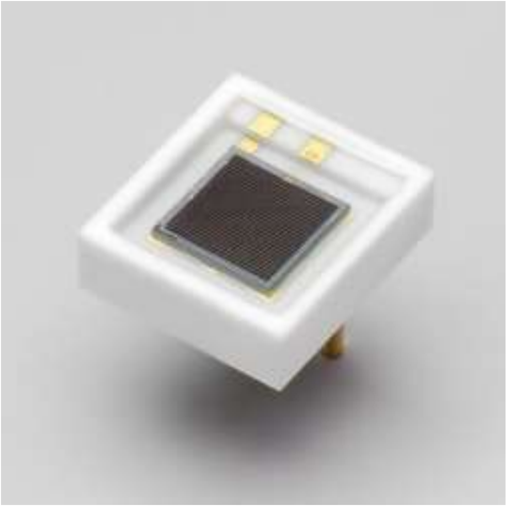
- Work Package 9.4:
  - Emergent Detector Technologies for neutron scattering and muon spectroscopy
    - Sub Task 3: Silicon photomultipliers for muon spectroscopy

Silicon photomultipliers: Dead-time characteristics for high count rate application



Daniel Pooley

Steve Cottrell

Peter Baker

Zi-Wen Pan (Vincent)

Luca Pollastri

Myron Huzan

Lakshan Ram Mohan

STFC Rutherford Appleton Laboratory, UK

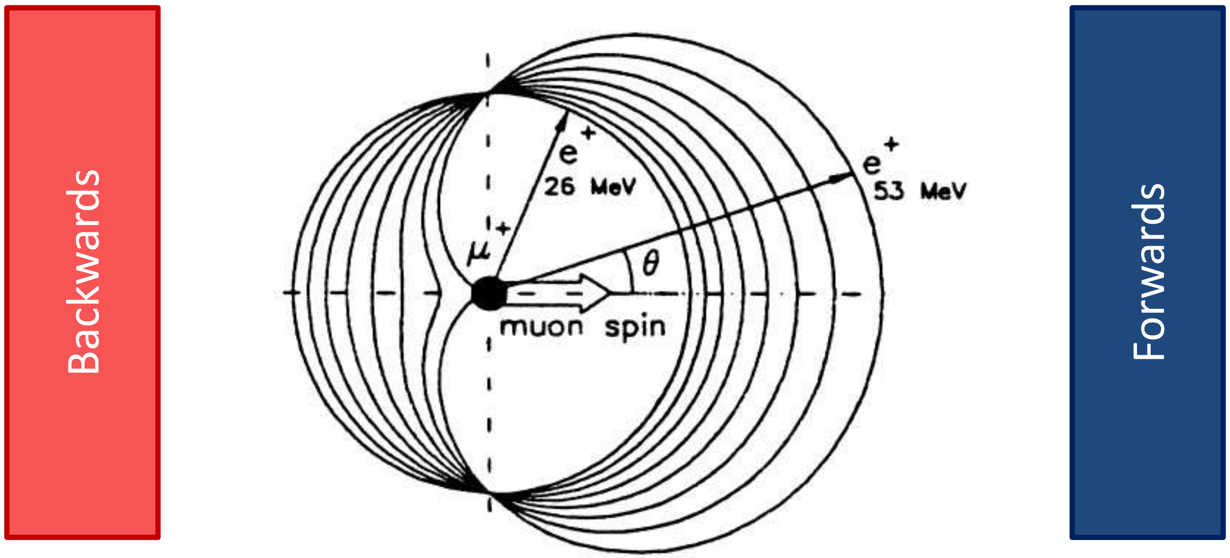
Science & Technology Facilities Council

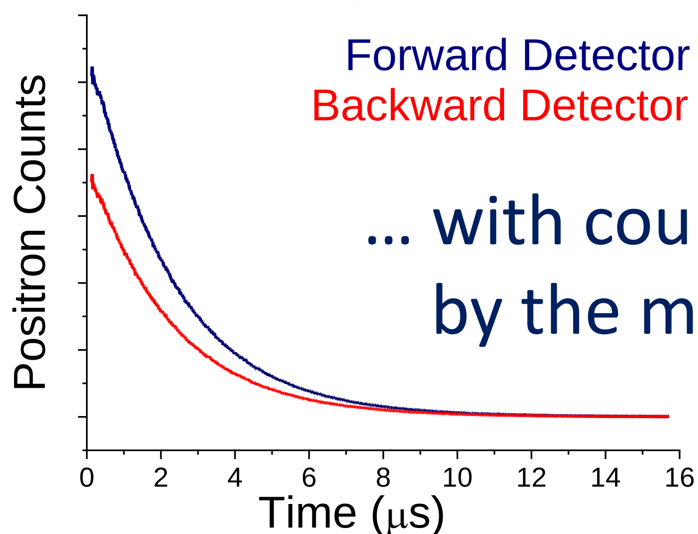
ISIS

The Experiment… …count positron arrival time

… in a symmetric geometry

Scintillation (BC408) Detectors



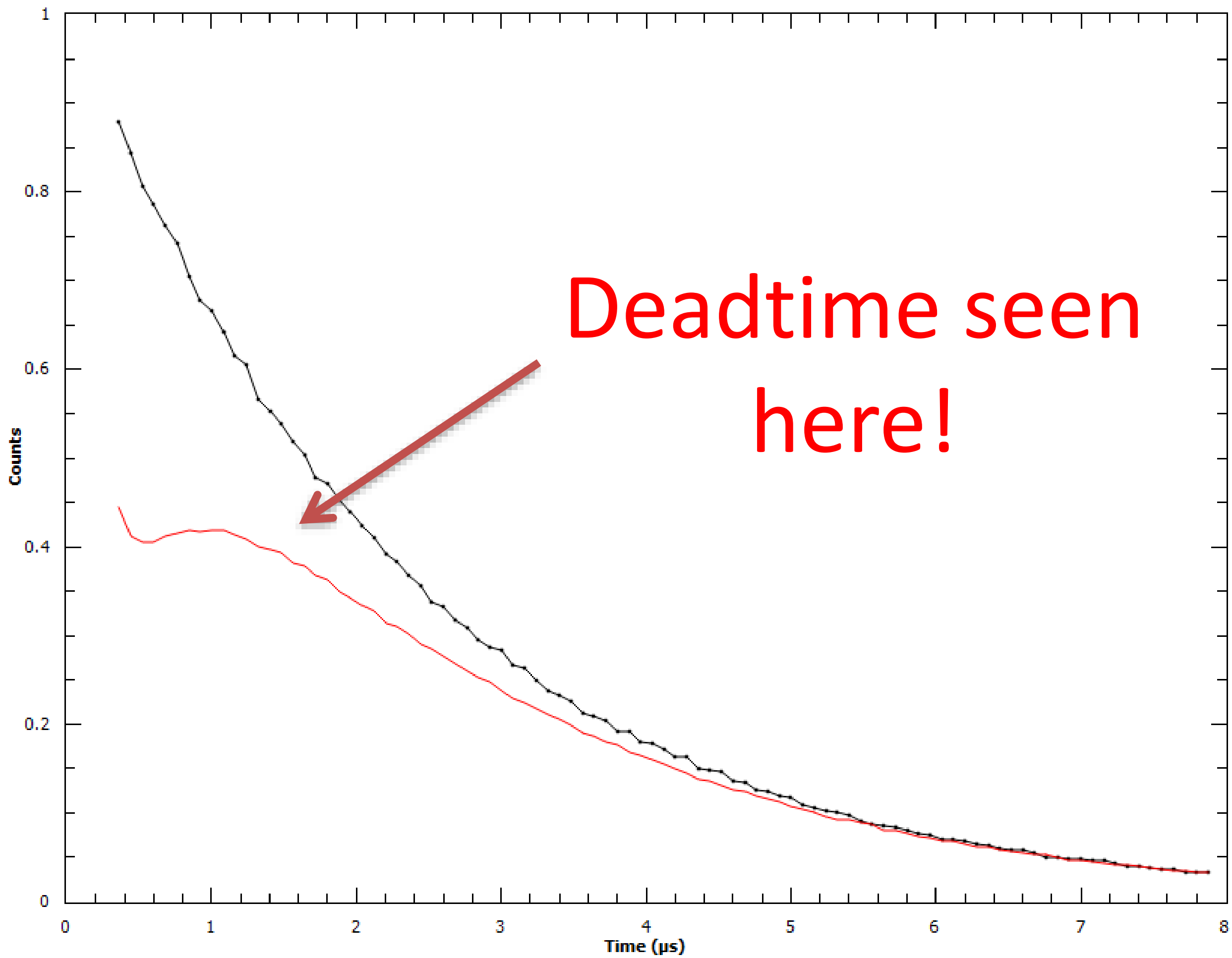


… with count rate modulated by the muon lifetime

Count rate: A Limiting Factor

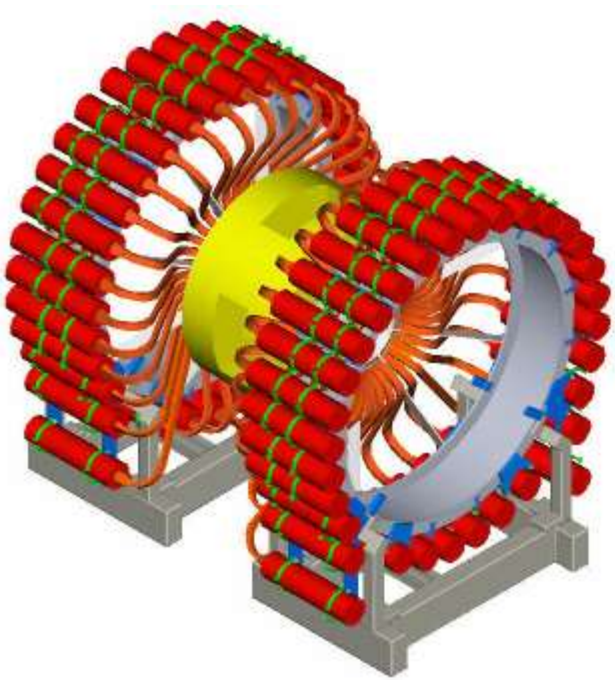
40Hz Spallation generates *high instantaneous rate…*

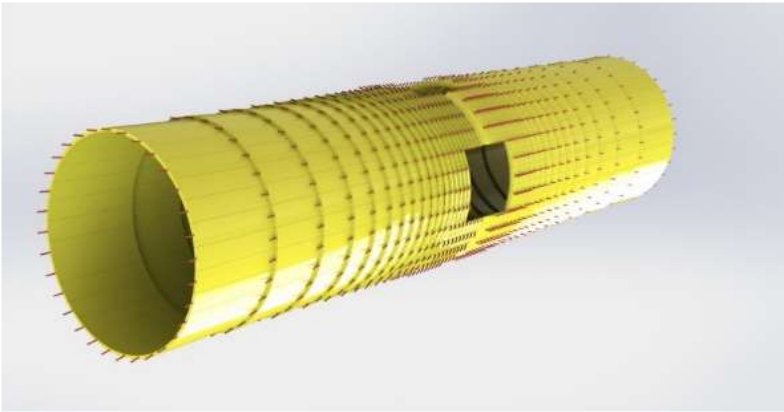
Not only are there 1000's of muons per frame, they are most *likely* to be at the *start of a frame*!

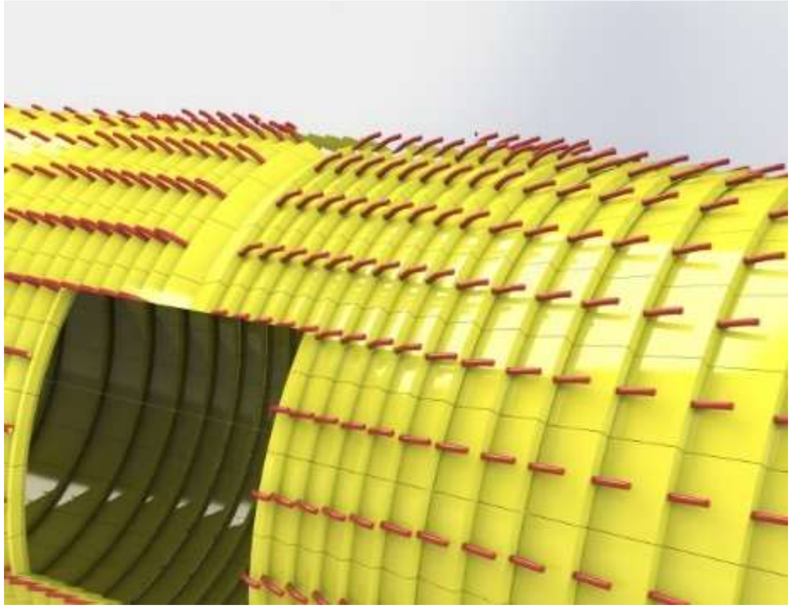


Application: MuSR -> Super_MuSR

64 detectors to 1216 detectors.





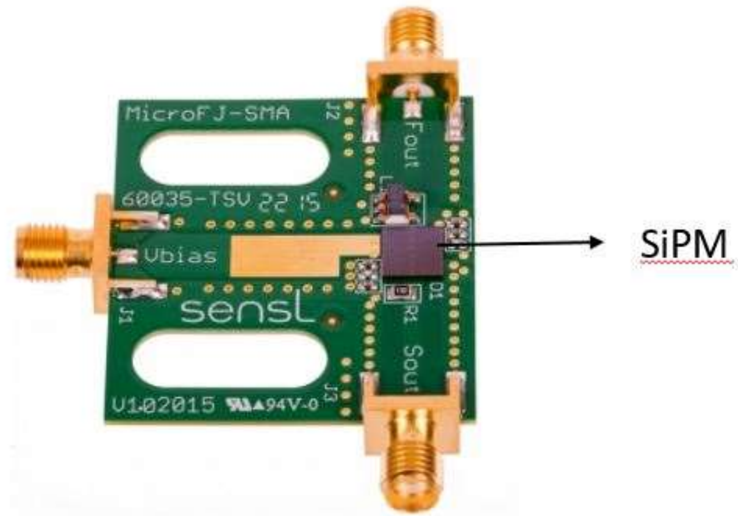


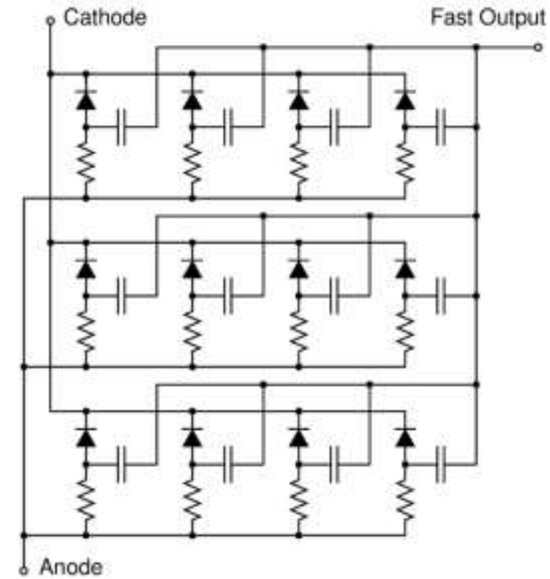
Courtesy: P. Baker, R. Afonso, P. Singkanipa

SiPM Recap

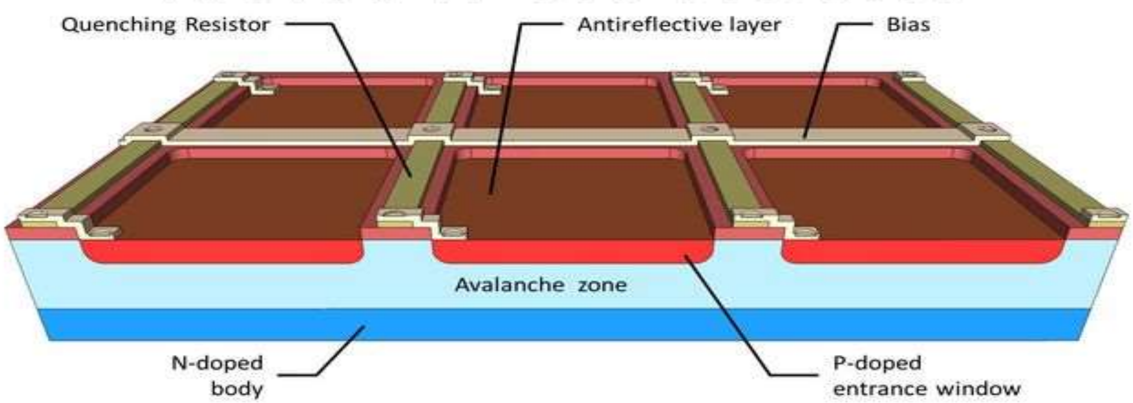
SiPMs

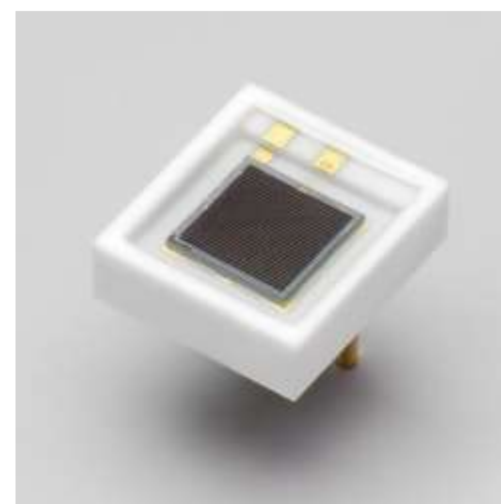
sensL
sense light



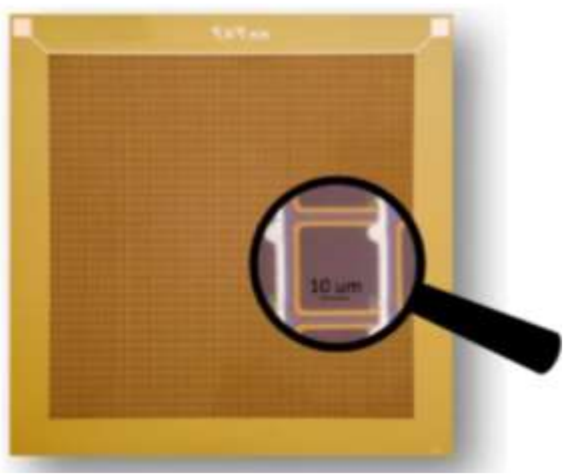


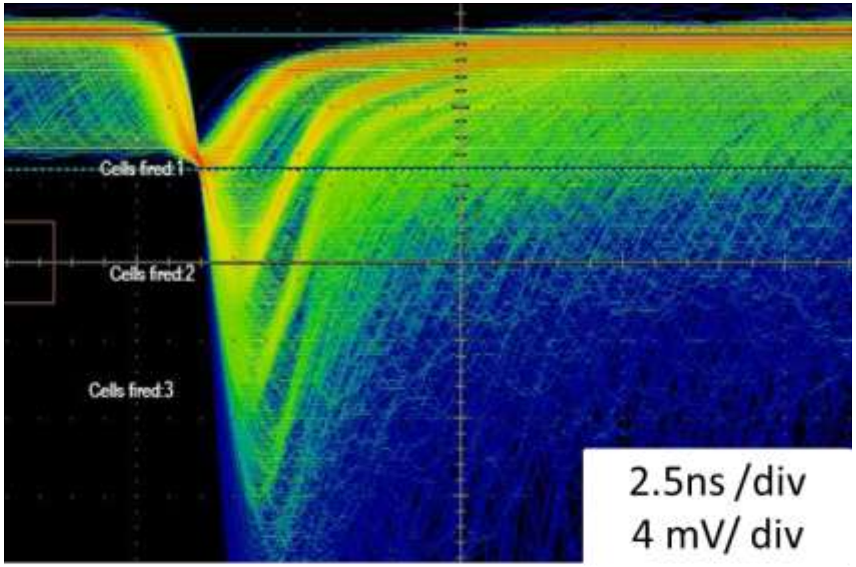
HAMAMATSU
PHOTON IS OUR BUSINESS





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

Examples from our investigations

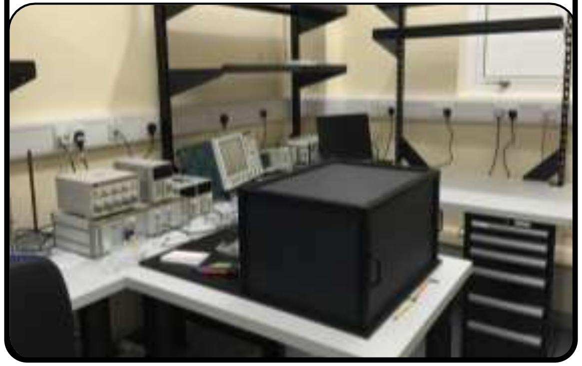
Comprehensive evaluation of SiPMs:

MuSR Beamline

- Detector chain can be investigated in a realistic environment.

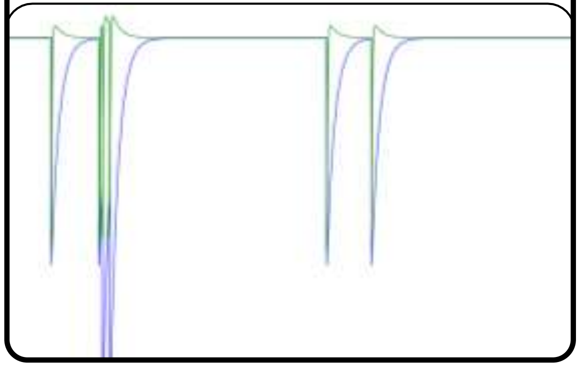
Optical Investigation

- Photon flux accurately parameterised within a controlled environment.



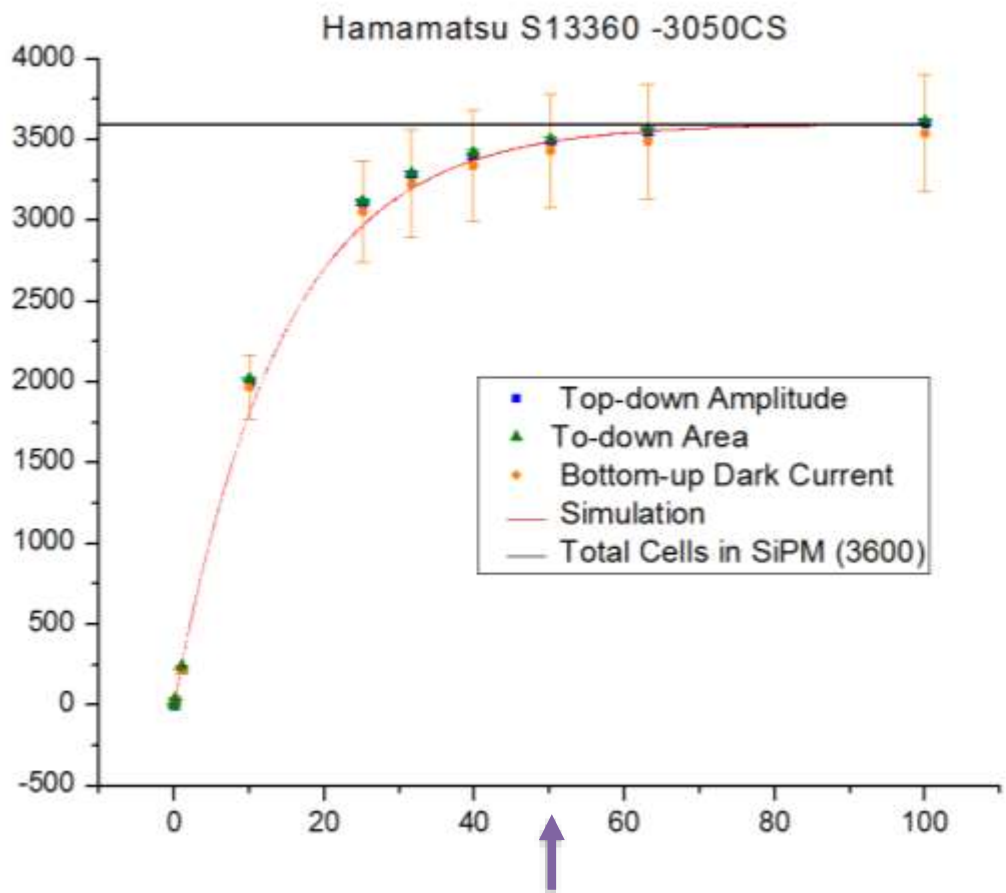
Monte Carlo Simulation

- Accurately simulate a statistical investigation in detector performance.



Example optical investigation: Cells Discharged

How many cells discharge



Brightness of flashing diode [arb. units]

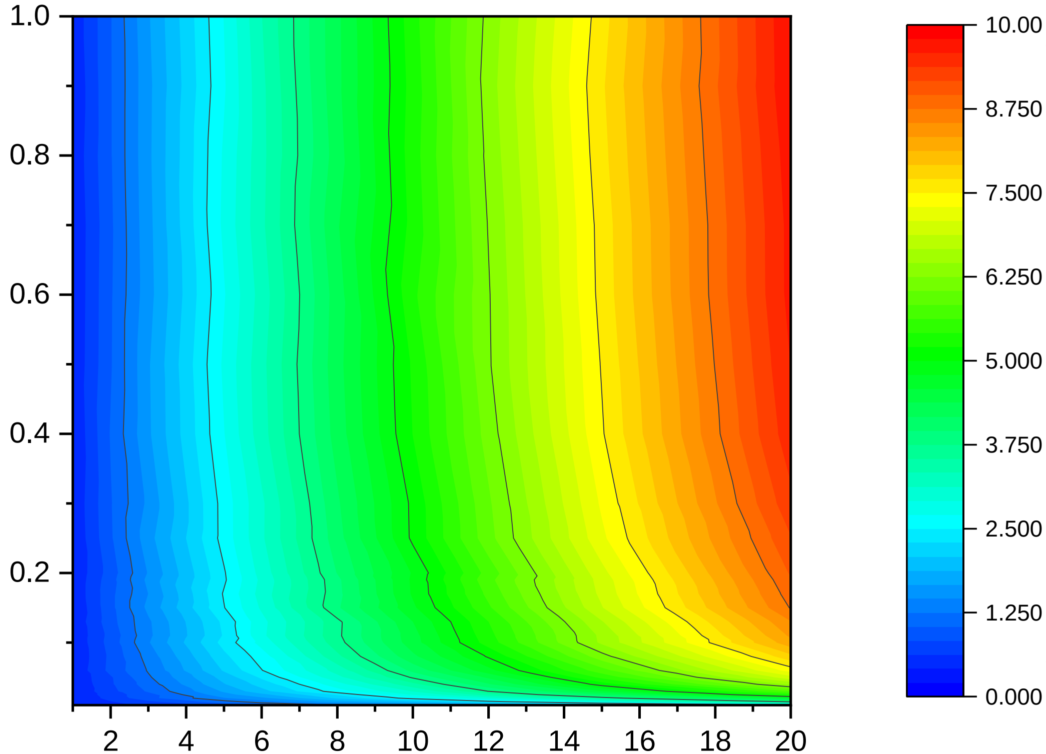
Project Conclusions:

- 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)



How many counts missed [%]

(dead time distortion)

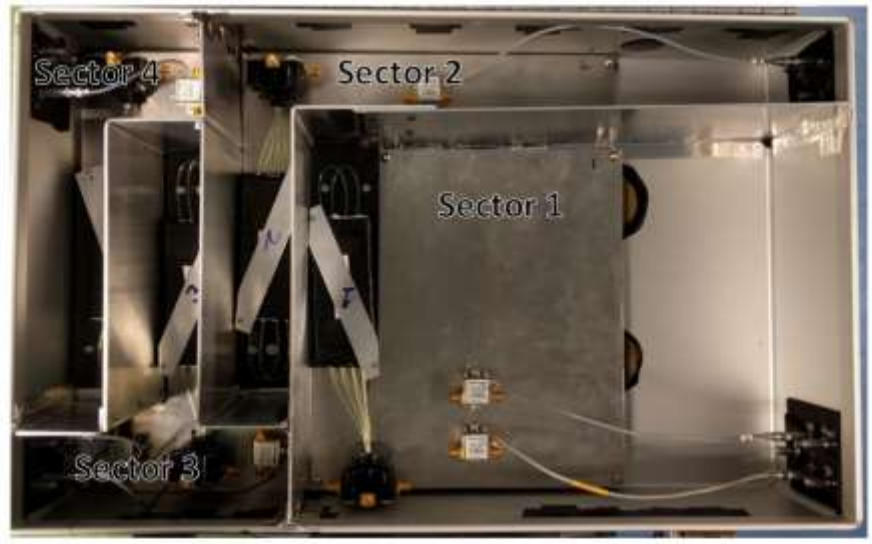
Counts per frame (muon flux)

Project Conclusions:

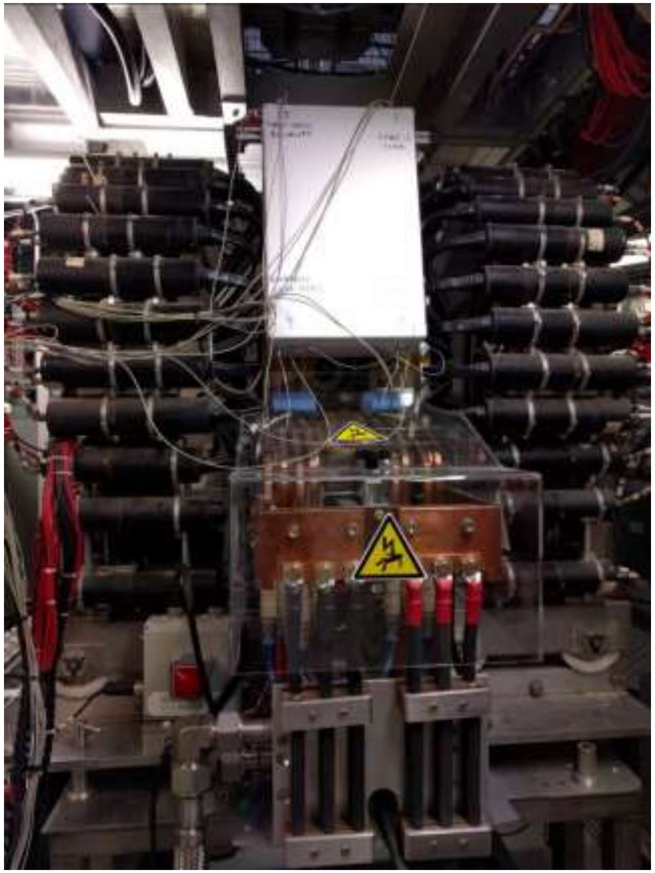
- Signal processing essential to achieve more than 10 c/frame
- Gains in count rate capability below 20% cells discharges

M Huzan

MuSR Experimental Data

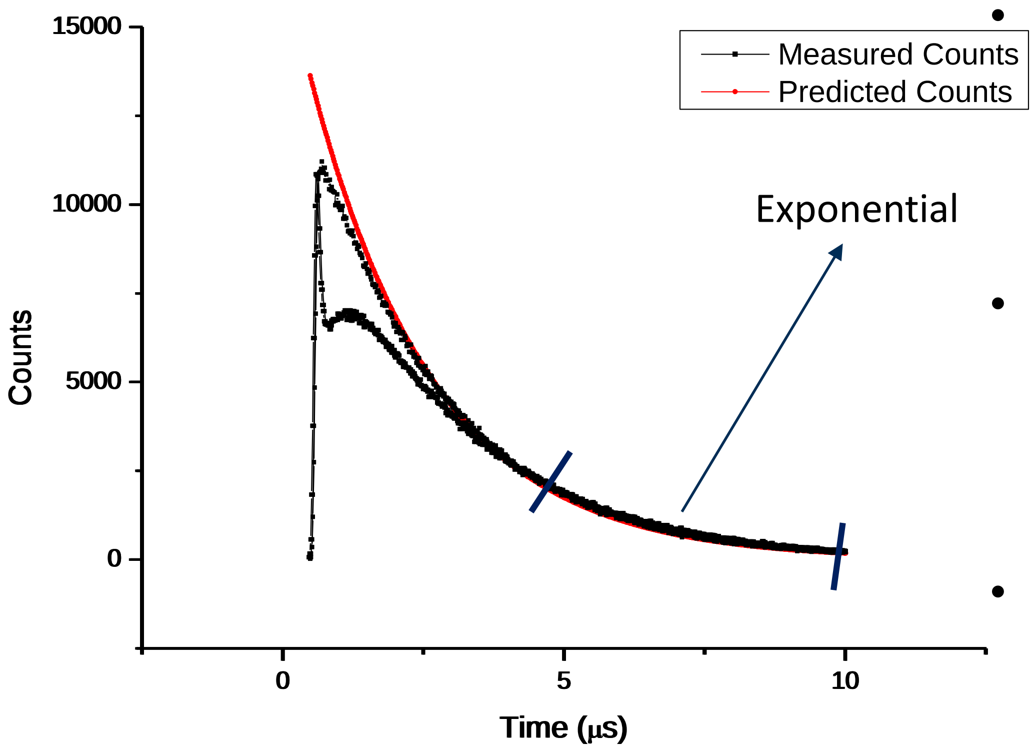


SiPM
SensL MFJ-30035 Fast
SensL MFJ-30035 Slow
Hamamatsu S13360-3050CS
SensL MFC-30050 Slow
SensL MFC-30050 Fast
Hamamatsu S13360-3050CS



L R Mohan

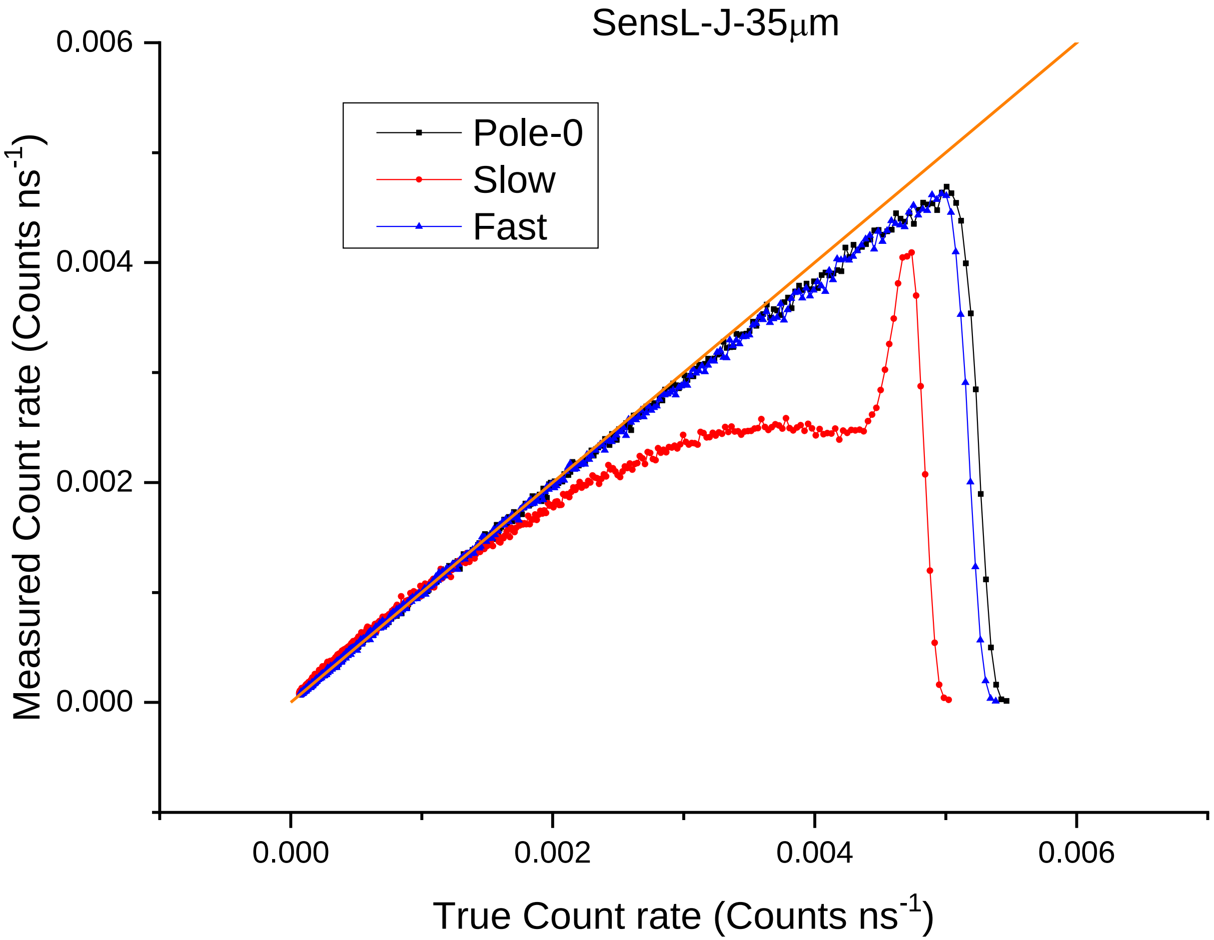
Example: Beam Data Parameterisation



- 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

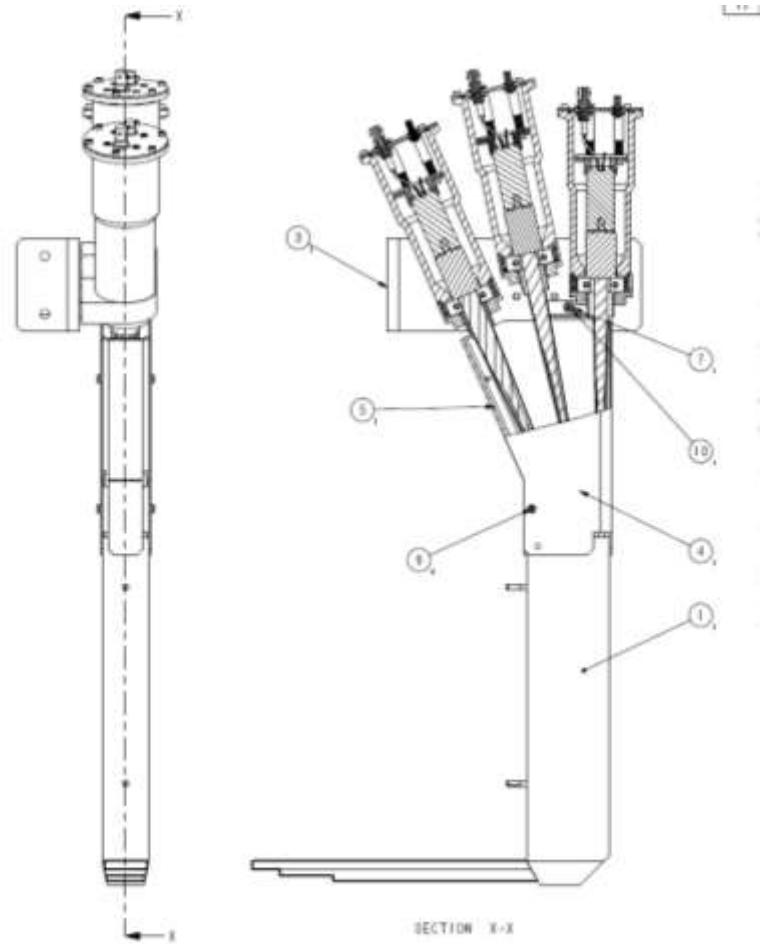


Project Conclusions:

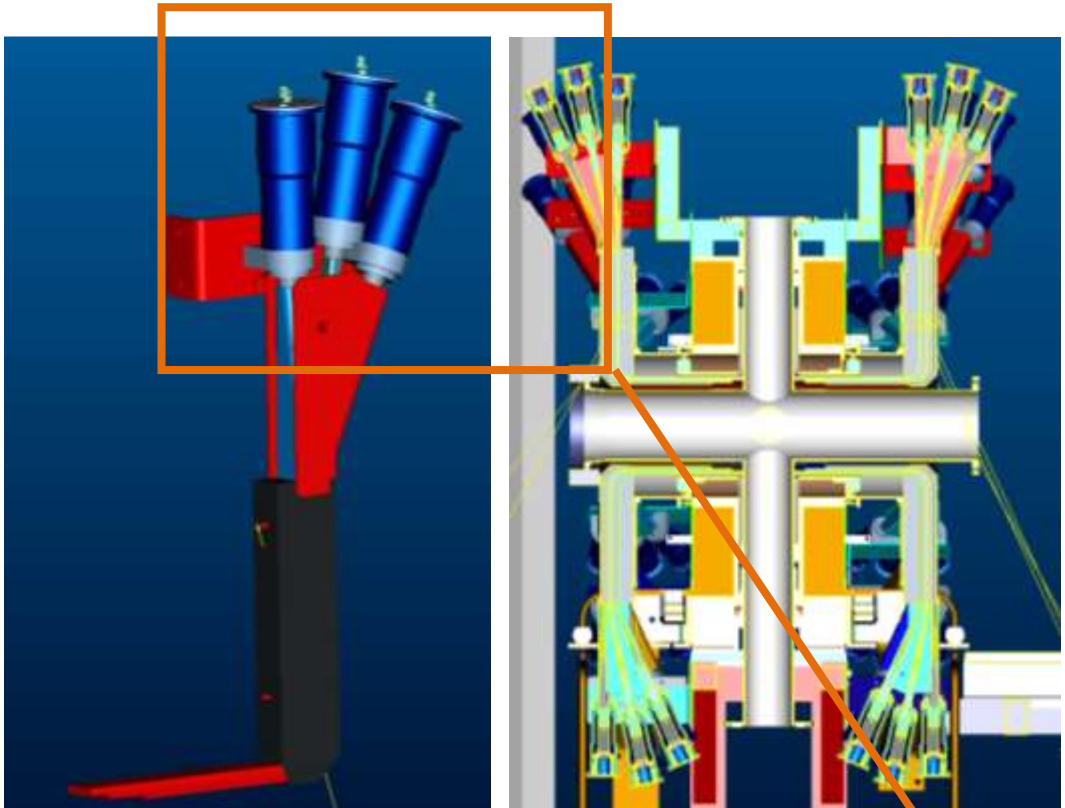
- Signal processing can be either in-silicon (Sensl Fast) or via pole-zero electronics
- SiPM shows minimal dead time distortion at same rates as PMT

L R Mohan

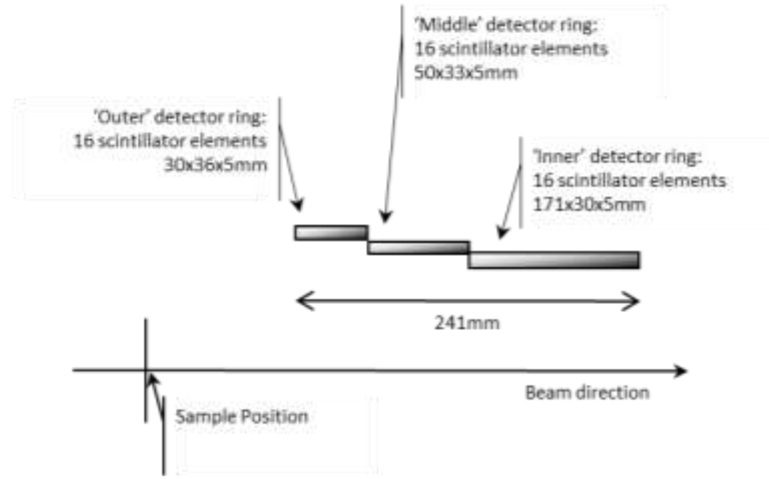
Next steps:
Demo detector module on EMU Spectrometer



EMU Spectrometer

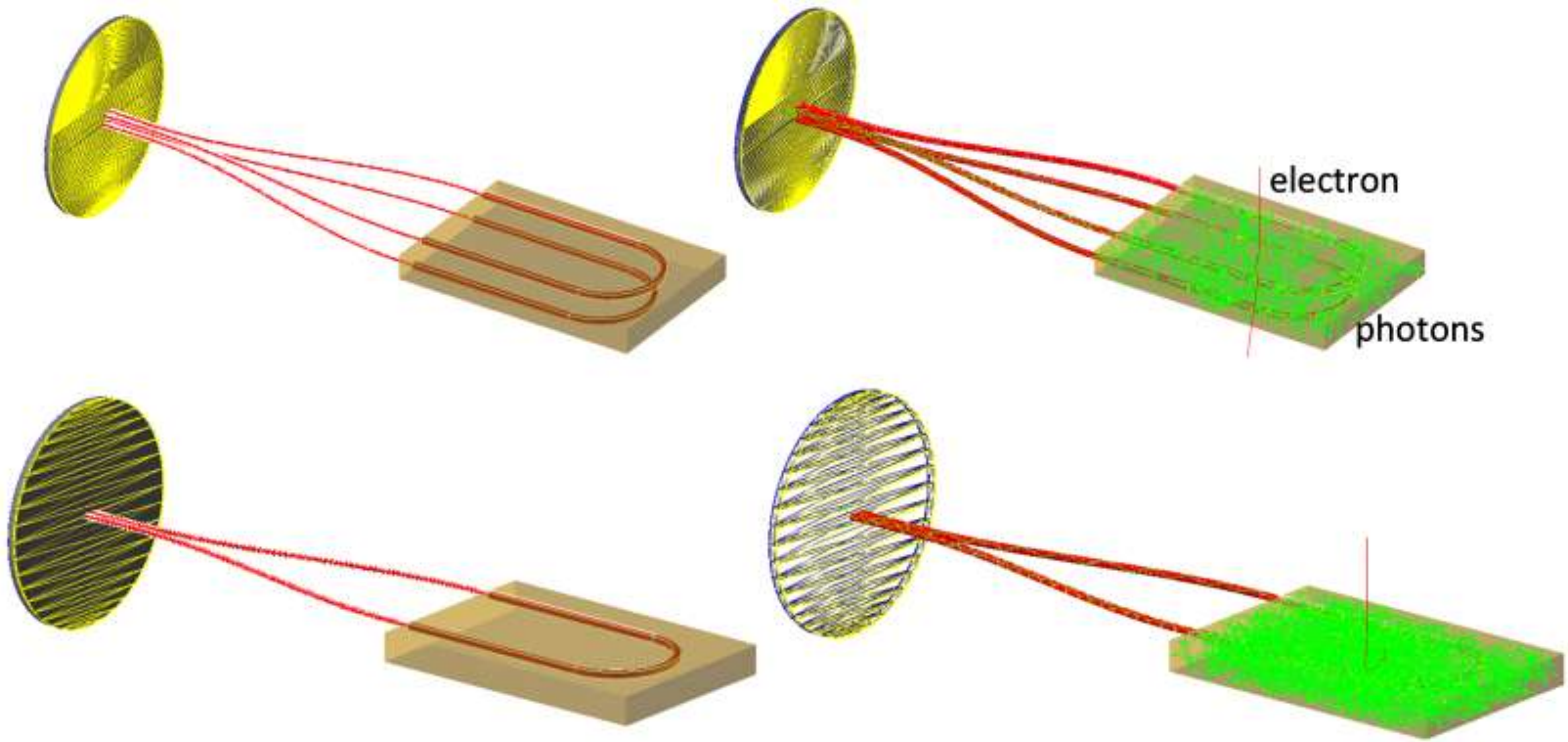


Current Detector Array



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

Simulation of reflectors and light collection

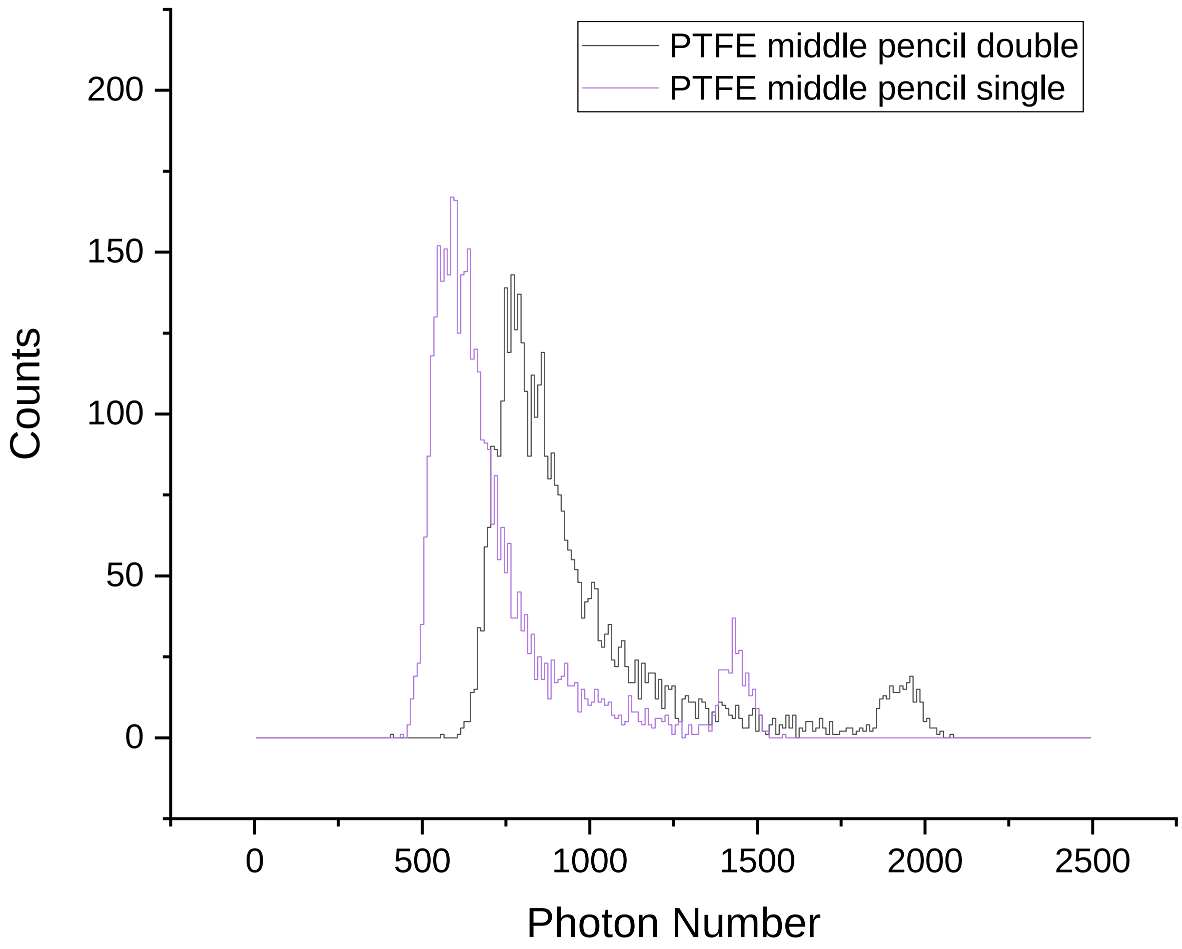


Investigate reflectors, fibre number, and homogeneity.

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

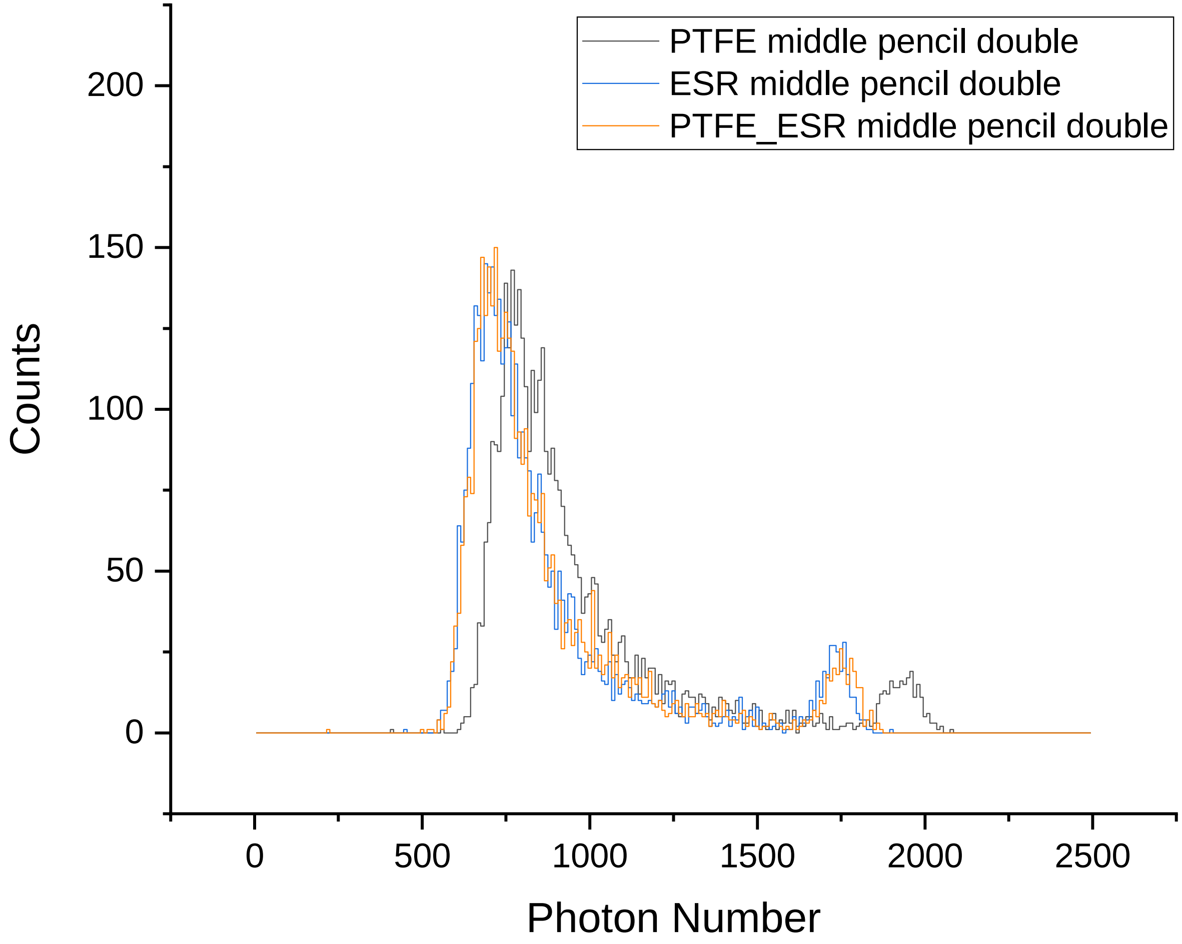
Light collection: fibre number



Going from 2 to 1 fibres ~ -25%

Zi-Wen Pan

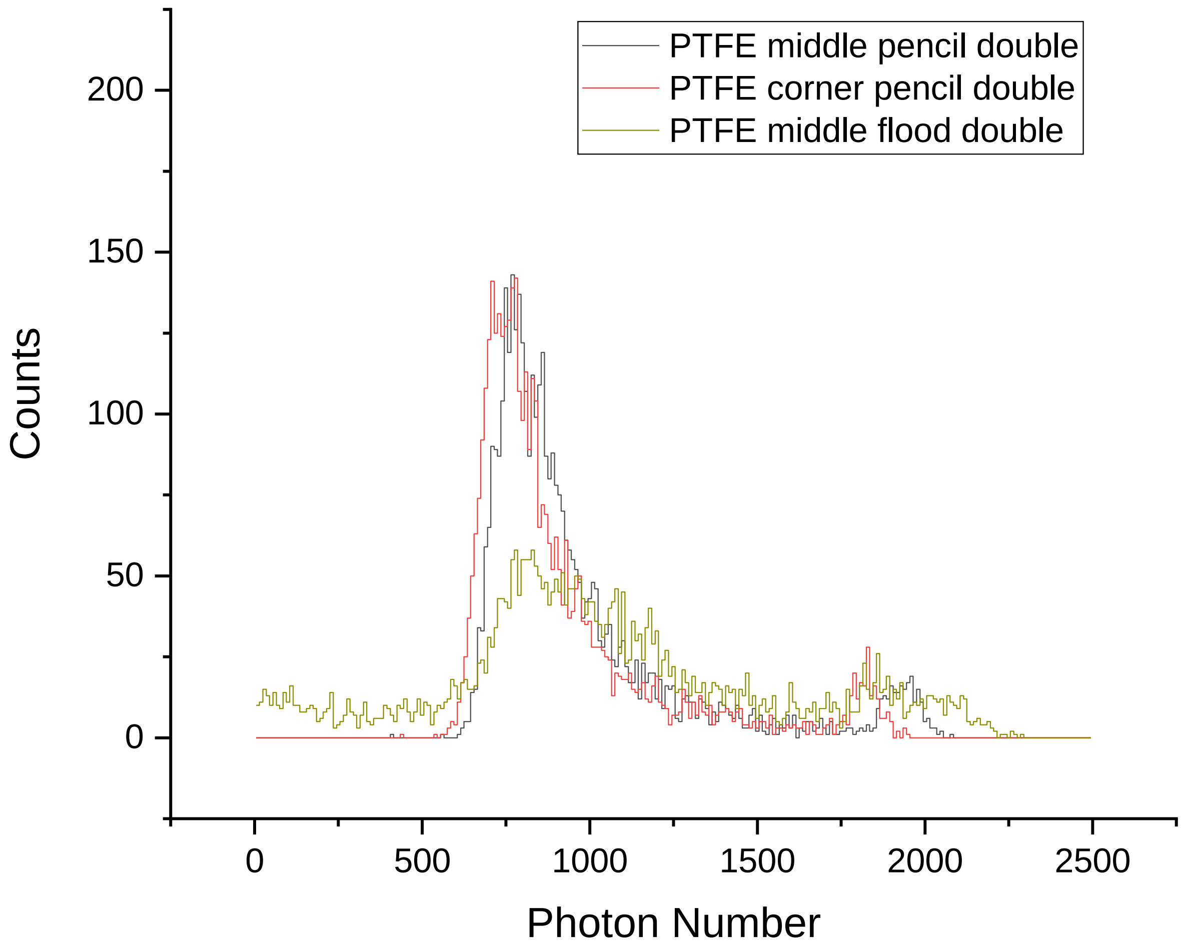
Light collection: reflector type



Going from PTFE ~ 10%

Zi-Wen Pan

Light collection: beam position/flood



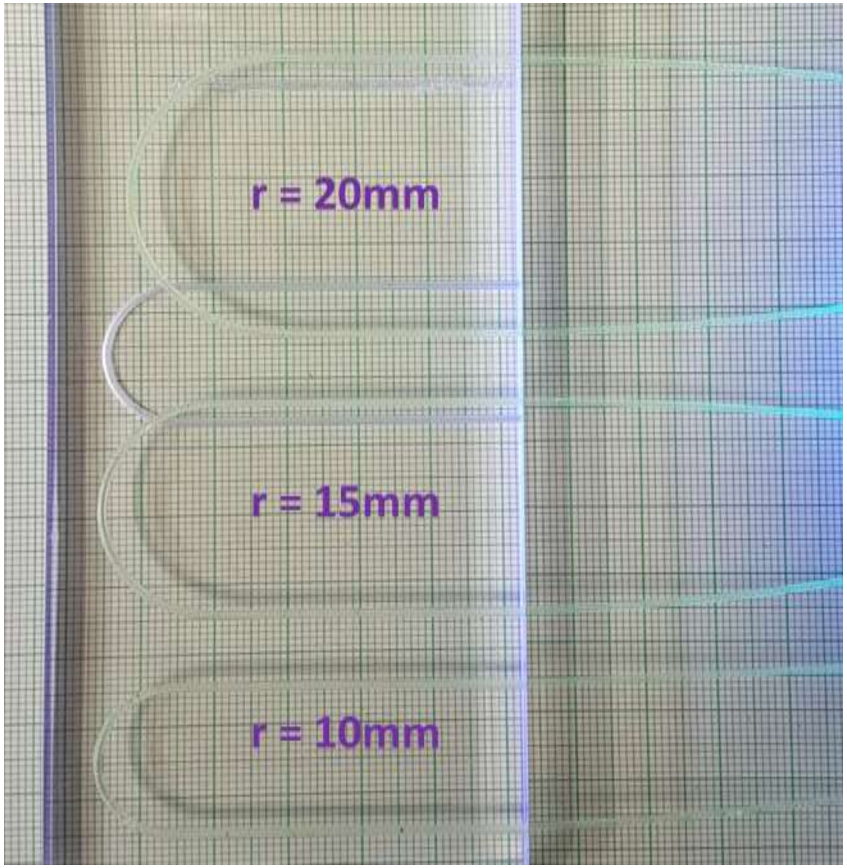
Pencil beam to flood beam – broadening ~ x2 but also
brings in edge effects and glancing paths.

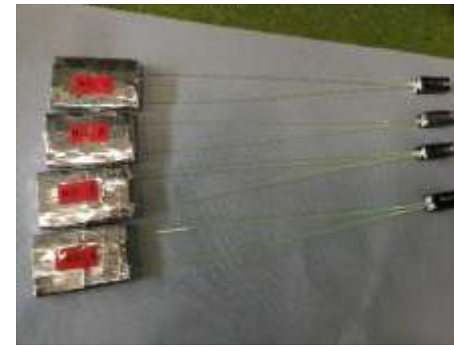
Zi-Wen Pan

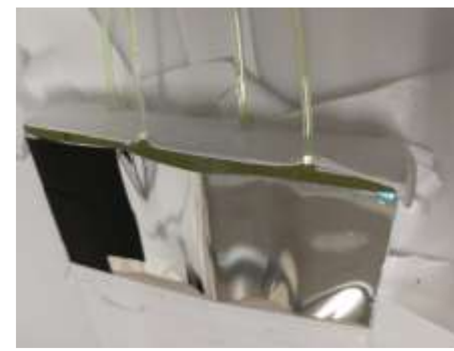
Testing and Prototyping

- Bend radius, potting method, reflector type etc. are under evaluation

- Favourite for building ease: PTFE, 1 fibre at ~15mm radius.



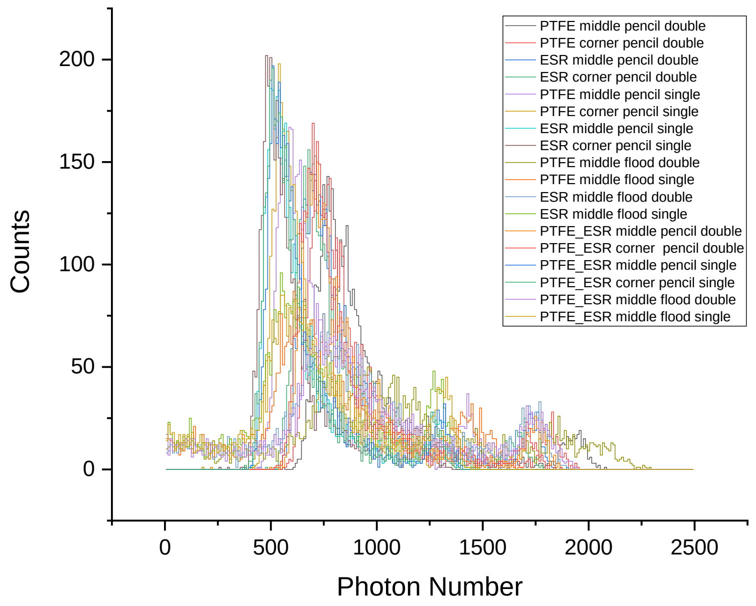




Zi-Wen Pan

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.



Thank you, Questions?

Performance Parameters

	Today	Proposed	Benefit
Detectors	64	~1216	20x data rate
Muons admitted	8%	100%	Best use of larger samples
Solid angle coverage	40%	75%	Best use of muons on sample
Zero field data quality (a_0^2 * rate)	4.7	95 (full pulse) 6.3 (10ns)	Higher quality data
Maximum frequency (field)	8 MHz 0.06T	~80 MHz ~0.6T	Enables experiments not previously done at ISIS
Spin rotation	None	60°	Higher field TF measurements
Maximum field	0.35T	0.65T	Broader range of experiments

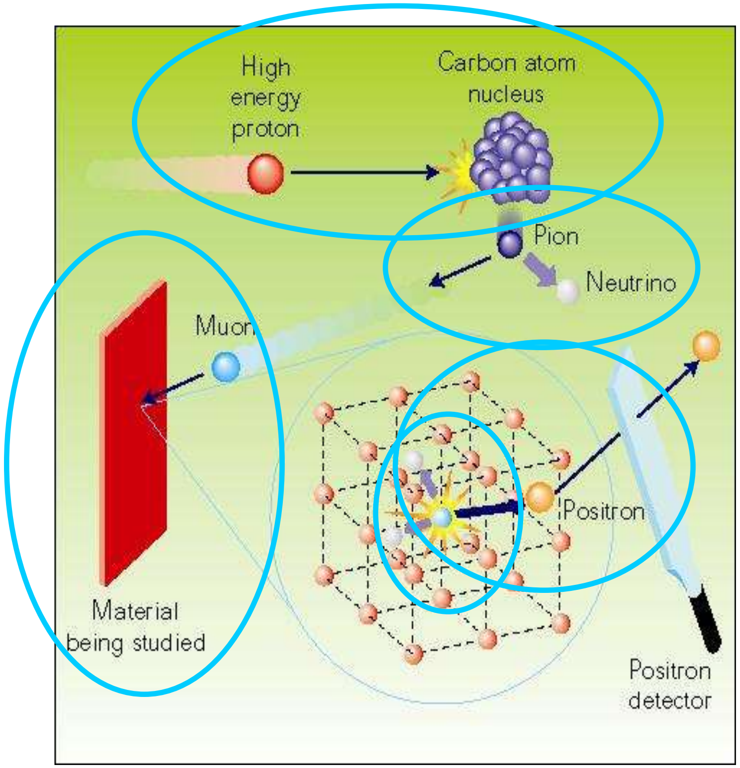
Courtesy: P. Baker, R. Afonso, P. Singkanipa

The μSR technique…

High energy protons
(800 MeV at ISIS)

Stop in sample,
(stopped in ~1mm water)

Stop as μ^+ or
Muonium (Mu: μ^+e^-)



$\pi^+ \rightarrow \mu^+ + \nu_\mu$
4 MeV **muons** are **100% spin polarised**
spin ½, mass $0.11m_p$

Decay, lifetime ~2.2μs
$\mu^+ \rightarrow e^+ + \nu_e + \nu_\mu$
Detect Positrons

Positrons preferentially emitted in direction of muon spin

Simulation of reflectors and light collection

Reflectivity Spectra for Commonly Used Reflectors

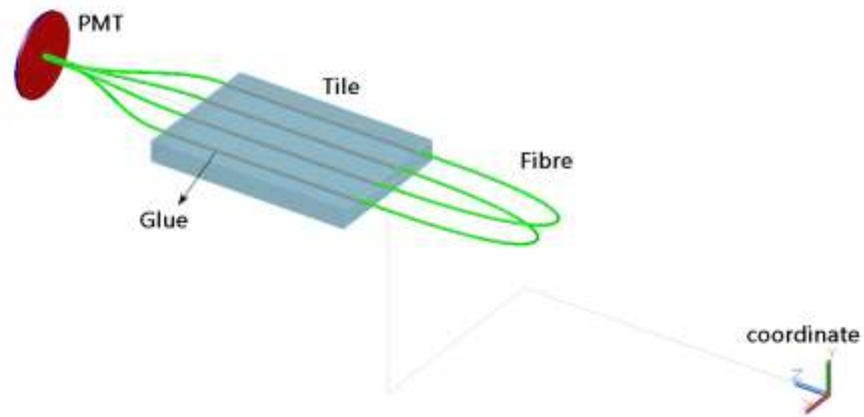
Martin Janecek

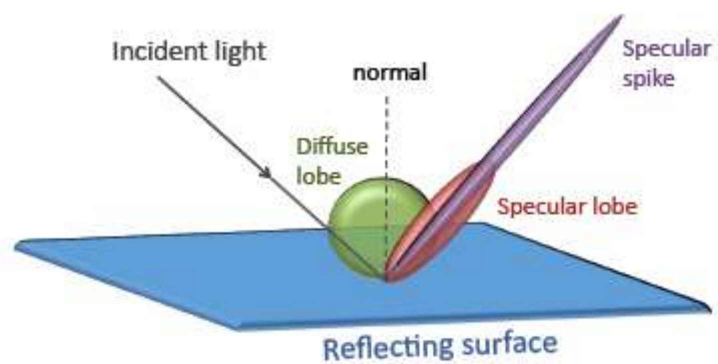
TABLE I
EXAMINED REFLECTORS

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]



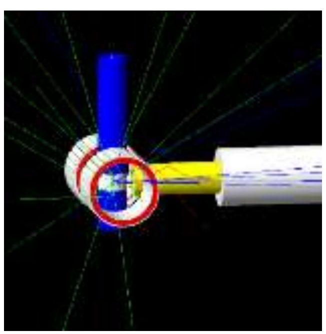


Zi-Wen Pan

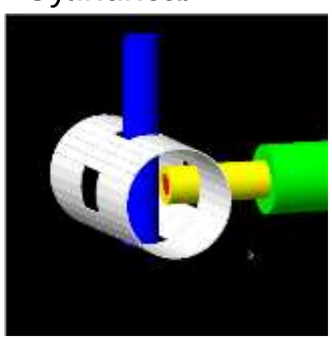
Scoping detector arrays

Detector design	Solid Angle Coverage (%)	Signal collected per muon (ZF, LF)	Signal collected per muon (TF)
2014 instrument (Old beam pipe, Current Degrader Ring)	42	1.00	1.00
2017 instrument (New beam pipe, Current Degrader Ring)	42	1.13	1.07
Cylindrical	75	2.65	3.42
Stepped	63	1.66	2.73
Spherical	78	1.22	3.02

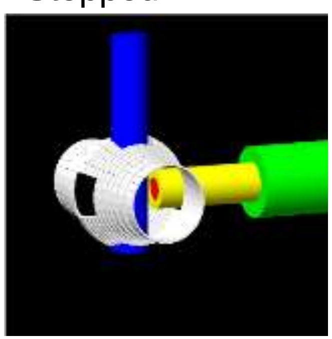
Current



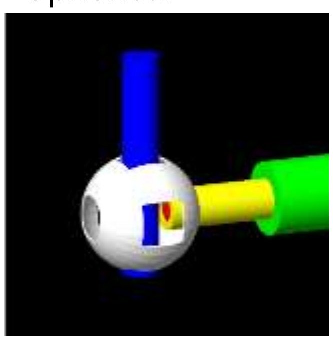
Cylindrical



Stepped



Spherical



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

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.

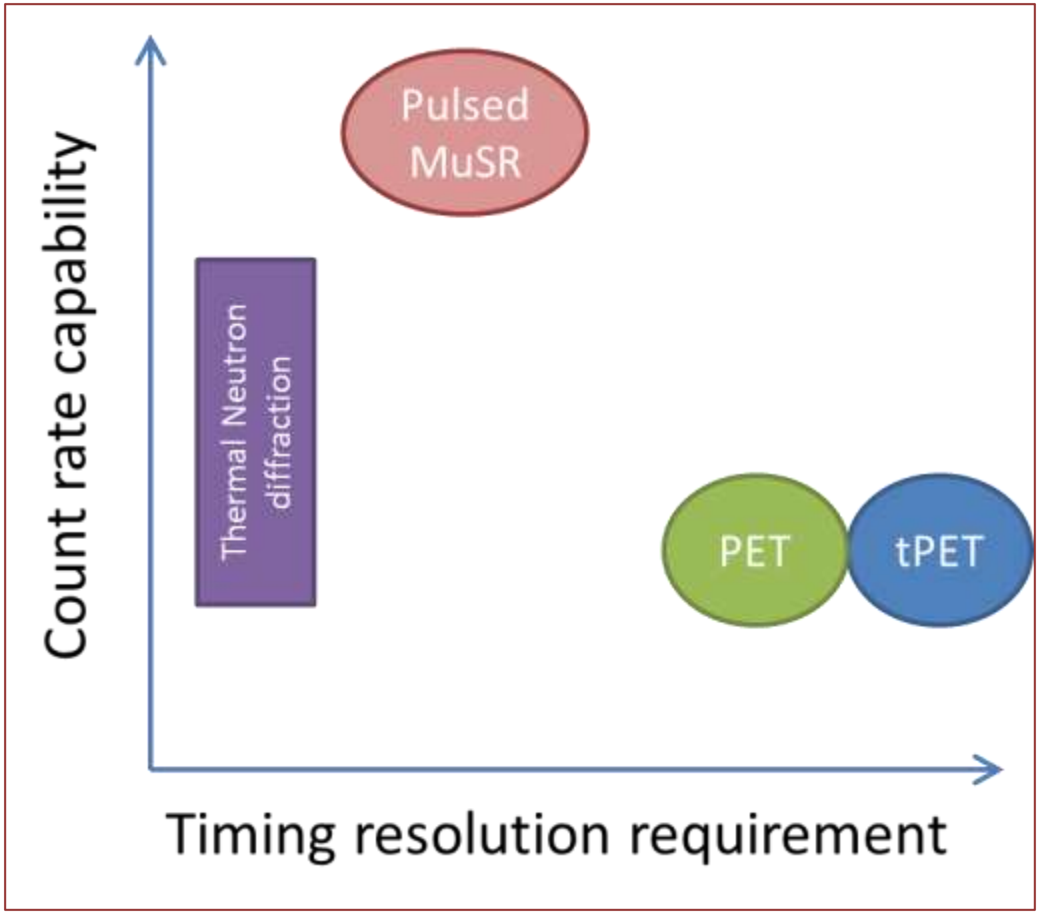
  E.G HiFi Transverse Field Bank

  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.**

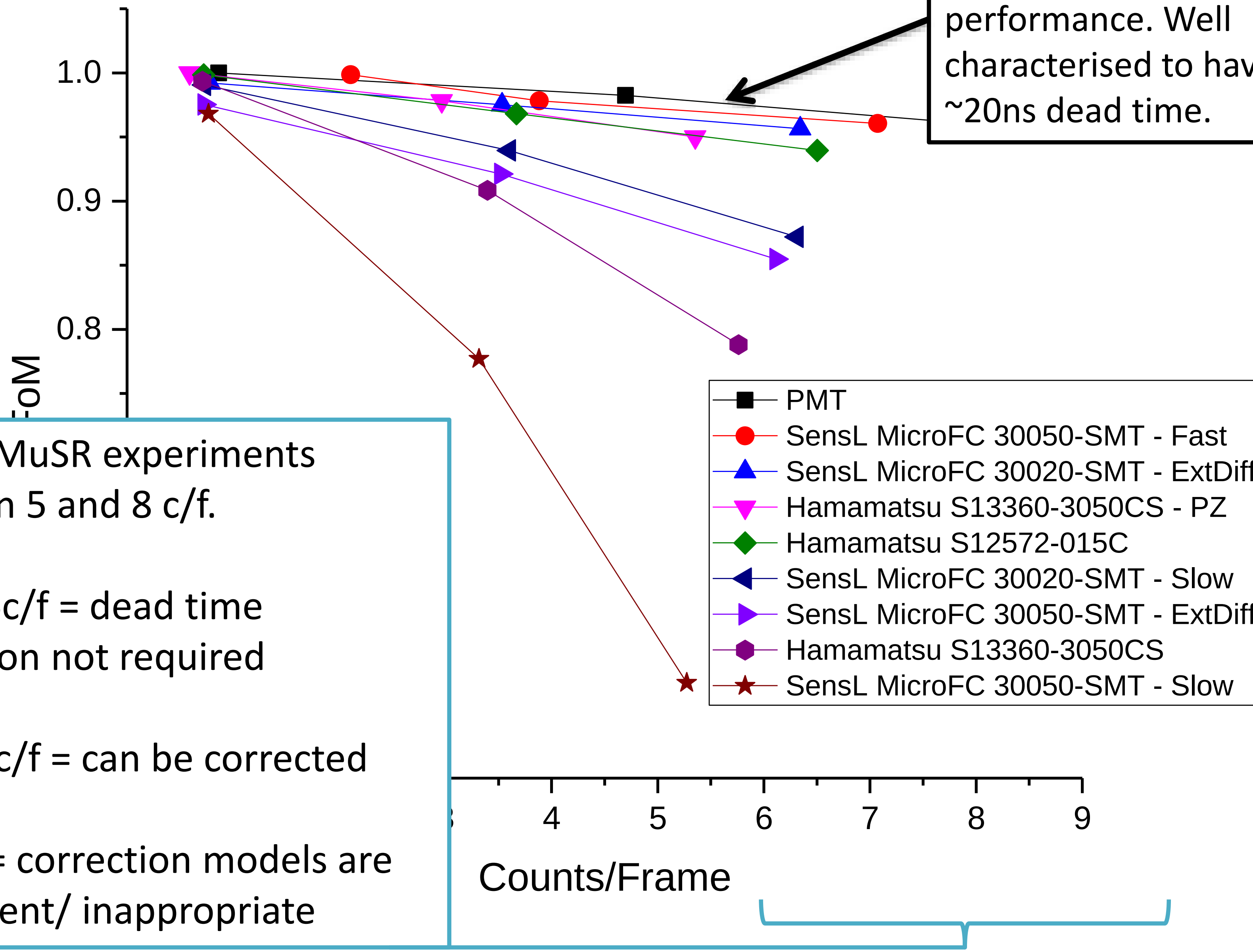
Specification: some context



Conclusions

- Photon density (cells fired) is critical to control
- I.E we need to de-convolved the effects of hit fraction, micro cell recovery time and signal processing *as a function of rate.*

MuSR Data using FoM



PMT + detector chain. Baseline for equivalent performance. Well characterised to have ~20ns dead time.

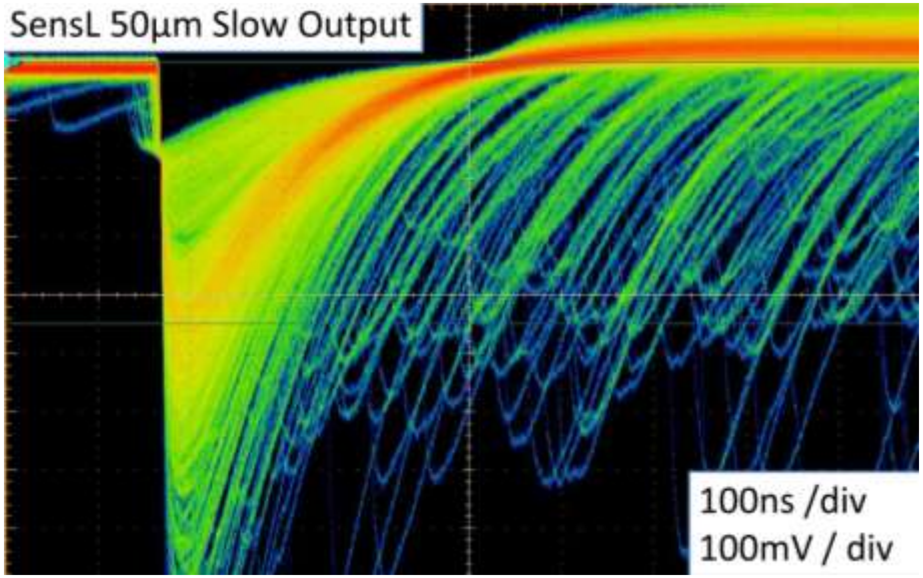
Typical MuSR experiments between 5 and 8 c/f.

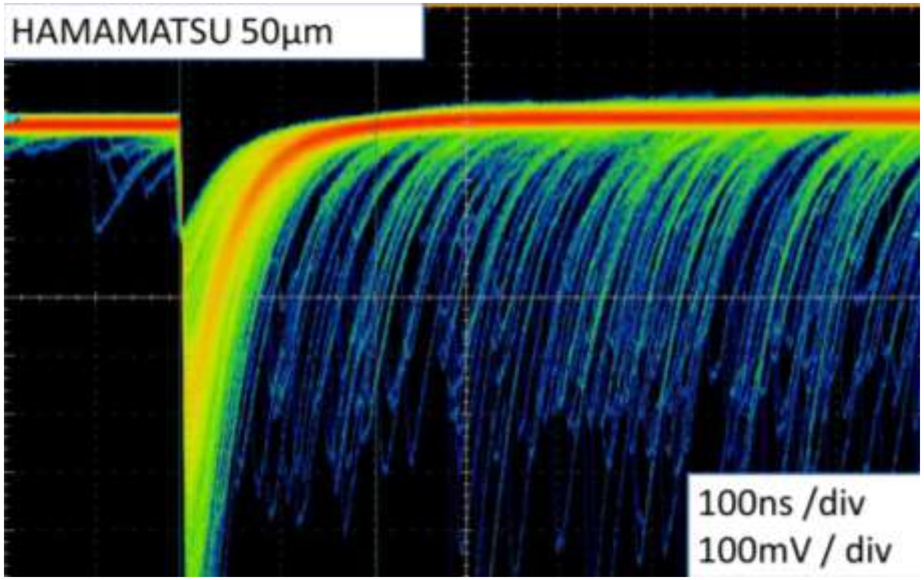
Below 6c/f = dead time correction not required

6 to 10 c/f = can be corrected

10+c/f = correction models are insufficient/ inappropriate

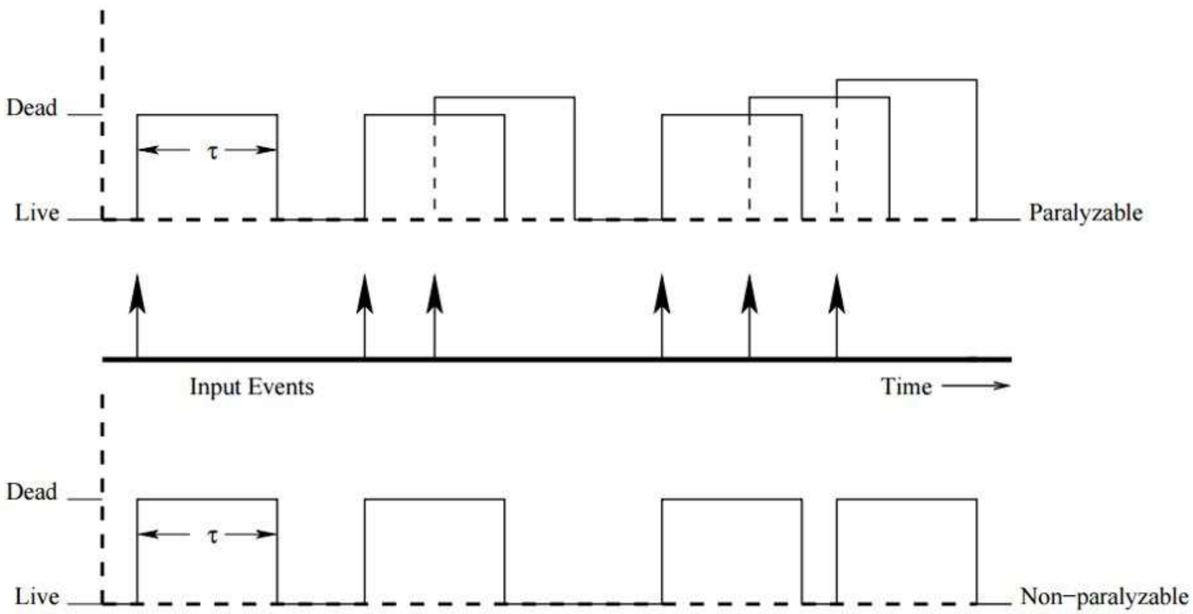
Deadtime- Lets have a look at Signals first





MuSR Beamline Work

Dead-time models



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

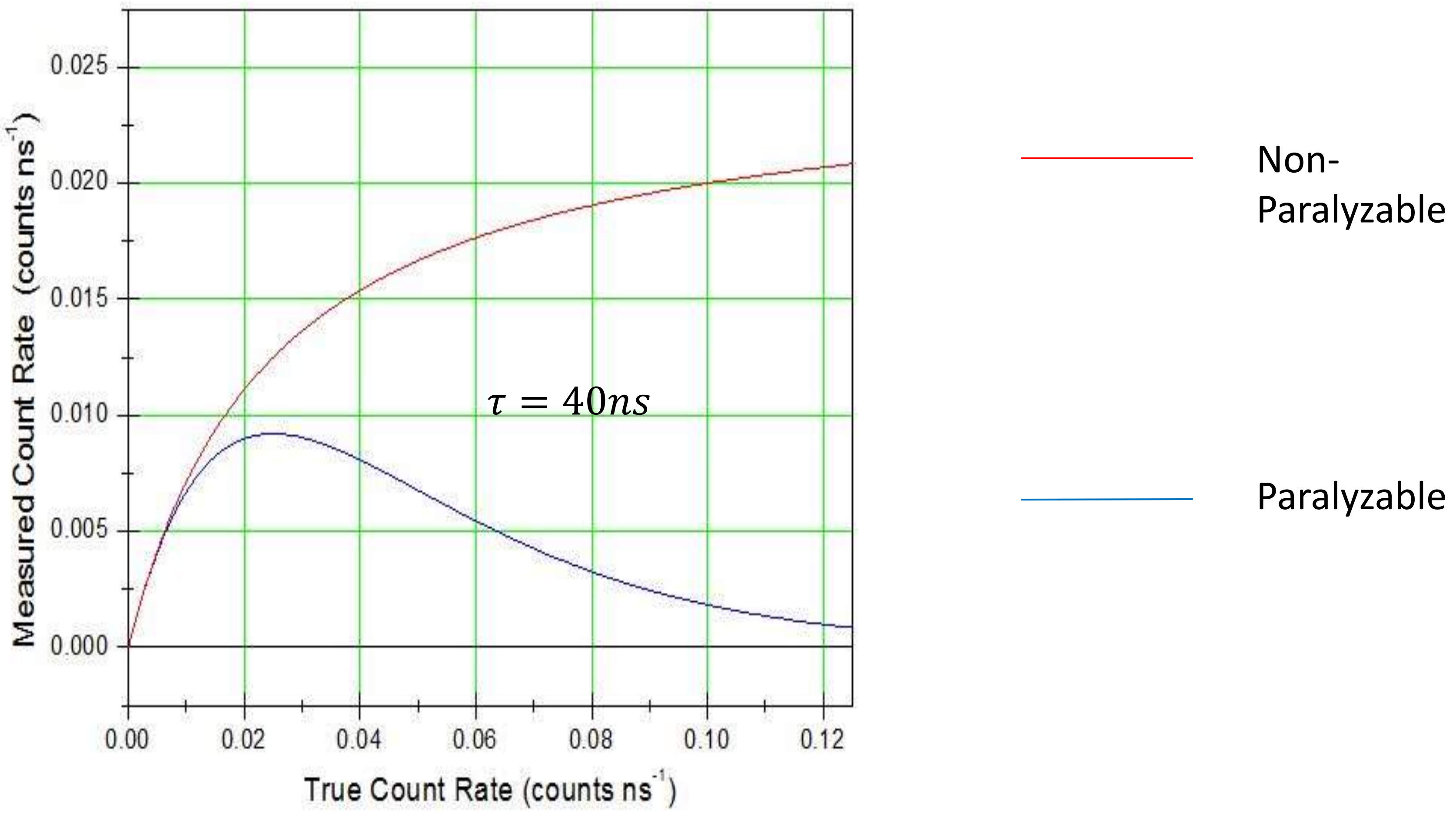
n--- true rate

m--- measured rate

τ--- dead-time

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

Measured rate as a function of true rate



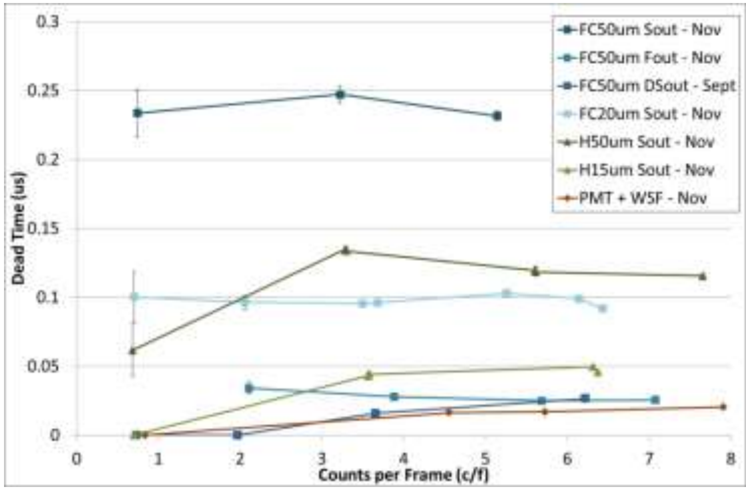
Parameterising the detector performance using a Figure of Merit with MuSR data

- Intuitive FoM to parameterise the 'missed counts' in a MuSR experiment.

- Moved away from non-extendable dead time model as one dead-time value is not appropriate for SiPM (reported at kick off meeting in Abingdon)

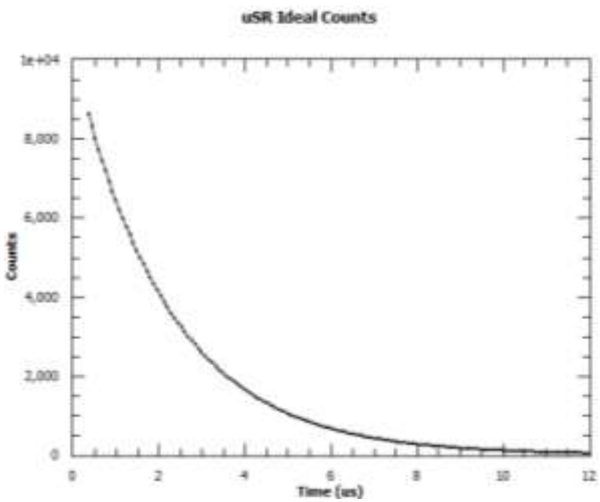
- Encapsulates the operational parameters and usability of the detector. For example, 'any' detector can count at 1 c/f at a pulsed source!

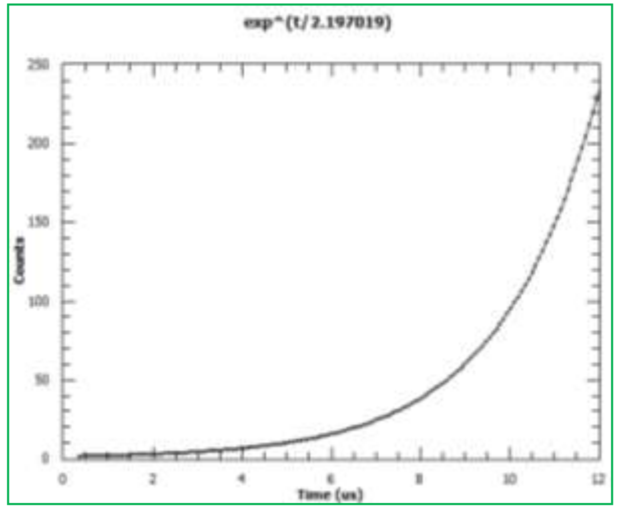
- Based on realistic 'user' experience rather than determining absolute values and comparison to data sheets.

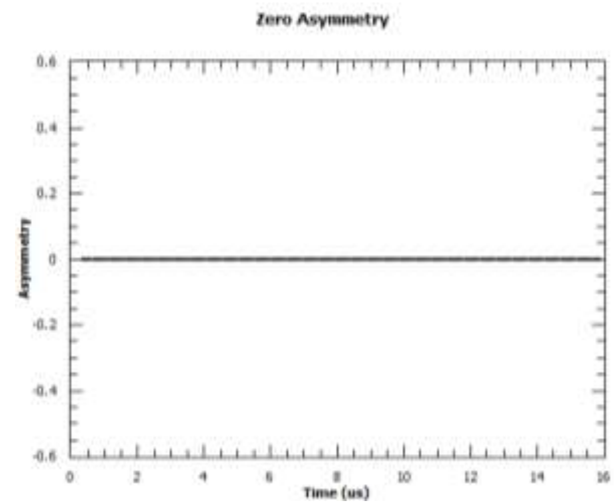


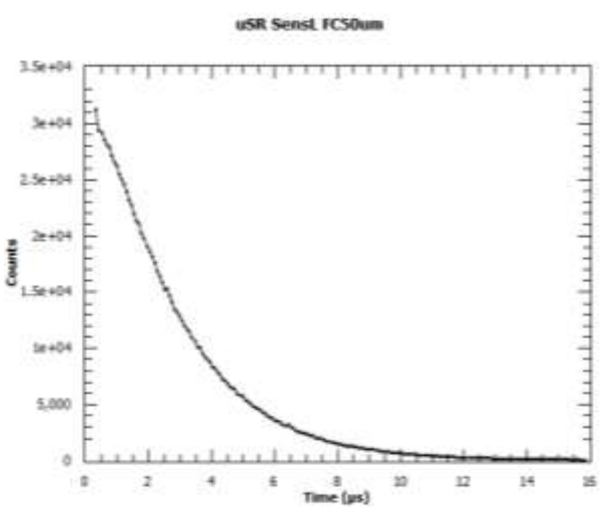
μSR – Asymmetry

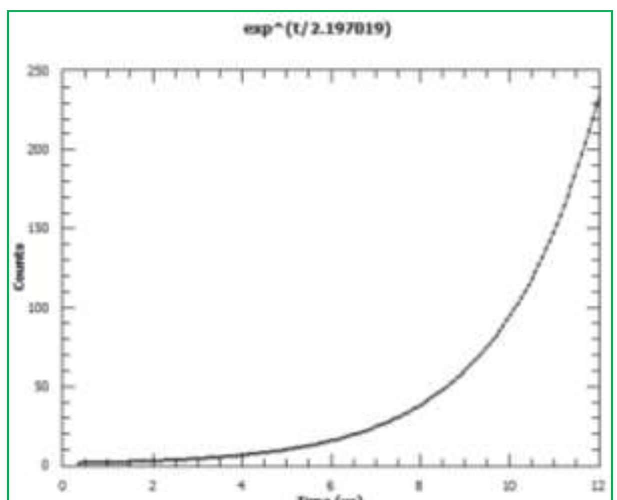
$$Asymmetry = ((Counts \cdot e^{\frac{t}{\mu}})/N_0) - 1$$

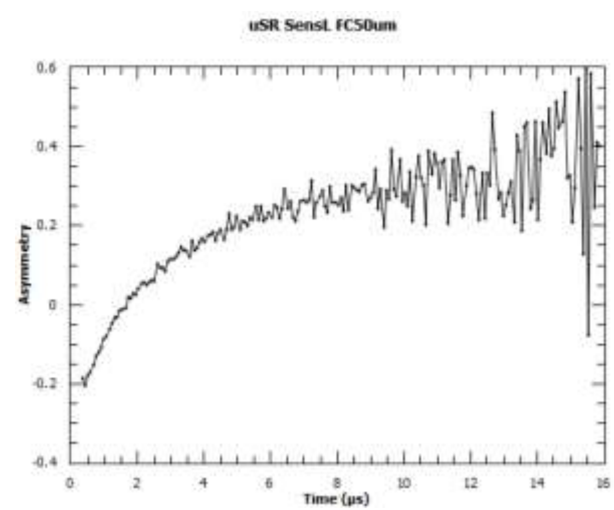








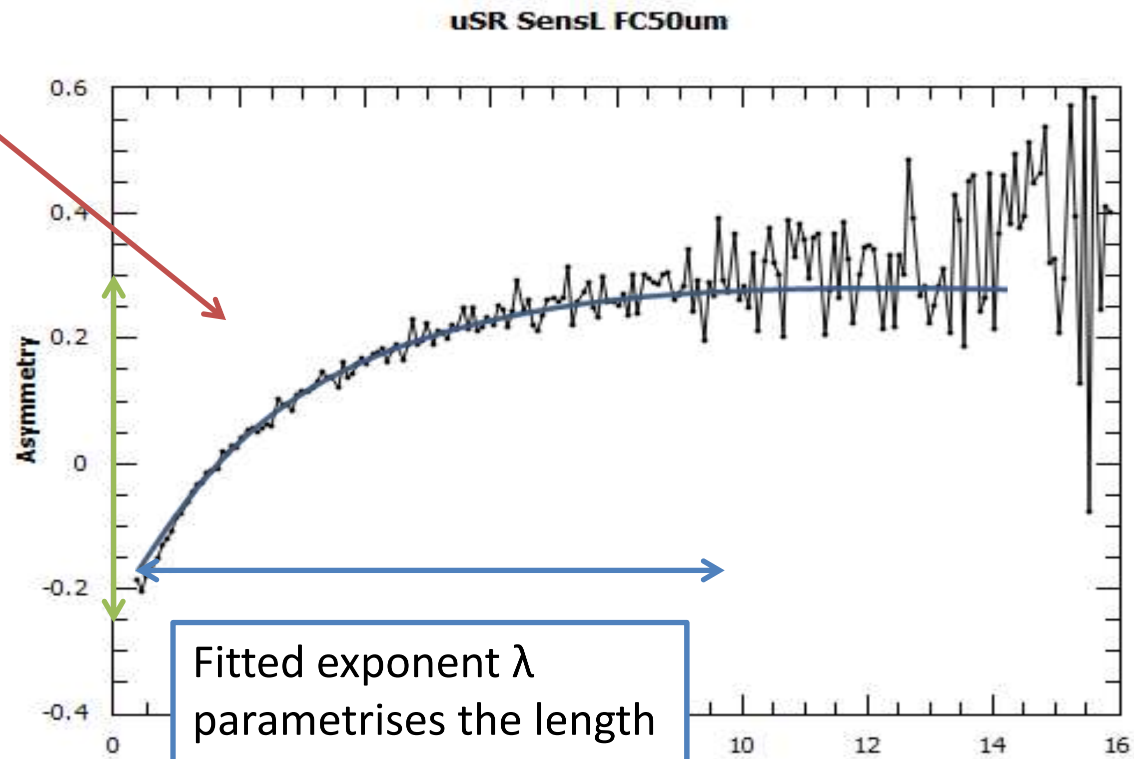




μSR – FoM

Missed counts cause this type of distortion in asymmetry

A_0 parameterises the height of the distortion

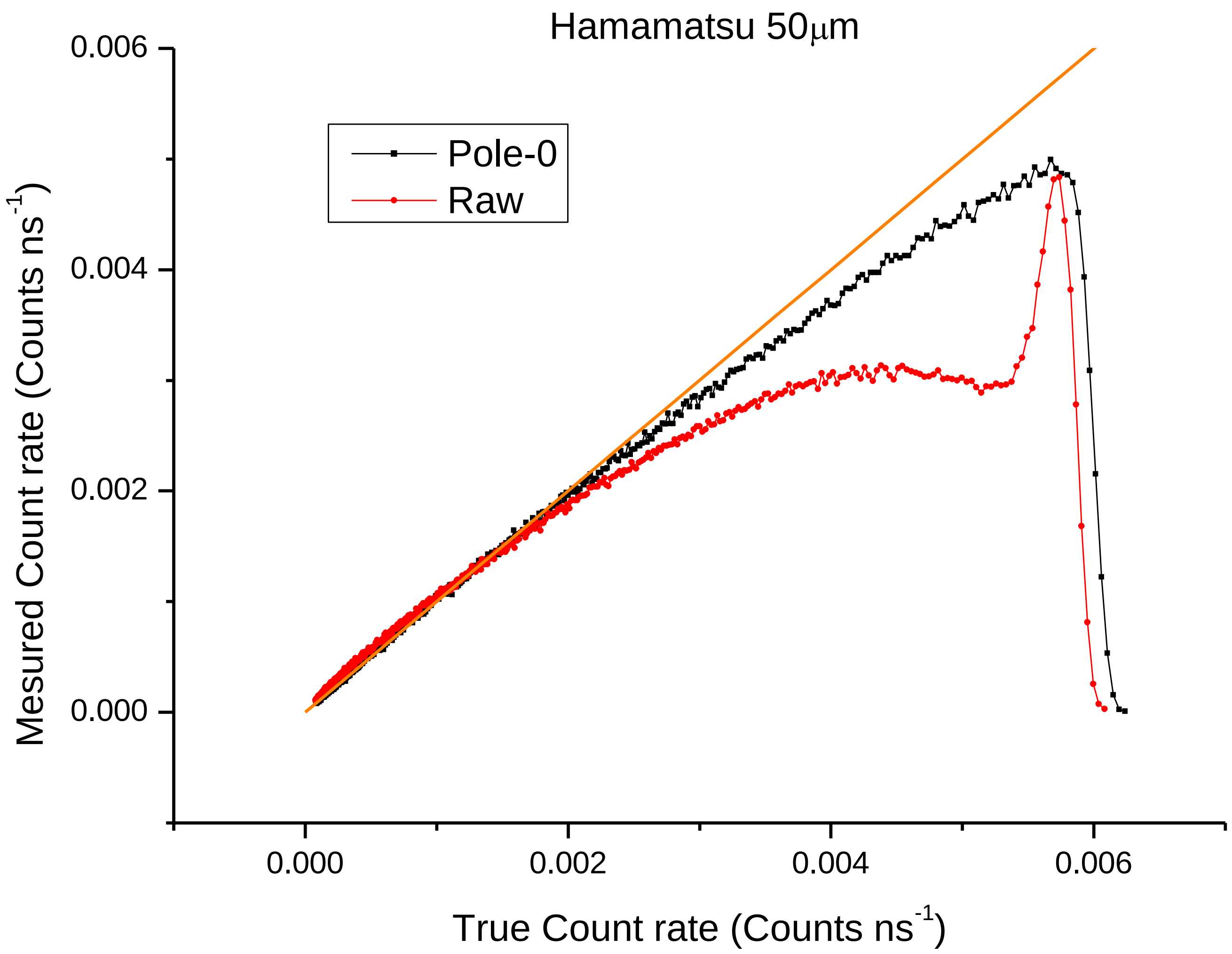


Fitted exponent λ parametrises the length of the distortion

Combine to give: $\mathbf{FOM = 1 - |A_0 \cdot \lambda|}$

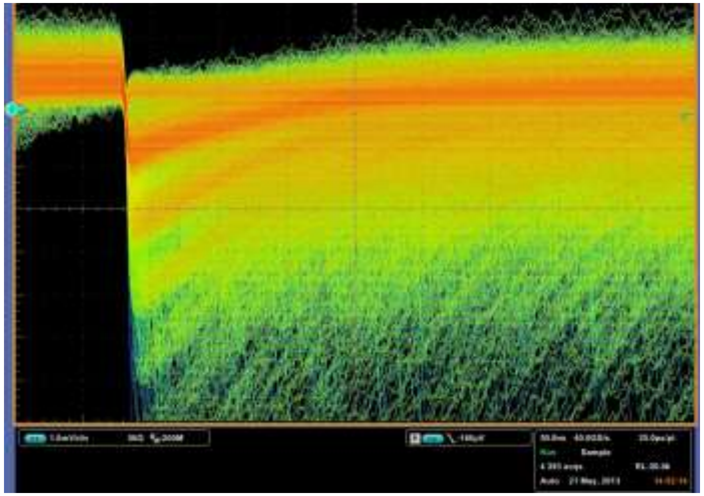
NOTE- μSR scientists will run a detector with some deadtime distortion and correct for this if possible. The FoM allows us to compare the rate at which detectors can be run, which is more useful than absolute deadtime numbers.

Example: Hamamatsu SiPM

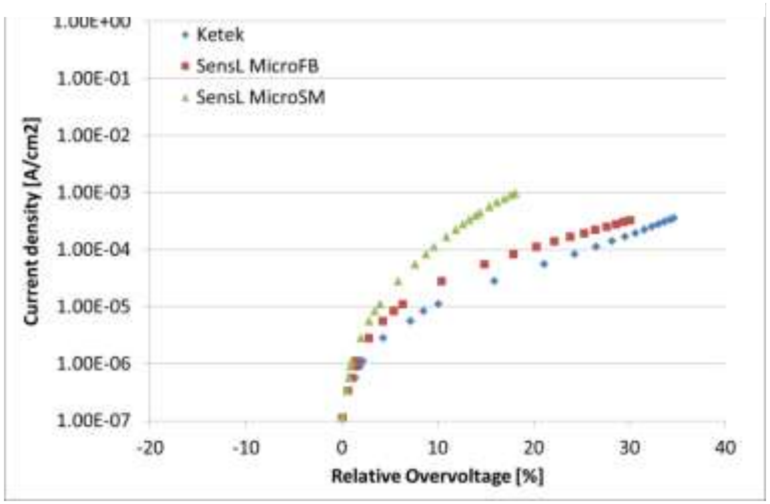


First Investigations & Prototypes

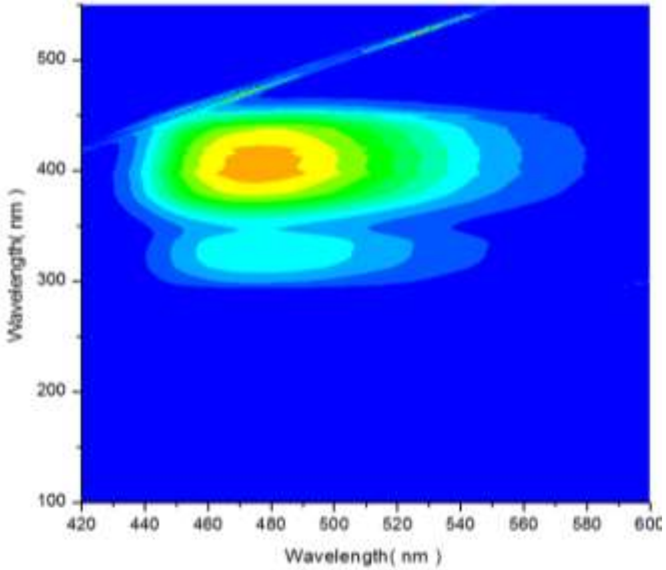
Signal Characterisation



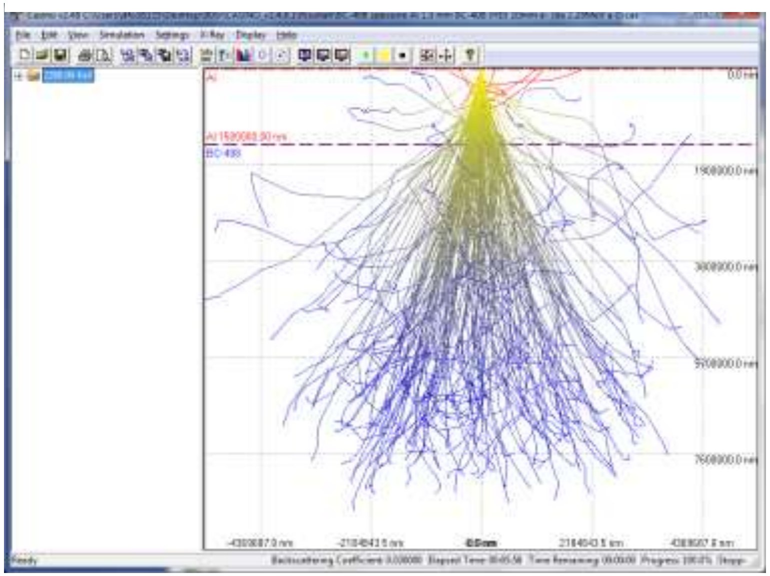
Electronic Characterisation



Optical Characterisation

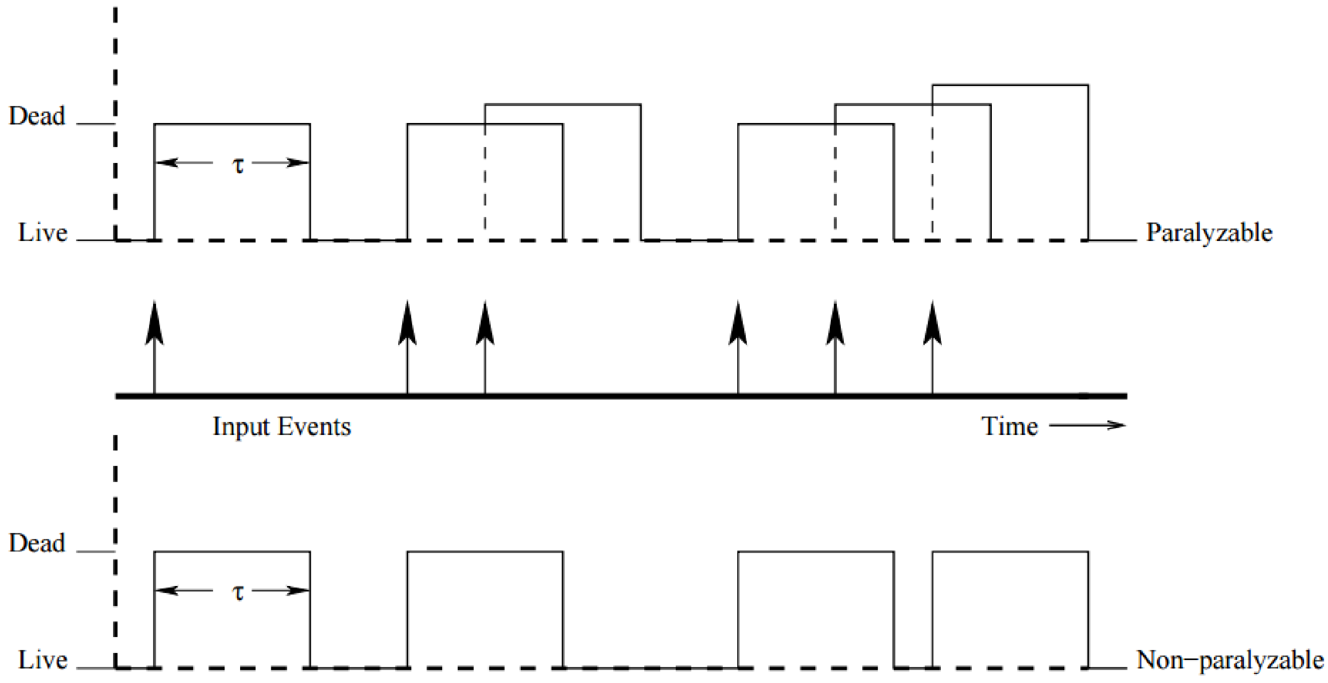


Model Energy Deposition



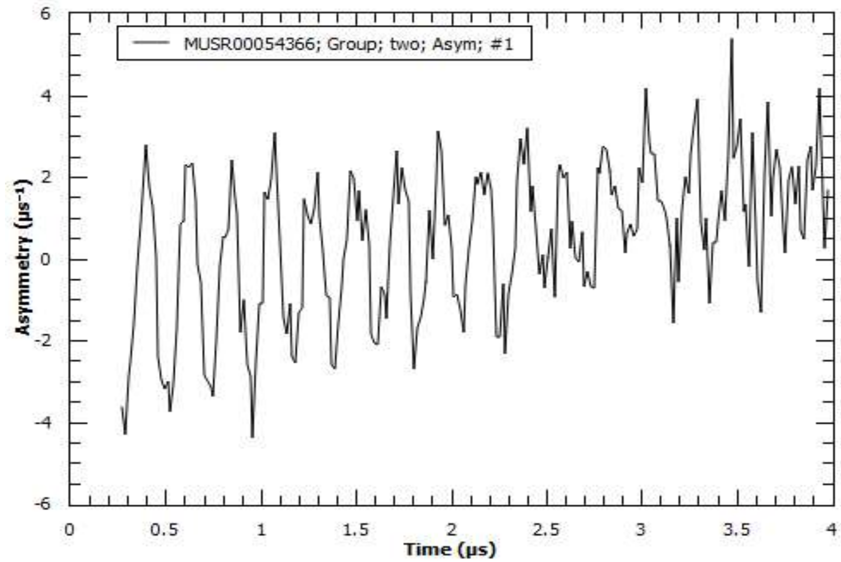
Deadtime Investigation using MuSR

Myron Huzan



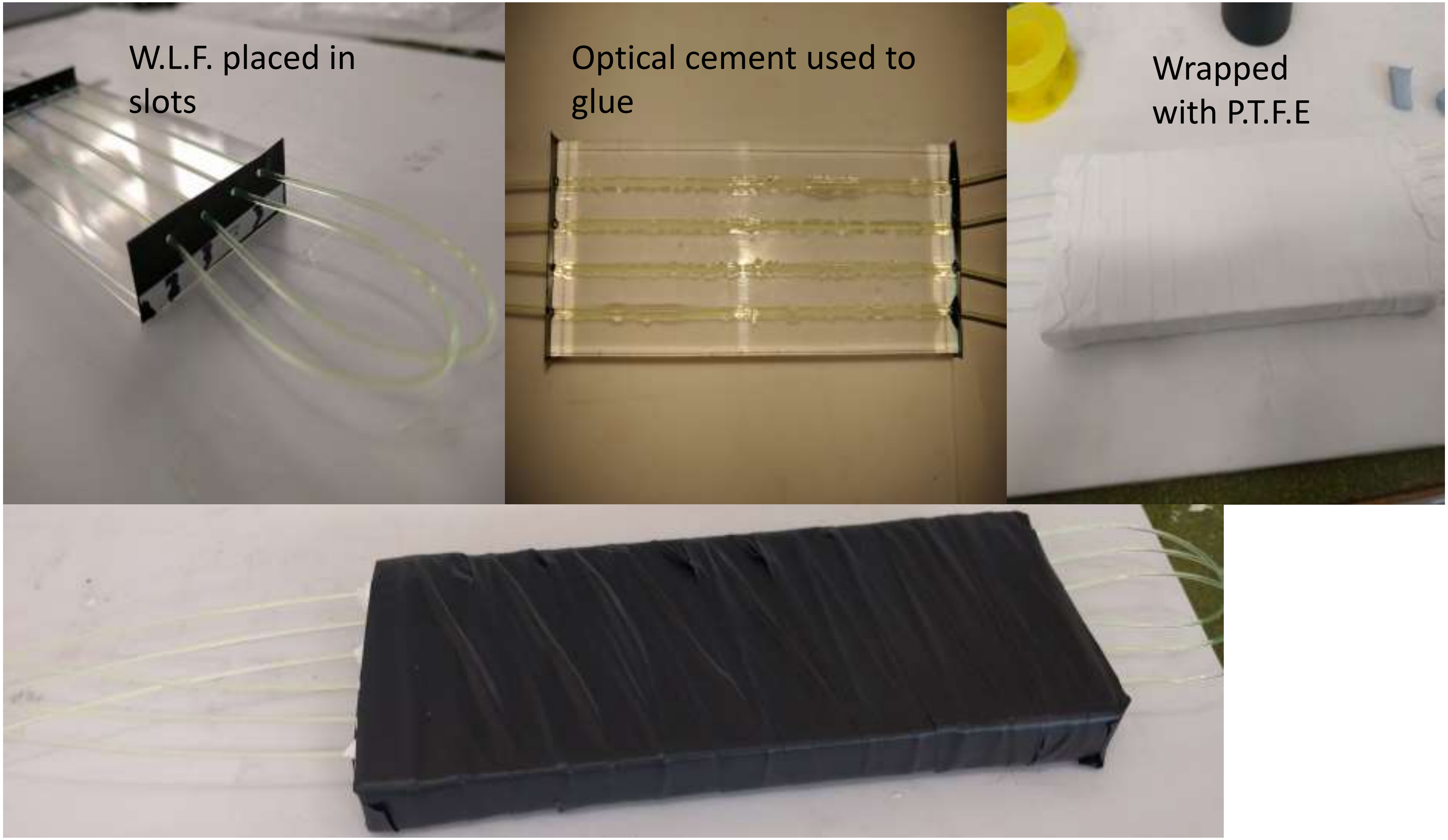
Although paralyzable model is the appropriate one for partial hit fraction, the way in which dead time is calculated (fitting at late times with known lifetime) this is still a good parameterisation)

Muonium in 20 G Field



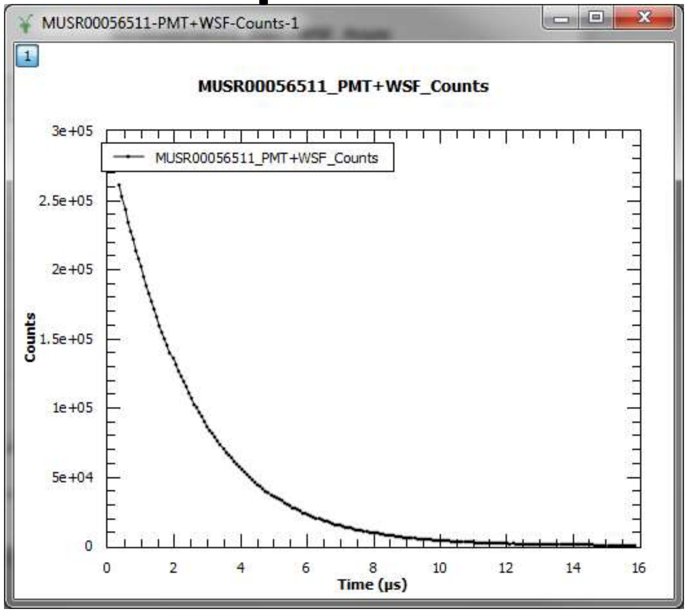
Frequency ~5 MHZ - as calculated

- Light Tight box/Faraday Cage
- 4 detectors
- 6 Channels
- Option of including Amplifiers
- Hinges are being replaced with non-magnetic ones.

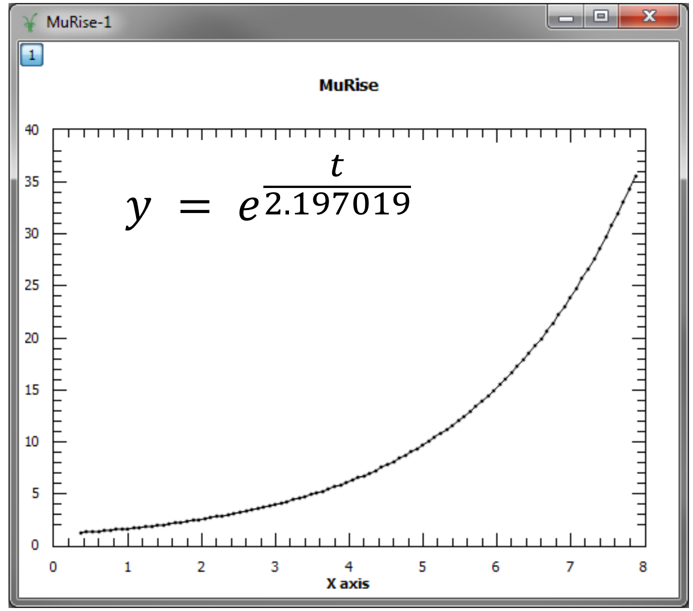

W.L.F. placed in slots
Optical cement used to glue
Wrapped with P.T.F.E

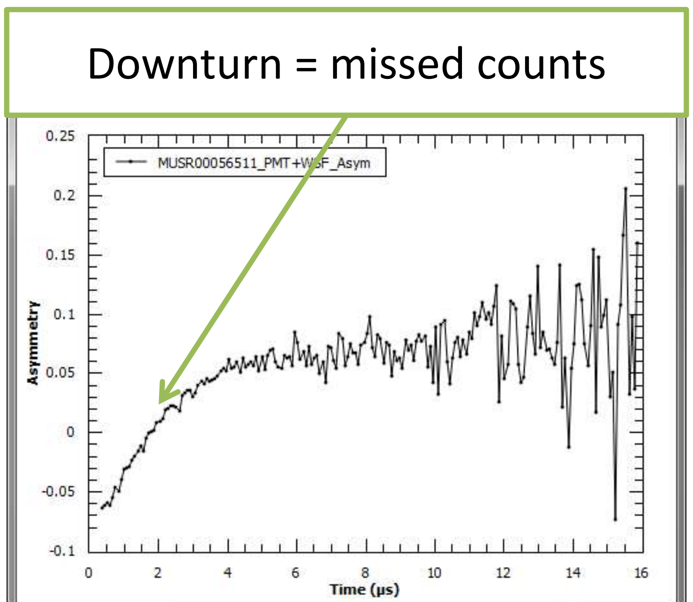
Sealed

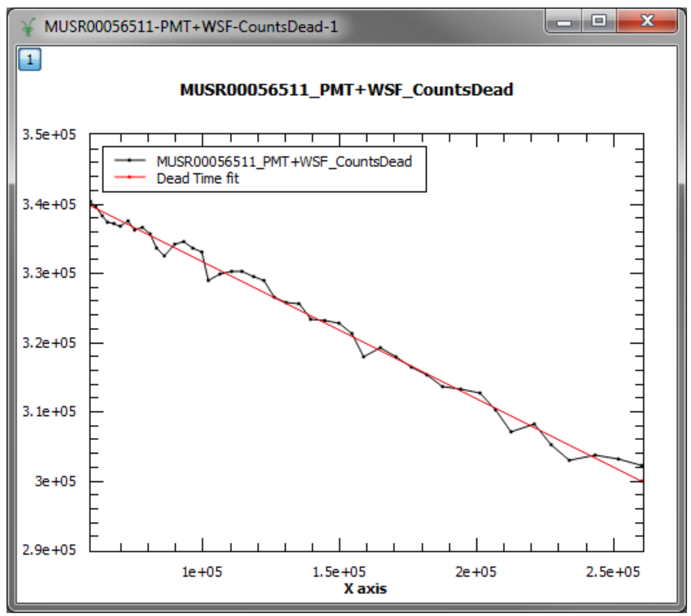
Example – PMT with WSF tile



X







CalMuonDeadTime

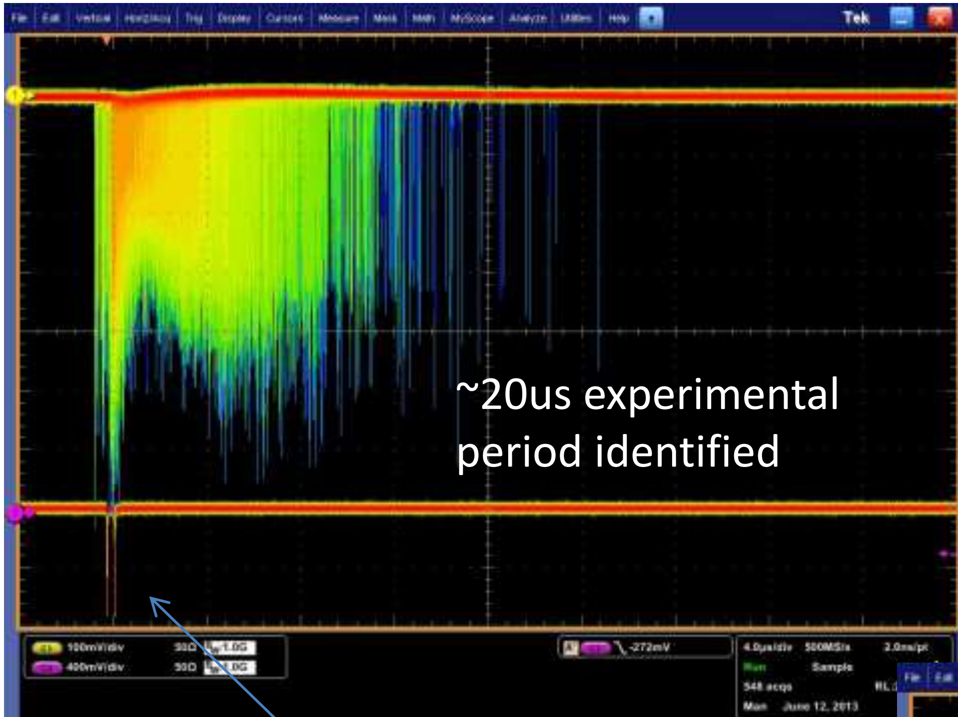
Equation:

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

Dead Time: 0.023 us

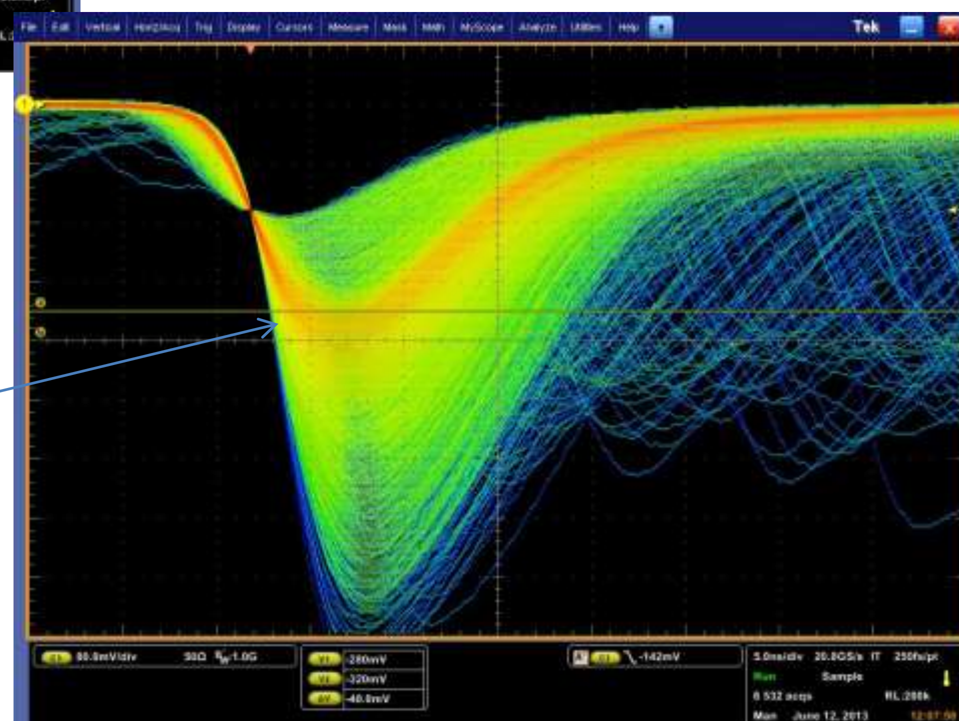
Counts/Frame: 15

BC scintillator disk on PMT – Pulse height spectrum

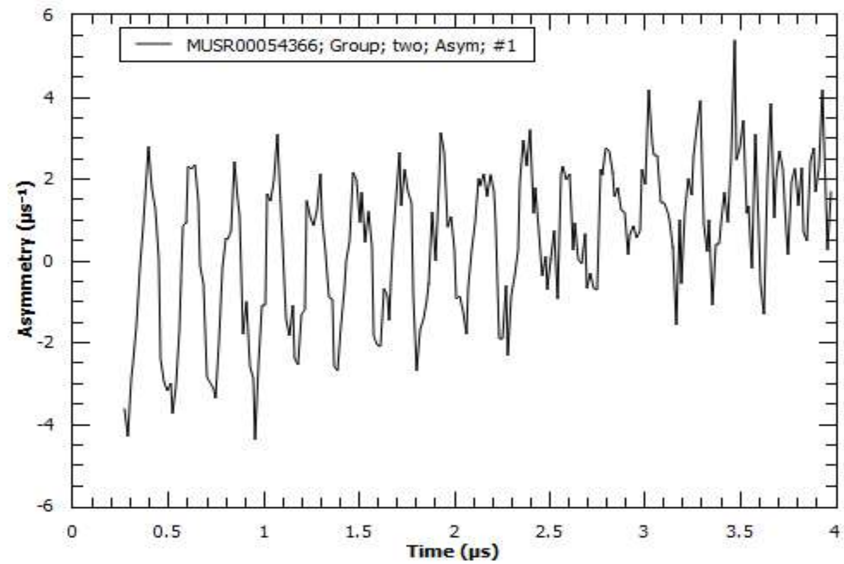


T0 from Cherenkov detectors

Clear pulse height band



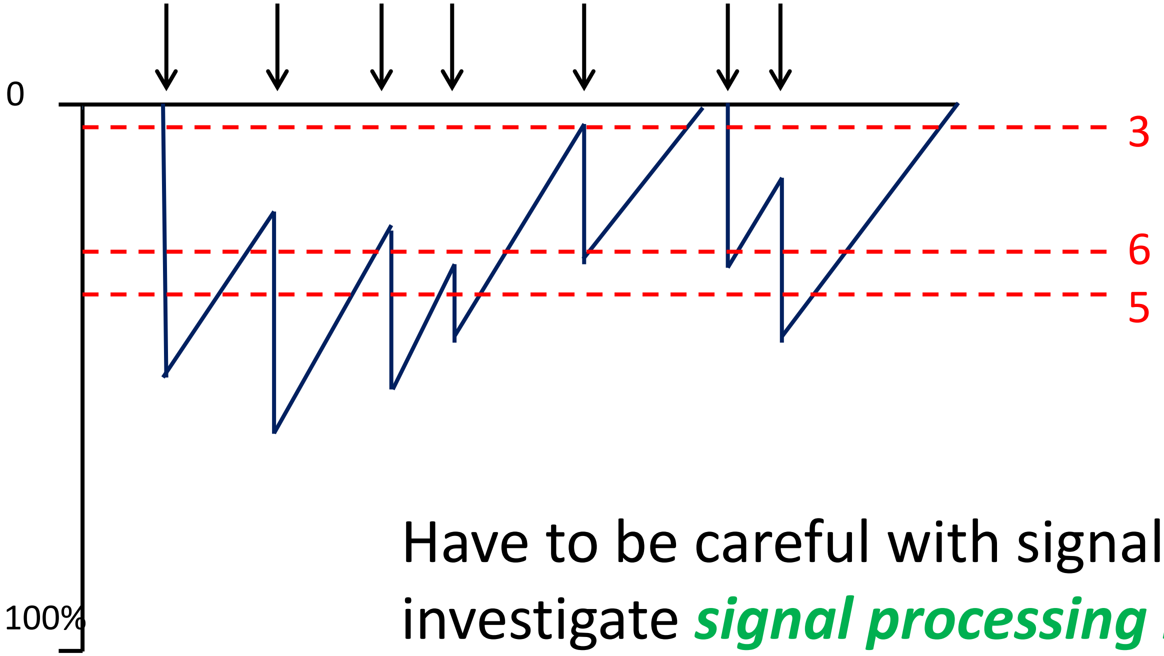
Muonium in 20 G Field



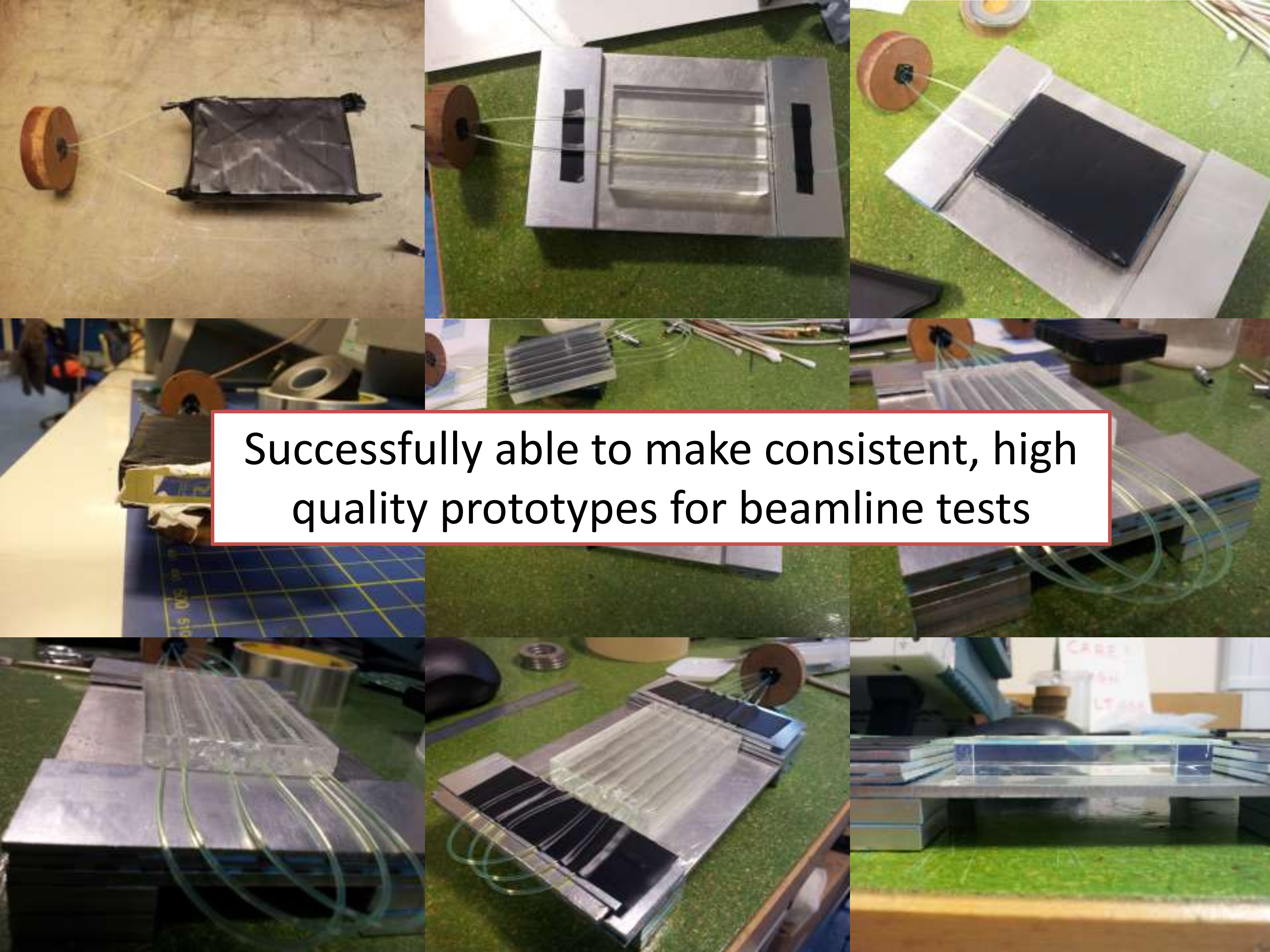
Frequency ~5 MHZ - as calculated

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.***



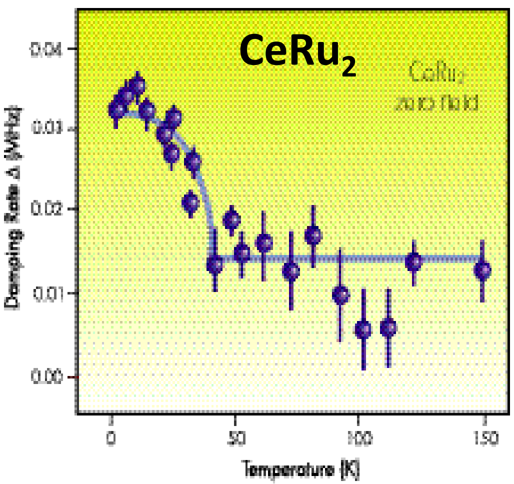
Successfully able to make consistent, high quality prototypes for beamline tests

Future Investigations

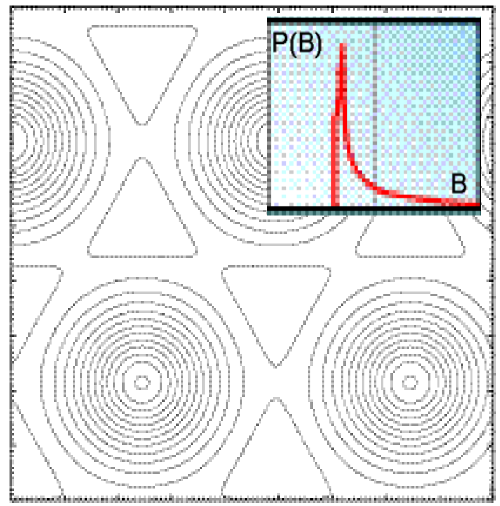
Temperature
Sensitivity tests

Applications of µSR …
The muon as a magnetometer

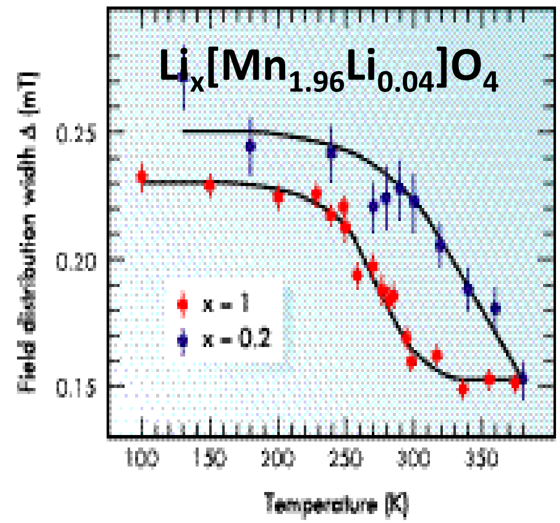
Magnetism



Superconductivity



Ionic Conductors

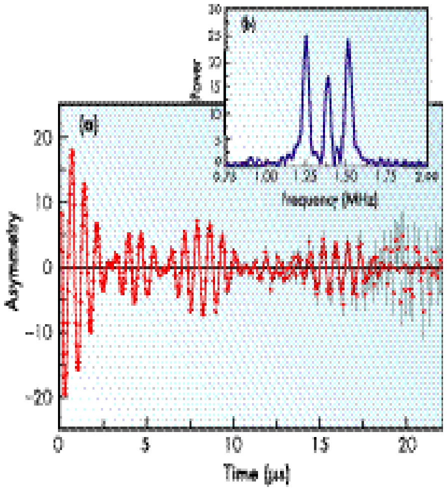


Probe internal fields:

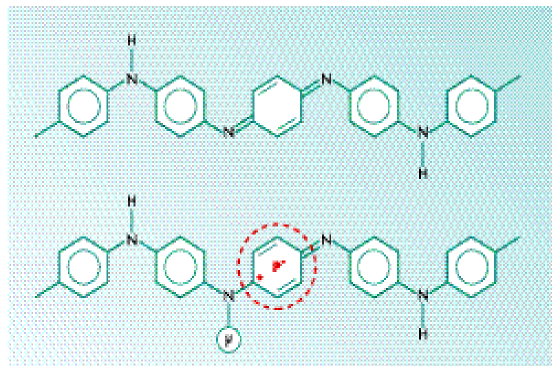
sensitive to small moments (nuclear and electronic) and spin fluctuations

Applications of μSR …
The muon as an analogue for 'H'

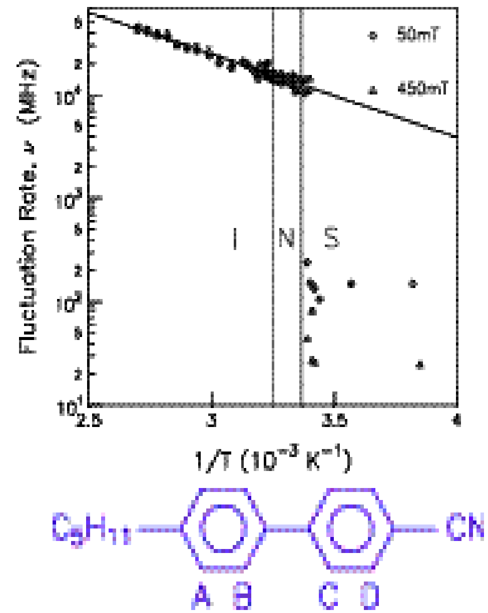
Semiconductors



Polaron/Soliton Motion



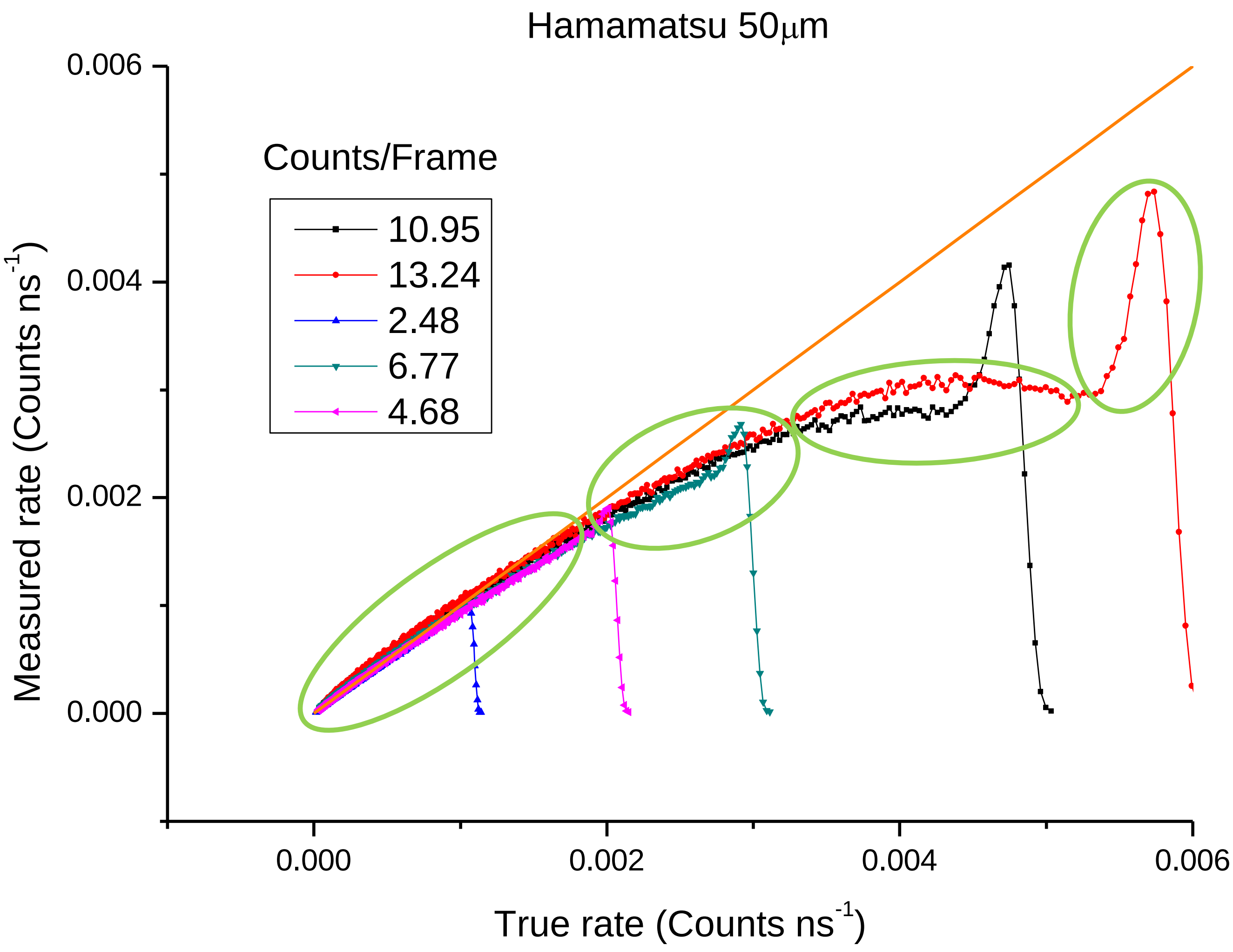
Molecular Dynamics



Probe for 'hydrogen' states and reactions:

sensitive method of studying charge states, dynamics and reactions

Lifetime mapped to rate plot



Solution to Deadtime (1)

Minimise intrinsic detector dead time

- Fastest flurophore
- Direct optical coupling
- Fastest Photo-detector
- Fast TDC/DAE chain

Compromise with many other factors but no one component should be severely limiting

PMT based detector deadtime ~15ns

Solution to Deadtime (2)

Pixelate the detector array

Paisley

MuSR 64

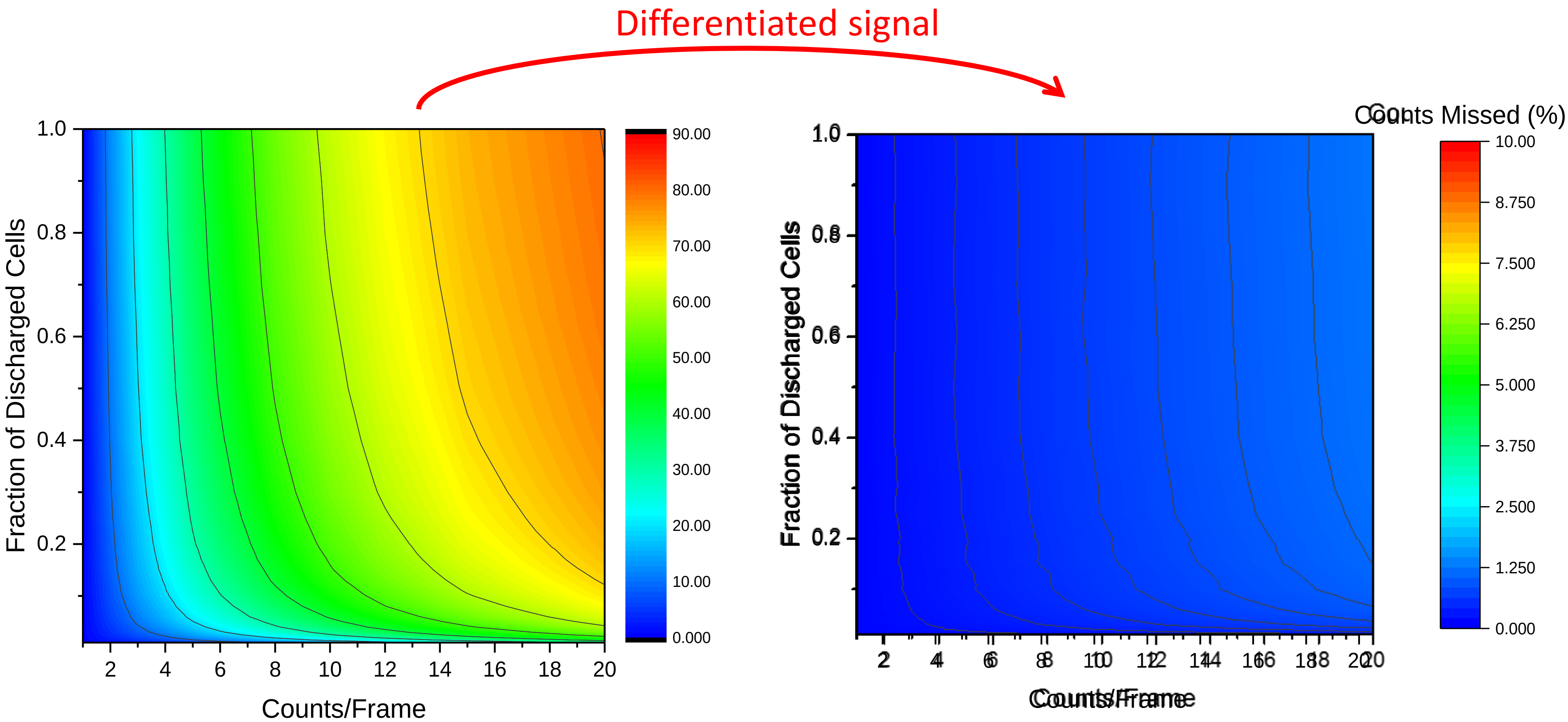
EMU = 96

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

Monte-Carlo Simulation

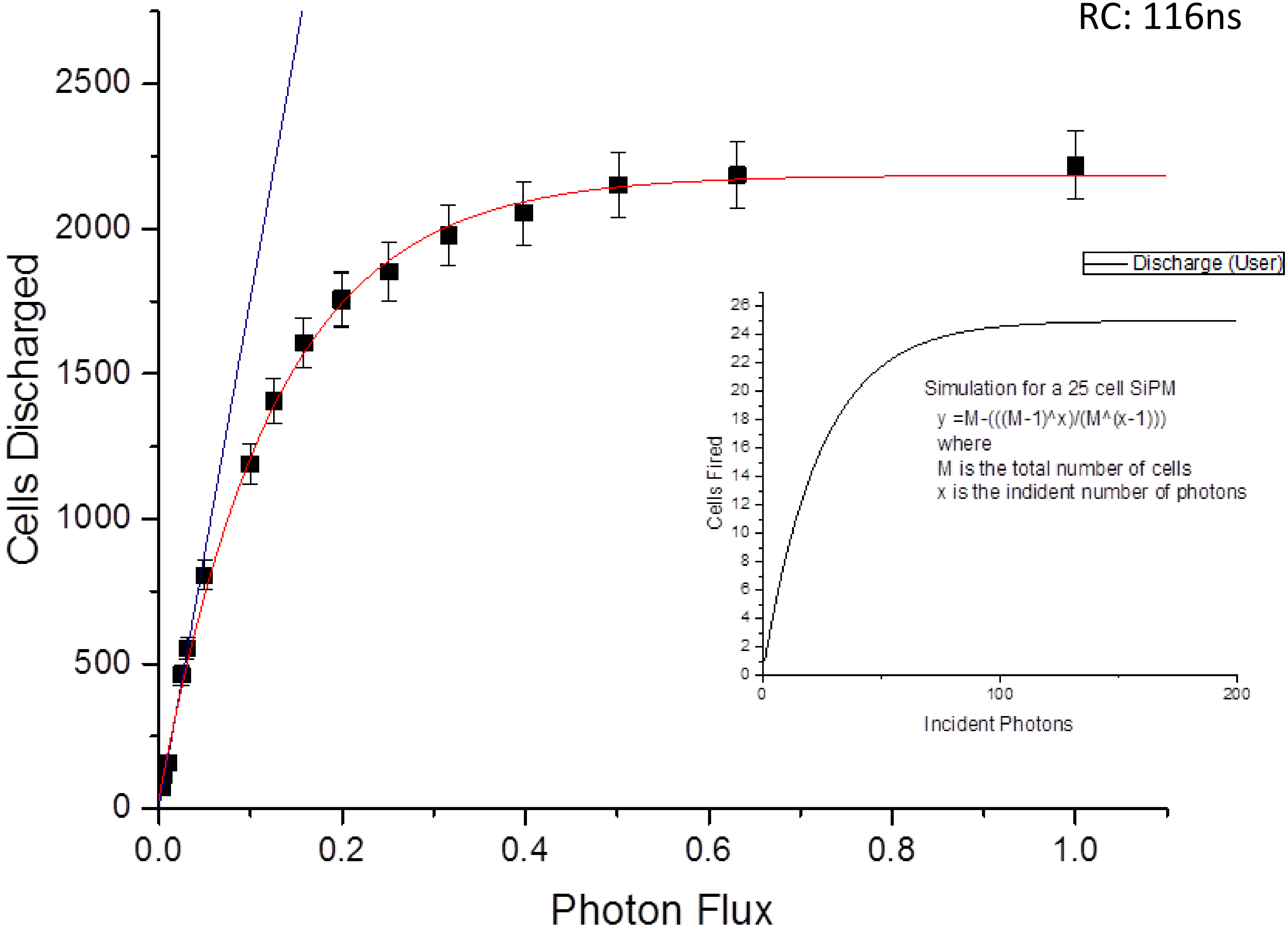
SensL 50µm

SensL 50µm



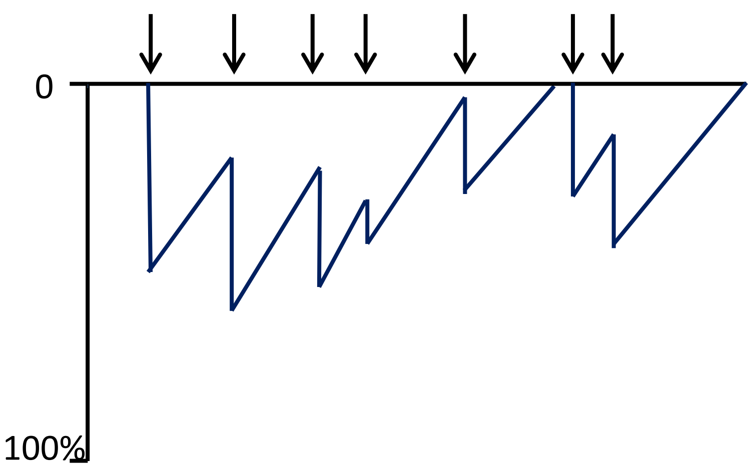
Cells fired – optical investigation

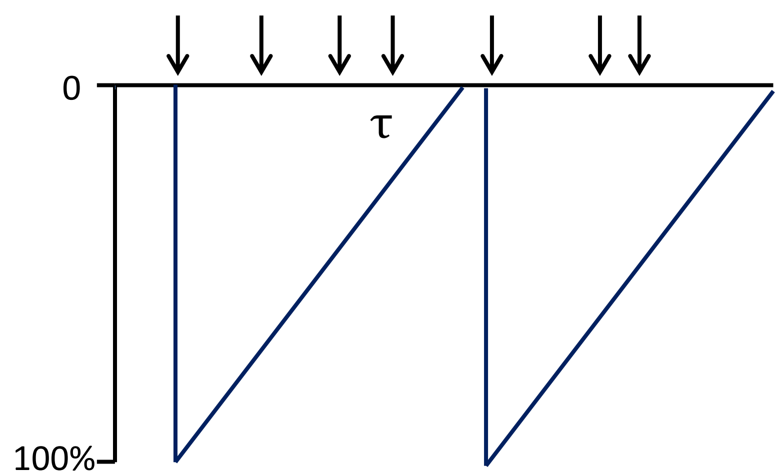
SensL FC50um
Cells 2668
RC: 116ns

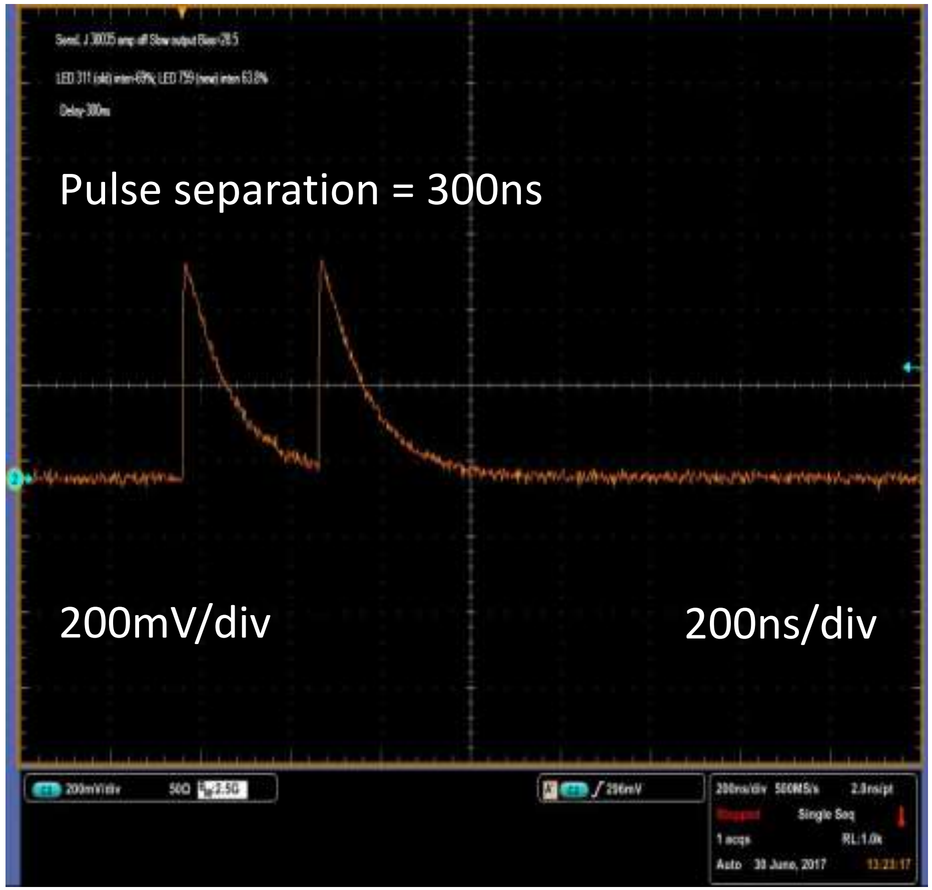


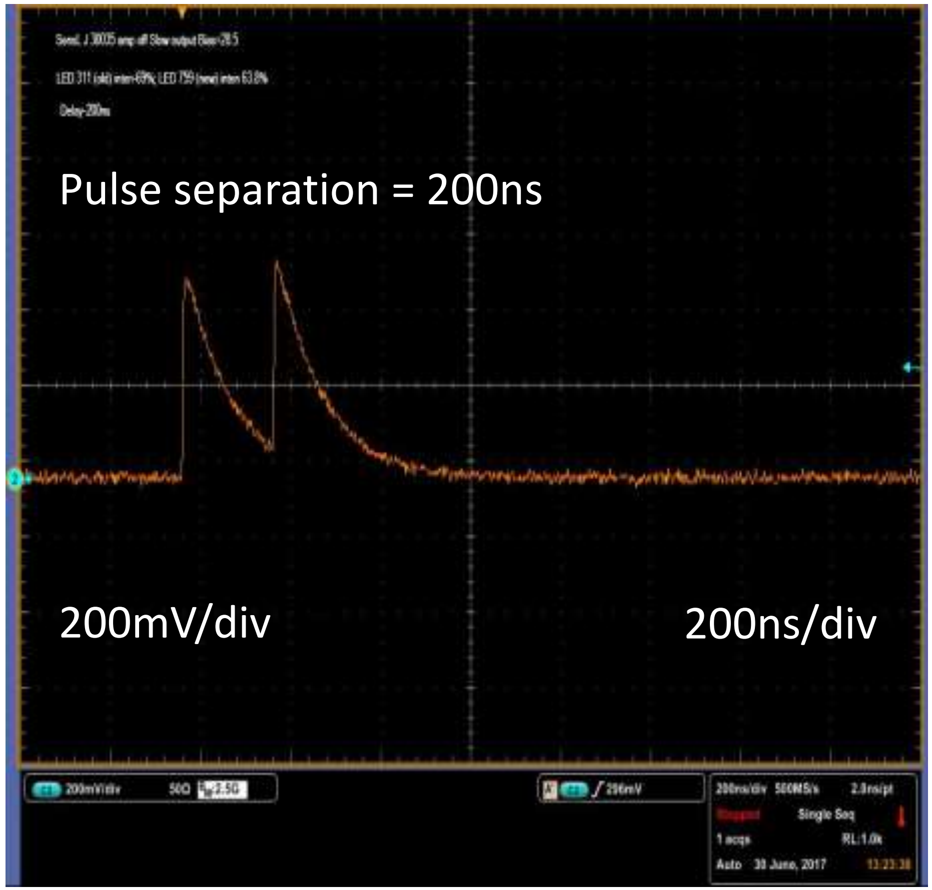
What is the Deadtime of a SiPM?

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

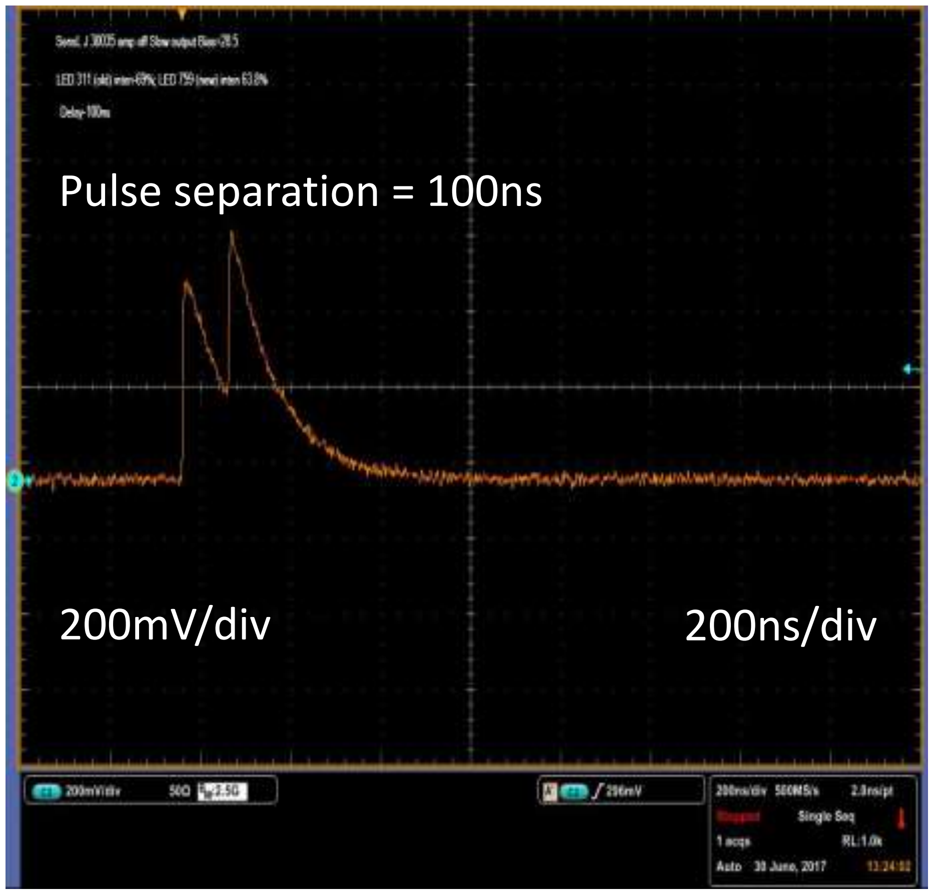


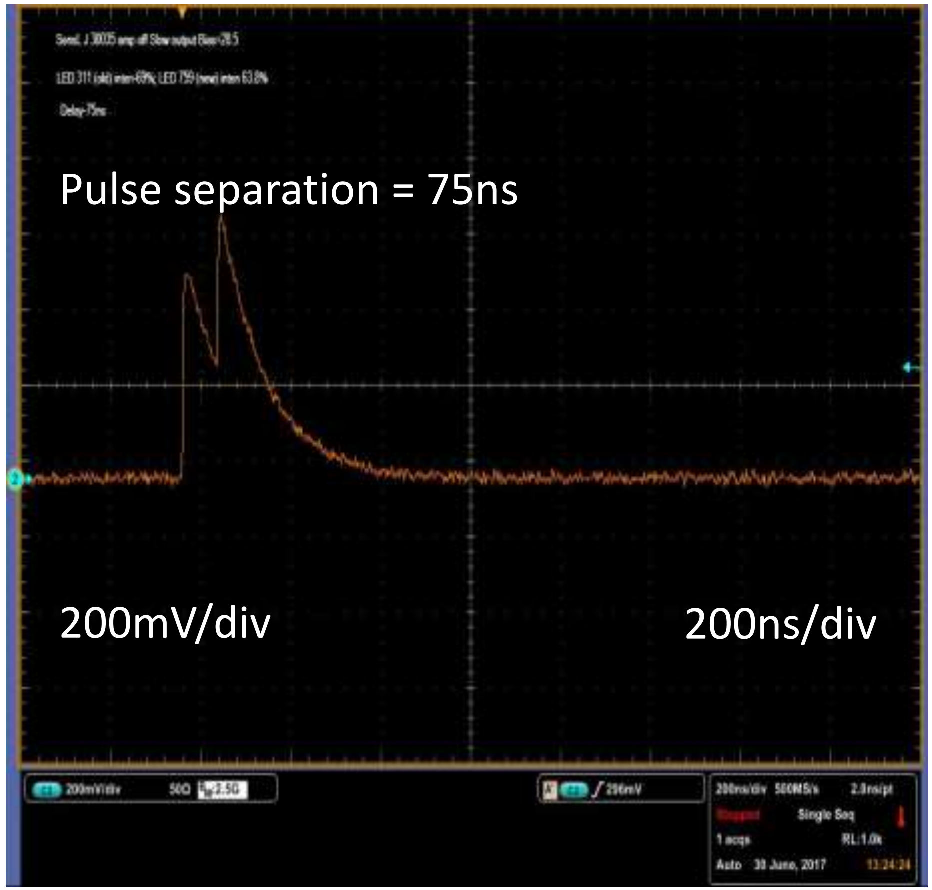


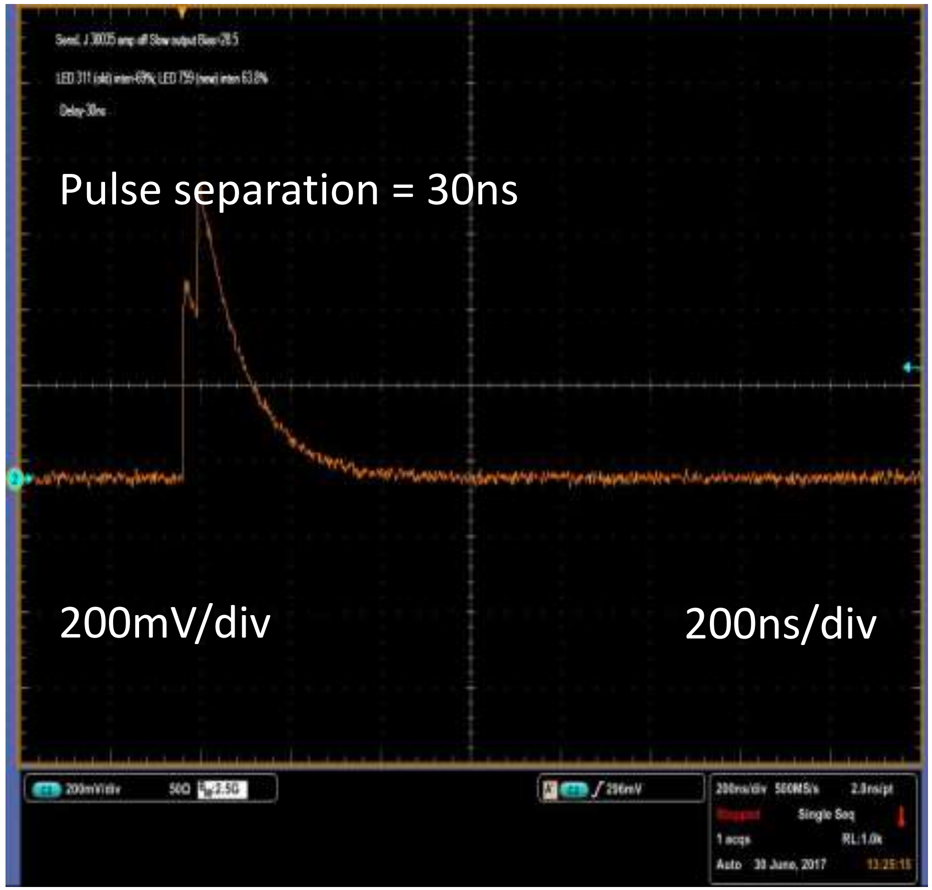

Pulse separation = 300ns
200mV/div
200ns/div

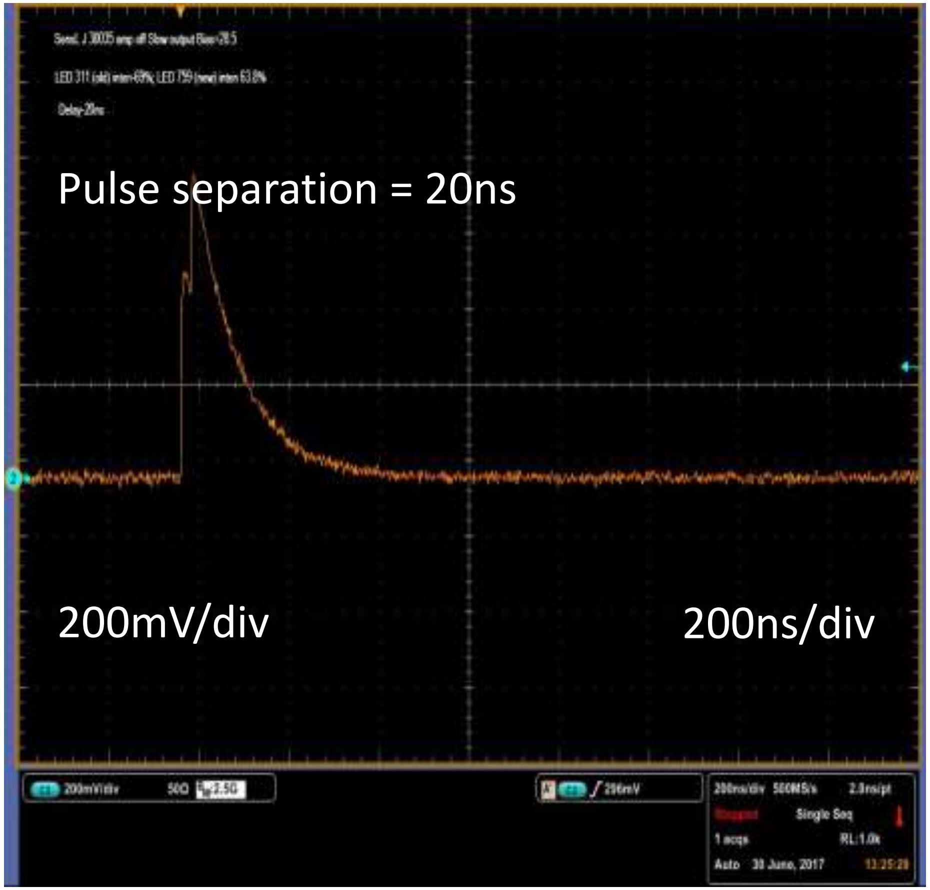


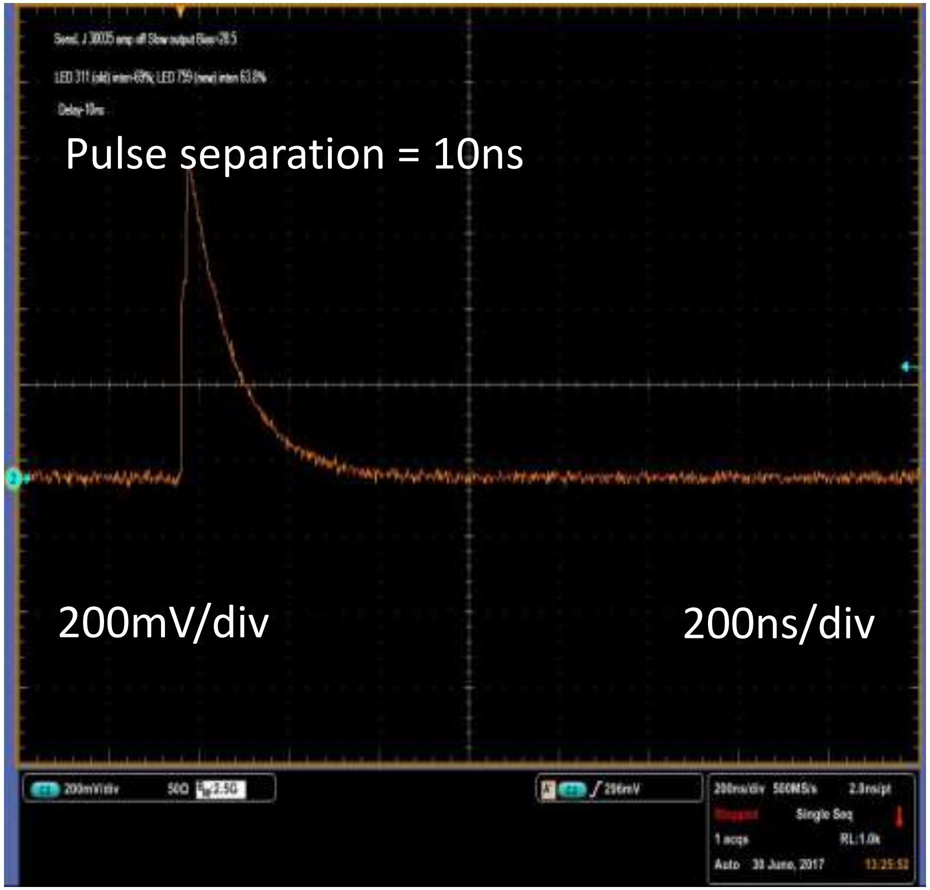
Pulse separation = 200ns
200mV/div
200ns/div


Pulse separation = 100ns
200mV/div
200ns/div


Pulse separation = 75ns
200mV/div
200ns/div


Pulse separation = 30ns
200mV/div
200ns/div


Pulse separation = 20ns
200mV/div
200ns/div
Single Seq
Auto 30 June, 2017


Delay-10ns
Pulse separation = 10ns
200mV/div
200ns/div
200mV/div
50Ω
200ns/div 500MS/s 2.0ns/pt
Single Seq
1 acqs
RL:1.0k
Auto 30 June, 2017
13:25:52

Amplifiers (PSI and miniCircuit)