeV ultra-short pulsed gamma rays

TiSa Laser: Wavelength 0.8 μm, Pulse energy 2.5 mJ,
Repetition rate 1 kHz, Pulse width 130 fs, 90 degree injection

Gamma ray: Intensity 6×10^5 photons/s, Pulse width sub-ps~ps

2 5.5 MeV CW gamma rays

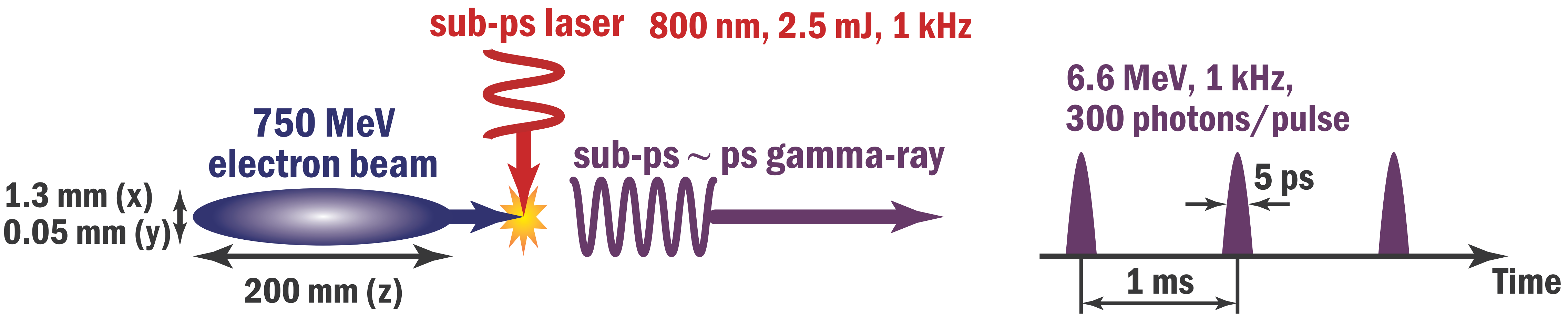
Fiber laser: Wavelength 1.95 μm, Power 50 W, Head-on collision
(Kyoto U., Ohgaki Lab. bring your own)

Gamma ray: Intensity 10^8 photons/s

3 (Free electron laser gamma rays)

Generation of ultra-short pulsed gamma-ray

90 degree interaction between an electron beam and a laser



An ultra-short pulsed gamma-ray can be generated by a 90-degree collision by utilizing the flat shape of an electron beam circulating in a storage ring.

The time resolution of the positron annihilation lifetime spectroscopy is 120 ps (FWHM) in the best instruments.

By using gamma rays with a pulse width sufficiently shorter than 120 ps, the positron lifetime can be measured without deteriorating the time resolution.

Defects analysis using positrons

What is a positron?

A positron is an antiparticle with the same mass as the electron but a positive charge.

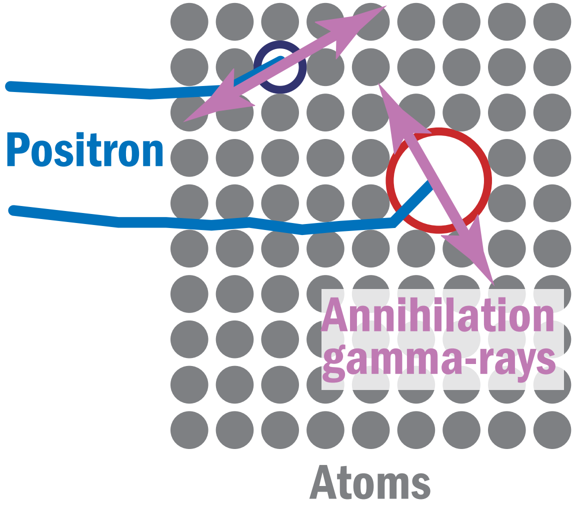
It annihilates with an electron and emits two annihilation gamma-rays in the direction of 180 degrees.

Probe of defects

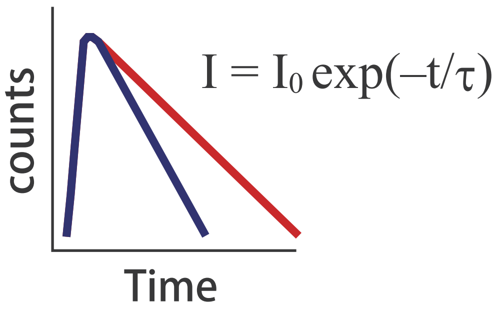
Positrons are excellent probes of atomic scale defects in solids and free volumes in polymers.

Materials that can be measured:
metals, semiconductors, polymers, and glass.

Measurement methods

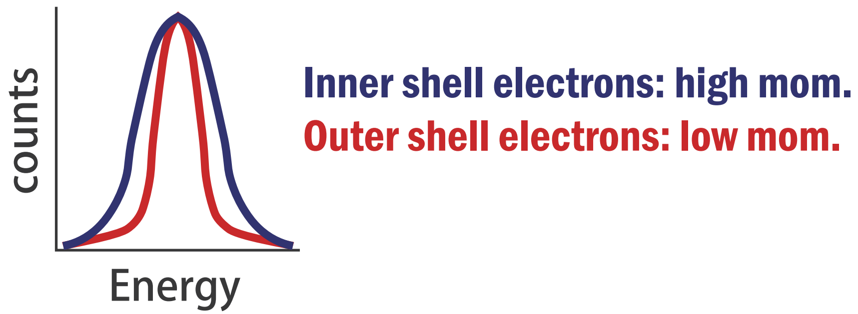


Positron lifetime depends on electron density



Size, concentration, and type of vacancies

Doppler broadening depends on electron momentum



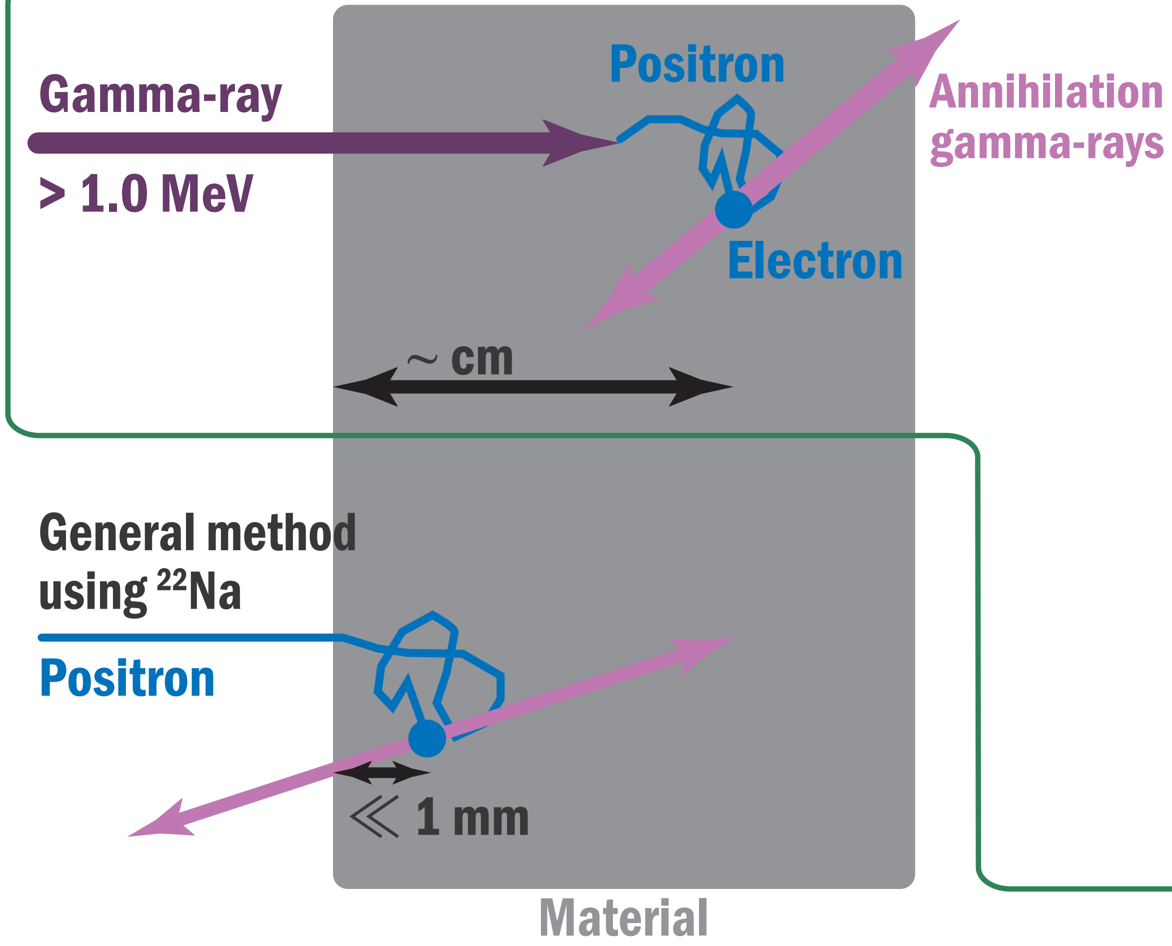
Elemental identification

An example of a review paper: J. Cizek, J. Mat. Sci. Tech. 34 (2018) 577.

Generation of positrons by high-energy gamma rays

Gamma-ray-induced positron annihilation spectroscopy (GiPAS)

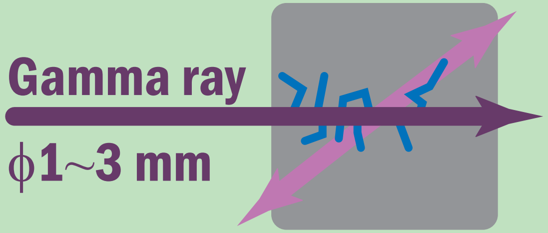
Developed at Idaho State U., ELBE, TERAS, UVSOR, NewSUBARU.

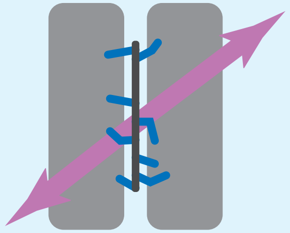


- **Capable of measuring a bulk sample**
  Positrons can be generated almost uniformly from the surface to a depth of several cm.
- **Source component is negligible**
  The lifetime of Kapton film used to seal the ^{22}Na source does not appear in the lifetime spectrum.
- **In-situ measurement is possible**
- **Gamma-ray generation can be fully controlled by the laser**

Y. Taira et al., Rev. of Sci. Instr. 93 (2022) 113304.

Difference between gamma-ray-induced and RI methods

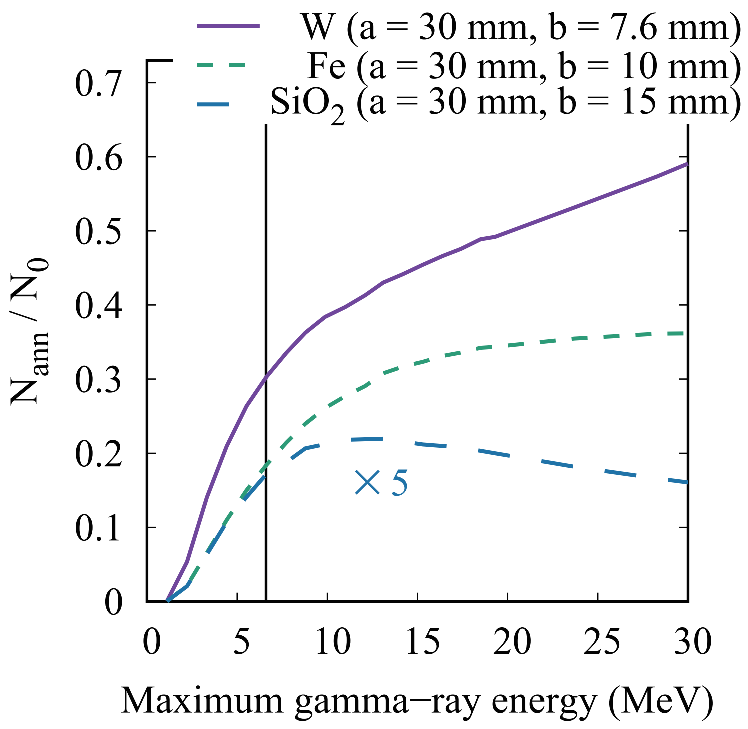




Parameter	Gamma-ray induced method	Radioisotope (RI) method
Positions of positron annihilation	Positrons diffuse around the gamma-ray beam axis	Positrons diffuse from the location of RI
Start signal	Laser	1.28 MeV gamma ray (^{22}Na)
Stop signal	Two annihilation gamma rays (coincidence)	One ann. gamma ray or two ann. gamma rays (coincidence)
Positron generation on time axis	Controllable at rep. rates of kHz~MHz (if e^- beam has higher rep. rate than laser)	Random

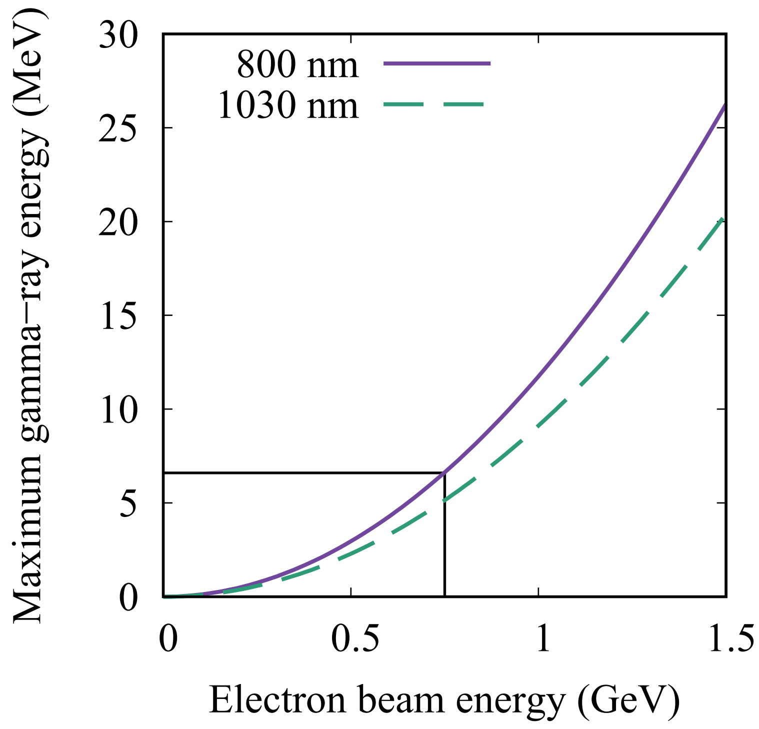
Energy of positrons and gamma rays

Generation efficiency of annihilation gamma rays



It is appropriate to use gamma rays near 10 MeV

Gamma-ray energy as a function of electron energy



Electron beam energy is near 1 GeV

Low energy synchrotron radiation accelerators are very well suited for producing 10 MeV gamma rays.

Global status of GiPAS

UVSOR (Japan)

Ultra-short pulsed gamma-rays by inverse Compton scattering

A public beamline of storage ring.

UVSOR is the only synchrotron radiation facility that can measure positron lifetime.

ELBE

Ultra-short pulsed gamma-rays by Bremsstrahlung

40 MeV superconducting electron linac

GiPALS, GiAMOC, GiCDB have been developed.

NewSUBARU, TERAS (Japan)

Continuous gamma-rays by inverse Compton scattereing

The gamma-ray beamline at NewSUBARU is available on a limited basis.

TERAS has been shut down at 2013.

Idaho state U. (Dr. Selim group)

Pulsed gamma-rays by Bremsstrahlung

This group was the first in the world to demonstrate GiPAS.

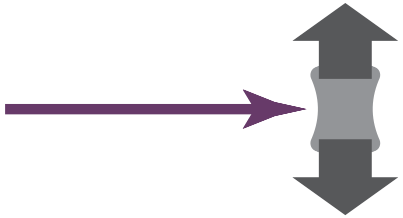
Examples of measurement in UVSOR

A bulk sample

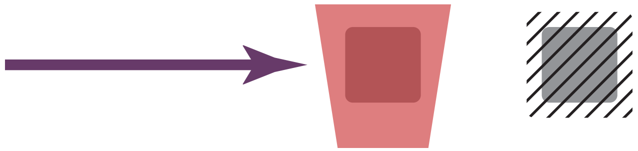
Gamma rays

at atmosphere

Stress load



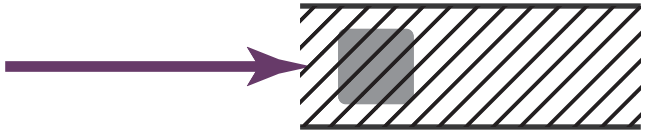
High/Low temperature



Infrared heater

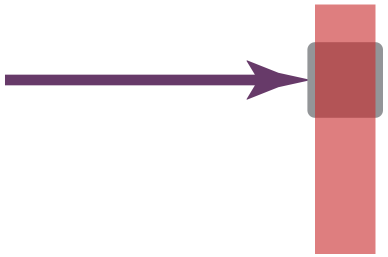
Liquid N_2

Gas atmosphere/immersion



If there is material around the sample, positron annihilation there should be taken into account.

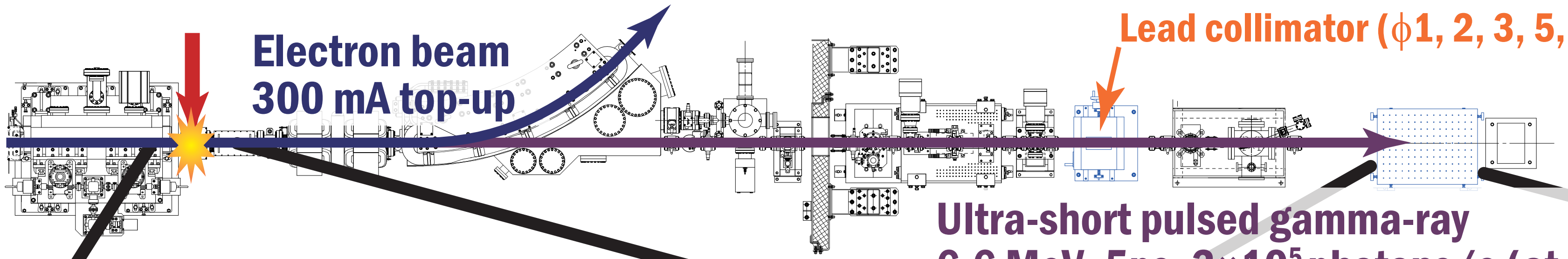
Laser illumination



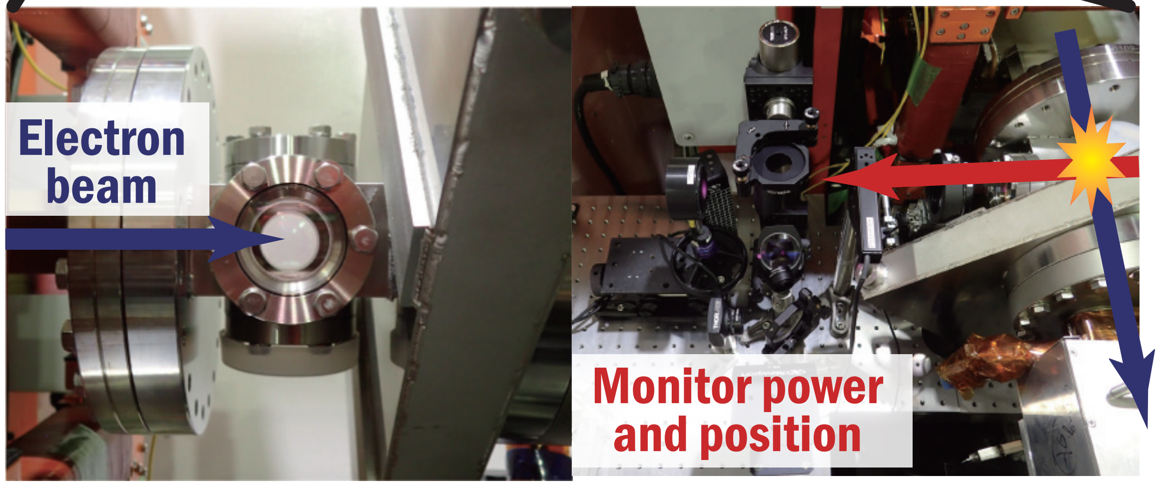
Fund. 800 nm
Second har. 400 nm
Third har. 266 nm

Laser
(used for gamma-ray genration)

Gamma-ray beamline, BL1U at UVSOR

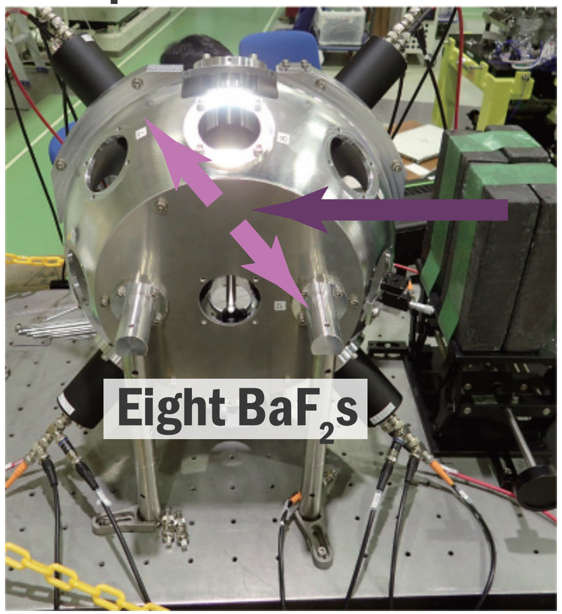


Ultra-short pulsed gamma-ray
6.6 MeV, 5ps, 3×10^5 photons/s (at the generation point)

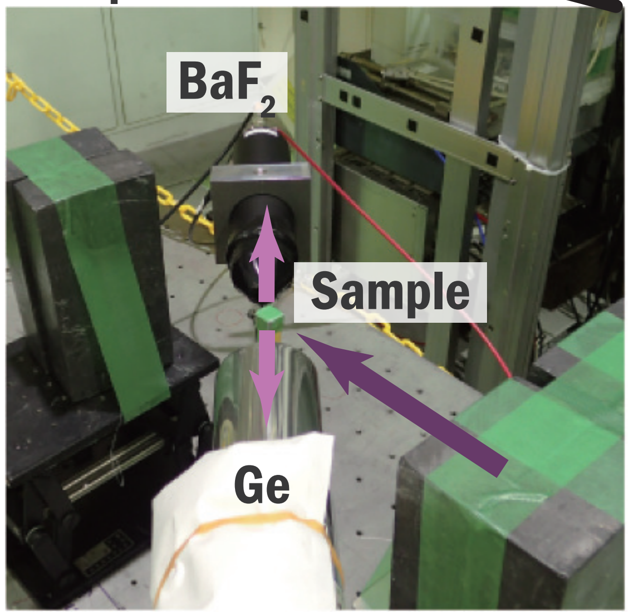


Stability of laser at the collision point (standard deviation)
Average power for 10 hours: <0.1%
Position for few tens of seconds: 1.3 μm (H), 2.0 μm (V)

Set-up of GiPALS

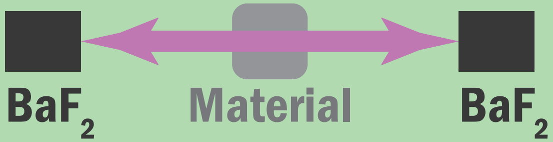


Set-up of GiAMOC



Measurement methods in UVSOR

Positron annihilation lifetime spectroscopy (PALS)

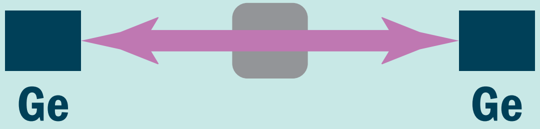


Coincidence measurement using fast response detectors

Y. Taira et al., J. Phys. Conf. 3029 (2025) 012022.

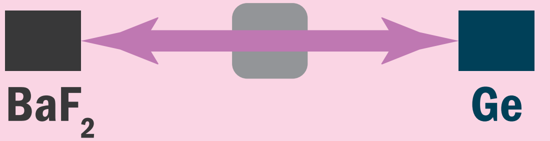
Available

(Coincidence) Doppler broadening



Coincidence measurement using high energy resolution detectors

Age-momentum correlation (AMOC)

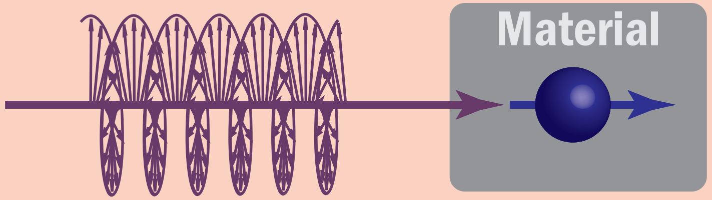


Coincidence measurement using a fast response detector and a high energy resolution detector

Y. Taira et al., Rev. Sci. Instr. 93 (2022) 113304.

Available

Spin polarized positron

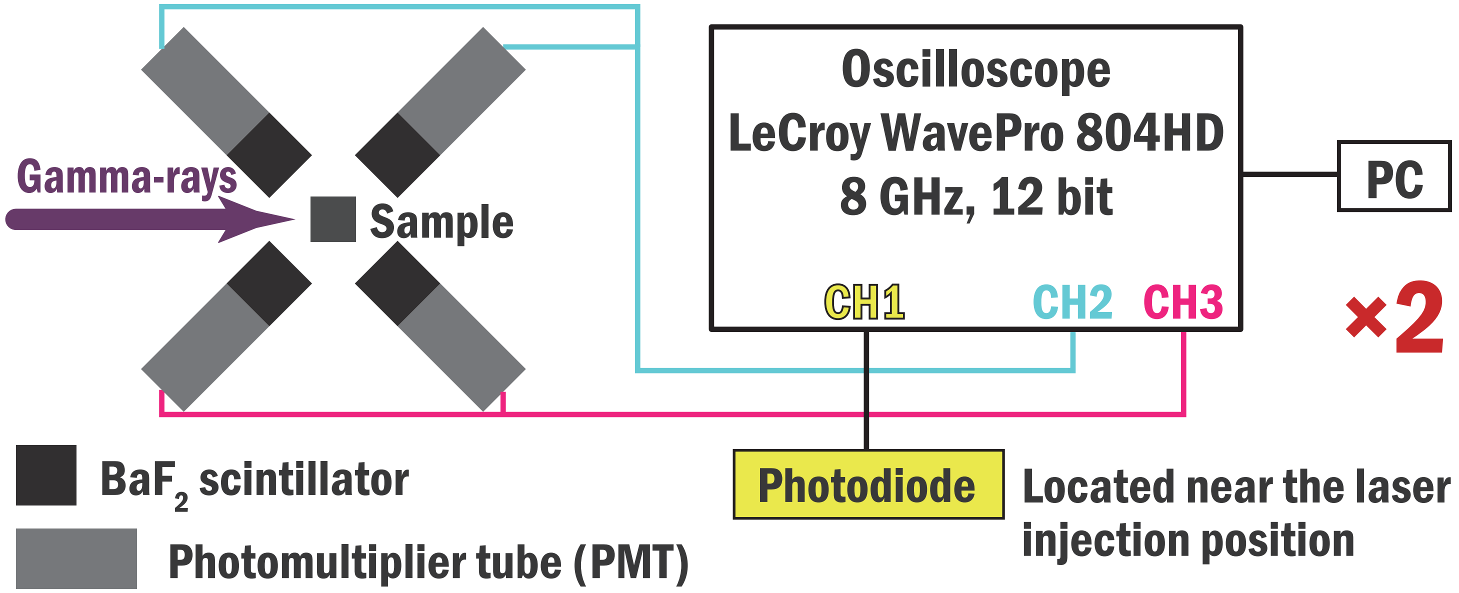


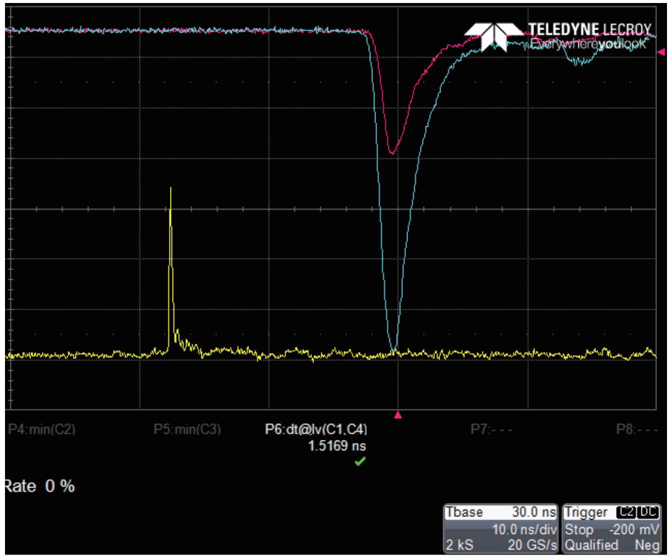
Circularly polarized gamma-rays

Spin polarized positrons

Under development

Data taking of GiPALS

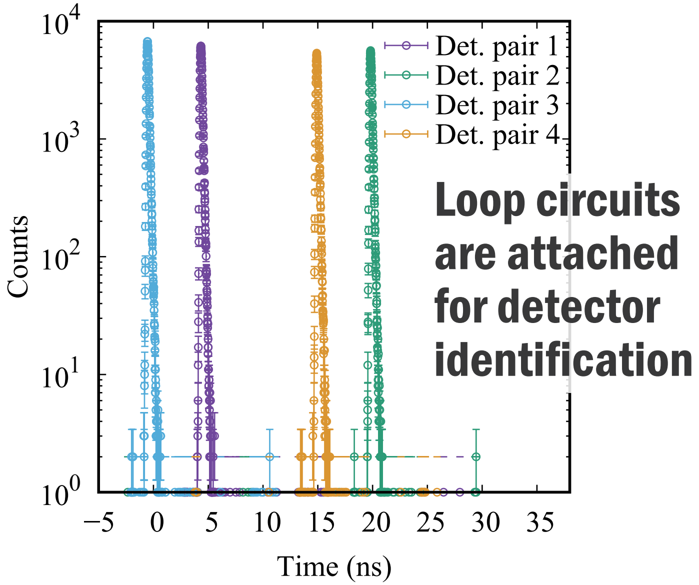


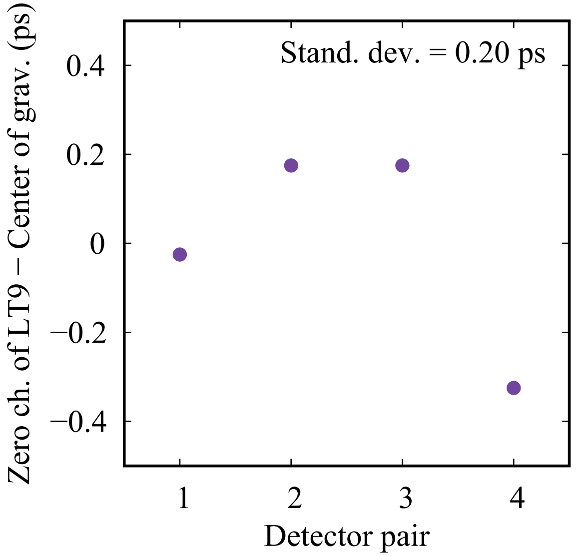


A trigger: Photodiode (CH1)
B trigger: PMT (CH2 and CH3)
Save all waveforms with AB trigger and analyze the data with PC.

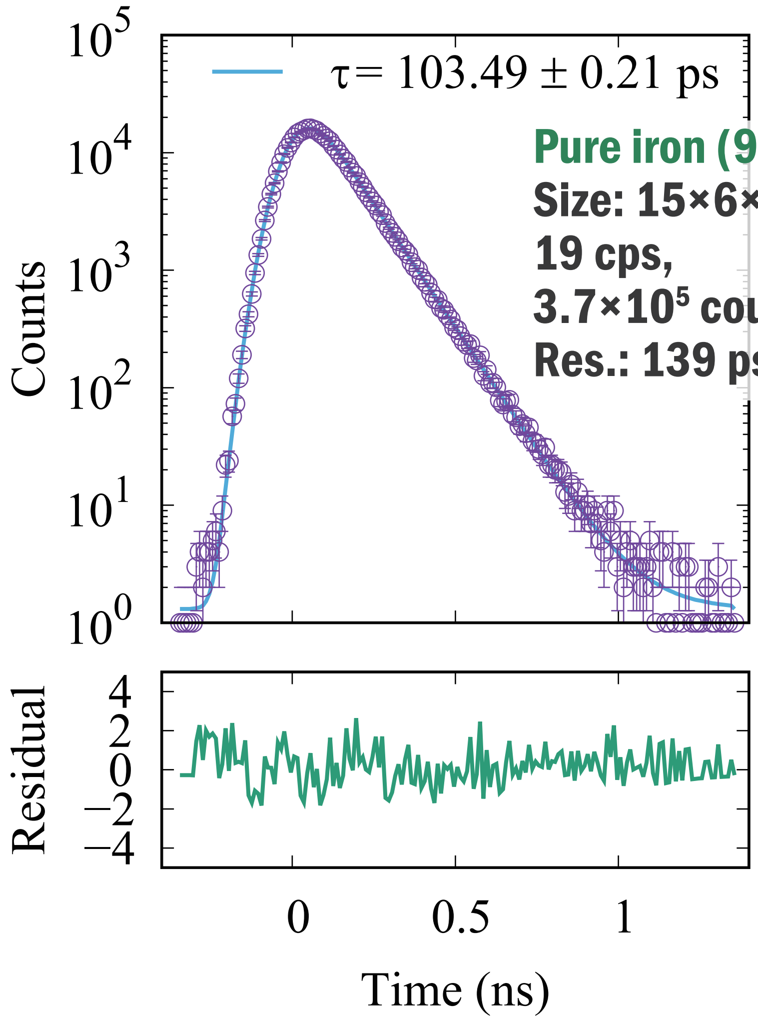
Make a histogram of the time difference between the photodiode output and the photomultiplier tube output.

Lifetime spectrum was calculated by the double stop method.





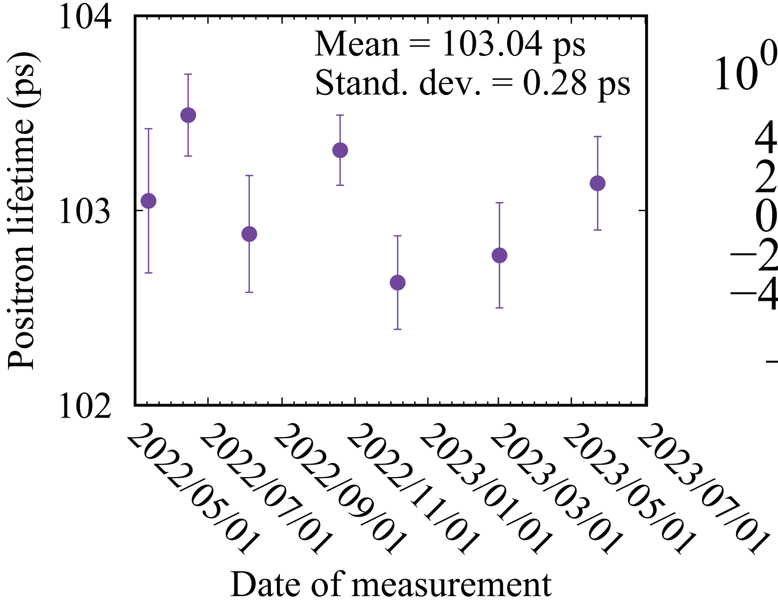
Positron annihilation lifetime spectra

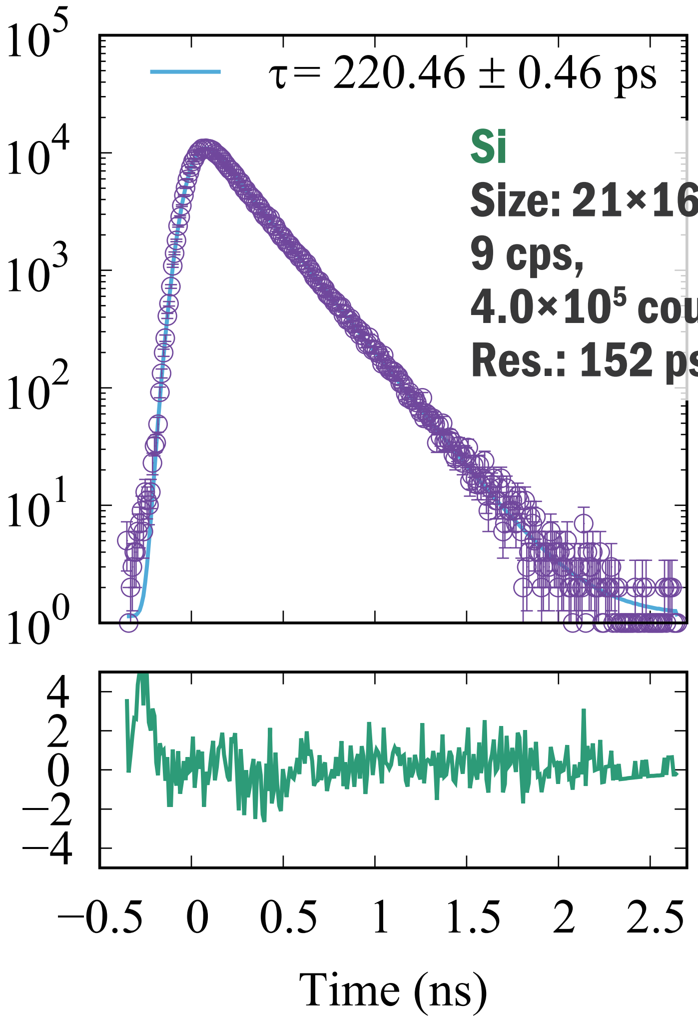


Pure iron (99.99 %)
Size: 15×6×15 mm
19 cps,
3.7×10^5 counts
Res.: 139 ps (FWHM)

Four sets of detectors

Reproducibility

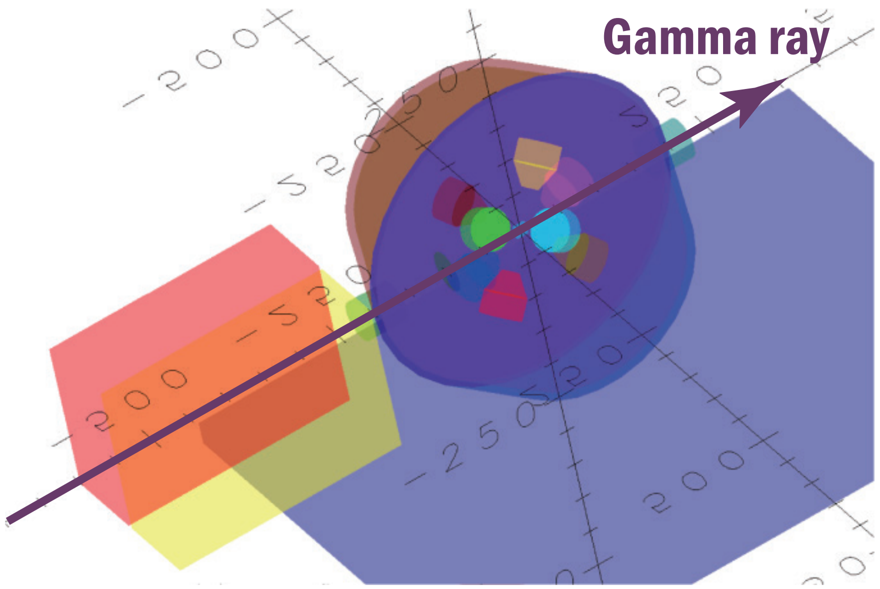




Si
Size: 21×16×17 mm
9 cps,
4.0×10^5 counts
Res.: 152 ps (FWHM)

Y. Taira et al., J. Phys. Conf. 3029 (2025) 012022.

EGS5 simulation



Multiple gamma rays are generated per pulse because the repetition rate of gamma rays is low.

The code was modified to define the average number of gamma rays per pulse and to track multiple gamma rays.

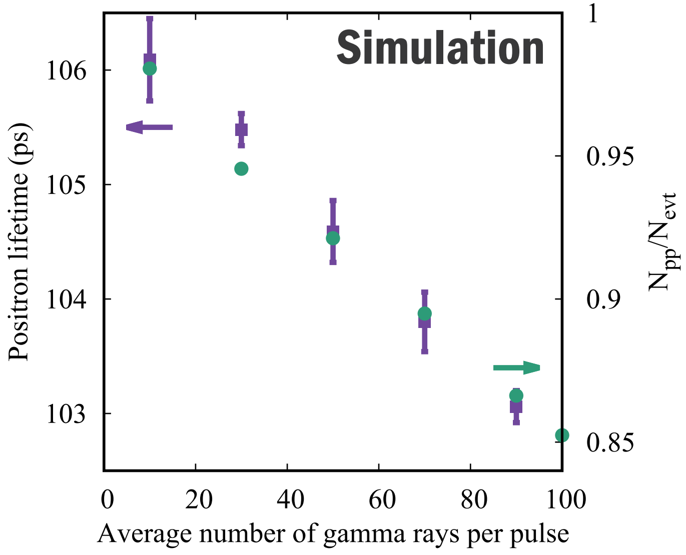
When a positron annihilates, time is delayed by a random number that follows an exponential function.

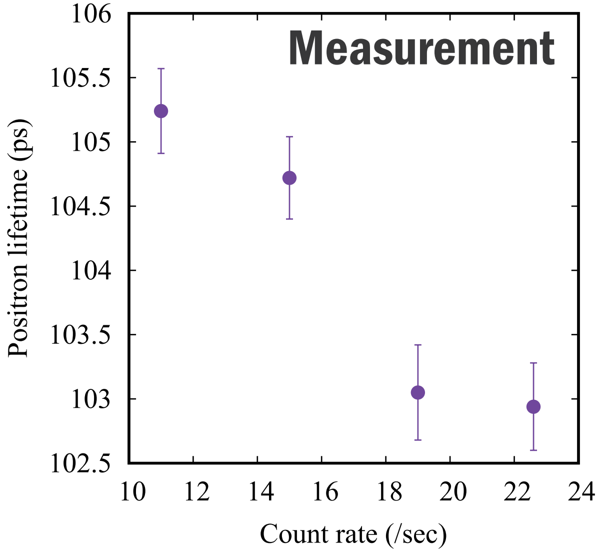
N_{pp} : the number of events in which pair production occurred in the sample and energy loss occurs in both opposing detectors.

N_{evt} : the number of events for which the lifetime spectrum is calculated.

N_{pp}/N_{evt} is less than 1 for the following reasons: coincidence between pair production and Compton scattering, and different Compton scattering.

Results of pure iron (size: 15×6×15 mm)

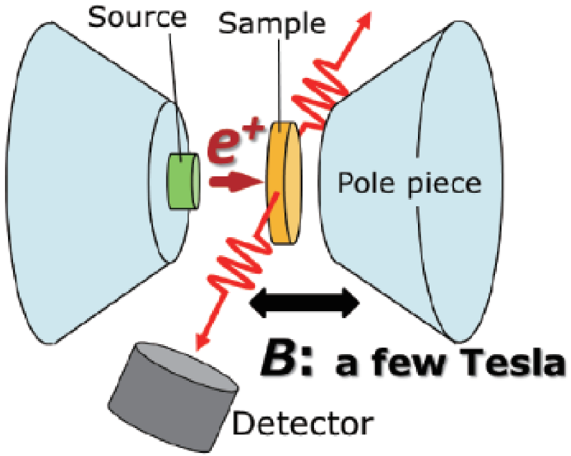




Generation of spin polarized positrons

Methods using radioisotopes

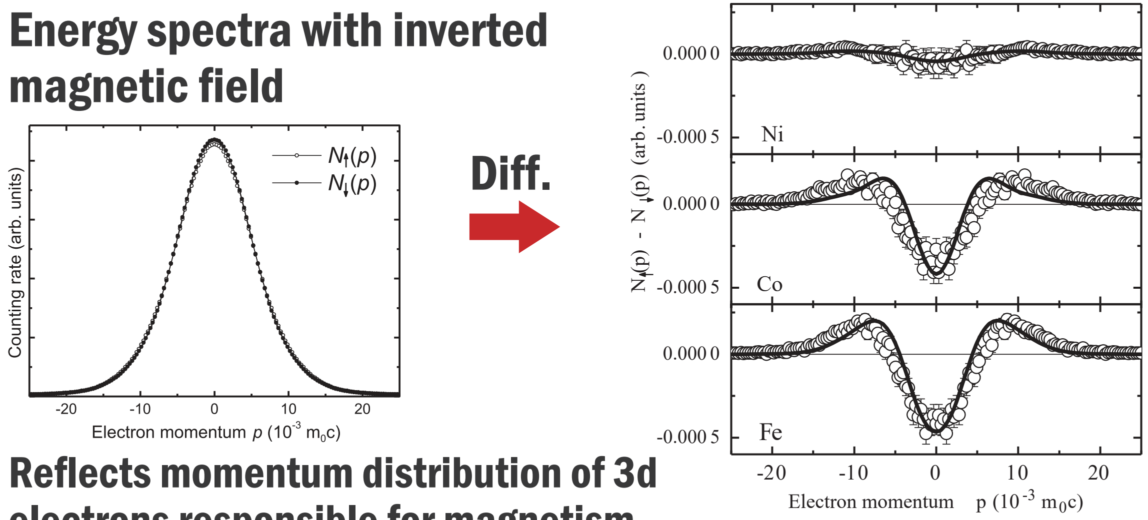
A. Kawasuso, PRB 83 (2011) 100406.



P_{e+} ~70%

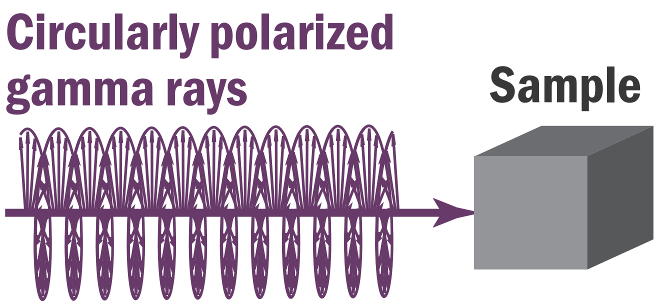
Samples:
ferromagnetic materials, vacancy-origin magnetic materials, etc.

Energy spectra with inverted magnetic field



Reflects momentum distribution of 3d electrons responsible for magnetism.

Method of generating spin-polarized positrons in UVSOR



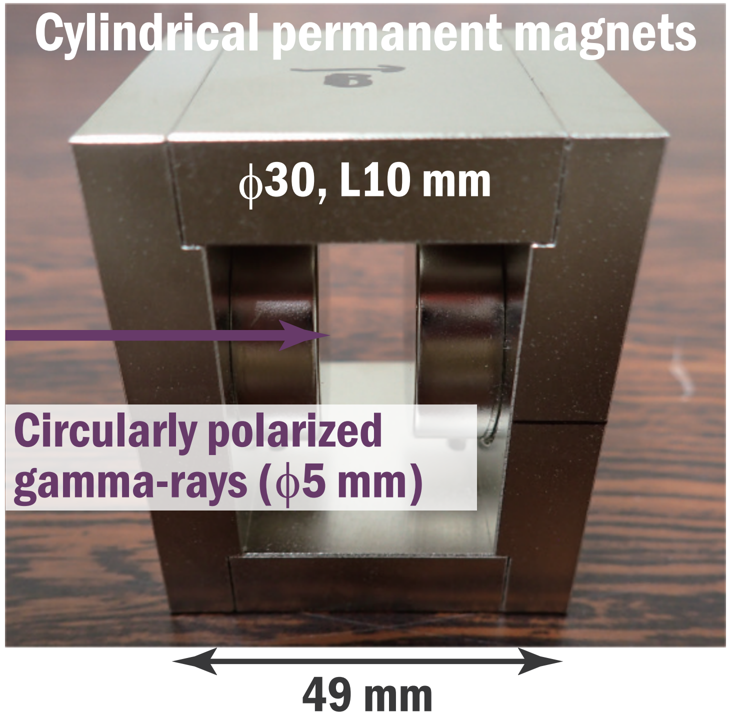
The positron spin direction can be changed by the helicity of the laser.

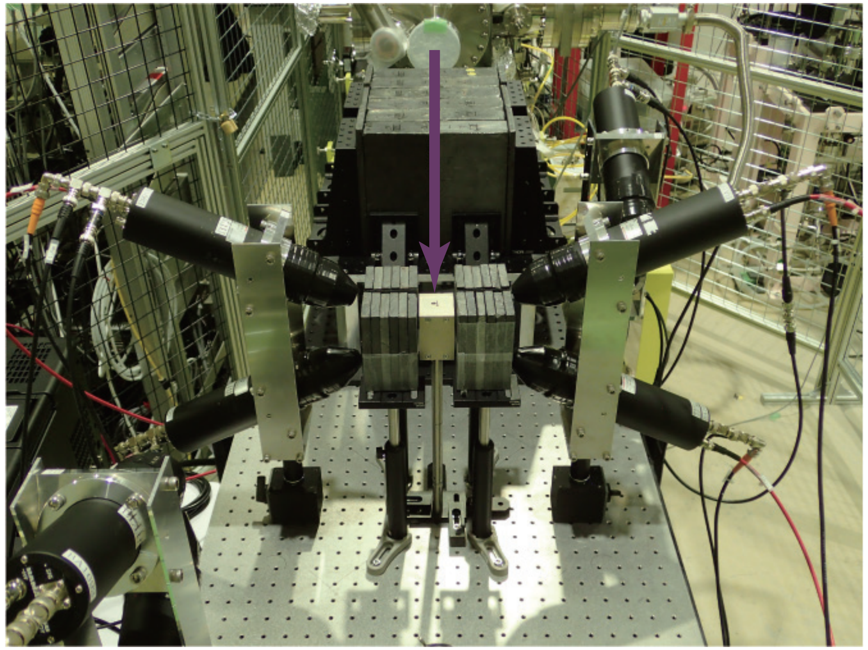
The positron lifetime, like the energy spectrum, is also asymmetric due to the orientation of the electron spin.

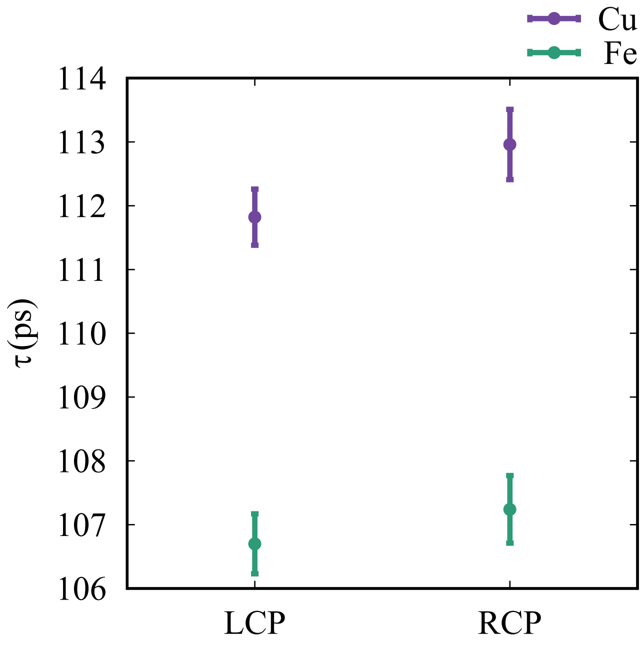
	Majority spin	Minority spin	Diff.
Fe	95.2 ps	107.0 ps	11.8 ps
Co	94.5 ps	98.2 ps	3.7 ps
Ni	101.1 ps	96.8 ps	-4.3 ps

J. Lin et al., JJAP 53 (2014) 053002.

Positron annihilation lifetime measurement







Samples: Pure Cu and Fe
Size: ϕ5 mm, L10 mm

It has been measured that the positron lifetime varies with the element.

No distinct difference in positron lifetime was measured due to the helicity inversion of circularly polarized gamma rays.

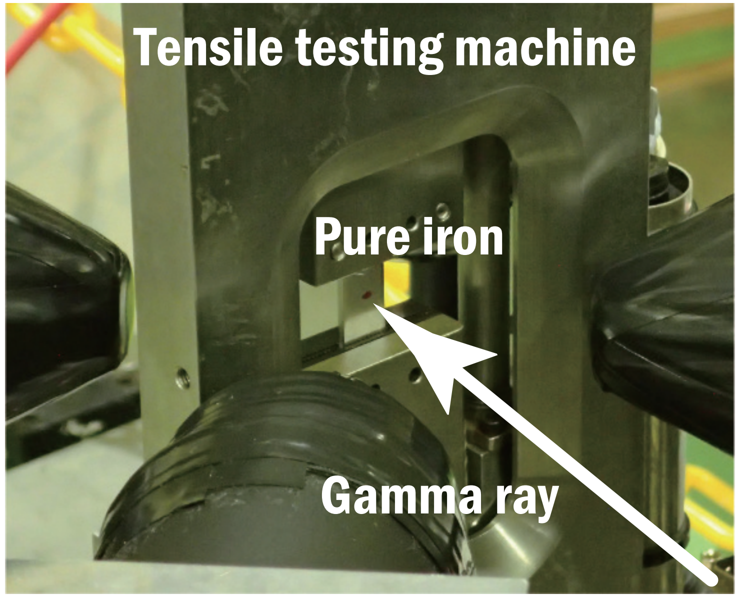
User applications of GiPALS

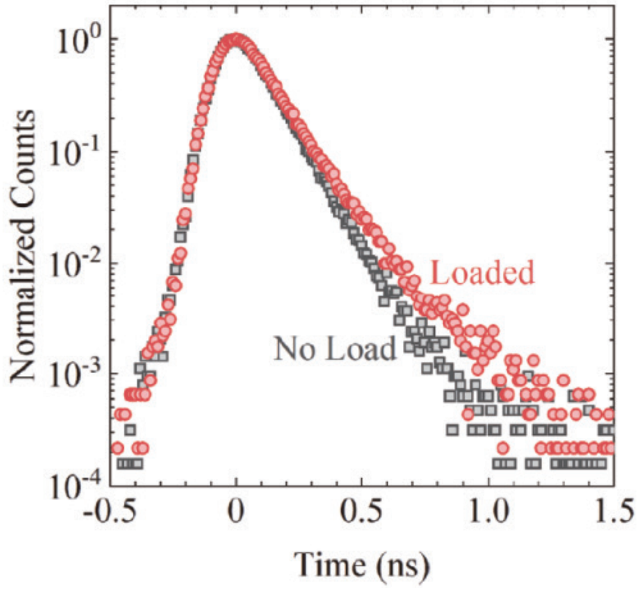
Samples: Scintillators, thermoelectric materials, catalysts, metals, etc.

Sample environment: atmosphere, stress loading, high temperature, gas atmosphere, laser irradiation, immersion (hydrogenation)

In addition to measurements of bulk samples in atmosphere, measurements of samples under special environments that are difficult to measure with conventional methods are also performed.

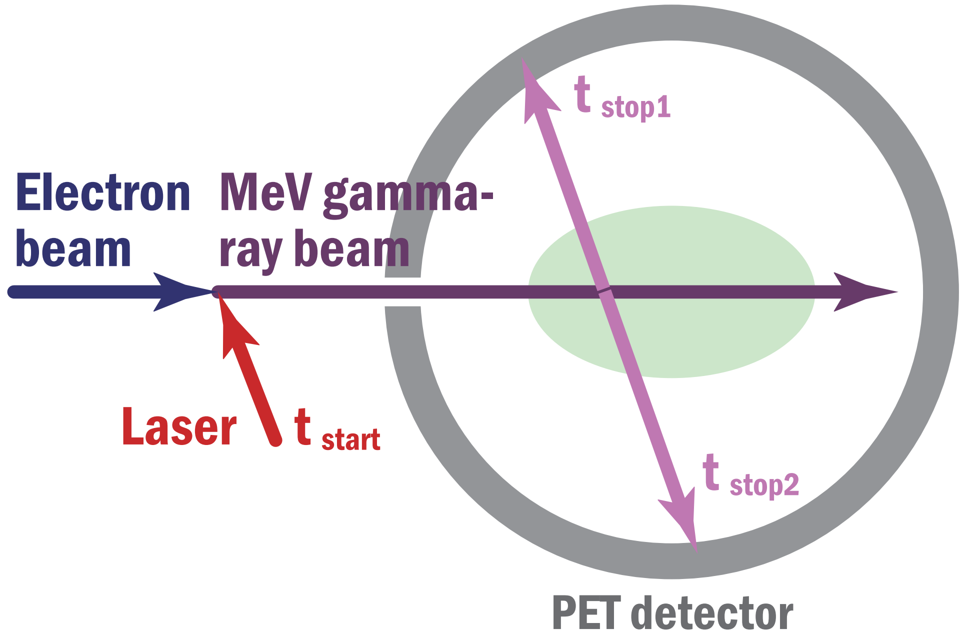
In-situ measurement of defects formed during stress loading

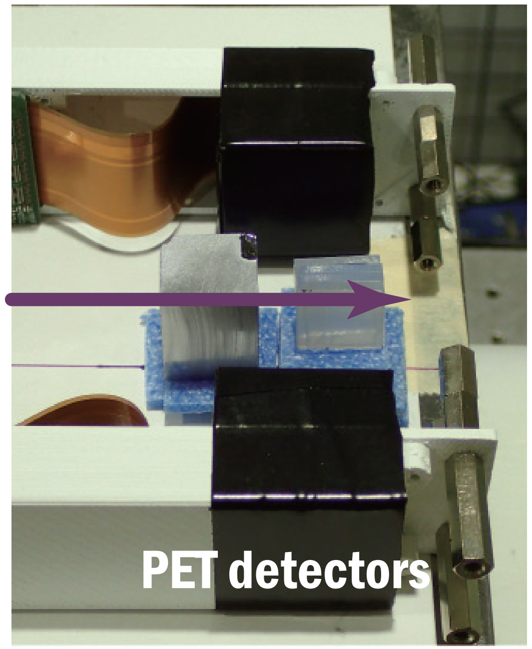




A. Yabuuchi et al., UVSOR acitivity report 2021.

Positron lifetime imaging using a PET detector





Feasibility study was started by Dr. Takyu at QST.

The positron lifetime distribution is imaged by identifying the location of gamma ray annihilation using a PET detector.

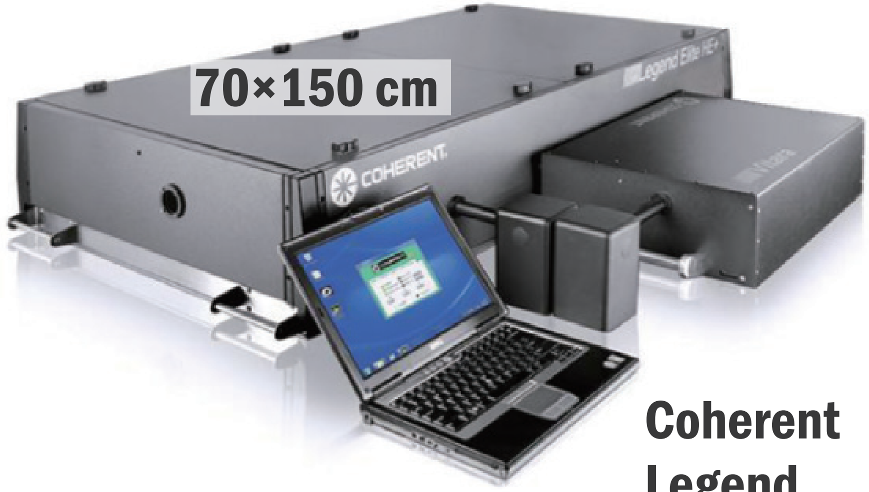
This can be achieved simply by inputting a laser start signal to an existing PET.
Improvements in the time resolution of TOF-PET have made it possible to measure lifetime using a PET detector.

This can be applied to measuring the distribution of defects in metal and the oxygen partial pressure of tumors.

Improvement of gamma-ray average power

Present

2.5 W, 2.5 mJ, 1 kHz, 800 nm, 0.13~1.8 ps



Coherent
Legend

Laser equipment renewal

20 W, 0.2 mJ, 100 kHz, 1030 nm, 0.29 ps

Gamma-ray average power 10 times

Light conversion
Pharos
$200k

Use of UVSOR gamma rays and positron spectroscopy

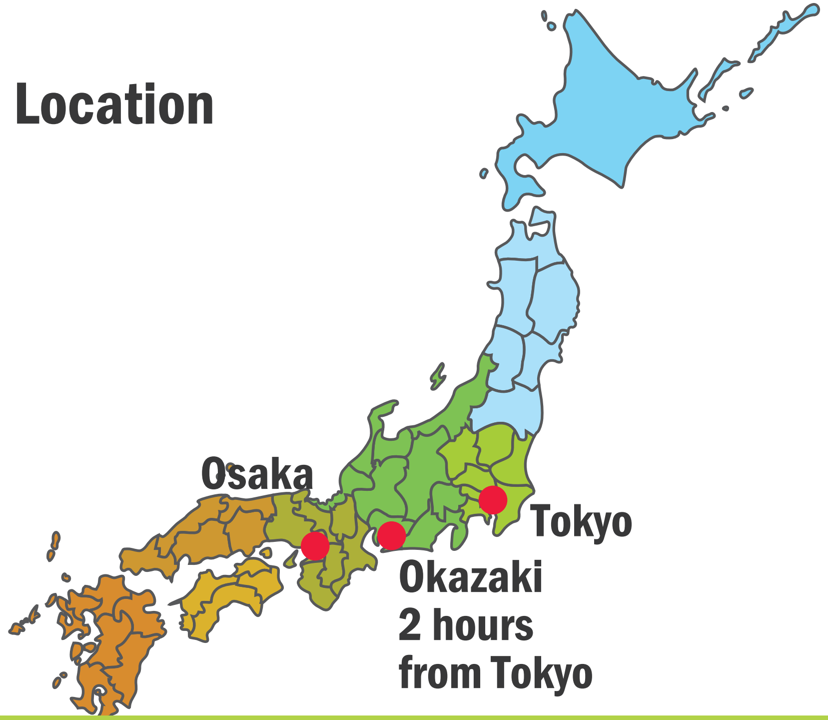
Operation time

60 hours/week
38 weeks/year (2280 hours)

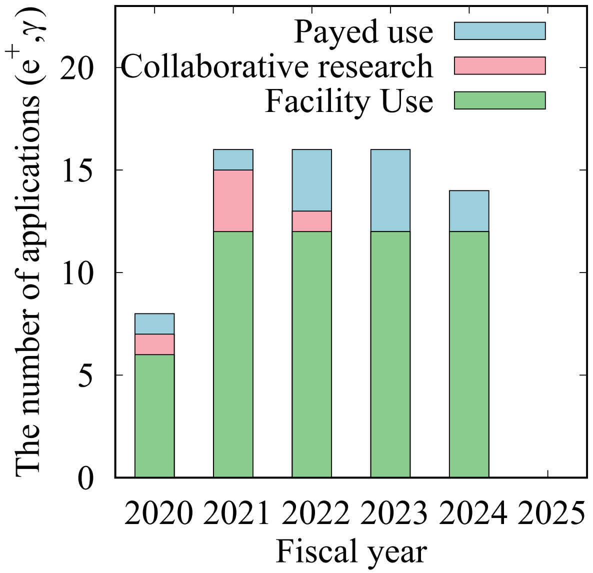
Charge

free for academic users

Location



Number of applications



Nuclear physics experiment

Evaluation of detectors
using polarized gamma rays

GiPALS

Contanct

If you are interested in the gamma-ray beamline, please contact me at yostaira@ims.ac.jp or speak to me directly.

Summary

- **Gamma-ray induced positron annihilation spectroscopy is developed at UVSOR BL1U using the ultra-short pulsed gamma rays.**

  Positron lifetime spectra with low background and without source components can be measured.

  User applications, including in-situ measurements, are currently ongoing.

- **We are also developing measurement techniques for polarized gamma rays.**

  Ref.: PRA 107 (2023) 063503, PRA 110 (2024) 043525, PRR 7 (2025) 033130.

Acknowledgement

We would like to thank K. Shimizu, J. Yamazaki, K. Hayashi, and UVSOR staffs.
This work is supported by JSPS KAKENHI Grant Number 21H03740.
The lifetime spectra were analyzed using LT9 developed by Prof. Kansy.

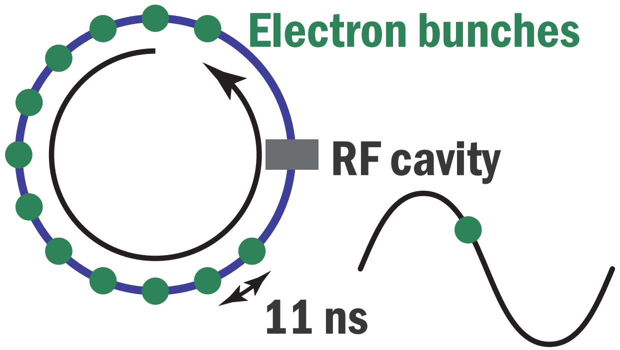
Thank you for your attention!

RF bucket height

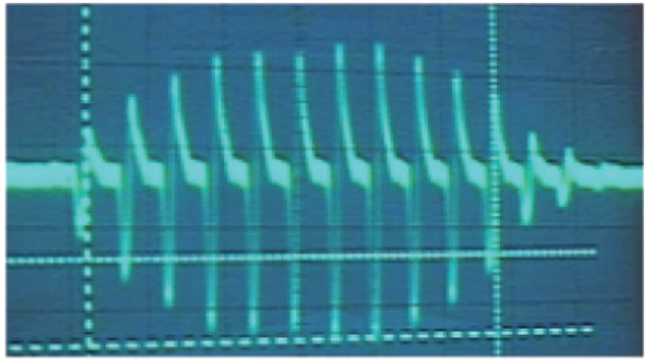
Electron beams circulating the electron storage ring generate synchrotron radiation by bending magnets and lose their energy.

The lost energy is compensated for by the radio-frequency cavity.
A stable acceleration range exists and is called the bucket height.

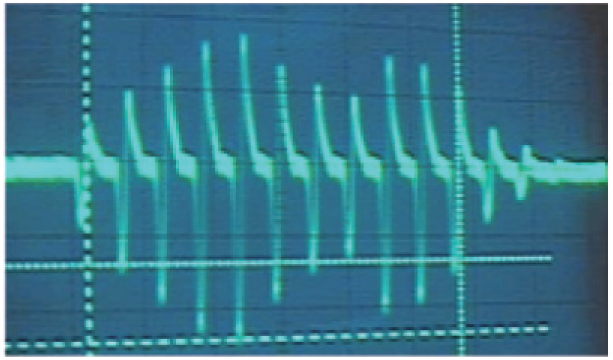
In the case of UVSOR, it is 1.2%, so if the energy loss of the electron beam is less than 9 MeV, the electron beam will circulate stably.



Filling pattern of electorn bunches



9.9 MeV gamma ray generation

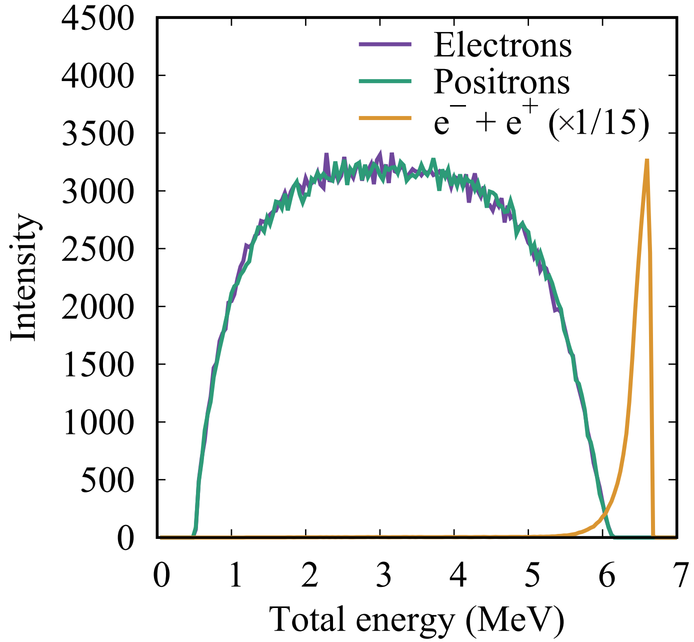


At NewSUBARU, experiments are conducted at night because gamma-ray generation and synchrotron radiation use cannot coexist if the gamma-ray energy exceeds the bucket height.

Simulation of positron annihilation

EGS5 simulation, without magnetic field

Inside a sample



The degree of polarization of positrons

$$P_{long} = \frac{4(T_+/E)-1}{3(T_+^2+T_-^2)/E^2+2(T_+T_-/E^2)} P_c$$

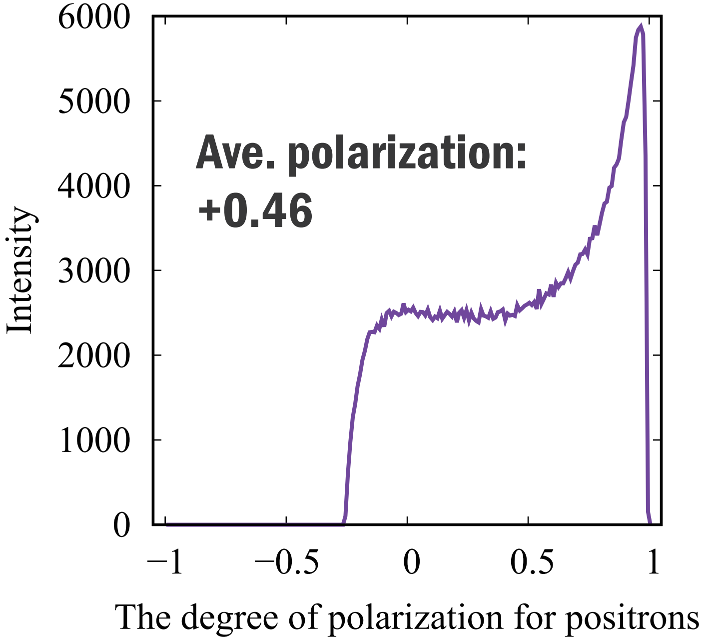
T_+: Total energy of positrons

T_-: Total energy of electrons

E: Gamma-ray energy

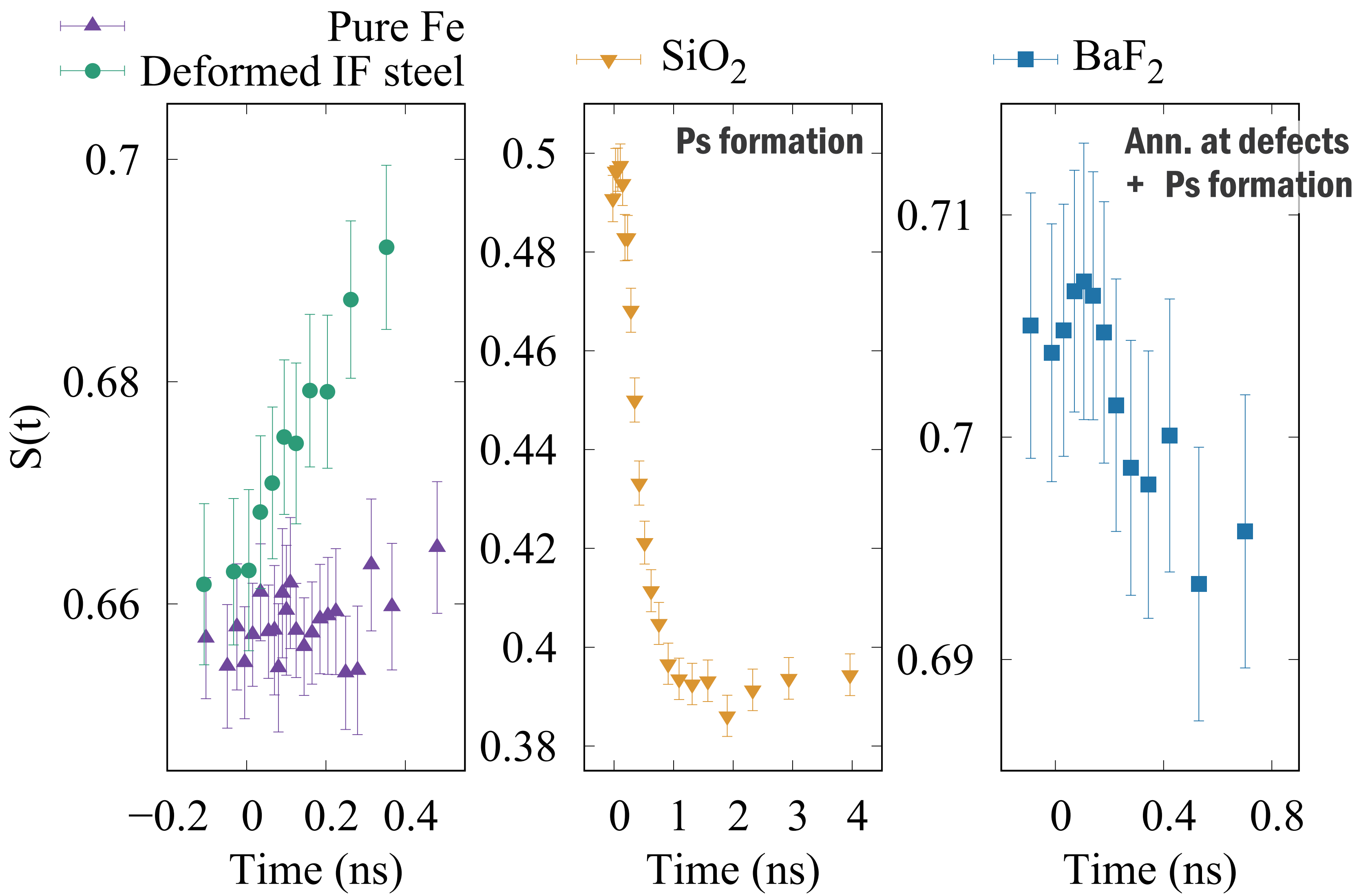
P_c: The degree of circular polarization

A. P. Potylitsin, NIMA 398 (1997) 395.



Num. of gamma rays at the generatin point: 10^8
Num. of gamma rays injecting into the sample (ϕ2 mm collimator): 4.6×10^6 ($\delta E/E = 4\%$)
Num. of positrons generated in the sample: 3.5×10^5
Num. of detected events: 1.9×10^3

GiAMOC: time evolution of S-parameter



One or two sets of detectors (BaF_2 and HPGe)

Pure iron (99.99 %)
Size: 15×6×15 mm
9.7 cps, 9.2×10^5 counts

Deformed IF steel
Size: 10×4×60 mm
4.4 cps, 2.7×10^5 counts

SiO_2
Size: 30×10×10 mm
5.8 cps, 7.4×10^5 counts

BaF_2 single crystal
Size: 15×10×10 mm
7 cps, 4.8×10^5 counts

Y. Taira et al., Rev. of Sci. Instr. 93 (2022) 113304.