Spatial and temporal correlations in undulator radiation

EVAN ANGELICO, FAST/IOTA Collaboration Meeting, June 16, 2020

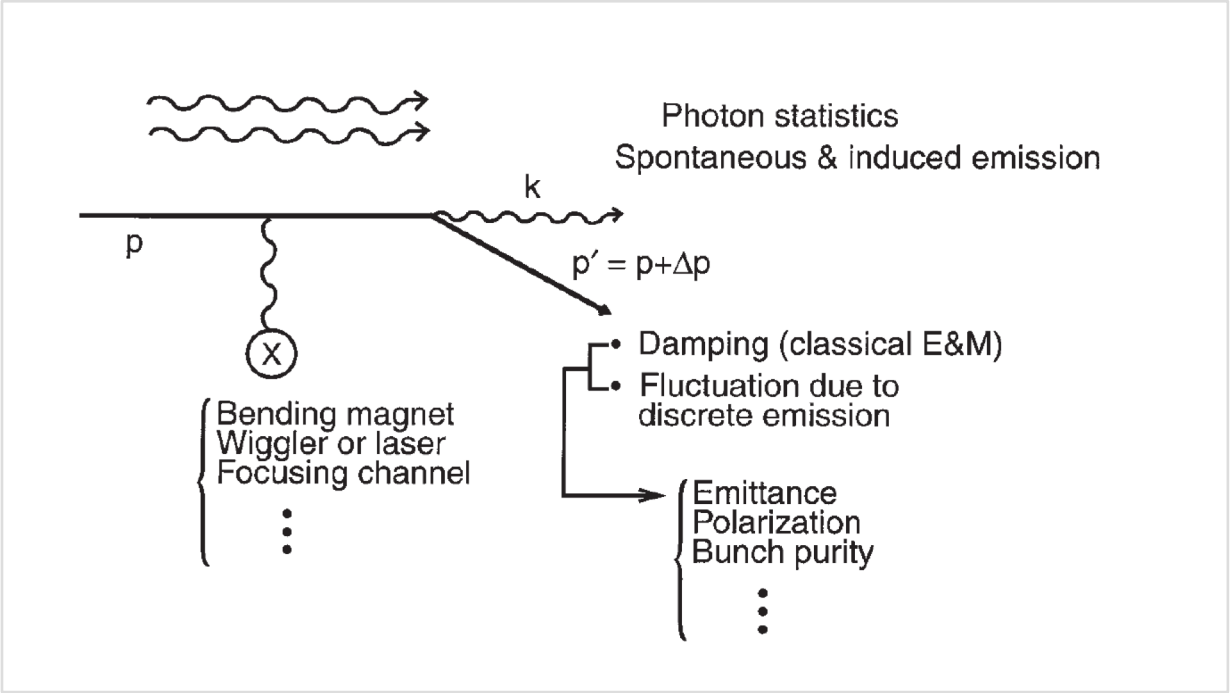
Outline

- What we can learn from scrutinizing single electrons passing through an undulator
- How to analyze single photons using micro-channel plate photomultipliers
- The AMPUR experiment at IOTA, phase 0 preliminary results
- Outlook for a phase 1 with a Large Area Picosecond Photodetector (LAPPD)

Quantum-optical properties of undulator radiation

Great reviews by Kwang-Je Kim and others, for example https://doi.org/10.1103/PhysRevSTAB.10.034801
Also Kwang-Je Kim, Quantum Fluctuations in Beam Dynamics, LS-271 ICFA 1998

Figure 1 from above: quantum recoils



Dynamics of extremely high brightness beams may become sensitive to quantum recoils and wavefunction degeneracy – Summarized from K.J. Kim

We should measure the properties of photons from a single electron as best as we can to gain a practical understanding of quantum effects

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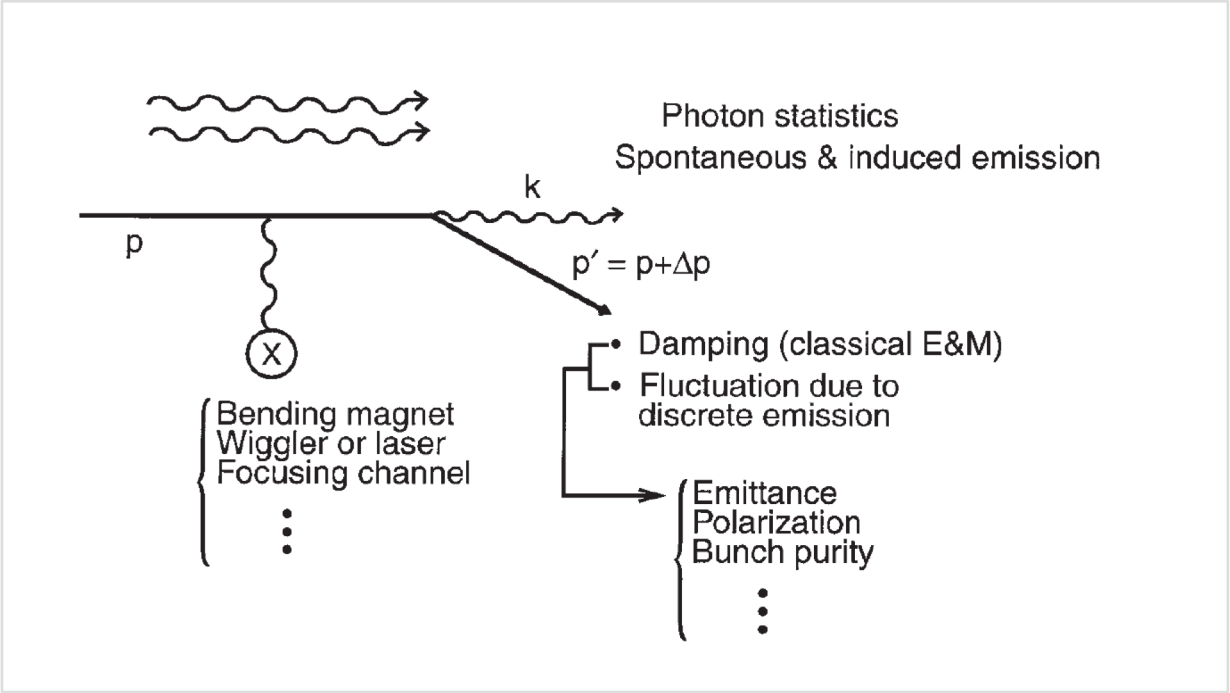

Measure the properties of undulator radiation

Will simultaneously be developing instrumentation useful for optical stochastic cooling (OSC)

A place for possible quantum-classical discrepancy

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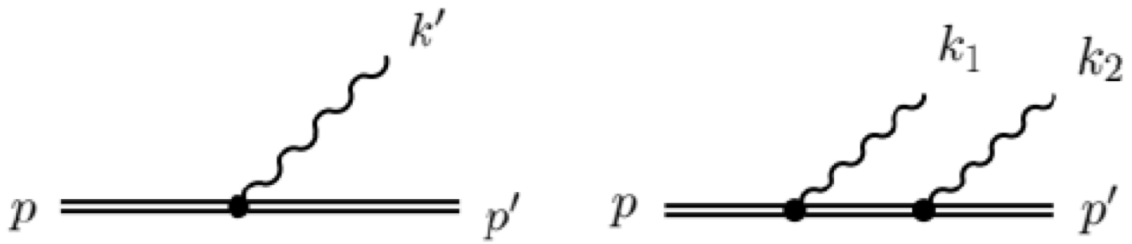
Feynman diagrams from Ihar Lobach's talk 2018, Single-electron experiments in IOTA



- Two photons emitted from single electron passing through undulator
- Theoretically, photons / interactions are uncorrelated and not entangled
  - Assumes small recoils of electron
  - Assumptions about electron wavefunction "size" and spin

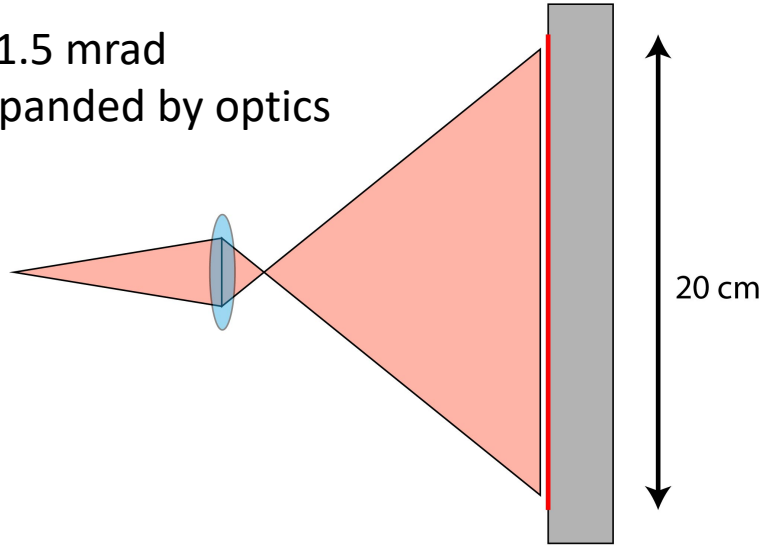
Should scrutinize these photons, are assumptions correct and extrapolate to high intensity

Angular correlation measurement

- Any correlations in 2-photon emission would also indicate energy correlation

$$\frac{\Delta\lambda}{\lambda_m} = \frac{\gamma^2}{1 + K^2/2}\theta^2$$

In 100 MeV IOTA, 1.5 mrad undulator cone expanded by optics



Angular correlation resolution goes like
(position resolution)/(radius of undulator cone at detector surface)

Sensitively coupled to #-of-channels, active area, dark-noise …

Can be expanded by optics

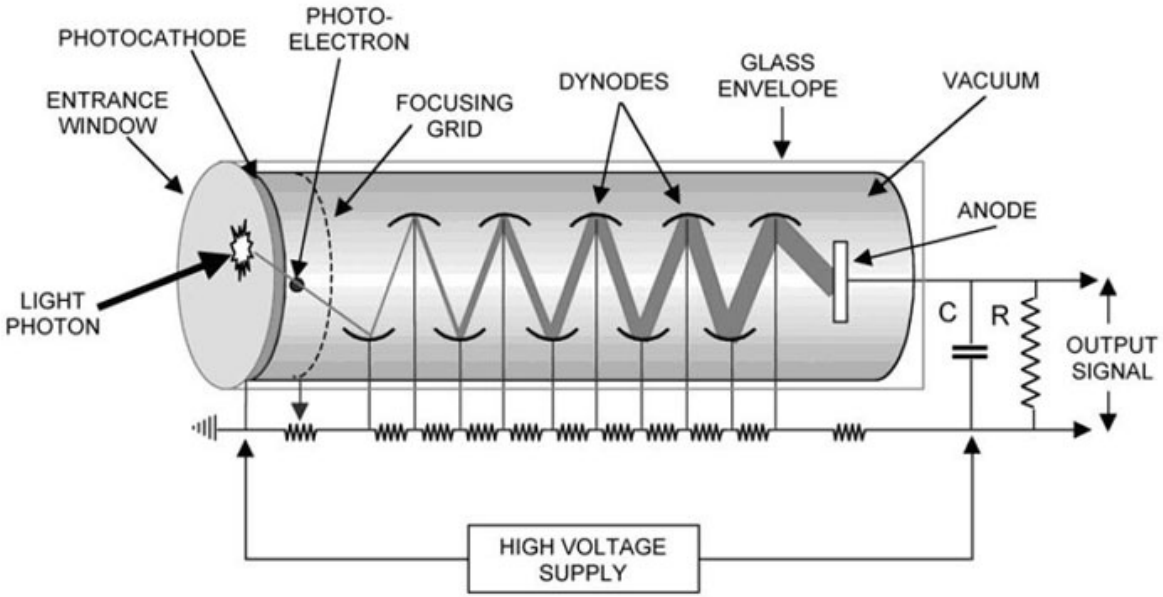
Angular Measurement of Photons from Undulator Radiation (AMPUR) in IOTA's Single Electron Mode

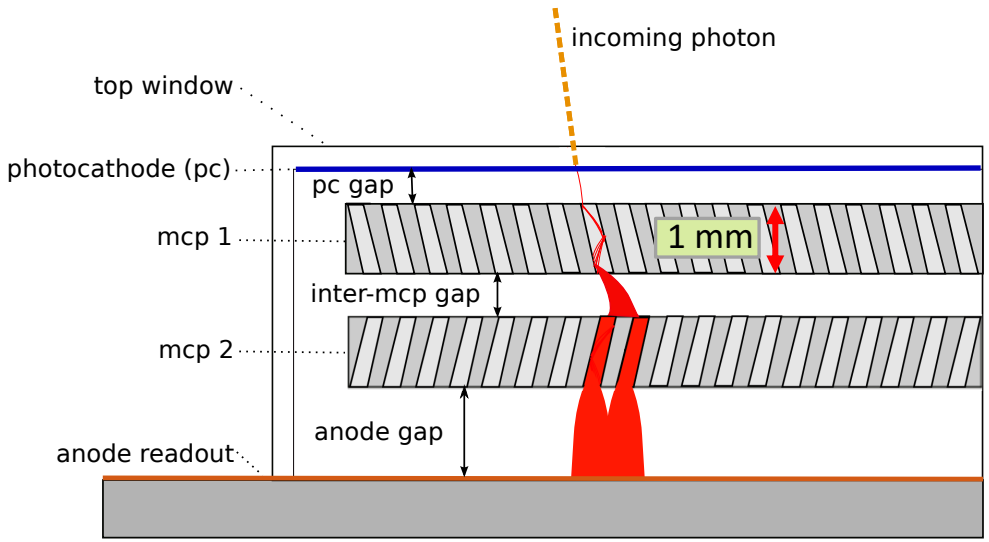
Proposal can be found: https://cdcvs.fnal.gov/redmine/projects/ampur/repository

I. PERSONNEL

- *Principal Investigator*: Evan Angelico, University of Chicago, PhD Student: experiment design, detector testing and setup, data acquisition, data analysis
- *Co-Principal Investigator*: Sergei Nagaitsev, Fermilab, Head of Accelerator Science Programs: experiment design, funding
- Ihar Lobach, University of Chicago, PhD Student: theory and modeling, apparatus design, data taking, data analysis
- Giulio Stancari, Fermilab, Senior Scientist: experiment design, detector setup, signal processing, data analysis

Micro-channel plate (MCP)-PMTs





Vanilla photo-multiplier tube (PMT):

- **Single pixel, one channel (area = pos. resol.)**

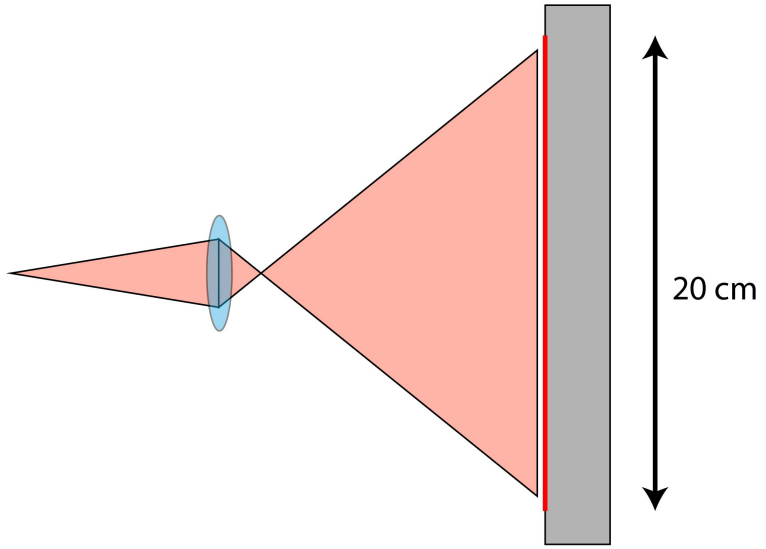
MCP-PMT:

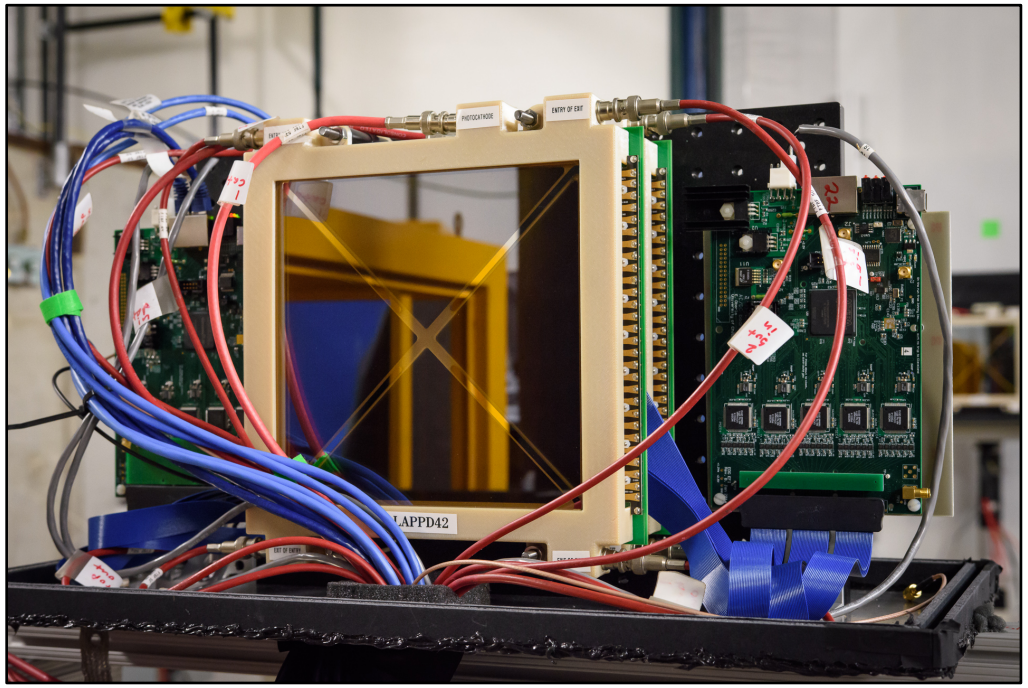
- 10-100 ps timing resolution
- **Many channels, continuous pos. res.**

1 mm spatial resolution over 100s of square cm is typical for MCP-PMTs, single-photon detectors

Angular correlation measurement with LAPPD

Large Area Picosecond Photodetectors (LAPPDs) being used now at the **Fermilab Test-Beam and ANNIE experiment at Fermilab**

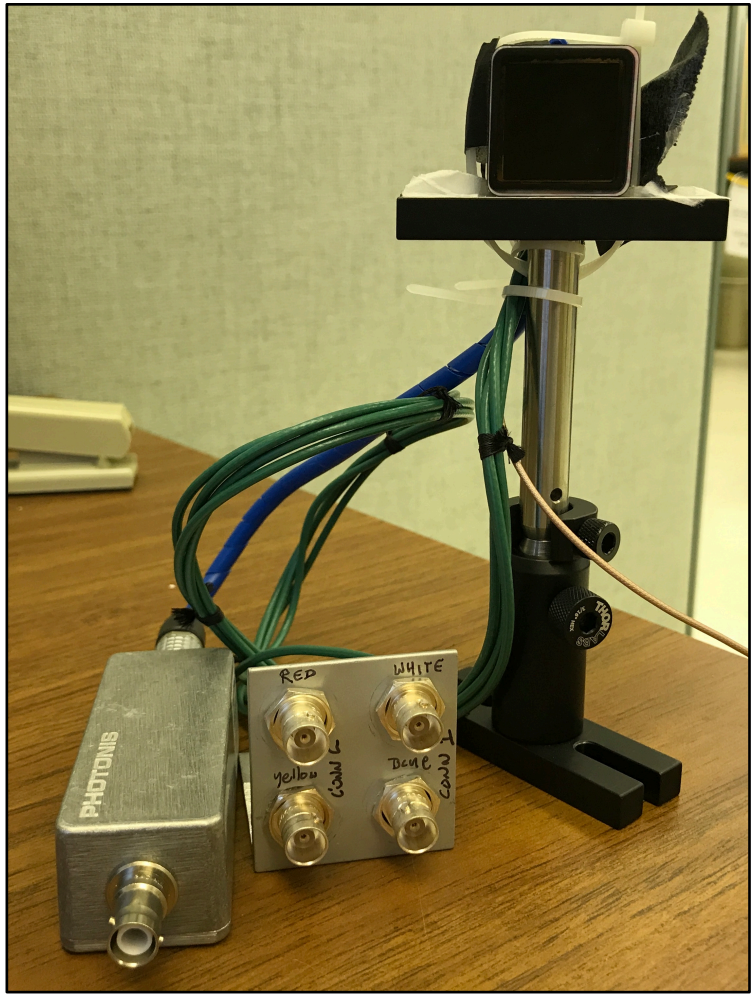




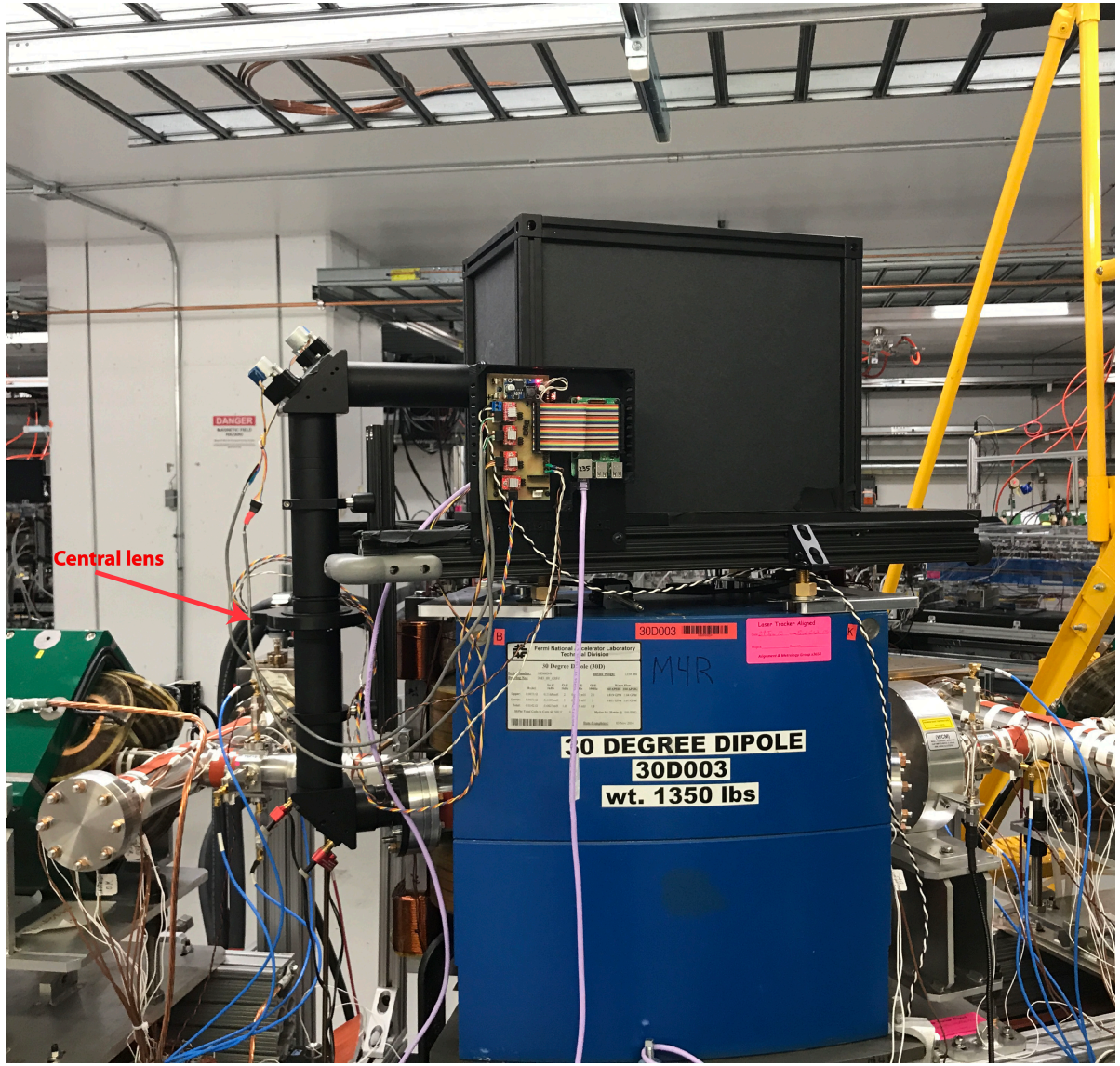
about 15 micro-rad sensitivity

(1) large area, (2) low channel count per area, (3) mm spatial resolution over that area, (4) can select events with 1 vs 2 photons

First phase measurement has been made in IOTA

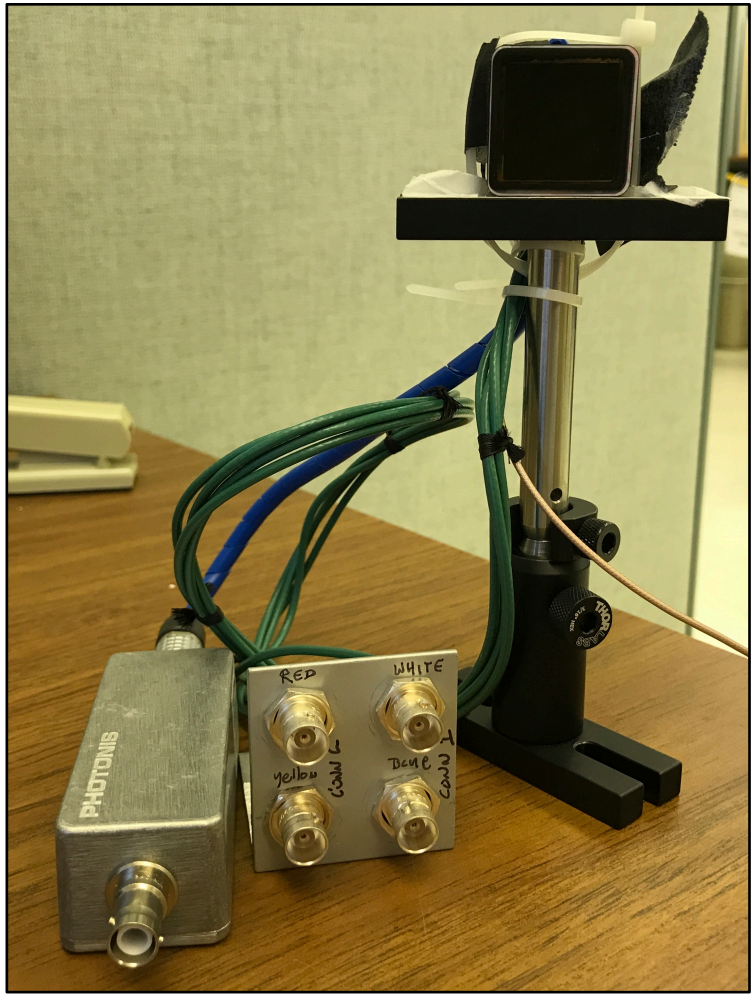


2 cm Planacon



Undulator radiation

First phase measurement has been made in IOTA



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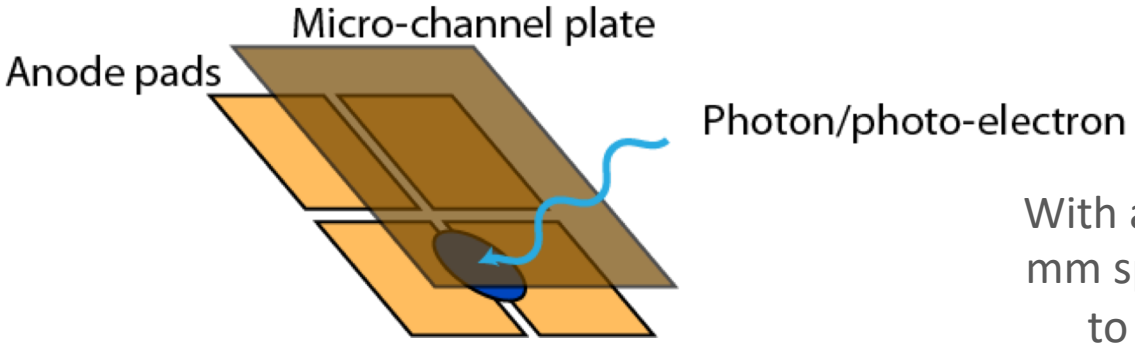
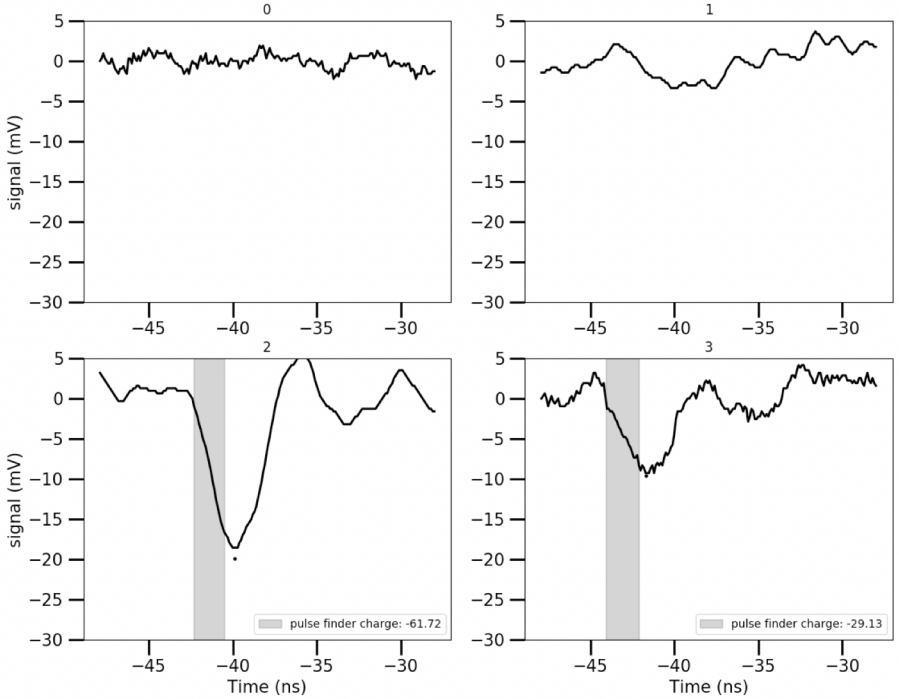




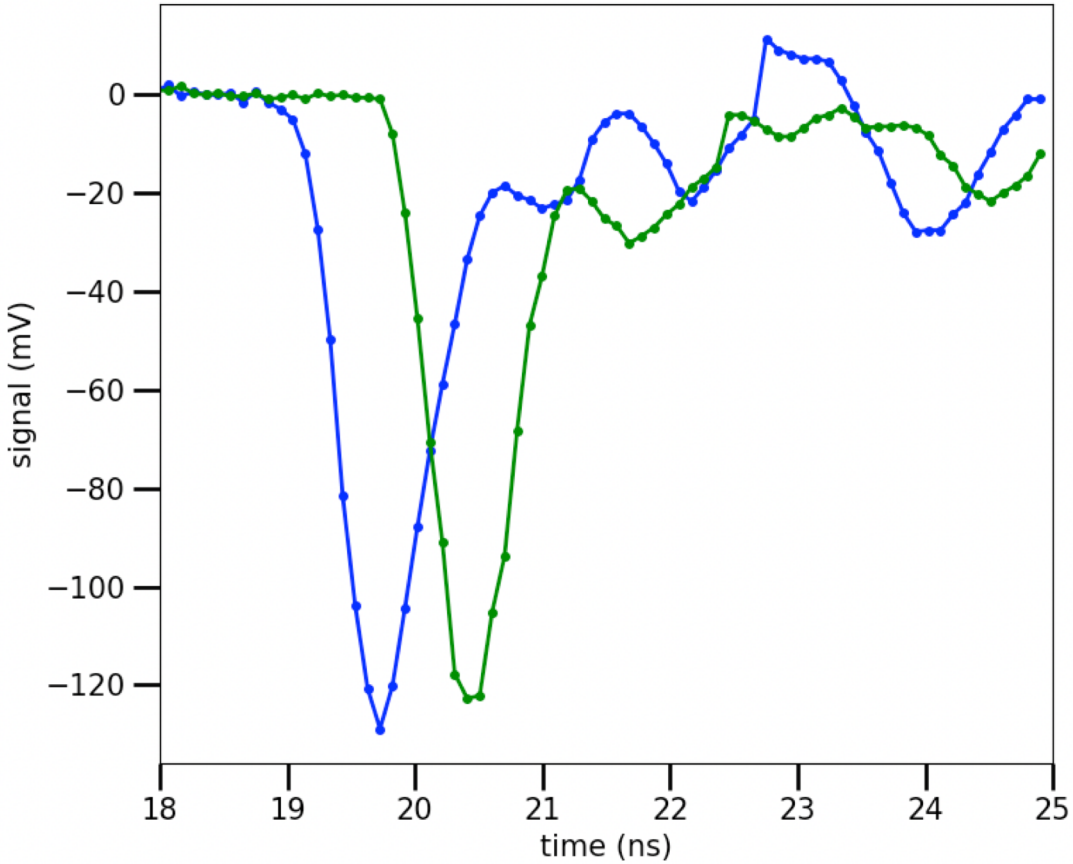
With a good calibration, 1-3 mm spatial resolution leads to 300-850 micro-rad angular resolution

$$r_{\text{reco}} = \frac{1}{\sum_i q_i} \sum_i q_i r_i$$

What do signals look like?

Strip-line anode captures and shares MCP charge

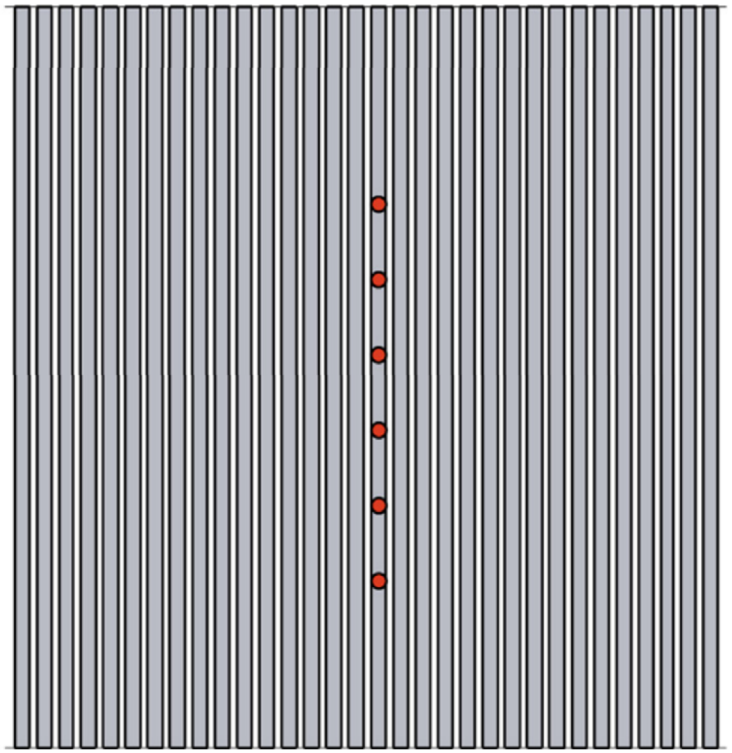
Example LAPPD pulse

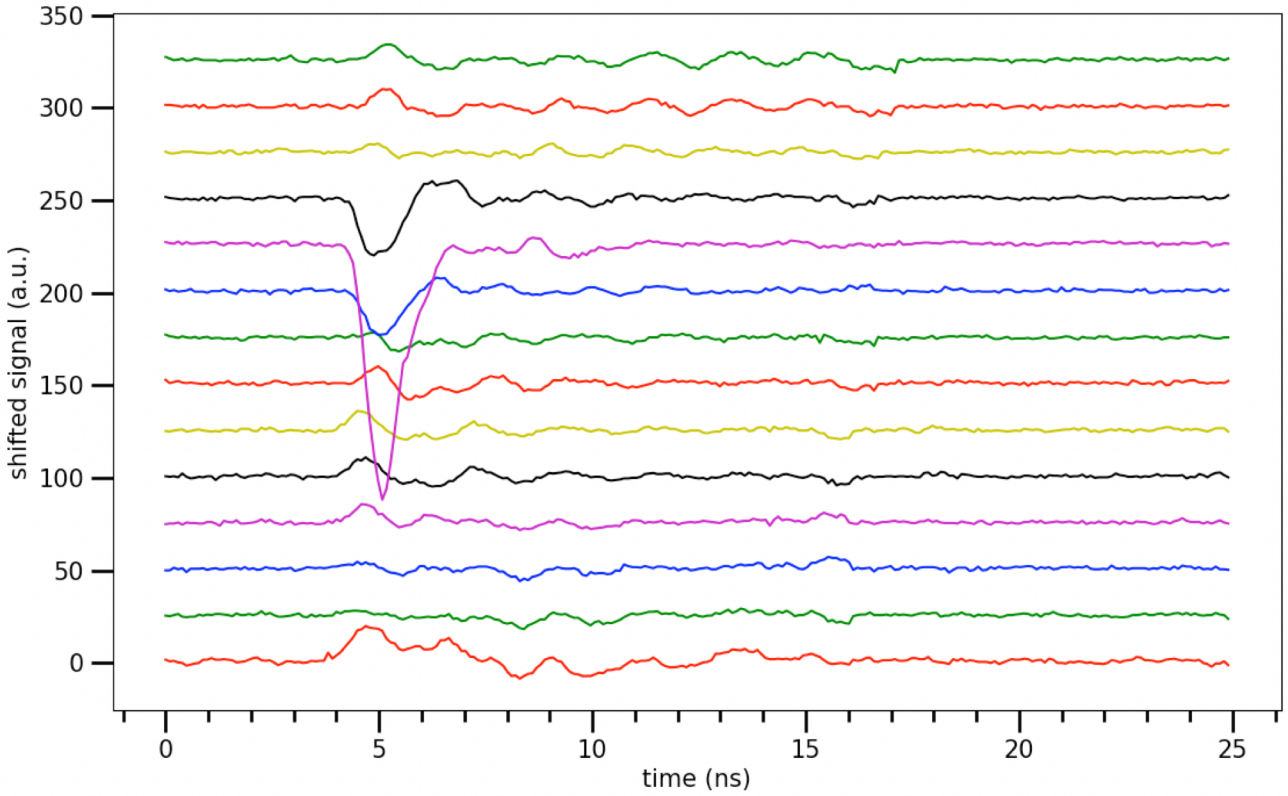


Leading edge, about 750 ps
Width about 1-2 ns

Strip-line anode, basic reconstruction principle

Adams et al: https://doi.org/10.1016/j.nima.2015.05.027 on timing properties using these anodes in LAPPDs



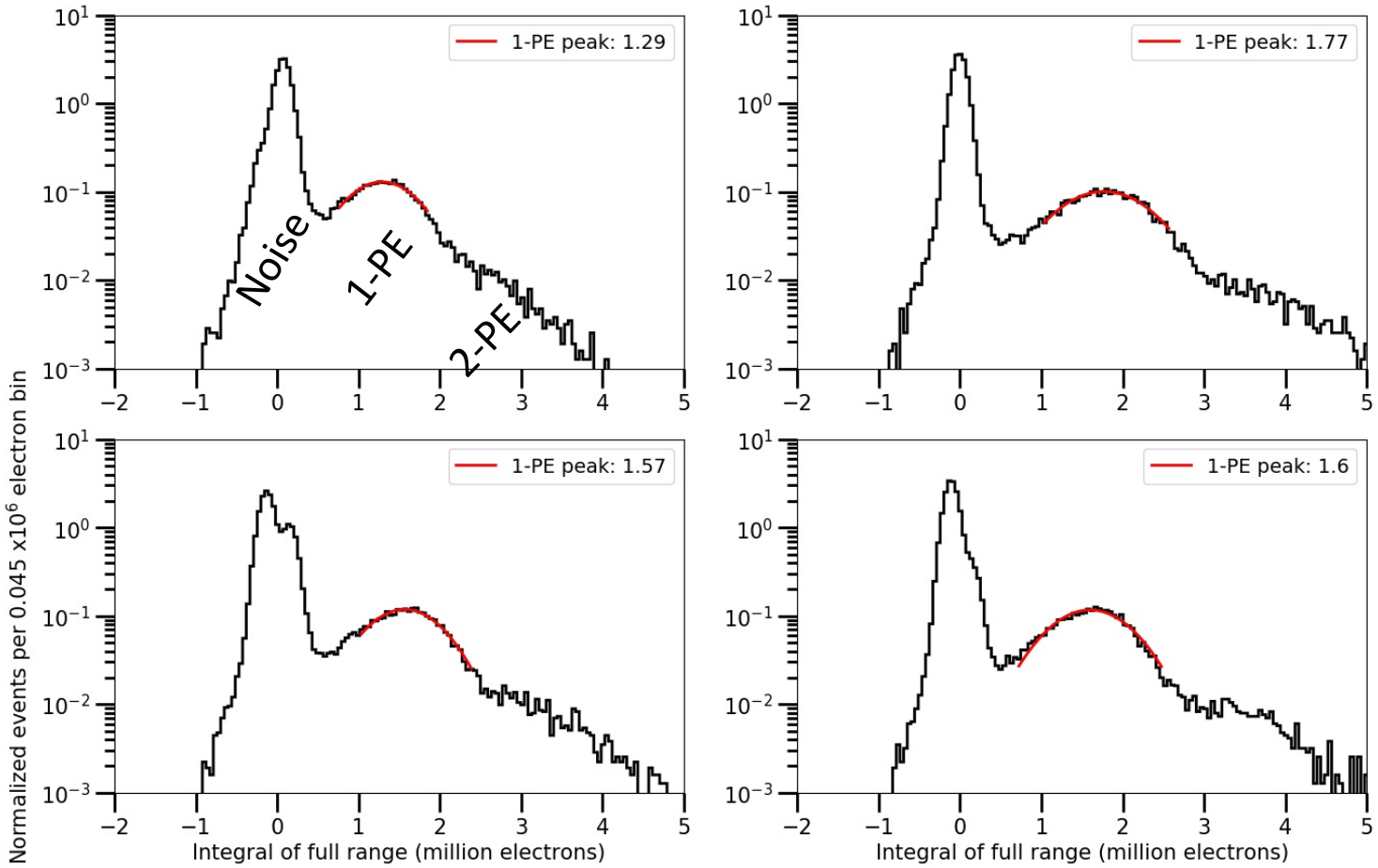


Position reconstruction transverse to strips:

charge is shared, compare amplitudes on neighboring strips (centroid) = ~1 mm or less

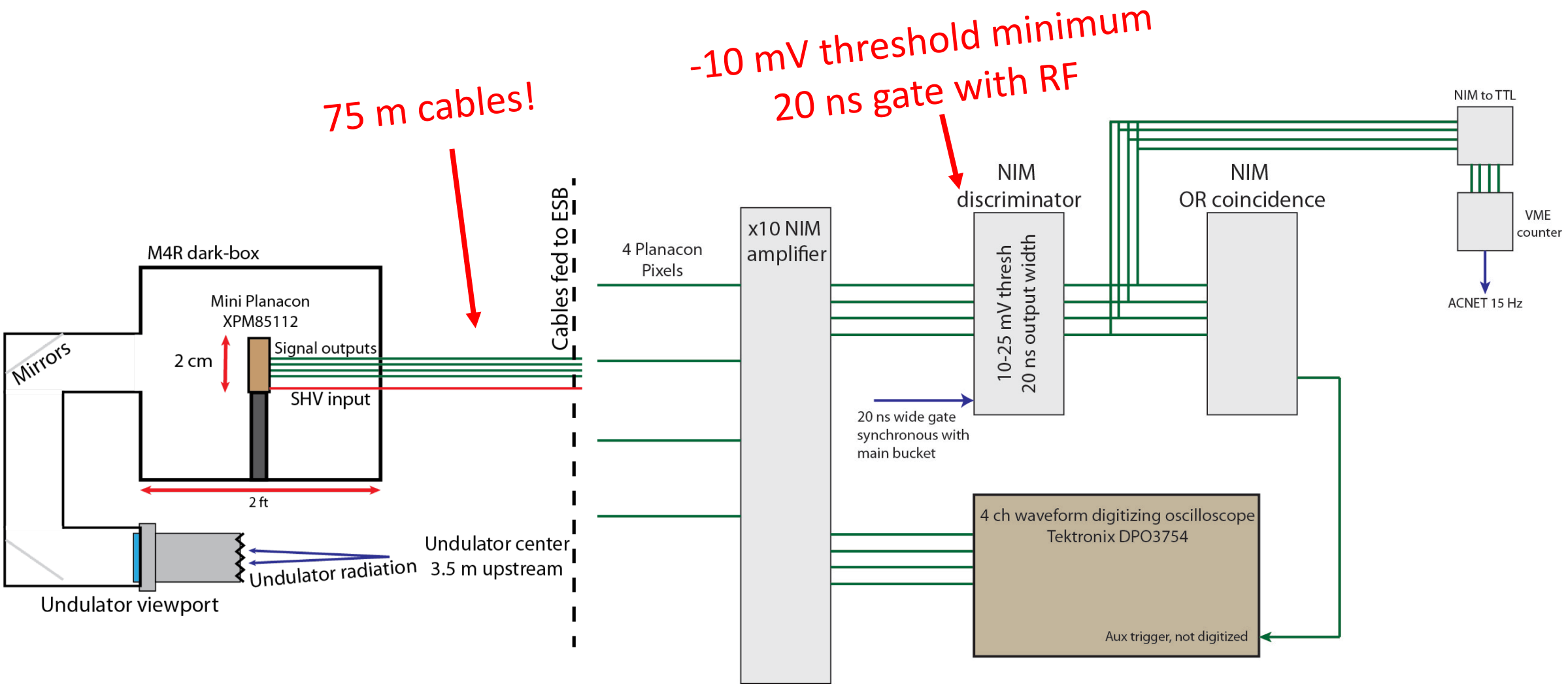
Photon number measurement with MCP-PMTs

- **Pulsed laser**
- Attenuate until only 1 pulse every 10 or so laser triggers
- Calibrates charge as a function of PE number
- Observe 1-PE and 2-PE in the experimental environment…



Here 1e6, LAPPDs have gain typically at 1e7 or greater

Phase 0 configuration for Planacon charge readout



Effect of amplifying after 75 m of cable

Laser calibration:
6.6 – 8.9 mV 1-PE amplitude
~15 mV 2-PE amplitude

-20 dB from
75m RG58

→

+20 dB
NIM amplifier

→

-15 mV threshold discr.

-15 mV 2-PE amplitude
+amplified noise

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Increase HV to 2480V:
Expected increase to
~15 mV 1-PE amplitude
~30 mV 2-PE amplitude

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Rates are consistent with being sensitive to 2-photon emission and some small fraction of 1-photon events. About 50 Hz on a background of 150 Hz per channel

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~30 mV 2-PE amplitude

-20 dB from 75m RG58 →

+20 dB
NIM amplifier →

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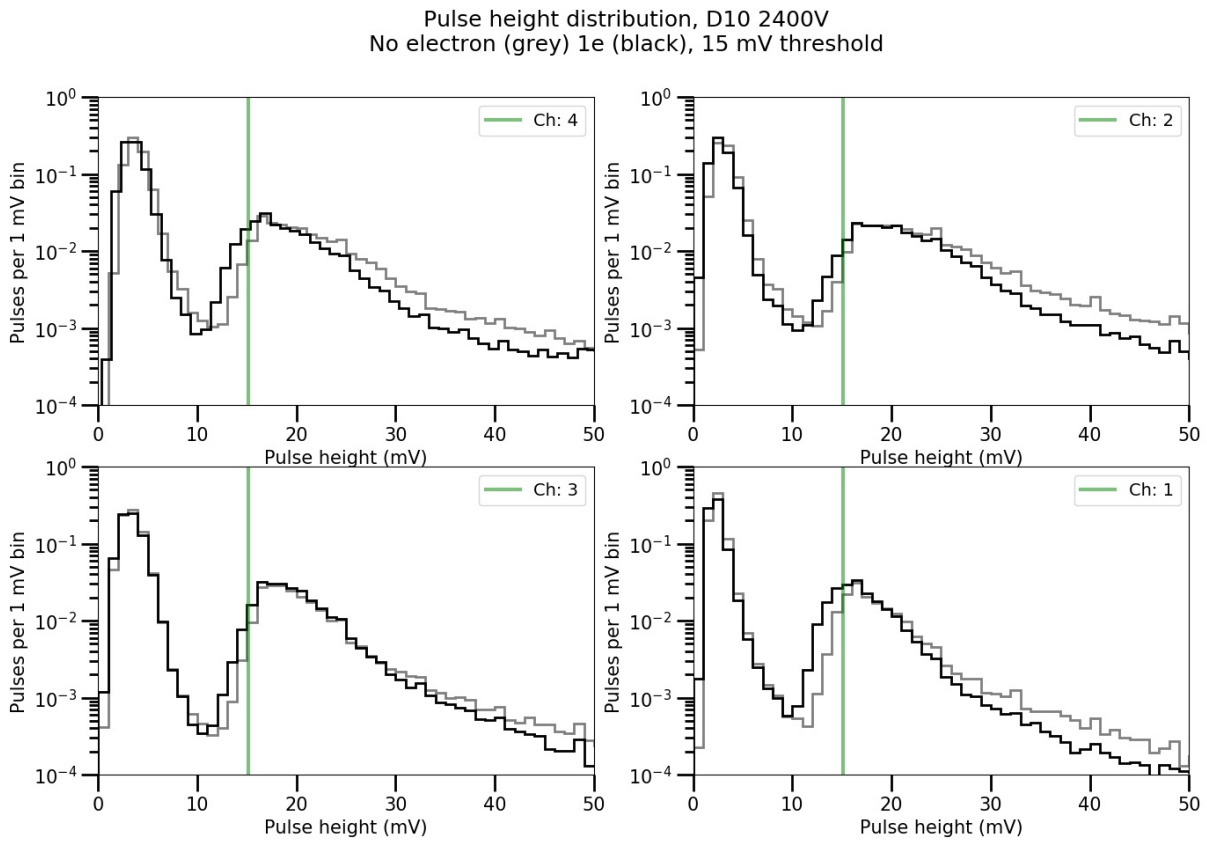
+amplified noise

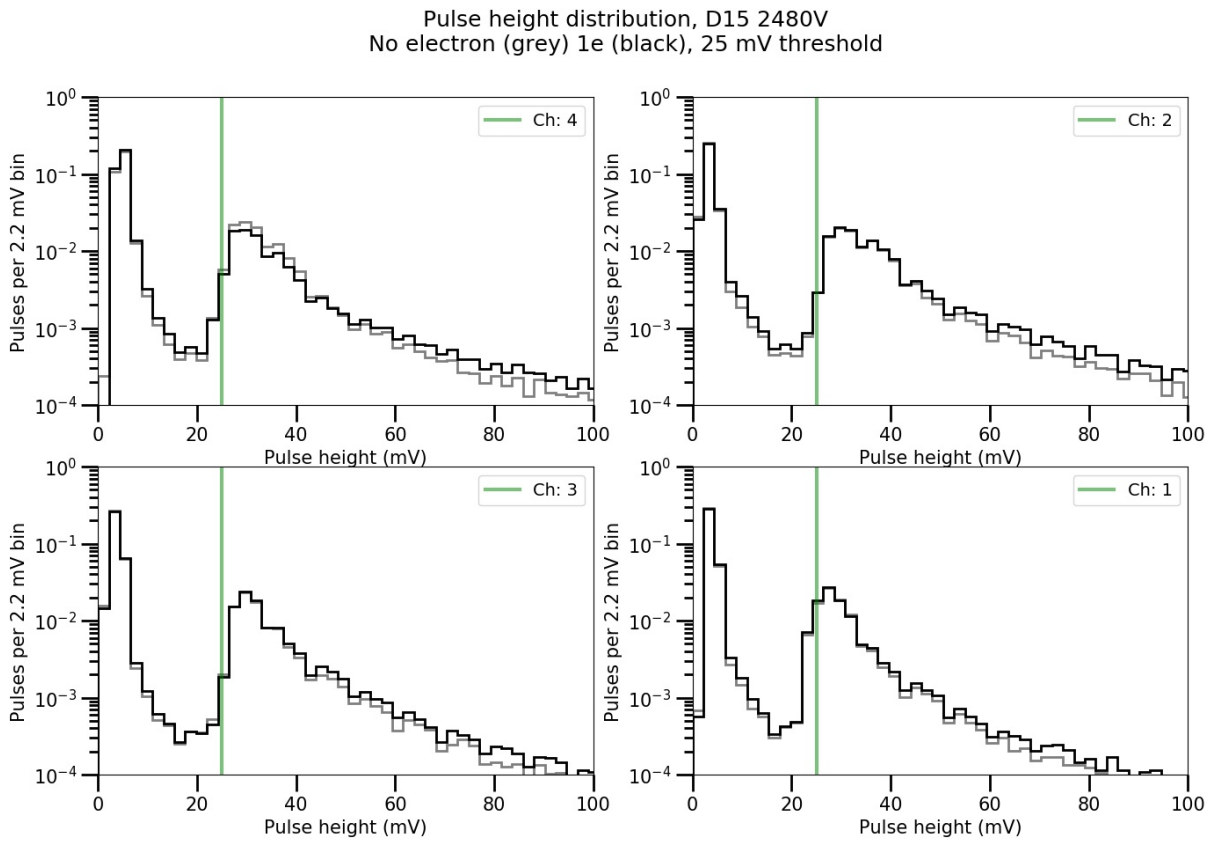
Data-sets

Data-set name	# electrons	Applied HV	Disc. Threshold	Events digitized
D5	500-1000	2400 V	15 mV	400k
D6	0	2400	15	200k
D10	1	2400	15	450k
D9	0	2400	15	135k
D15	1	2480	20	450k
D17	0	2480	20	225k

About 10 minutes of consecutive beam time for each pair of data-sets, not storing every turn, only turns that have detector signal(s)

Measured pulse height distributions



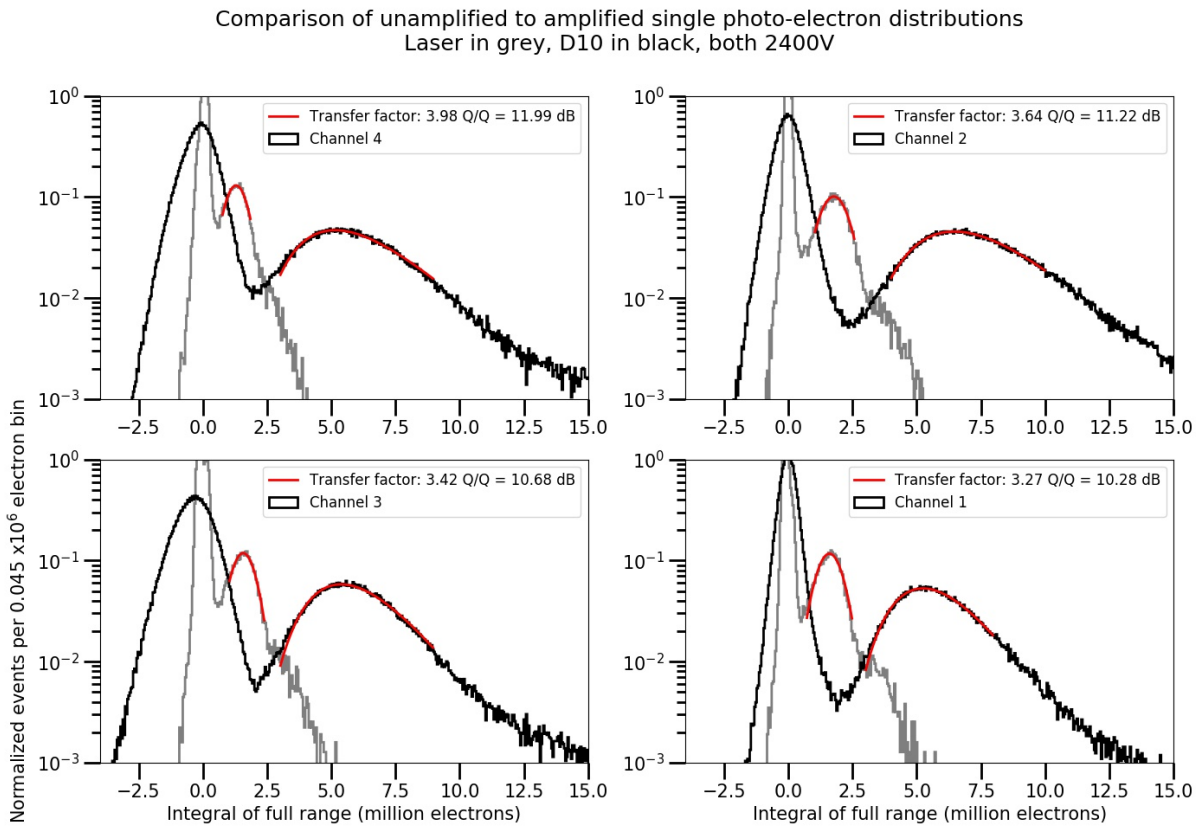


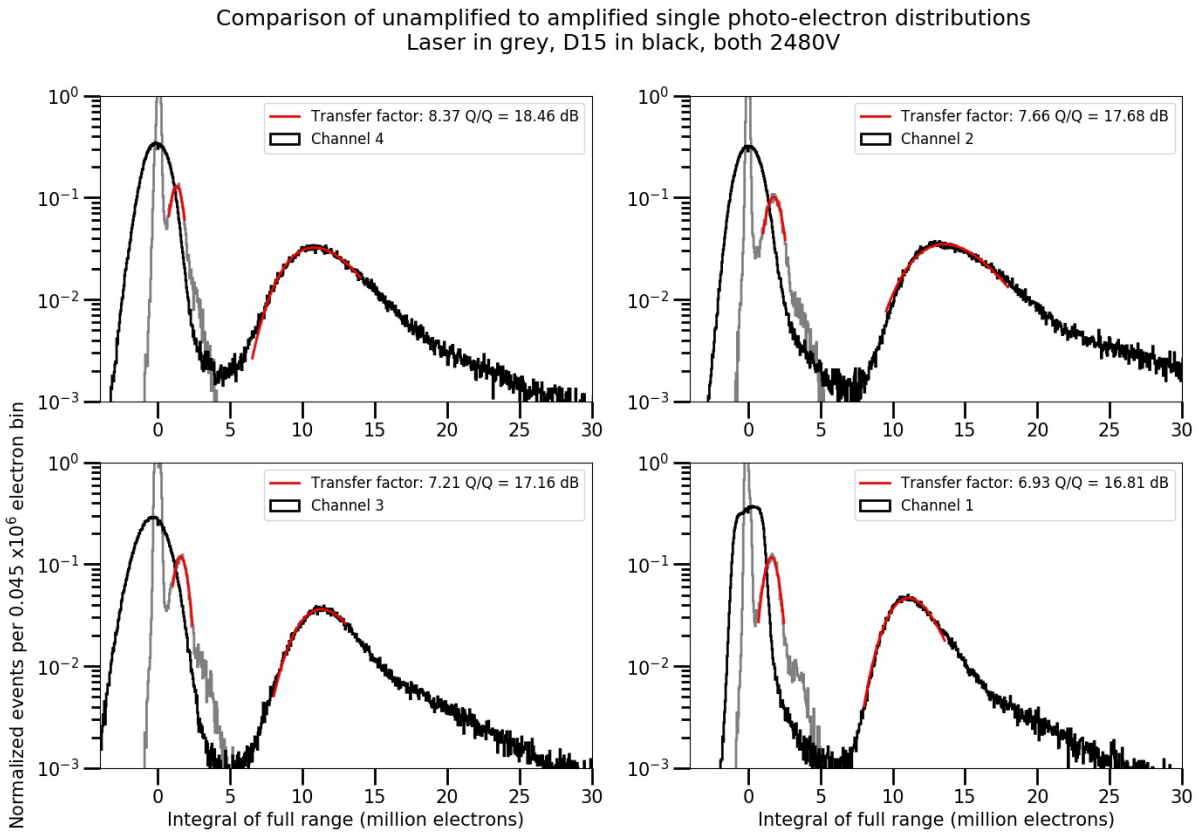
2400 V, 15 mV threshold

2480 V, 20 mV threshold

Threshold seems to cut into the 1-PE/2-PE distribution, accepting only a portion

Measured charge distributions





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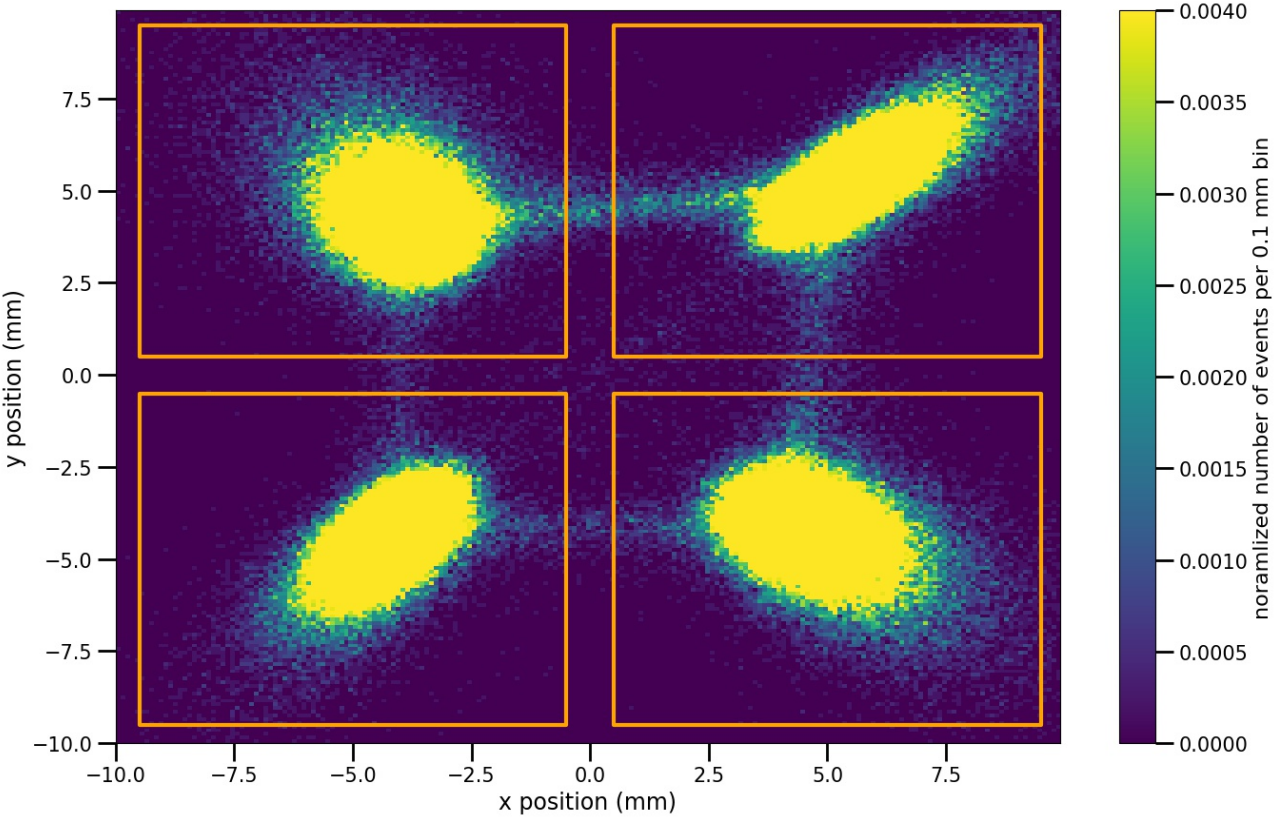
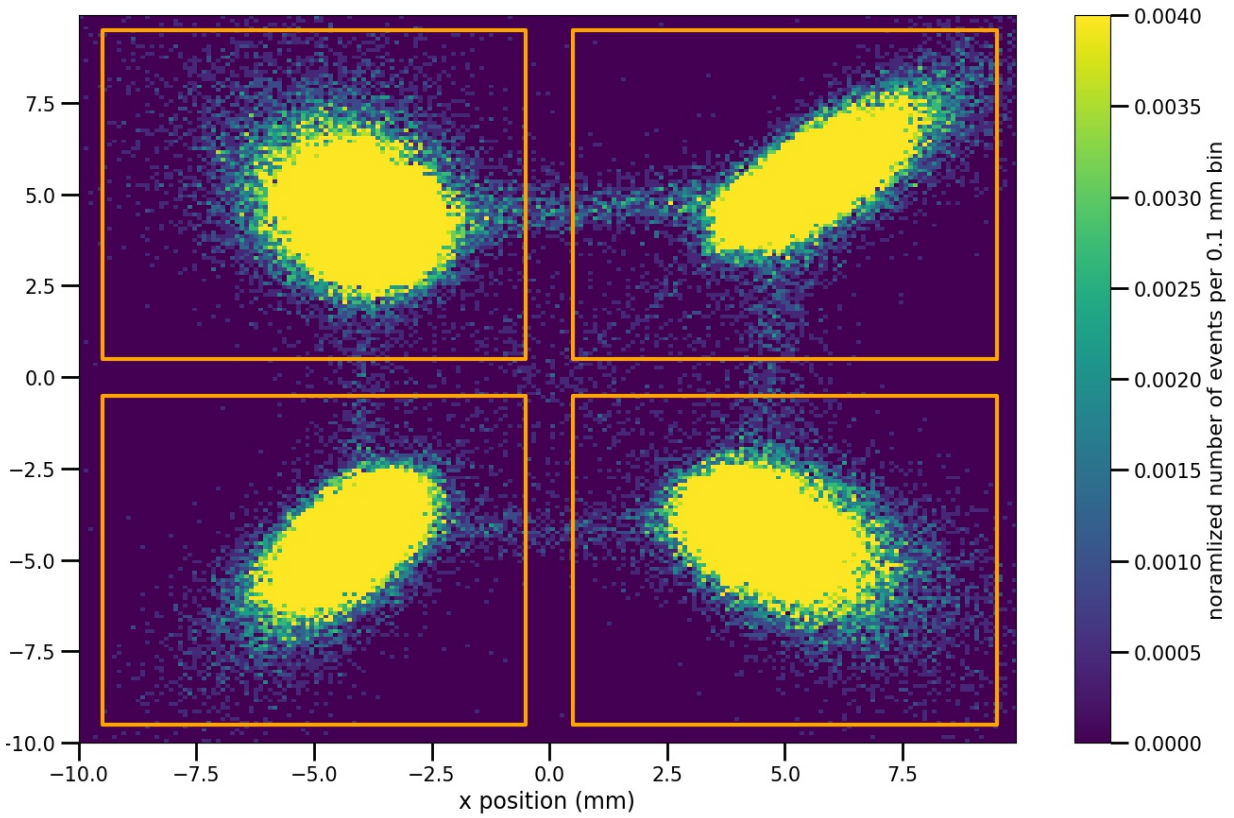
2D histogram of events, at least 1 channel $r_{\mathrm{reco}} = \frac{1}{\sum_i q_i} \sum_i q_i r_i$



1-electron circulating, 460k events

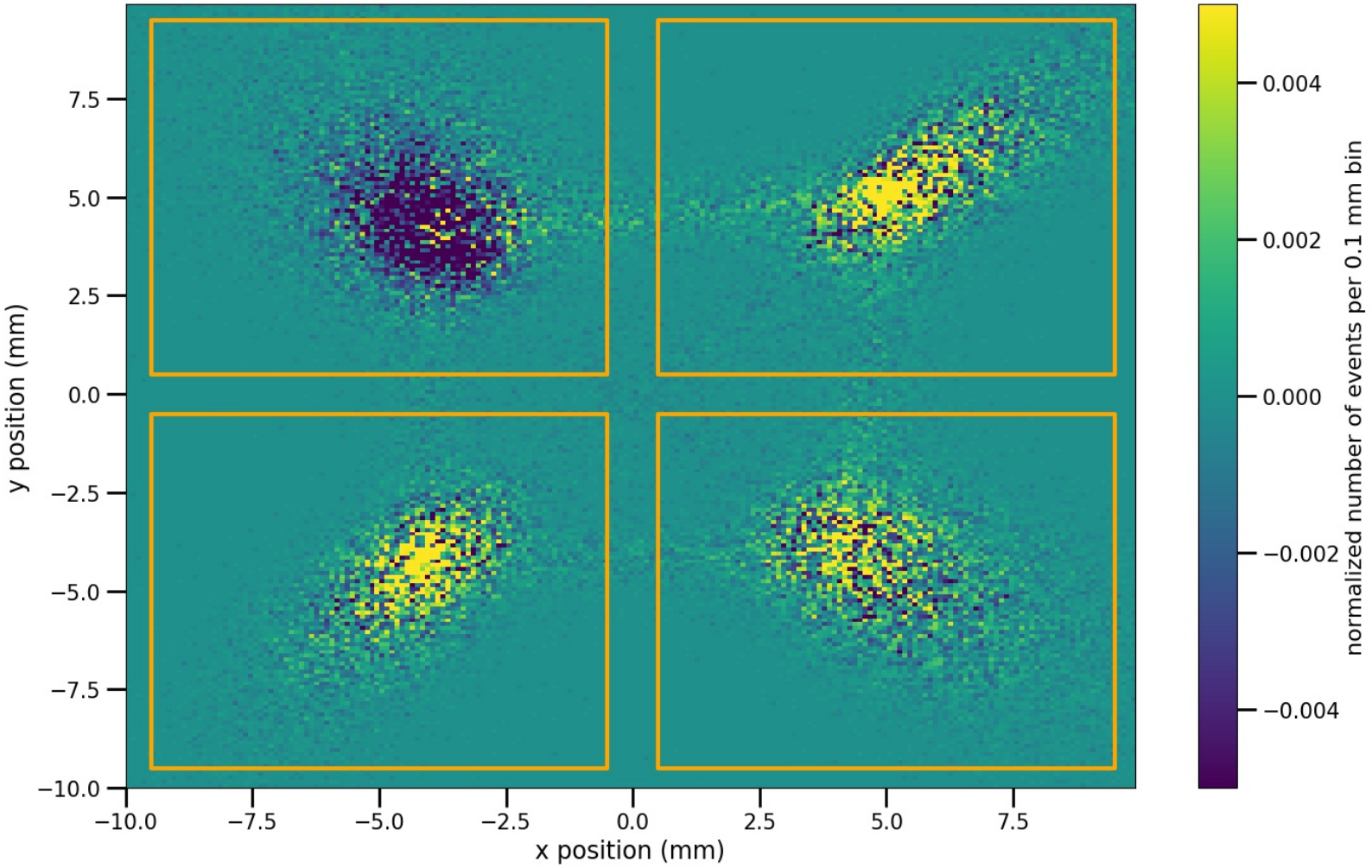


0-electron circulating, 225k events

Event statistics are biased toward center of pad due to high threshold relative to amplitude

2D histogram of events, at least 1 channel

$$r_{\text{reco}} = \frac{1}{\sum_i q_i} \sum_i q_i r_i$$

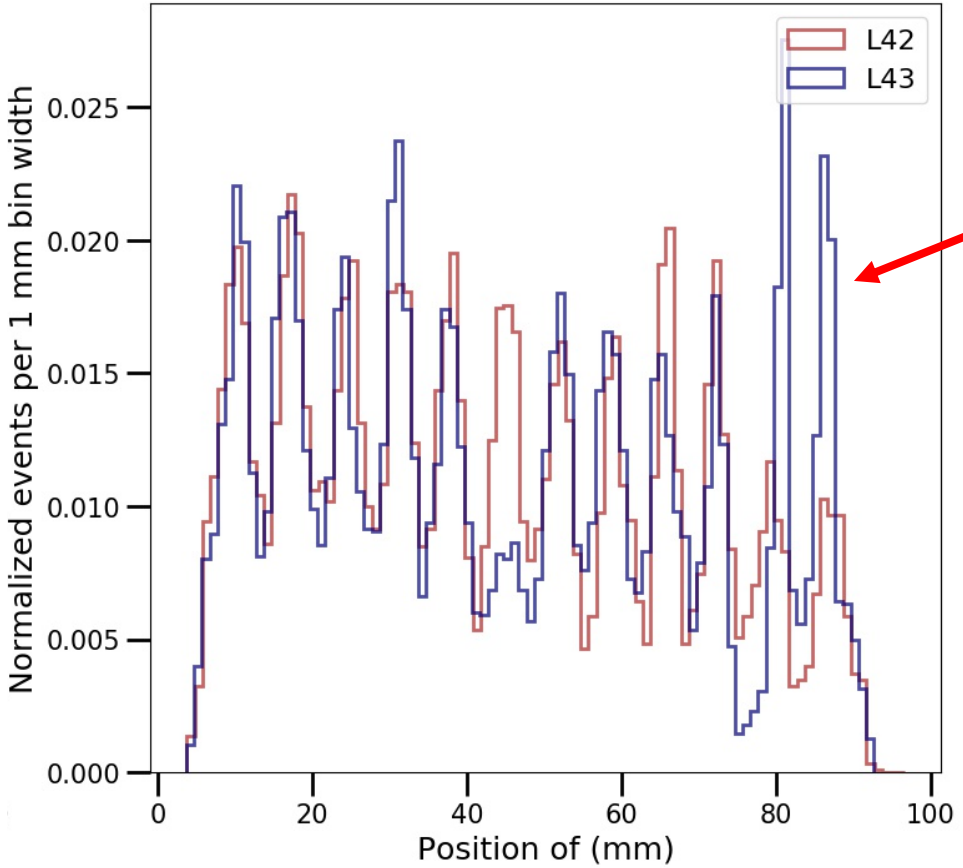


1-electron circulating, 460k events – 0-electron circulating, 225k events

Thresholds biasing event collection vs. hit position

This data:
Uniform flux of cosmic rays on an LAPPD

Relatively large trigger threshold



Peaks are at strip locations

This data from thesis experiment in test-beam with Incom LAPPDs: high voltage thresholds will bias event statistics towards events where most of the charge is deposited on one conductor, in contrast to events where charge is equally shared

Some prospects for the next phase with LAPPD (Precision Angular Measurement … or PAMPUR)

<u>Primary goals/challenges</u>

- Large amplitude-to-threshold ratio
- Configurable trigger system
- Distinguishing dark-noise vs 1 and 2 PE events

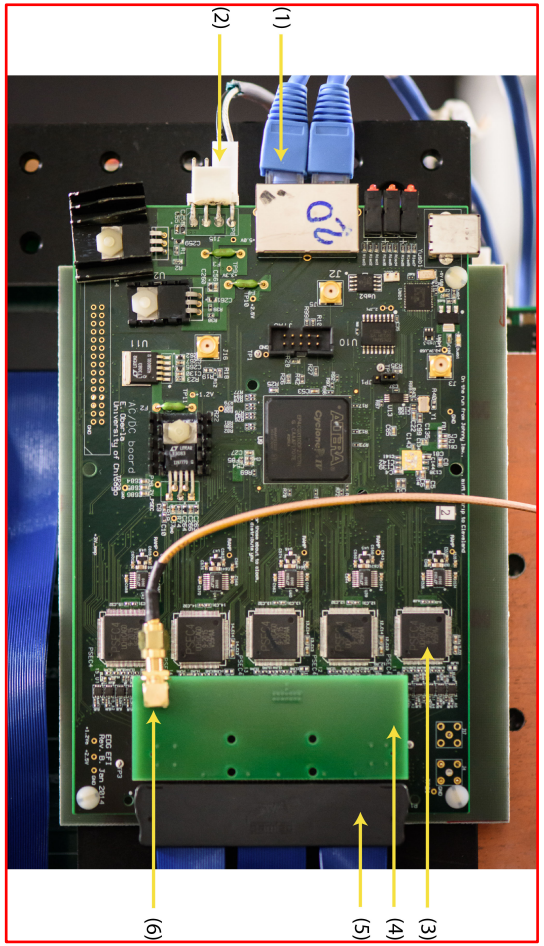
- Spread the radiation cone over more, smaller pixels. On average, photons will be separated in space

Some prospects for the next phase with LAPPD (Precision Angular Measurement … or PAMPUR)

Primary goals/challenges

- Large amplitude-to-threshold ratio
- Configurable trigger system
- Distinguishing dark-noise vs 1 and 2 PE events

- Front-end digitizing system used for LAPPDs
- FPGA-controlled trigger logic
- On-line selection of 1-to-2 PE events



Front-end electronics: PSEC4

Eric Oberla and Mircea Bogdan designed the chip and the boards. See Eric Oberla's U. of C. PhD thesis

PSEC4:

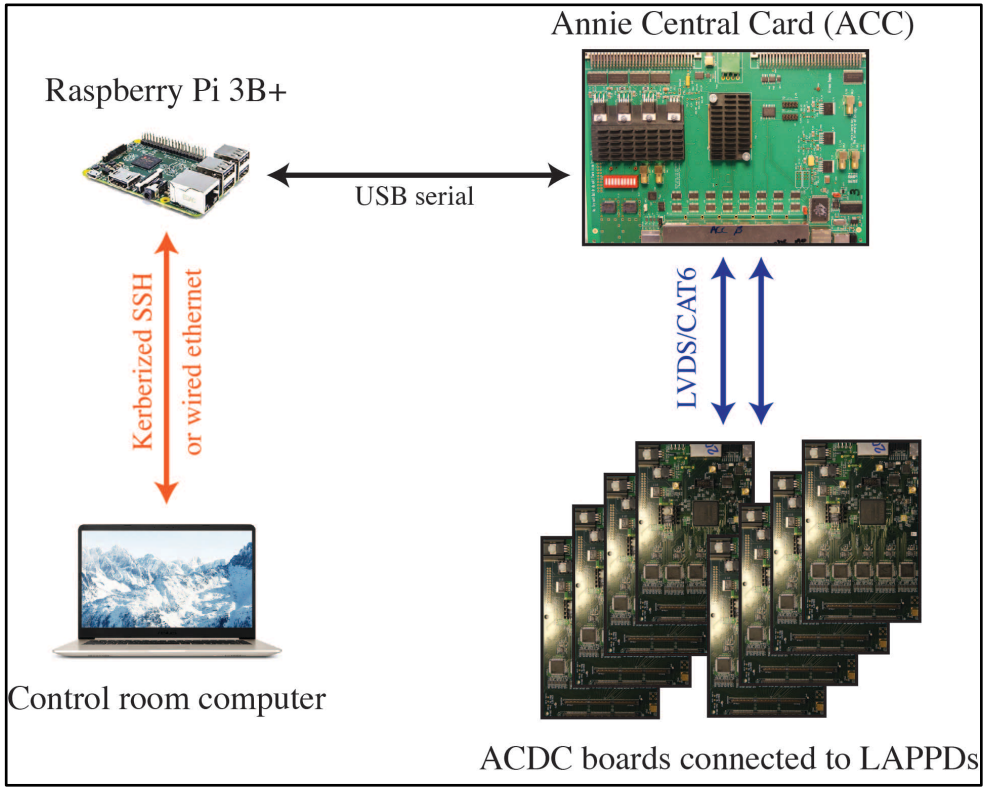
66 – 160 ps per sample, 6 channels, 1.6 GHz bandwidth, ~7ps on MCP pulses, ~25ns = 256 sample depth, 10.5 bit-effective resolution, 1.2V dynamic range

ACDC:

Front-end board, Cyclone IV GX FPGA, controls 5 PSEC4 chips = 30 channels

ANNIE Central Card (ACC):

Top-level board, Aria V FPGA, controls 4 ACDC boards, interprets commands from control computer



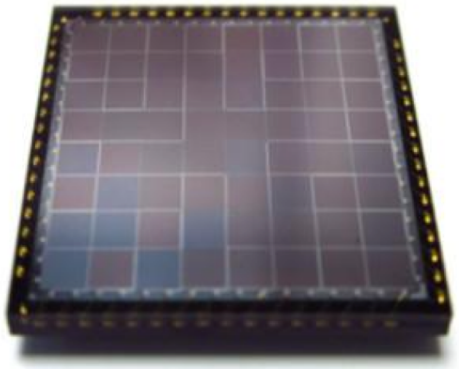
Major component of my PhD thesis: firmware is presently being re-written to be configurable/debuggable by a physicist

Comparing technologies

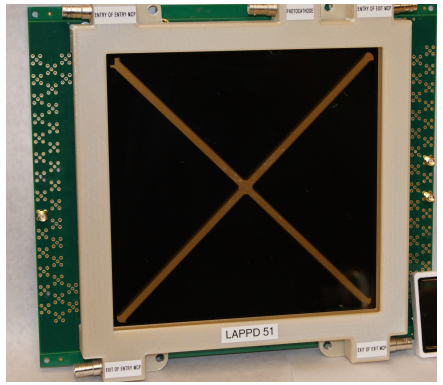
Silicon Photo-multipliers (SiPM)

From AdvanSiD http://advansid.com/products/product-detail/asd-rgb-nuv-1-5s-p-8x8a

- Array shown here has 1.45 mm pixels (1.45 mm spatial resolution)
- 64 channels = 1.4 cm^2 active area
- 10-100 kHz / mm^2 dark rates
- Amazing 1-to-2 photon separation
- **LAPPD equivalent: 18k channels, 400-4000 MHz dark-rate**



1.2 cm



20 cm

Strip-line LAPPD

- 1 mm or less spatial resolution
- 60 channels = 400 cm^2 active area
- 0.001 - 0.01 kHz / mm^2 dark rates
- OK 1-to-2 photon separation
- **LAPPD equivalent: 60 channels, 40 - 400 kHz dark-rate**

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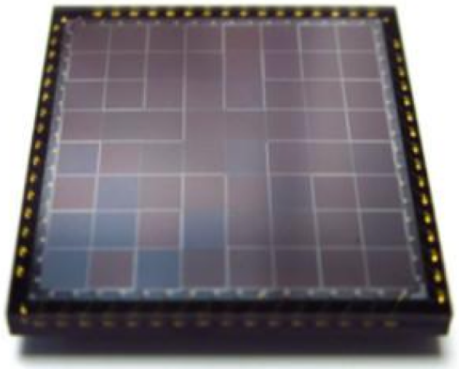

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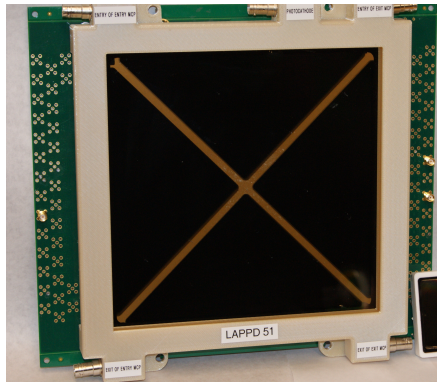

20 cm

There may be others more suitable, lets discuss

Strip-line LAPPD

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With further development… additional x10 in precision

Figures (and lots of development) credit to Oswald Siegmund

See paper: Advanced Photon Counting at https://amostech.com/TechnicalPapers/2006/Telescope/Siegmund.pdf

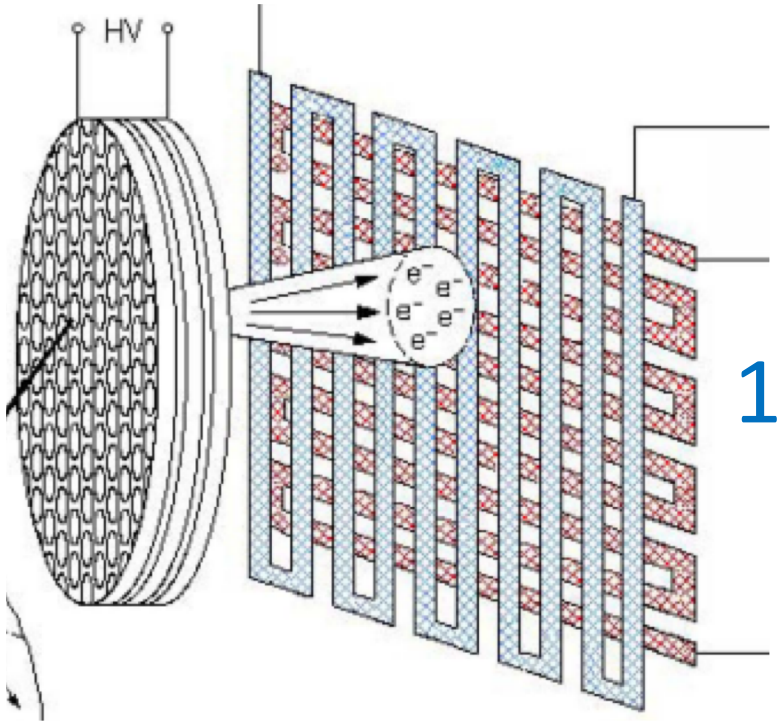
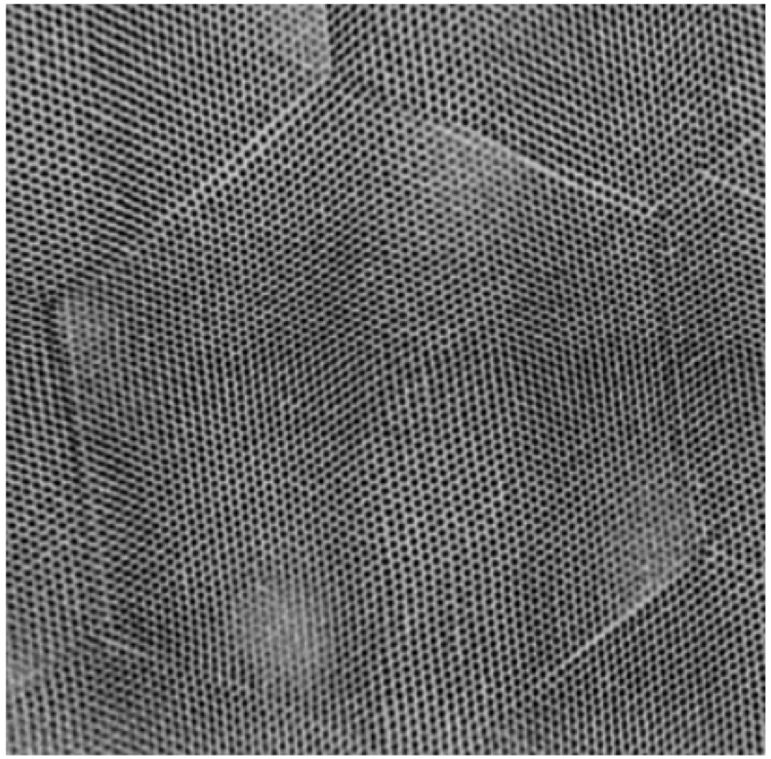


Figure from Berry et. al. DOI: 10.1109/NSSMIC.2012.6551091

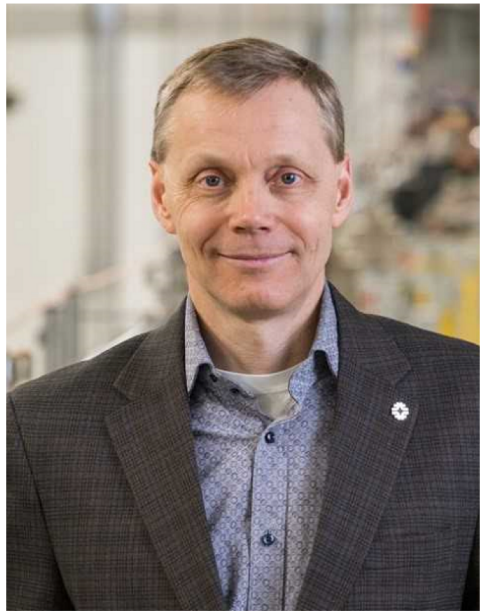
Delay-line anode
10 micron precision
4-channels



- Not yet implemented with commercial LAPPDs
- Clear path, PCB fabrication and design
- **Completely different trigger/electronics system**

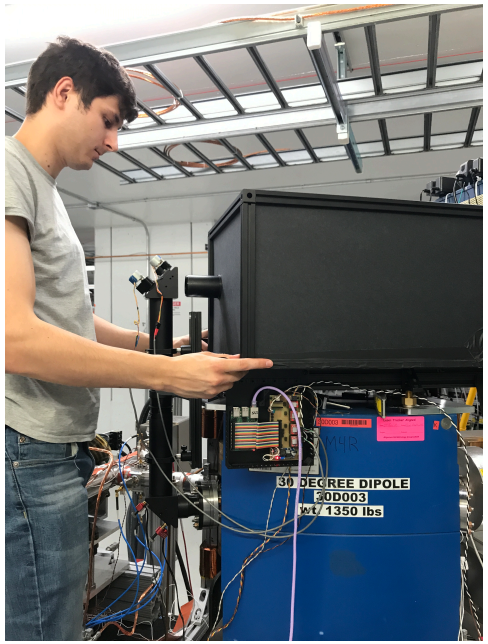
In IOTA, 40 micron spatial would lead to 600 nano-rad sensitivity (likely limited by optics)

Acknowledgements



Sergei Nagaitsev

Giulio Stancari



Ihar Lobach

Sergei Nagaitsev, Giulio Stancari, Ihar Lobach, Jamie Santucci, Dan Broemmelsiek, Alexander Valishev, many others at the IOTA facility

Special thanks to Aleksandr Romanov who helped us acquire critical hardware

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Summary

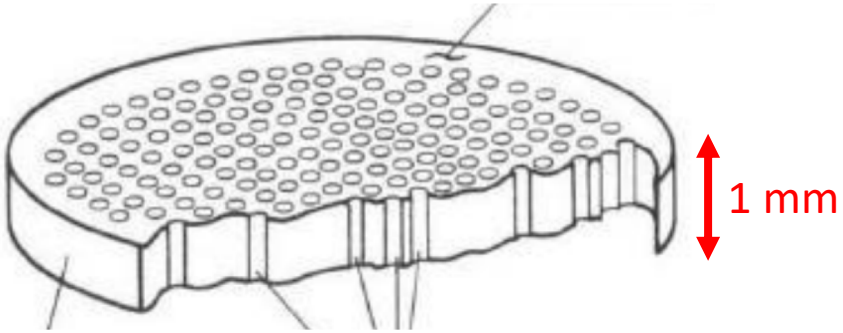
- Micro-channel plate photo-multiplier tubes may be an optimal technology for measure undulator radiation angle
  - Low number of channels/area, great resolution/channel
  - Low dark noise
  - LAPPDs are in use at Fermilab

- Preliminary results from a coarse measurement, AMPUR
  - Pixelization of the 2 cm Planacon is too coarse to spatially separate 2-photon events
  - Important to have small thresholds compared with 1-PE amplitudes
  - Measured rates agree roughly with expected 1 and 2 photon emission, given information about trigger thresholds and cable attenuation

- Perspectives for the future
  - Imperative to have a front-end electronics system, with configurable coincidence and on-line charge reconstruction
  - LAPPDs with large area and small pixels/strips will be able to separate 2-photons spatially

Additional information/backup

Introducing micro-channel plates (MCPs)



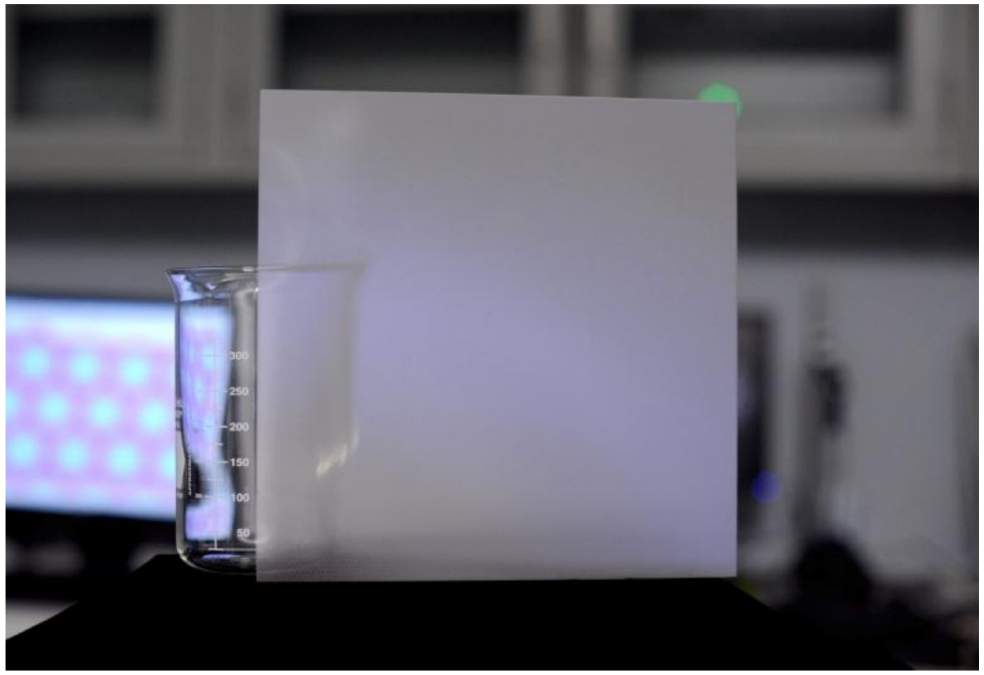


Photo courtesy of Michael Minot, Incom Inc.

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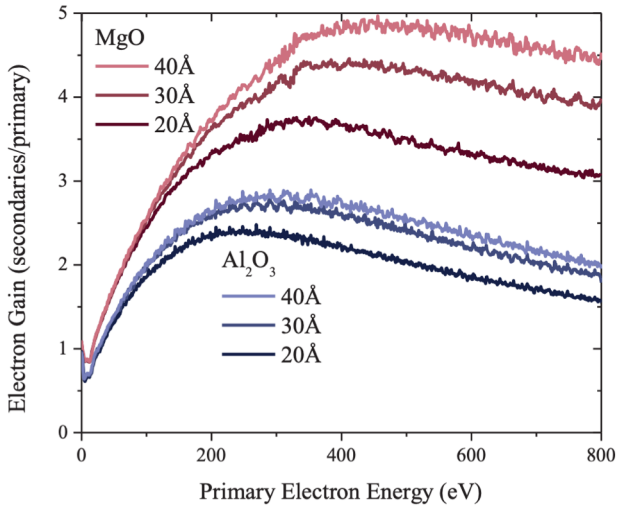

Figure 2. Secondary electron yield from select thicknesses of ALD MgO and Al_2O_3. See Figure 3 for the entire data set.

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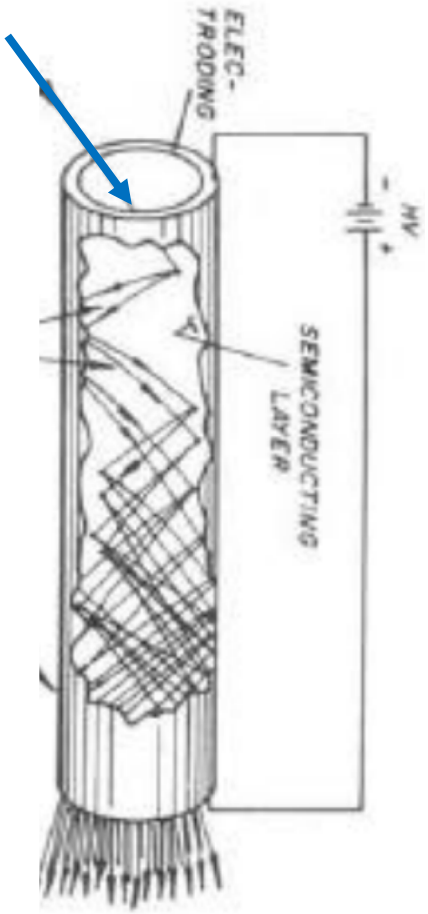


"Secondary emission" coating

Figure from Jokela et al., doi:10.1016/j.phpro.2012.03.718

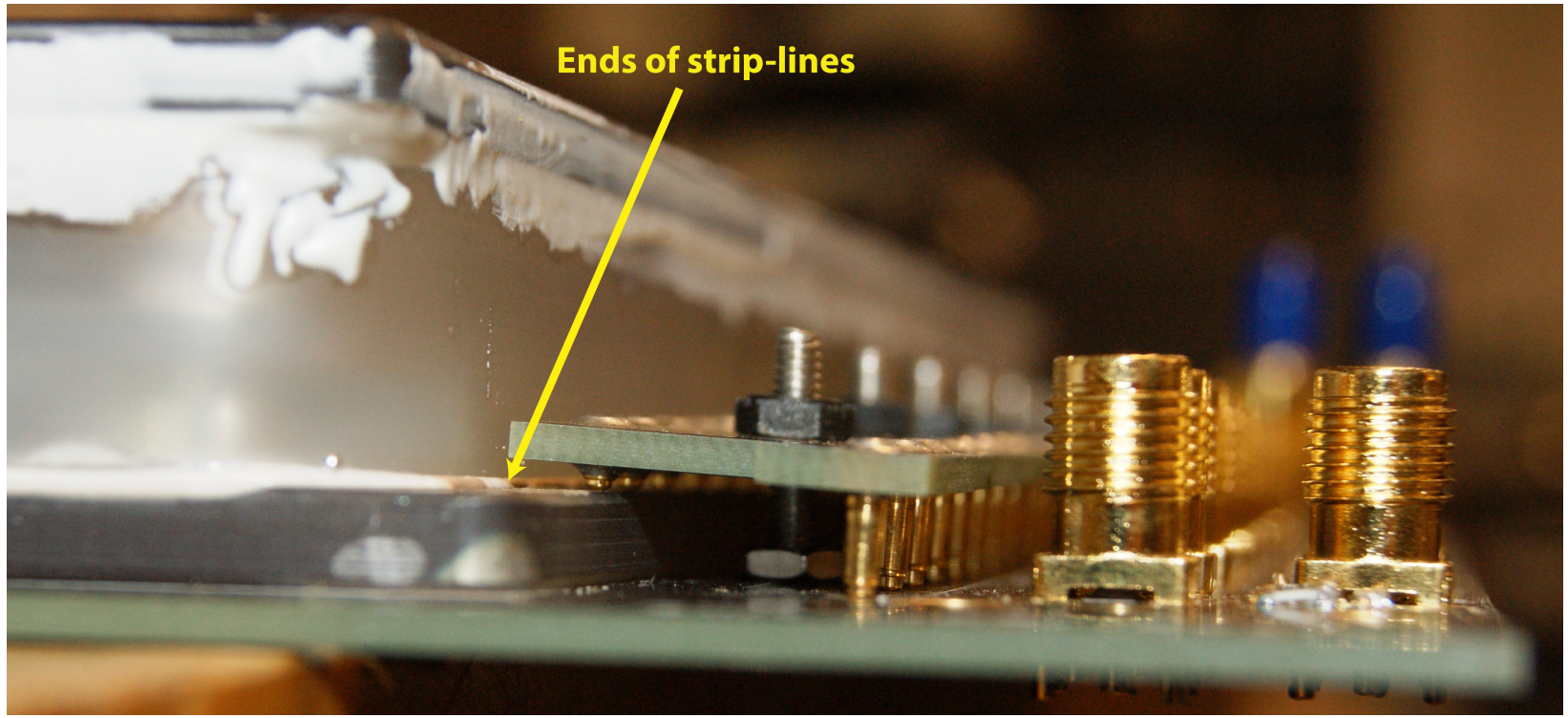
Cartoon diagrams from Wiza, NIM V162

How to connect strip-lines to electronics

Bernhard Adams, Incom & U. of C., observing the setup at FTBF

Bernhard designed boards transferring signals to electronics for the ANNIE experiment

About ¼'' of strip-lines extend from the glass packaging of the Incom LAPPD



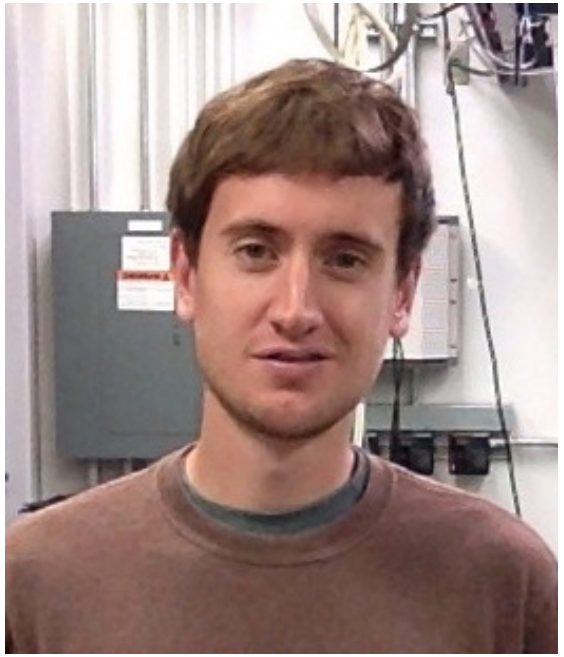
Pogo-pins transfer strip-line signals to printed circuit board

Front-end electronics: PSEC4

Evan

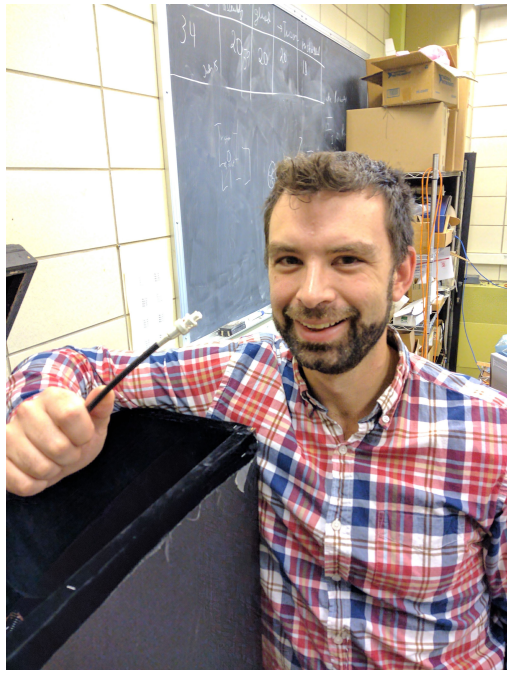
ANNIE Experiment

People

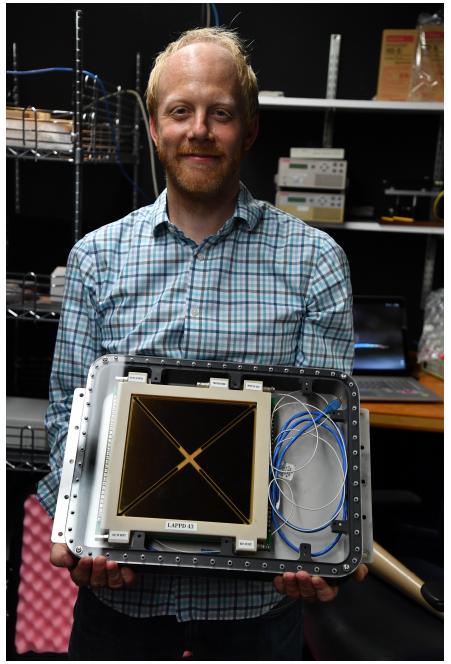


Eric Oberla
(KICP, U. of C.)

Mircea Bogdan
(EFI, EDG)



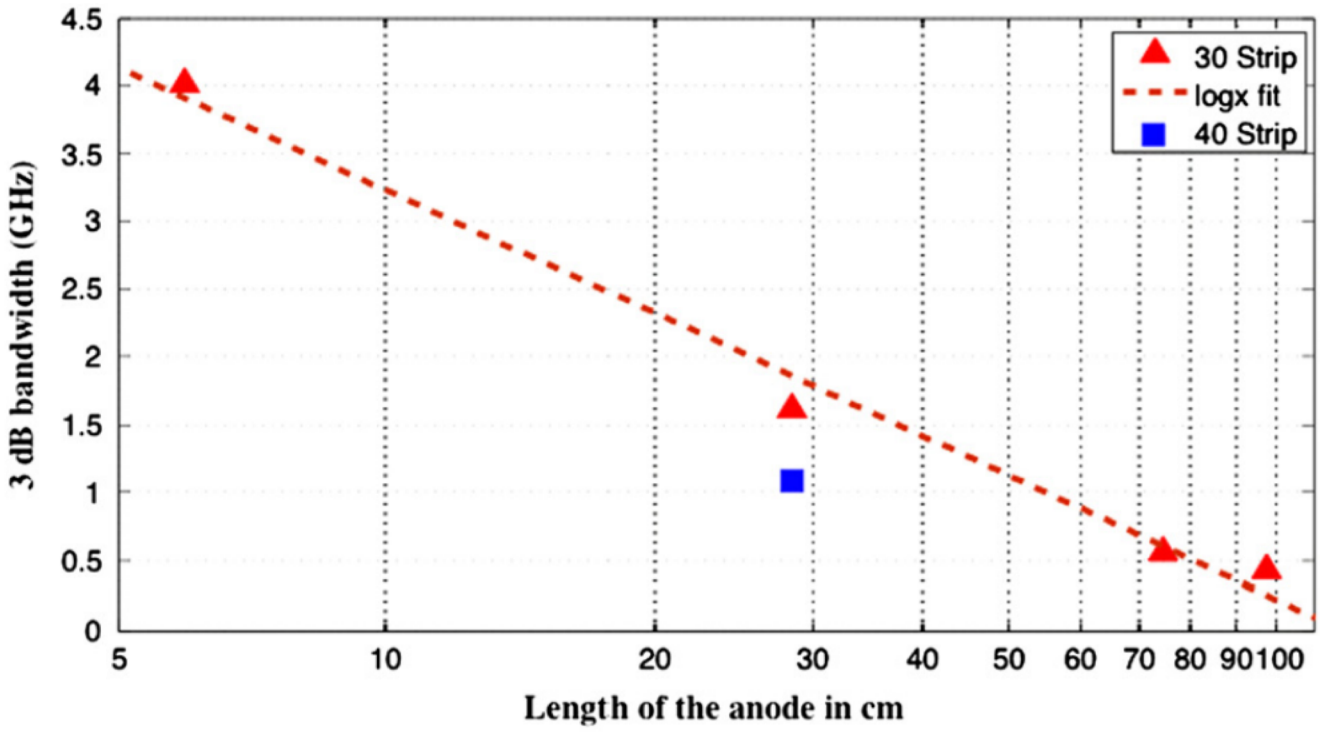
Jonathan Eisch
(Iowa State)



Matthew Wetstein
(Iowa State)

Strip-line anode, attached to the hermetic package

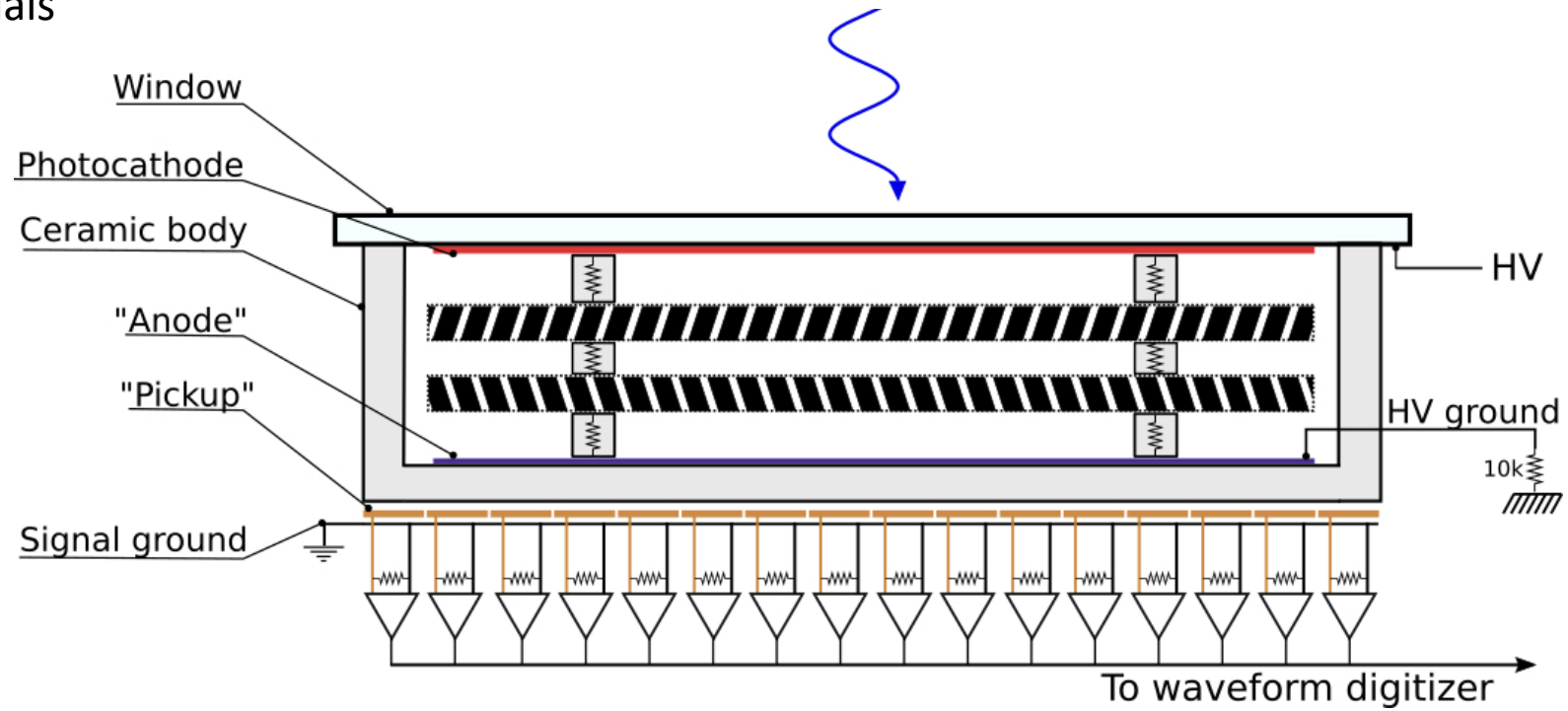
Grabas et. al: https://doi.org/10.1016/j.nima.2013.01.055 on rf-striplines for LAPPDs



Capacitively coupled anode and pickup

RF-timescale charge showers can transmit signals through a resistive layer to a set of pickup conductors outside.

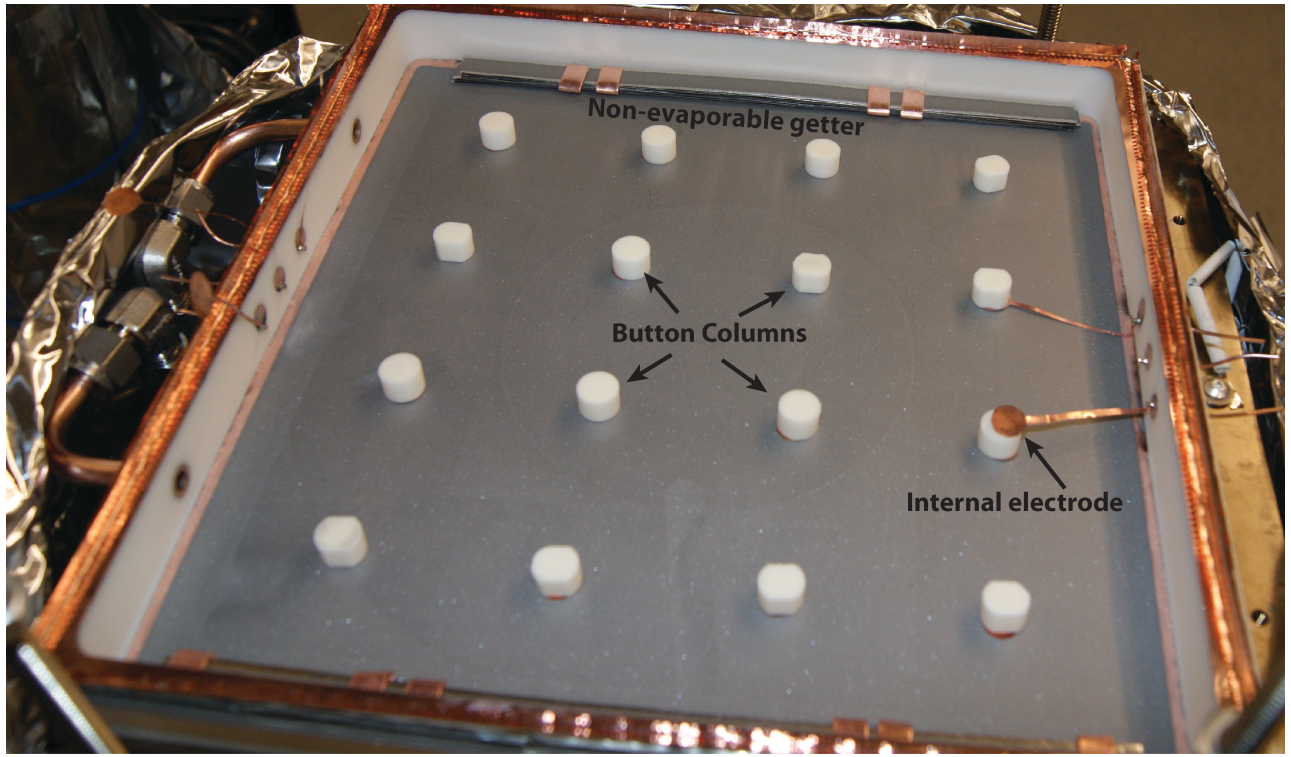
For example, Jagutzki et al http://dx.doi.org/10.1117/12.371099 and http://dx.doi.org/10.1117/12.2016016, Photek at http://dx.doi.org/10.1117/12.616732, and RoentDek at http://www.roentdek.com/detectors/ - all using Germanium or high resistance materials

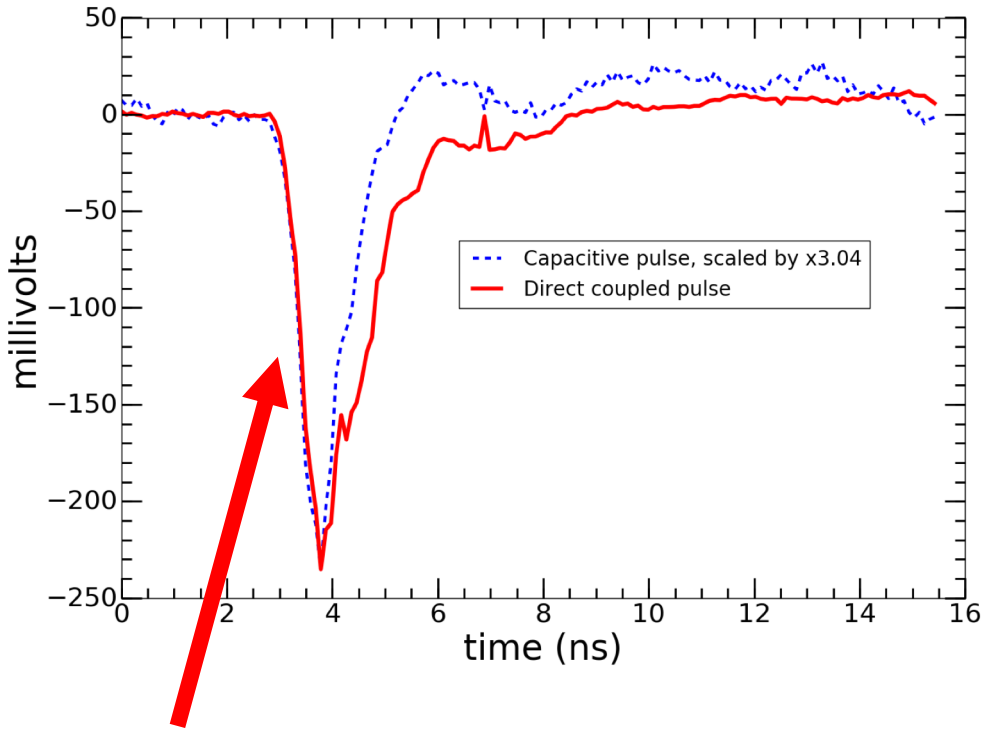


Decouple the readout pattern and the hermetic detector body; separate objects

Capacitively coupled anode and pickup

Inside of an LAPPD, **grey layer is 10 nm NiCr**





We showed that a 10 nm NiCr layer is resistive enough, possibly easier to deposit in batch production chain

Performance does not sensitively depend on resistance of layer

Rising edge of pulses are preserved: high-pass RC filter

See E. Angelico et al, https://doi.org/10.1016/j.nima.2016.12.008

Lessons learned from the thesis effort

One output of this thesis is an outline of changes to firmware that would have the largest impact on (1) the test-beam and (2) future LAPPD digitization efforts

Primary issues:

- Event recording limitation
  - LAPPDs up to 100 kHz/cm^2
  - PSEC4 chips up to 40 kHz
  - Firmware/data transfer: 5 Hz …
- Threshold discriminator variations
- Trigger timing

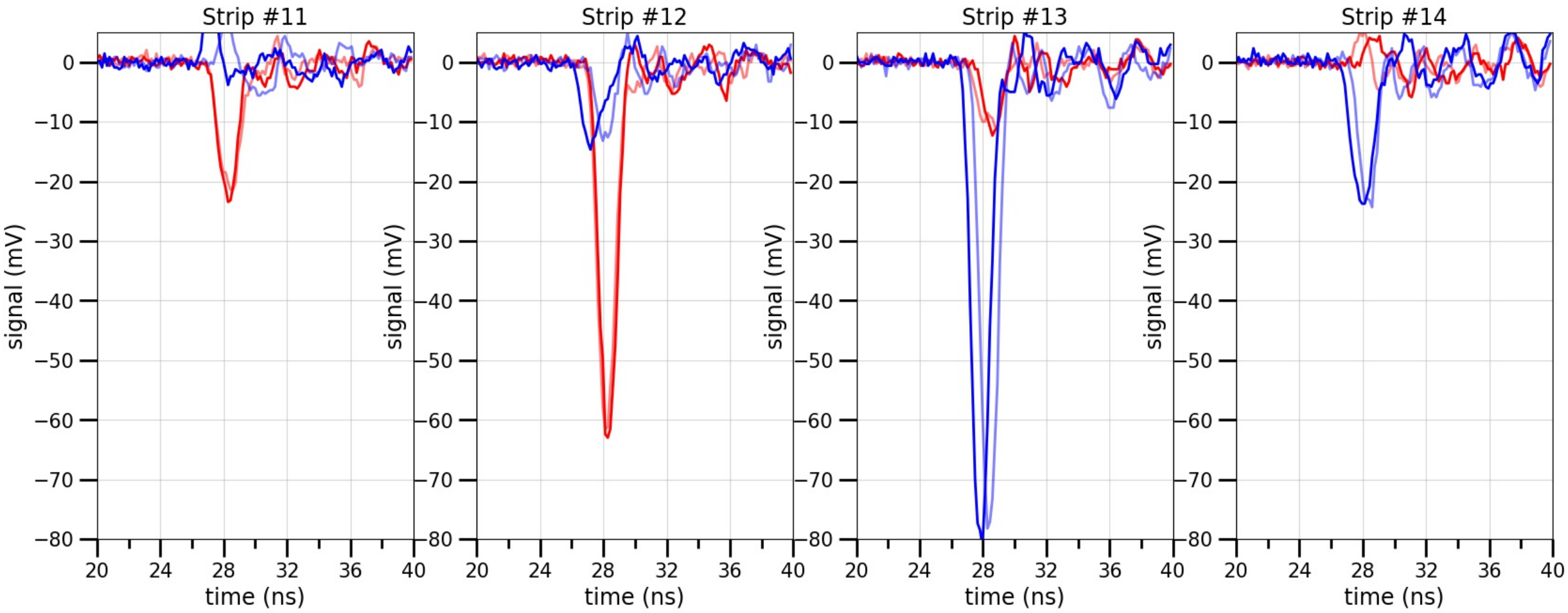
Suggested firmware tasks:

- Multiple event buffering using FPGA ram
- Move from USB to Ethernet I/O
- Restructuring of communication and command hex-encoding
- New board has been fabricated thanks to help from Eric Oberla:
  - Individual trigger thresholds
  - More robust clock scheme for timing
  - 10W power down-to 0.5W

Firmware is the limiting factor in the time-of-flight system, detailed discussion in thesis

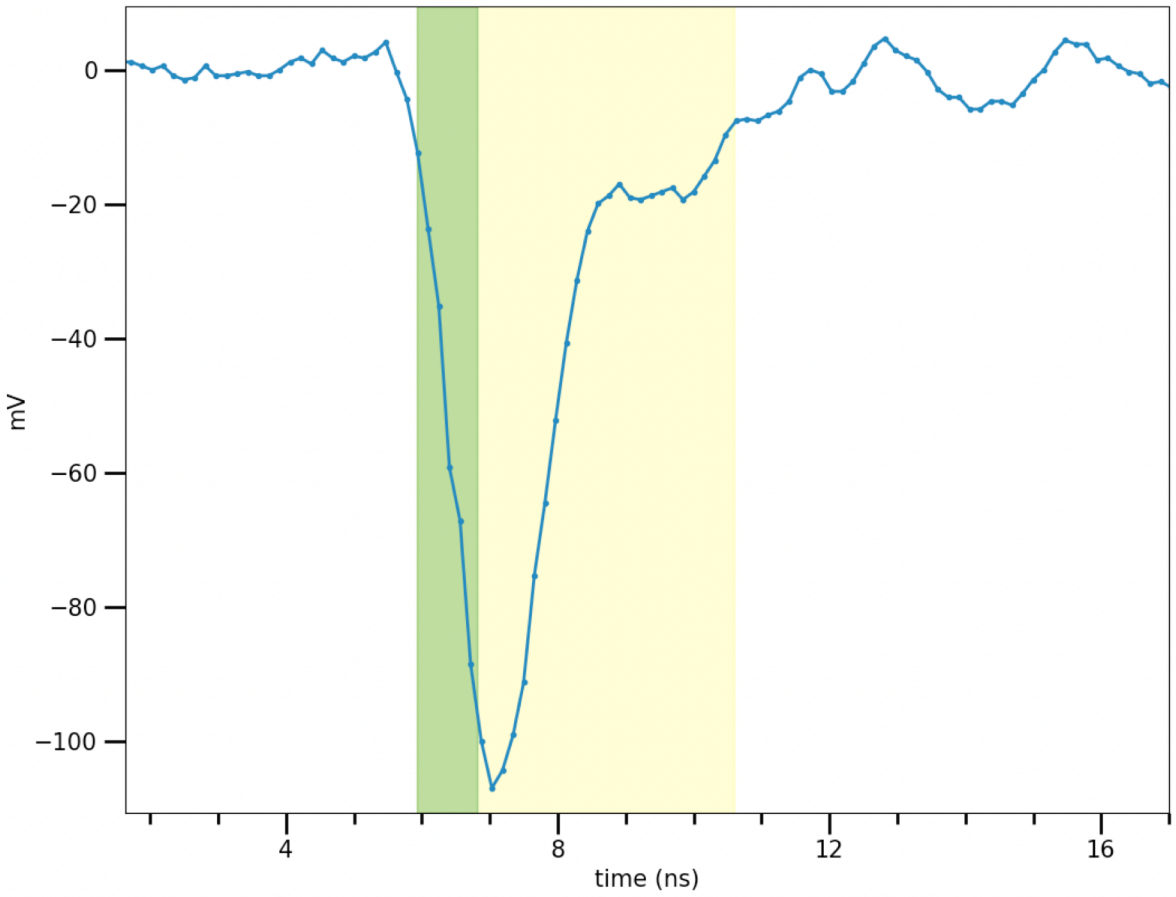
Analysis methods developed

An example of raw data: red is LAPPD 42 and blue is LAPPD 43

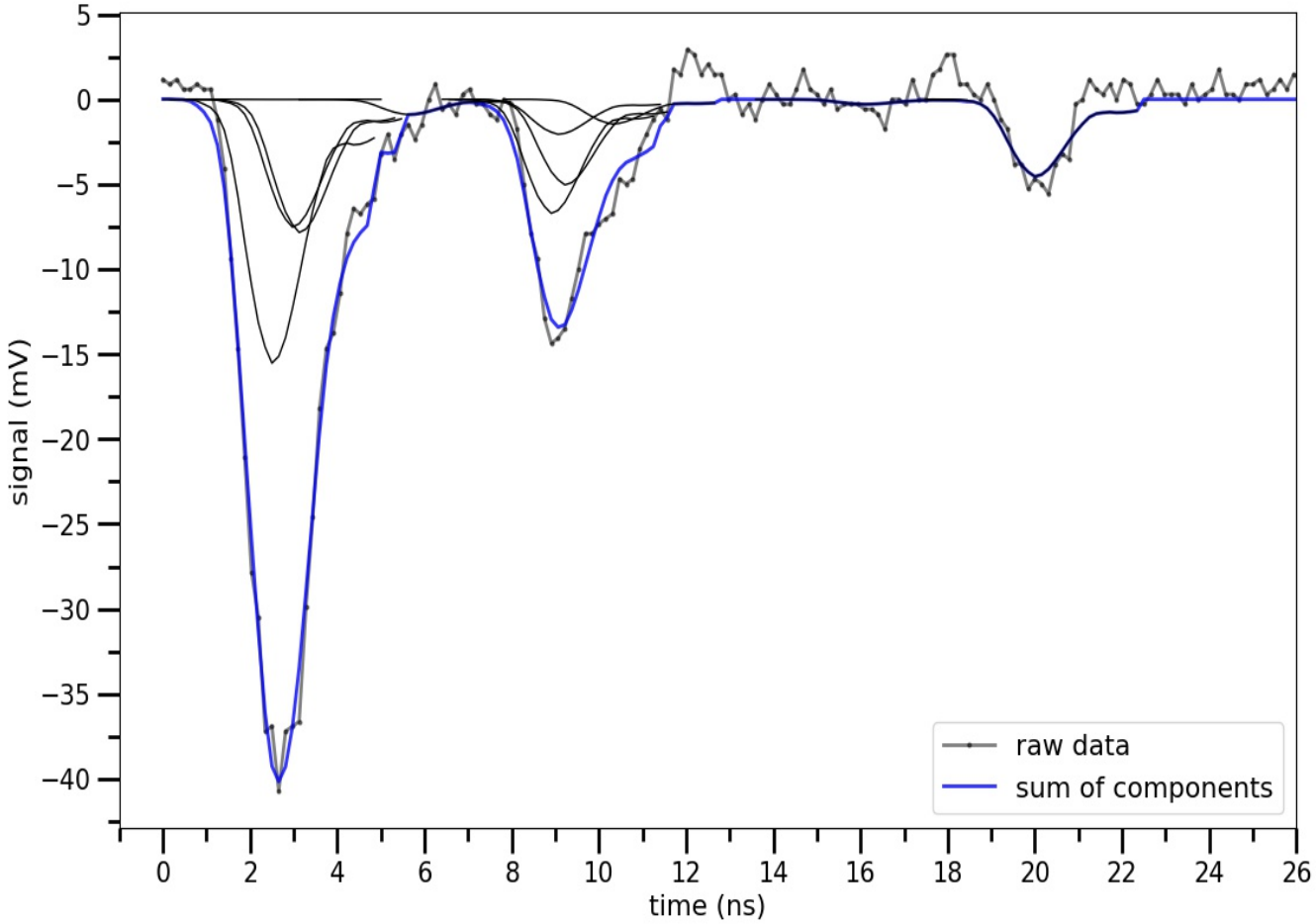


Analysis methods

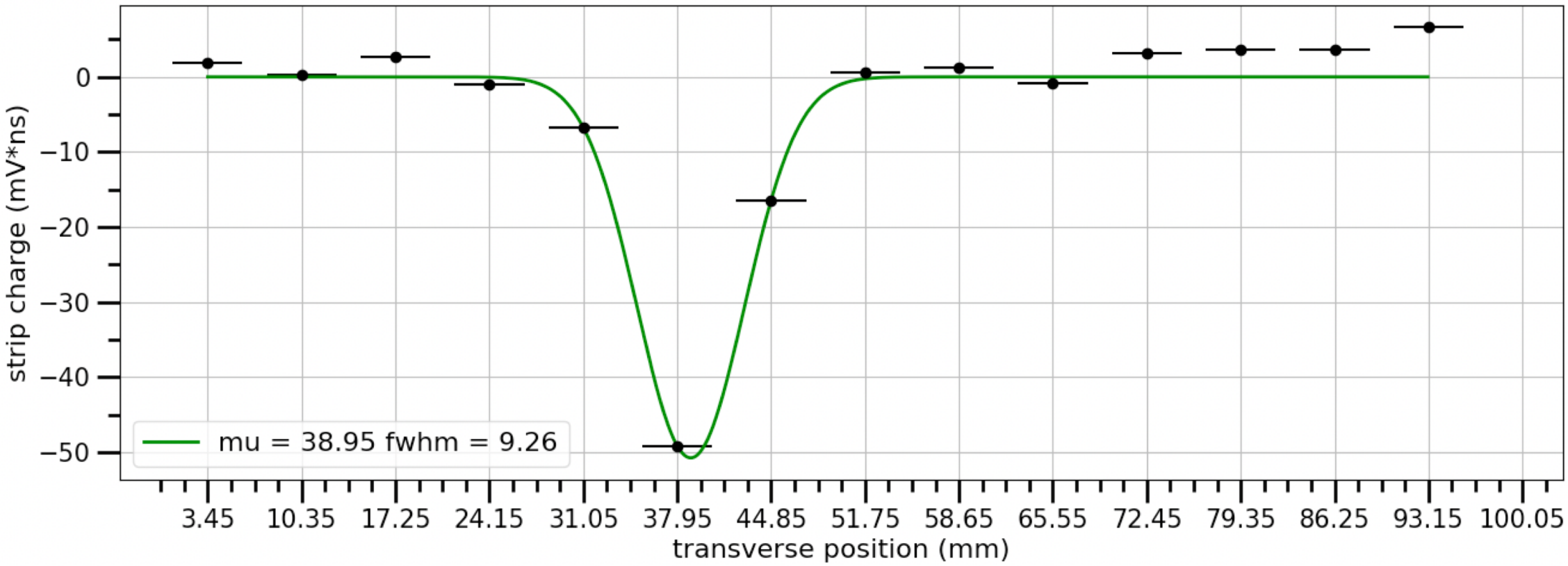
Constant fraction discrimination (CFD)



Template fit method using non-negative least squares

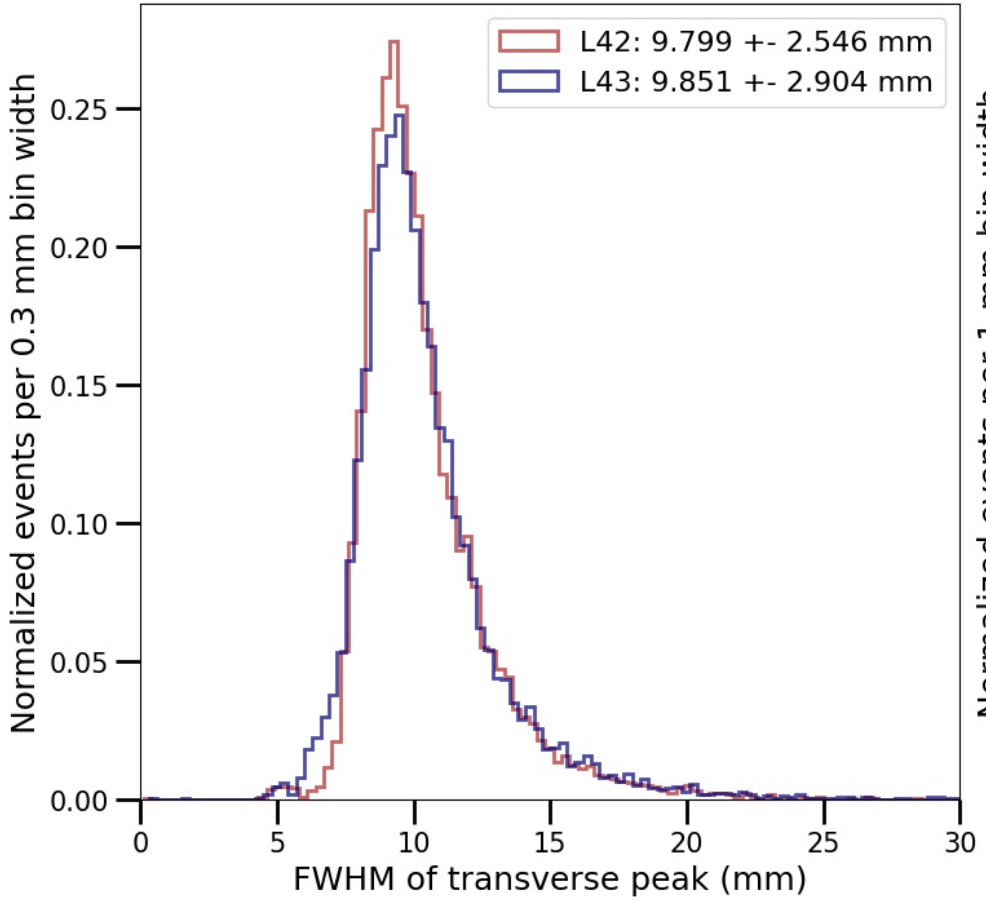


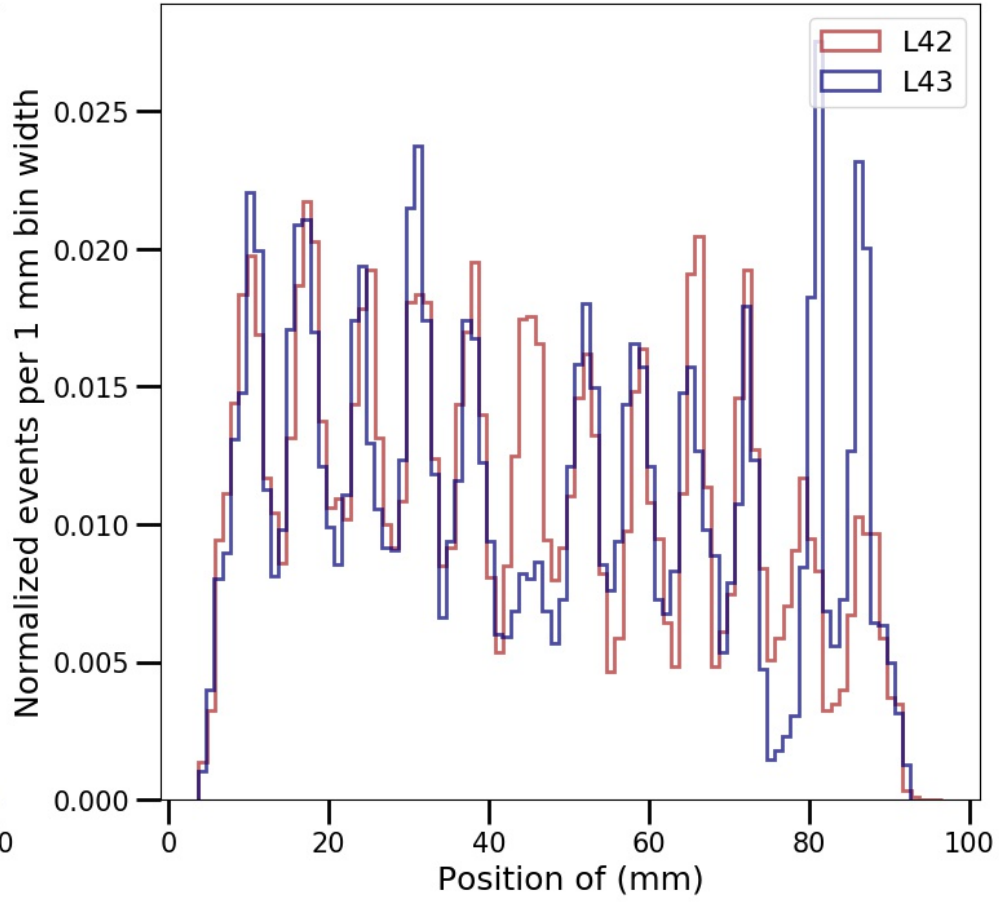
Characterization of charge sharing on strips



Black points/bars represent strips and their widths, y-axis is charge; fit gaussian to the peak to find position

Characterization of charge sharing on strips

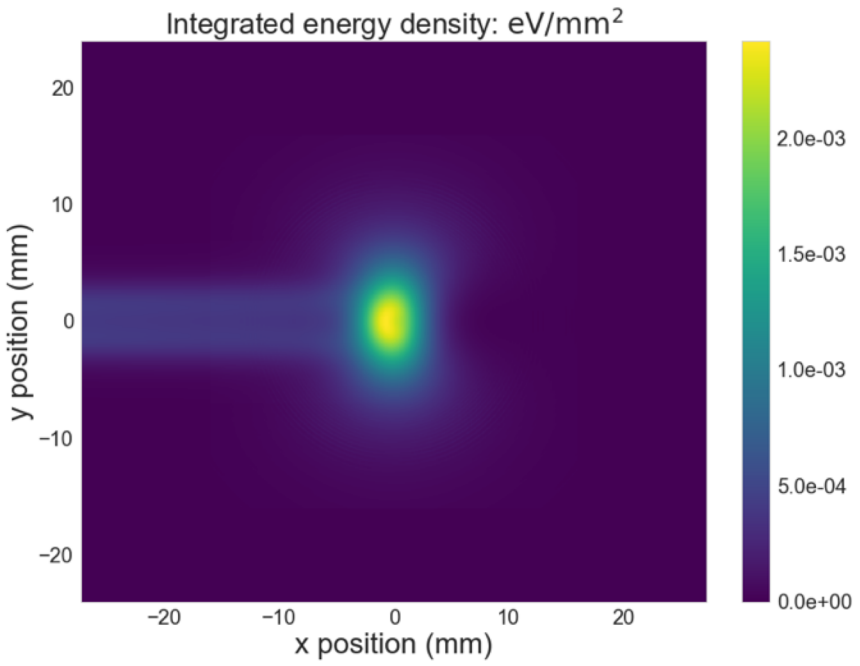


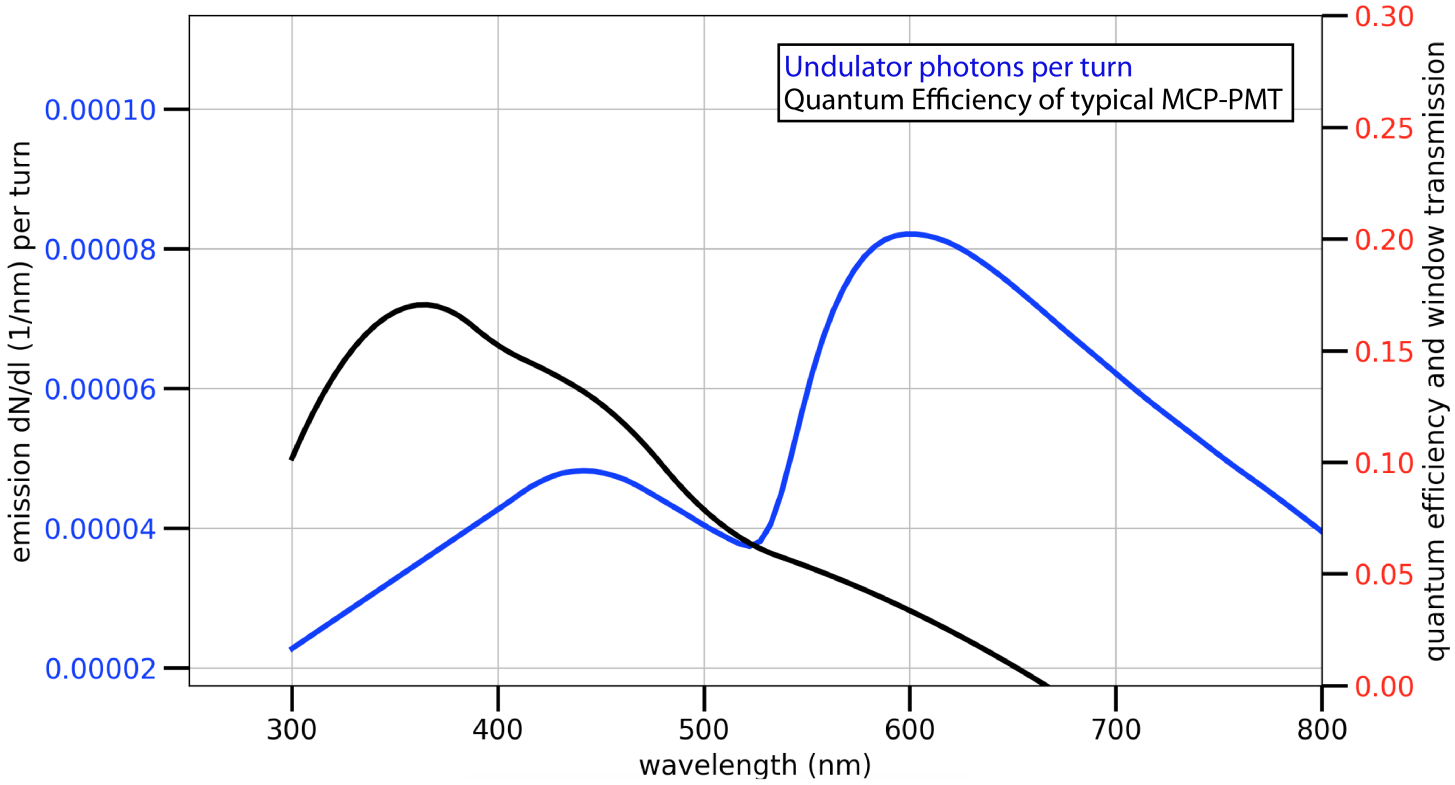


About 1 cm diameter charge sharing

Threshold trigger biases statistics toward strip-line centers

The undulator





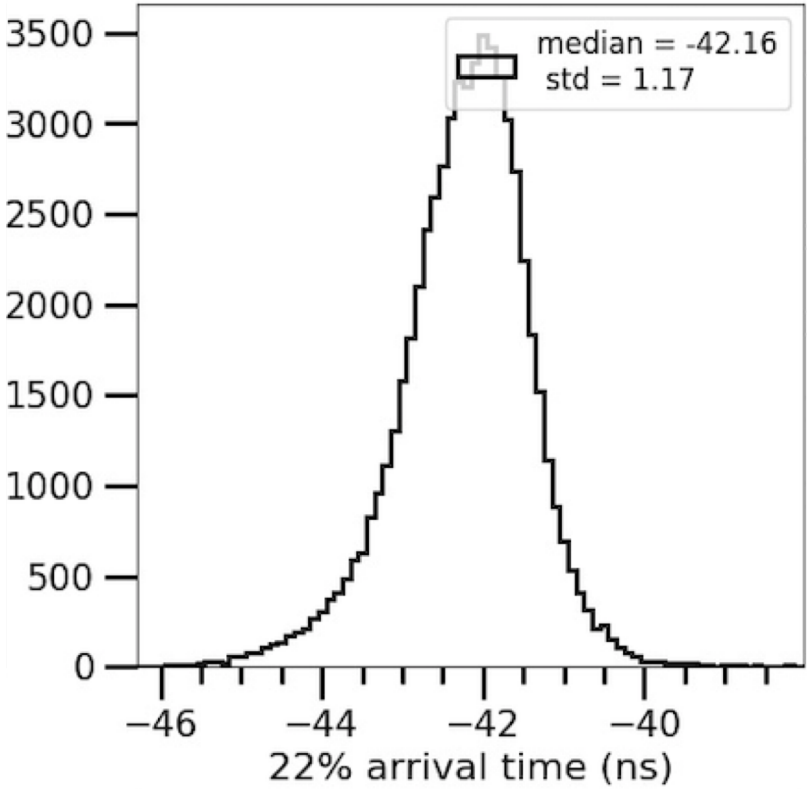
Dipole and undulator radiation in all wavelengths at 3.5 m from center of undulator (location of dark-box)

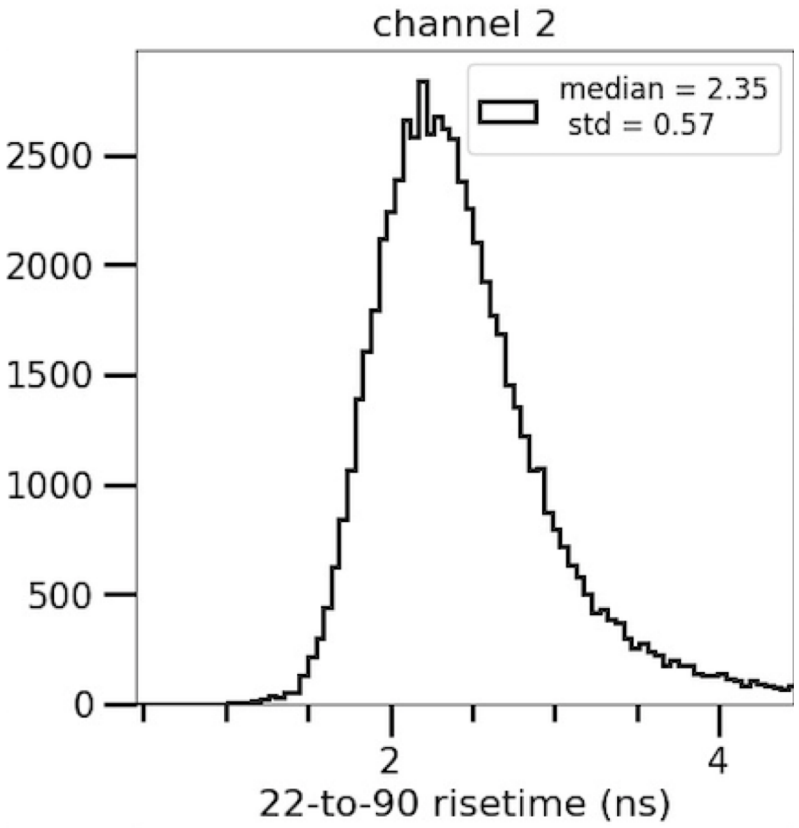
Estimation of rates from this simulated data on next slide

[4] Ihar Lobach, Valeri Lebedev, Sergei Nagaitsev, Alexander Romanov, Giulio Stancari, Aliaksei Halavanau, Zhirong Huang, Kwang-Je Kim. "Intensity Fluctuations in Undulator Radiation". To be submitted to PRAB. 2019

[5] Code for calculations of undulator emissions found at https://cdcvs.fnal.gov/redmine/projects/fur/files

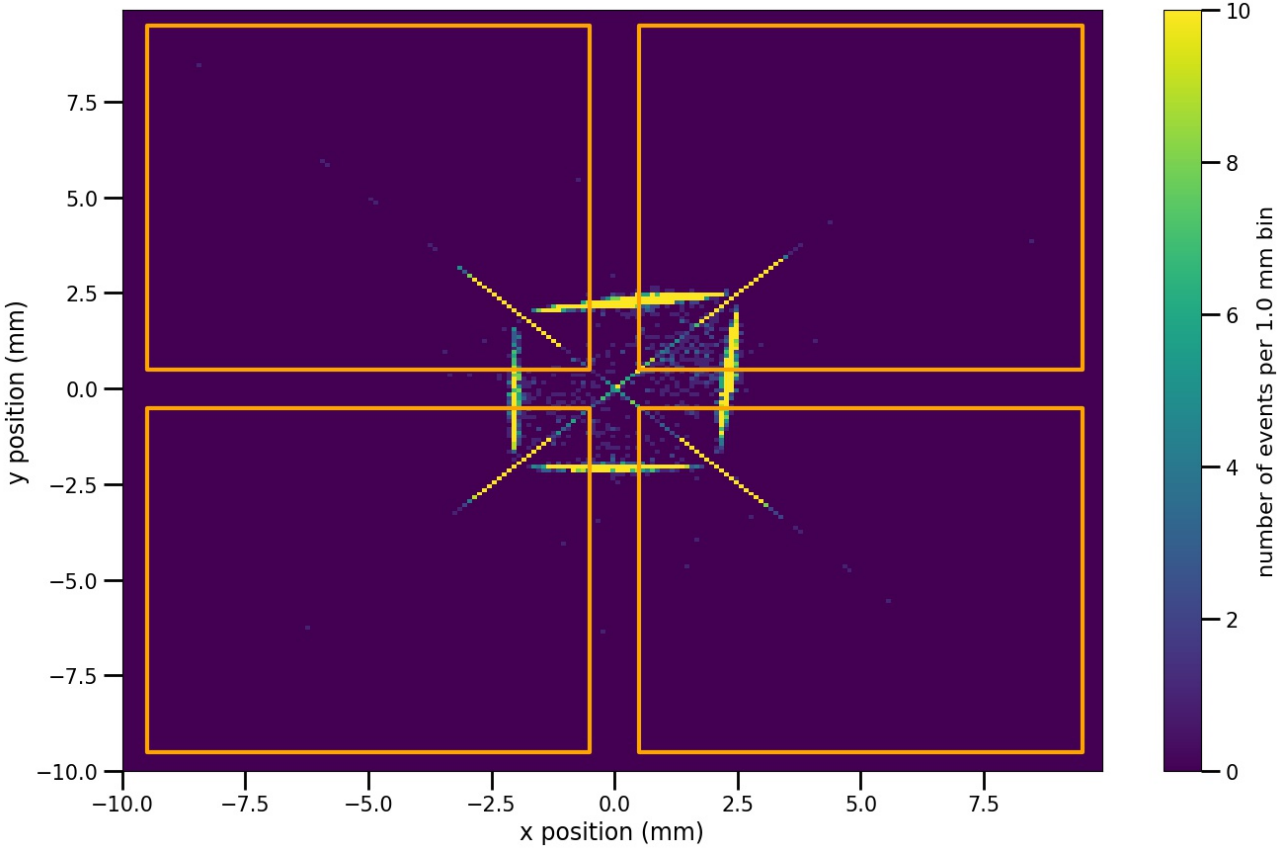
Time of arrival of pulses relative to RF-gated discriminator trigger



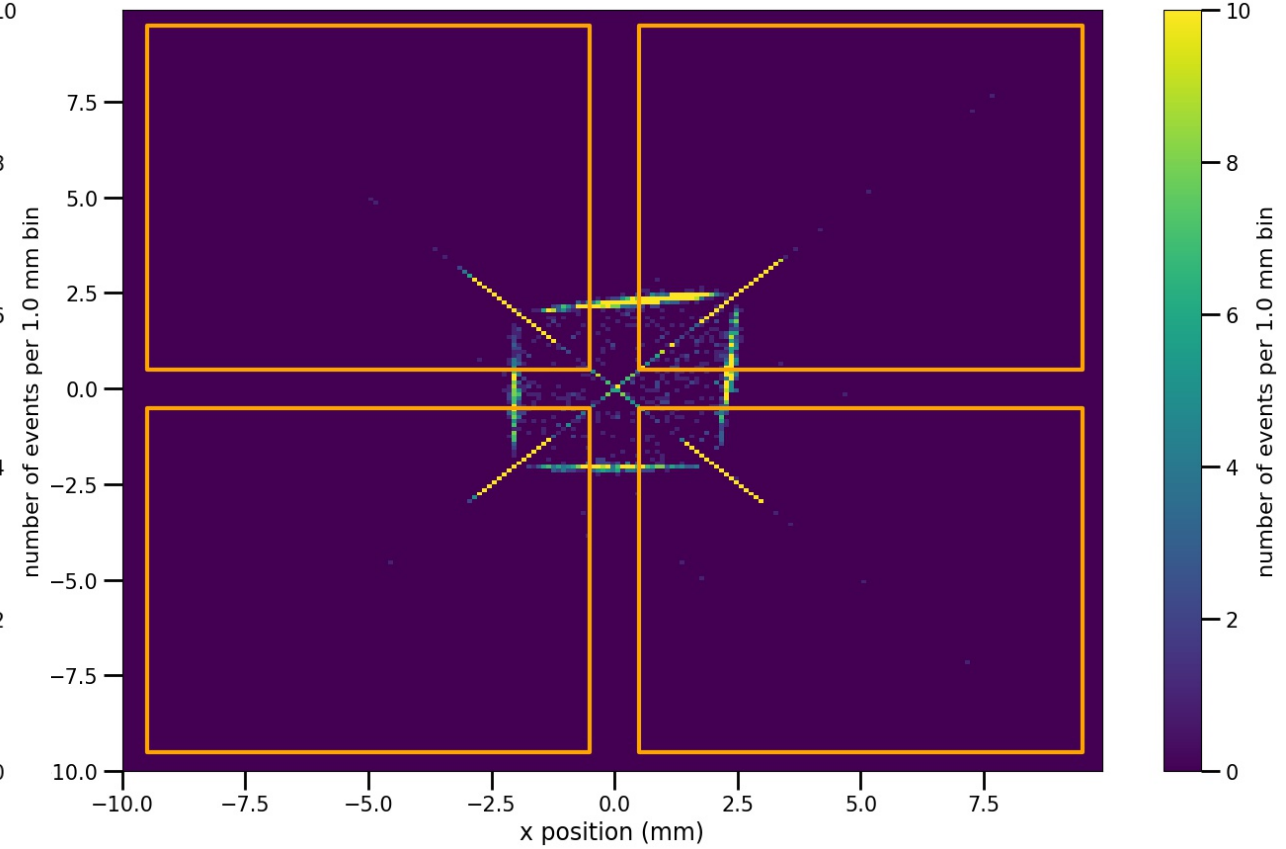


Pulses are always in a small window (not related to undulator length) relative to scope trigger. Used to identify / integrate pulses

Only accepting pulses with charge above threshold



1-electron circulating, 460k events



0-electron circulating, 225k events

With this coarse pixelization, positions are very dependent on data interpretation