# Future detector technologies for μSR


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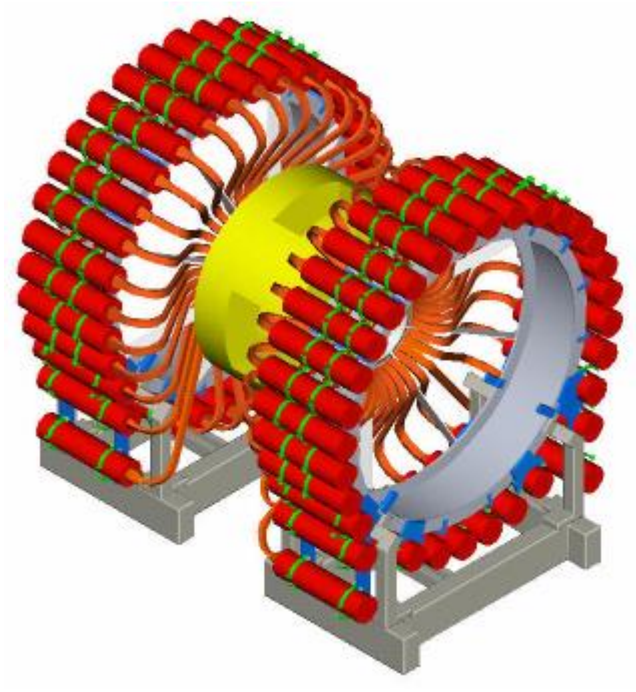
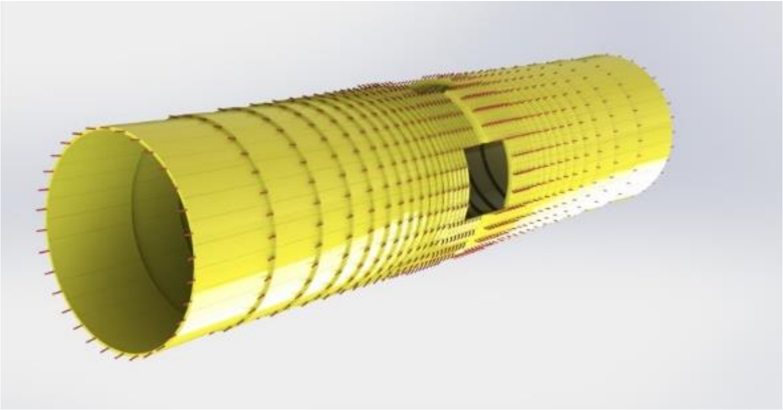
- SINE2020 Work Package 9.4:
  - Emergent Detector Technologies for neutron scattering and muon spectroscopy
    - Sub Task 3: Silicon photomultipliers for muon spectroscopy

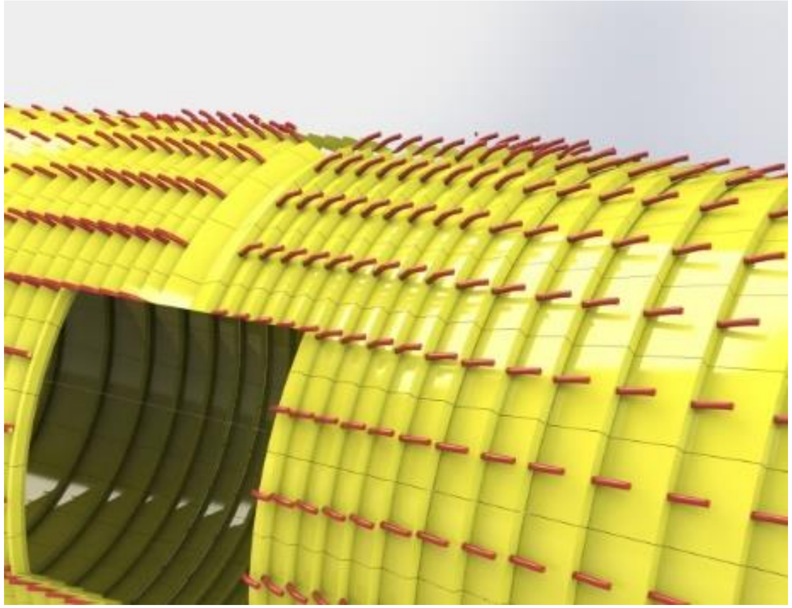
Science & Technology Facilities Council
ISIS

# Application: MuSR →


64 channels to 1216.







**Courtesy: P. Baker,** R. Afonso, P. Singkanipa

# Light Collection Otpions

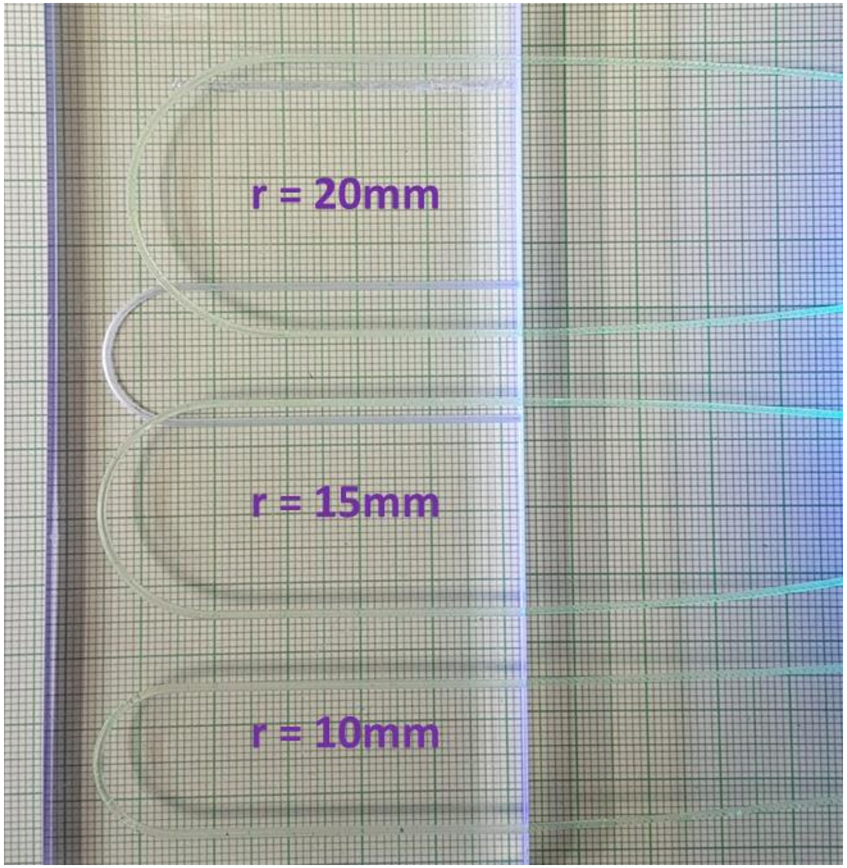
**Light Guide**

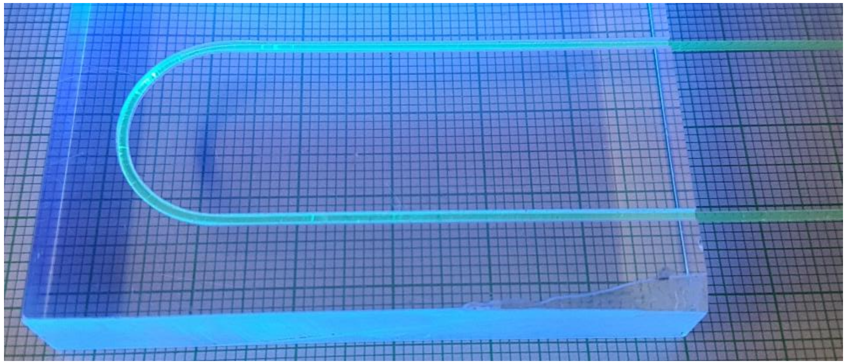
- Good light transport
- Self-supporting
- Expensive + difficult assembly
- Have to stick to Liouville's theorem

**Wavelength shifting fibre**

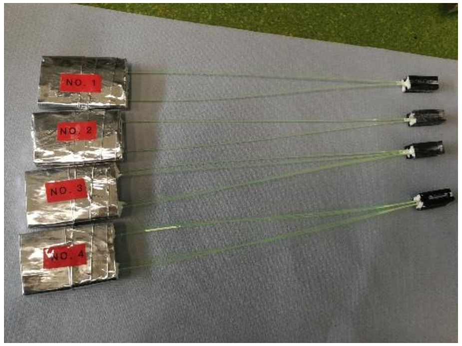
- Unique light collection geometries ('light from the side')
- Flexible and compact ' bend like wires'
- Homogenous light collection
- Huge light loss (single %'s collected) due to absorption and re-emissision, self absorption and attenuation mechanisms.

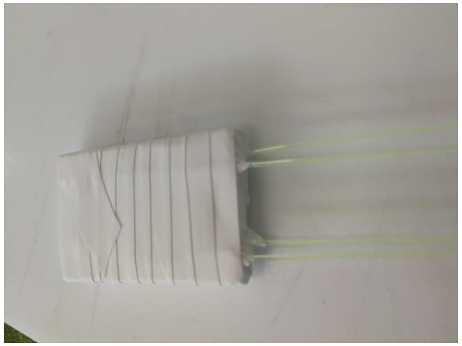
# Testing and Prototyping



- Bend radius, potting method, reflector type etc. are under evaluation
- Favourite for building ease: PTFE, 1 fibre at ~15mm radius.



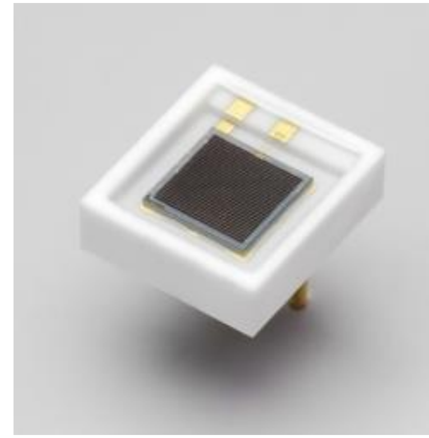


*Zi-Wen Pan*

# (Some of the) Technologies

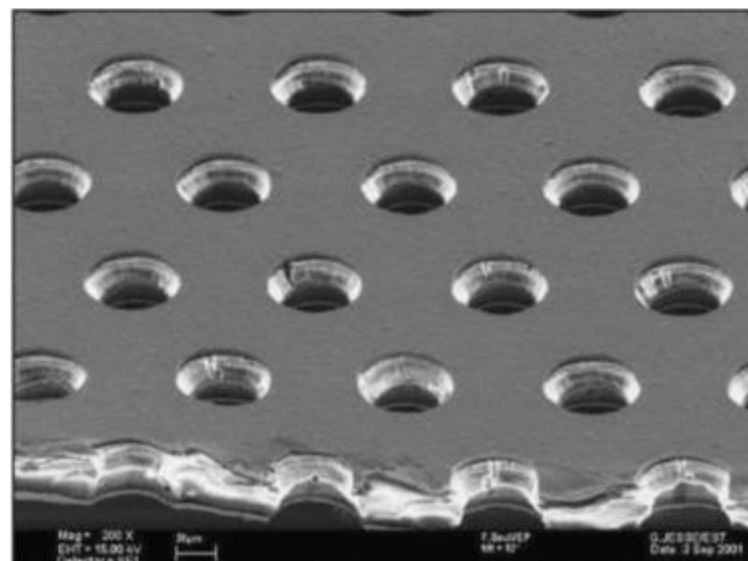
**Photo-Multiplier Tubes (PMT)**

**Silicon Photo-Multipliers (SiPM)**



**Multi-Anode PMT (64ch!)**

**Gas Electron Multiplier (GEM)**



# Major Pro's and Con's

(for μSR at ISIS)

## Photo-Multiplier Tubes (PMT)

- Cheap, reliable, tested
- Fast rise (~1ns) and fall (~10ns)

- Magnetic field sensitivity
- Bulky

## Silicon Photo-Multipliers (SiPM)

- Magnetic field insensitive
- Very fast rise ( sub 1ns time resolution)

- Long fall time ~100ns
- Signal/noise
- Temperature sensitivity

## Multi-Anode PMT

- PMT plus:
  Compact and highly pixelated

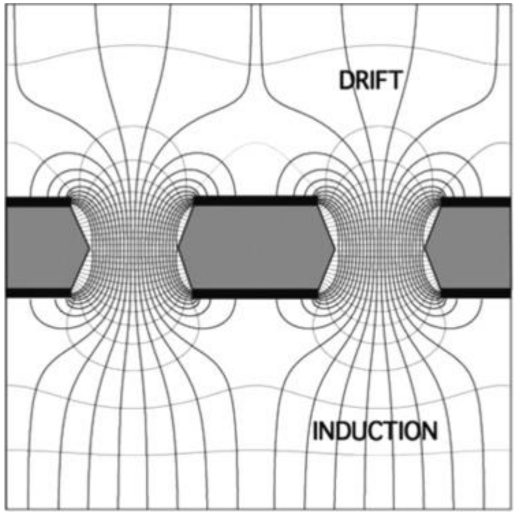
- Magnetic field sensitivity
- 64ch relatively untested

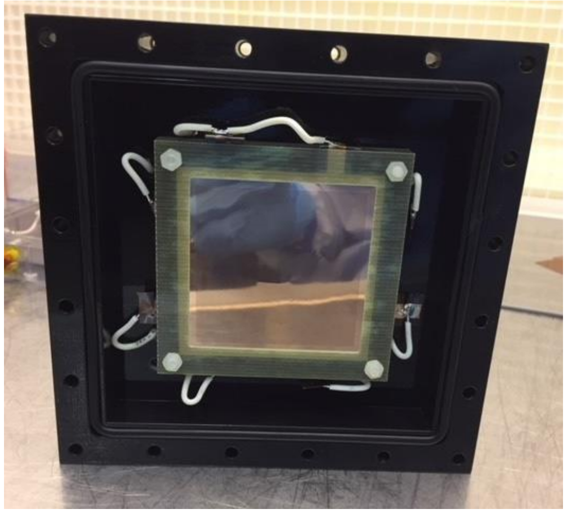
## Gas Electron Multiplier (GEM)

- Very high rate (100kHz $mm^2$) for GEM (readout etc may be lower)
- Magnetic field insensitive

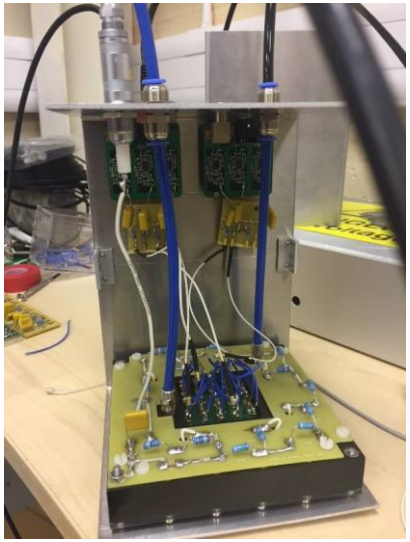
- Construction – Sparking, noise and gas vessel limitations.

# GEM Detector Prototype on HiFi





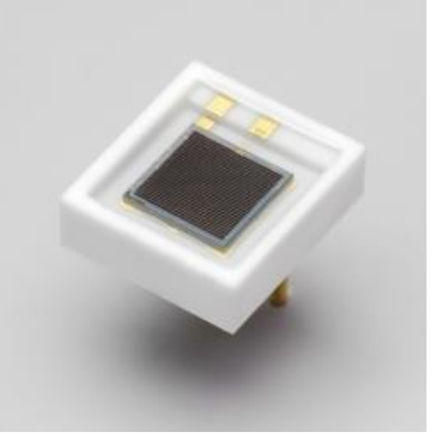




Thomas Astles, <u>Davide Raspino</u>

# This talk

## Silicon Photo-Multipliers (SiPM)



Investigated in NMI3 and SINE2020 European work packages.

Successfully utilised at PSI, JPARC and other facilities

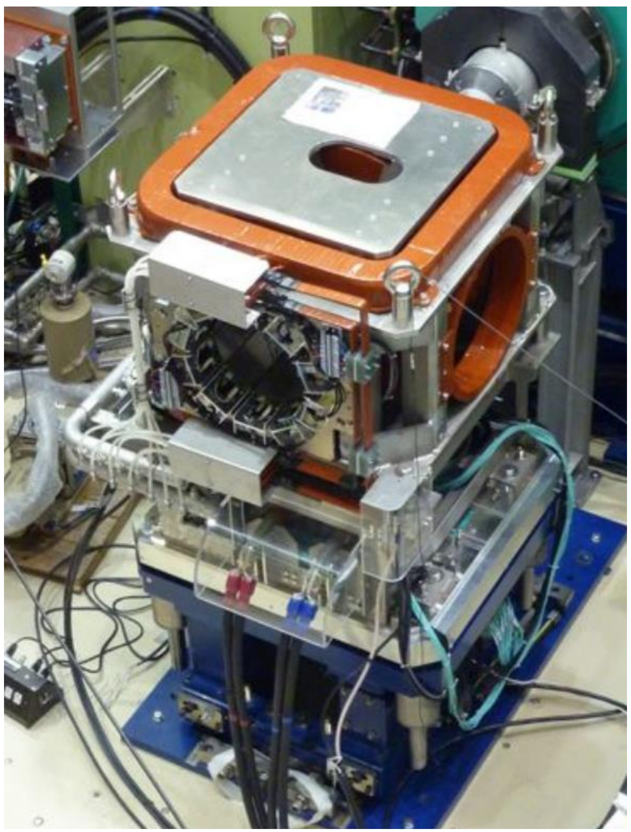
## Multi-Anode PMT

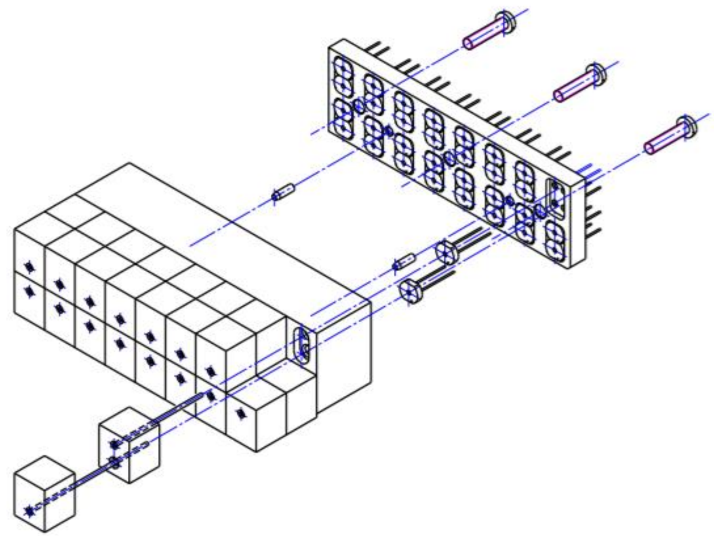
16 channel version utilised on other instruments (CHRONOS for muons) and neutron instruments.

# Examples from the facilities

New *μ*SR spectrometer at J-PARC MUSE based on *Kalliope* detectors

To cite this article: K M Kojima *et al* 2014 *J. Phys.: Conf. Ser.* **551** 012063

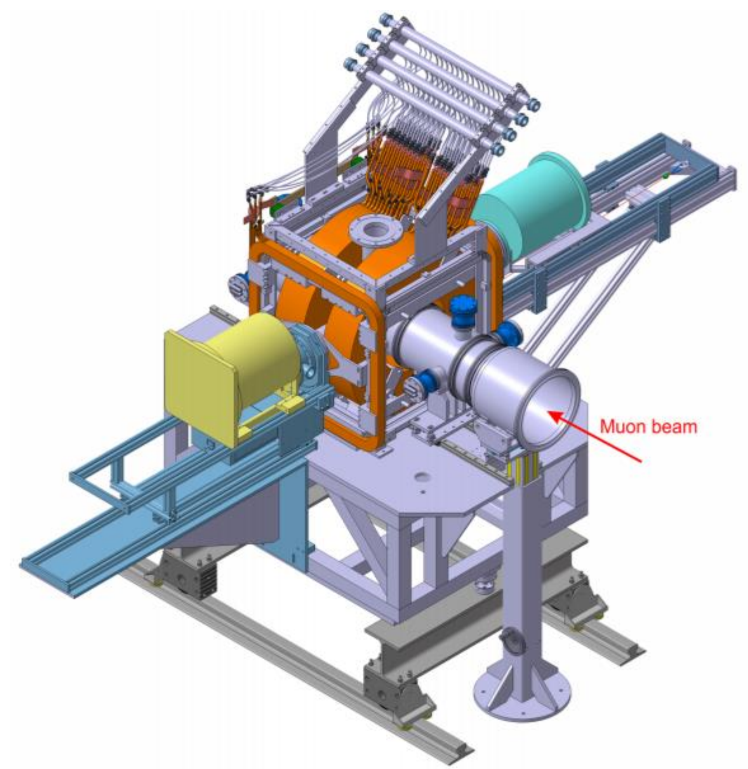




# Examples from the facilities

**The new versatile general purpose surface-muon instrument (GPS) based on silicon photomultipliers for $\mu$SR measurements on a continuous-wave beam**

A. Amato,[1,a)] H. Luetkens,[1] K. Sedlak,[2] A. Stoykov,[3] R. Scheuermann,[1] M. Elender,[1] A. Raselli,[4] and D. Graf[4]

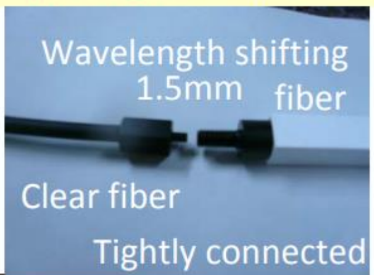


# Examples from the facilities

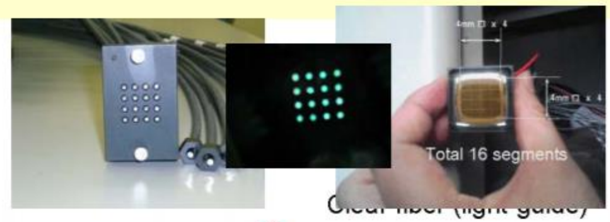
## Fiber read-out detector

**spindle scintillator + wavelength shifter fiber+ clear fiber light-guide + multi-anode PMT**

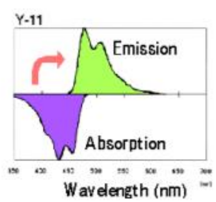
- Magnetic field : Install PMT remote from the magnets by flexible clear fiber light-guides
- Direction sensitivity : threshold separation with spindly scintillator
- Compact : wavelength shifter fiber read-out -> easily increase segments, very compact
- Small costs : multi-anode PMT ~ $2,000 / 16ch

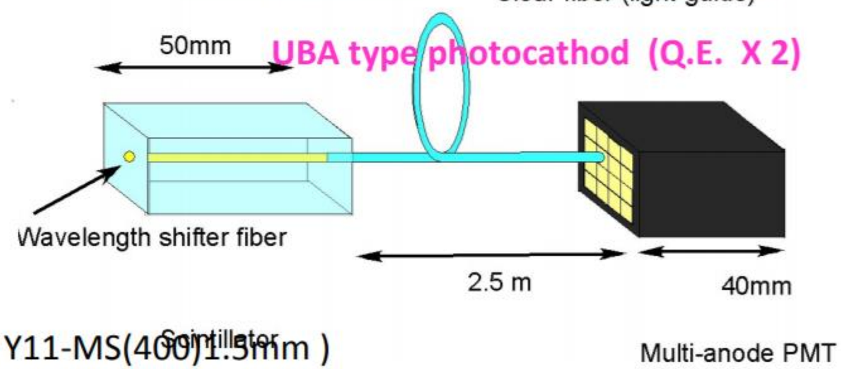



eff > 90%








- Wavelength shifter fiber (kuraray Y11-MS(400)1.5mm )
  clear plastic fiber (Kuraray 1.5mm)
  Ultra-Bialkari type MAPMT (H6568-200-10mod, 7 x 106 @ -900V)
- 1x1x5 cm3 Scintillator (originally for the neutrino near detector at T2K experiment)
- Hole scintillator for mass production ( produced by intruding )

Dai Tomono RIKEN 2010 @ RCNP
http://www-kuno.phys.sci.osaka-u.ac.jp/~sato/100223muonWS/slides/23-12_Tomono.pdf

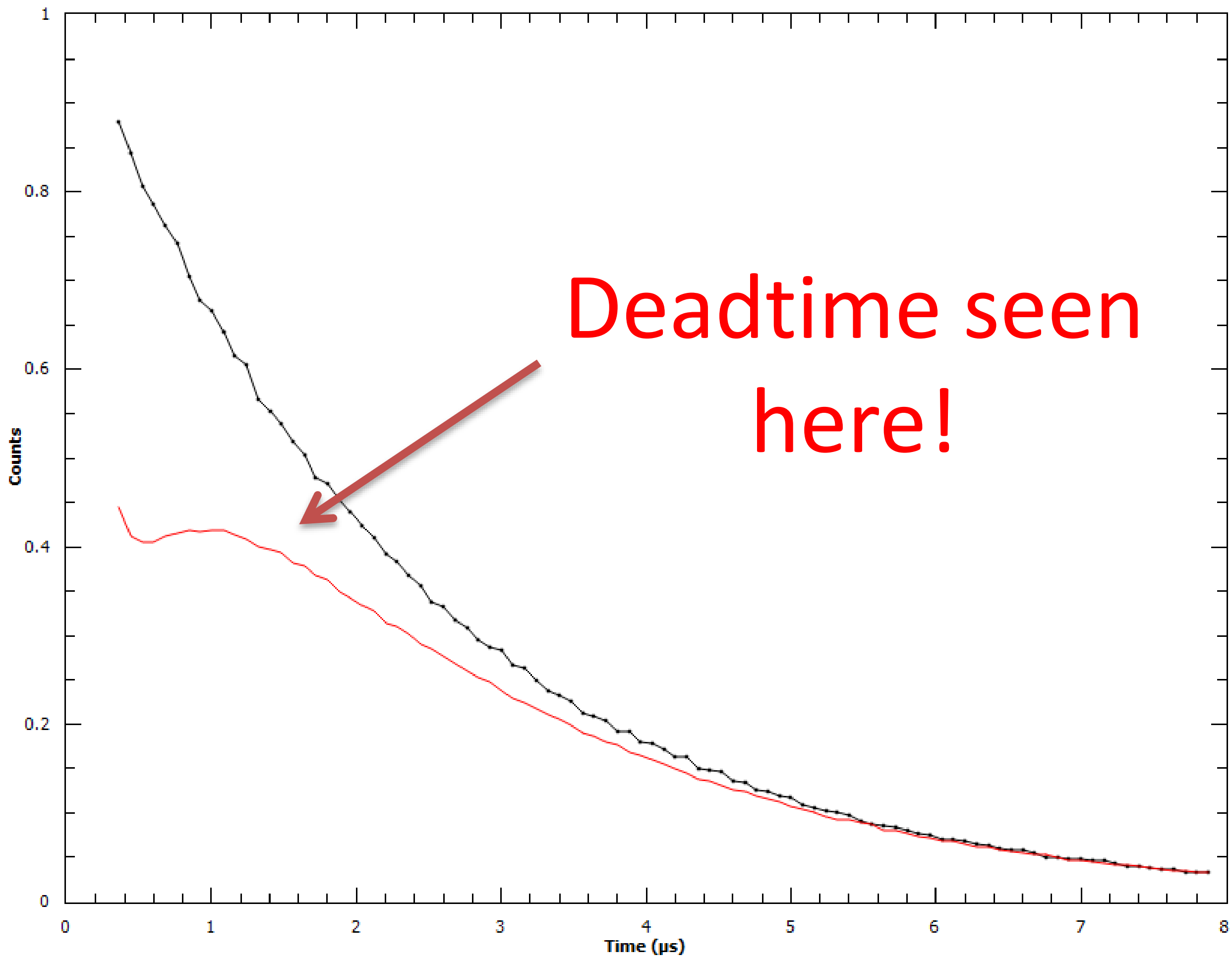
# SiPMs and MAPMTs

# SiPM main drawback: deadtime

# Count rate: A Limiting Factor

40Hz Spallation generates *high instantaneous rate…*

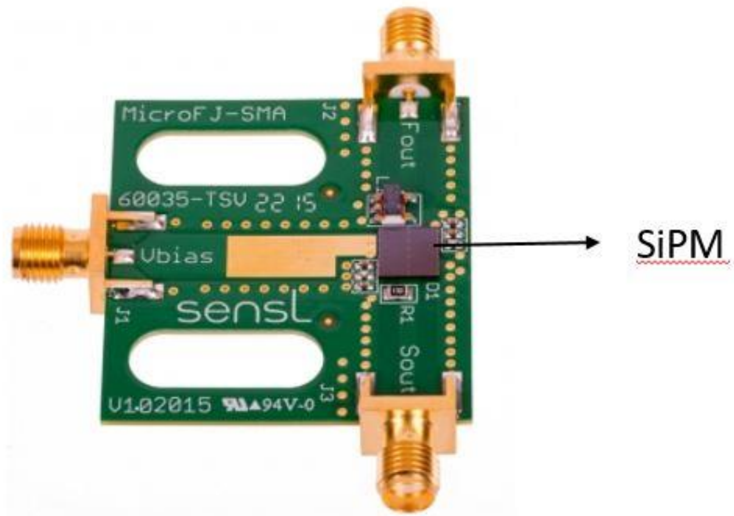
Not only are there 1000's of muons per frame, they are most *likely* to be at the *start of a frame*!

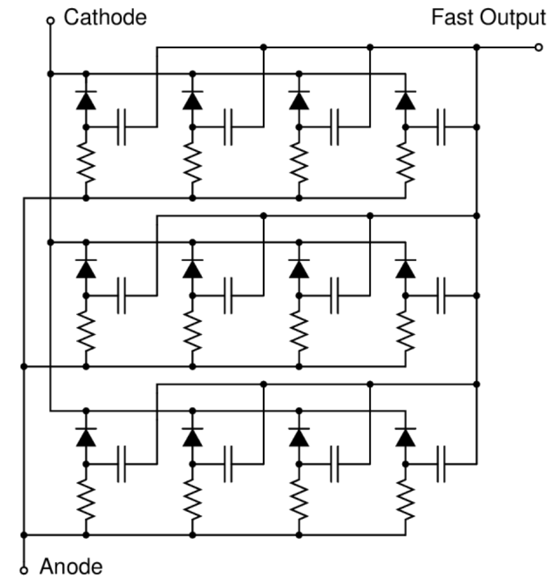


# SiPM: Technology Intro

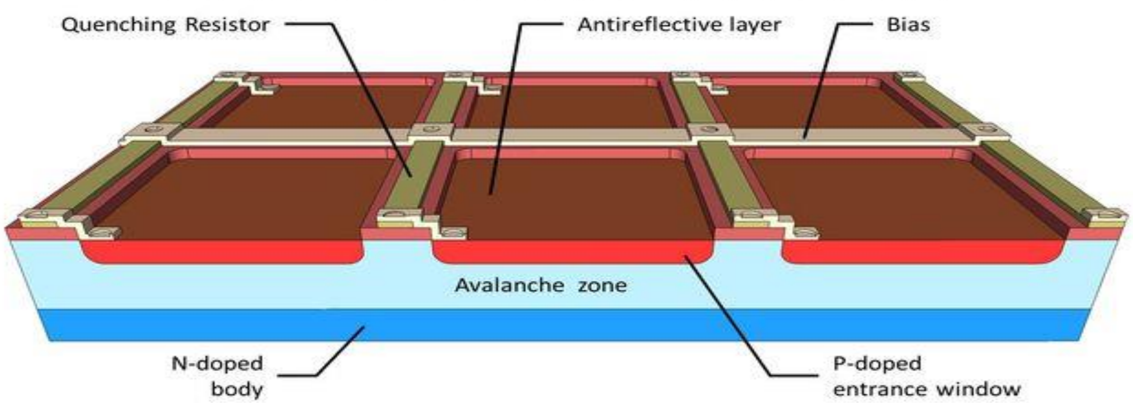
# SiPMs

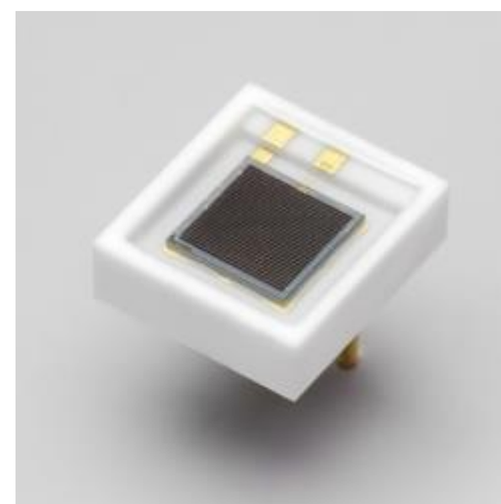
sensL
sense light



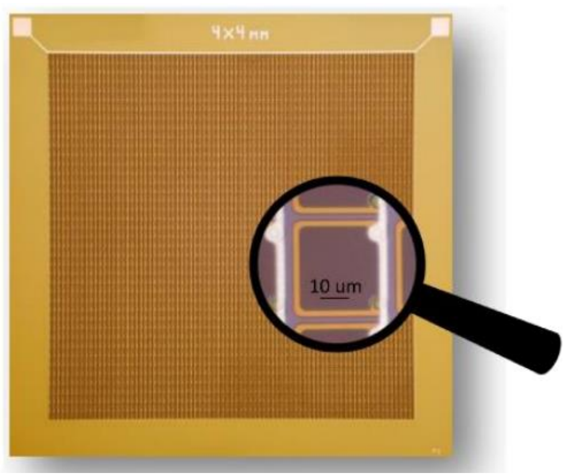



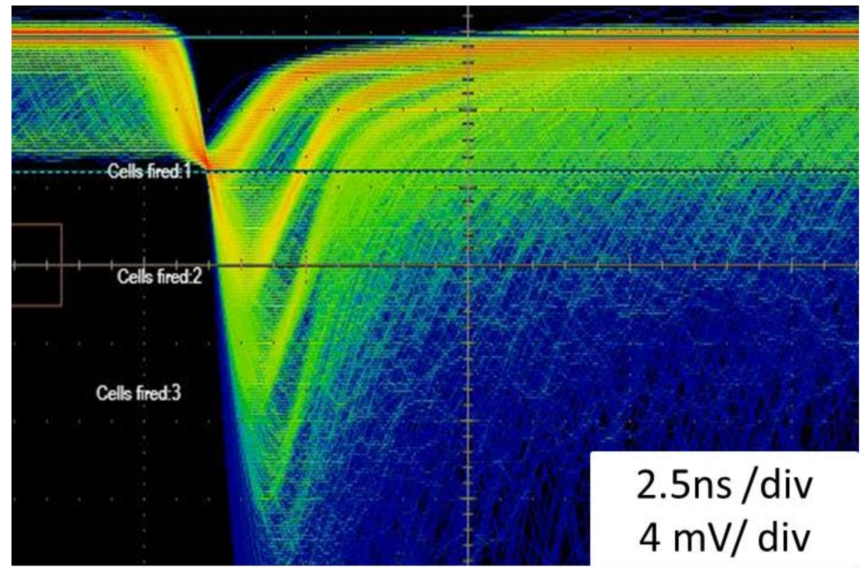

HAMAMATSU
PHOTON IS OUR BUSINESS



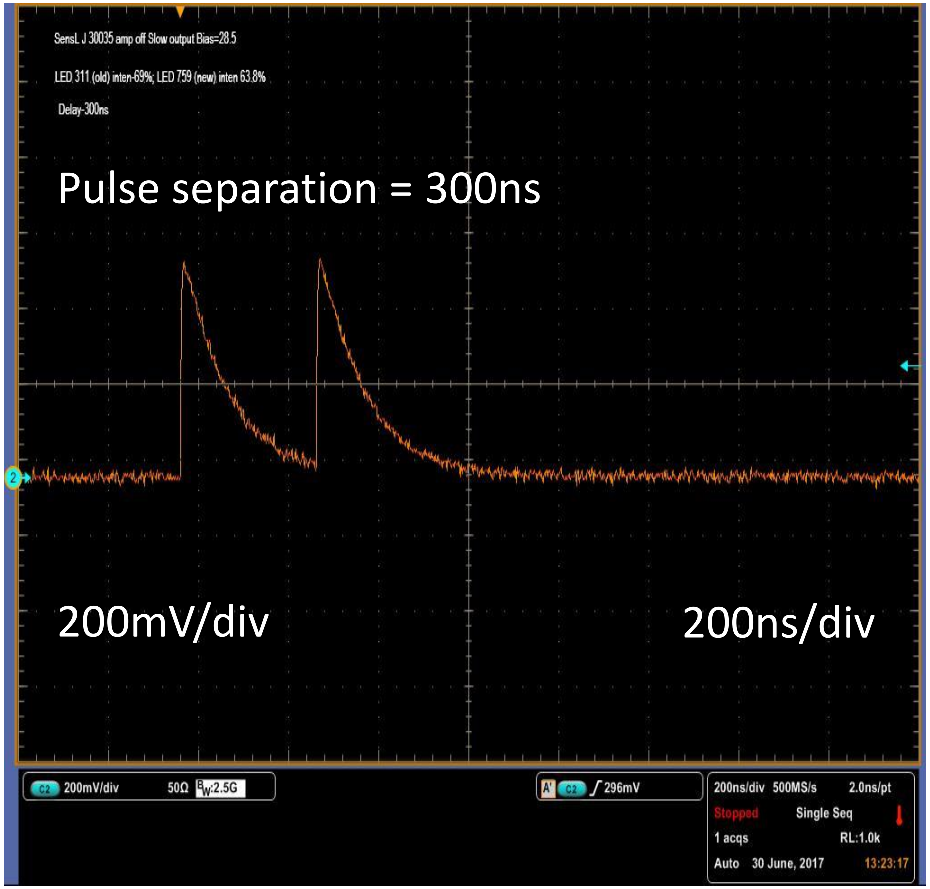
# The Unique Character of SiPMs

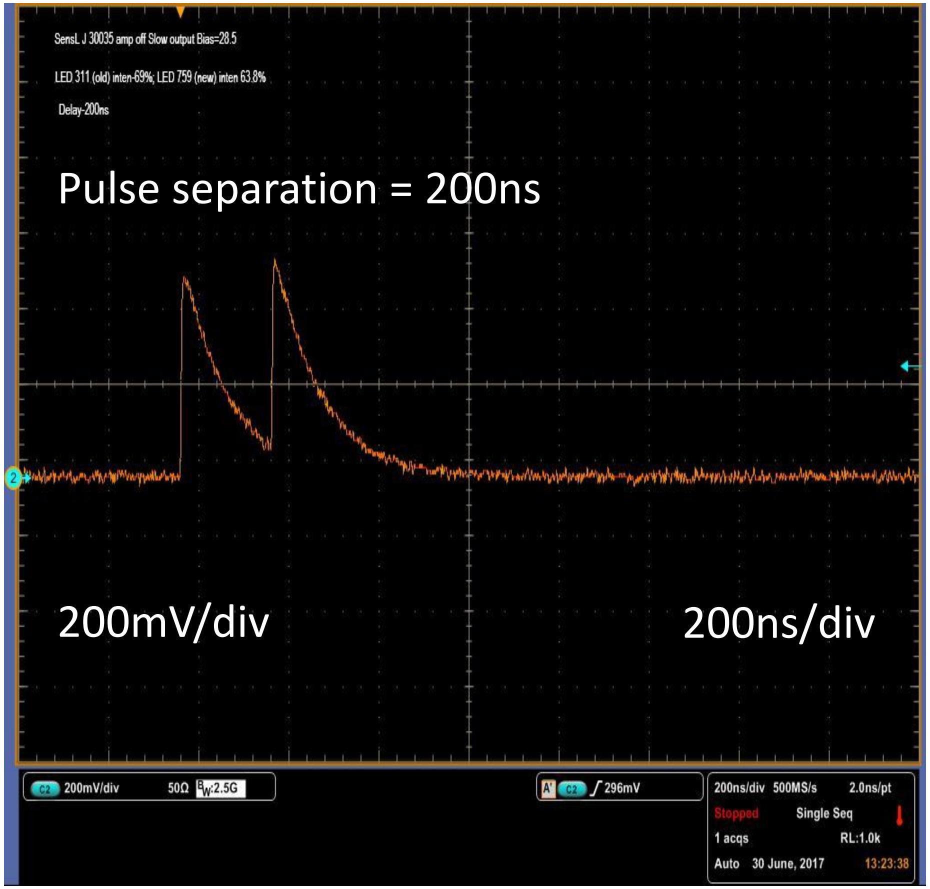



- Silicon Photomultiplier (SiPM) is a Multi-Pixel Photon Detector
- Parallel arrangement of GM-APD with each their own quenching resistor
- **Each cell gives out a quantised amount of charge**

| Cell Size | # Cells |
|---|---|
| 20um= | 10998 |
| 50um= | 2668 |


SensL J 30035 amp off Slow output Bias=28.5
LED 311 (old) inten-69%; LED 759 (new) inten 63.8%
Delay-300ns
Pulse separation = 300ns
200mV/div
200ns/div
C2 200mV/div 50Ω BW:2.5G
A C2 296mV
200ns/div 500MS/s 2.0ns/pt
Stopped Single Seq
1 acqs RL:1.0k
Auto 30 June, 2017 13:23:17


SensL J 30035 amp off Slow output Bias=28.5
LED 311 (old) inten-69%; LED 759 (new) inten 63.8%
Delay-200ns
Pulse separation = 200ns
200mV/div
200ns/div
C2 200mV/div 50Ω BW:2.5G
A' C2 296mV
200ns/div 500MS/s 2.0ns/pt
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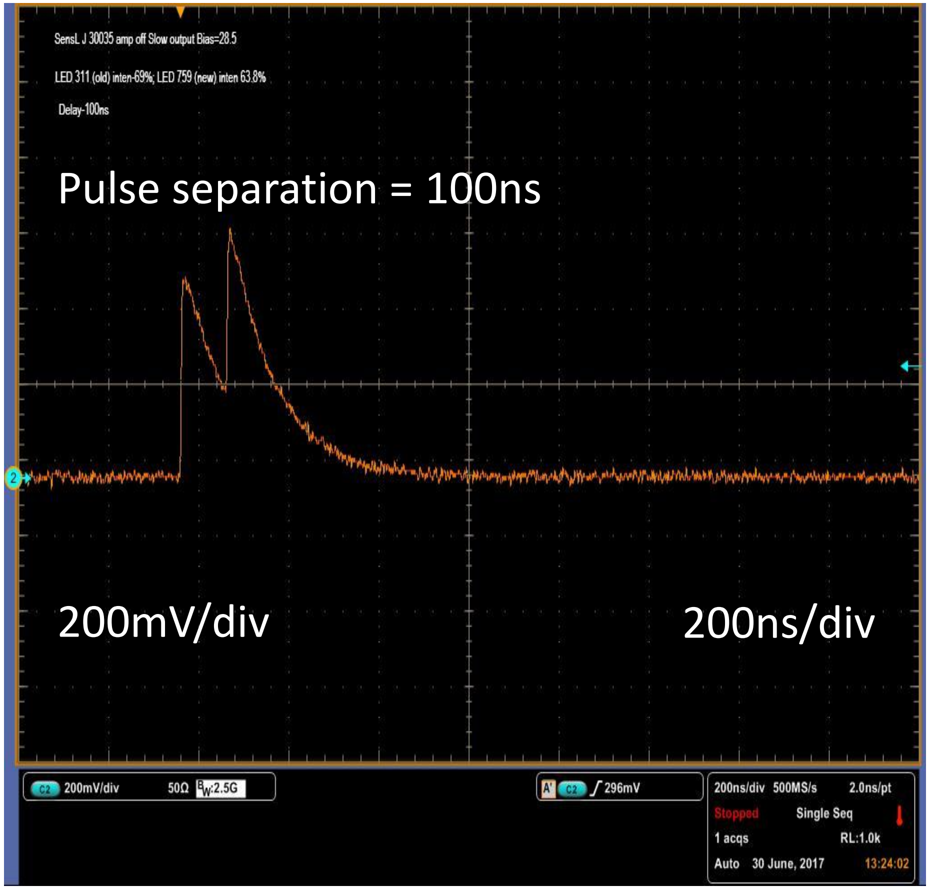
SensL J 30035 amp off Slow output Bias=28.5
LED 311 (old) inten-69%; LED 759 (new) inten 63.8%
Delay-100ns
Pulse separation = 100ns
200mV/div
200ns/div
200mV/div 50Ω BW:2.5G
296mV
200ns/div 500MS/s 2.0ns/pt
Stopped Single Seq
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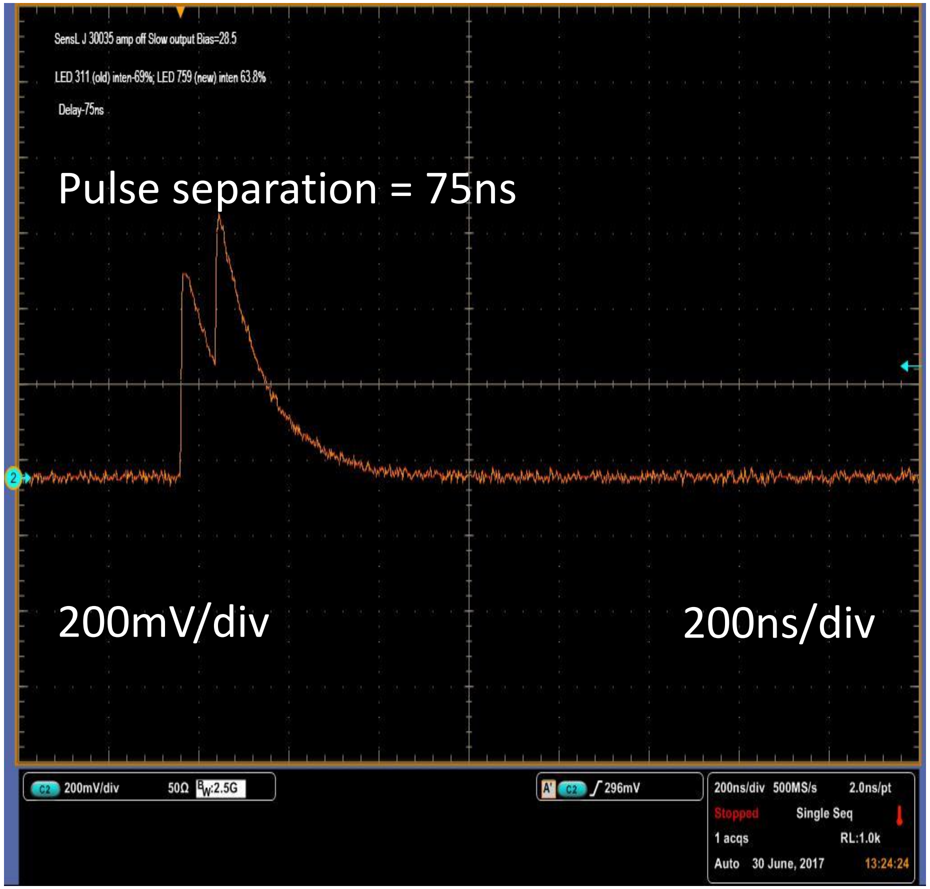
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Delay-75ns
Pulse separation = 75ns
200mV/div
200ns/div
C2 200mV/div 50Ω BW:2.5G
A C2 296mV
200ns/div 500MS/s 2.0ns/pt
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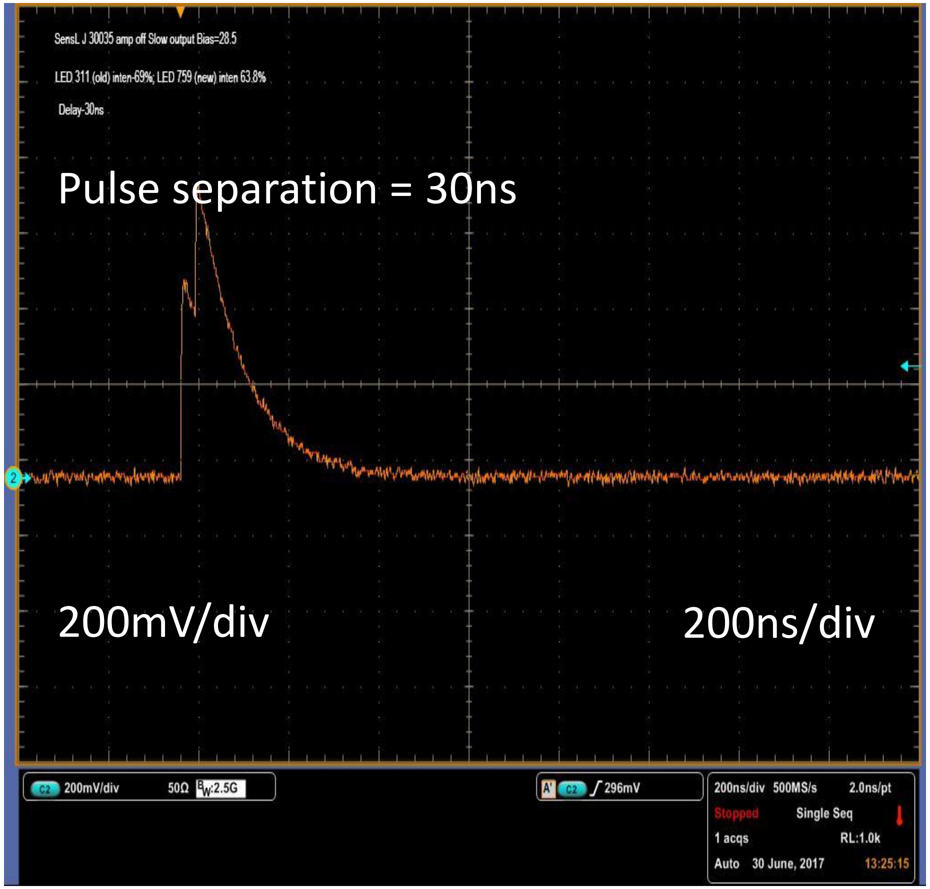

SensL J 30035 amp off Slow output Bias=28.5
LED 311 (old) inten-69%; LED 759 (new) inten 63.8%
Delay-30ns
Pulse separation = 30ns
200mV/div
200ns/div
C2 200mV/div 50Ω BW:2.5G
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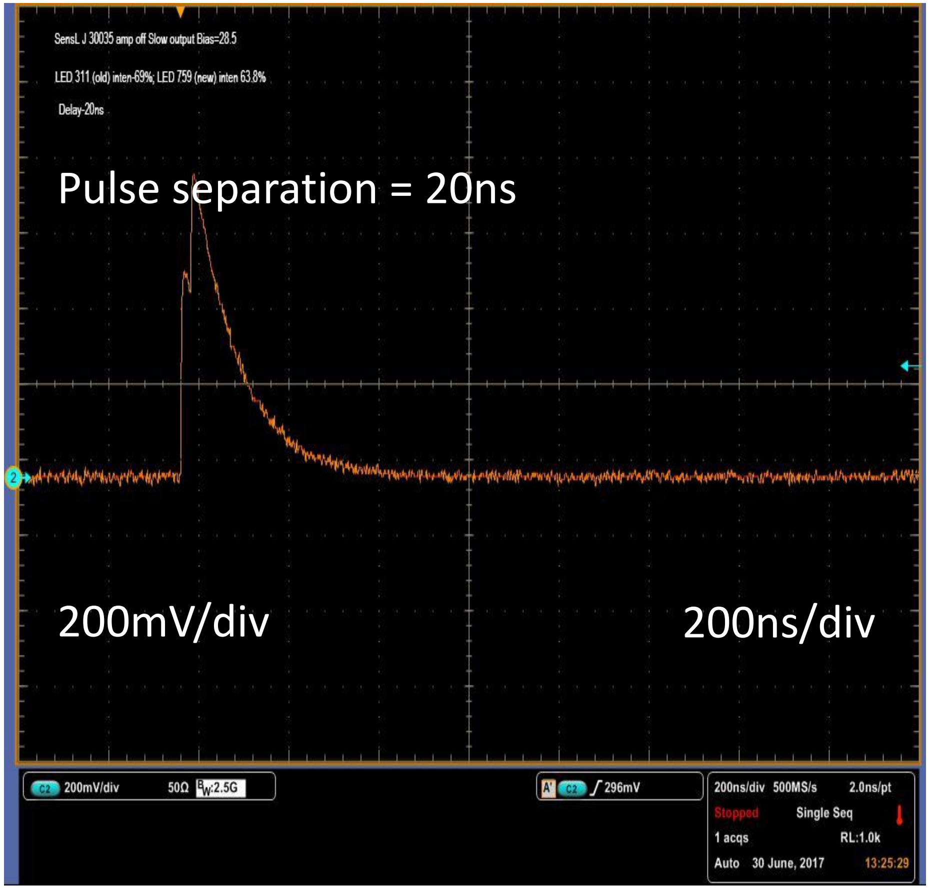
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Pulse separation = 20ns
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200ns/div
C2 200mV/div 50Ω BW:2.5G
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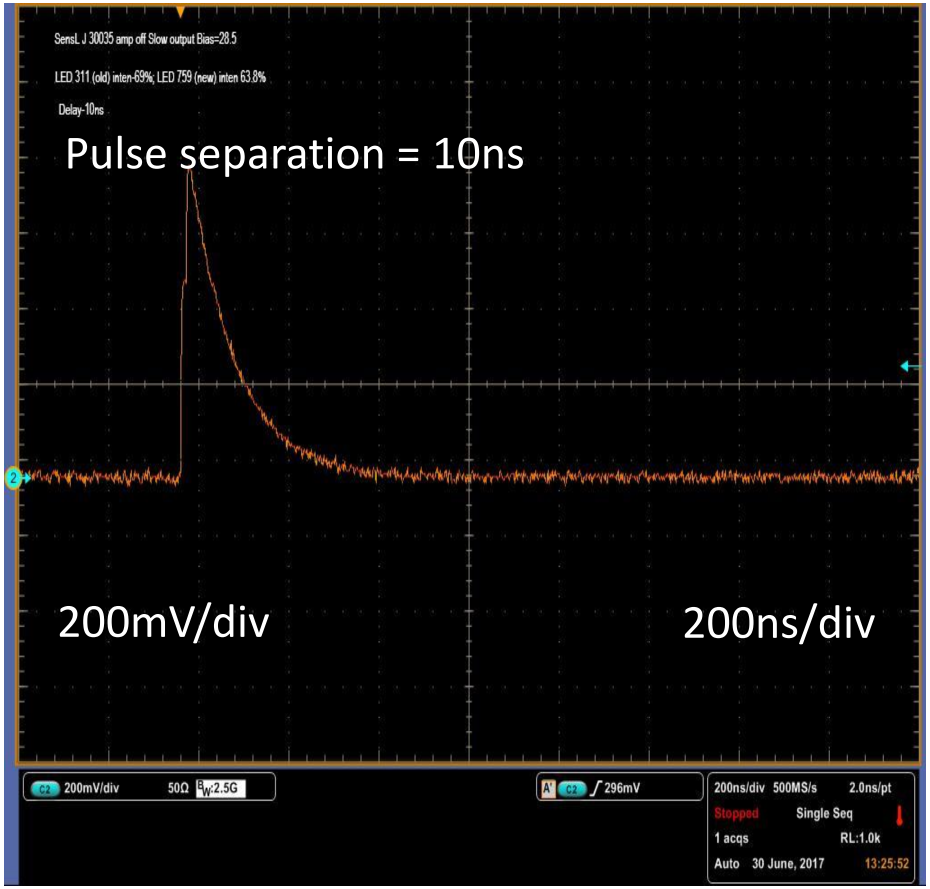
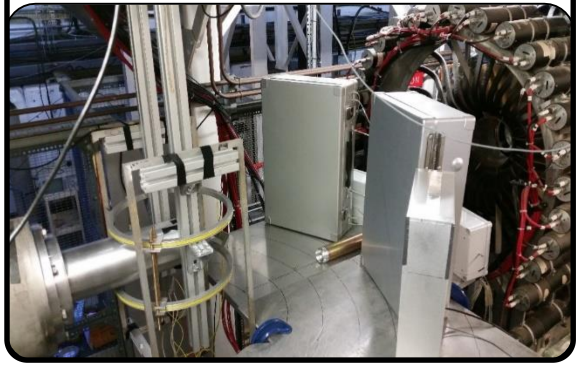

SensL J 30035 amp off Slow output Bias=28.5
LED 311 (old) inten-69%; LED 759 (new) inten 63.8%
Delay-10ns
Pulse separation = 10ns
200mV/div
200ns/div
C2 200mV/div
50Ω BW:2.5G
A' C2 296mV
200ns/div 500MS/s 2.0ns/pt
Stopped Single Seq
1 acqs RL:1.0k
Auto 30 June, 2017 13:25:52

# Examples from our investigations

# Comprehensive evaluation of SiPMs:

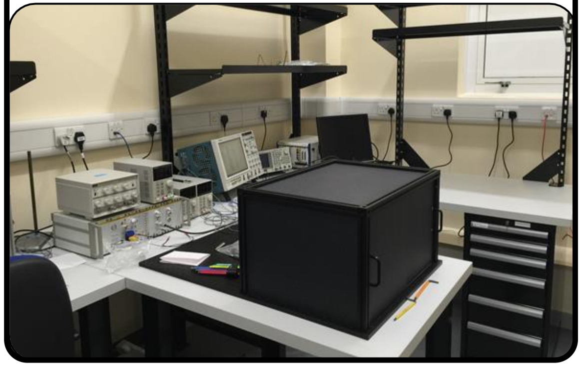
**MuSR Beamline**

- Detector chain can be investigated in a realistic environment.



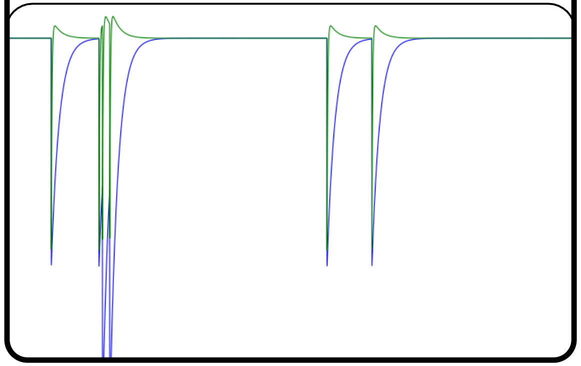
**Optical Investigation**

- Photon flux accurately parameterised within a controlled environment.



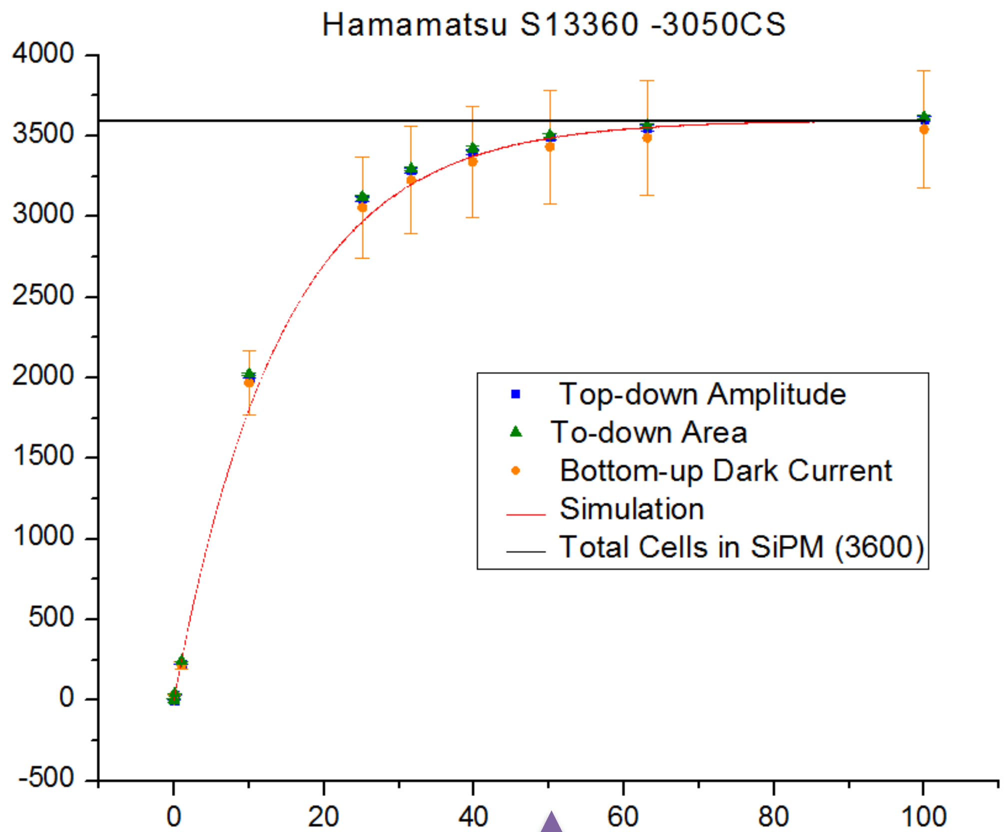
**Monte Carlo Simulation**

- Accurately simulate a statistical investigation in detector performance.



# Example optical investigation: Cells Discharged

How many cells discharge

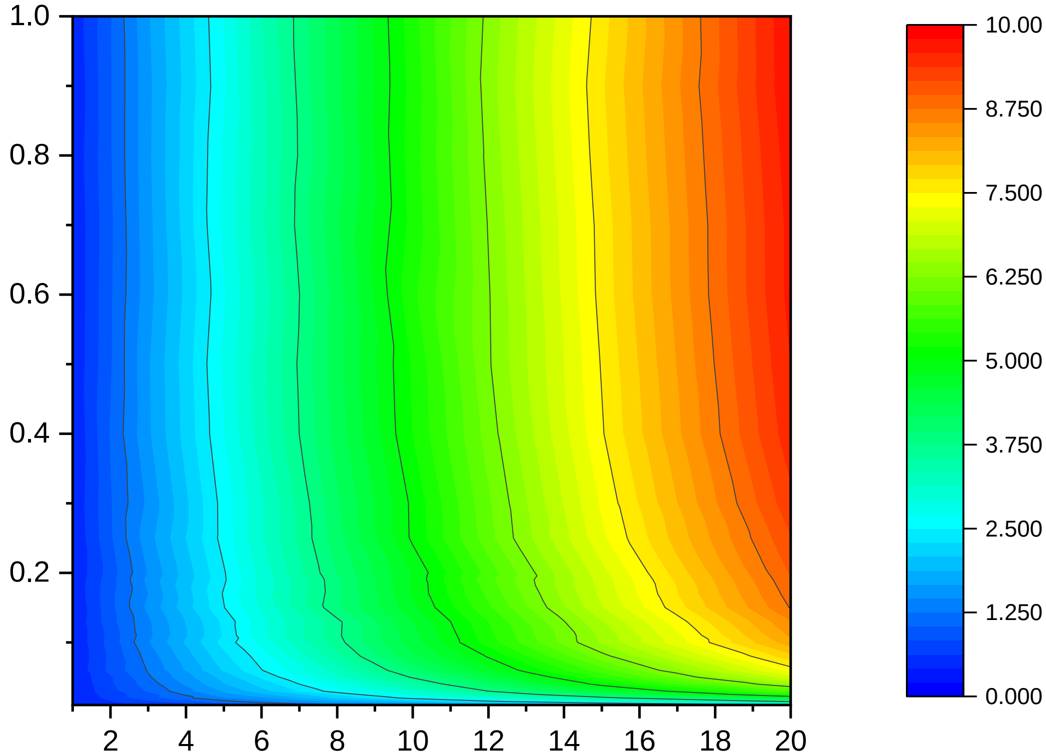



Brightness of flashing diode [arb. units]

**Project Conclusions**:

- Improved photon collection efficiency = diminishing returns
- Not all SiPMs can be 100% discharged
- Can be modelled or directly calculated (balls in boxes)

# Monte-Carlo Simulation
# Example: SensL 50µm with Pole-Zero




How many cells discharge

(photon flux)

Counts per frame (muon flux)

How many counts missed [%]

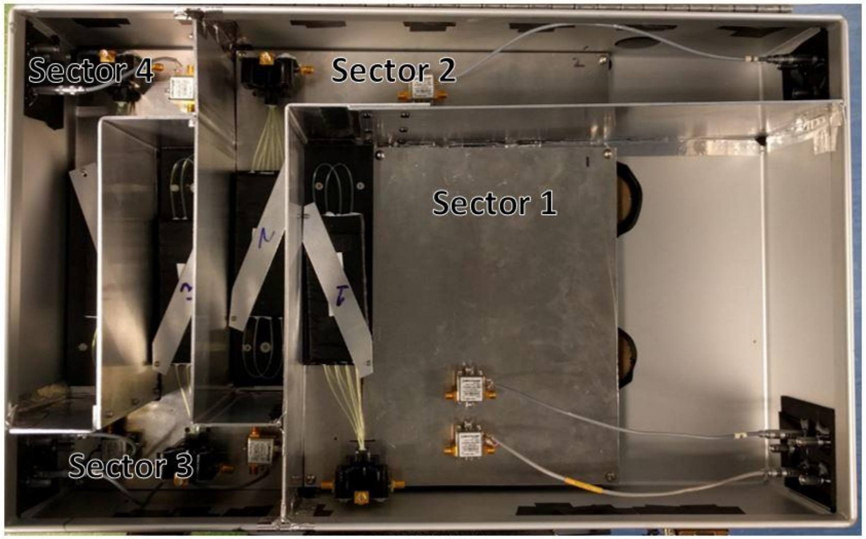
(dead time distortion)

**Project Conclusions**:

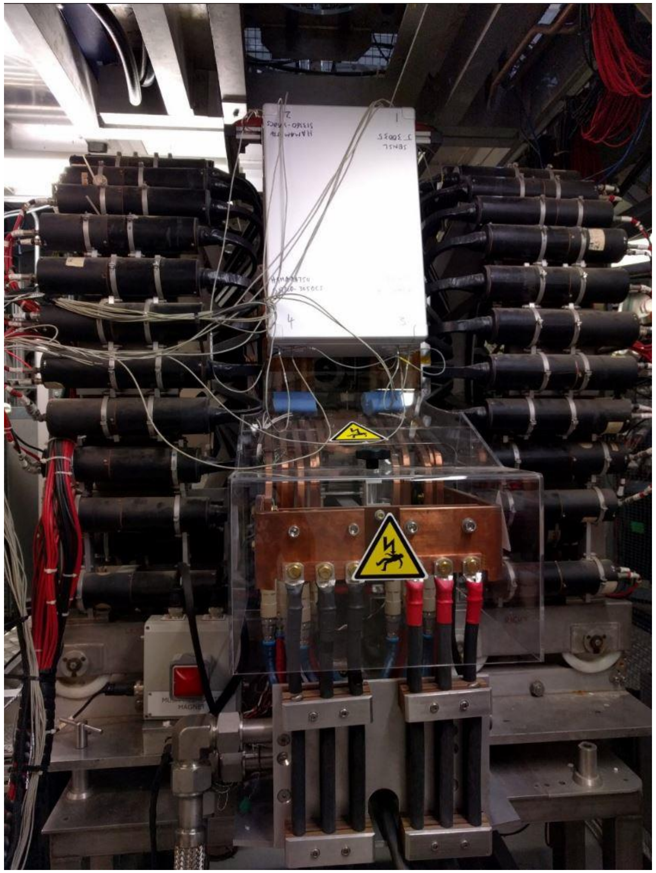
- Signal processing essential to achieve more than 10 c/frame
- Gains in count rate capability below 20% cells discharges

*M Huzan*

# MuSR Experimental Data

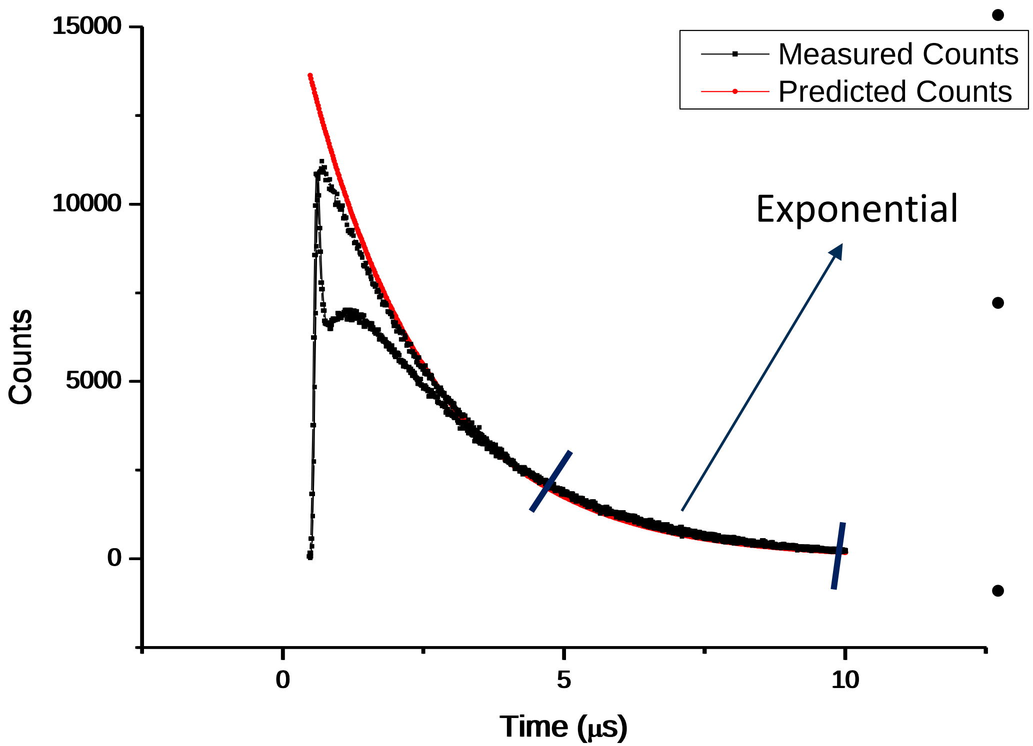



| SiPM |
| --- |
| SensL MFJ-30035 Fast |
| SensL MFJ-30035 Slow |
| Hamamatsu S13360-3050CS |
| SensL MFC-30050 Slow |
| SensL MFC-30050 Fast |
| Hamamatsu S13360-3050CS |



*L R Mohan*

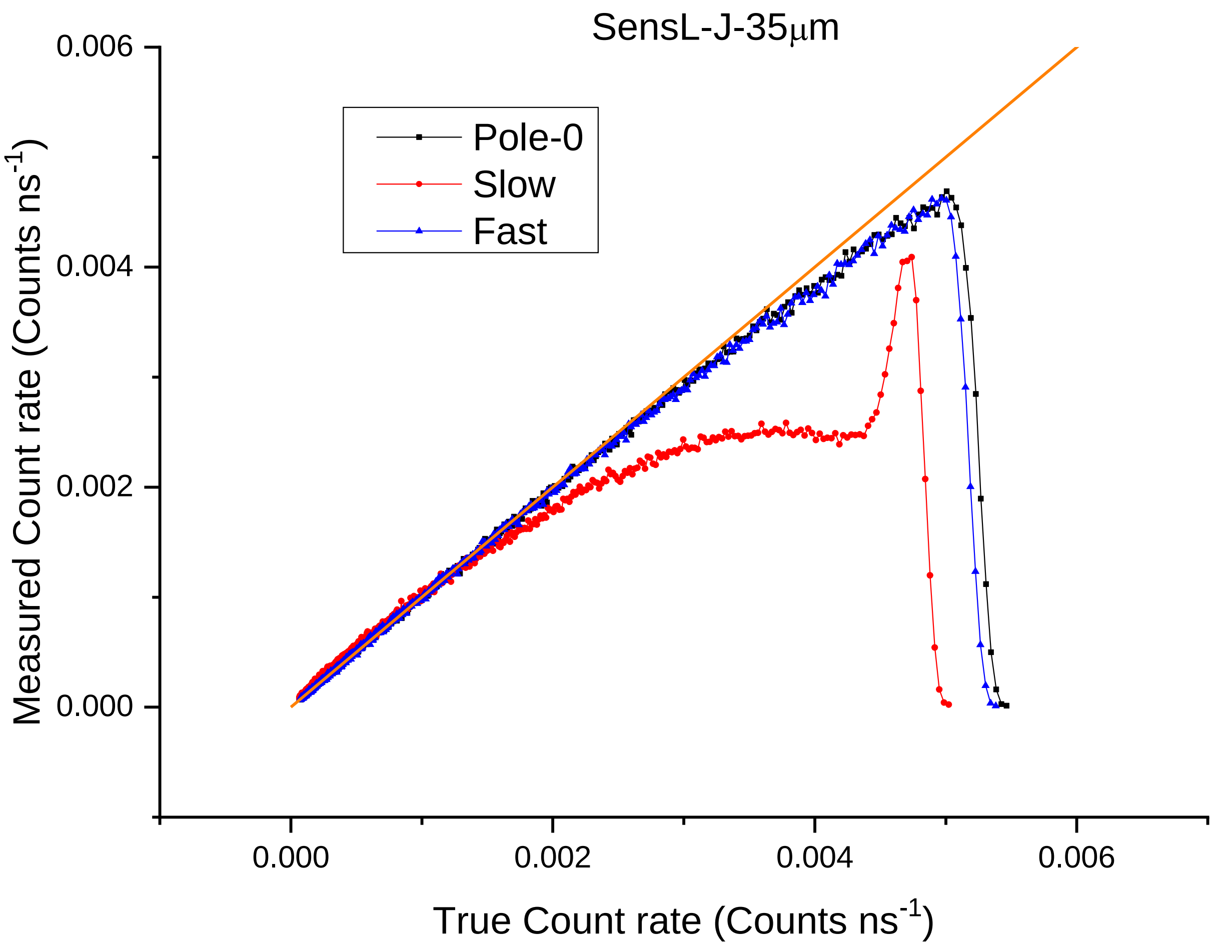
# Example: Beam Data Parameterisation




- In the later part of the data set dead-time effects are assumed to be negligible.
- This region is fitted with an exponent with fixed decay constant and extrapolated back to earlier times.
- Each data point from the measured data set can be plotted against its counter part from the predicted data set.

*L R Mohan*

# Example: Compare in-silicon Vs external signal conditioning




**Project Conclusions**:

- Signal processing can be either in-silicon ( Sensl Fast) or via pole-zero electronics
- SiPM shows minimal dead time distortion at same rates as PMT

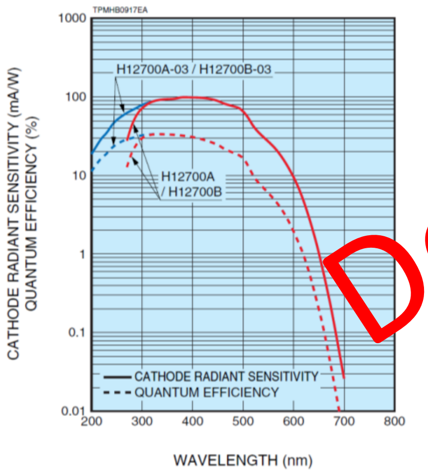
*L R Mohan*

# 64 Channel PMT

- Wavelength shifting fibre with 64 channel Flat Panel MAPMT
  - ✓ Fewer fibres
  - ✓ Easy to assemble
  - ✓ Many geometries
  - ✓ Back plane electronics
  - ✓ Very few cables
  - ✓ Efficient fibre coding

Hamamatsu H12700A


Figure 1: Typical Spectral Response




Does it work?

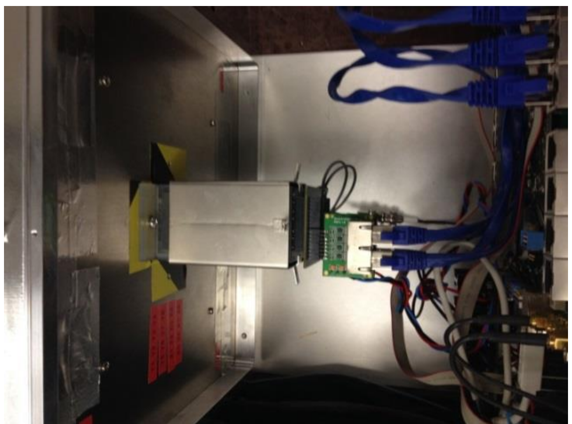
- $10^6$ Gain
- Improved Single Electron Response (SER)
- 6.5 x 6.5 $mm^2$ pixels
- 2:1 pixel uniformity

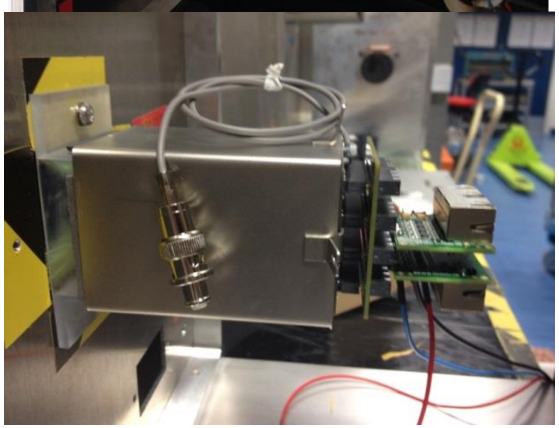
https://www.hamamatsu.com/resources/pdf/etd/H12700_TPMH1348E.pdf

*Slide Crdit: G. J. Sykora et al. IEEE NSS 2017*

# Electronic readout options

- Discrete preamps – used for 16 ch MAPMT
  - Ethernet cables to discriminator
  - Power dissipation = 10W for 64 channels



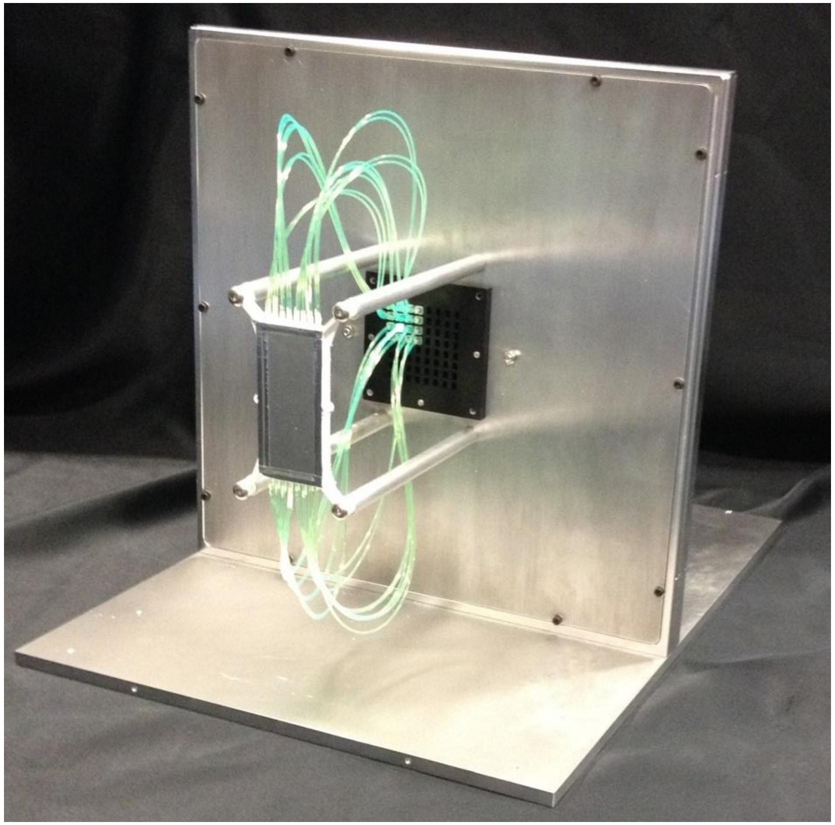


- Semi-discrete preamps
  - Directly attached to a discriminator
  - +12V in
  - USB/Ethernet out
  - Power dissipation = **1.2W** for 64 channels

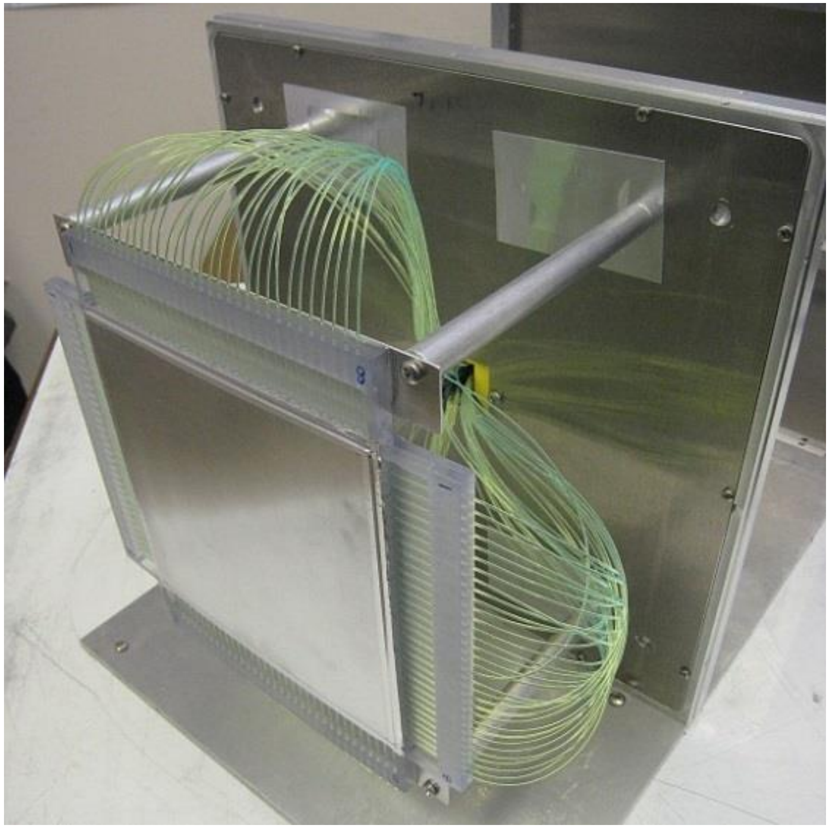
Simple/maintainable

*Slide Crdit: G. J. Sykora et al. IEEE NSS 2017*

# Does it work?
# Testing (for neutron detector RnD)



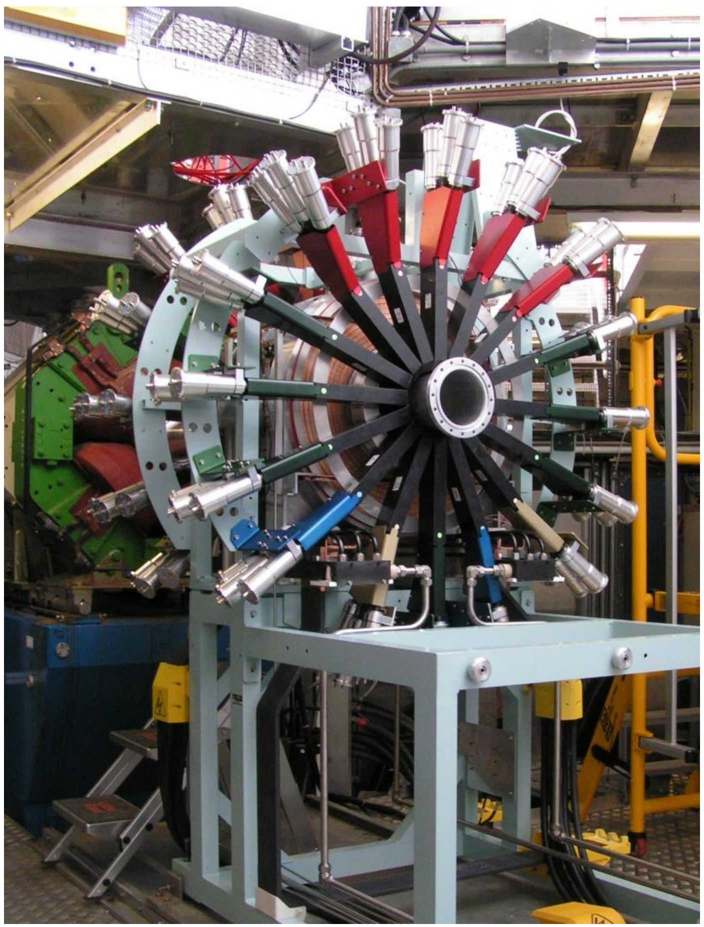
➢ Fundamental comparisons

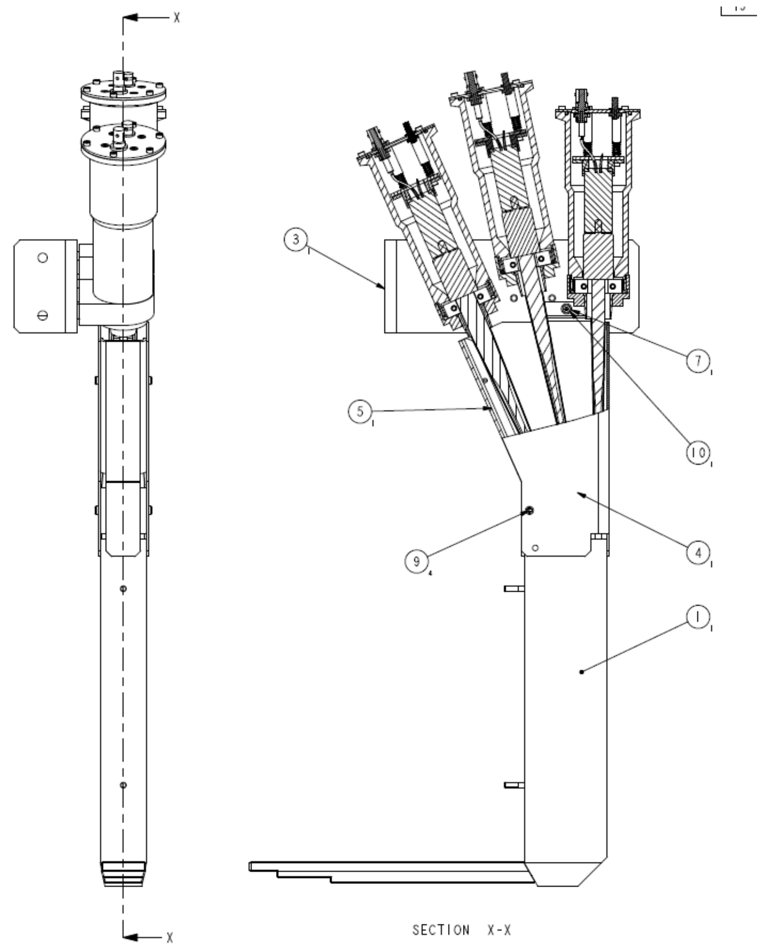


➢ Large area prototype

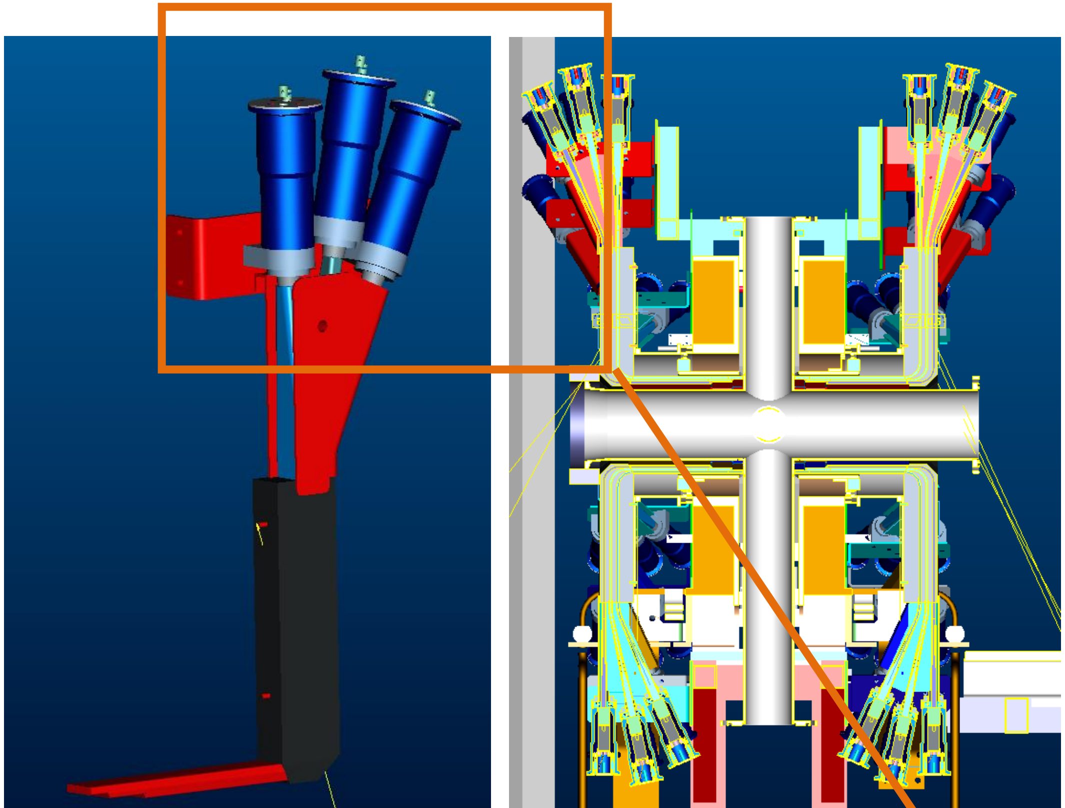
*Slide Crdit: G. J. Sykora et al. IEEE NSS 2017*

# Next steps:
# Demo detector module on EMU Spectrometer

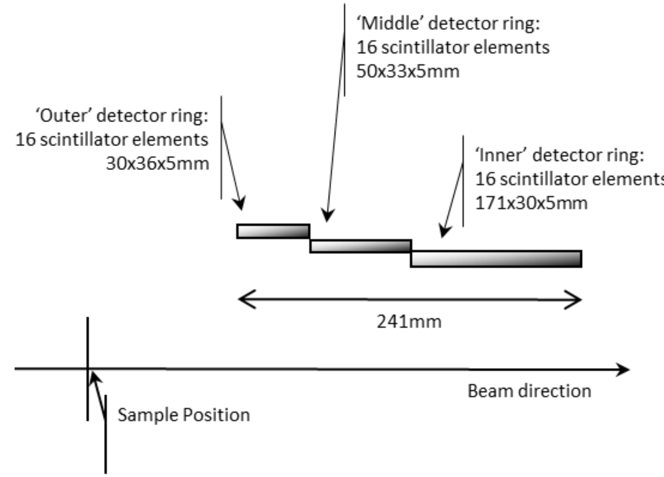




# EMU Spectrometer

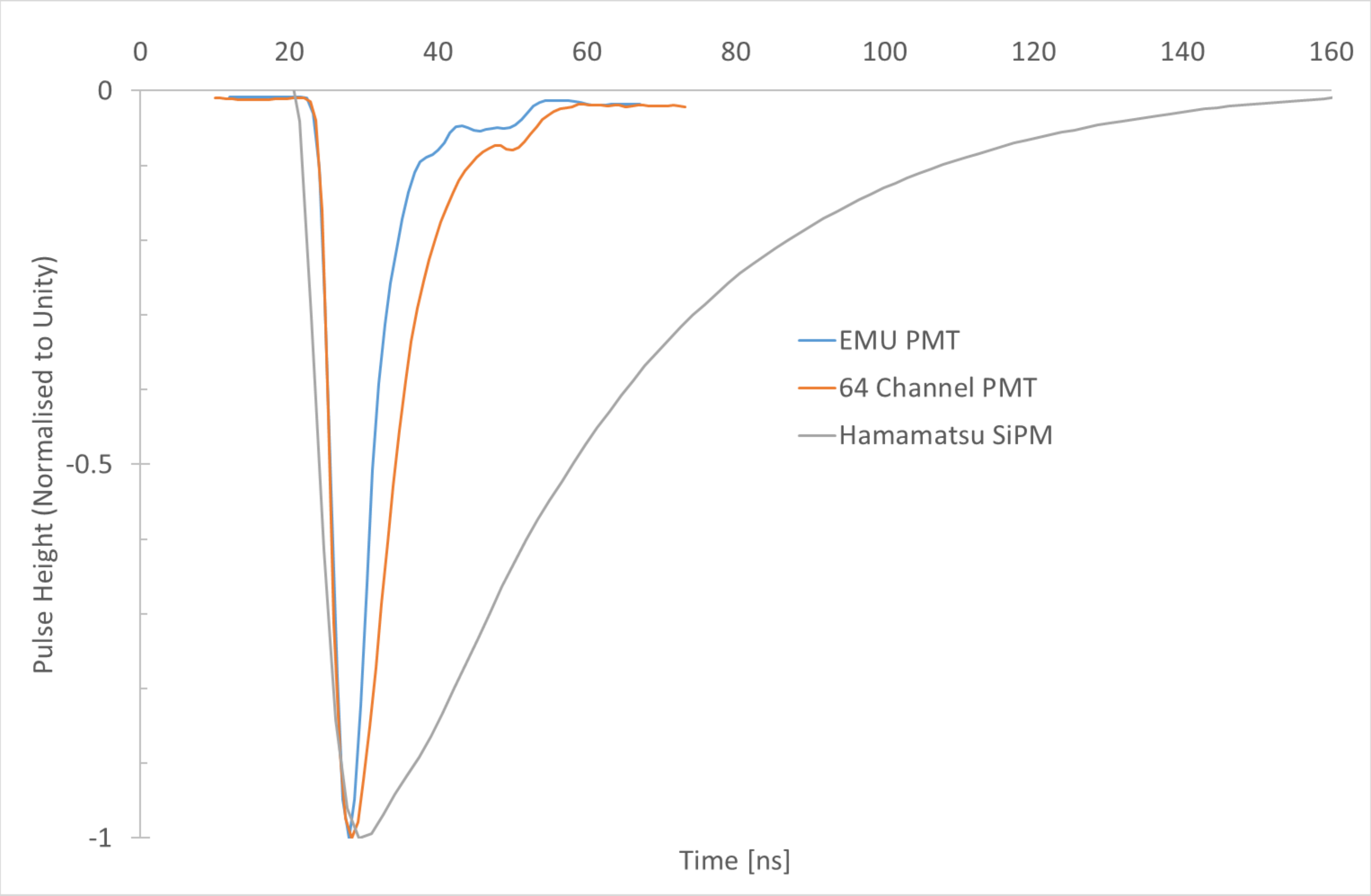


Current Detector Array




Pot fibres in a general use large light tight enclosure for electronics, photo detector and signal processing evaluation.

# Initial results from EMU tests

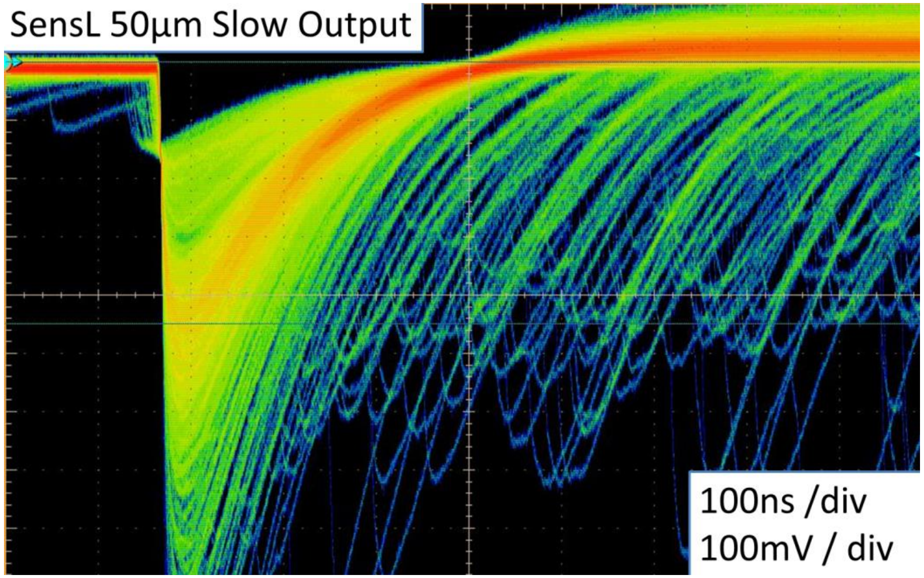


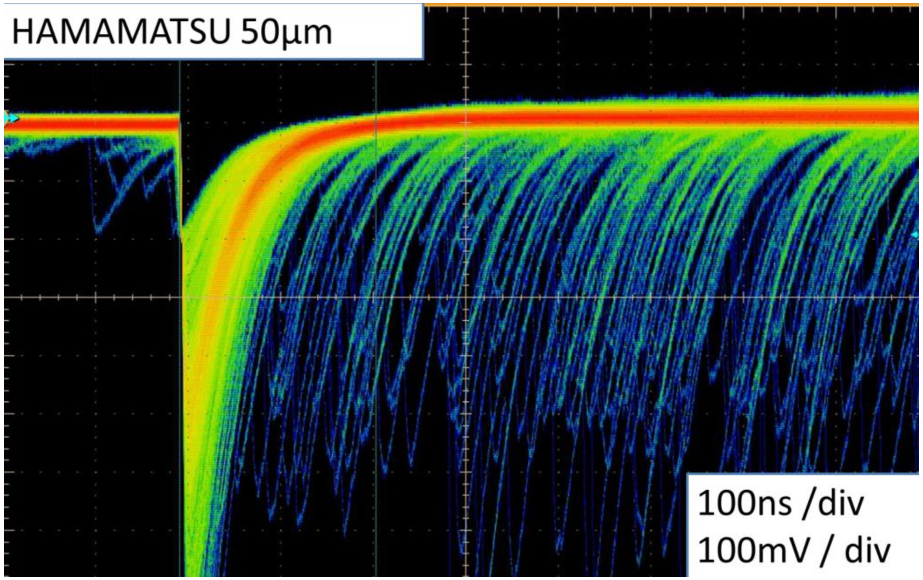
# Take home messages

- No one technology is perfect
- PMTs and MA PMTs have many benefits, and are preferred IF the stray magnetic fields are within tolerances.
- SiPMs can handle similar count rates to PMTs IF you apply heavy signal processing and discriminate appropriately.

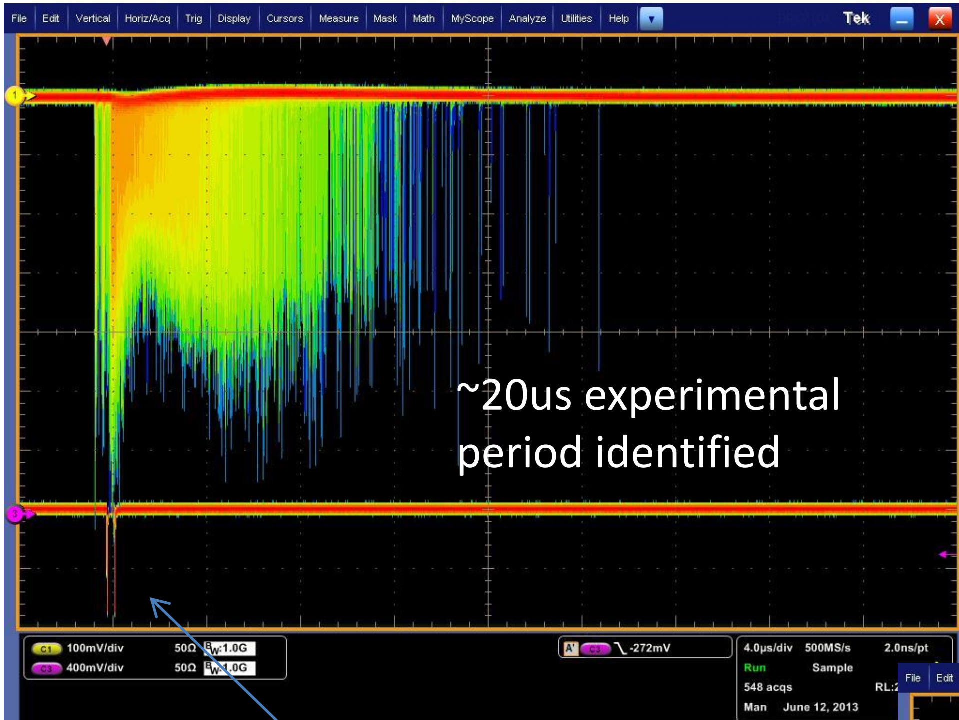
# Thank you, Questions?

# Dead time: Lets have a look at Signals first



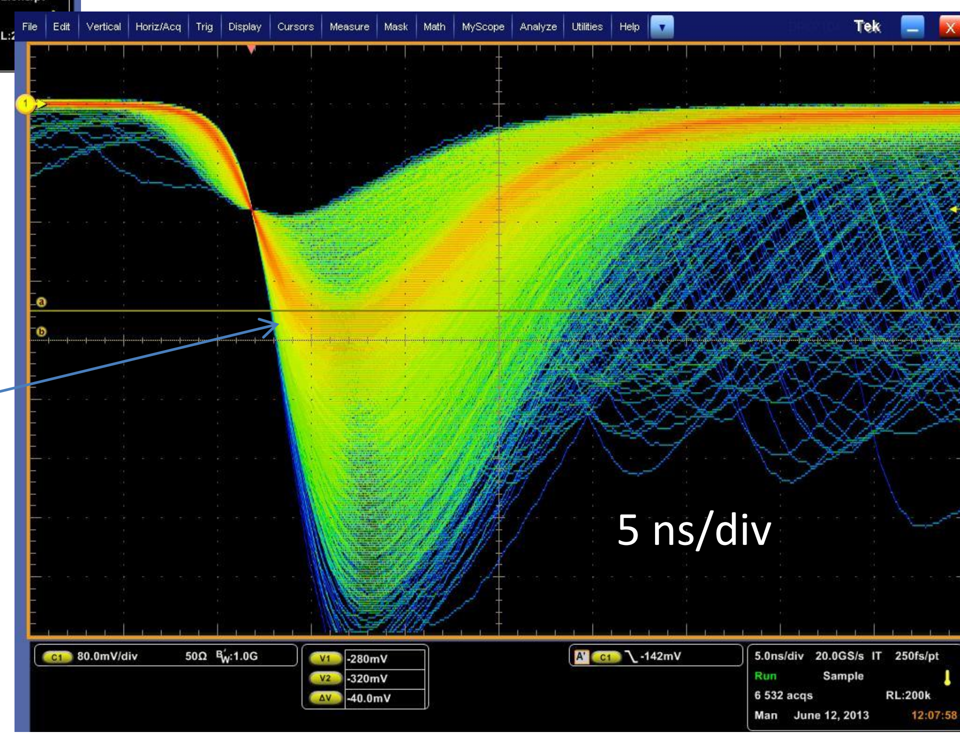



# BC scintillator disk on PMT – Pulse height spectrum




T0 from Cherenkov detectors

Clear pulse height band



# Application if deadtimes are…

## … much worse than PMT’s

- Niche applications that require compact magnetically insensitive detectors that do not need high count rates.
  - Diagnostic
  - Portable
  - Low count rate (many muon lifetimes later?)

## … comparable to PMT’s

- Applications that require compact magnetically insensitive detectors and a decent count rate.

  **E.G  HiFi Transverse Field Bank**

  Apply RF field, rotating muon spin effectively ‘beating the timing resolution governed by the pulse width’. Increase frequencies accessible on HiFi- expanded science programme!

## … better than PMT’s

- Technology uptake with added benefits of magnetic insensitivity and very compact designs.
- New geometries such as directly viewing scintillator possible.
- **Achieve higher rates, do muon science faster, better and more efficiently.**

# Simulation of reflectors and light collection

490 IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 59, NO. 3, JUNE 2012

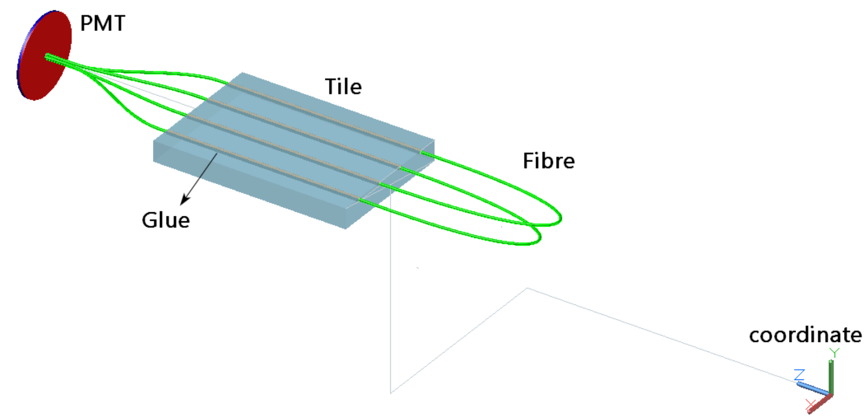
## Reflectivity Spectra for Commonly Used Reflectors

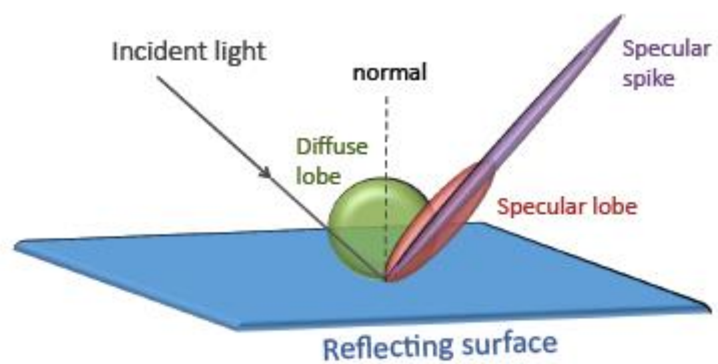
Martin Janecek

TABLE I
EXAMINED REFLECTORS

| Reflector | Refl. Coeff. @ 440nm | Thickness [mm] | Source | Refl. Ref. |
|---|---|---|---|---|
| SRS-99 (White Standard) | 0.988 | 10 | Labsphere, Inc. North Sutton, NH | *company** |
| Spectralon (WS-1-LS) | 0.993 | 10 | Ocean Optics, Inc. Dunedin, FL | *company** |
| Teflon® tape (matte) | 0.99 | *n* x 0.06 | ACE Hardware Oak Brook, IL | [18-20] |
| PTFE tape (glossy) | 0.99 | *n* x 0.08 | *unknown origin* | [18-20] |
| Tetratex® film (matte) | 0.99 | *n* x 0.16 | Tetratec™ Corp. Feasterville, PA | [18-20] |
| Titanium dioxide paint | 0.955 | 0.14–0.18 | Saint-Gobain Hiram, OH | *company** |
| Magnesium oxide | 0.98 | 1.0 | Mallinckrodt, Inc. Paris, KY | [11, 15] |
| GORE® diffuse reflector | 0.99 | 0.50 | W.L.Gore & Associates, Inc. Newark, DE | *company** |
| Nitrocellulose | 1.02† | 0.12 | Advantec MFS, Inc. Dublin, CA | *measured* |
| Lumirror® | 0.98 | 0.24 | Toray, Japan | [7] |
| Melinex® | 0.98 | 0.125 | Dupont™ Wilmington, DE | [7] |
| Tyvek® paper | 0.97 | *n* x 0.11 | Dupont™ Wilmington, DE | [7] |
| ESR film | 0.985 | 0.065 | 3M St. Paul, MN | *company**, [25] |
| Aluminum foil | 0.78 | 0.025 | Kaiser Foil Northbrook, IL | [7] |

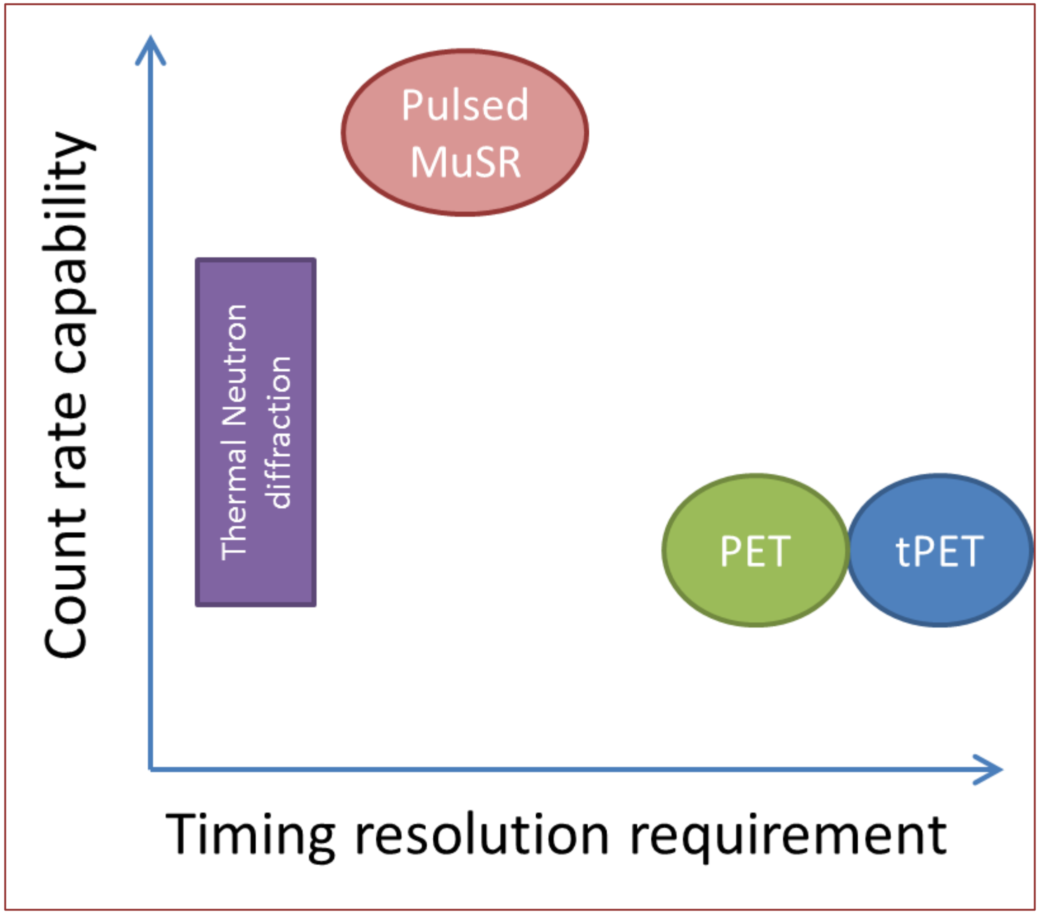
** the reflection coefficient data provided by the manufacturer were used*
*† the reflection coefficient was measured to be 103% of the reflection coefficient of four layers of ACE Teflon® tape at 440nm (i.e., 1.03 x 0.99) [7]*



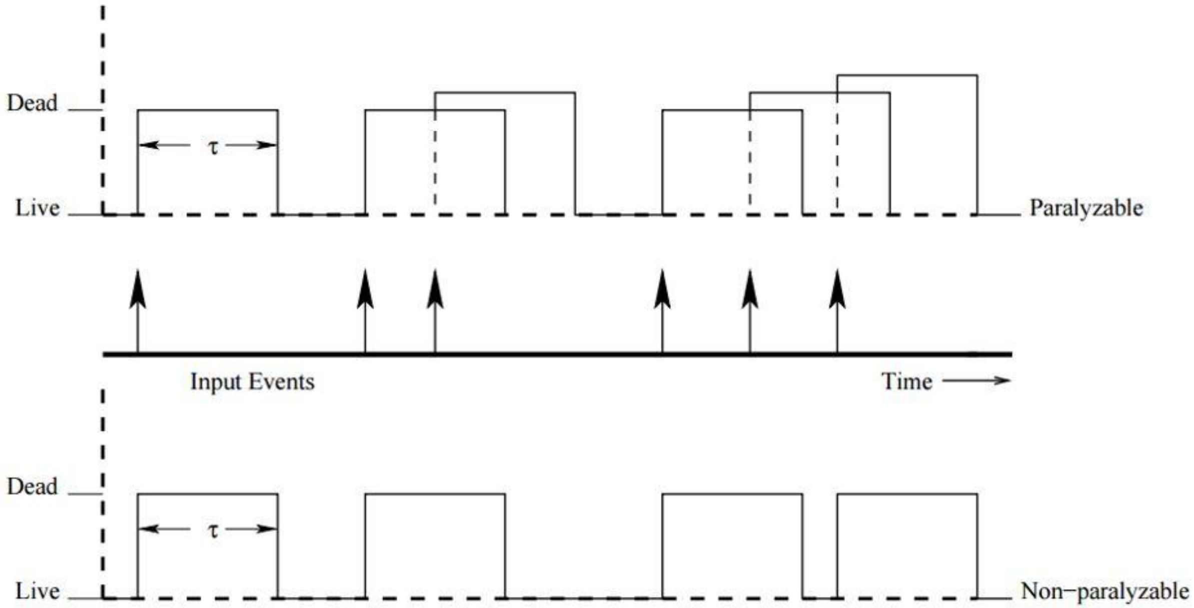

*Zi-Wen Pan*

# Specification: some context



# MuSR Beamline Work

# Dead-time models

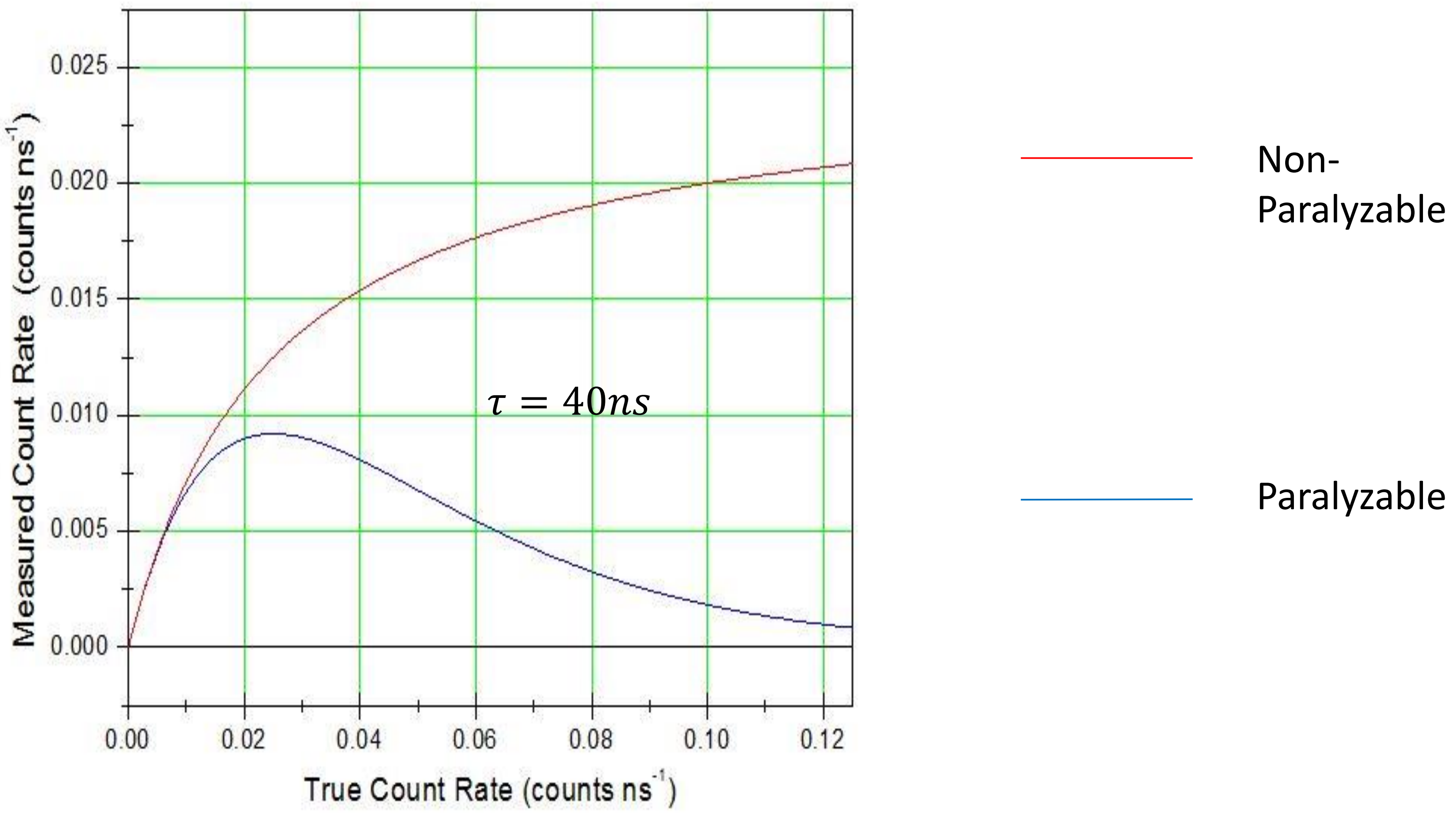



$$m = ne^{n\tau}$$

n--- true rate
m--- measured rate
$\tau$--- dead-time

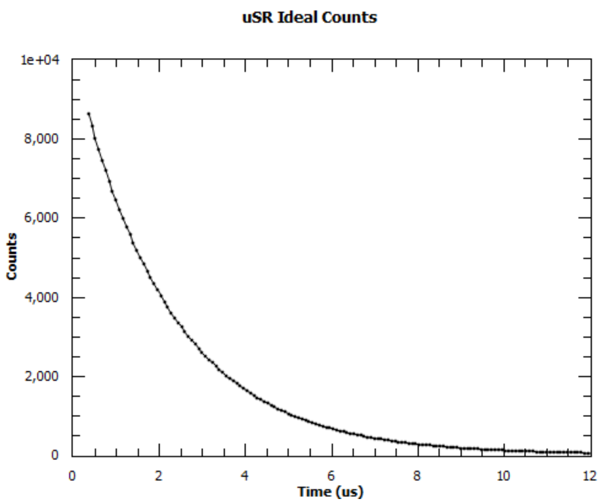
$$m = \frac{n}{1 + n\tau}$$

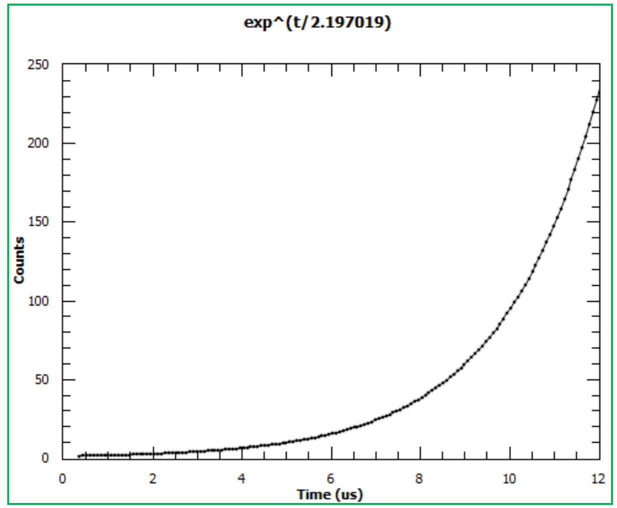
# Measured rate as a function of true rate

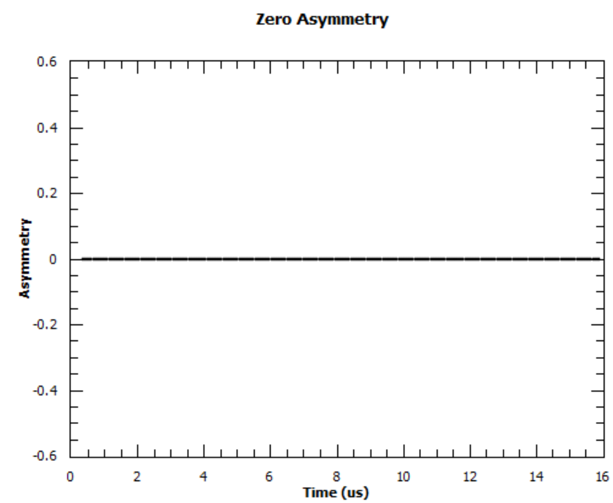


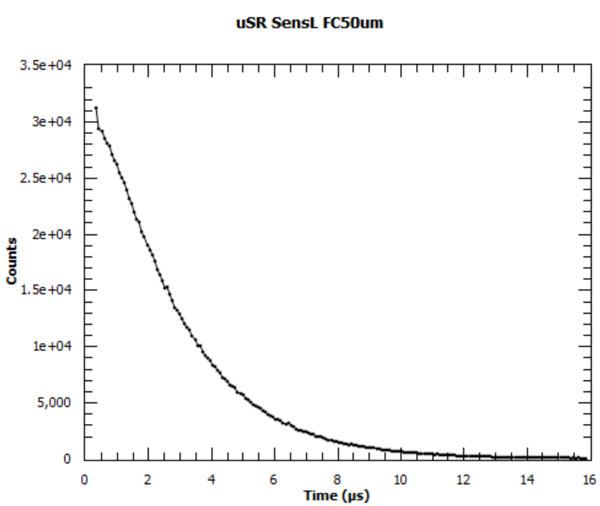
# μSR – Asymmetry

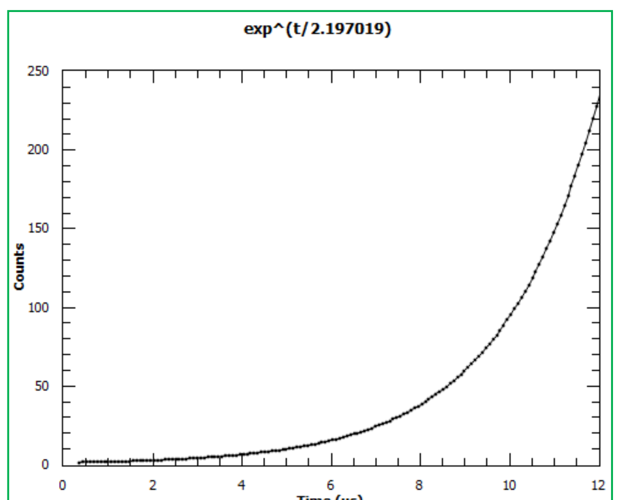
$$Asymmetry = \left(\left(Counts \cdot e^{\frac{t}{\mu}}\right)/N_0\right) - 1$$

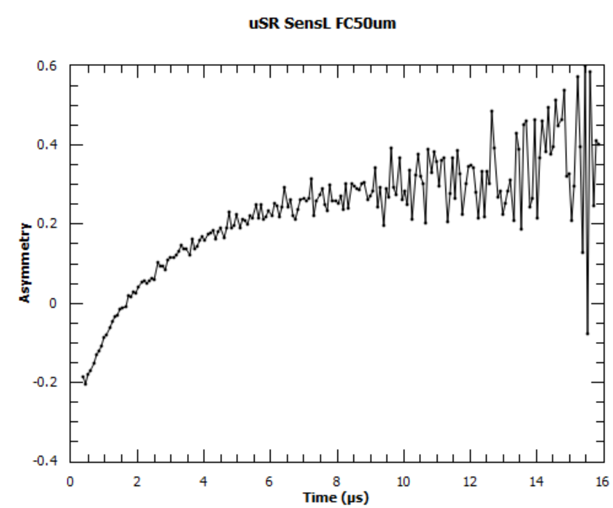


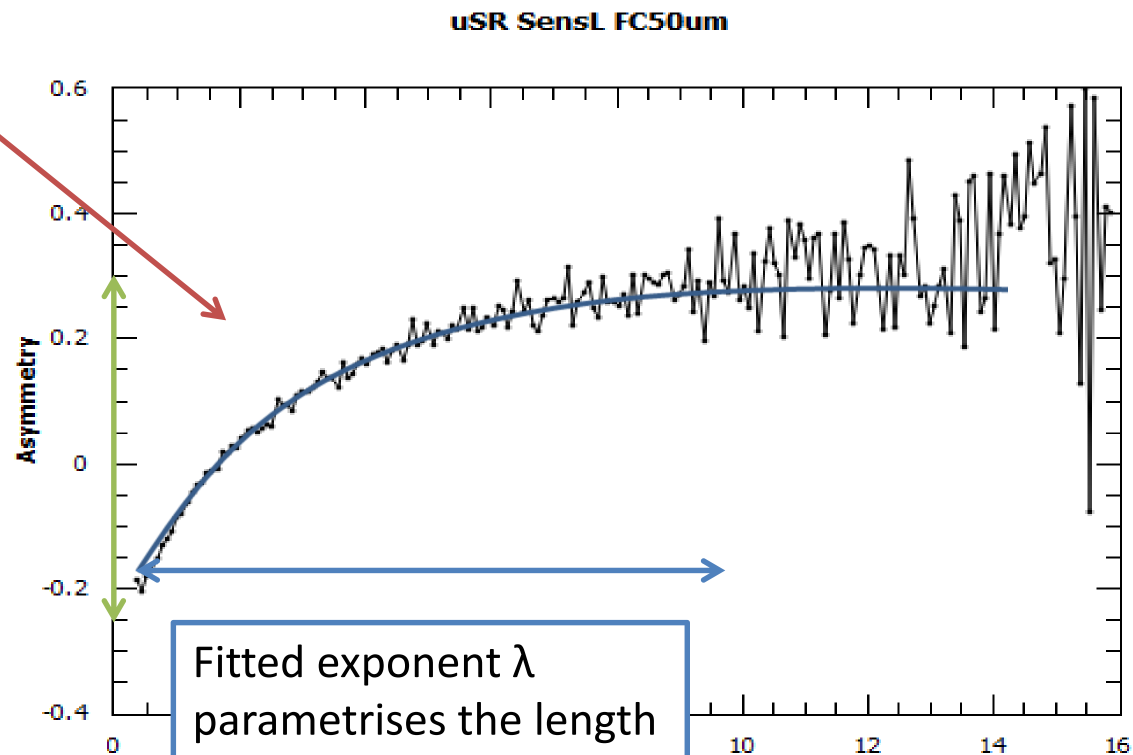



# μSR – FoM

Missed counts cause this type of distortion in asymmetry



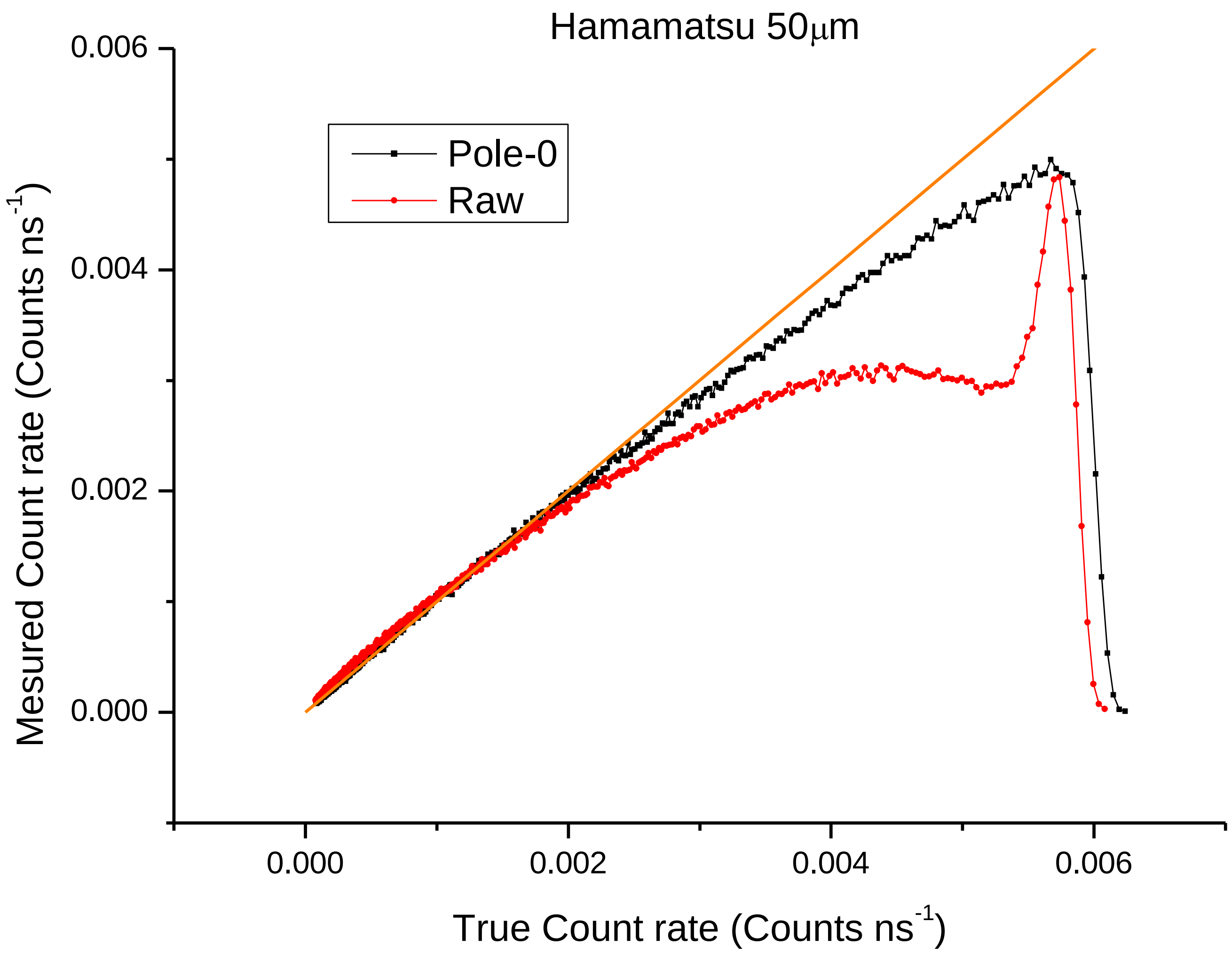

$A_0$ parameterises the height of the distortion

Fitted exponent λ parametrises the length of the distortion

Combine to give: **FOM = 1 - $|A_0 \cdot \lambda|$**

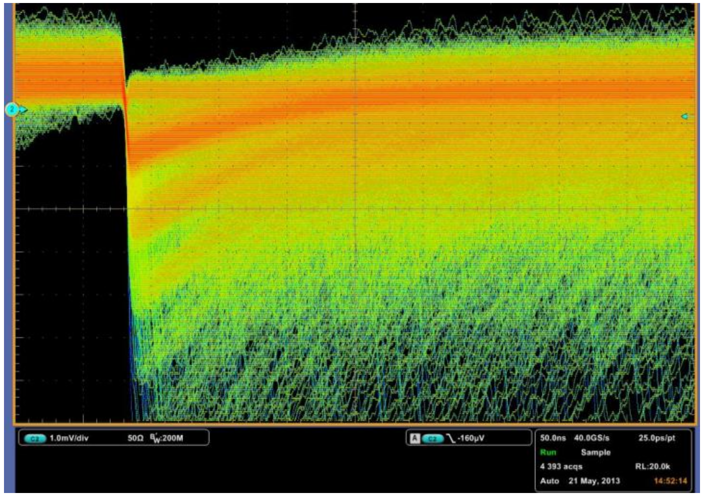
NOTE- μSR scientists will run a detector with some deadtime distortion and correct for this if possible. The FoM allows us to compare the rate at which detectors can be run, which is more useful than absolute deadtime numbers.

# Example: Hamamatsu SiPM

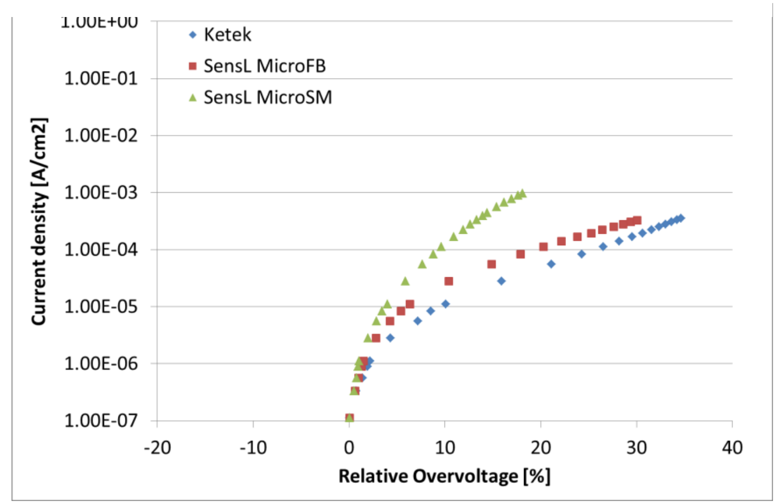


# First Investigations & Prototypes

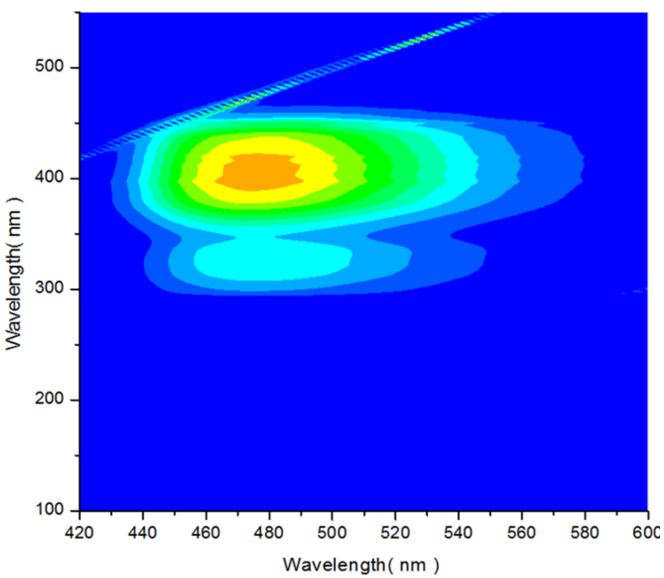
## Signal Characterisation



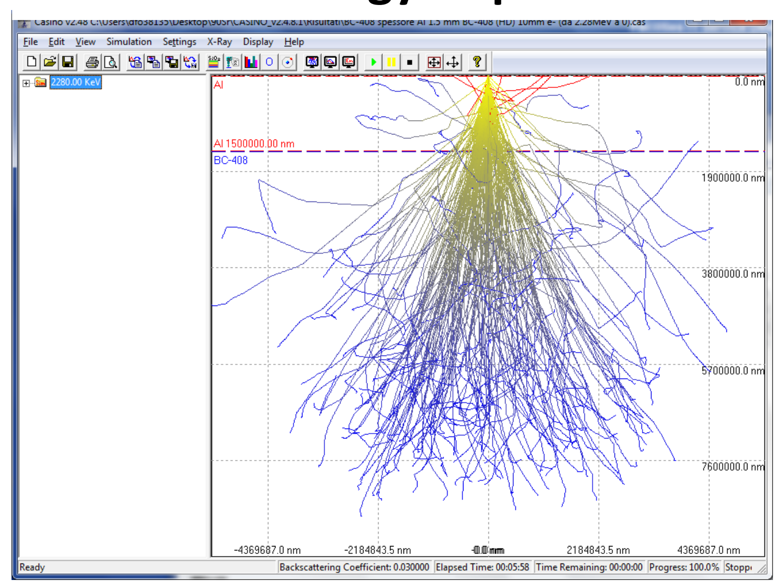
## Electronic Characterisation



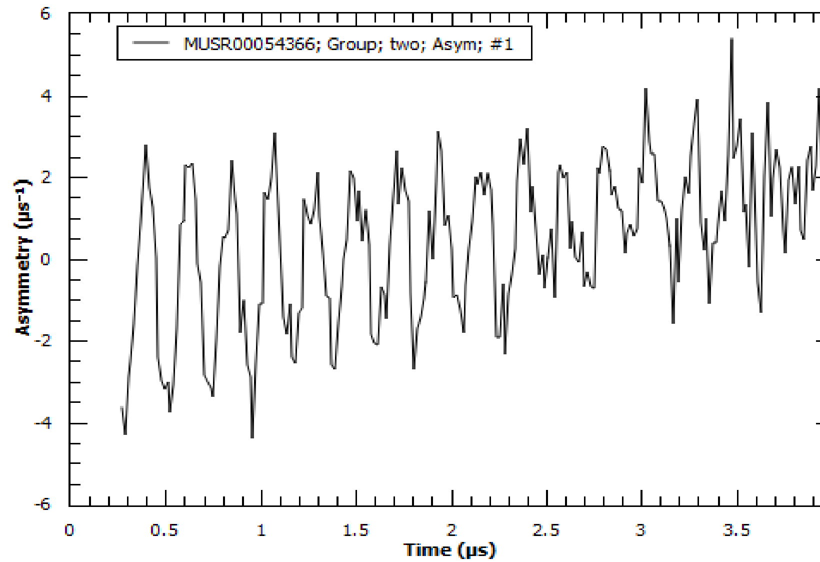

## Optical Characterisation




## Model Energy Deposition

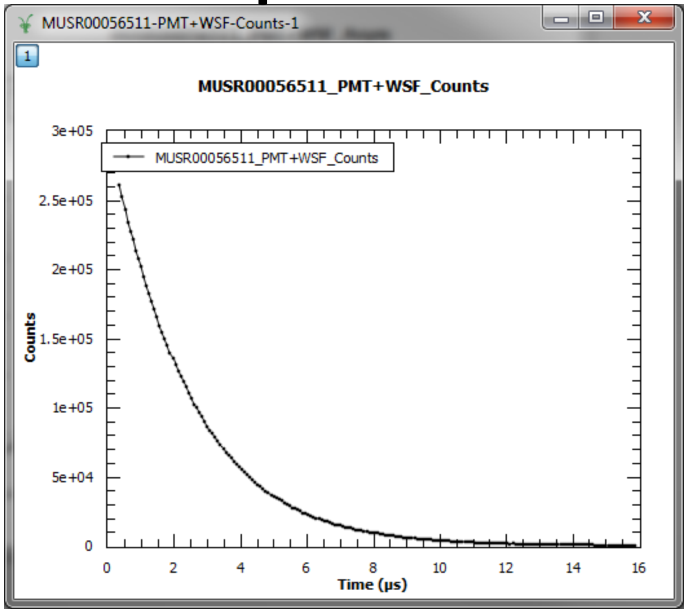


# Muonium in 20 G Field

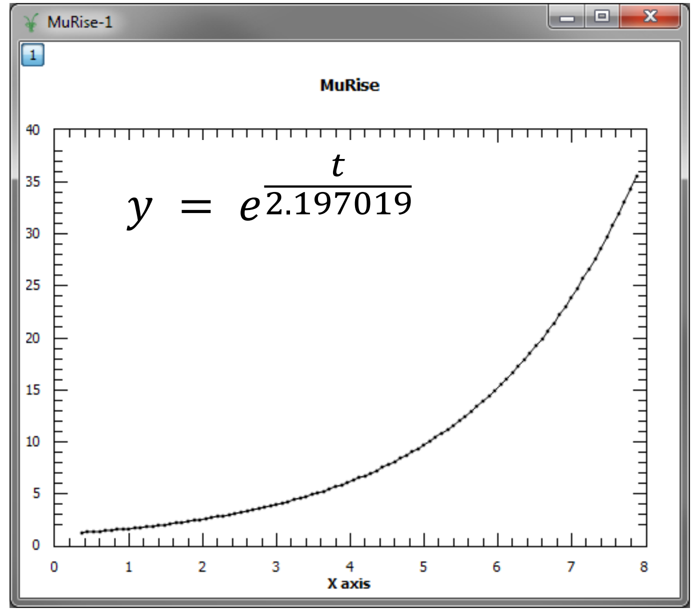



Frequency ~5 MHZ - as calculated

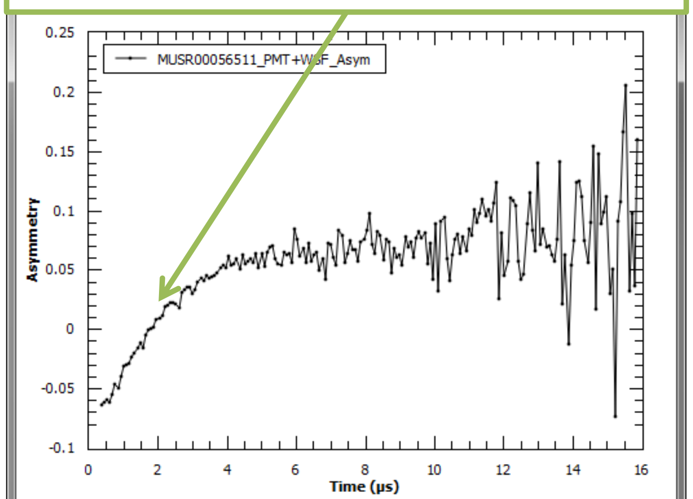
# Example – PMT with WSF tile

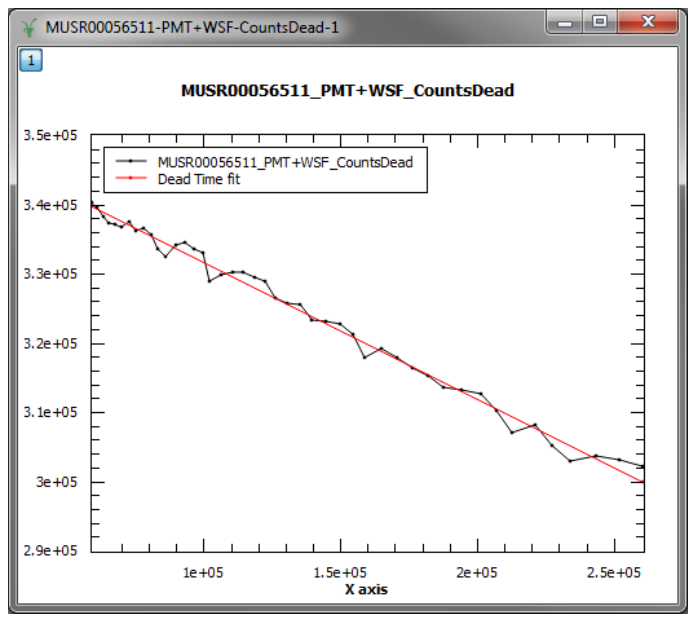



x




Downturn = missed counts




CalMuonDeadTime

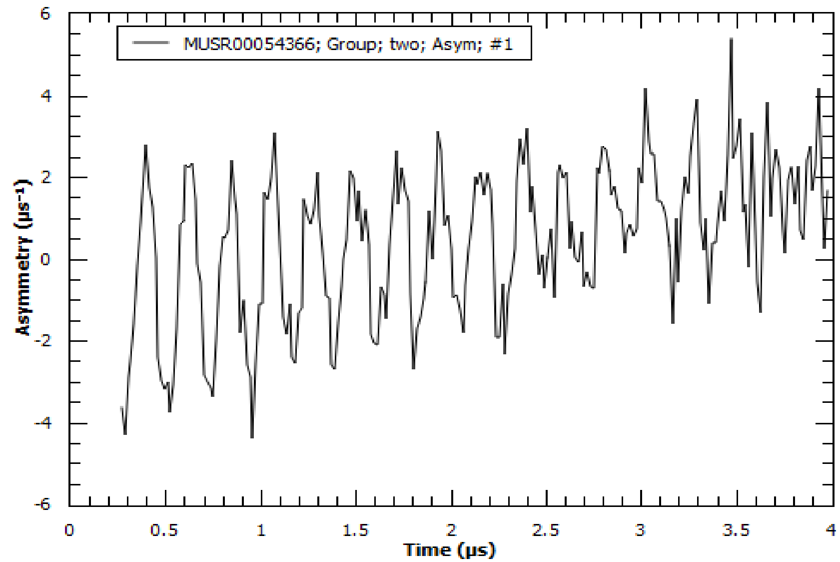
Equation:

$$M e^{\frac{t}{\tau}} = N_0 - M\, N_0 \left(\frac{t_{dead}}{t_{bin}\, F}\right)$$

Dead Time: 0.023 us

Counts/Frame: 15

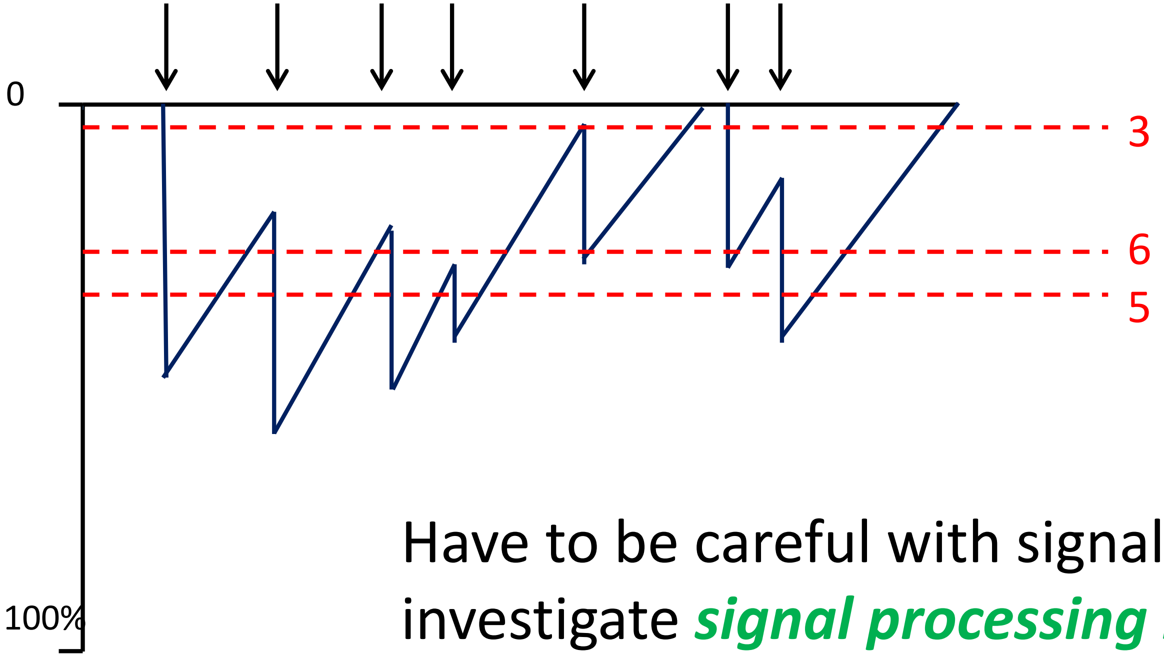
# Muonium in 20 G Field




Frequency ~5 MHZ  - as calculated

# SiPM Deadtime Continued

Low hit fraction is giving clear peaks but where to place the discriminator?



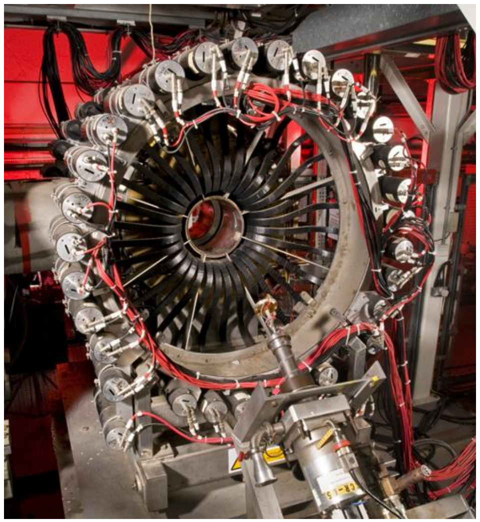

Have to be careful with signal processing, and investigate ***signal processing methods.***

# Future Investigations

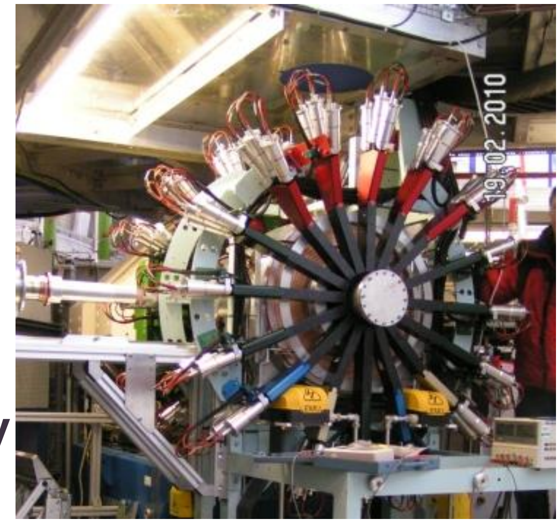
Temperature
Sensitivity tests

# Solution to Deadtime (2)

Pixelate the detector array



Paisley

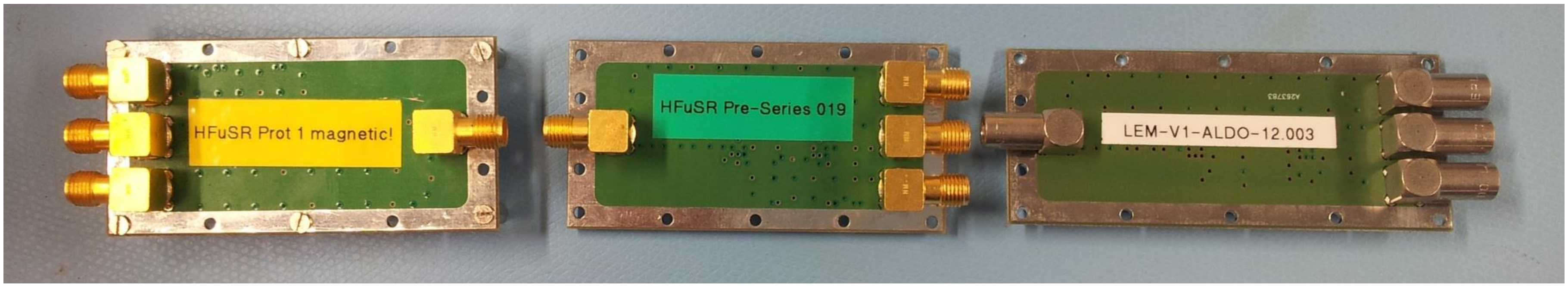



MuSR  64

EMU = 96

- Cost per channel
- Active volume effects
    - Positron traversing multiple elements
    - Dead space
- Difficult assembly

# Amplifiers (PSI and miniCircuit)




## ZFL-1000+
## ZFL-1000


## ZX60-43+

## ZX60-14012L+

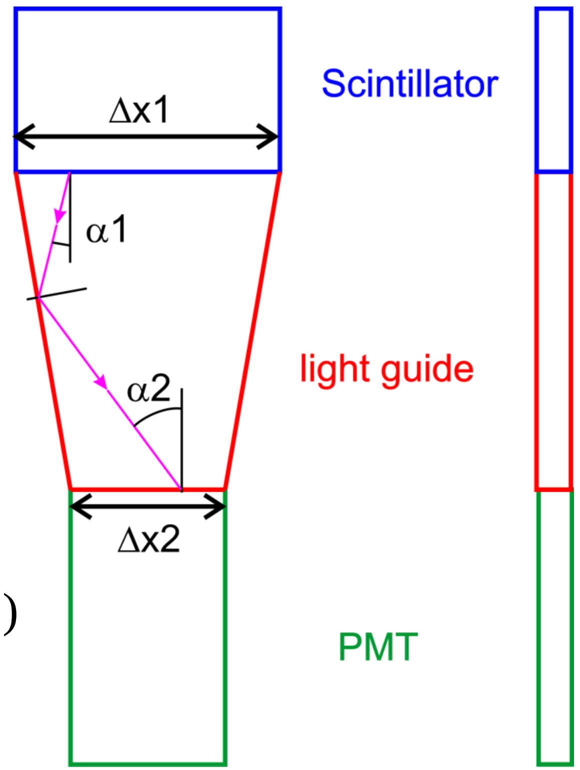
# Light guides

- Liouville's theorem
- Phase space volume element:

$$\Delta x_1\ \Delta p_1 = 2\,\Delta x_1\, n \sin(\alpha_1) \qquad \Delta x_2\ \Delta p_2 = 2\,\Delta x_2\, n \sin(\alpha_2)$$

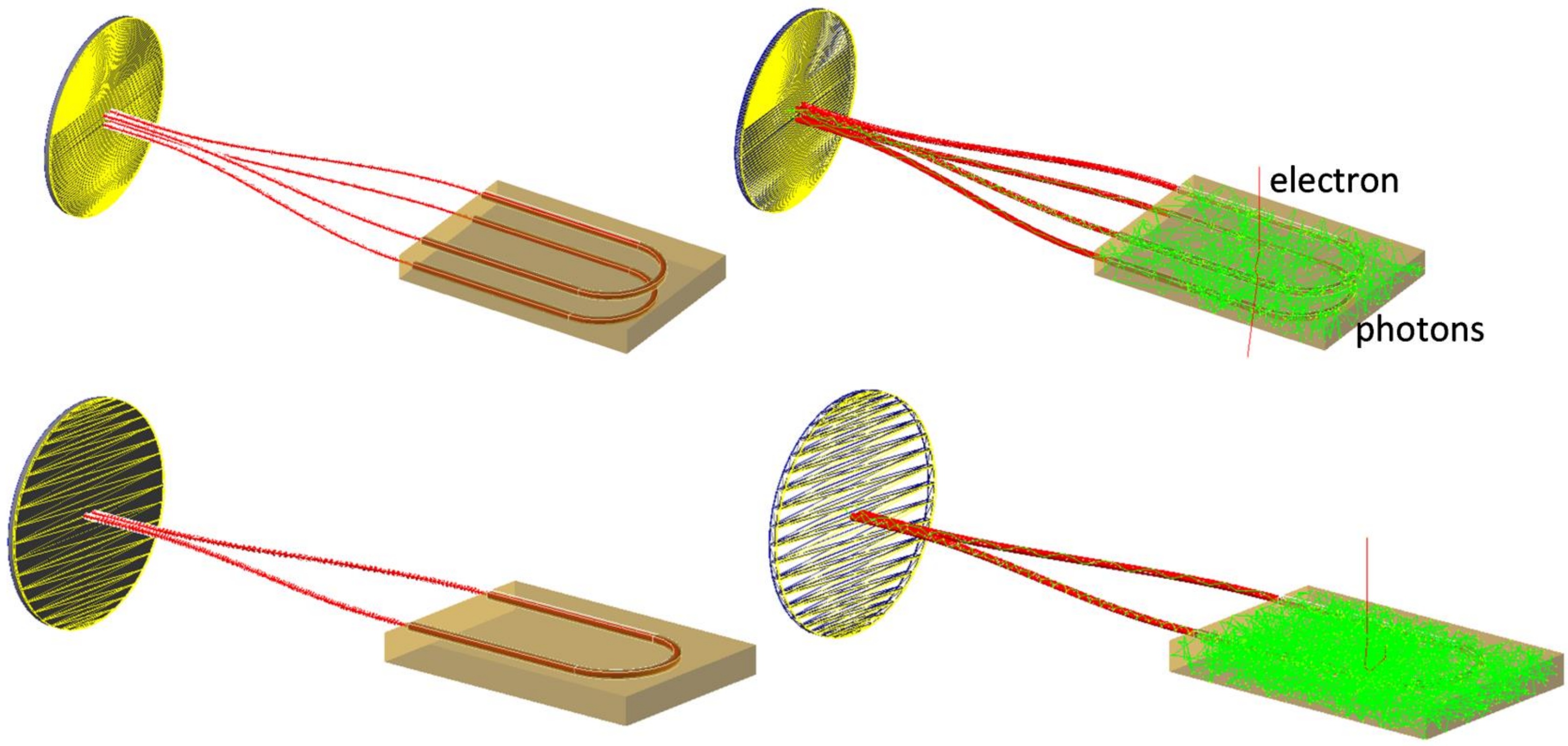
- Conservation of phase space:

$$2\,\Delta x_1\ n_1 \sin(\alpha_1) = 2\,\Delta x_2\ n_2 \sin(\alpha_2) \Rightarrow \sin(\alpha_1) = \frac{\Delta x_2}{\Delta x_1} \sin(\alpha_2)$$




➢ Area * number of photons is constant

# Simulation of reflectors and light collection



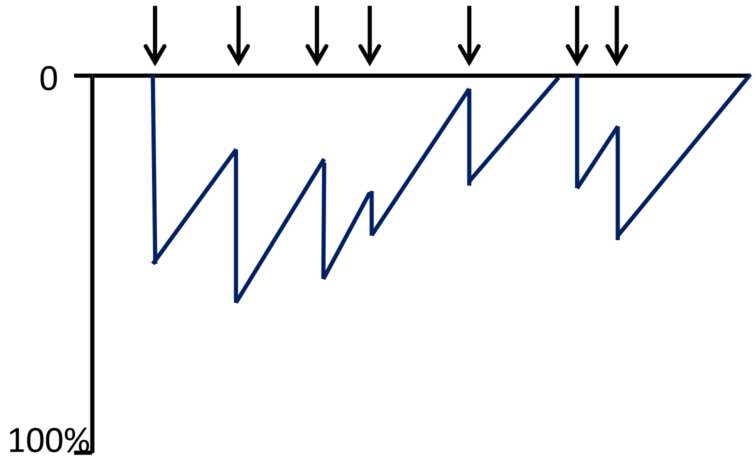

Investigate reflectors, fibre number, and homogeneity.

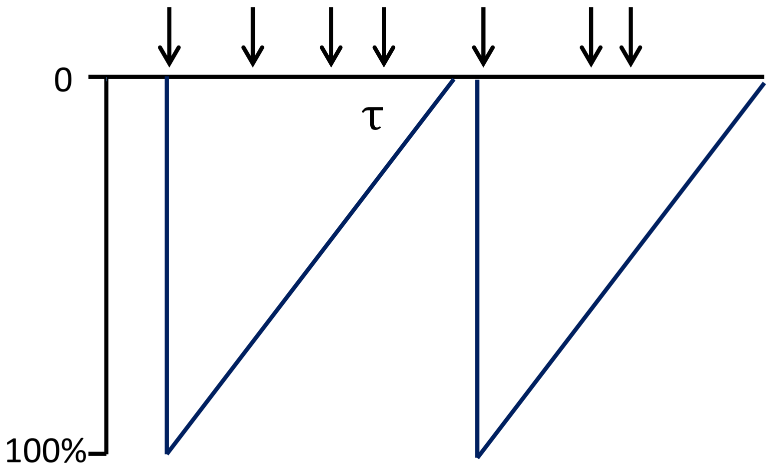
| Material | Refractive index | Bulk absorption length / cm | Wave length of maximum emission / nm | Light yield Counts/MeV | Decay time / ns | Rise time / ns |
|---|---|---|---|---|---|---|
| BC408 | 1.58 | 380 | 425 | 10000 | 2.1 | 0.9 |
| Air | 1.0 | Very long (1000m) | - | - | - | - |
| BC600 | 1.56 | 12.5 | - | - | - | - |
| grease | 1.47 | 20 | - | - | - | - |
| BCF-92 | 1.59 | 3.5 | 492 | - | 2.7 | - |
| Fibre clad | 1.49 | 3.5 | - | - | - | - |

Zi-Wen Pan

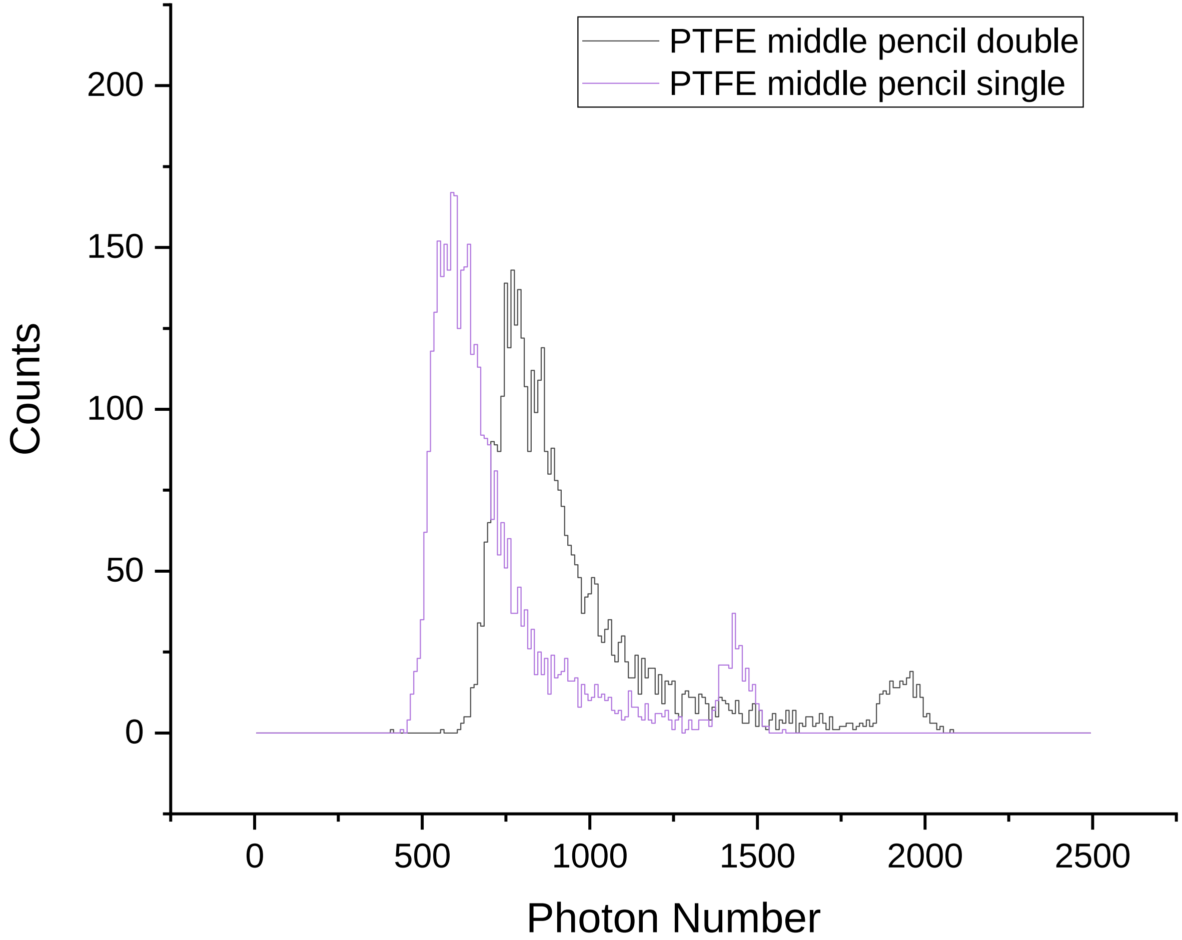
# What is the Deadtime of a SiPM?

| Minimal Deadtime | Long (100's of ns) |
| --- | --- |
| Lowering hit fraction gives reduction in apparent deadtime | Higher hit fraction means deadtime tends toward cell recovery time |



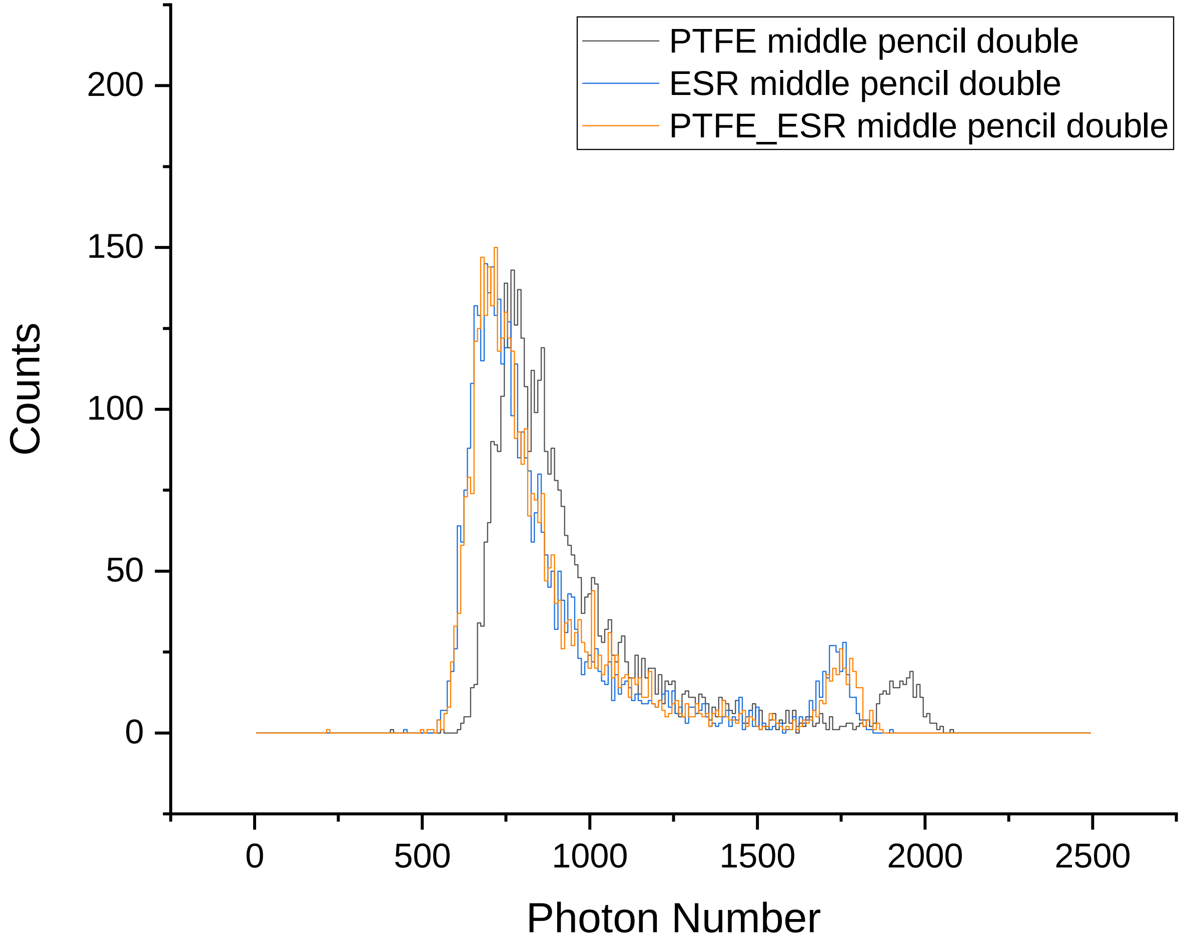
# Light collection: fibre number




Going from 2 to 1 fibres ~ -25%

*Zi-Wen Pan*

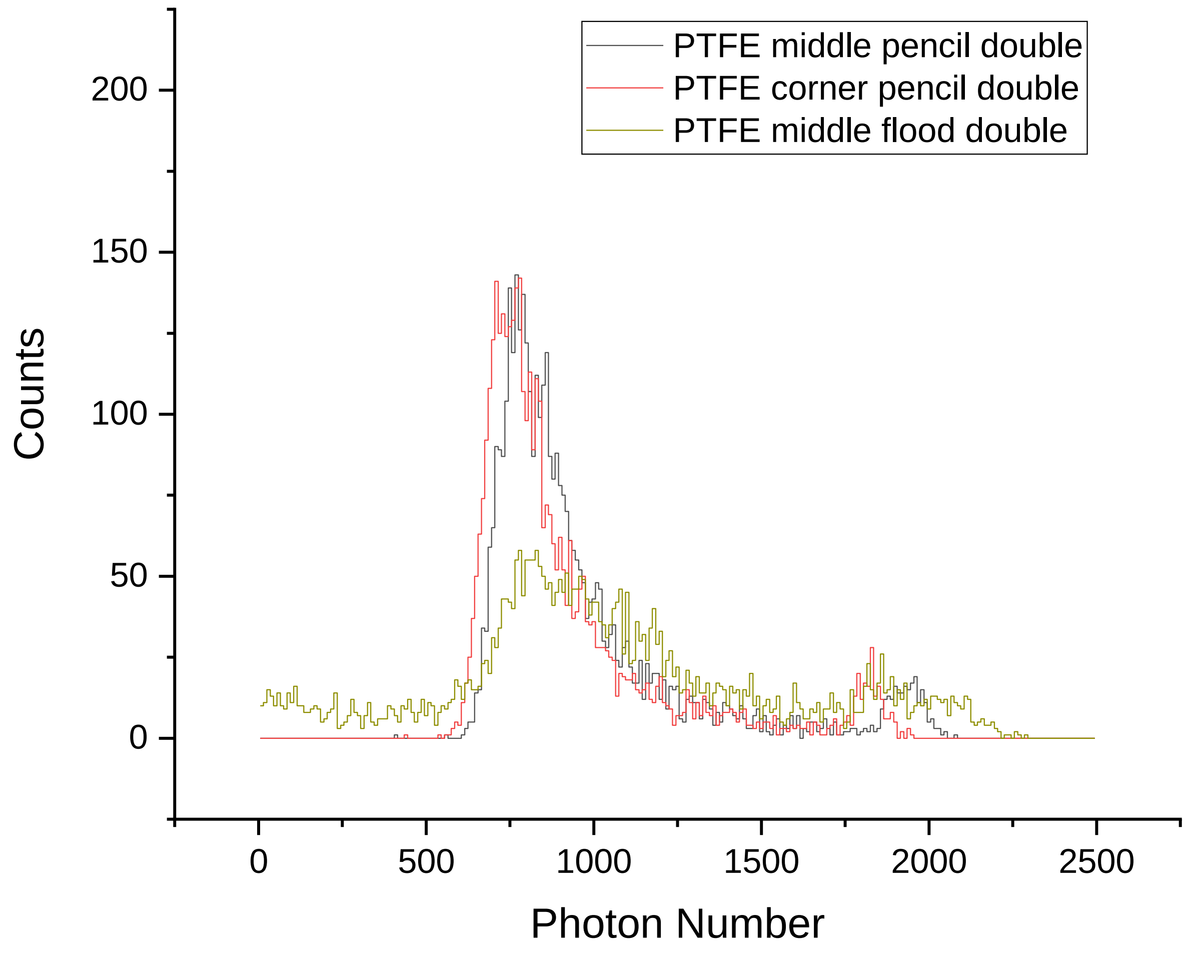
# Light collection: reflector type




Going from PTFE ~ 10%

*Zi-Wen Pan*

# Light collection: beam position/flood




Pencil beam to flood beam – broadening ~ x2 but also brings in edge effects and glancing paths.

*Zi-Wen Pan*

# Current direction

- PTFE wins in simulation but require confirmation.
- Using PTFE very attractive due to assembly ease
- Can we take 30% fewer photons by using 1 fibre. Signal band moves to 500 photons but need to account for QE of detector. SiPM – single, double..10x photon noise. Could be okay.
- Testing in June cycles.