Detector development for the MuSEUM experiment at J-PARC

Sohtaro Kanda / THE UNIVERSITY OF TOKYO

for the MuSEUM Collaboration

2014. 11. 21 at J-PARC

MuSEUM Collaboration

MuSEUM : Muonium Spectroscopy Experiment Using Microwave

MuSEUM Collaborators

Univ. of Tokyo
Y. Higashi, T. Higuchi, S. Kanda, Y. Matsuda, T. Mizutani, M. Tajima, K.S. Tanaka, H.A. Torii, Y. Ueno

KEK
Y. Fukao, H. Iinuma, Y. Ikedo, R. Kadono, N. Kawamura, A. Koda, K. M. Kojima, T. Mibe, Y. Miyake, K. Nagamine, K. Nishiyama, T. Ogitsu, R. Okubo, N. Saito, K. Sasaki, K. Shimomura, P. Strasser, M. Sugano, A. Toyoda, K. Ueno, A. Yamamoto, M. Yoshida

RIKEN
K. Ishida, M. Iwasaki, O. Kamigaito, D. Tomono (Currently @ Kyoto Univ.)

ICU
K. Kubo

Univ. of Massachusetts
D. Kawall

Osaka University
M. Aoki

University of Yamanashi
E. Torikai

MuSEUM

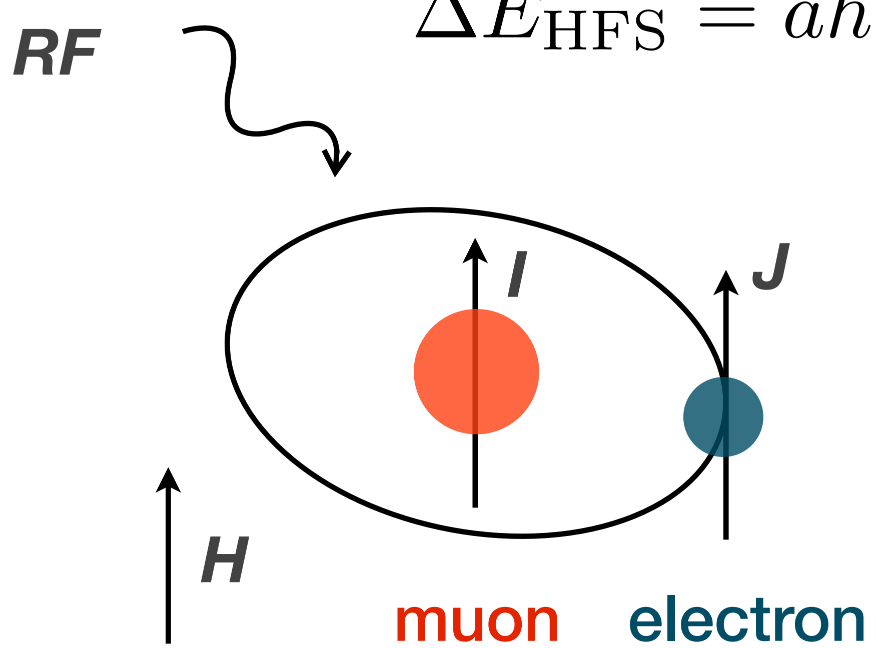
5 Universities, 3 Institutions
39 people

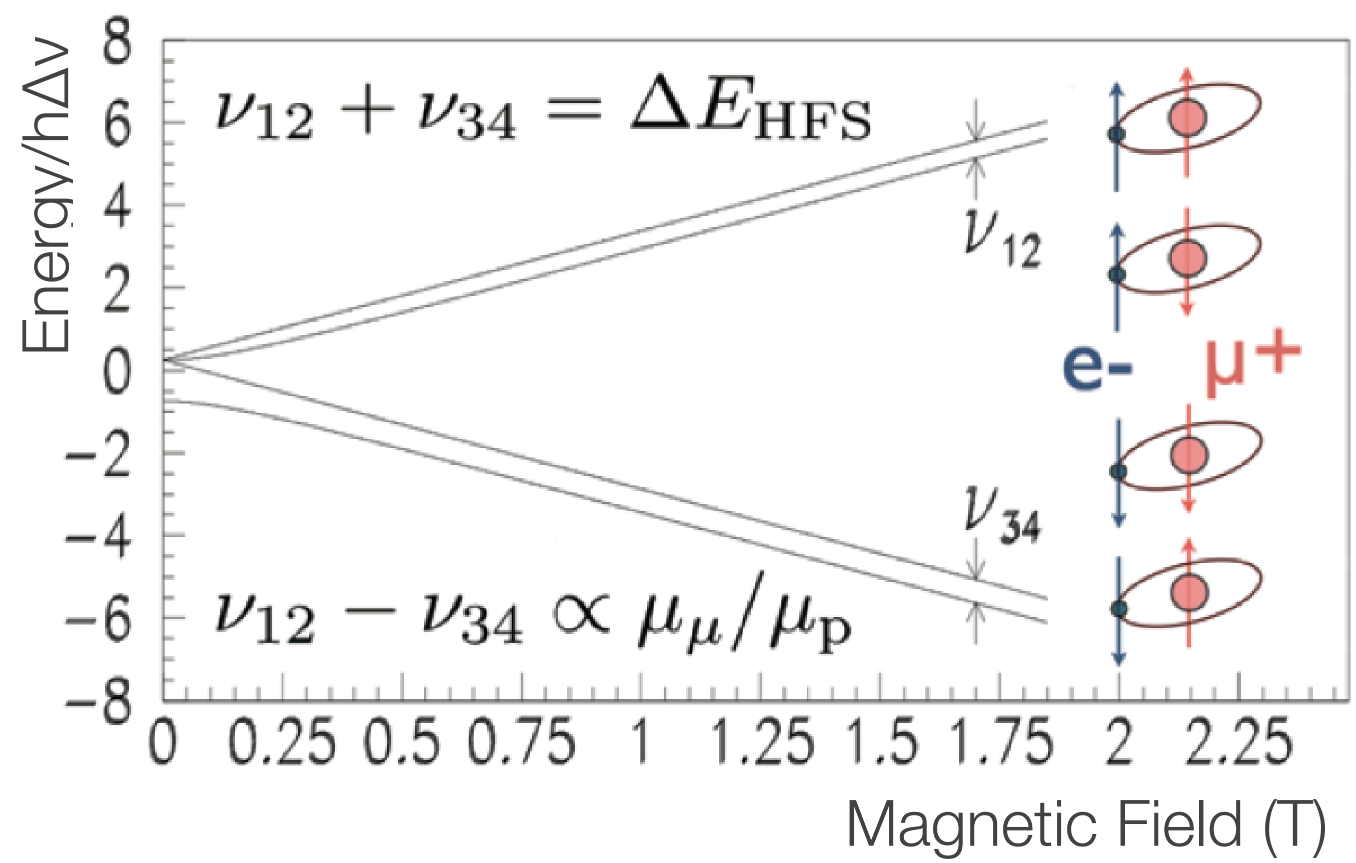
The System and Motivation

Hamiltonian of Muonium

$$\mathcal{H} = \underbrace{a\,\vec{I}\cdot\vec{J}}_{\text{HFS}} + \underbrace{\mu_B^e g_J\,\vec{J}\cdot\vec{H} - \mu_B^\mu g_\mu^{'}\,\vec{I}\cdot\vec{H}}_{\text{Zeeman Splitting}}$$ **+ RF term**

$$\Delta E_{\mathrm{HFS}} = ah\Delta\nu$$





Muonium:

- Bound state of μ+ and e-
  (Less affected by recoil than Ps)
- Pure leptonic system
  (Composite particle free)

Objectives:

- Precision test of bound state QED
- Muon mass determination
  - Muon g-2
- Test of Lorentz invariance

Impact of MuSEUM

- **Precision test of the Bound state QED**

$$\Delta E_{\mathrm{HFS\ Exp}} = 4.463302765(53)\ \mathrm{GHz}$$ **(12 ppb)**

W. Liu *et al.*, PRL, 82, 711 (1999)

$$\Delta E_{\mathrm{HFS\ Theory}} = 4.463302891(272)\ \mathrm{GHz}$$ **(63 ppb)**

D. Nomura and T. Teubner, Nucl. Phys. B 867, 236 (2013)

The most precise test of bound state QED

- **Muon g-2**

$$a_\mu = \frac{\mathcal{R}}{\lambda - \mathcal{R}}$$

540 ppb (for a_μ), 26 ppb (for $\mathcal{R}$)

R : From storage ring experiment

λ : From Muonium HFS

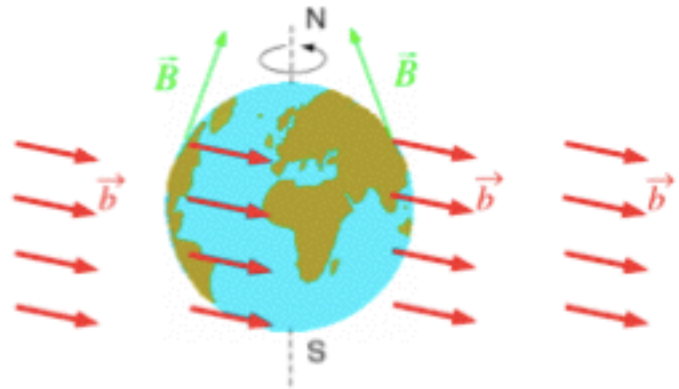
$$\lambda = \frac{\mu_\mu}{\mu_p}$$ (B-field is obtained via proton NMR)

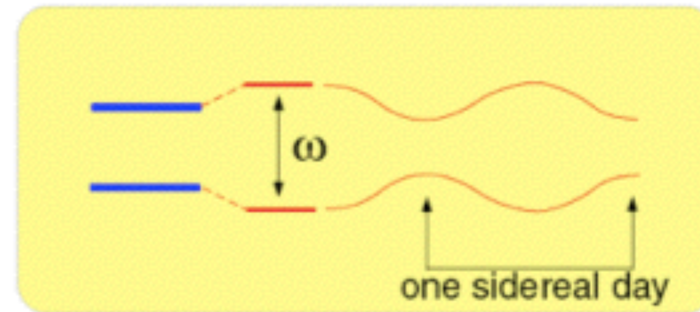
The possible clue to the beyond standard model physics

MuHFS is one-half of the experimental input

Test of Lorentz Invariance

- **Principle : Sidereal oscillation of transition frequency**

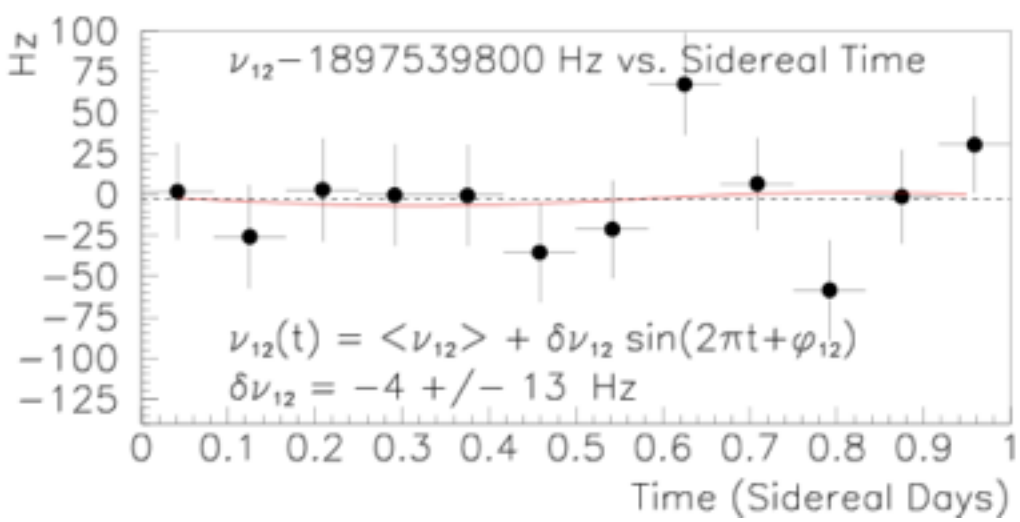


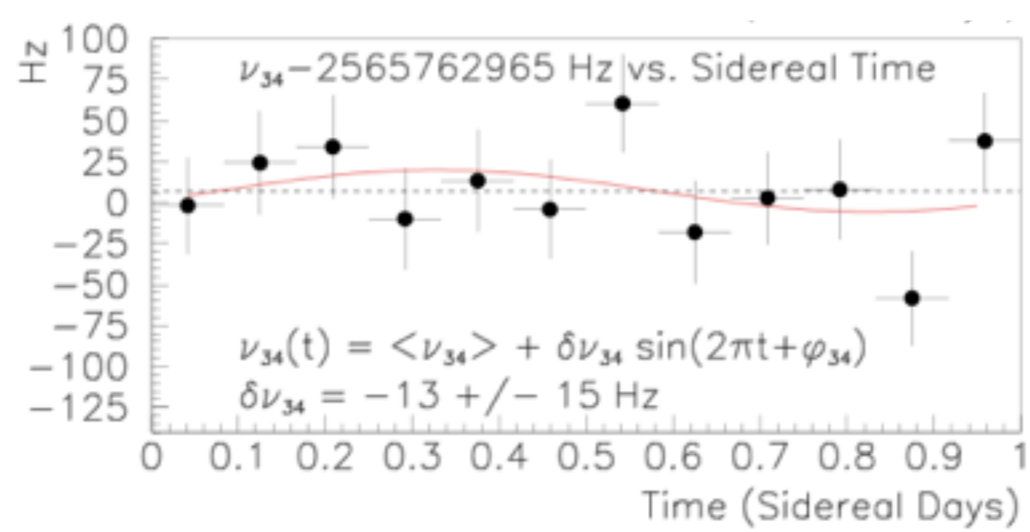


cited from
R. Bluhm's slide

R. Bluhm, V. A. Kostelecký, and C. Da Lane, Phys. Rev. Lett. 84, 1098 (2000)

- **The most recent experimental result**



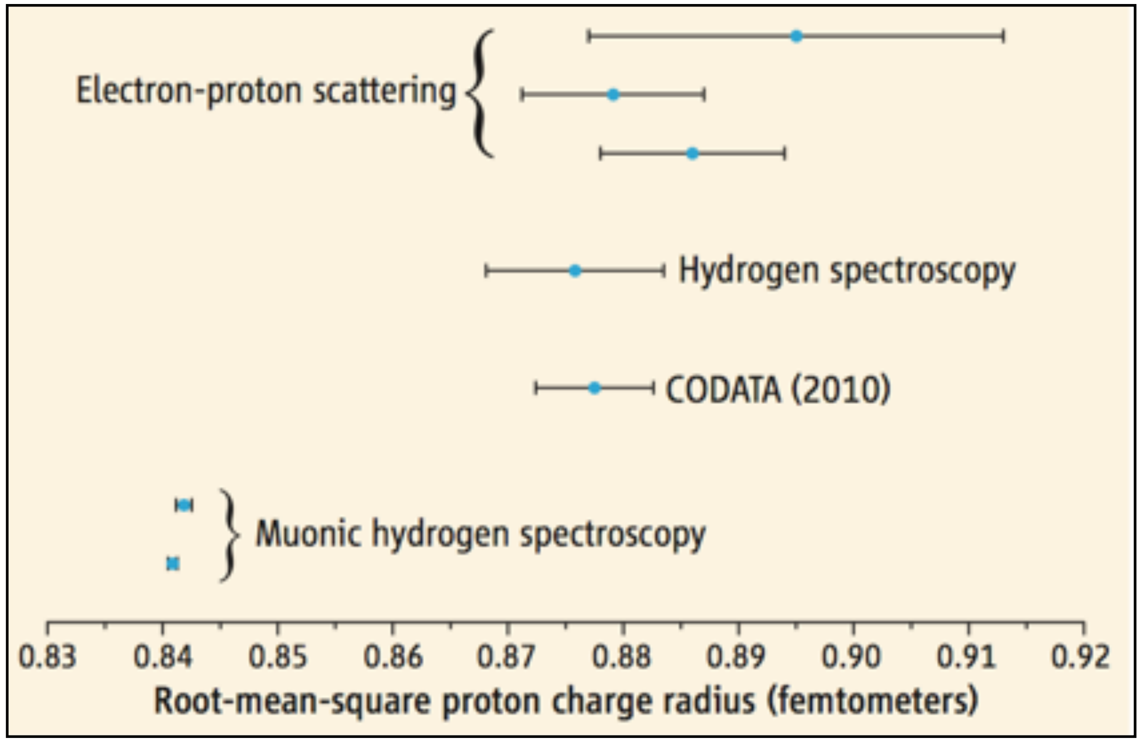


$$|\sin\chi|\sqrt{(\tilde{b}_X^{\mu})^2 + (\tilde{b}_Y^{\mu})^2} \lesssim 2 \times 10^{-22}\ \mathrm{GeV}$$

V.W. Hughes et al., Phys.Rev.Lett.87, 111804 (2001)

Proton Radius Puzzle

- The discrepancy between the muonic hydrogen result and the CODATA value remains with the difference being 7σ



Helen S. Margolis, Science, 339, 6118, pp. 405-406

- Proton charge radius

$$r_p \equiv -6\frac{dG_E}{dQ^2}|_{Q^2=0}$$

- Zemach radius (convolution of charge and magnetic distribution)

$$R_p = \int d^3r\, r \int d^3r'\, \rho_E(\mathbf{r}-\mathbf{r}')\, \rho_M(\mathbf{r}')$$

- Zemach radius can be obtained from muonium HFS and hydrogen HFS

$$E_{\rm HFS}(e^- p) = (1 + \Delta_{\rm QED} + \Delta_R^p + \Delta_S)E_F^p,$$

$$E_{\rm HFS}(e^- \mu^+) = (1 + \Delta_{\rm QED} + \Delta_R^\mu)E_F^\mu.$$

ΔQED: QED correction term
Δs: proton structure term
ΔR: recoil term
E_F: Fermi energy

S. J. Brodsly *et al*., Phys. Rev. Lett. 94, 022001

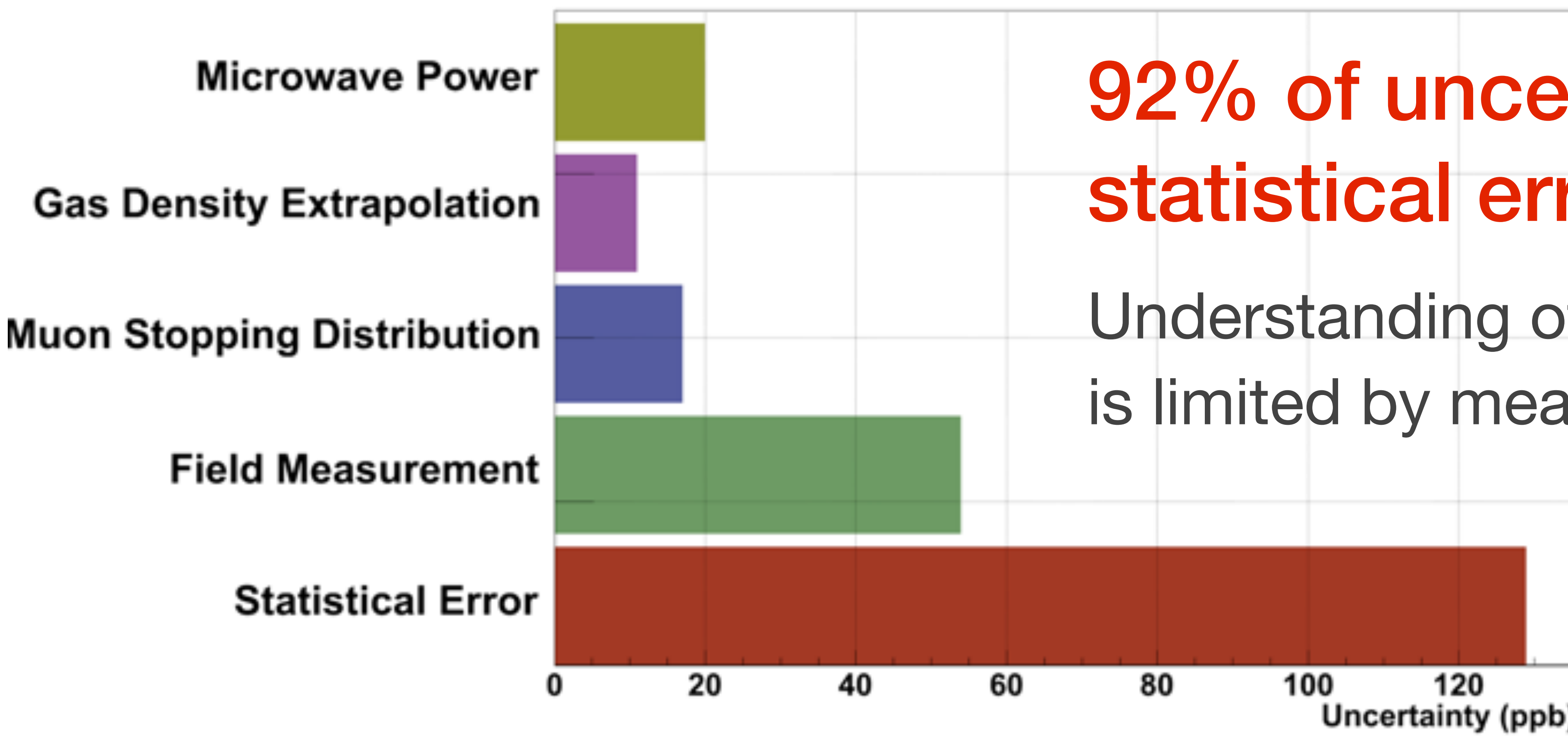
Our Goal of Precision

$$\Delta E_{\mathrm{HFS}} = 4.463302765(53)\ \mathrm{GHz}$$ **(12 ppb)**

$$\mu_\mu/\mu_p = 3.18334513(39)$$ **(120 ppb)**

W. Liu *et al.*, PRL, 82, 711 (1999)

Error Budget (frequency sweep, μμ/μp)



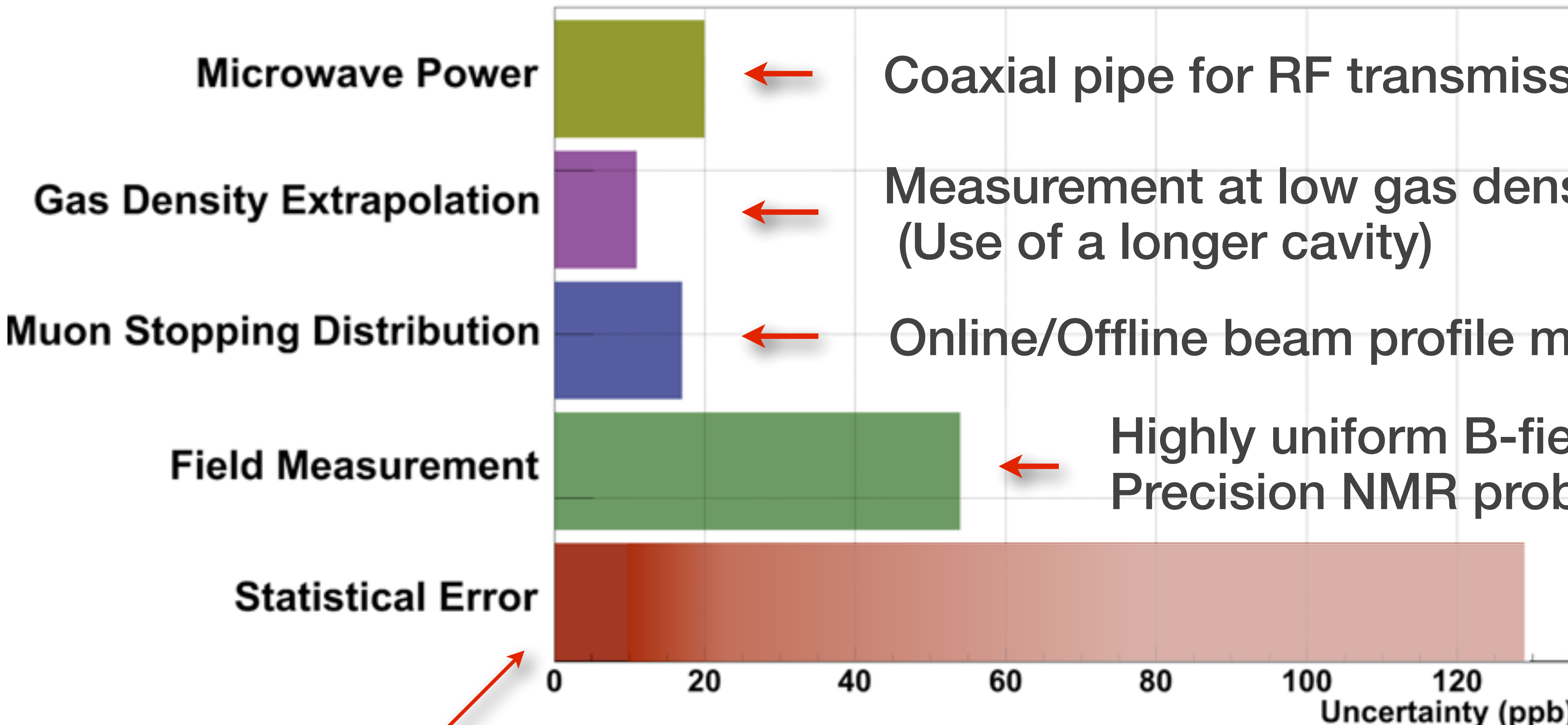
92% of uncertainty is statistical error

Understanding of systematics is limited by measurement time

Our goal : 200 times of statistics and minimization of systematic uncertainty

Approach to Improvement

Error Budget (frequency sweep, μμ/μp) and our approach to improvement

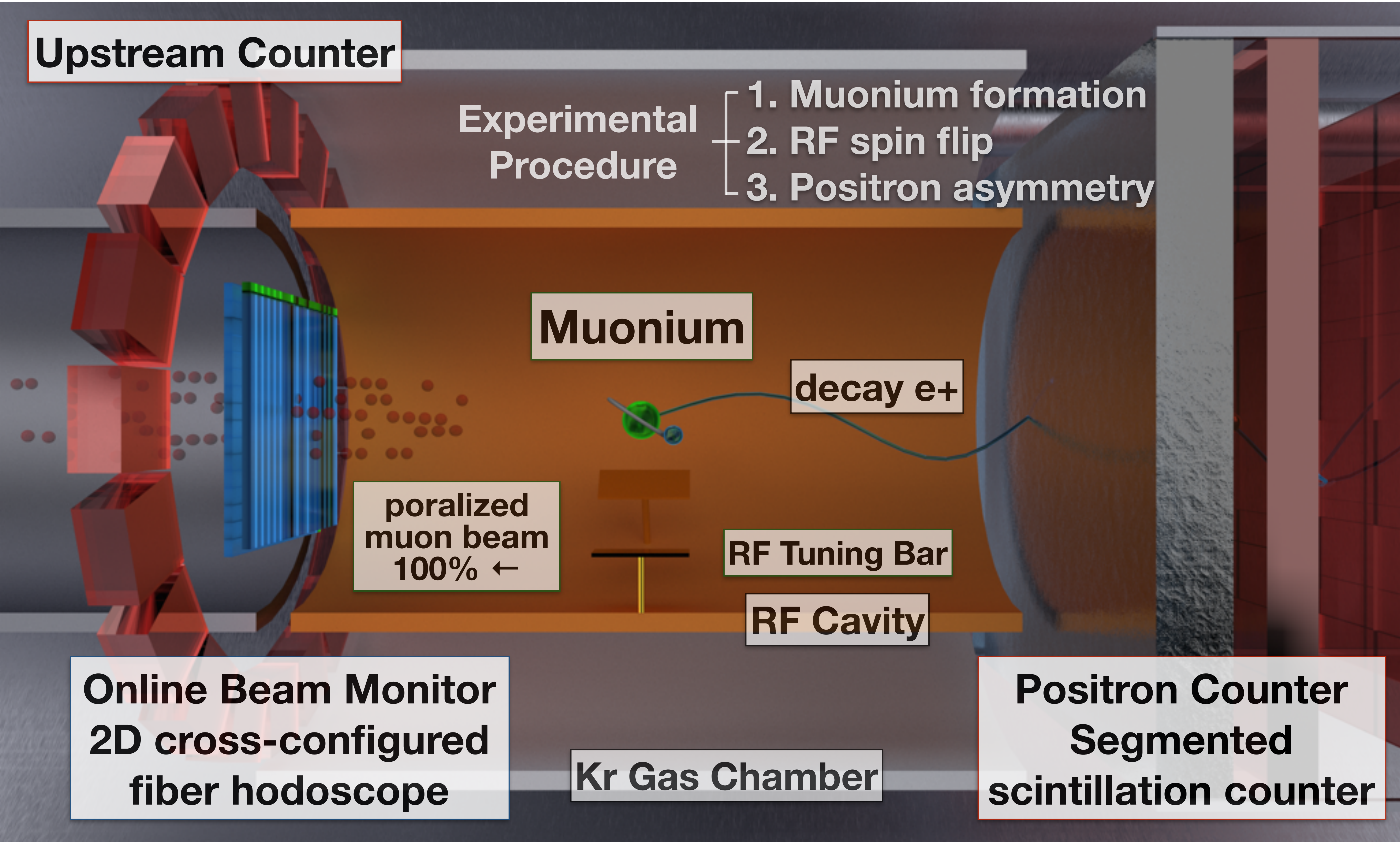


- Microwave Power ← Coaxial pipe for RF transmission
- Gas Density Extrapolation ← Measurement at low gas density (Use of a longer cavity)
- Muon Stopping Distribution ← Online/Offline beam profile monitor
- Field Measurement ← Highly uniform B-field and Precision NMR probes

The Keys:
- Highest intensity pulsed muon beam at J-PARC
- Calibration runs for well understanding in systematic errors

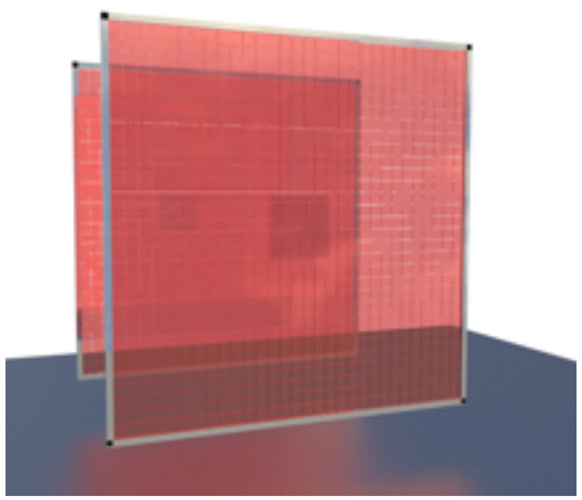
Requirement: High rate capable positron counter

Overview of the MuSEUM



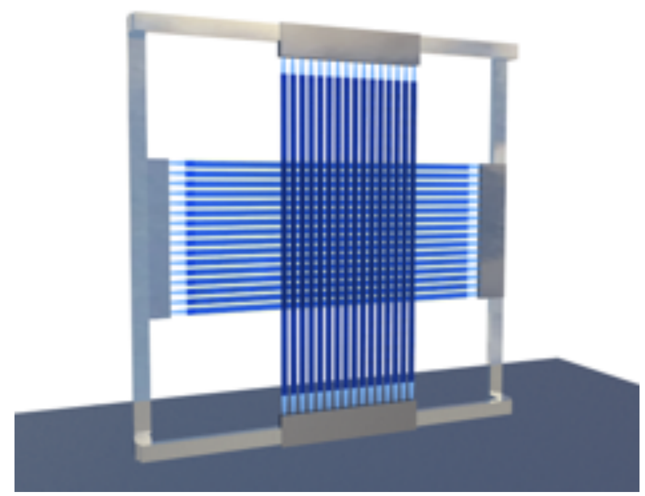
Detectors for the MuSEUM

Downstream positron counter



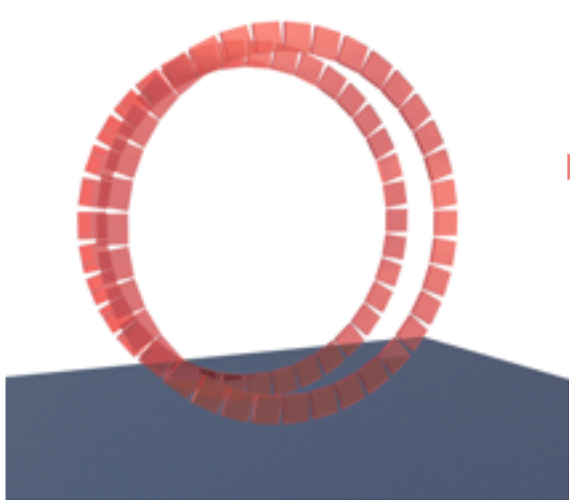
- Spectrometer for HFS measurement
- Segmented scintillator+SiPM
- High rate capability is required

Online beam profile monitor



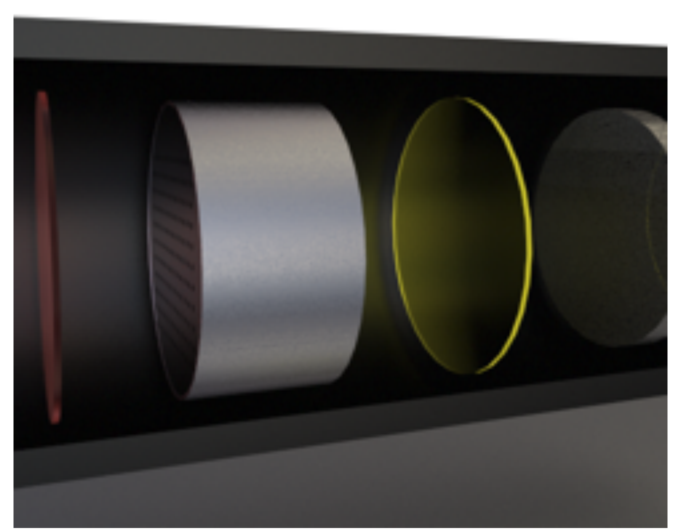
- Fiber hodoscope for beam stability monitoring
- Pulse by pulse measurement of profile and intensity

Upstream positron counter



- Spectrometer for HFS measurement
- Additional counter for asymmetry measurement

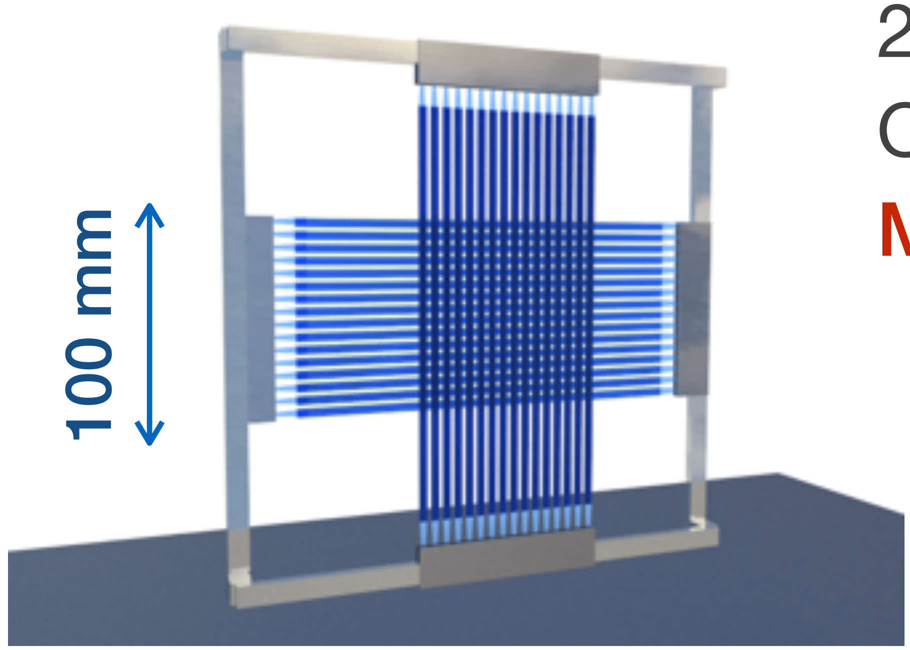
Offline beam profile monitor



- IIF+CCD beam imager for muon stopping distribution
- Measurement for syst. uncertainty suppression

Detectors for the MuSEUM

- Online Beam Profile Monitor : 2D minimum destructive muon monitor



2D beam profile monitor for stability monitoring

Online measurement (minimum destructive)

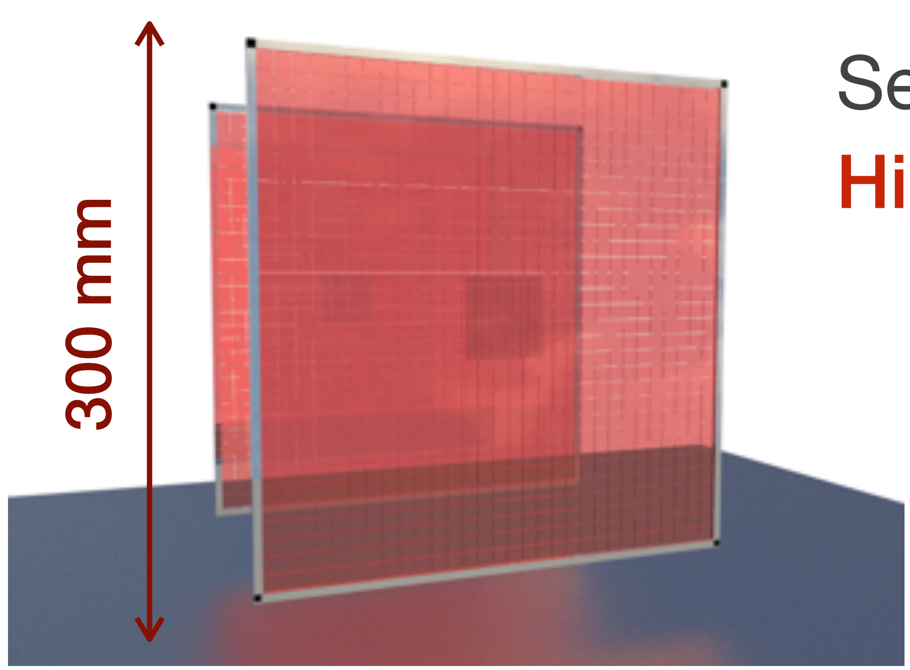
Minimum amount of material is required

Scintillating fiber+SiPM (HPK MPPC)

Prototype was developed and tested

M. Tajima *et al,* Japan Phys. Soc. Ann. Meeting (2013)
S. Kanda, *et al*., J-PARC2014 proceedings

- Positron Counter : Main detector for positron counting



Segmented scintillation counter for spectroscopy

High-rate capability is required (~3500 e+/pulse)

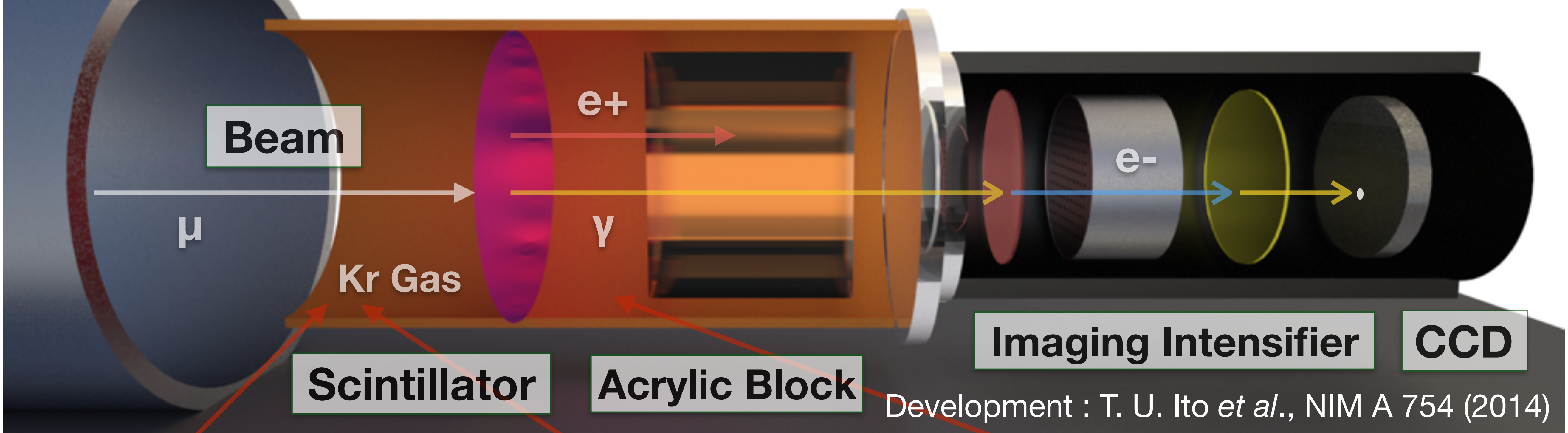
Plastic scintillator + SiPM (HPK MPPC)

Prototype was developed and tested

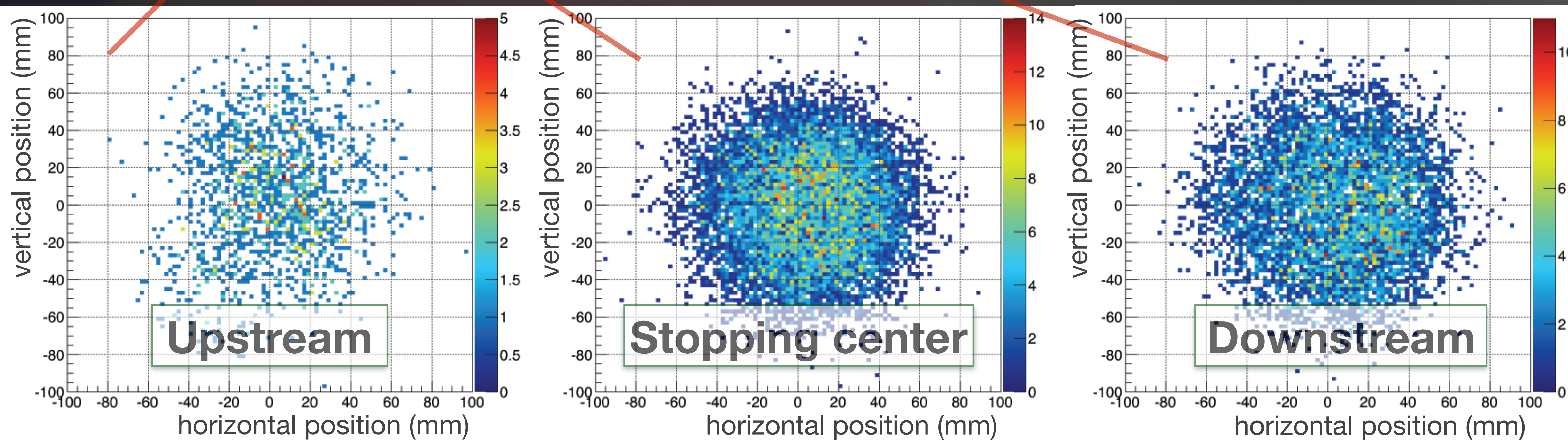
S. Kanda, RIKEN APR Vol. 47 (2014)
S. Kanda, KEK-MSL Progress Report 2013 (2014)
S. Kanda, The 8th g-2/EDM Collaboration Meeting (2014)

Offline Muon Beam Monitor

- Muon stopping distribution is measured by an offline muon beam monitor contains IIF+CCD

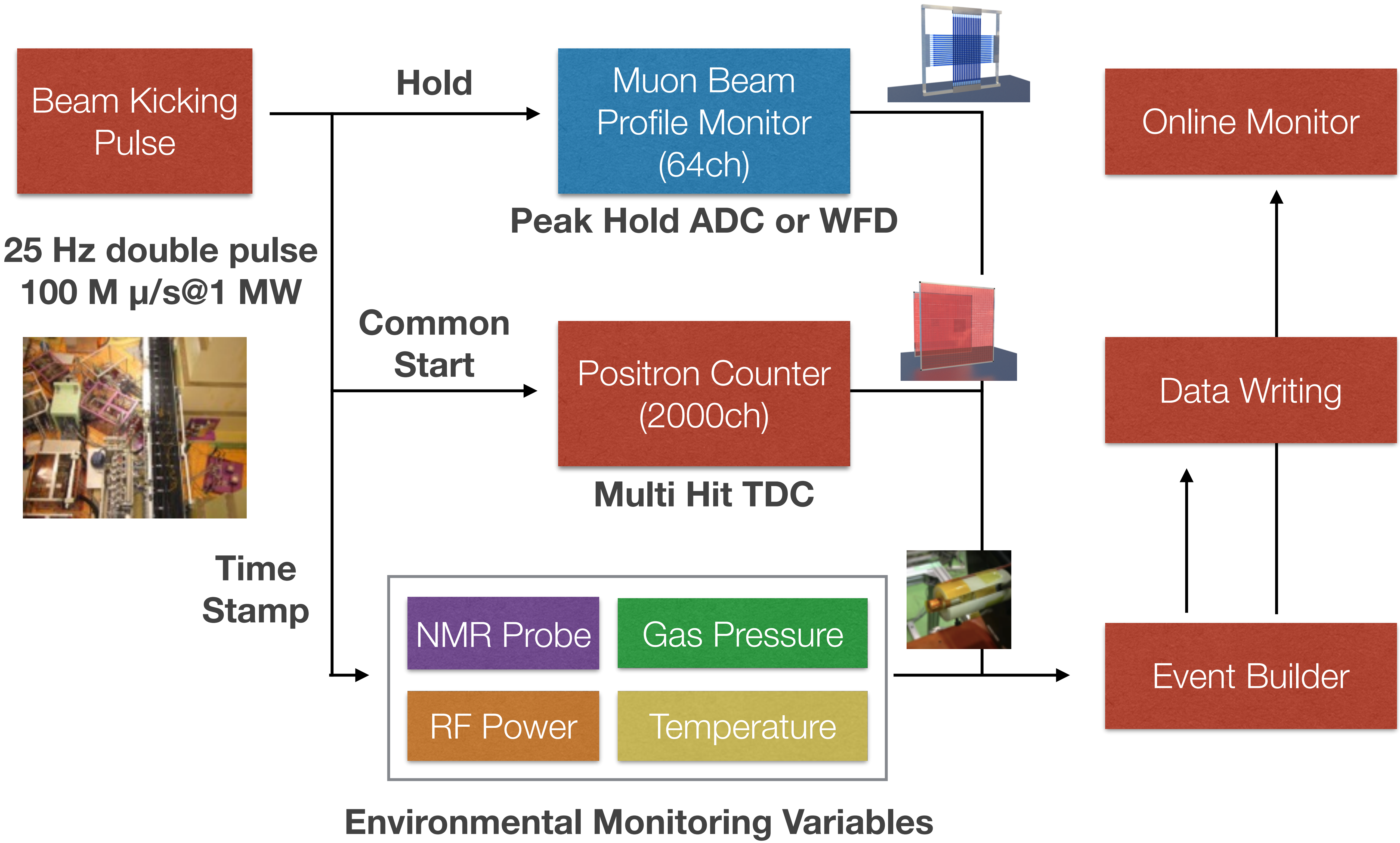


Development : T. U. Ito *et al.*, NIM A 754 (2014)



Simulated muon stopping distribution

DAQ Schematic

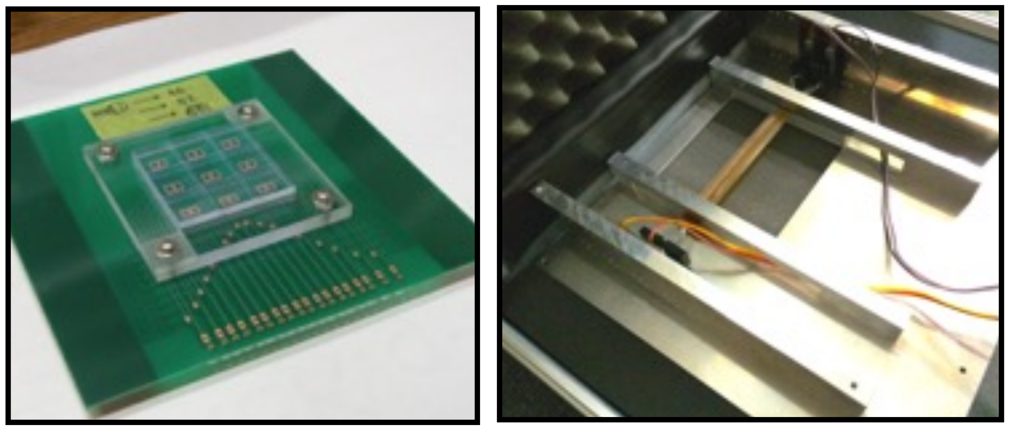


System Components

Component	Requirements	Current setup
Muon Beam Profile Monitor (64ch)	**Minimum beam destruction (muon energy~4 MeV)** **High uniformity (~100 mm)** **High stability (200 days)**	**scintillation fiber+MPPC** **EASIROC+home made DAQ** **(KEK, Tohoku, Osaka)**
Positron Counter (2000ch)	**High rate capability (4M μ/pulse)** **High stability**	**segmented scintillator+MPPC** **Kalliope+DAQ developed by KEK CRC** **(S. Y. Suzuki)**
NMR Probe, Gas Pressure, RF Power, Temperature	**High precision (NMR: 60 ppb, RF power: 0.1%)** **Combination of several monitors**	**individual monitors** **Lab view based DAQ** **(T. Mizutani)**
DAQ Framework	**MIDAS based integrated DAQ (under study)**	

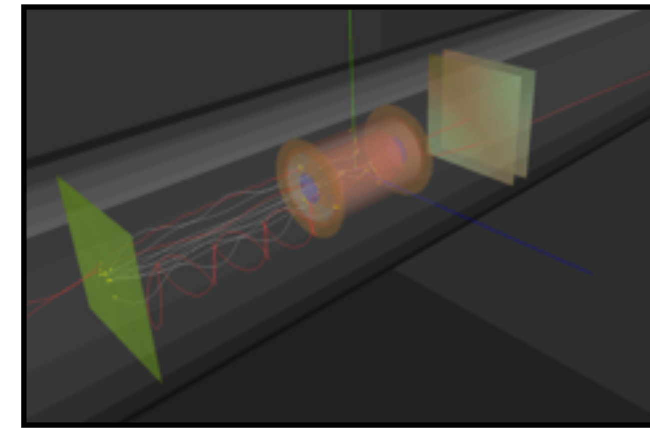
Development Strategy

Prototype development



Readout circuit evaluation

Monte-Carlo Simulation



Basic characteristics of
MPPC+scintillator detector
Photon yield, event rate

Analog signal
Circuit response
Digital signal, DAQ

Event structure
Hit map, Hit rate
Energy deposit
Background

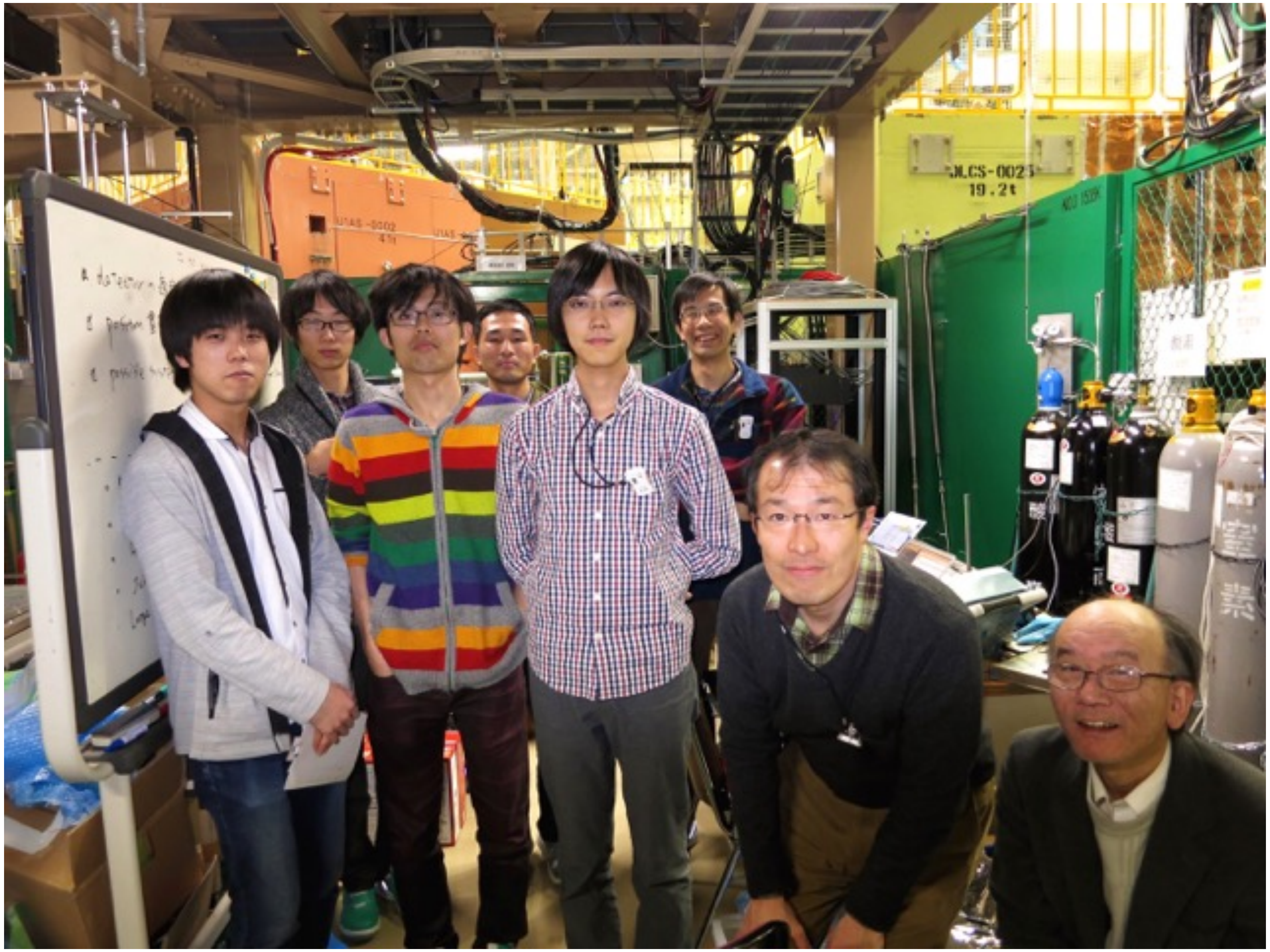
↓

Development of realistic simulator for the MuSEUM experiment

↓

Feedback to detector designing and upgrade
Estimation of systematic uncertainties

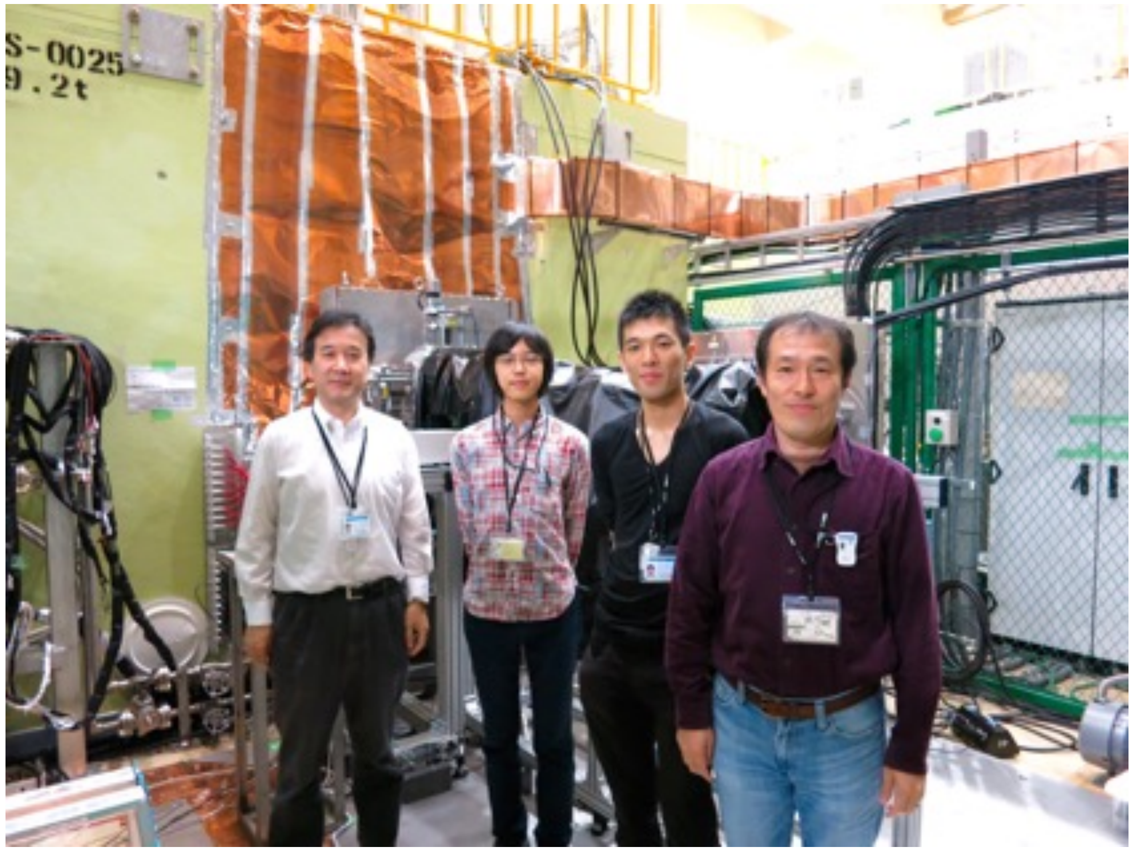
MLF 2013B Beam Test



2014. Feb. 24-26 (Halfway stopped due to LINAC trouble)
Test experiment for a positron counter prototype

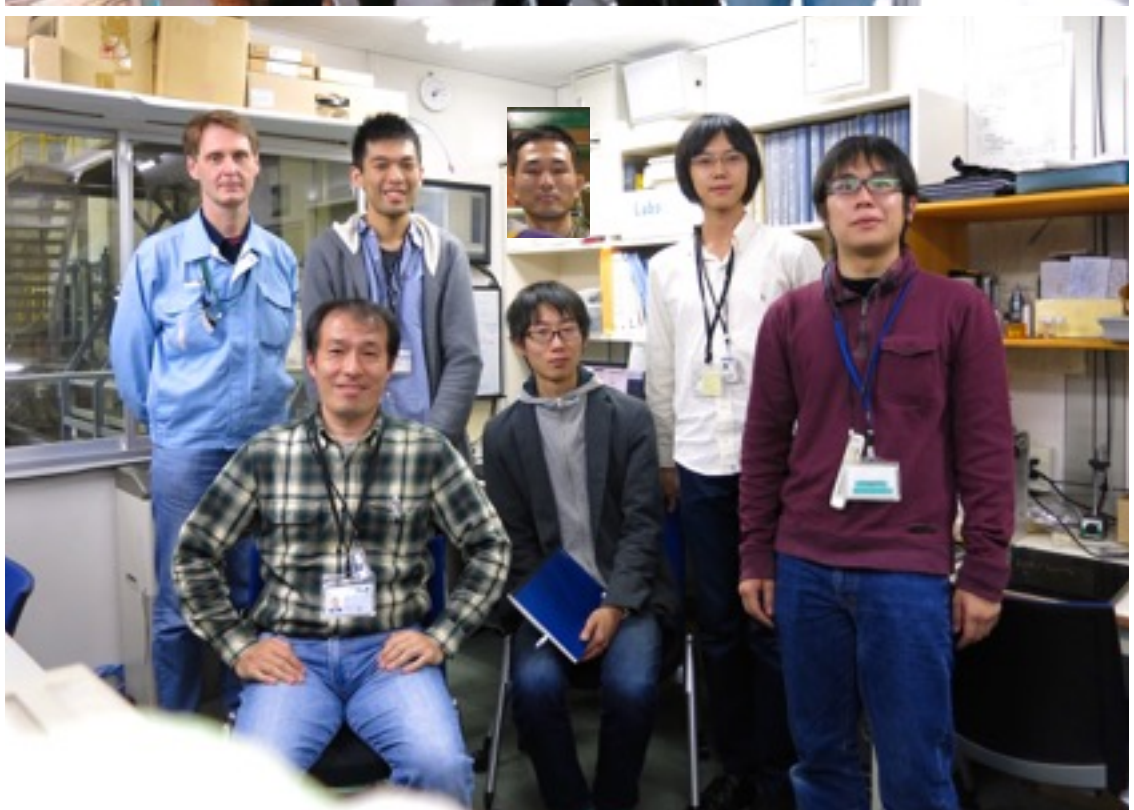
Photo credit: H. A. Torii

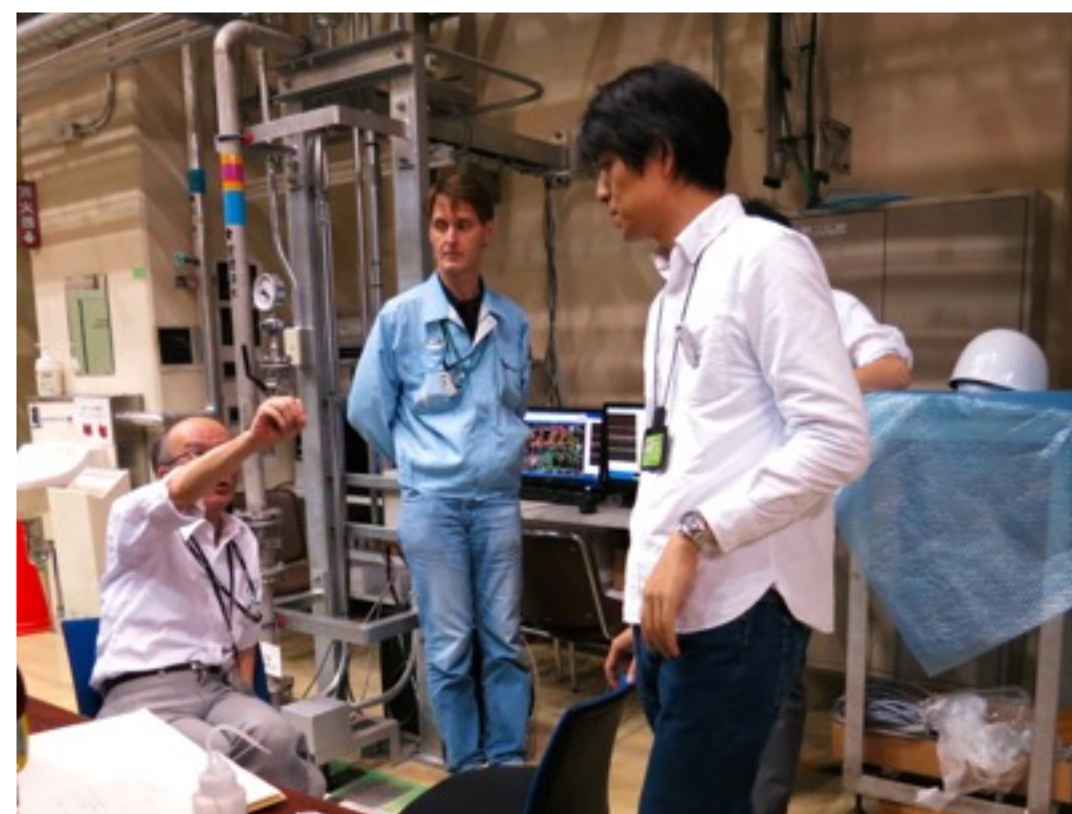
MLF 2014A Beam Test



2014. Nov. 8-9
Test experiment for an online beam profile monitor prototype and an offline beam profile monitor

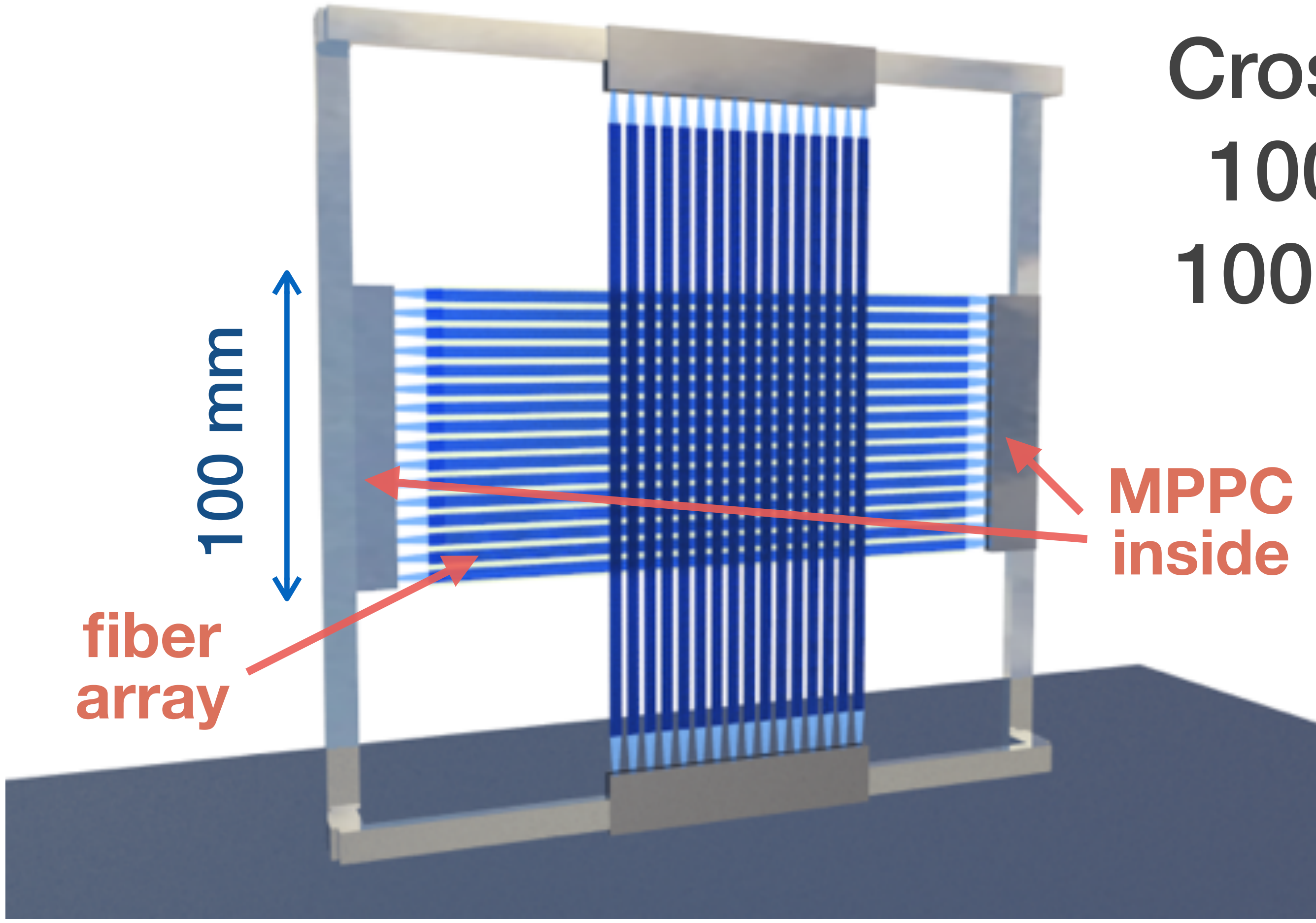
Photo credit: H. A. Torii and Y. Ueno





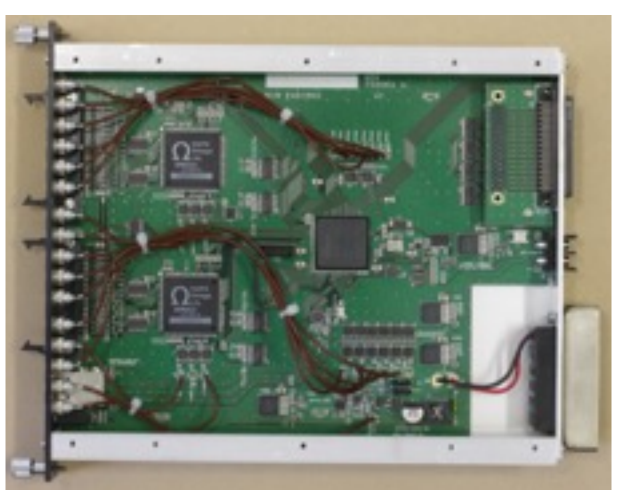
Online Beam Profile Monitor

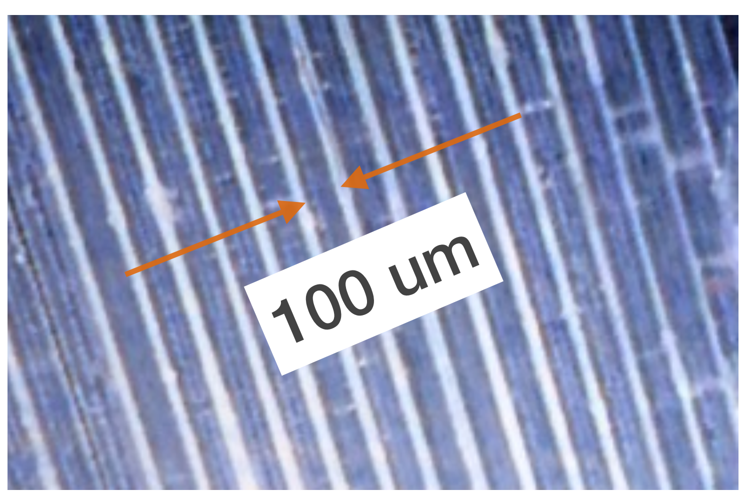
- 100 umϕ Scintillation fiber+MPPC+EASIROC(ASD+peak hold ADC)



Cross-configured fiber hodoscope
100 mm×100 mm detection area
100 um fiber + resin (total 150 um)

- **Stability of beam profile and relative beam intensity are measured pulse by pulse (in high B-field)**
- **Prototype was developed and a beam test was performed in Nov. 2014**
- **Photon yield and stability were evaluated**
- **Readout: NIM-EASIROC**


NIM-EASIROC



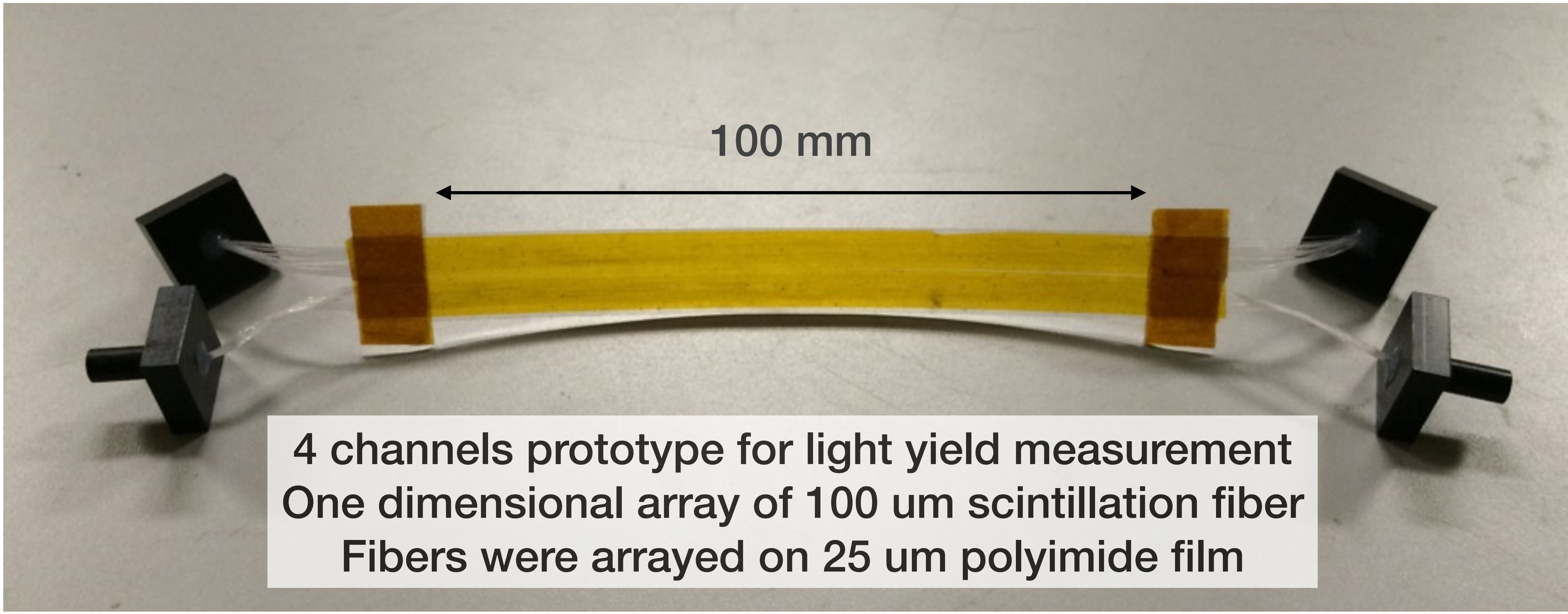
Array of 100 um fiber

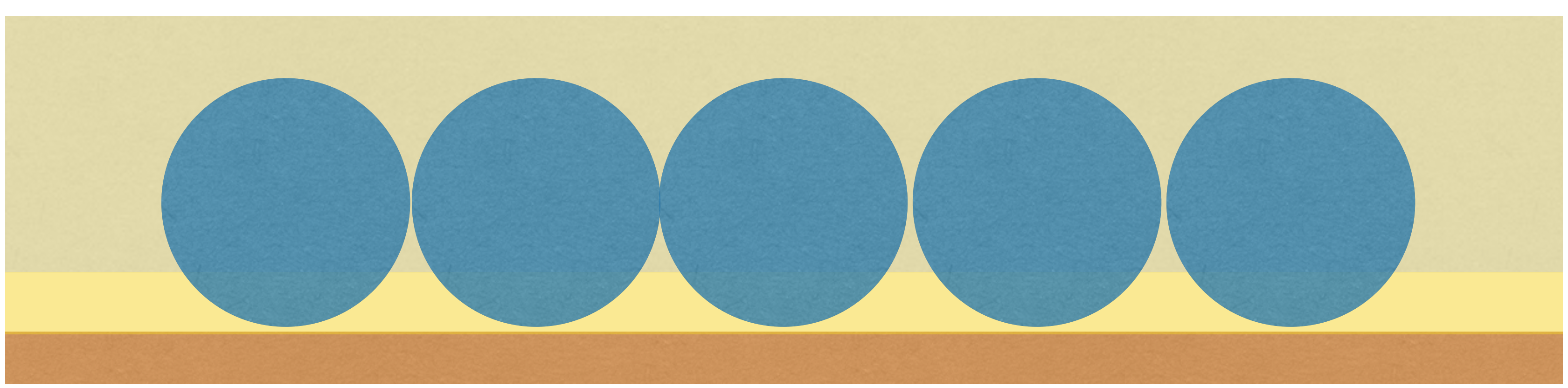
N. Ishijima *et al*, Japan Phys. Soc. Autumn. Meeting (2013)

Stephane Callier *et al*., Physics Procedia Vol. 37, 1569-1576, Proceedings of the TIPP 2011 (2012)

100 um Scintillation Fiber Array

Prototype of Front Beam Profile Monitor



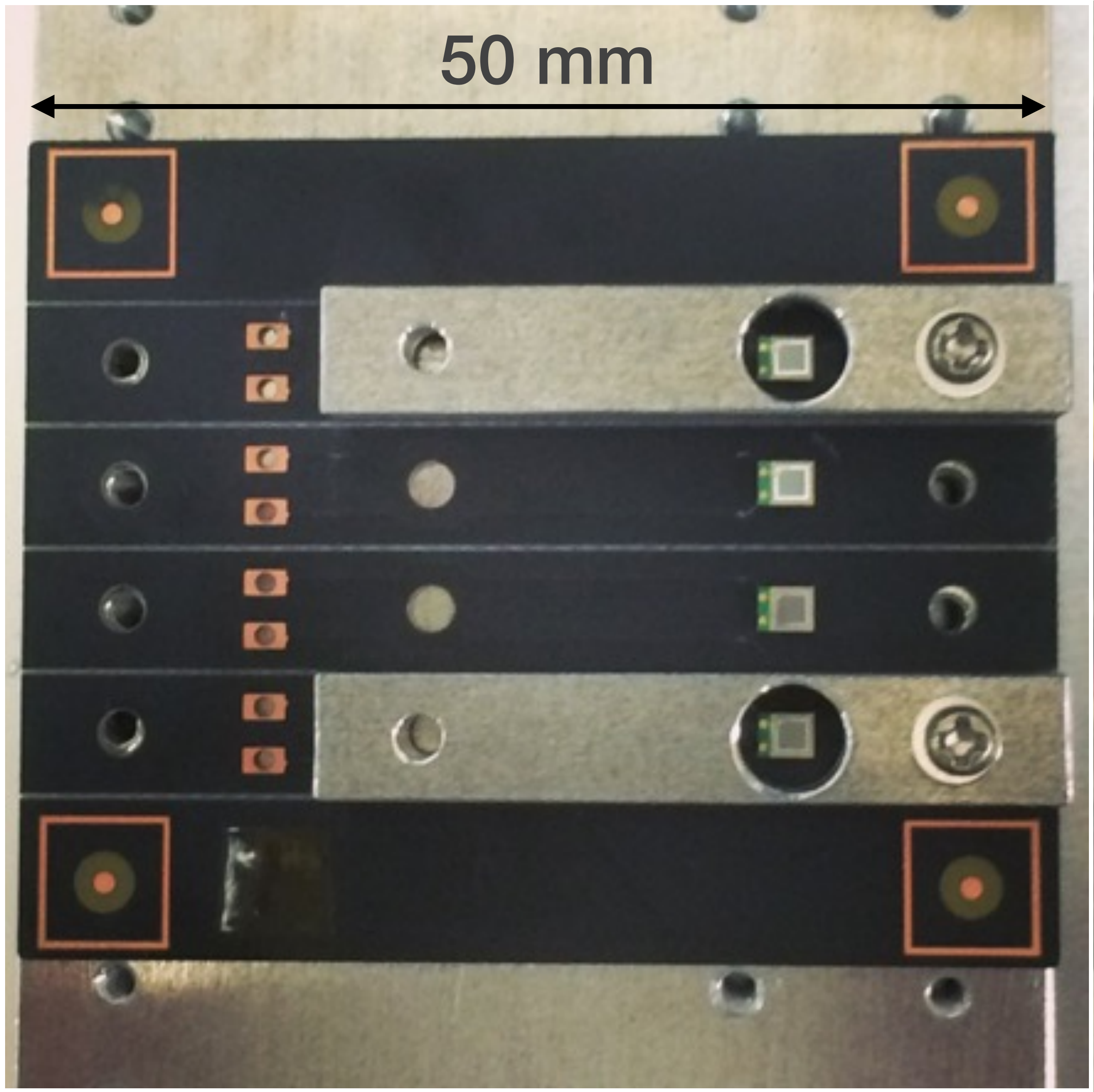


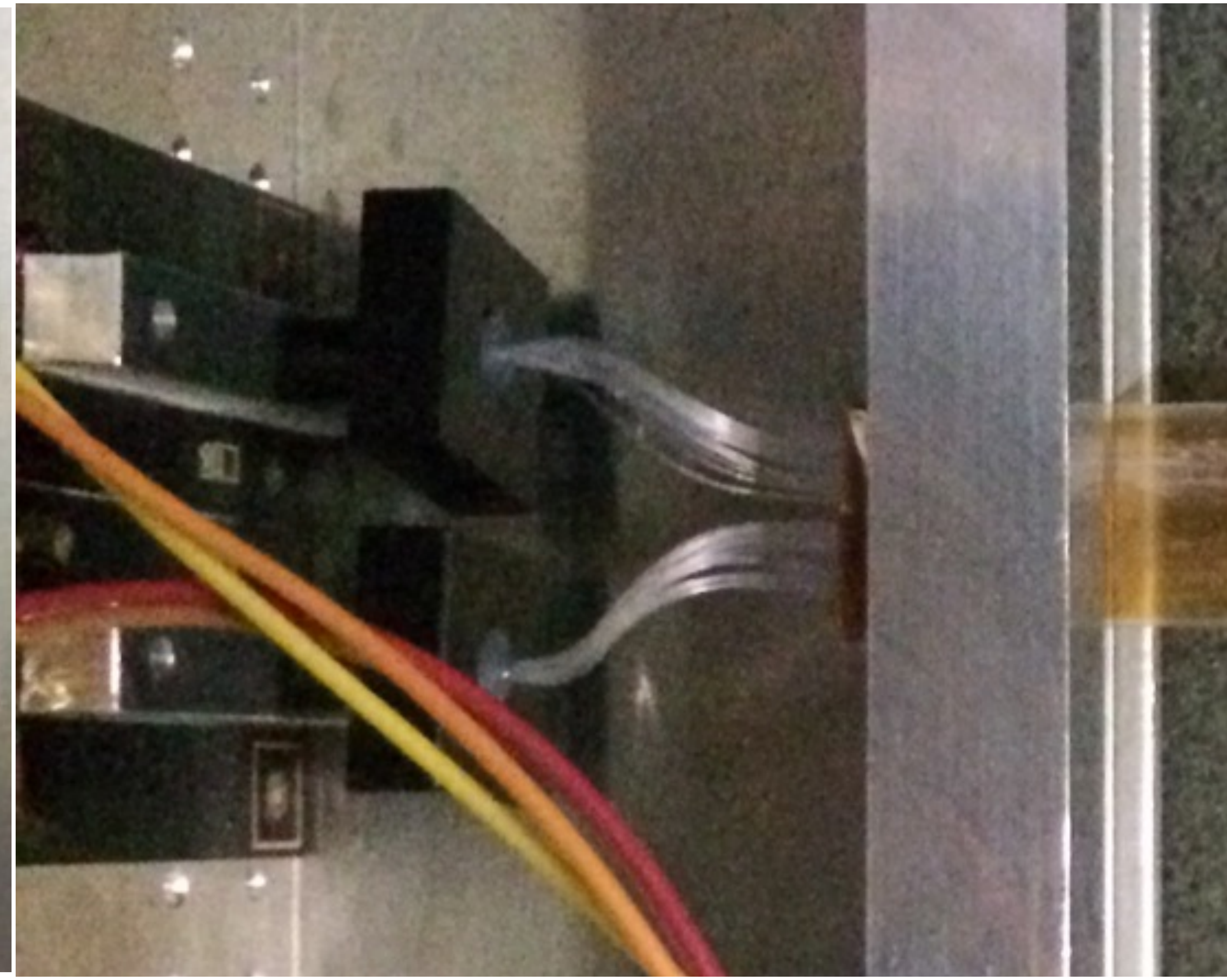
Resin 25 um
(175 um this time)

Fiber 100 um

Polyimide 25 um

MPPC and Light Connection



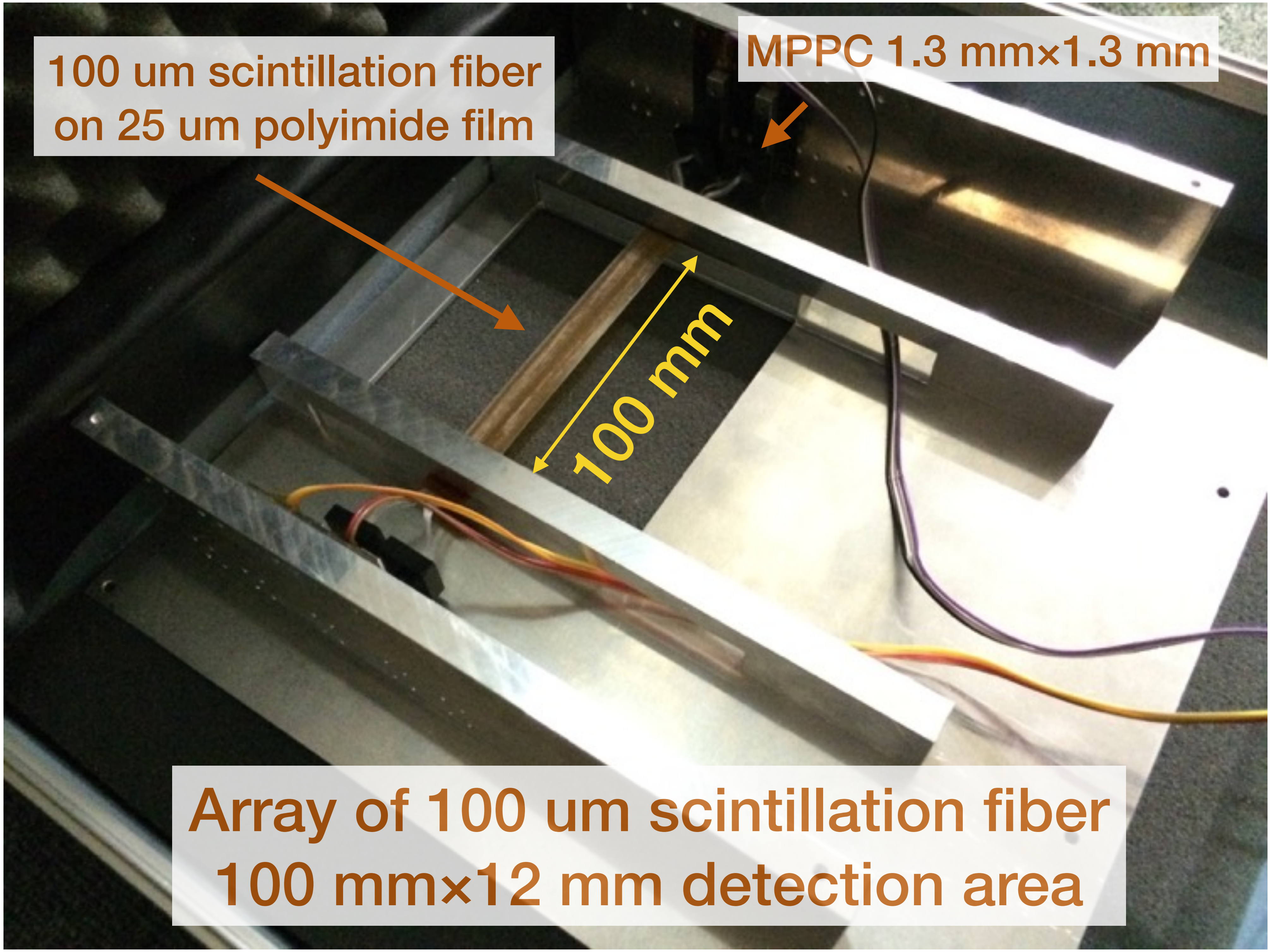


MPPCs were mounted on a PCB

Bound fiber (0.9 mmϕ) is directly connected to MPPC's active area

MPPC spec: 1.3 mm×1.3 mm active area, 50 um pitch, 667 pixels

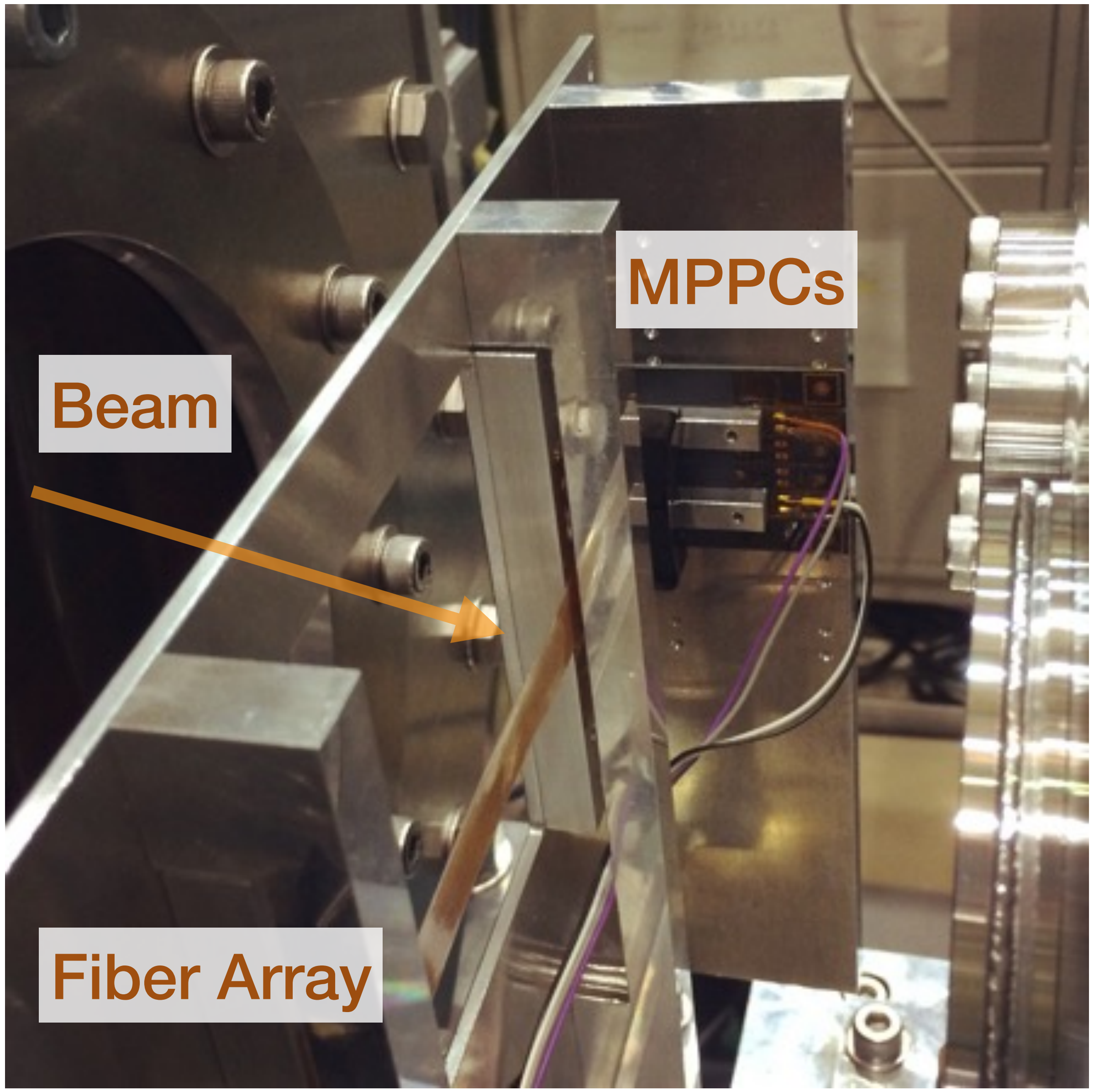
Profile Monitor Prototype



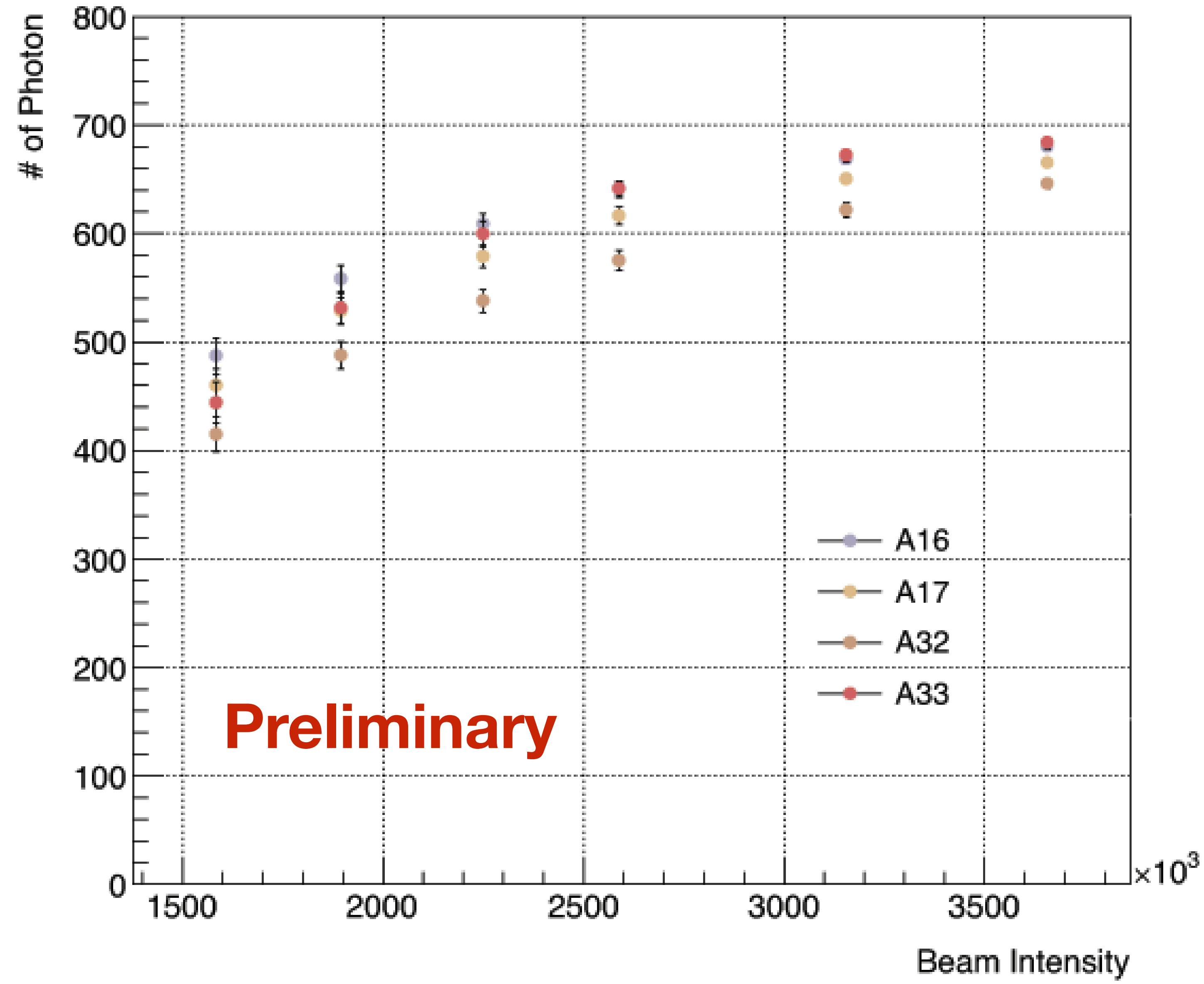
Prototype of Front Beam Profile Monitor

Profile Monitor Beam Test

- Beam test setup and result



Data taking was triggered by beam sync. pulse

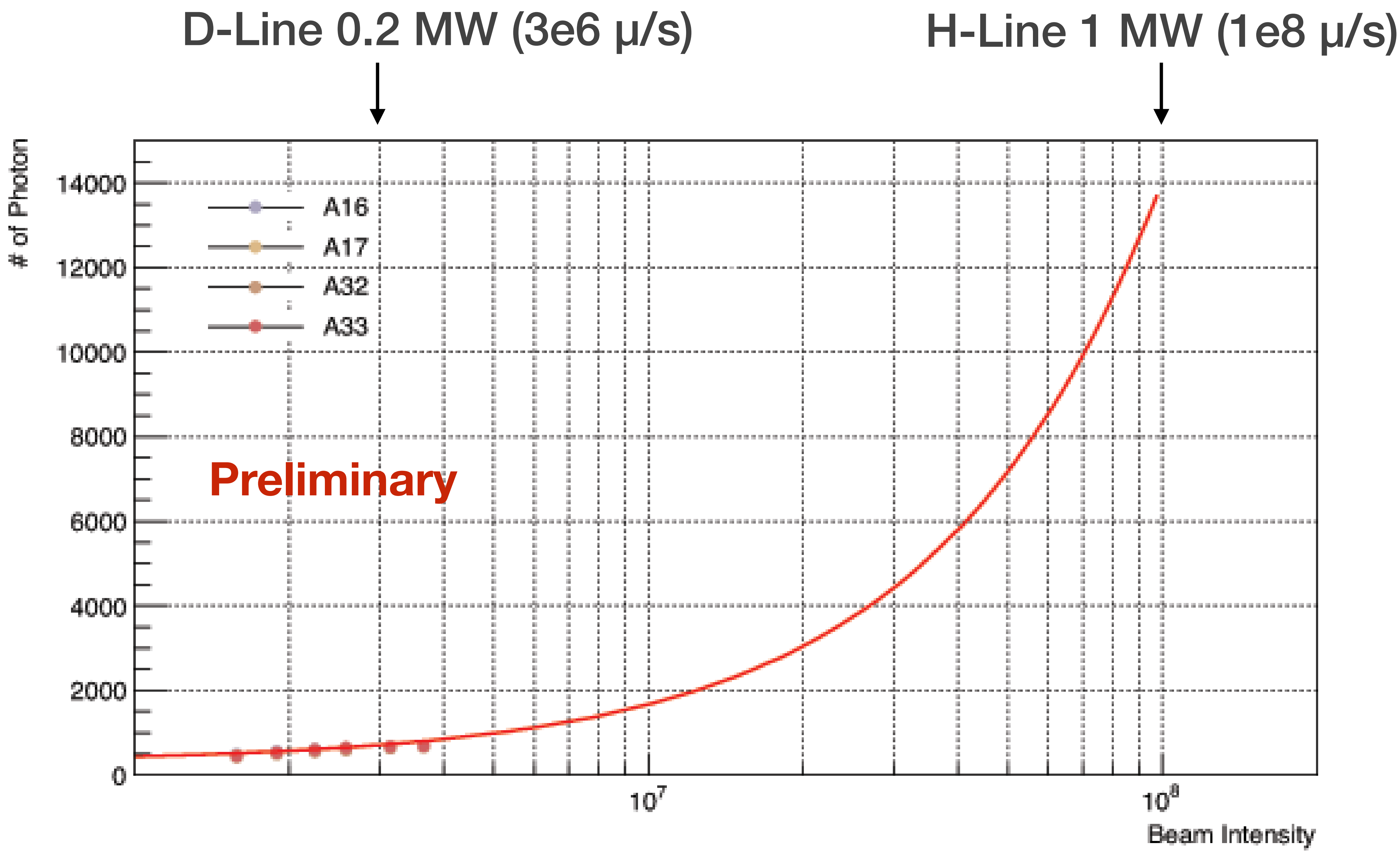


Photon number distribution

Muon beam was detected by the prototype

Profile Monitor Beam Test

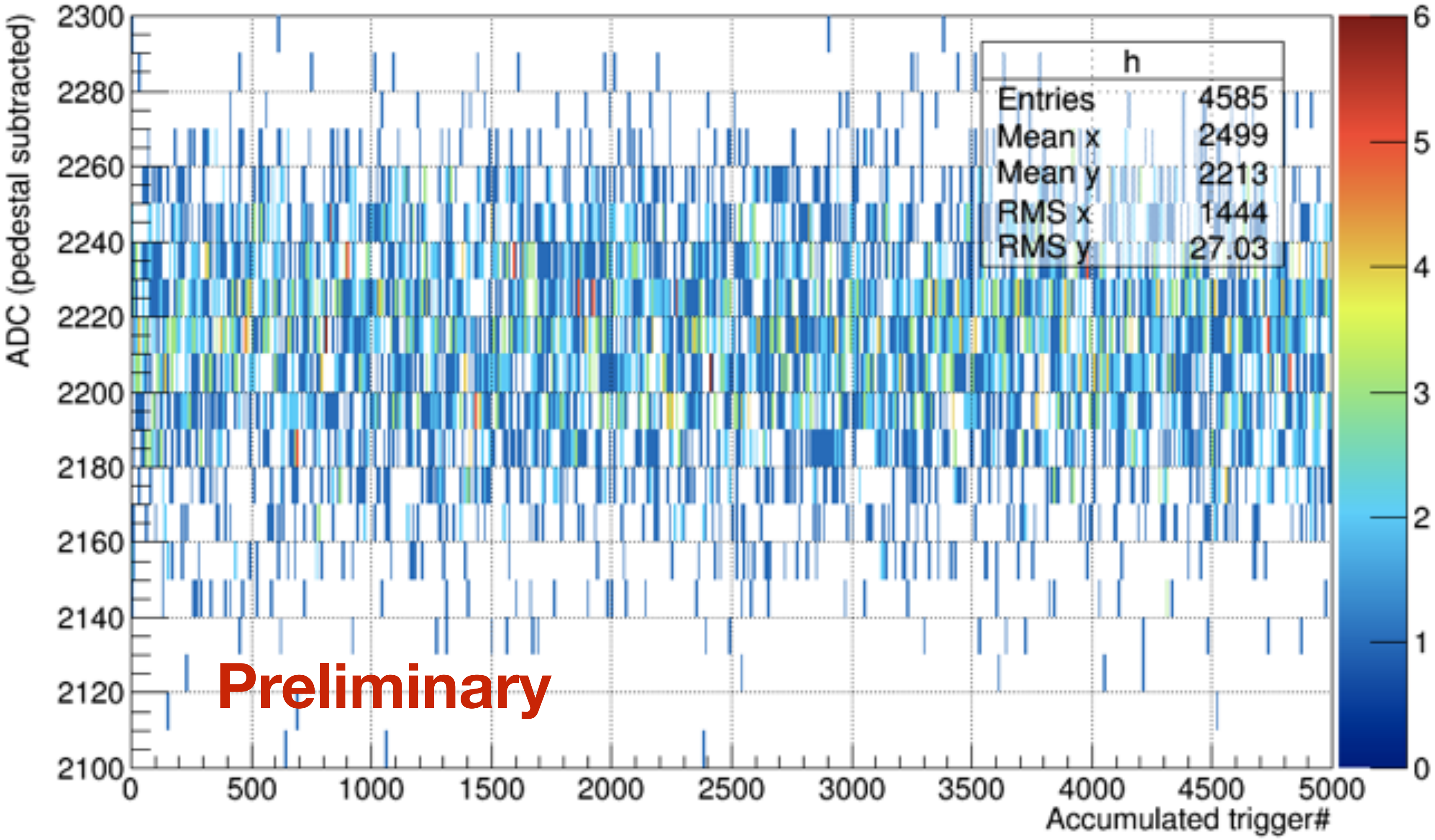
- Extrapolation to the H-Line intensity

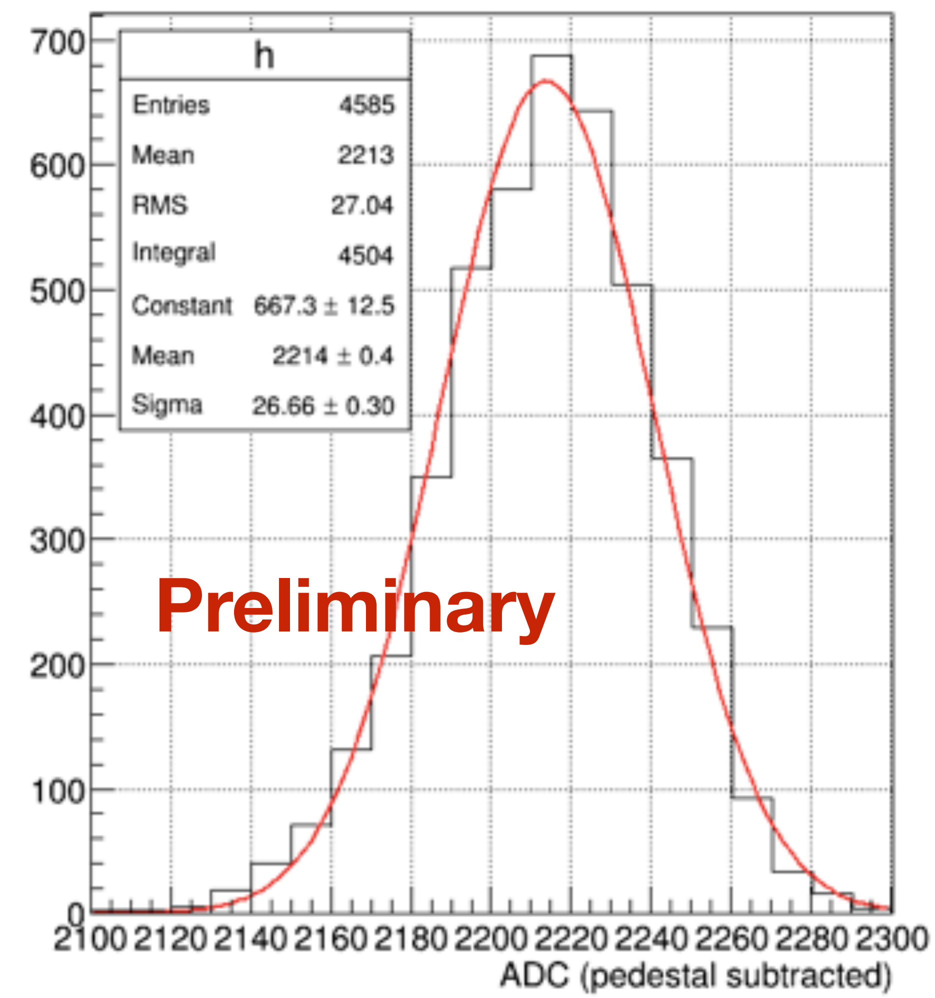


10 um pitch MPPC (16675 pixel) can be the solution for H-Line@1 MW case

Profile Monitor Beam Test

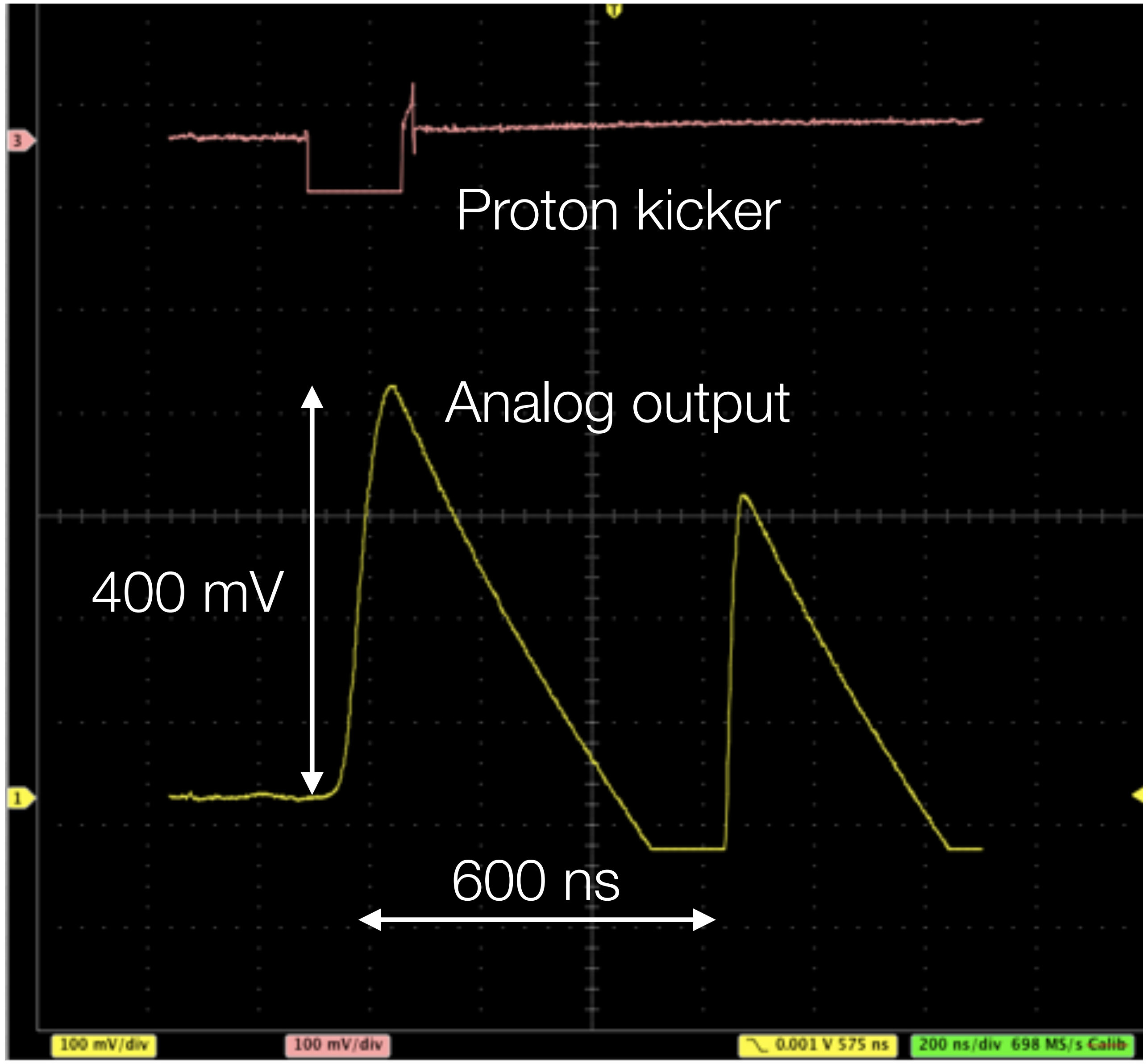
- Beam intensity monitoring





Sigma of ADC ~ 1% (summation of four channels)
Prototype is sensitive to ~3% beam fluctuation (three sigma)
Proton beam current was stable in ~0.4% during measurement

Waveform Analysis

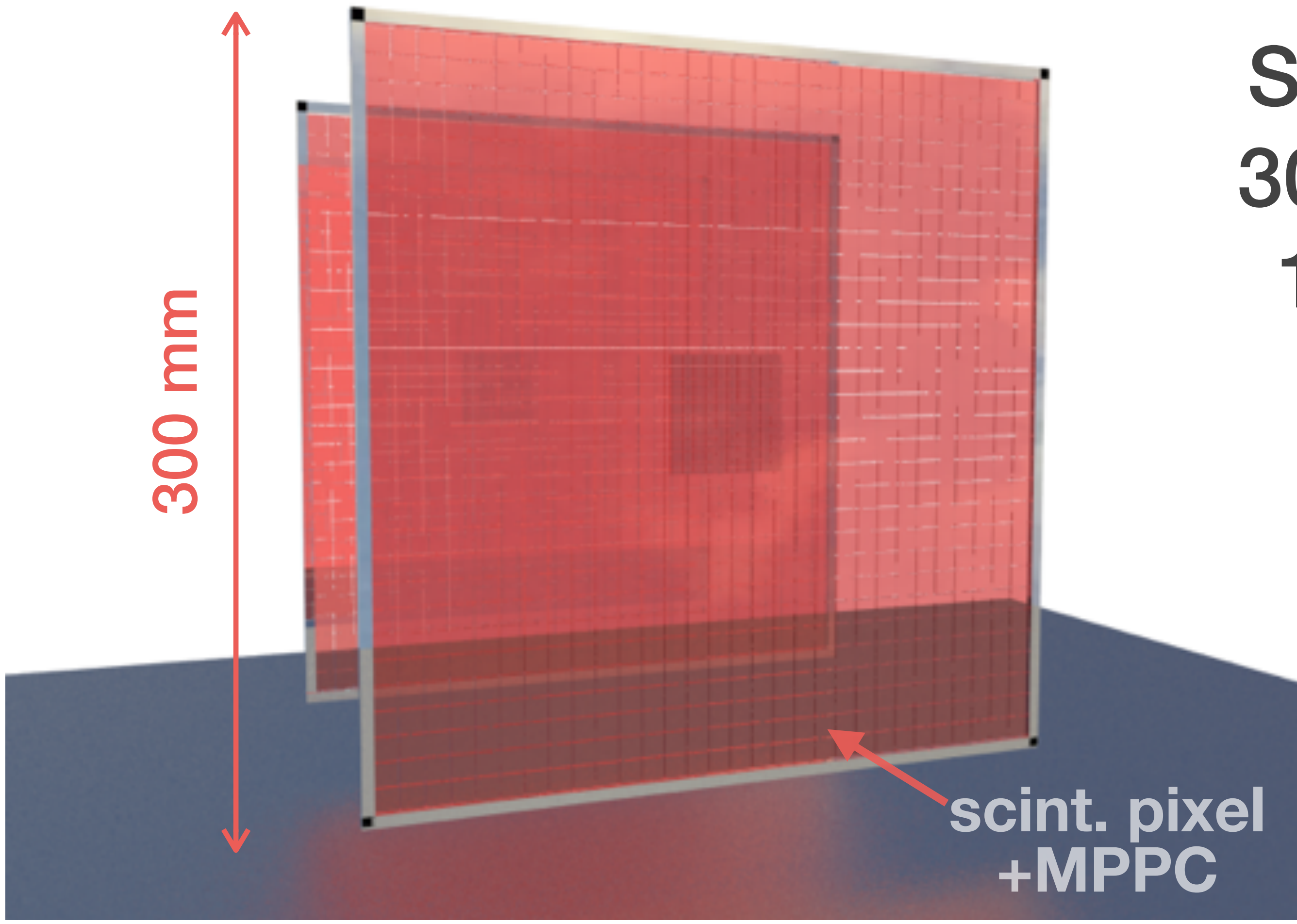


Waveform was measured by DRS4 evaluation board
Data analysis is in progress

http://www.psi.ch/drs/evaluation-board

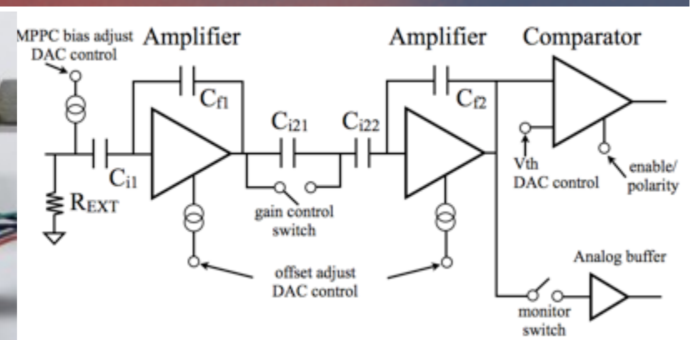
Positron Counter

- Scintillator pixel+MPPC+Kalliope (ASD+multi-hit TDC)



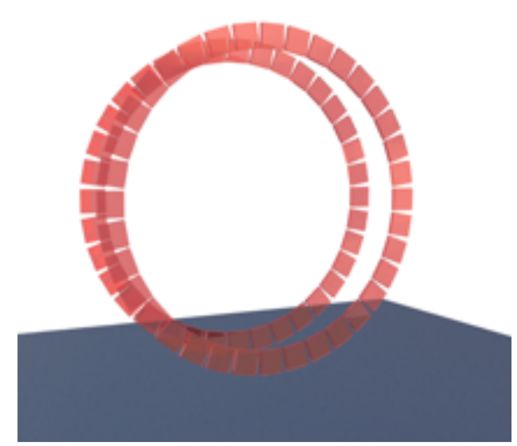
Segmented scintillation counter
300 mm×300 mm detection area
10 mm×10 mm×3 mmt uni cell

- **Prototype was developed and a beam test was performed in Feb. 2014**
- **Event-rate and photon yield were measured**
- **Readout: Kalliope**



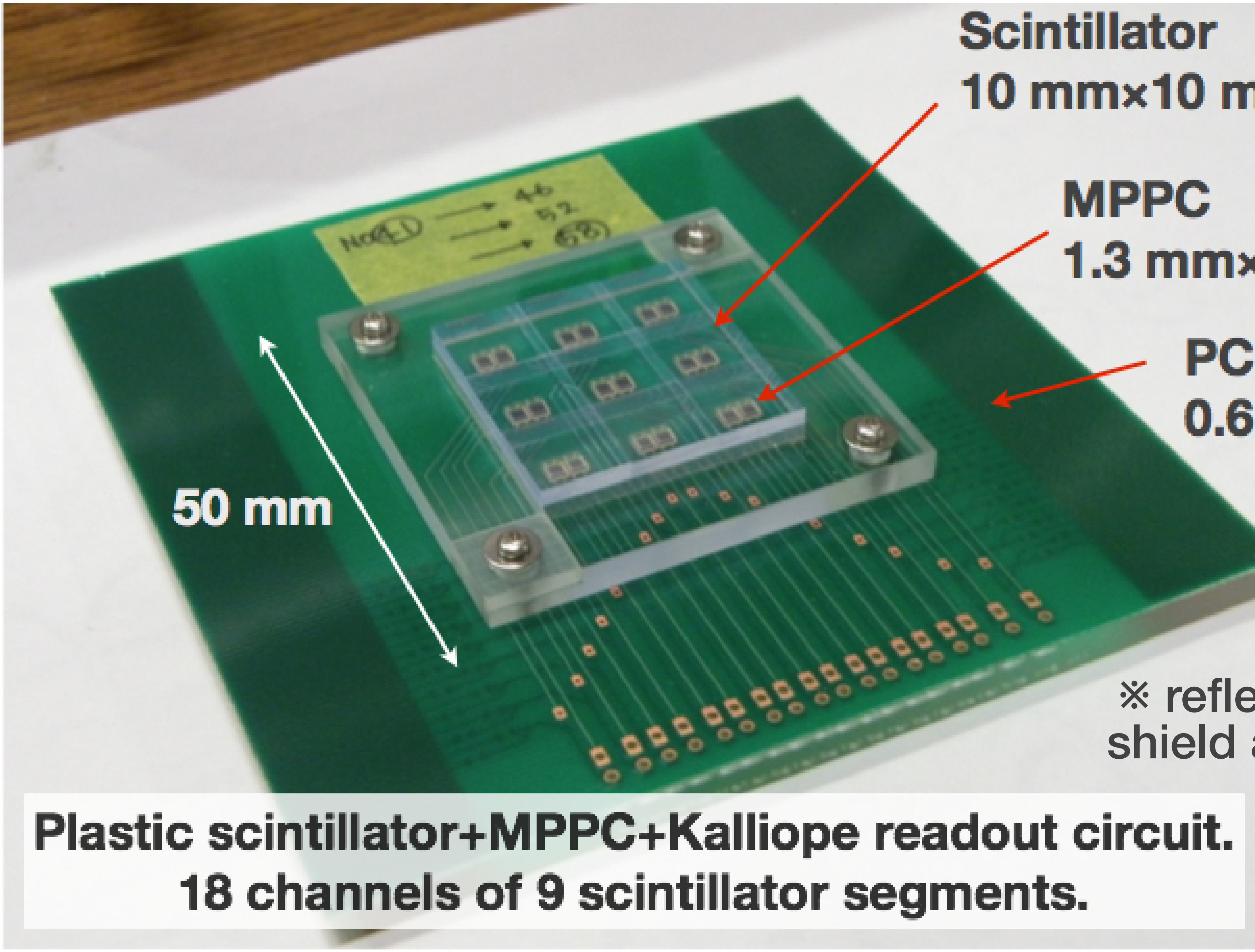
Kalliope electronics

M. M. Tanaka, K. M. Kojima, T. Murakami, S. Kanda, C. de la Taille and A. Koda (to be published)



- **Principle is same for the upstream positron counter**

Positron Counter Prototype

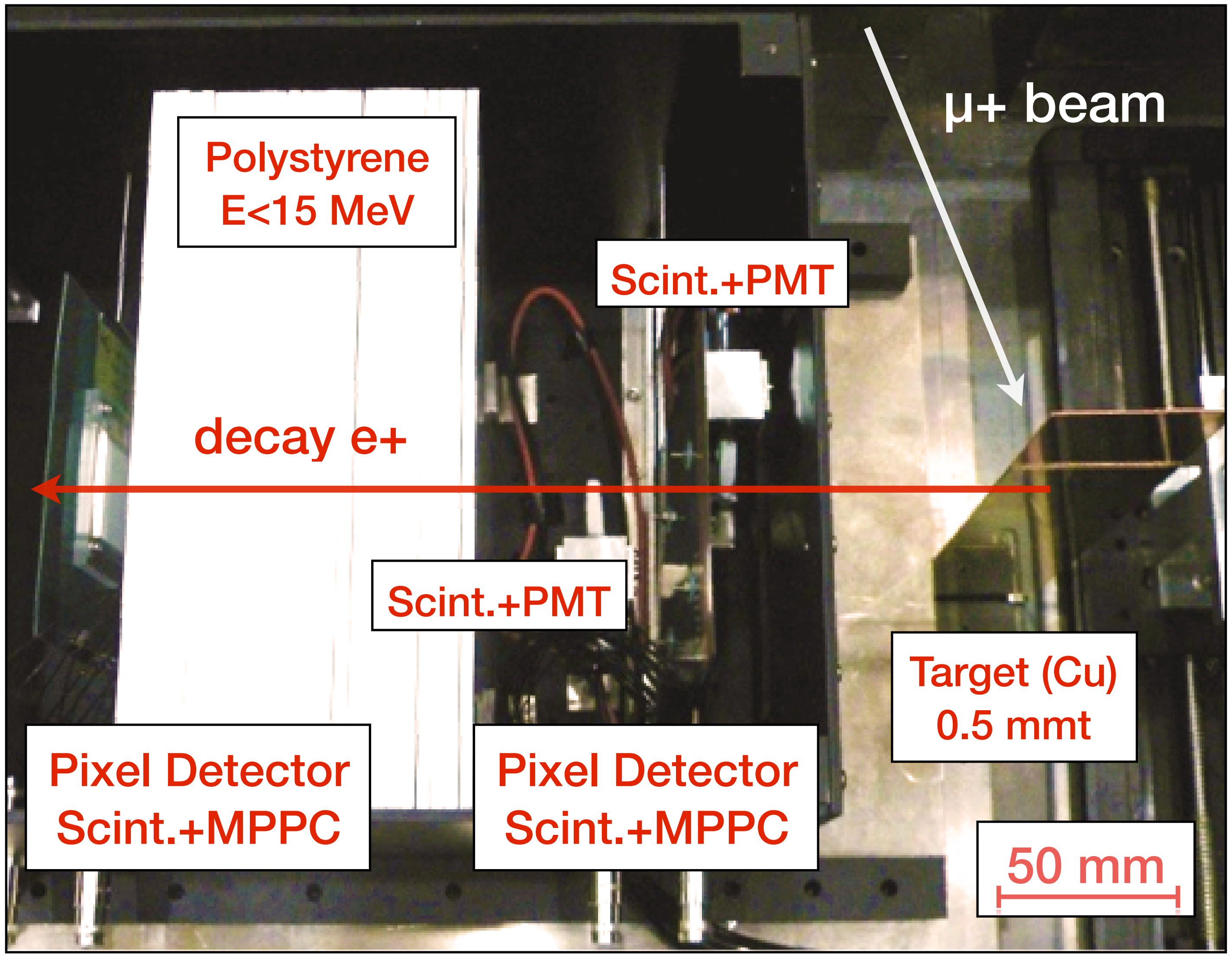


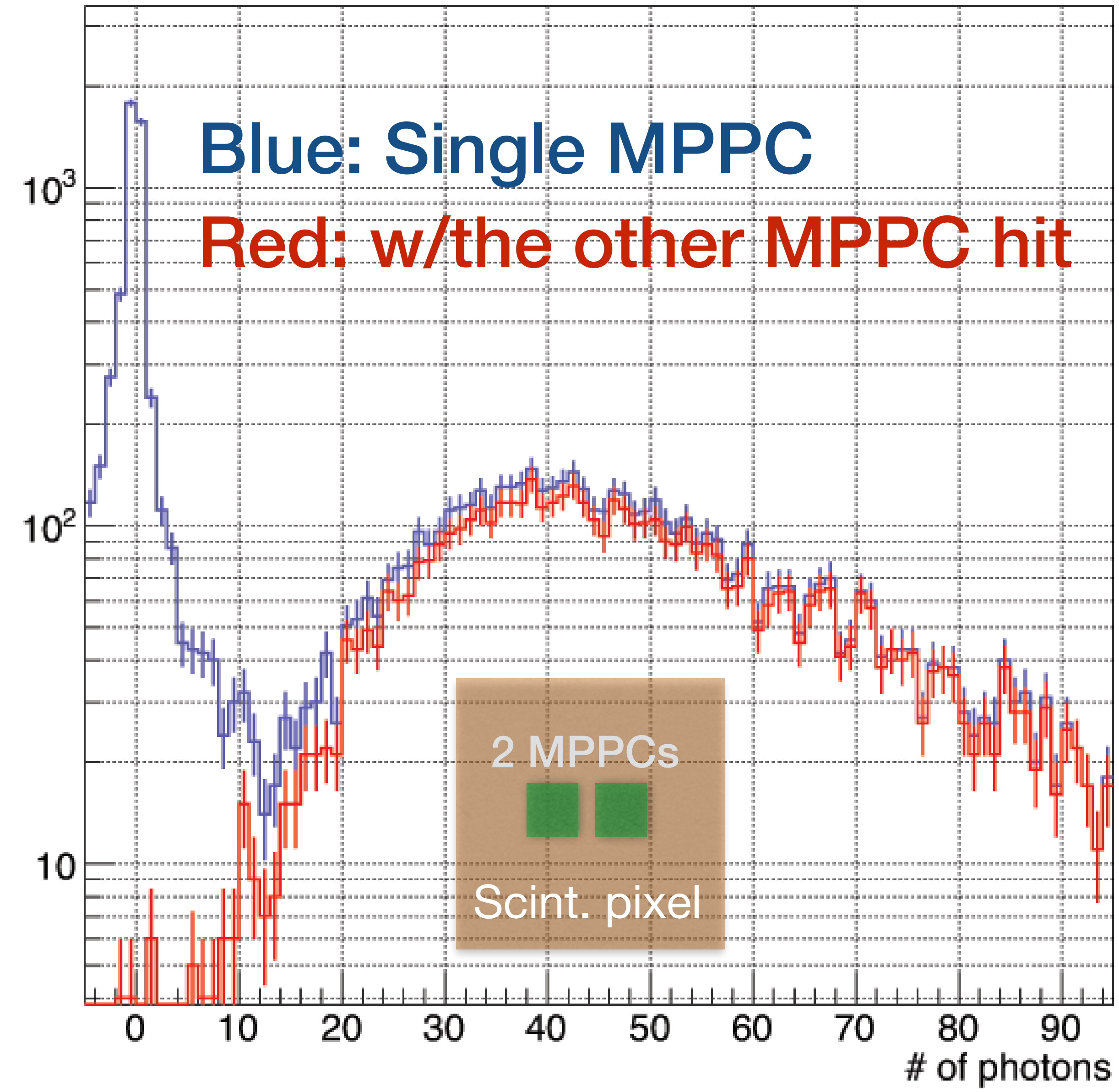
※ reflector and light shield are not shown

Prototype of Positron Counter

Positron Counter Beam Test

- Beam test setup and result



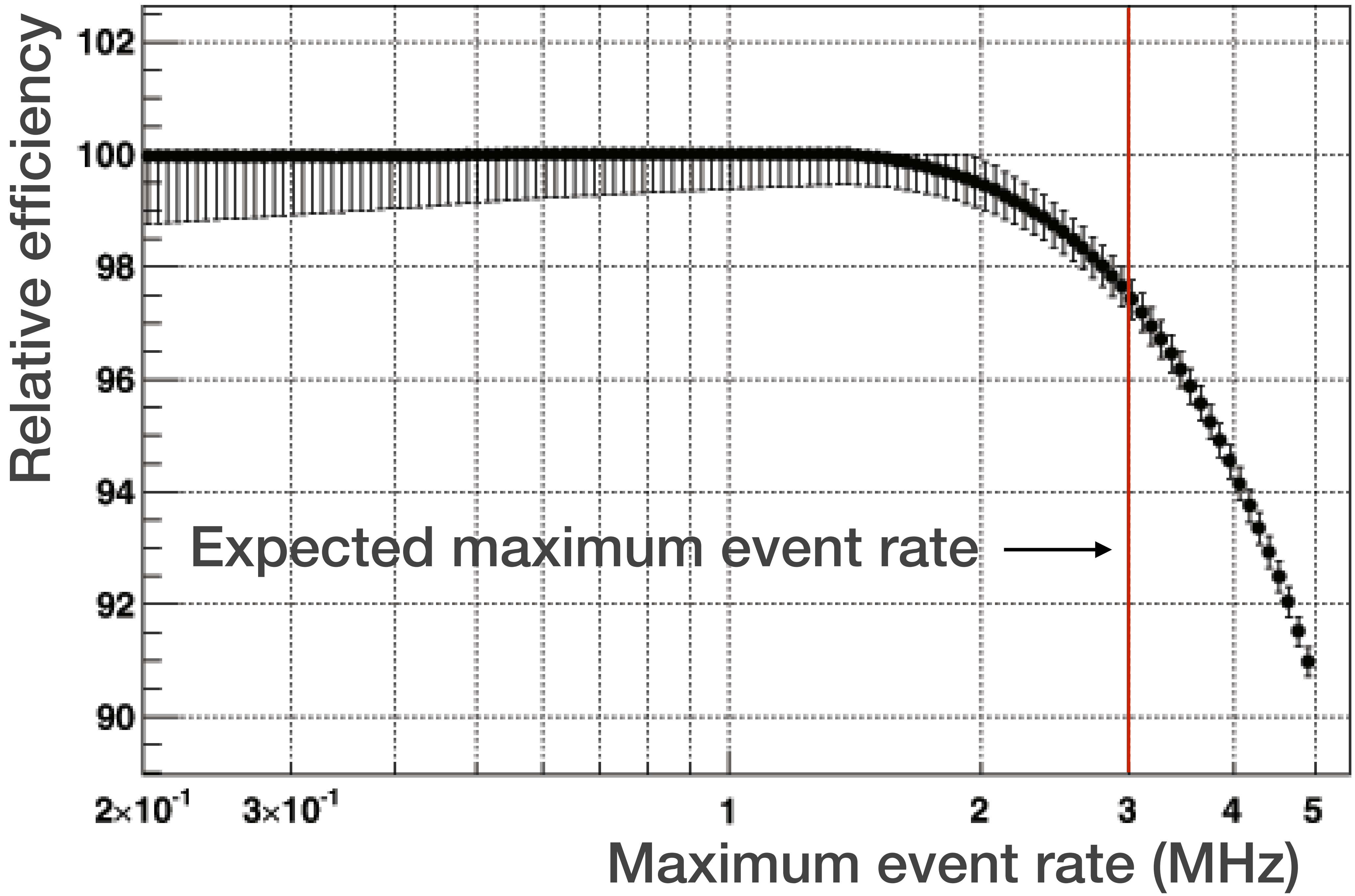


Data taking was triggered by coincidence of front/behind scintillation counter

photon number distribution

Positron signal can be separated from dark noise of MPPC

High-rate capability



Pileup loss at 3 MHz/ch is about 2% of total events

Correction is under study

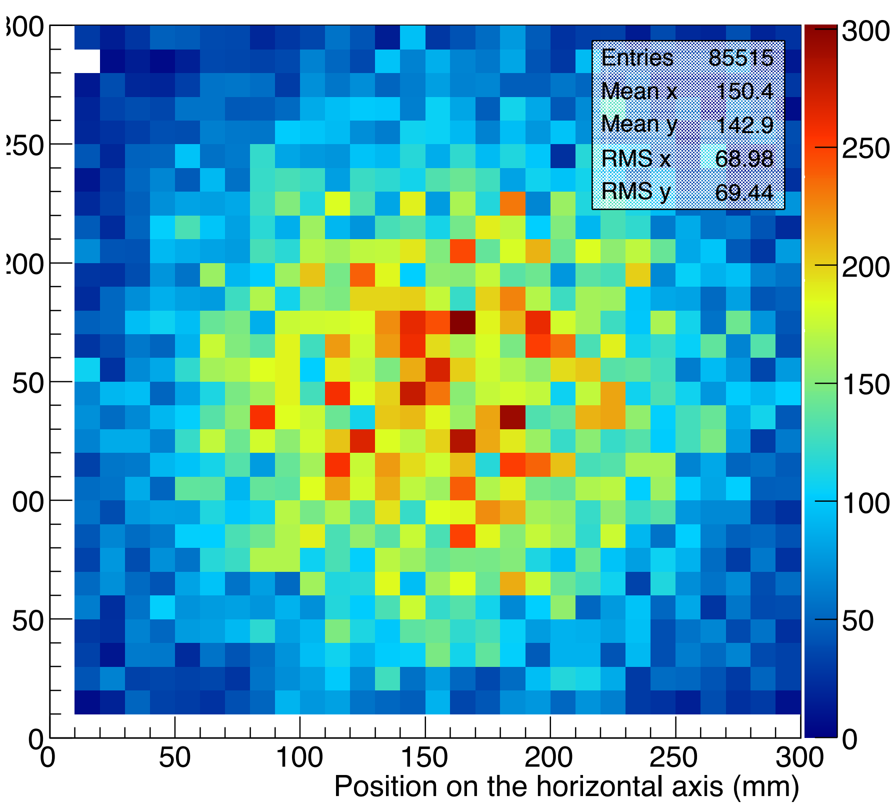
Systematic Uncertainty Evaluation

- Simulation flowchart and possible systematics

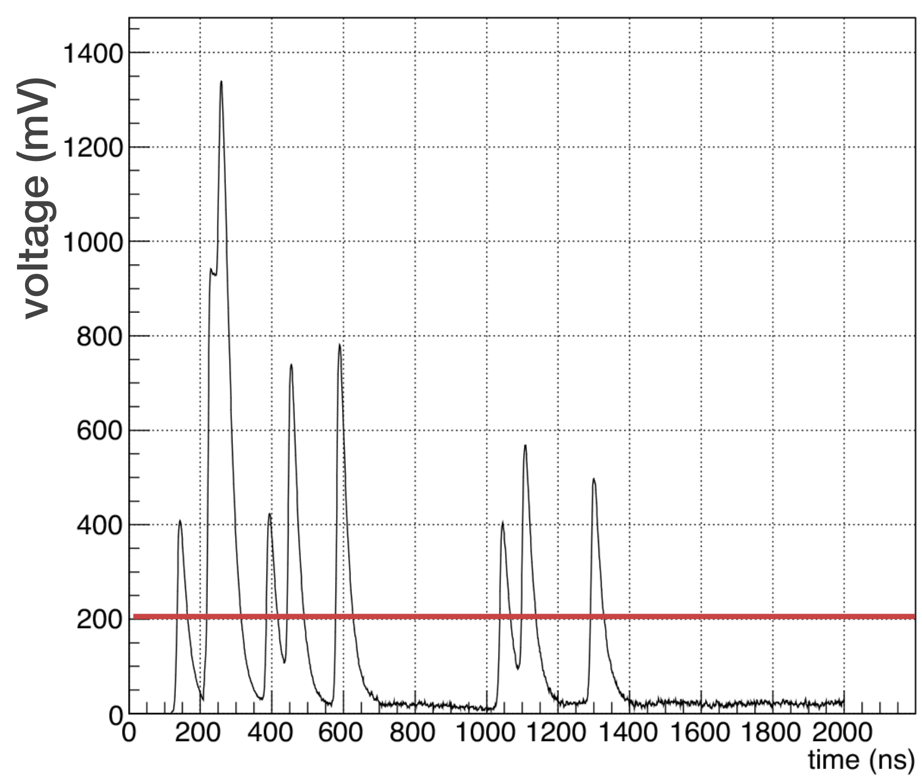
Muon beam → Muon stopping in the target → Muon spin time evolution → Positron Detection → Resonance Line shape

Possible sources of systematic uncertainties

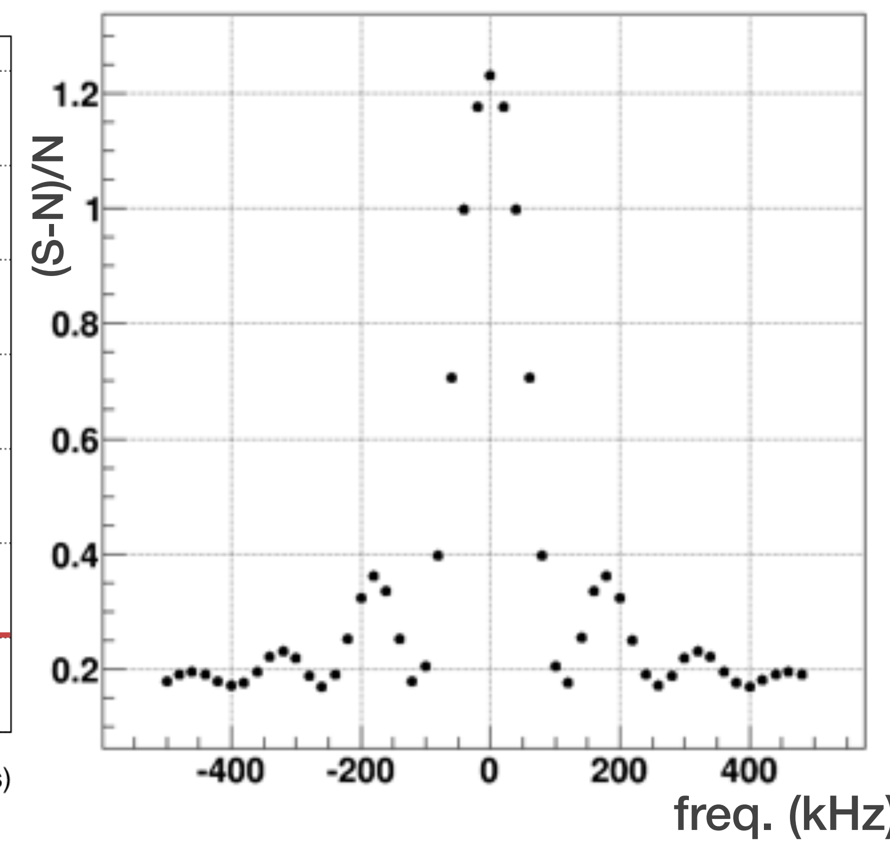
- Beam fluctuation
- B-Field
- RF fluc.
- Stopping distribution
- Pileup
- Gas density



Detector hit map



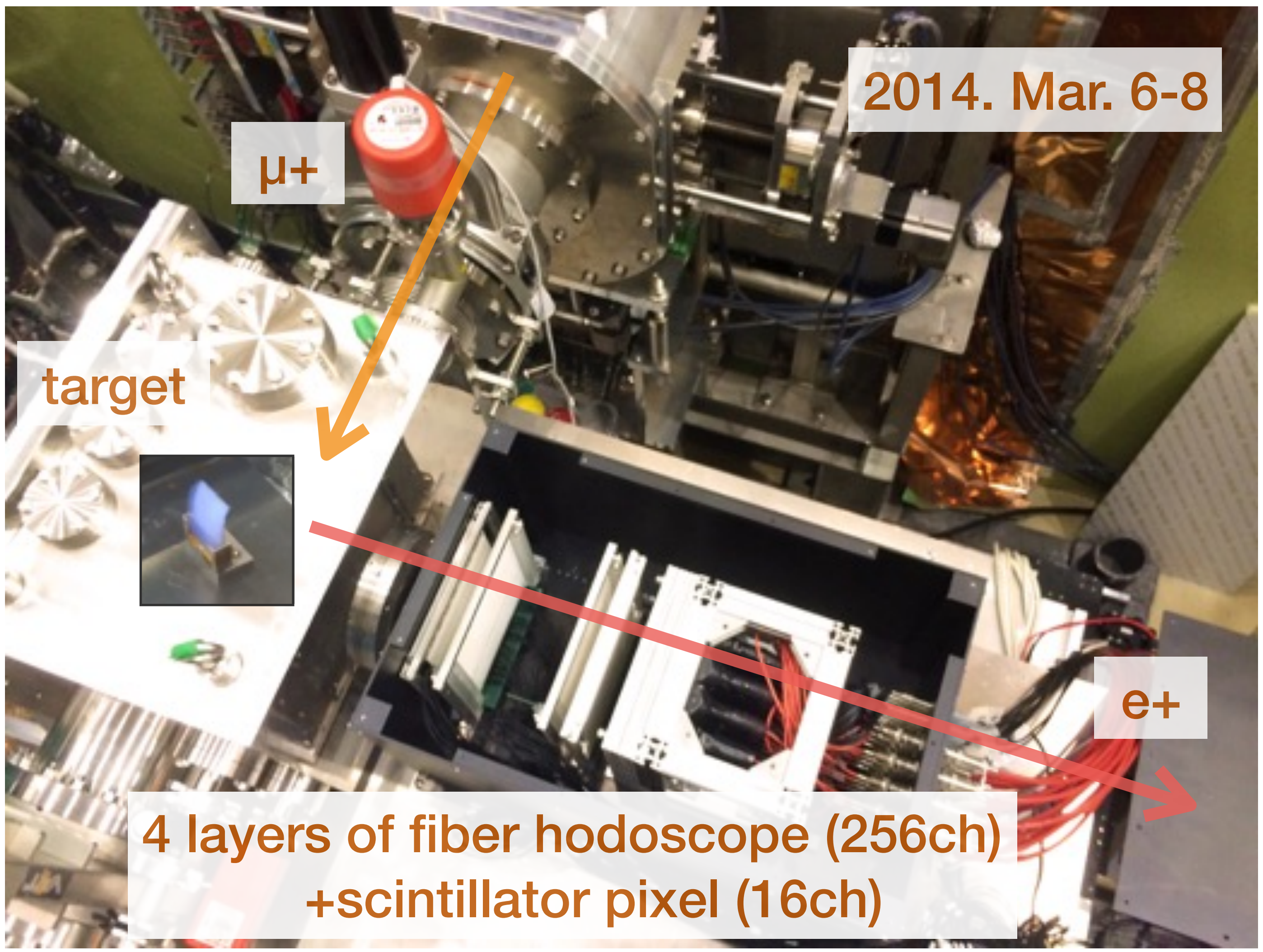
Analog signal



Resonance line

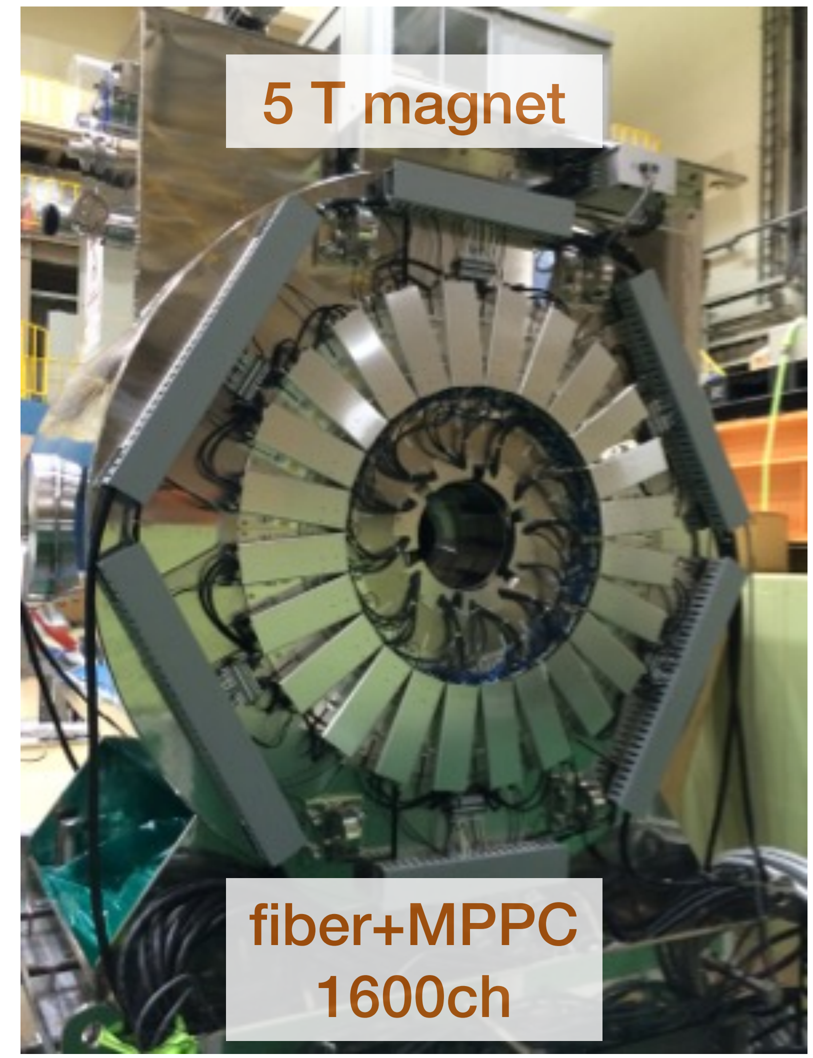
Relevant Projects

Muonium production in vacuum



S. Kanda *et al.,* Japan Phys. Soc. Ann. Meeting (2014)

High field μSR



K. M. Kojima *et al.*

Both experiments utilize the detector consists of scintillation fiber+MPPC+Kalliope

Summary

- We are preparing the new experiment for measurement of muonium hyperfine splitting (MuSEUM experiment at J-PARC)
- Muonium HFS can be the most precise probe for testing of bound state QED and we can determine the muon mass at the highest precision
- We are developing the integrated detector system for high-intensity pulsed muon beam experiment
  - It contains high-rate capable positron counters and minimum-destructive beam monitor
    - We succeed in proof of the principle for both detectors
- Realistic full simulator of the experiment is under development
- The experiment will be ready for data taking in FY2015