Summary of SiPM studies and overview of applicability for Beam Loss Monitoring systems

LAser Applications at Accelerators
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E. Nebot del Busto [1,2] , L. Devlin [2,3], E. B. Holzer [1], M. Kastriotou [1,2], S. Vinogradov [2,4] and C.P Welsch [2,3]

(1) CERN, Geneva, Switzerland.
(2) The University of Liverpool, Department of physics, Liverpool, U. K.
(3) The Cockcroft Institute, Warrington, U.K.
(4) The Lebedev Physical Institute, Moscow, Russia

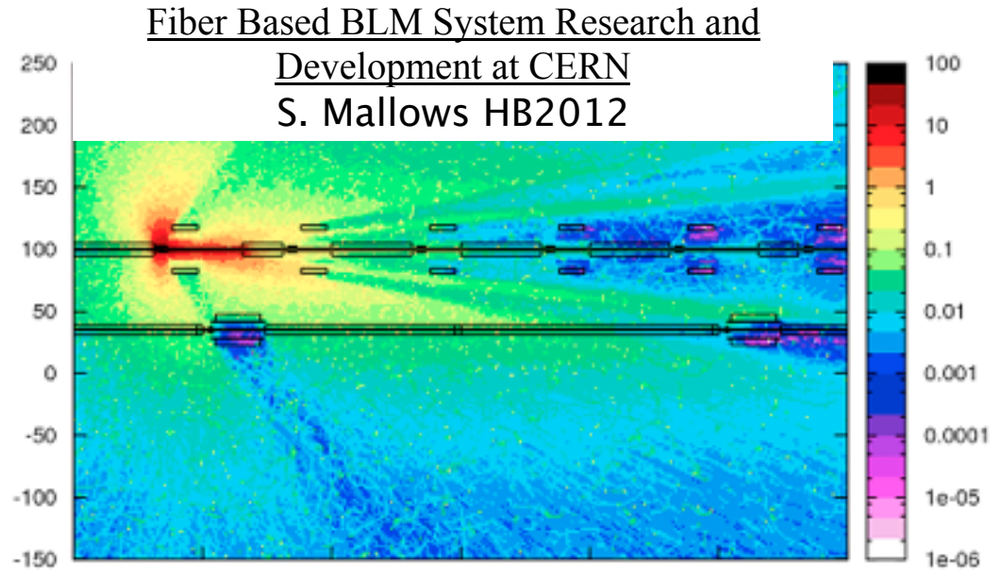
Outlook

- **Introduction**
  - Beam Loss Monitoring (BLM)
  - Silicon PhotoMultipliers (SiPM)
  - SiPM limitations
  - Motivation for the studies
- **SiPM response and dynamic range limitations/estimations**
  - Single fast pulse
  - Double fast pulse
  - Square pulse
- **Conclusions**

Introduction to Beam Loss Monitoring

Beam Losses

- Particles that deviate from the design orbit hitting the aperture limit and producing secondary showers
- Particle detector outside of the vacuum chamber are necessary to monitor beam losses



Beam Loss Monitoring system

- Machine Protection
- Diagnostics
- Keep activation levels low

Detector technology

- choice depends on many factors: Radiation levels, time response, lifetime, remote test-ability.....
- In this presentation we focus on **optical based** sensors due to the advantages on achievable time resolution and bandwidth

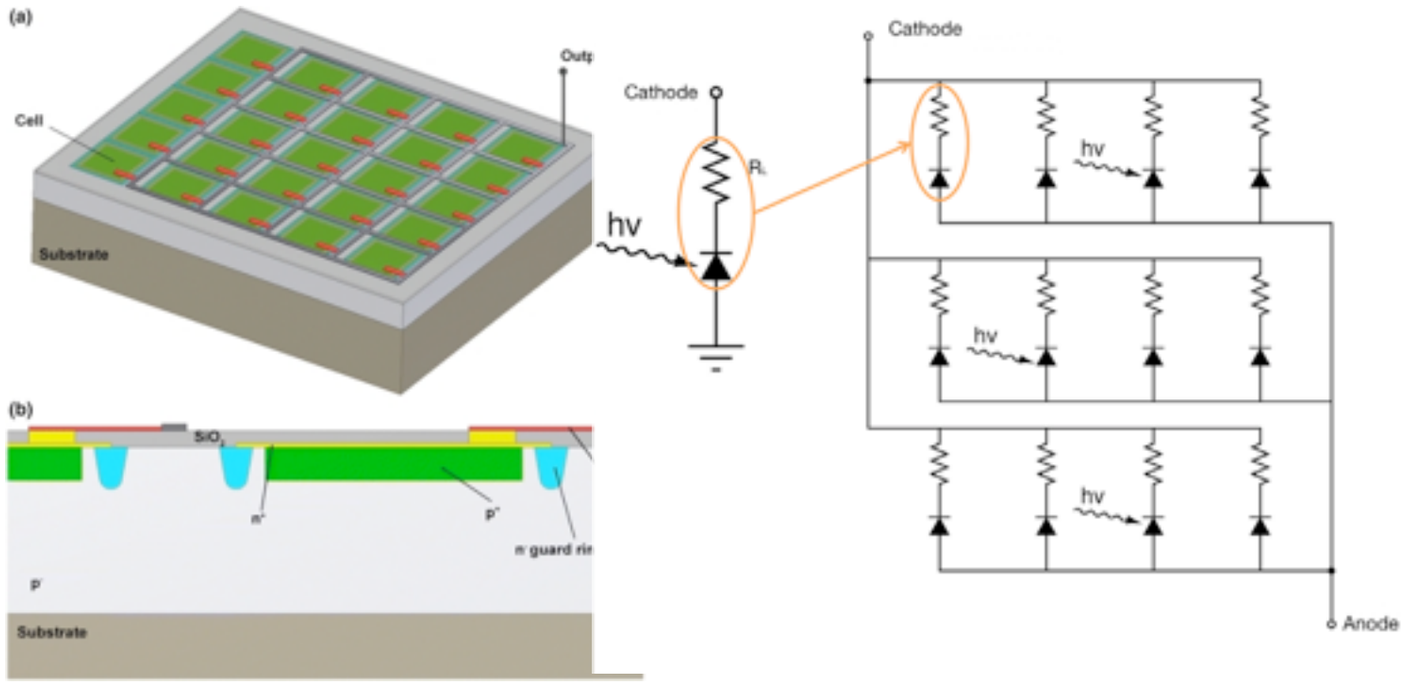
BLM requirements

- **High sensitivity**
  - Subtle instabilities, beam-gas etc
- **Time resolution**
  - Bunch spacing: LHC (25 ns), CLIC (0.5 ns)
  - Bunch length: PS (4 - 100 ns), LHC (1 ns, CFT3 ~ 10ps)
- **High dynamic range:**
  - LHC DR ~10^{+6}
  - CLIC DR~10^{+5}

Introduction to SiPMs

SiPMs :

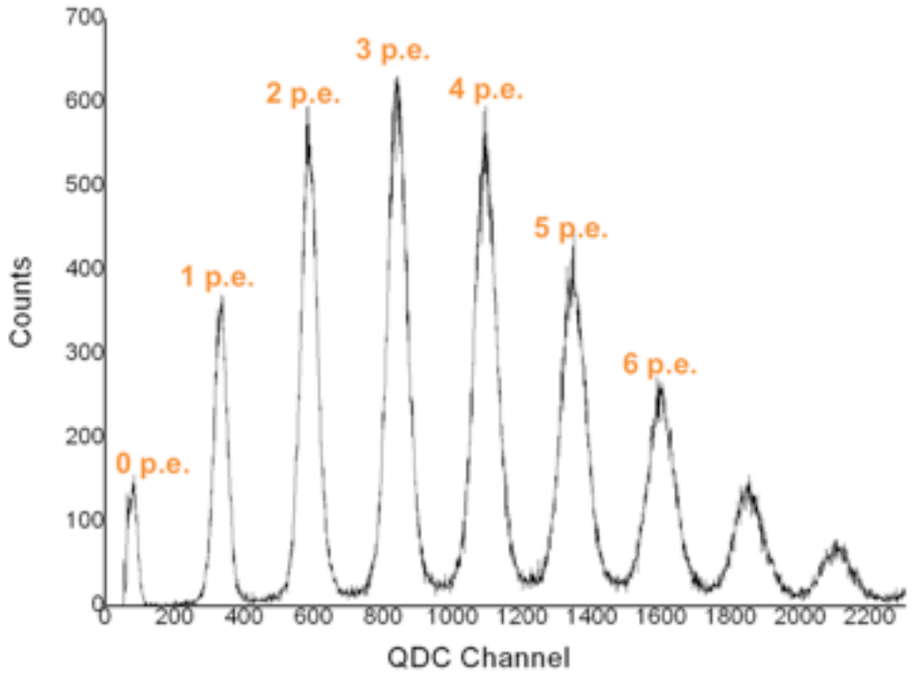
- Array of independent limited Geiger mode APDs
- Common output produces a sum of binary signals



Competitive in fast and low light pulse conditions

- Single photon resolution
- fast (time resolution ~ 100ps)
- Multiple applications: HEP, medical imaging, astrophysics, telecom ...

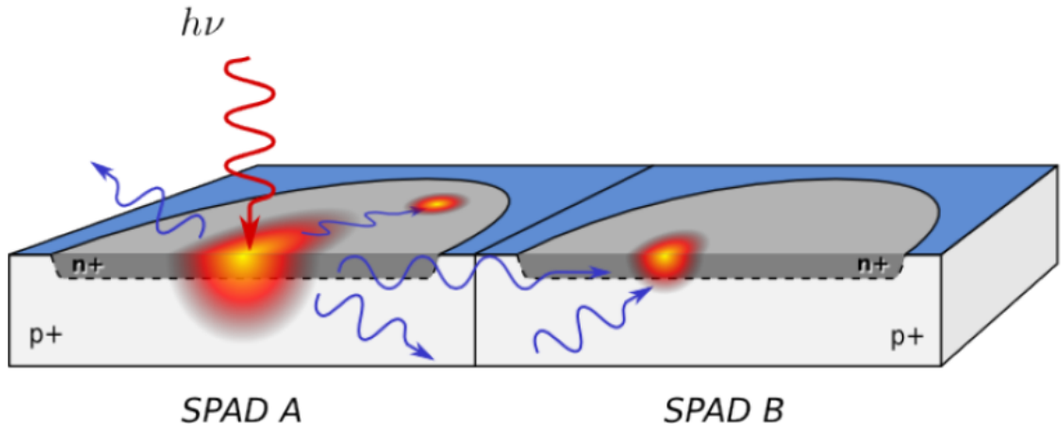
	PMT	SiPM
Gain	10^{+6}	10^{+5}-10^{+6}
Time response	fast	fast
Photon counting	yes	yes (single photon)
Bias Voltage (V)	~1000	70
Dynamic range	10^{+4} (space charge)	< 10^{+5} (number of
B field	sensitive	insensitive
Cost	expensive	inexpensive
Size	small	compact



SiPM Drawback and limitations

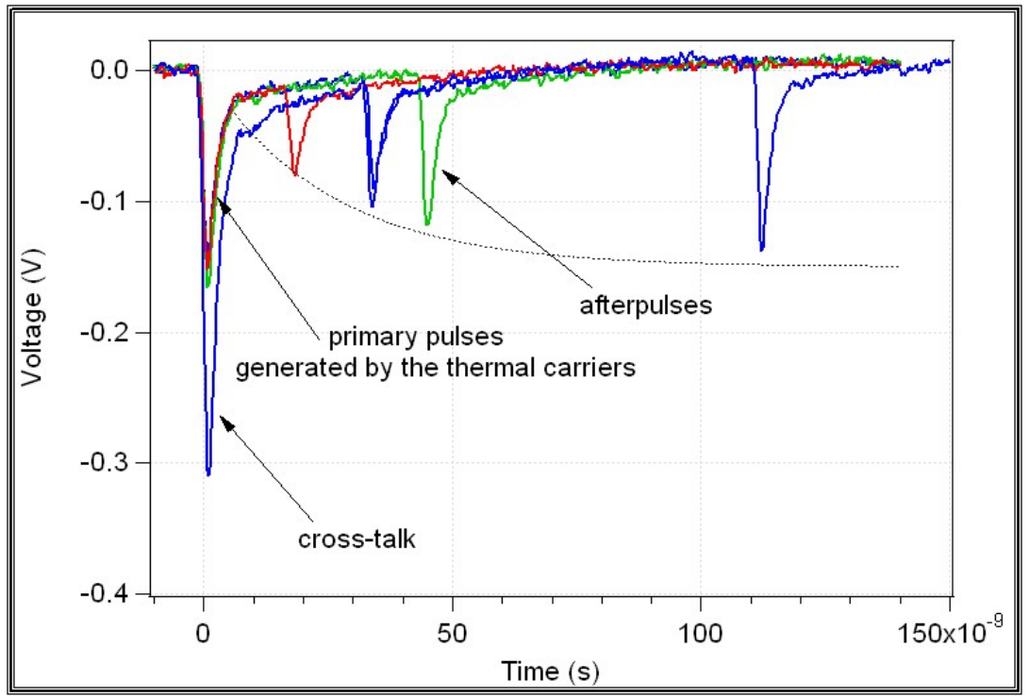
Xtalk

- High energy photons generated during the avalanche process may trigger and avalanche in neighboring pixels
- Typical values: 5 - 40%



After-pulsing

- Electrons captured by impurities and released with some (~>10ns) delay triggering an avalanche
- Typical values: 5 - 20%



Recovery time (τ_{rec})

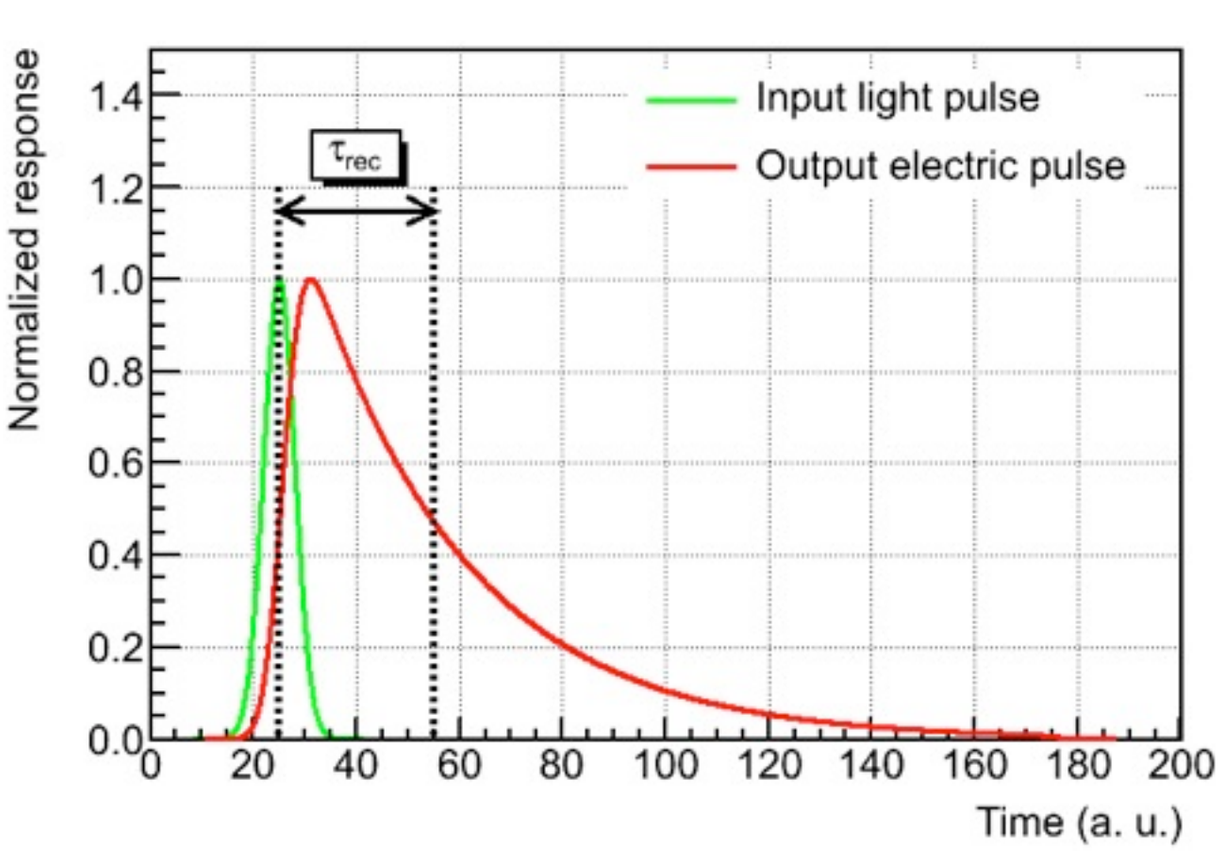
- $\Delta V = V_0(1- \exp(\Delta t/\tau_{rec}))$ affects gain (G) and Photon Detection Efficiency (PDE)
- Typical values: 10-120 ns

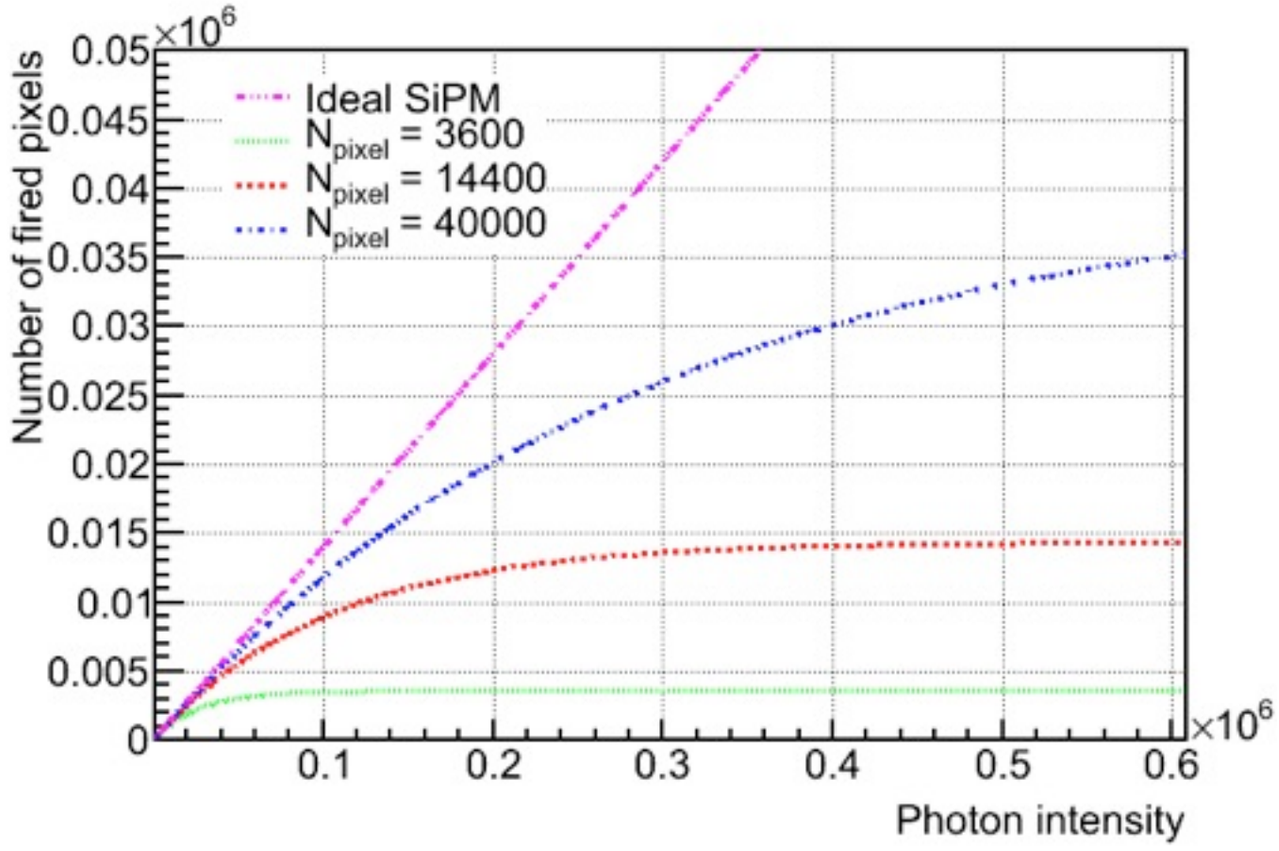
Number of pixels

- Typical values: 10^{+2}-10^{+5}

SiPM response

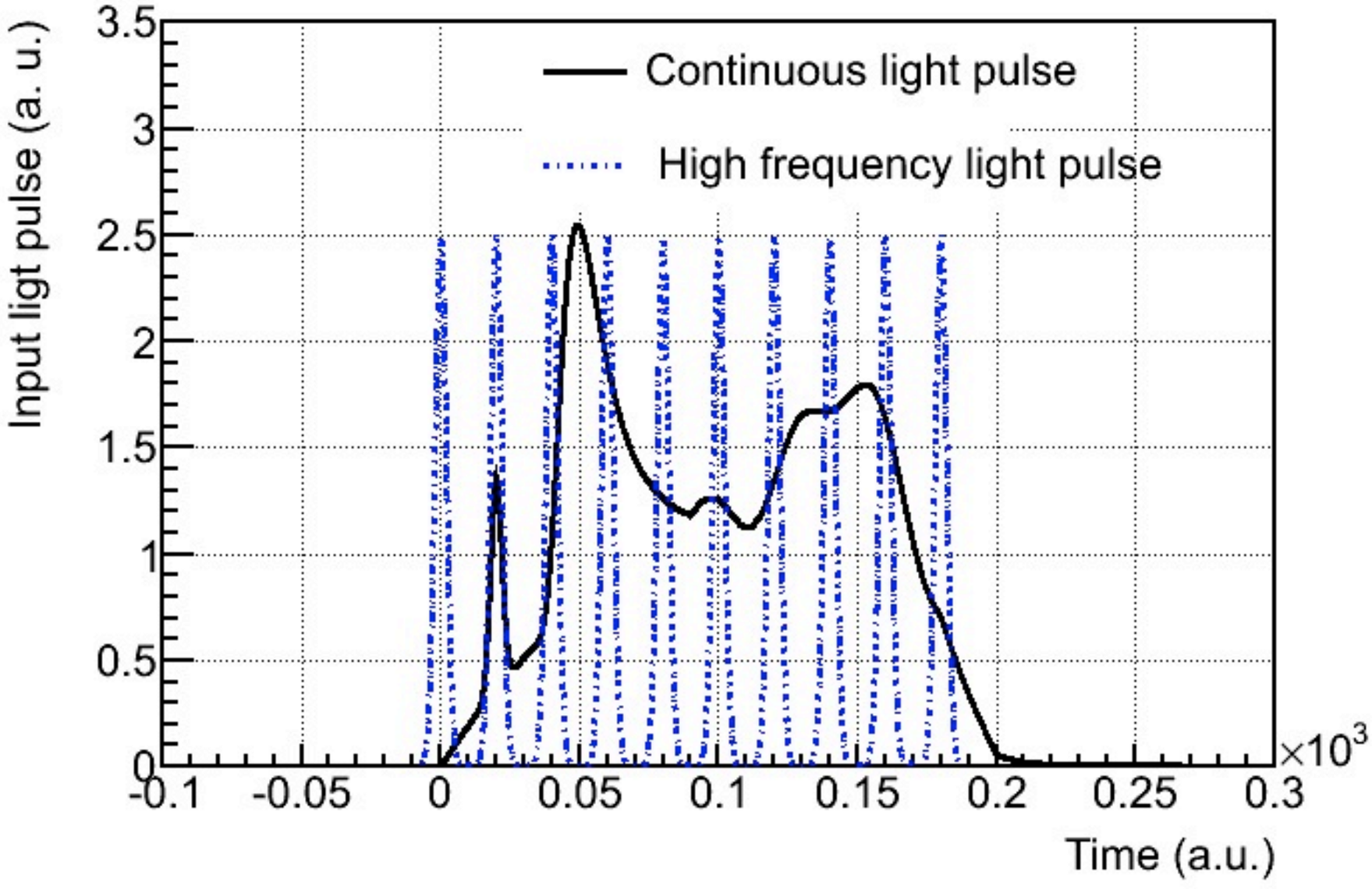
- **Saturation effects well understood for light pulses much shorter than the single cell recovery time**
  - output pulse = input shape convoluted with the Single Electron Response (SER)
  - Dynamic range of device limited by the number of single pixels





SiPM response II

- **BLM request a linear response under an arbitrary light pulse**
  - output pulse = input shape convoluted with SER
  - Dynamic range of device limited by the number of single pixels and recovery time

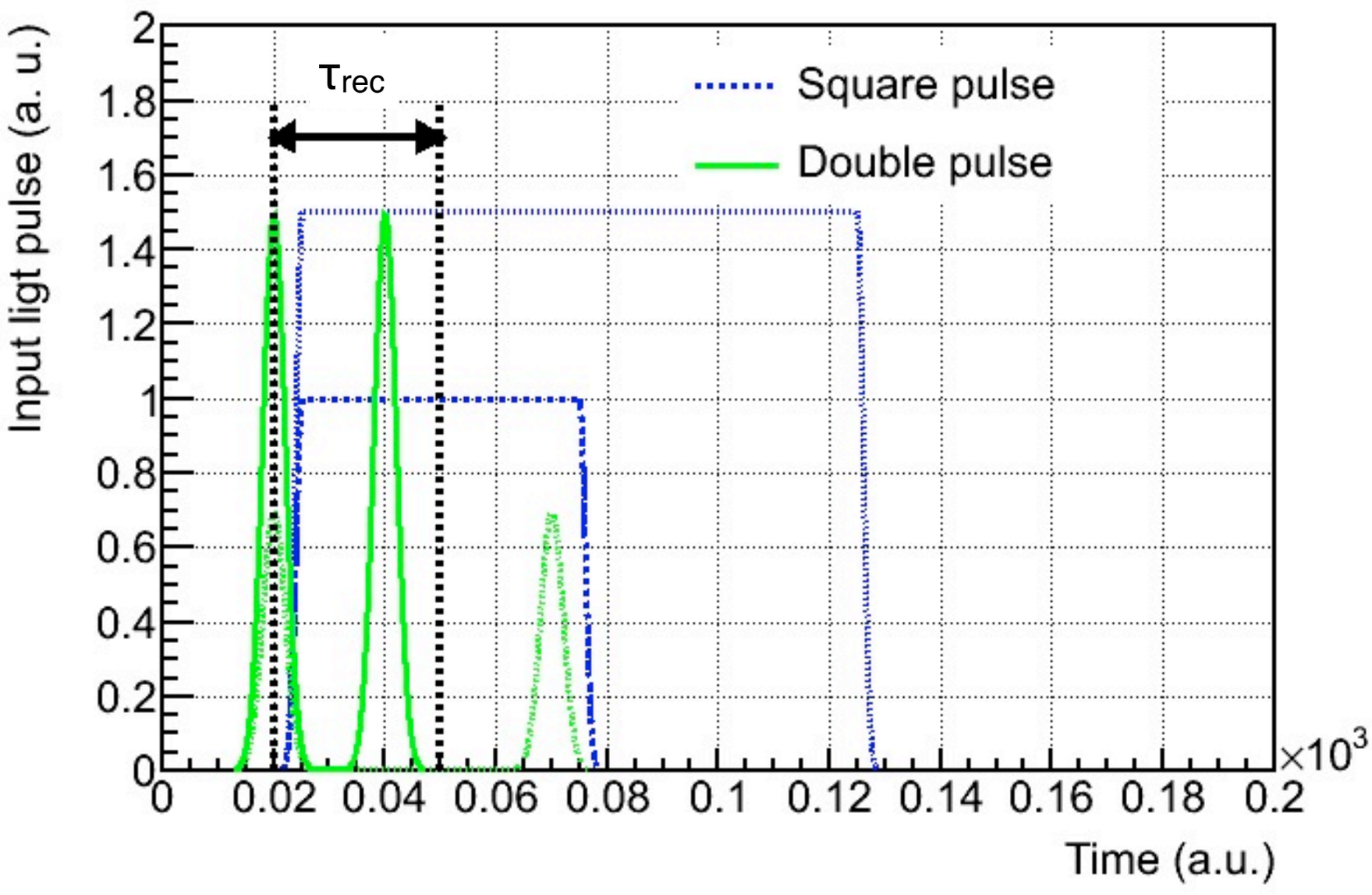


Output Electric Pulse

?!

SiPM response III

- **Two study cases to extrapolate to arbitrary shape**
  - Double pulsed SiPM. Parameters: Laser intensity and delay
  - Long LED pulsed SiPM. Parameters: LED intensity and pulse length

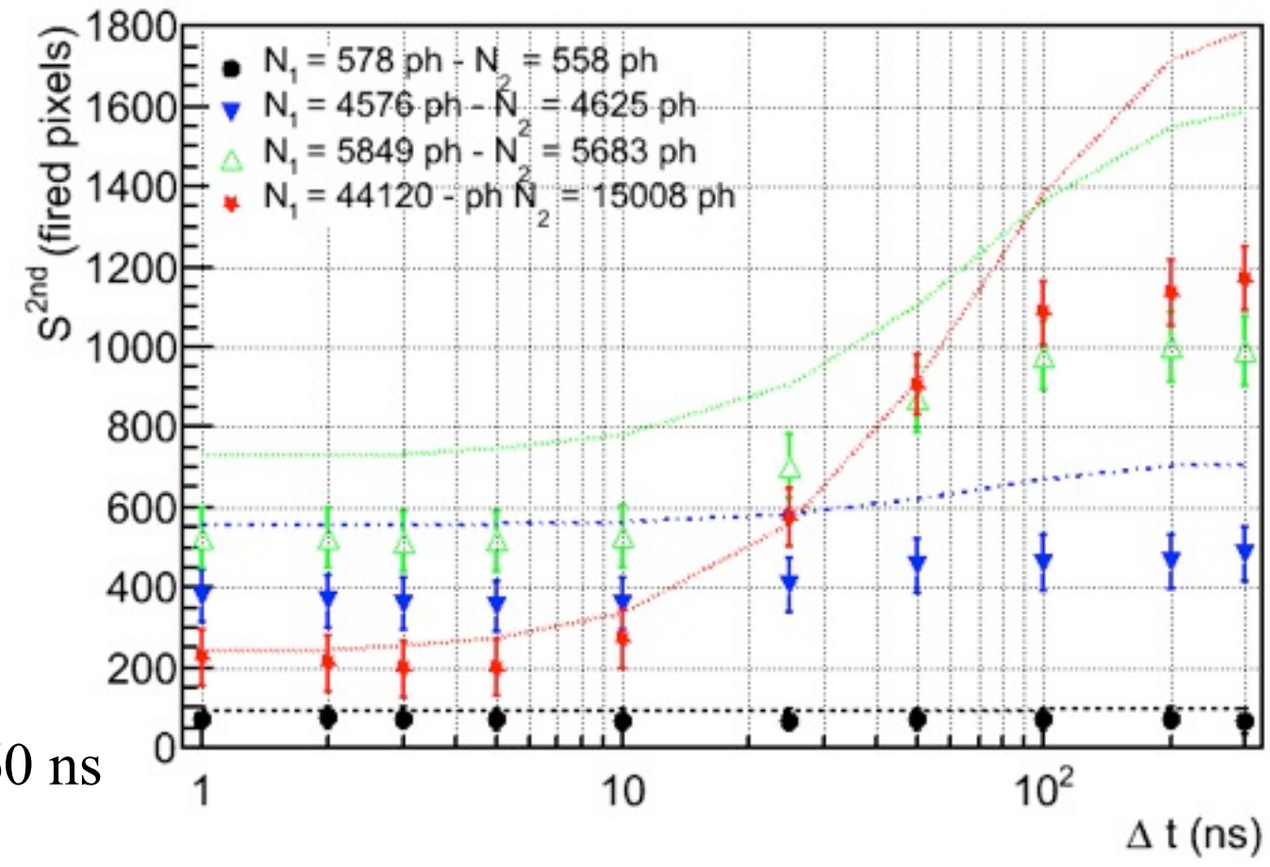


Double pulse I: The model/experiment

"*Studies of SiPM nonlinearities and transients at short light pulse detection*"
E. Nebot et al. This conference, POSTER session.

Study of the simultaneous effect of recovery time (τ_{rec}) and N_{pixels}

- Illuminating SiPM with 2 pulses of controlled intensity separated by Δt
- $I = 10^{+2}$-10^{+6} photons (680 nm)
- Δt = 0 - 300 ns



Multi-parameter (I_1, I_2, Δt , PDE, τ_{rec}, Xtalk, Gain) model based on statistical arguments

- Achieved good qualitative agreement
- Total agreement within 50 %
  - PDE = 14%, Xtalk=25% and τ_{rec} = 60 ns

Double pulse II: Parameter selection

- **Statistical model used to extrapolate performance of SiPMs**

- **Arguments for parameter selection**
  - N_{pixels} reaching the limit (10μm)
  - τ_{rec}
  - X-talk (trenches)
  - After-pulsing (Si purity)

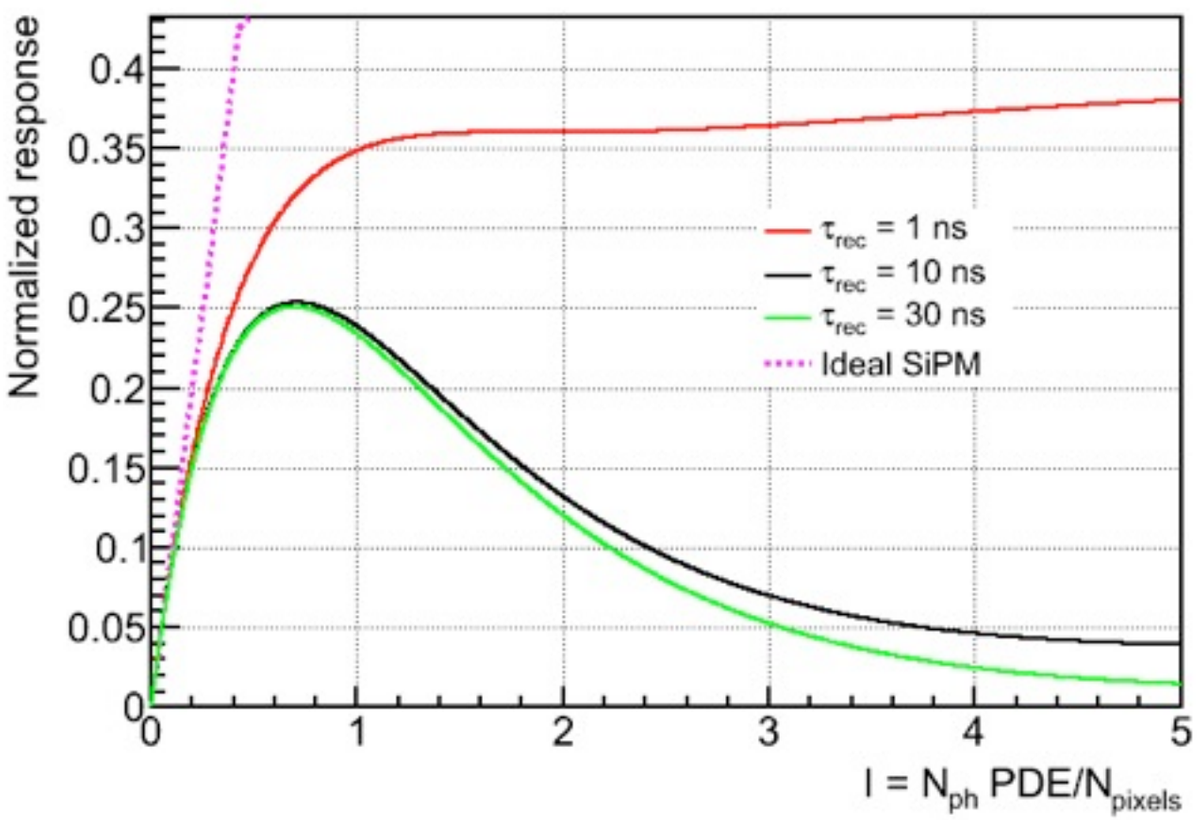
Param	Typical	Model
N_{pixels}	up to 10^{+5}	10^{+5}
τ_{rec} (ns)	10-120	1
X-talk (%)	5 - 40	0
Gain	10^{+5}-10^{+6}	10^{+6}

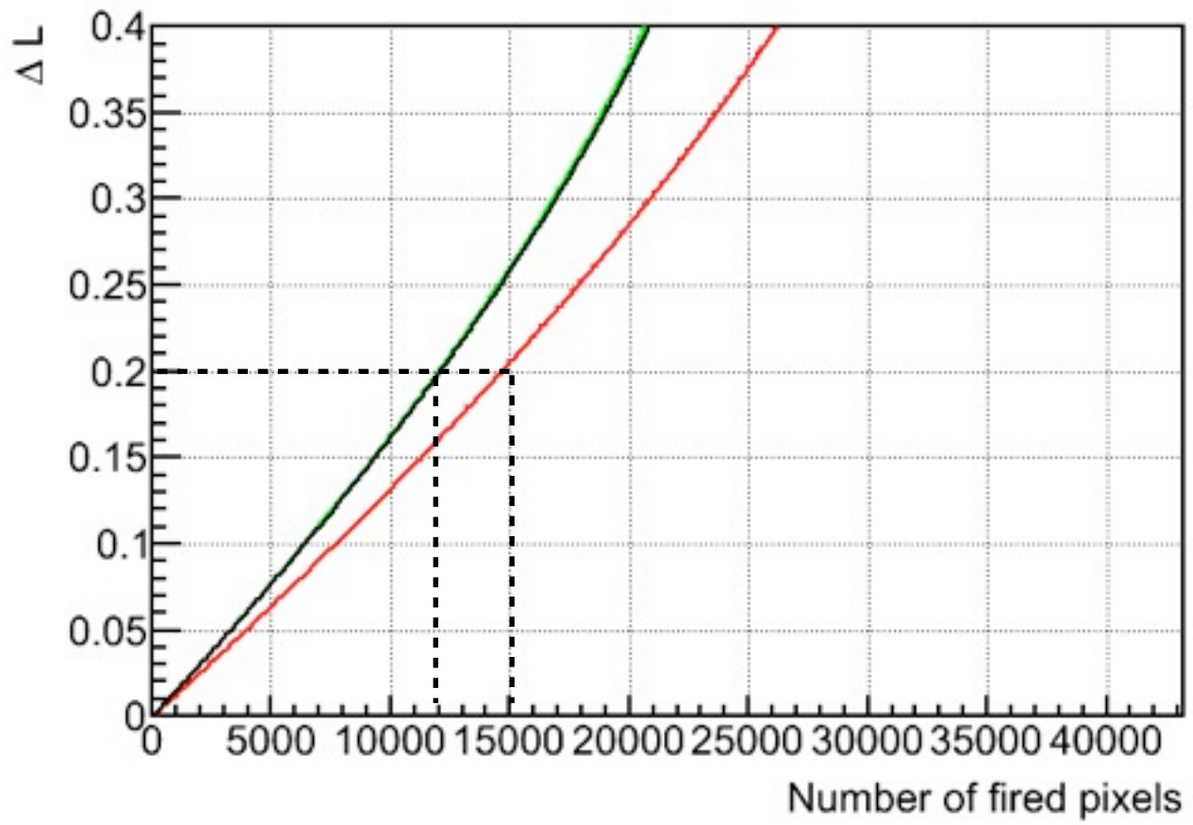
- **Time lapses between pulses (Δt) of interest in the range of bunch spacing of different machines (0.5ns)**

- **Results studied in terms of deviation from linearity (ΔL)**
  - ΔL= (response - ideal)/ideal with ideal = N_{ph} x PDE

Double pulse III: Extrapolations

- **Estimation of dynamic range as values for which non linearity exceeds 20%**
  - $\Delta t = 0.5$ ns
  - Achievable DR~ $1.5 \times 10^{+4}$



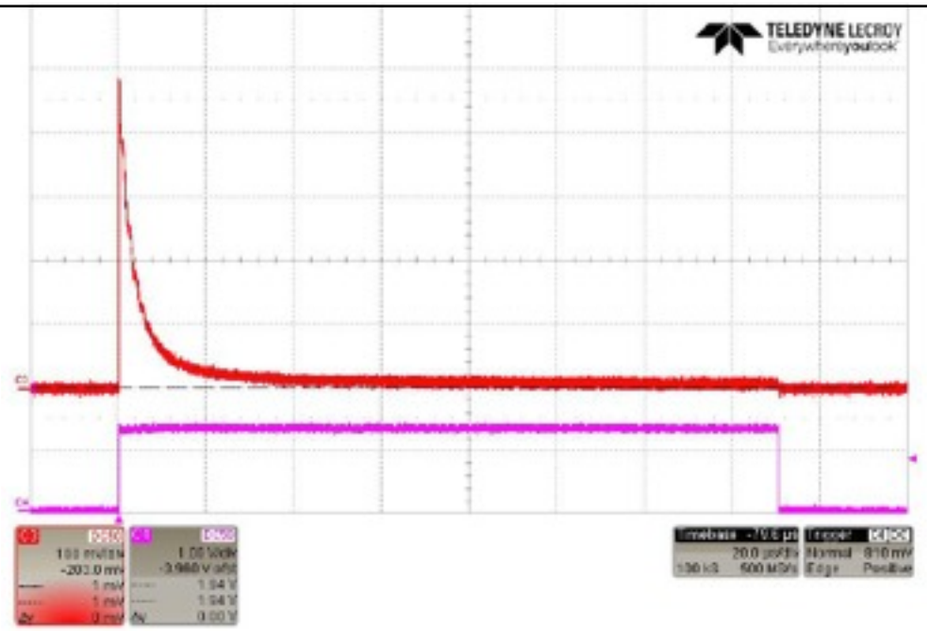


Square Pulse I: The model/experiment

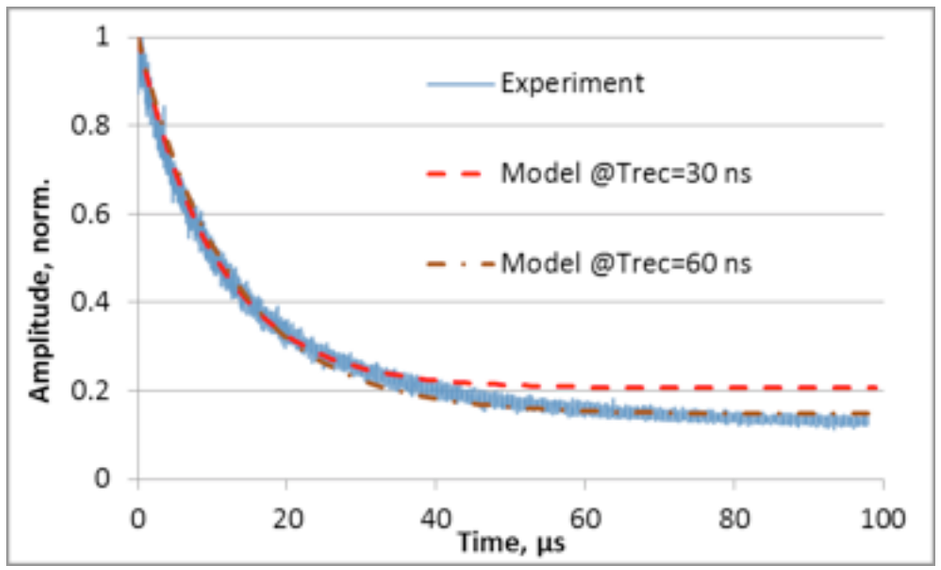
"SiPM response to long and intense light pulses"
S. Vinogradov et al, NIMA

"*Investigations into the effect of long intense light pulses on SiPMs for the purpose of Beam Loss Monitoring*". L. Devlin et al. This conference, POSTER session.

- **Study of the (simultaneous) effect of recovery time (τ_{rec}) and N_{pixels}**
  - Illuminating SiPM with 1pulses of controlled intensity of length $\Delta t > \tau_{rec}$



- **Multi-parameter (I_{ini}, I_{std-st} , PDE, τ_{rec}, Xtalk, after-pulse) model based on statistical arguments**
  - Good agreement within and τ_{rec} = 60 ns
  - $I_{resp} = I_{bin} + I_{steady}$



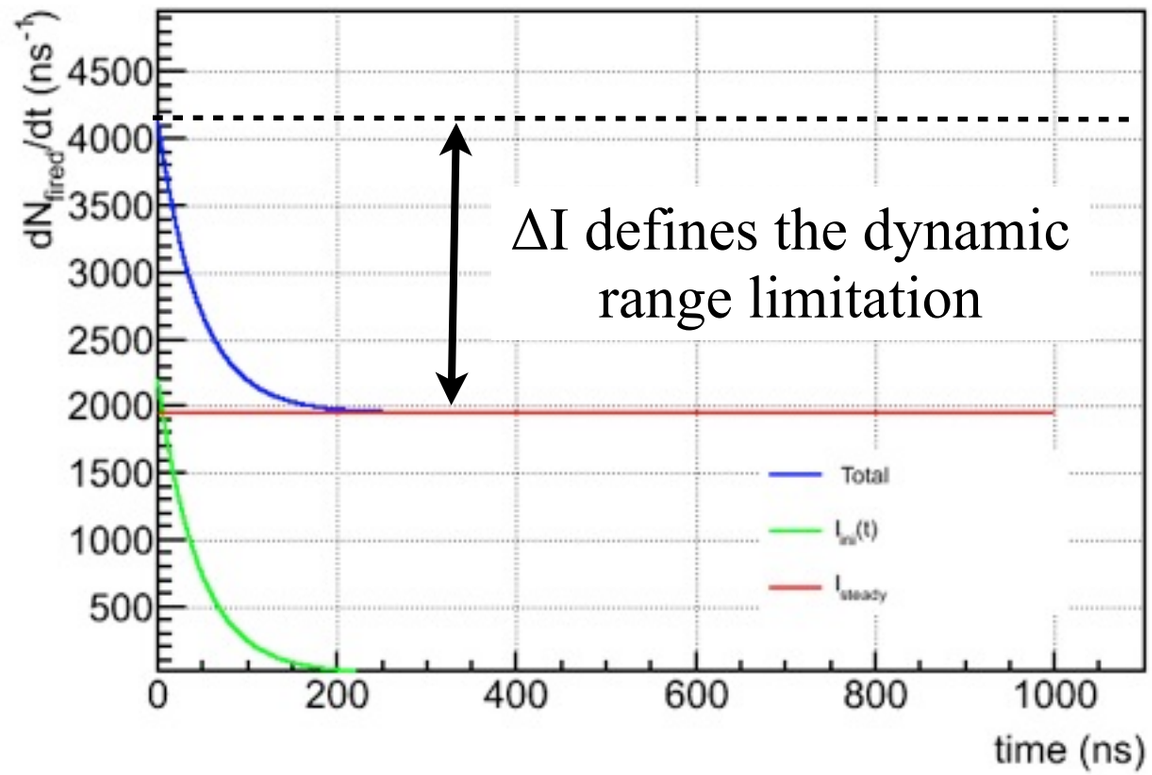
Square Pulse II: Parameter selection

- **Statistical model used to extrapolate performance of SiPMs**

- **Similar parameters as used for previous model**
  - Including after-pulsing

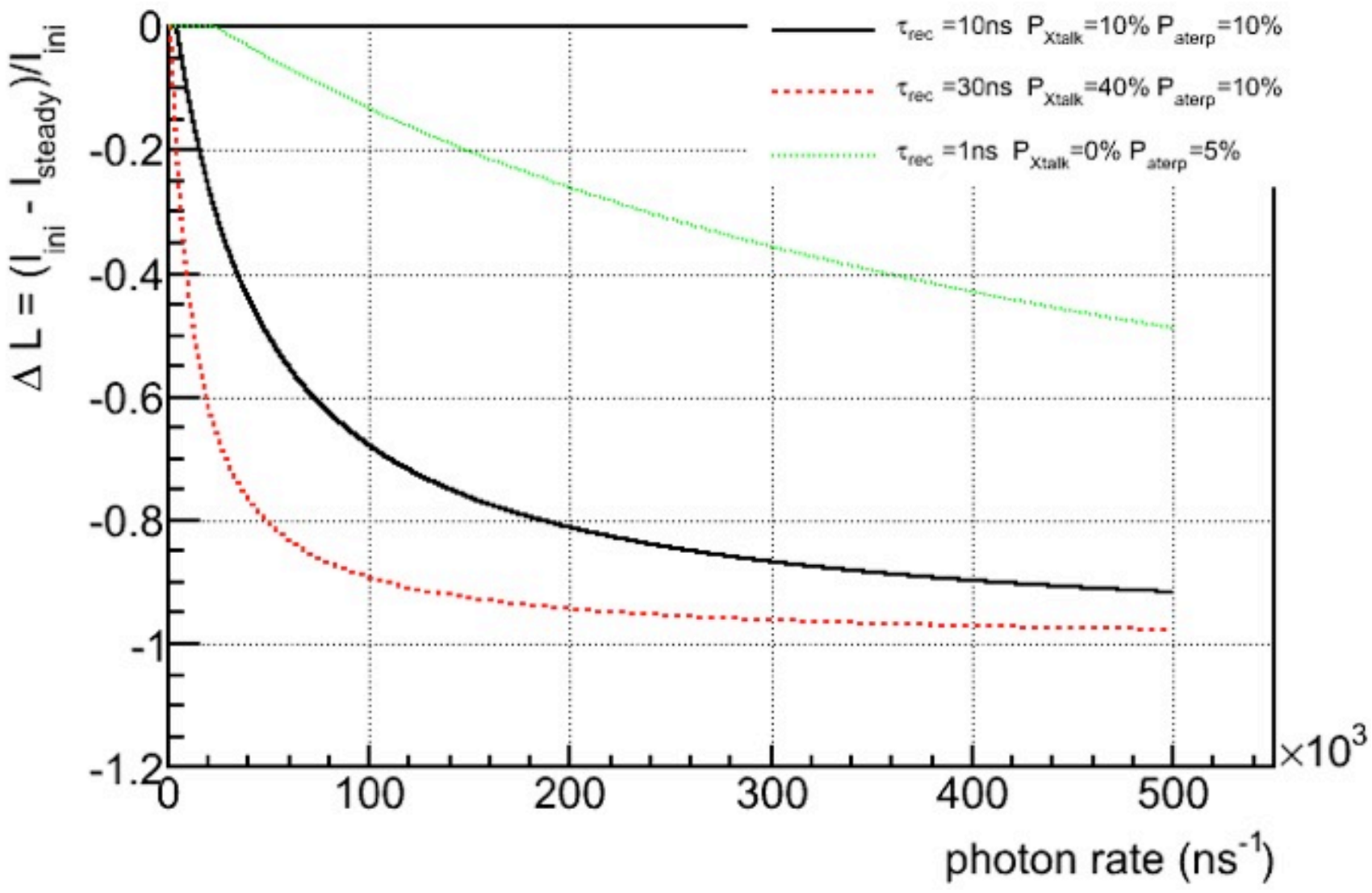
Param	Typical	Model
N_{pixels}	up to 10^{+5}	10^{+5}
τ_{rec} (ns)	10-120	1
X-talk (%)	5 - 40	0
Gain	10^{+5}-10^{+6}	10^{+6}
After-pulsing (%)	5-20%	0

- **Results studied in terms of deviation from linearity (ΔL)**
  - $\Delta L = (I_{ini} - I_{steady})/I_{ini}$



Square pulse III: Extrapolations

- **Estimation of dynamic range as values for which non linearity exceeds 20%**
  - 5 10^{+3} ph/ns / 1.5 10^{+4} ph/ns / 1.4 10^{+5} ph/ns @ τ_{rec} = 30/10/1 ns



Summary and Conclusion

- **SiPMs have many advantages**
  - Fast, sensitive, cheap, compact, insensitive to B fields
  - Limitations in dynamic range from τ_{rec} and N_{pixels}
  - Challenge reconstruct (linearly) an arbitrary shaped light pulse

- **Extrapolations have been made based on statistical models:**
  - Double pulsed SiPM (pulses much faster than τ_{rec})
  - Squared pulse SiPM (pulse much longer than τ_{rec})

- **Future SiPM performance:**
  - Choice of parameters $N_{pixels} = 10^{+5}$ / $\tau_{rec} = 1$ ns / Xtalk ~ 0% / Afterp ~ 5%
  - Dynamic range :
    - 10^4 (instantaneous)
    - 10^5 (ns^{-1})

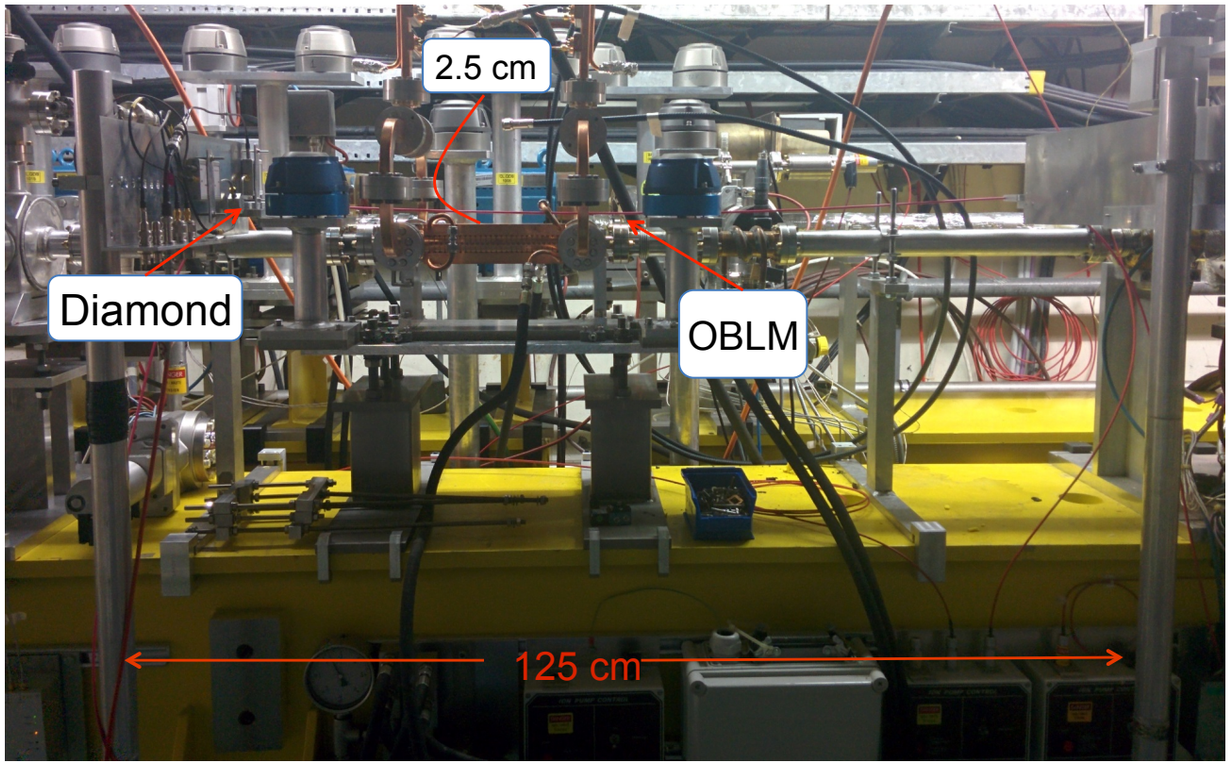
Thank you for your attention !

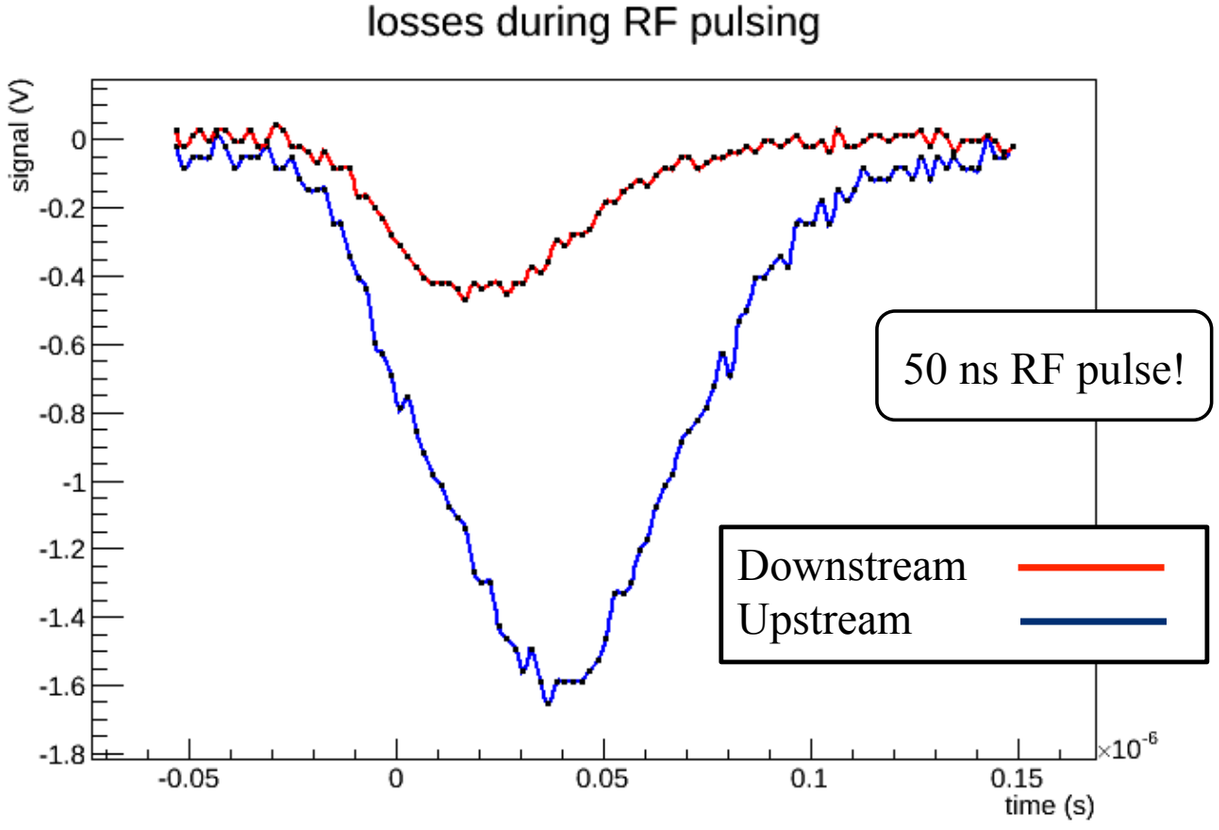
Diagnostics with SiPMs I

"*Studies of SiPM nonlinearities and transients at short light pulse detection*"
M. Kastriotou at al. This proceedings POSTER session.

High sensitivity diagnostics

- Exploding single photon counting and single photon resolution



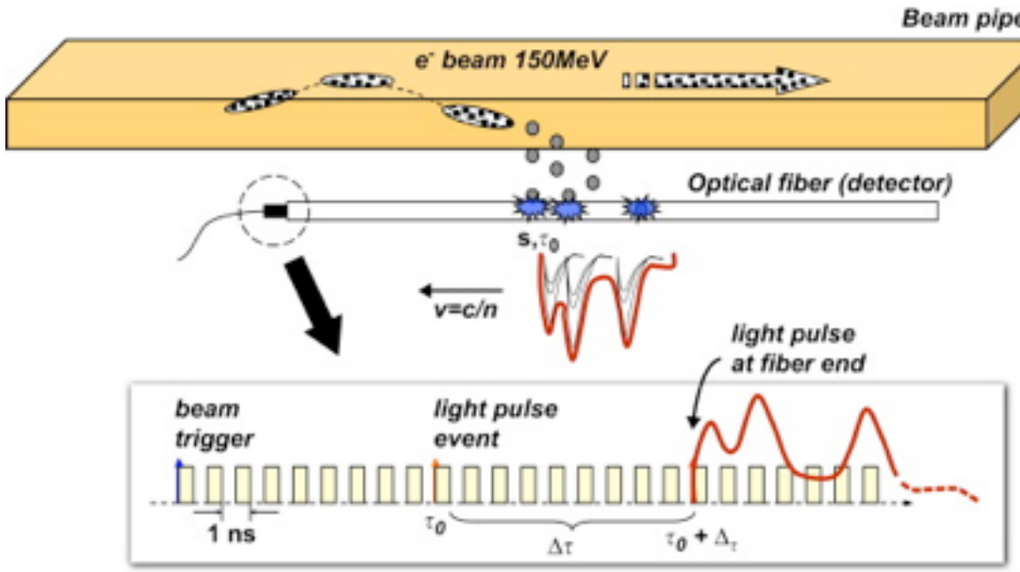


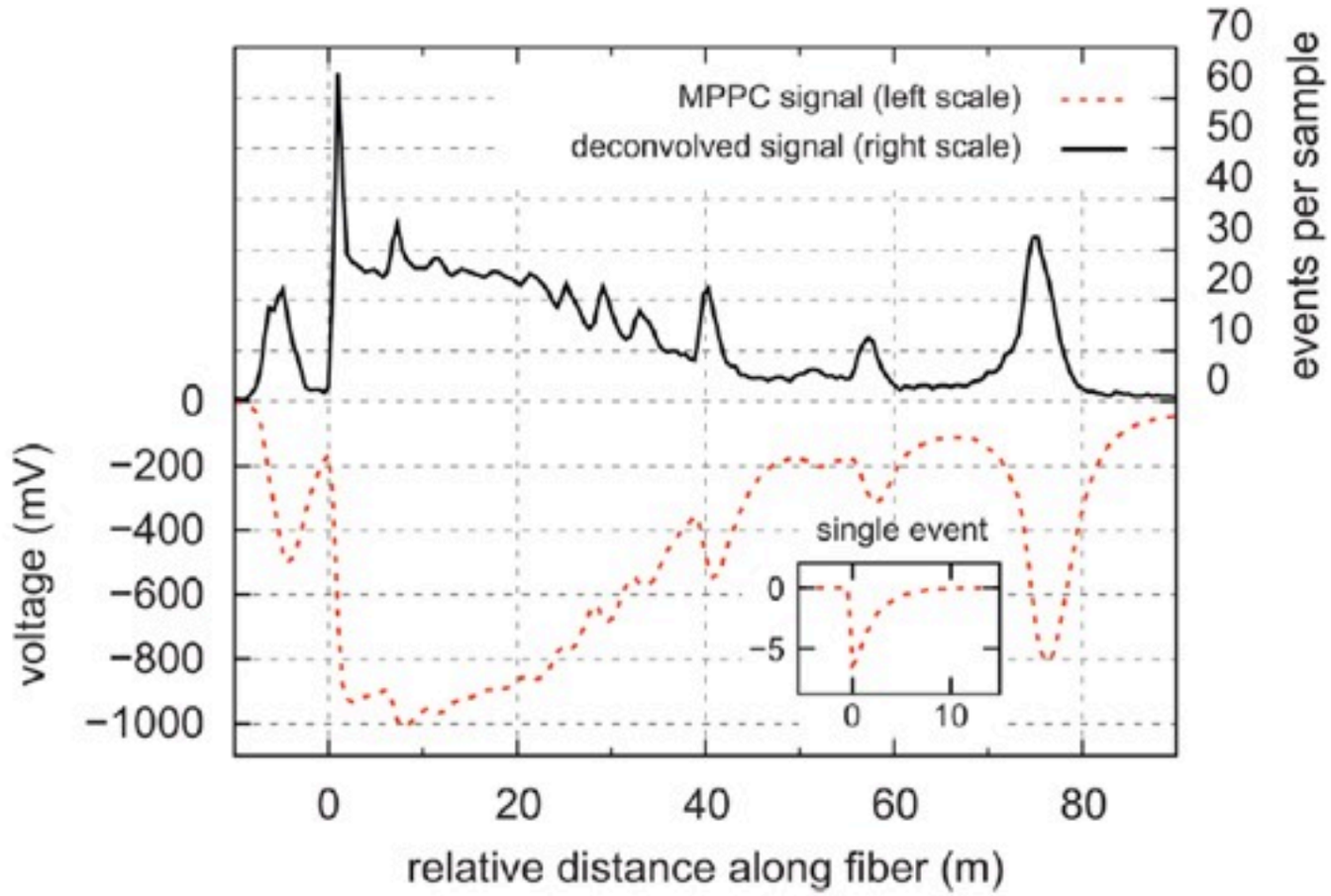
Diagnostics with SiPMs II

"A read-out system for online monitoring of intensity and position of beam losses in electron linacs"
D. di Giaovenale at al. Nucl.Instrum.Meth. Phys.Res.A.665(33–39) (2011),

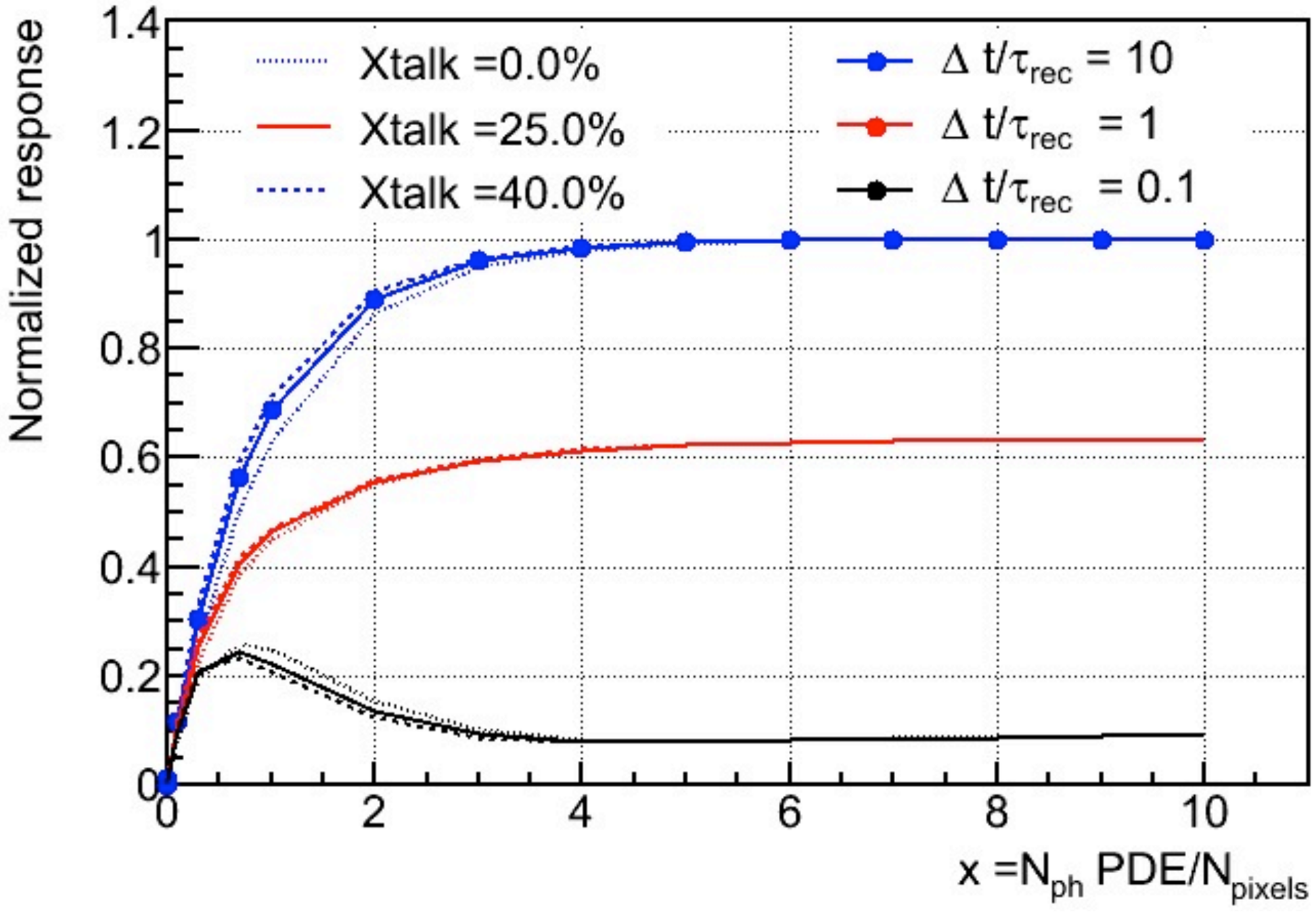
High sensitivity diagnostics

- Exploding TOF to obtain position resolution of beam losses.

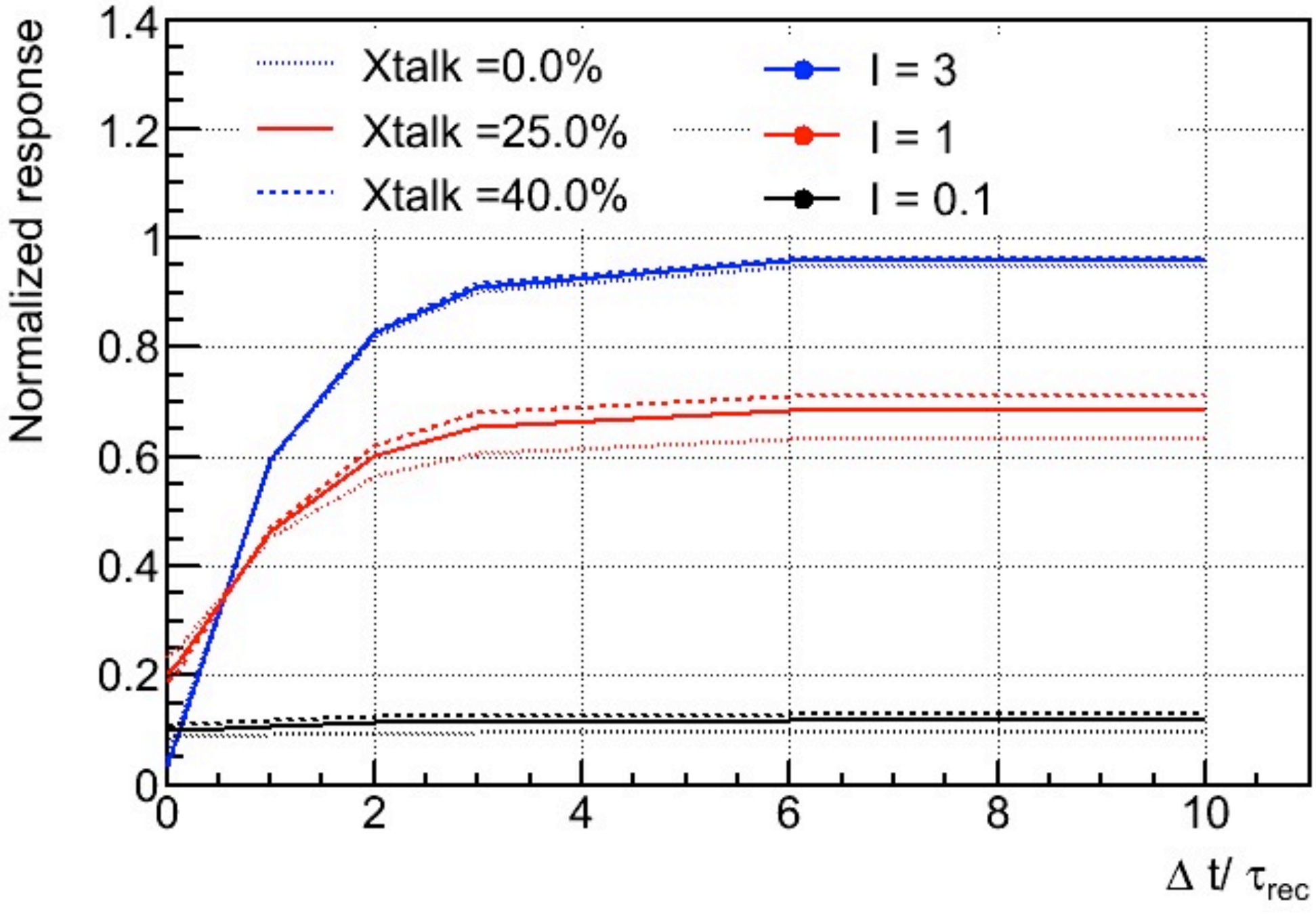




Double pulse model: X-talk



Double pulse model: X-talk



Double pulse model: τ_{rec}

- **N_{pixel}= 3600/ PDE = 0.14/ Xtalk = 0 (I = Nph PDE/N_{pixel})**