Deep Diffused Avalanche Photodiodes for Charged Particle Timing

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Motivation: Minimum Ionizing Particle Timing

- Tracking
- Calorimetry
- PID

**Counteract HL-LHC pile-up**

200 p-p collisions per bunch crossing

collisions time spread \( \approx 180 \) ps

time resolution on track \( \approx 30 \) ps

\( \Rightarrow \) disentangle primary collisions

- Different devices: silicon detectors, gas detectors, etc.
- Many active groups

HL-LHC: With the current vertex resolution a significant fraction of the vertices will not be resolved

Technical proposals for MIP timing detectors: ATLAS collaboration, CMS collaboration
Deep Diffused Avalanche Photo Detectors

- Charge multiplication
- Gain: $\approx 500$
- Bias: $\approx 1800$ V
- Never fully depleted
- Die dimensions: $2.8 \times 2.8$ mm$^2$ and $10 \times 10$ mm$^2$
- Nominal active area: $2 \times 2$ mm$^2$ and $8 \times 8$ mm$^2$
- Thickness: $230 – 280$ $\mu$m
- Custom fabrication process
- Produced by Radiation Monitoring Devices (RMD)

Diffusion (non-depleted Si)
- Drift (depleted Si)
- Multiplication

Deep Diffused Avalanche Photo Detectors

Doping profile

- Maximum of electric field at pn-junction
- Field exceeds 200 kV/cm enabling impact ionization


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DD APDs for Charged Particle Timing
Radiation Hardness Study Using $2 \times 2 \text{mm}^2$ APDs
Packaged
Irradiated in Ljubljana (reactor neutrons)
Characterized using a pulsed infrared laser
$\Phi_{eq} = 0, \ 3 \cdot 10^{13}, \ 6 \cdot 10^{13}, \ 3 \cdot 10^{14}, \ 10^{15} \text{ cm}^{-2}$
Annealing of $\approx 70 \text{ min @ 21}^\circ \text{C}$
Sensor irradiated to $\Phi_{eq} = 3 \cdot 10^{14} \text{ cm}^{-2}$ is quite unstable
N-irradiated $2 \times 2$ mm$^2$ APDs, $-20^\circ$C

- Increase with irradiation
- Change of shape

The gain is reduced by irradiation

- Decrease with irradiation
- $\Phi_{eq} = 10^{15}$ cm$^{-2}$: little to no gain
N-irradiated 2 × 2 mm$^2$ APDs, −20°C, IR Laser, 0.8 MIPs

Jitter vs Bias Voltage

- $\Phi_{eq} \leq 6 \cdot 10^{13}$ cm$^{-2}$: jitter of 8 - 10 ps
- $\Phi_{eq} = 10^{15}$ cm$^{-2}$: low SNR
  Jitter $\approx 0.5$ ns

**Time resolution maintained at least up to** $\Phi_{eq} = 6 \cdot 10^{13}$ cm$^{-2}$, higher bias required

**Radiation hardness estimated to be** $\Phi_{eq} \approx 10^{14}$ cm$^{-2}$
Beam Test of $8 \times 8$ mm$^2$ APDs
Acknowledgments
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* RD51 website
1 CERN, Switzerland
2 Synchrotron SOLEIL, France
3 CEA Saclay, France
4 HIP, Finland
**8 × 8 mm² APDs**

Uniformity of response improved through metallization or mesh readout

**DC coupled readout**
- Aluminum deposited on both sides
- Metallization on single dies at CMi-EPFL

**AC coupled readout**
- Mesh on Kapton layer
- Sintered gold on back side
- Studied in previous beam tests ($\sigma_{\Delta t} = 19$ ps)
  S. White, CHEF 2013
  J. Va’vra, NIMA 876 (2017) 185-193
Today’s Data

- 2 metallized $8 \times 8 \text{ mm}^2$ APDs
- 1775 V
- Room temperature

1\textsuperscript{st} run:
- Full sensor illumination
- Homogeneity, efficiency, time resolution

2\textsuperscript{nd} run:
- Incomplete sensor illumination
- Higher statistics on detector
- Detailed homogeneity study
Beam Test Setup

- 100 GeV $\mu$, CERN North Area, H4 beamline
- Amplifier: CIVIDEC 2 GHz 40 dB
- Oscilloscope: Agilent 2.5 GHz 10 Gs/s
- Readout configuration not optimal for timing (due to mechanical constraints)
- Tracking and timing provided by RD51
- MCP-PMT signal shaped to have a few points on leading edge
MCP-PMT Time Reference, 100 GeV \( \mu \)

Median Amplitude

20 to 80% Risetime (within geom. cuts)

- Higher signal toward detector center
- Coverage of photocathode with Č light

L. Sohl, NIMA (2018)

- Average 190 ps
- Values outside peak: few points on leading edge

Time resolution better than APDs
MCP-PMT Time Reference, 100 GeV $\mu$

Higher signal toward detector center

Coverage of photocathode with Č light
L. Sohl, NIMA (2018)

20 to 80% Risetime (within geom. cuts)

- Average 190 ps
- Values outside peak: few points on leading edge

Time resolution better than APDs
Metallized $8 \times 8$ mm$^2$ APD, 1775 V, 100 GeV $\mu$

Median Amplitude

Section Y (between vertical lines)

Section X (between horizontal lines)

Red points: Median amplitude, excluding events below threshold or saturating the scope scale

Amplitude uniform over the detector
Metallized 8 × 8 mm² APD, 1775 V, 100 GeV μ

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Metallized $8 \times 8 \text{ mm}^2$ APD, 1775 V, 100 GeV $\mu$

Detection Efficiency

\[
\text{Efficiency} = \frac{\text{Number of events above threshold}}{\text{Number of tracks}}
\]

Threshold = 30 mV

Detection efficiency above 99%
Metallized $8 \times 8$ mm$^2$ APD, 1775 V, 100 GeV $\mu$

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Metallized 8 × 8 mm² APD, 1775 V, 100 GeV μ

20 to 80% Risetime

Section X (between horizontal lines)

Red points: Average risetime
- Longer risetimes at detector edges
- Most probable value: ≈ 600 ps
- Tail in distribution to be understood

Risetime uniform over the detector
Metallized 8 × 8 mm² APD, 1775 V, 100 GeV μ

20 to 80% Risetime

Section X (between horizontal lines)

Distribution (within geom. cuts)

Red points: Average risetime

- Longer risetimes at detector edges
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Risetime uniform over the detector
Metallized 8 × 8 mm² APD, 1775 V, 100 GeV µ

Time of arrival $\Delta t$

**Distribution (within geom. cuts)**

- $\chi^2 / \text{ndf} = 92.58 / 37$
- Constant: $138.4 \pm 5.7$
- Mean: $3.975 \times 10^{-9} \pm 1.311 \times 10^{-12}$
- Sigma: $4.38 \times 10^{-11} \pm 1.24 \times 10^{-12}$

- Red points: Average $\Delta t$
  - Algorithm: CFD, 2 pt interpolation
  - Uniform over the detector
  - Tails at detector edges

Time resolution of $44 \pm 1 \text{ ps}$
over a 8 × 8 mm² detector
Metallized $8 \times 8$ mm$^2$ APD, 1775 V, 100 GeV $\mu$

**Time of arrival $\Delta t$**

Section X (between horizontal lines)

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**Time resolution of $44 \pm 1$ ps**

over a $8 \times 8$ mm$^2$ detector

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DD APDs for Charged Particle Timing

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Homogeneity study (Different sensor)

**Δt Section on X** (between horizontal lines)

**APD metallized, mean Δt, 1775 V**

Mean Δt CFD Ch1 - Ch4 plane Ch1 ampli cut for both Ch

Red points: Average Δt

- CFD, 2 pt interpolation

Region of broader Δt at detector center

**Std. Dev. of Δt (not a fit)**

Std Dev Δt CFD Ch1 - Ch4 vs plane Ch1 X, y slices and amplitude cuts fulfilled for both Ch

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DD APDs for Charged Particle Timing
Homogeneity study (Different sensor)

Mean $\Delta t$ vs $X$ for one bin [25.5,26] mm

- Different $\Delta t$ at detector center
- Std. dev. is similar to the rest of the detector
- Position corresponds to the hole in the metallization of p-side

Remedy: change metallization pattern

Mean $\Delta t$ (zoomed Z to see effect)

- Mean $\Delta t$ CFD Ch1 - Ch4 plane Ch1 ampli cut for both Ch

Std. Dev. $\Delta t$ vs $X$ for one bin (no fit)
Homogeneity study (Different sensor)

Mean $\Delta t$ vs $X$ for one bin [25.5, 26] mm

- Different $\Delta t$ at detector center
- Std. dev. is similar to the rest of the detector
- Position corresponds to the hole in the metallization of p-side

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Homogeneity study (Different sensor)

Mean $\Delta t$ vs $X$ for one bin [25.5,26] mm

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Remedy: change metallization pattern
Summary

Radiation Hardness Study Using 2 × 2 mm² APDs

- Radiation effects studied using a pulsed IR laser
- Jitter \( \leq 10 \text{ ps} \) maintained until at least \( \Phi_{eq} = 6 \cdot 10^{13} \text{ cm}^{-2} \)
- Detectors expected to work until \( \Phi_{eq} \approx 10^{14} \text{ cm}^{-2} \)

Beam Test of 8 × 8 mm² APDs

- Today’s data from two metallized APDs
- Uniform response with efficiency > 99%
- Time resolution for metallized APD is 44 ps at 1775 V
- Readout scheme not optimal at beam test \( \Rightarrow \) better performance expected

Future studies

- Improve readout scheme and perform timing measurements using a radioactive source
- Study stability of metallized APDs
Backup Material
Timing

\[ \Delta t = t_2 - t_1 \quad \sigma_{\Delta t}^2 = \sigma_{t_1}^2 + \sigma_{t_2}^2 \quad \sigma_t^2 = \sigma_J^2 + \sigma_{TW}^2 + \ldots \]

Jitter

The noise influences the time at which the threshold is crossed

\[ \sigma_J = \sigma_n / \frac{dV}{dt} \propto \frac{t_{\text{rise}}}{\text{SNR}} \]

Countermeasures:
- Reduce rise time
- Improve noise figure

Time walk

Variations in the amplitude influence the time at which the threshold is crossed

Countermeasures:
- Algorithm e.g. CFD
Timing

2pt interpolation

Constant Fraction Discrimination

20-80% Rise time

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DD APDs for Charged Particle Timing
MCP-PMT Signal Map

Sketches from L. Sohl contribution at the 14th Pisa Meeting on Advanced Detectors (2018)

https://agenda.infn.it/event/17834/contributions/83549/

This work
APD Section (Not to Scale)
Beam Test Setup

- Sensor box placed downstream first tracking GEM
- Coating on detectors and PCBs to reduce discharges
- Amplifiers: CIVIDEC 2 GHz, 40 dB
- Data acquisition: Agilent 2.5 GHz, 10 Gs/s
  - Ch1: APD
  - Ch2: APD
  - Ch3: Telescope bit pattern (Trigger)
  - Ch4: MCP-PMT
- Temperature, bias, and current logged
  - MCP-PMT readout and shaping

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Analysis:

- Extract signal properties (ampli, risetime, tCFD, ....)
- The signal is selected in a window around the peak
- Points preceding the selection are used for baseline
- The leading edge is isolated to extract risetime and tCFD
- The tracking info is extrapolated to each plane
- Only events with one track are used