Development of detector system for the experiments with high-intensity pulsed muon beam

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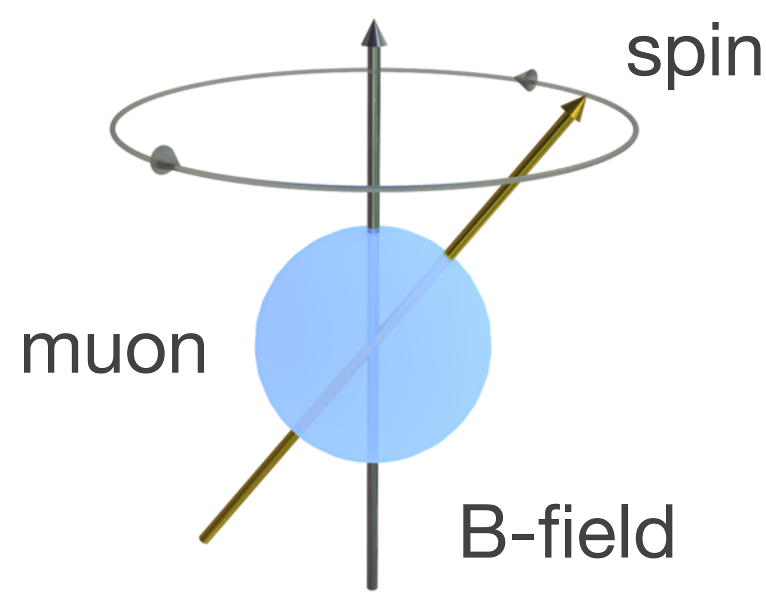
2015. 07. 26 at RCNP 計測システム研究会

Muon Spin and Decay

- **Muon spin rotation and relaxation (μSR)**

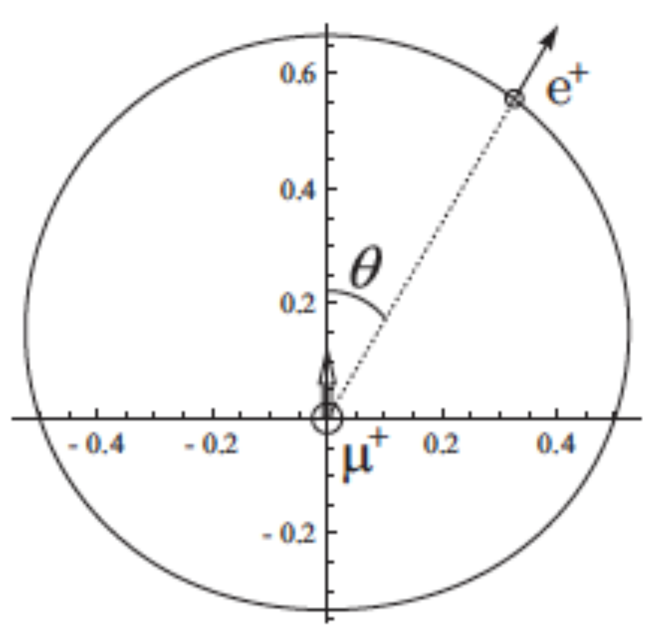


In the presence of B-field, muon spin rotates with Larmor frequency

$$\boldsymbol{\omega_\mu} = -\frac{q g_\mu}{2 m_\mu}\boldsymbol{B}$$

Spin relaxation occurs due to the B-field distribution

- **Parity violating decay of muon**



Muon from pion decay is polarized and the parity violating muon decay

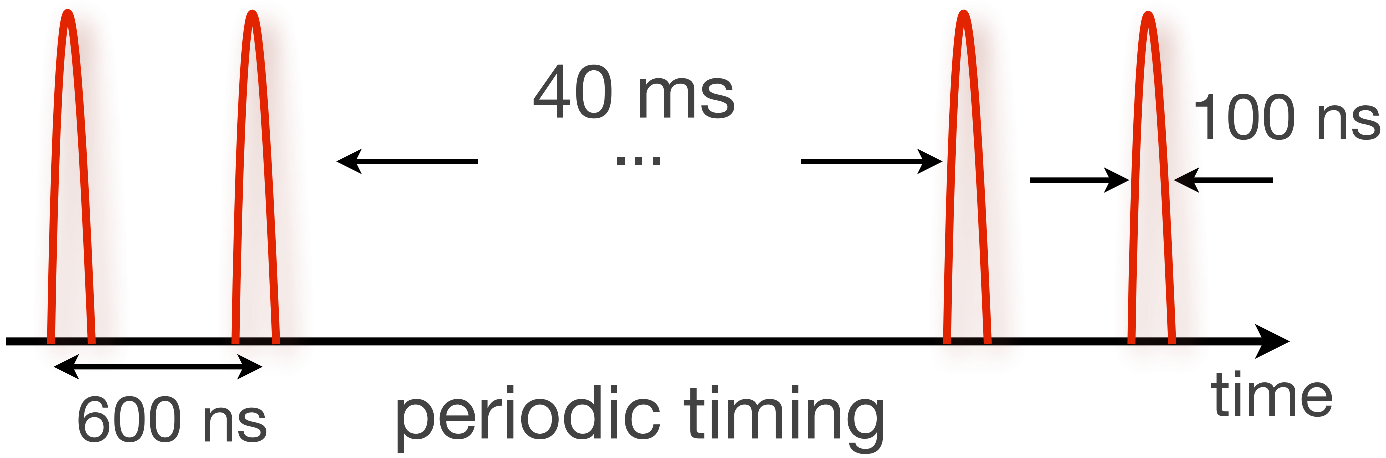
$$\mu^+ \to e^+ + \nu_e + \overline{\nu_\mu}$$

determines the muon spin via the correlation between the positron momentum and the muon spin direction

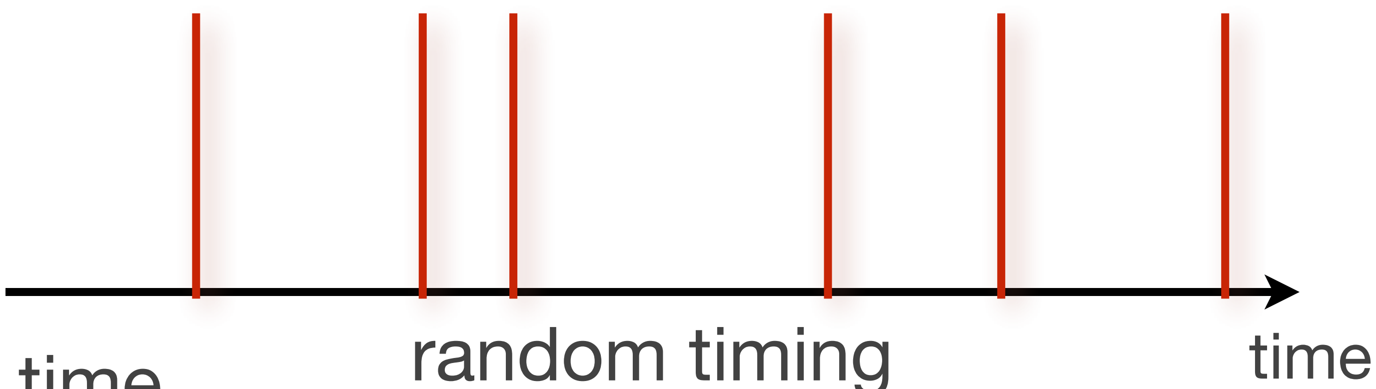
Pulsed and Continuous Muon Beam

- **Typical energy of poralized beam is 4 MeV (1 mm range in water)**

- **Pulsed beam**
  - J-PARC, RAL
  - high instantenious event rate
  - high statistics
  - accel. sync. trigger
  - pileup should be cared

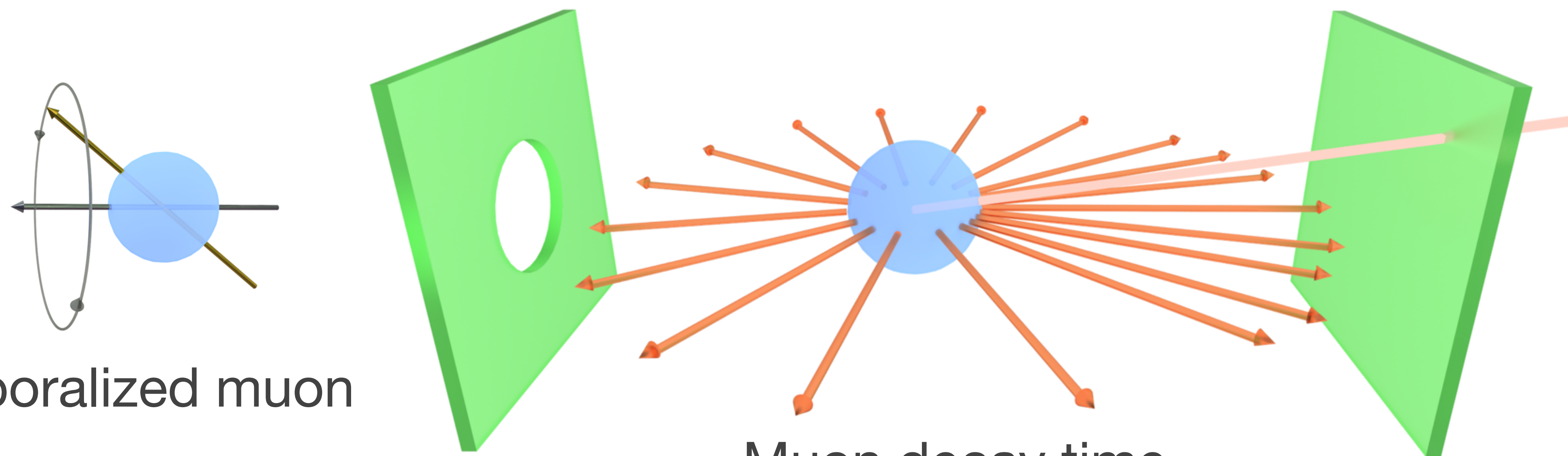


- **Continuous beam**
  - PSI, TRIUMF, MuSIC
  - less instantenious event rate
  - statistics depends on DAQ live time
  - muon trigger counted is needed
  - event-by-event analysis is possible
  - beam destruction should be minimized



Experiment with Muon Beam

- **Typical experimental setup and observables**



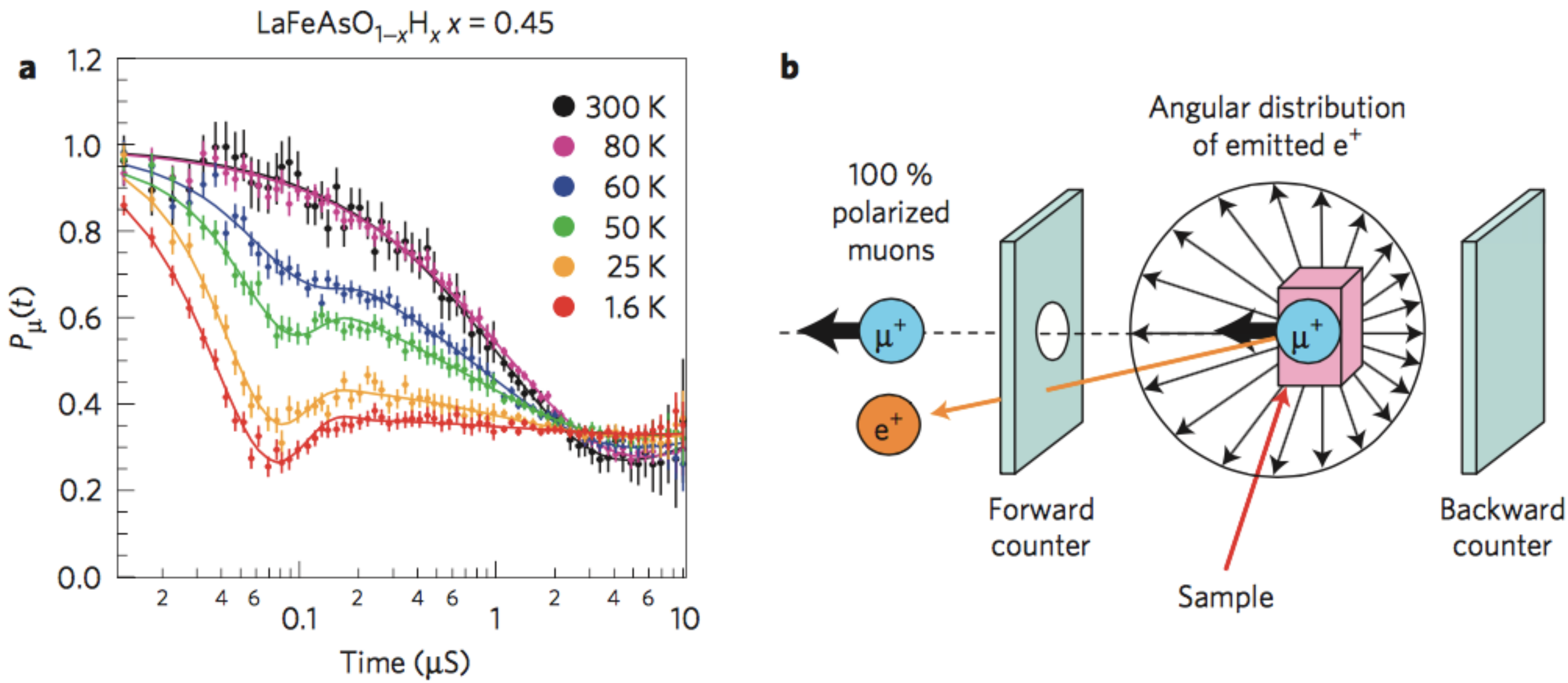
Spin rotation due to magnetic field → Local spin inside of material
Dipole moments

Spin flip induced by RF of laser → Muon/Muonium/Muonic atom
spectroscopy

Decay products → Decay branching ratios

µSR for Material Science

- **Investigation of the properties of a superconductor**

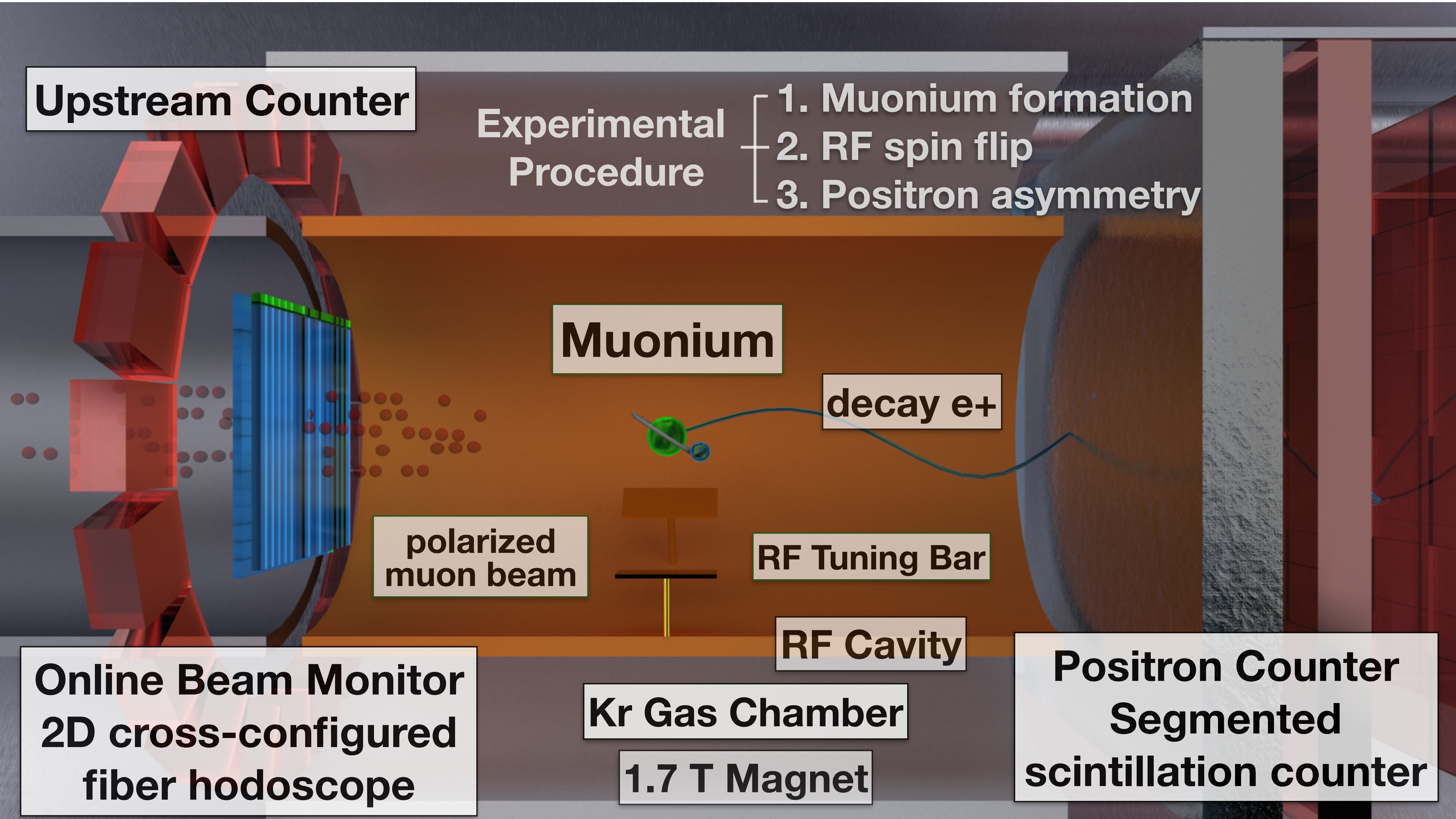


Superconducting shielding volume fraction is obtained via muon spin relaxation in a sample. Relaxation function contains the information about magnetic field distribution inside.

M. Hiraishi *et al*, Nature Physics 10, 300 (2014)

μSR for Particle Physics

- **MuSEUM : Muonium Spectroscopy Experiment Using Microwave**



S. Kanda *et al*., Proceedings of J-PARC2014 (to be published)

Fundamental Physics with Muon

- **Muon properties derived from experiments**

	Precision	Stat.	Syst.	Method	Ref.
mass	120 ppb	117 ppb	38 ppb	Muonium HFS spectroscipy	Liu1999
life	11 ppm	9.6 ppm	5.2 ppm	Decay positron counting	Chitwood2007
g-2	540 ppb	463 ppb	283 ppb	Decay positron tracking in storage ring	Bennet2007
decay parameter (ρ case)	346 ppm	160 ppm	307 ppm	Decay positron tracking	Bayes2013

Fundamental Physics with Muon

- **Beyond standard model physics search by muon experiments**

	Method	Limit	Exp.
μ->eγ	52.8 MeV e and γ back to back	$\mathrm{Br} < 5.7 \times 10^{-13}$	MEG
μN->eN	105 MeV electron	$\mathrm{Br} < 6.1 \times 10^{-13}$	SINDRUM-II
μ->eee	electron tracking	$\mathrm{Br} < 1.0 \times 10^{-12}$	SINDRUM-I
g-2	muon in storage ring	$a_{\mathrm{ex}} - a_{\mathrm{th}} = 3\sigma$	BNL E821
EDM	muon in storage ring	$\mathrm{EDM} < 1.0 \times 10^{-19} \mathrm{e \cdot cm}$	BNL E821
Mu LV	muonium spectroscopy	$2 \times 10^{-23} \mathrm{GeV}$	LAMPF MuHFS
Mu - anti Mu	e+ e- annihilation	$P_{M\bar{M}} < 8.3 \times 10^{-11}$	PSI

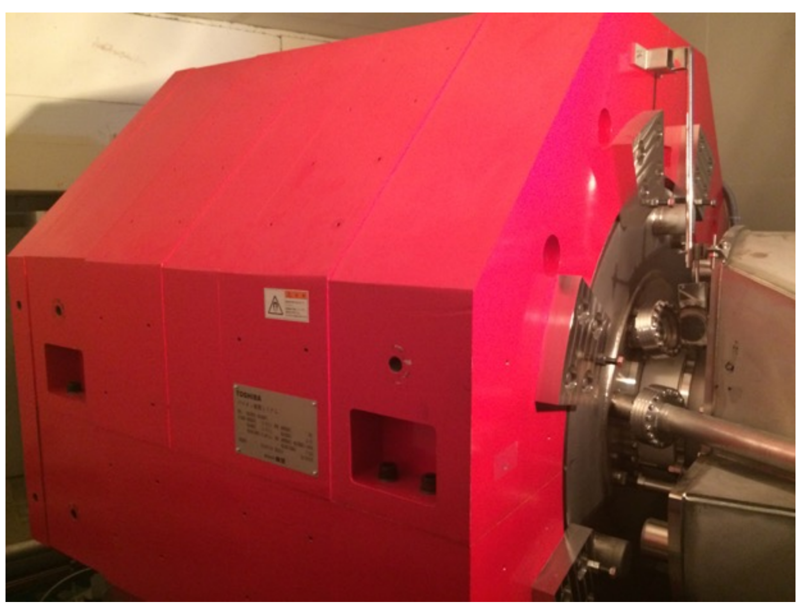
Limitation of the Experiments

- Muon property measurement and spectroscopy
  - Mostly limited by statistics
    - Higher beam intensity
    - Higher rate capability of the detector
- Muon rare decay search
  - Mostly limited by background events
    - Accidental coincidence (MEG, SINDRUM-I)
    - Beam related (SINDRUM-II)
      - Higher resolution of the detector
  - Higher statistics improve single event sensitivity

Beyond the Limits

- **High intensity muon beam**

J-PARC
MLFMUSE
1×10^{8} μ/s
double pulsed
at 1 MW



RCNP
MuSIC
6.7×10^{8} μ/s
continuous
at 784 W

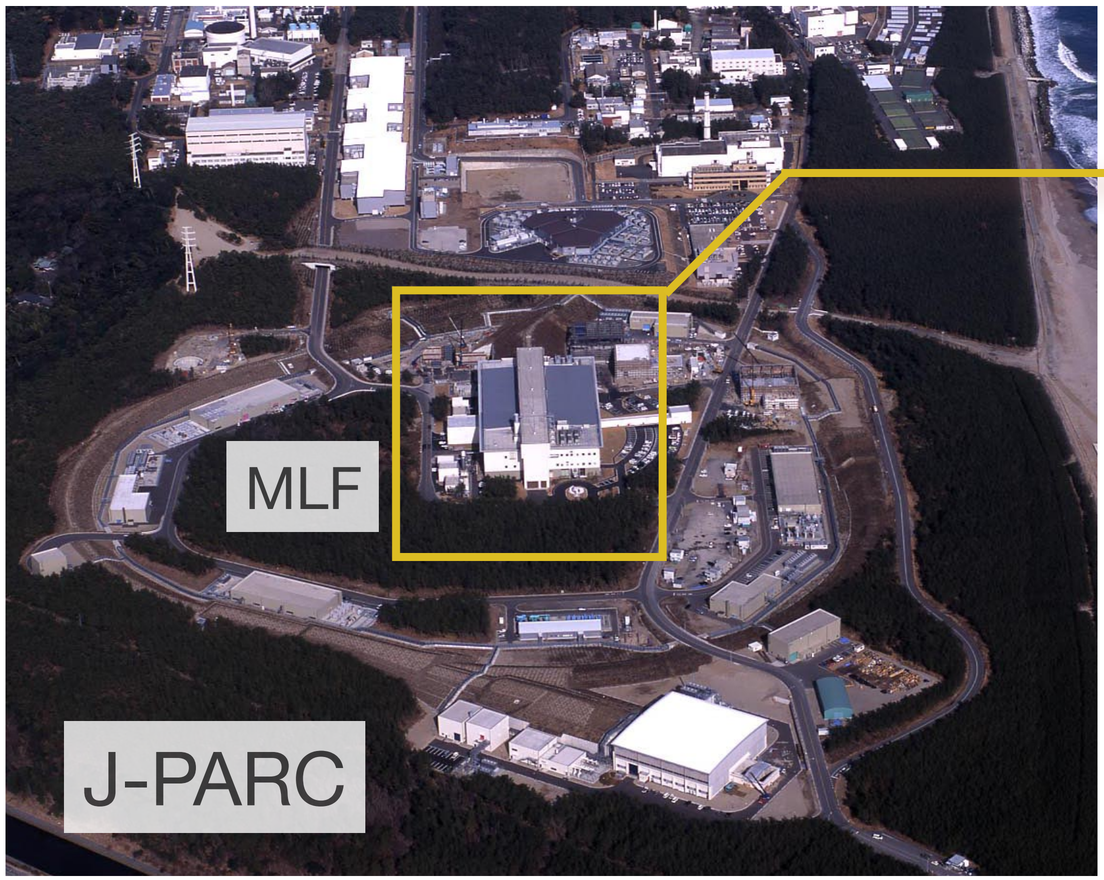
- **High rate capable detector**

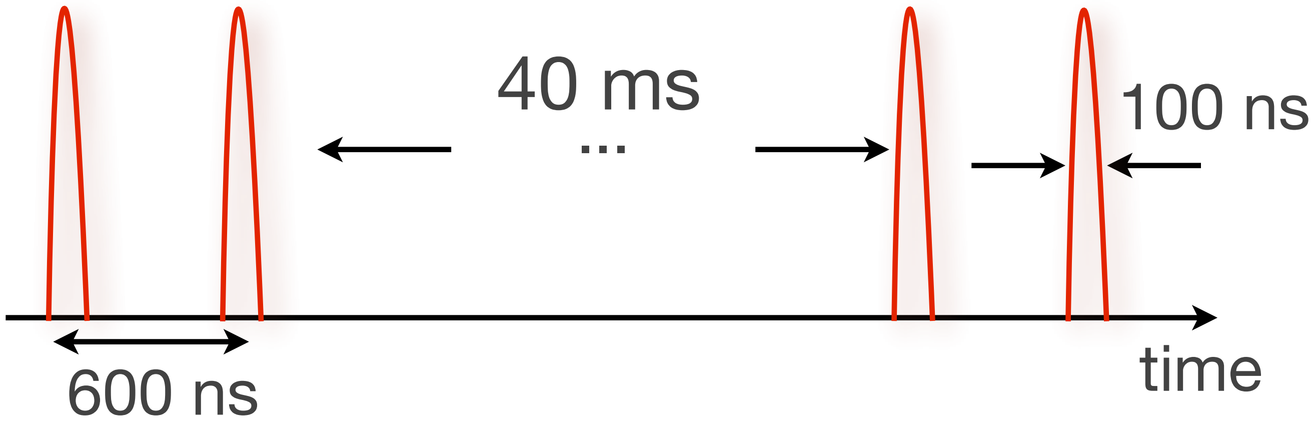
Scintillation fiber+MPPC
+Kalliope, 3008 ch

M. Miyazaki, K. M. Kojima, S. Kanda *et al*,, JPS Annual Meeting (2014)

J-PARC Muon Beam

- **Japan Proton Research Accelerator Complex has the highest intensity pulsed muon beam**

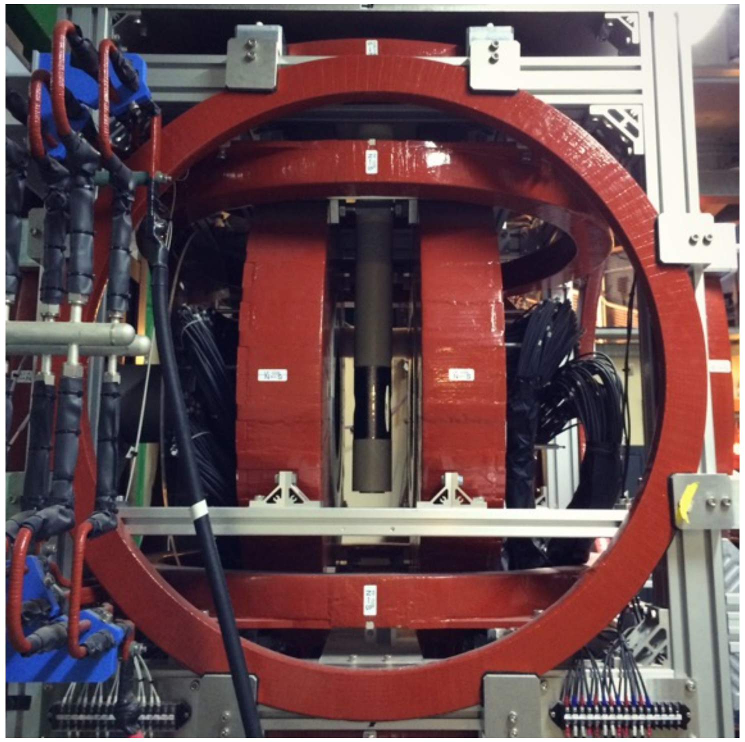




Double pulse beam with 600 ns interval in 25 Hz repetition cycle

μSR Spectrometers at J-PARC

- Beam intensity is expected 1.0 x 10^8 muon/s at 1 MW beam power
  - High rate capable positron counting system is essential
- 4 beamlines, 10 branches
  - D-Line: Two branches
  - U-Line: Two branches
  - S-Line: Four branches (partly constructed)
  - H-Line: Two branches (under construction)
    - Cost effective composition is desirable
- Operation in the presence of (high) B-field

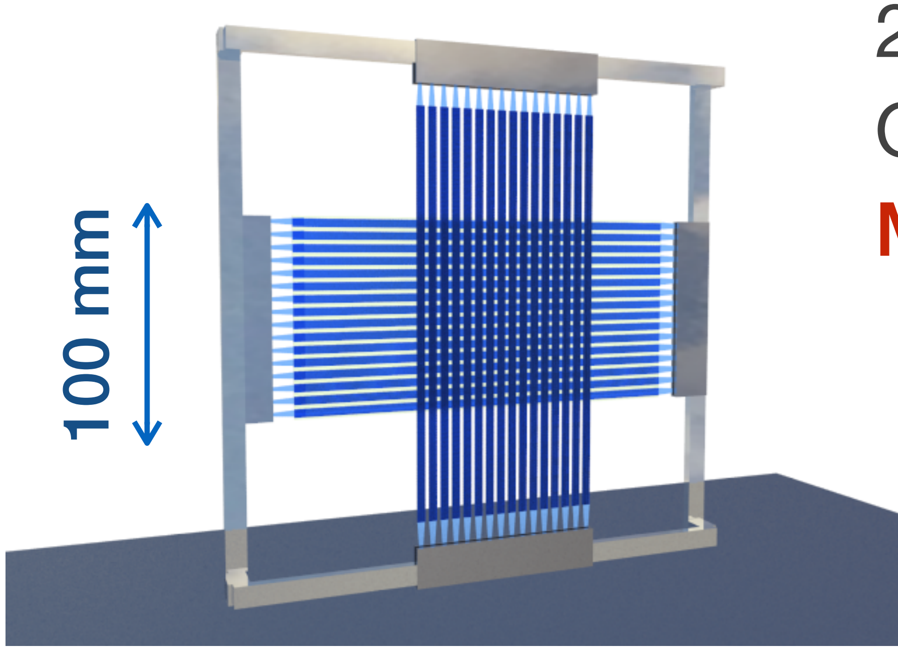


CHRONUS at RIKEN RAL
(MAPMT+VME discrim.)

Possible solution: Segmented plastic scintillator
Silicon photomultiplier
Custom integrated readout electronics

Detectors for the MuSEUM

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



2D beam profile monitor for stability monitoring

Online measurement (minimum destructive)

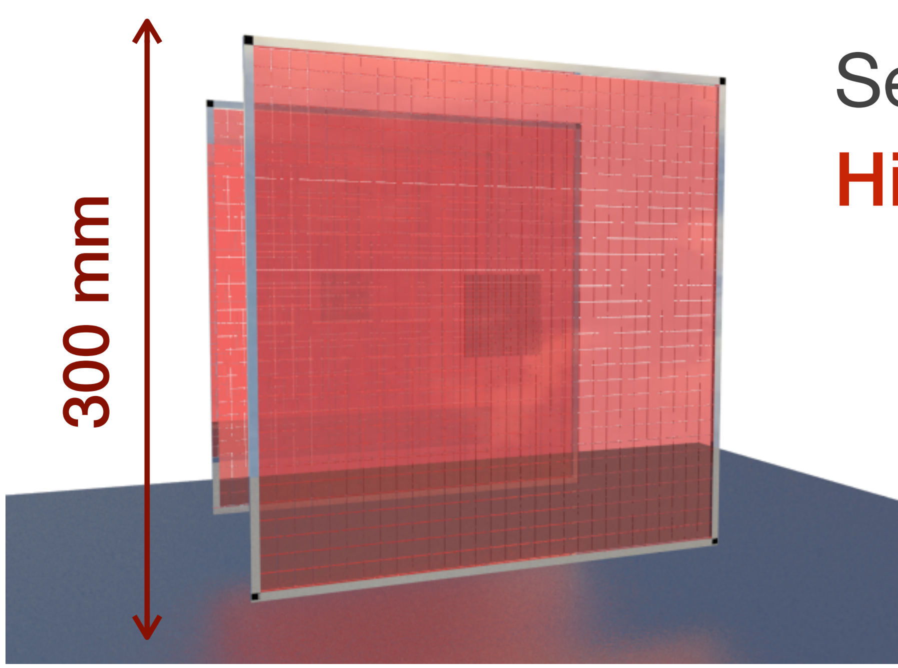
Minimum amount of material is required

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

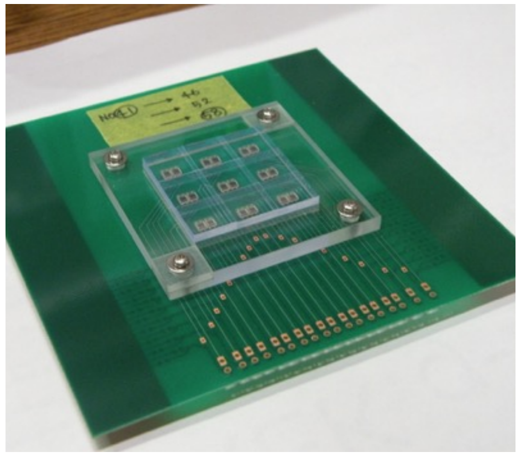
High-rate capability is required (~3500 e+/pulse)

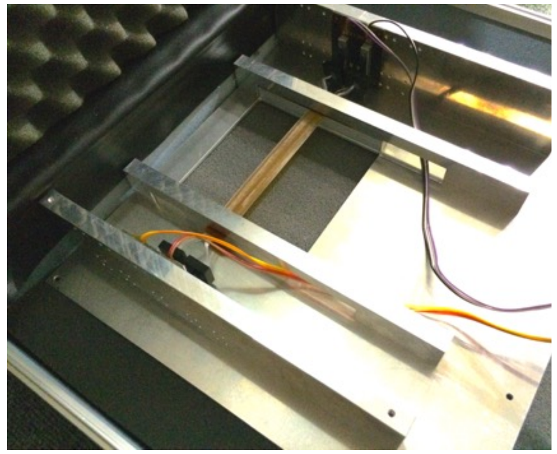
Plastic scintillator + SiPM (HPK MPPC)

Prototype was developed and tested

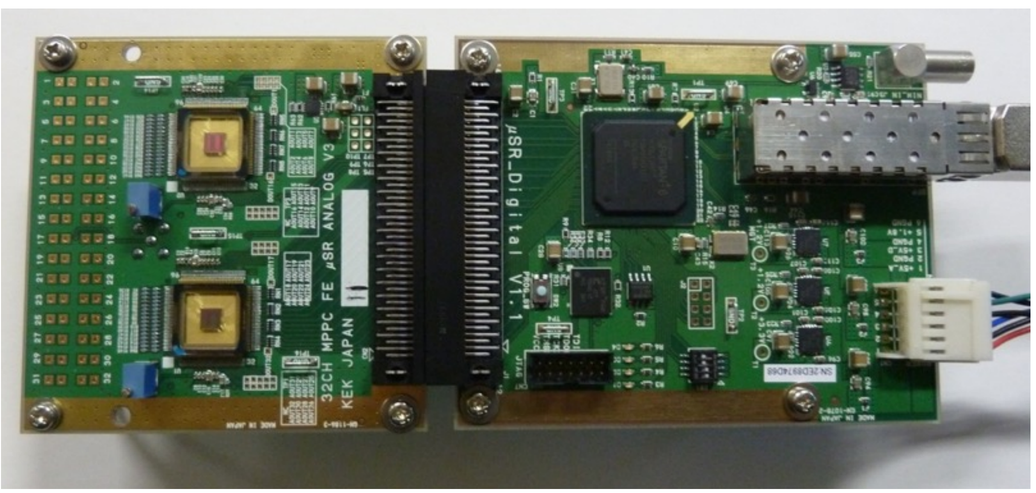
S. Kanda, RIKEN APR Vol. 47 (2014)
S. Kanda, KEK-MSL Progress Report 2013 (2014)
S. Kanda, The 8th g-2/EDM Collaboration Meeting (2014)

Development Overview

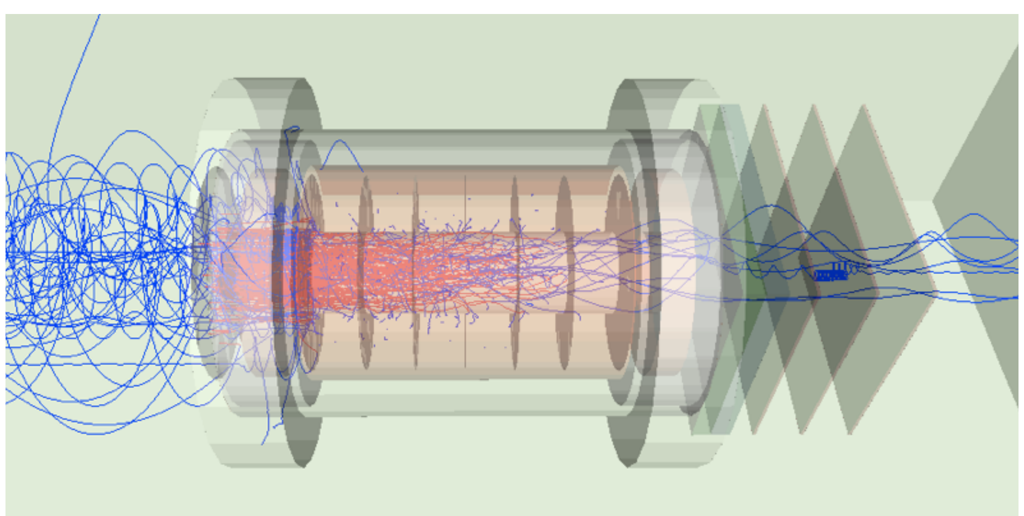




- **Prototype development**
  - Proof of the principle
  - Optimization of options
  - Experimental inputs for simulation



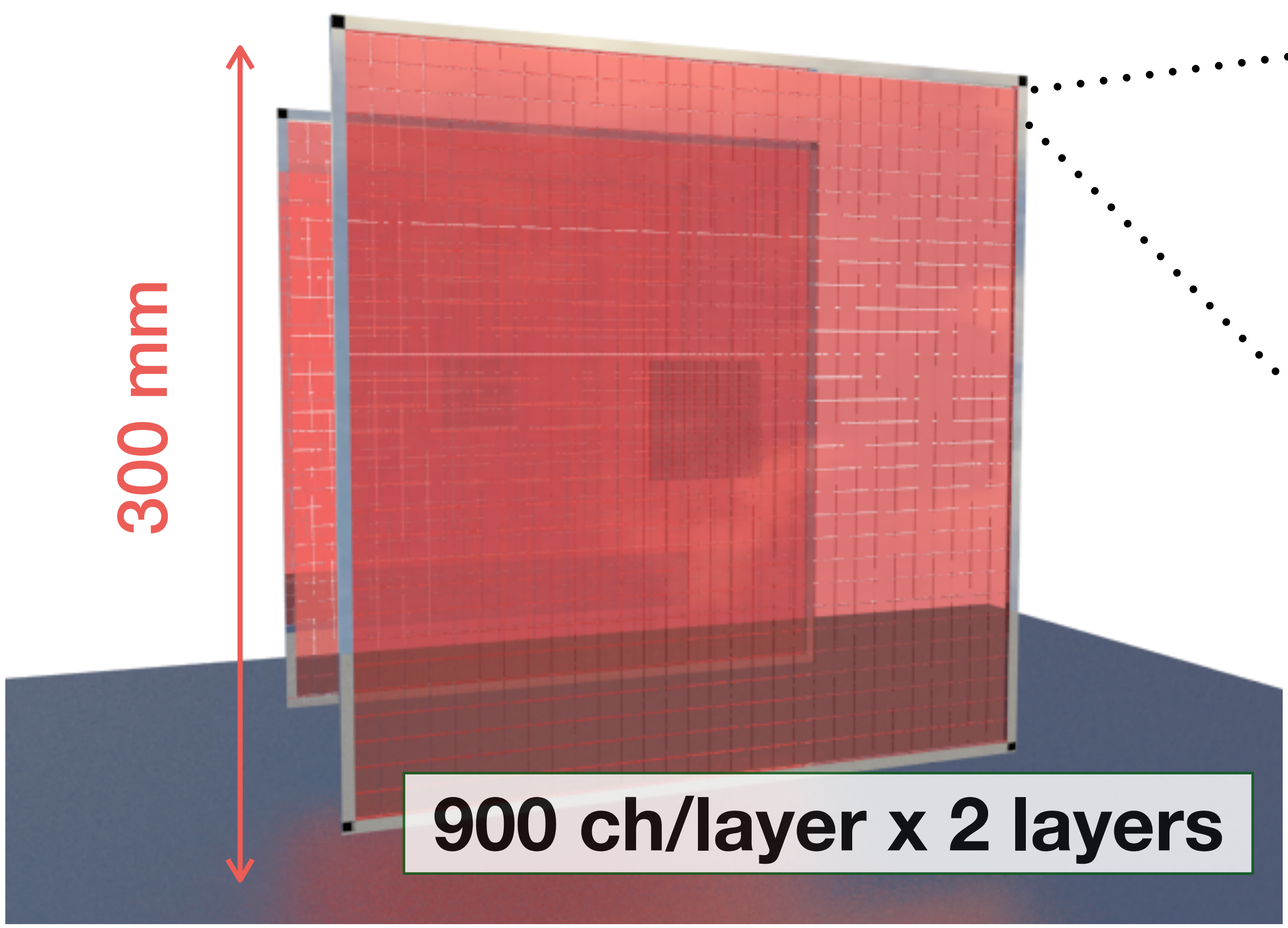
- **Readout circuit development**
  - ASIC evaluation
  - Circuit parameters optimization
  - FPGA implementation

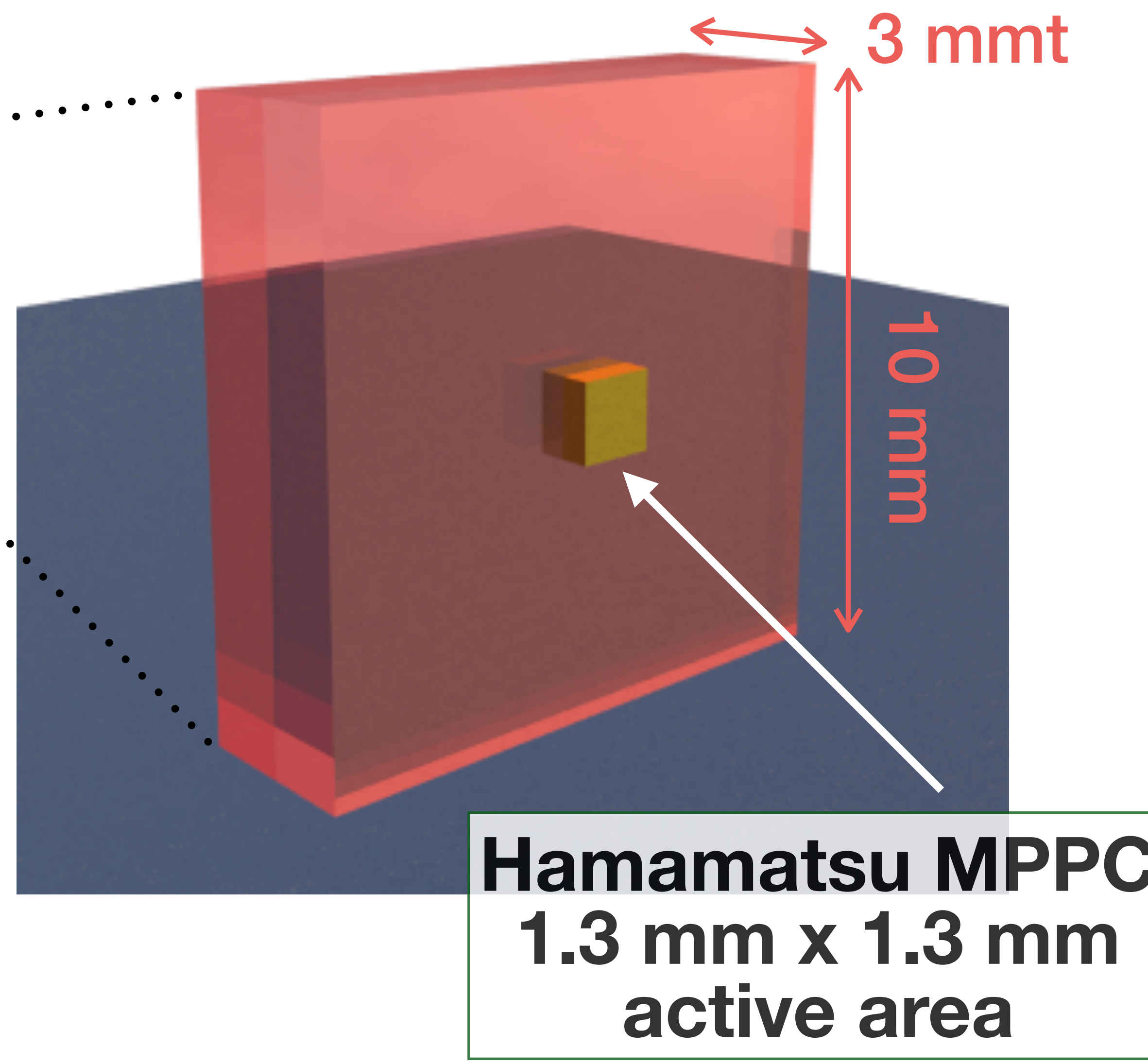


- **Monte-Carlo Simulation**
  - Detector designing
  - Event rate estimation
  - Systematic Uncertainty evaluation

Positron Counter for MuSEUM

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



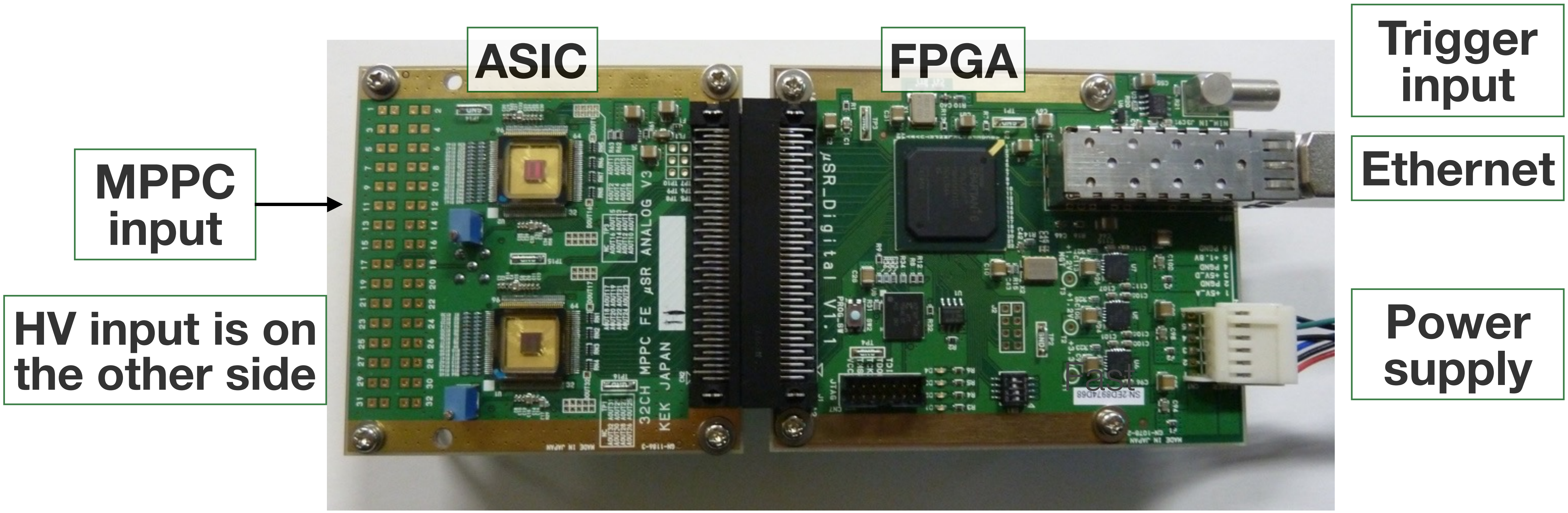


- Segmented scintillation counter
- 300 mm×300 mm detection area
- 10 mm×10 mm×3 mmt uni cell

- Prototype was developed and a beam test was performed in Feb. 2014

Kalliope Readout Circuit

- KEK Advanced Linear and Logic-board Integrated Optical detectors for Positrons and Electrons

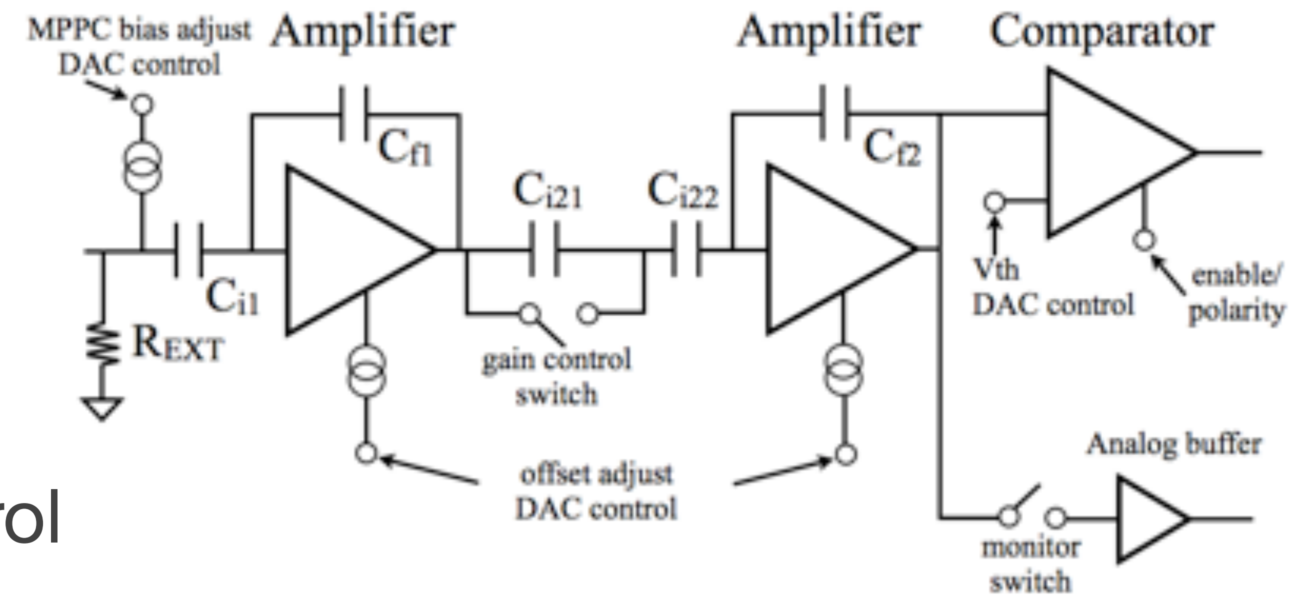


- 32ch inputs for MPPC
- ASIC implemented amplifier, shaper, discriminator
- FPGA programmed multi-hit TDC (common start)
- SiTCP data transfer

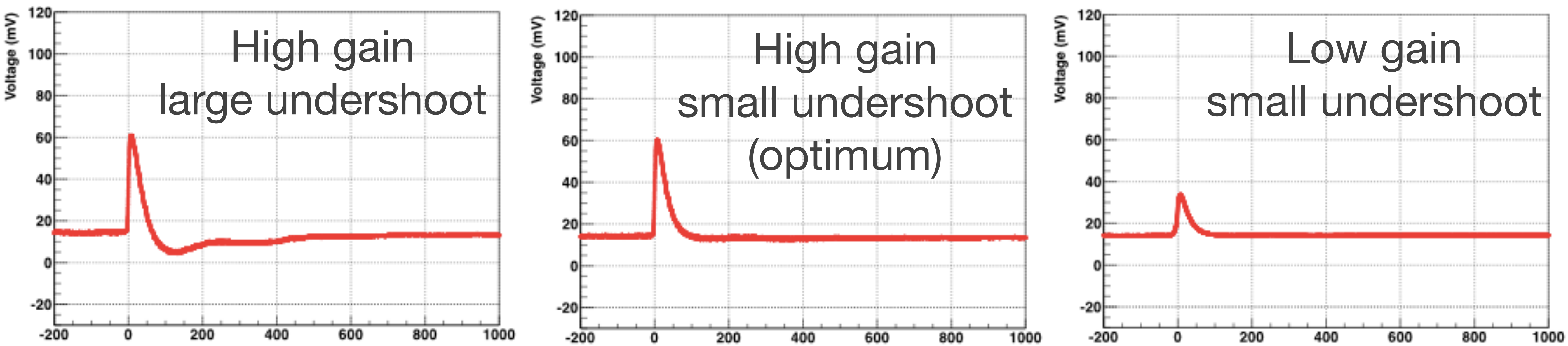
M. M. Tanaka, K. M. Kojima, T. Murakami, S. Kanda, C. de la Taille and A. Koda, “MPPC frontend module for muon spin resonance spectrometer” (to be published)

Kalliope Analog

- **ASIC diagram**
  - 40 dB gain
  - 100 MHz bandwidth
  - 4 bit MPPC bias control
  - 4 bit Threshold control
  - 2 x 4 bit amplifier bias control



Two stages of voltage amplifier and comparator
Bias voltage of each amplifier is DAC controlled

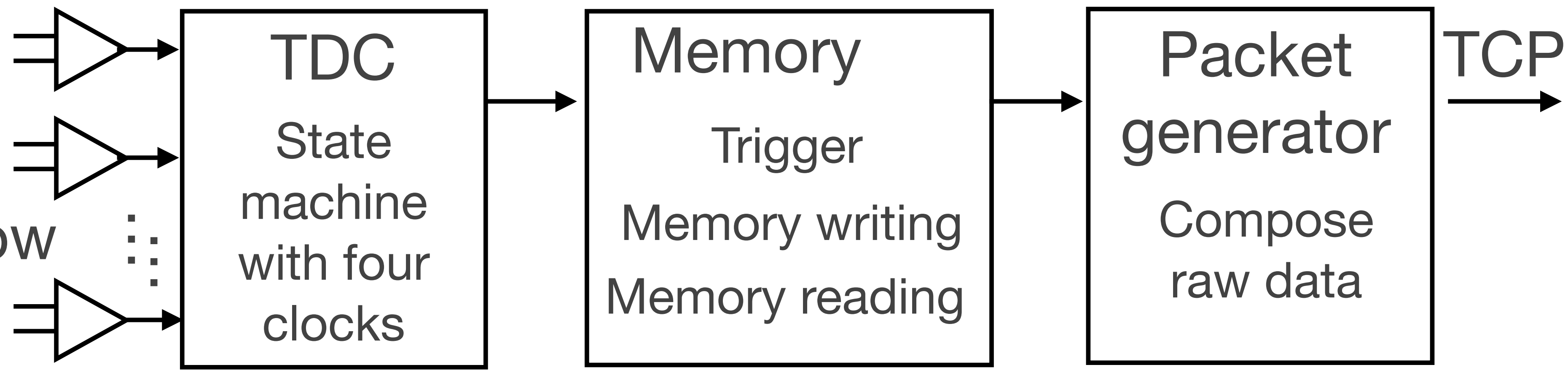


Waveform dependence on amplifier parameters

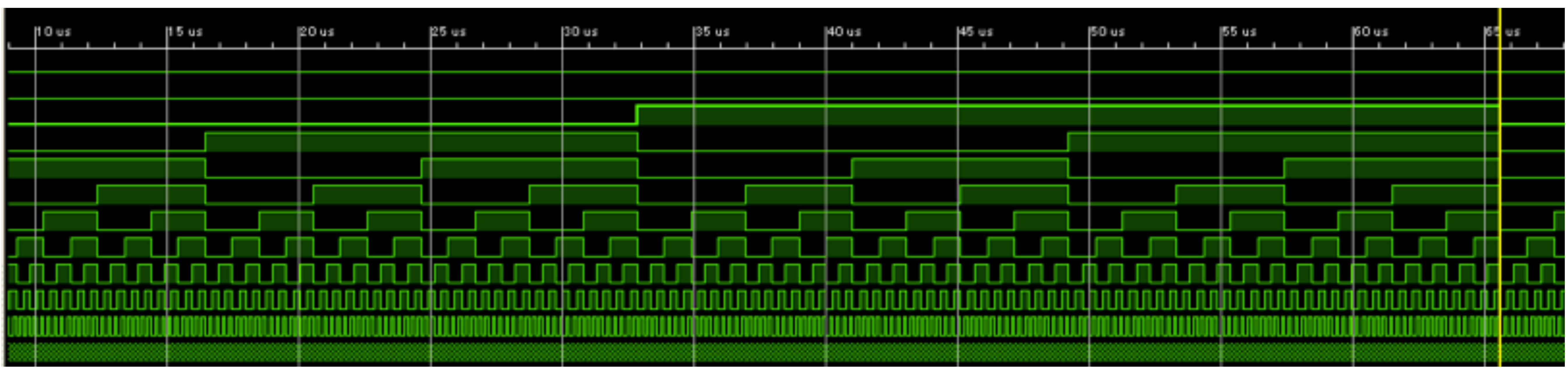
Kalliope Digital

- **TDC implementation**

- Multi-hit TDC
- 1000 hits depth
- 1 ns resolution
- Adjustable DAQ window
  - up to 64 μs



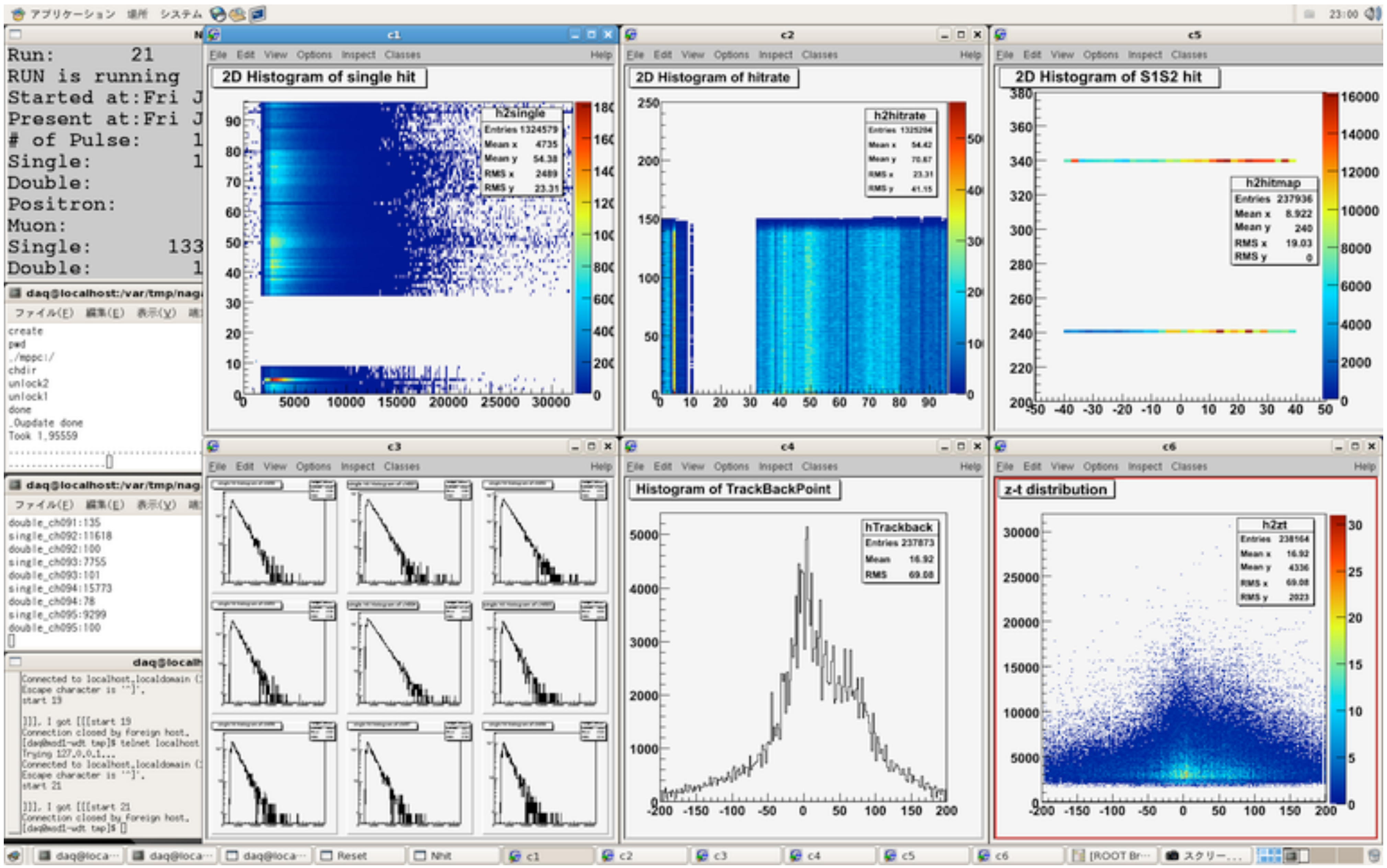
Four phase rotating 250 MHz clock realize 1 ns resolution



Simulated state machine for time counting

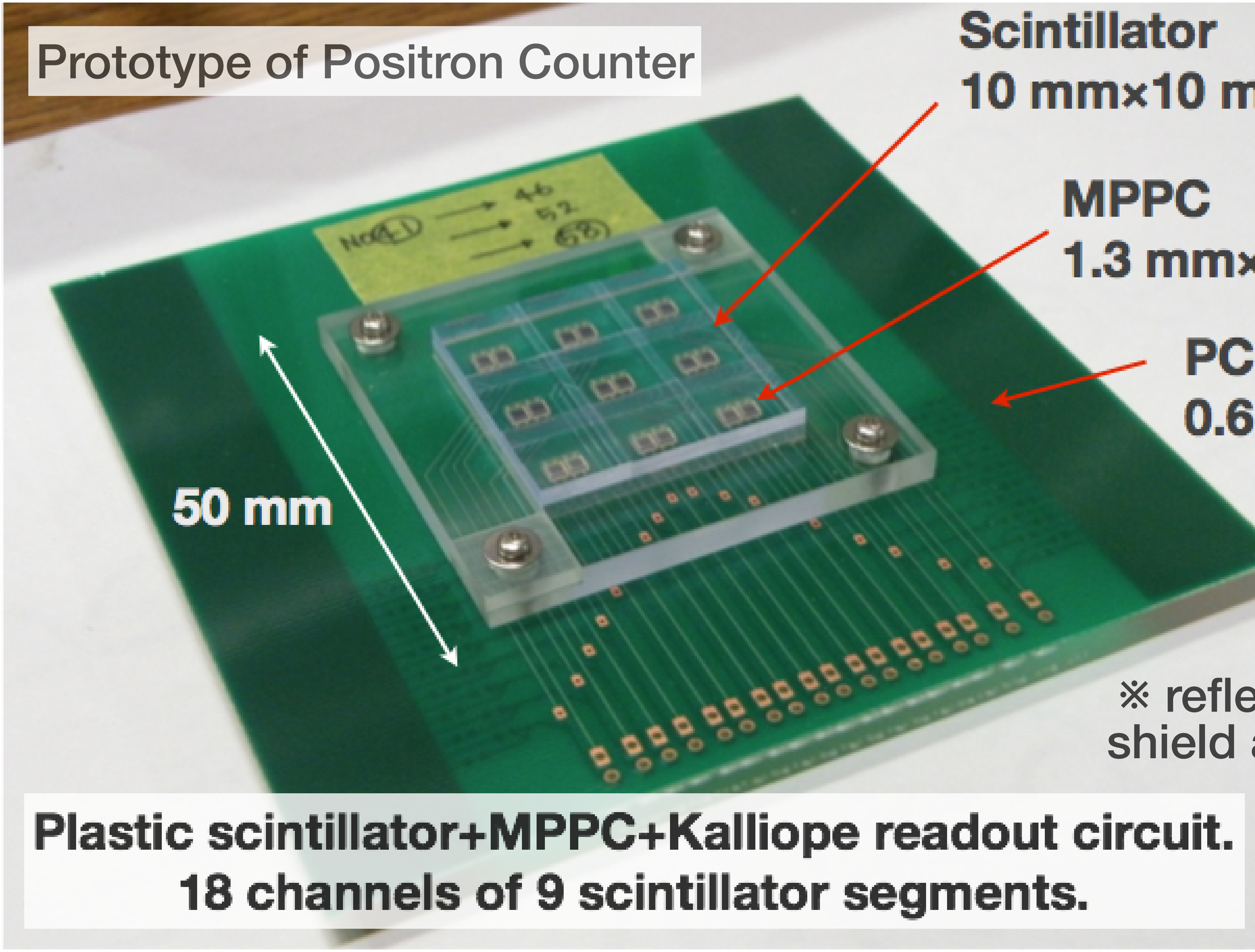
Kalliope DAQ

- DAQ software including ROOT based online monitors



DAQ windows and online monitors

Prototype Study

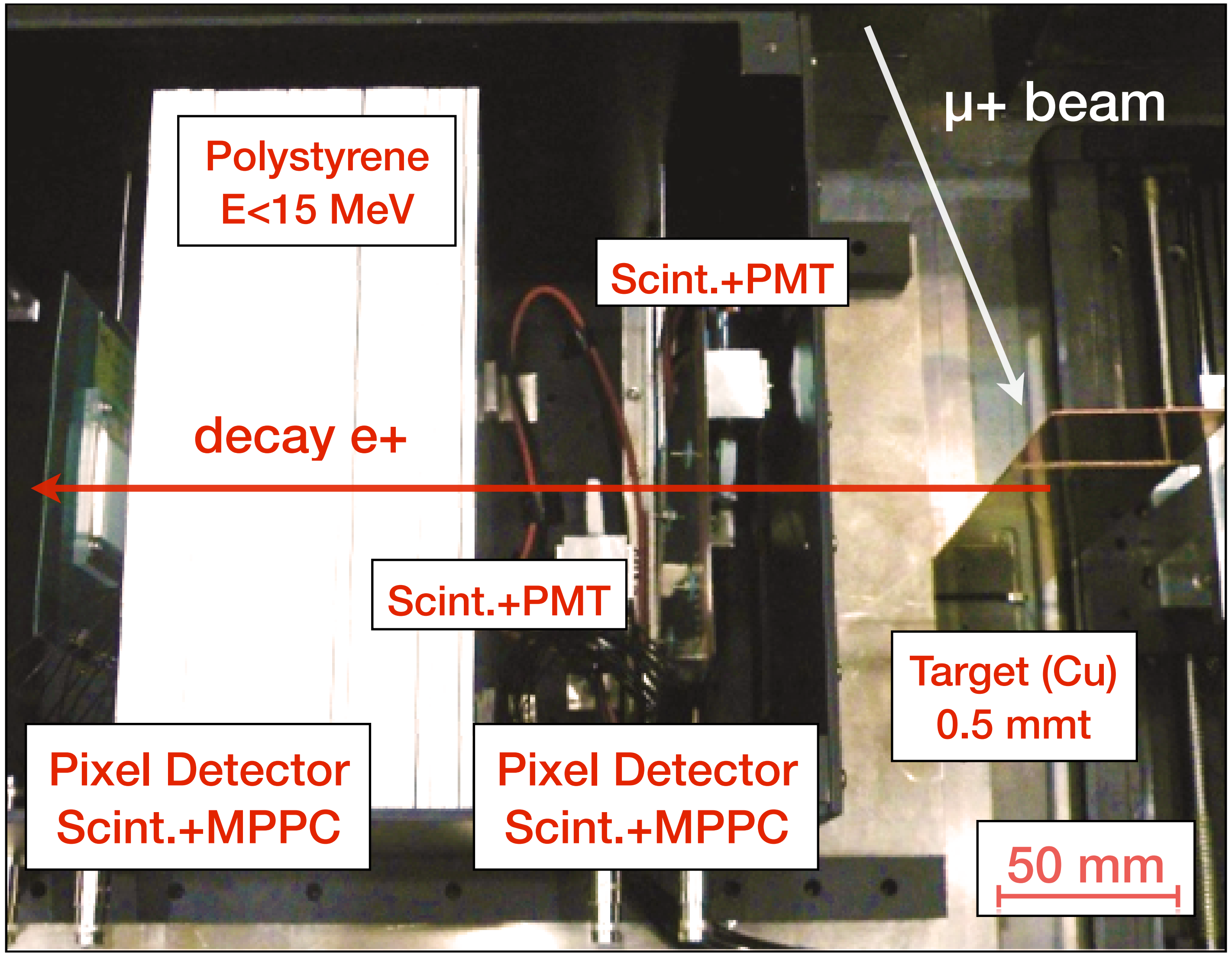


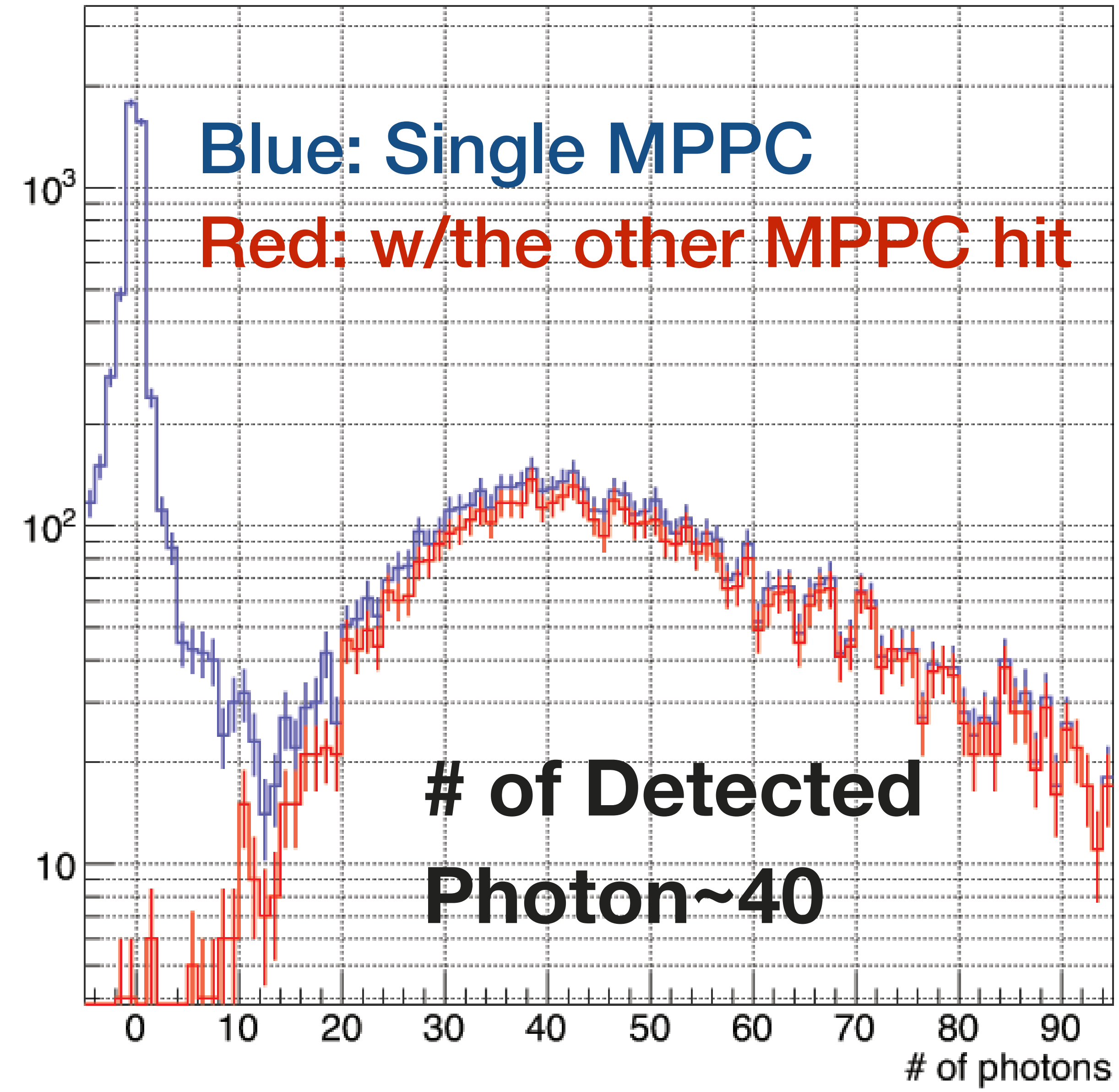
※ reflector and light shield are not shown

S. Kanda *et al*., Proceedings of J-PARC2014 (to be published)

Prototype Study

- Beam test setup and result





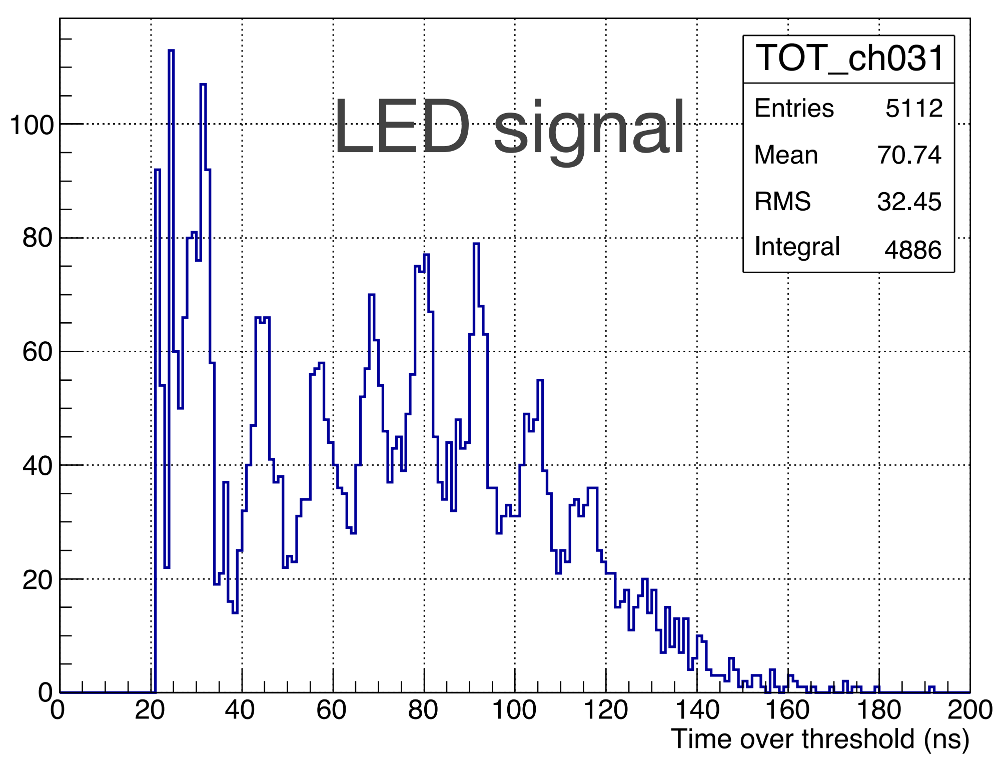
Positrons from muon decay were detected at J-PARC MLF MUSE D2

photon number distribution

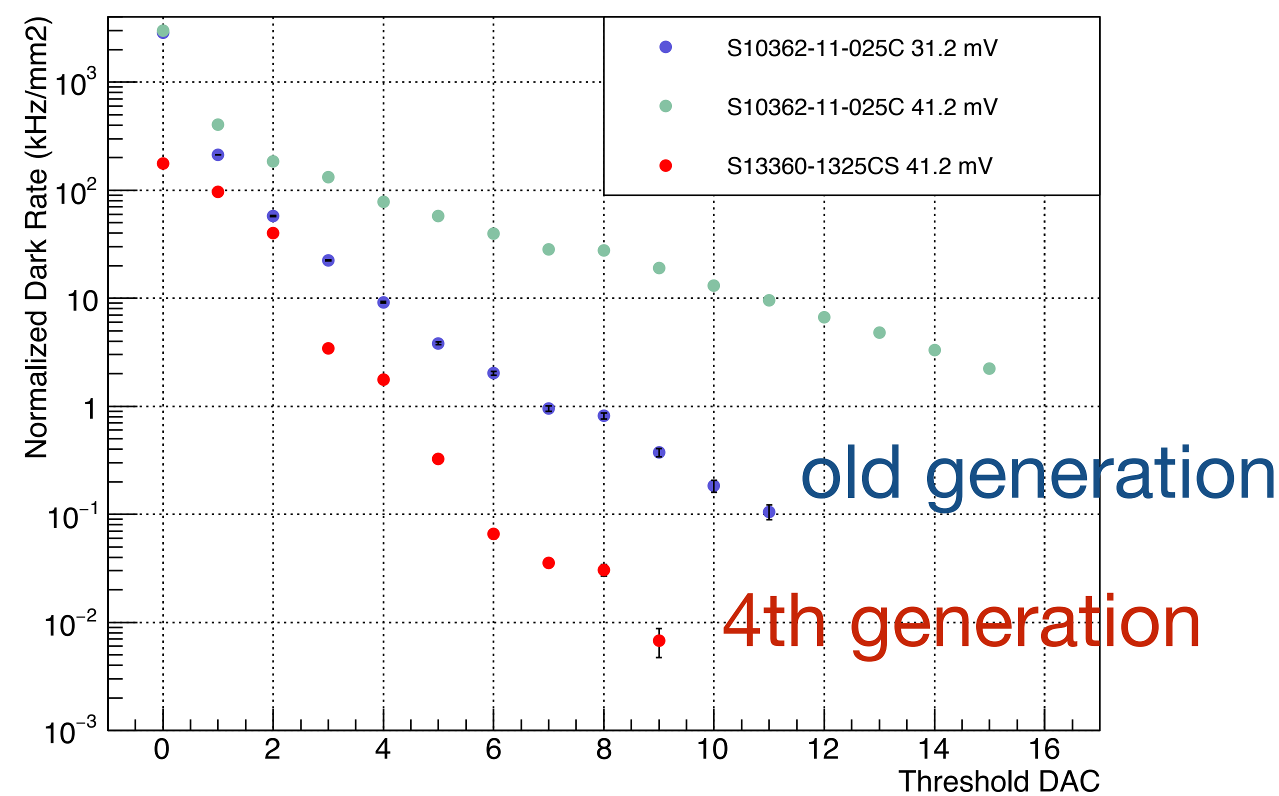
Positron signal can be separated from dark noise of MPPC

Upgrade Plans

- **ASIC upgrade**
  - Pole zero cancelation
  - Simplified DAC parameters
- **FPGA upgrade**
  - Time over threshold
- **Temp. feedback**
- **WFD readout**
- **4th generation of MPPC**
  - Less dark count rate
  - Higher PDE



TOT spectrum
Y. Matsumoto (Osaka Univ.)

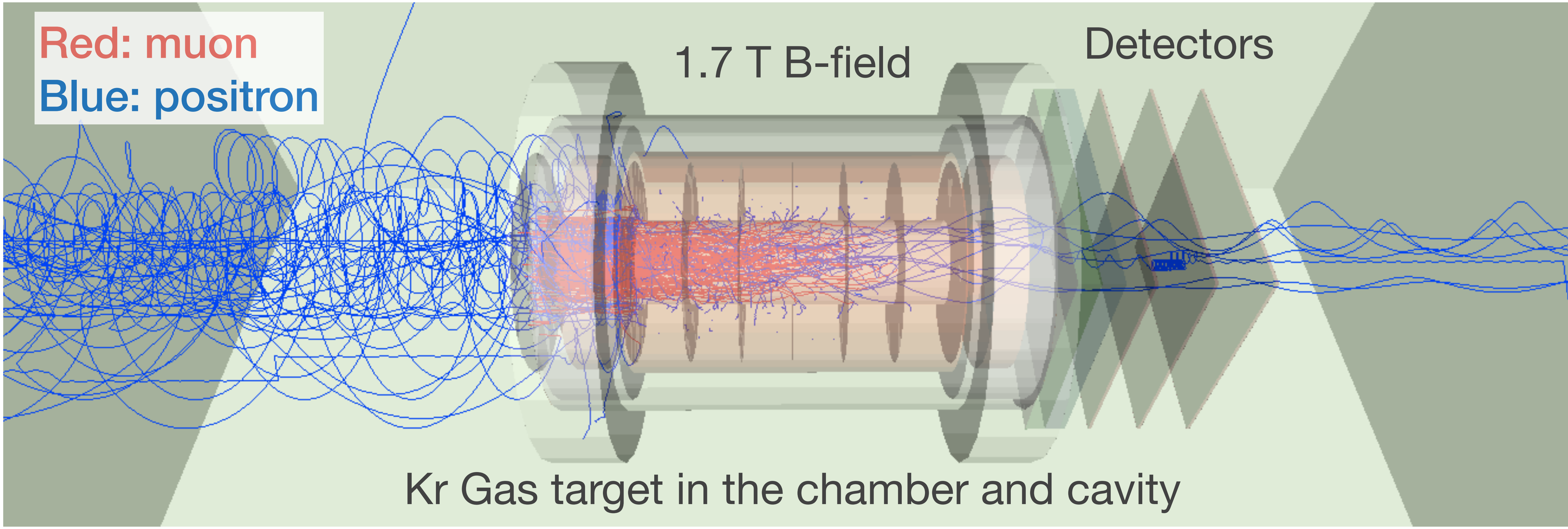


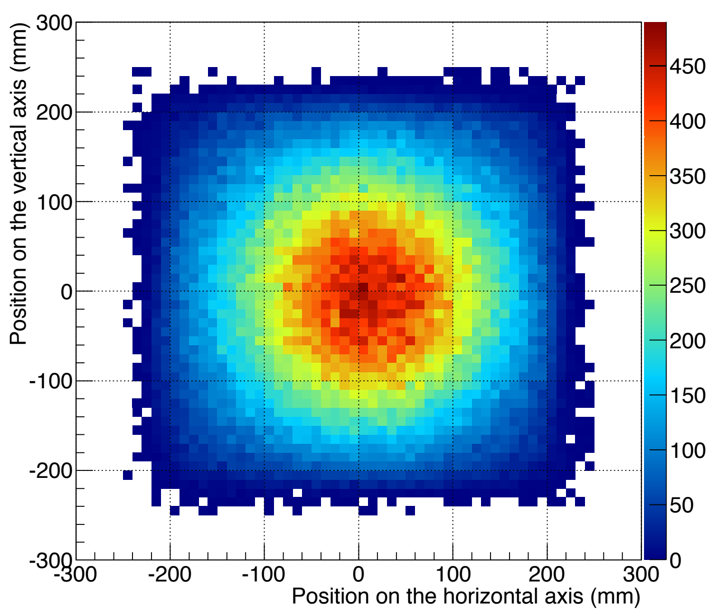
Dark count threshold scan

Items to be considered

- **MPPC calibration**
  - 1 p.e. level measurement
    - Conversion board + EASIROC
    - TOT implementation in Kalliope FPGA
- **Detection efficiency correction**
  - Particle from a radioactive source
    - Moving stage automation
- **<u>Better pileup correction</u>**
  - Several independent analysis
  - Waveform measurement
- **Analog output**
  - Selective analog output

Simulation Study





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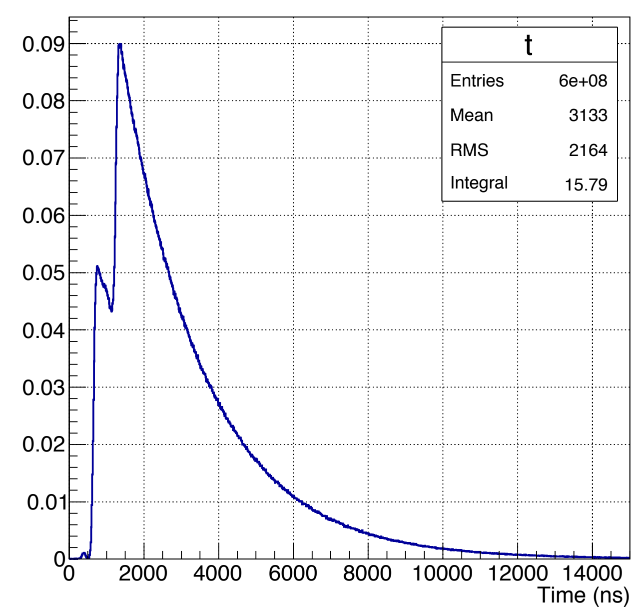

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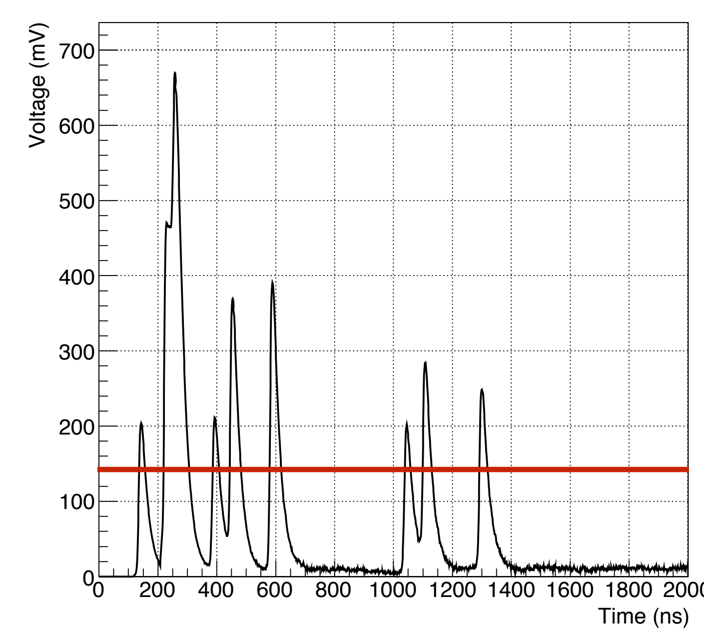


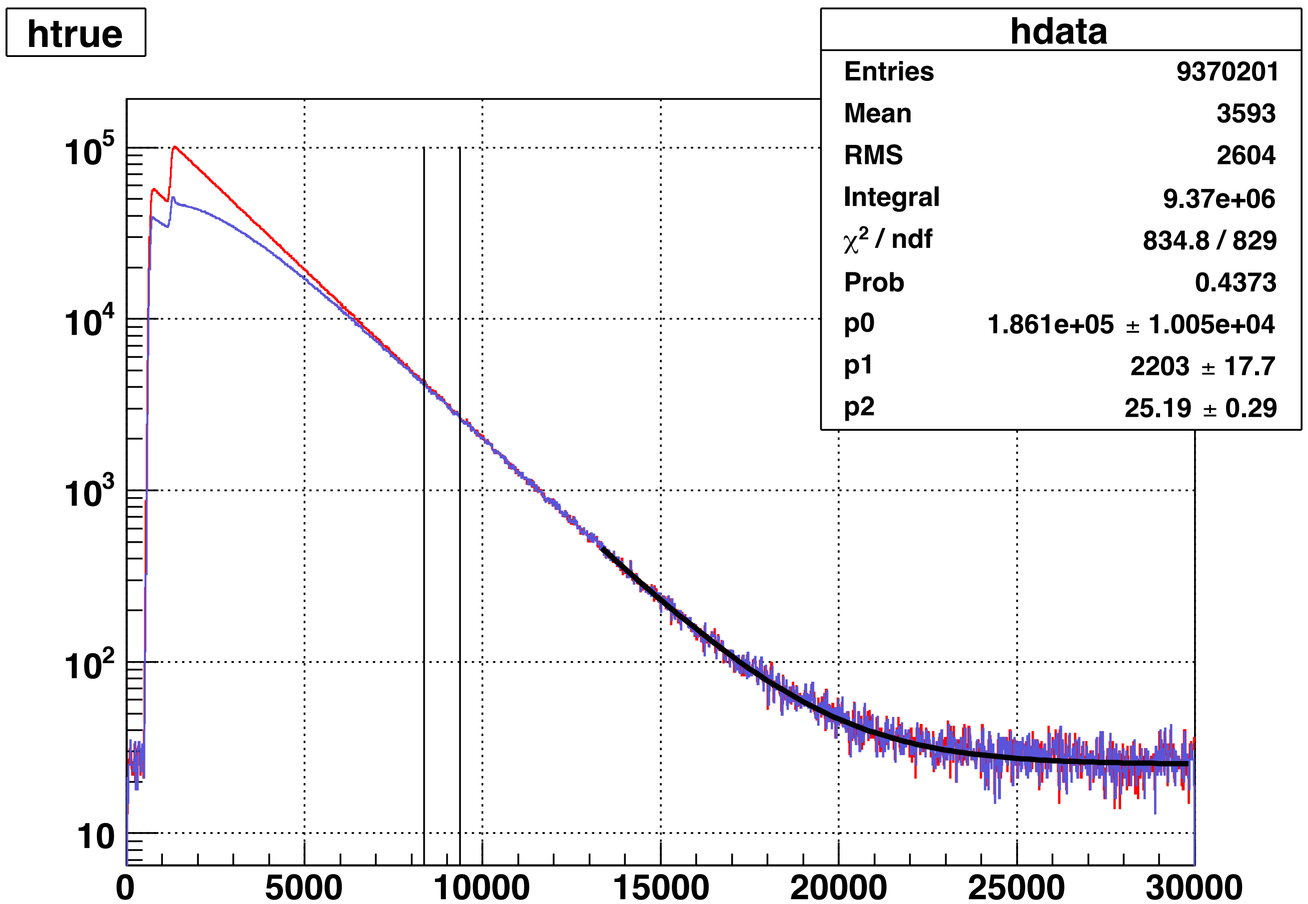
Hit map on a detector plane

Time spectrum

Analog output generation

Simulation Study

- **Pileup correction**

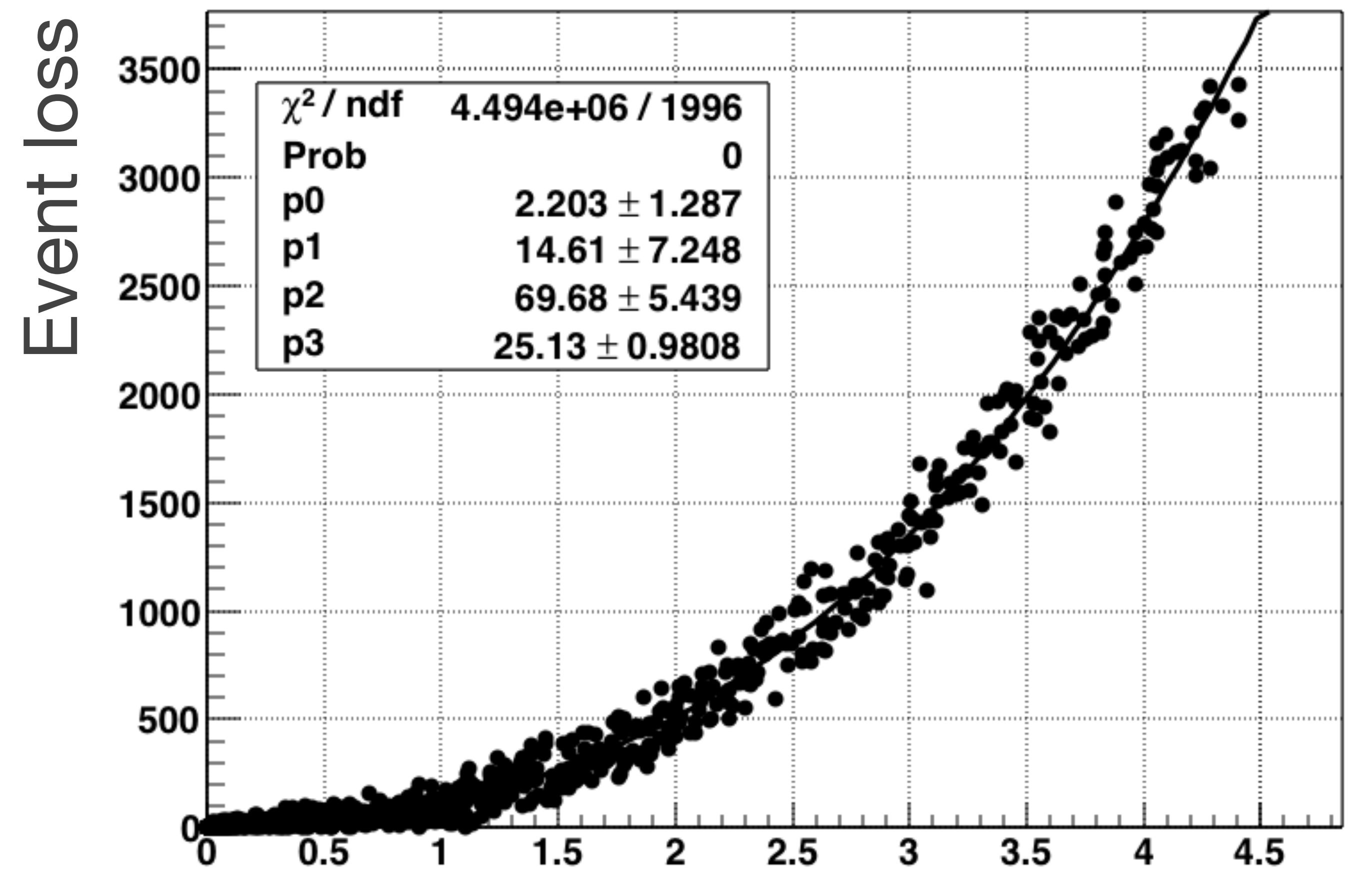


Time (ns)

Red: Ideal detector

Blue: Pileup considered

Fitting of time spectrum in lower event rate region and extrapolation

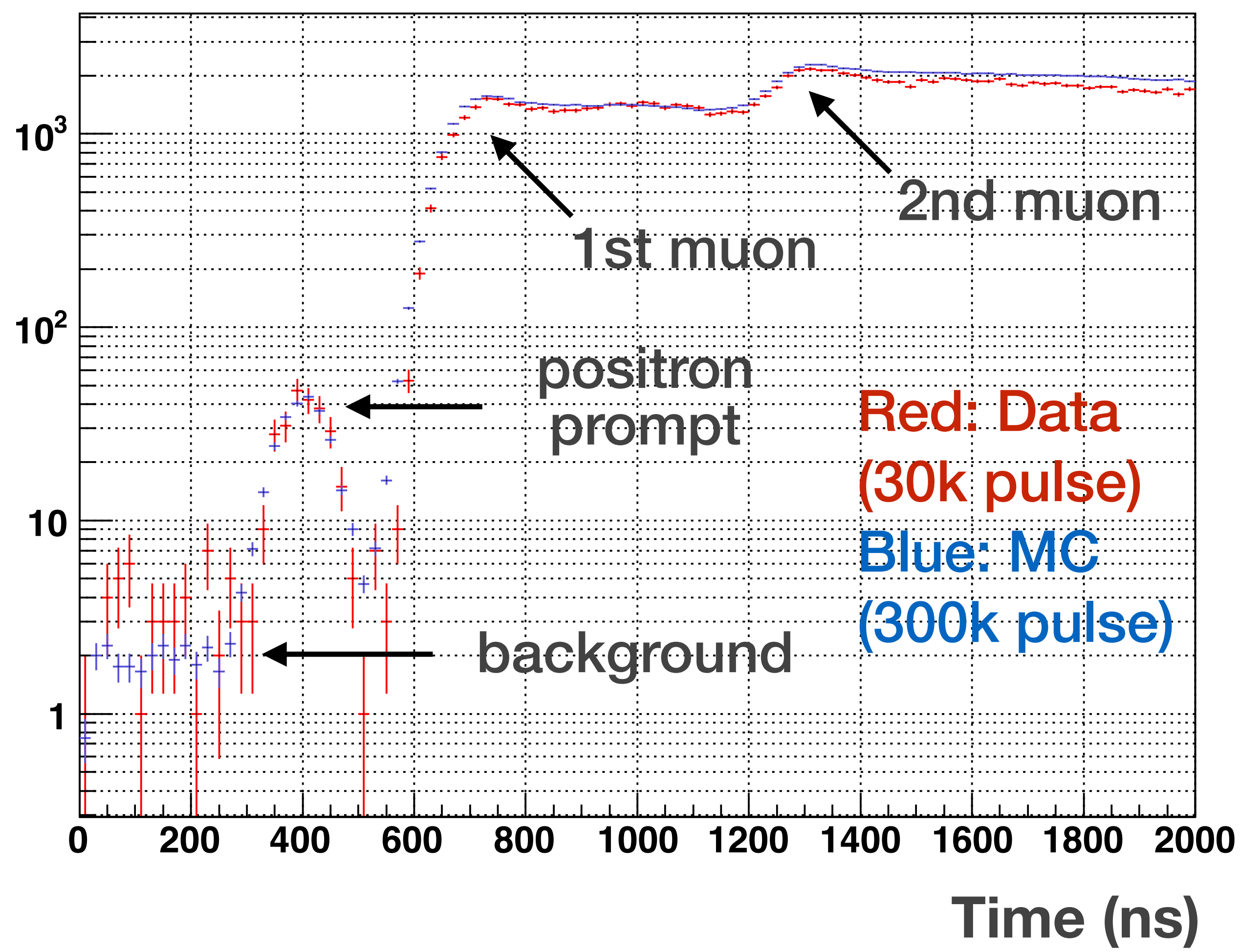


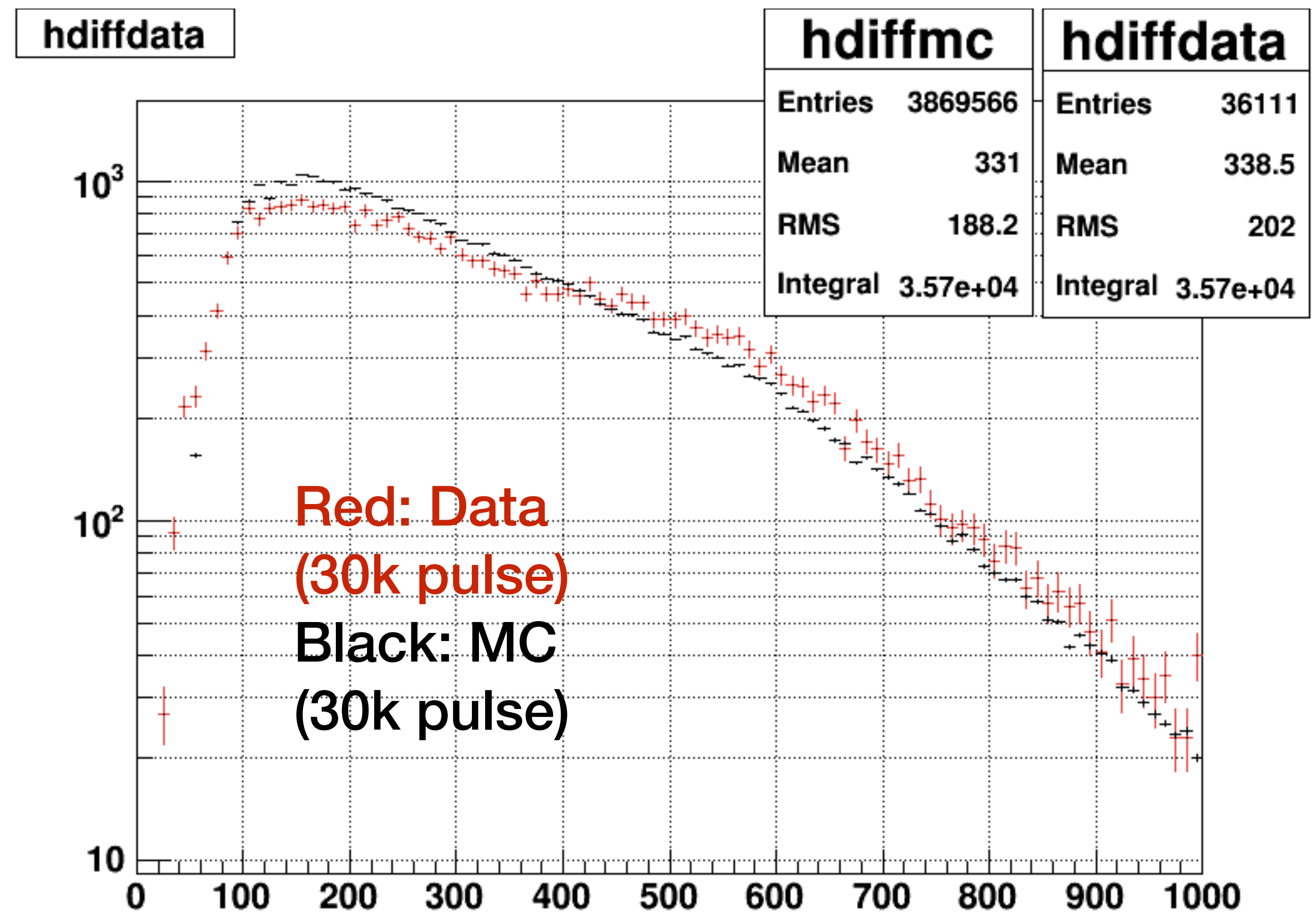
Maximum event rate (MHz)

Pileup correction factor is obtained from event loss as a function of maximum event rate

Simulation Study

- **Data and simulation comparison**



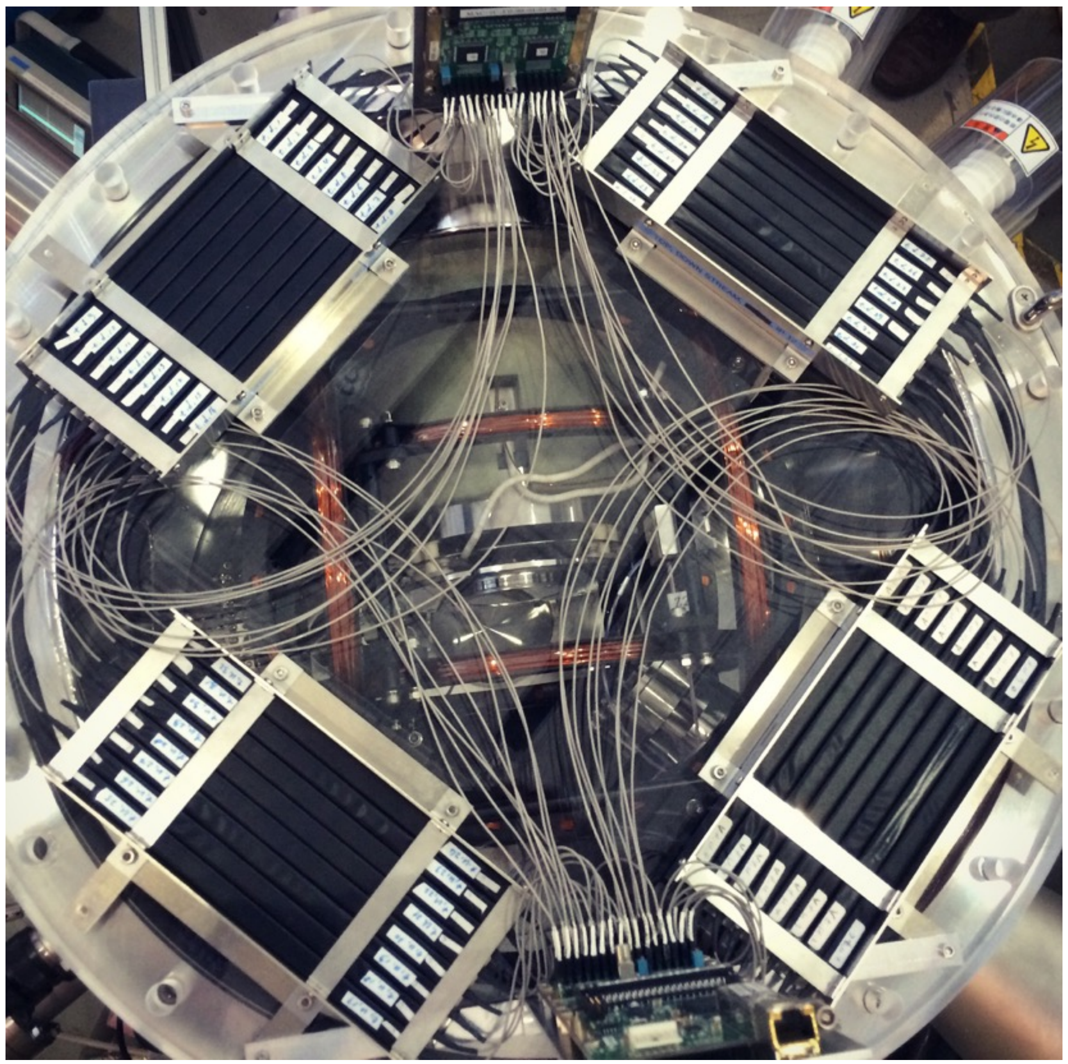


Measured and simulated time spectra of muon decay positron

Measured and simulated detector deadtime

Commissioning at RIKEN-RAL

- **At RIKEN-RAL port3 7/19-24**



Muonium asymmetry counter
Scint.+MPPC+Kalliope

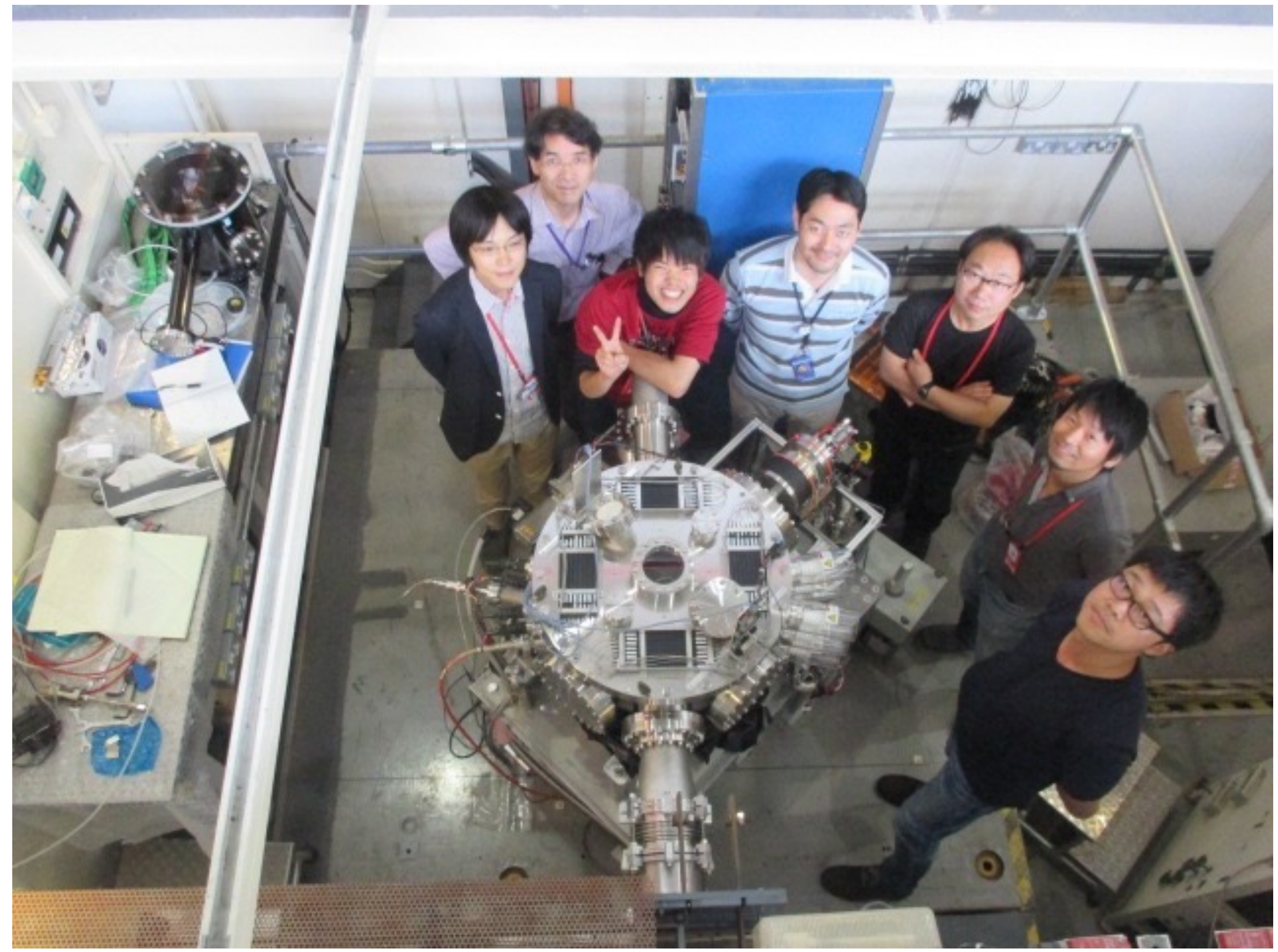
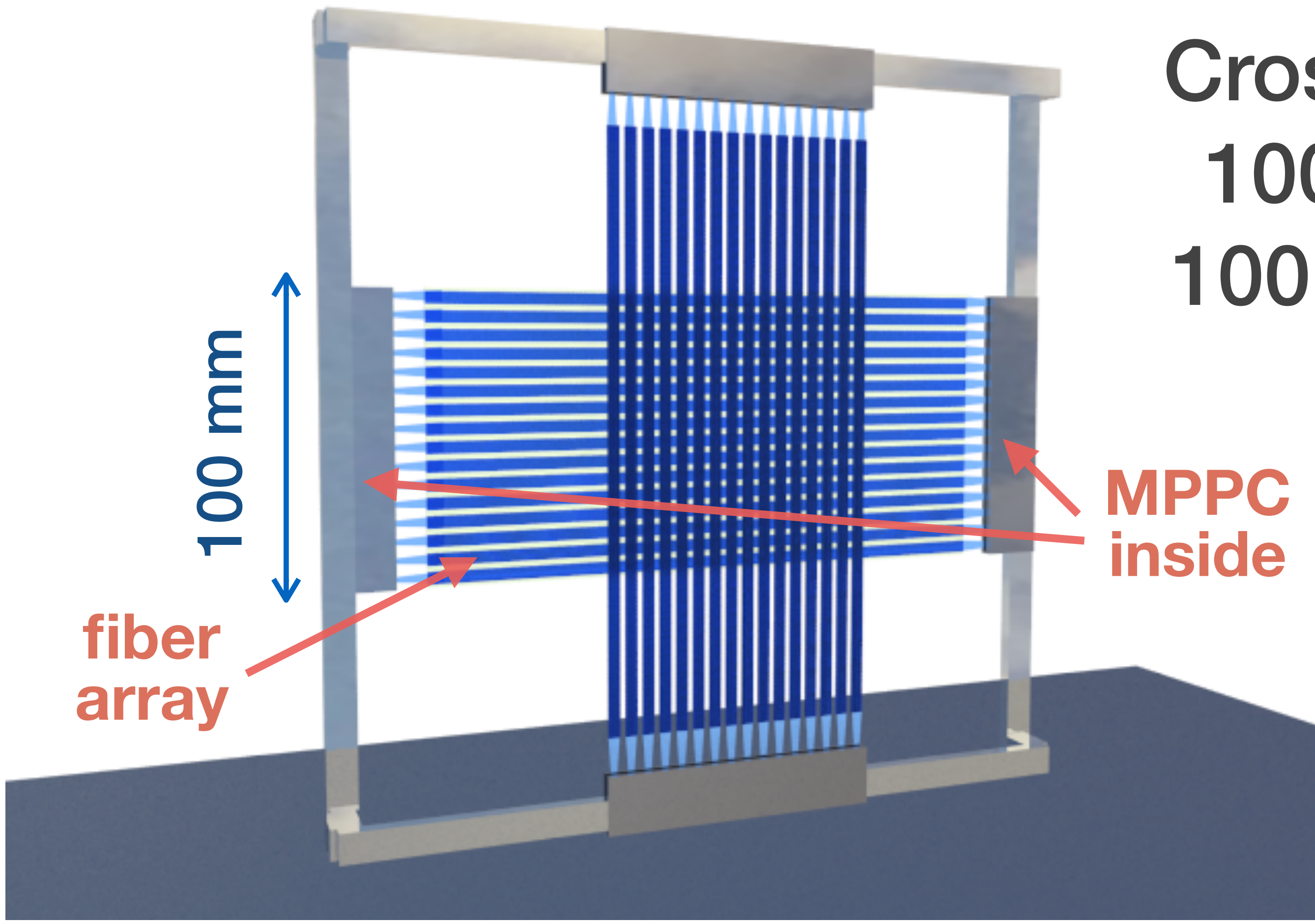


photo by S. Aikawa (TiTech)

Detector installation and preparation was done
Beam time is scheduled in Sep. 2015.

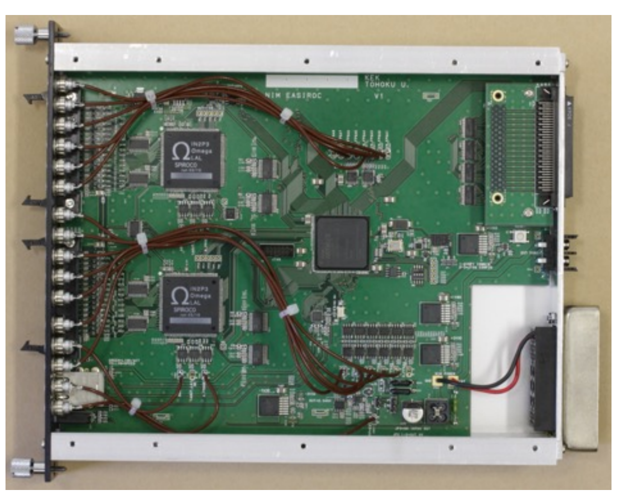
Online Beam Profile Monitor

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

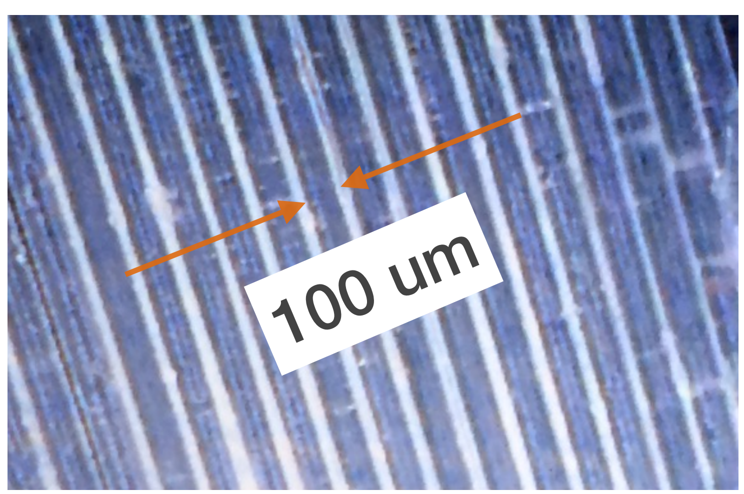


Cross-configured fiber hodoscope
100 mm×100 mm detection area
100 um fiber + resin (total 150 um)

- **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



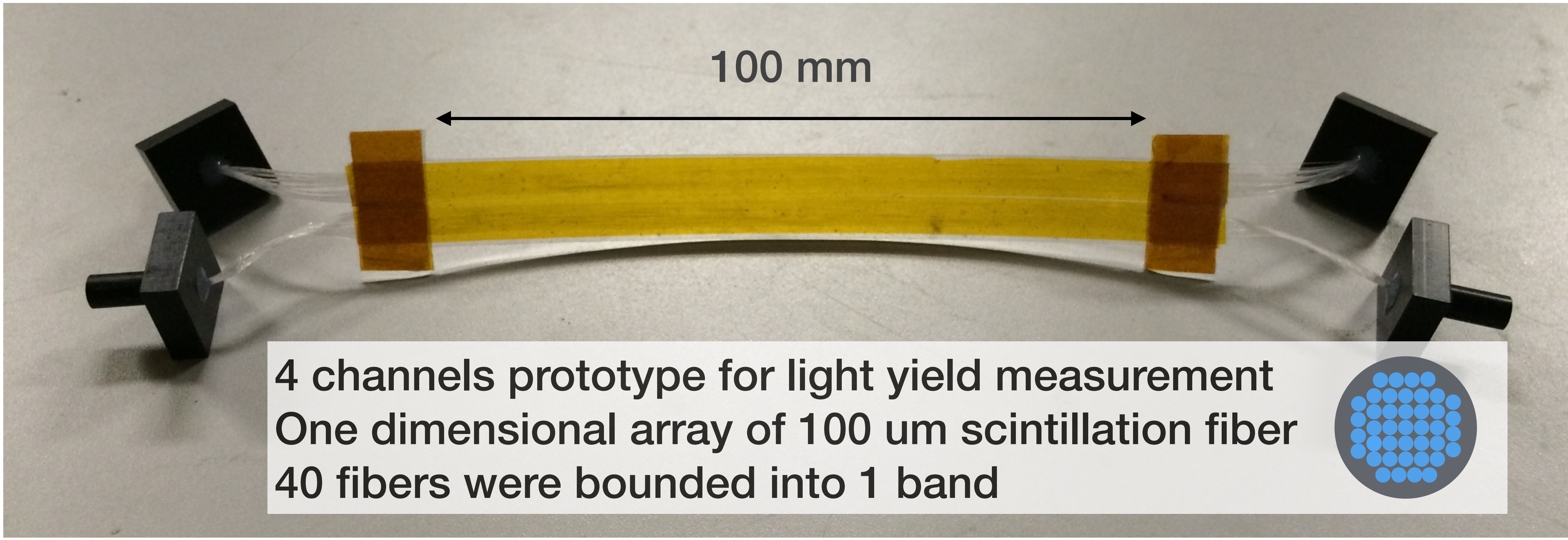
Array of 100 um fiber

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

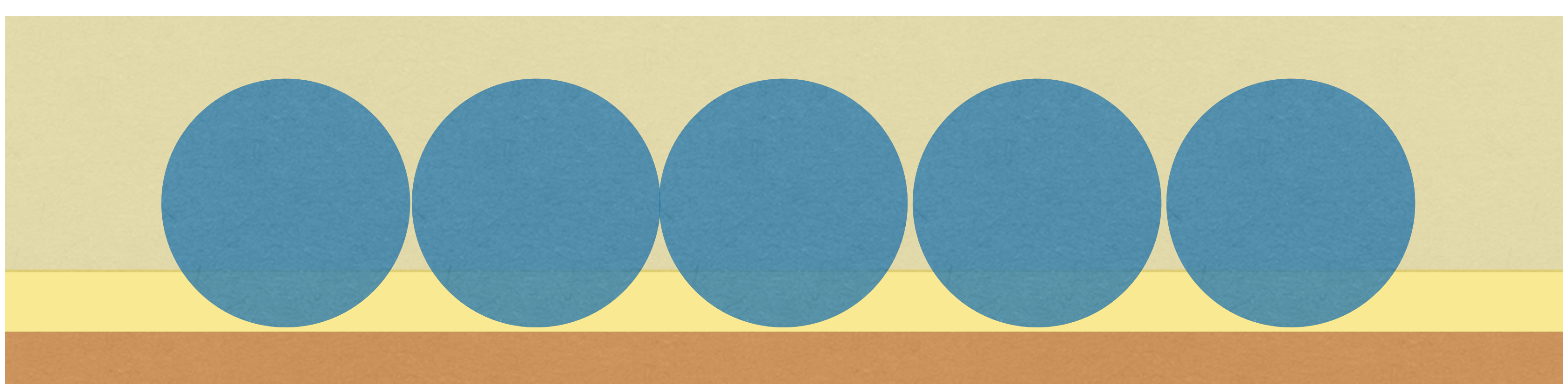
Stephane Callier *et al*., Physics Procedia Vol. 37, 1569-1576, Proceedings of the TIPP 2011 (2012)

100 um Scintillation Fiber Array

Prototype of Front Beam Profile Monitor



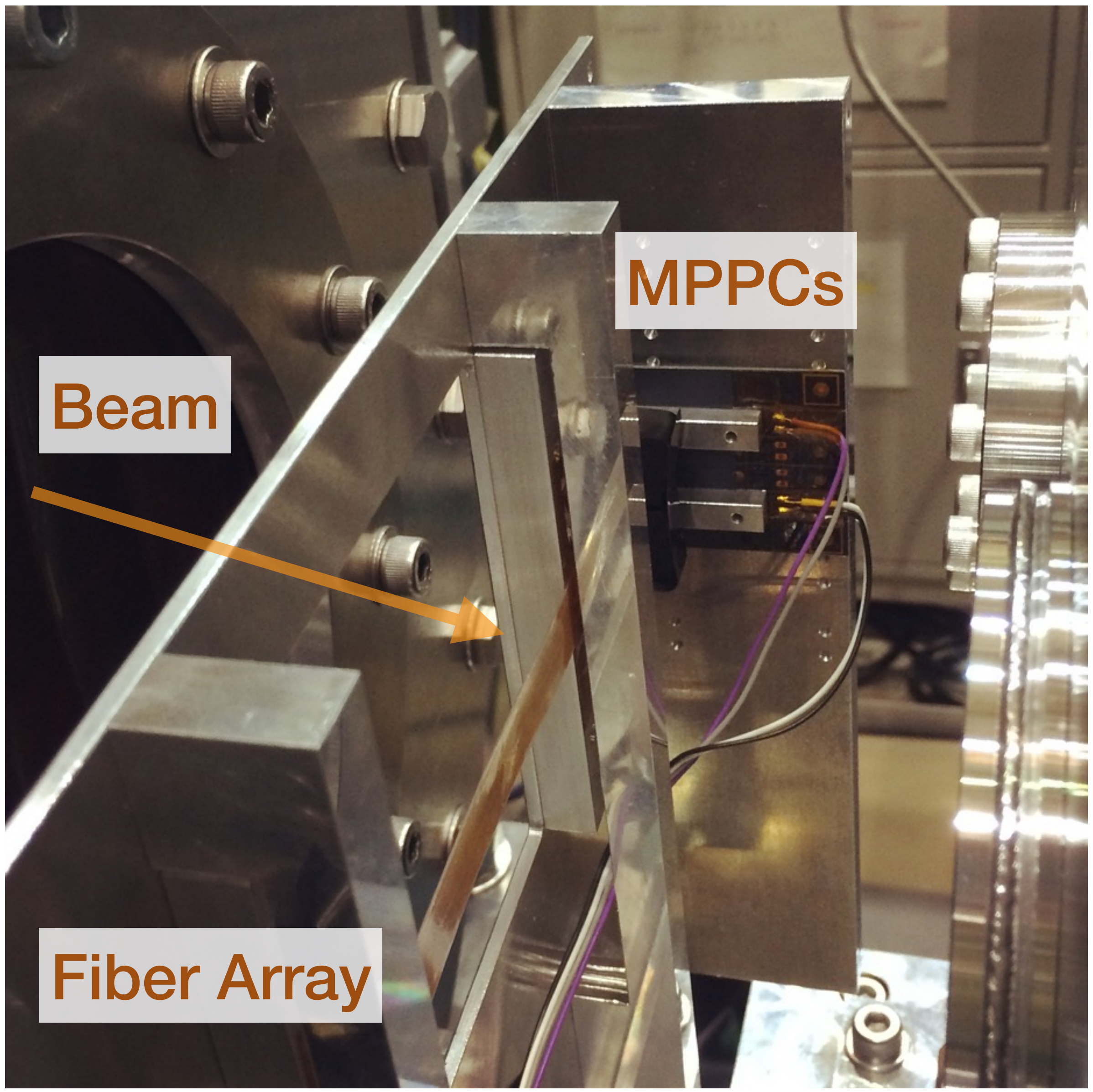
4 channels prototype for light yield measurement
One dimensional array of 100 um scintillation fiber
40 fibers were bounded into 1 band



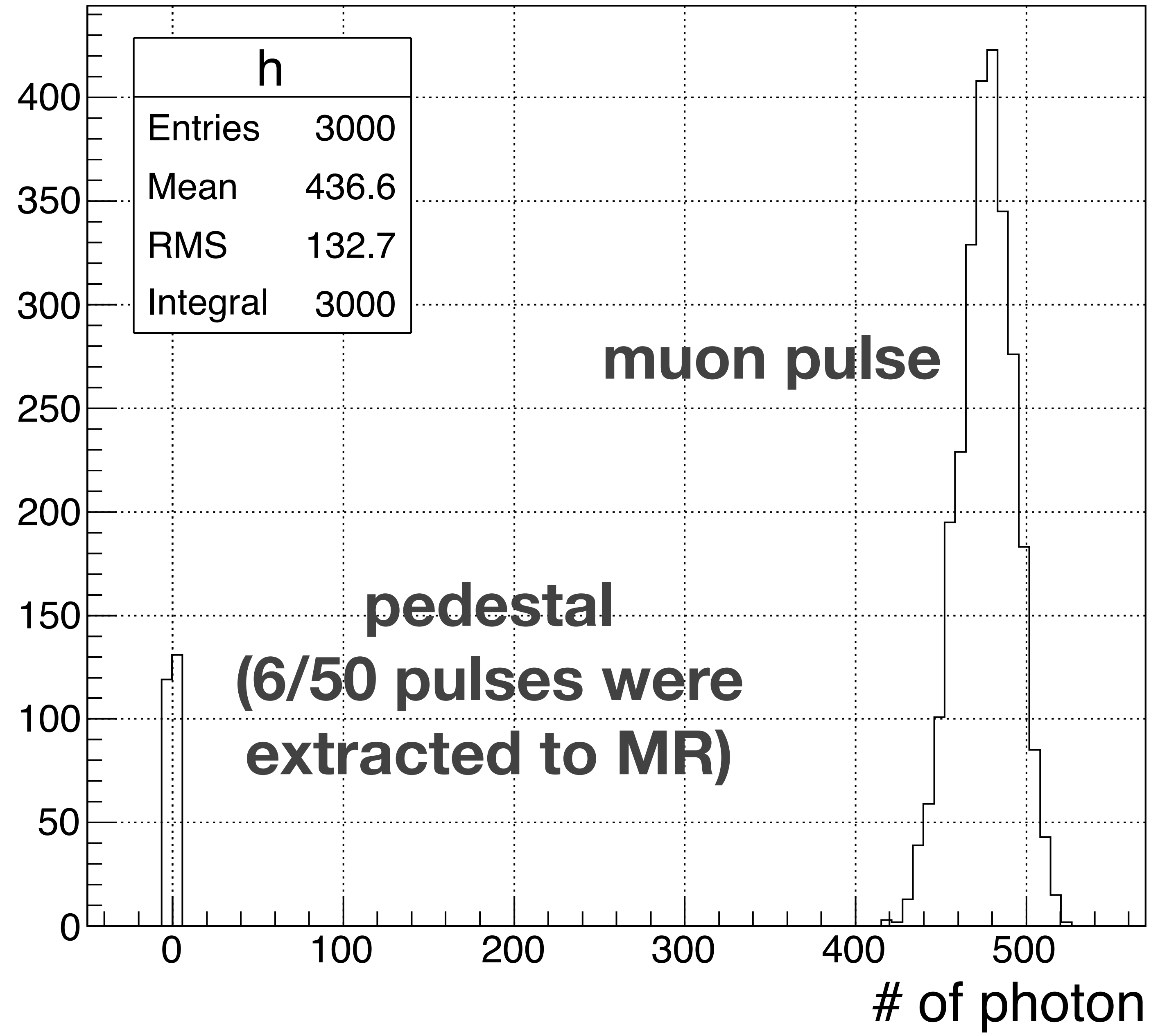
S. Kanda, RIKEN Accel. Prog. Rep. Vol. 48 (to be published)

Profile Monitor Beam Test

- **Beam test setup and result**



Data taking was triggered by beam sync. pulse

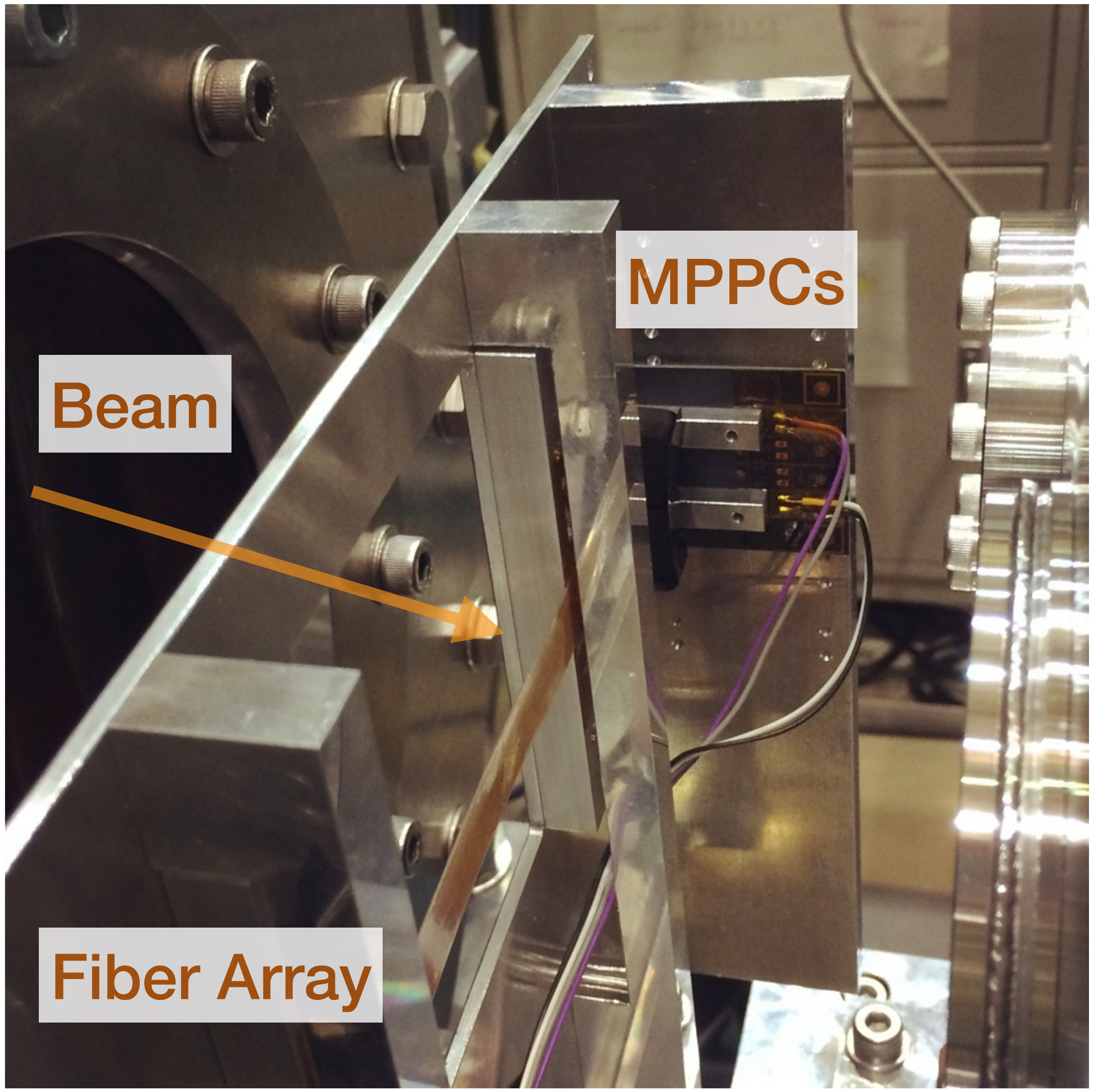


Photon distribution (3.2e4 μ/event)

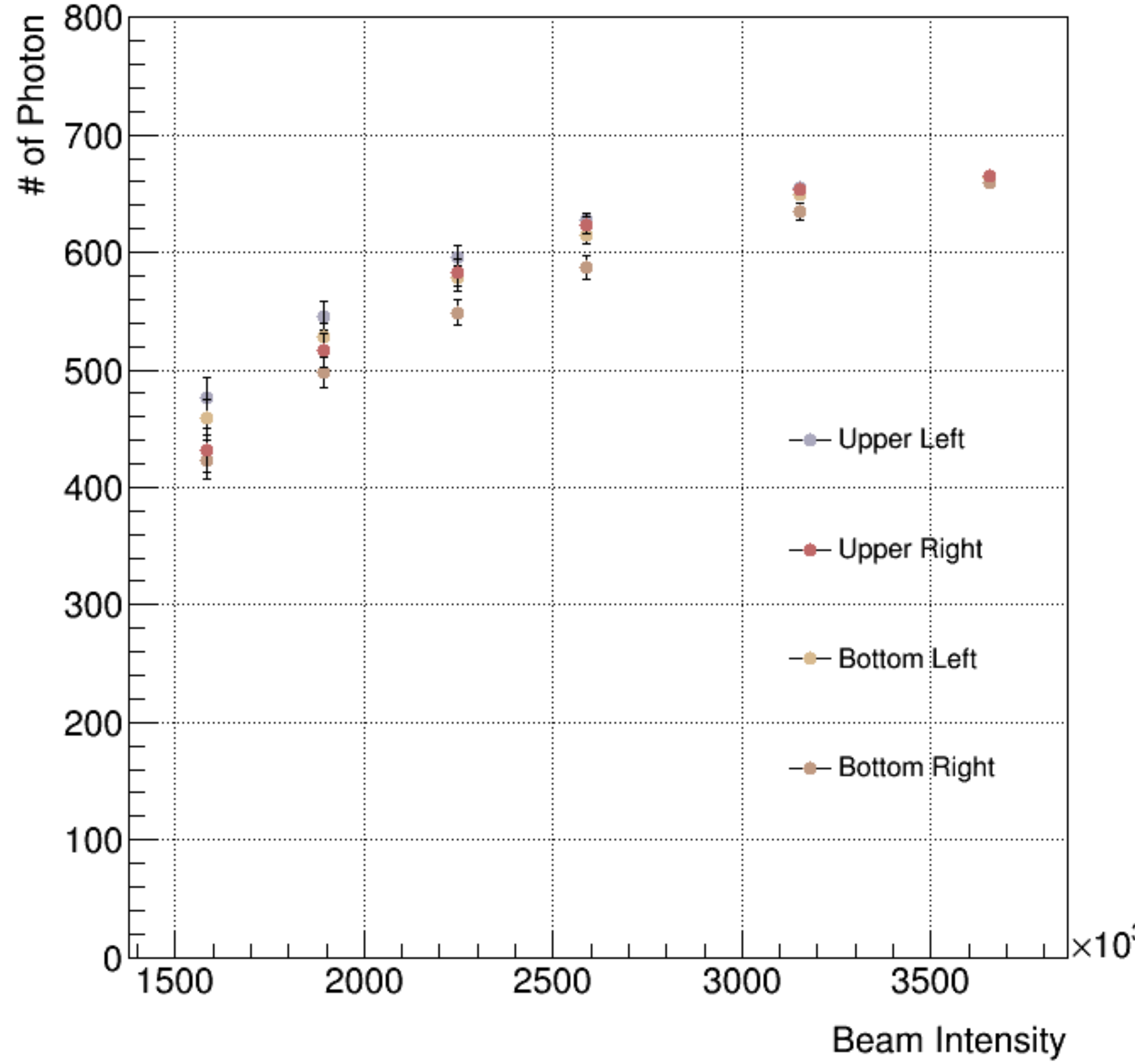
Light yield is quite enough even with 100 um thin fiber

Profile Monitor Beam Test

- **Beam test setup and result**



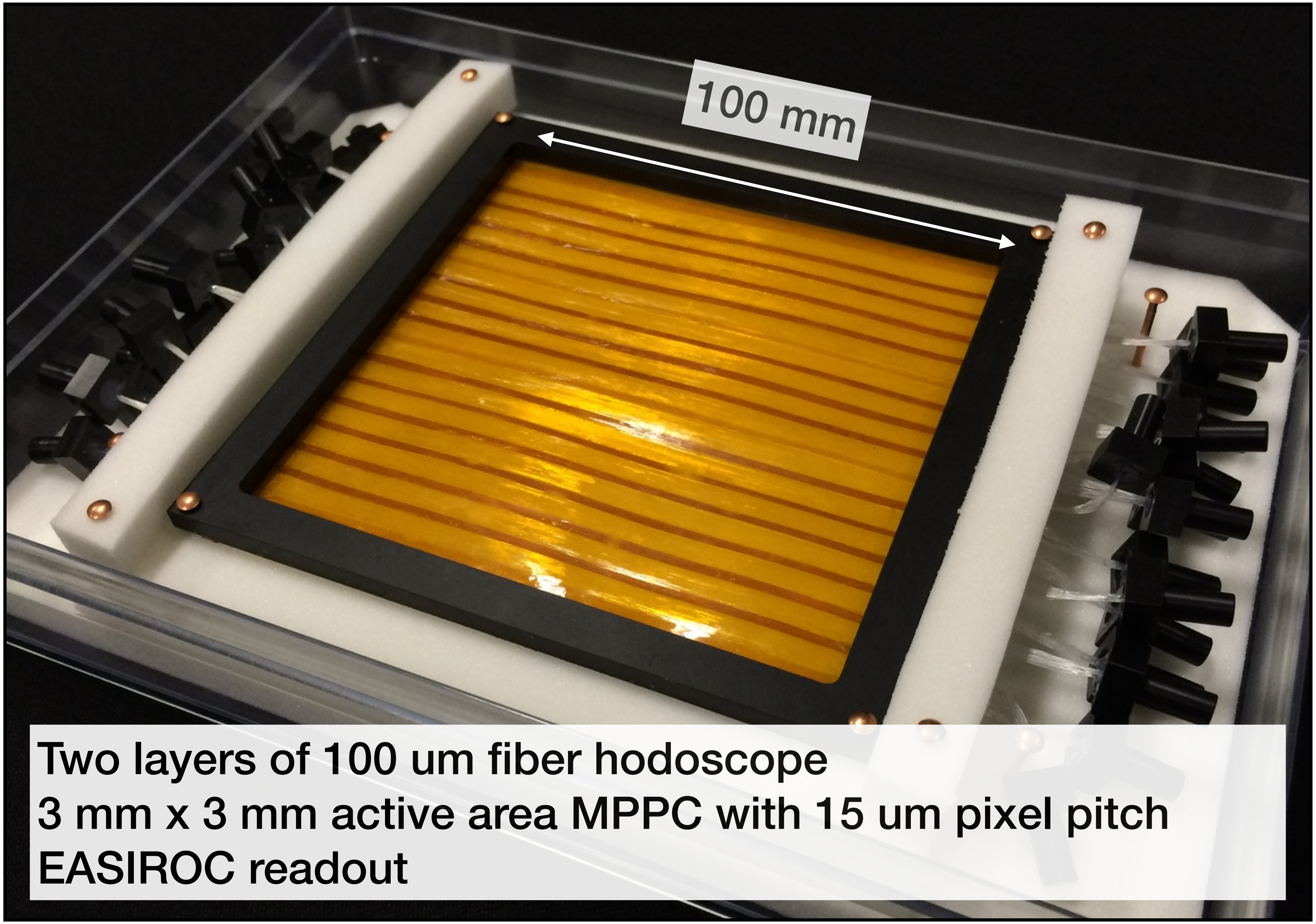
Data taking was triggered
by beam sync. pulse



Photon number distribution

Light yield is quite enough even with 100 um thin fiber

Detector for Physics Run

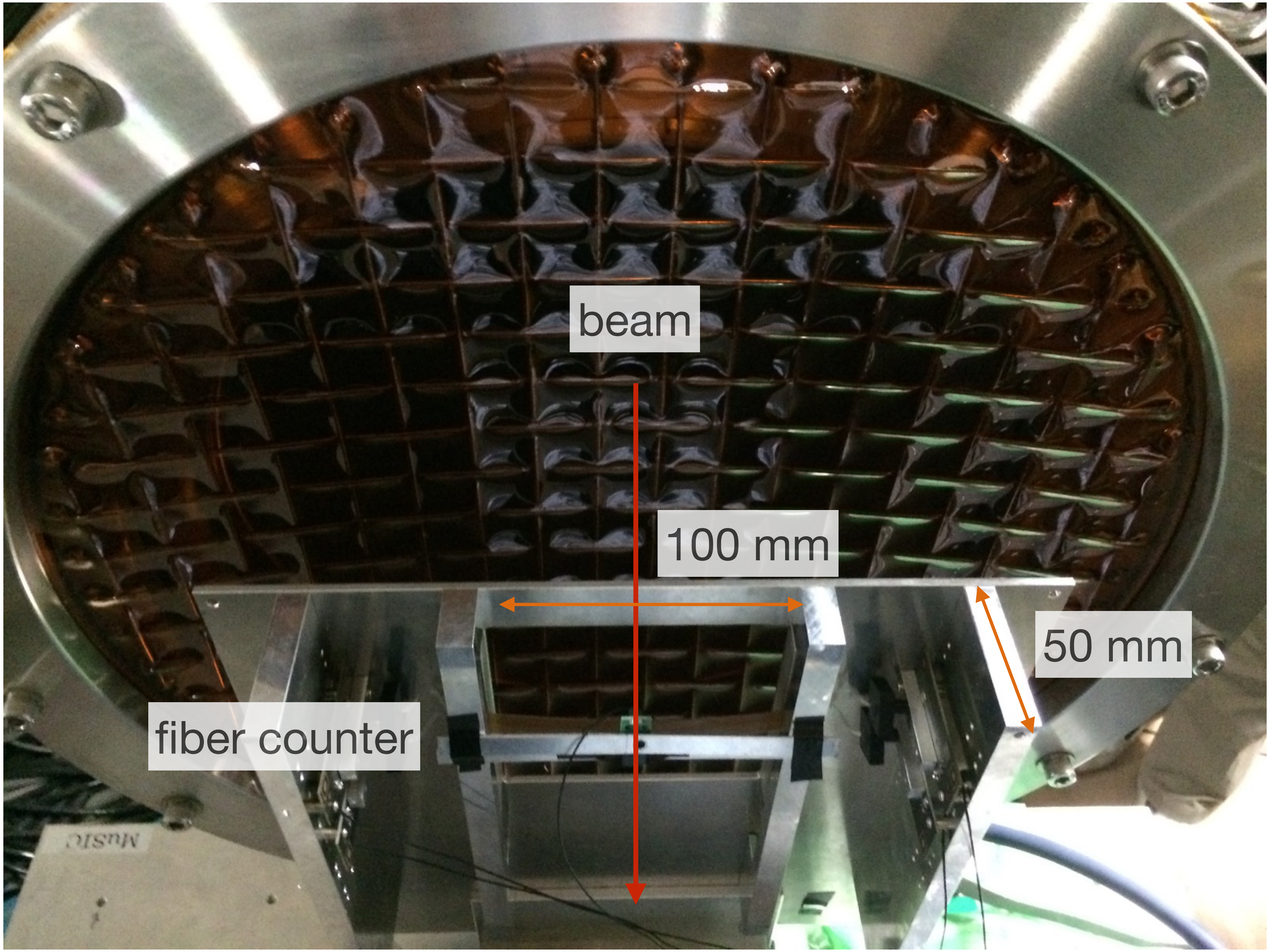


S. Kanda *et al.*, JPS 70th Ann. Meeting (2015)

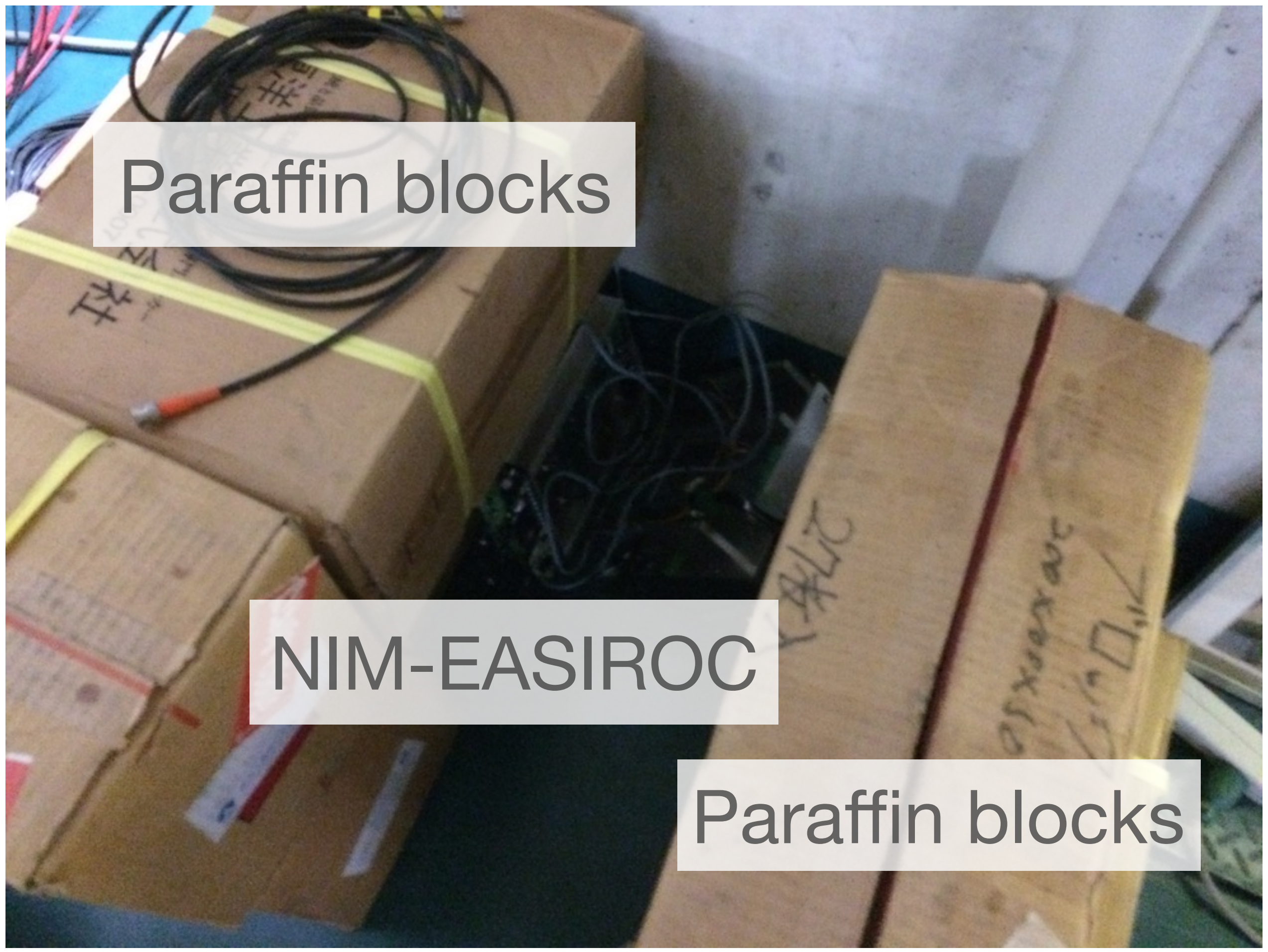
Items to be considered

- **Thickness control**
  - Fiber assembly process
    - Optimization of resin potting procedure
- **Uniformity evaluation**
  - Film thickness meter
    - 150 um +-25 um uniformity was observed
- **Detector efficiency**
  - DC beam measurement
    - Single muon detection trial at RCNP MuSIC (6/27-30)

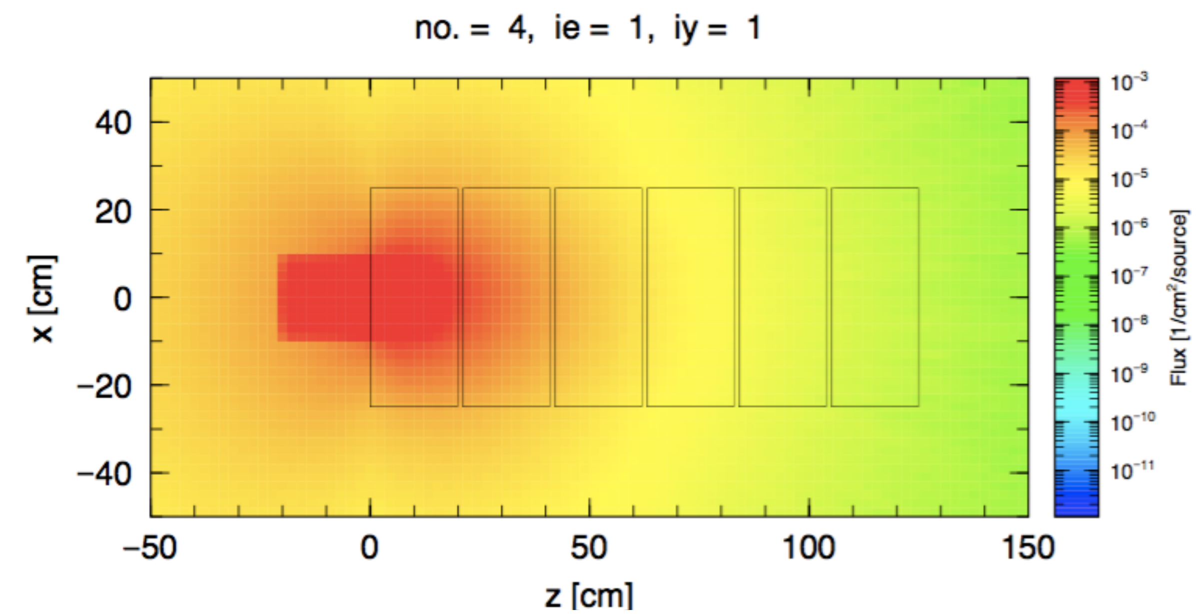
Beam Test at MuSIC M1

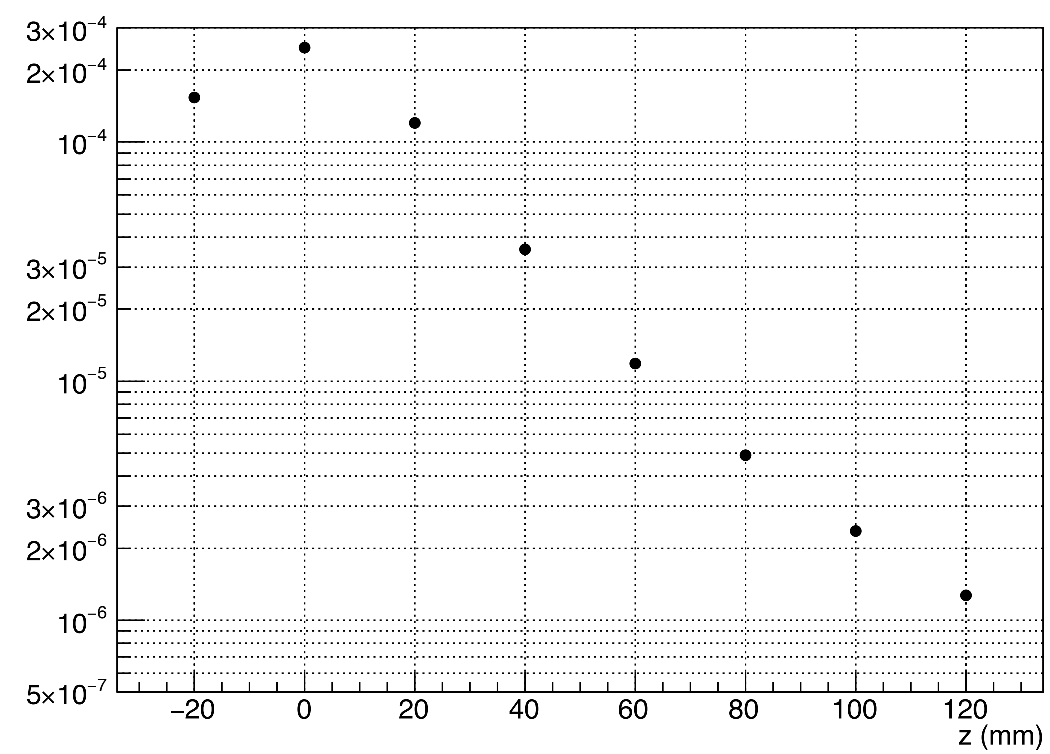


Neutron Shielding



Readout circuit was placed inside of a paraffin wall in order to shield neutrons

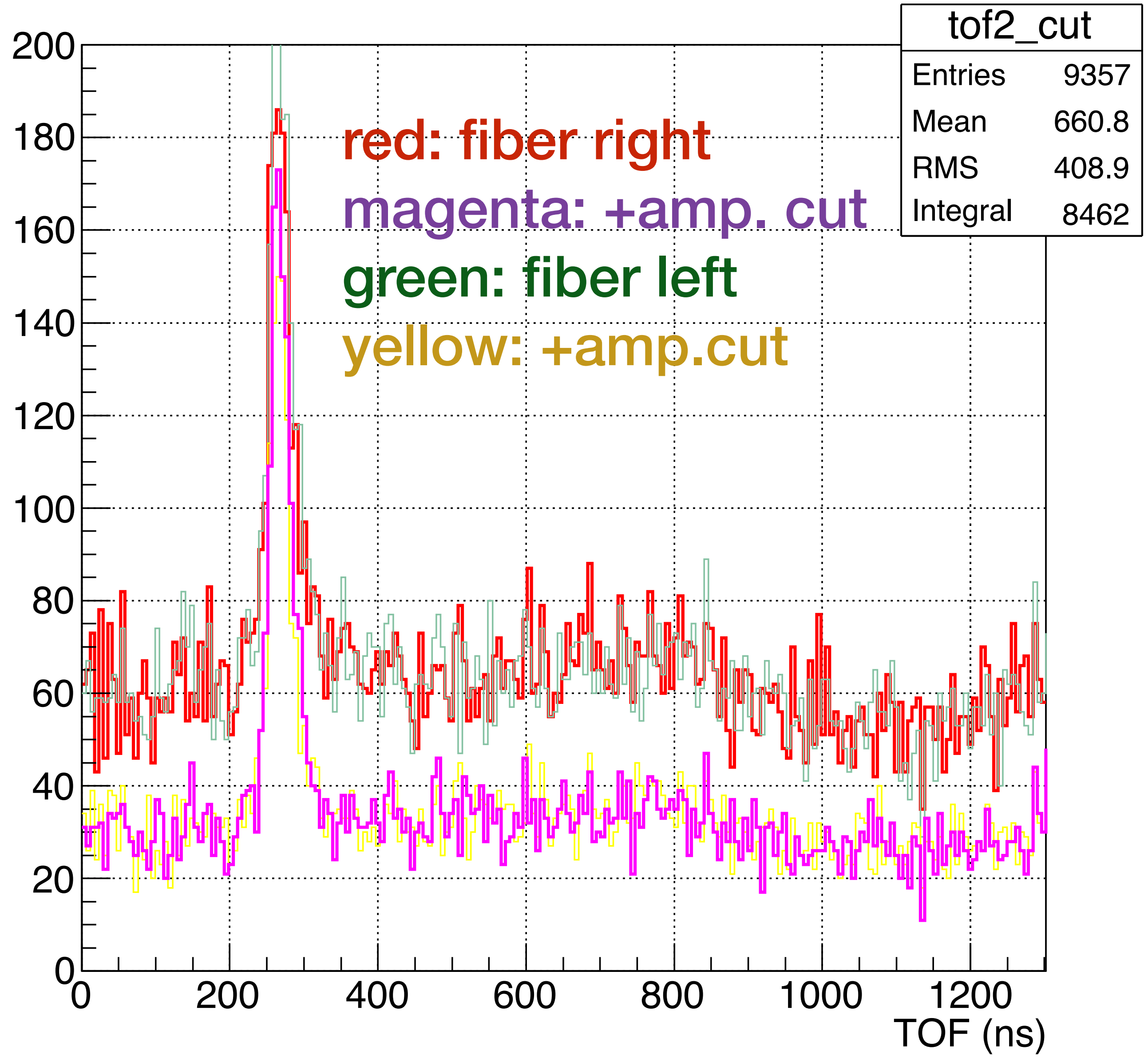




Neutron flux calculation by PHITS

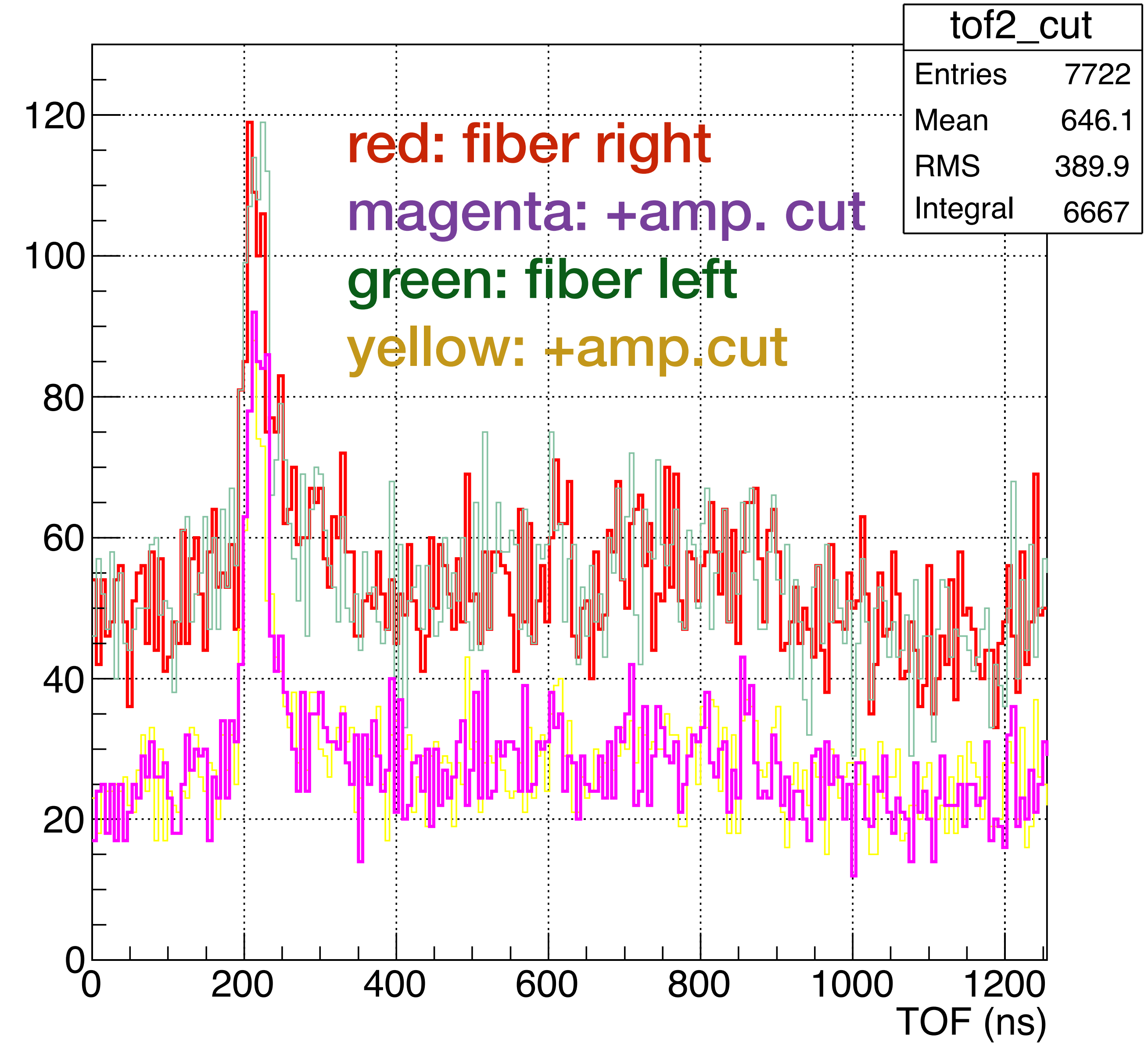
Beam test at MuSIC

40 MeV/c



peak center ~ 267 ns
TOF = peak center-rise time~217 ns
(expectation: 213 ns)

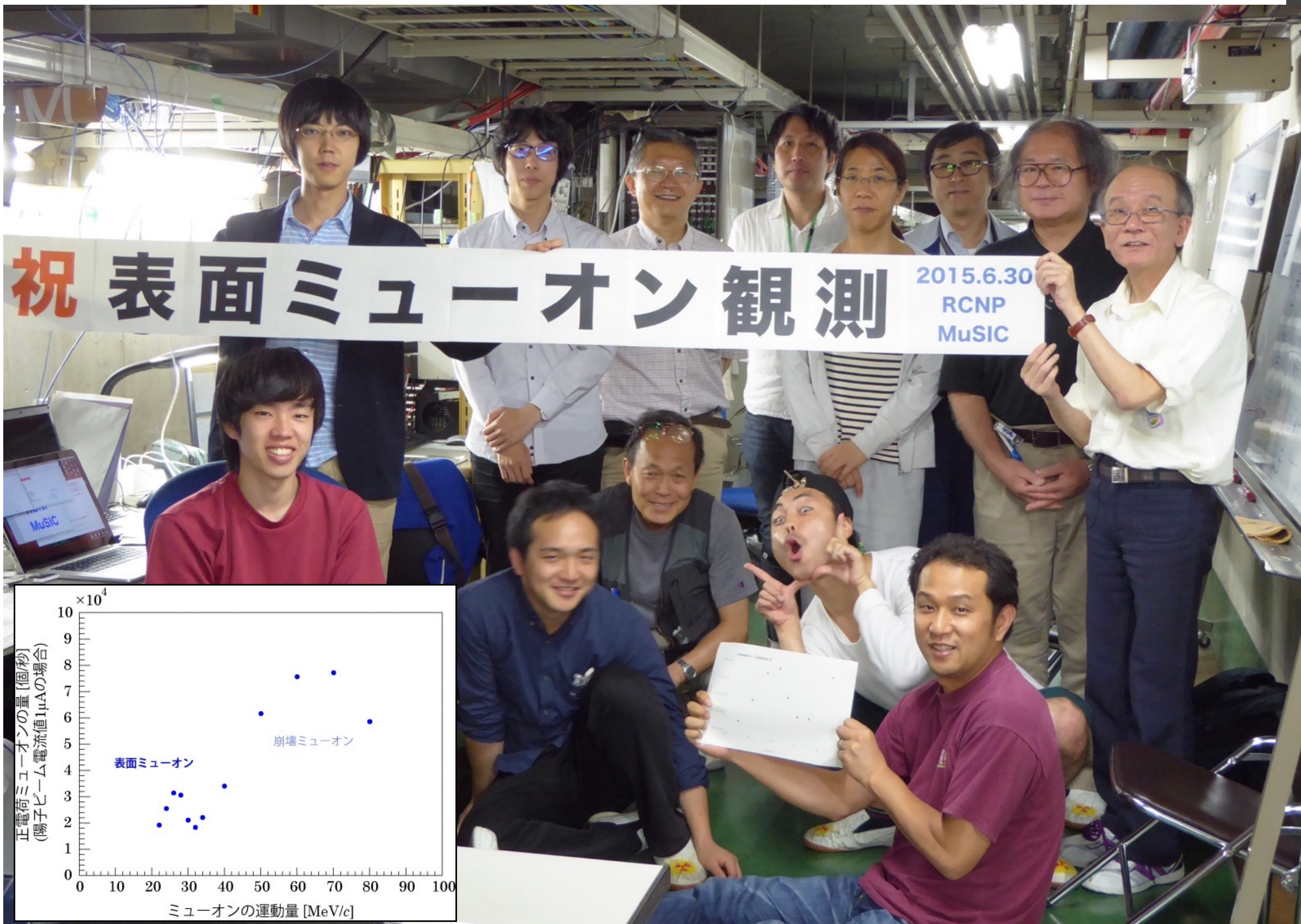
60 MeV/c



peak center ~ 216 ns
TOF = peak center-rise time~156 ns
(expectation: 152 ns)

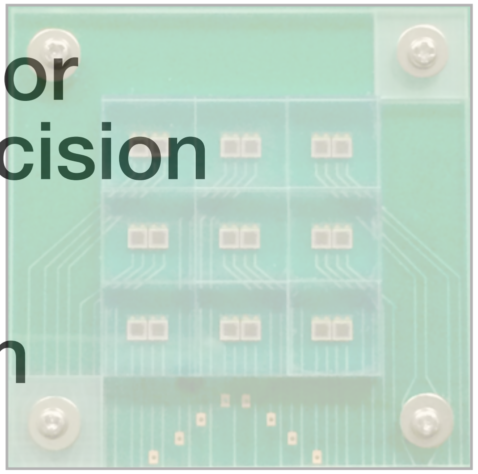
amp. cut: amplitudes of fiber right and left > 0.02 V

MuSIC Surface Muon Obervation



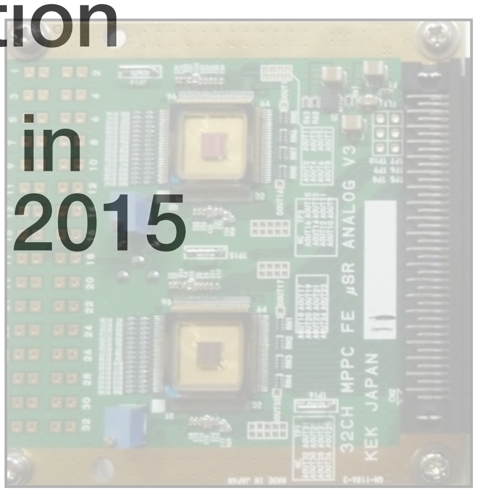
https://www.rcnp.osaka-u.ac.jp/RCNPhome/ja/news/detail.php?id=40

Summary and Prospects



- High beam intensity and high-rate-capable detector system are essential to the next generation of precision physics with muon
- Highly segmented scintillation counter for positron measurement
- Extremely thin fiber hodoscope for muon measurement

- We are preparing the new experiment for measurement of muonium hyperfine splitting (MuSEUM experiment at J-PARC)
  - Detector prototypes were developed and evaluated
  - Final version of the detector are under preparation
- MuSEUM experiment will be ready for data taking in FY2015 and pilot experiment is scheduled in Nov. 2015



Supplements

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
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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

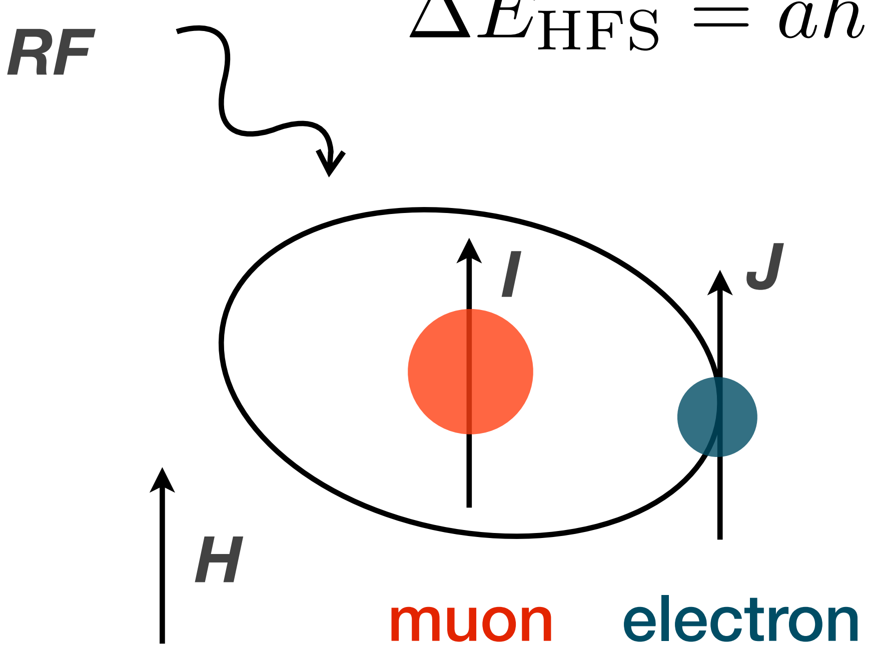
MuSEUM

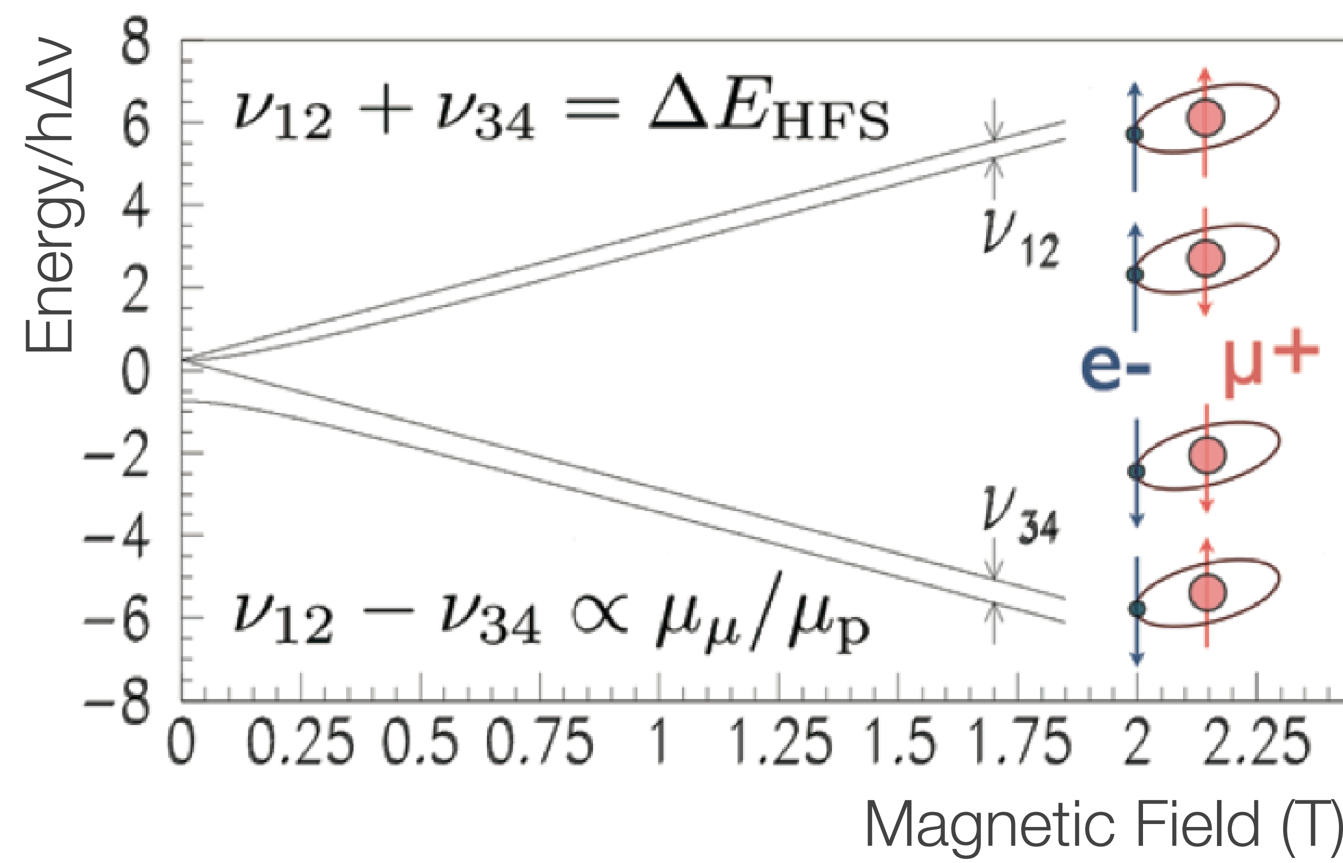
5 Universities, 3 Institutions
39 people

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)

Major Objectives:

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

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)

Theoretical updates: M. I. Eides and V. A. Shelyuto, Phys. Rev. Lett. 112, 173004 (2014) : Light-by-Light

The most precise test of bound state QED

- **Muon g-2**

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

540 ppb   26 ppb

R : From storage ring experiment

λ : From Muonium HFS

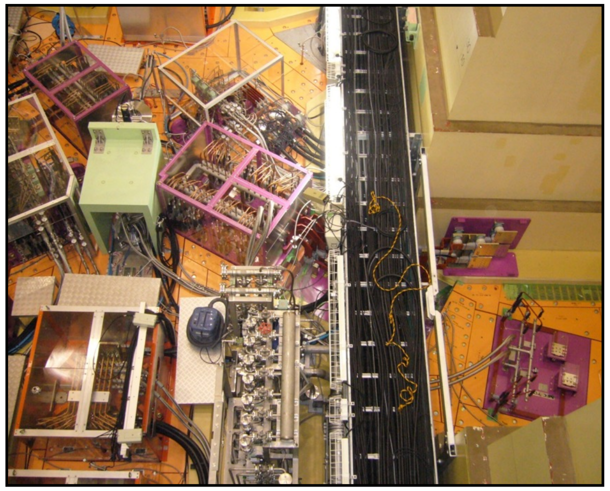
$$\lambda = \frac{\mu_\mu}{\mu_p}$$ (B-field is obtained via proton NMR)

The possible clue to the beyond standard model physics

MuHFS is one-half of the experimental input

Muon Beam and Magnet

- **H-Line : The highest intensity pulsed muon beam at J-PARC (Under construction)**



H-Line under construction

The highest intensity pulsed muon beam

1×10^8 μ/s at 1 MW beam power (4M μ/pulse)

Profile at final focus σx=13 mm, σy=13 mm

Leakage field 0.5 G at focus (Requirement < 1.7 G)

A. Toyoda *et al.* J.Phys.Conf.Ser. 408 (2013)
N. Kawamura *et al*., JPS Autumn meeting (2014)

- **Magnet : 1.7 T high precision superconducting magnet (Installed at J-PARC)**

Magnet at J-PARC

Requirement to the magnet:

1ppm homogeneity in z300 mm, r100 mm region

Specification of the magnet:

Field strength 1.7 T, Bore diameter 925 mm

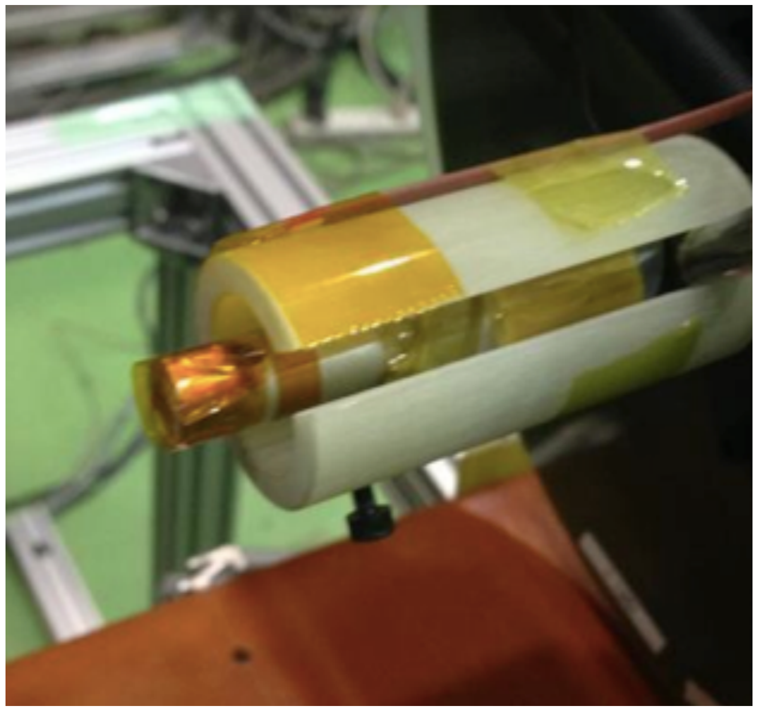
Field correction is performed by main coil, iron shim, and shim coil

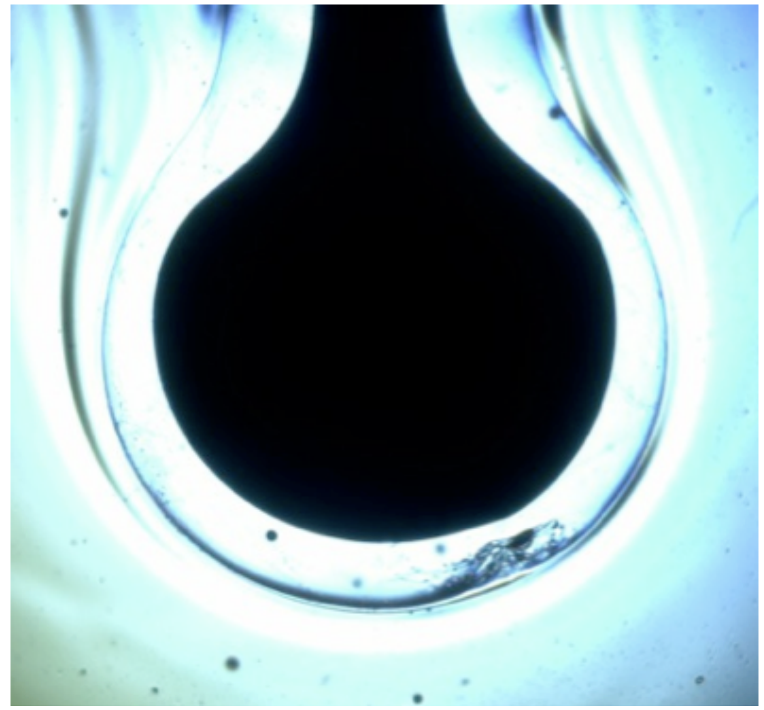
Field strength is monitored by NMR probes (next talk by Y. Ueno)

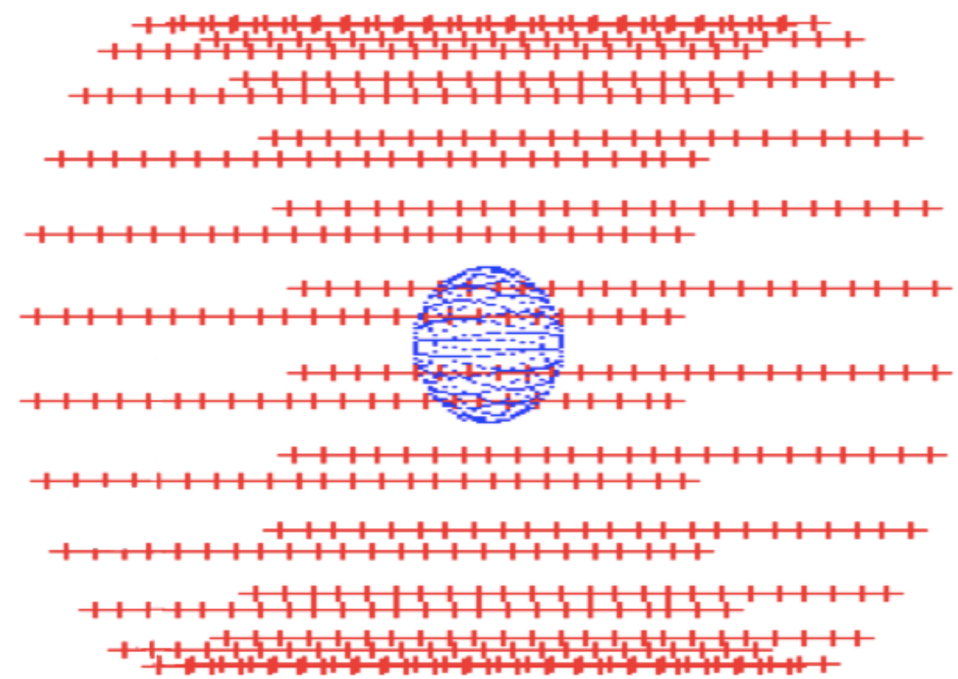
K. Sasaki and M. Sugano, The 5th and 6th g-2/EDM Collaboration Meeting (2012)

Field Measurement and Adjustment

- NMR Probe
- Diamagnetism Correction
- Shimming







- Pulse NMR with the precision of 100 ppb
- Prototype test is scheduled in this winter

- Numerical calculation and measurement of probe's shape effect

- Fine tuning with iron small pieces
- Linear algebraic optimization for 1 ppm local precision of B-field

T. Mizutani, Y. Ueno, Y. Higashi, The 8th g-2/EDM Collaboration Meeting (2014)
Y. Ueno, JPS Annual Meeting (2014)