Radiation tolerance of a diamond radiation detector for space use

Yoshiyuki Ando

Ryota Heibatake, Kaito Ozawa, Shutaro Ueda, Makoto Arimoto, Tatsuya Sawano, Daisuke Yonetoku, Kimiyoshi Ichikawa, Norio Tokuda, Shoya Matsuda, Satoshi Hatori [A], Kyo Kume [A], Shinko Sando [A], Satoshi Mizushima [A]

Kanazawa University, The Wakasa Wan Energy Research Center [A]

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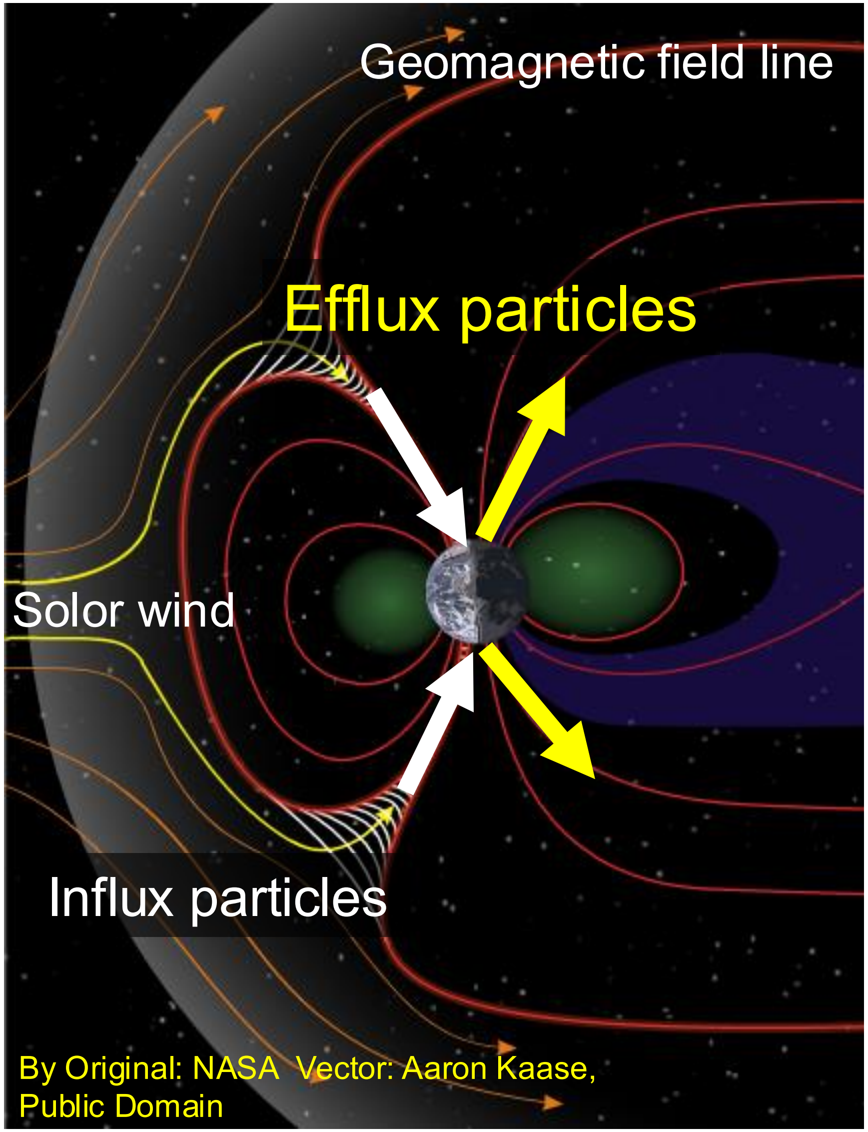
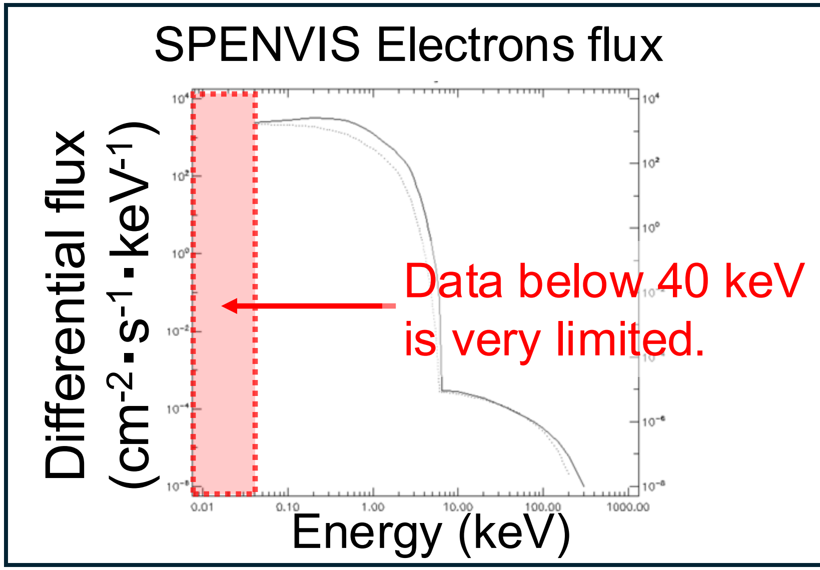
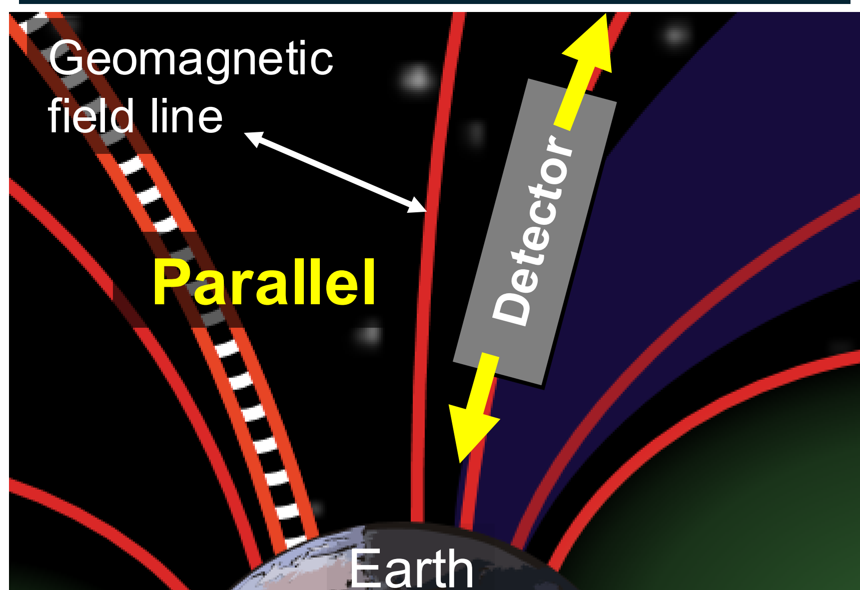
Talk plan

Scientific motivation:
To study the material cycle between Earth and space

This will clarify the material cycle and the Earth's radiation environment.







Device performance of a diamond

Diamond has great potential for various applications.

Jan Isberg et al. 2002

Physical properties	Diamond (C)	Si	CdTe
Band gap (eV)	5.5	1.1	1.4
Carrier Mobility (cm/V・s）	4500(e) 3800(h)	1900(e) 1400(h)	1100(e) 100(h)
e-h pair creation energy (eV)	13.3	3.6	4.4
Optical blocking filter	No need	Need	Need

Diamond’s wide bandgap is not sensitive to visible light.

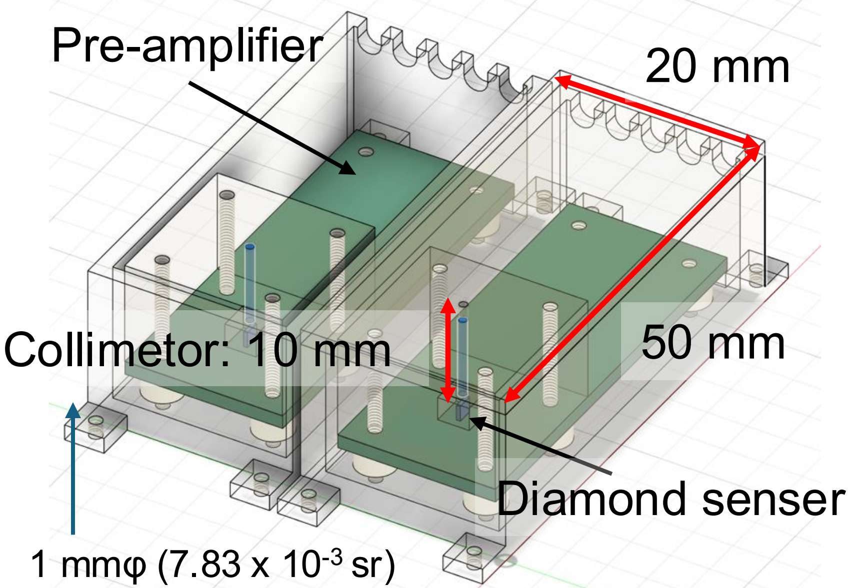
It canenable the observation of low-energy charged particles.

And we want to know the radiation tolerance of diamond in space.

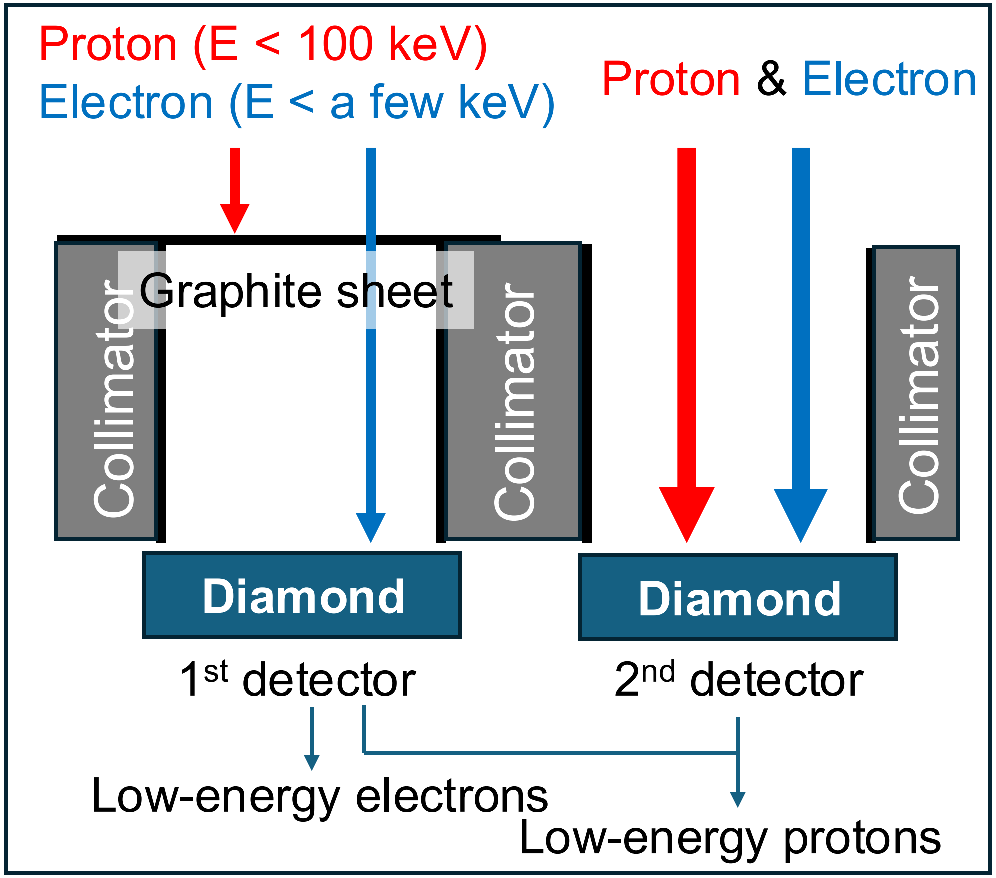
The operational method of the diamond detector onboard the CubeSat

Sun-synchronous polar orbit at 400 - 600 km altitude, Mission size :1U (10 x 10 x10 cm^3)
Mission duration: 0.5 – 1 year, 1.4 W for mission system

Pre-amplifier & diamond detector



1 mmφ (7.83 x 10^{-3} sr)
→ 1 kHz event rate in auroral zone



Diamond senser is shielded by 11mm of Aluminum (Al).

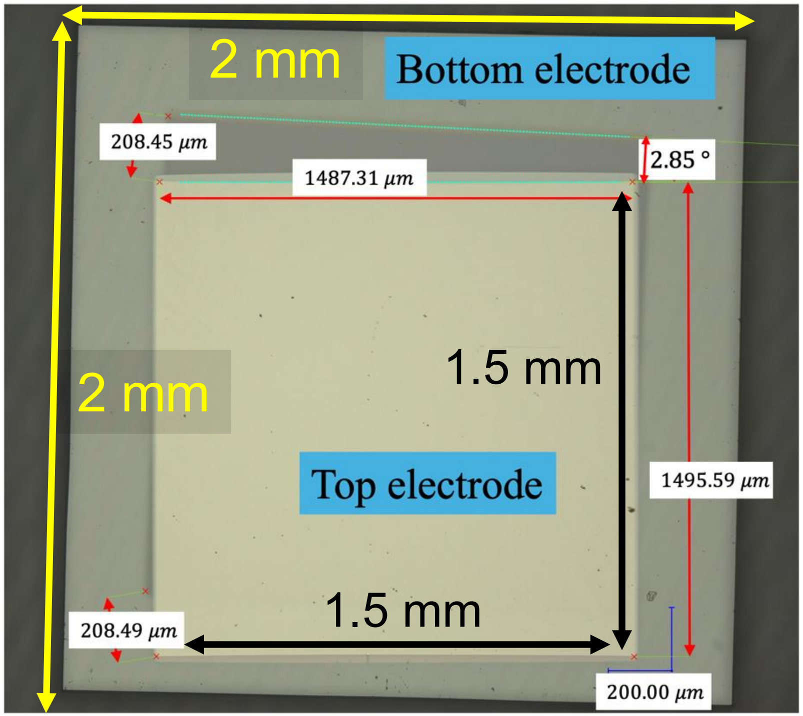
100 MeV protons are the dominant.

The proton (100 MeV) irradiation dose was calculated with SPENVIS and PSTAR (a stopping power calculation tool).

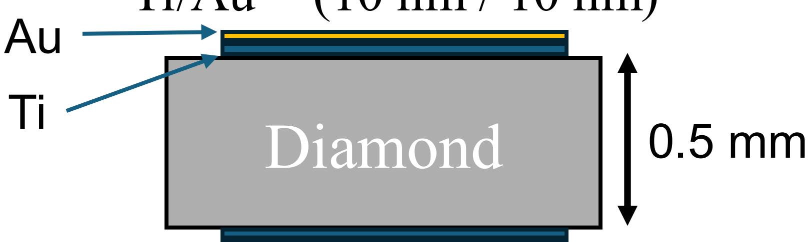
Two types of diamond senser

Element Six diamond

- Commercial product
- High-quality standard



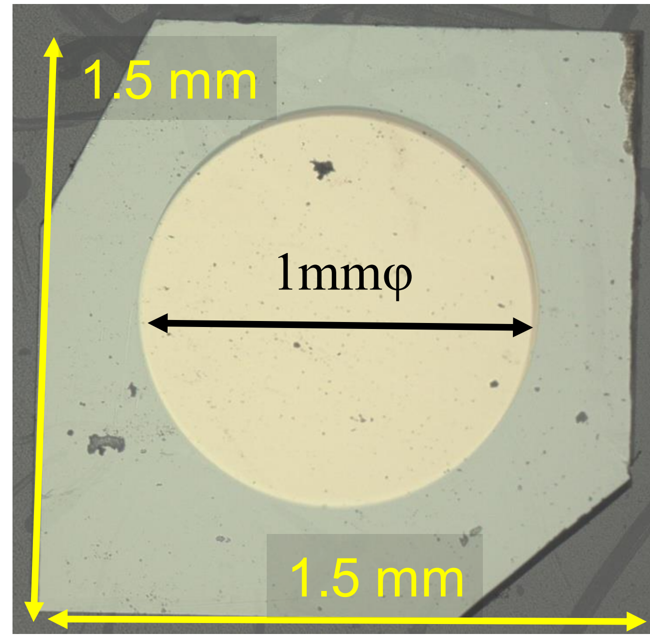
Ti/Au = (10 nm / 10 nm)



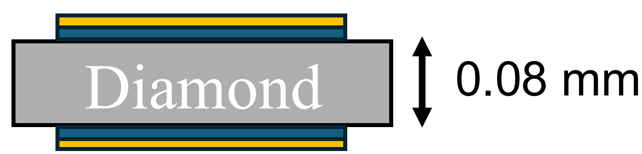
Ti/Au = (10 nm / 10 nm)

Kanazawa University diamond

- In-house fabrication
- High customizability
- Readily available



Ti/Au = (1mmφ, 10 nm / 10 nm)

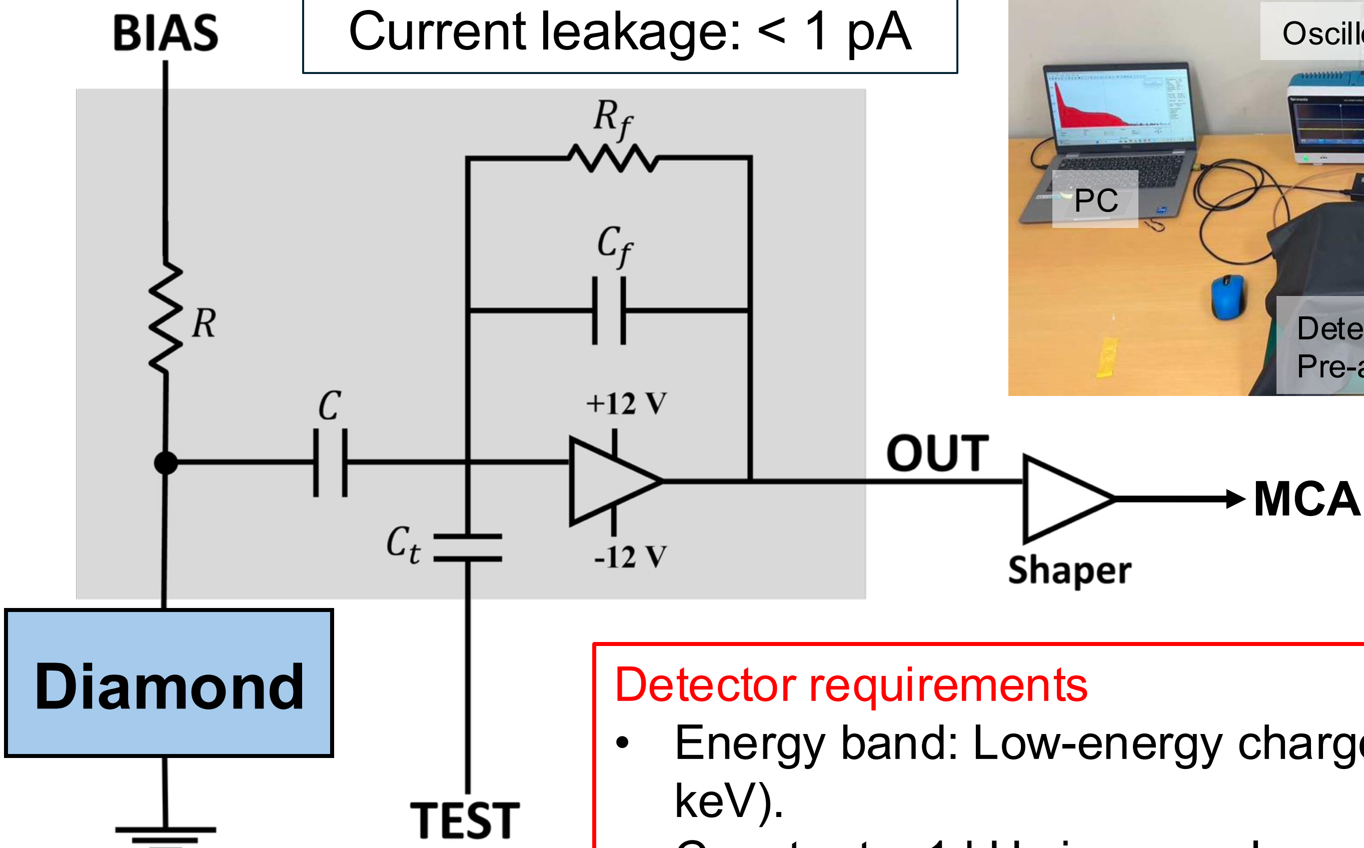


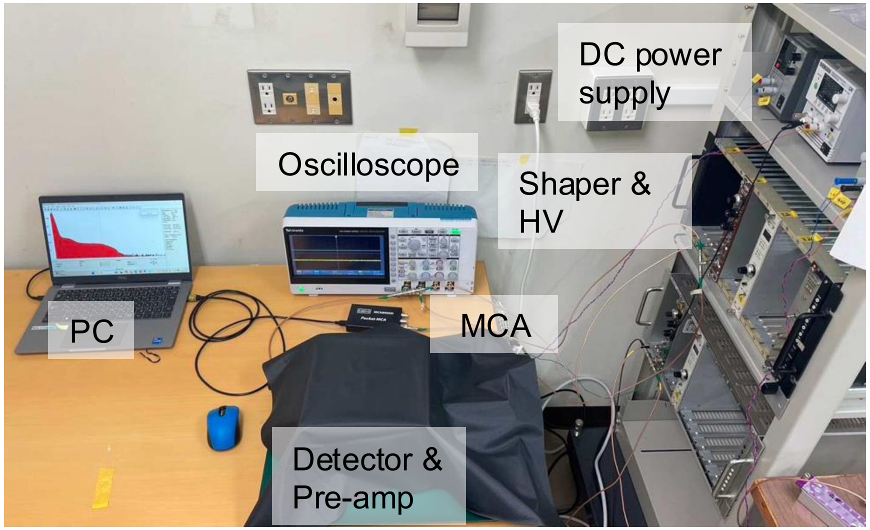
Ti/Au = (1mmφ, 10 nm / 10 nm)

Diamond detector for CubeSat applications

Basic configuration of the diamond detector under development

Gain: ~ − 2 V/pC
Feedback: 5 GΩ, 0.5 pF
Current leakage: < 1 pA

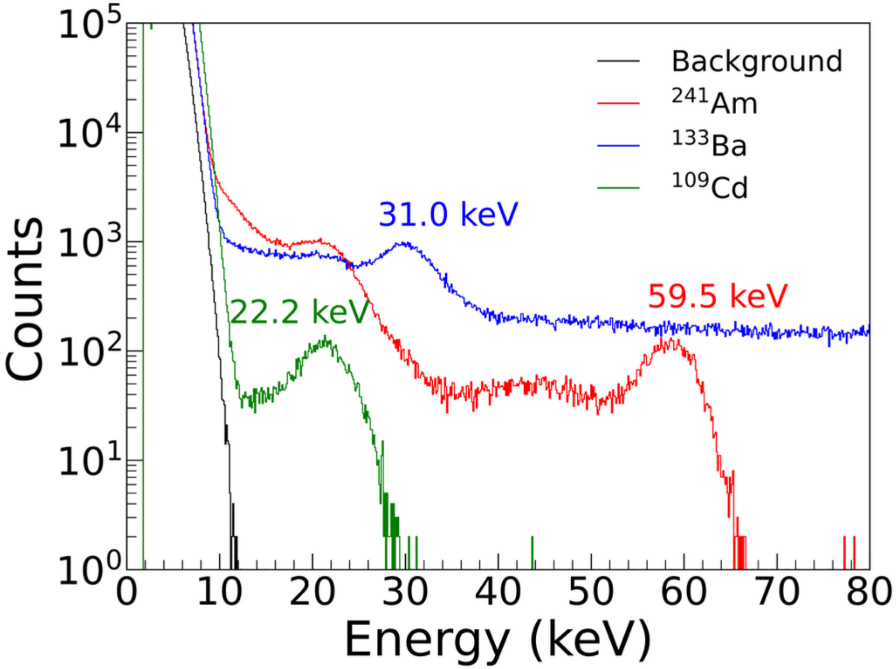




Detector requirements
- Energy band: Low-energy charged particles (E < 100 keV).
- Count rate: 1 kHz in auroral zone.
- Radiation tolerance: high for space use

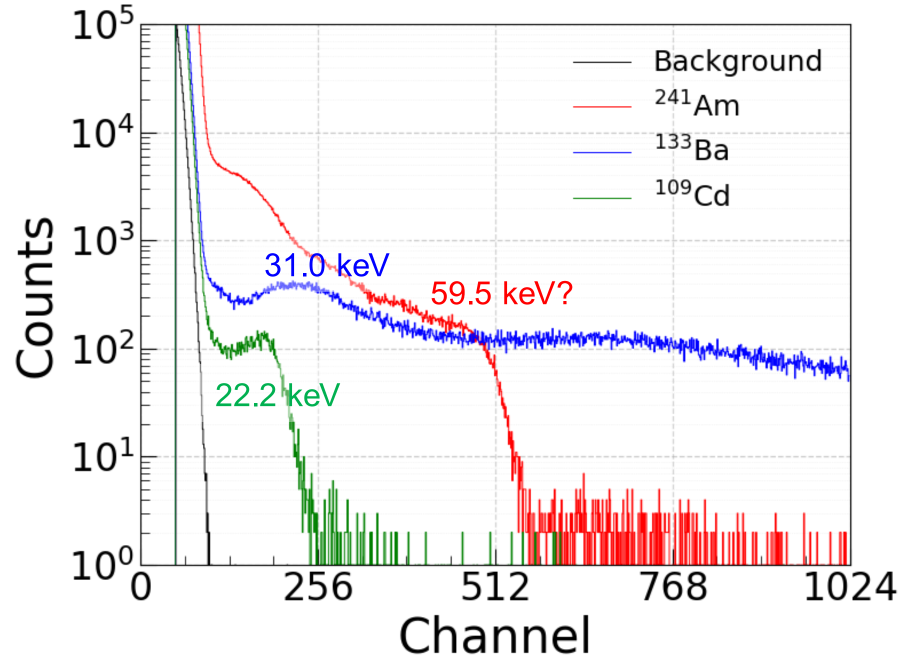
Spectrodcopic performance measurement of the diamond detecor

Element Six diamond



This diamond detects down to about 10 keV.

Kanazawa University diamond



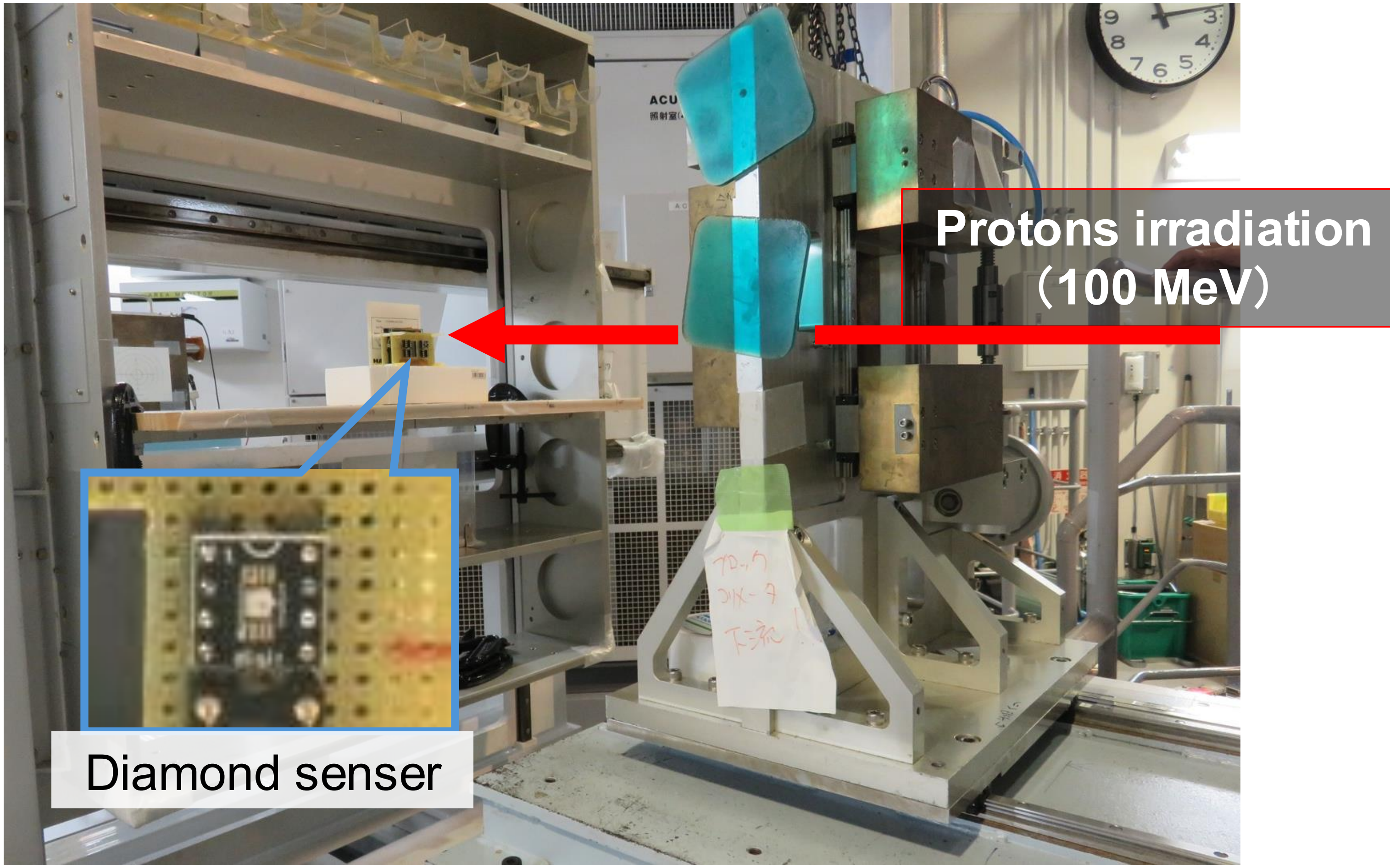
This diamond can detect 22.2 keV and 31.0 keV peaks.

Radioisotope	FWHM (keV)
^{241}Am	1.54 $(+0.39/-0.37)$
^{133}Ba	4.98 $(+0.14/-0.13)$
^{109}Cd	2.55 $(+0.24/-0.22)$

They can detect low-energy charged particles (a few keV).

Peaks detected using radioisotope (^{241}Am, ^{133}Ba, and ^{109}Cd).
Linearity (channel-energy relationship) and energy resolution (FWHM) derived from the acquired spectra.

Radiation irradiation dose setup



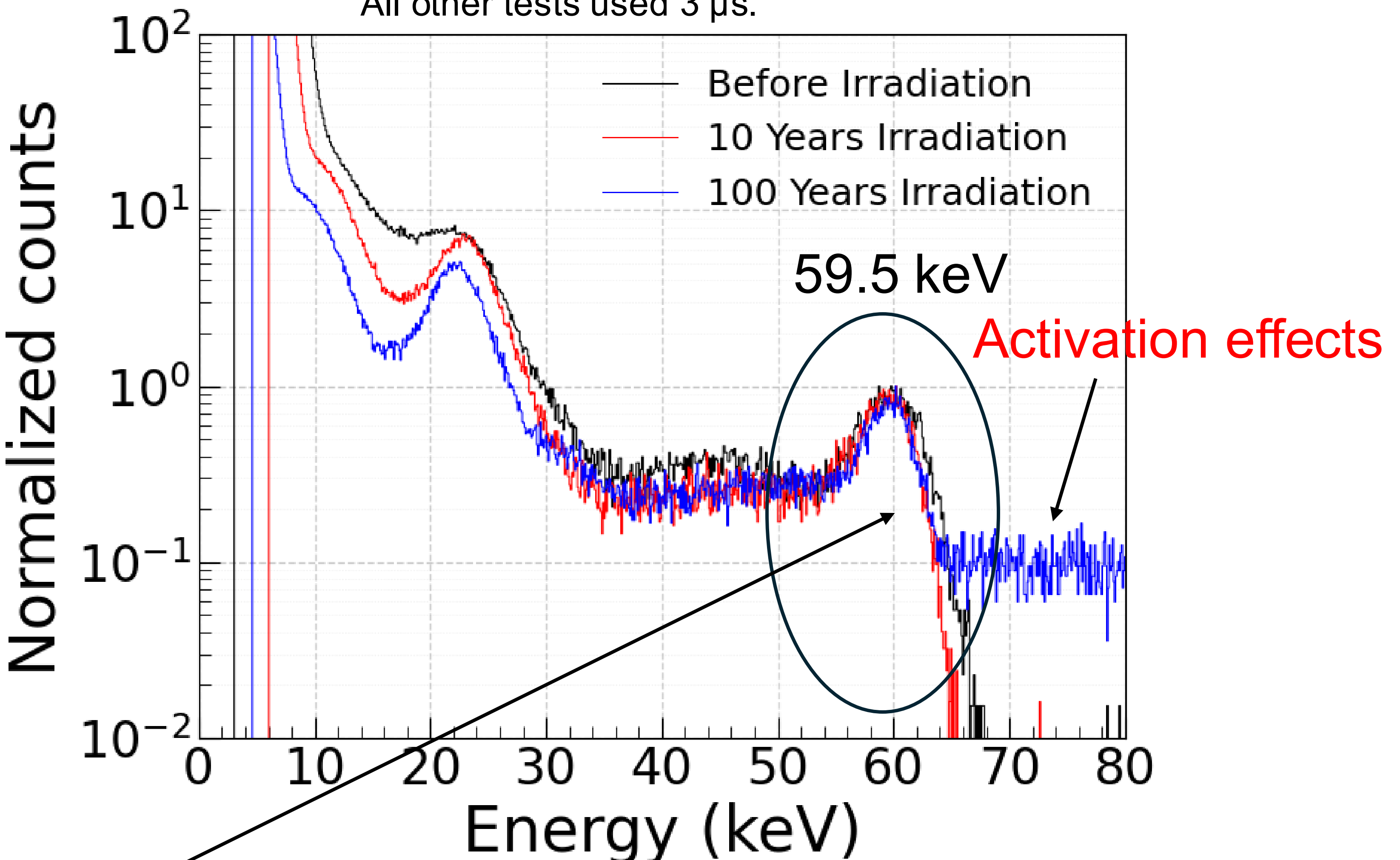
Proton irradiation test (Max 100 years in orbit equivalent)
for radiation tolerance evaluation (calculated with SPENVIS/PSTAR).

Proton fluence: 8.89 x 10^8 protons/cm^{-2}/yr

(Sun-synchronous polar orbit at 600 km altitude)

Result: Energy spectra of Element Six

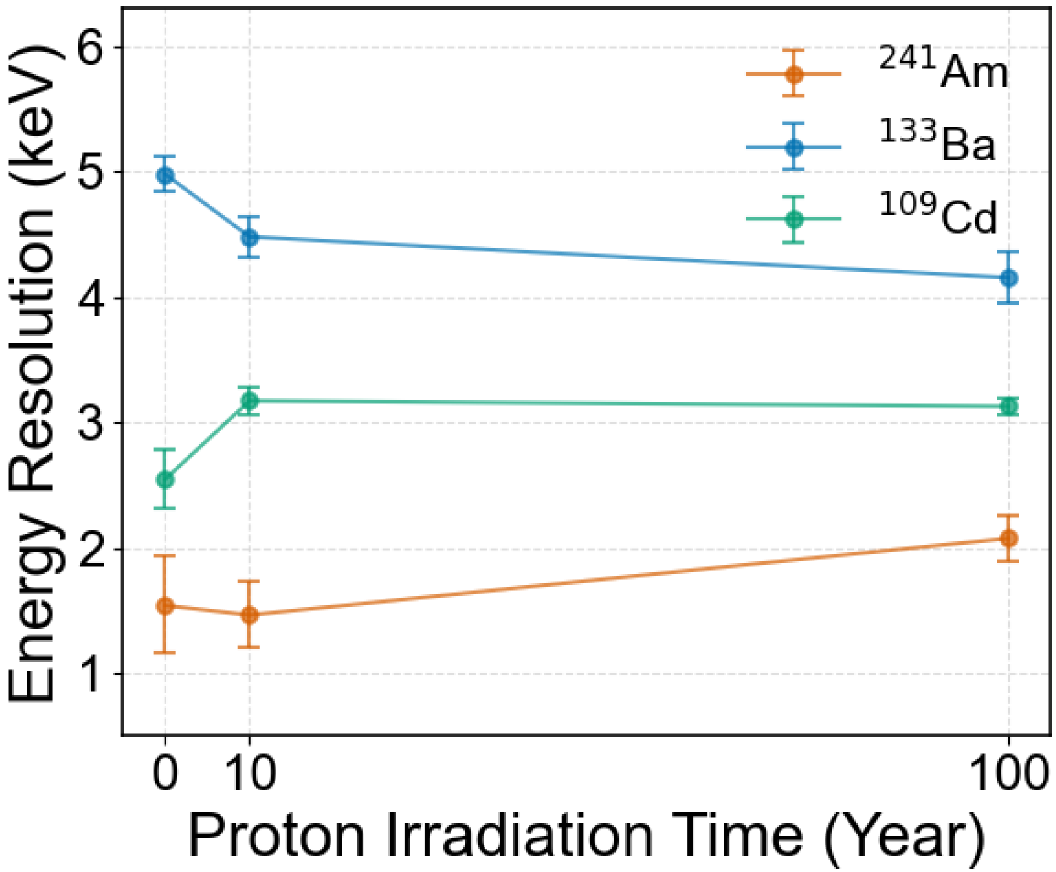
The before-irradiation data used a 1 μs time constant of shaper.
All other tests used 3 μs.



The 59.5 keV peak from each dataset overlaps, with no observable changes in energy resolution of photo peak.

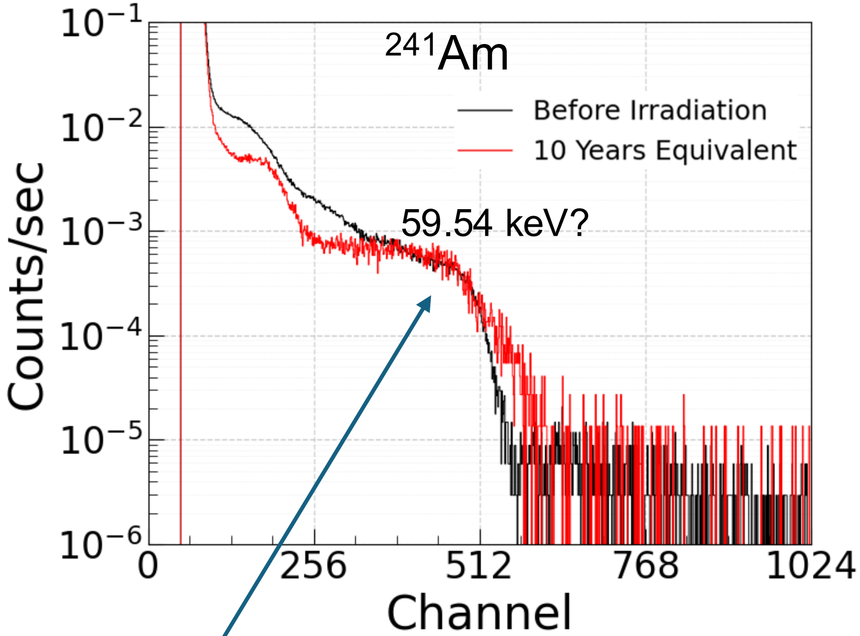
Result: Energy resolution of Element Six

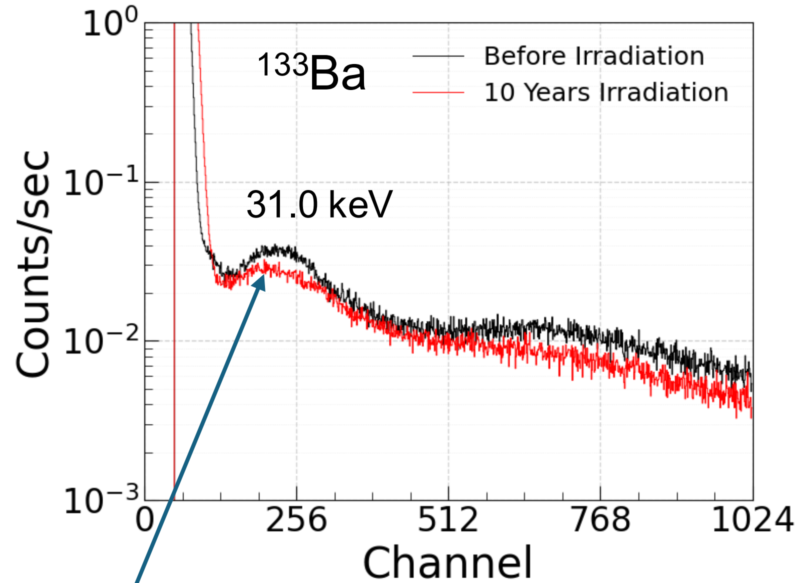
The intrinsic semiconductor deviation was calculated by removing the contribution of electronic noise from the total system sigma.

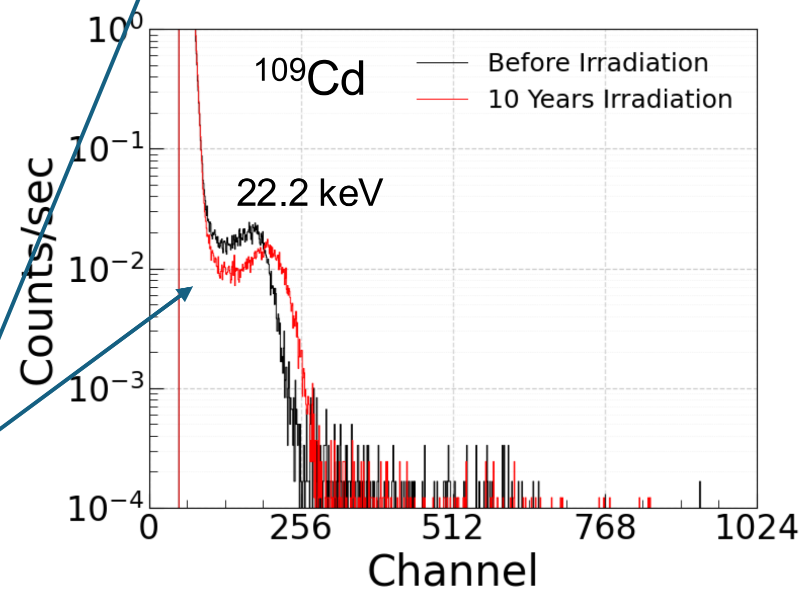


The all FWHM did not show any signs of getting worse.
Since all FWHM values are below ~ 5 keV, the detector meets the requirement for measuring low-energy particles.

Result: Energy spectra of Kanazawa Univ







Effect: Kanazawa Univ diamond surface is roughened due to the polishing process.

Even after proton irradiation, the detector still meets the requirement for measuring energies below 40 keV.

Summary and future plan

Summary

We tested radiation tolerance on two diamonds using proton irradiation.

Element Six diamond

- This diamond received up to 100 years of proton dose.
- At the 10-year dose, we saw no performance degradation.
- At the 100-year dose, performance also did not degrade.
- Even after proton irradiation, the detector still meets the requirement for measuring energies below 70 keV.

Kanazawa Univ diamond

- Even after proton irradiation, the detector still meets the requirement for measuring energies below 40 keV.
- Kanazawa Univ diamond surface is roughened due to the polishing process.

Future plan

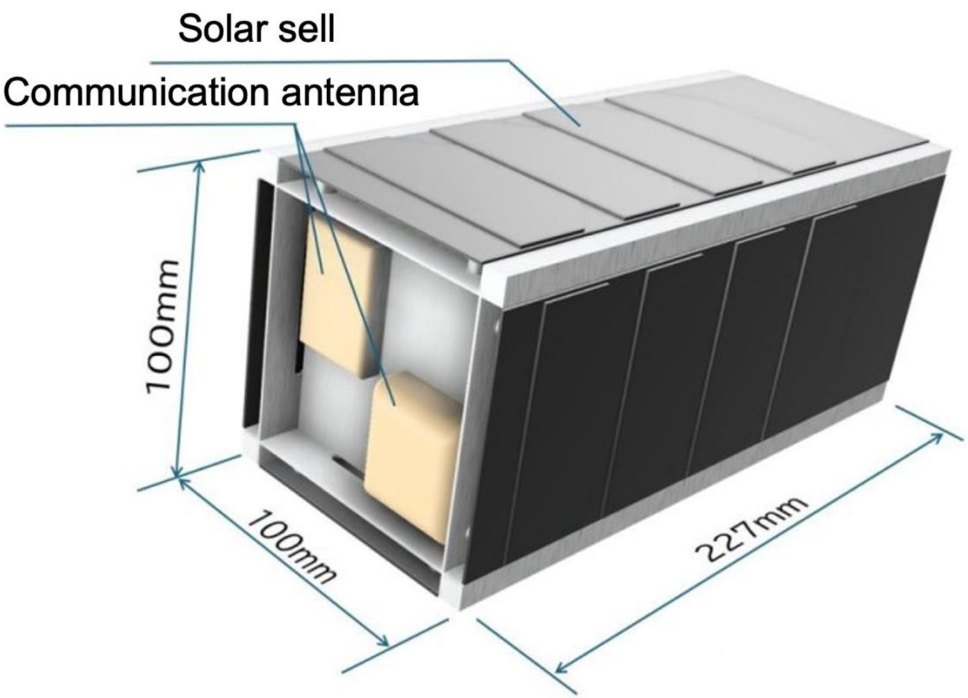
- We will evaluate Boron-doped diamonds.
- This may improve Kanazawa University diamond's low performance.
- Our diamond detectors measure charged particle.

END

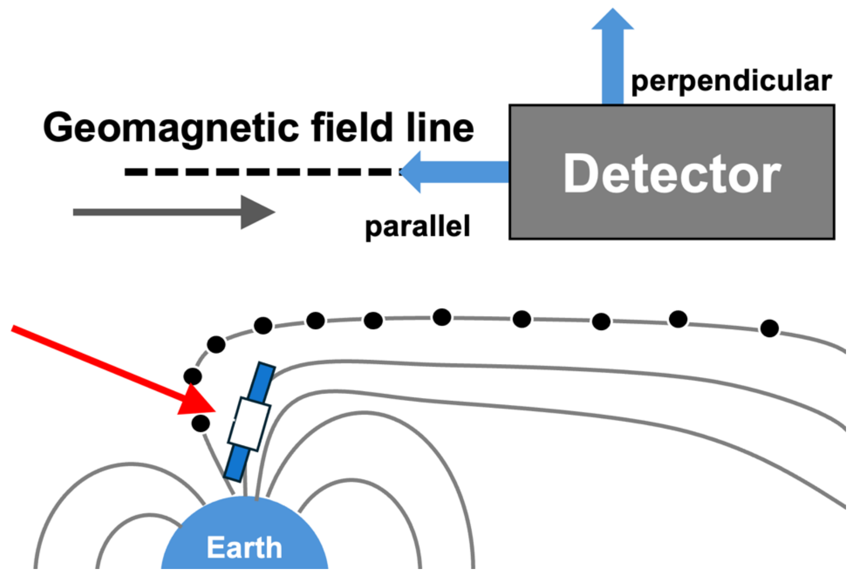
Appendix

Kanazawa Univ CubeSat mission

- Kanazawa university has a satellite project organization called ARC-SAT.
- Within this group, students are developping the nano satellite project KSAT-3X for more timely launches.
- Fore the first unit, we are developing a nano satellite equipped with a diamond detector.

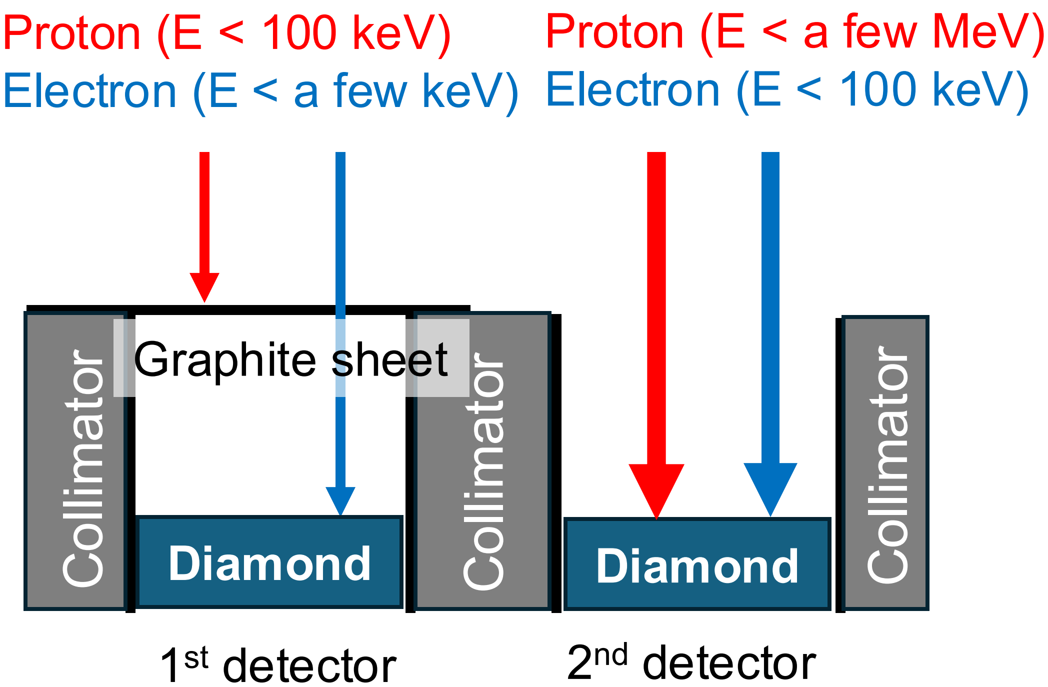


Concept design of 3U CubeSat
with a diamond detector



- We will use two diamond detector.
- We measure the flux by pointing them parallel to the geomagnetic field using attitude control.

The operational method of the diamond detector onboard the CubeSat



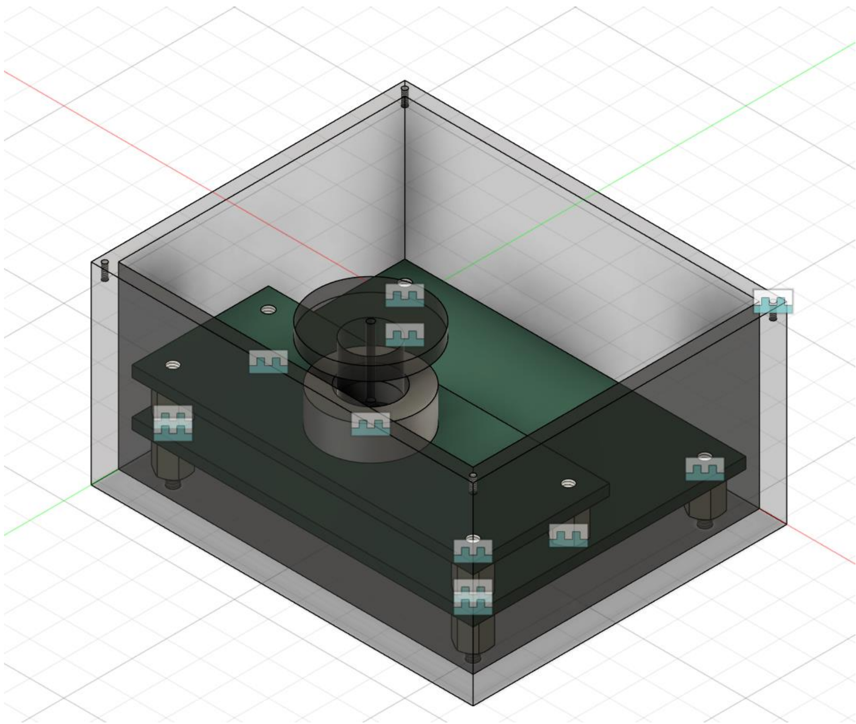
Graphite sheet

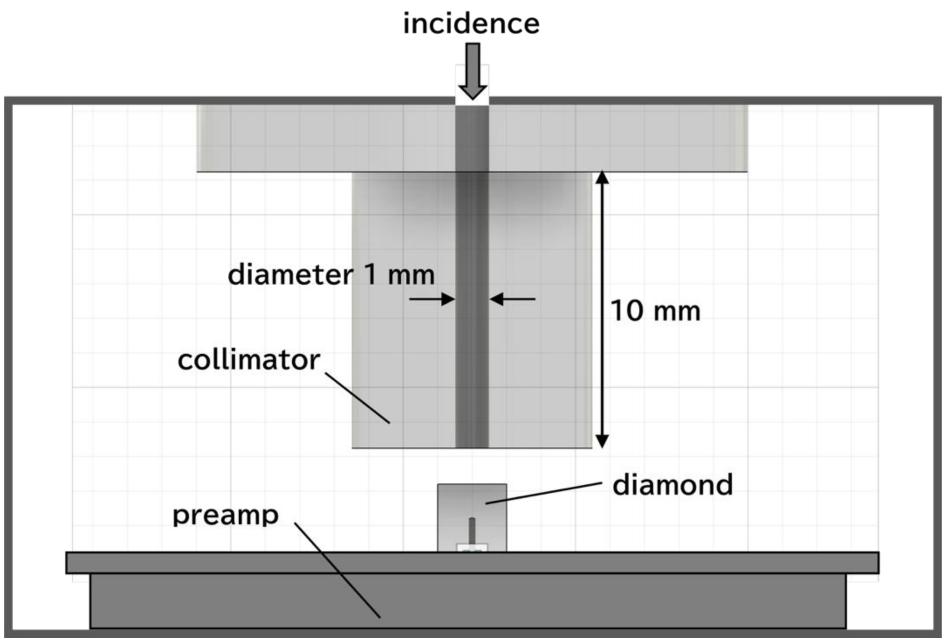
Low-energy protons are stopped by a graphite sheet.
Graphite-transmitted particles is electrons.

1. 1st detector measures only low-energy electrons (E < a few keV).
2. 2nd detector measures protons (E < a few MeV) and electrons (E < 100 keV).
3. protons (E < a few MeV) and electrons (E < 100 keV) − electrons (E < a few keV)
   = protons (E < a few MeV) and electrons (a few keV < E < 100keV)
   → Low-energy particles (a few keV) is only protons.
4. It can separate low-energy electrons and low-energy protons.

Basic Design of the Mission Module

To observe only particles incident along the Earth's magnetic field, the incident angle is restricted by a collimator.
The collimator parameters, such as thickness, are optimized while considering particle transmission.

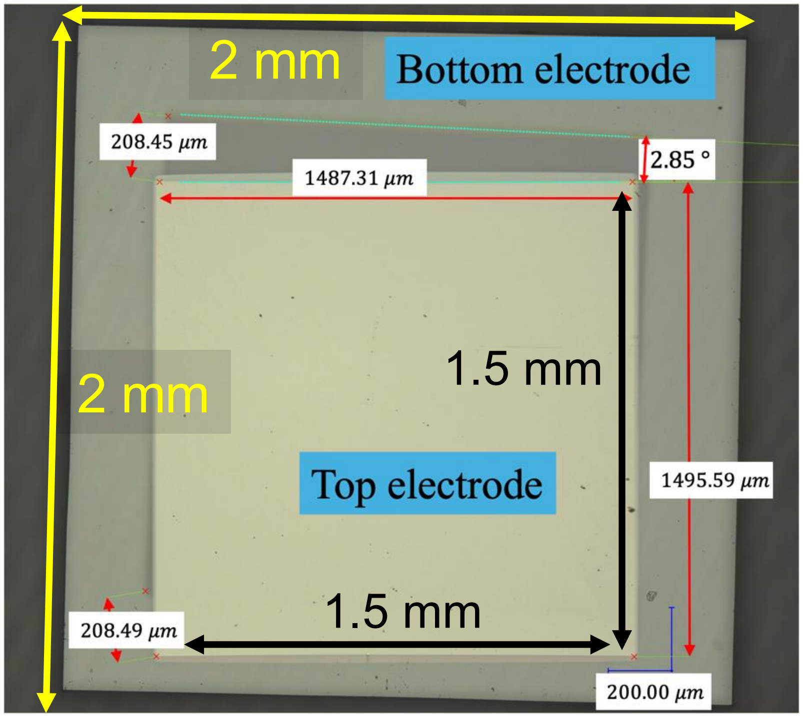


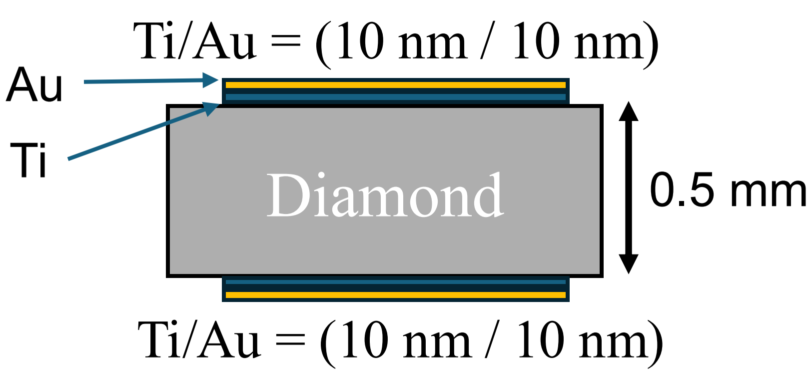


Two types of diamond senser

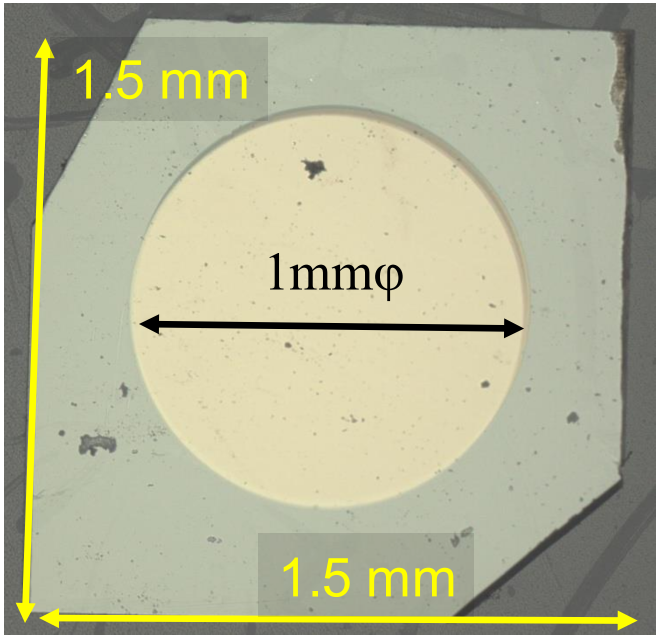
I will show you the two diamond samples we used.

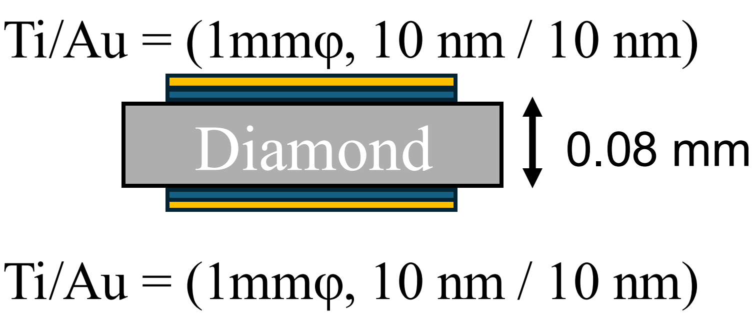
Element Six diamond





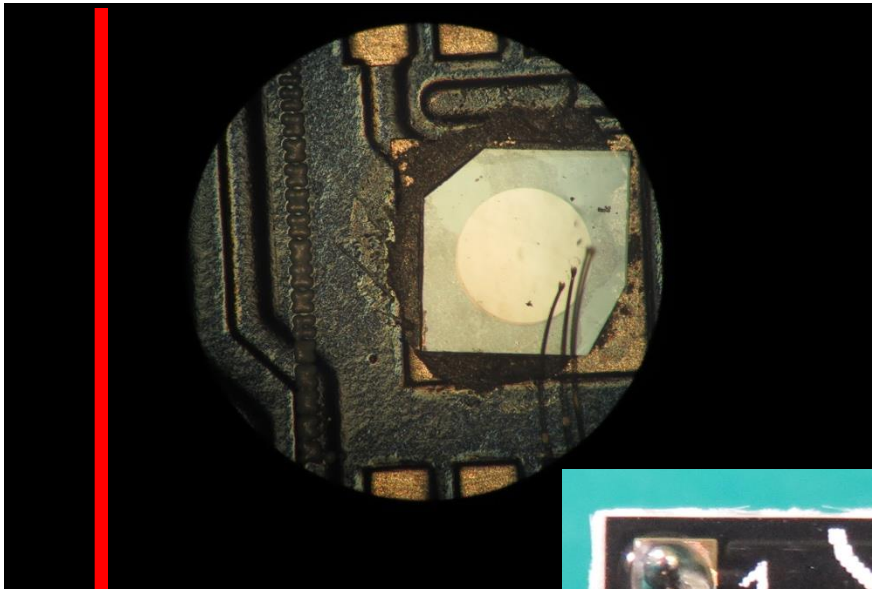
Kanazawa University diamond



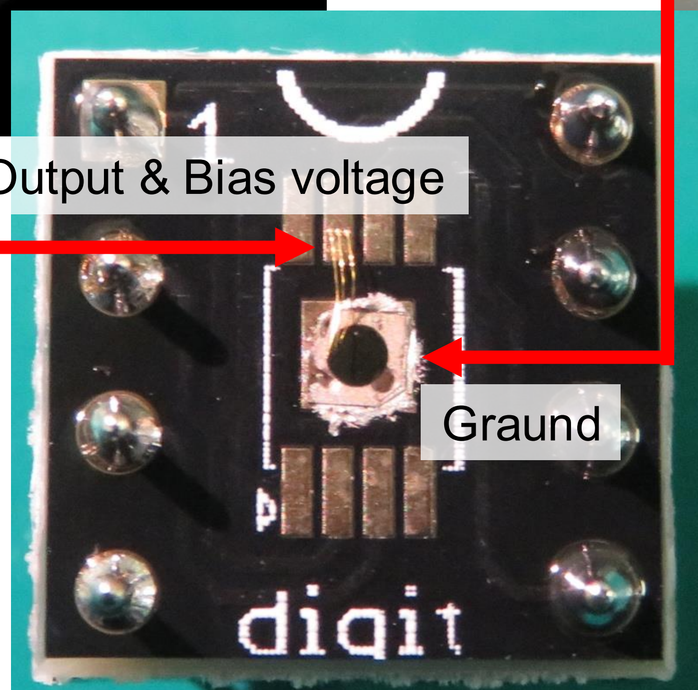


The connection to a diamond

Wire bonding (Au), Readout & Bias voltage

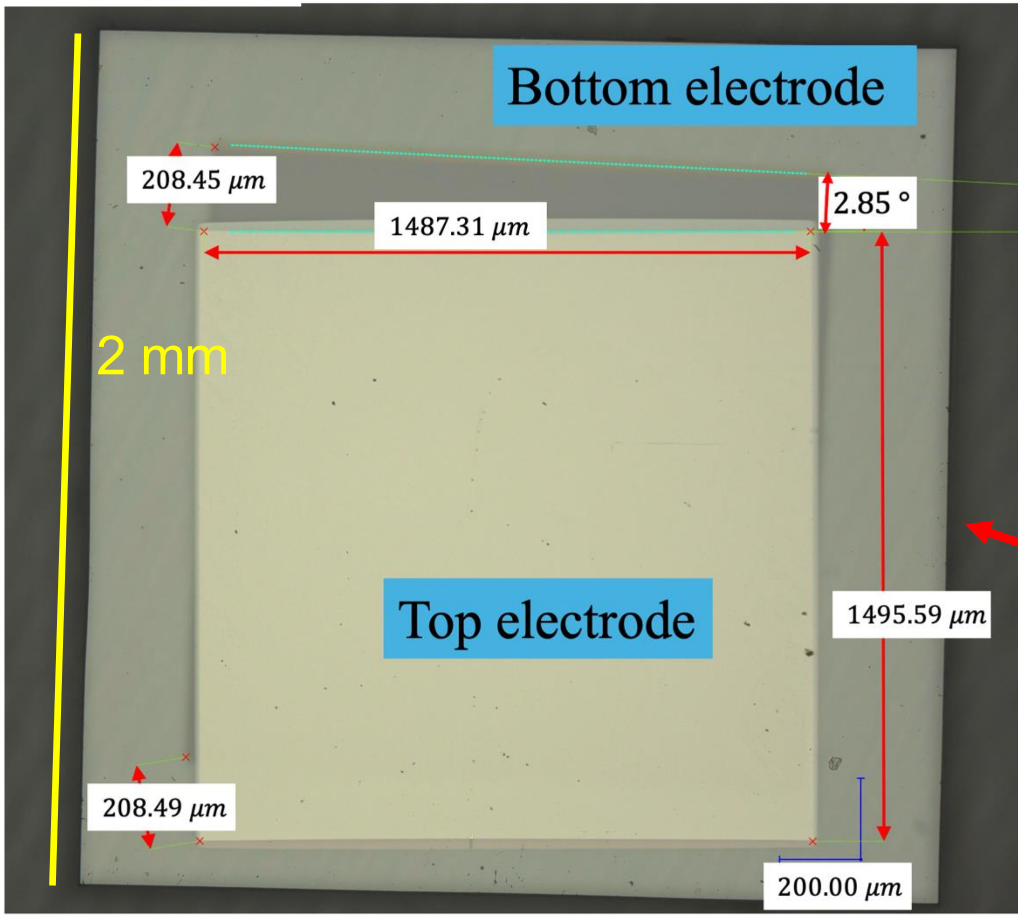


Silver paste, Ground

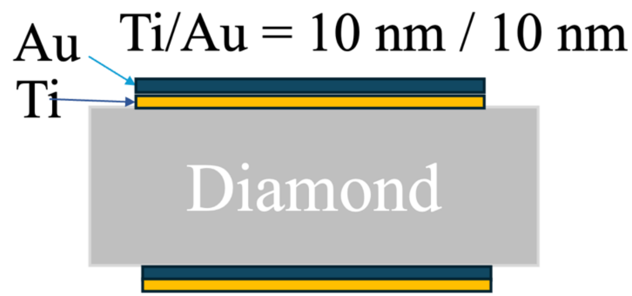


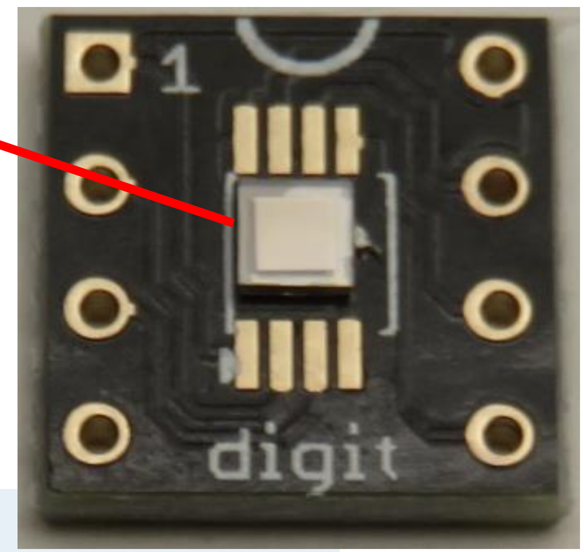
Diamond semiconductor

1. Element six



Cross-sectional structure



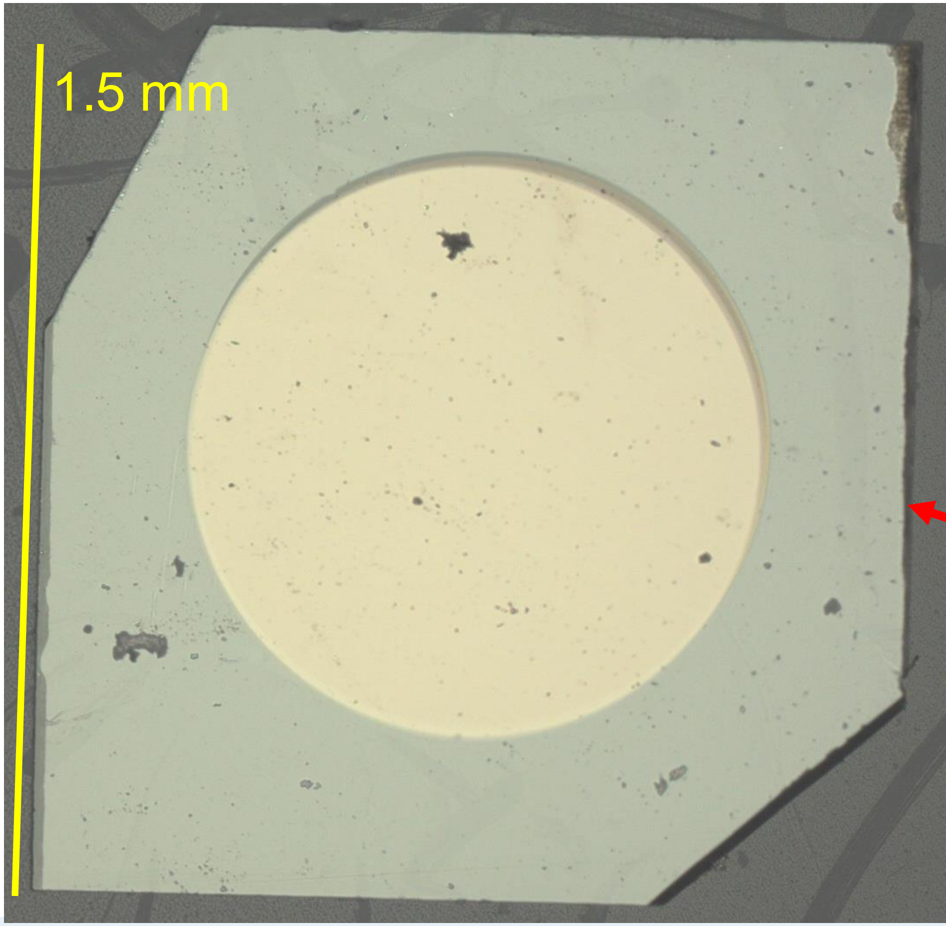


- Made in Element six
- Diamond size: 2.0 x 2.0 x 0.5 mm^3
- Electrode size: 1.5 x 1.5 mm^2
- Electrode thickness: Au (10 nm) + Ti (10 nm)

Electrostatic capacity: 0.23 pF

Diamond semiconductor

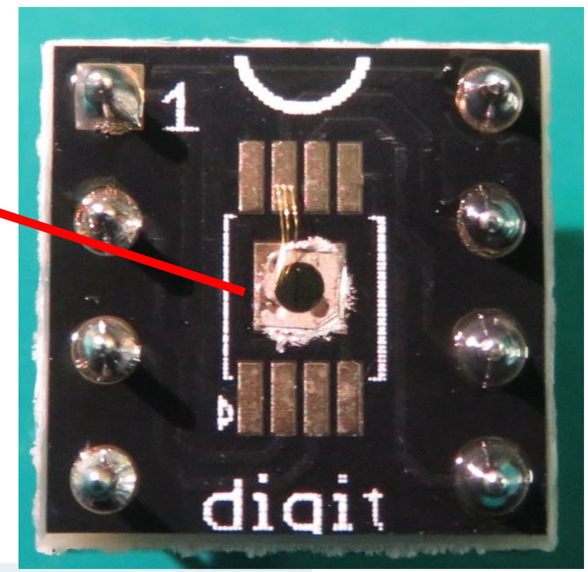
2. Kanazawa university



Cross-sectional structure

Ti/Au = (1mmφ, 10 nm / 10 nm)

Ti/Au = (1mmφ, 10 nm / 10 nm)



- Made in Kanazawa university
- Diamond size: 1.5 x 1.5 x 0.08 mm^3
- Electrode size: 1mmφ
- Electrode thickness: Au (10 nm) + Ti (10 nm)

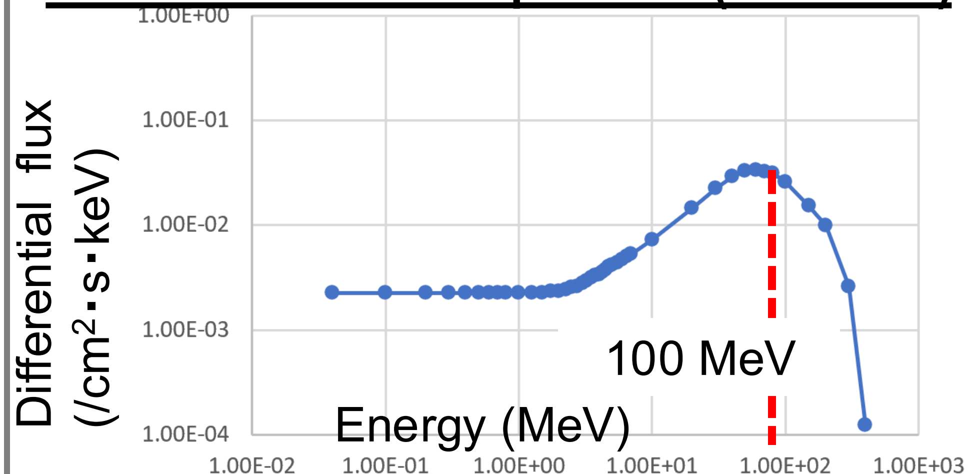
Electrostatic capacity: 0.79 fF

Calculation of Proton Fluence

SPENVIS

Calculates the **proton flux** along the orbit assuming an **Al (11.1 mm) shield**.

Differential Proton Spectrum (SPENVIS)



The detector is irradiated by protons from 40 keV to 1000 MeV, with the largest contribution at **100 MeV**.

PSTAR

Considers the stopping power of the detector material.
(The diamond was approximated as amorphous carbon in the calculation.)

The energy loss of protons in the detector is summed over **40 keV – 1000 MeV**.

Assuming all protons have **100 MeV**

8.89 × 10^8 protons/cm^2

per year

(Sun-synchronous polar orbit at 600 km altitude)