P.N.Lebedev Physical Institute of the Russian Academy of Science

UNIVERSITY OF LIVERPOOL

The Cockcroft Institute of Accelerator Science and Technology

SEVENTH FRAMEWORK PROGRAMME

SiPM

cost EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

FAST Fast Advanced Scintillator Timing

SUMMARY:
SiPM nonlinearity and saturation

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On behalf of the topical group:

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Scope & outline

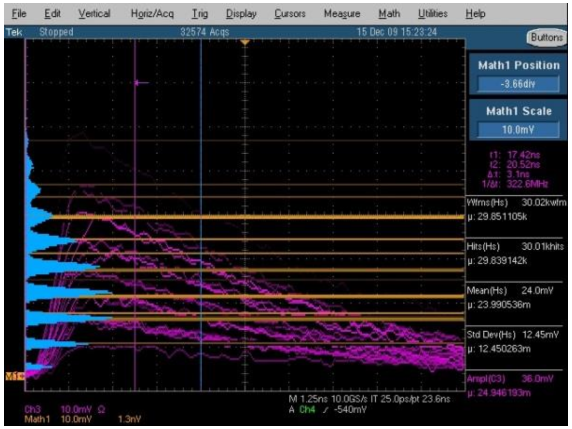
- **Our session – on SiPM nonlinearity and saturation in photon-number-resolving detection**
  - Introduction & summary – Sergey Vinogradov
  - Statistics & models – Sergey Vinogradov
  - Physics & experiments – Elena Popova
  - Methods of measurement and calibration of SiPM
    - Double Light Superposition Method by NDL – Jian Liu
    - Measurement and calibration for particle calorimetry by CALICE – Sascha Krause
- Discussion

- Applications of SiPMs, in general:
  - **Multi-photon pulse detection:**
    - **A) Measure a number of photons (typical figure of merit - photon number /energy resolution) – is in focus of our session**
    - B) Measure a time-of-flight (figure of merit - time resolution)
    - C) A + B (TOF PET, LIDAR…)
    - D) Detection of arbitrary time-varying light signals to measure intensity I(t)

Observable quantities

- SiPM convert photons to electrons (… AQC – electrons to some units, e.g. [V]…)
  - SiPM response charge is the best observable quantity
    - - response amplitude is AQC-dependent (application & user specific)
      - - response shape is weakly dependent on incident light
- Response charge Q is a random quantity (Probability distr., Mean, StdDev)
  - as well as a number of photons Nph (assumed to be Poisson random variable)
- Responsivity (calibration) function is defined for Mean quantities <Q> = f(<Nph>)
- $Responsivity = \frac{<output\ electrons>}{<input\ photons>} \quad R = \frac{<Q>}{<Nph>}$ if Gain is known → $R_{pix} = \frac{<Nfired>}{<Nph>}$

Low Nph



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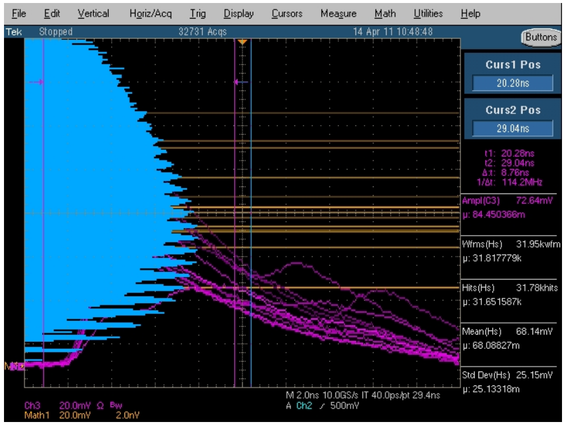
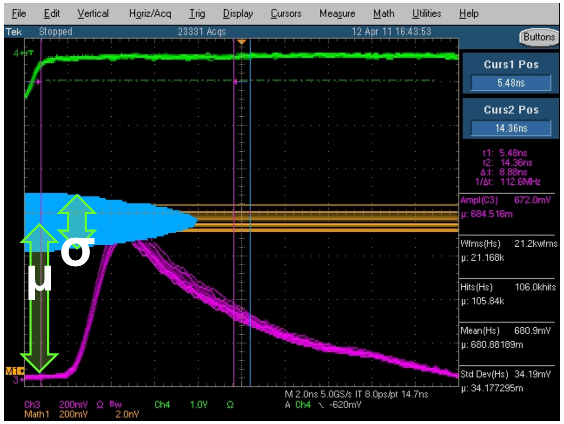
Tek   Stopped   32574 Acqs   15 Dec 09 15:23:24
Math1 Position   -3.66div
Math1 Scale   10.0mV
t1: 17.42ns
t2: 20.52ns
Δt: 3.1ns
1/Δt: 322.6MHz
Wfms(Hs)   30.02kwfm
μ: 29.851105k
Hits(Hs)   30.01khits
μ: 29.839142k
Mean(Hs)   24.0mV
μ: 23.990536m
Std Dev(Hs)   12.45mV
μ: 12.450263m
Ampl(C3)   36.0mV
μ: 24.946193m
M 1.25ns 10.0GS/s IT 25.0ps/pt 23.6ns
A Ch4 ⸝ -540mV
Ch3   10.0mV Ω
Math1   10.0mV   1.3nV
```

Moderate



```
Tek   Stopped   32731 Acqs   14 Apr 11 10:48:48
Curs1 Pos   20.28ns
Curs2 Pos   29.04ns
t1: 20.28ns
t2: 29.04ns
Δt: 8.76ns
1/Δt: 114.2MHz
Ampl(C3)   72.64mV
μ: 84.450366m
Wfms(Hs)   31.95kwfm
μ: 31.817779k
Hits(Hs)   31.78khits
μ: 31.651587k
Mean(Hs)   68.14mV
μ: 68.08827m
Std Dev(Hs)   25.15mV
μ: 25.13318m
M 2.0ns 10.0GS/s IT 40.0ps/pt 29.4ns
A Ch2 ⸝ 500mV
Ch3   20.0mV Ω Bw
Math1   20.0mV   2.0nV
```

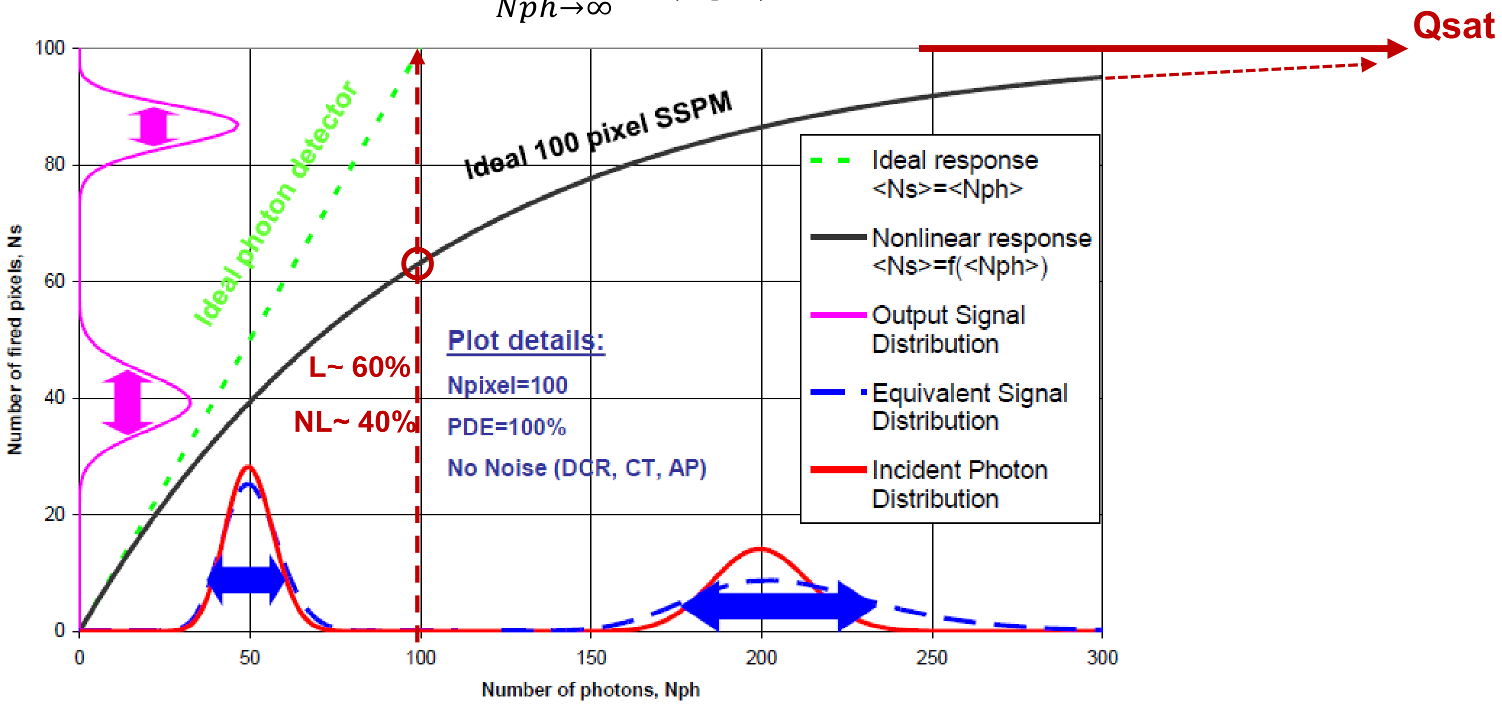
High



```
Tek   Stopped   23331 Acqs   12 Apr 11 16:43:53
Curs1 Pos   5.48ns
Curs2 Pos   14.36ns
t1: 5.48ns
t2: 14.36ns
Δt: 8.88ns
1/Δt: 112.6MHz
Ampl(C3)   672.0mV
μ: 684.516m
Wfms(Hs)   21.2kwfms
μ: 21.168k
Hits(Hs)   106.0khits
μ: 105.84k
Mean(Hs)   680.9mV
μ: 680.88189m
Std Dev(Hs)   34.19mV
μ: 34.177295m
M 2.0ns 5.0GS/s IT 8.0ps/pt 14.7ns
A Ch4 ⸜ -620mV
Ch3   200mV Ω Bw   Ch4   1.0V   Ω
Math1   200mV   2.0nV
```

Definitions

- *"Ideal" linearity:* $R = \frac{<Q>}{<Nph>} = const$ *for any <Nph>*
- *Linearity L:* $L = \frac{Rmin}{Rmax}$ *for <Nph> = Nmin … Nmax*
- *NonLinearity NL:* $NL = 1 - L = \frac{\Delta R}{Rmax}$ *where Rmax ~ linear responsivity*
- *Dynamic range DR:* $DR = \frac{Nmax}{Nmin}$ *for given L*
- *Nmin by threshold:* *SNR(Nmin)=1* *Nmax by some L (say, 90%; NL=10%)*
- *Saturation Qsat:* $Qsat = \lim_{Nph \to \infty} (Q(Nph))$ *! TBD for oversaturation !*

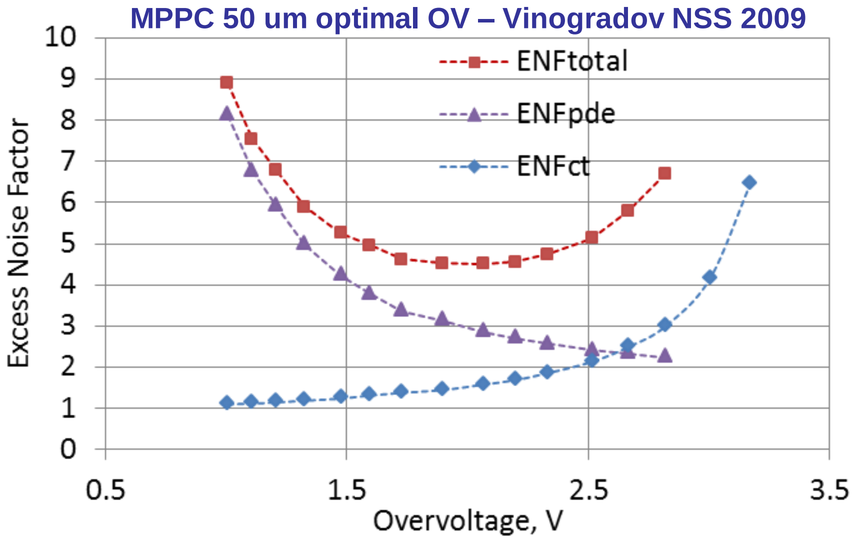


Characterization of nonlinearity

- Full: by Probability distr. Pr(Q | Nph, pulse shape(t), λ, Ubias, T…)
- Short: by 1st and 2nd statistical moments of Q
  - Mean_Q vs Nph – <u>calibration curve</u>
  - StdDev_Q vs Nph – calibration error
  - StdDev_Q/Mean_Q (in Nph scale) vs Nph – calibrated resolution
- How to define "standard" condition of measurements?
  - Light pulse: shape, duration, wavelength
  - SiPM: bias voltage, temperature
  - SiPM + Light: <u>uniformity over active area, light on peripheral area</u>
- If we can't define that, the calibration becomes
  - Multi-parametric function – in general
  - Application-specific – in particular
- How to resolve or balance out the trade-off?

Standardization of characterization

- Pulse shape and duration could be fixed to two distinct cases:
  - A) Short ~ sub-ns (<< recovery time) / shape is out of spec
  - B) Long ~ µs…ms (>> recovery time) / CW light on/off
- Wavelength-related variability could be eliminated:
  - Nonlinear effects are determined by Npe/cell; Npe is an invariant input
  - Linear range: Npe = PDE(λ)·Nph; (correlated events to be accounted)
  - Calibration in Npe @ known PDE(λ) (vendor spec; more at PDE session)
- Bias voltage should be fixed at optimal value for linear range
  - Linear range: Min ENF_total or max DQE vs Ubias (see my talk on Noise and ENF, 13/06/2018)
- T → room temperature… some other?
- Something missed?


MPPC 50 um optimal OV – Vinogradov NSS 2009

Methodical issues

- Dynamic range > 10^6 : (e.g. MAPD of 40K cells/mm^2, 3x3mm^2)
  - Light sources (… filters?)
  - Reference photodetectors (SPAD … PIN diode?)
  - Acquisition electronics (… direct coupling to scope/HDR digitizer?)
- Spatial effects
  - Uniformity of illumination over active area (%?)
  - Light on peripheral area – collection of extra Npe (%?)
  - Low-gain at periphery with low E-field regions (Gain ~ 1000 @Ubias=Ubd)
- Load-dependent effects
  - Thermal – overheating of SiPM – dependent on heat dissipation/casing
  - Voltage drop – under-biasing of SiPM – dependent on quenching and external circuitry resistors
- Something missed?
- Welcome to the brave new world of high light and nonlinearity!

The end

Thank you for your attention!

Questions?
Objections?
Opinions?
…

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