30-ps Time Resolution with Segmented Scintillation Counter for MEG II

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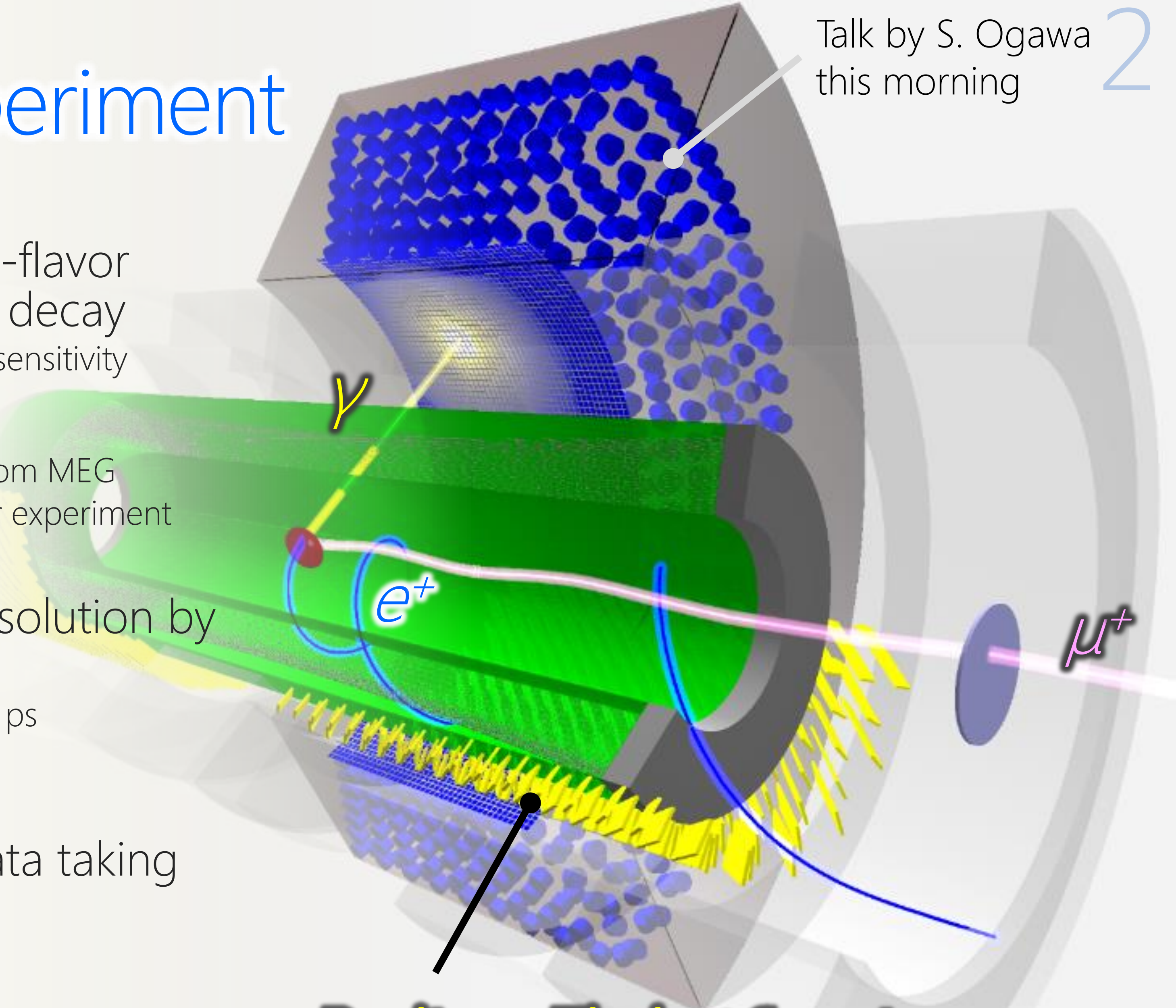
- 14th Vienna Conference on Instrumentation (16 Feb, 2016)

MEG II Experiment

- Search for lepton-flavor violating $\mu \rightarrow e\gamma$ decay
  - With unprecedented sensitivity
    4×10^{-14}
  - $\times$10 improvement from MEG
  - High-intensity frontier experiment
- Improve every resolution by factor 2
  - e^+ timing with $\sigma \sim 30$ ps
- Aim at physics data taking from 2017

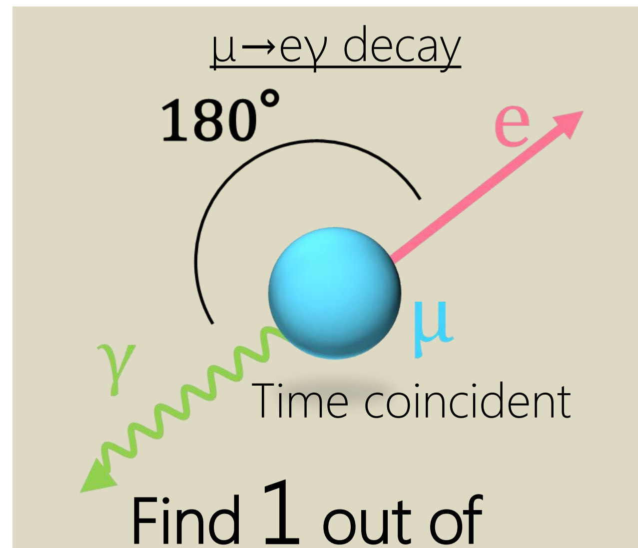


$\mathcal{O}$(10 ps) Time Resolution

- Limits with Scintillator (+PMT) TOF
  - ☐ Best achieved $\sigma_{counter}$~50 ps* (* for a MIP)
    Thick bar, directly coupled to Fine-mesh PMTs, typically ~1 m
  - ☐ More limited in **practical** usage (σ_{total}~70 – 80 ps)
    - *Variation of photon-arrival time due to position/angle dependence*
    - *PMT degradation in B-fields*
    - *Inter-bar time jitter*
    - *Quality control in mass production*

Next targets of timing measurements: $\mathcal{O}$(10 ps)

- (M)RPC
- Cerenkov counters
- Ultra-fast silicon detectors
- Scintillation counters with SiPMs



Find 1 out of 10^{14}

Strategy

- Pursue the ultimate time resolution of single detector?
  - Many developments underway
  - May suffer from some degradation in practical usage
    - Easily limited by: Noise, degradation of device, electronics jitter, inter-counter time alignment, quality in mass production, etc.

Performance in lab hasn't been necessarily achieved in real experiments

- Yet another way: **Multiple measurements**
  - Easier & more robust way
  - Able to overcome such practical issues, as well.
  - Ideally, expected to improve as

$$\sigma_{\mathrm{total}}(N_{hit}) = \frac{\sigma_{\mathrm{total}}^{\mathrm{single}}}{\sqrt{N_{hit}}} = \sqrt{\frac{\sigma^2_{\mathrm{counter}} + \sigma^2_{\mathrm{inter-counter}} + \sigma^2_{\mathrm{elec}}}{N_{hit}}}$$

Merits of **SiPM-Scintillator** counters

1. Intrinsic high time resolution

- High light yield
  but finite time response of scint.
- σ=15 ps $/\sqrt{E/(1\ \mathrm{MeV})}$ is achievable,
  better than the best result with PMT

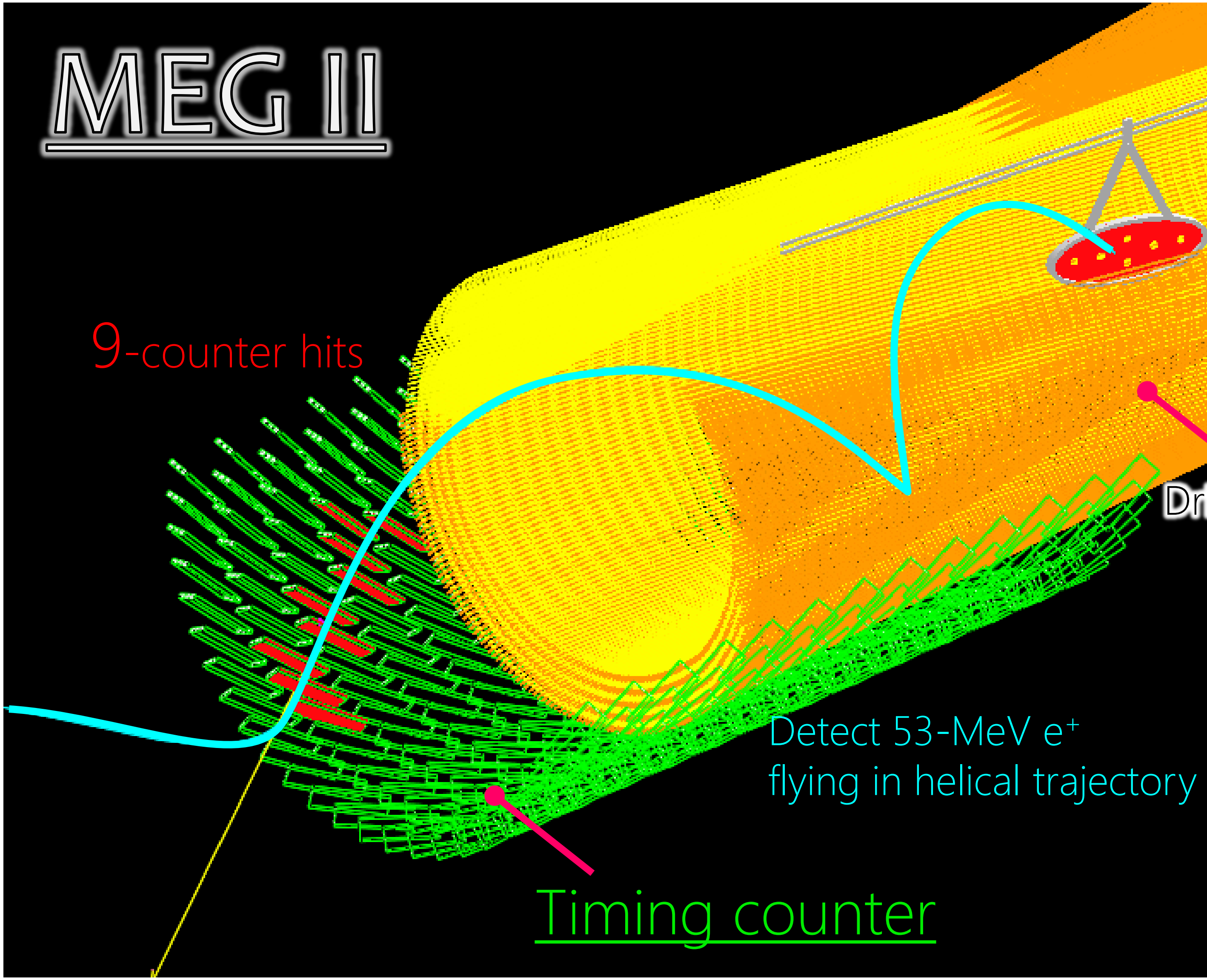
⇔ Cerenkov counter
Prompt response
but low light

2. Flexible detector layout

- Compact, cheap, B-field immunity, etc.
- ⇒ Multiple hits measurements

Highly Segmented Detector

- Ex.



Preceding study

- Pioneering study by A. Stoykov *et.al.*

  - σ = 18 ps/$\sqrt{E/(1\ \mathrm{MeV})}$

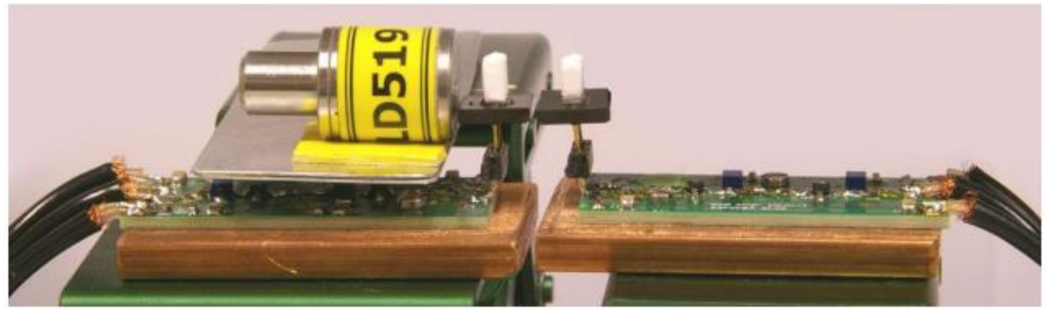
  Compared with the best results with PMTs

  - σ = 19 ps/$\sqrt{E/(1\ \mathrm{MeV})}$

    - Scintillator: NE111 (Φ:25 mm × H:10 mm)
    - PMT: XP2020UR-M
    - Time pickoff unit: CFD

    M.Moszynski, NIMA 337 (1993) 154

A. Stoykov et.al., NIM-A **695** 202 (2012)



Scint.: **BC422** (3x3x2 mm^3), reflector – Teflon tape, coupling with optical grease via 3x2 mm^2 face

G-APDs: **MPPC S10362-33-050** (3x3 mm^2)
$U \sim 70$ V, $I_0 = 1.0\ \mu$A

- What's the progress since the last VCI?
- How to enlarge?

Limitations?

SiPM characteristics,
coverage of SiPMs & the connection method

① **Scintillator** Light yield, Time response × **SiPM** PDE ⊕ ② **SiPM dark count** (incl. afterpulsing) × **Pulse shape** SiPM × Elec.

Scintillator choice
& the dimension

Electronics design

* SPTR (or TTS) of SiPM is not so relevant to scintillation counter ⇔ Cerenkov counter
(already good enough (~100 ps))

- Predominant limitation comes from photon statistics ①.
  ⇒ Increase effective **sensor area** to improve resolution or to enlarge counter size
- Then, the other contributions ② become severe issues

Amplifier

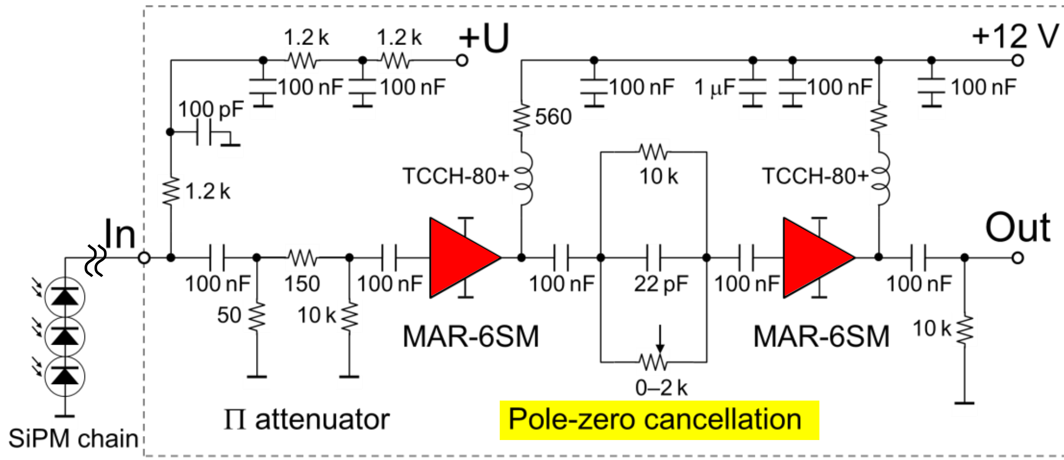
- For higher flexibility and applicability, **simple readout system** is important
- High-bandwidth low-noise **voltage** amplifier (2-cascade) with **50Ω** input impedance
  - ☐ Allows long signal-transmission.
  - ☐ However, forms slow RC time constant with SiPM high capacitance, especially with larger area.

<u>Two counter-measures</u>

1. **Pole-zero cancellation** circuit to pickup leading-edge part signal and to quickly restore stable baseline

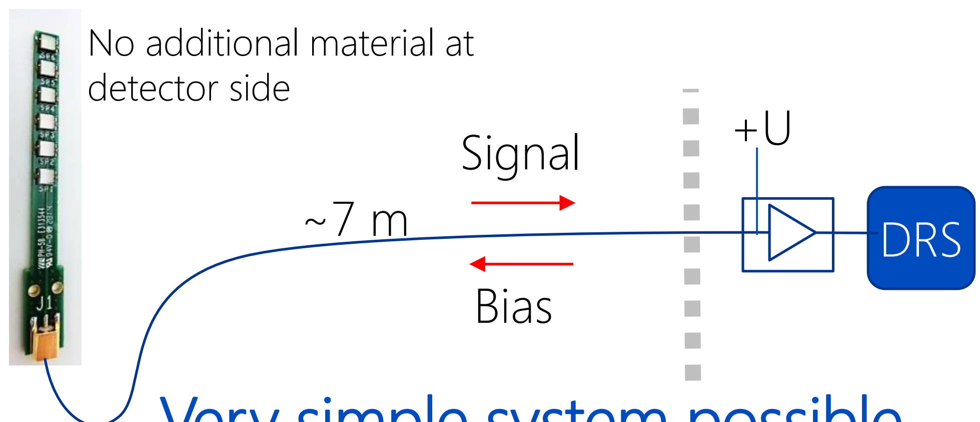
✓ <u>Against high dark count</u>

By U. Greuter & A. Stoykov (PSI)



Input impedance: ~50Ω
Gain: 970 V/A
Bandwidth: 800 MHz

No additional material at detector side



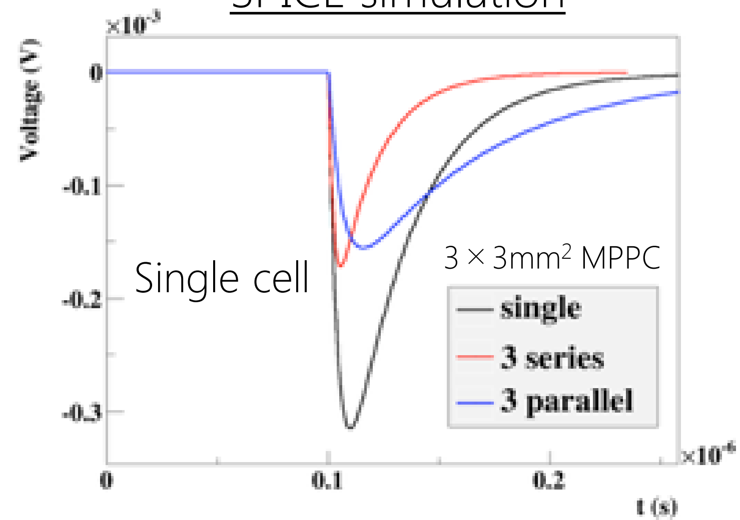
Very simple system possible

Series connection of SiPMs

- SiPMs have high capacitance
  - Terminal capacitance ~300 pF for 3 × 3 mm^2 SiPM
- This forms a slow RC time-constant with amplifier input impedance
  - 3 × 3 mm^2 : 300pF × 50Ω = 15 ns
  - 3 × 9 mm^2 : 900pF × 50Ω = 45 ns !!

    → *One of limitations for large area SiPMs or array of SiPMs with parallel connection*

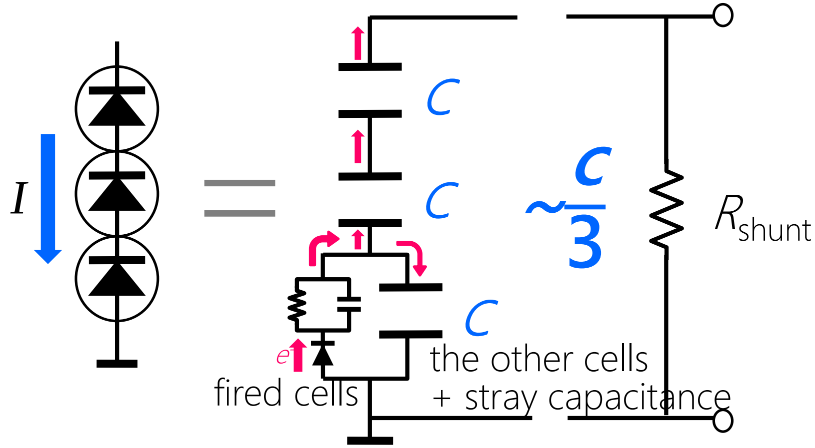
SPICE simulation



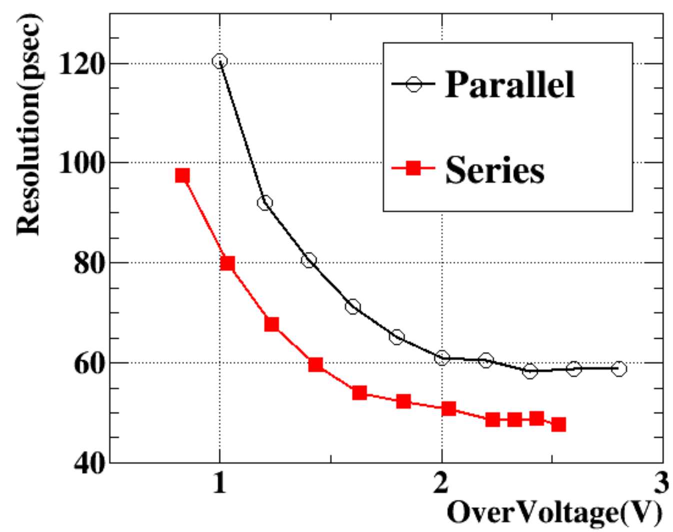
- This large capacitance works as capacitive coupling when connected **in series**

Bias voltage is divided to have common leakage current

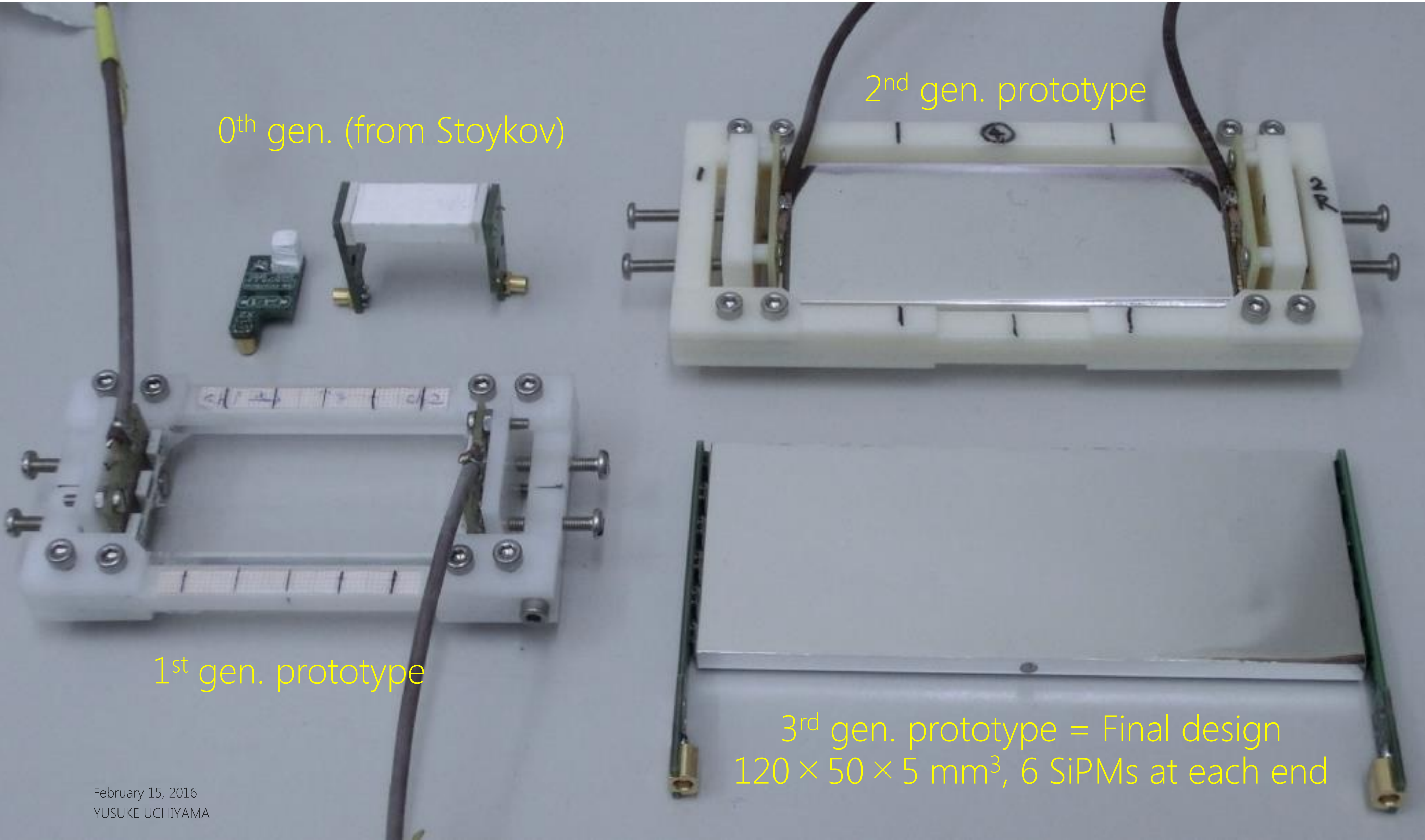
Automatically equalizes the over-voltages



Measurement with 3 MPPCs

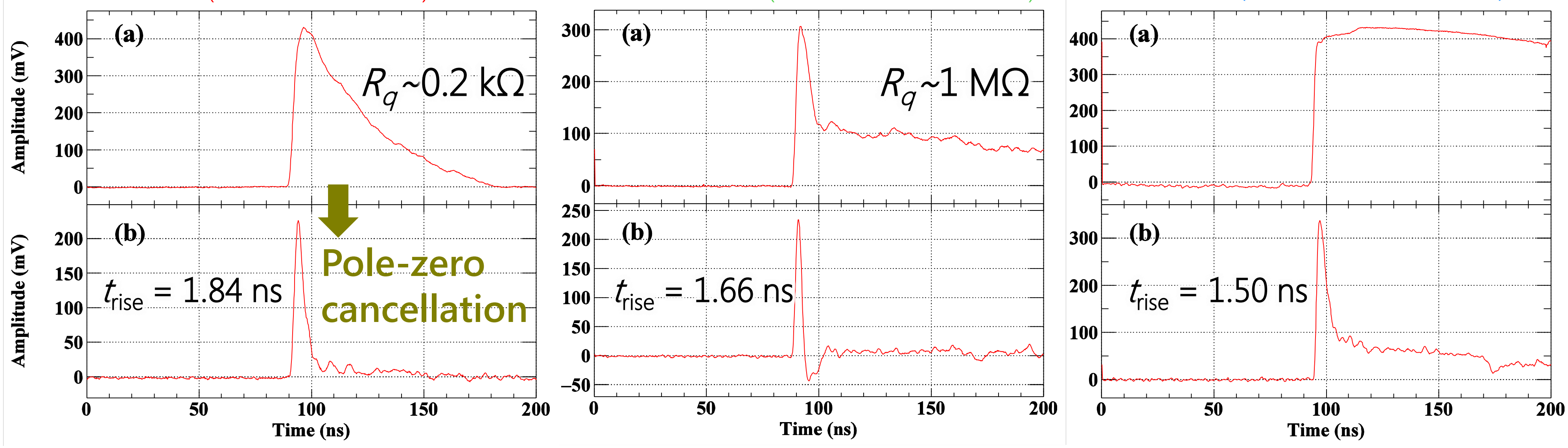


Tested Counters

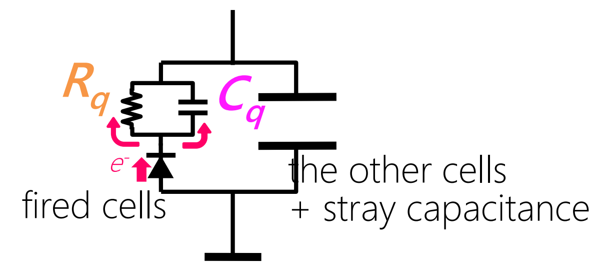


SiPM Comparison: Pulse shape (3-series)

HPK (S10362-33-050C) | AdvanSiD (ASD-NUV-SiPM3S-P) | SensL (MicroFB-30050-SMT)

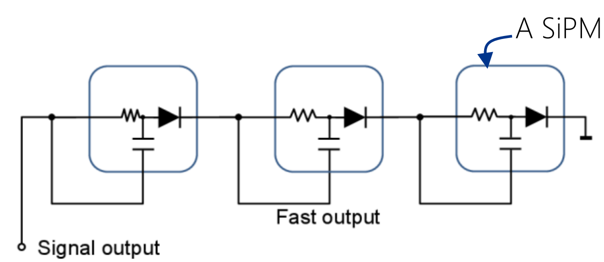


- Pulse shape depends on R_q & C_q
  - C_q is important for the fast signal
  - Slow tail by larger R_q can be omitted with pole-zero cancellation



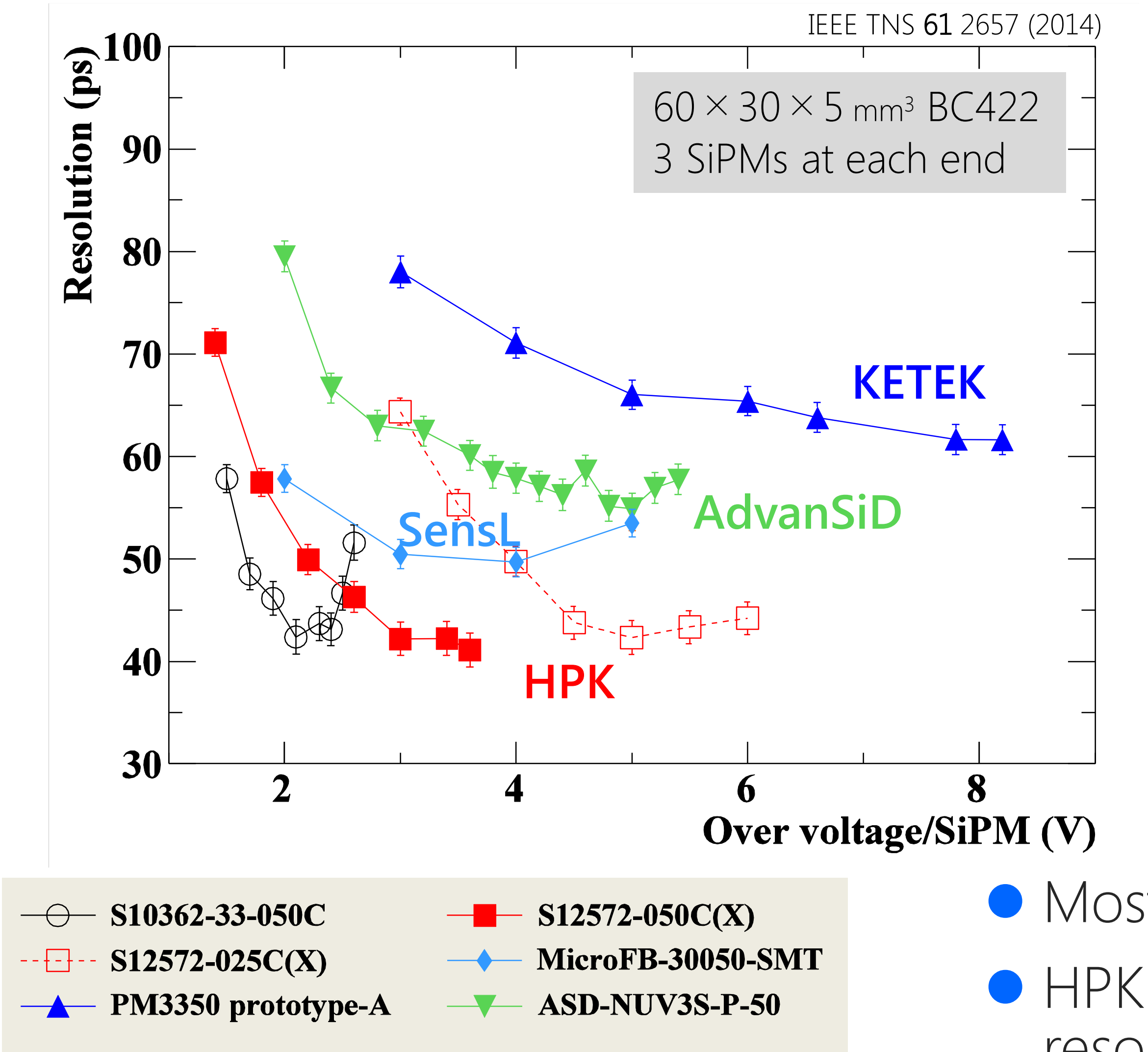
- SensL's fast output terminal can be used to make very fast rise time

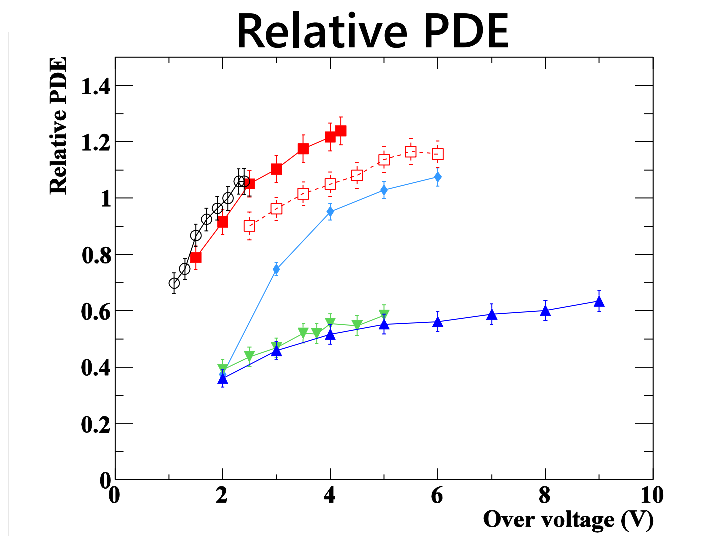
A method to combine the fast output into the normal signal line (by N. Pavlov)



SiPM Comparison

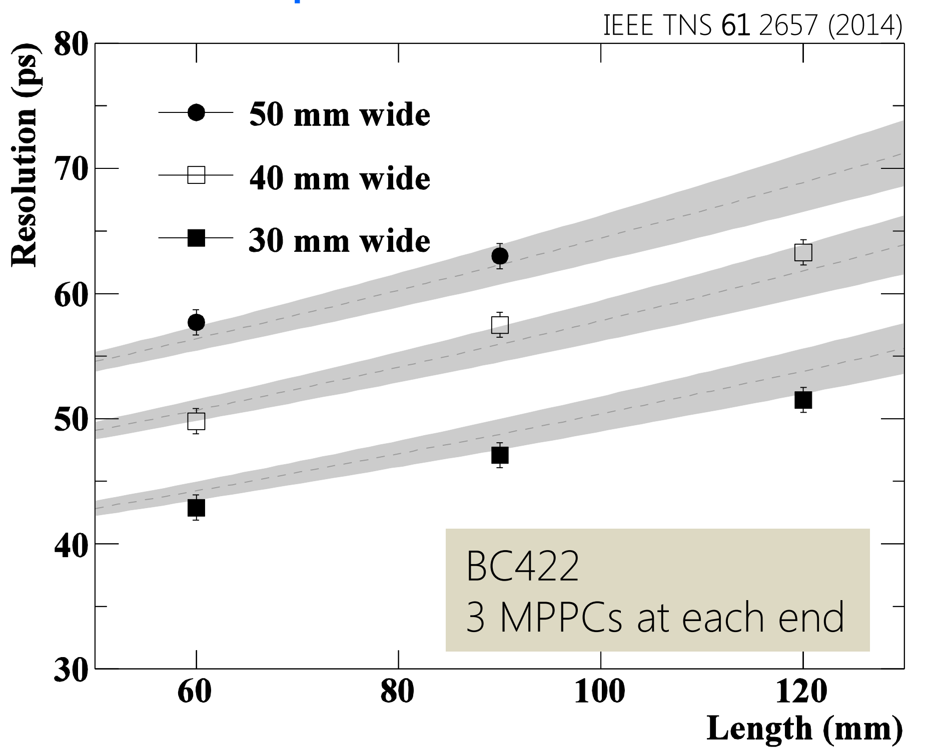
As of 2013



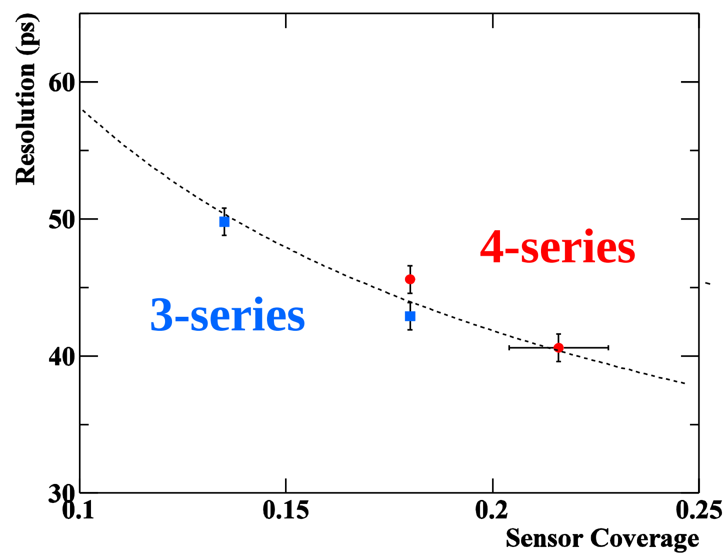


- Most relevant parameter is **PDE**
- HPK MPPCs give the best time resolution

Size dependence



- Final choice is given by optimization between
  - Single counter resolution (small size) and Hit multiplicity & efficiency (larger size)
  - Performance of SiPMs and Number of SiPMs (cost)

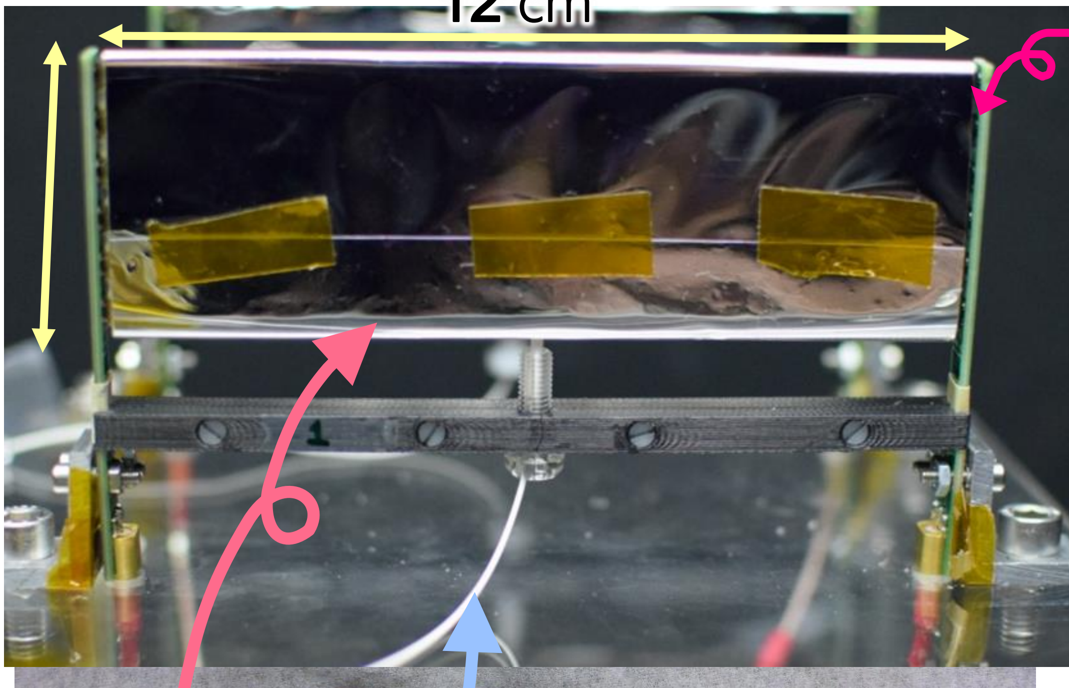


- Size dependence is well on the photon statistics calculated with
  - Sensor coverage × Scint. light attenuation
- σ<70 ps achieved up to
  - Length = 120 mm
  - Width = 50 mm

Final Design

12 cm

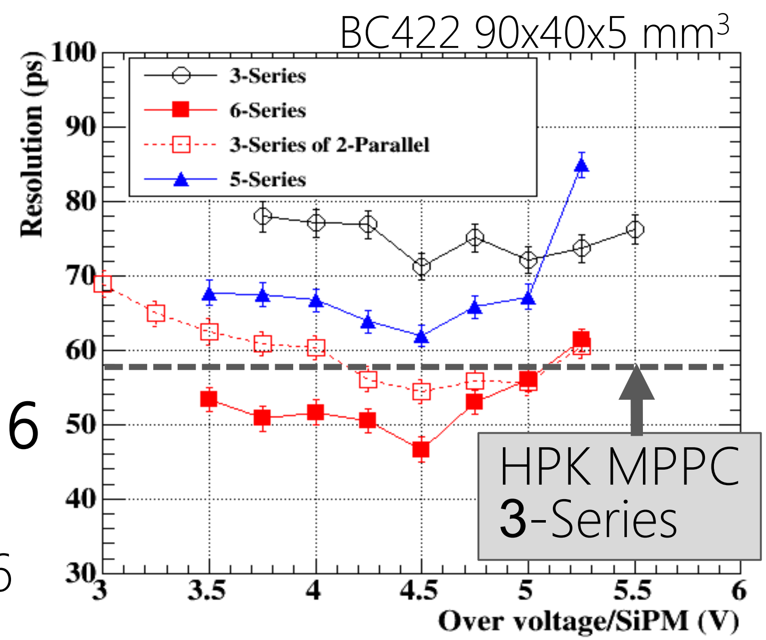
4 cm or 5 cm



6 SiPMs in series at the both ends

AdvanSiD **3x3** mm^2, **50x50** μm^2 pixels

$V_{breakdown}$ ~ 24 V (145 V for 6 series)



Fast Plastic Scintillator
BC422
wrapped in ESR2 film

Optical Fiber
Inter-counter time calibration with laser

Resolution

HPK ×3 > AdvanSiD ×6

Cost

HPK ×3 ≈ AdvanSiD ×6

We decided to employ AdvanSiD SiPM

Intrinsic Resolution

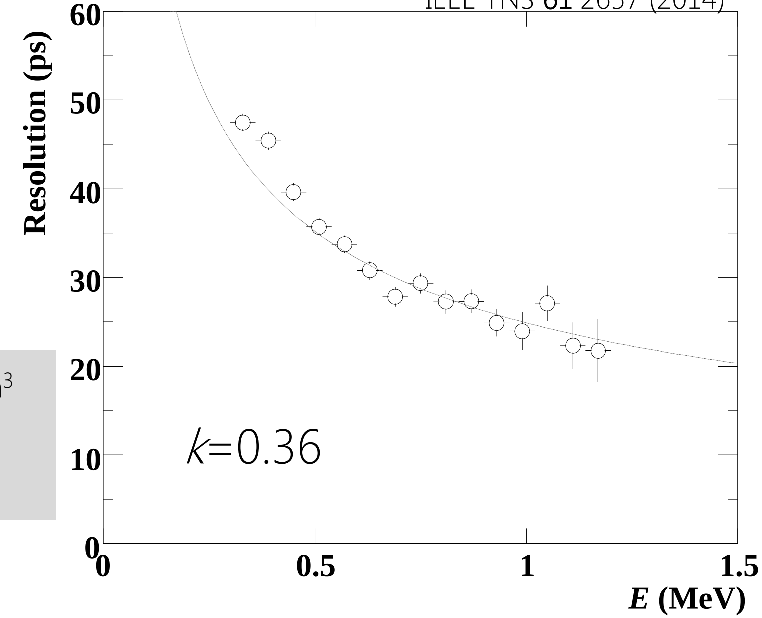
- Measured with small counters

$$\sigma \cdot (kE)^{0.5}$$
$$= 15\ \mathrm{ps} \cdot \mathrm{MeV}^{0.5}$$

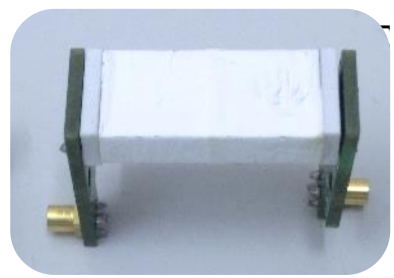
(k: SiPM coverage to scint. cross-section)

$5 \times 5 \times 5$ mm[3]
BC422
1 MPPC

IEEE TNS **61** 2657 (2014)

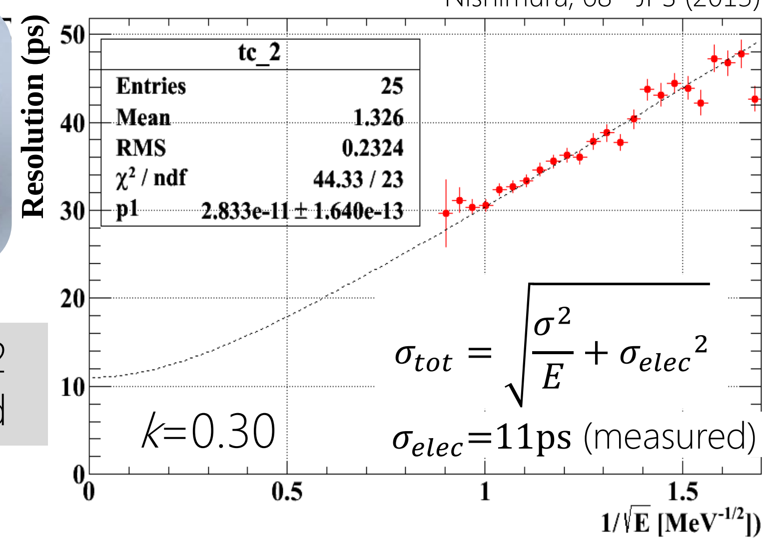


This is the **best** achievable resolution to date with scint. + PMTs/SiPMs.



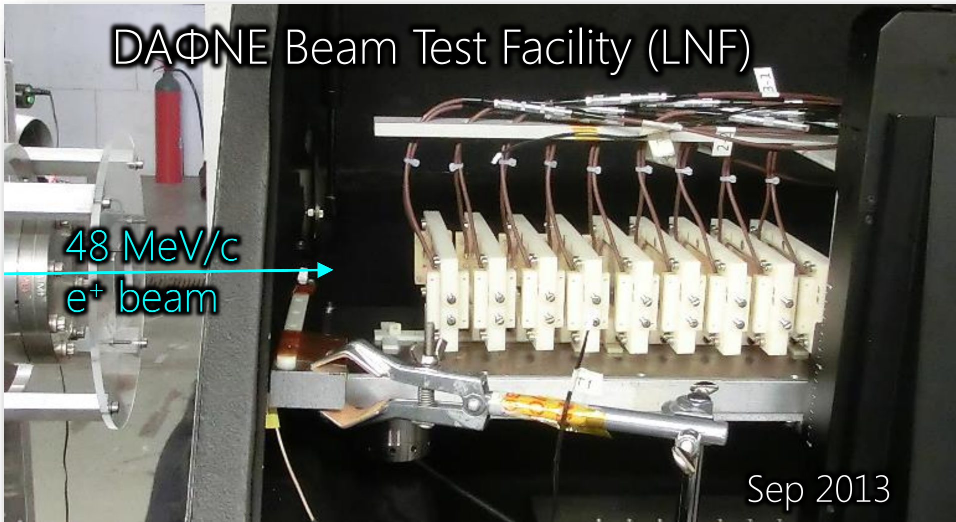
$25 \times 12 \times 5$ mm[3] EJ232
2 MPPCs at each end

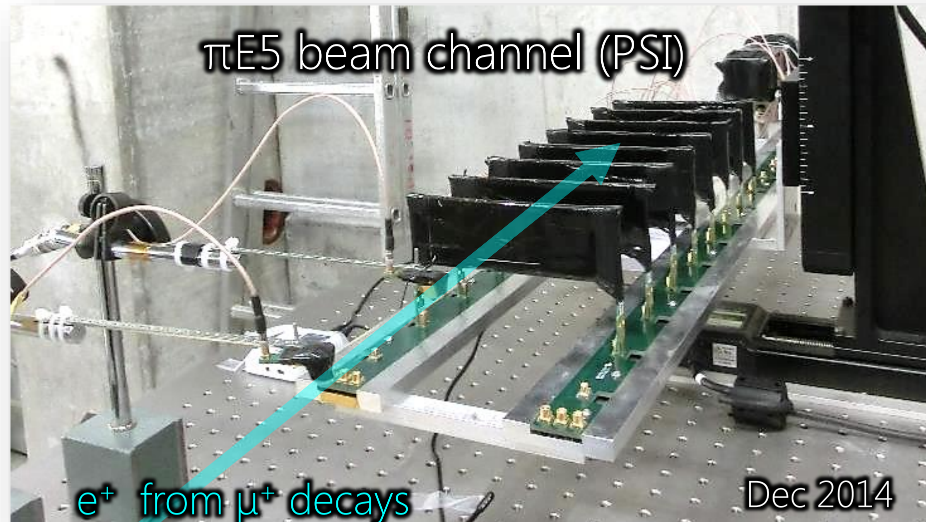
Nishimura, 68th JPS (2013)



Beam Tests

- To demonstrate the multi-hits measurements



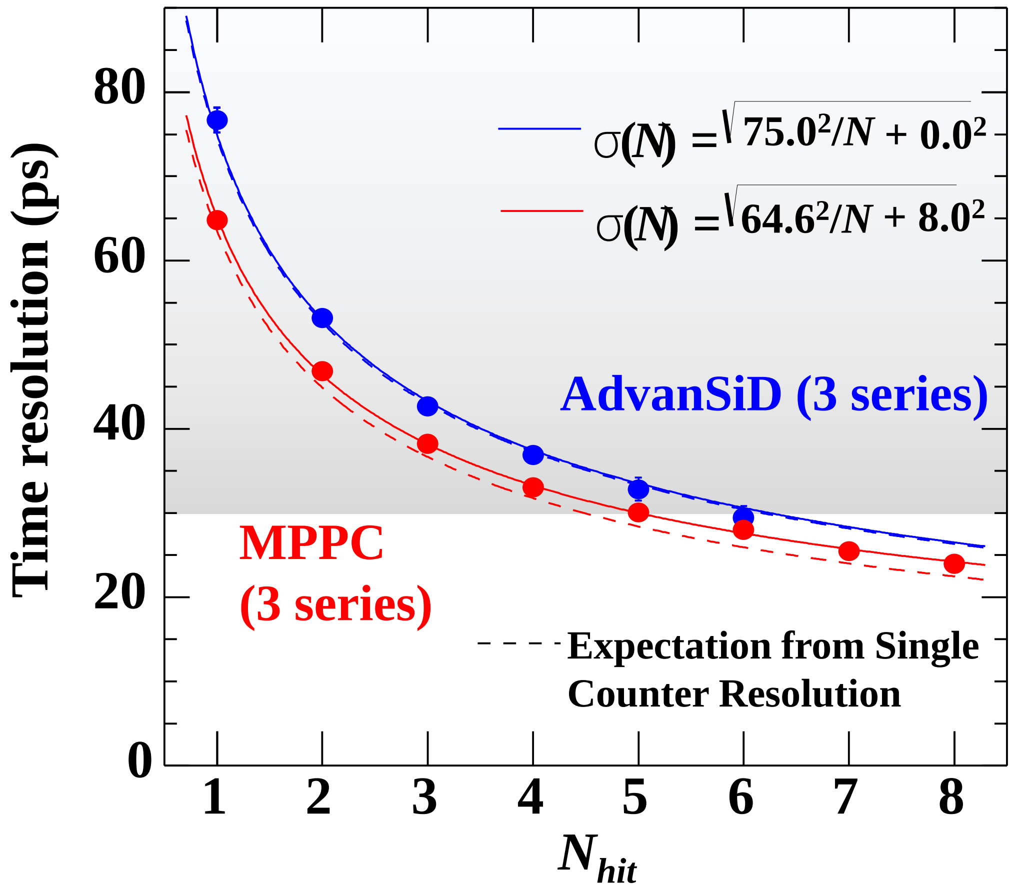


- 2nd gen. prototype counters
  - $90 \times 40 \times 5$ mm^3, BC418
  - Test MPPC & AdvanSiD
- Monochromatic e^+ beam
- 50 Hz repetition

- 3rd gen. prototype counters
  - $120 \times (40 \text{ or } 50) \times 5$ mm^3, EJ232
  - AdvanSiD
- e^+ from muon decays (10^8 μ^+/s)
- MEG-II expected hit rate

Results

arXiv:1511.03891 (2015)



Scintillator: BC418, 90 × 40 × 5 mm^3
MPPC: S10943-2547(X) (3 × 3 mm^2, 50 µm)
AdvanSiD: ASD-NUV-SiPM3S-P (3 × 3 mm2, 50 µm)

- Multi-counter measurement improves the time resolution closely as

$$1/\sqrt{N_{hit}}$$

- $\sigma(N_{hit}=8)$ = 24 ps
  achieved with HPK MPPCs

- Note that,
  1. Thickness of N_{hit}=8 is 4 cm, corresponding to 1 scint. bar of typical TOF
  2. This result is with the SiPM coverage k=0.135, still large room for further improvement

At MEG-II expected hit rate

- Small degradation was observed at higher hit rates.
- At MEG-II rate, degradation is moderate and still good resolution is obtained.

AdvanSiD: ASD-NUV3S-P-50 (3 × 3 mm2, 50 μm)
This prototype model was found to have worse performance
Scintillator: EJ232, 120 × (40 or 50) × 5 mm^3

From MC study (height is **4** cm)

Length [cm]	Average Rate (kHz)	Highest Rate (kHz)
12	70.2	174

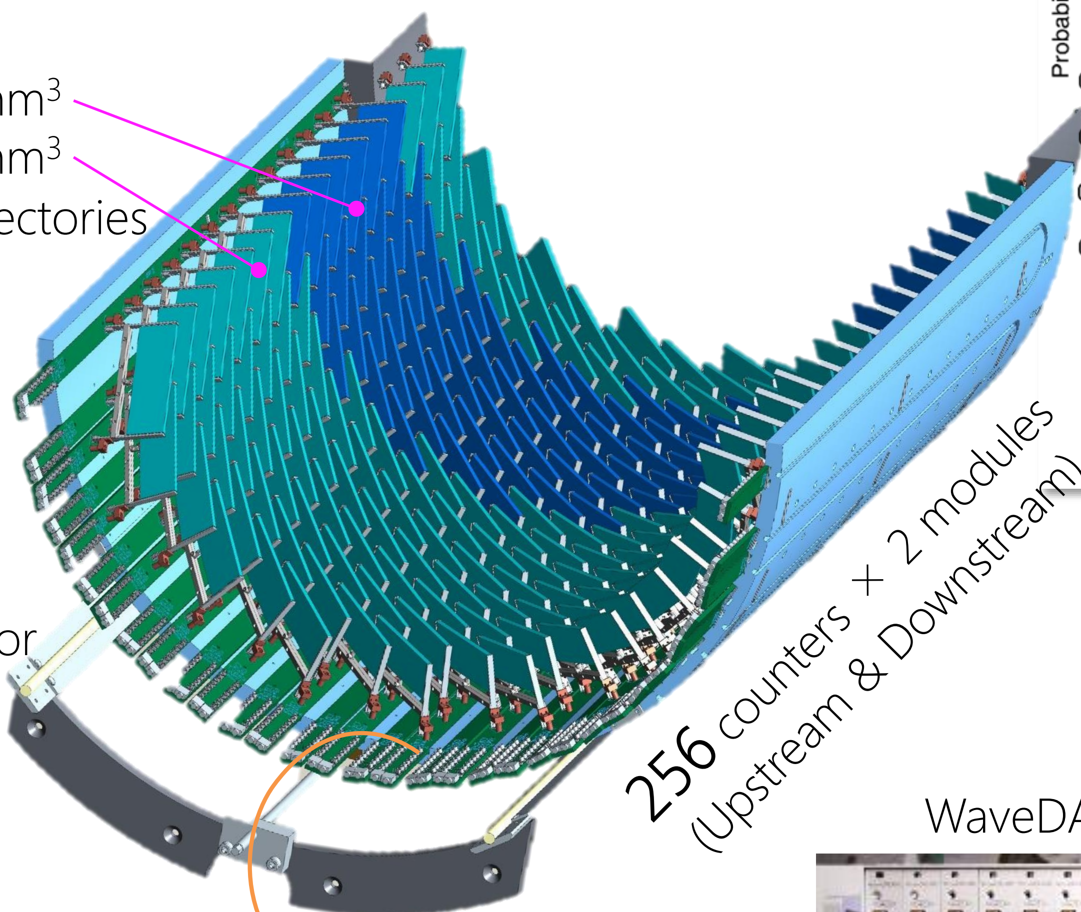
R&D completed

Proved **30-ps** resolution with MEG II TC design

Final detector construction

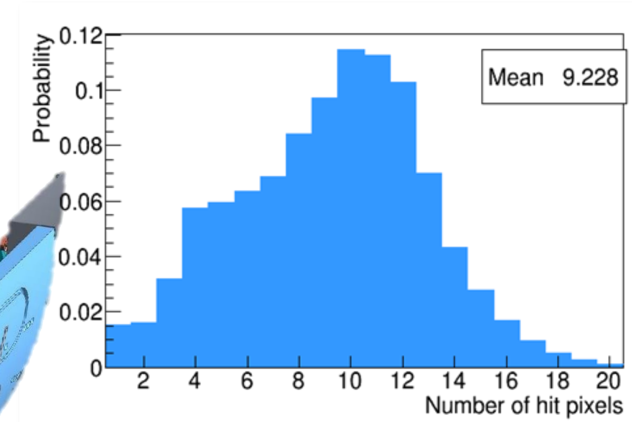
Design of MEG-II Timing Counter

2 different sizes
$120 \times 50 \times 5\ \mathrm{mm}^3$
$120 \times 40 \times 5\ \mathrm{mm}^3$
to follow e^+ trajectories



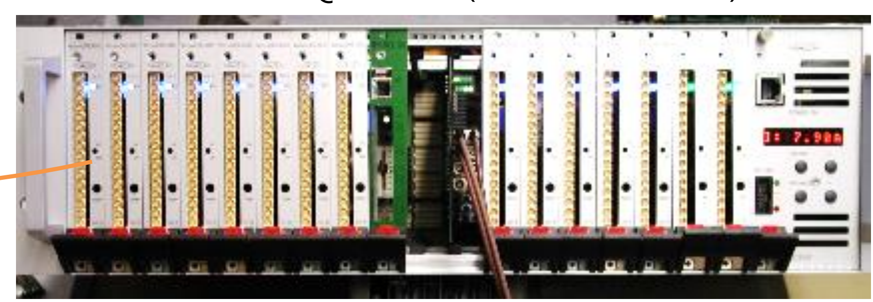
1-m long PCBs
transmit signal
to outside detector

256 counters + 2 modules
(Upstream & Downstream)



Number of hits per e^+ track
from $\mu \to e\gamma$ (MC)

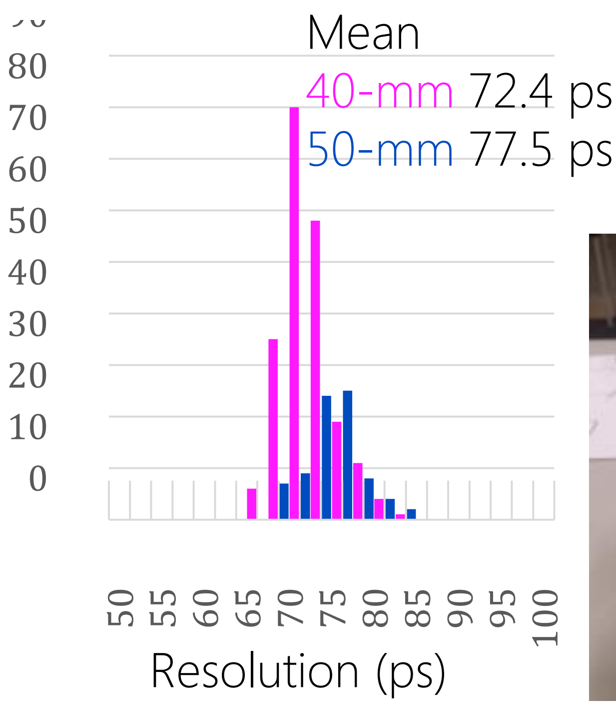
WaveDAQ crate (256 ch/crate)

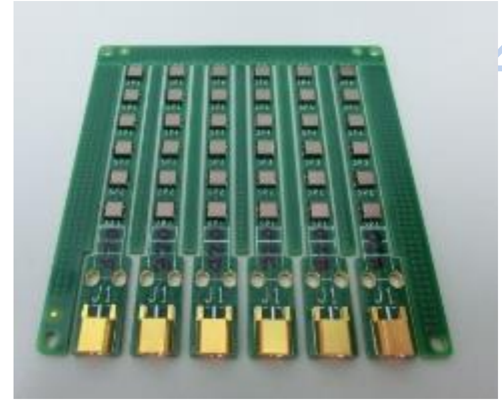


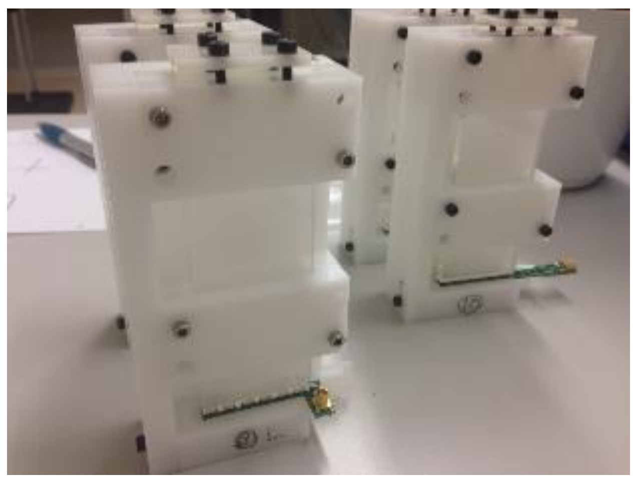
7-m coaxial cable (RG178)

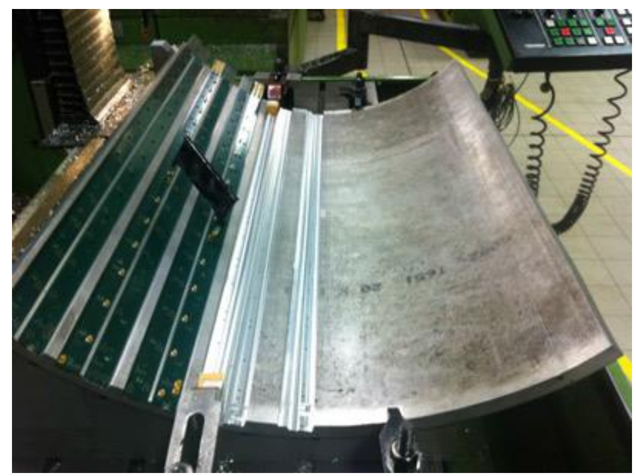
Construction

- All material procurements done in 2015
- Counter assembly by hand
  - Scintillator replacement for bad production by Saint-Gobain
  - Variation of SiPM performance was observed
  - For those reasons, mass-produced counters have slightly worse resolutions on average.

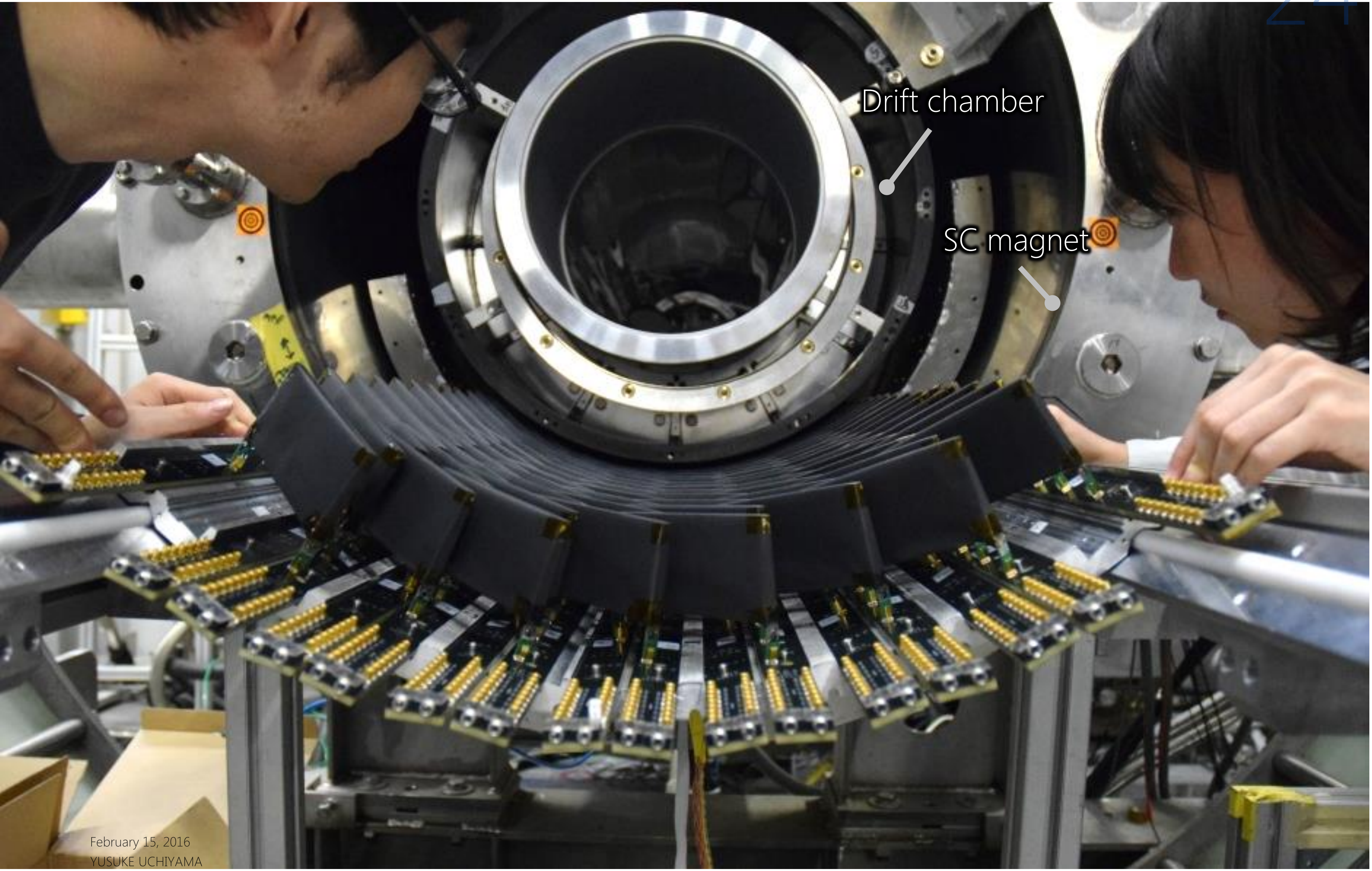









128 counters (half of downstream module)

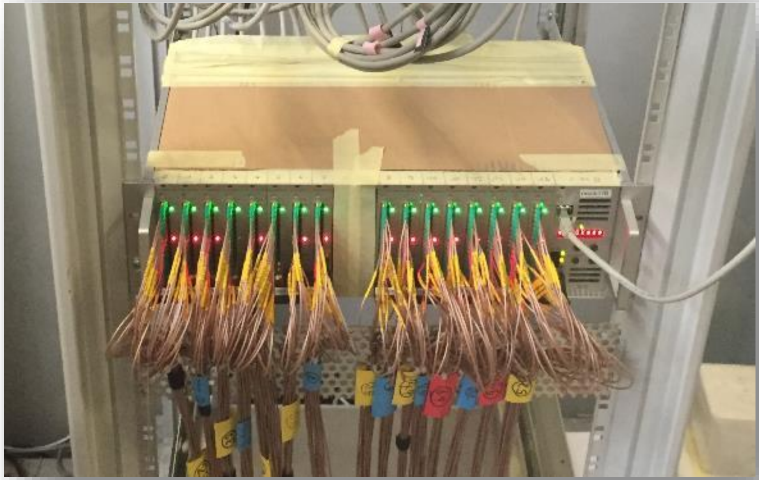

Drift chamber
SC magnet

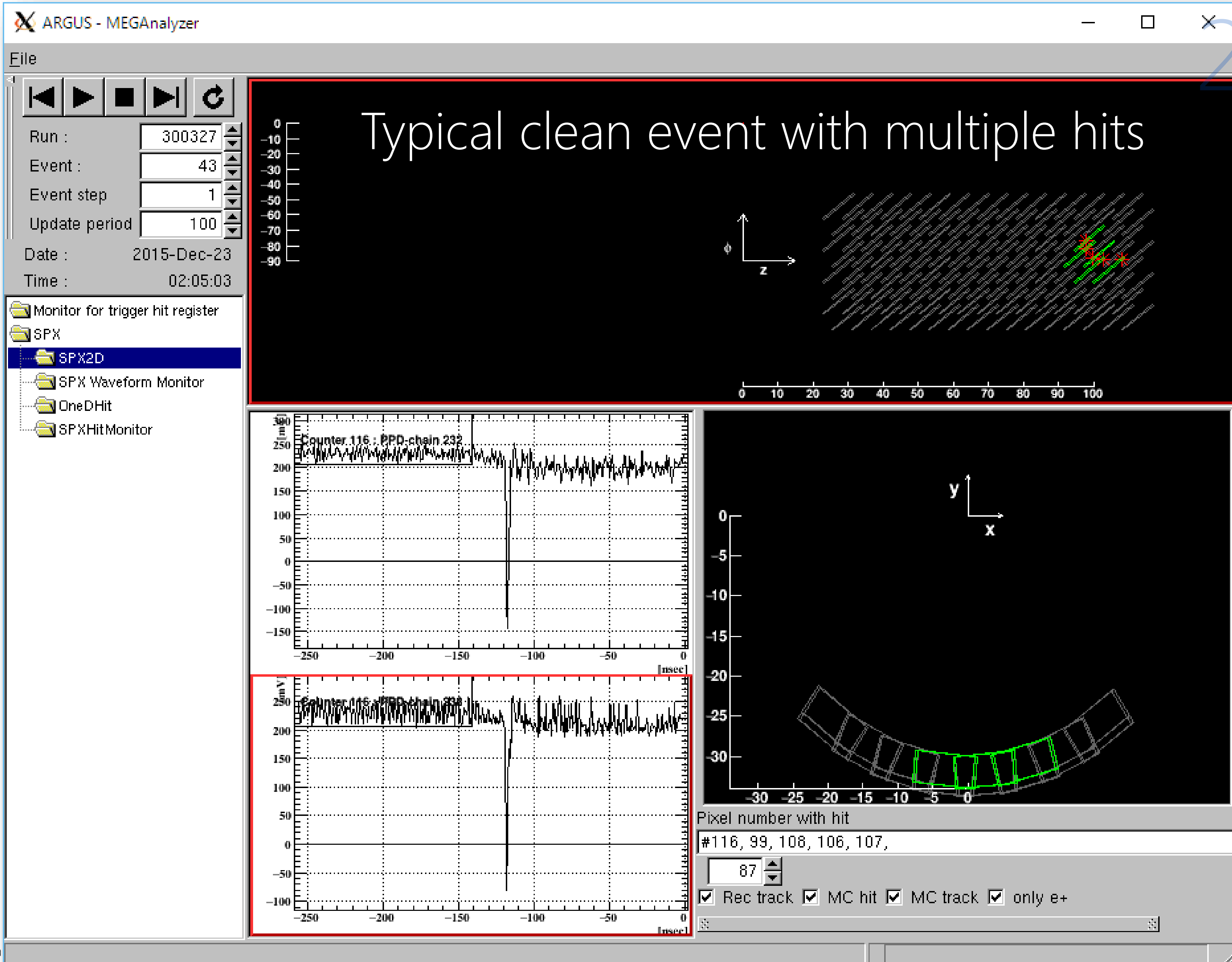
Pilot Run in 2015

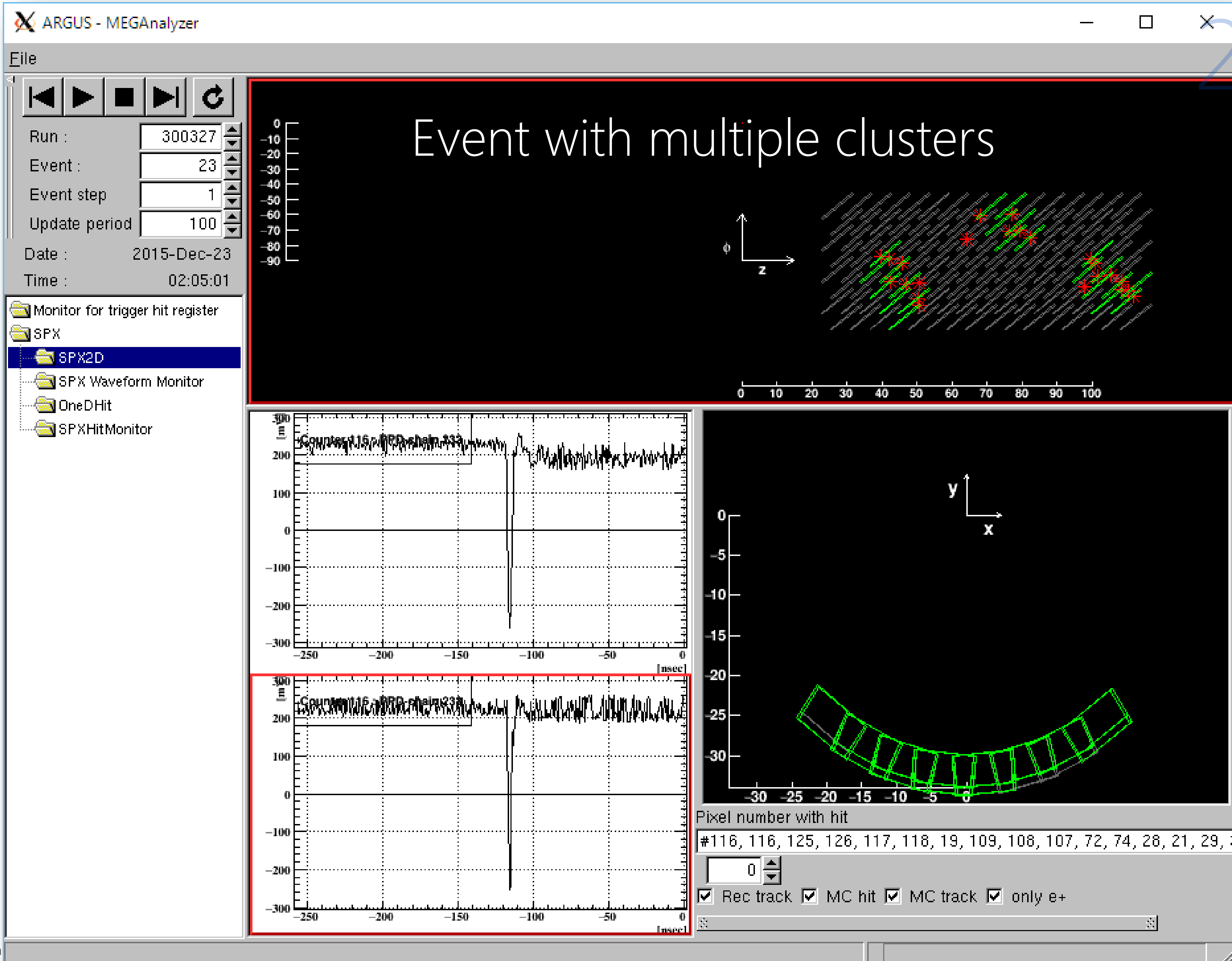
<u>We achieved</u>

- Build ¼ detector
- Hardware works properly
  - NO dead channel
- Test Laser calibration system
  - Laser pulse distribution into 8 counters.
- Test MEG-II electronics system
  - Biasing OK, trigger works well.
  - Figured out several problems in readout system.
- Test counters in MEG-II beam (Dec.)

◆ Analysis of the data underway




ARGUS - MEGAnalyzer
File
Run : 300327
Event : 43
Event step 1
Update period 100
Date : 2015-Dec-23
Time : 02:05:03
Monitor for trigger hit register
SPX
SPX2D
SPX Waveform Monitor
OneDHit
SPXHitMonitor
Typical clean event with multiple hits
Counter 116 : PPD-chain 232
[nsec]
Pixel number with hit
#116, 99, 108, 106, 107,
87
Rec track
MC hit
MC track
only e+


ARGUS - MEGAnalyzer
File
Run : 300327
Event : 23
Event step 1
Update period 100
Date : 2015-Dec-23
Time : 02:05:01
Monitor for trigger hit register
SPX
SPX2D
SPX Waveform Monitor
OneDHit
SPXHitMonitor
Event with multiple clusters
Pixel number with hit
#116, 116, 125, 126, 117, 118, 19, 109, 108, 107, 72, 74, 28, 21, 29,
Rec track
MC hit
MC track
only e+

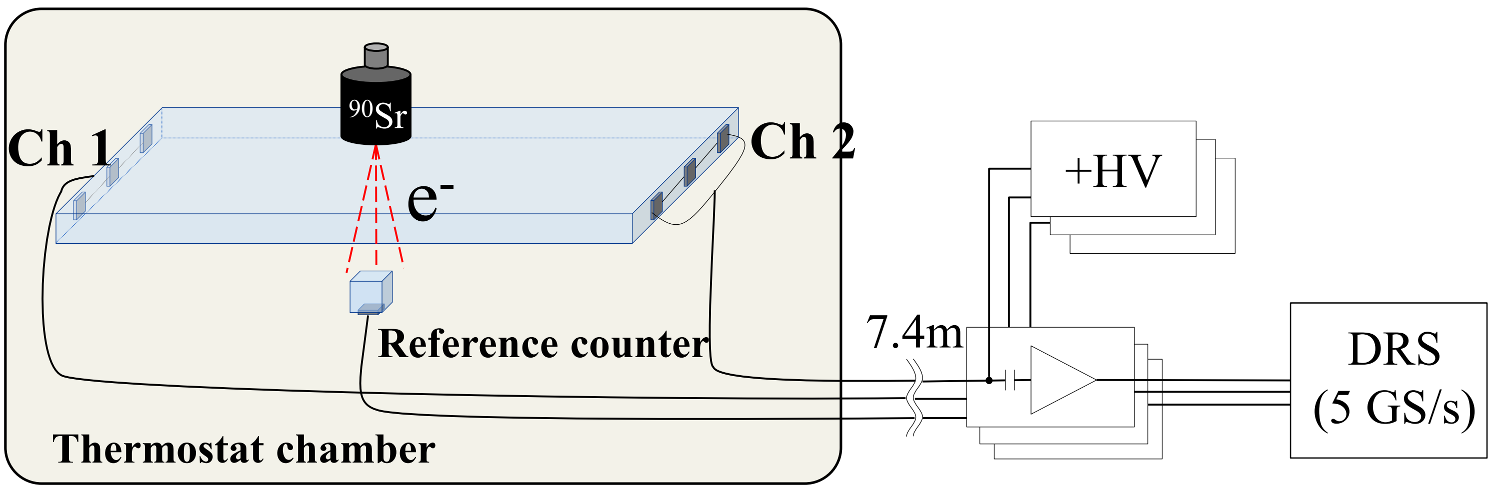
Summary

- SiPM-based scintillation counters can provide <30 ps time resolution
  - Intrinsic resolution of $\sigma=$**15 ps**$/\sqrt{E/(1\ \mathrm{MeV})}$ is achievable with a single small counter
  - More importantly, SiPM application allows flexible design of your detectors
  - ⇒ Multiple measurements of a particle time, improving closely as $\mathbf{1/\sqrt{\mathit{N}_{hit}}}$
- R&D for the MEG-II Timing Counter was completed
  - 30-ps resolution was demonstrated
  - Tested first ¼ detector in 2015
  - Full detector will be ready by this summer

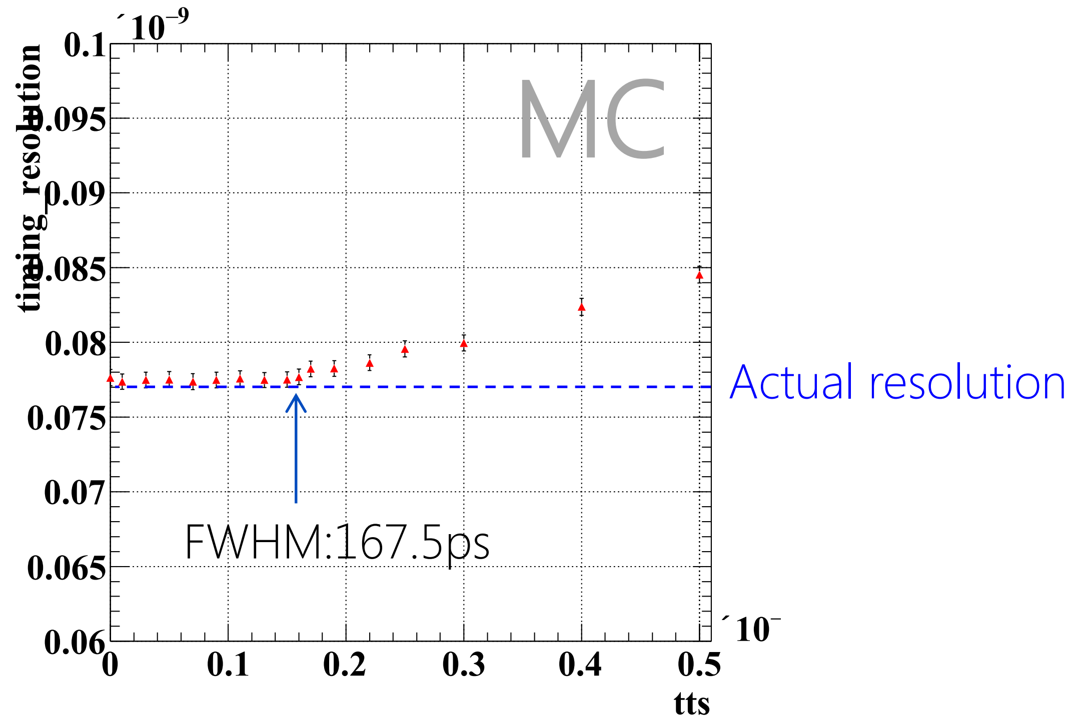
Material & Methods

- Scintillator
  - **BC422**
    The best for timing performance with small dimensions
    Ultra fast rise time (< 20 ps reported)
  - Test several sizes
- SiPMs & their connection
  - Use multiple 3 × 3-mm^2 SiPMs
  - Connected in series
  - Test several candidates
- Readout elec.

<u>Lab test setup</u>

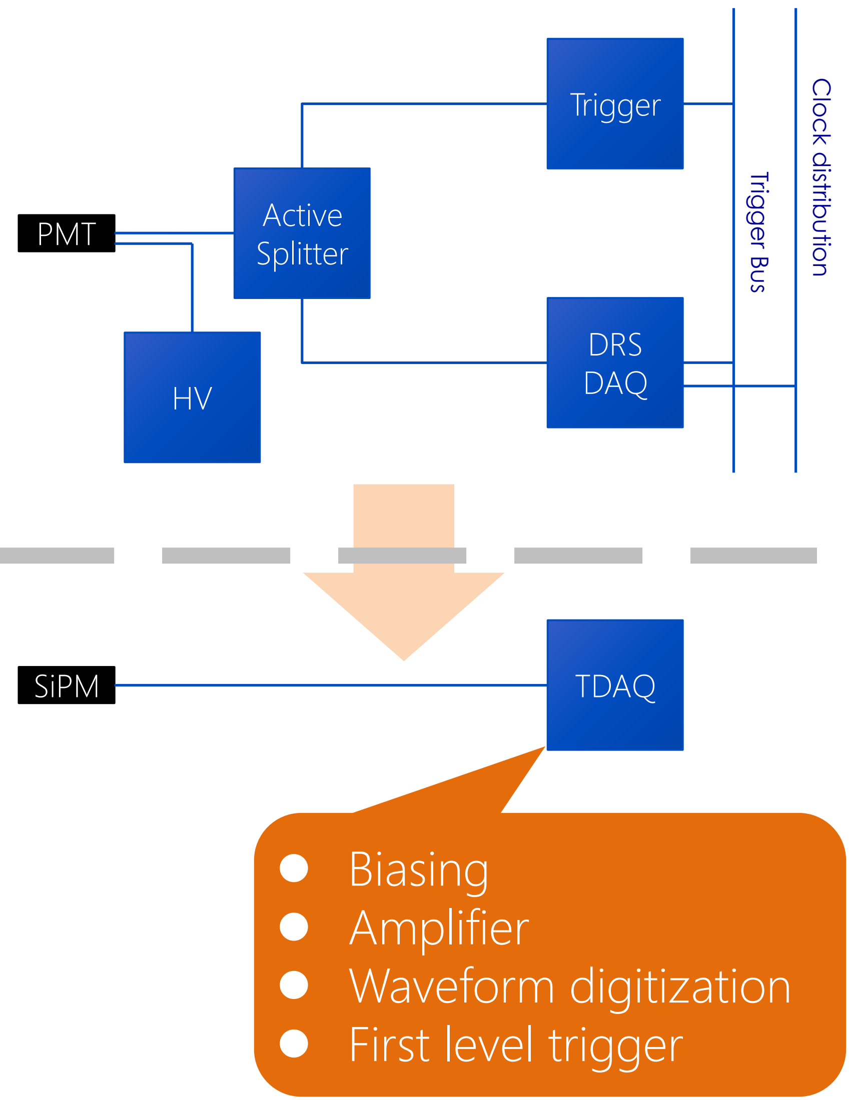


Transit Time Spread

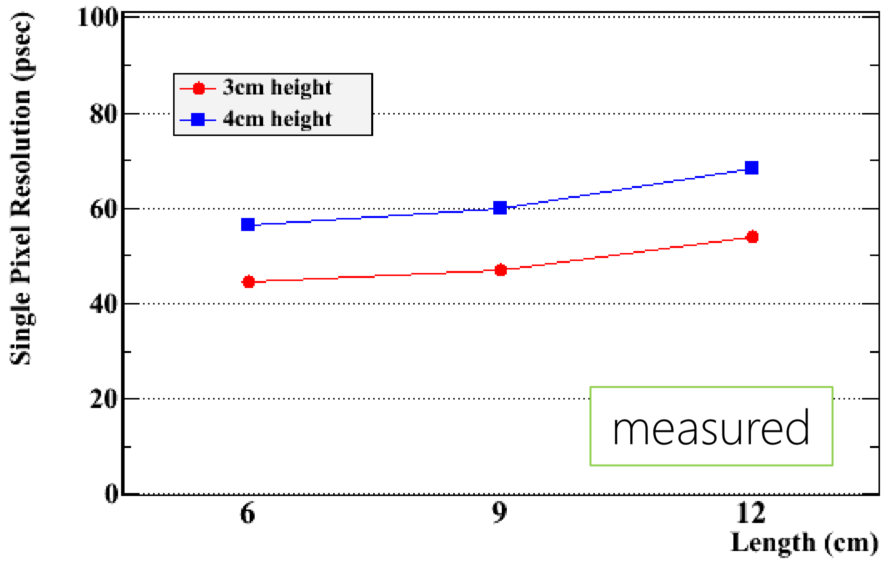


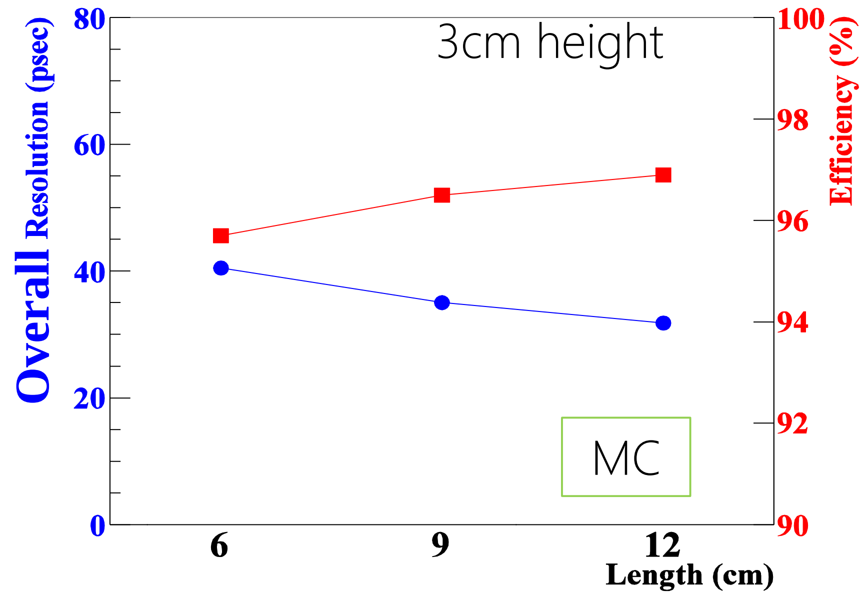
Concept of Readout

- Simplify the system
  - To deal with increased number of channels
  - No additional material at the detector side
- A single line for signal transmission & biasing
- No pre-amplification
- Amplifier & shaper at the digitization board
- Waveform digitization at Giga-Sampling



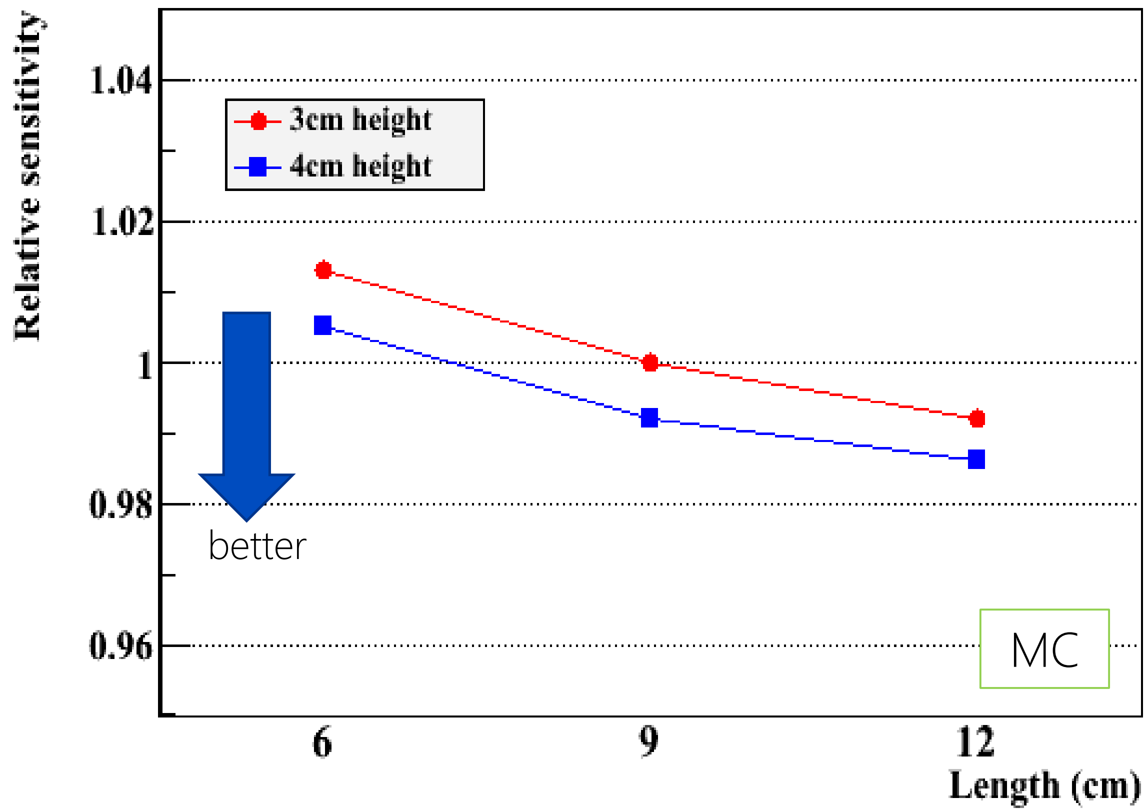
Size Optimization





- Single resolution is worse with larger counter.
- However # of hit counters increases with larger counters.

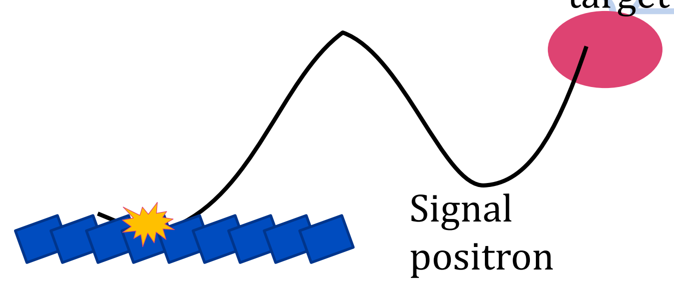
Result of size optimization

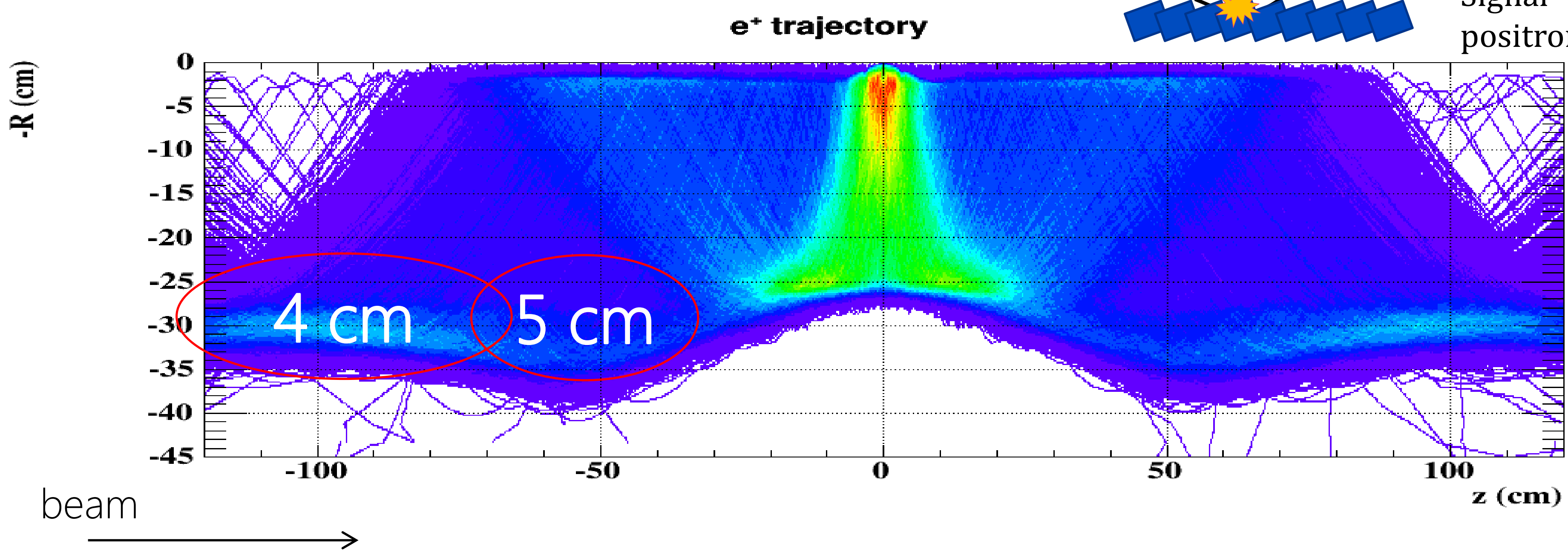


Larger pixel is counter.

(Effect of high rate is not included.)

Counter Size Optimization

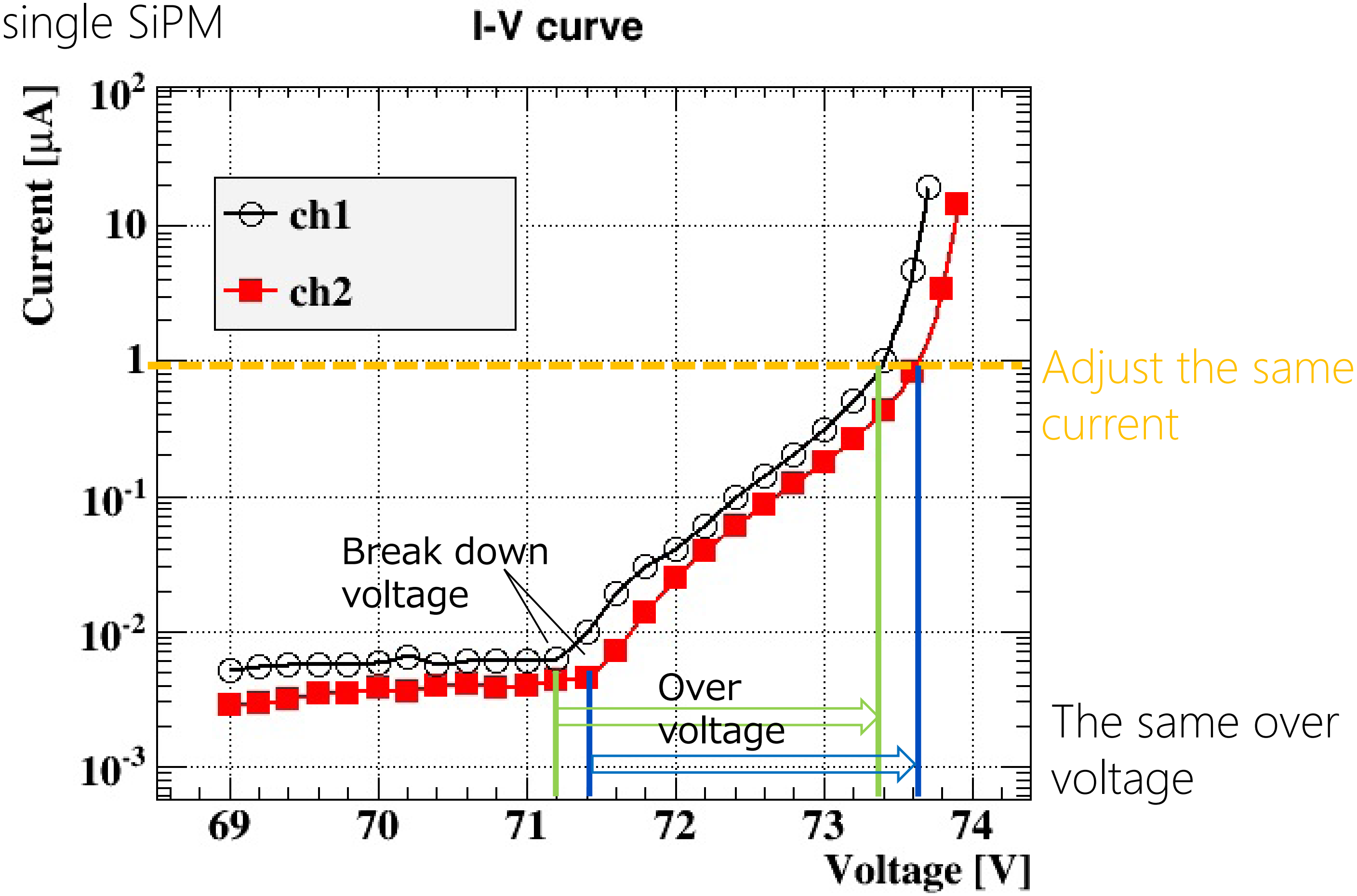




- 5 cm for positron spreading region.
- 4 cm for the other region.

Bias Voltage

I-V curve of single SiPM



Shape of I-V curve is almost same for every SiPM.

Only break down changed for each SiPM.

⇒ If the current is the same for SiPMs, their over-voltages are adjusted to be same automatically.