Upgrades to the Beam Position and Profile Interlock Scheme for the J-PARC Neutrino Beam Line

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12th International Workshop on
Neutrino Beams and Instrumentation

About T2K Experiment

- Neutrino sector might have ~1000 times larger CP violation than quark sector's one.

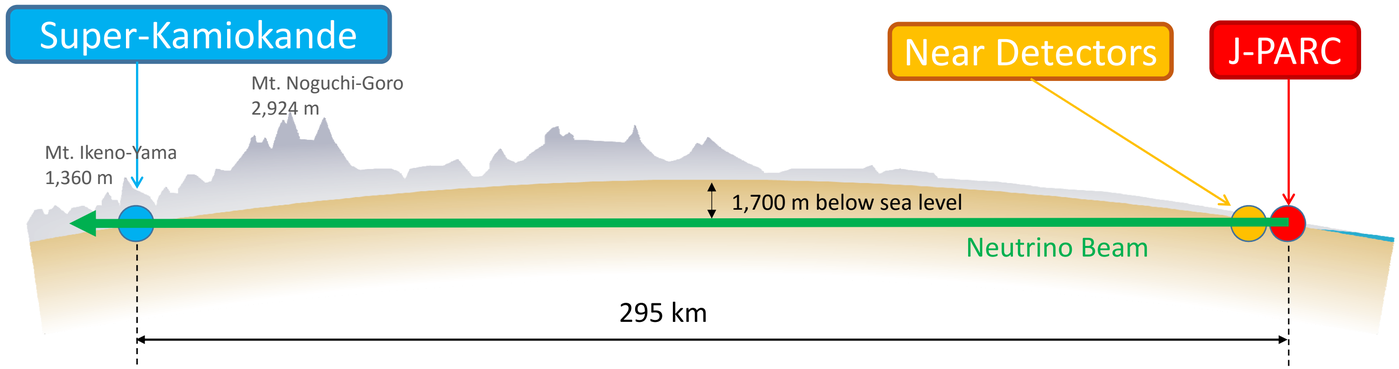
- The T2K experiment has observed neutrino oscillation and measured oscillation parameters. CP conservation scenario is discarded with ~2σ confidence level.
  →We need more statistics!

3 generation neutrino mixing matrix：

$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Mixing angle：$c_{ij} \equiv \cos\theta_{ij}$, $s_{ij} \equiv \sin\theta_{ij}$

Complex phase：δ_{CP}



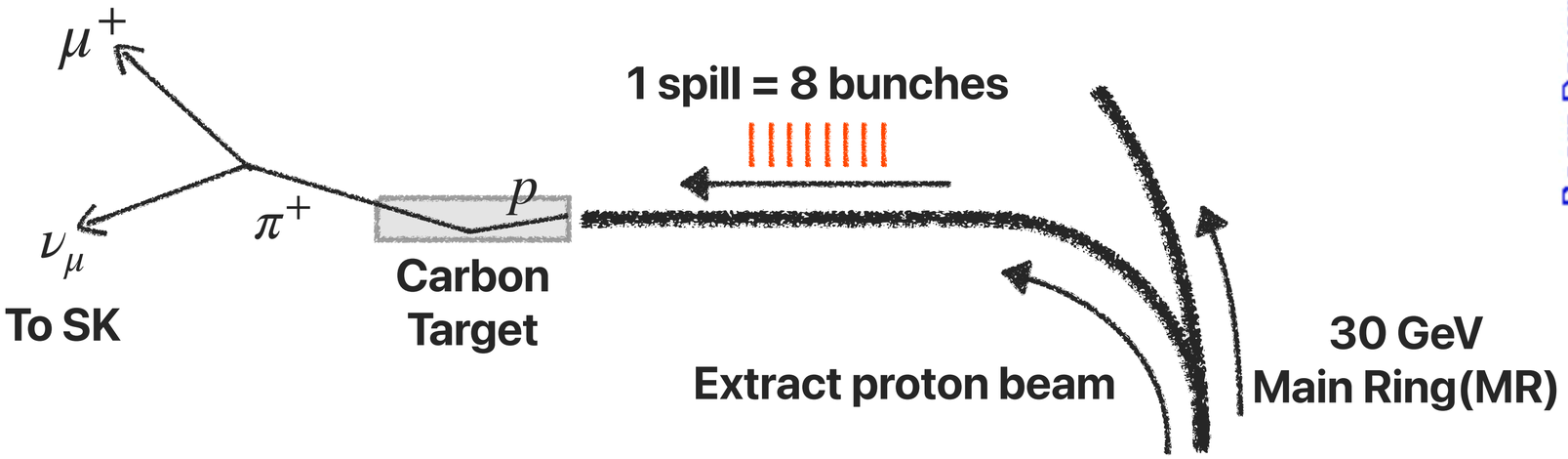
ν_μ, ν_e, ν_τ / $\bar{\nu}_\mu, \bar{\nu}_e, \bar{\nu}_\tau$ ← Neutrino Oscillation ← ν_μ / $\bar{\nu}_\mu$

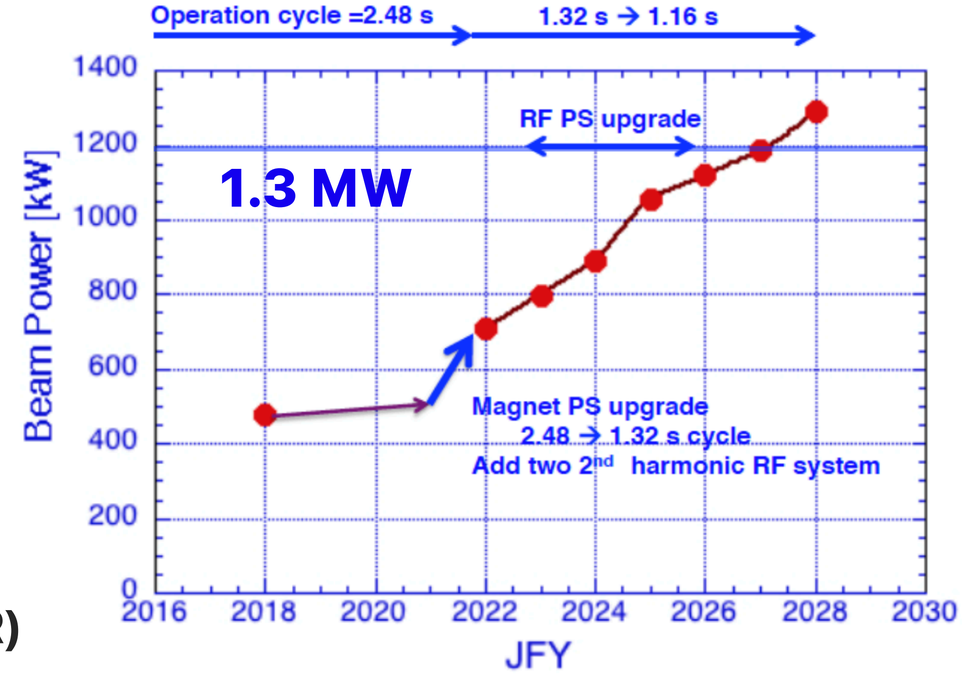
Proton Beam Intensity Upgrade for T2K

- Proton beam upgrade from 510 kW→1.3 MW for more statistics.

	Repetition Cycle	Protons Per Pulse	Beam Intensity
Now	2.48 s	2.6×10^{14}	510 kW
Upgrade Goal	1.16 s	3.2×10^{14}	1.3 MW

- MR has prepared for 1.3 MW operation.
  →Plan to be available higher intensity neutrino beam from the next T2K run.





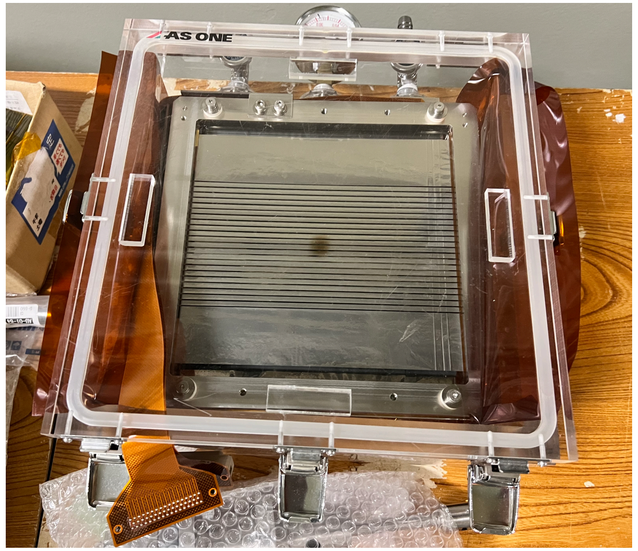
https://doi.org/10.18429/JACoW-IPAC2018-TUPAK005

Beam Interlock System (Legacy Method)

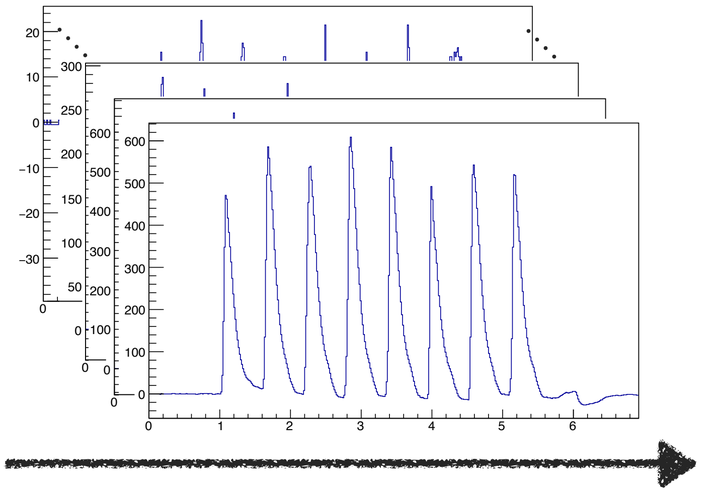
- Need machine protection system to prevent to break the target or other instruments from high proton beam intensity.

- Current method:
  Calculate beam irradiation position and width from the measured beam profile via software.
  - Beam position → mean of fitted gaussian
  - Beam width → RMS of fitted gaussian

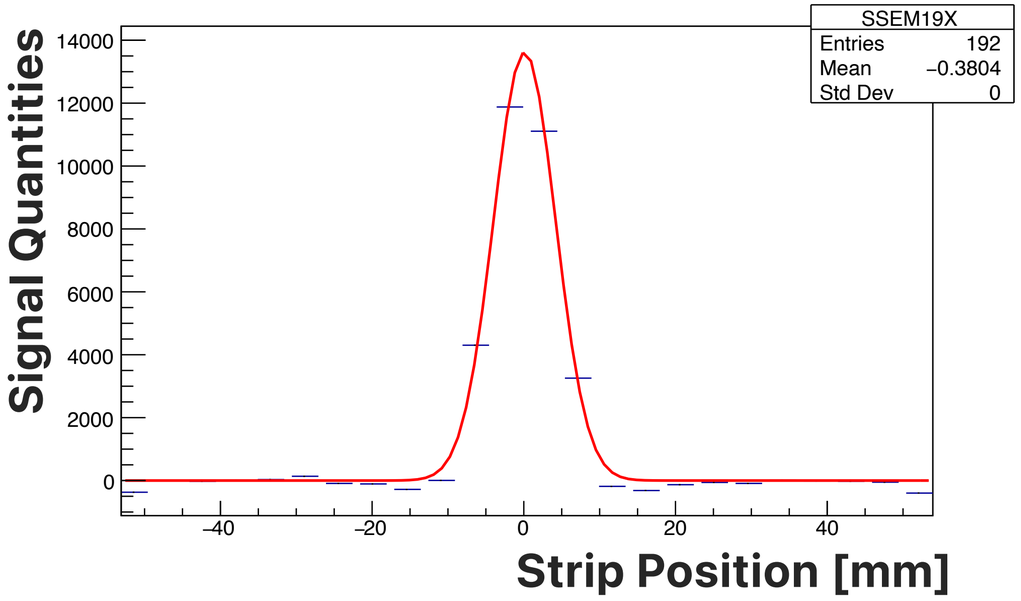
Beam Profile Monitor (24 Ti strips)



Beam Profile (24 channels)



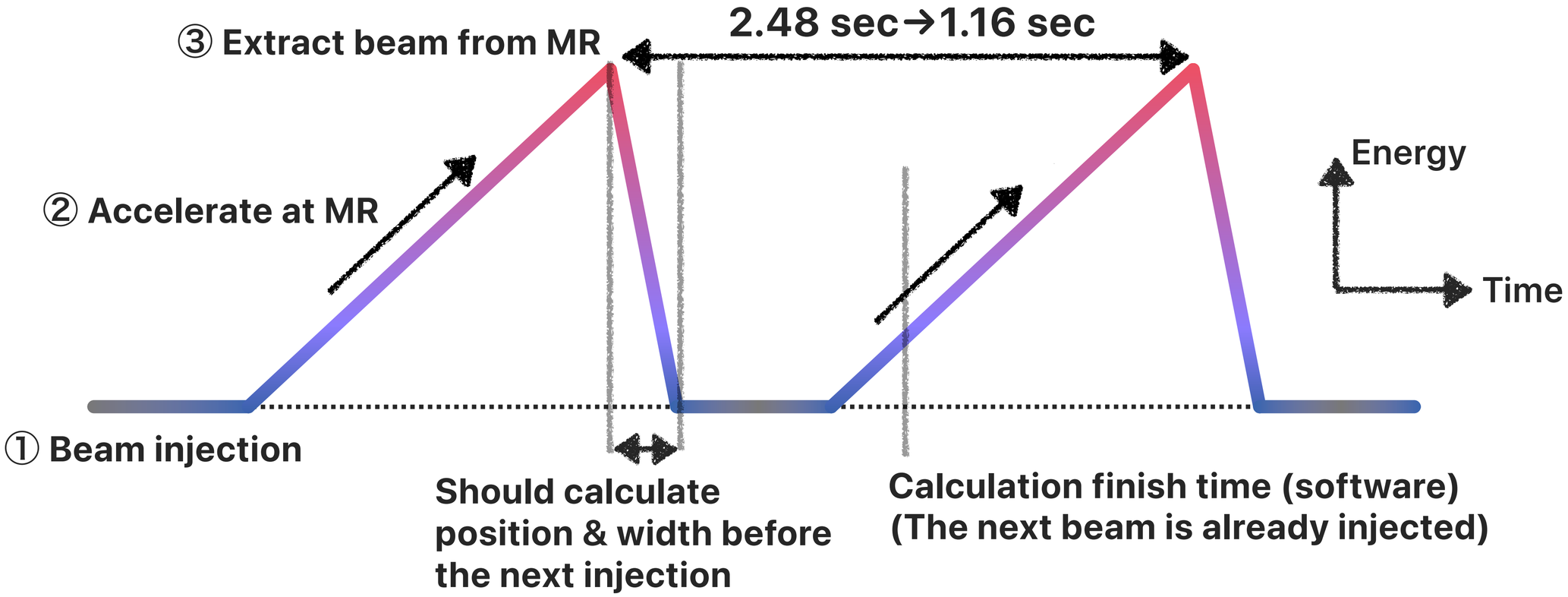
Fit with Gaussian



Tasks towards Beam Intensity Upgrade

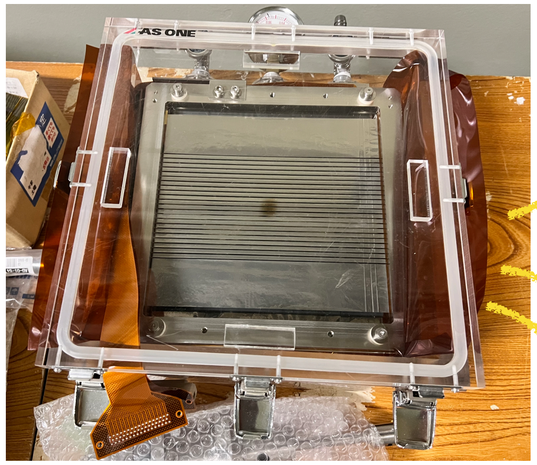
- The software calculation takes ~1 sec.
  →We can not calculate beam position and width before the next collision for 1.16s interval…

- **Develop new interlock module that calculates with faster time at FPGA** (This study).
  In this talk, we will show…
  - the results of beam test in April, 2021 @ J-PARC
  - development of new firmware and the results of its device test

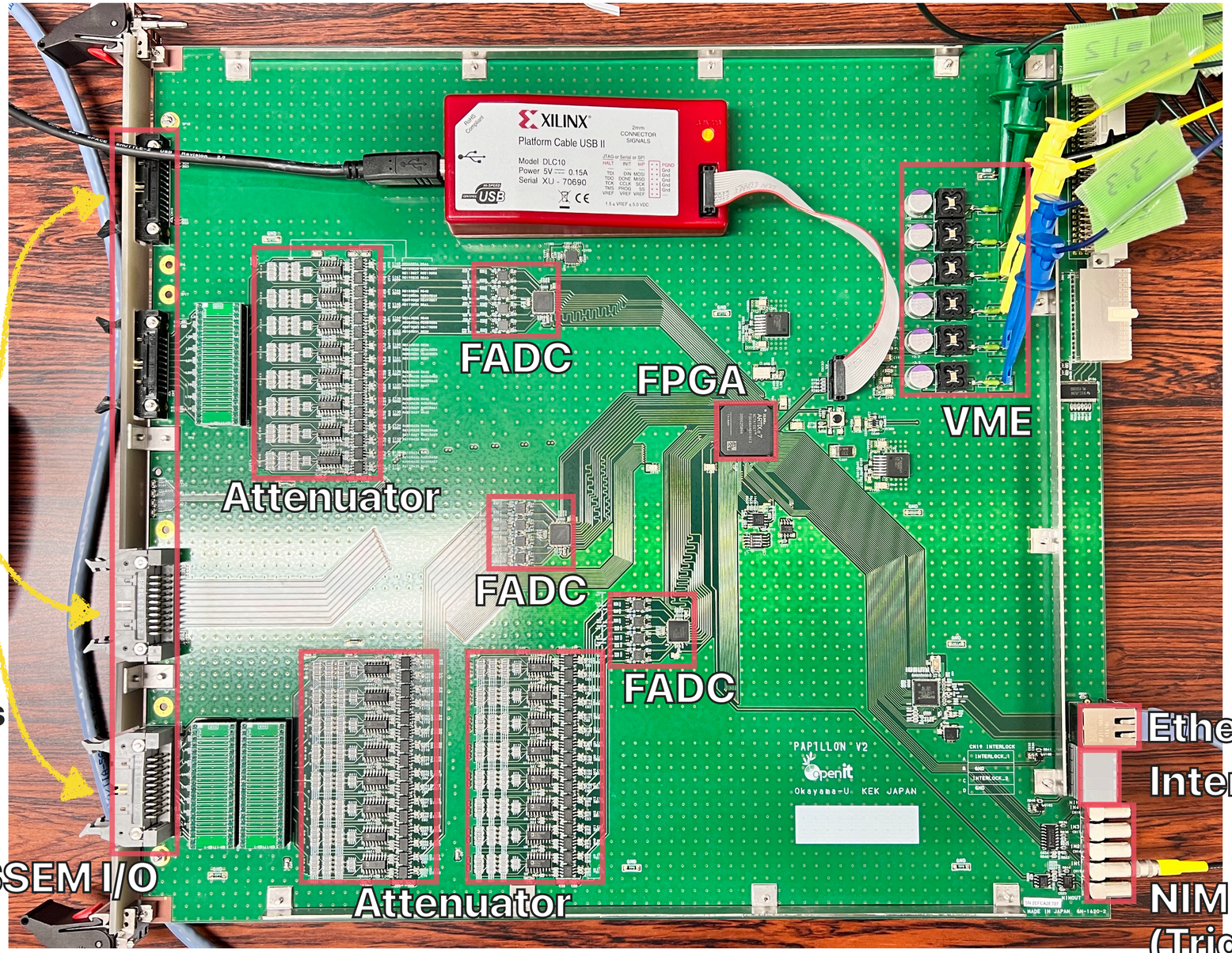


New Beam Interlock Module; PAPILLON

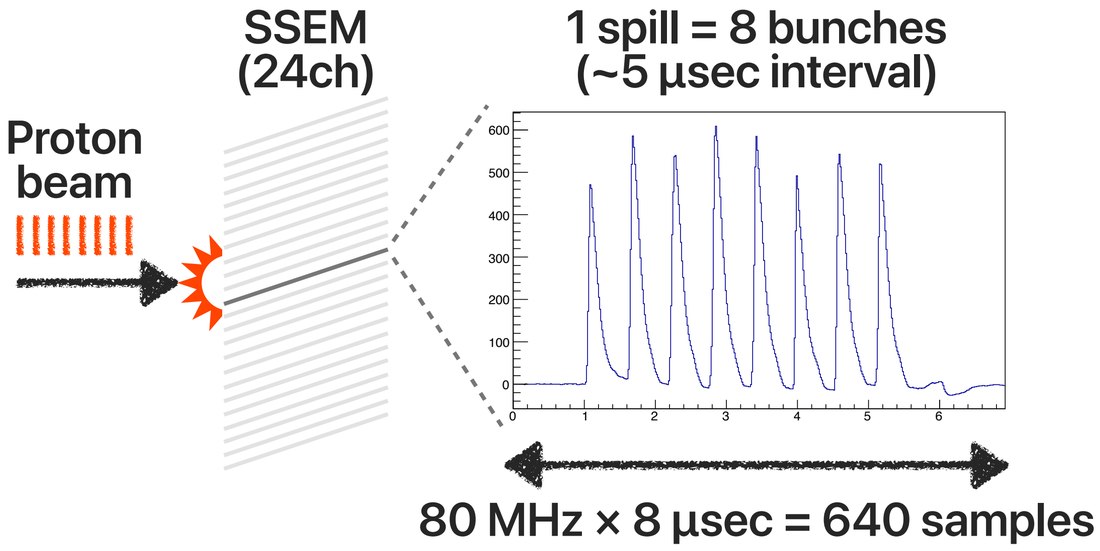
Beam Profile Monitor
(Segmented Secondary Emission Monitor; SSEM)

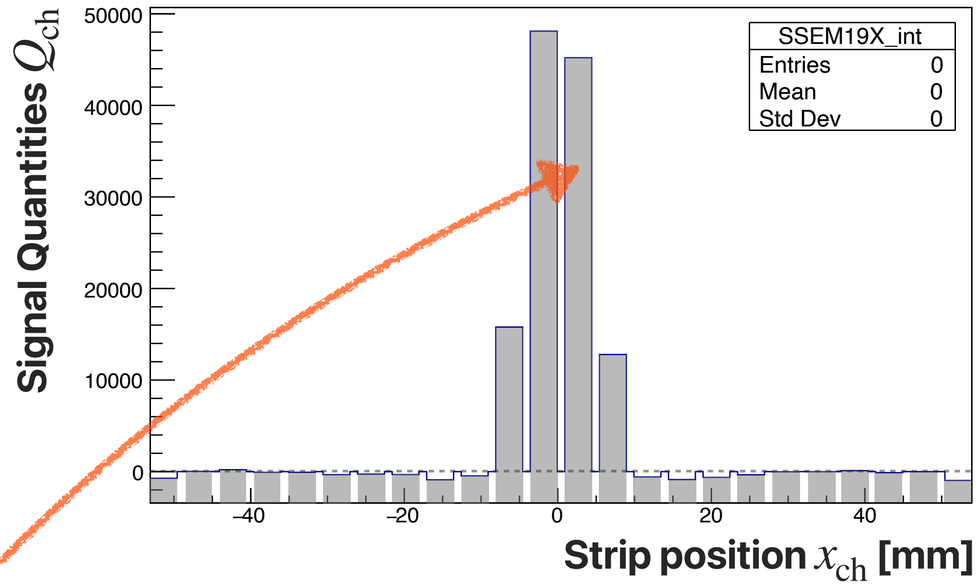


24ch inputs

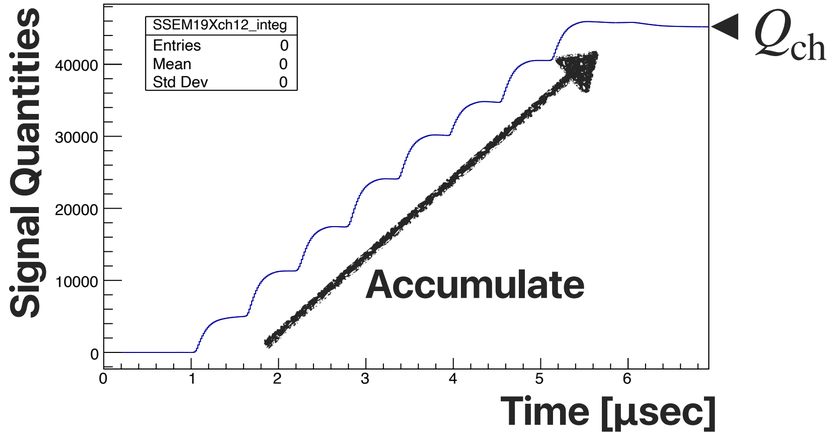


Calculation in PAPILLON Firmware (2018ver)





①Accumulate signal quantities Q_{ch} for 8 μsec time window



②Get Q_{ch} for 24 channels, and calculate beam position & width

Beam position: $X[\mathrm{mm}] = \dfrac{\sum_{ch=0}^{23} Q_{ch} \times x_{ch}}{\sum_{ch=0}^{23} Q_{ch}}$

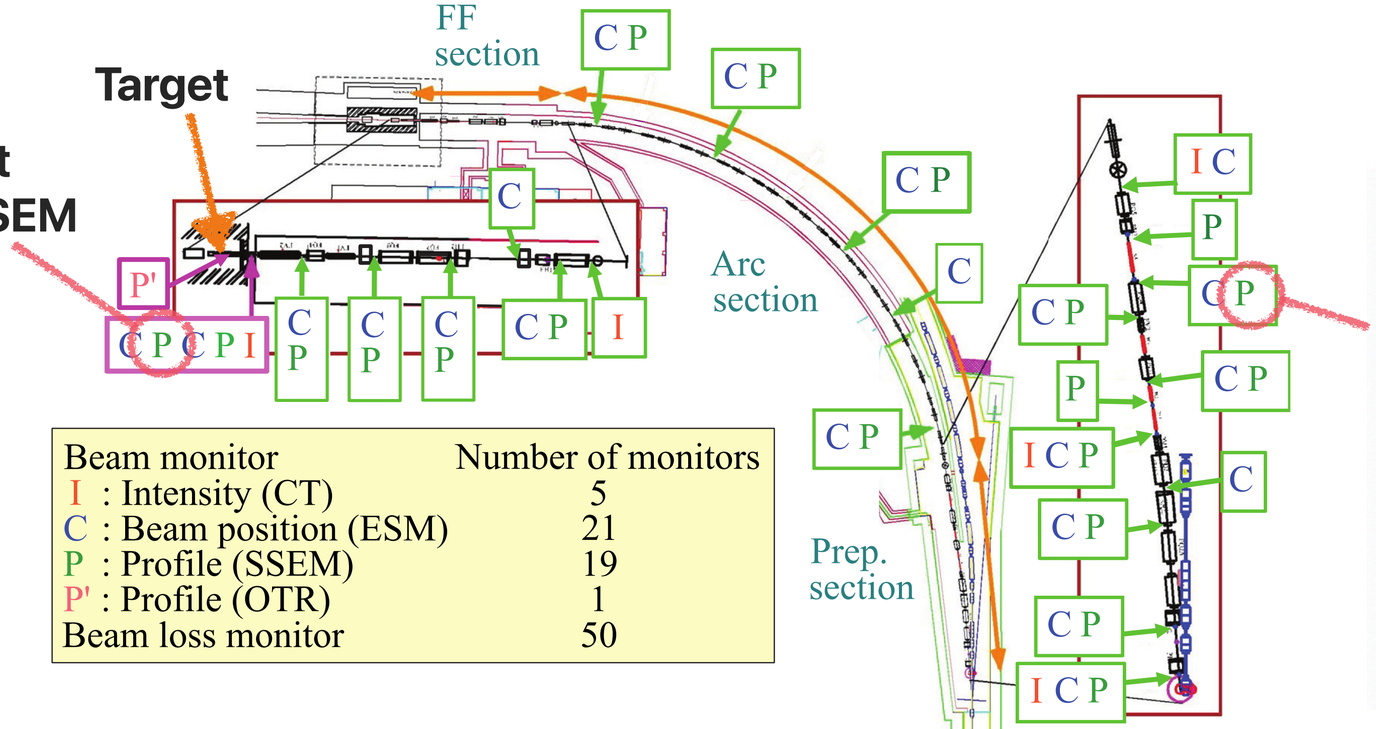
Beam width: $\sigma_X[\mathrm{mm}] = \sqrt{\dfrac{\sum_{ch=0}^{23} Q_{ch} \left(x_{ch} - X \right)^2}{\sum_{ch=0}^{23} Q_{ch}}}$

Beam Test in April, 2021

- We already confirmed that PAPILLON realized the offline analysis results with upper stream SSEM(06).

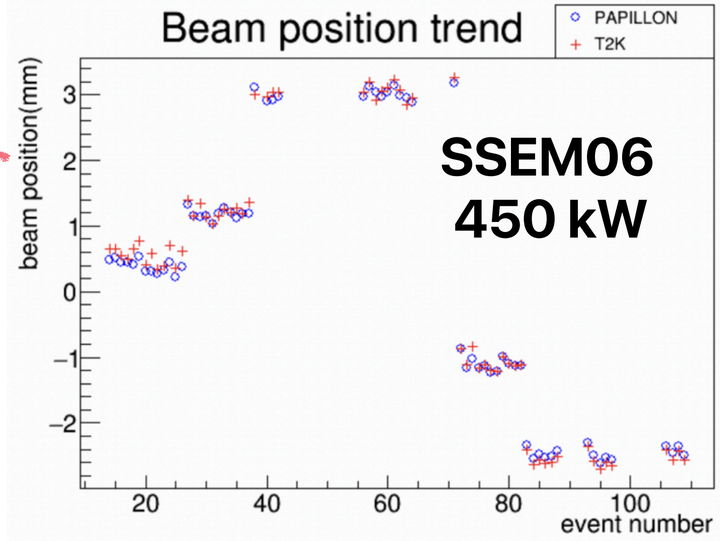
- But, only the most down stream SSEM(19) is installed at actual T2K run.
  →Performed beam test with SSEM19 in April, 2021 at J-PARC.
  1. **Can PAPILLON realize offline analysis with the most downstream SSEM?**
  2. **Is PAPILLON calculation stable?**

Use the most down stream SSEM



Beam monitor	Number of monitors
I : Intensity (CT)	5
C : Beam position (ESM)	21
P : Profile (SSEM)	19
P' : Profile (OTR)	1
Beam loss monitor	50

Results with sixth SSEM (Previous study in 2018)

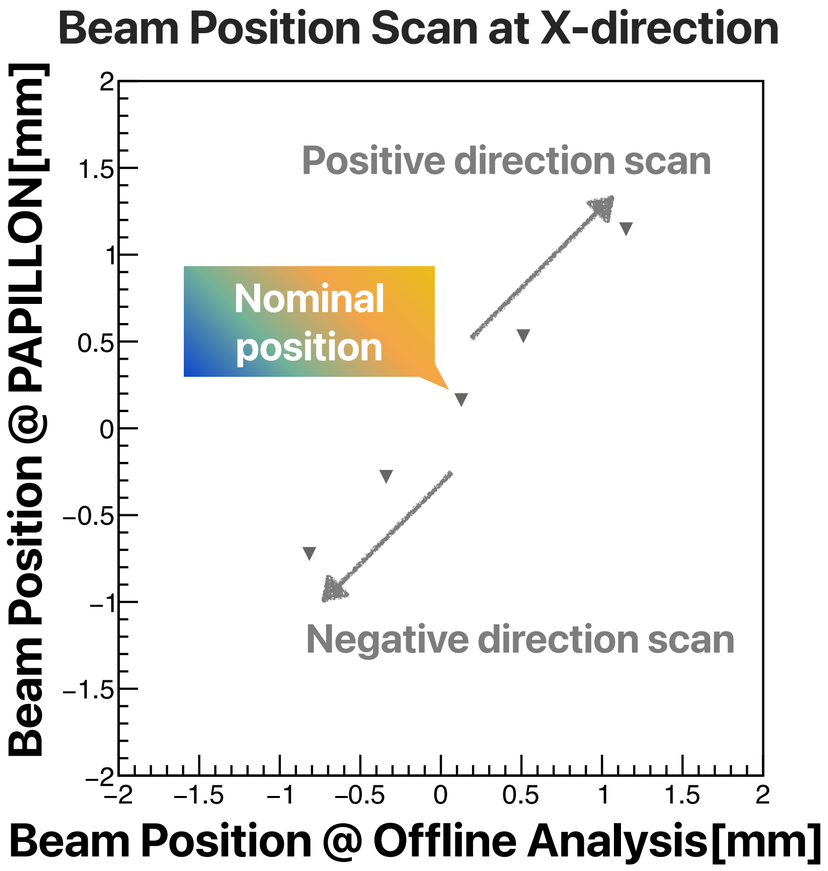


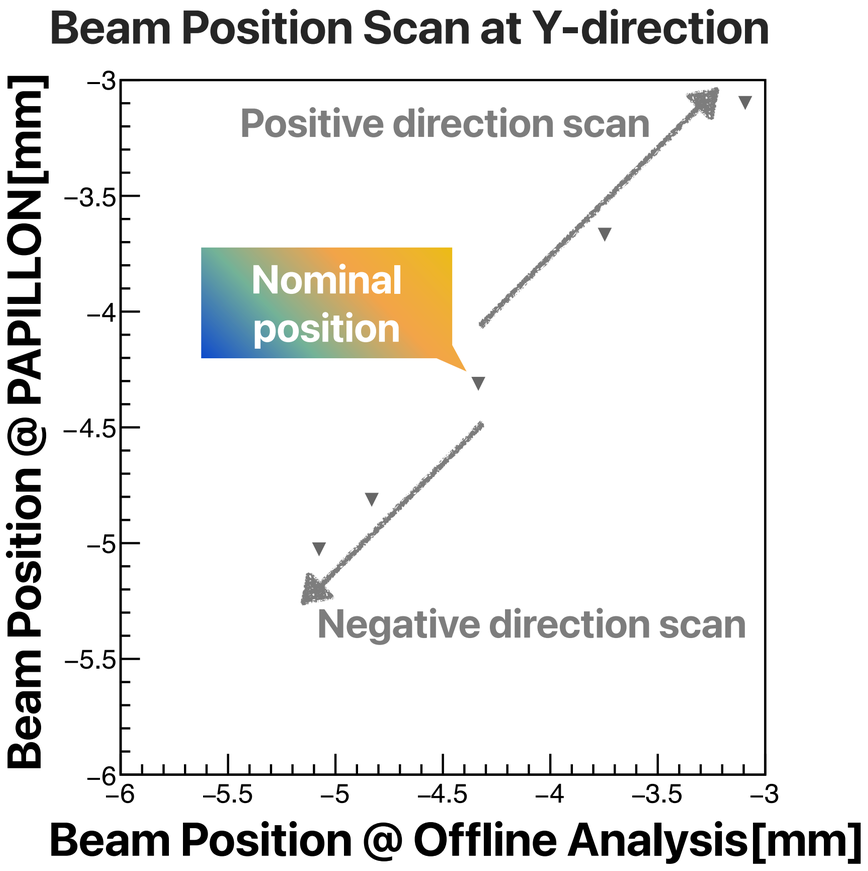
Linearity Test of Beam Position Calculation

Test Item ①

Can PAPILLON realize offline analysis with SSEM19?

- Took 10 shot data for each beam position scan ± 0.5 - 1 mm from the nominal position.
  →Good linear correlation between PAPILLON and offline analysis was confirmed.



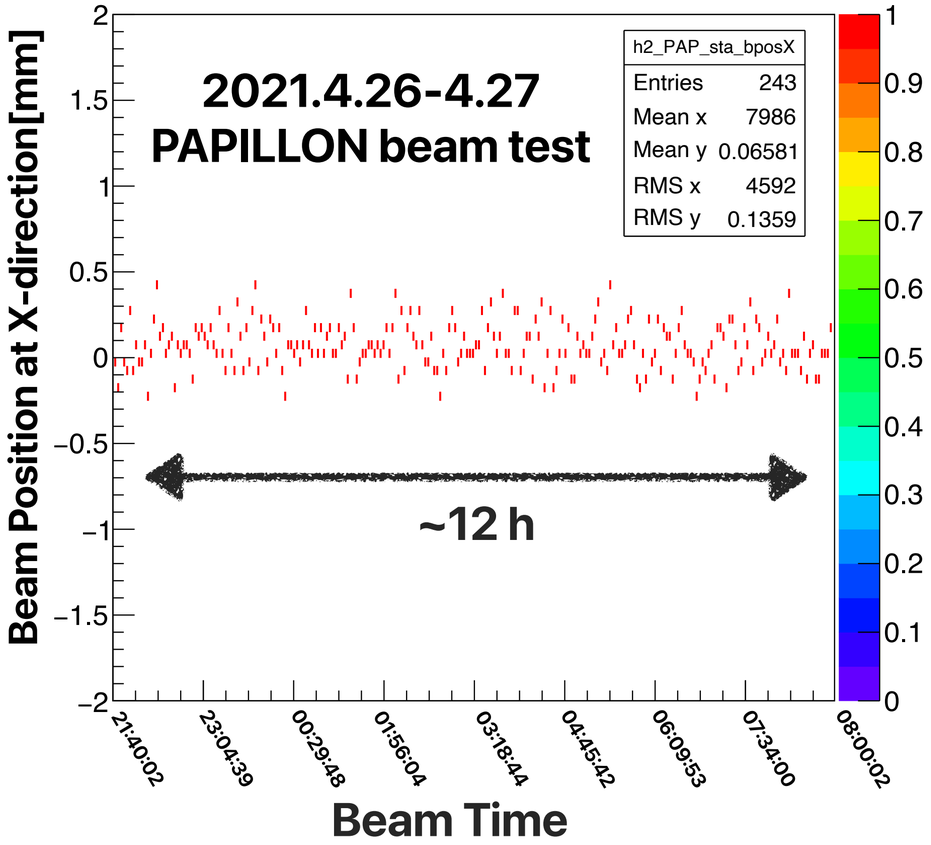


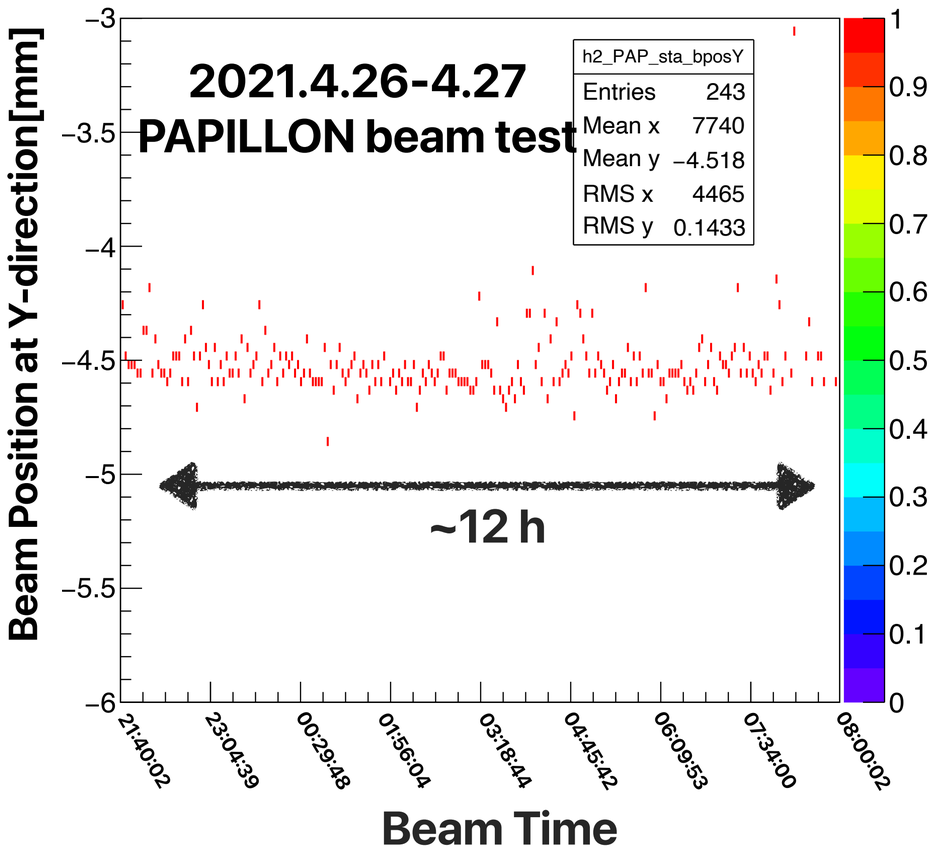
Stability Test of PAPILLON Calculation

Test Item ②

Is PAPILLON calculation stable?

■Checked stability of PAPILLON calculation by long run of ~12 h.
→Position calculation is stable with smaller fluctuations than the interlock threshold(<1.5 mm).





Summary of Beam Test

- Performed beam test with SSEM19 in April, 2021 at J-PARC.
  1. Can PAPILLON realize offline analysis with SSEM19?
  2. Is PAPILLON calculation stable?

- We could confirm
  - **good linearity** of beam position calculation between PAPILLON and offline analysis
  - **good stability** of PAPILLON calculation with fluctuations smaller than interlock threshold

- What we should develop as a new firmware:
  - **Calculate pedestal for each spill in PAPILLON firmware.**

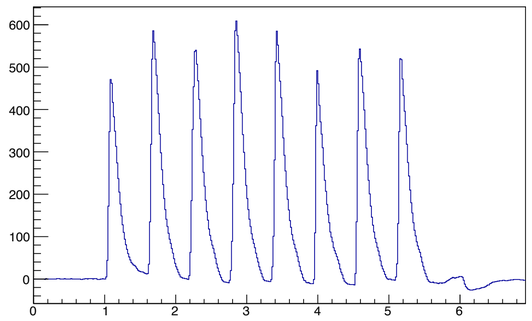
    (Currently, the fixed pedestal values are input from outside)
  - **Implement the interlock condition of beam width.**

    (Beam width calculation itself is already implemented)

Pedestal Calculation at PAPILLON

- Current firmware:
  Input pedestal values as parameters from outside of the board.
  →This method is not practical at actual run 🥺

- Can we calculate pedestal in firmware?
  PAPILLON ADC takes 640 samples per spill.
  →Use former 64 samples for pedestal calculation
  and later 576 samples for position & width calculation.



640 samples

64 samples | 576 samples

Use in pedestal calculation

Calculate position and width from pedestal-subtracted wave form

Behavior of New Firmware at Test Bench

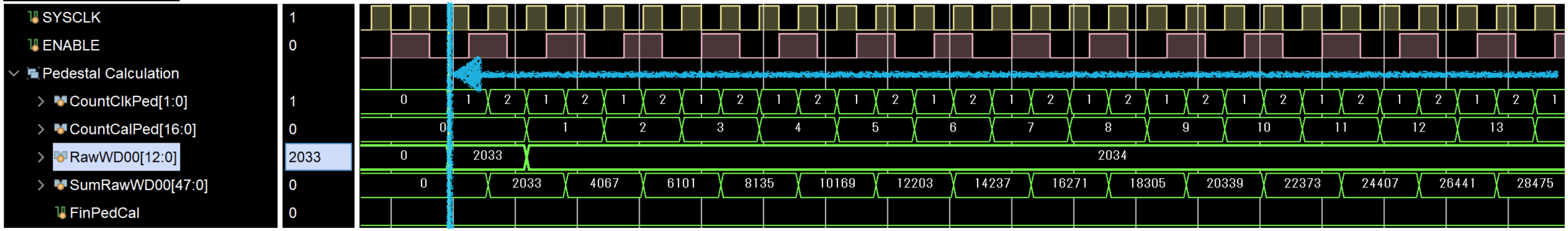
Development Item ①

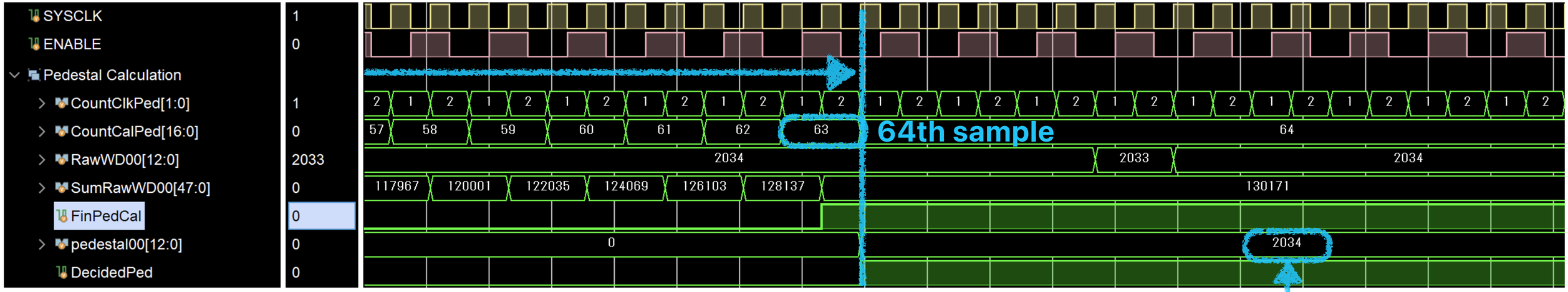
Pedestal calculation at firmware

→Implemented pedestal calculation as average of former 64 samples.

Test Bench

Start summation (up to 64th sample)





Calculated!

Behavior of New Firmware at Test Bench

■Current firmware:
Interlock condition is applied for only beam position (if <1.5 mm, fire)

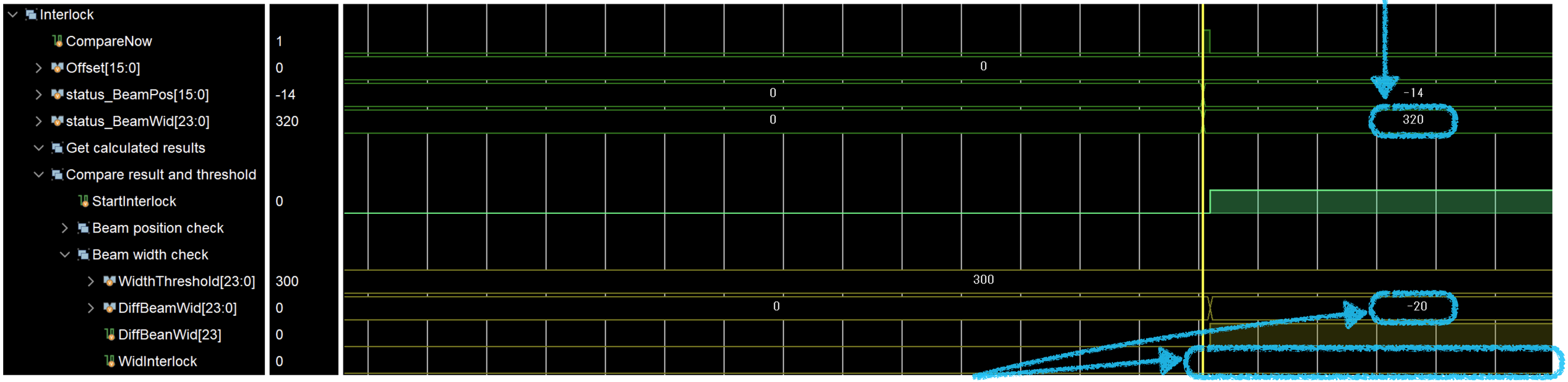
Development Item ②

Implementation of interlock condition of beam width

Implemented condition: If $W < W_{\mathrm{min}} \Rightarrow W_{\mathrm{min}} - W > 0$, fire interlock ($W_{\mathrm{min}} = 3\ \mathrm{mm}$)

Test Bench

Beam width was 3.2 mm

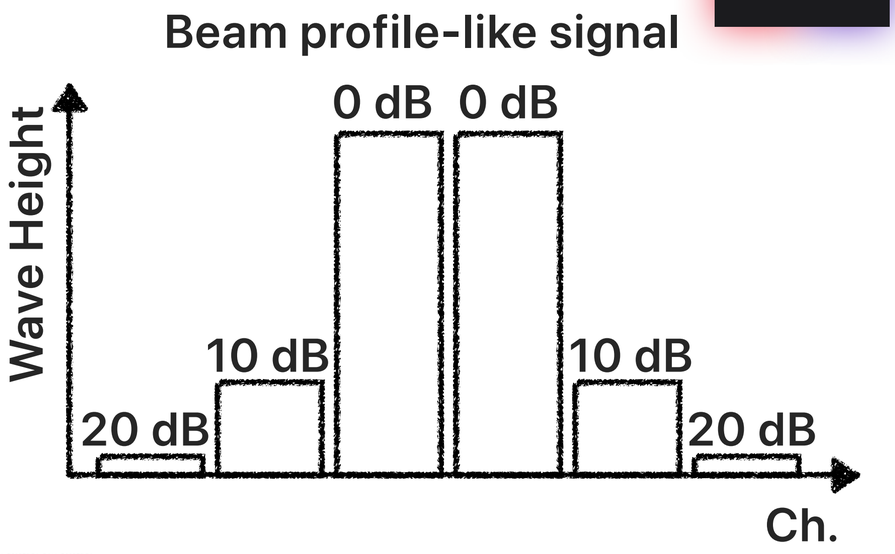


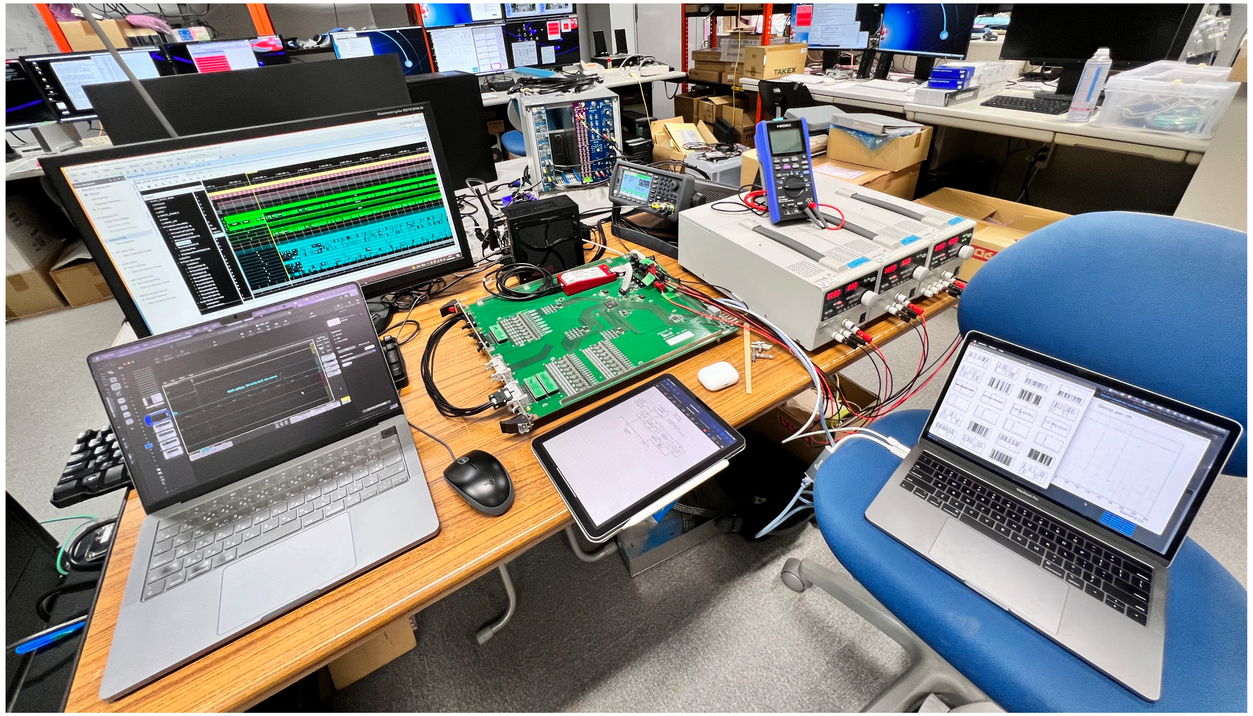
Since $W_{\mathrm{min}} - W = -0.2\ \mathrm{mm}\ (W > W_{\mathrm{min}})$, interlock was LOW here.

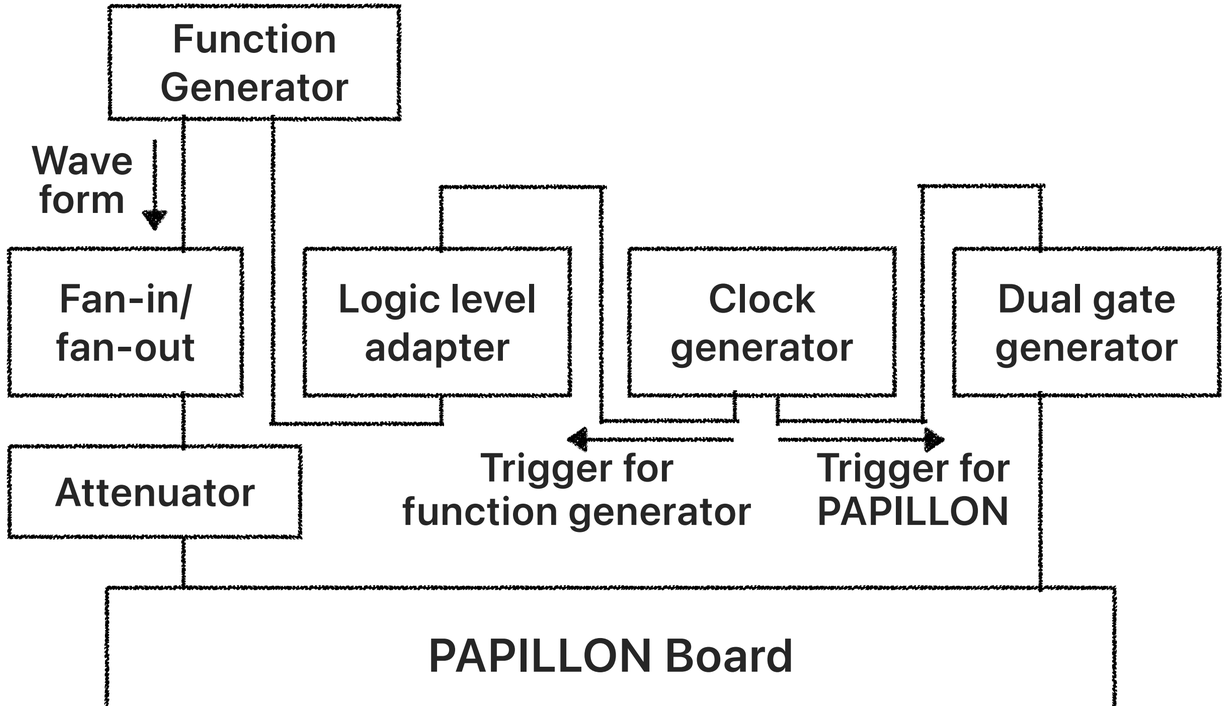
Actual Device Test of New Firmware

- T2K has been shutting down until beginning of 2023.
  →Performed “pseudo-beam test” by beam profile-like signal.

- Use six channels, and input 800 mVpp half sin wave.

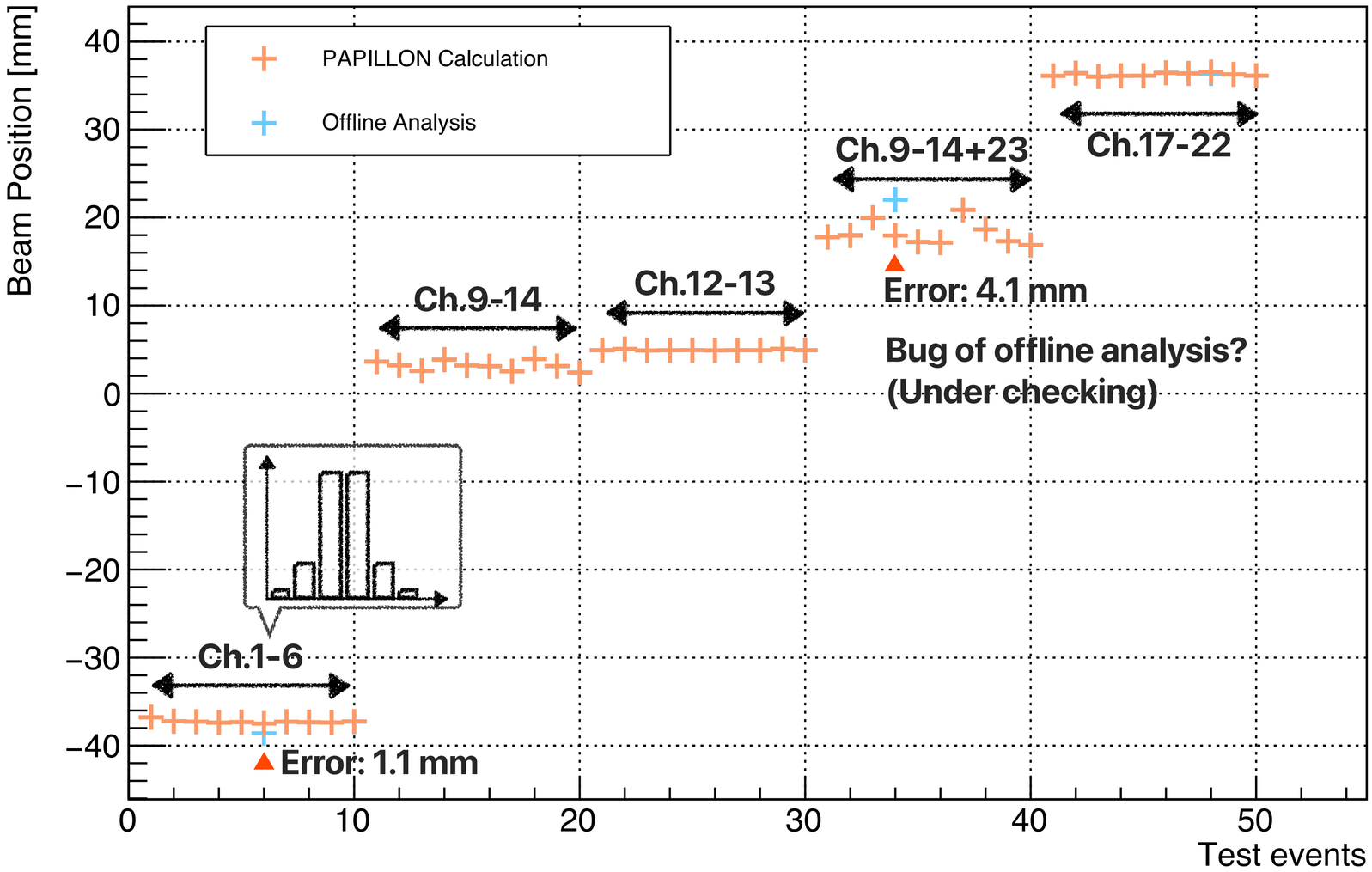






Results of Actual Device Test (Beam Position)

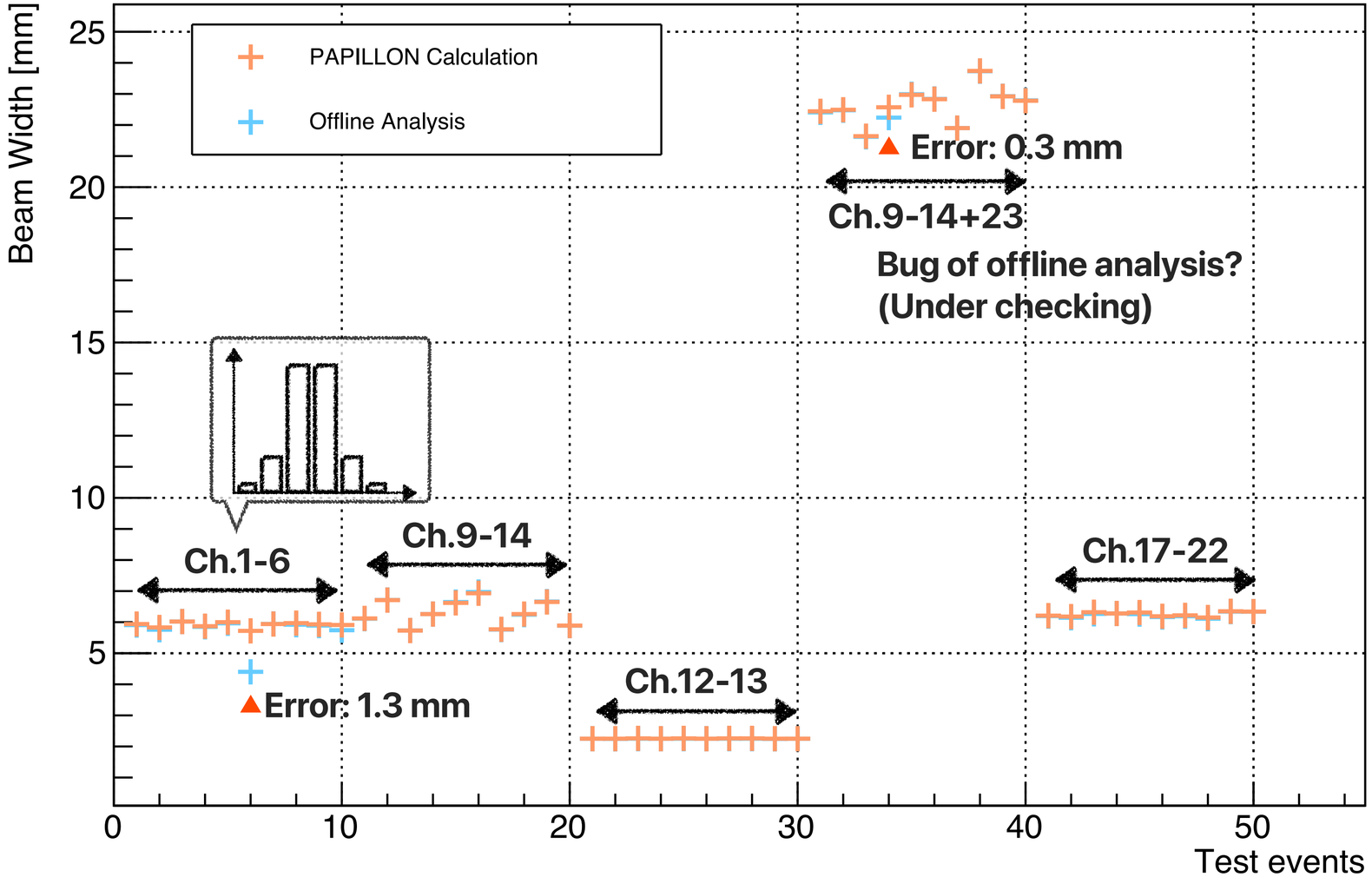
- 800 mVpp, 3 MHz half sin wave.
- Change strip channels in which dummy signal are injected, and took 50 data as total.
- Matched by O(0.01) mm level, but we have two points with several mm level discrepancies.



NOTE)
Offline analysis means the same calculation method as PAPILLON on software here.

Results of Actual Device Test (Beam Width)

- 800 mVpp, 3 MHz half sin wave.
- Change strip channels in which dummy signal are injected, and took 50 data as total.
- Matched by O(0.01) mm level, but we have two points with several mm level discrepancies.



NOTE)
Offline analysis means the same calculation method as PAPILLON on software here.

Summary

- T2K experiment has prepared 1.3 MW operation for much statistics.
  Repetition time: 2.48 sec→1.16 sec

- Beam interlock system can calculate beam position & width with the sufficient short time?
  Now: calculate with software (~1 sec)
  →**Develop new interlock module(PAPILLON) that calculates with faster time at FPGA**.

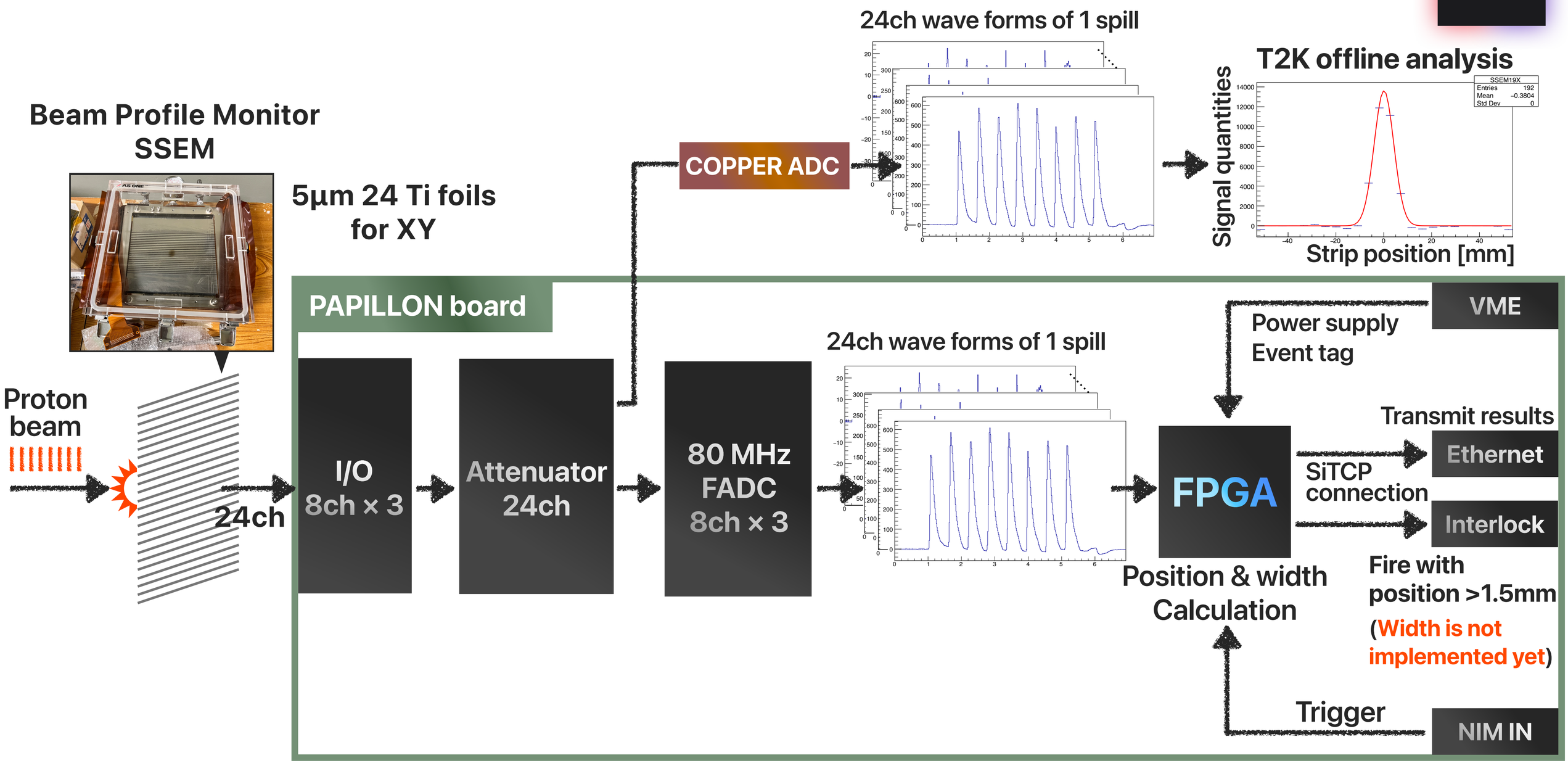
- Development items:
  - Calculate pedestal for each spill in PAPILLON firmware.
  - Implement the interlock condition of beam width.

  →Performed the actual device test with beam profile-like signal.
  Matched by O(0.01) mm level between PAPILLON and software calculation.

- We plan to conduct final test of PAPILLON with real beam at J-PARC next year.
  - Linearity of beam width calculation?
  - Value of interlock threshold of beam width?

Back up

Block Diagram of PAPILLON Board

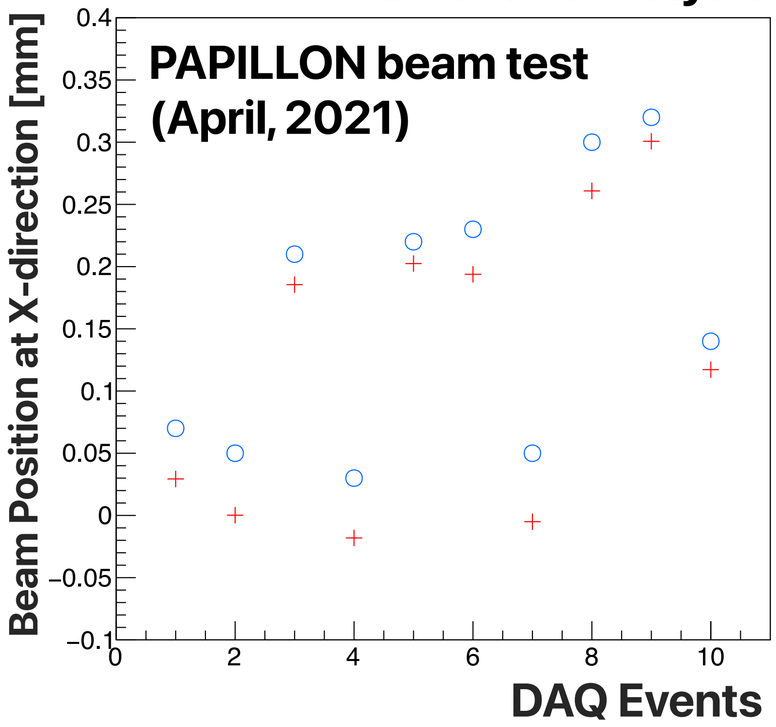


Calculation Results Event by Event

■Checked beam position and width with beam test data event by event.
→Beam position has good agreement with offline analysis results.
Beam width also realizes the trend of offline analysis results.

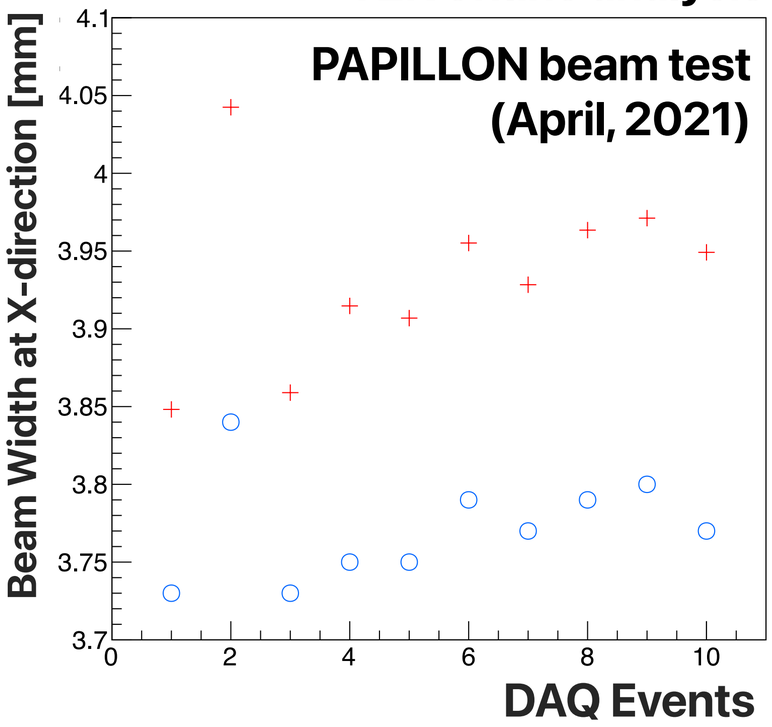
Beam Position Calculation

○ : PAPILLON
＋ : T2K offline analysis



Beam Width Calculation

○ : PAPILLON
＋ : T2K offline analysis



Large Discrepancy?

- 800 mVpp, 3 MHz half sin wave @ ch.1-6.
- Signal is small @ Ch.10, 11 → inductors were broken.
- What is the reason? (Because of the board or inductors? or something bug?)