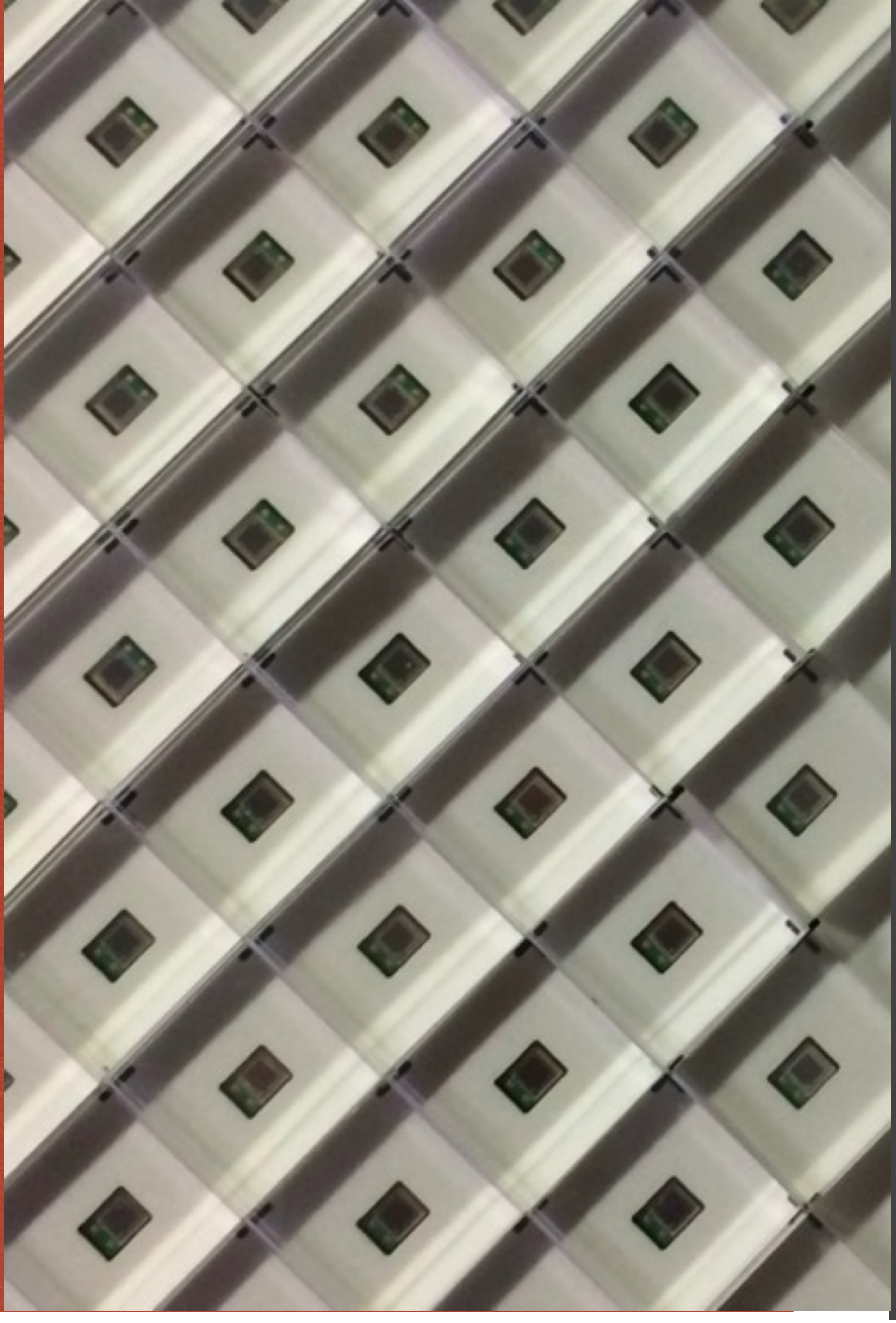
Instrumentation for experiments with high-intensity pulsed muon beam

MuSEUM experiment



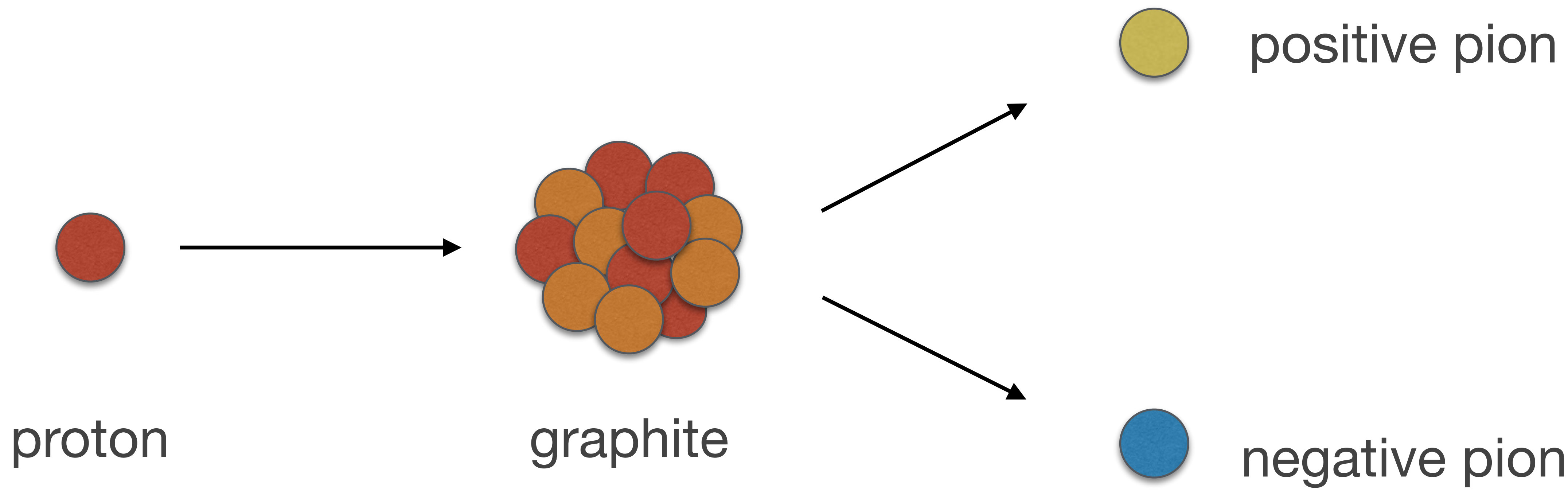
Sohtaro Kanda / THE UNIVERSITY OF TOKYO

kanda@post.kek.jp

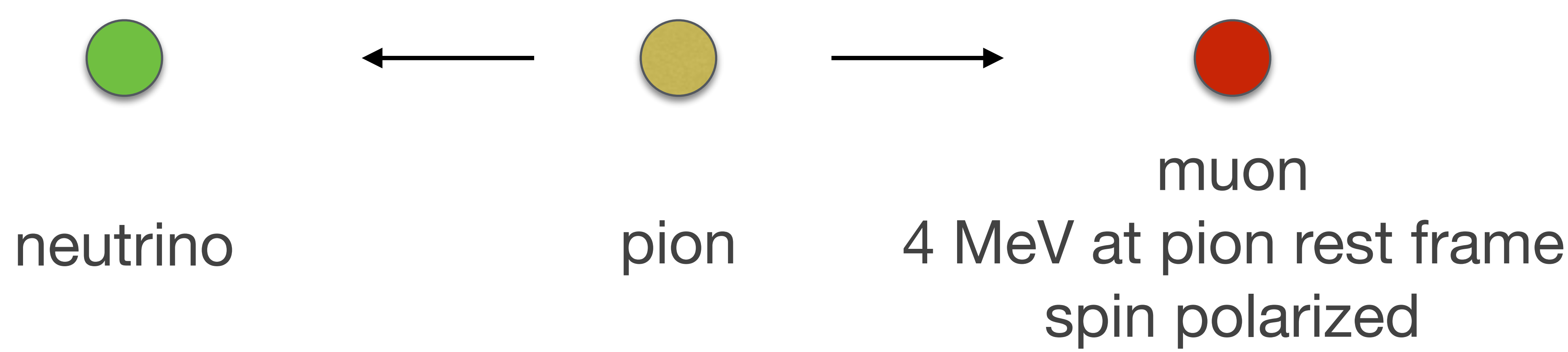
2016. 10. 13 at J-PARC dsys workshop

Production of Muon

- **Proton driver**

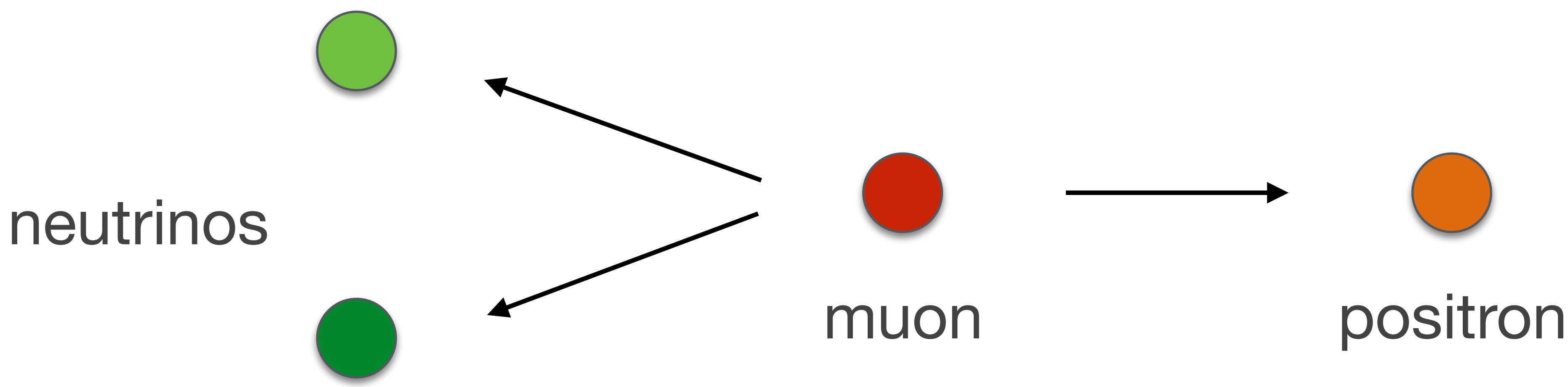


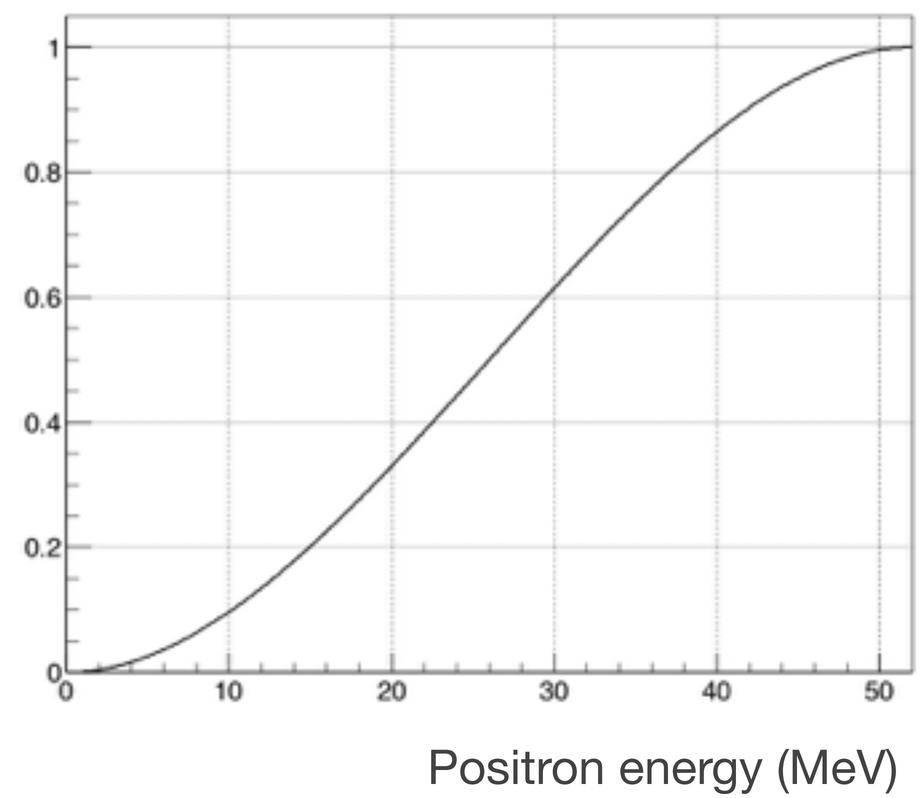
- **Parity violating pion decay**



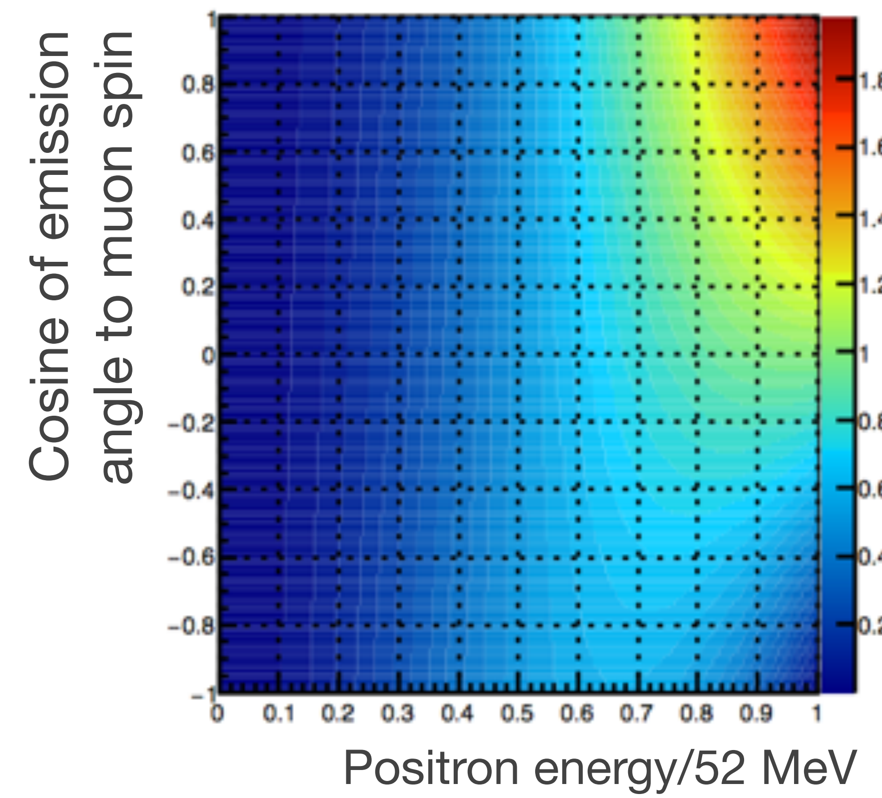
Decay of Muon

- **Parity violating muon decay** $\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu_\mu}$





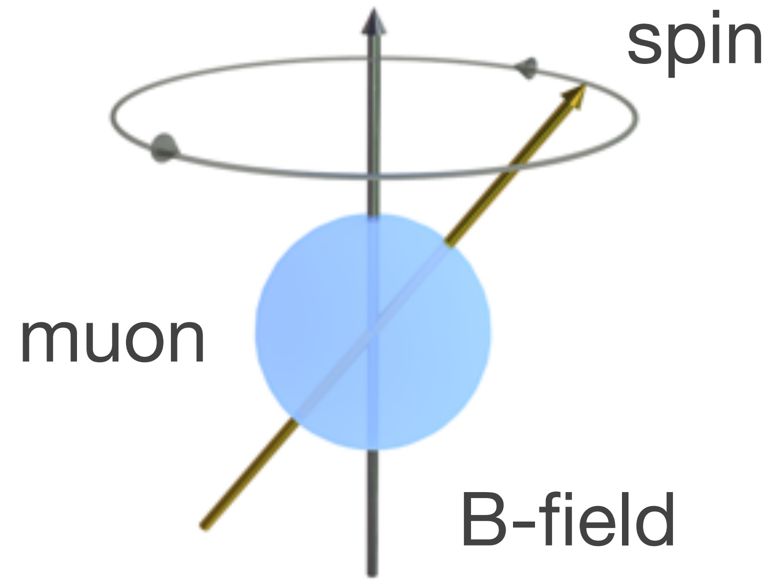
Positron energy spectrum



Positron angular asymmetry

Muon Spin Dynamics

- **Muon spin rotation and relaxation**

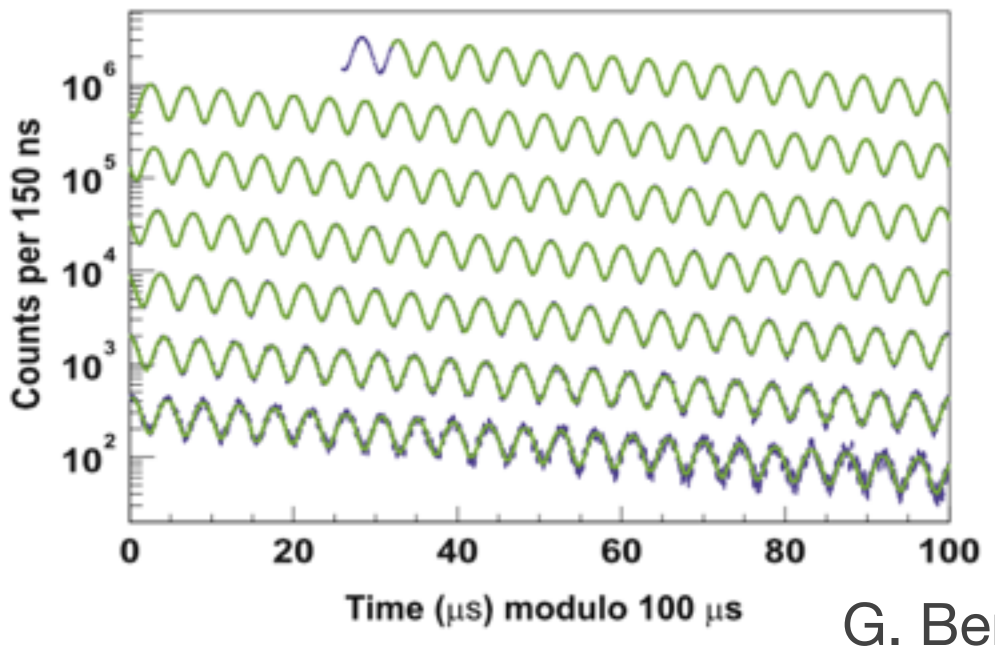


In the presence of B-field, muon spin rotates with Larmor frequency

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

Spin relaxation occurs due to the B-field distribution

- **Decay positron time spectrum**

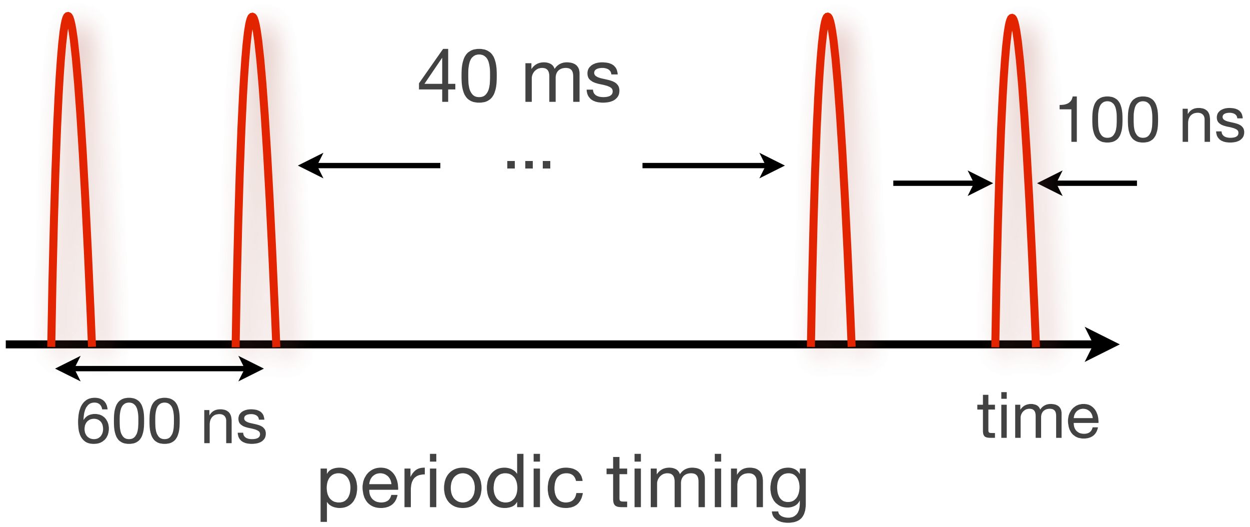


G. Bennett, *et al*., PRD 73 (2006)

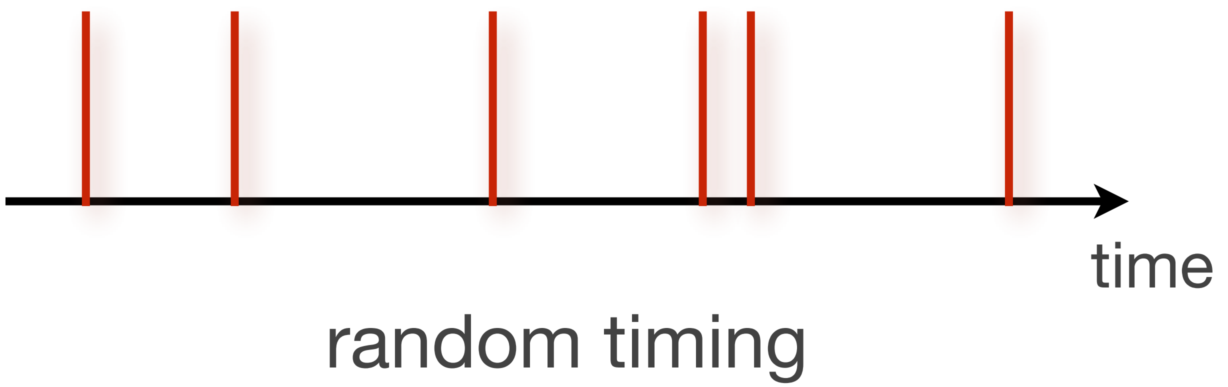
Muon is a powerful probe for local magnetic field thanks to its spin dynamics and self-analyzing feature

Pulsed and Continuous Muon Beam

- **Pulsed beam : J-PARC, RAL**
  - Higher event rate
  - Higher S/N
  - Limited timing resolution
  - Pulse synchronized trigger
  - Ensemble average



- **Continuous (DC) beam : PSI, TRIUMF, MuSIC**
  - Less event rate
  - Less S/N
  - High timing resolution
  - Necessity of trigger counter
  - Event-by-event analysis



Muon Precision Physics

- **Measured muon properties**

	Method	Beam	Precision	Stat.	Syst.	Ref.
Mass	Muonium HFS spectroscopy	DC (Chopped)	120 ppb	117 ppb	38 ppb	Liu 1999
Mean lifetime	Decay positron counting	DC (Accumulated)	1 ppm	0.96 ppm	0.32 ppm	Tishchenko 2013
g-2	Decay positron tracking in storage ring	Pulse	540 ppb	463 ppb	283 ppb	Bennet 2007

Muon Precision Physics

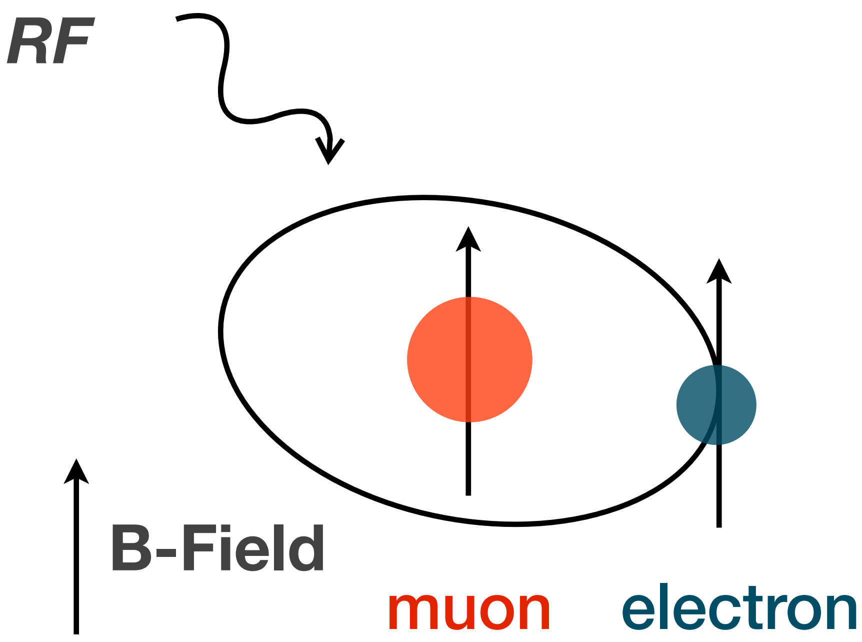
- **Muon as a probe for new physics search**

	Method	Beam	Limit	Exp.
$\mu^+ \to e^+\gamma$	52.8 MeV e^+ and γ back to back	DC	$Br<4.2\times10^{-13}$	PSI MEG 2016
$\mu^- N \to e^- N$	105 MeV e^-	DC	$Br<7\times10^{-13}$	PSI SINDRUM-II
$\mu \to eee$	e^- tracking	DC	$Br<1.0\times10^{-12}$	PSI SINDRUM-I
g-2	μ^+ in storage ring	Pulse	Δa_μ(Exp.-Th.)=289(80)$\times10^{-11}$	BNL E821 2006
EDM	μ^+ in storage ring	Pulse	$d\mu<1.9 \times 10^{-19}$ e cm	BNL E821 2009
Lorentz Violation	μ^+e^- spectroscopy	DC	2×10^{-23} GeV	LAMPF 1999
μ^+e^- - μ^-e^+ conversion	$e^+ e^-$ annihilation	DC	$P<8.3\times10^{-11}$	PSI 1999

Towards Higher Precision

- **Precision muon physics with continuous muon beam has been limited by statistical uncertainty.**
- **When statistical precision is improved severalfold, systematic uncertainty limits the measurement precision**
- **To explore the new frontier of precision muon physics with high-intensity pulsed muon beam, both**
  - **High-rate capable detector**
  - **Precision control and monitoring of environment**
    - **are of importance**
- **In this talk, as an example of new generation of muon precision measurement, MuSEUM experiment is introduced.**

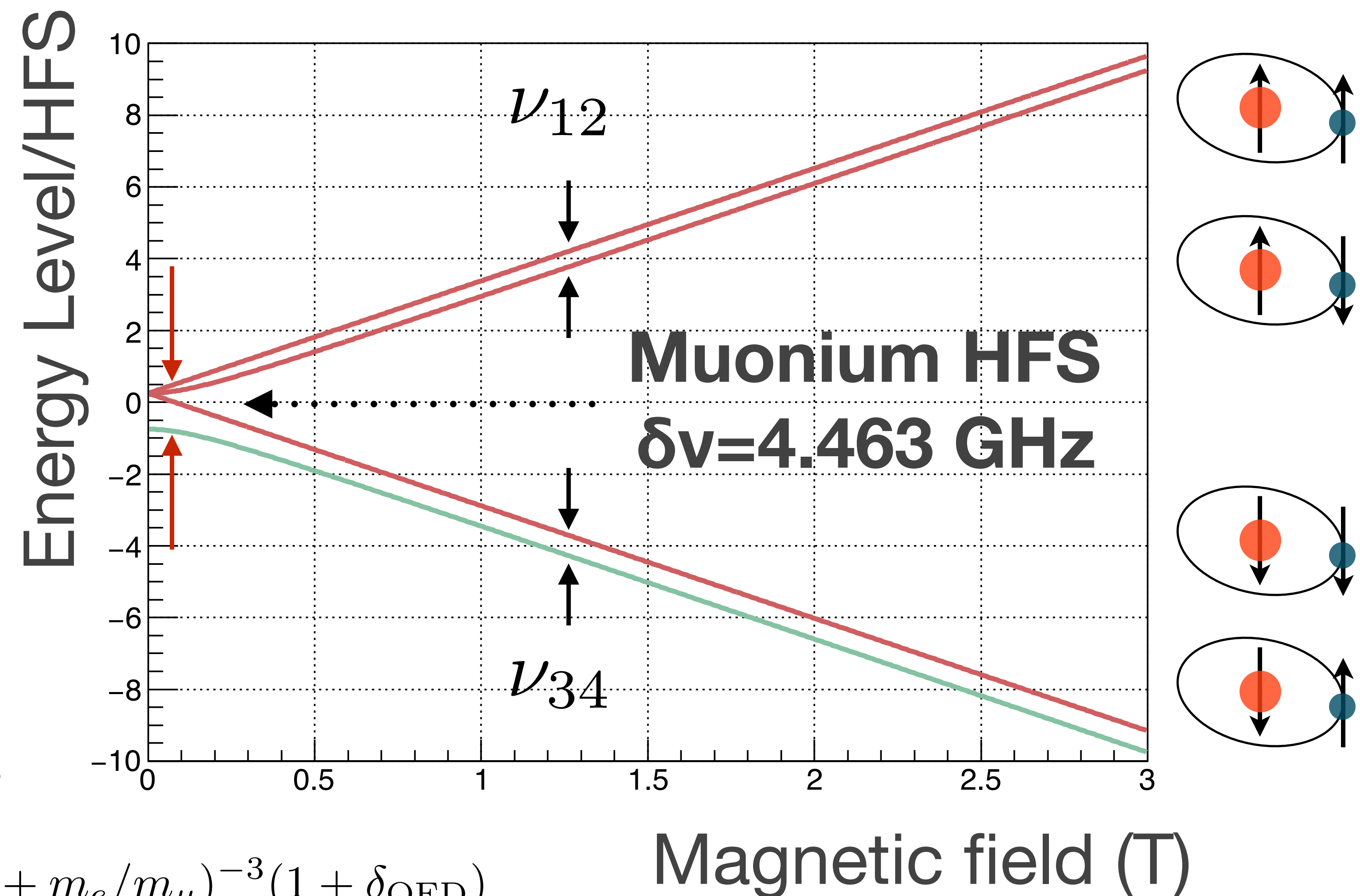
Muonium Energy Levels



$$\nu_{12} + \nu_{34} = \delta_\nu$$

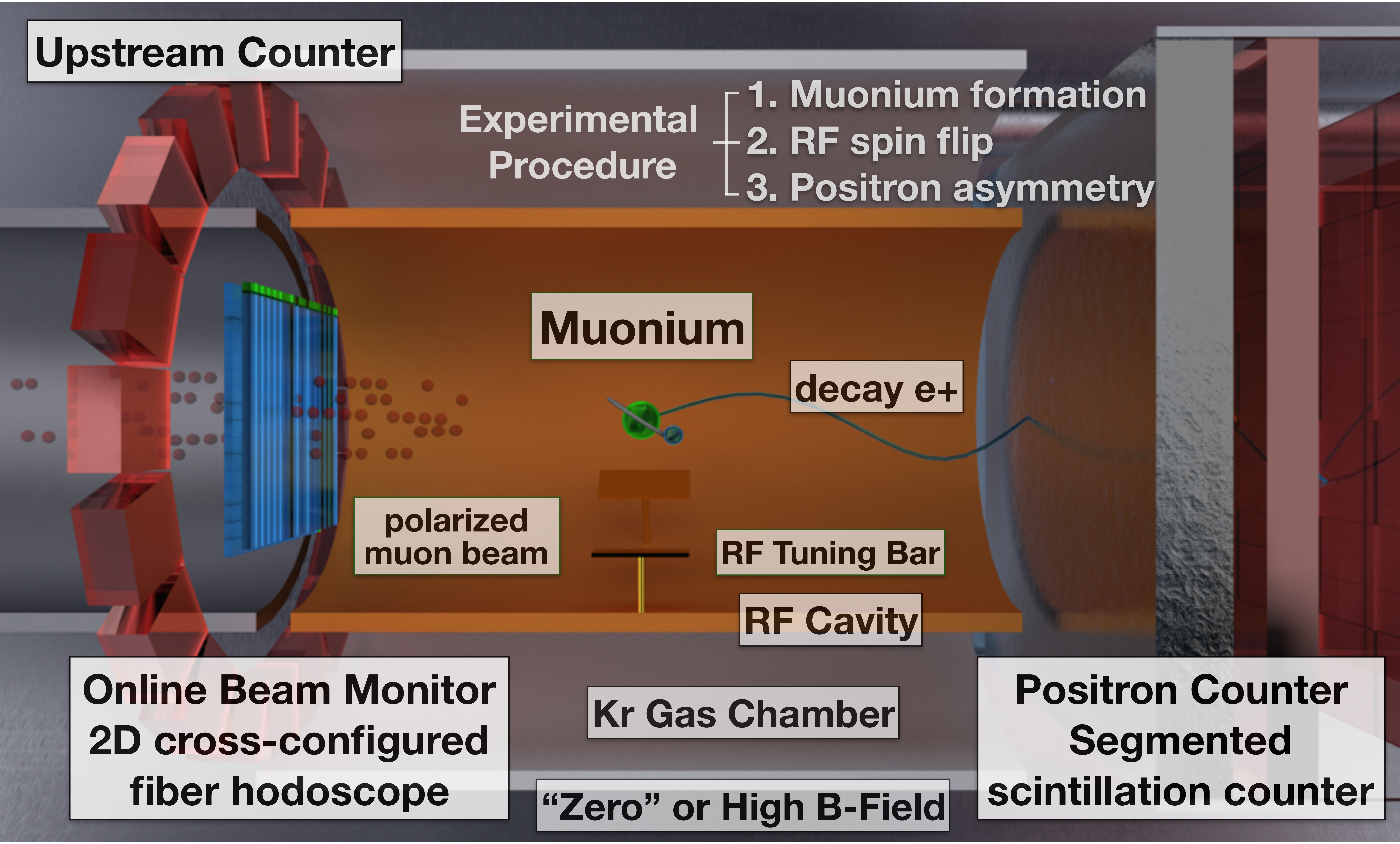
$$\nu_{12} - \nu_{34} \propto \mu_\mu / \mu_p$$

or $\delta_\nu = (\frac{16}{3}\alpha^2 R_\infty c g_e g'_\mu)(1 + m_e/m_\mu)^{-3}(1 + \delta_{QED})$



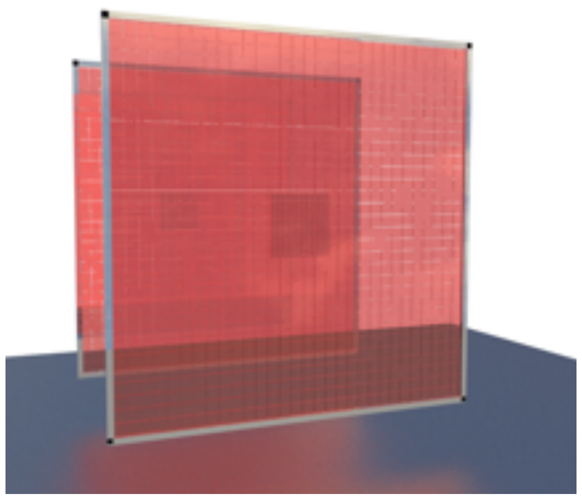
- Direct measurement at zero magnetic field (δν)
- Indirect measurement under a high magnetic field (ν_{12} and ν_{34})
- Our goal is x10 improvement for both experiments

MuSEUM Experiment



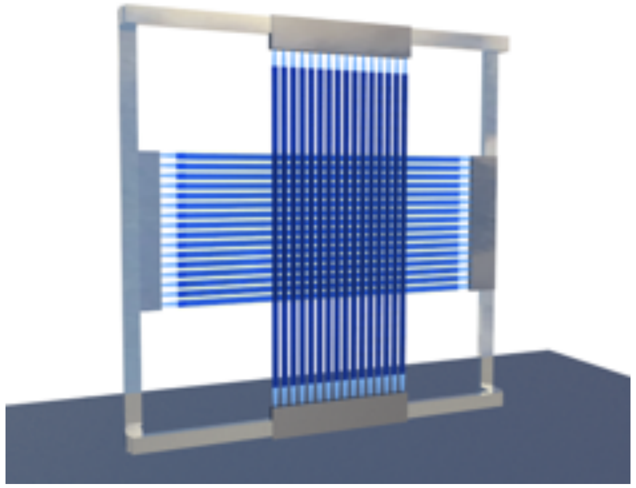
MuSEUM Instruments

Positron counter



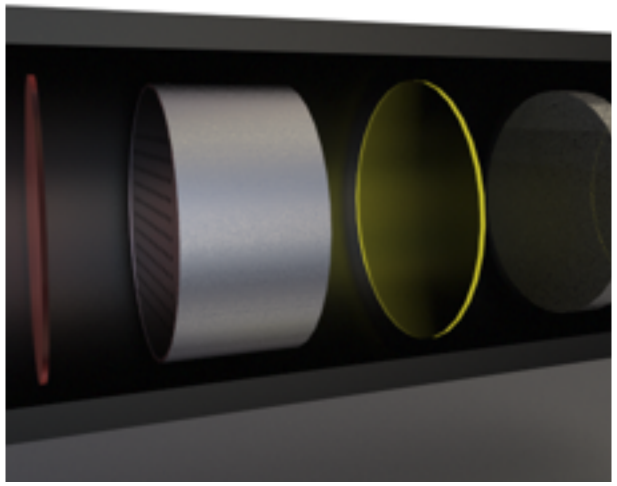
- Segmented scintillator+SiPM
- Positron counting
- High rate capability is required

Online beam profile monitor



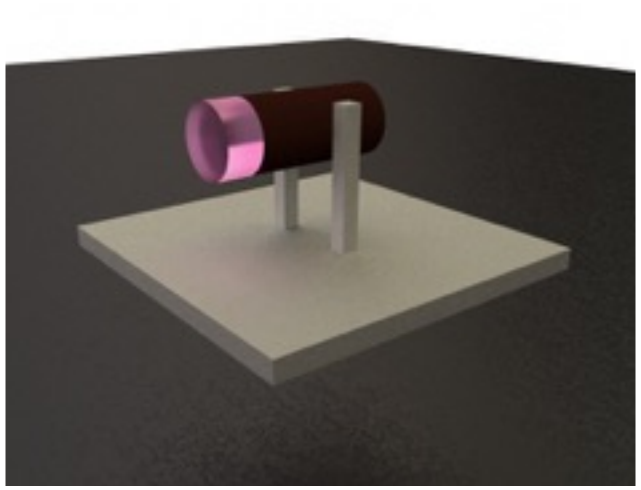
- Fiber hodoscope
- Beam monitoring
- Minimum amount of material is required

Offline beam profile monitor



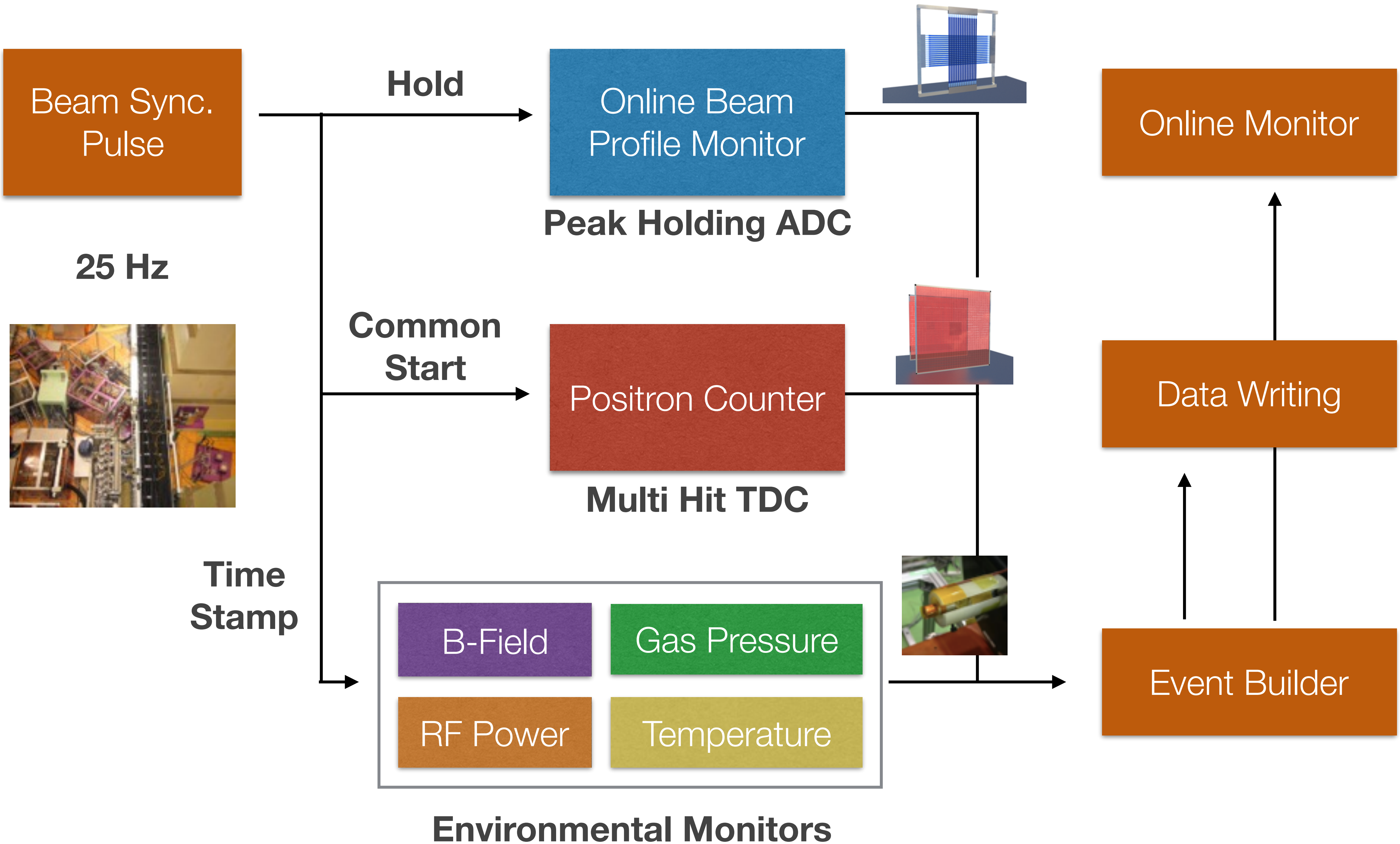
- IIF+CCD beam imager
- 3D muon stopping distribution
- Beam tuning

Background monitor



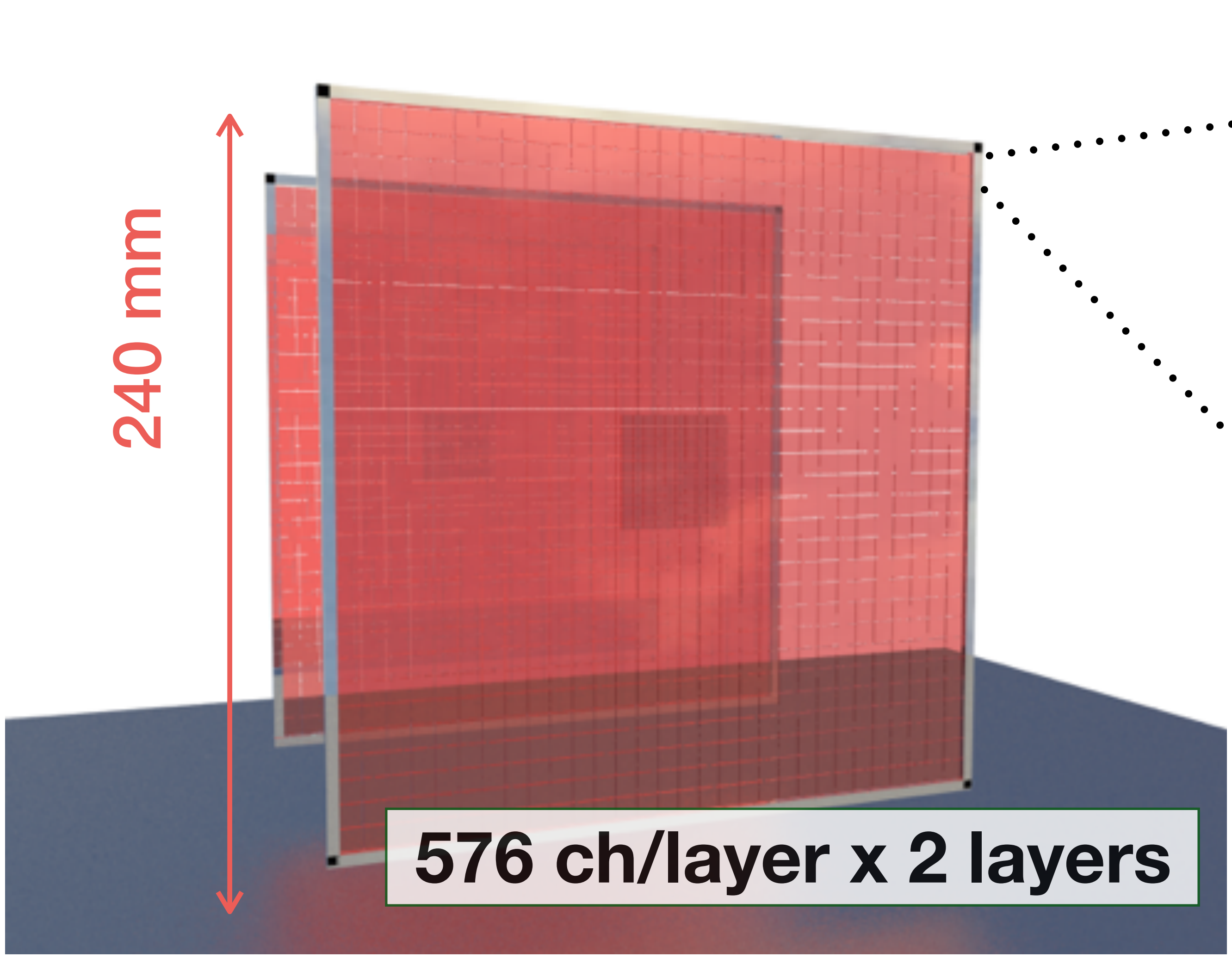
- Lq. scint.+WFD
- Neutron/Gamma/Positron discrimination
- Self trigger

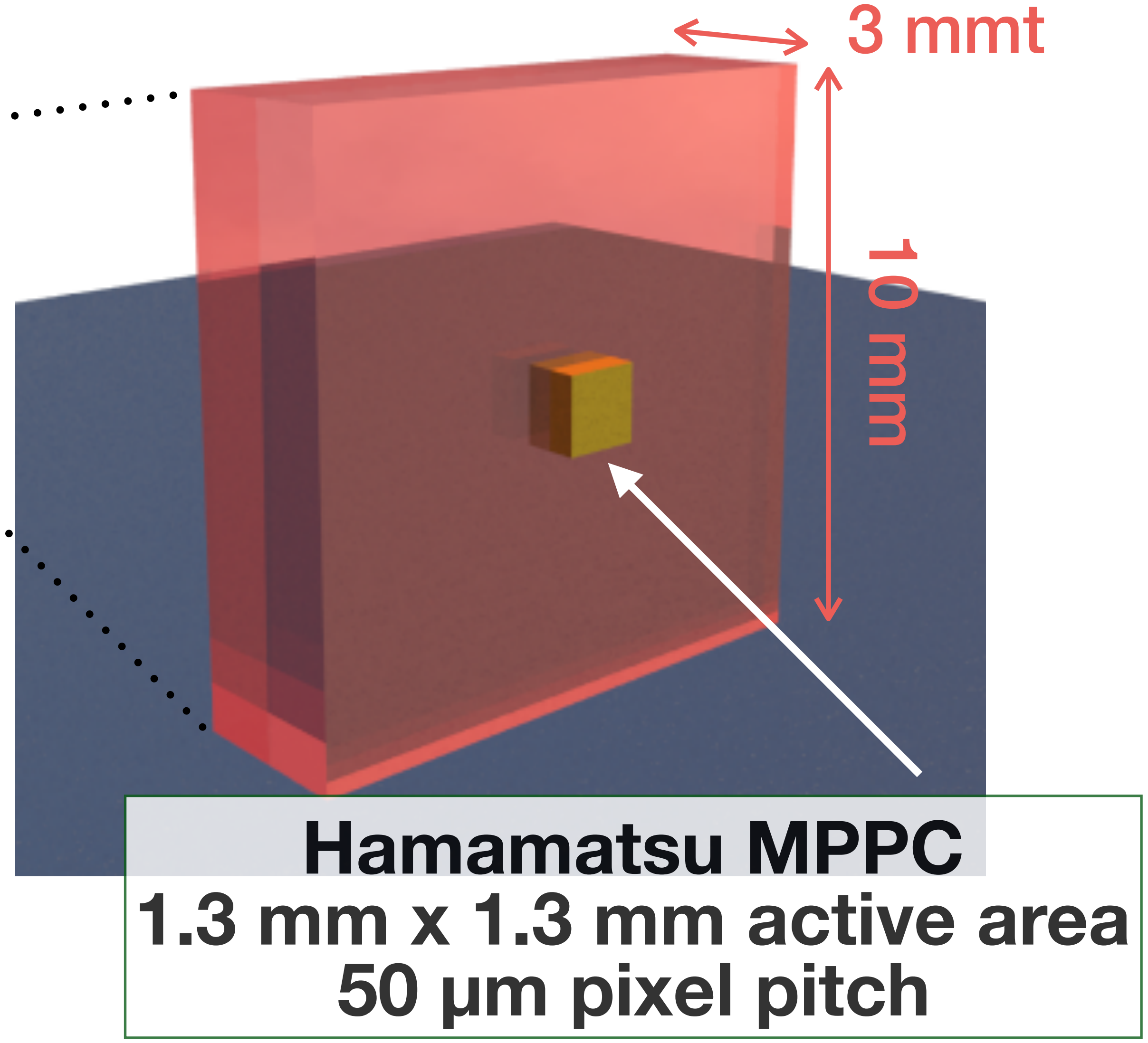
DAQ Overview



Positron Counter

- **Scintillator pixel+SiPM+Kalliope (ASD+multi-hit TDC)**



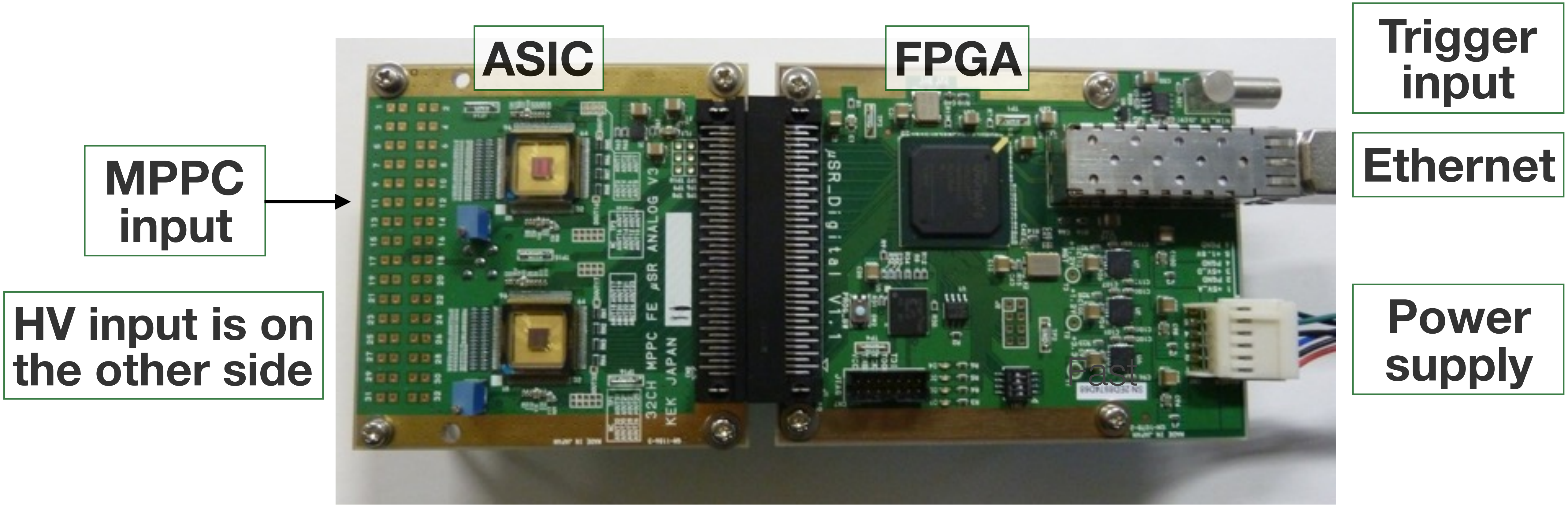


- Two layers of segmented scintillation counter
- 10 mm×10 mm× 3 mmt unit cell , 240 mm × 240 mm detection area
- High rate capability and tolerance to a high magnetic field

S. Kanda, PoS(PhotoDet2015) 039 (2016)

Frontend Electronics

- Kalliope: KEK Advanced Linear and Logic-board Integrated Optical detec for Positrons and Electrons

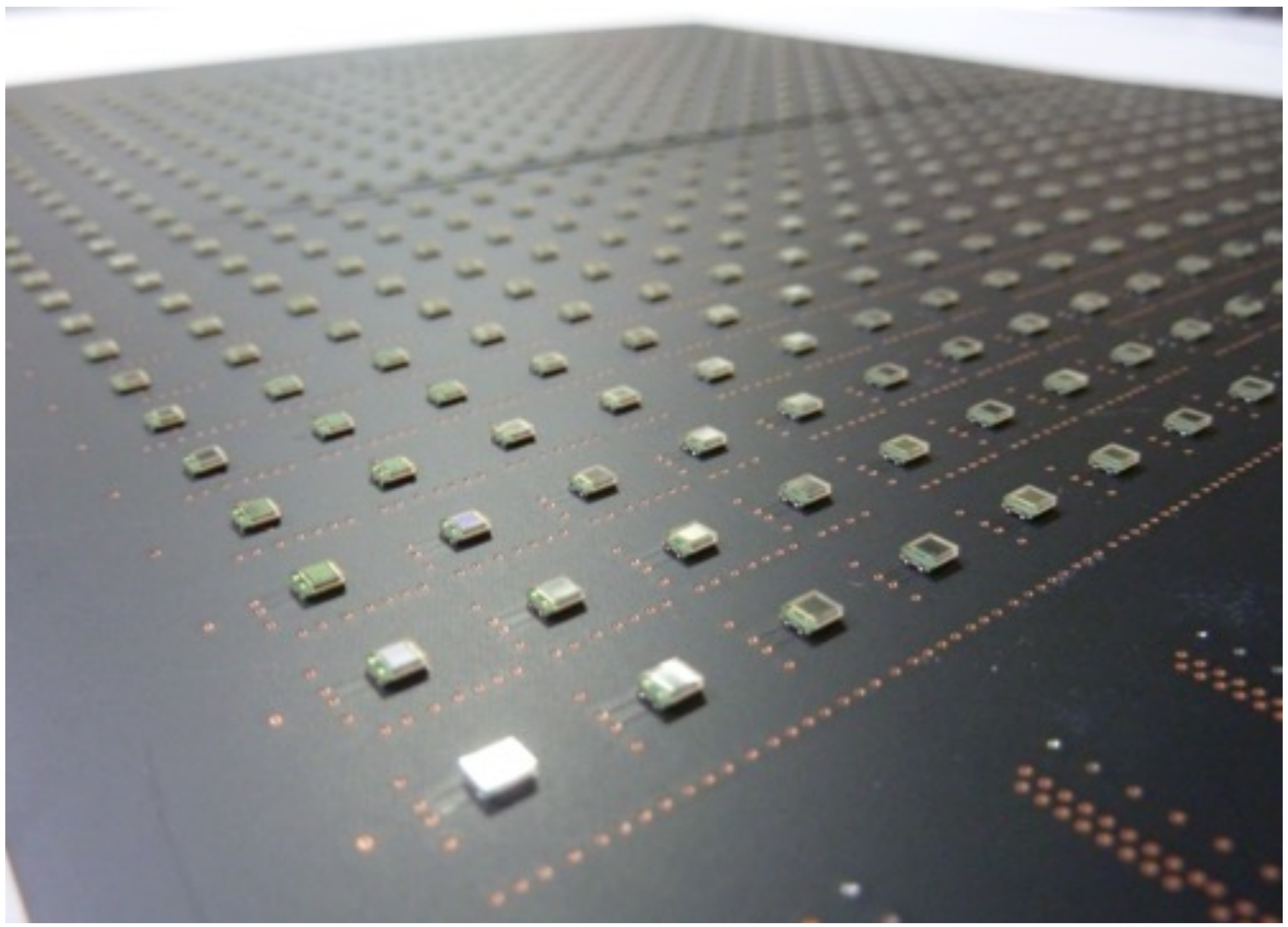


- 32ch inputs for MPPC
- ASIC implemented amplifier, shaper, discriminator
- FPGA programmed multi-hit TDC (common start)
- SiTCP data transfer

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)

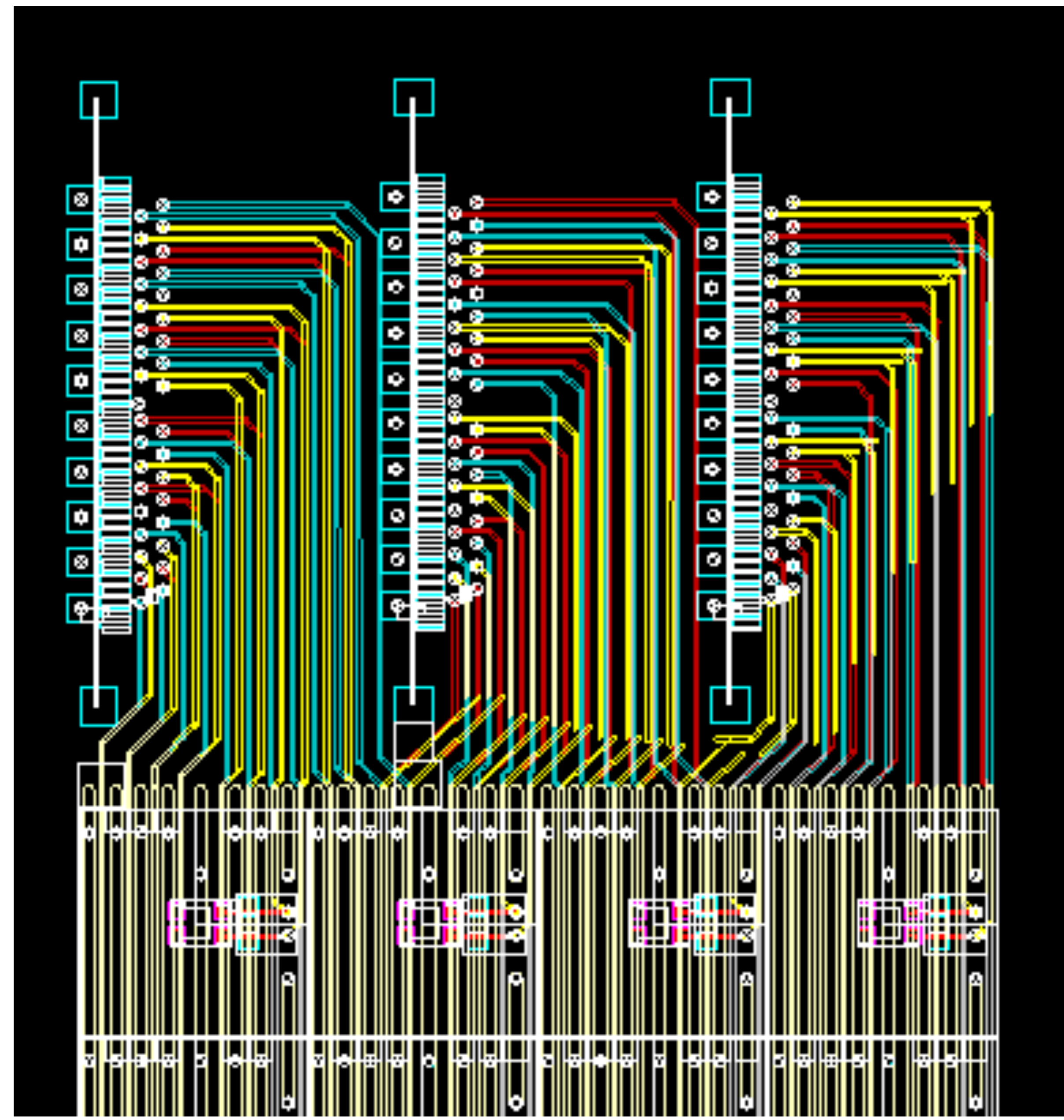
MPPC on PCB

- **Eight layered PCB for MPPC mount**



PCB with mounted MPPCs

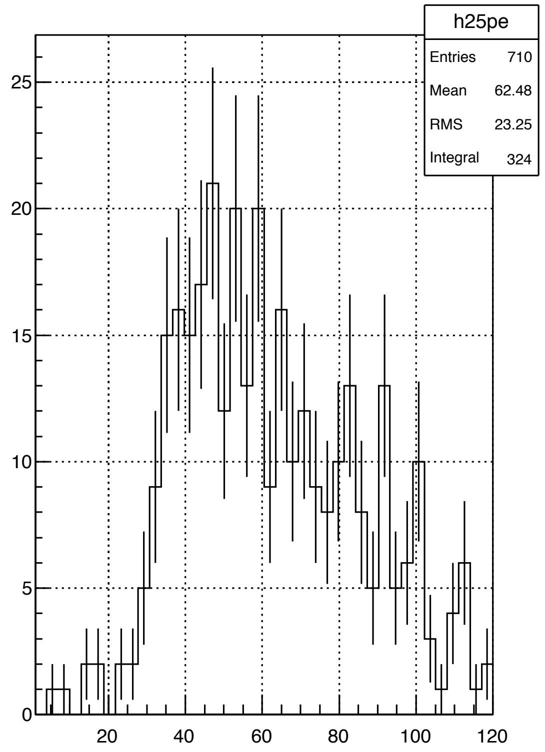
Micro strip line impedance was adjusted to 50 Ohm



Circuit Design

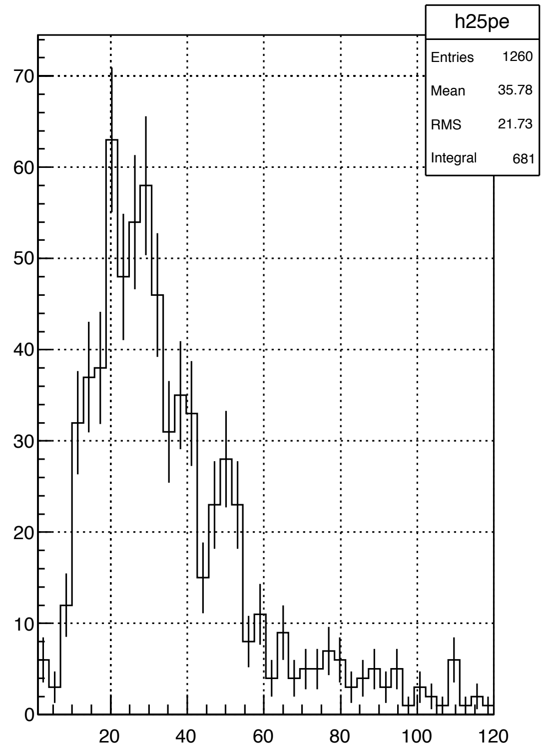
White Paper Mask

- **White paper mask for light diffused and position marker**



# of photon

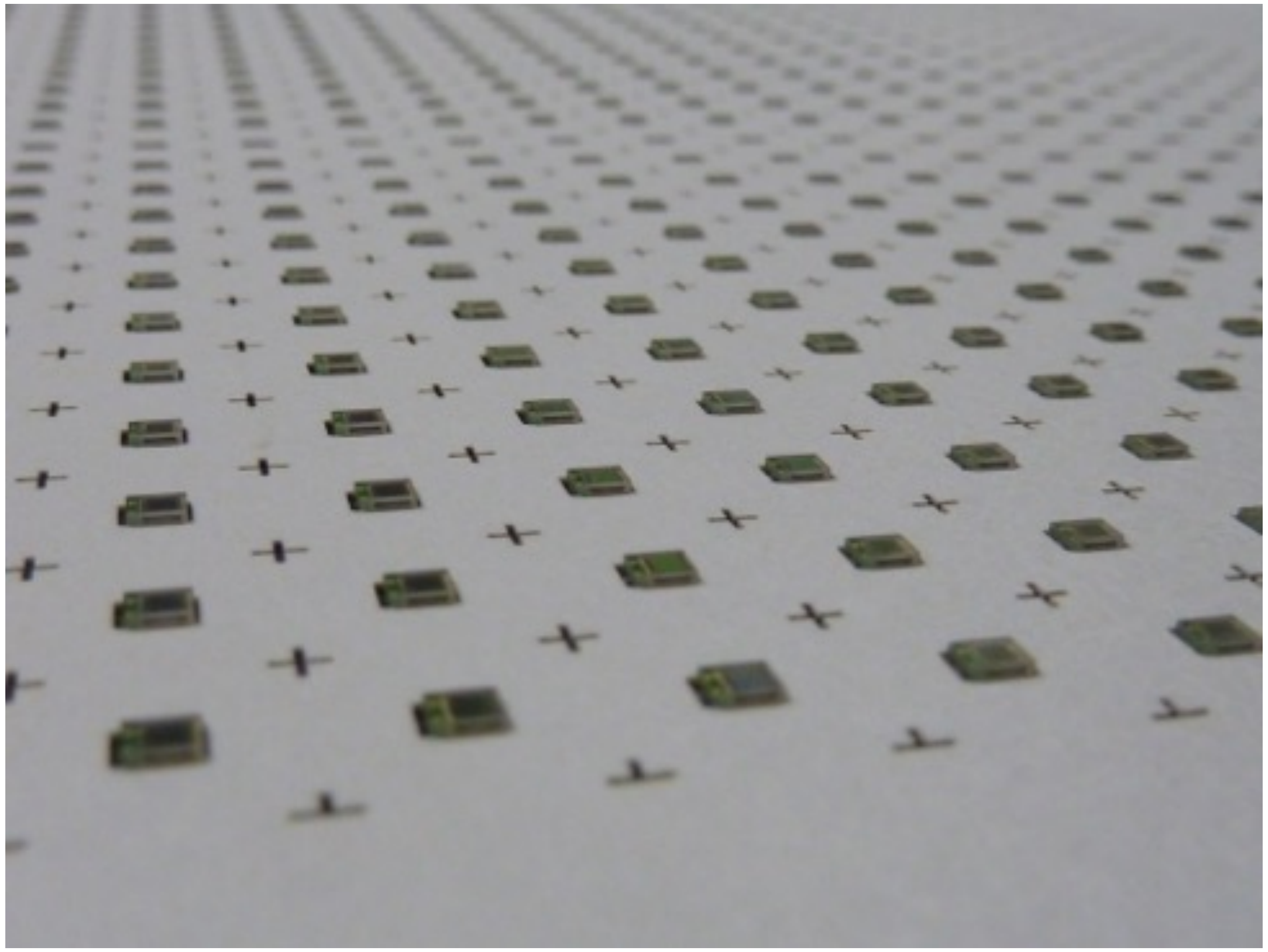
White paper



# of photon

Black paper

Photo detection comparison between black and white paper mask



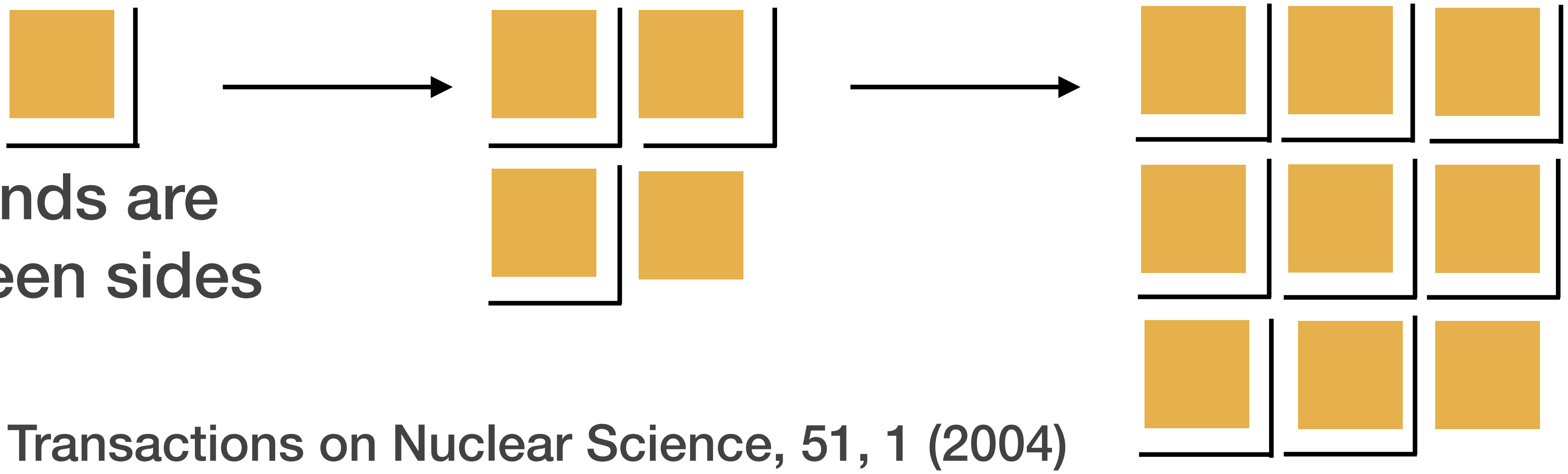
White paper mask on a PCB as position marker and reflector

Reflector Film

- **Thin polymer film with folding for light reflection**

Laser cut ESR

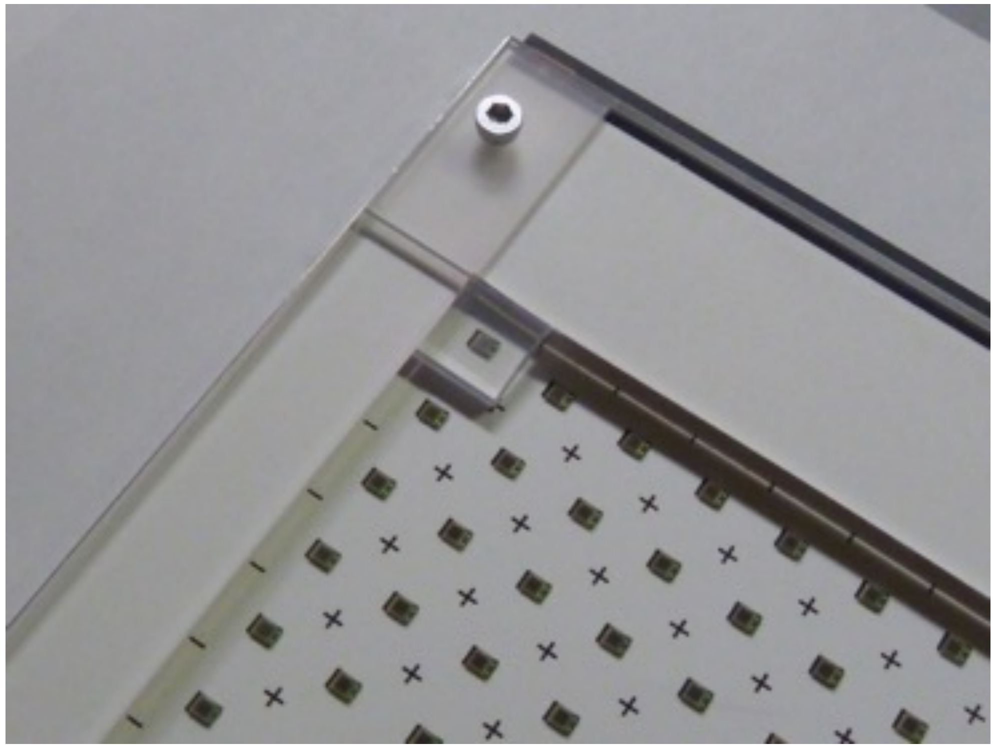
ESR ribbons to be inserted

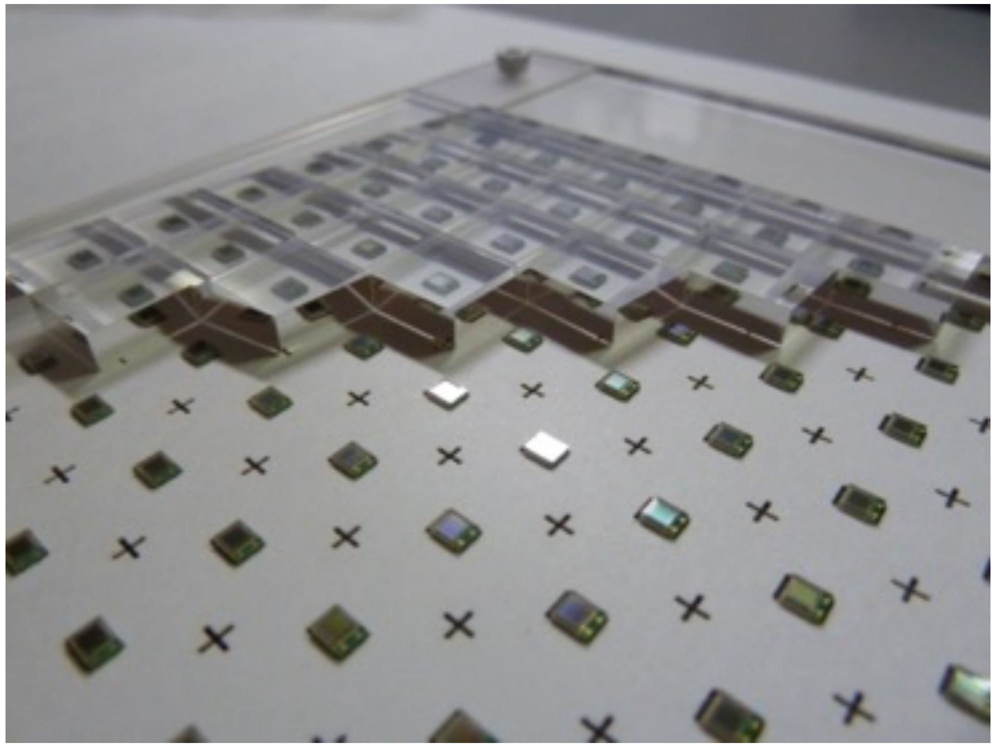


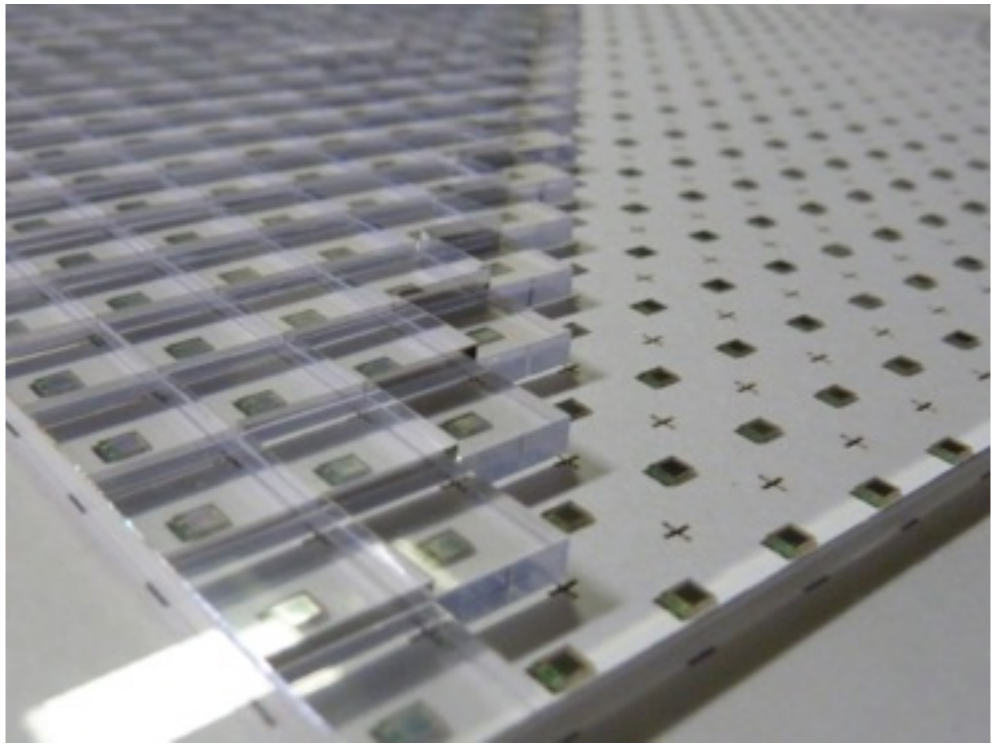
Folded film bands are inserted between sides of scintillators

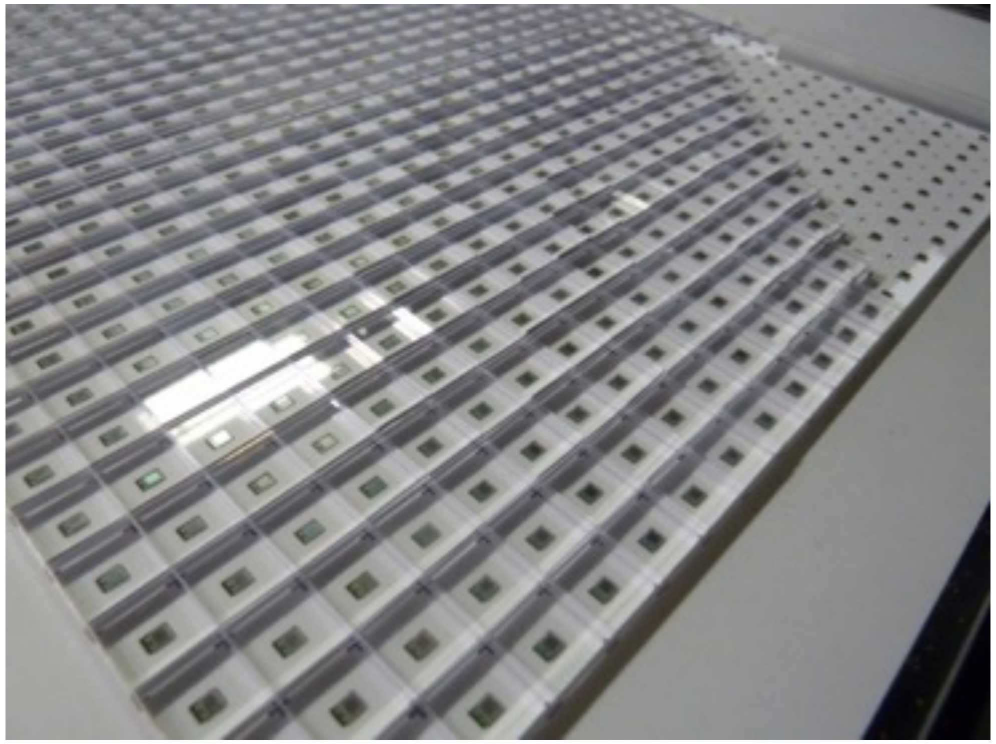
N. Inadama *et al*., IEEE Transactions on Nuclear Science, 51, 1 (2004)

Positron Detector Assembly

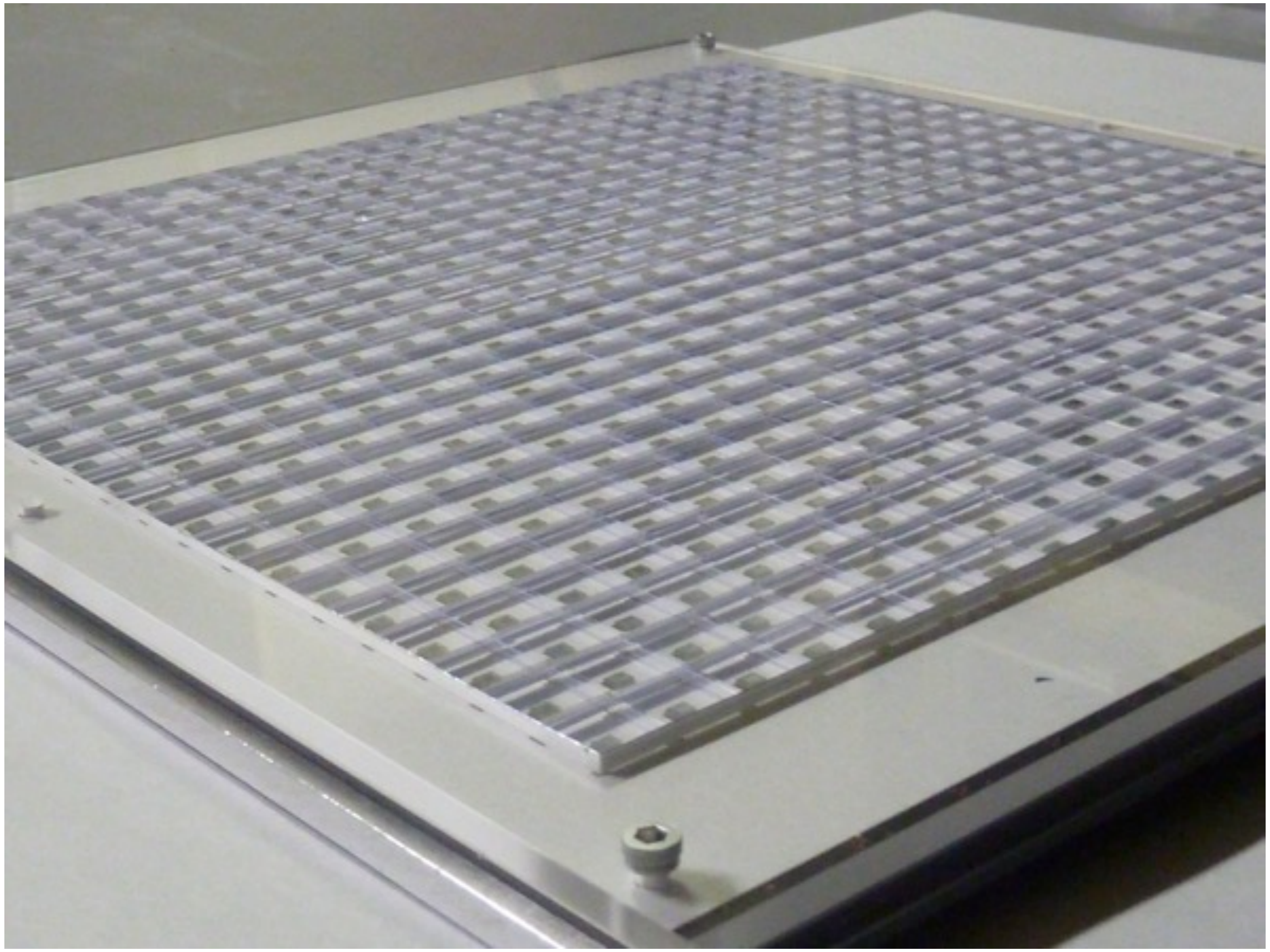








Assembled Positron Detector

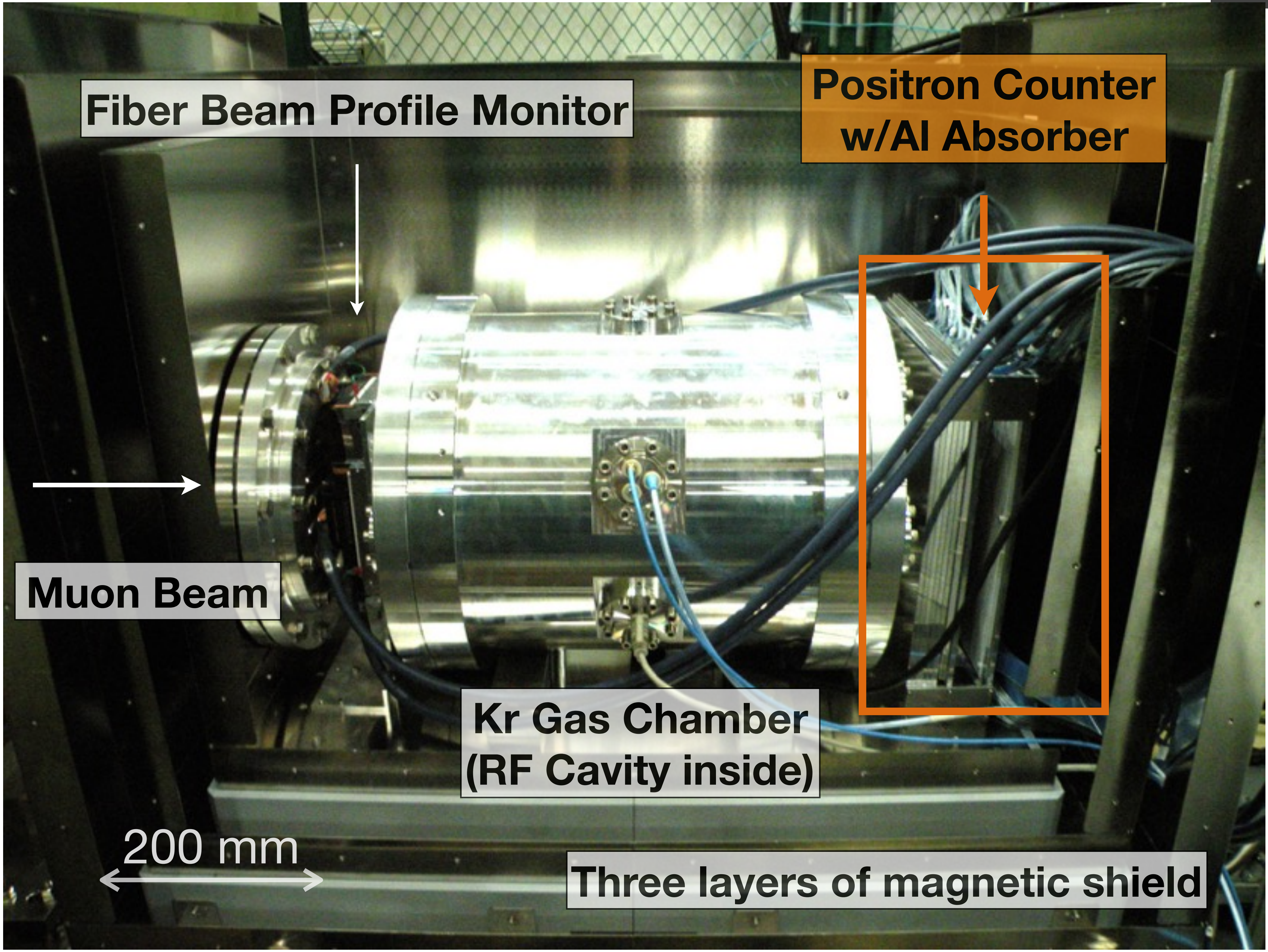


Fully assembled scintillator segments

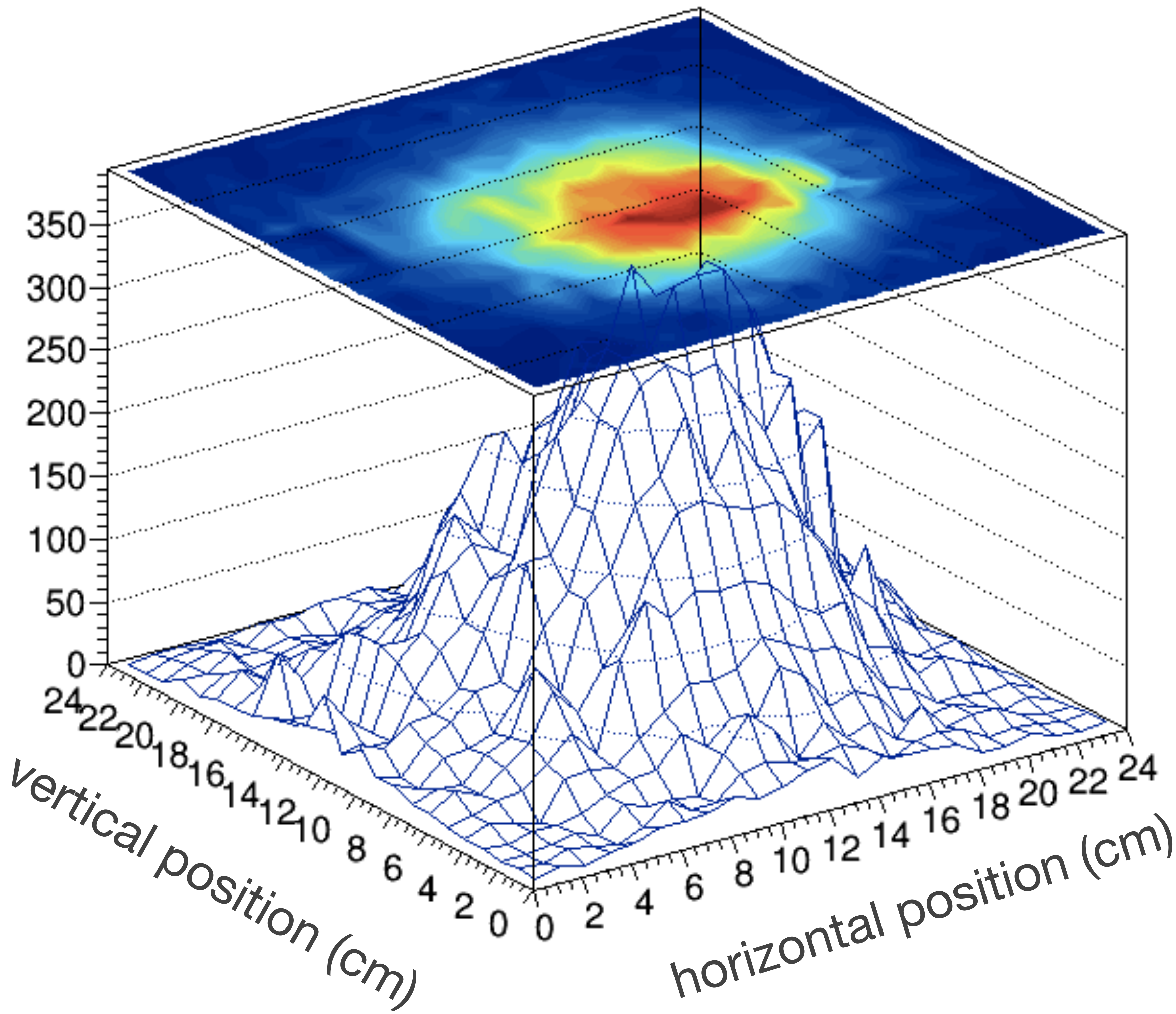
ESR top cover

Top cover was placed for scintillator protection

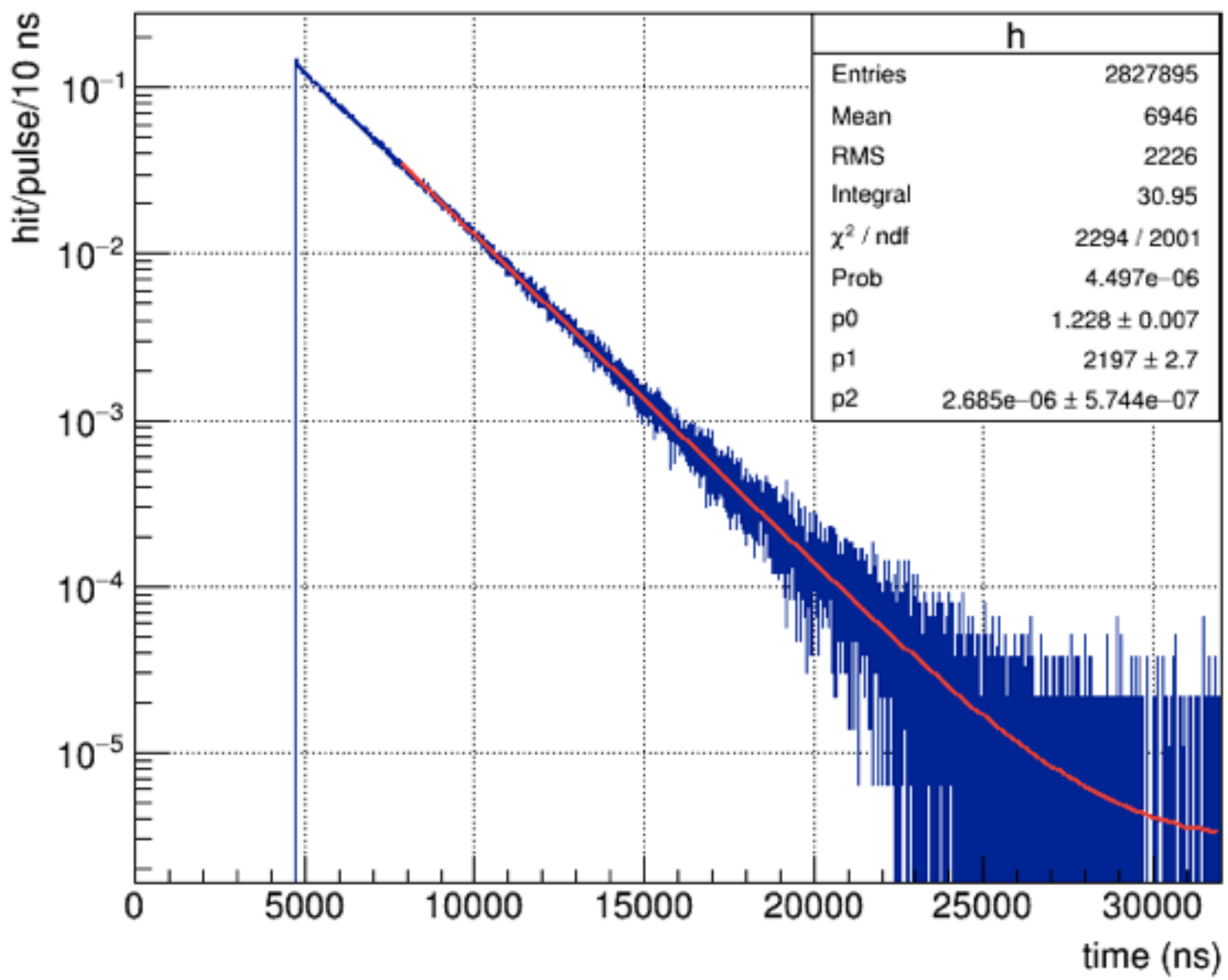
Installation



Hit Map on the Detector Plane

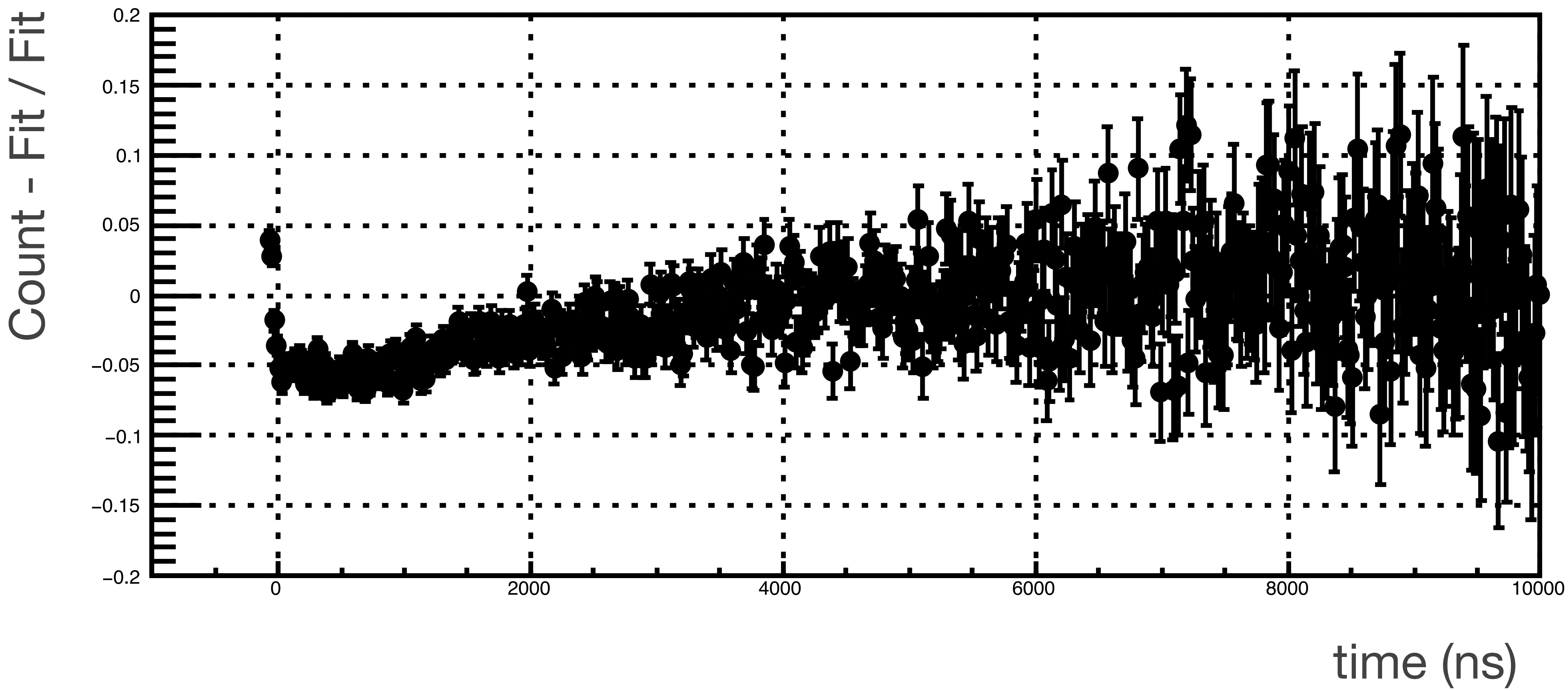


Time Spectrum



Time spectrum of coincidence hit
Instantenious event rate was 10 MHz at maximum
30 coincidence hit per pulse

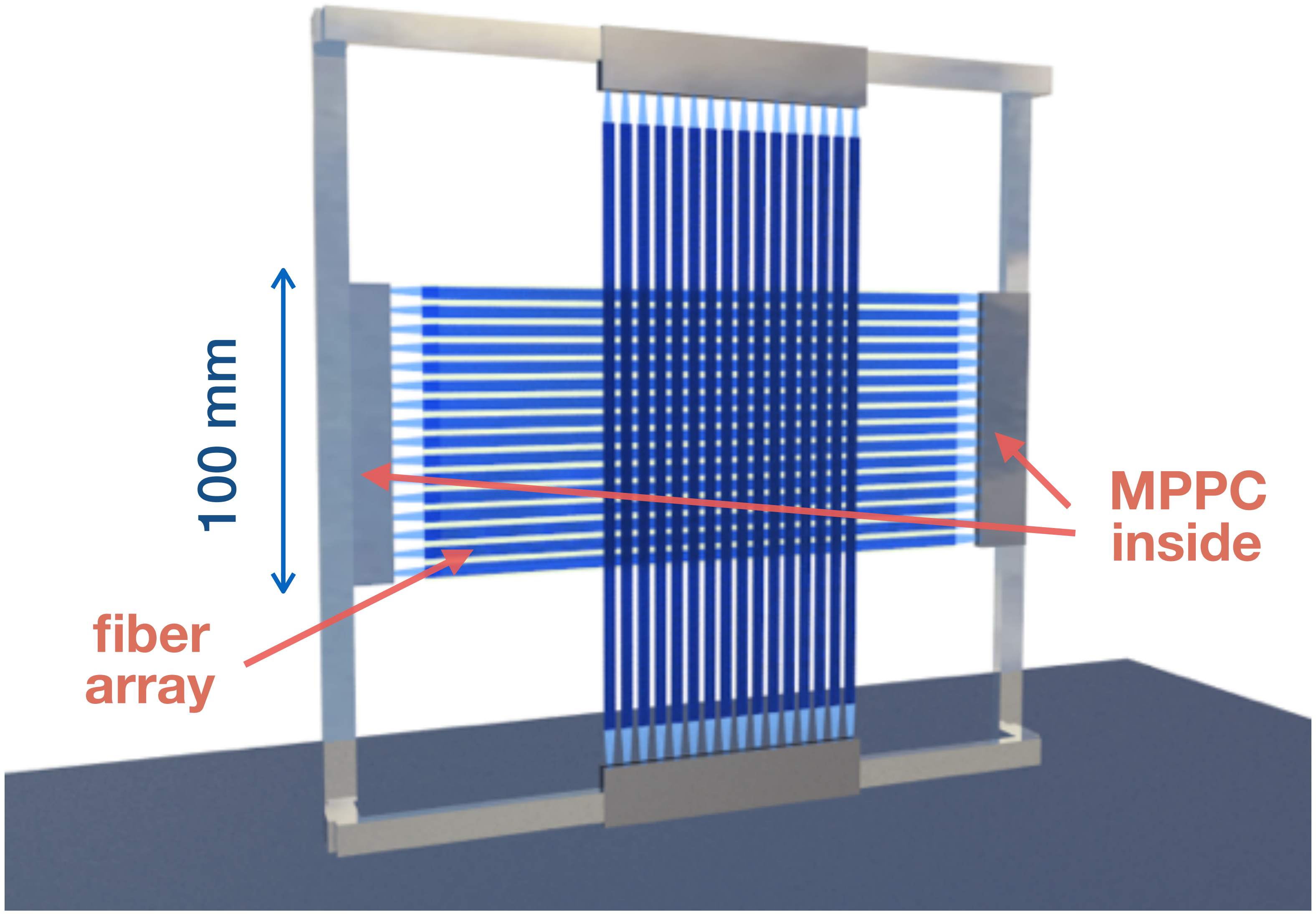
High-Rate Capability



5% of pileup loss at the highest event rate

Systematic uncertainty due to the pileup loss is negligible

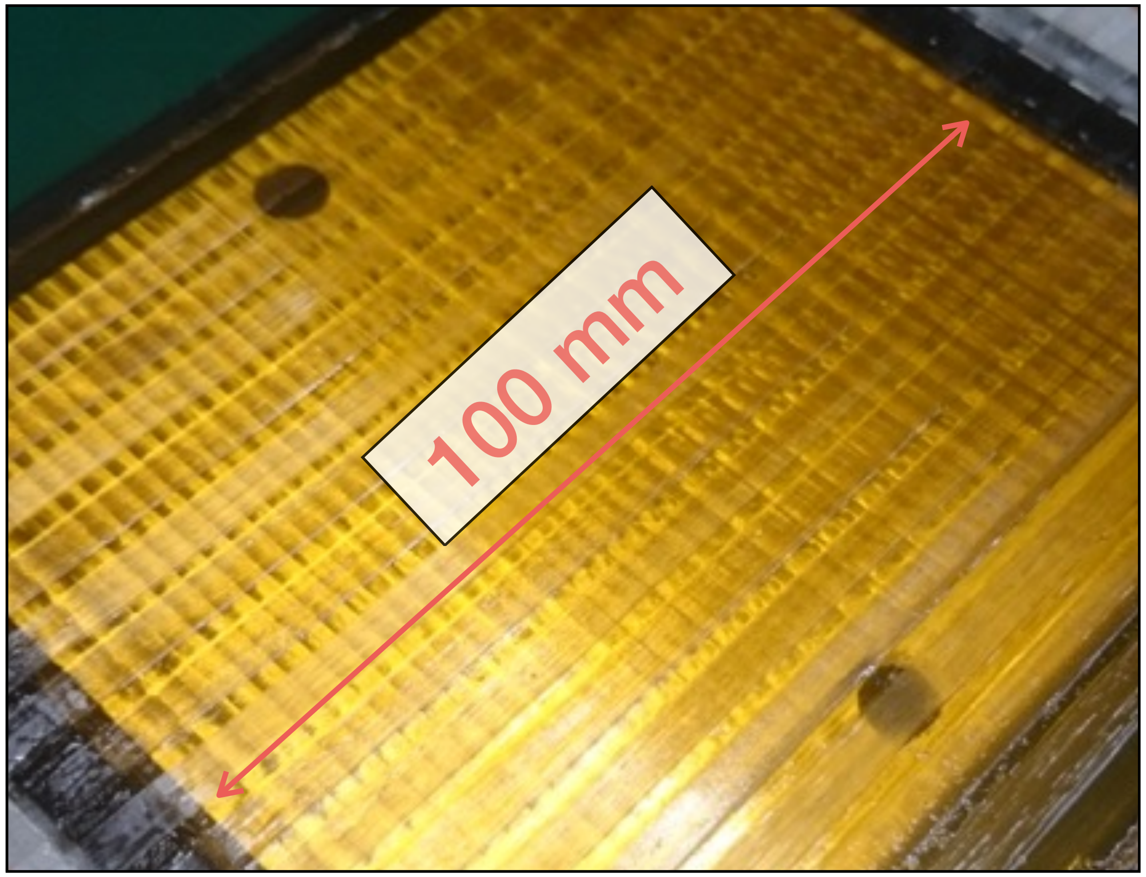
Fiber Beam Profile Monitor

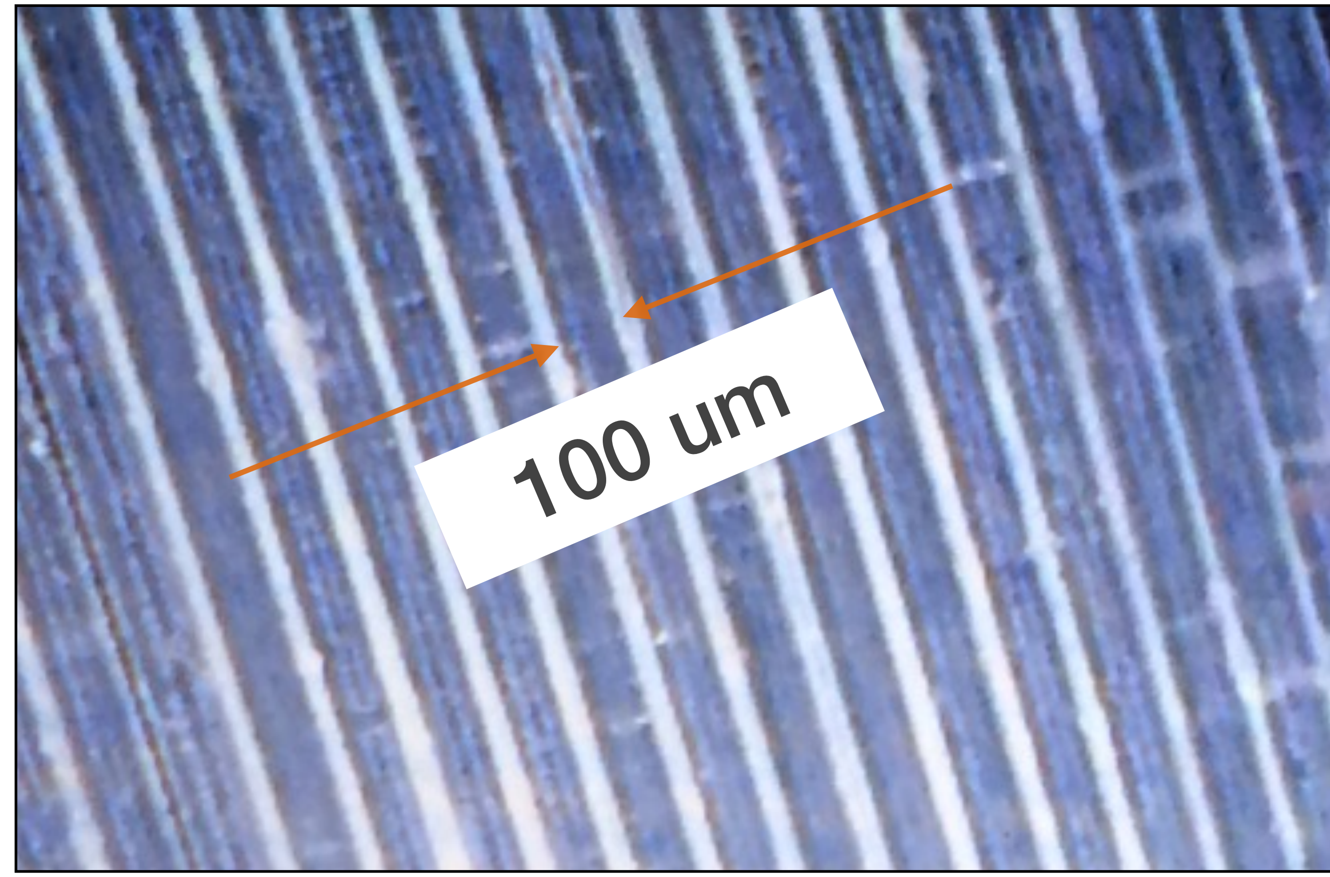


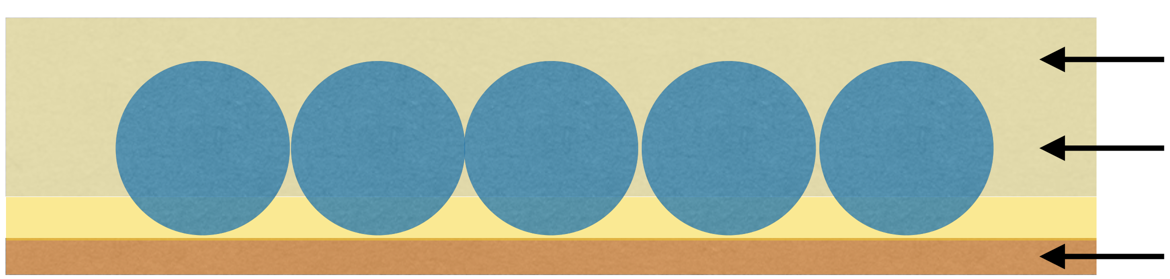
- Cross-configured fiber hodoscope with SiPM readout
- To be placed in front of the target chamber
- Online monitoring of beam profile and intensity
- Minimum amount of material is required

S. Kanda, RIKEN Accelerator Progress Report Vo. 48 (2015)

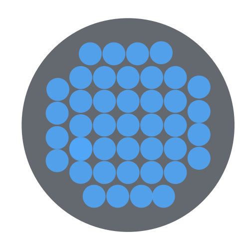
Scintillation Fiber Array





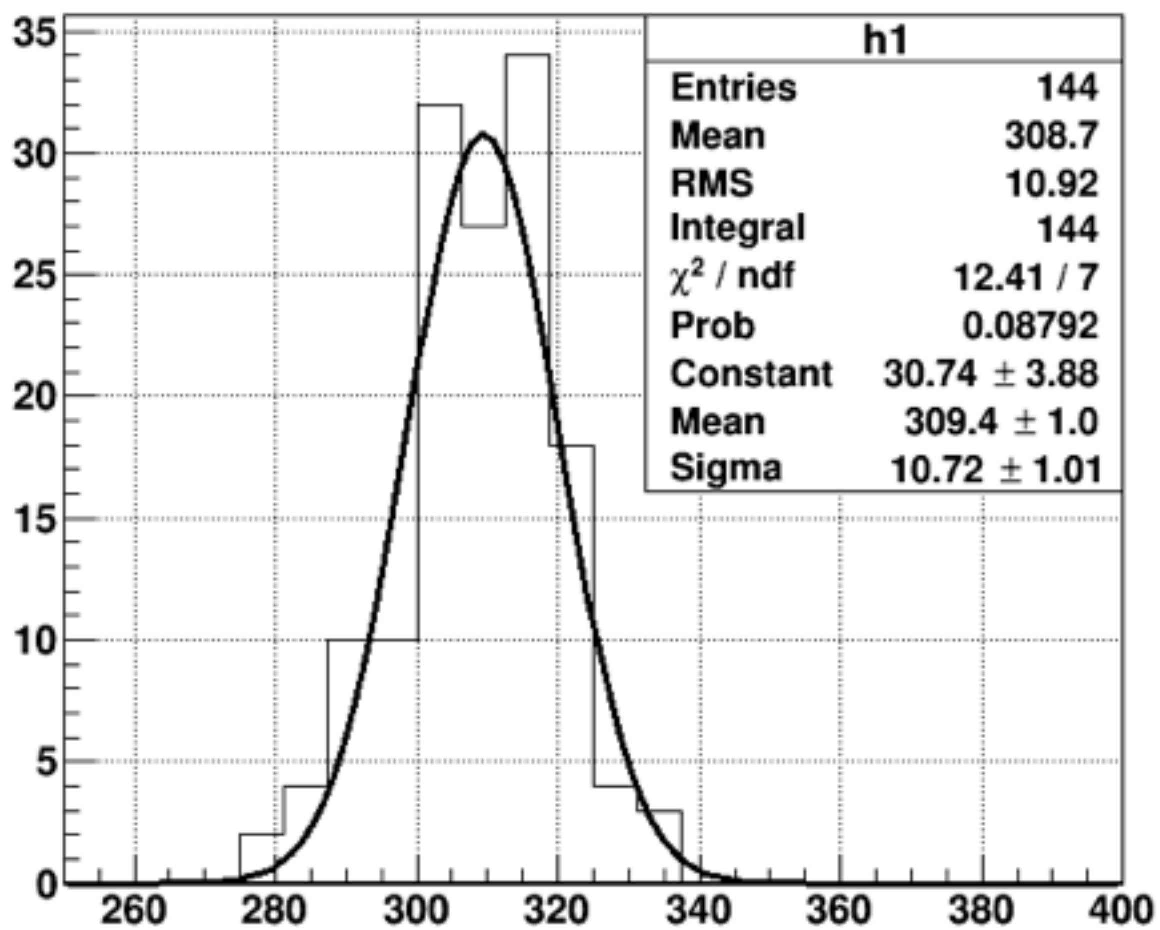


Fiber array layer structure

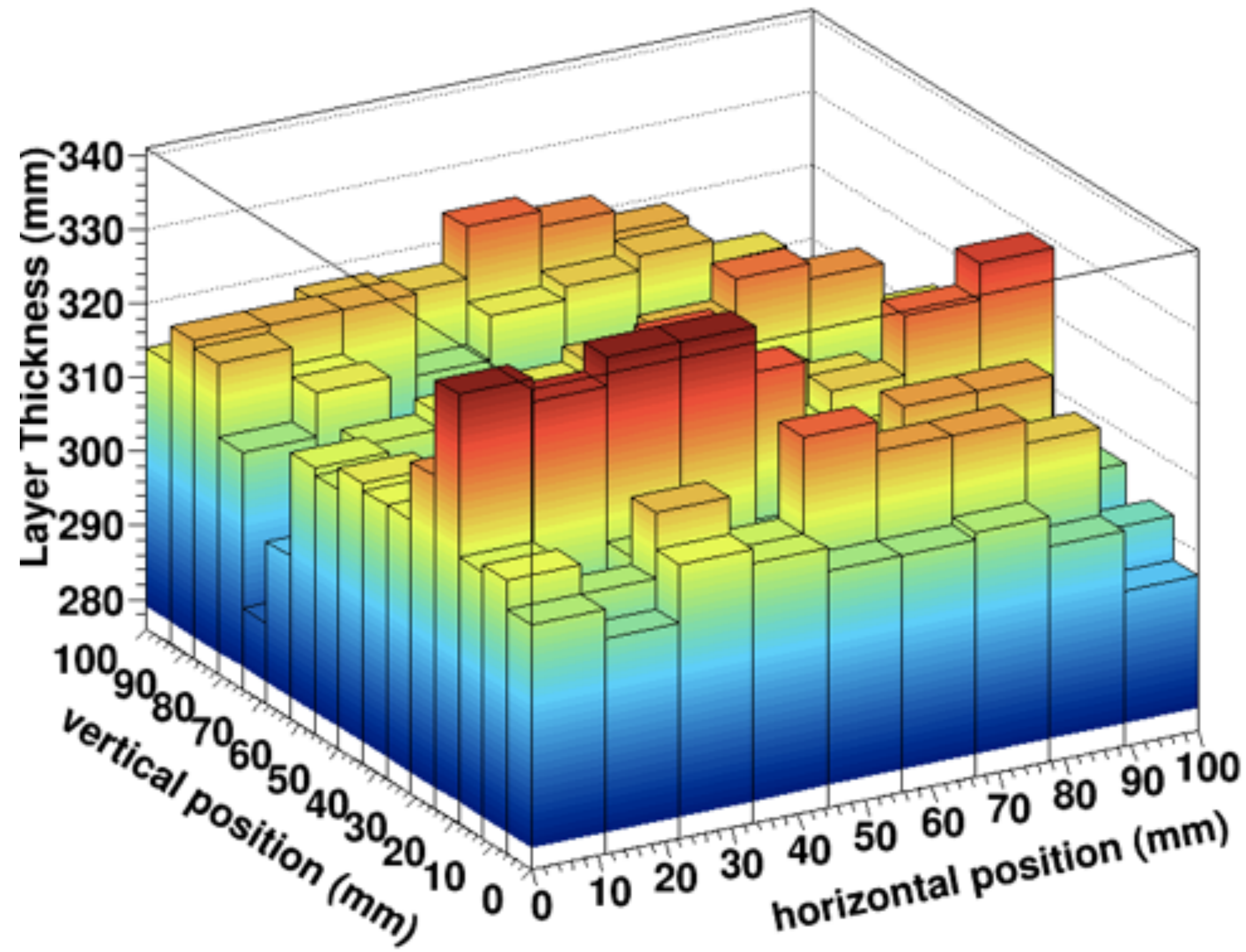


40 fibers are bundled for a ch. and connected to MPPC

Fiber Thickness Uniformity



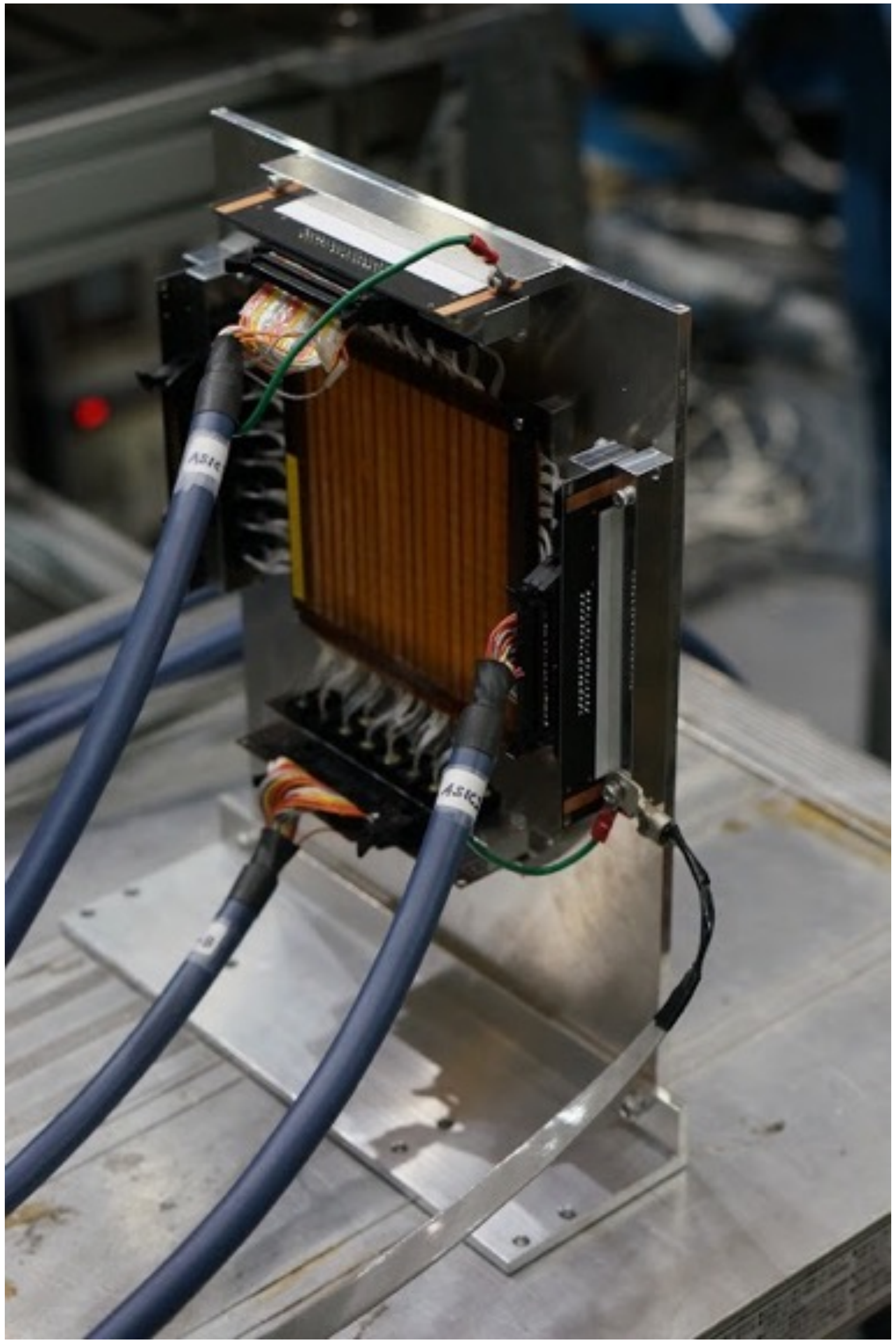
layer thickness (um)

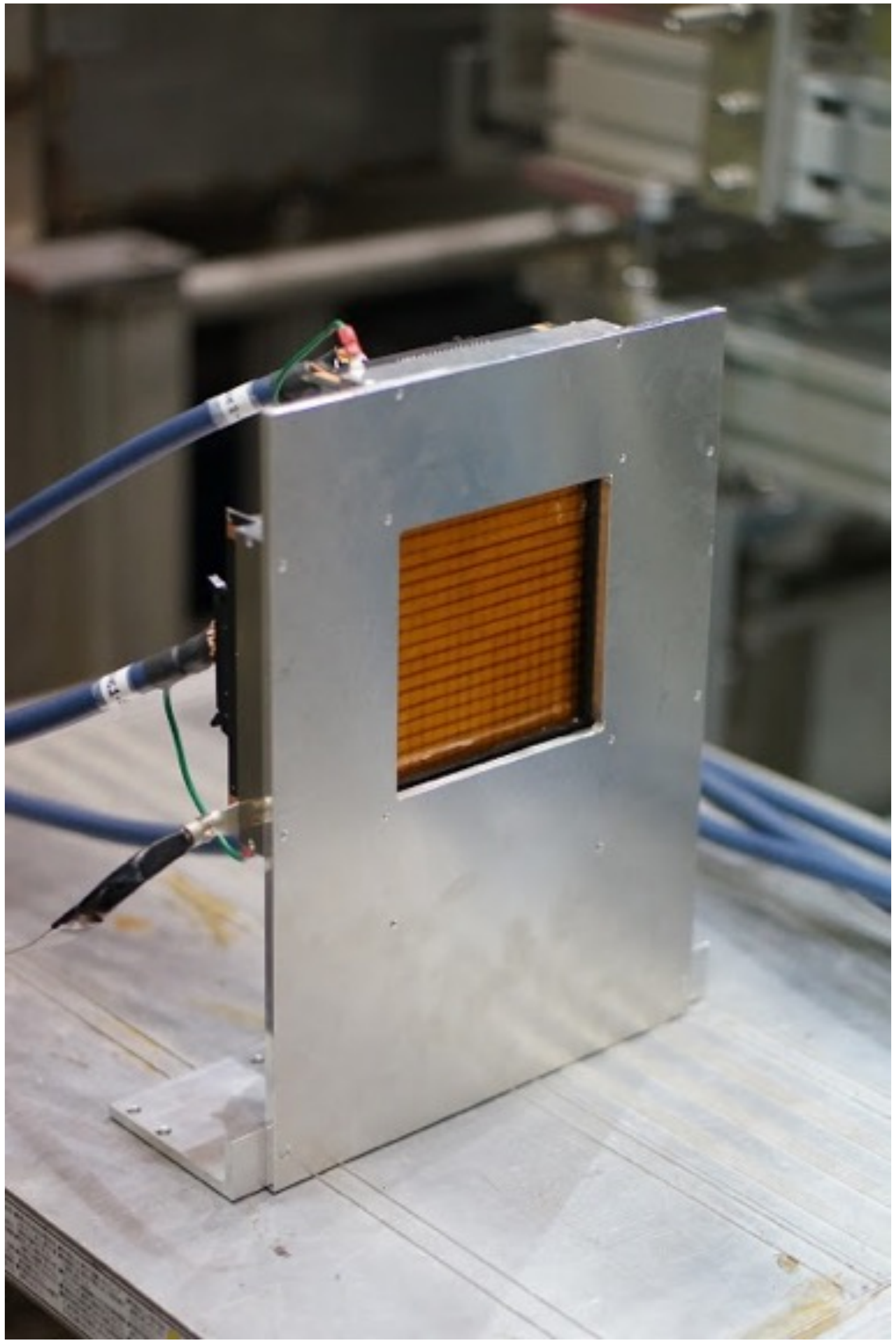


3% of Uniformity

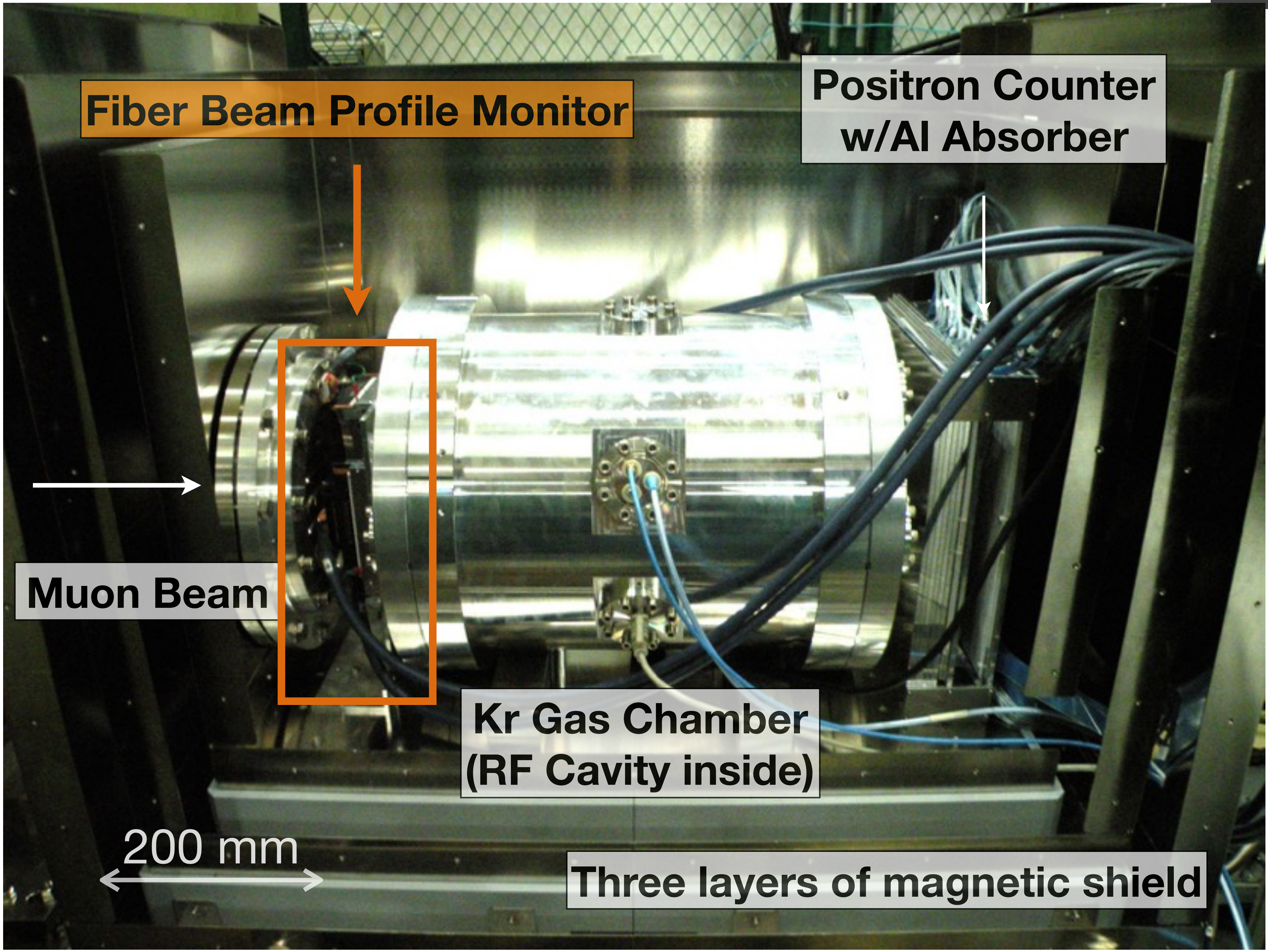
Total thickness including fibers, resin, and substrate

Assembled Fiber Monitor

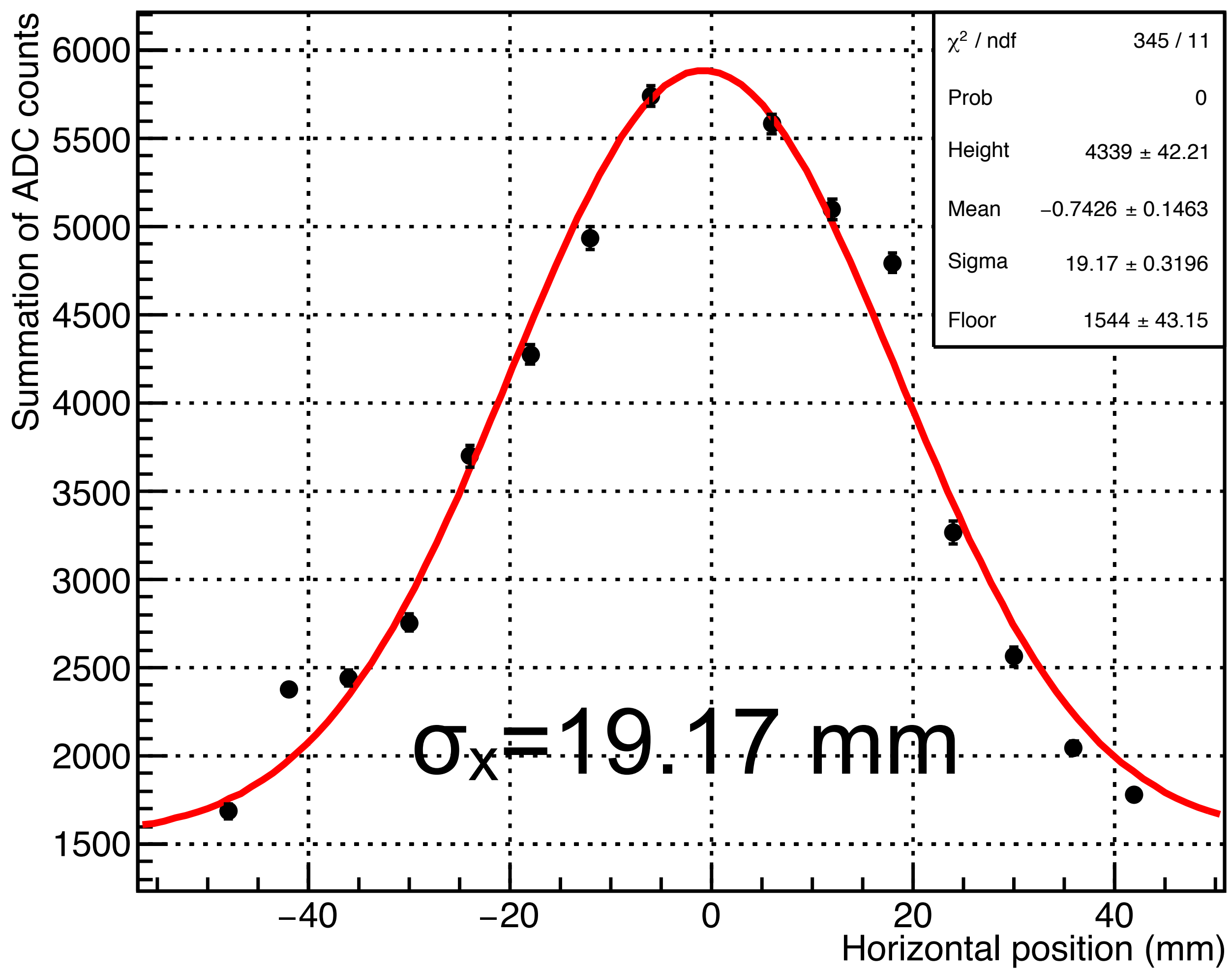




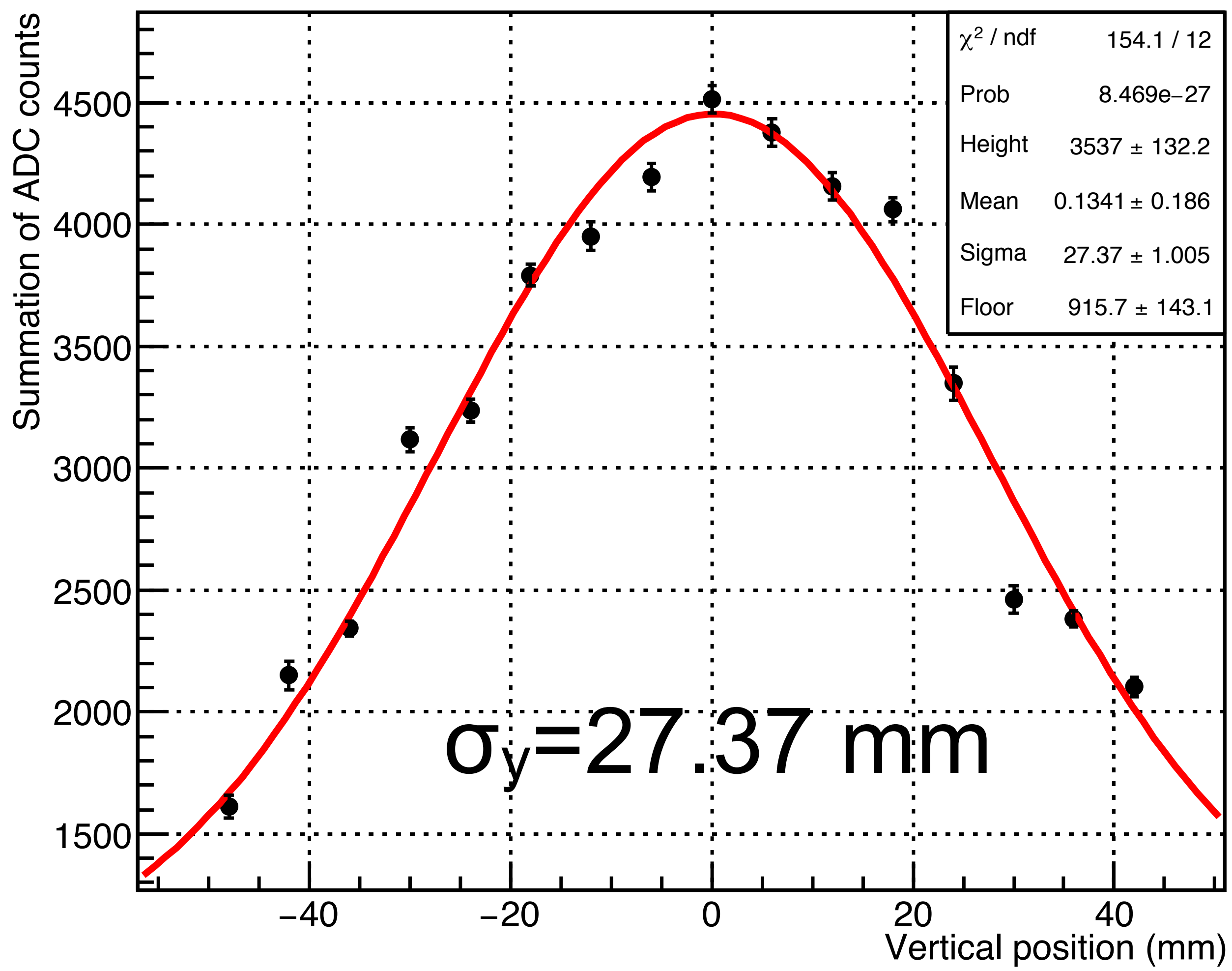
Installation



Measured Beam Profile



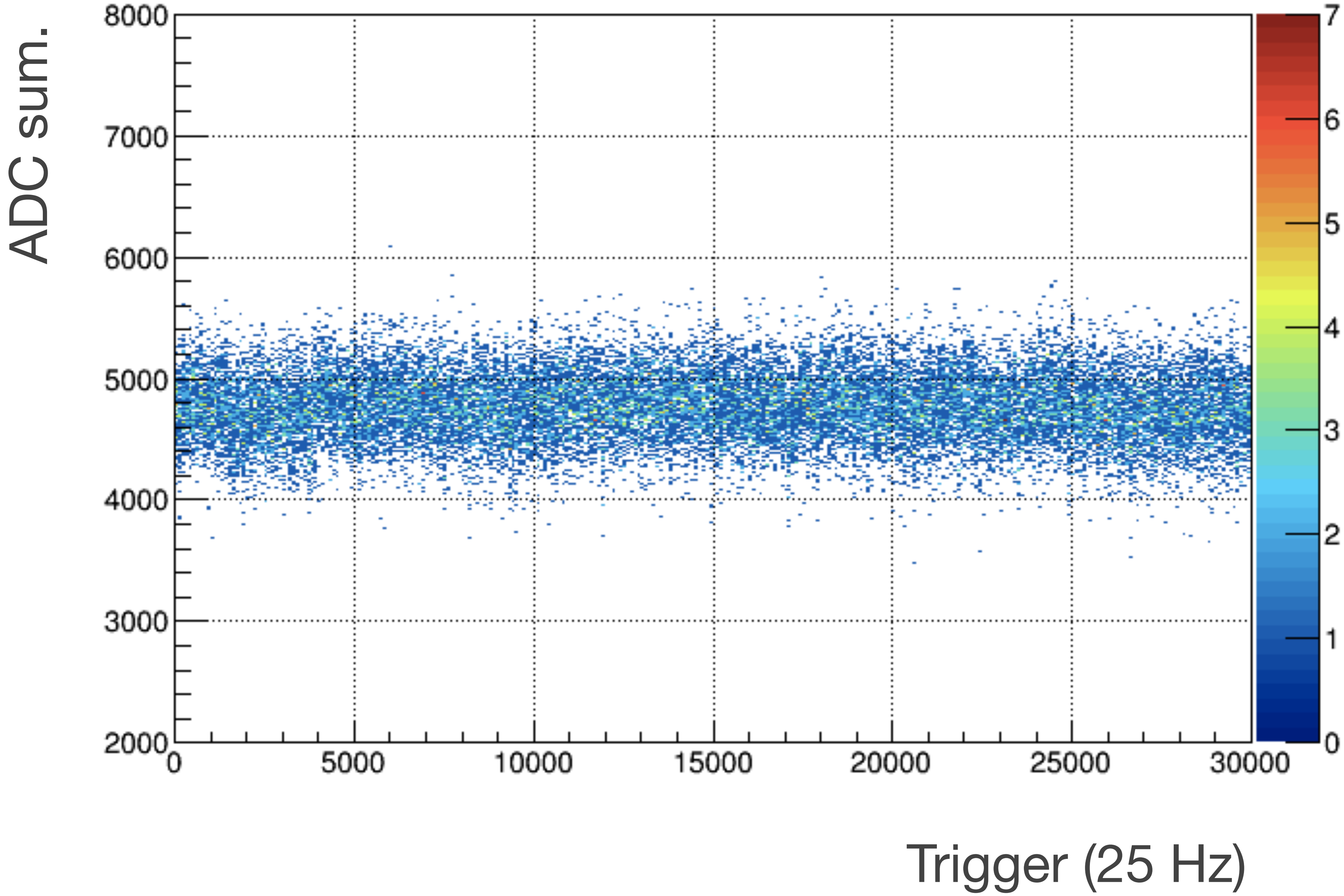
Horizontal projection



Vertical projection

- Muon beam profile was measured by fiber beam profile monitor
- Correction for light attenuation is to be applied

Beam Intensity Stability



Detailed analysis is in progress

Summary

- **Precision muon physics with continuous muon beam has been limited by statistical uncertainty.**
- **Experiment with high-intensity pulsed beam has great potential to improve precision muon physics.**
- **To explore a new frontier of precision physics with high-intensity pulsed muon beam,**
  - **High-rate capable detector and**
  - **Precision control and monitoring of environment**
    - **are essential.**
- **MuSEUM has got underway as a new generation of precision measurement with the highest intensity pulsed muon beam.**

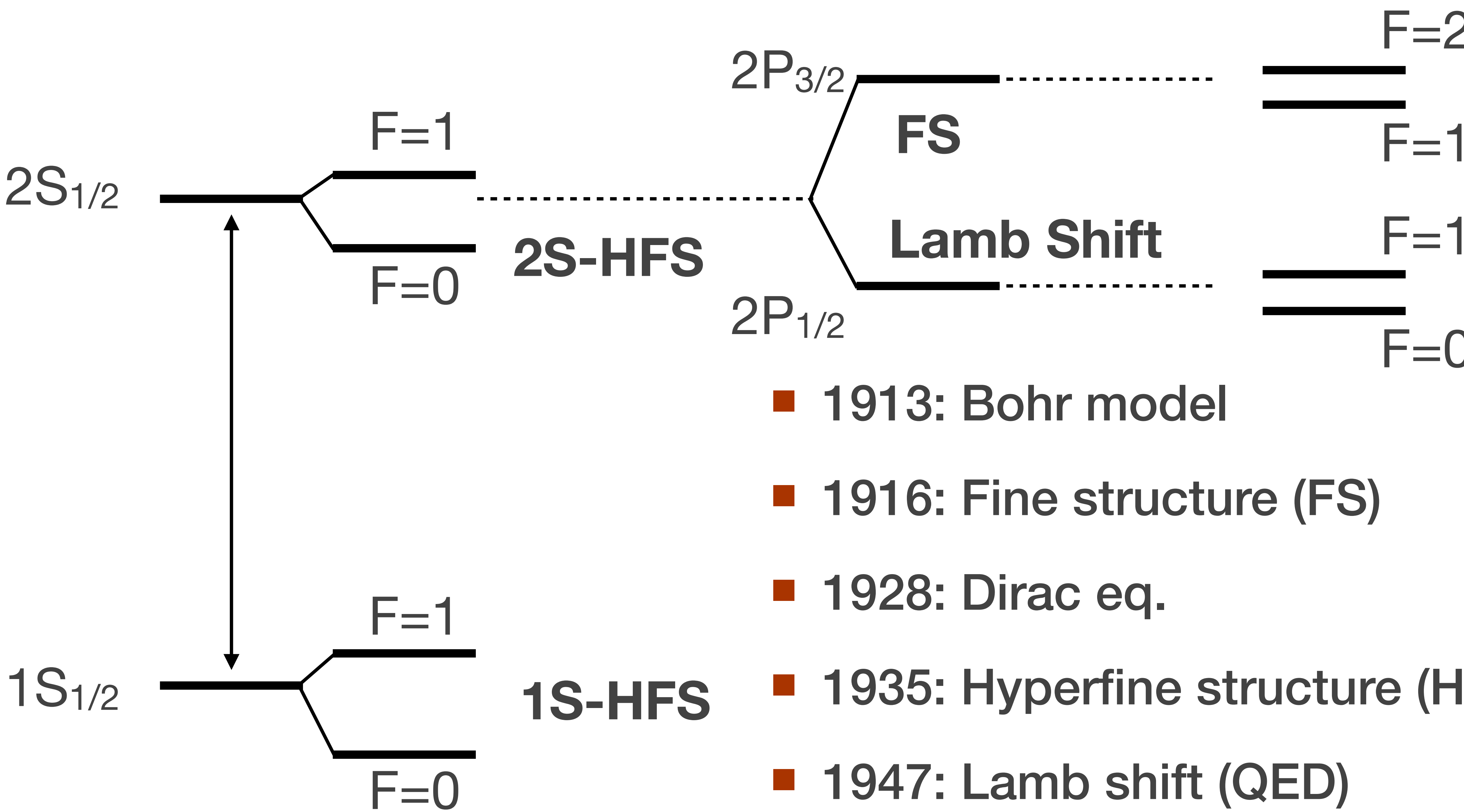
Supplements

Environment Monitors

Object	Instrument
Static B-Field	Fluxgate probe
RF Power	Thermal power sensor
Gas Pressure	Capatitance gauge
Gas Purity	Q-Mass
Temperature	Thermocouple

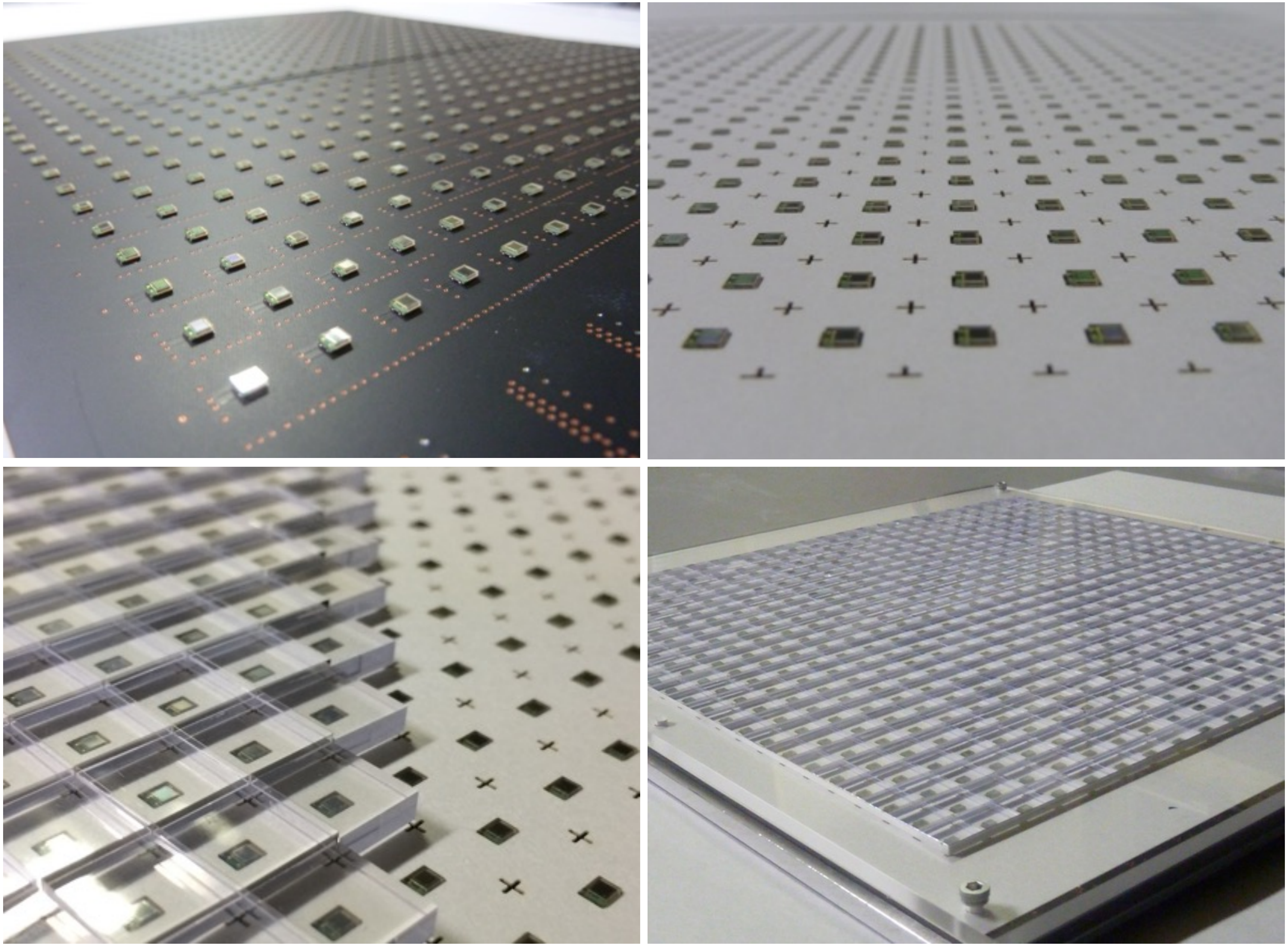
Hydrogen Atom Spectroscopy

- The progress of hydrogen atom spectroscopy had brought evolution of quantum mechanics



- 1913: Bohr model
- 1916: Fine structure (FS)
- 1928: Dirac eq.
- 1935: Hyperfine structure (HFS)
- 1947: Lamb shift (QED)

Positron Detector



MPPC on PCB