New muon monitor for J-PARC neutrino experiment

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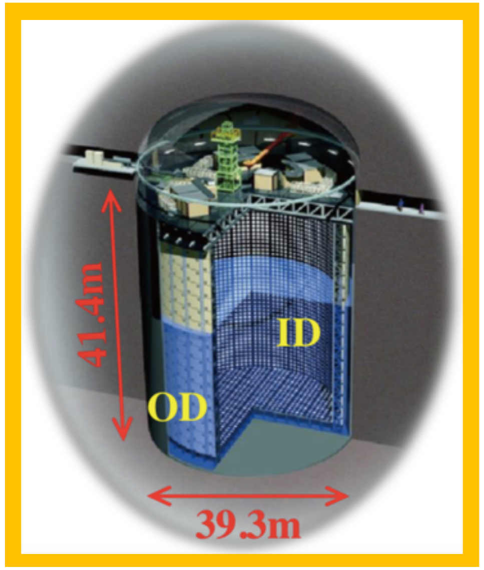
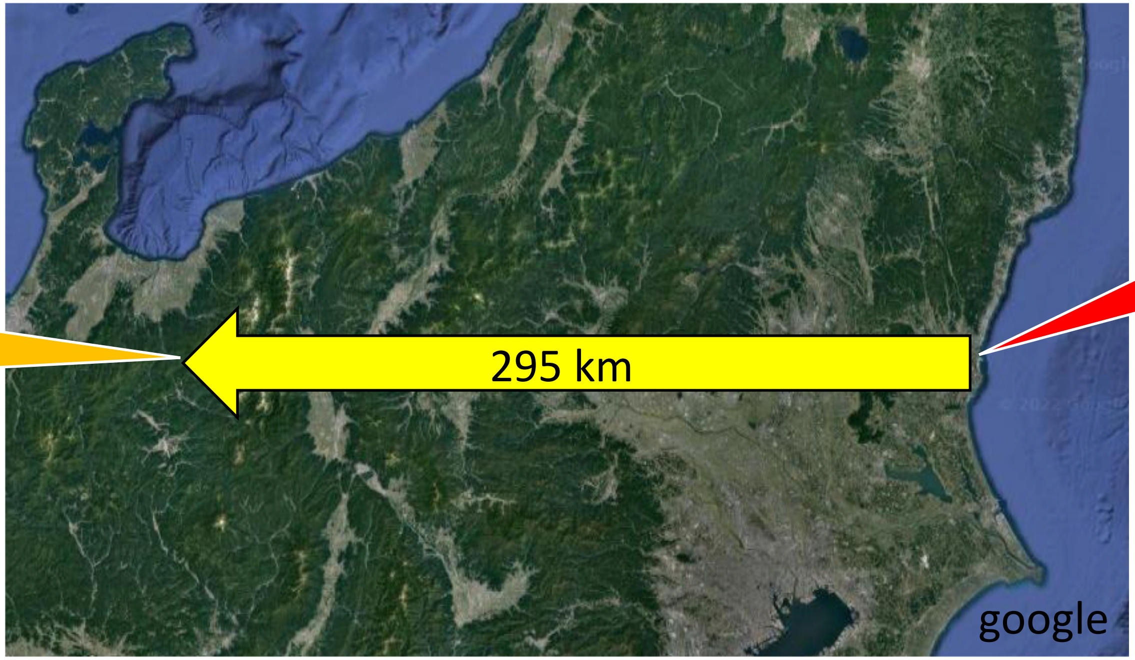
Outline

- Introduction
  - T2K experiment & beam
  - Beam monitor (muon)
- Electron-Multiplier Tube development for muon monitor
  - Temperature dependence
  - Radiation damage
  - Next beam test plan
- Summary

T2K experiment



Super-Kamiokande



J-PARC

Long base line neutrino oscillation experiment

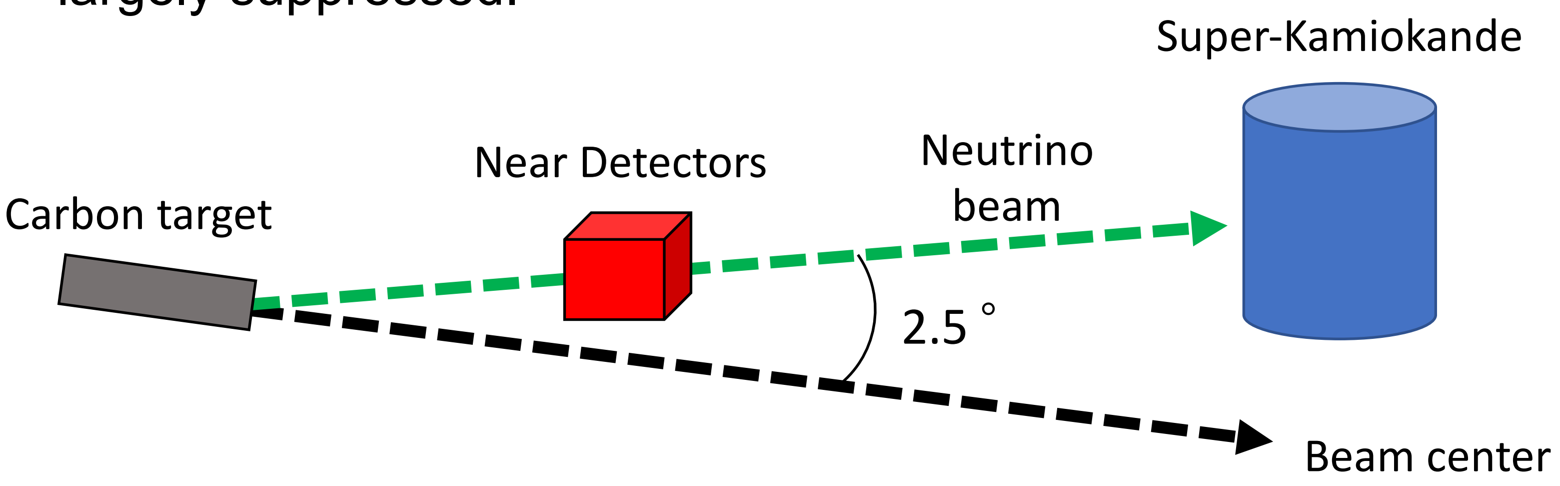
Produce ν_μ or $\bar{\nu}_\mu$ at J-PARC and detect neutrinos after oscillation at Super-Kamiokande

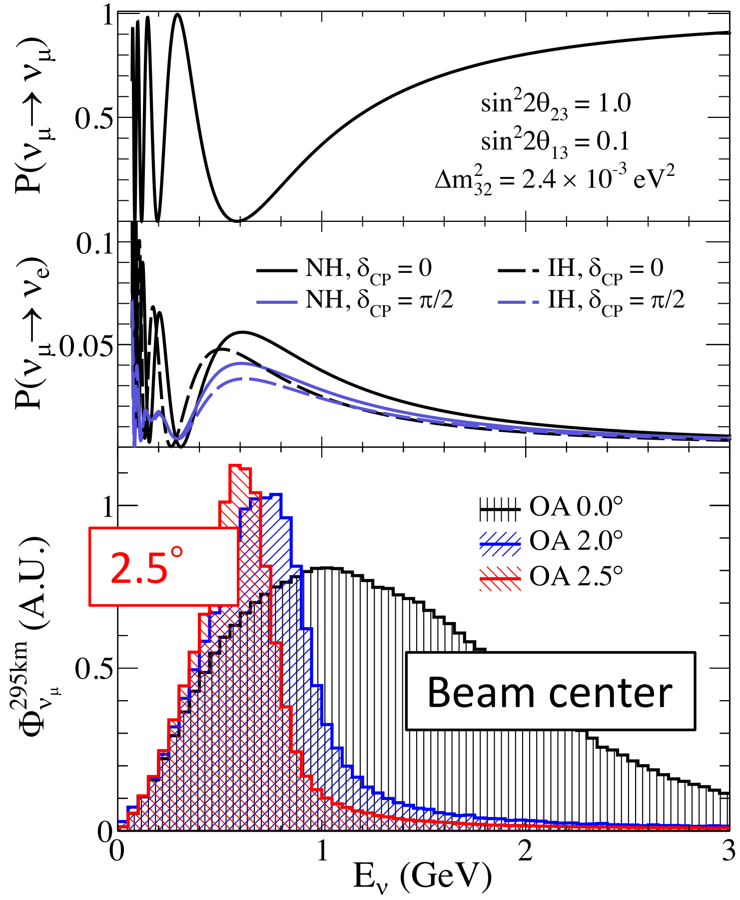
Search for CP violation in the lepton sector

Increase the beam power (Proton beam: 500 kW → 1.3 MW)

T2K neutrino beam

- Neutrino beam axis is shifted from the direction of Super-Kamiokande.
  - Narrower neutrino spectrum
  - Background from the high energy tail is largely suppressed.





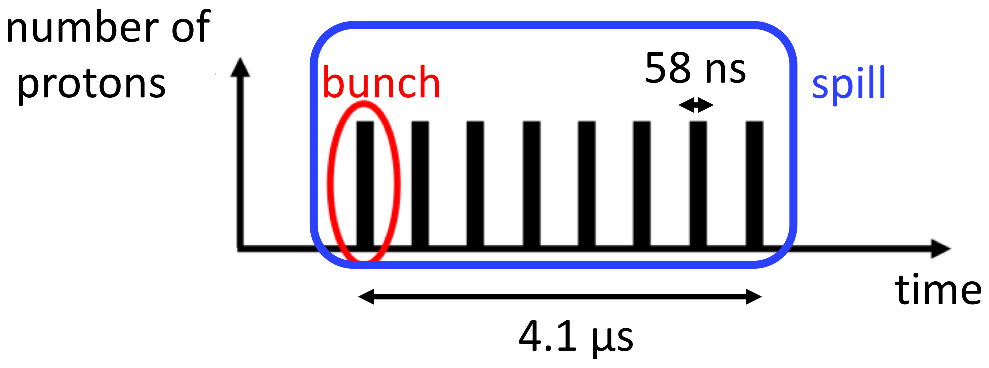
- Neutrino flux at Super-Kamiokande changes with the beam direction.
  → We have to monitor the beam direction with a precision better than 0.3 mrad.

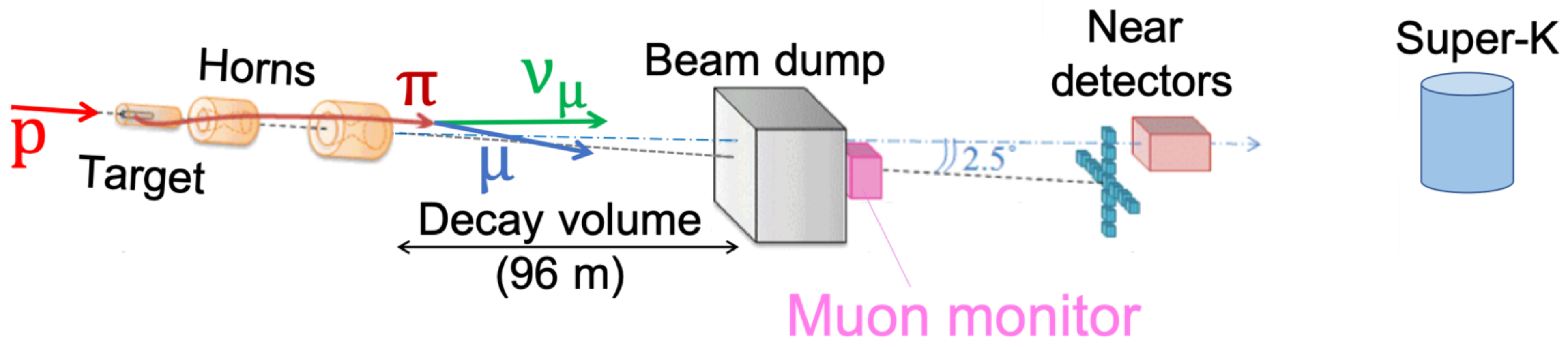
J-PARC beamline

How to produce neutrino beam

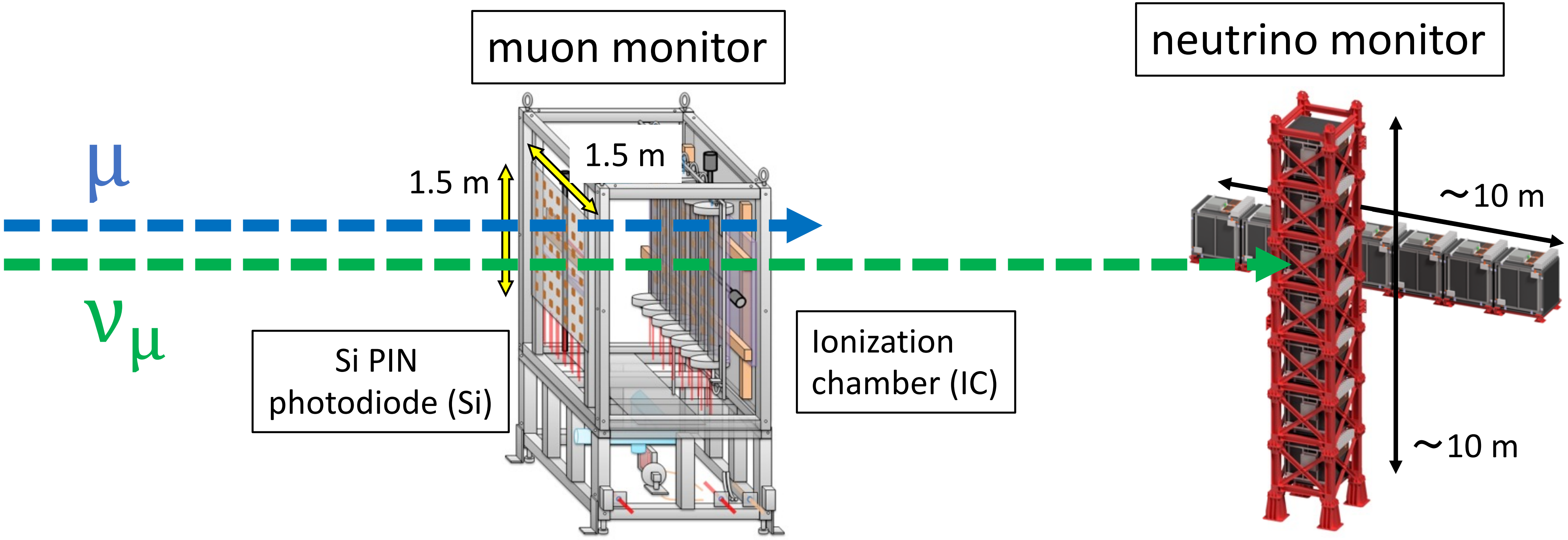
1. 30 GeV protons hit the carbon target
2. Hadrons exit the carbon target
3. Pions are focused by magnetic horns
4. Pions decay into neutrinos and muons

J-PARC beam structure





Beam monitors downstream of the target

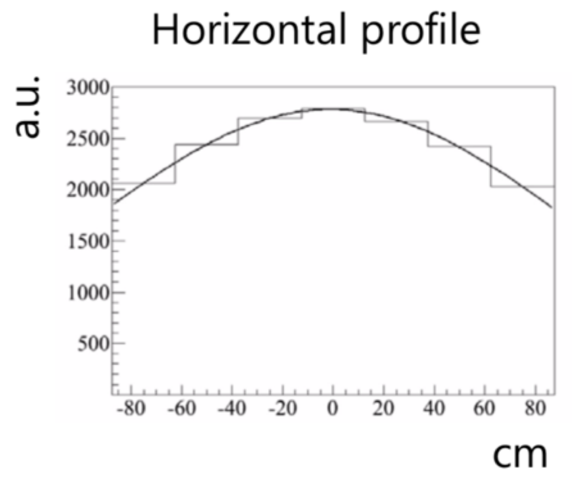


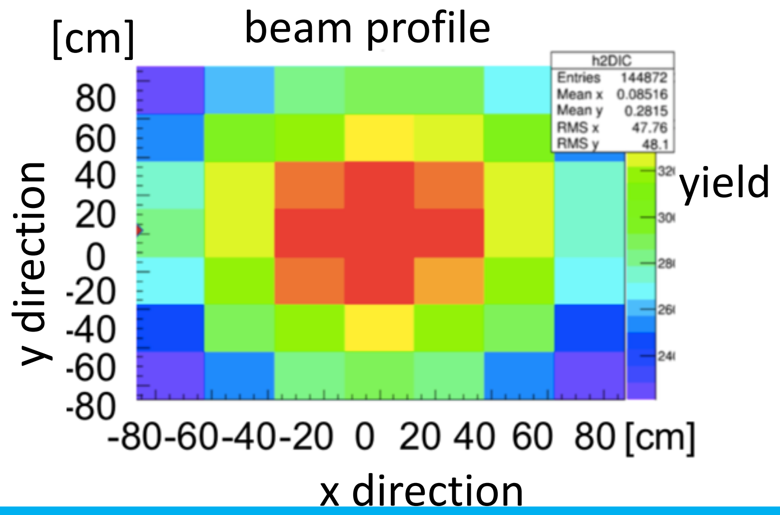
Monitor muon profile in real-time.
→ Indispensable monitor for T2K operation.
Si is main sensor for monitor.
IC is for cross-check and backup.

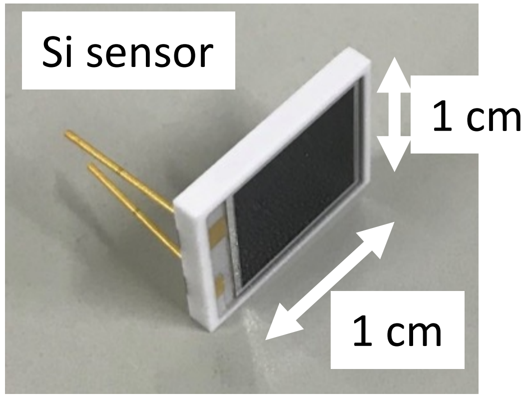
Scintillator and iron plates.
It takes about a day to see the profile.

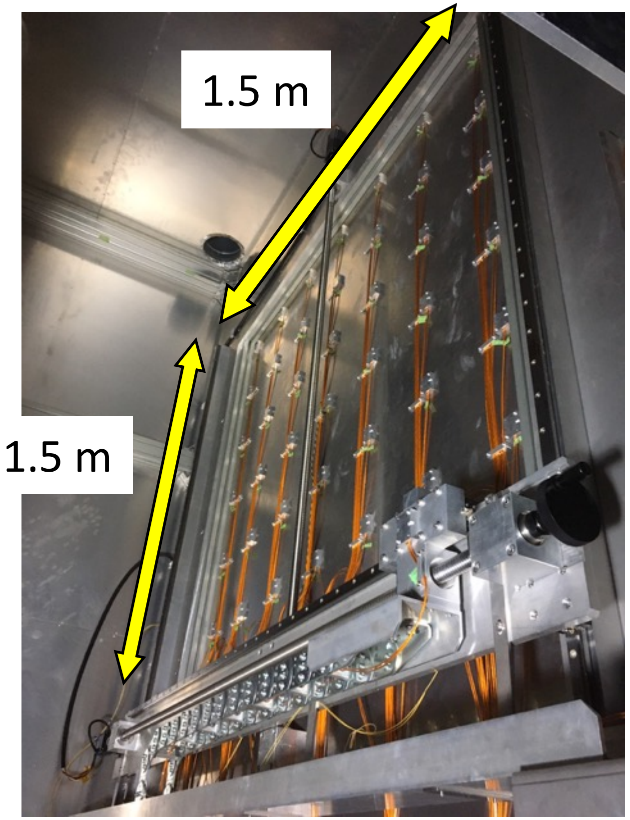
Present muon monitor

- Beam intensity and profile are measured by 7 × 7 Si sensors.
- Present muon monitor can measure the beam direction to the required precision (within 0.3 mrad).
- Half of Si sensors should be replaced after ~100 days operation (under the 2020 beam conditions) because of radiation damage.





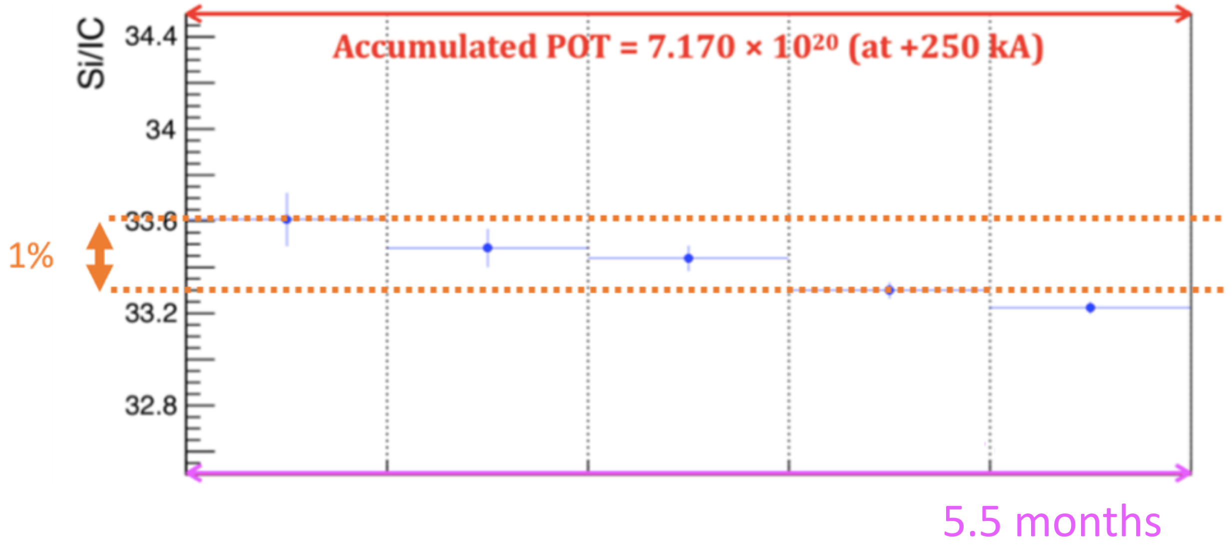




Radiation damage of Si

- Si signal drop by T2K operation.
- Beam upgrade
  - 1.5×10^6 muons/cm^2/s $\rightarrow 4.2 \times 10^6$ muons/cm^2/s $\times 2.8$
- After beam upgrade, Si will need to be replaced after about a month operation.

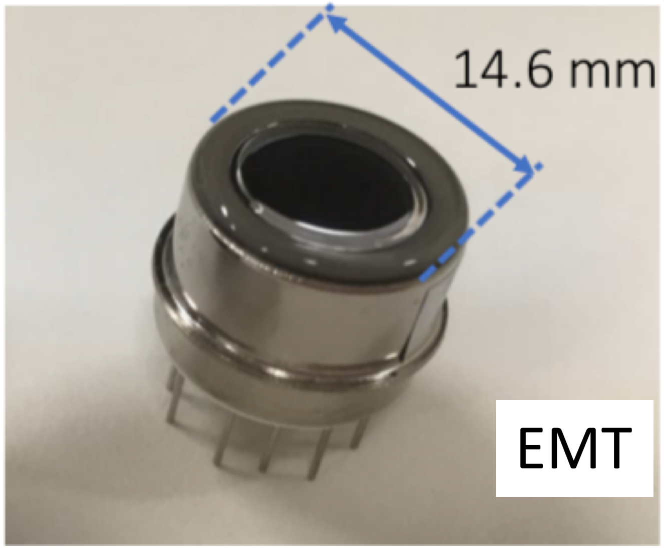
Si degradation (present beam power)

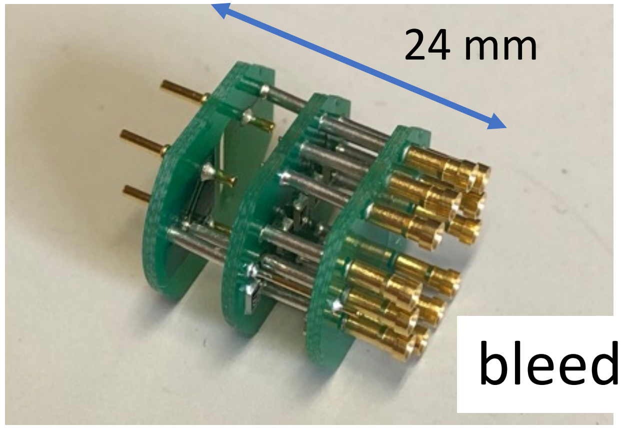


"High radiation tolerant" and "real-time"
beam profile monitor is essential to get future T2K working.

Candidates for new sensor

- Electron-Multiplier Tube (EMT)
  - Based on the same technology as Photo-Multiplier Tube (PMT).
  - Photocathode is replaced with an aluminum deposited glass.
  - Expected to be more radiation tolerant than Si.

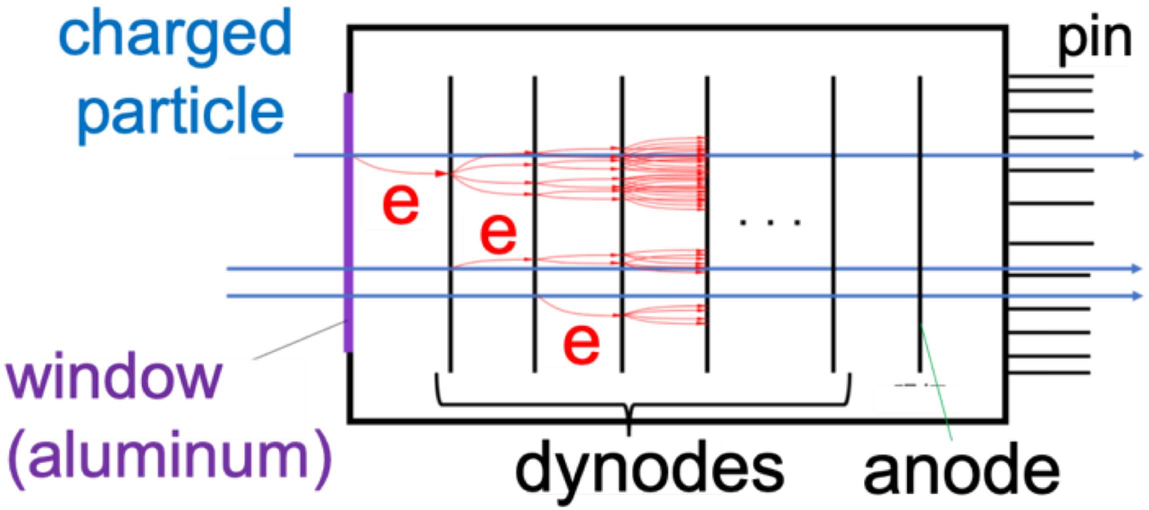




Bleeder circuit is made
of as little resin as possible.

Electron-Multiplier Tube (EMT)

- How the signal is output
  1. produce electrons at the cathode surface or dynodes
  2. accelerated by the electric field
  3. amplified at the following stages of dynode
  4. extracted as signal

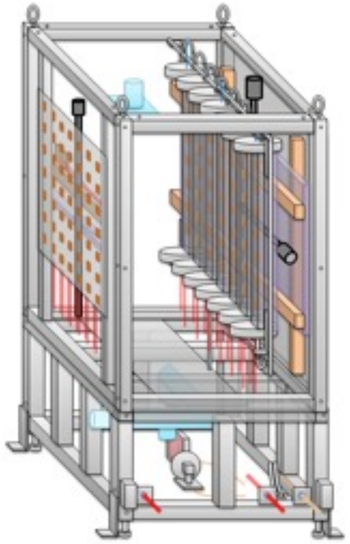


EMT performance check in T2K site

- EMTs were put outside of the support enclosure that houses Si and IC

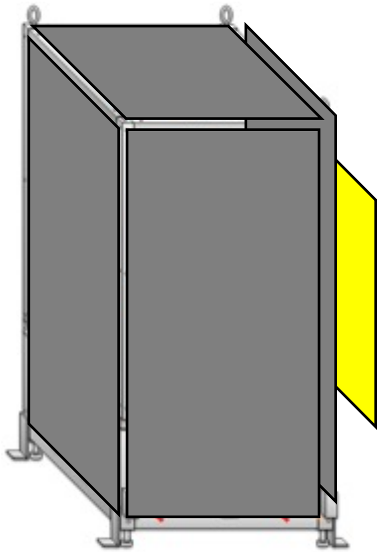
EMT

inside the support enclosure

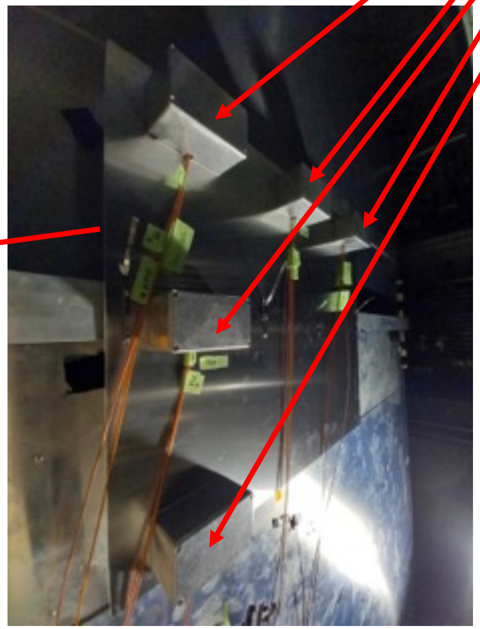


in operation

Al cover



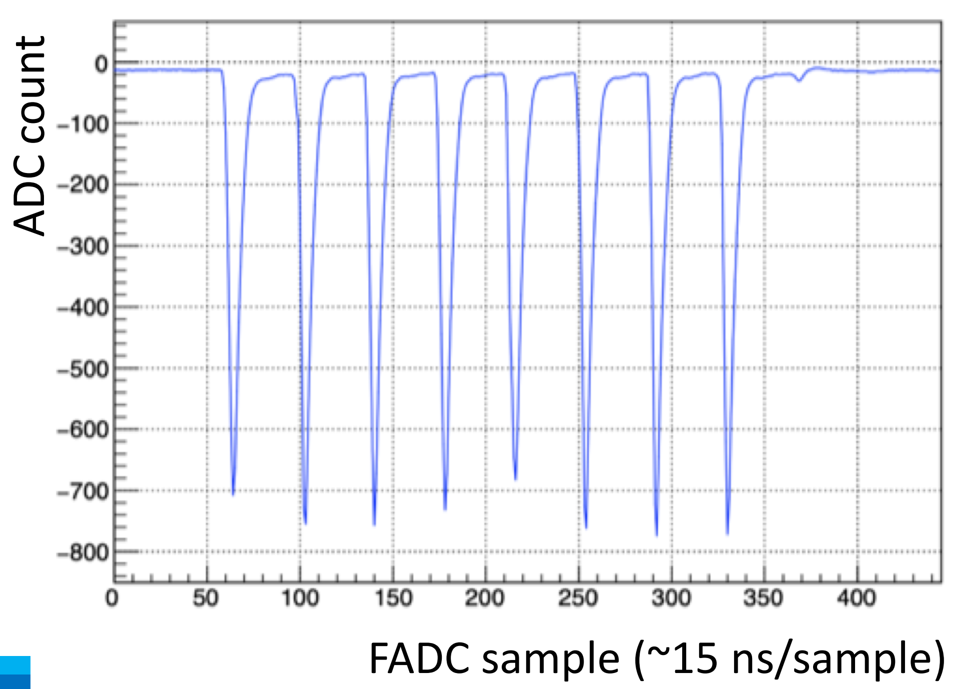
outside
the the support
enclosure



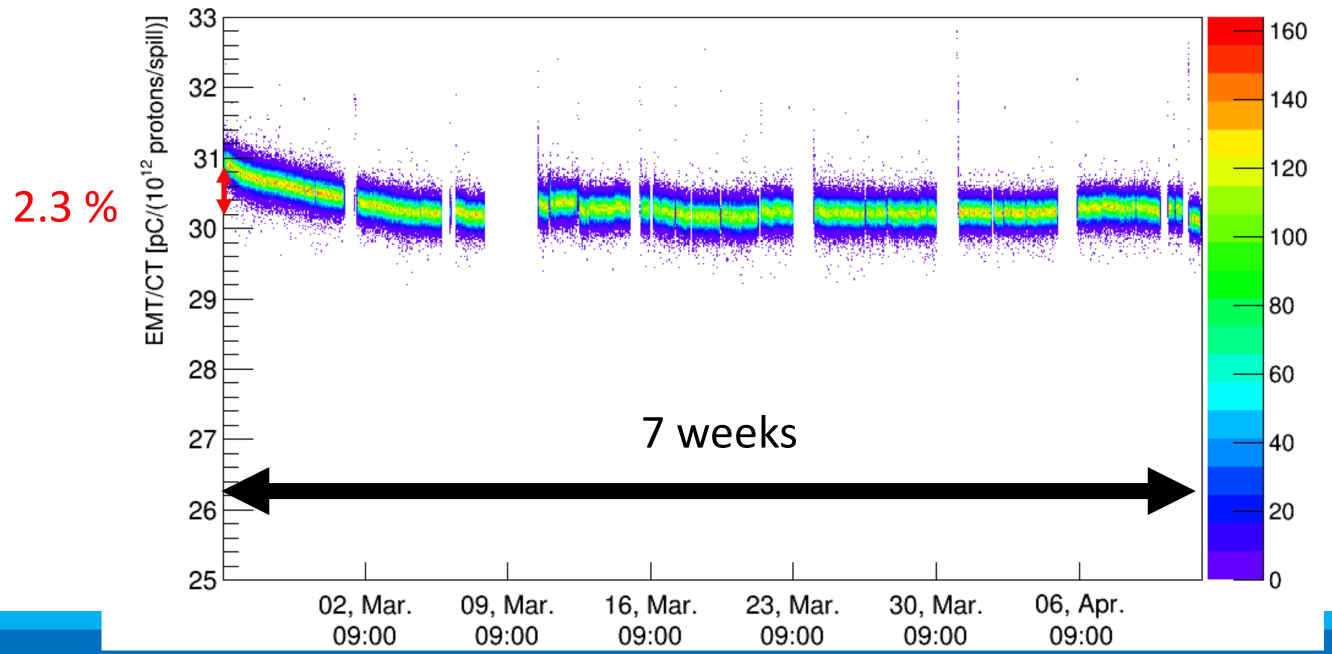
EMT performance check in T2K site

- Good performance of bunch-by-bunch monitoring.
- EMTs have a drift in the yield
  (two weeks from the beginning. We call it initial instability).
- After the initial drift period, the yield is basically stable within ±1%.

EMT wave form at ~460 kW



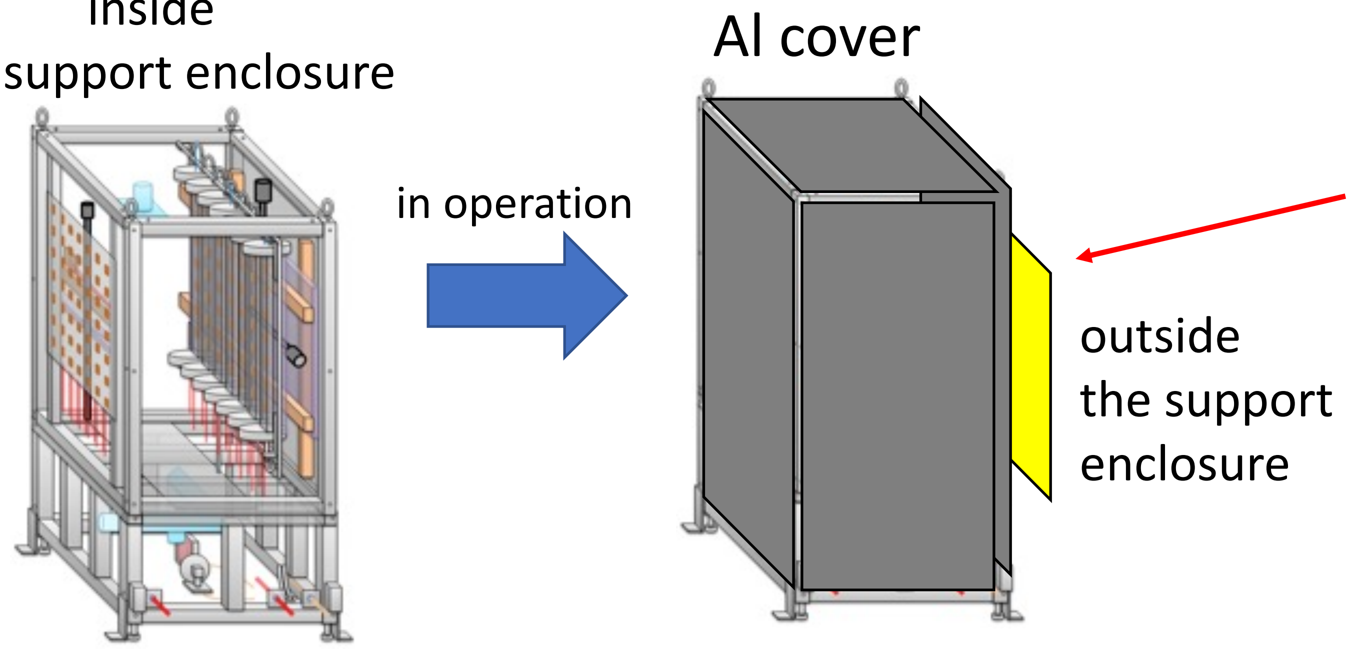
EMT stable after initial instability

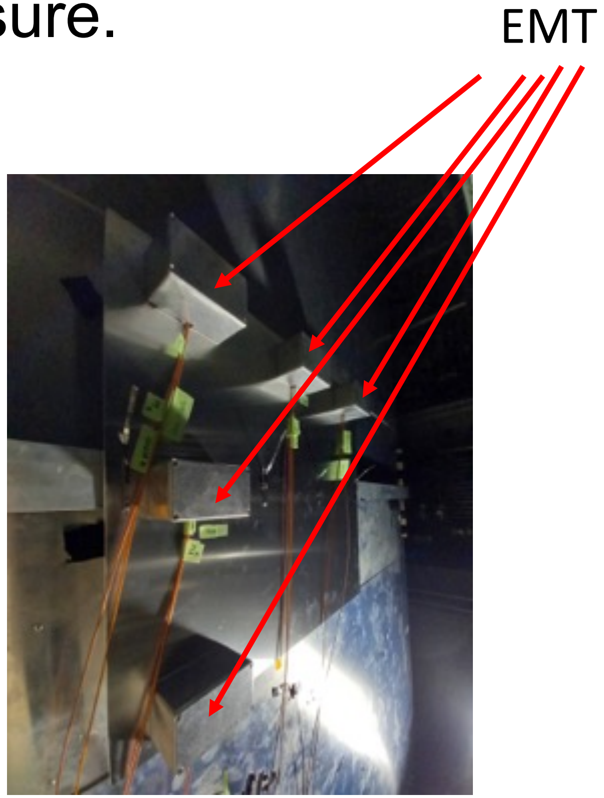


Initial instability and temperature dependence

- EMT's were placed outside the temperature-controlled enclosure.
  - Cooling water for beam dump is going through the pit. → heat source

inside
the support enclosure



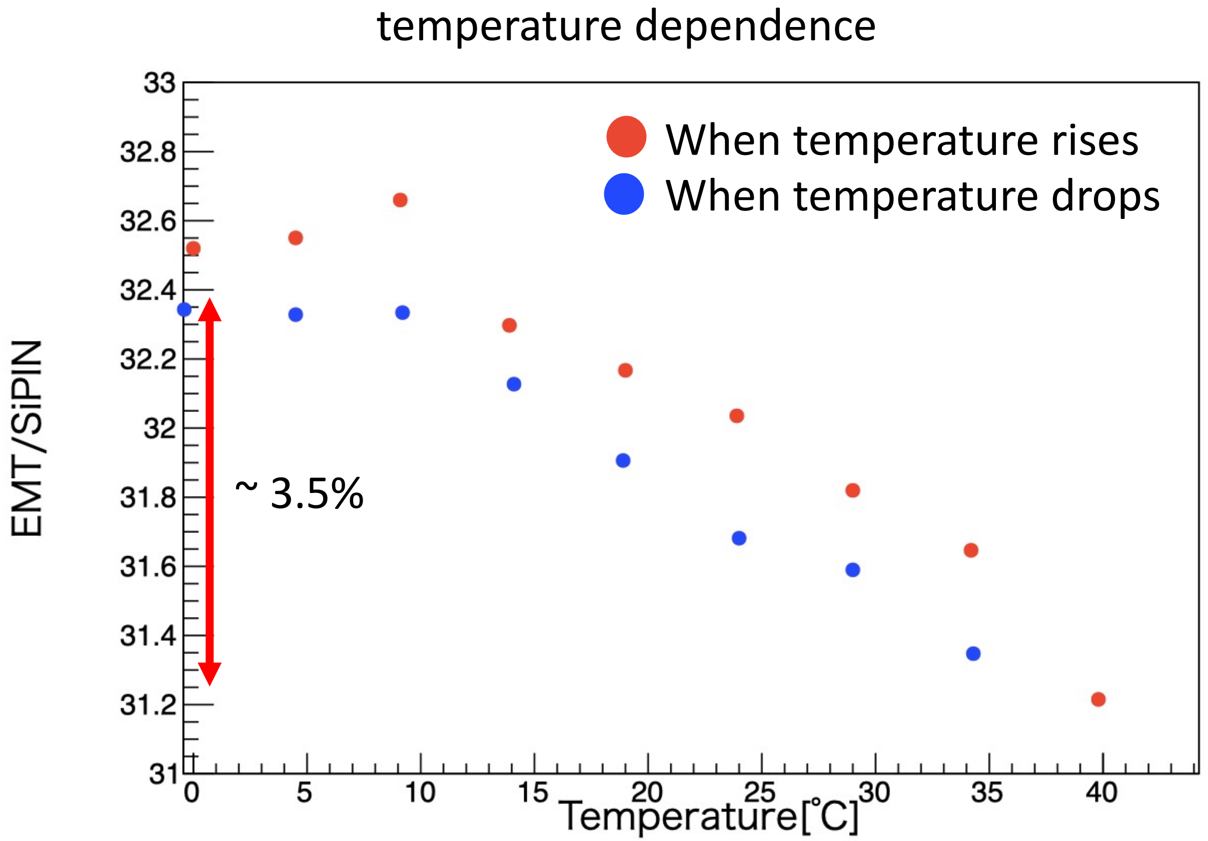


→ To measure temperature dependence, we checked yield in a thermostatic chamber.

Initial instability and temperature dependence

- EMT was placed in a thermostatic chamber and the response of the EMT was checked by the LED light.
- Response varied with surrounding temperature.
- There was a discrepancy between rising and falling temperatures.

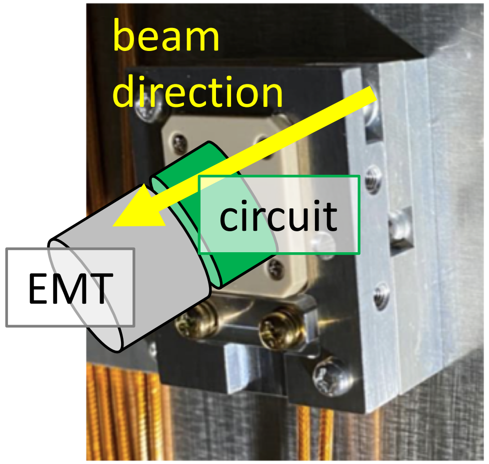
- The outside of the support enclosure at the T2K site may have temperature changes.



→ It is possible that the initial instability was actually temperature dependence.

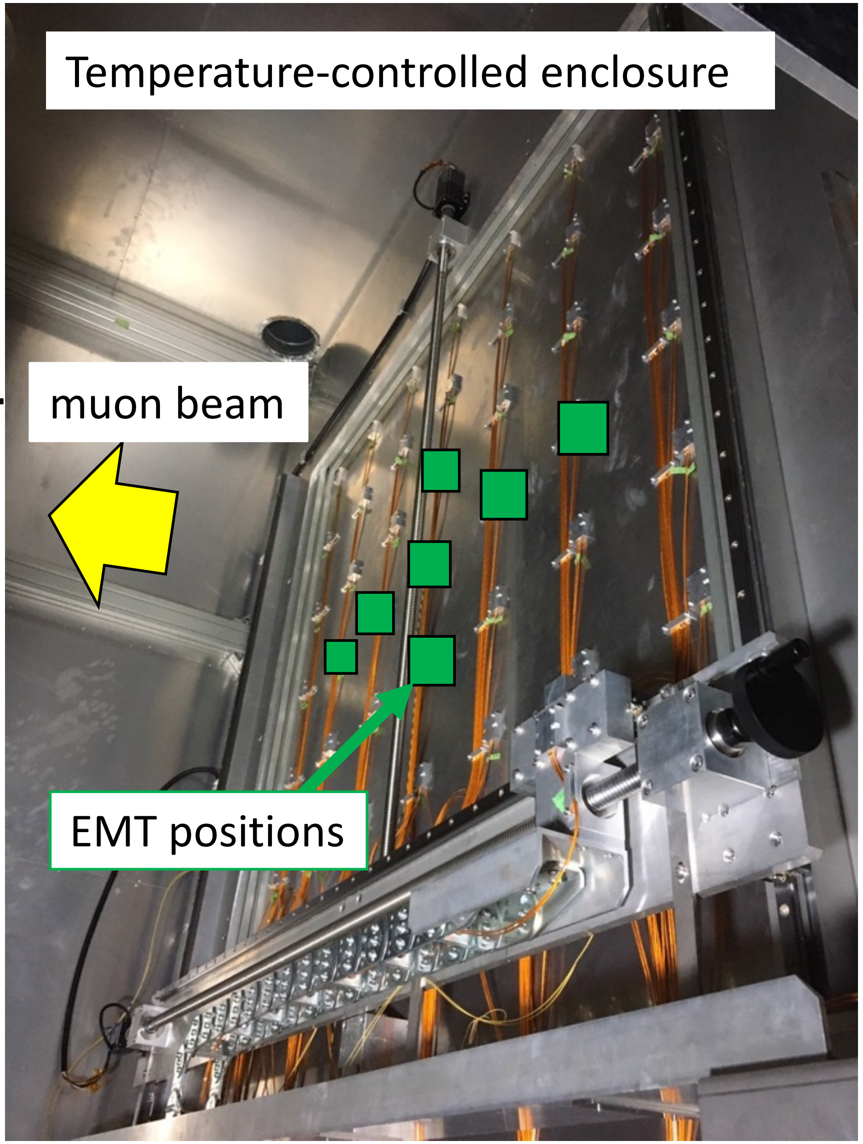
Plan in next T2K beam time

- Next beam time will be this winter.
- Will put the EMT in the temperature-controlled enclosure.
- Measure the temperature outside the support enclosure.
- Seven EMTs are placed in a cross-shaped pattern to demonstrate profile measurement.



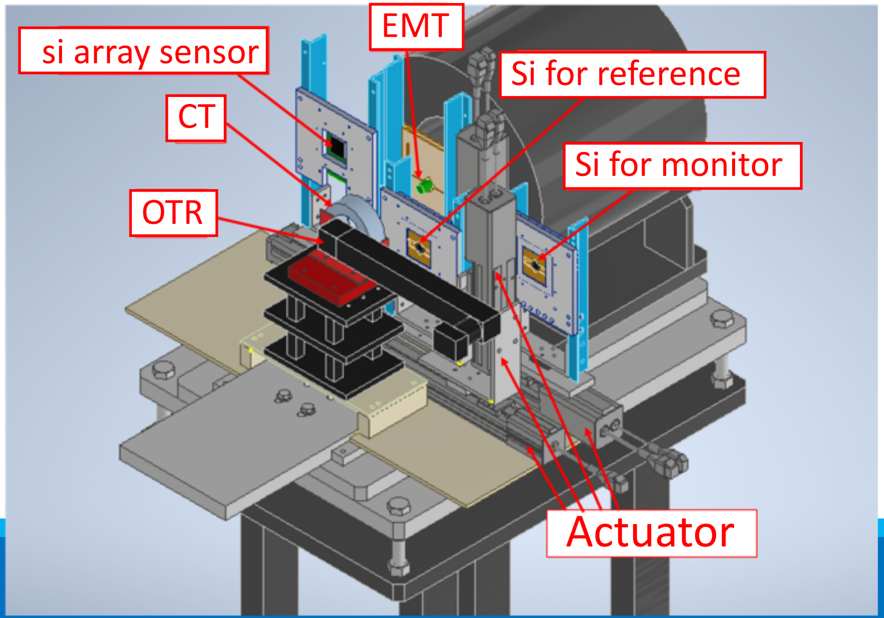
EMT is placed on top of Si jig

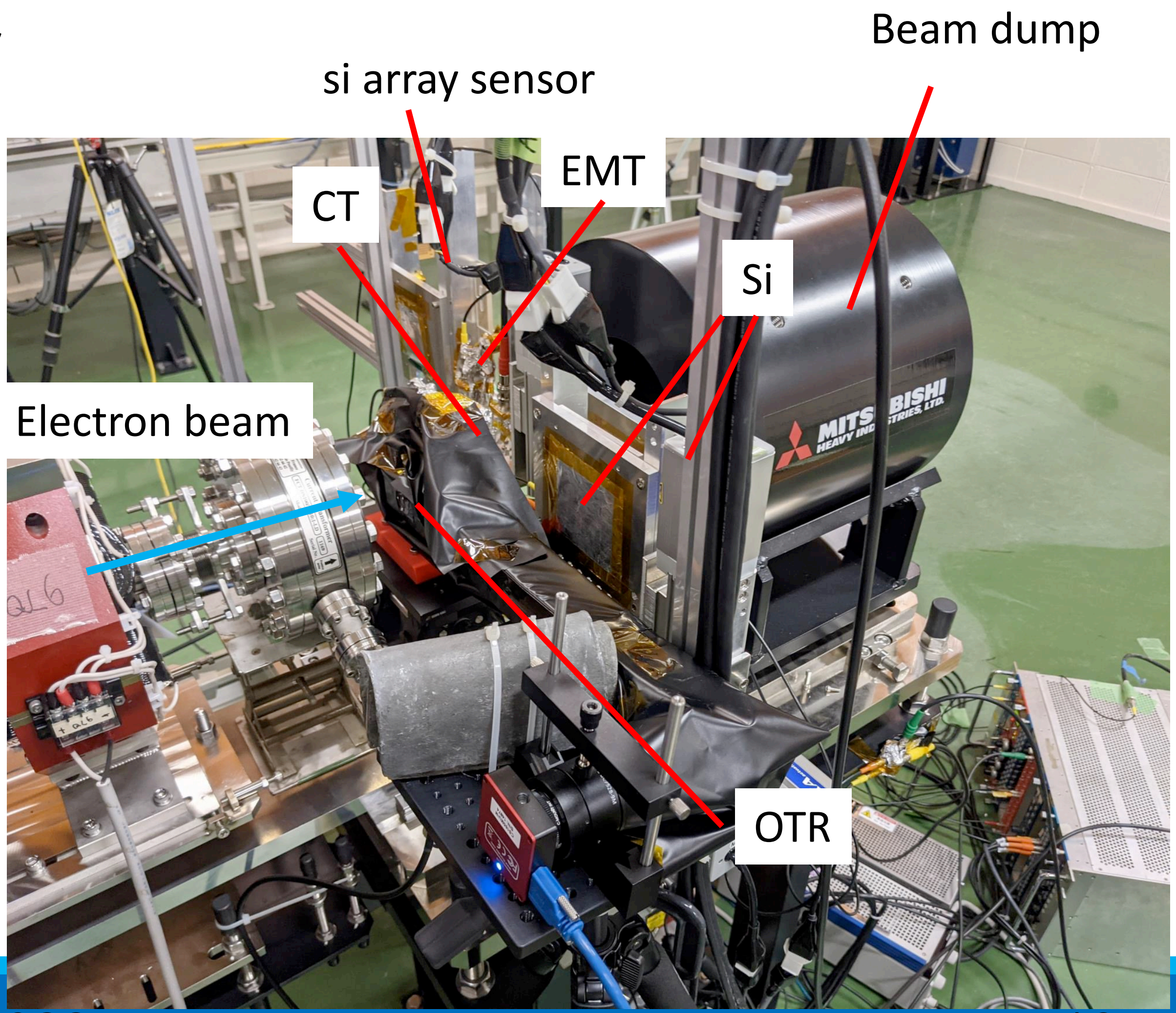
Installed with the cathode facing downstream to reduce the effect of cherenkov photons on the window.



Beam test for EMT

- In 10/2019, 11/2020, 9/2021
- At Tohoku Univ. (ELPH: Research center for electron photon science)
- ~90 MeV electron beam
- The first and second beam test purpose
  - Check response linearity and radiation tolerance



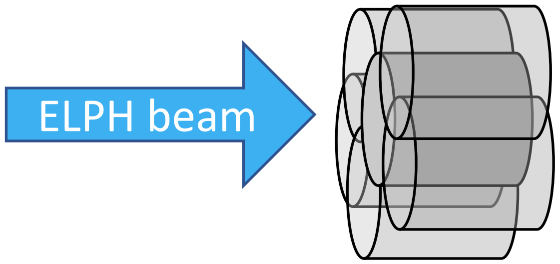


Beam test setup

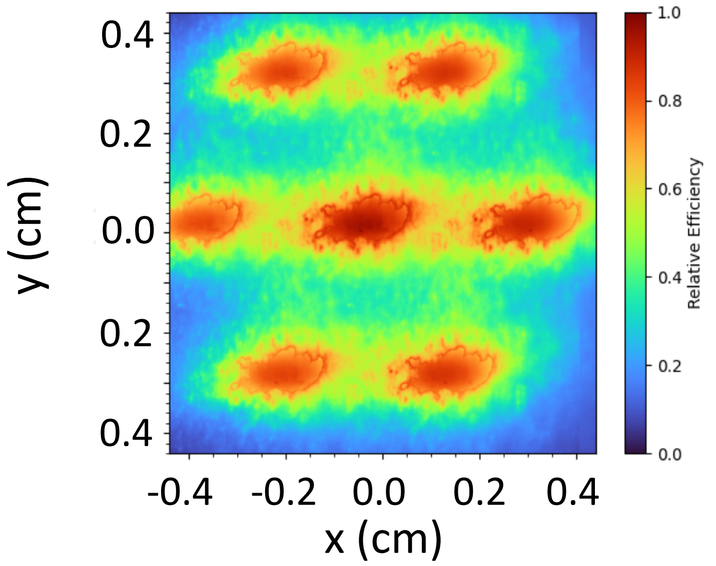
- The beam size of the T2K site (~1 m) and the beam test (~1 mm) were different.
- Moved EMT with respect to the beam to irradiate the whole region of the EMT window.

- An Optical Transition Radiation (OTR) detector was used to monitor the beam profile.

Concept of moving EMT



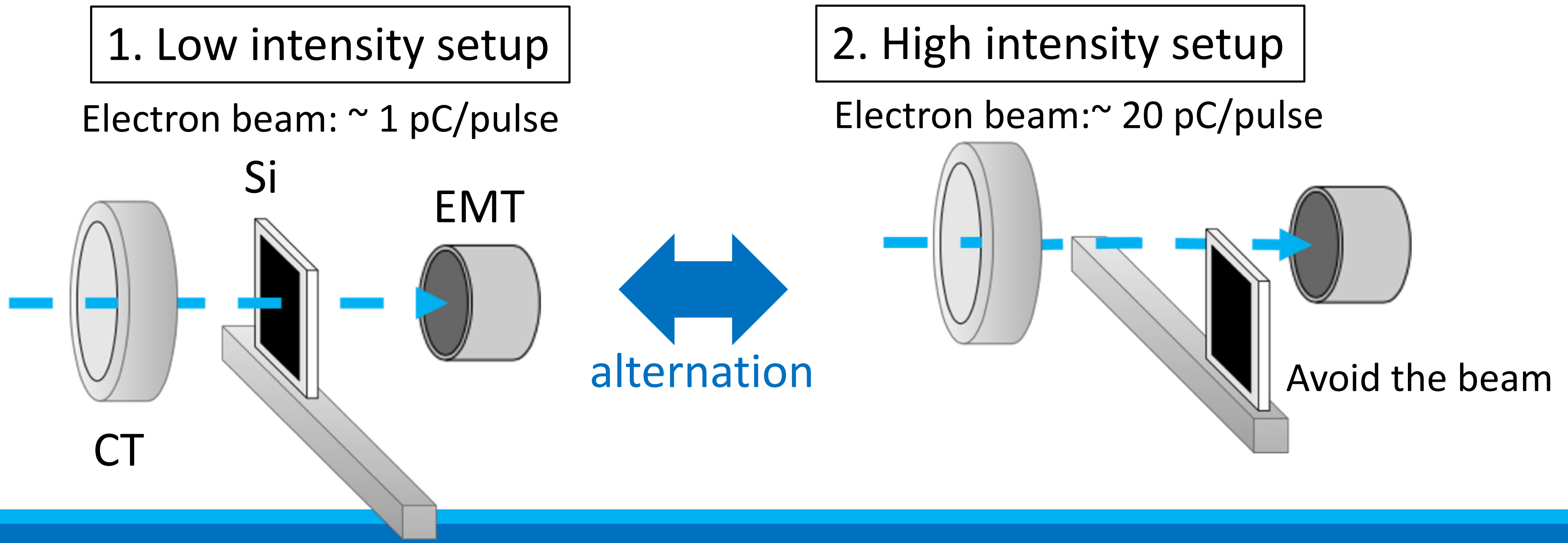
Irradiation profile
(superposed OTR image)



Beam test setup

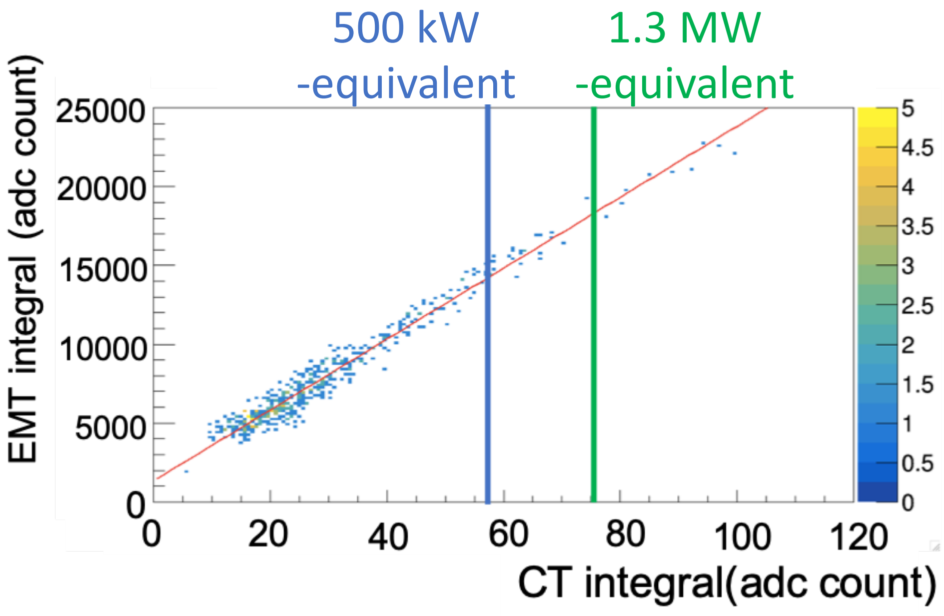
Electron beam with two different intensities

1. Charge in a pulse is equivalent to a bunch at J-PARC for checking EMT signal (Low intensity)
   - Si sensor for comparing to EMT
2. For radiation damage (High intensity)

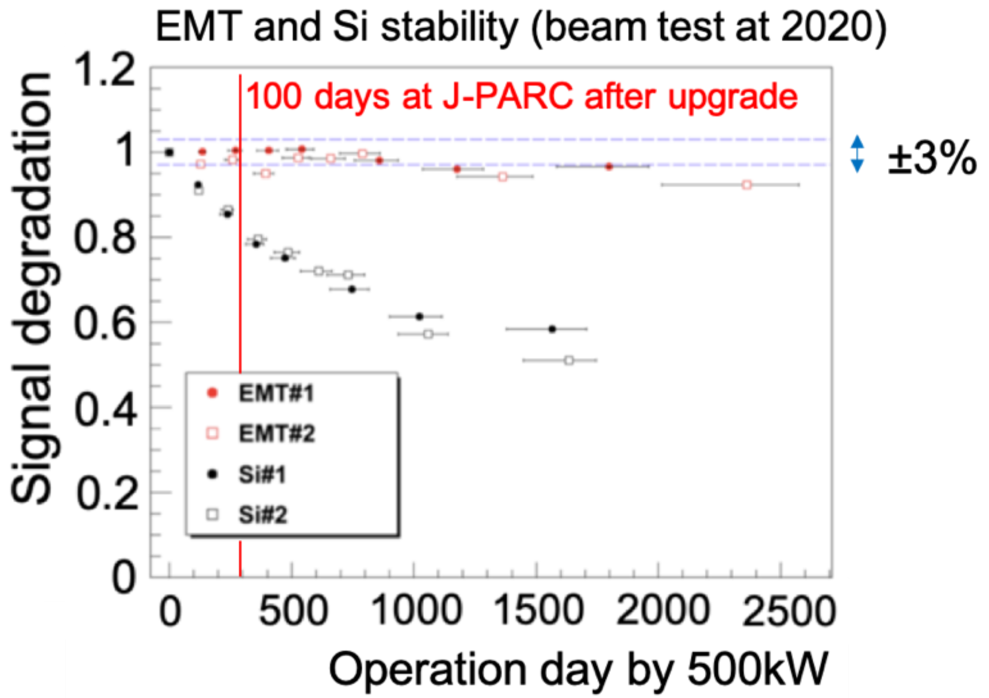


Result of the first and second beam test (Reported in previous NuFACT)

- Check radiation tolerance and response linearity.



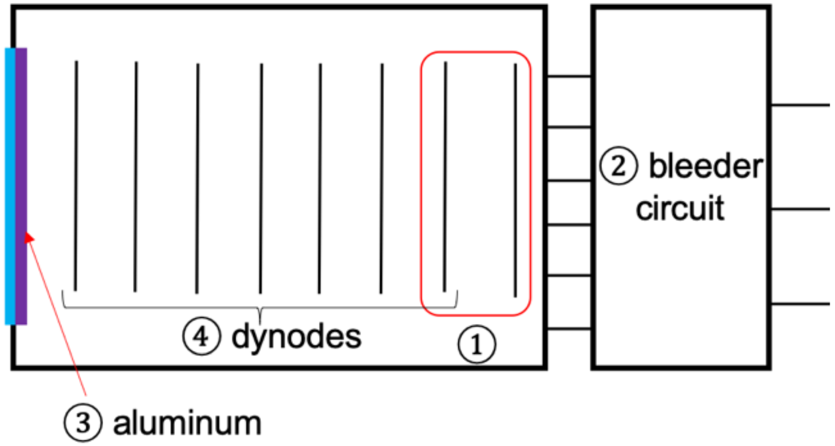
Good linearity even at upgraded beam power.



More radiation tolerant than Si.

→ There was a tendency for the signal to drop more than 3% by irradiating a large amount of beam, we would like to investigate the cause and extend the life of EMT.

Possible causes of radiation damage



1. Degradation of the last dynode by secondary electrons
2. Degradation of the bleeder circuit causes a change in the distribution ratio of resistance.
3. Degradation of aluminum cathode reduces the number of secondary electrons produced on there.
4. Damage of dynodes by incident charged particles.

→ Third beam test was conducted to investigate the cause 1 and 2.

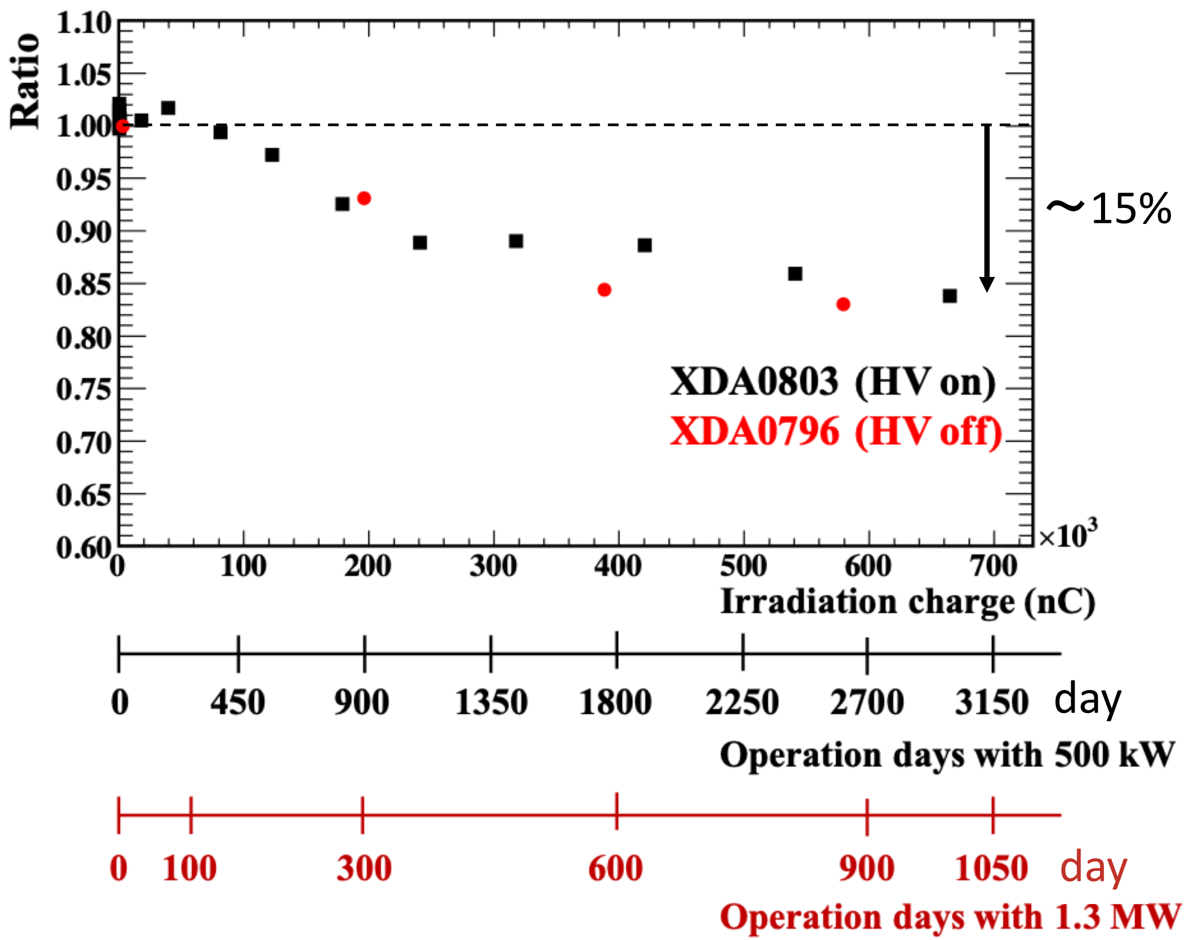
Check cause 1 (dynode damage by 2ndary electrons)

- Irradiated with HV turned off
  - No amplification by 2ndary electrons

- No significant difference from the case of applying HV of 450 V.

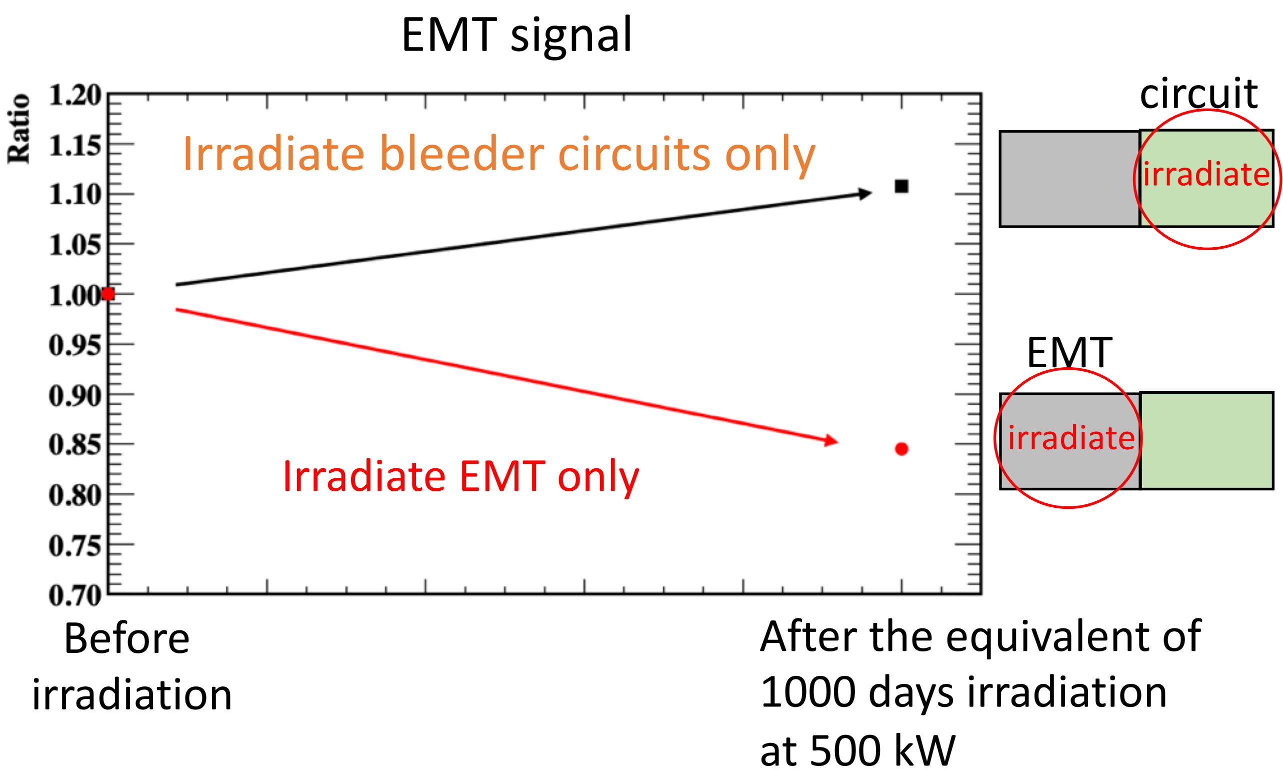
→ Doesn't seem to be the main cause.

EMT signal



Check cause 2 (bleeder circuit)

- Investigated whether the cause of degradation is in the EMT itself or in the circuit.
- Beams equivalent to 1000 days operation of the present J-PARC for each circuit and EMT.



- Signal was degraded by irradiating EMT only.
- Signal was increased by irradiating circuit only. (for unknown reasons)

→ The EMT itself seems to be main cause.

Planning next beam test

- Main purpose
  - To evaluate degradation of cathode aluminum (cause 3)
  - To evaluate degradation of the bleeder circuit (cause 2)
  - To measure temperature dependence by using electron beam (not LED)
- In this Fall @ Tohoku Univ. (ELPH)

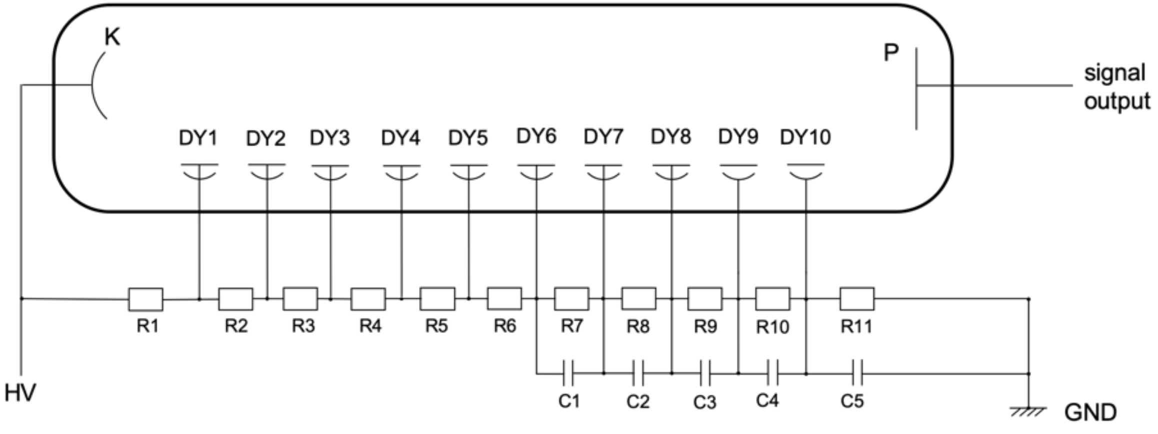
Plan of checking cause 3 (cathode aluminum)

- Remove the first resistance
- Adjust all resistances to make the EMT gain same as the nominal bleeder circuit.

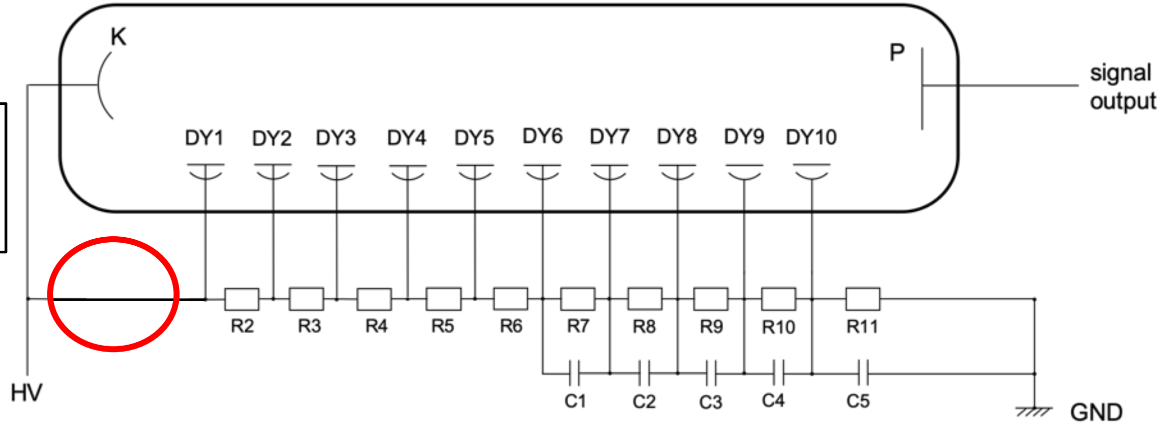
-> Start amplification from 2nd dynode

- Minimizes the effect of cathode degradation
  → longer time of use
- Ask HAMAMATSU to produce new bleeder.

Nominal bleeder

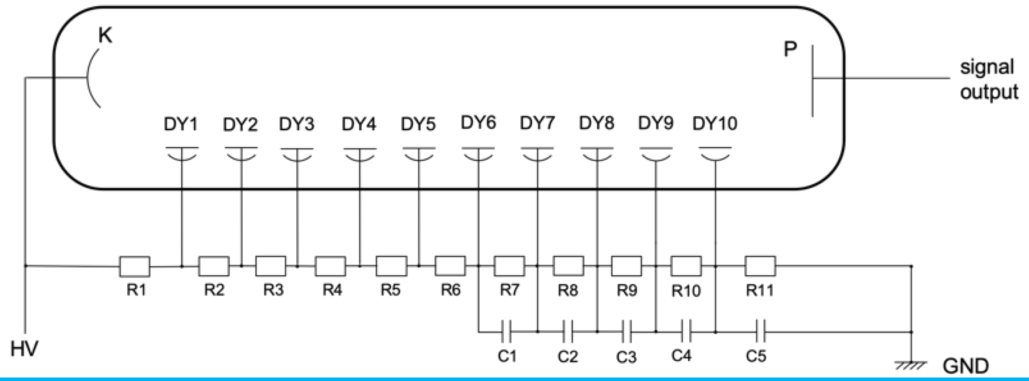


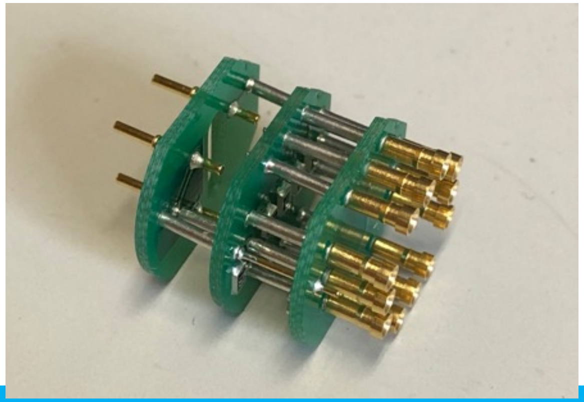
New bleeder



Further checking of cause 2 (bleeder circuit)

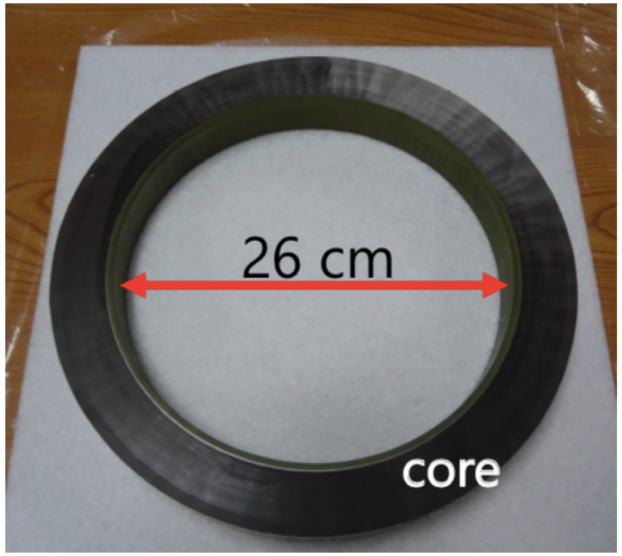
- Third beam test
  - A few months after the last beam test, the resistance values were measured.
    And they were nominal.
  - Since we didn't measure the resistance values before the beam test, we were not able to know the effect of radiation on the resistances.
- Fourth beam test (next plan)
  - Measure resistance and capacitance before and after beam irradiation.

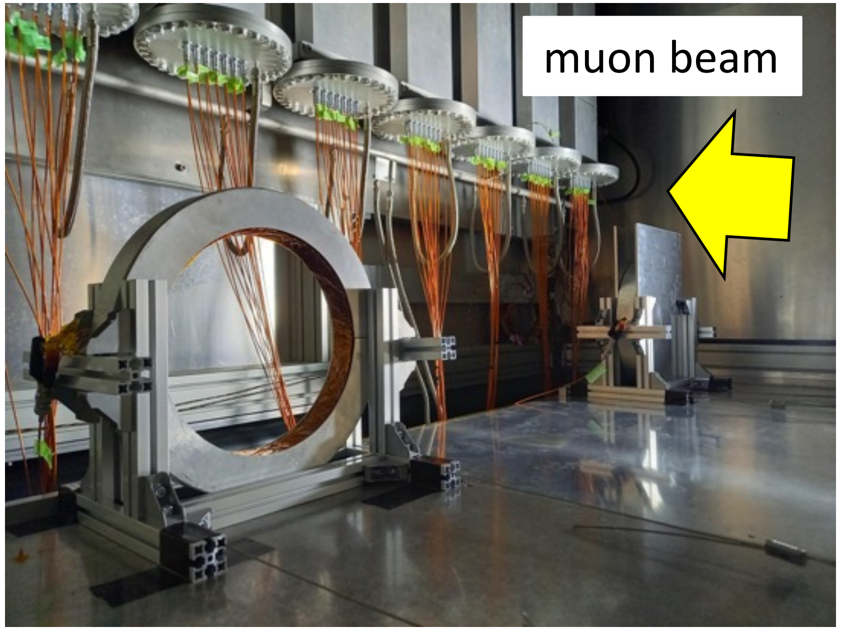


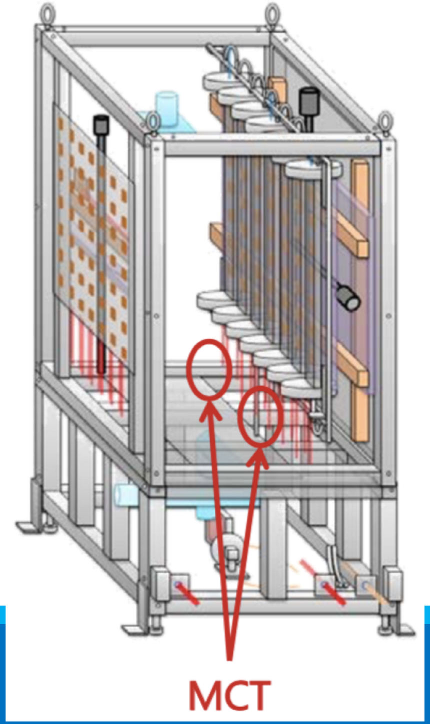


Muon monitor Current Transformer (MCT)

- Has different advantages from Si, IC.
- Difference of the number of μ^+ and μ^- can be measured.
- We are doing R&D.







Summary

- Motivation of EMT development
  - Muon monitor is measuring the beam direction in the T2K experiment. →indispensable for T2K beam operation
  - We plan to replace present sensors (Si) with new sensors for beam upgrade.
- EMT is a good candidate (fast response, linearity, radiation tolerance).
- temperature dependence ～0.1%/℃ (LED light)

  → Have to control temperature.
- Response degradation ～15% in 3000 days operation on 500 kW
  - Dynodes damage by electron amplification is not the main cause
- Next plan
  - Install EMTs at T2K site to demonstrate profile measurement (temperature controlled).
  - Fourth beam test to understand the effect of radiation damage in more detail.

backup

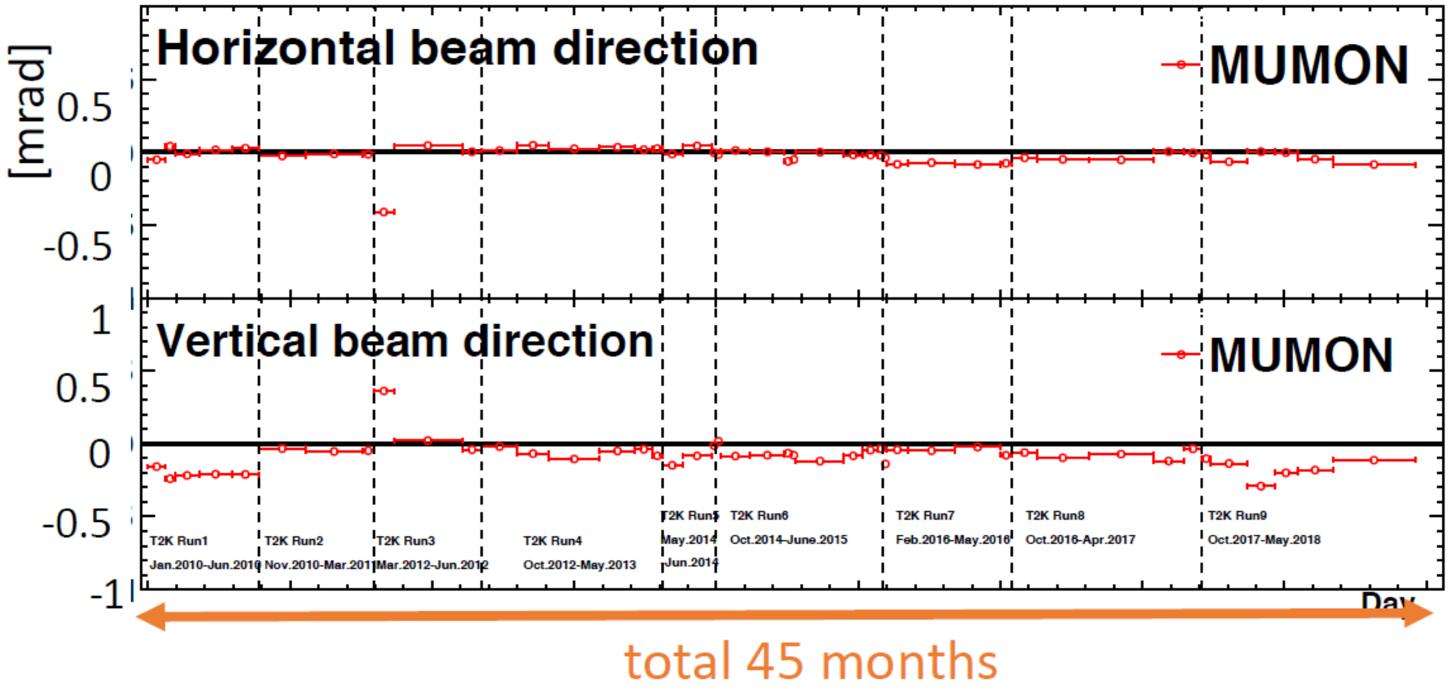
Reference

- K. Matsuoka et al., Nucl. Instrum. Meth. Phys. Res. A 624, 591 (2010)
- K. Suzuki et al., Prog. Theor. Exp. Phys., 053C01 (2015)
- Y. Ashida et al., Prog. Theor. Exp. Phys., 103H01 (2018)

Present muon monitor

- Si has worked fine up to now

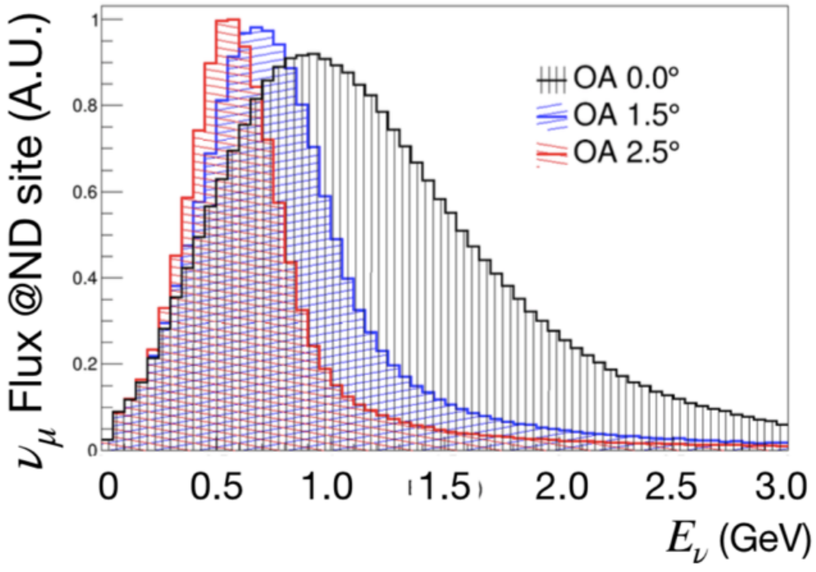
Measurement of beam center

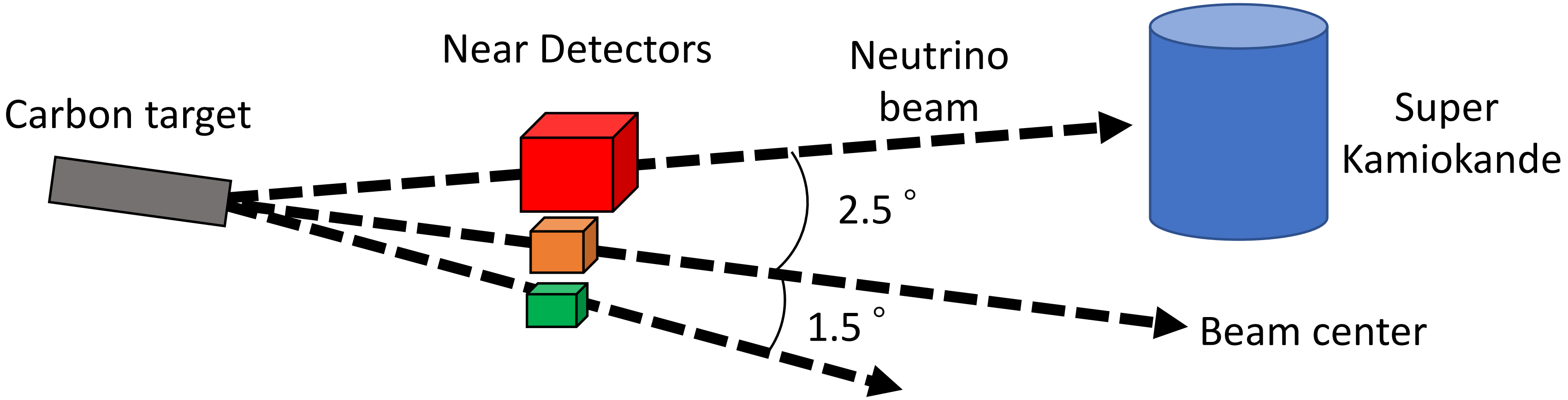


T2K neutrino beam

- Neutrino beam axis is shifted from the direction of Super-K.
  - Narrower neutrino spectrum
  - Background from the high energy tail is largely suppressed.

T2K neutrino beam

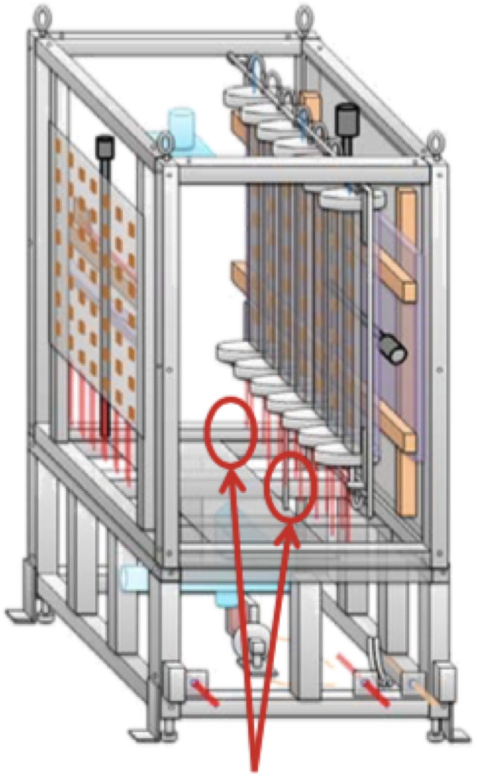


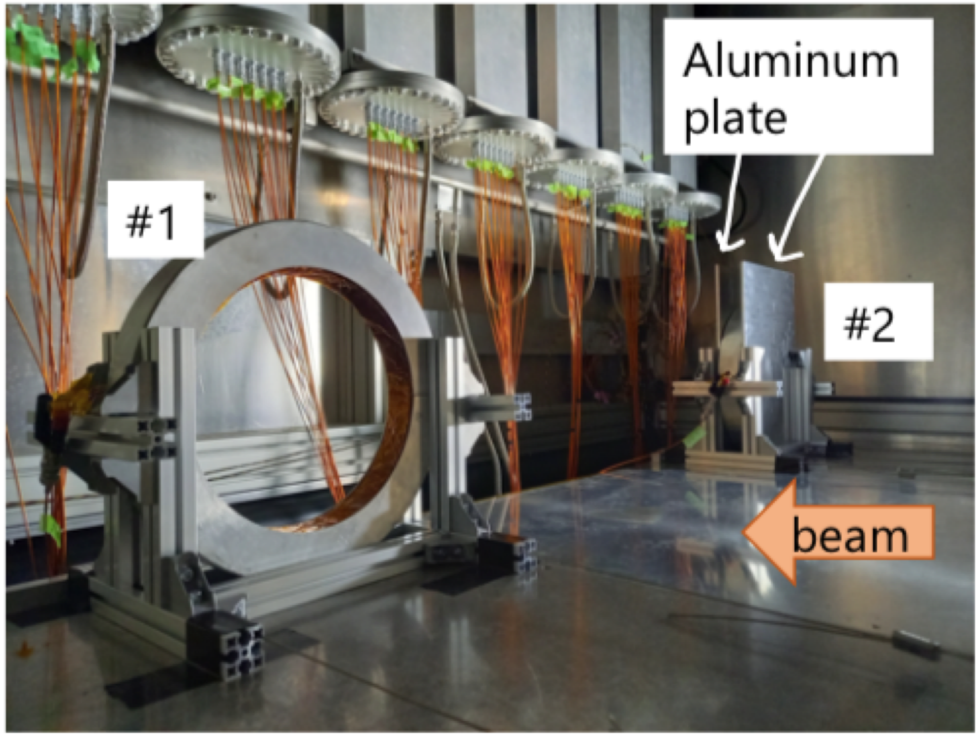


- Neutrino flux at SK changes with the beam direction.
  → We have to monitor the beam direction within 0.3 mrad.

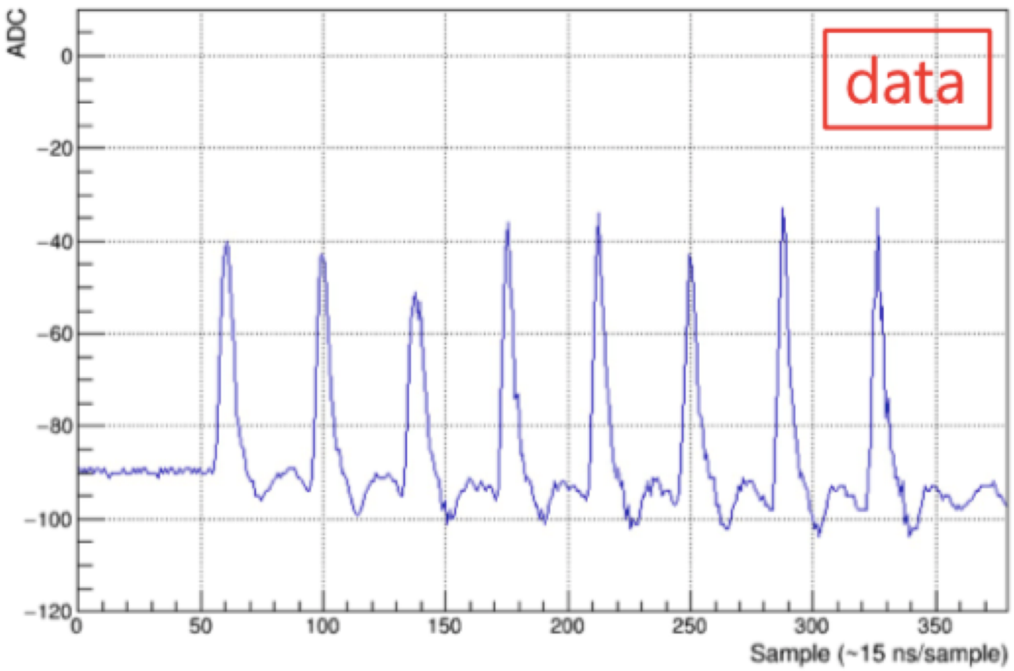
Installation and test run @ J-PARC

- We set two MCTs at MUMON. (Feb. 2021)
- The signals are measured during the operation of the T2K experiment. (Mar. - Apr. 2021)





First signal of MCT at MUMON



8-bunch structure is clearly seen!

Plan in next T2K beam time

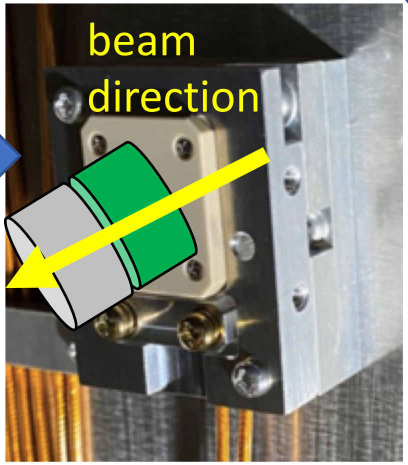
- Next beam time will be this winter.
- Will set the EMT in the temperature-controlled enclosure.
- Measure the temperature outside the support enclosure.

Temperature-constant enclosure

1. Si jig

2. EMT jig on the Si jig

3. set EMT



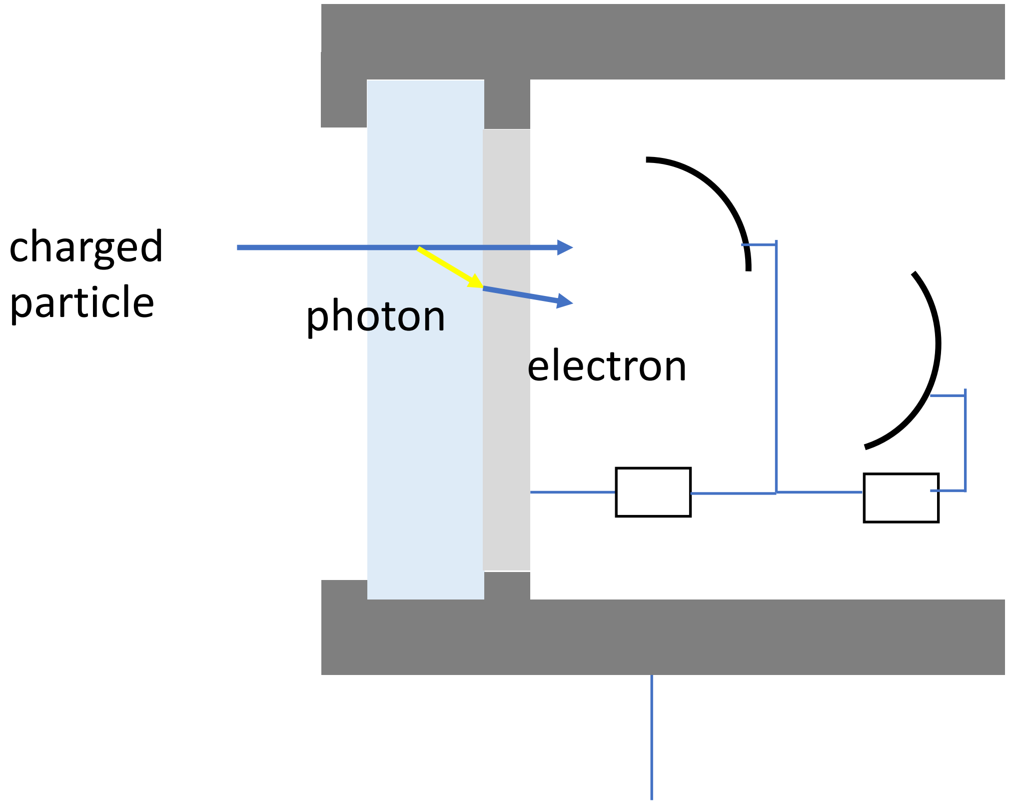
Used in reverse to reduce the effect of cherenkov photons on the window.

4. covered

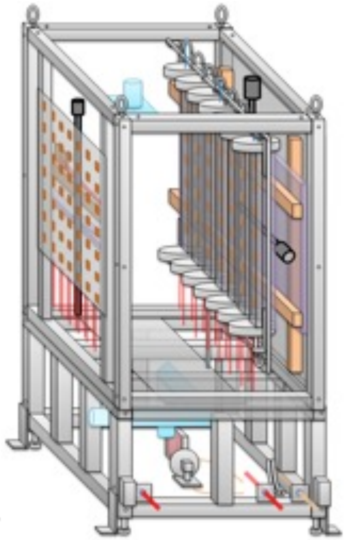
Cover
for noise suppression

→ Next, we would like to investigate radiation tolerance and causes of degradation.

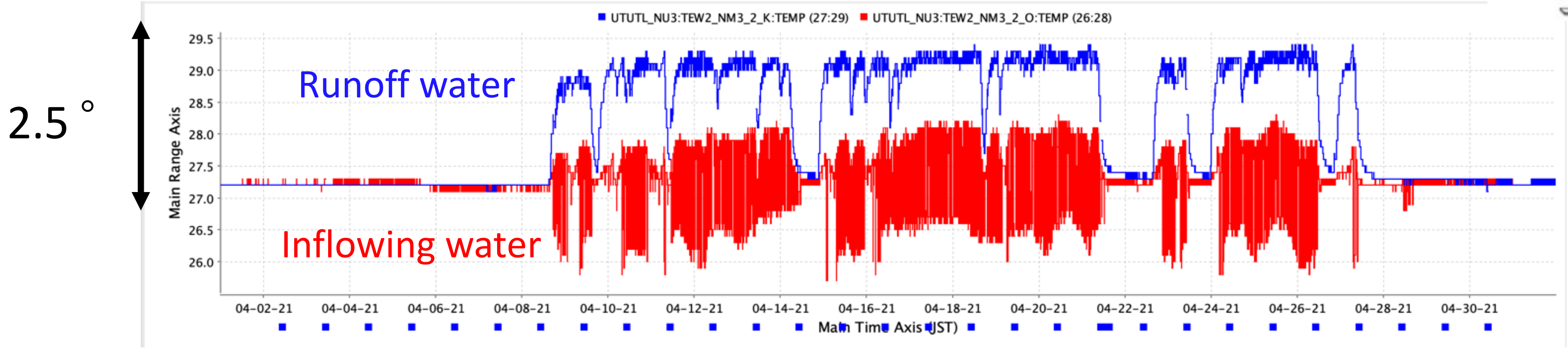
アルミ蒸着のイメージ



temperature in T2K site



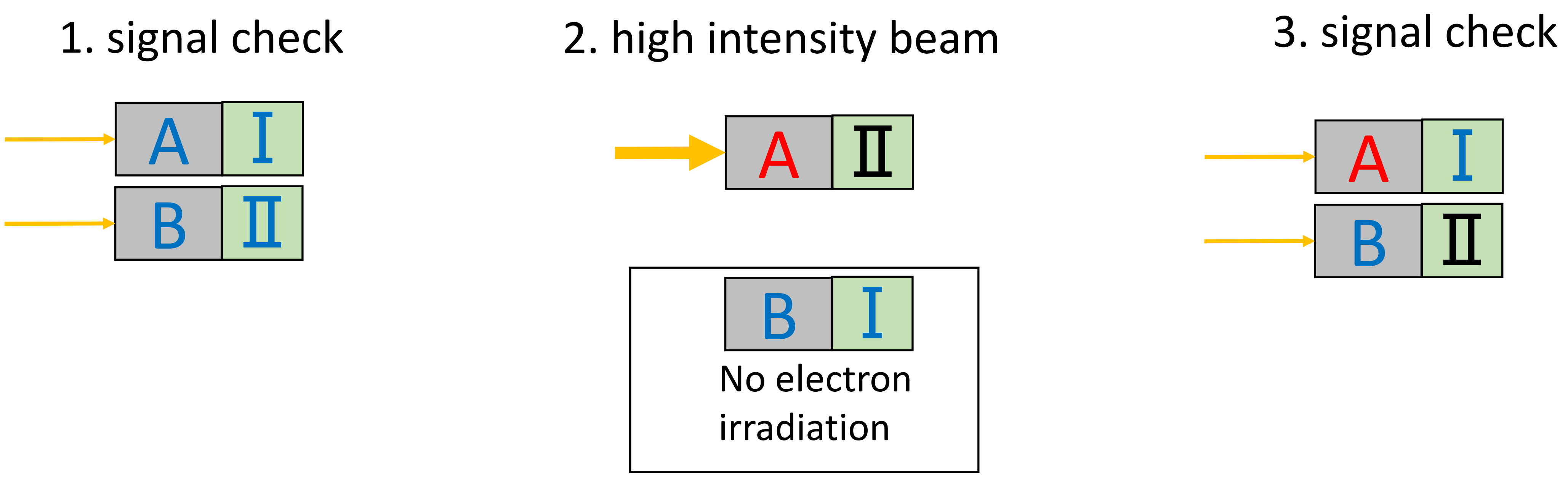
Temperature of water passing near the monitor

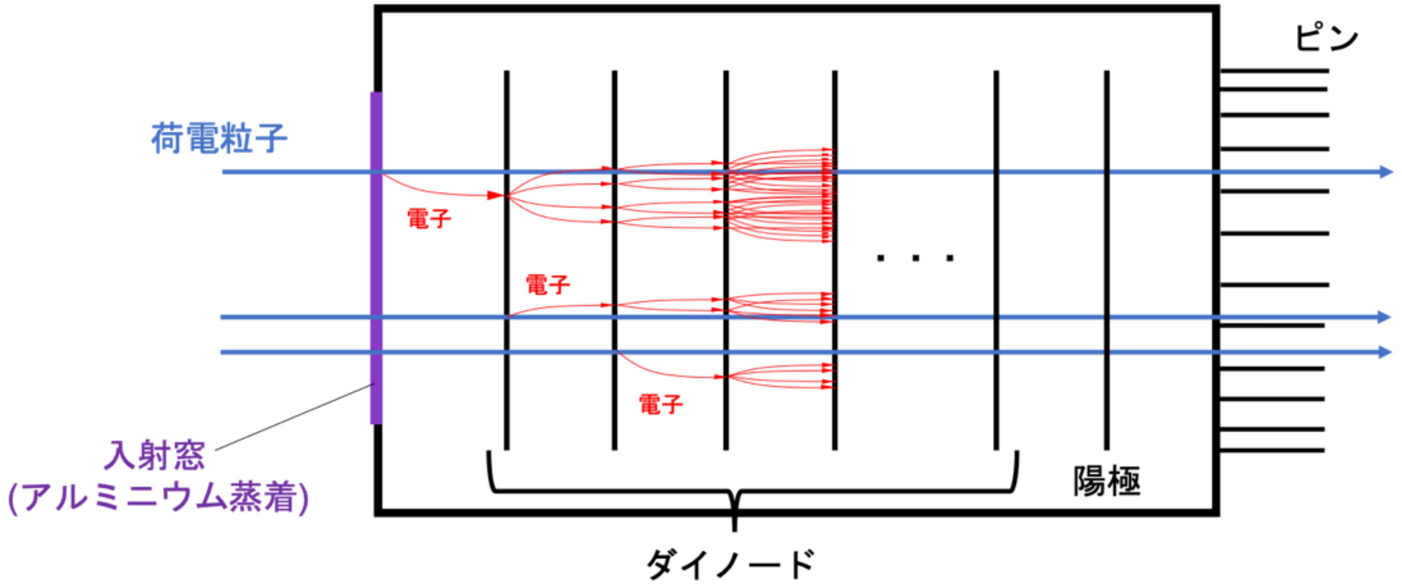


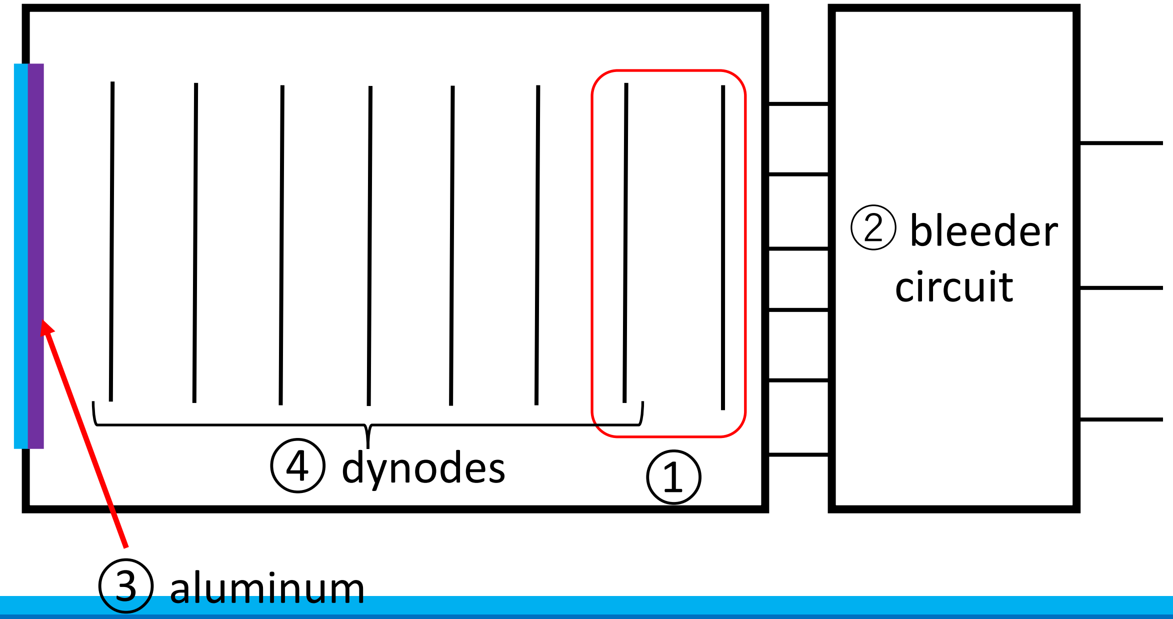
- Temperature rises when the beam is irradiated and falls when the beam is stopped.
- The outside of the support enclosure at the T2K site may have similar temperature changes.

2. Degradation of the bleeder circuit

- To evaluate whether the cause of degradation is in the EMT itself or in the circuit
- Two EMTs (A, B) and two bleeder circuits (Ⅰ , Ⅱ)




ピン
荷電粒子
電子
電子
電子
入射窓
(アルミニウム蒸着)
陽極
ダイノード


② bleeder circuit
④ dynodes
①
③ aluminum