Monitor developments for MW-power proton beam at J-PARC extraction beamline

Son Cao (IFIRSE, ICISE), M. Friend (IPNS, KEK),
and other T2K collaborators

2024 July 9th, 20th Rencontres du Vietnam - PASCOS

Ref: "The legacy of neutrino oscillation experiments" by Jose W. F. Valle
"Neutrino mixing from Modular Flavor Symmetries" by Mu-chun Chen
and other neutrino-related talks (T2K, NOvA, IceCube, ...)

Neutrino flux uncertainty

(Anti-)Neutrino interaction models

Sterile neutrinos?
Non-standard physics

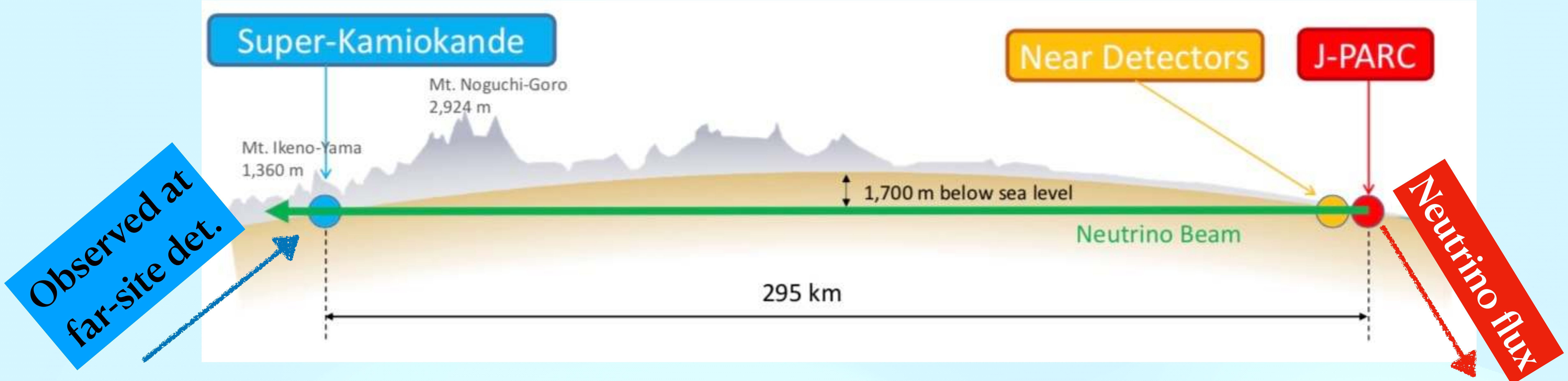
Neutrino mass ordering?

Leptonic CP violation?

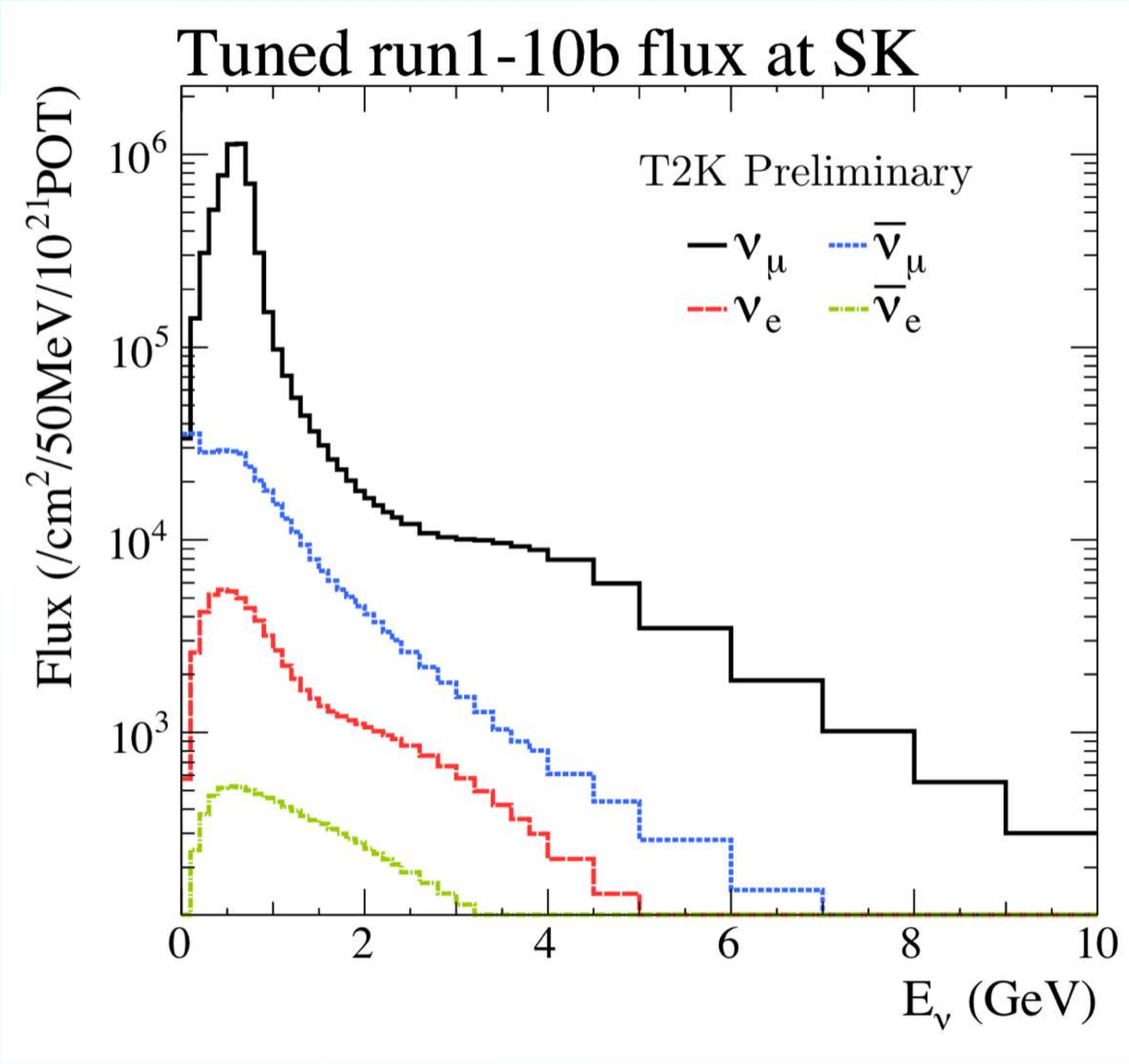
How close is θ_{23} to $\pi/4$?

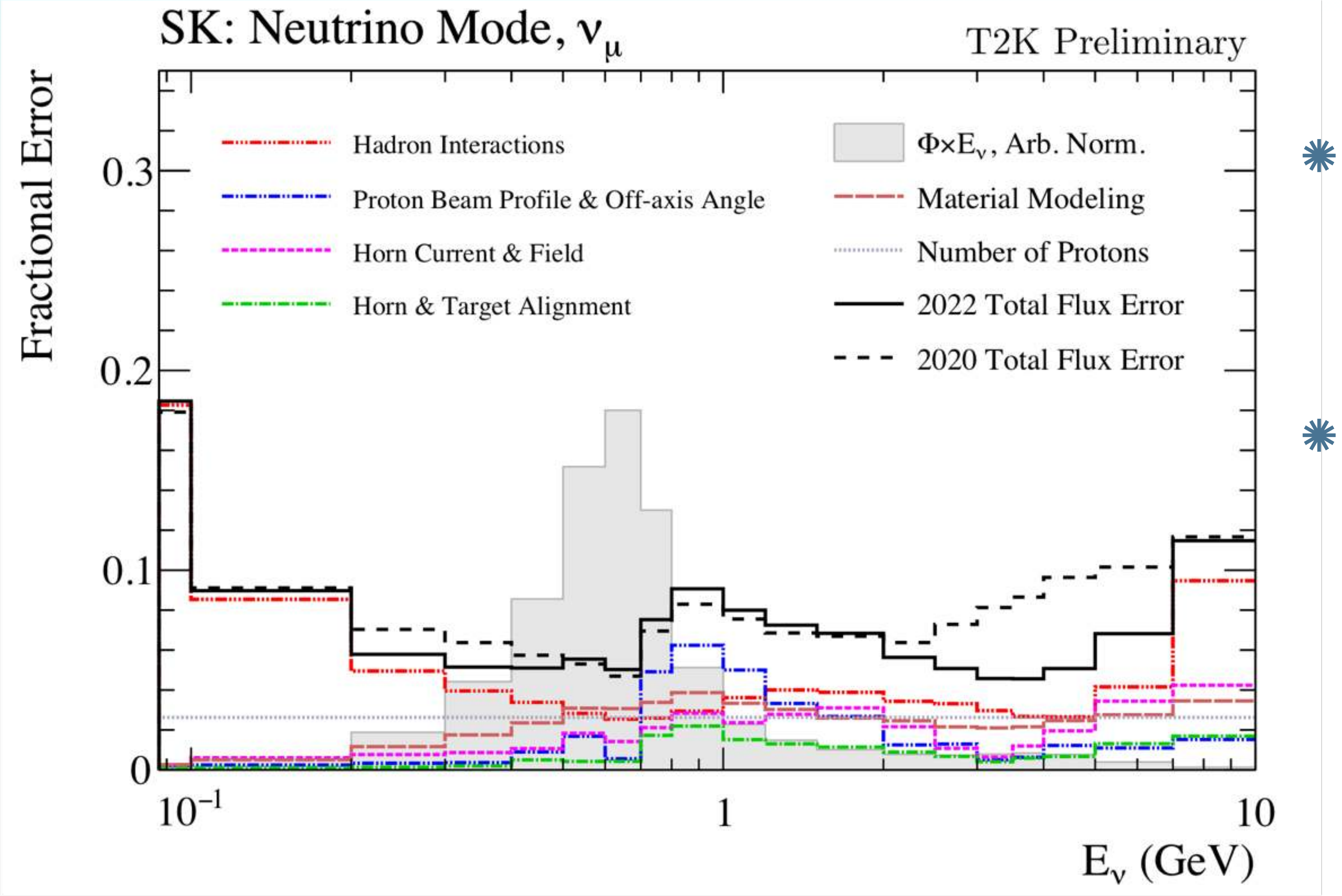
The completion for leptonic mixing and neutrino mass ordering is currently underway. Precision measurement of all relevant parameters will provide critical inputs for testing the flavor and neutrino mass models.

The need of intense and well-controlled neutrino beam



$$N^{\nu_\beta}(E_\nu^{reco.}, \vec{o}) = R_{det.}(E_\nu^{true.}, E_\nu^{reco.}) \times \sigma_{int.}^{\nu_\beta}(E_\nu^{true}) \times P(\nu_\alpha \to \nu_\beta \,|\, E_\nu^{true}, \vec{o}) \times \Phi_{flux}^{\nu_\alpha}(E_\nu^{true})$$



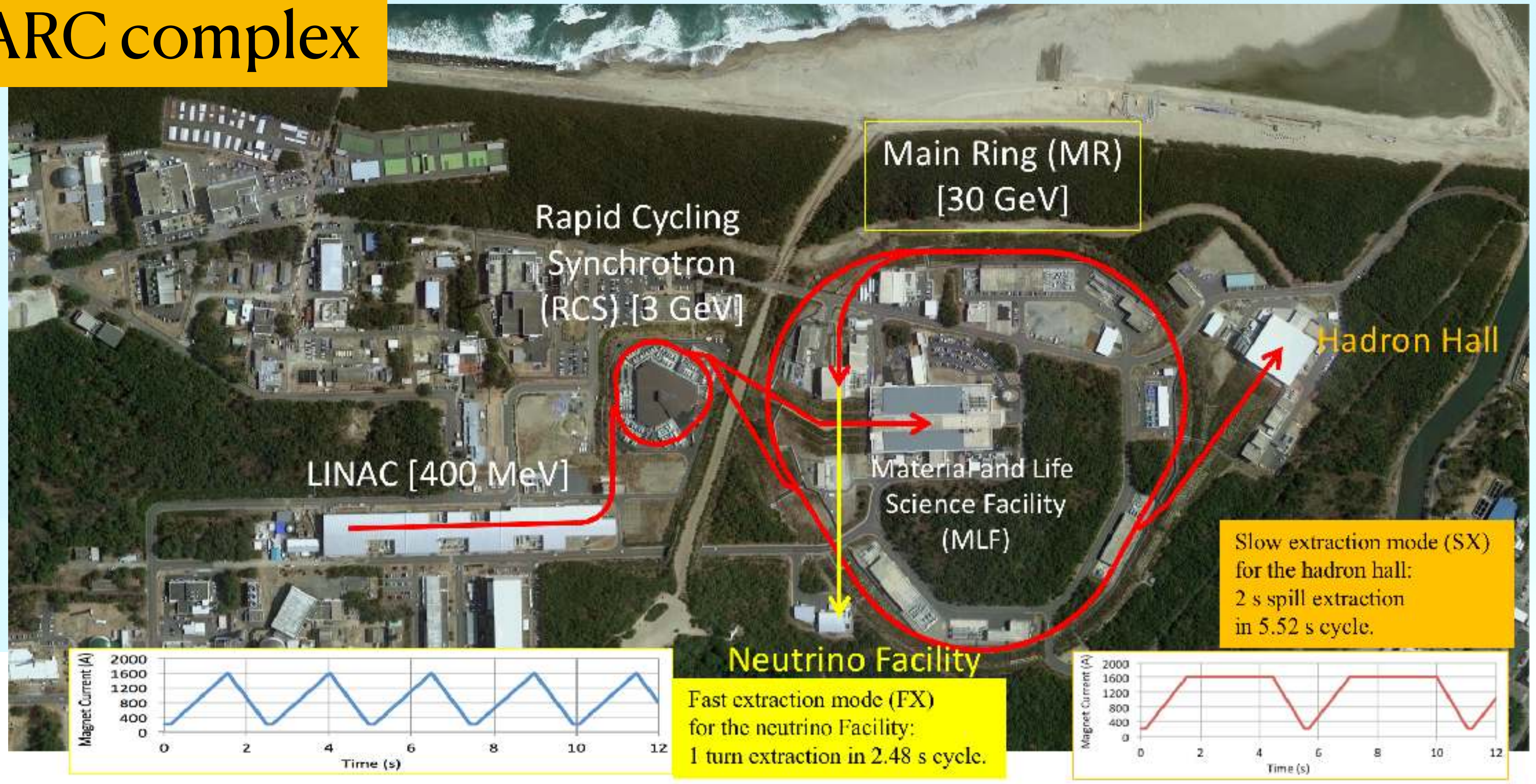


- Intense neutrino flux is needed for increasing the sample statistics
- Flux uncertainty mainly comes from ***hadron production, proton beam position at target, and horn condition***. ~5% at the peak energy (0.6 GeV)

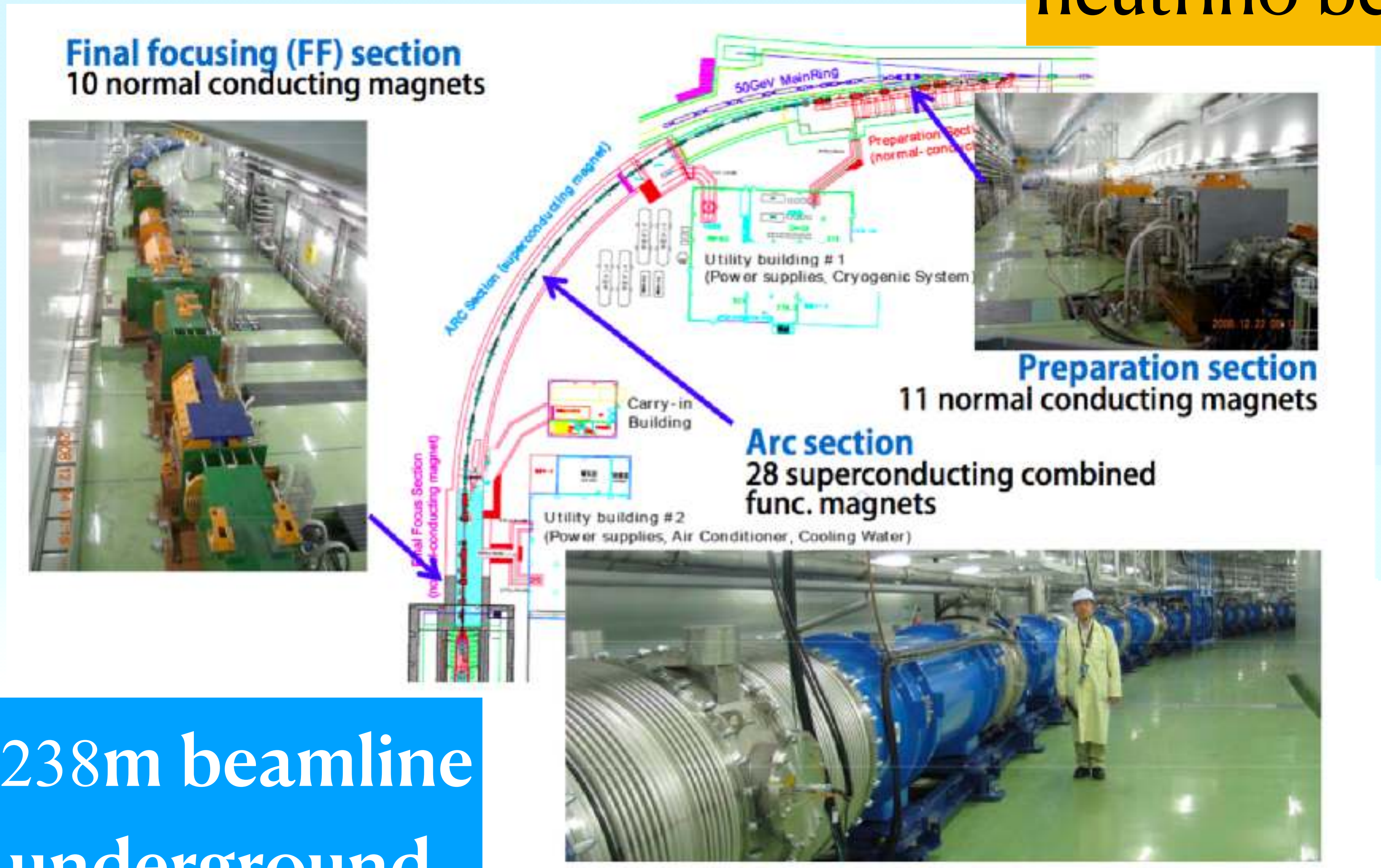
J-PARC extraction neutrino beamline

To provide intense and well-controlled neutrino beam for long-baseline neutrino oscillation experiments, on-going T2K and upcoming Hyper-Kamiokande

J-PARC complex



neutrino beamline

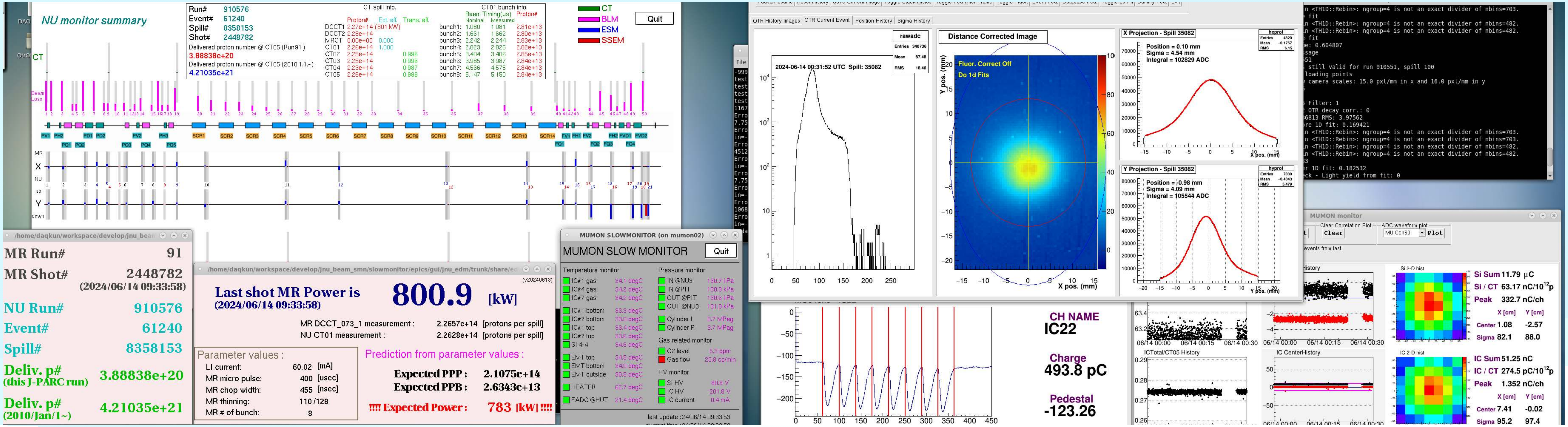


~238m beamline underground

Beam power	750kW (proposed)	800kW (achieved)	1.3 MW (targeted)
Beam intensity (proton-per-pulse)	2.1E+14	2.3E+14	3.2E+14
Repetition cycle	1.32s	1.36s	1.16s

To realize MW beam, equipment robustness against high intensity, **beam loss tolerability**, handling the radioactive waste and precisely and **continuously monitoring the beam profile** are essential.

Overview of beam monitors at J-PARC extraction neutrino beamline



A glance at beam monitor signals/ records with 800kW-power proton beam (June 2024)

Critical beam info. for continuous operation

- Beam loss (by x50 Beam Loss Monitors (BLMs))
- Beam intensity (by x5 Current Transformers (CTs))
- Beam position (by x21Electrostatic Monitors (ESMs))
- Beam transverse profiles (center position and width)
  - x19 Segmented Secondary Emission Monitors (SSEMs)
  - Optical Transition Radiation Monitor (OTR)
- MUMON detector to monitor profile of produced muons

Ref: T2K NIM paper / M. Friend IBIC 2018

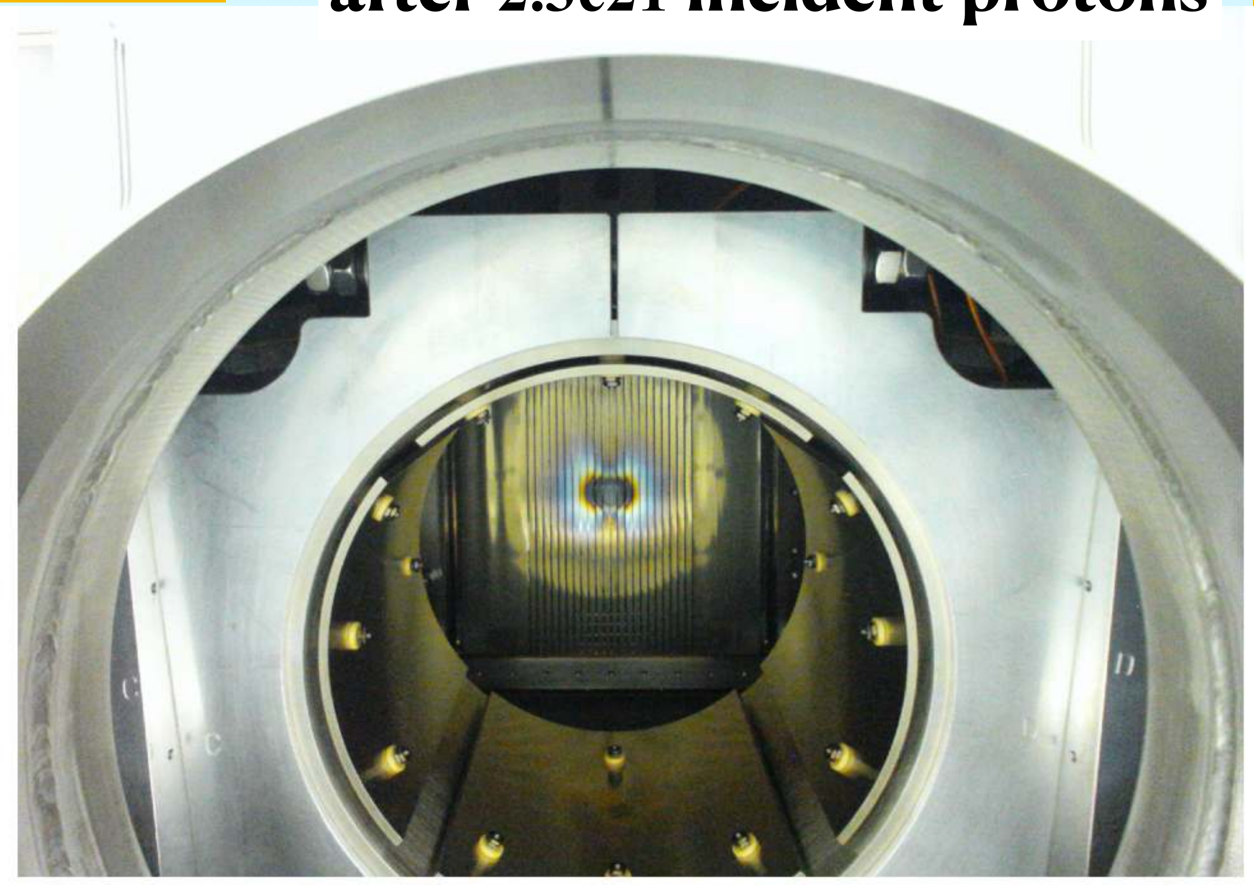
Consideration for beam monitor development

- Radiation-hard *or special arrangement considered*
- Minimal beam intercepting to *minimize the radioactive level*
- High precision *(~mm) for position and profile monitors*
- Remote control *(no physical access when the beam on)*
- *For bunch-by-bunch monitor*
  - Fast response*(~few nanosecond)*
  - Fast signal processing and parameter extraction

Beam profile monitors: destructive vs. non-destructive

SSEM

after 2.3e21 incident protons



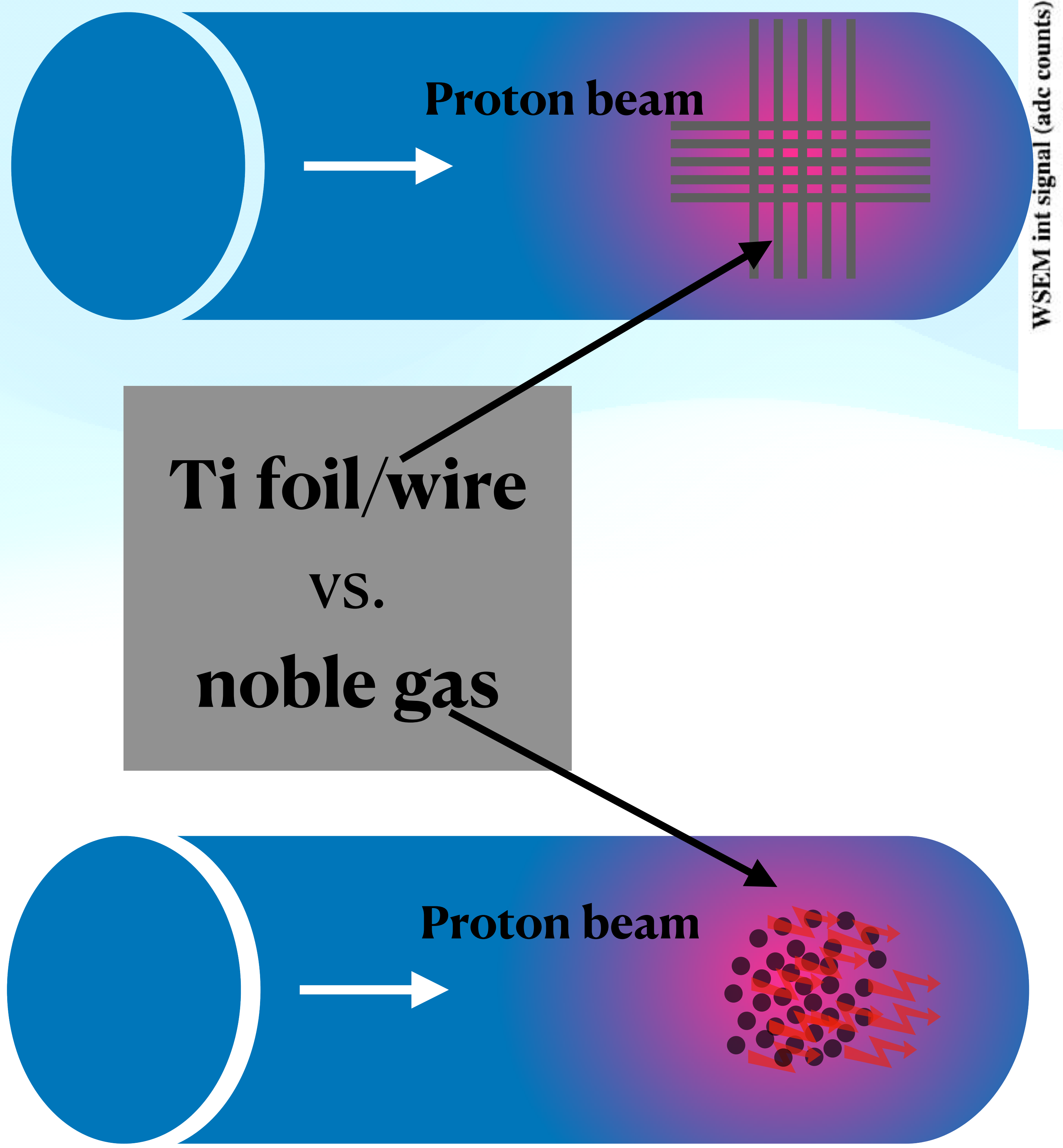
WSEM

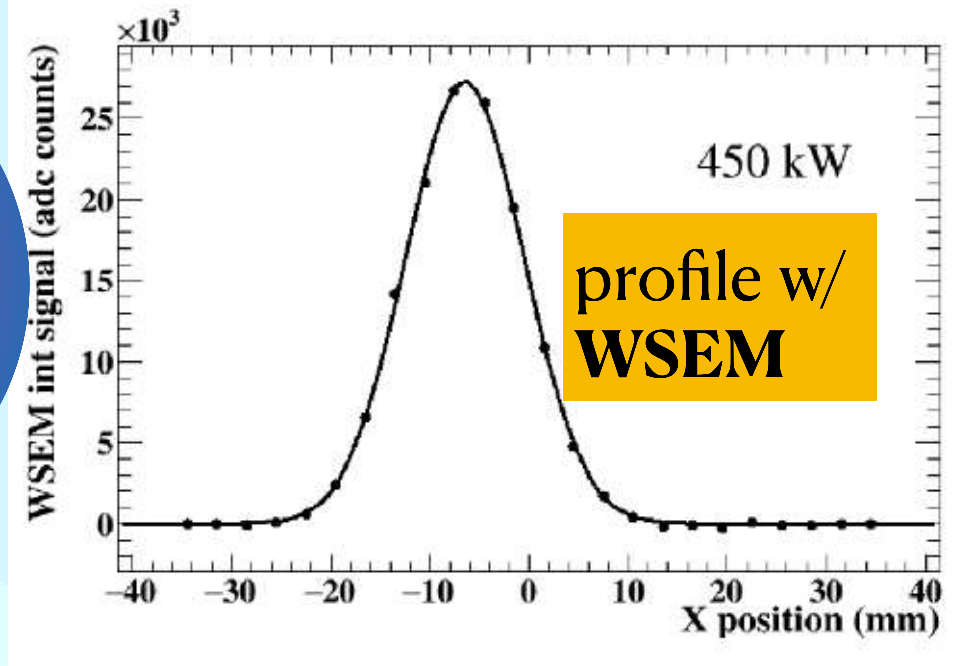
- **SSEM**: Three 5-μm-thick Ti foils, two stripped (2-5mm) vertically and horizontally → cause 0.005% beam loss
- **WSEM**: Like SSEM but 2x25-μm ϕ Ti twinned wire, beam loss is reduced x10: stable operation, consider carbon nano-tube as more-robust option

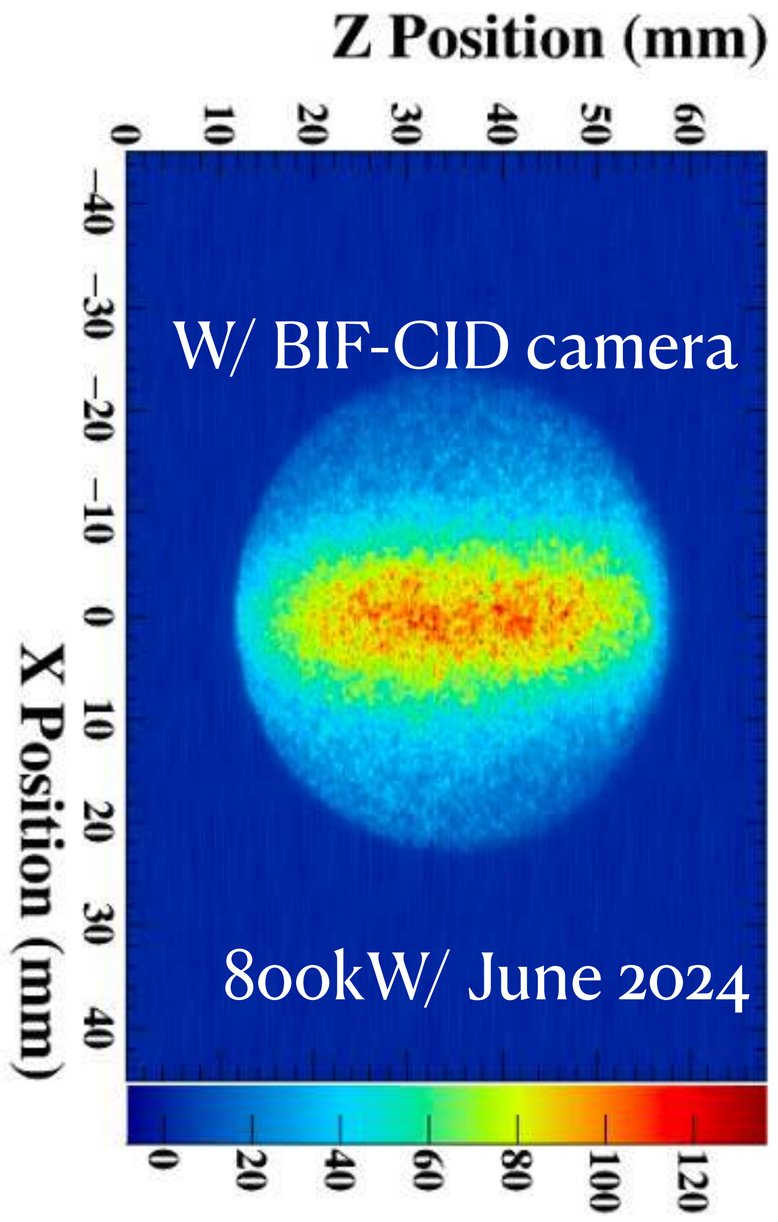
<u>Issue:</u> can't operate continuously due to high beam loss (except most-downstream one)

☞ *motivated for non-destructive monitor*

Signal obtained by profiling secondary electrons induced from proton-Ti foil/wire interaction



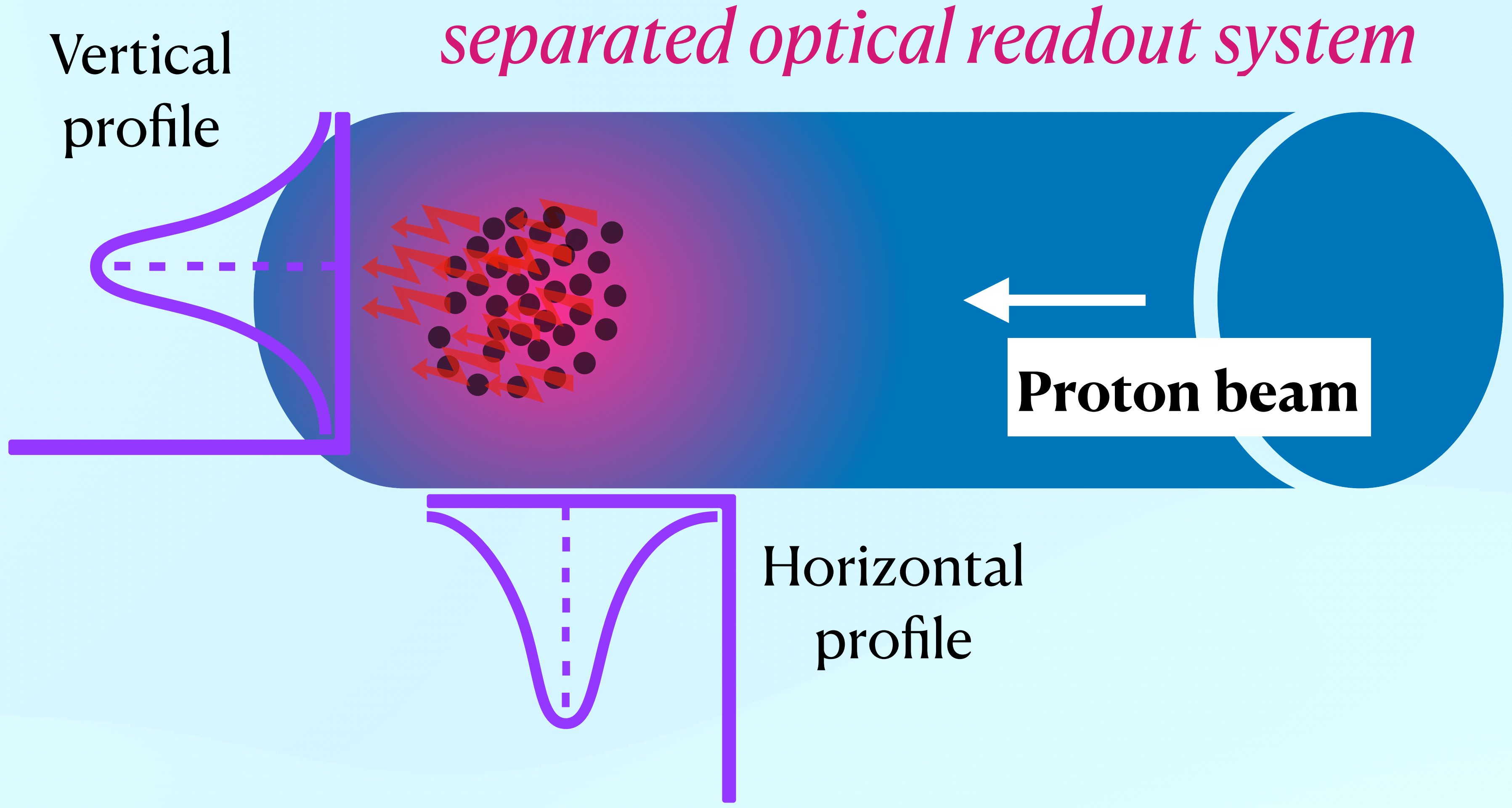


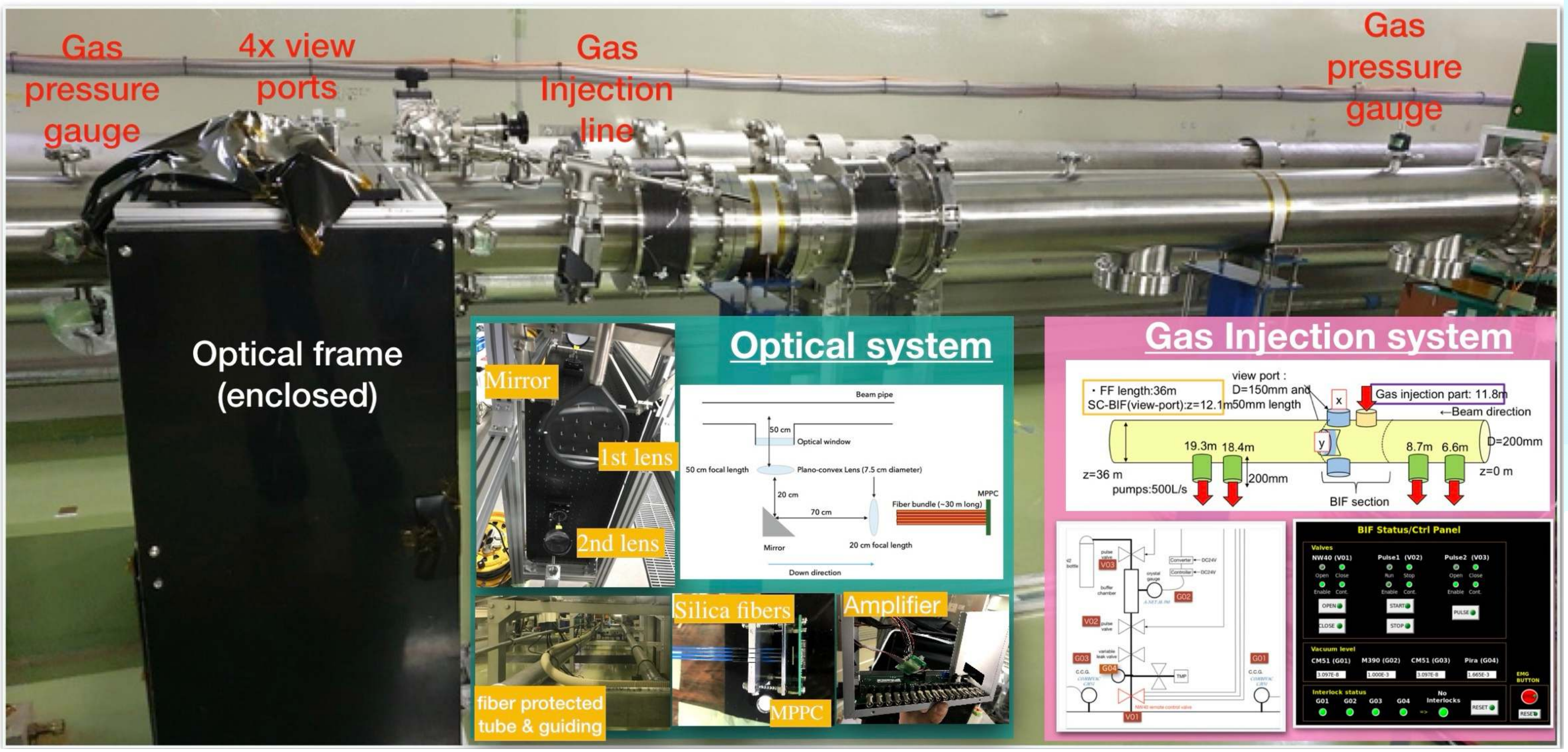


Transverse profile of fluorescence induced by proton interactions with injected gas matches its of proton beam

BIF concept & working prototype

Transverse profile is measured by two separated optical readout system





Some required specifications:

- **Gas needs to be injected in the beamline**: gas normally at ~ 10^{-6} Pa, is not enough to see signal. Also need to be localized (<10^{-3} Pa) near measurement point
- **Method to deal with space charge effect**: can use fast readout to capture the early fluorescence photons
- **High radiation environment near beamline**: non-rad-hard components, if use, must be in sub-tunnel

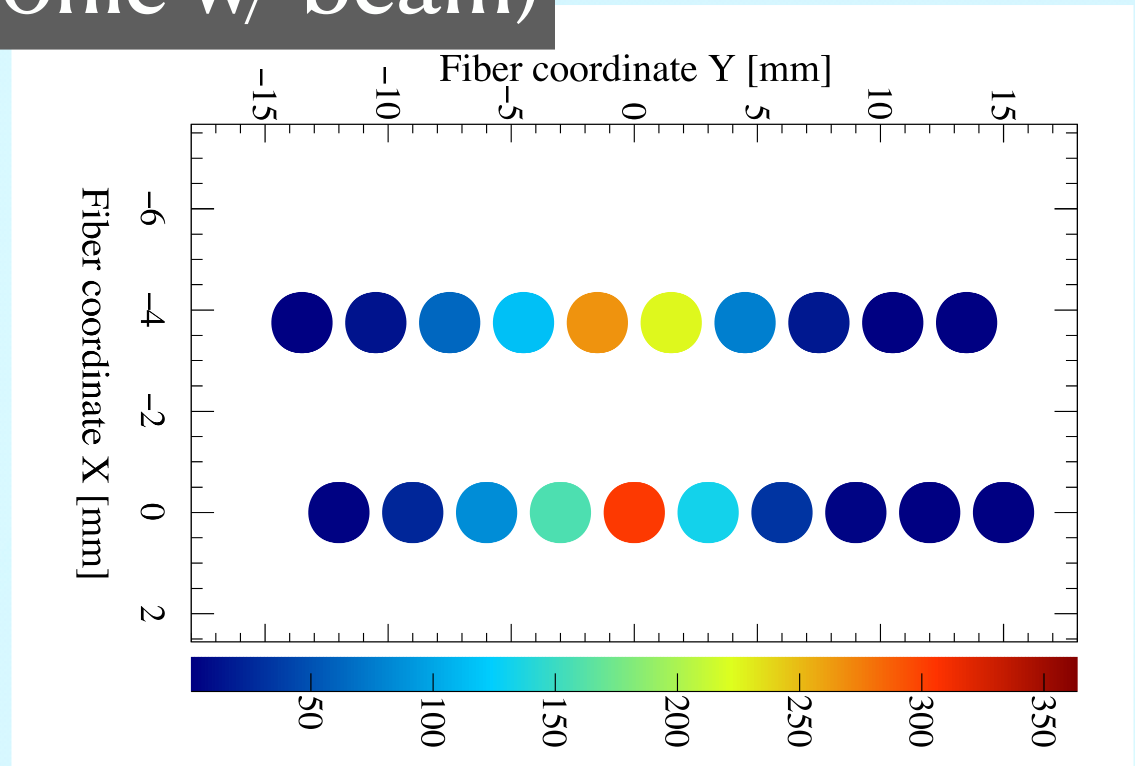
A complete prototype was installed in Summer 2019

- 1st beam test was carried out in early 2020
- 2nd beam test (Mar-Apr. 2021): w/ upgraded prototype
- 3rd beam test (Dec. 2023): fiber re-arranged/ electronics modified
- 4th beam test (June. 2023): upgrade image intensifier for CID camera

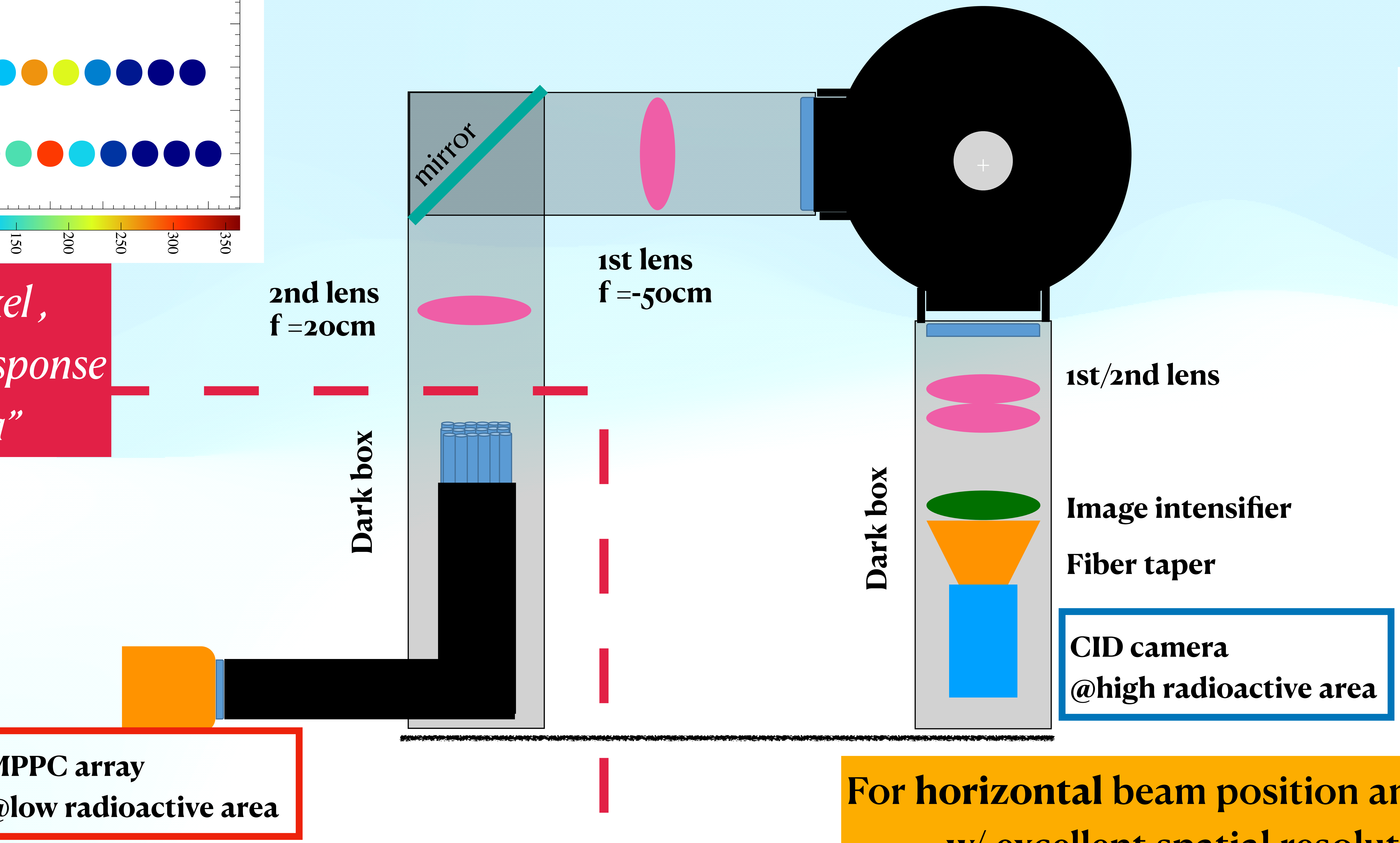
M. Friend *et al.*, Proceedings of IBIC2016, WEPG66, 2016
S. Cao *et al.*, Proceedings of IBIC2018, WEPC08, 2018
S. Cao *et al.*, Proceedings of IBIC2019, TUPP024, 2019
M.Friend *et al.*, Proceedings of IBIC2020, WEPP34, 2020

Two optical systems for fluorescence capture

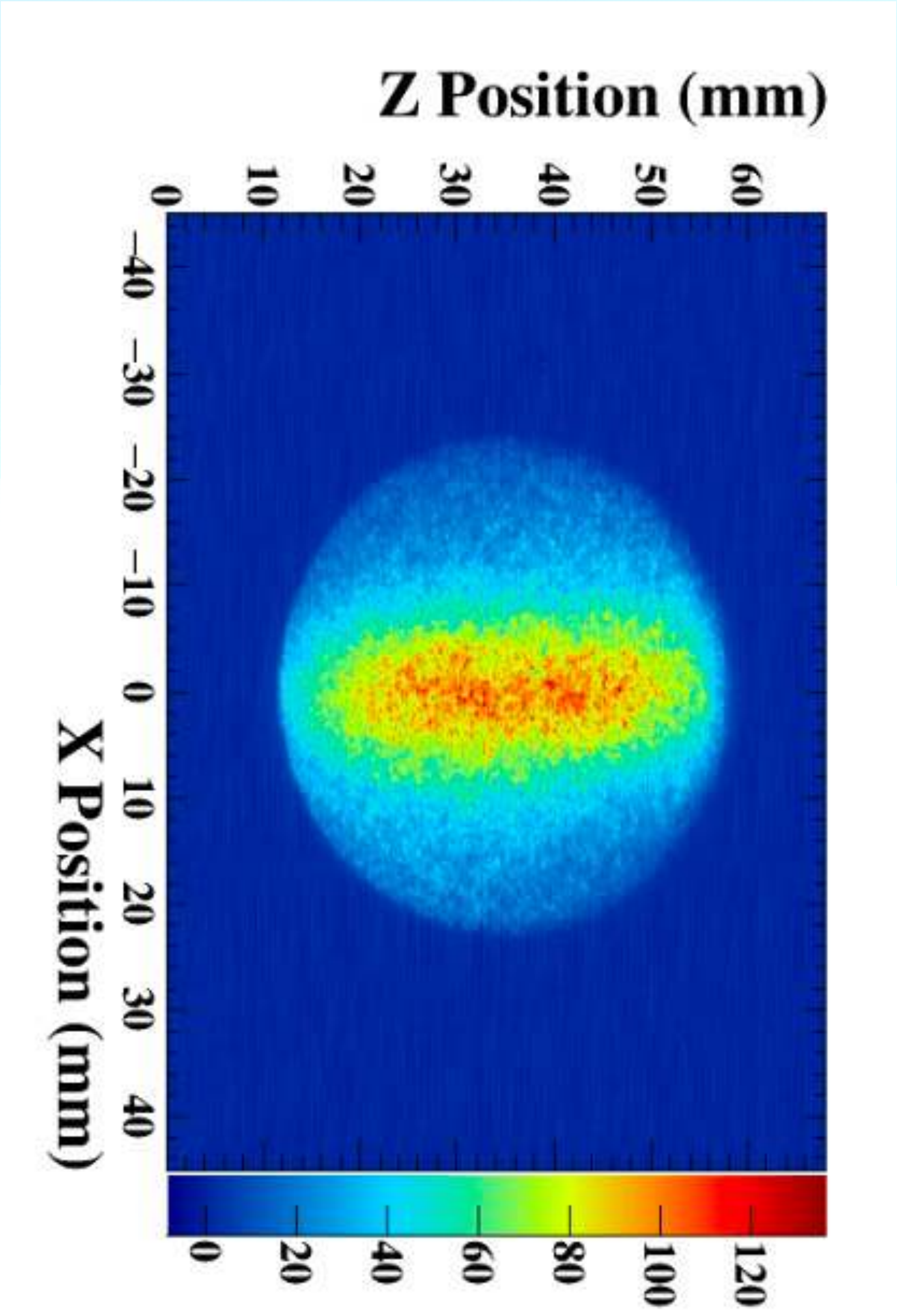
(BIF profile w/ beam)



"Low-pixel , (~ns)fast-response camera"



(BIF profile w/ beam)



For vertical beam position and profile w/ high spatial & timing resolution

For horizontal beam position and profile w/ excellent spatial resolution

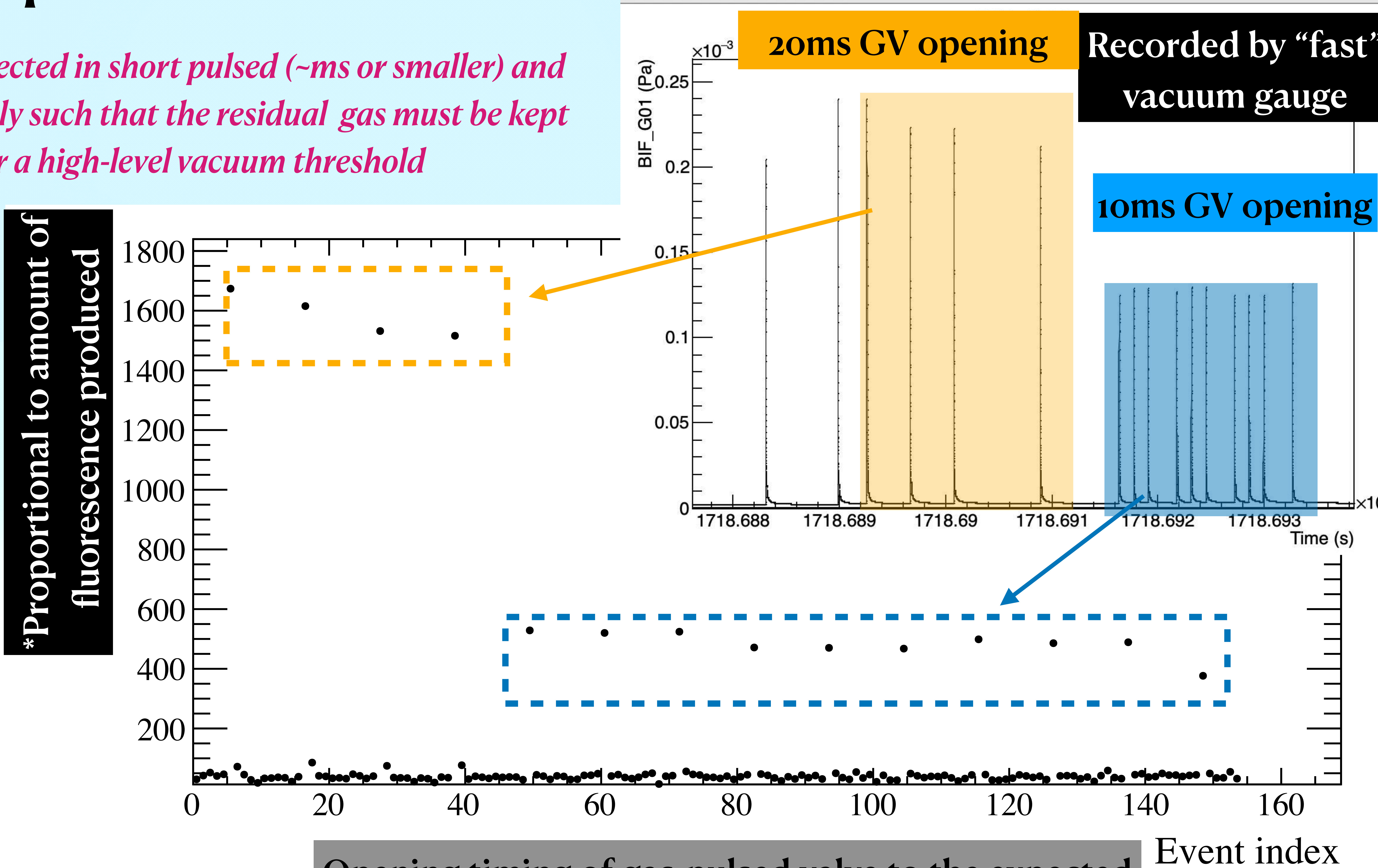
Cool fact: we captured these profiles almost in silence (*non-destructive way*) while beam keeps delivering normally to T2K

Gas injection and pressure monitors

2024/June.

Gas must be injected in short pulsed (~ms or smaller) and pump out quickly such that the residual gas must be kept under a high-level vacuum threshold

- Gas (use N_2) is injected remotely with a series of valve to localize gas pressure pump of $< 10^{-3}$ Pa
- Gas must be pumped out with ion pump to fall back $\sim 10^{-5}$ Pa btw. proton spills
- An interlock system to close a remotely-controlled pneumatic valve in case pressure higher than a set threshold
- Currently, gas is injected in a single spill as needed.
- Steady benchmarking a safe condition for gas-injection



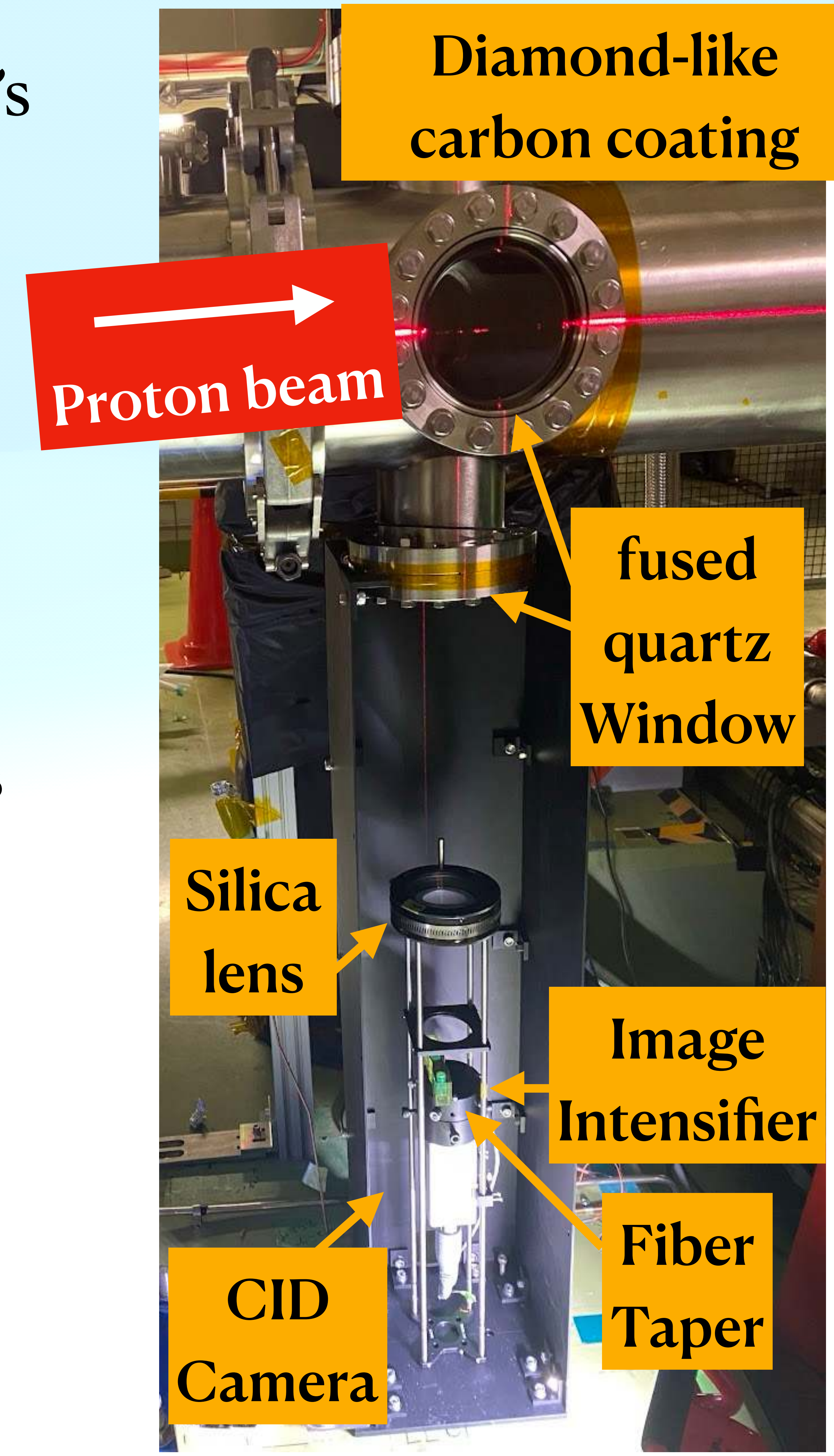
Opening timing of gas-pulsed valve to the expected beam arrival is adjusted for optimization study

*This fluorescence signal is recorded by 8mm-dia. metal-package PMT looked at the beam via a bi-convex lens (f=15cm)

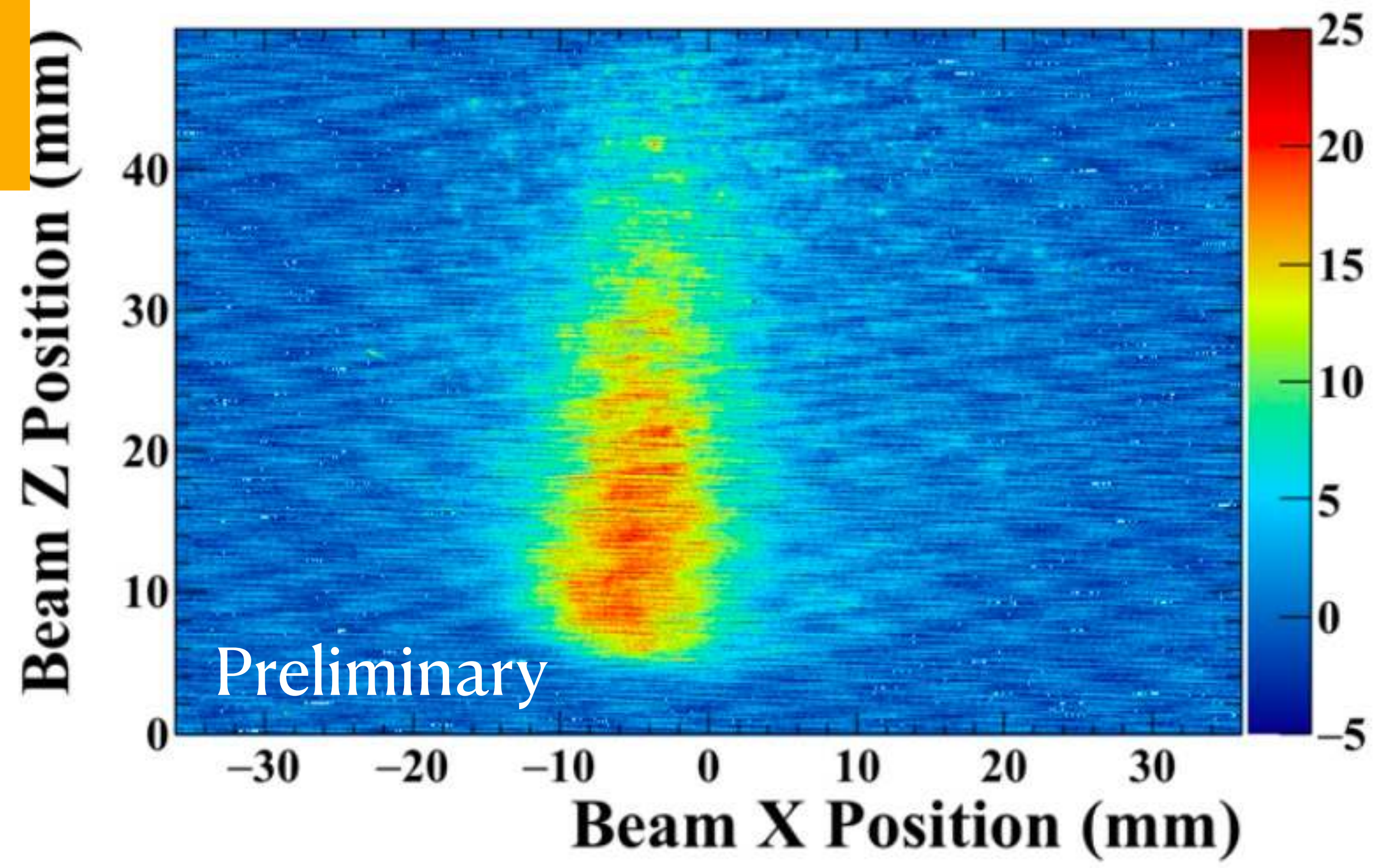
Optical readout with CID camera/ Image intensifier

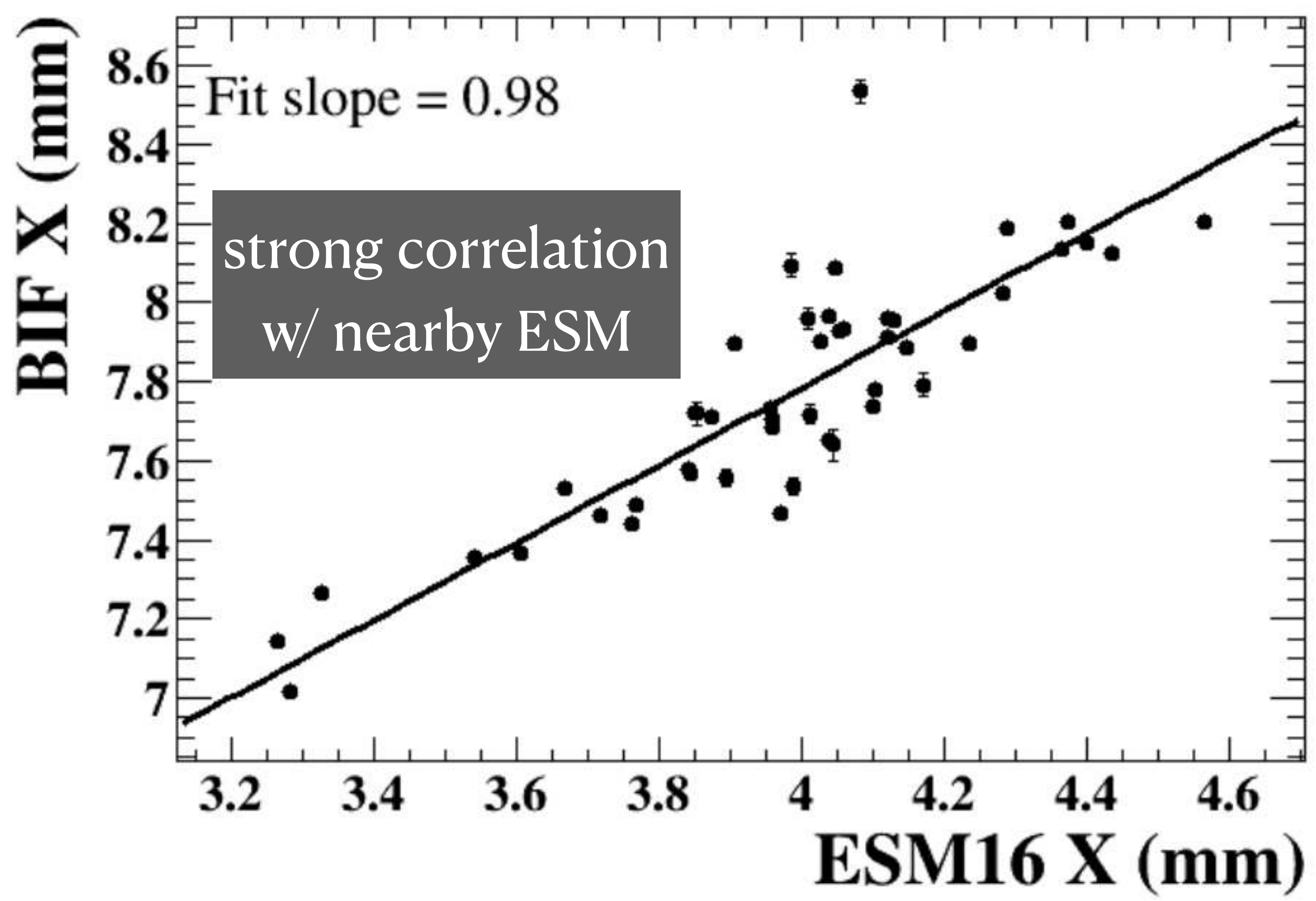
2021/Dec. Data.

- Camera is used to read out the proton beam's transverse profile in X-axis
- Two plano-convex lens to focus the fluorescence light onto the Micro-Channel Plate-based Image Intensifier, which is coupled to CID camera via a fiber taper
- Preliminary results
  - Beam position measured by camera shows a strong correlation w/ nearby ESM monitors.
  - The beam width measured by camera is slightly wider than the nearby WSEM *(further investigation is on-going)*



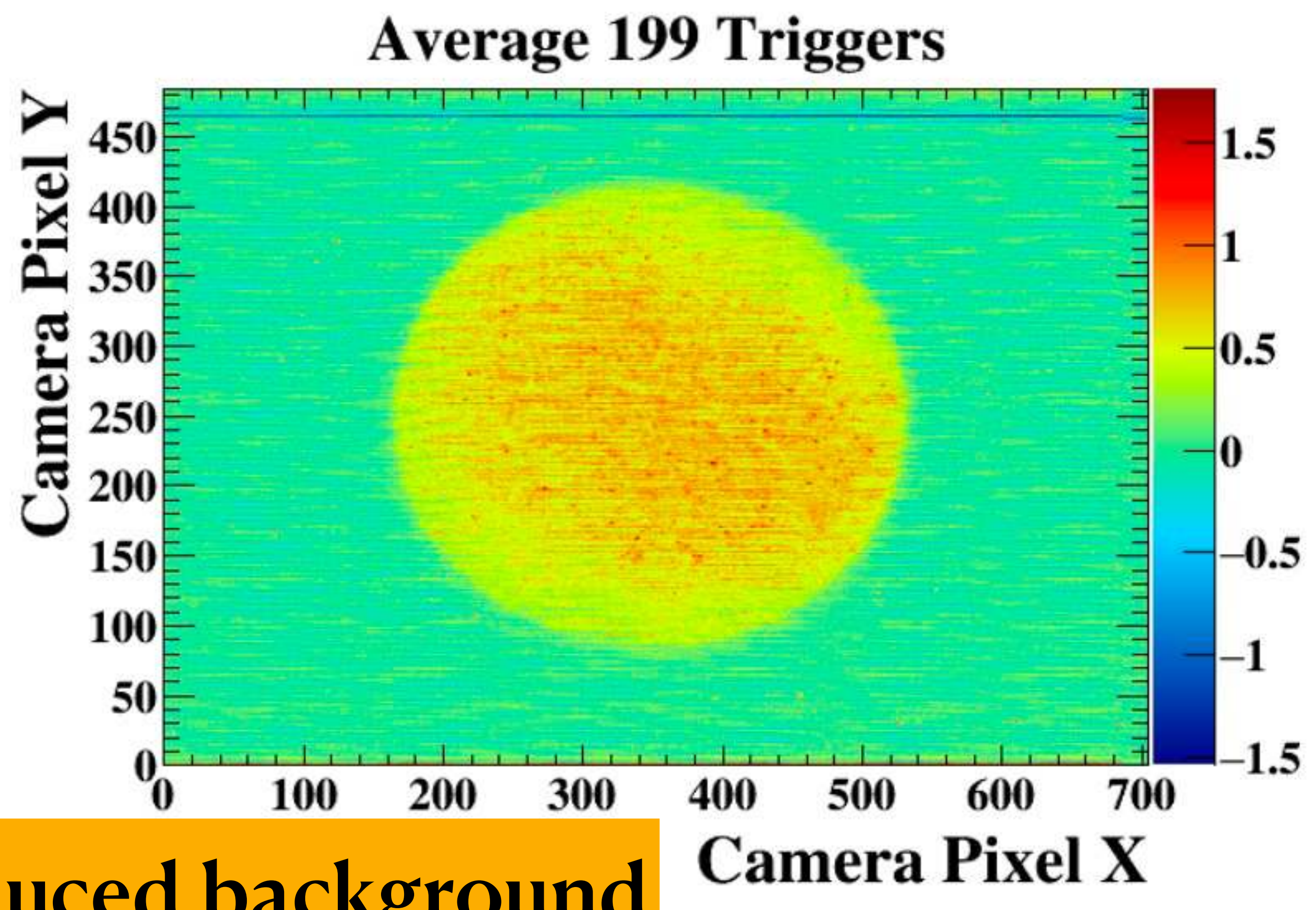
(Profile was distorted due to the lens)





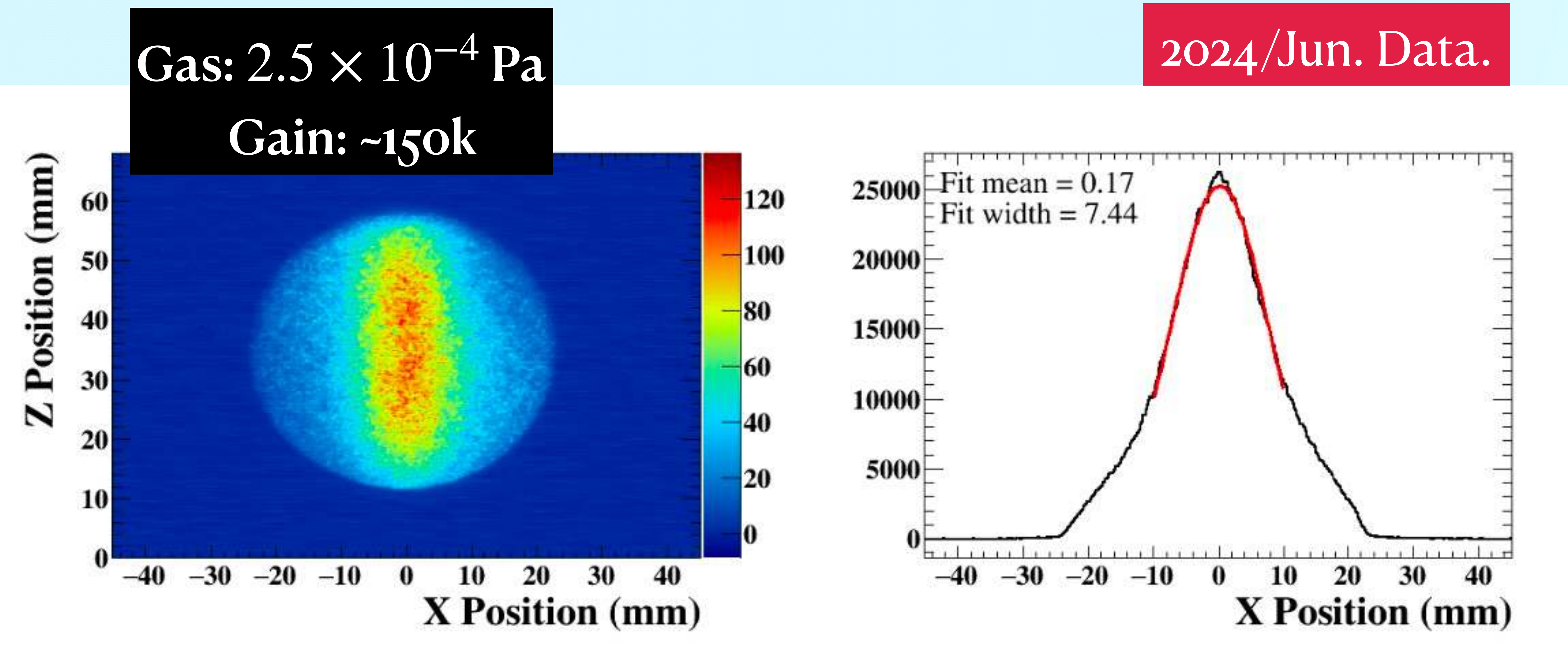
Reconstructed Beam position w/ CID camera/ Image intensifier

- **Update for 2024 test**: new fast-gateable image intensifier with higher gain to detect fainter light; photocathode w/ selective wavelength band for better signal-to-background ratio
- Beam-induced background is relatively small (*to the previous test*)
  - Beam loss itself is smaller (*observed by nearby BLMs*)
  - Narrower wavelength band of new image intensifier
- Fluorescence image has been observed with different gain settings and gas pressure

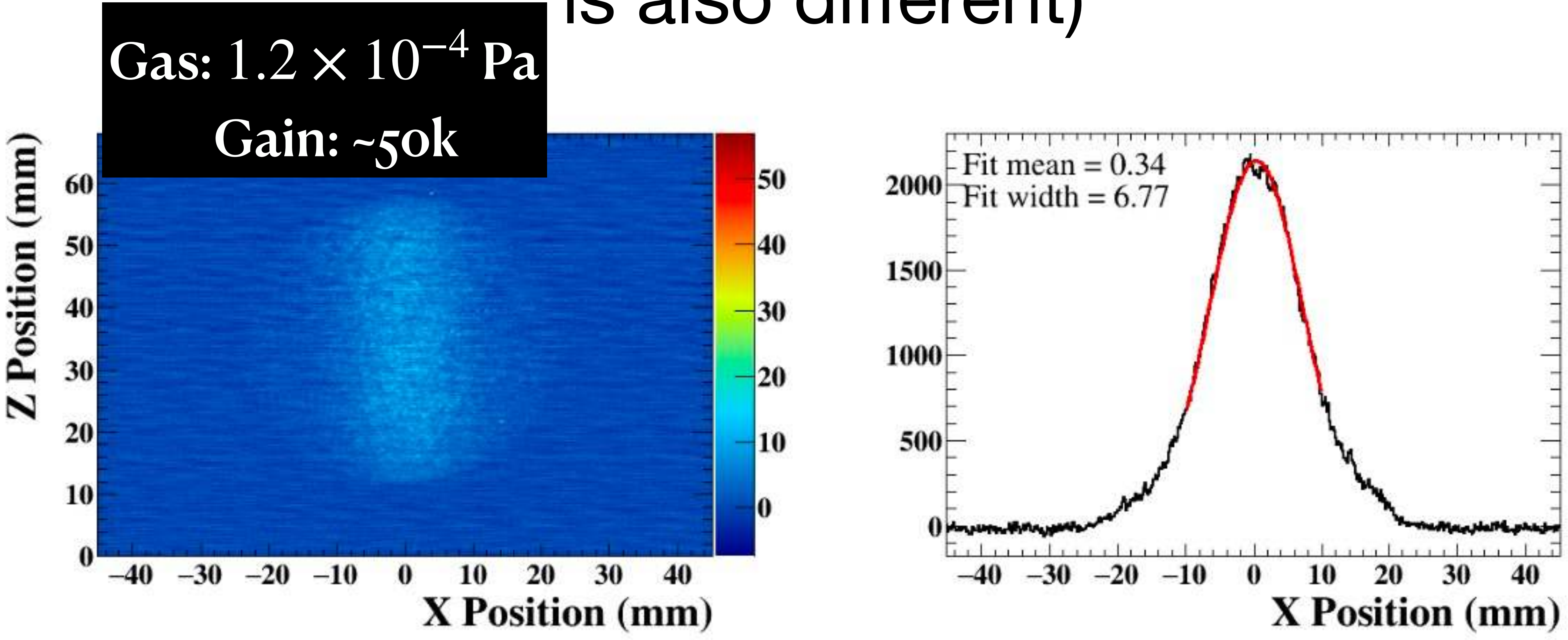


Beam-induced background

2024/Jun. Data.

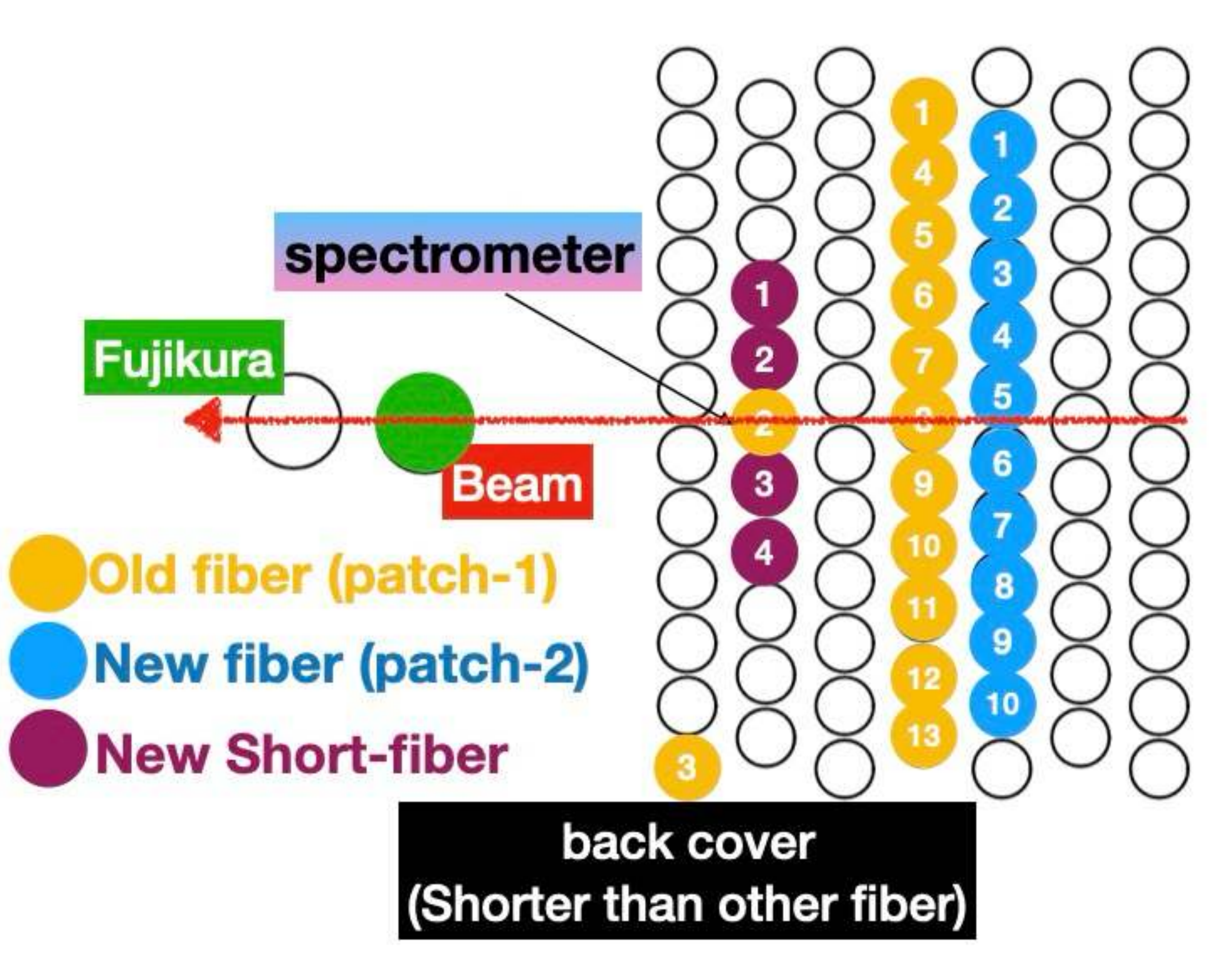


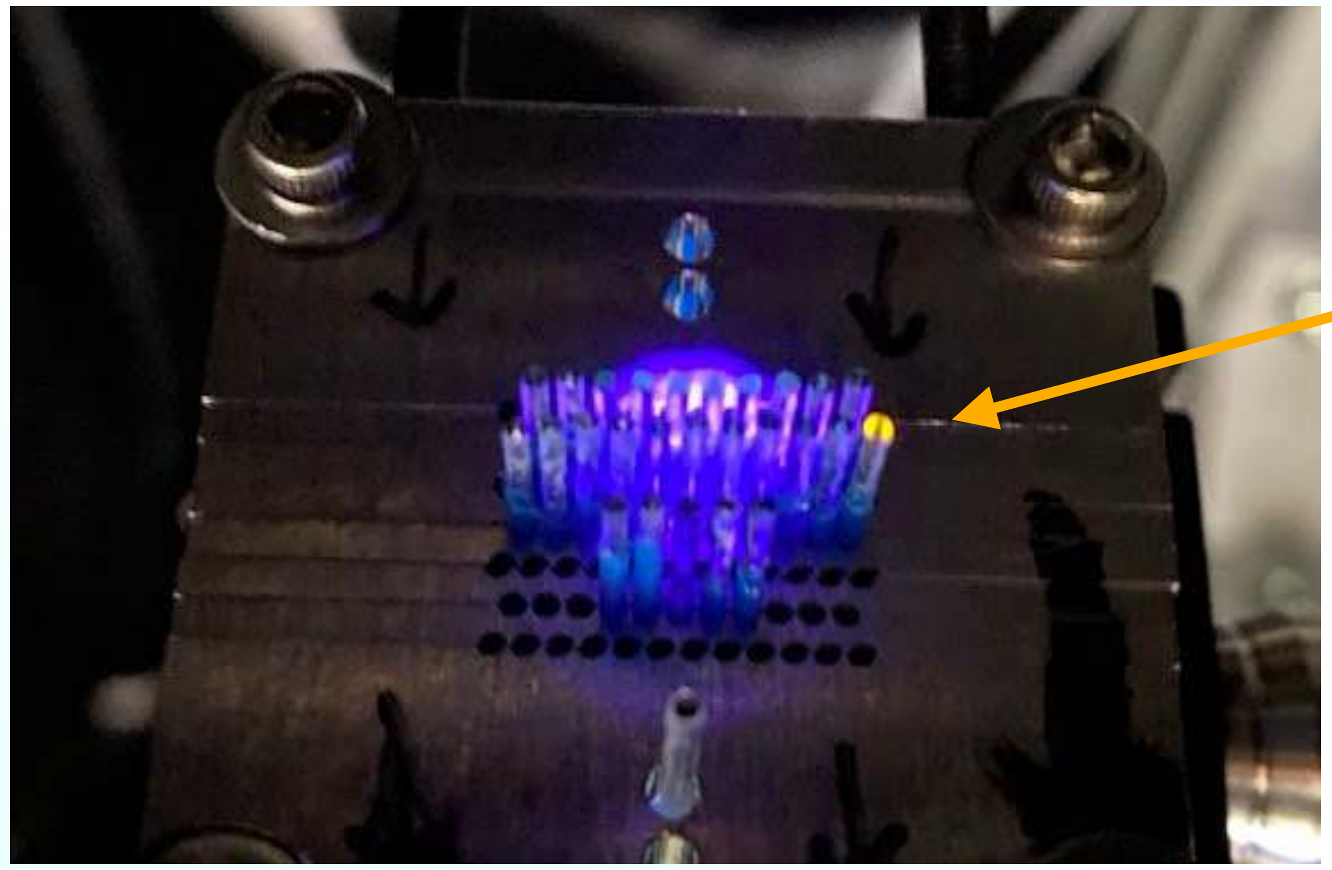
(Not the same gas amount, gain setting is also different)

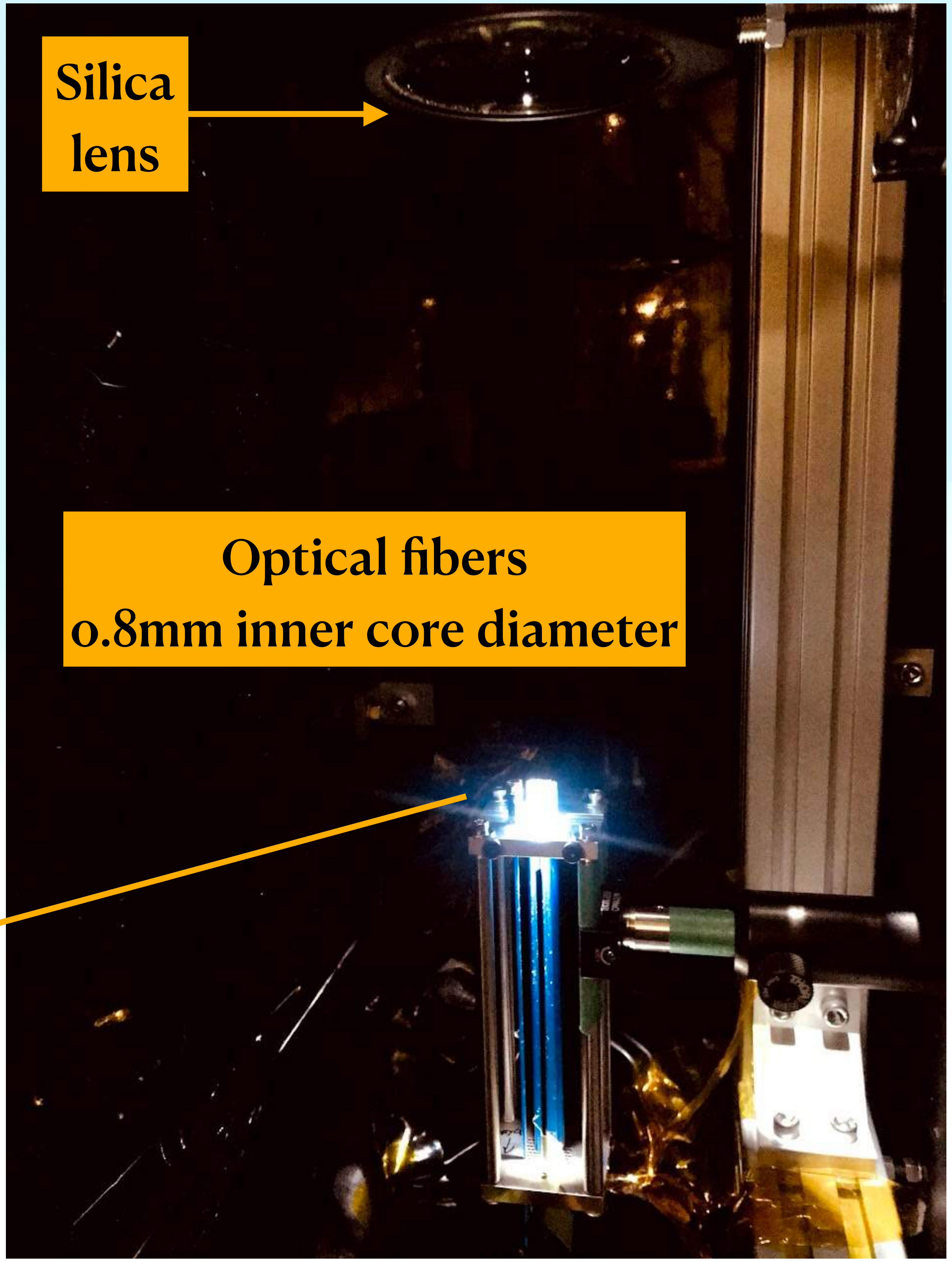


Optical readout with MPPC/ Fiber

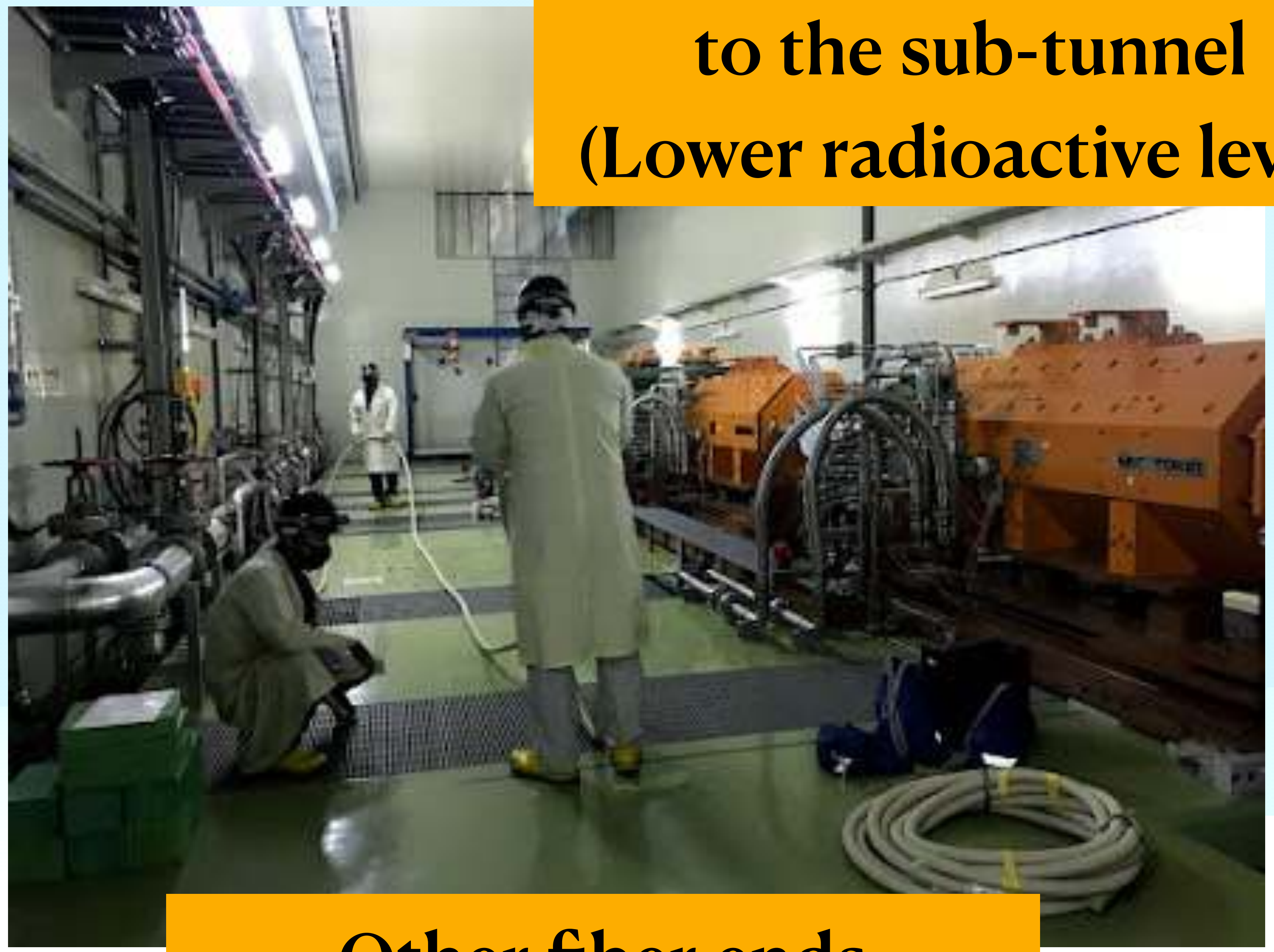
Layout of fiber ends
at image plane of optical len



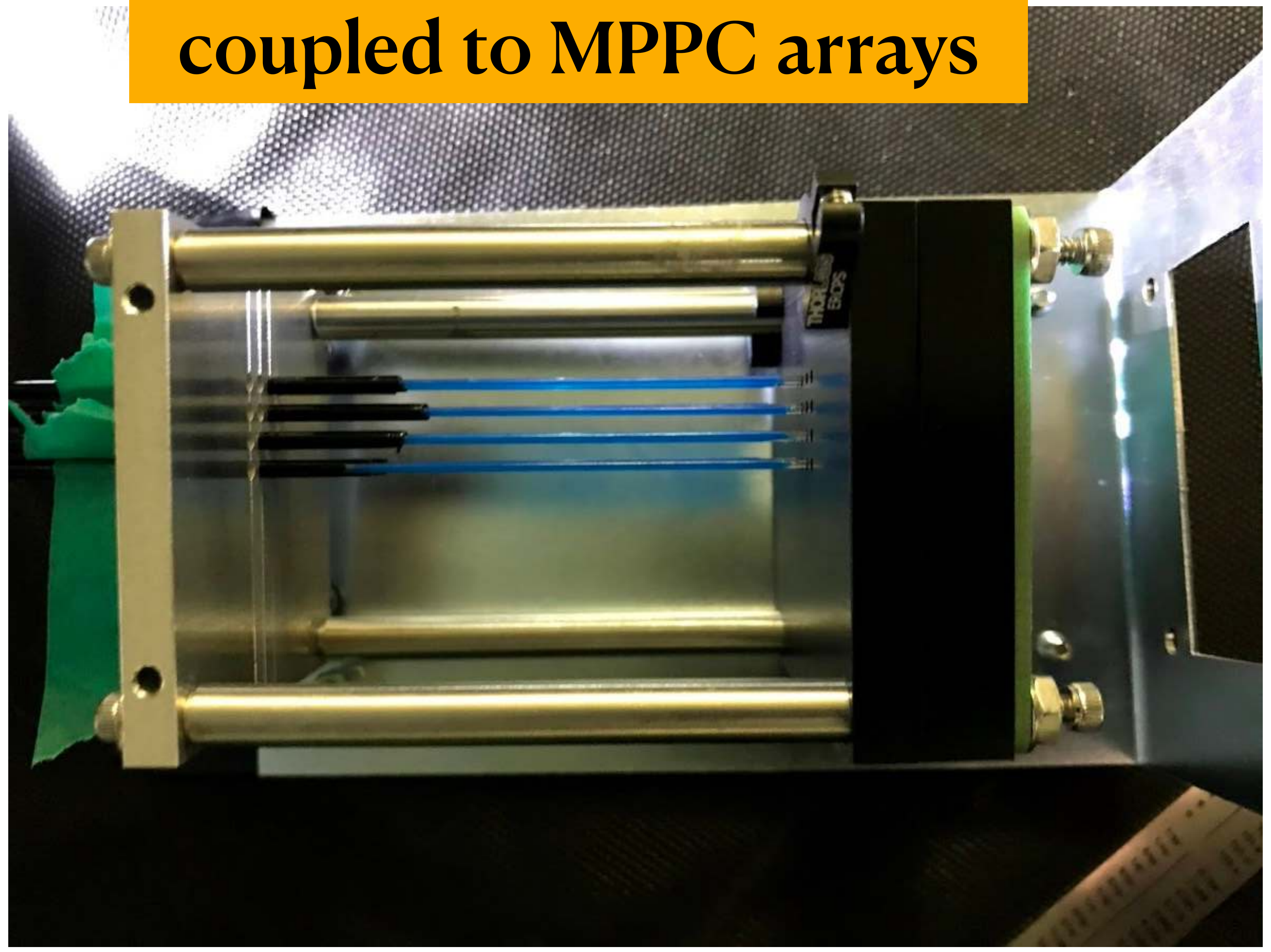




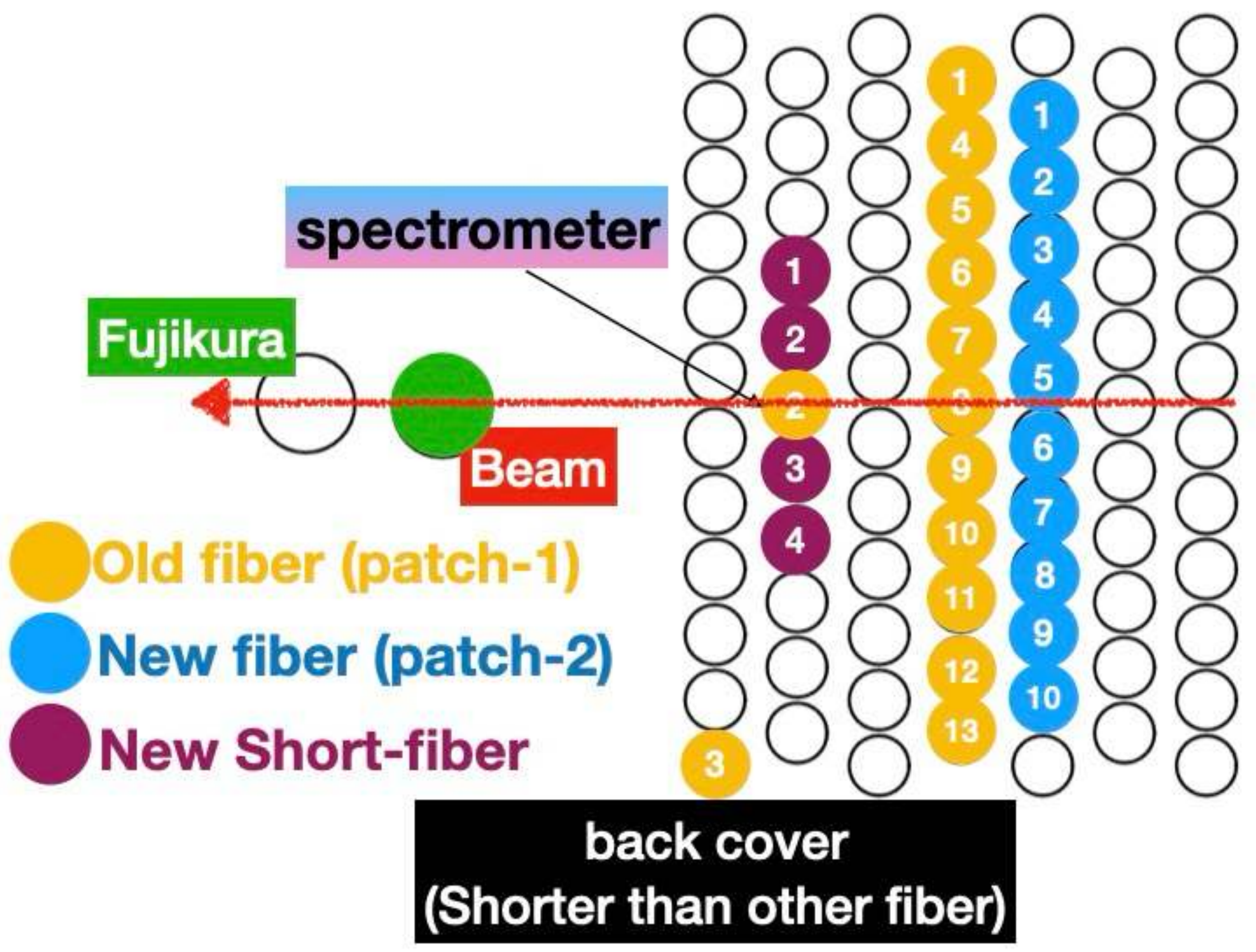
~30m-length fiber bundles
to the sub-tunnel
(Lower radioactive level)

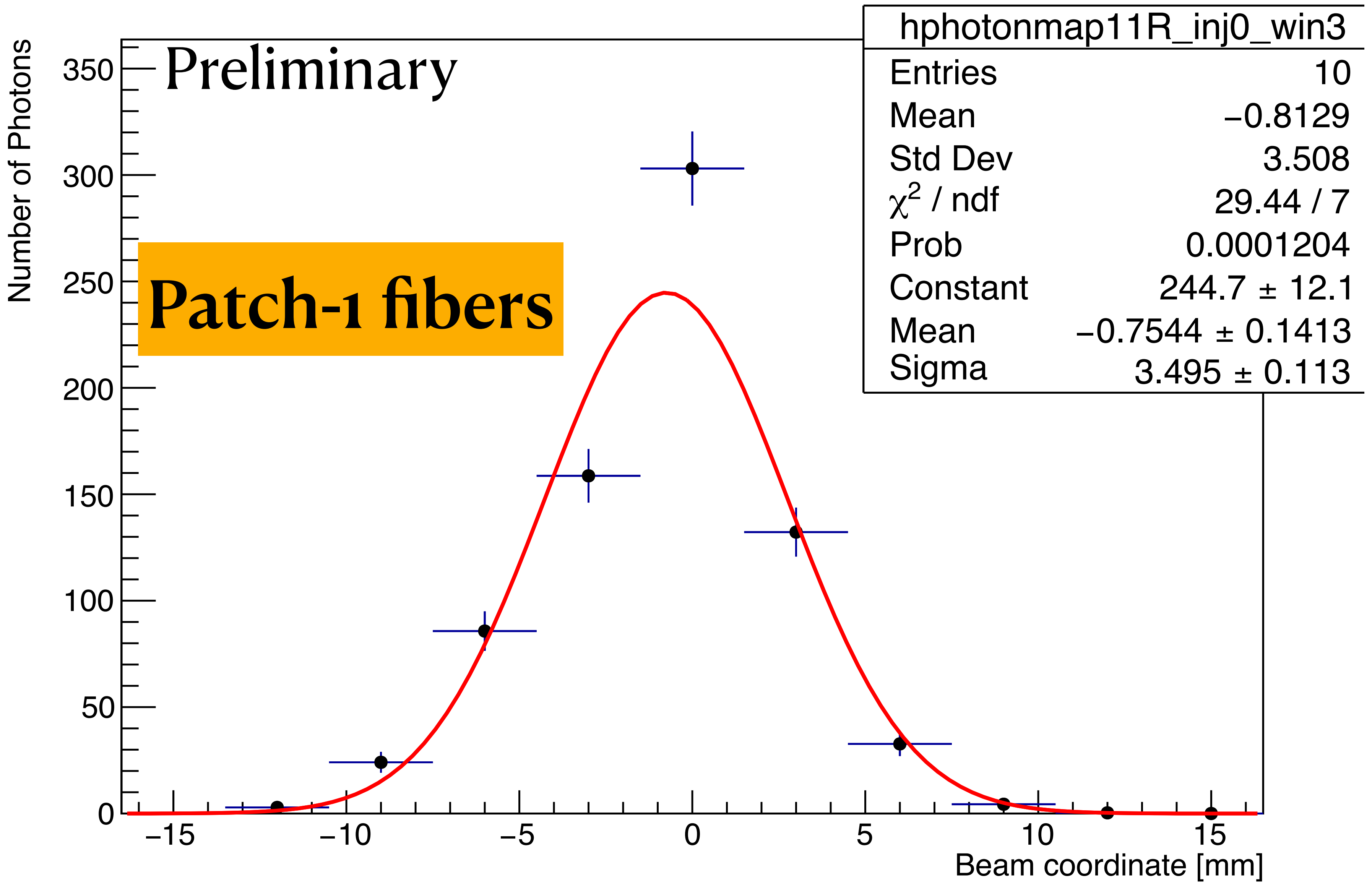


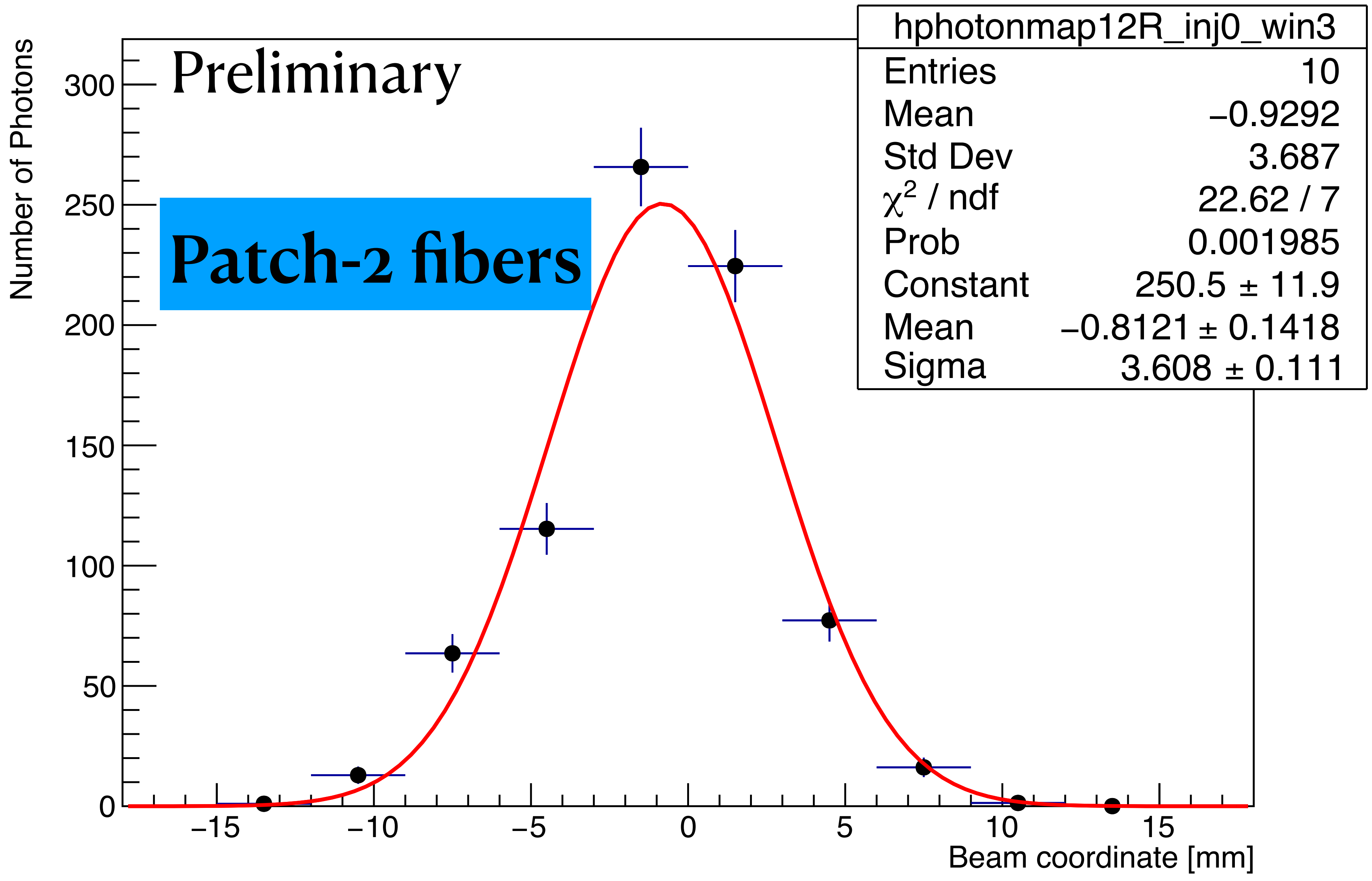
Other fiber ends
coupled to MPPC arrays

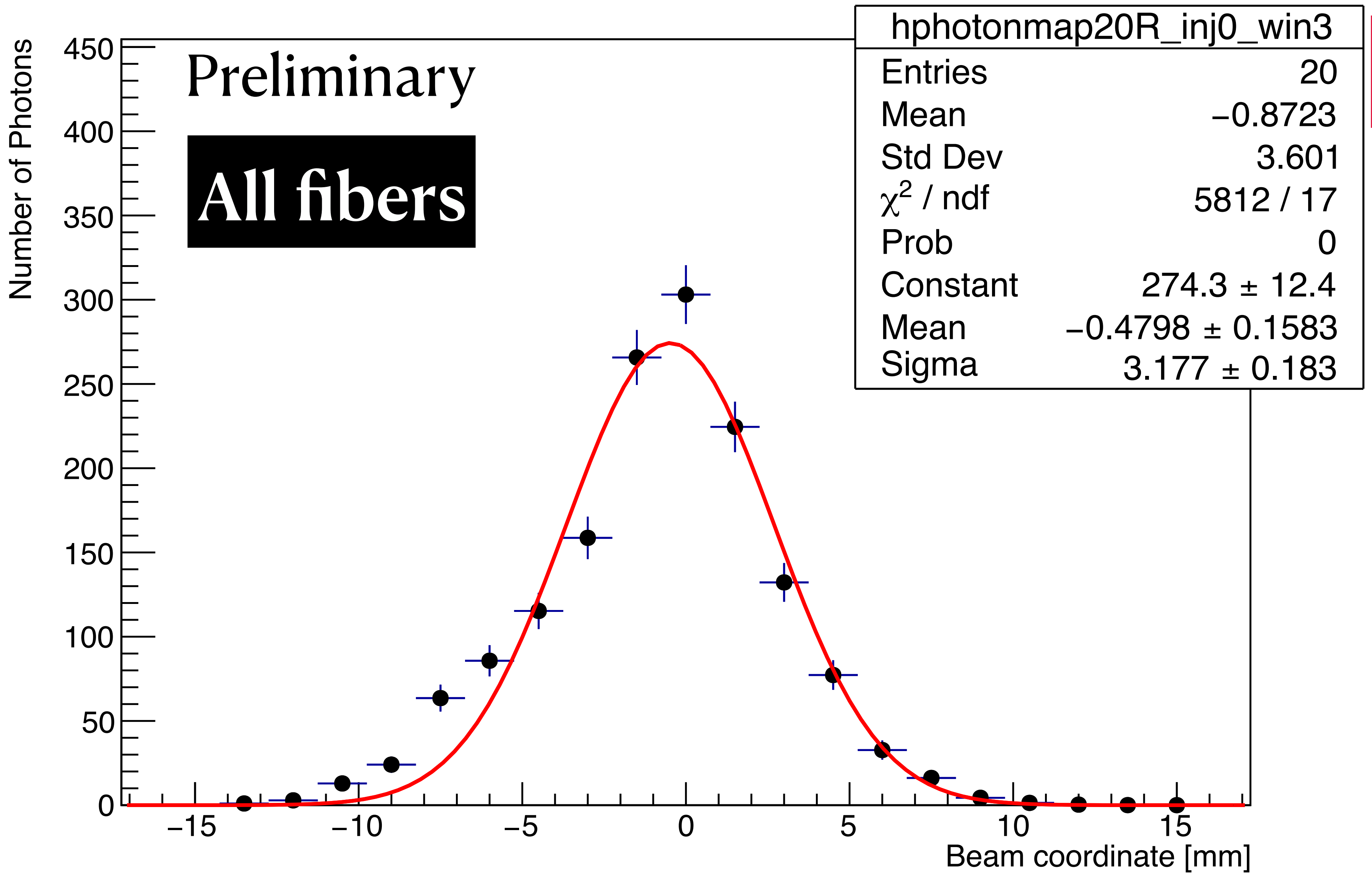


Reconstructed Beam profile with MPPC/ Fiber









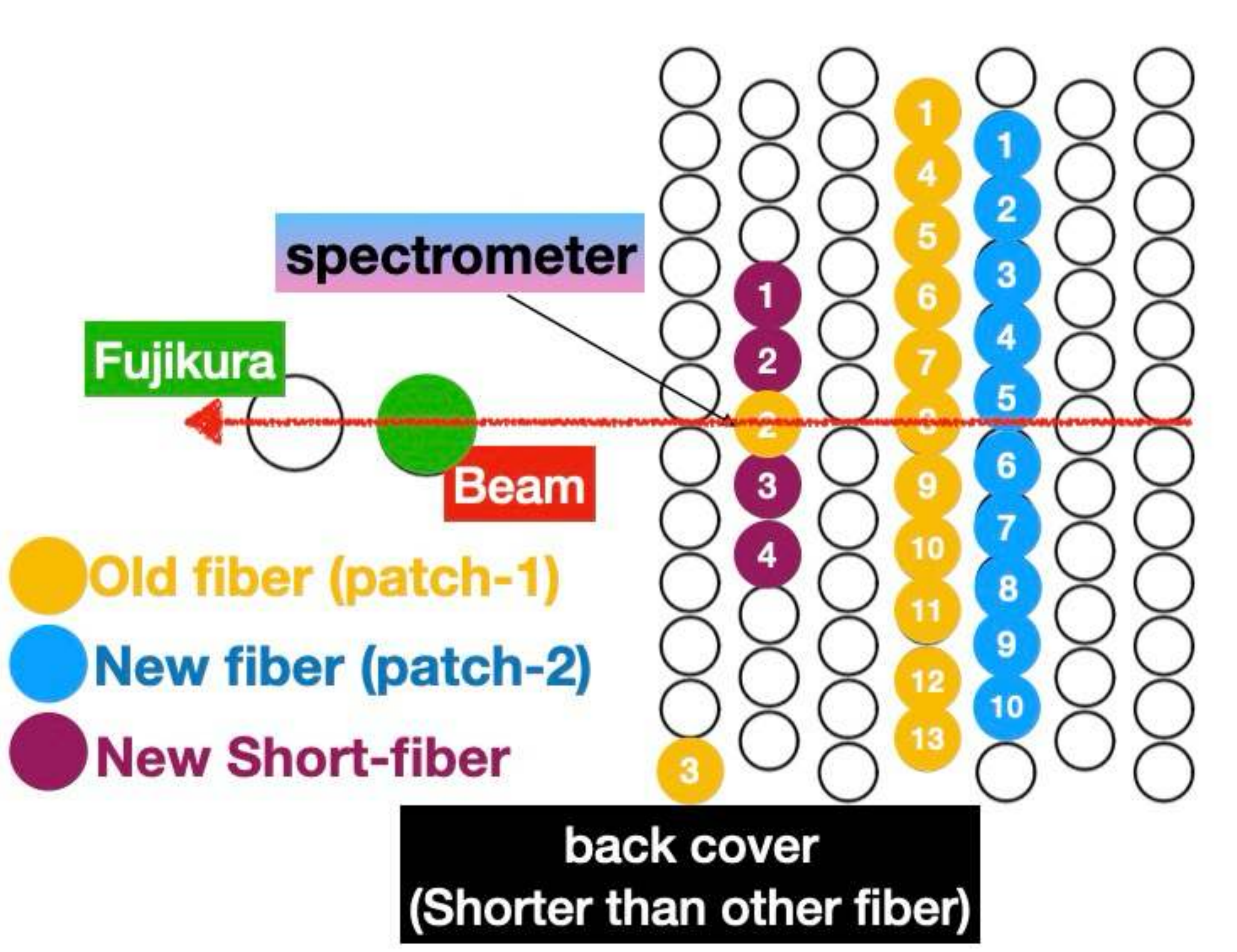
2024/Jun. Data.

The mean and RMS of profiles with different fiber sets match well. Gaussian fits, however, produce slightly varied results. Further inquiry is underway.

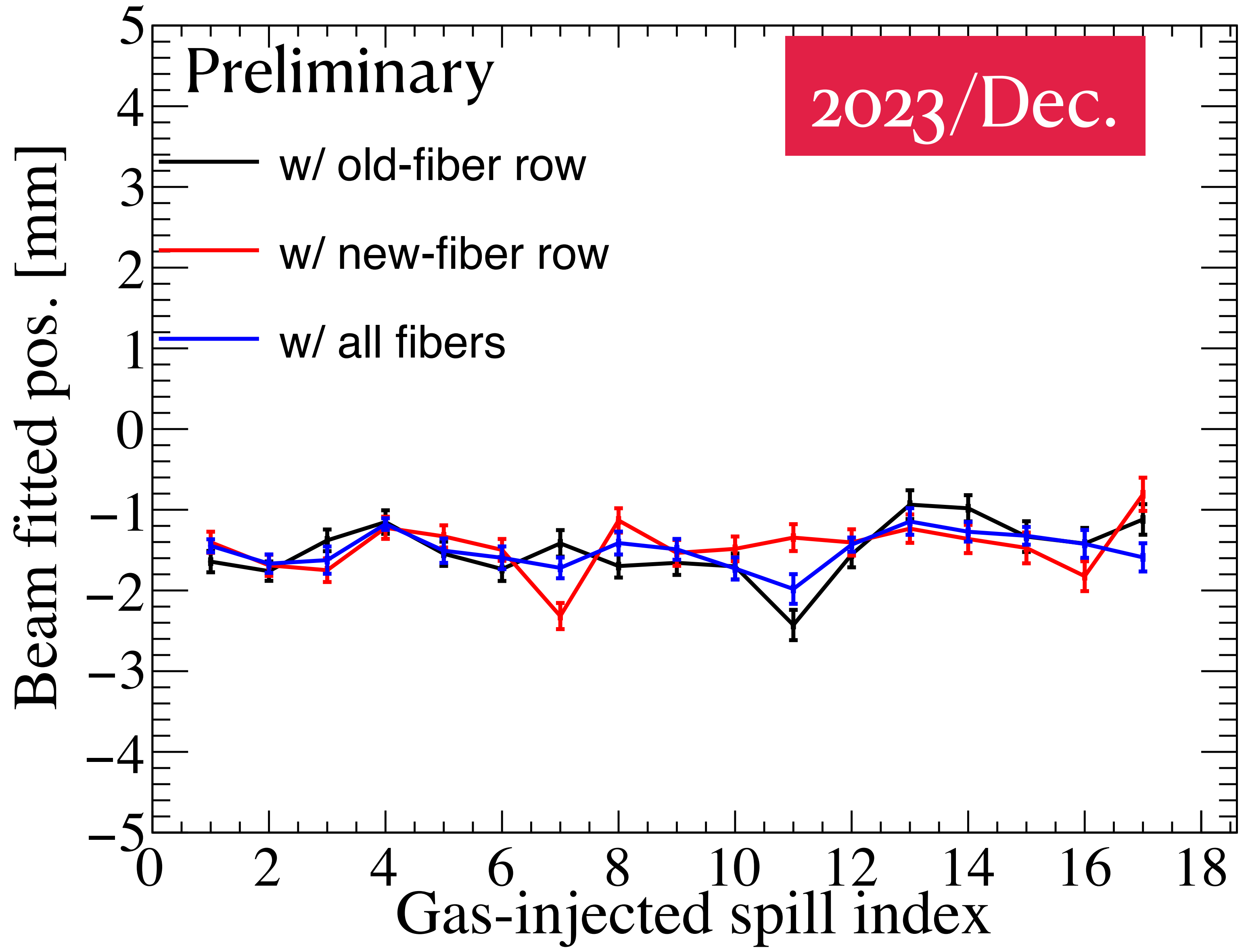
Reconstructed beam profile with different fiber sets are compared

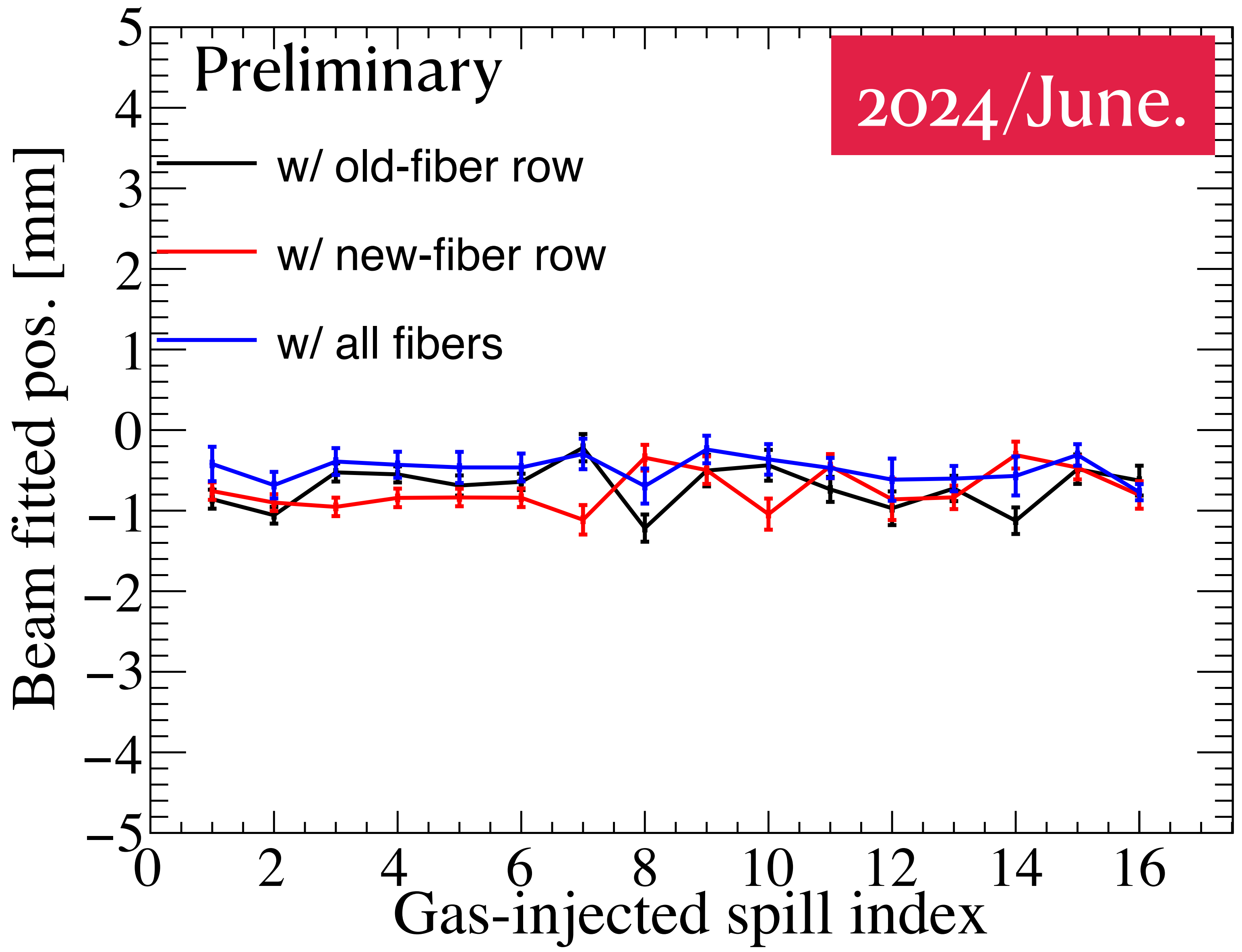
Reconstructed Beam profile with MPPC/ Fiber

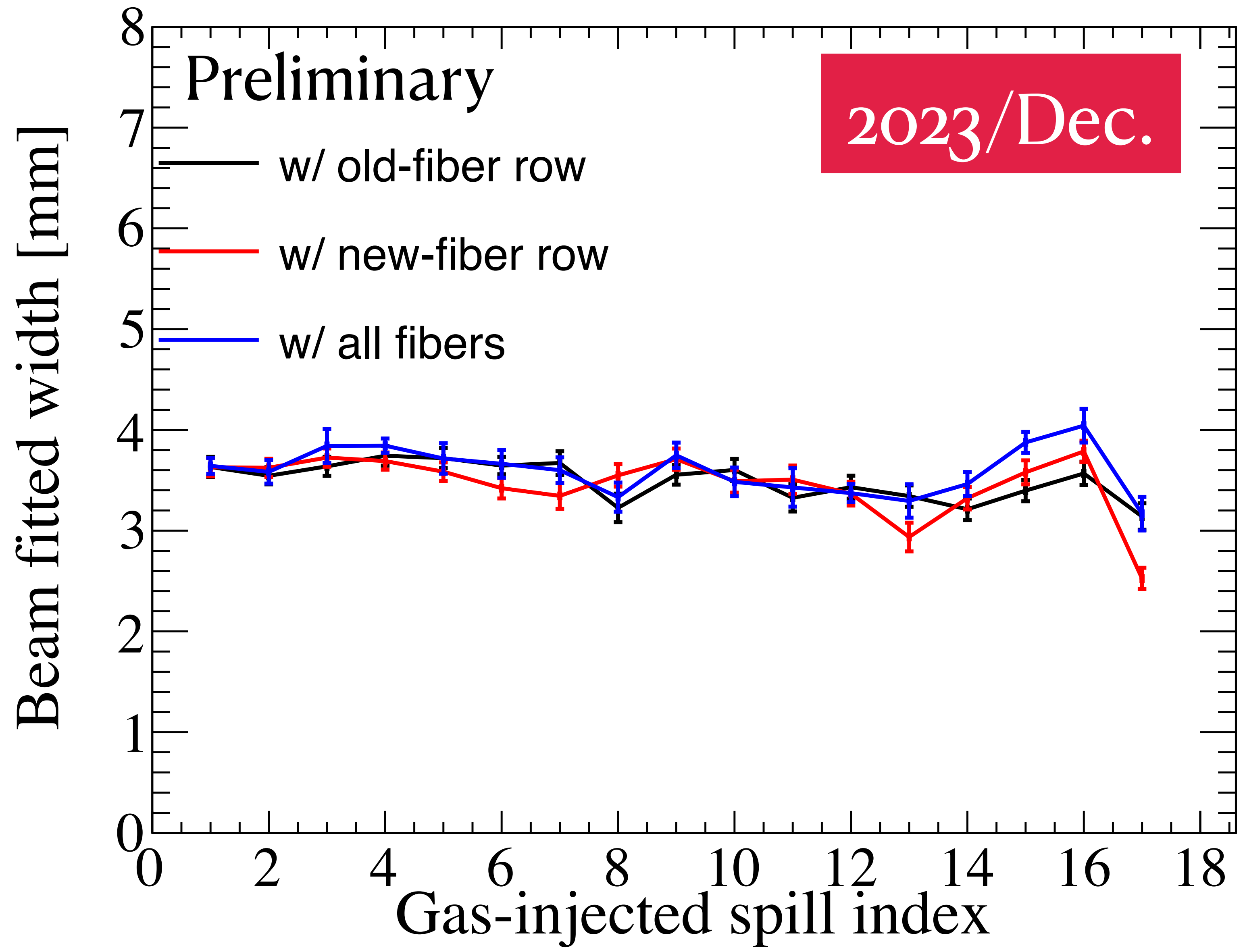
More center w/ 2024/June beam?

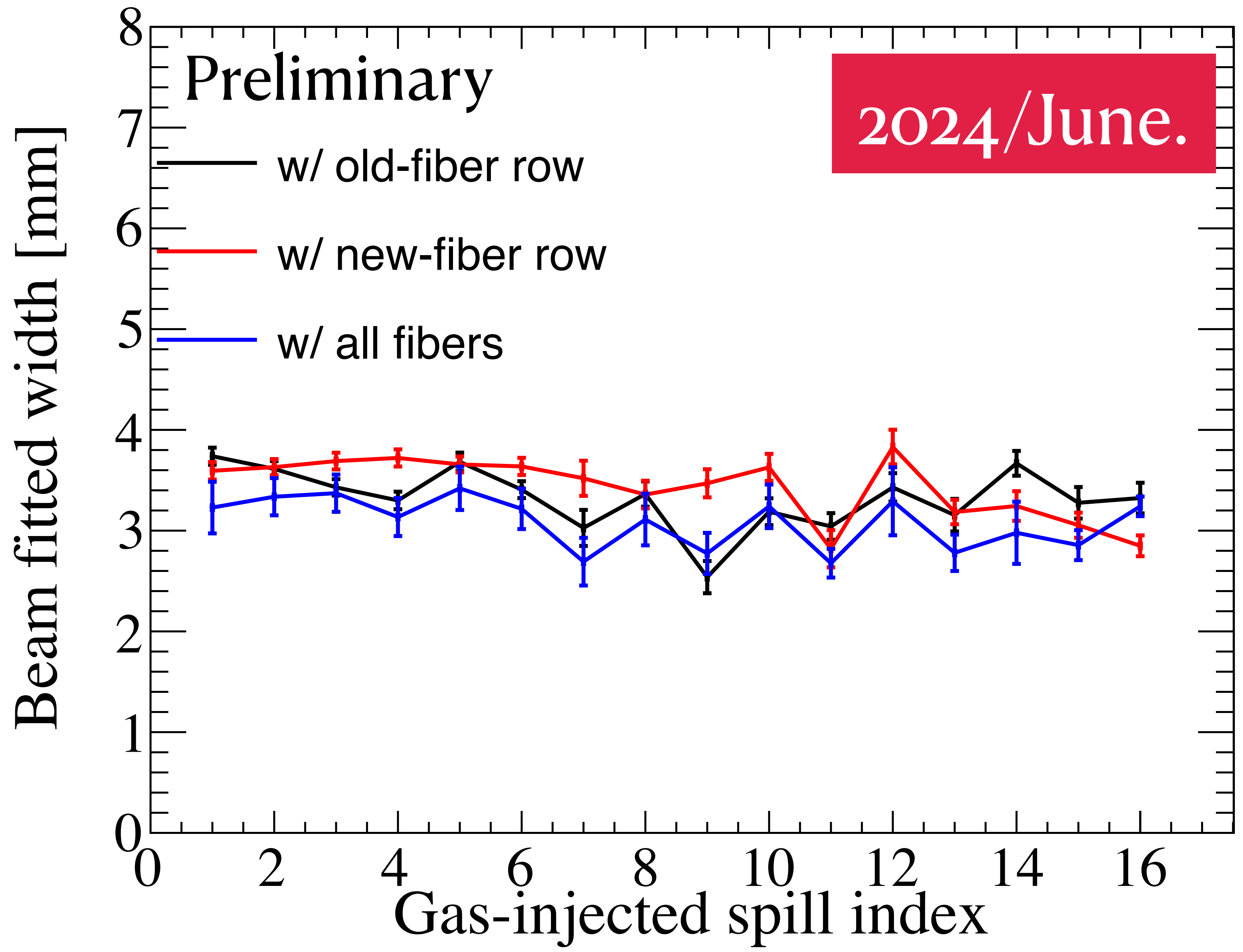


There is no direct comparison to standard SSEM/WSEM measurements, but some extrapolation based on beam optic fit with nearby monitors is underway.







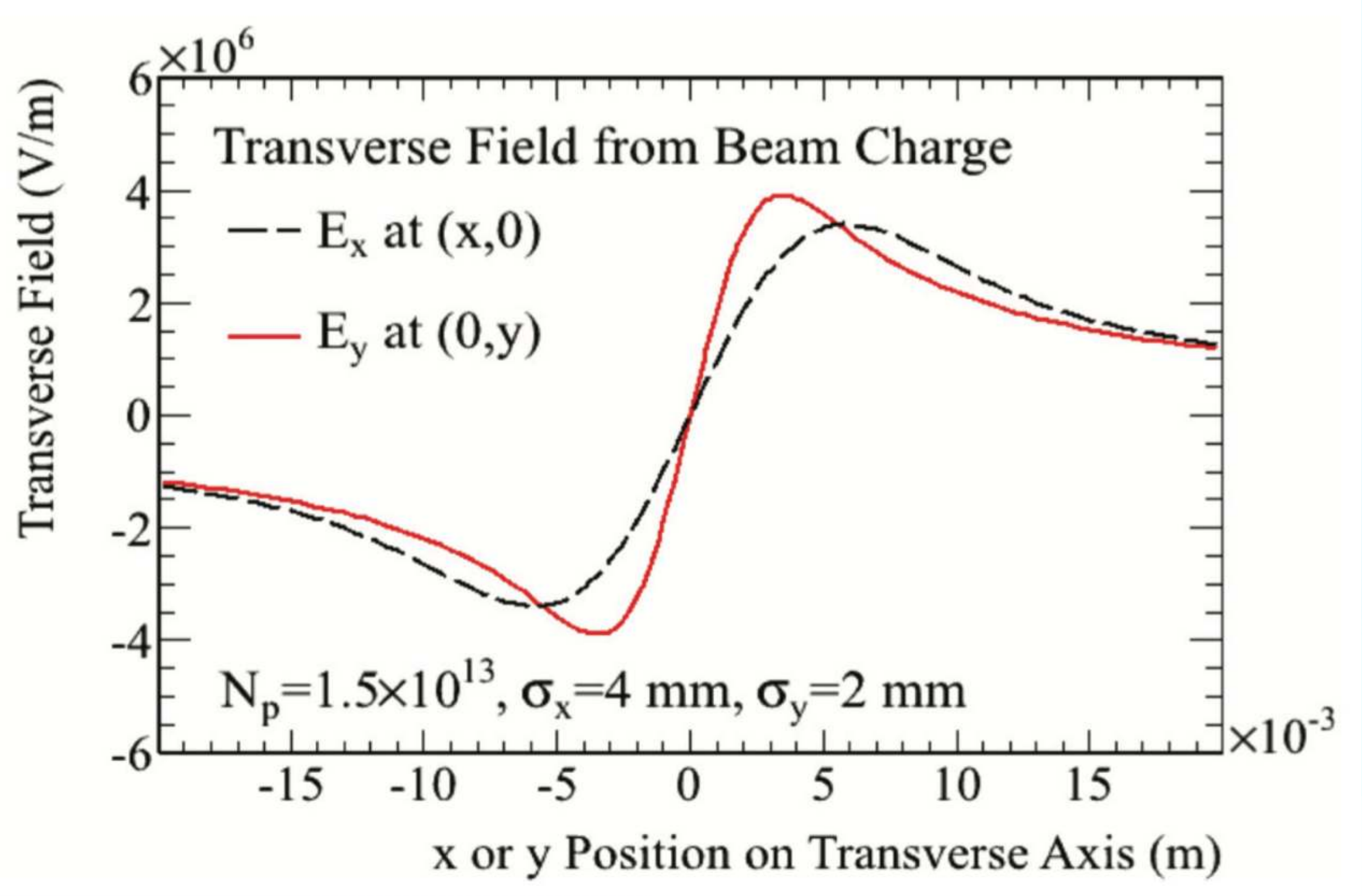


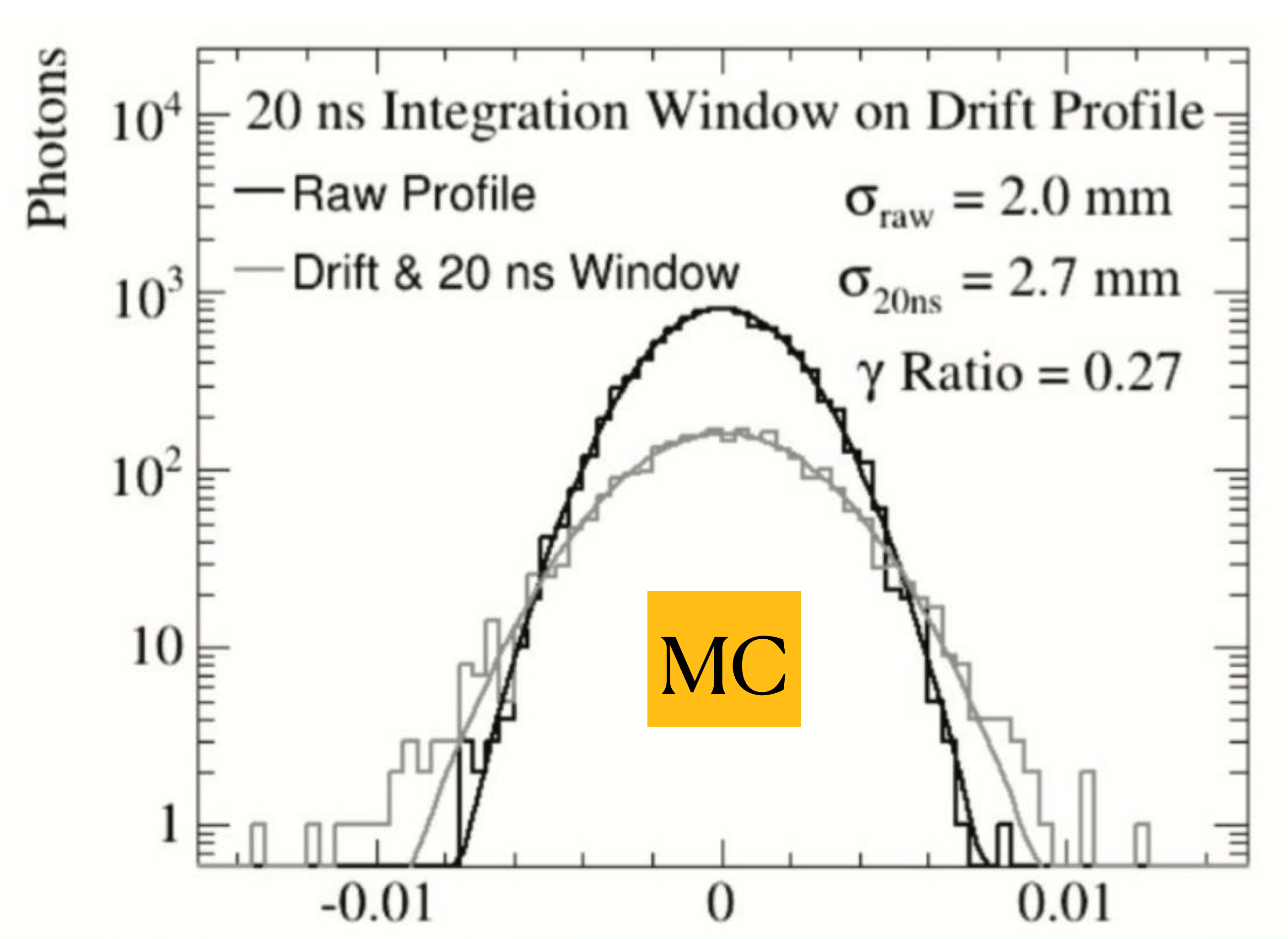
(In-)stability of the beam reconstructed position and width

Space charge effect?

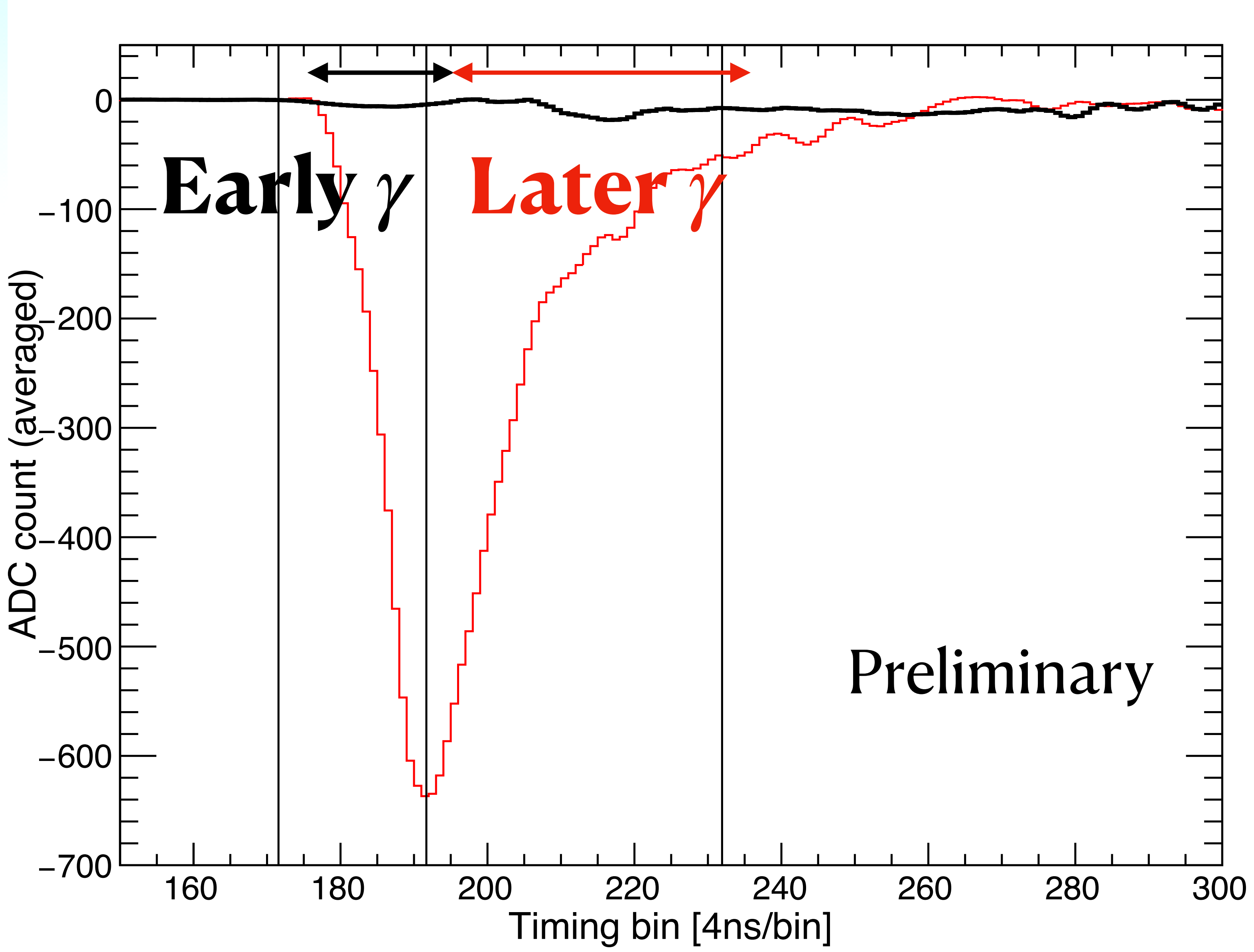
Ref. M. Friend, IBIC 2016

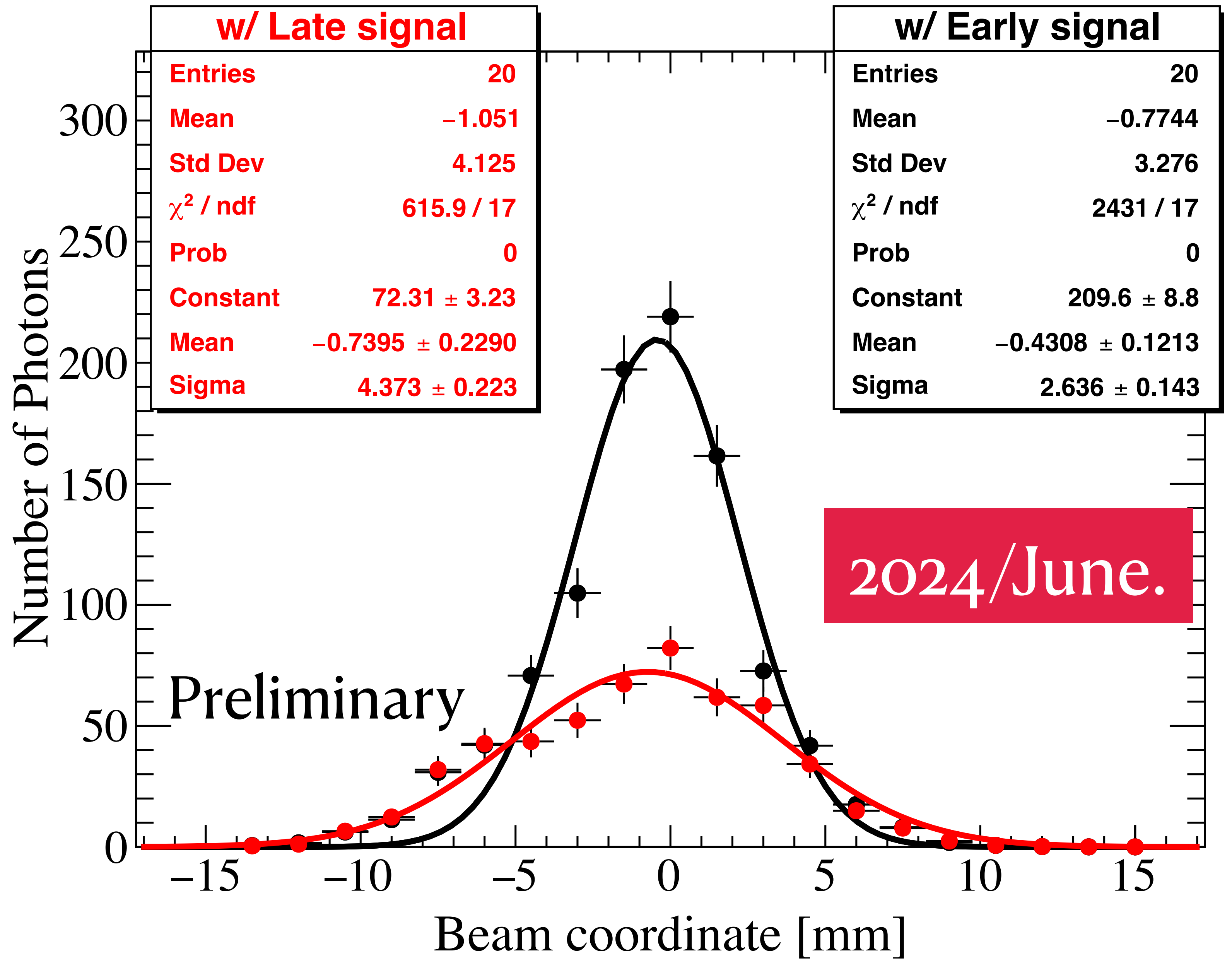
High transverse field from the charge of proton beam drift ionized gas particles before return to ground stage ➔ make distortion of the beam profile reconstructed from fluorescent light





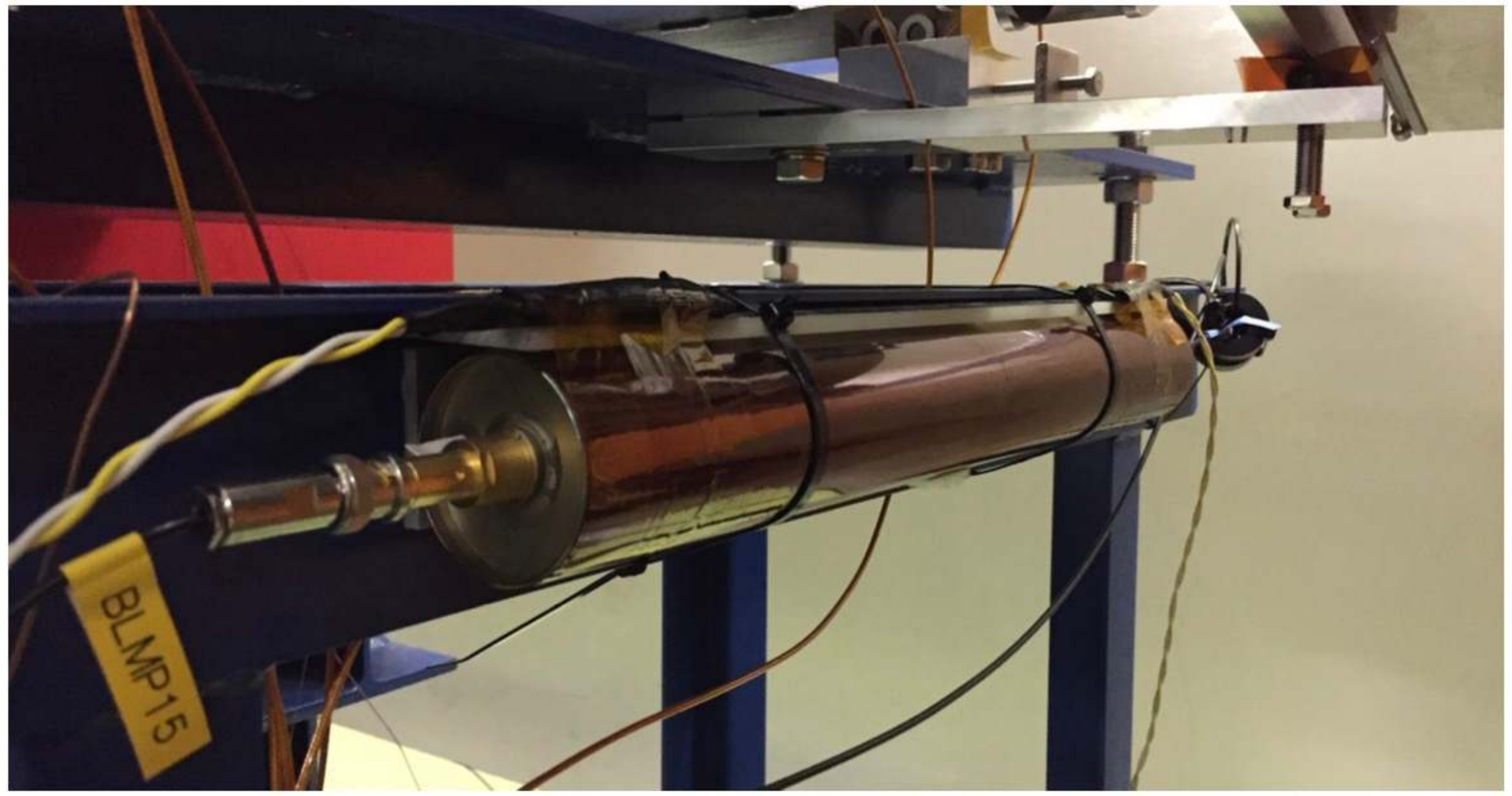
- Fast-responded MPPC allows us to collect light in a specific timing window ➔ enable to study space-charge-like effect
- Some preliminary observation indicates narrower profile can be reconstructed w/ early light capture.
- More study is carried out, particularly on MPPC's response and analysis methodology
- Also consider testing with different (heavier) gas to suppress this potential effect

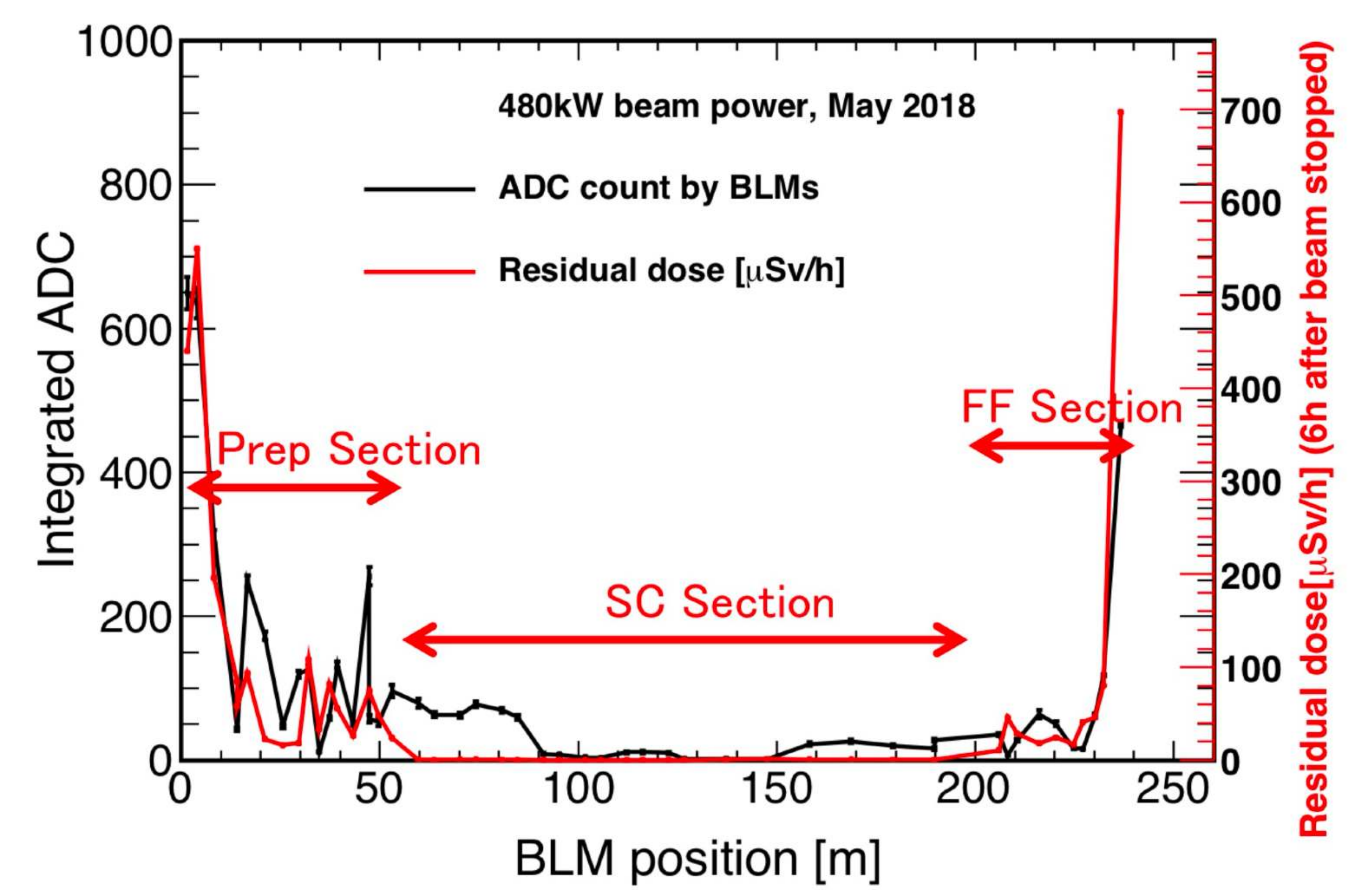




Optical fiber-based Beam Loss monitor R&D

Beam loss monitor





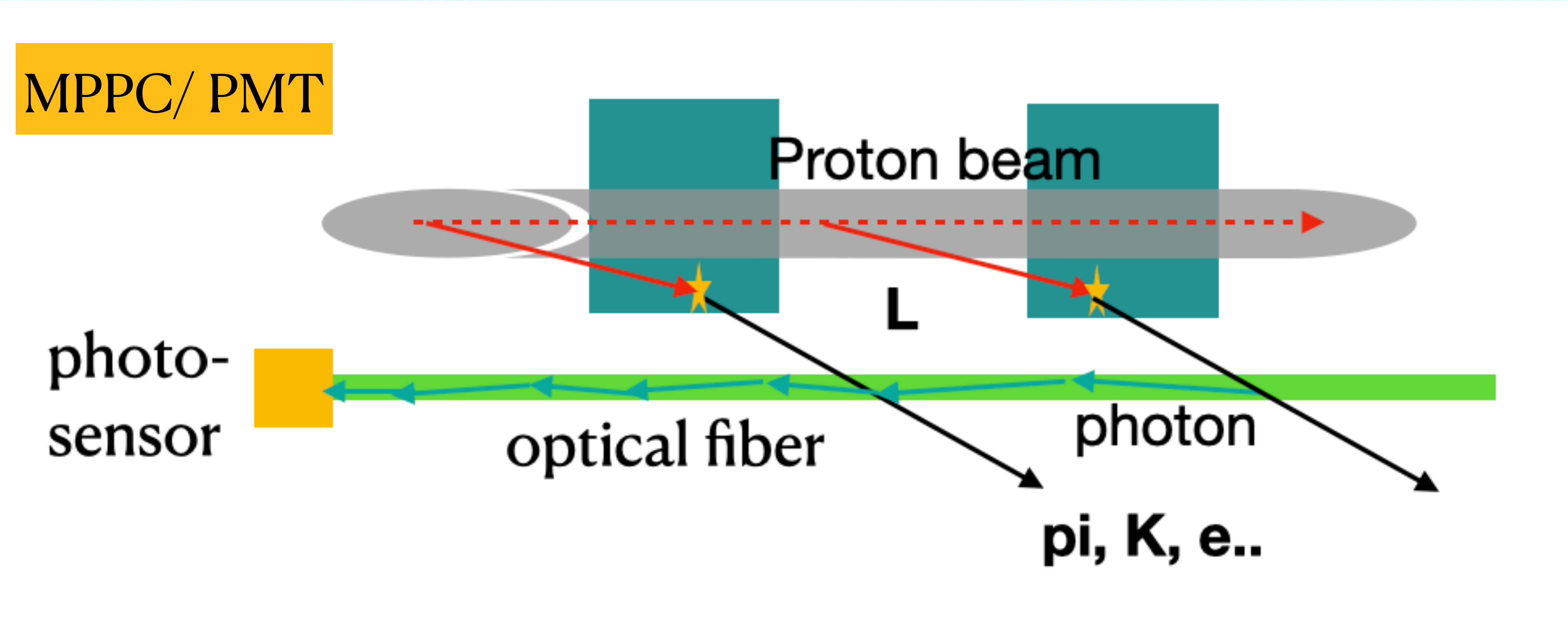
- 50 beam loss monitors (BLMs) distributed along 238m beamline
  - *Proportional counter with a mixture of Ar and CO2*
- It is essential for machine protection system : will fire signal to stop the proton if the signal is over pre-defined threshold.
- Also it is utilised for estimating the residual dose after the beam stop, which is useful for radiation survey and maintenance work

Wish to have additional features

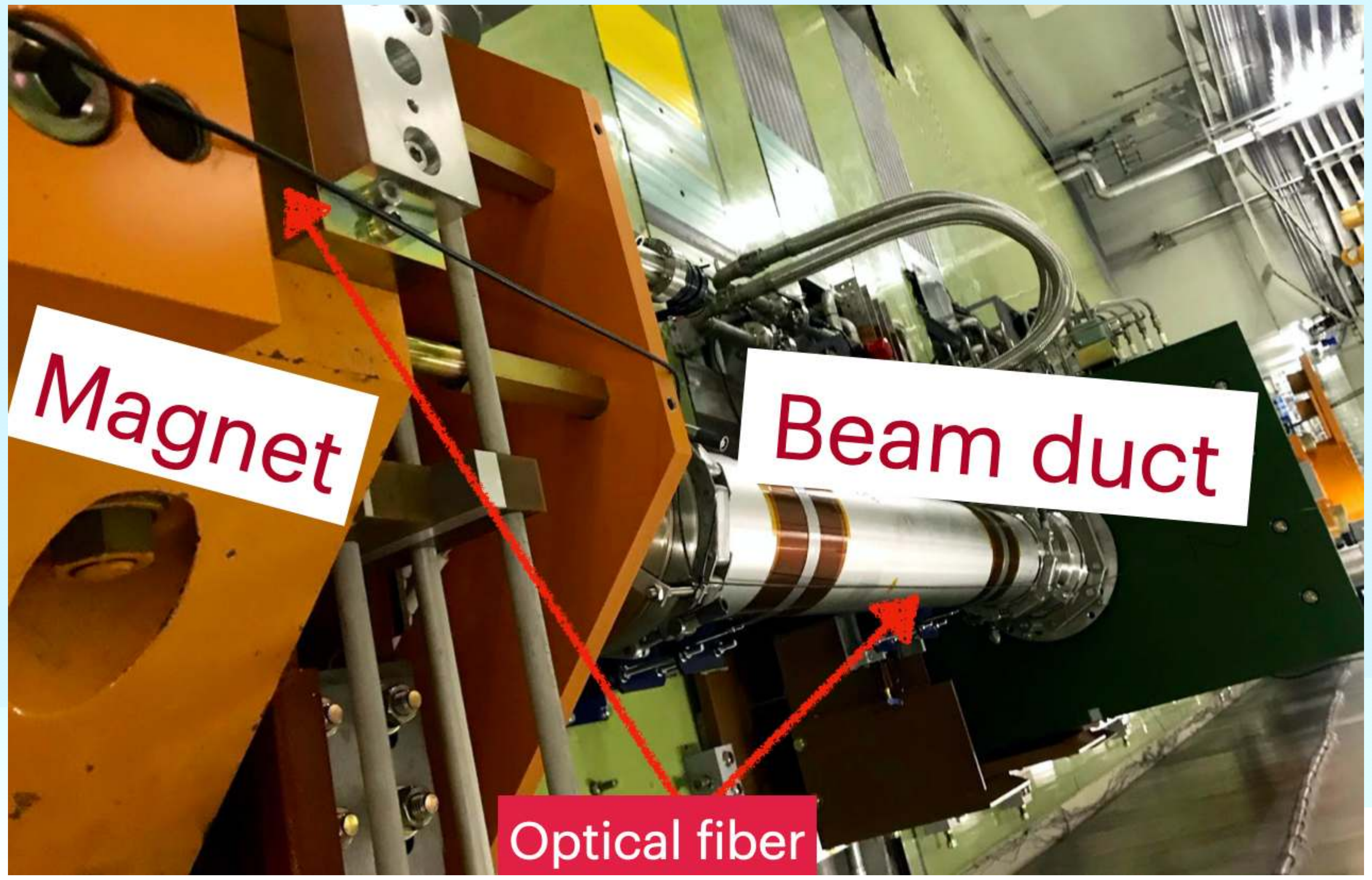
- Bunch-by-bunch (in)stability monitor
- Capability to locate the loss source
- Sensitivity to thermal and fast neutrons
- Beam halo detection
- In term of continuous monitoring: must watch beam loss at all times when accelerator operate (not only during neutrino experiment.)

Ref: T2k NIM paper / SC IBIC 2020

Motivation for the Optical fiber-based BLM (O-BLM)



Charge particles generate Cherenkov light when passing through the optical fiber, which also plays a role as a light guider to the fast photosensor. Number of observed photons are essentially proportional to the flux of charge particles, i.e beam loss

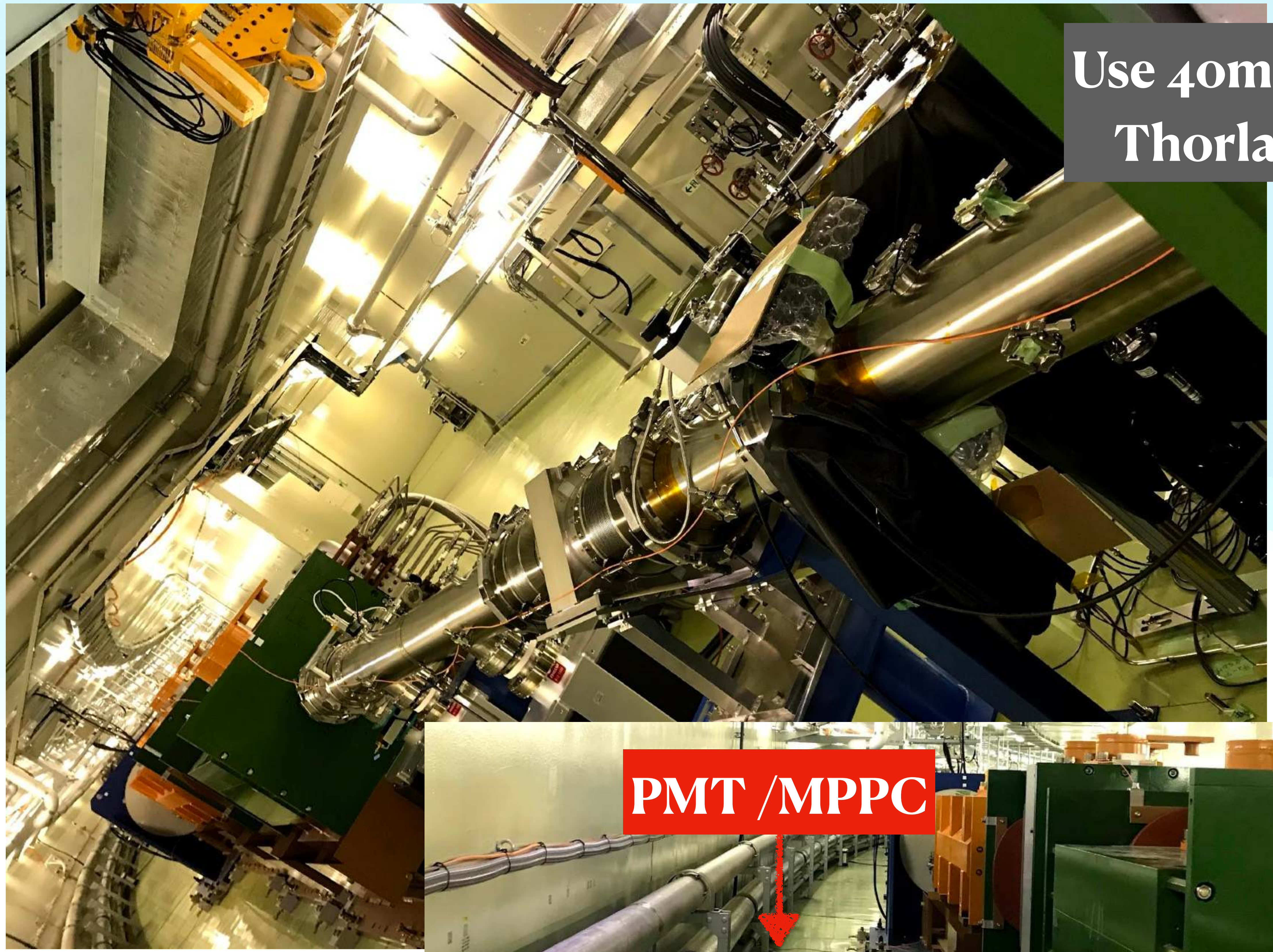


Key features:

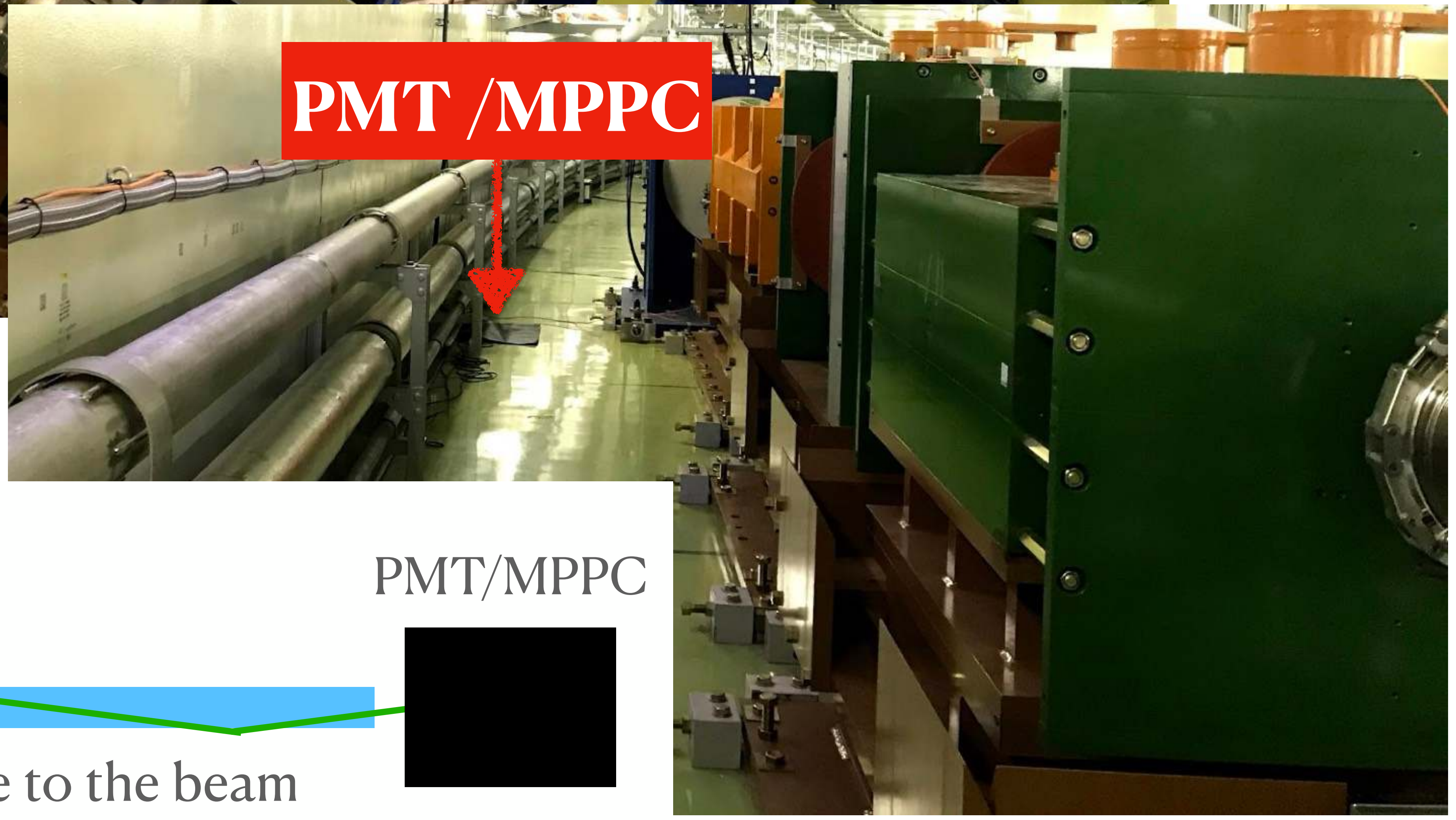
Fast-response, portable, economical

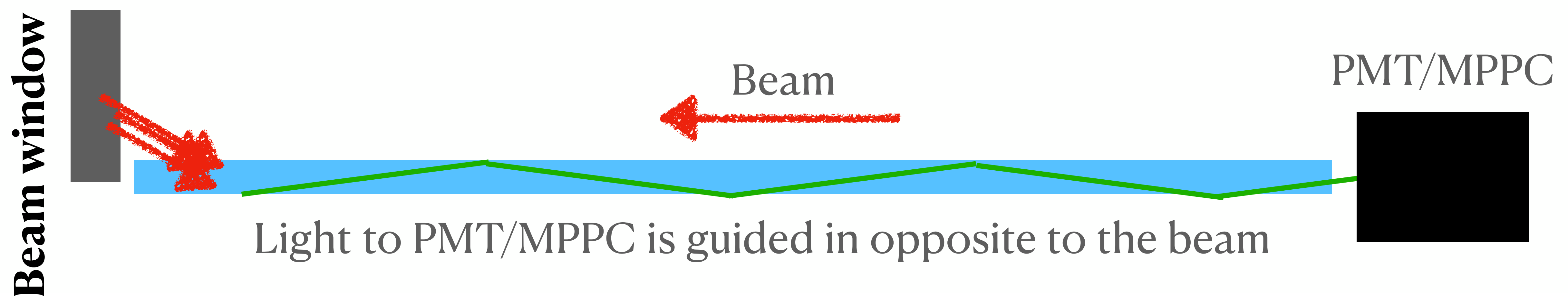
- Proton speed: 3.3ns/m
- Light propagation in fiber: 5ns/m
- Signal separation (maximal): 8.3ns/m
- Bunch width ~ 13ns; signal readout resolution 5ns ➔ well-separated if two signal-induced position separated by ~7m (*assumed background<<signal*)

Instrument 37m of the final focusing section

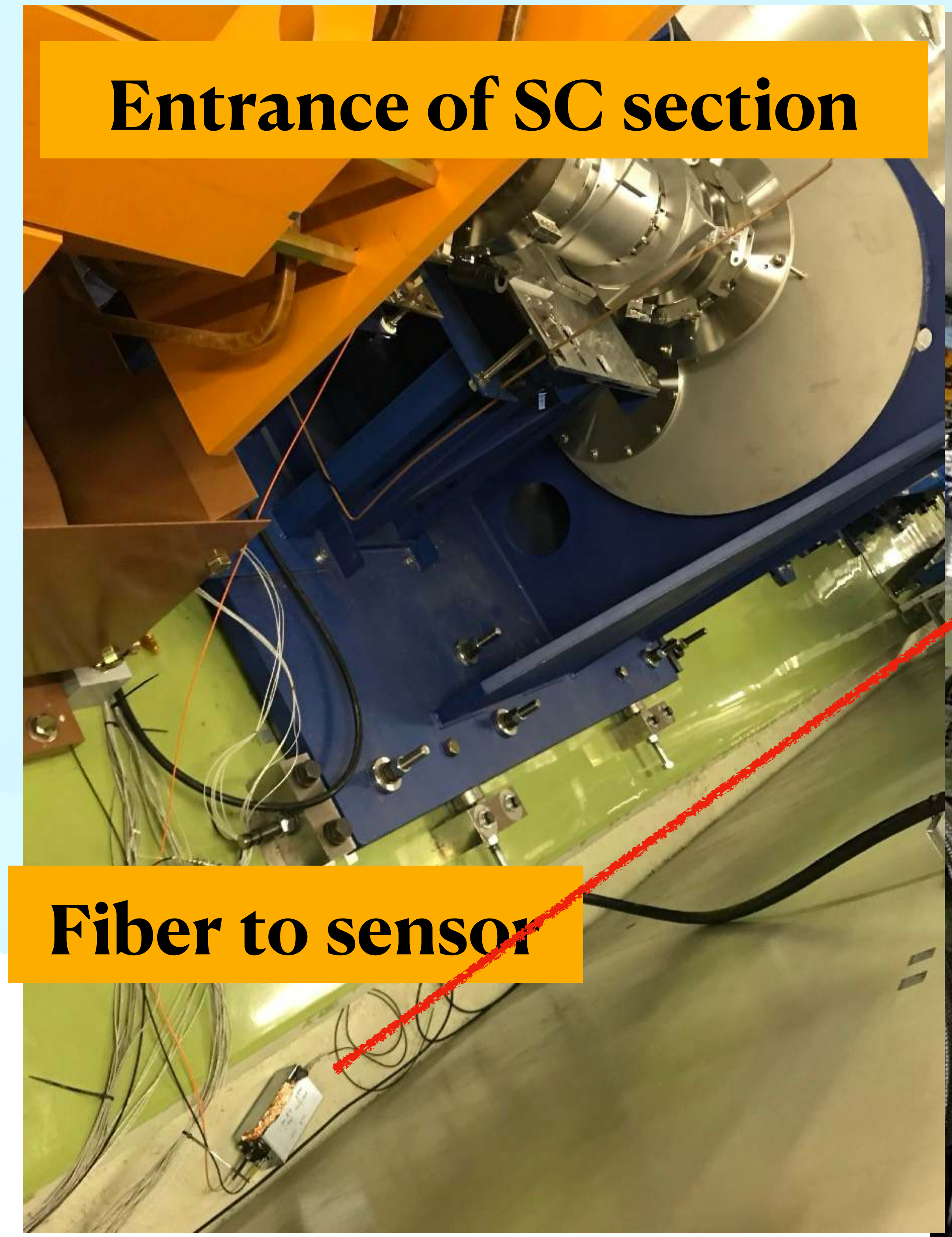


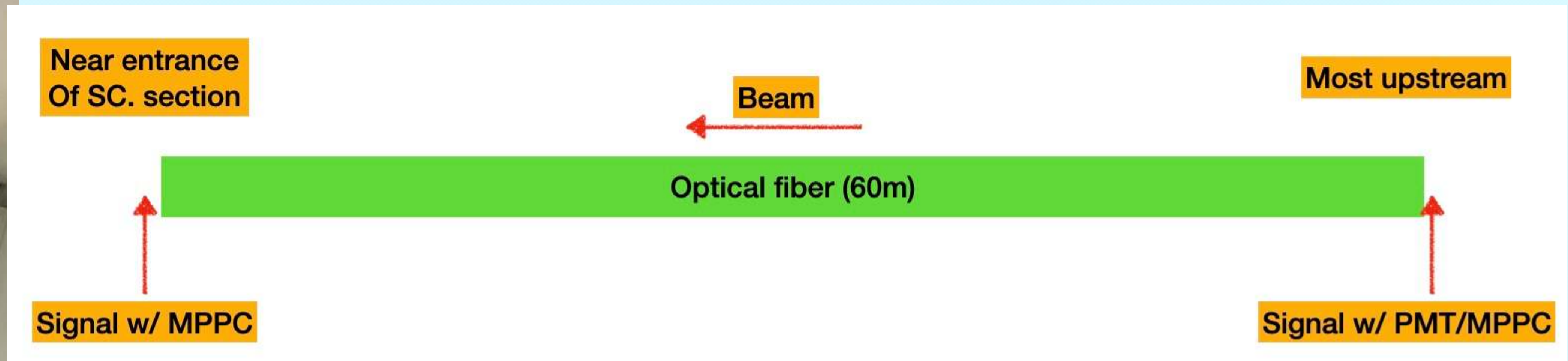
Use 40m-length 400um-core Thorlabs (NA=0.39) fiber

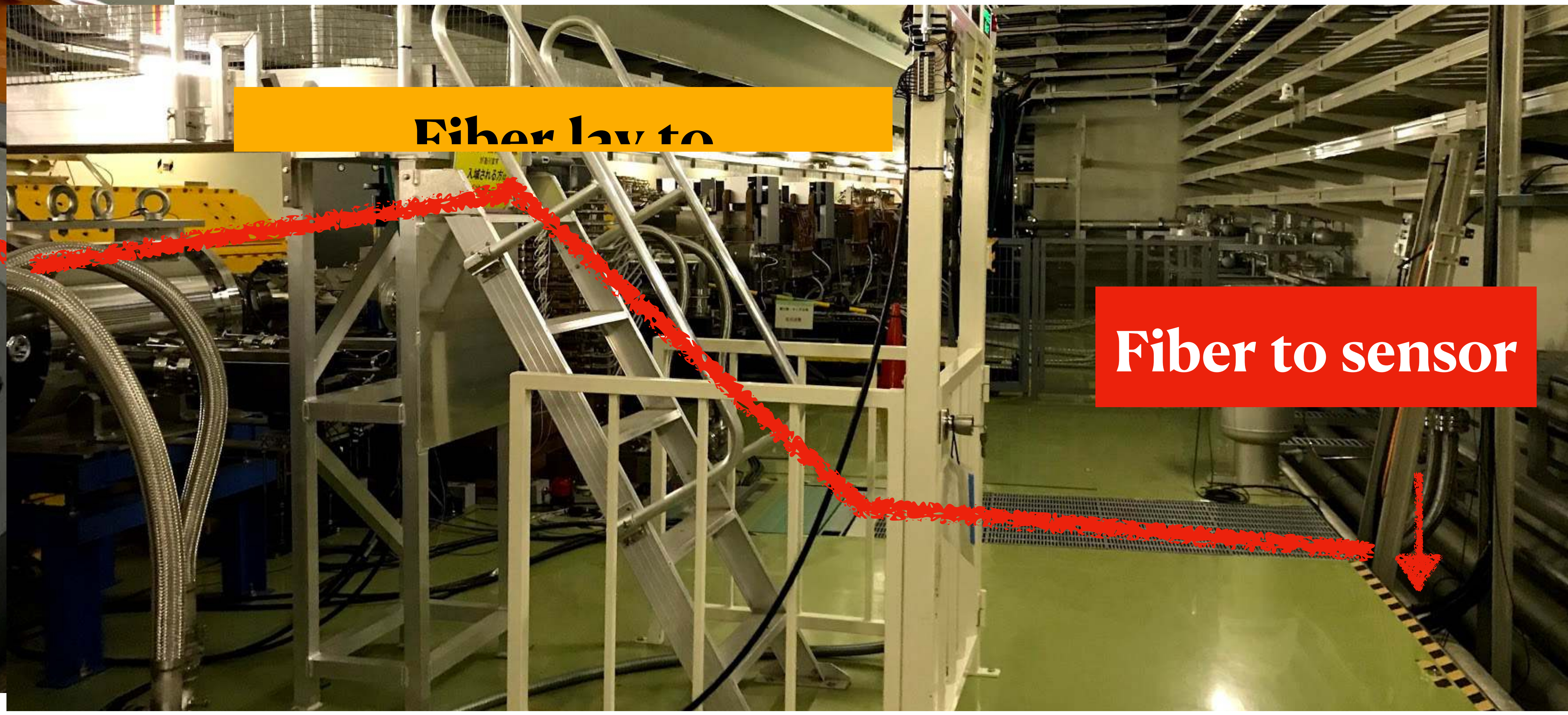




Instrument 54m of the preparation section

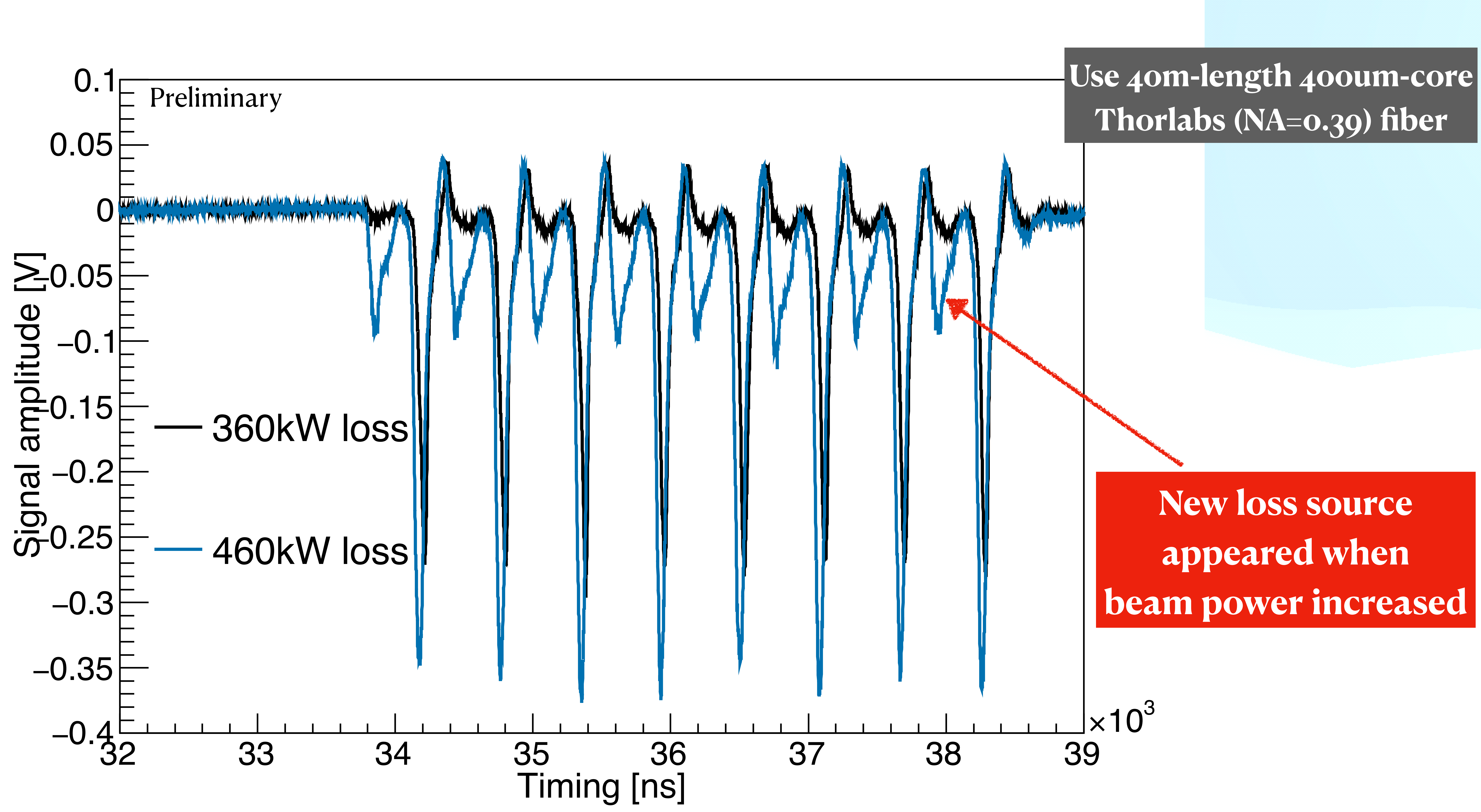






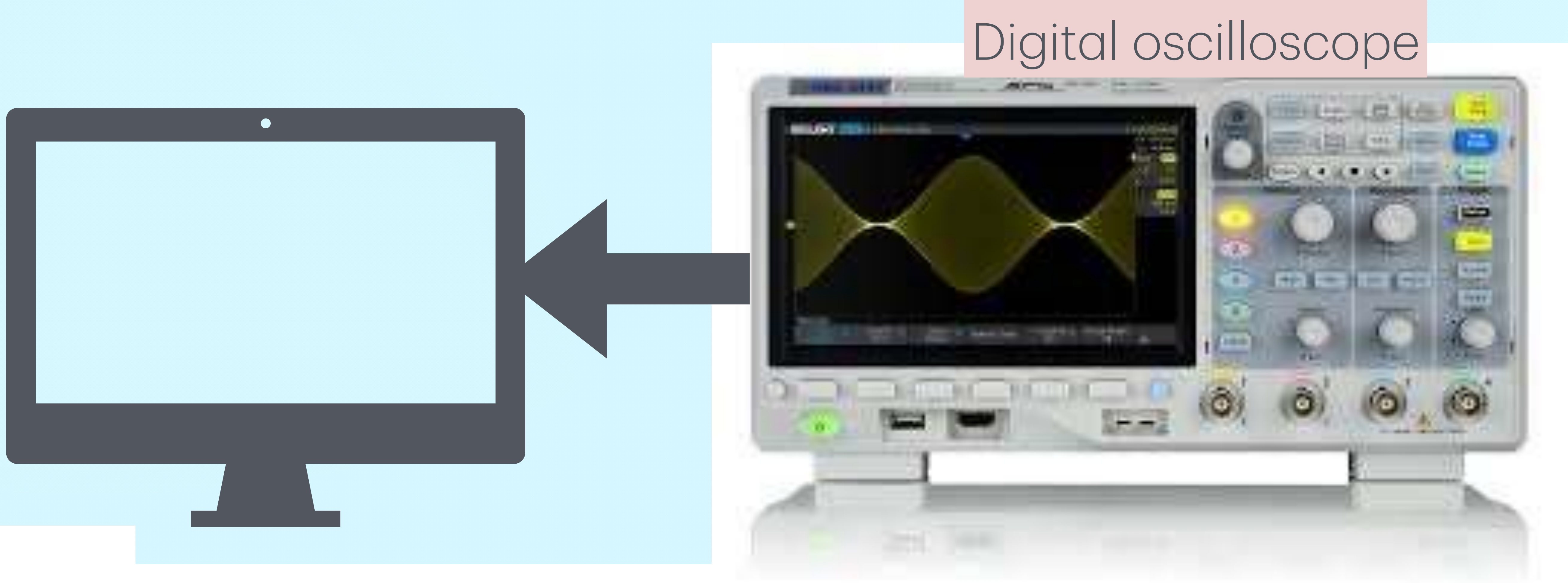
Use 60m-length 200um-core Fujikura (NA=0.22) fiber

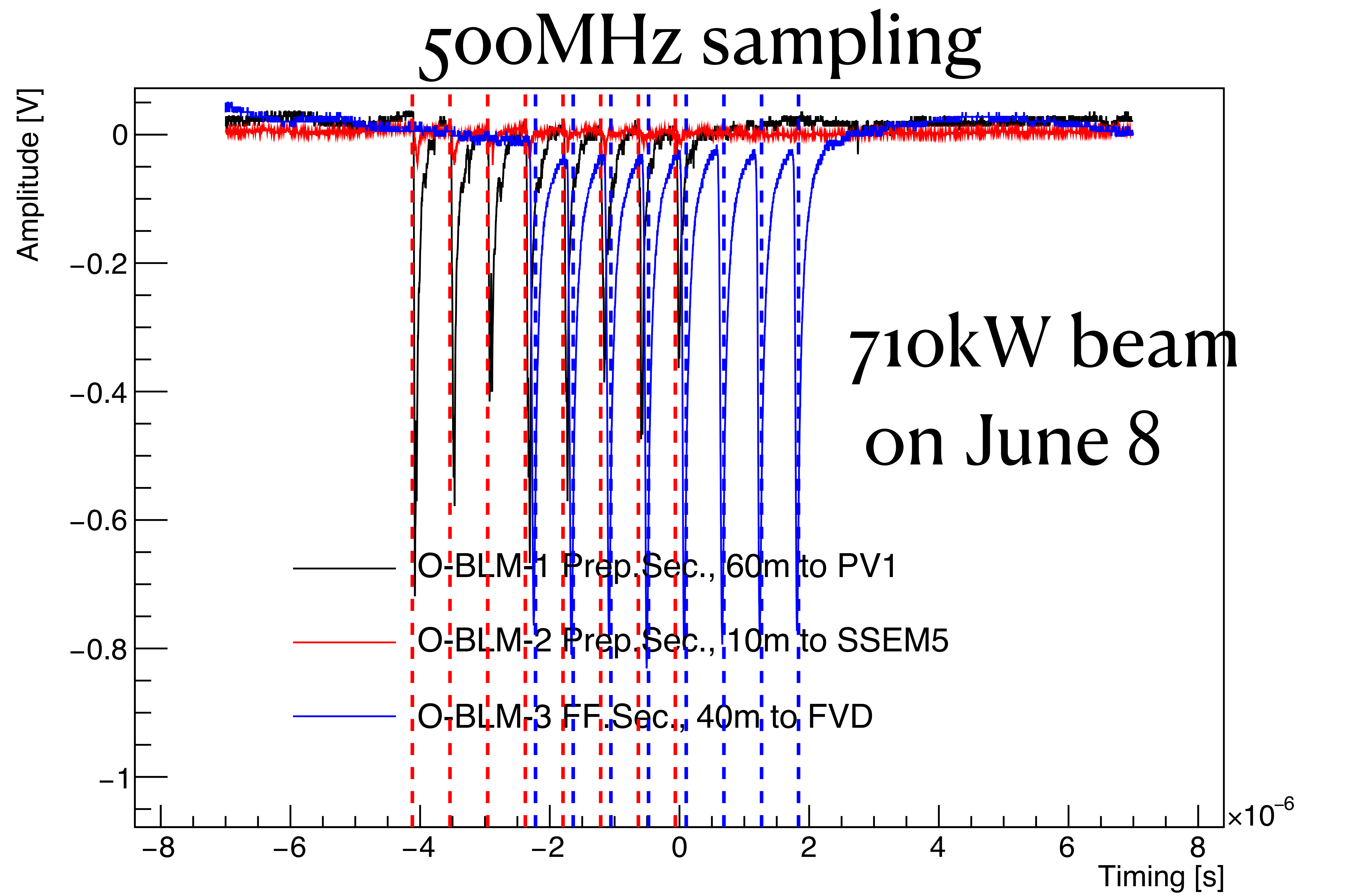
Beam loss pattern observed with O-BLM

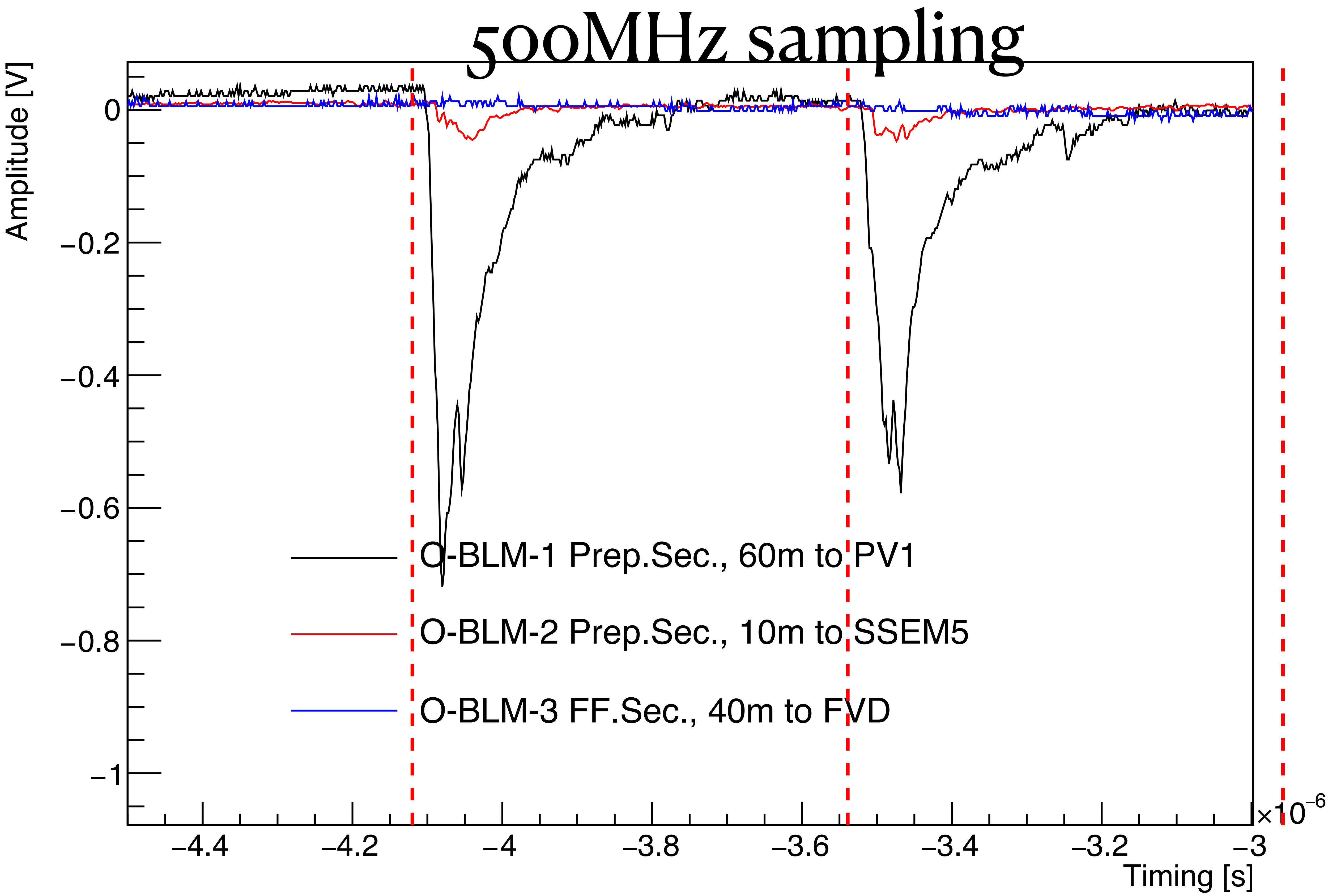


Read out O-BLM signals

- Two O-BLM cover ~90m beamline. One O-BLM couples with ~10m optical fiber for other studies
- Three channels are connected to 500MHz sampling oscilloscope and stream out data via Ethernet

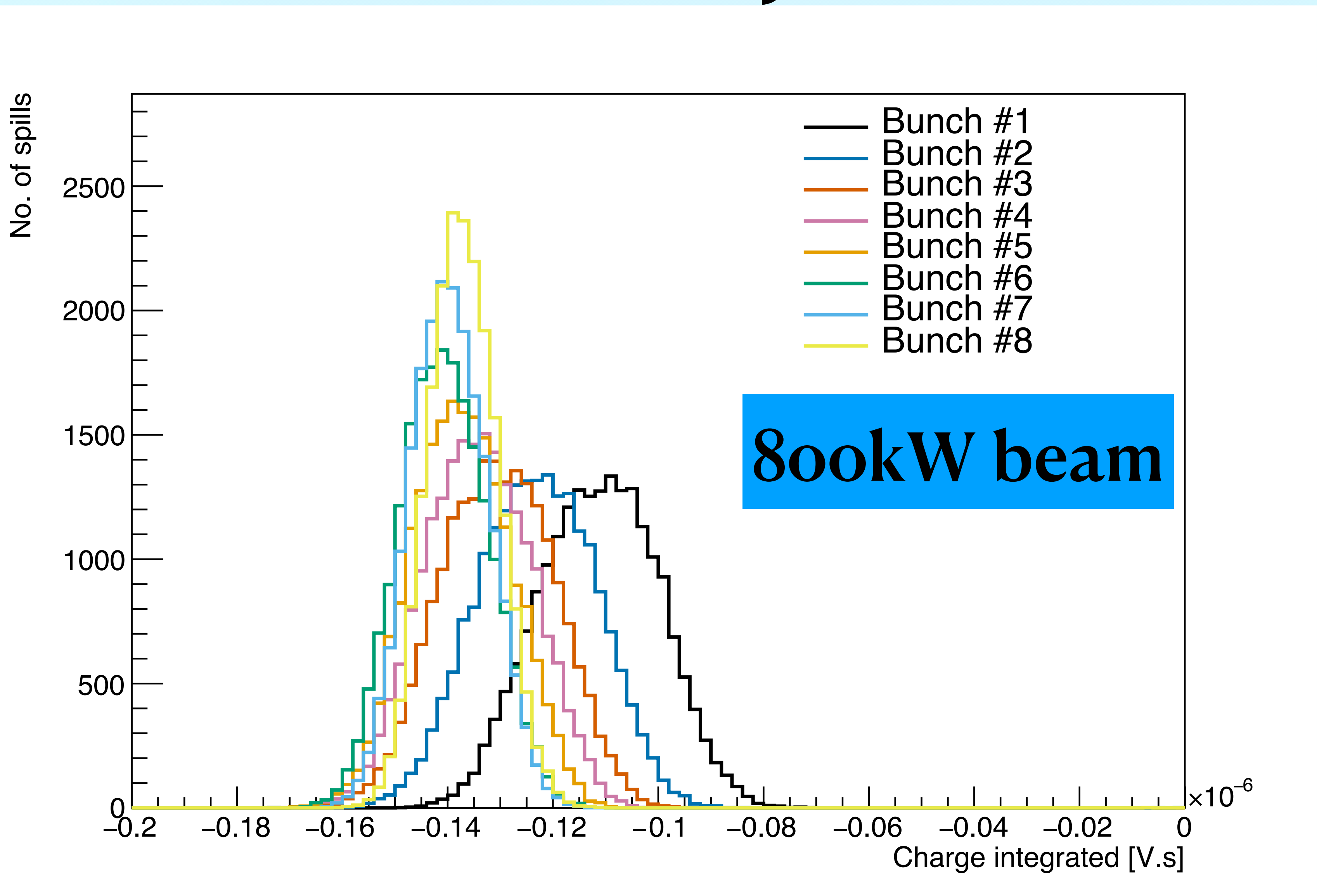


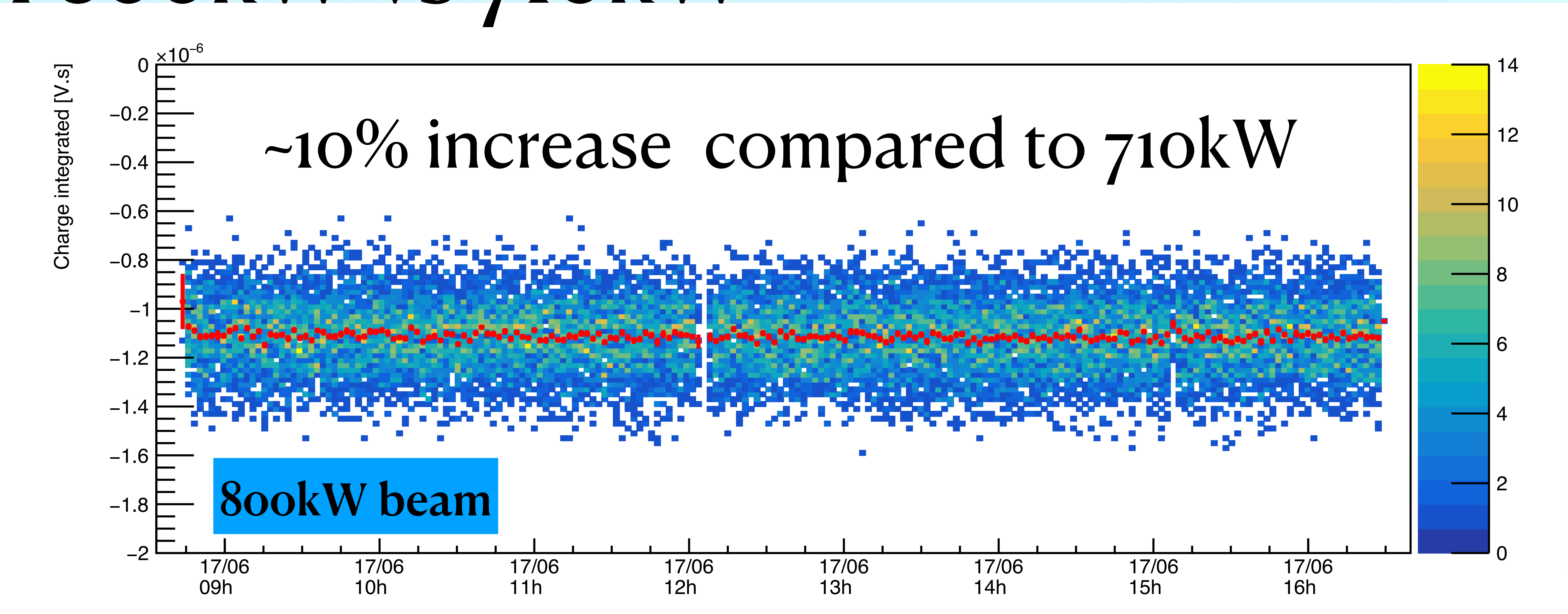


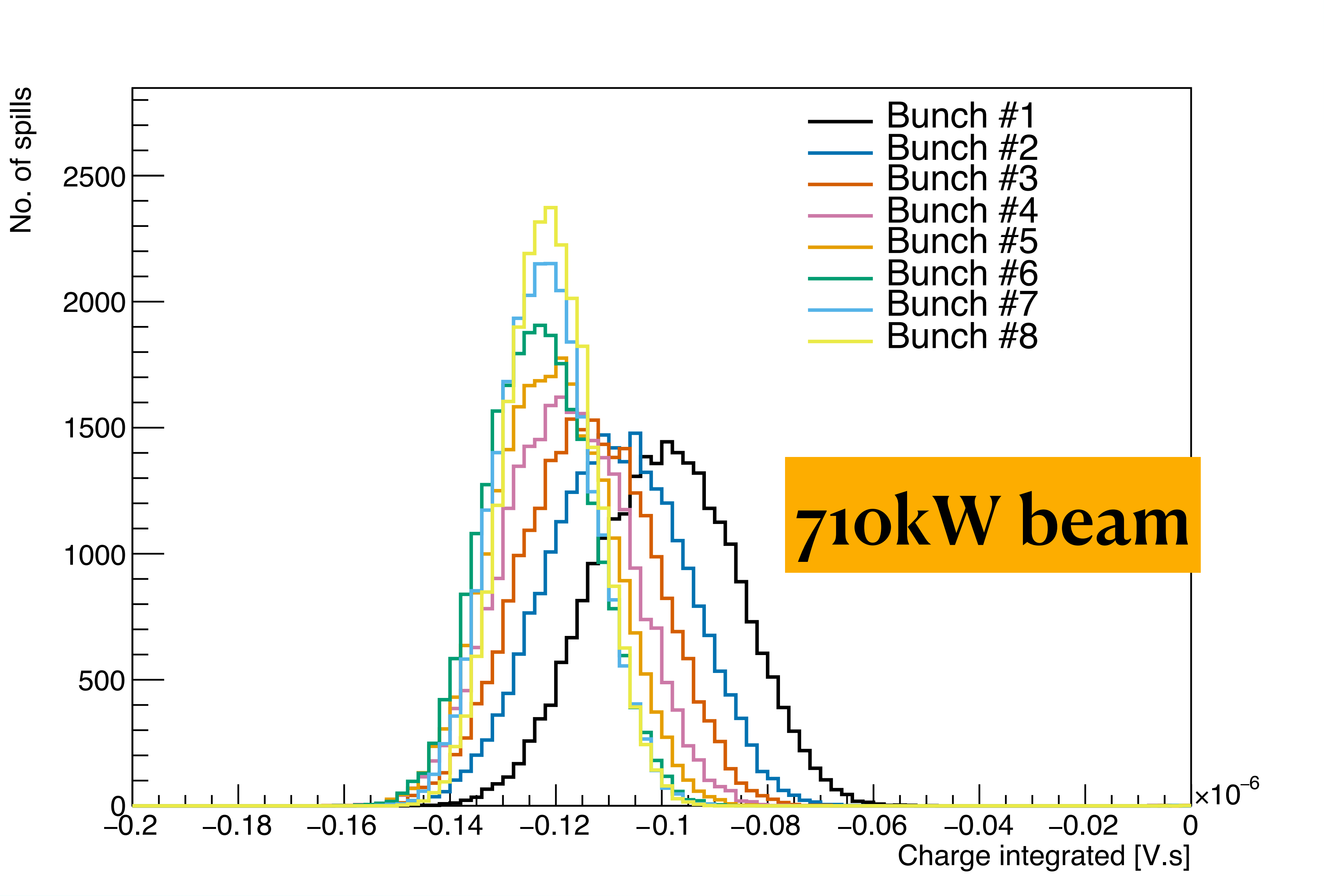


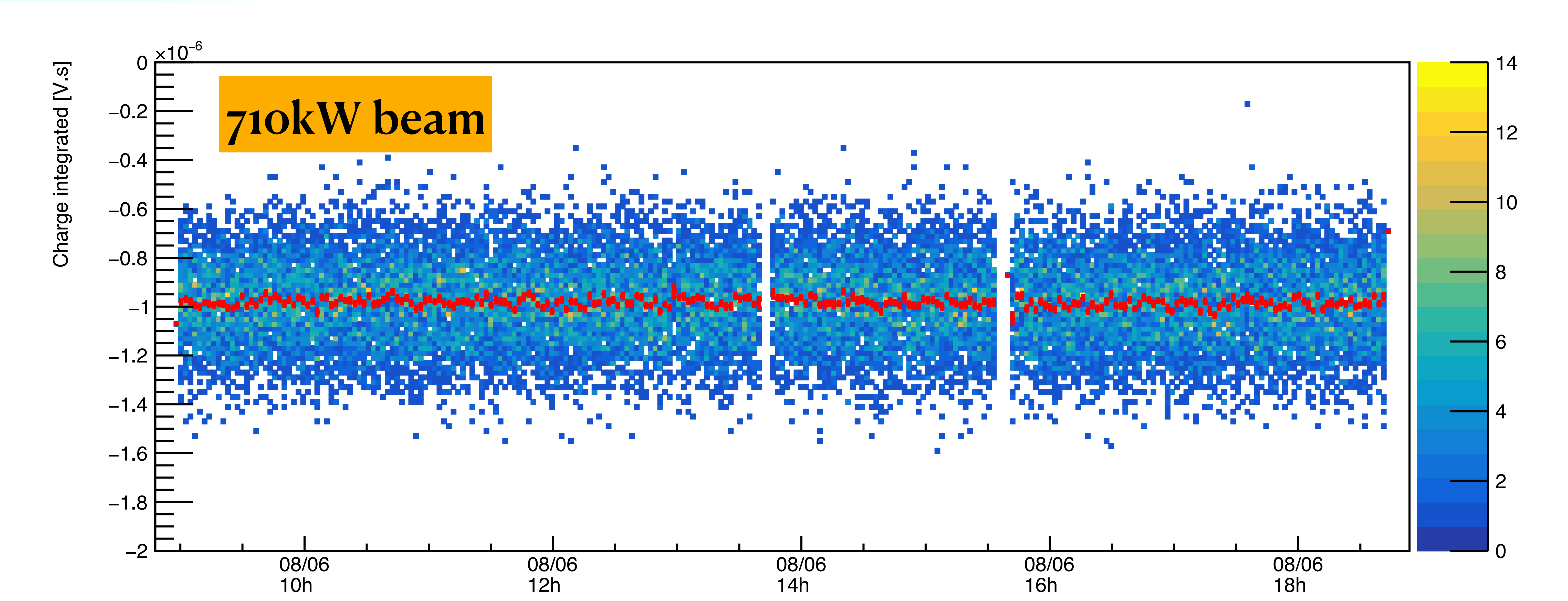
Significant delay btw O-BLMs is due to: (i) arrival time of beam itself and (ii) electric latency

(in-)stability of O-BLM 800kW vs 710kW









Bunch-by-bunch beam loss

Data from one O-BLM w/ ~9h continuous operation

Summary

- Monitoring beam profile and loss is essential for MW-power proton beam at J-PARC neutrino beamline
- Being developed non-destructive beam-induced fluorescence monitor (BIF)
  - Working prototype has been deployed and being tested with high-intensity beam to T2K experiments
  - Gas injection system for safe, continuous prescaled operation has been benchmarked
  - Transverse beam profiles are well-reconstructed with both optical readout systems. More comprehensive checks are underway to ensure that we understand the relevant effect (*space-charge, optical distortion, calibration…*)
- Being developed Optical fiber-based beam loss monitor (O-BLM)
  - Instrumented ~ 90m of beamline with two optical fibers and photosensors
  - Oscilloscope-based data acquisition has been developed and tested for "almost" continuous operation
  - Flexible in triggering allows us to take data with beam-trigger (when beam delivers to T2K) and self-trigger (when beam delivers to other experiments) ➜ important for continuous monitoring

We welcome additional collaboration to advance these important beam monitor developments.