Toward reading out a full-body LaBr3 TOF-PET scanner using waveform digitization

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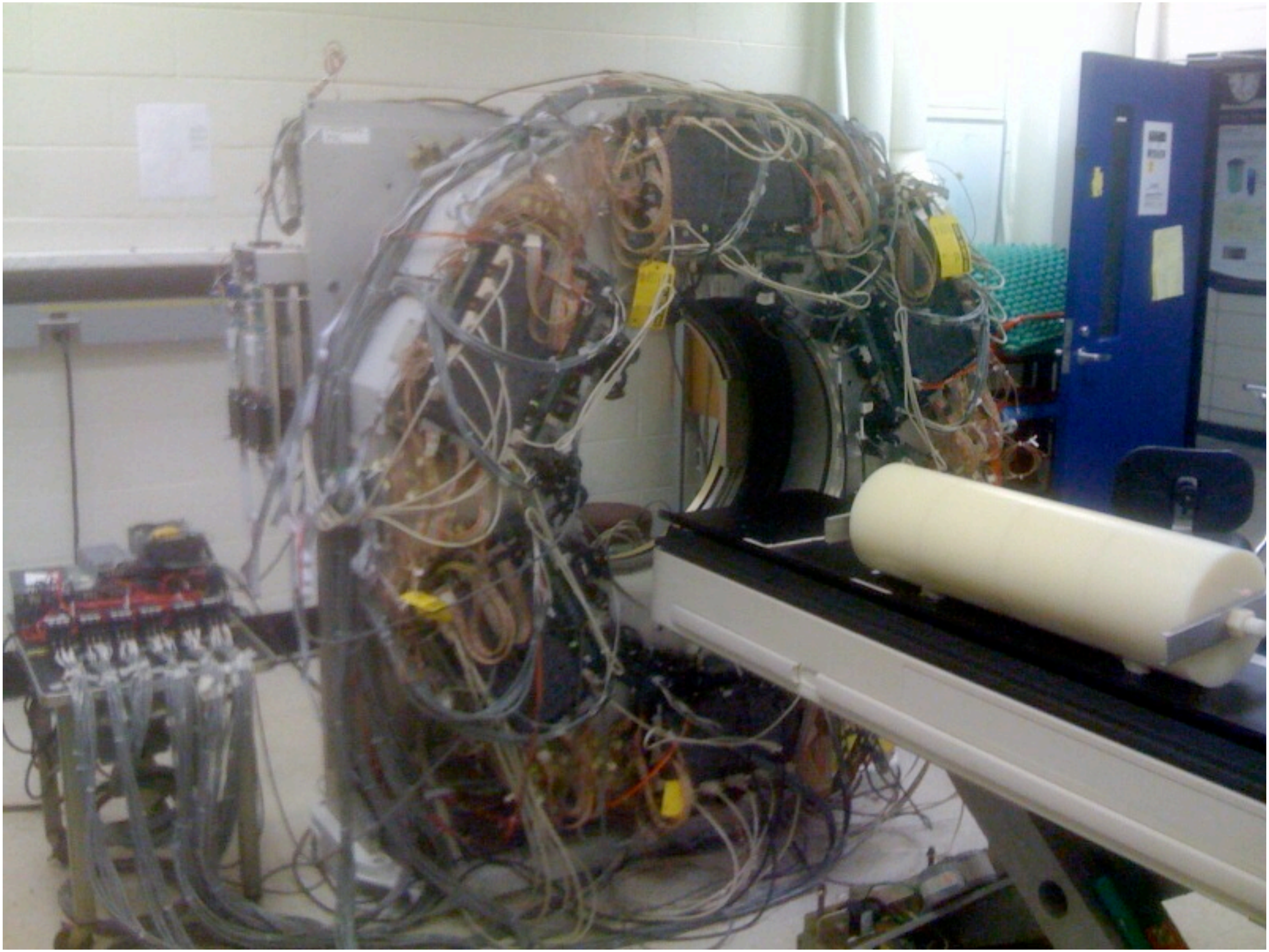
Motivation

- Existing $LaBr_3$ TOF-PET scanner
  - Significant investment -- hardware and experience
  - Performs well: 375 ps -> 420 ps vs. count rate
  - Can we do substantially better, making optimal use of existing hardware?
    - “best” region’s performance (~330ps) -> full system
      - more handles for calibration
    - low-rate performance -> realistic clinical rates
      - detect/correct/reject pile-up events
    - optimal extraction of timing info from PMT signals
      - could one do better than leading-edge benchtop results?



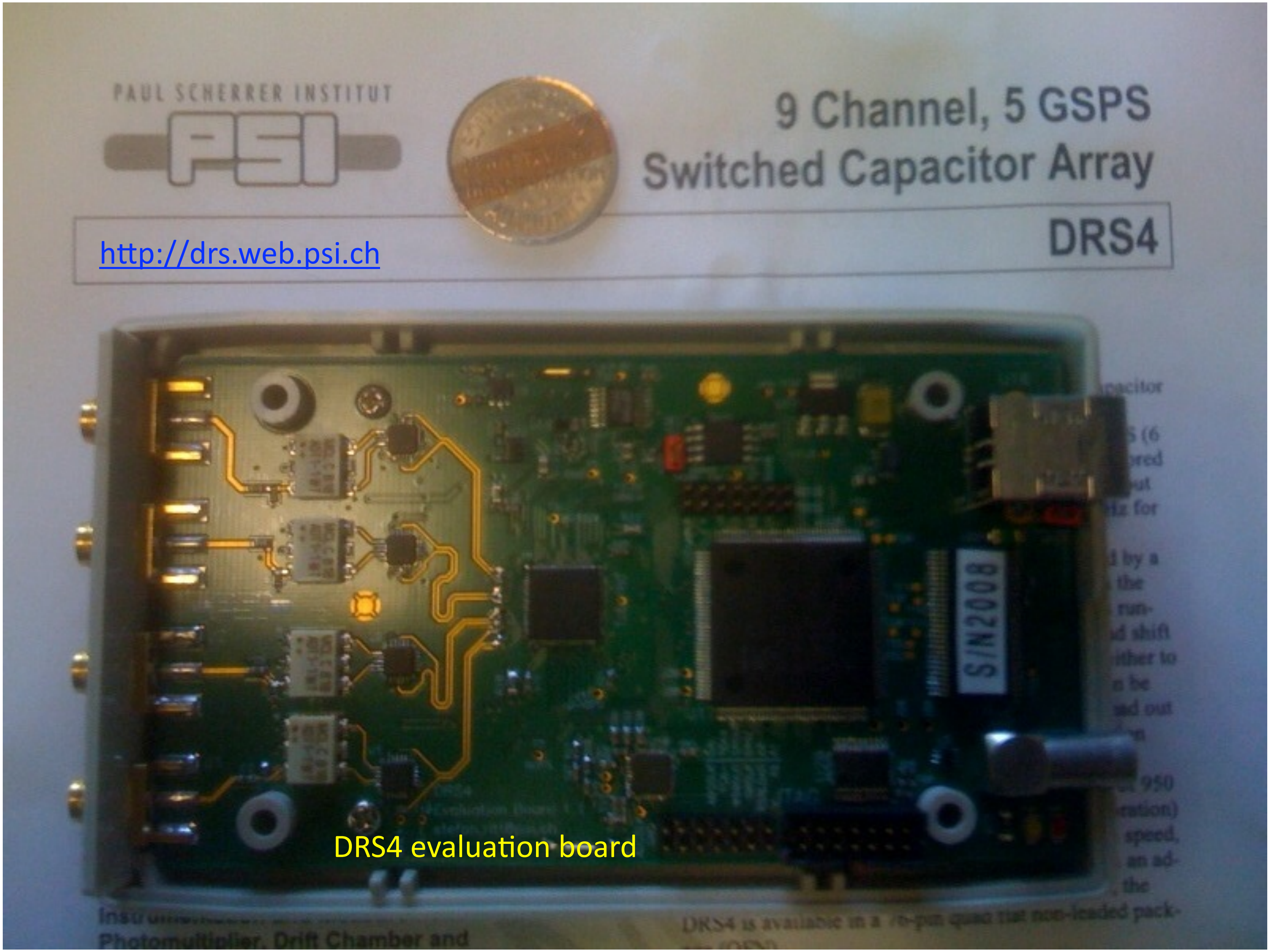
Inspiration

- Genat, Varner, Tang, Frisch `arXiv:0810.5590v1`
  - "We find that timing using pulse waveform sampling gives the best resolution in many cases ...."
- New HEP DAQ systems based on SCA ASICs, e.g. MEG/ DRS4 by Stefan Ritt at PSI
  - http://drs.web.psi.ch
- We've made some encouraging benchtop measurements, using commercial digitizer boards
- Experience that digital systems provide more handles for sophisticated processing
- Waveform digitization now looks economically feasible

First Steps

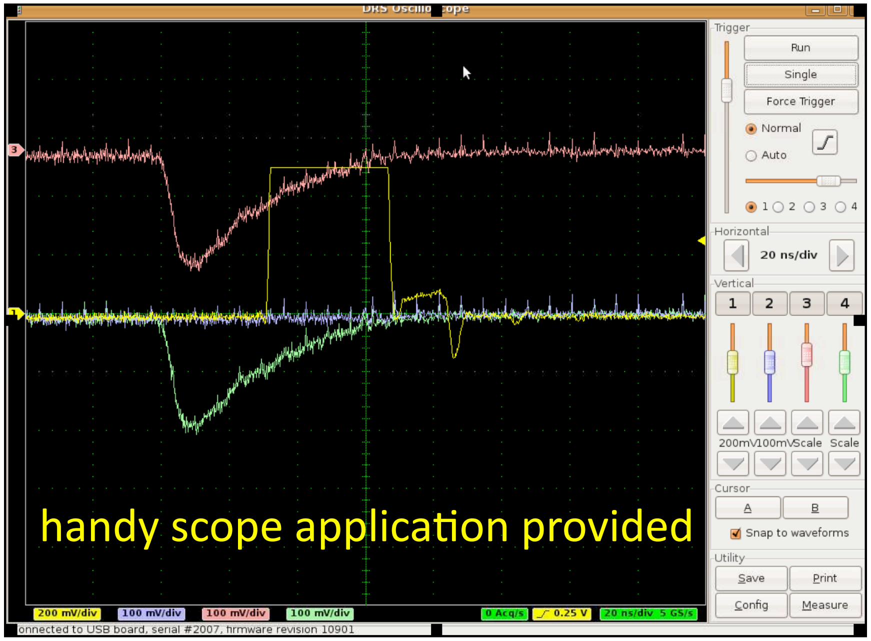
- Obtained two DRS4 evaluation boards 1/2009
- Essentially, a 4ch 5GSPS oscilloscope for ~ $1K
  - and scalable to full system, with custom boards
    - DRS4 chip has 9 channels, costs about $150
  - But some calibration effort needed for best results

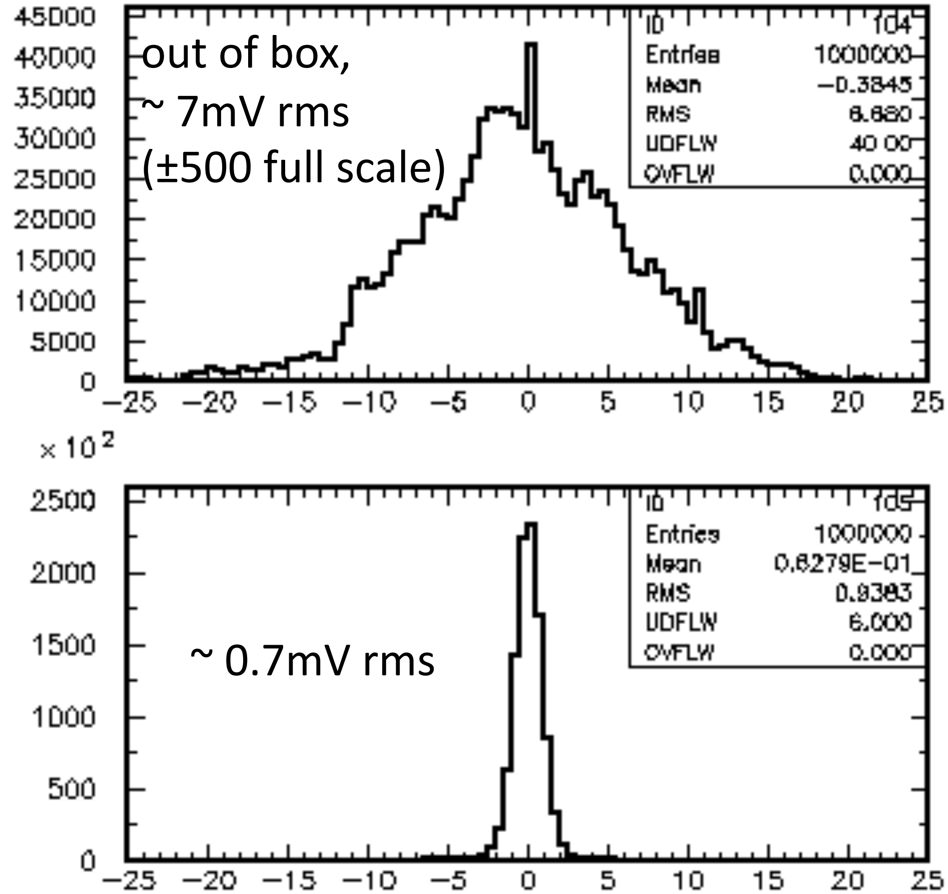
DRS4 evaluation board: http://drs.web.psi.ch

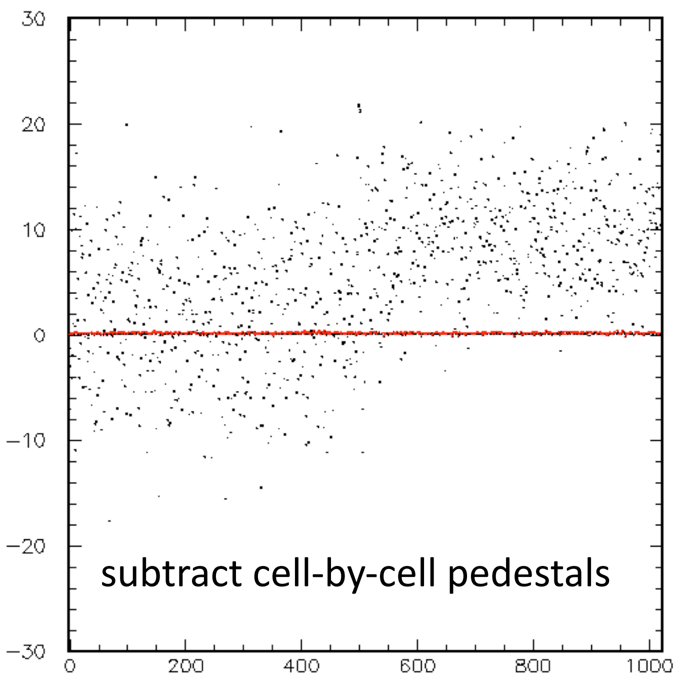


http://drs.web.psi.ch

DRS4 evaluation board

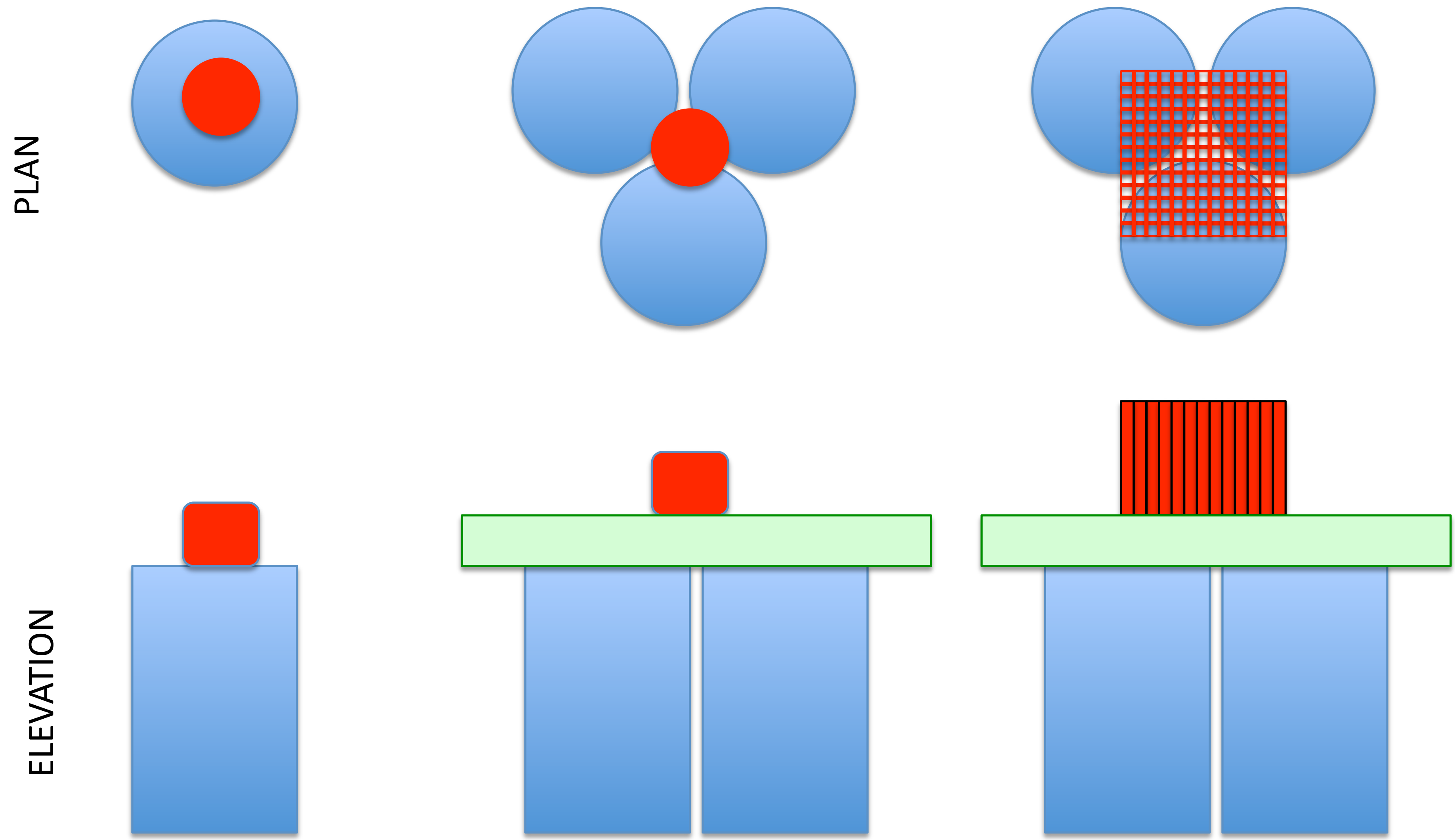






subtract unused chnl to work around artifact every 32 samples – FPGA➔ADC timing fix forthcoming

Other DRS4 users are implementing serious calibration software, so for now I've done just what I need to make progress.



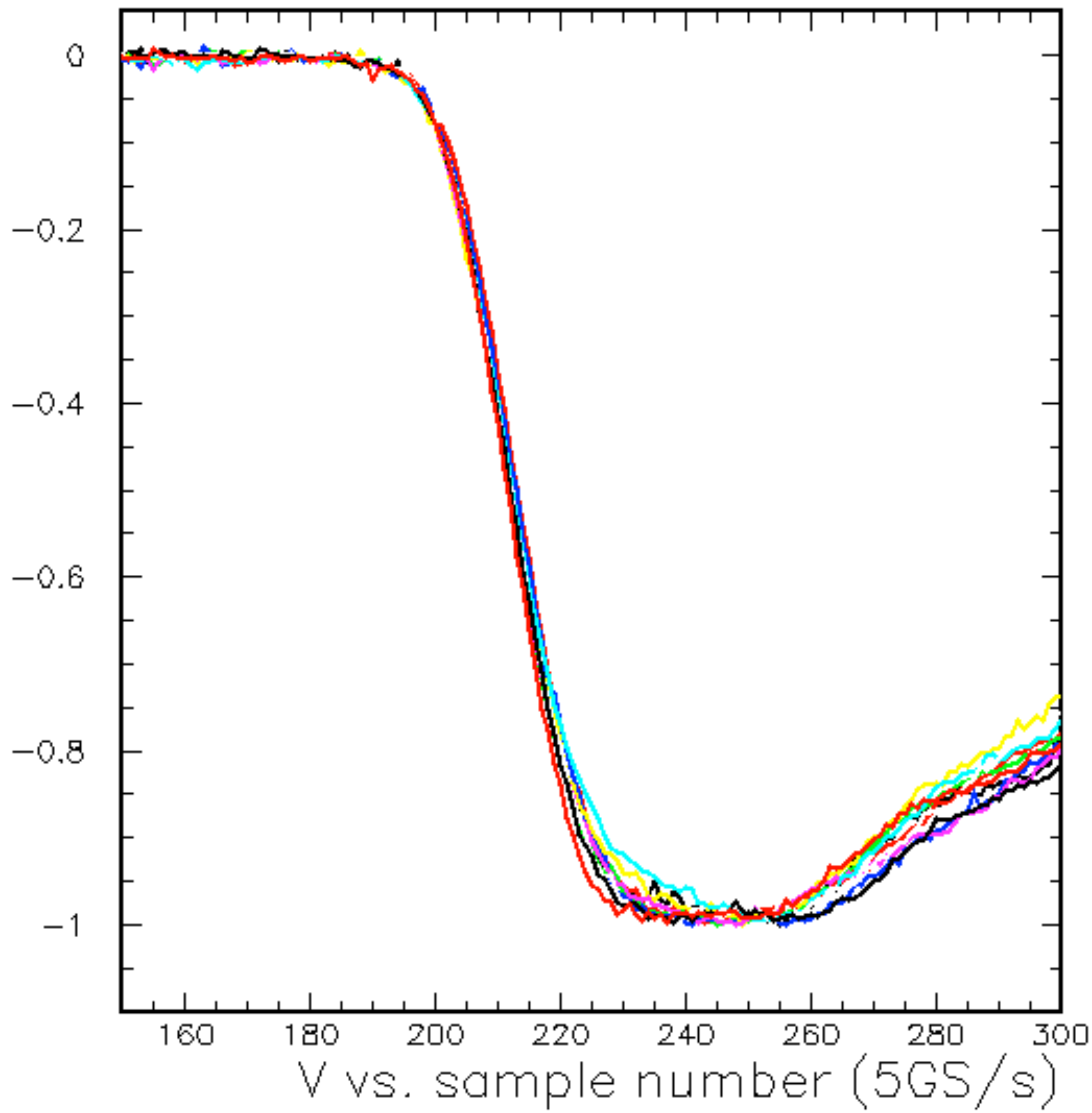
Button / pixels + (light guide) + PMT(s)

- Initial scintillator (LaBr3) +PMT (XP20D0) timing results similar to LE+TDC and to commercial boards
  - Uncertain whether sampling should beat LE+TDC
  - Bench tests continue

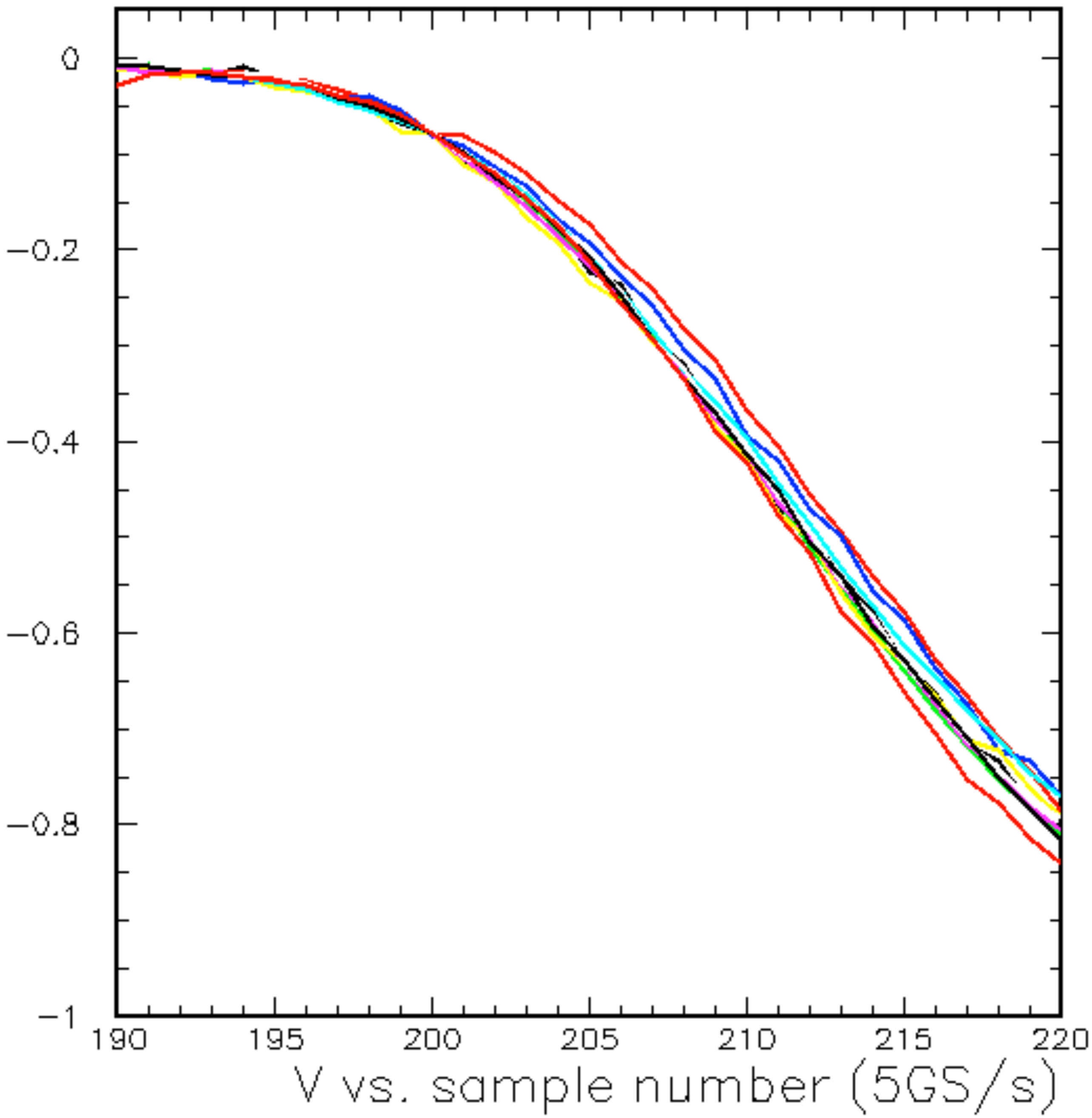
Configuration	LE discr + TDC	Agilent 2 GS/s	DRS4 5 GS/s
split signal from 12mm button on PMT	50 ps fwhm	50 ps fwhm	25-70 ps fwhm
2 x (button on PMT), positron source	205 ps fwhm	220 ps fwhm	202 ps fwhm
button where 3 PMTs meet vs. button on 1 PMT	277 ps fwhm	236 ps fwhm (270 before software time alignment)	
pixel array where 3 PMTs meet vs. button on 1 PMT	345 ps fwhm	325 ps fwhm	

Questions at this stage

- What is optimal method to extract event time from PMT pulse?
  - Pulse shapes not identical
  - What optimizes Δt(two copies of same pulse) may not optimize Δt(two sides of same positron decay)
  - e.g. in template fit, assigning weights to samples?
- Optimal sampling rate?
  - timing resolution vs. dead time, data throughput
- Optimal test bench?
  - β^+ source + 2*(crystal+PMT) vs. pulser vs. ...
    - pulser more easily reveals small effects in electronics
    - variability of real pulses needed to predict real timing resolution



0
−0.2
−0.4
−0.6
−0.8
−1
160
180
200
220
240
260
280
300
V vs. sample number (5GS/s)



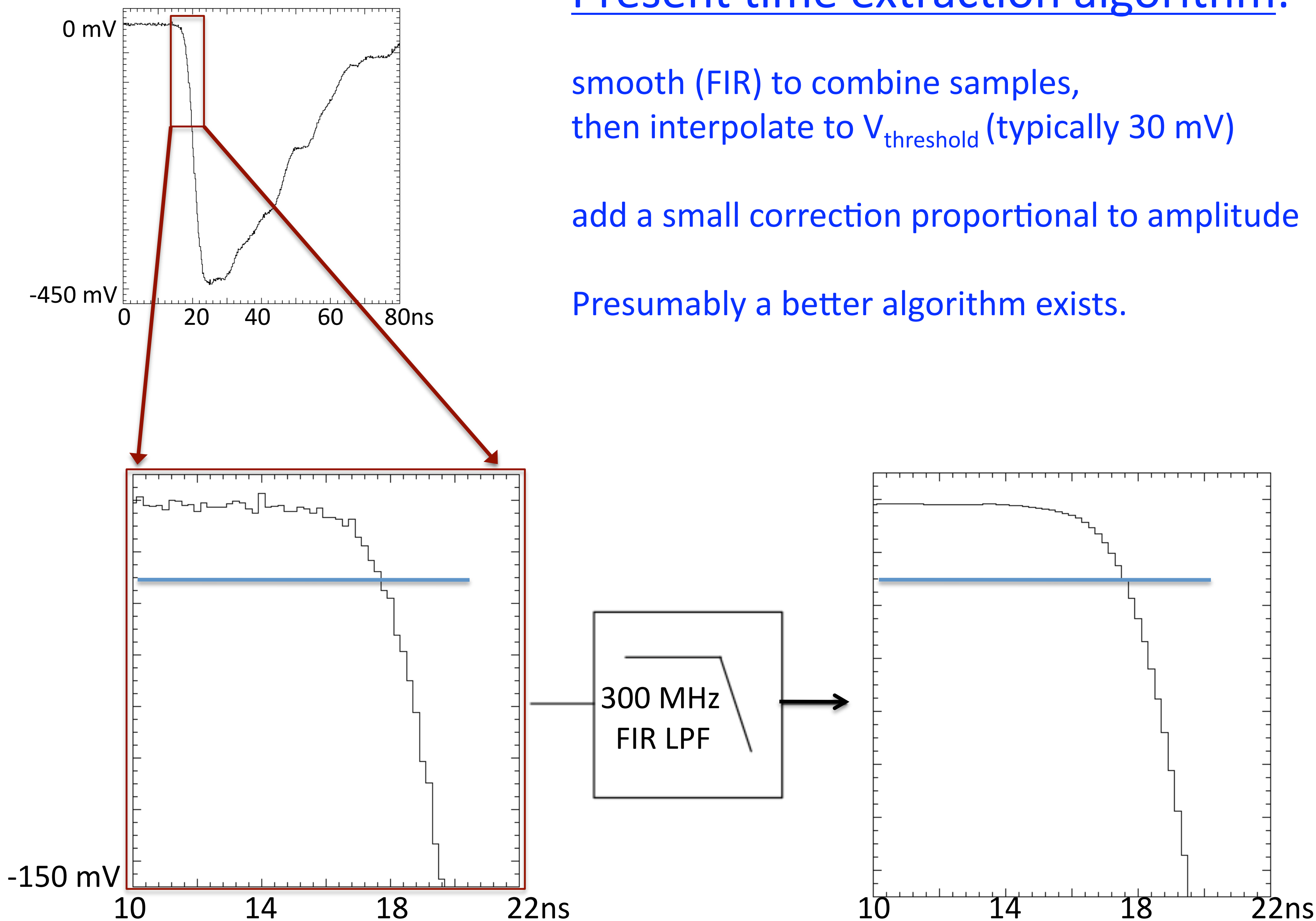
0
−0.2
−0.4
−0.6
−0.8
−1
190
195
200
205
210
215
220
V vs. sample number (5GS/s)

Present time extraction algorithm:

smooth (FIR) to combine samples,
then interpolate to $V_{threshold}$ (typically 30 mV)

add a small correction proportional to amplitude

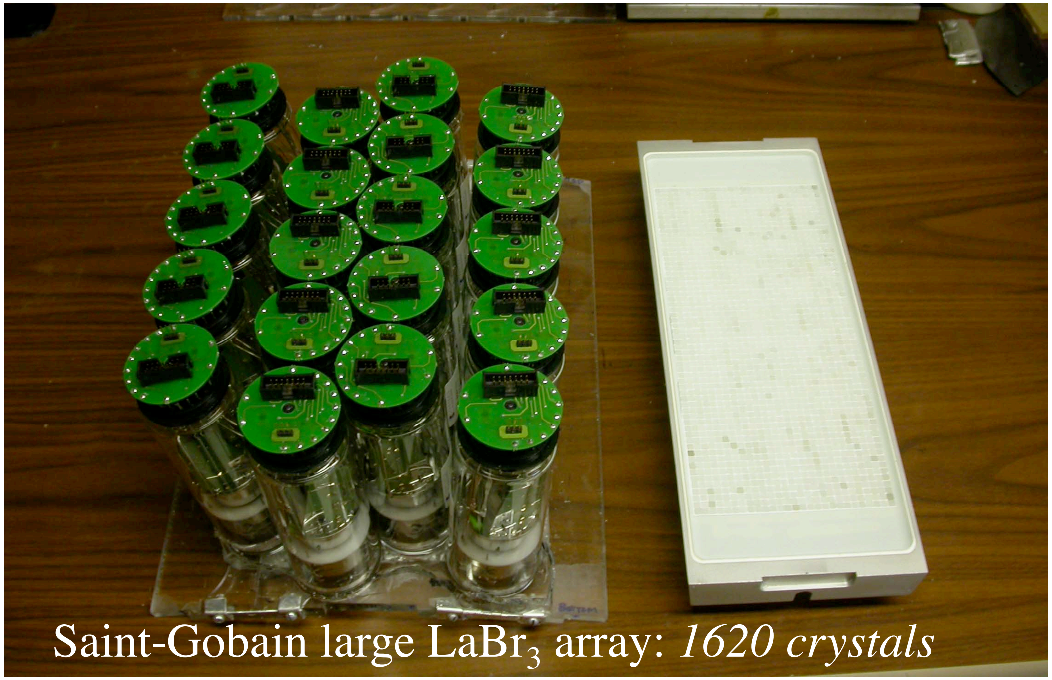
Presumably a better algorithm exists.

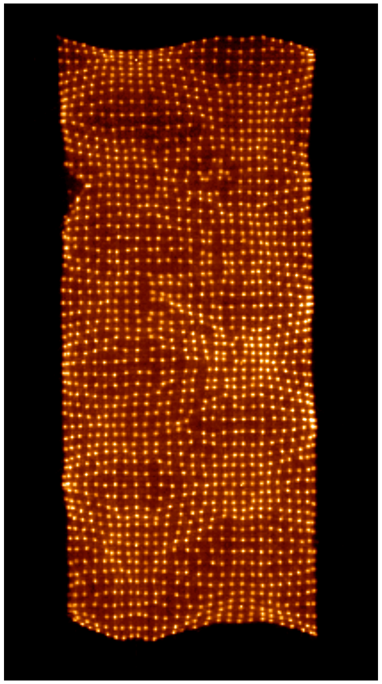


Next steps: custom board

- In coming months, we plan to design a PCB to read 24 PMTs with 10 (?) DRS4 chips
  - Handle 1/24 of LaPET's 432 PMTs (24x18: overlap)
  - Test with spare LaPET modules (1/24 in azimuth)
  - Spin off: read out proton therapy PET prototype

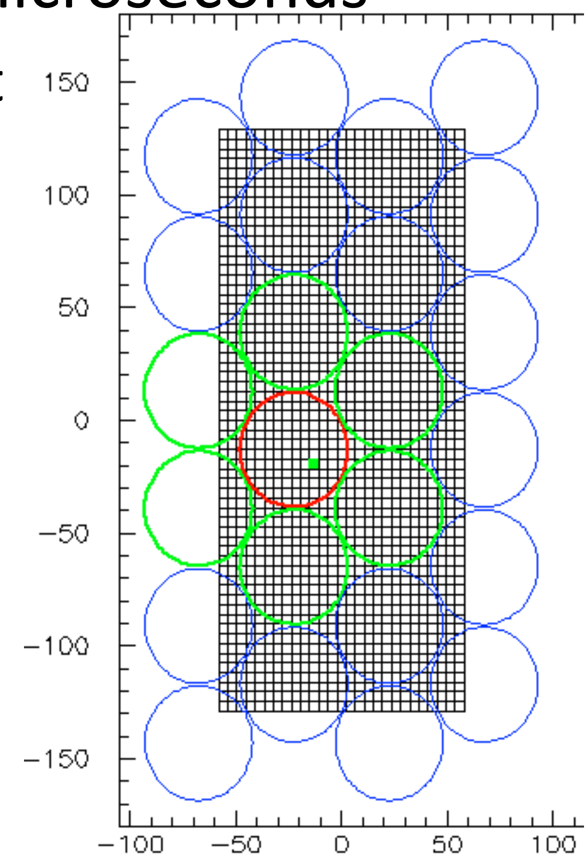
Module geometry: 27x60 array of $4x4x30mm^3$ $LaBr_3$(5% Ce) crystals, imaged by 24 Photonis XP20D0 PMTs

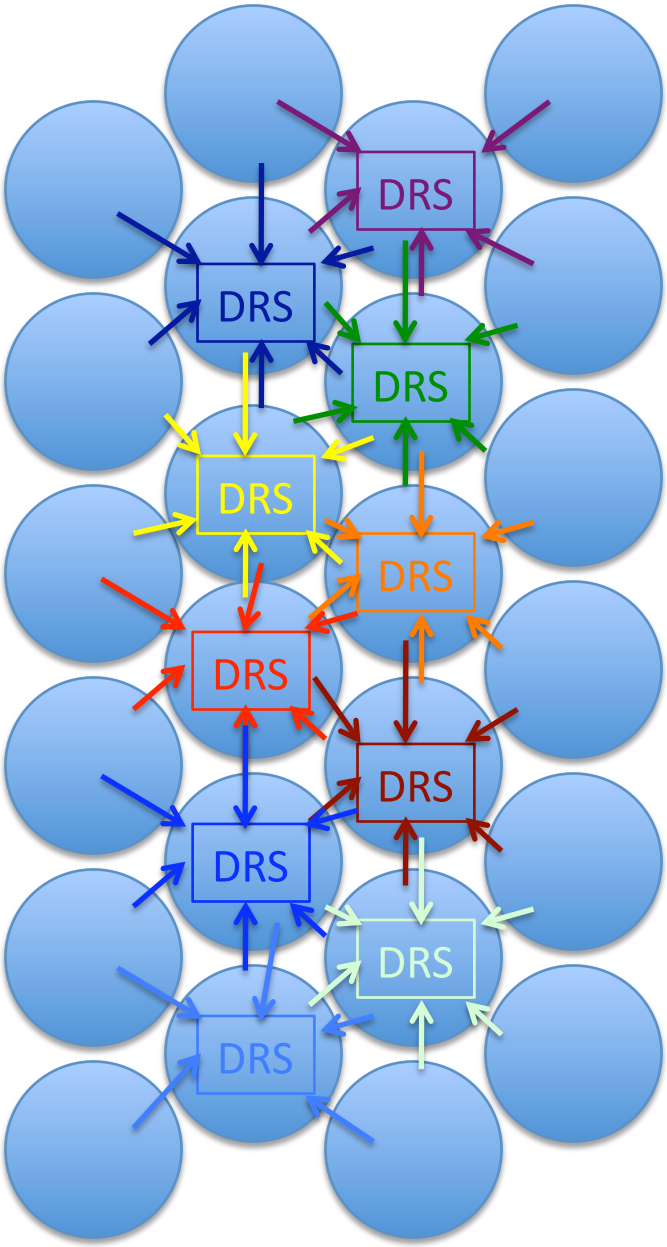




Next steps: custom board

– One DRS4 samples 7 PMTs + global clock
– Only one DRS4 chip needs to be stopped for readout, to collect all useful light from interaction
– Readout at 33 MSPS takes a few microseconds
  - Must be selective before reading out





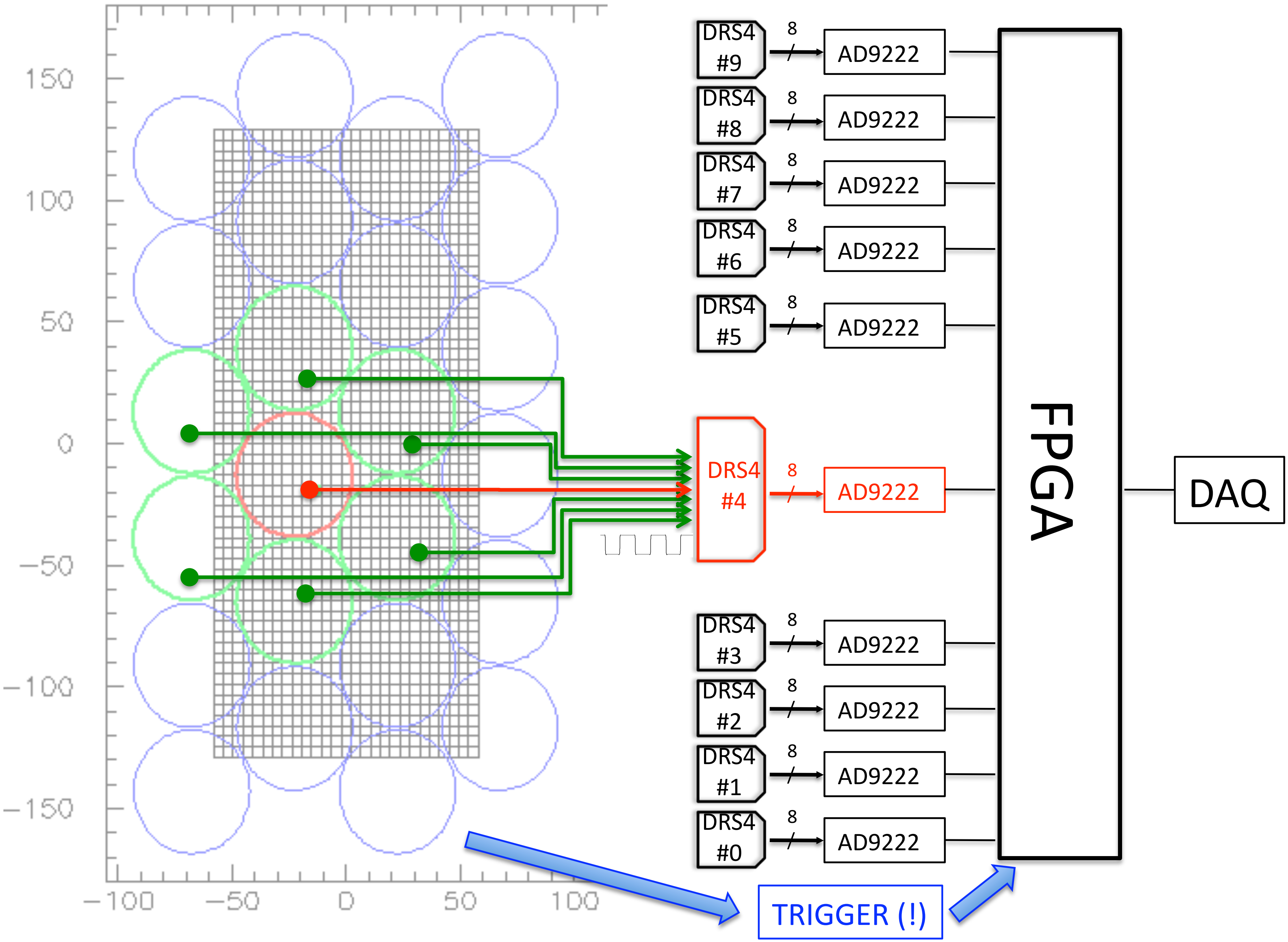
<u>hypothetical readout design</u>:
assign one DRS4 to each of the central 10 PMTs and its 6 (or 5) neighbors

a given event requires only one DRS4 to be stopped for readout

builds in some redundancy – in many cases can still collect most of the light from a second event nearby, if first-choice DRS4 is busy with readout

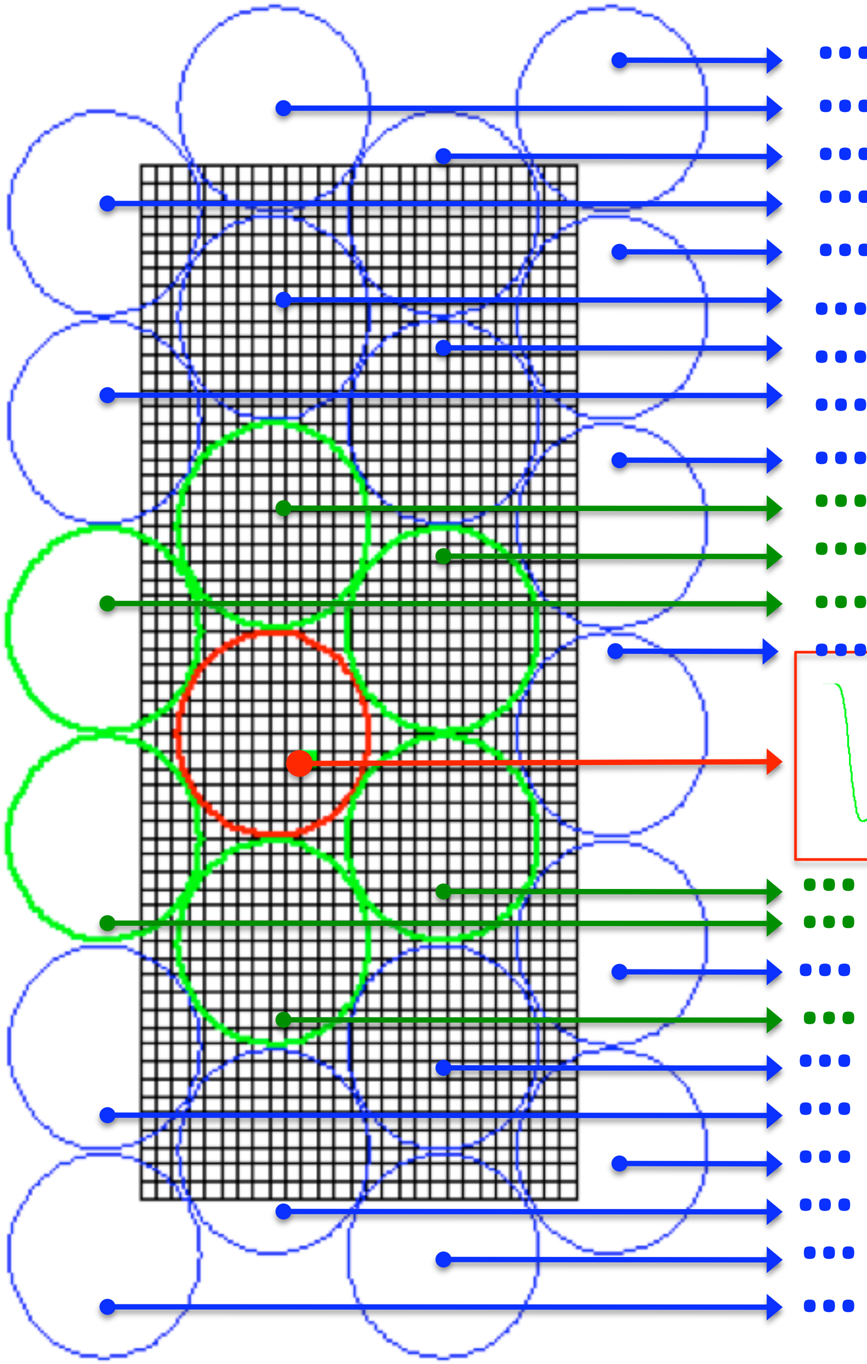
requires smart trigger

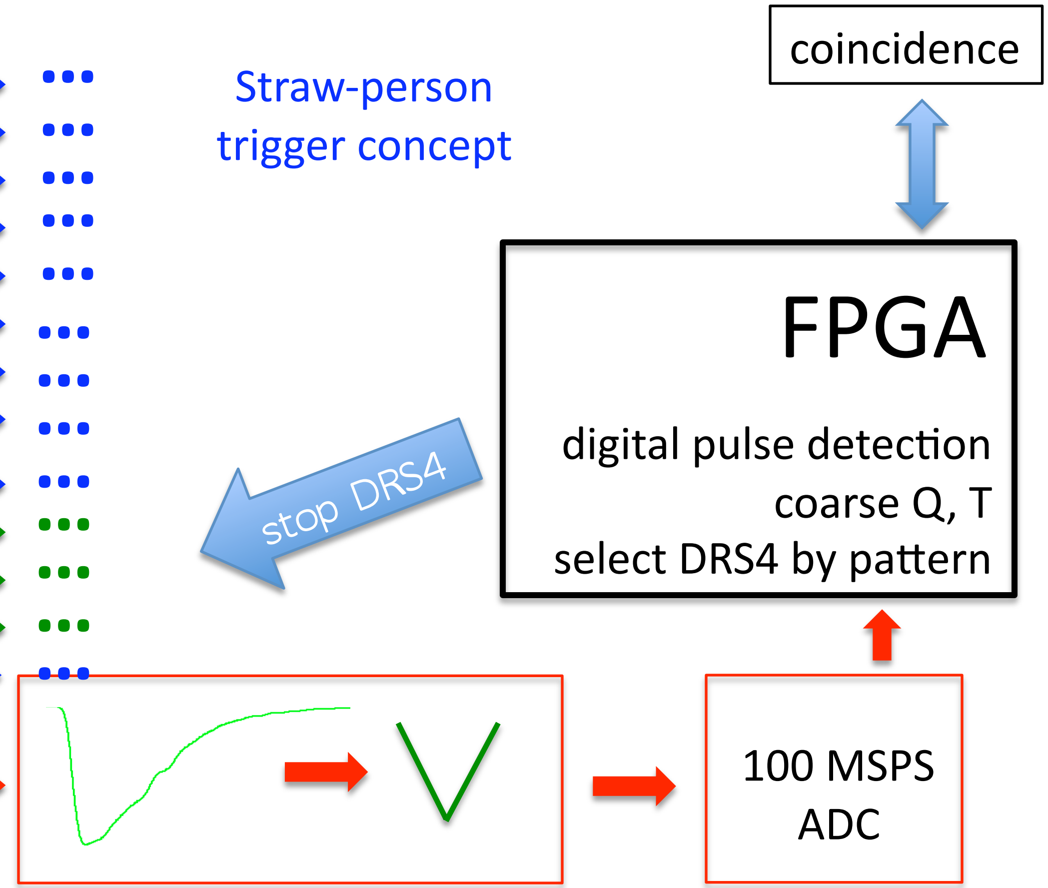
details/rates need careful study



150
100
50
0
−50
−100
−150
−100
−50
0
50
100
DRS4 #9
DRS4 #8
DRS4 #7
DRS4 #6
DRS4 #5
DRS4 #4
DRS4 #3
DRS4 #2
DRS4 #1
DRS4 #0
8
AD9222
FPGA
DAQ
TRIGGER (!)

Straw-person trigger concept





- Shape & sample every PMT signal
  - rise + fall in 10 + 10 ns
- Measure Q to ~ 5% ?
  - Coarse positioning possible?
- Measure time to 1ns or better
- If coincidence in 5 ns window, stop DRS

Design issues for 24-PMT board

- Trigger will be challenging. Present concept:
  - Shape & sample all PMT signals at ~ 100 MSPS
  - Measure E well enough to suppress Comptons
  - Measure t well enough to form coincidence
  - If passes, pick a single DRS4 to stop for readout
- Work through details using toy simulation of correlated occupancies, pulse shapes, etc.
  - Gain confidence that chosen algorithms & data flow will work well at clinical rates

Concluding thoughts

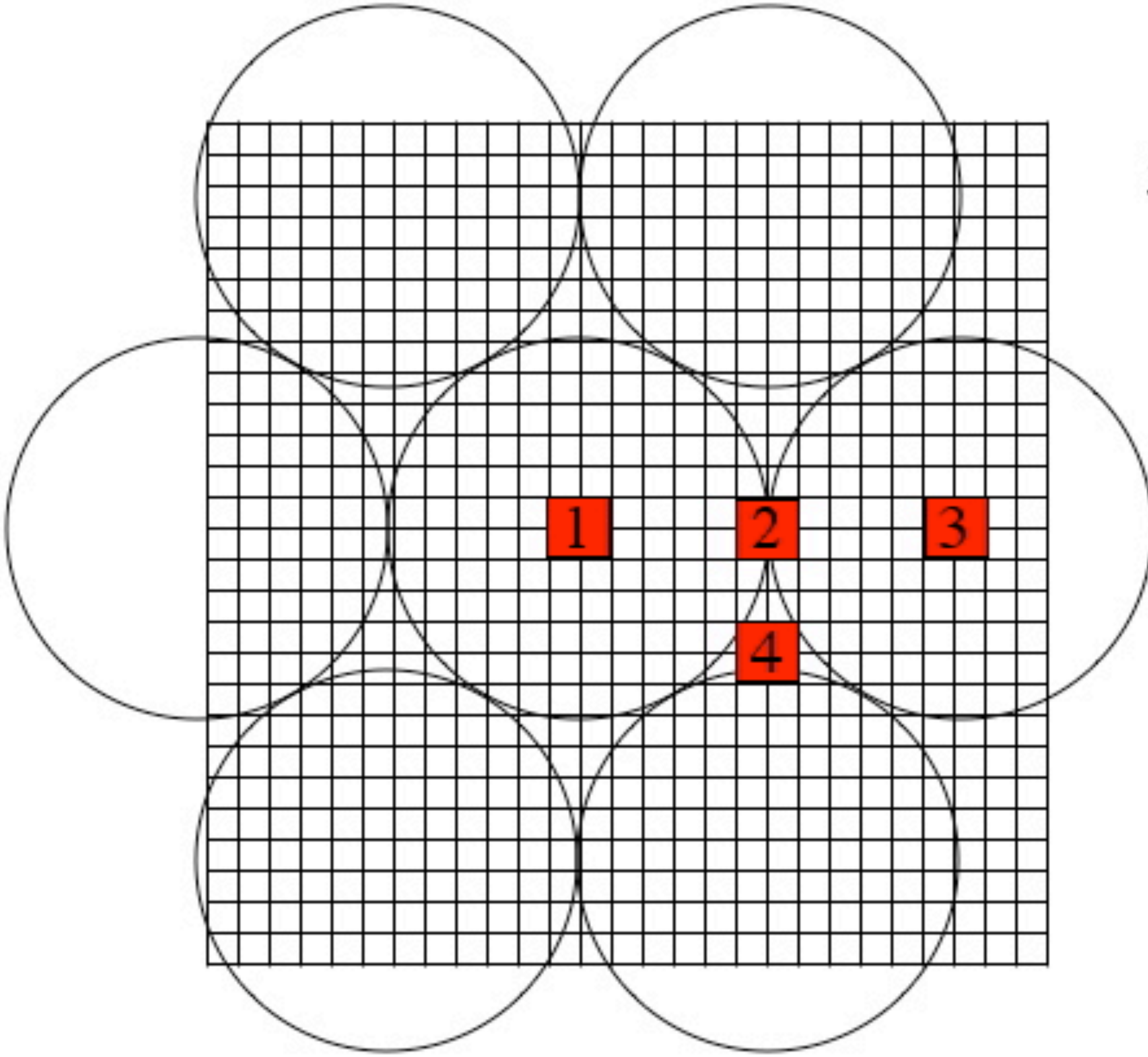
- TOF PET readout using DRS4 looks feasible
  - working to flesh out design in coming months
- We intend to build boards that
  - improve this scanner's performance
  - can potentially be used more broadly
- If you're considering something similar (for PET or HEP), perhaps we can keep in touch
- Feel free to email tips, tricks, or pointers to literature: ashmansk@hep.upenn.edu
  - We are particularly interested in fundamental understanding of pulse shapes for crystal+PMT, for optimal extraction of event time

backup

- backup slides

Dependence of timing resolution on pixel location

7 PMT Cluster

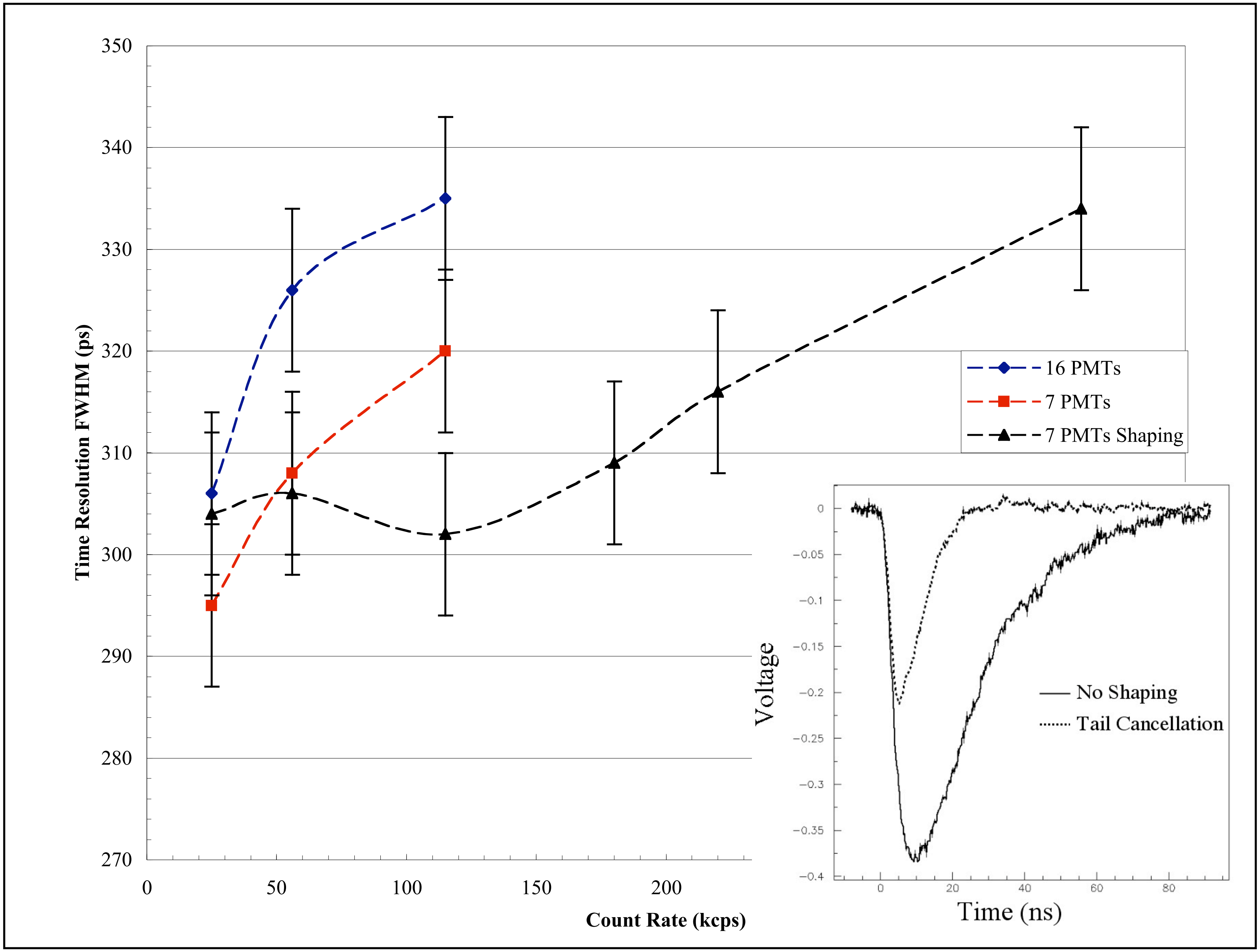


5%Ce LaBr vs. Plastic

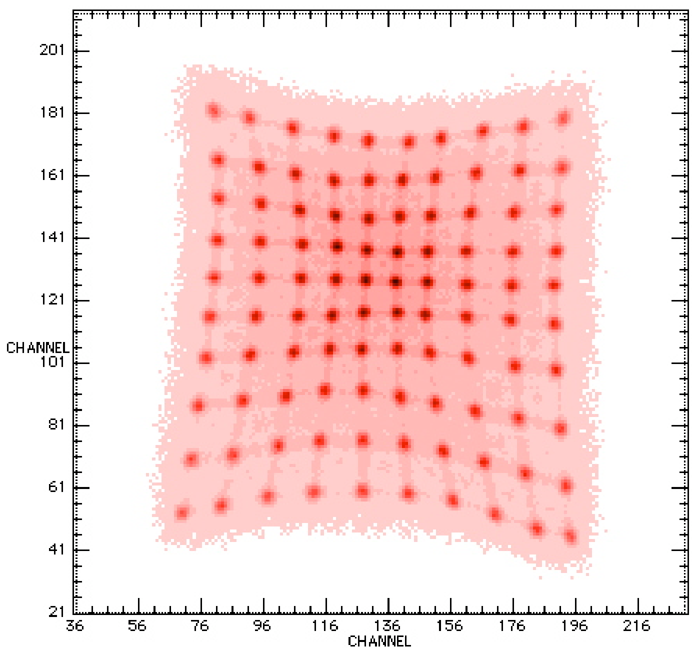
Position	Time Res. (ps)
1	295
2	326
3	338
4	345

Each Position is an average of the time resolution for 4 crystals

Dependence of timing resolution on activity

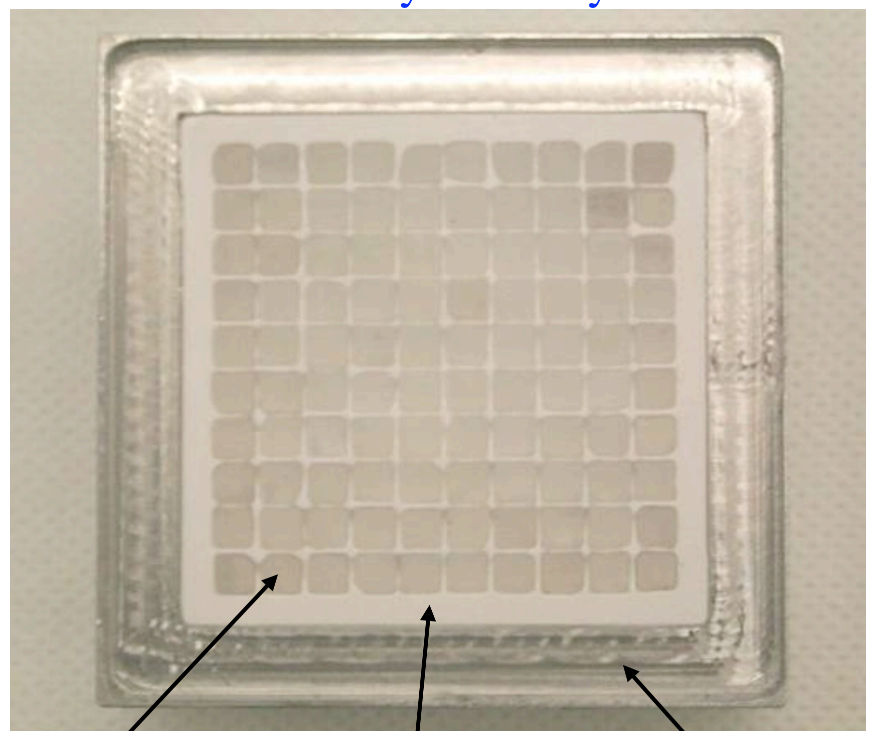


$LaBr_3$ Crystal Arrays



Measured 2D flood

100 Crystal Array



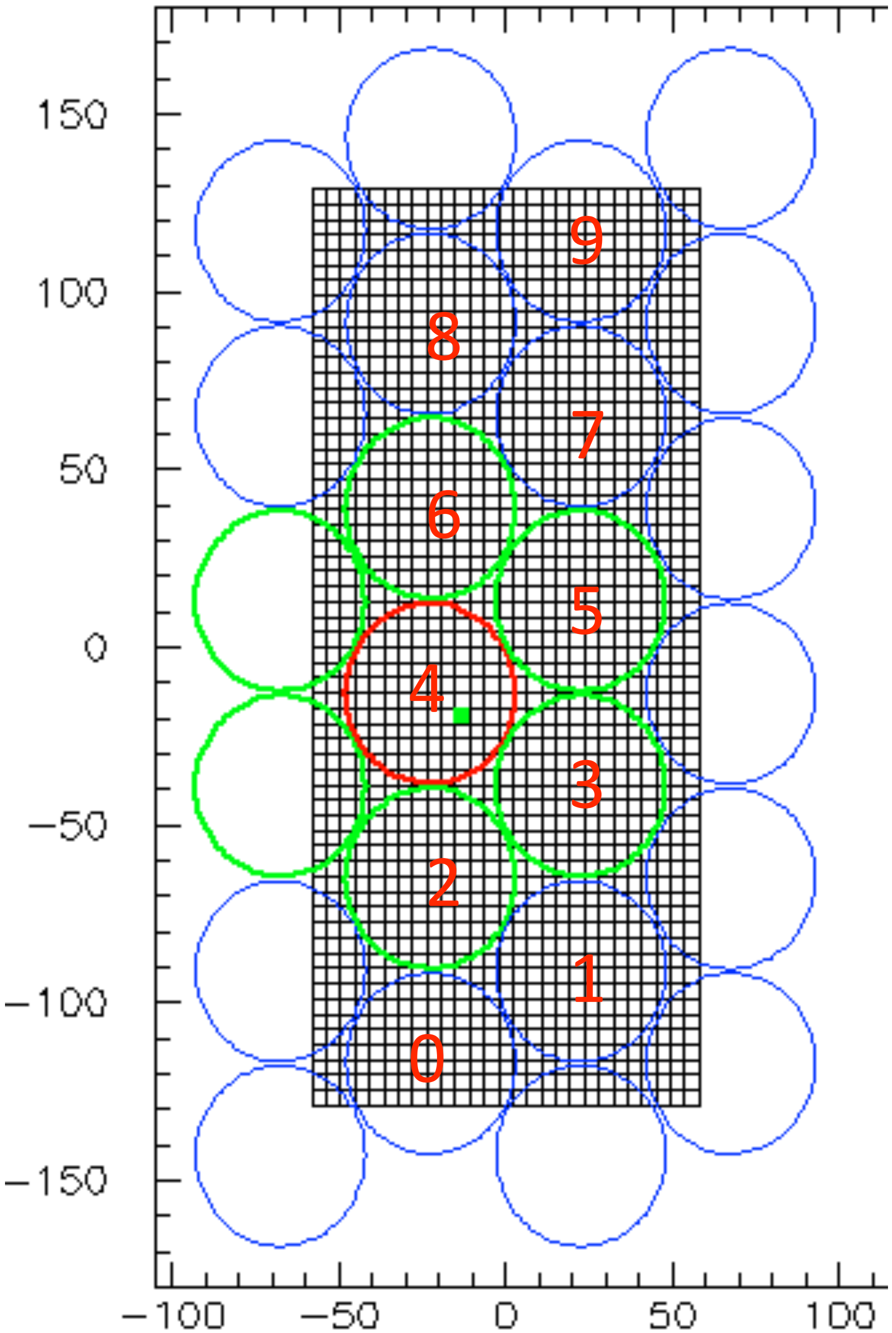
Crystal

Reflective Powder

Aluminum Housing

$\Delta E = 5.1\% \pm 0.4\%$ (fwhm)
Photonis 50-mm PMTs

Saint-Gobain Crystals



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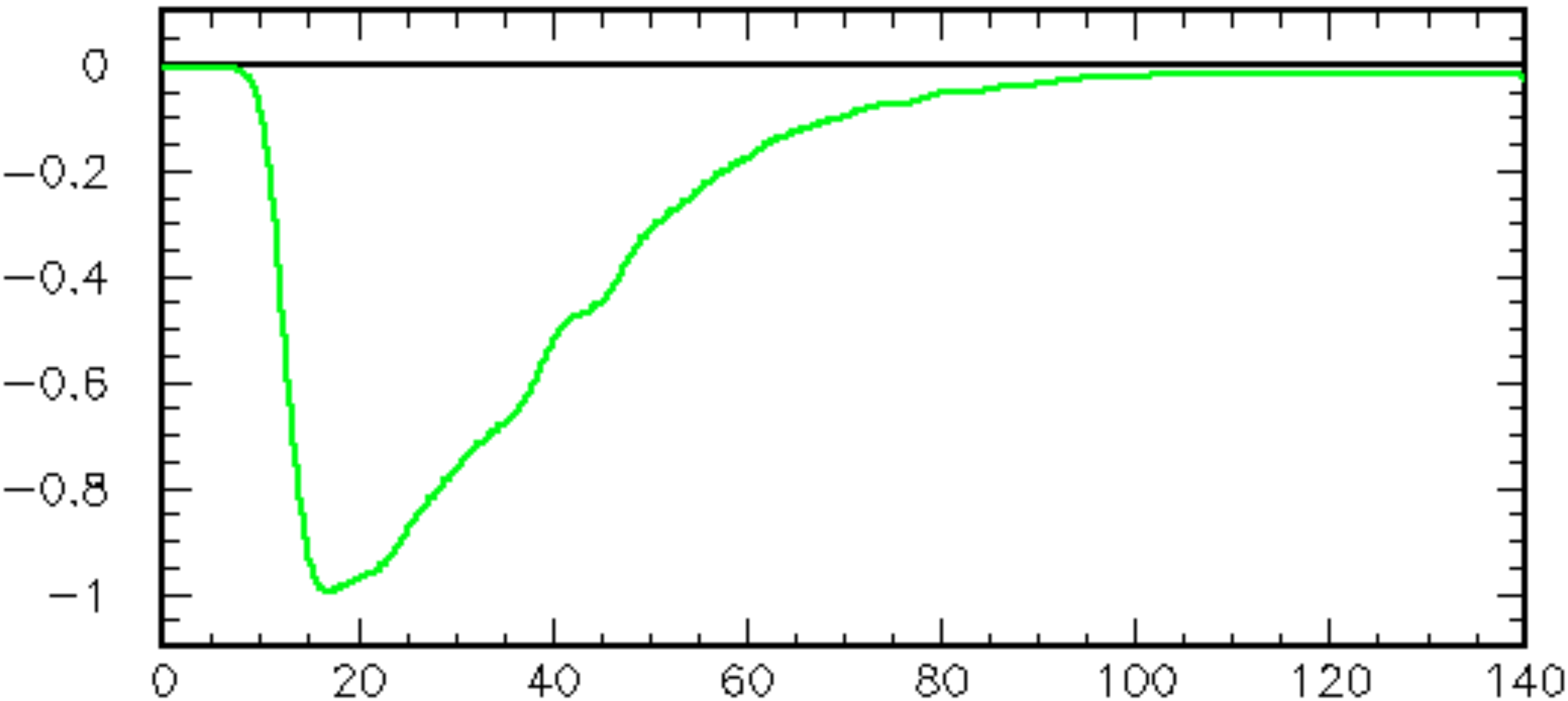

0
−0.2
−0.4
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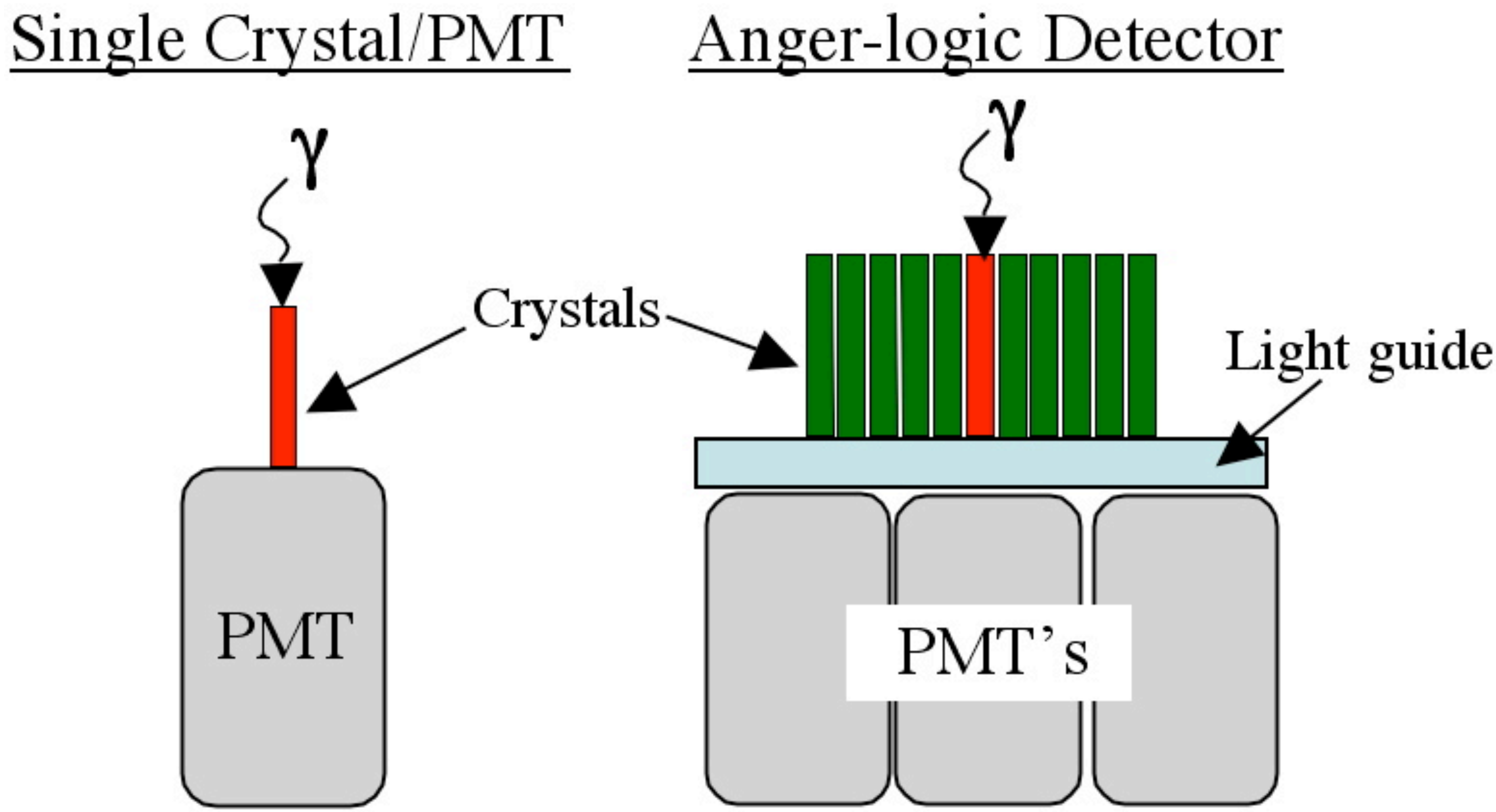
20
40
60
80
100
120
140


Single Crystal/PMT
Anger-logic Detector
γ
γ
Crystals
Light guide
PMT
PMT's

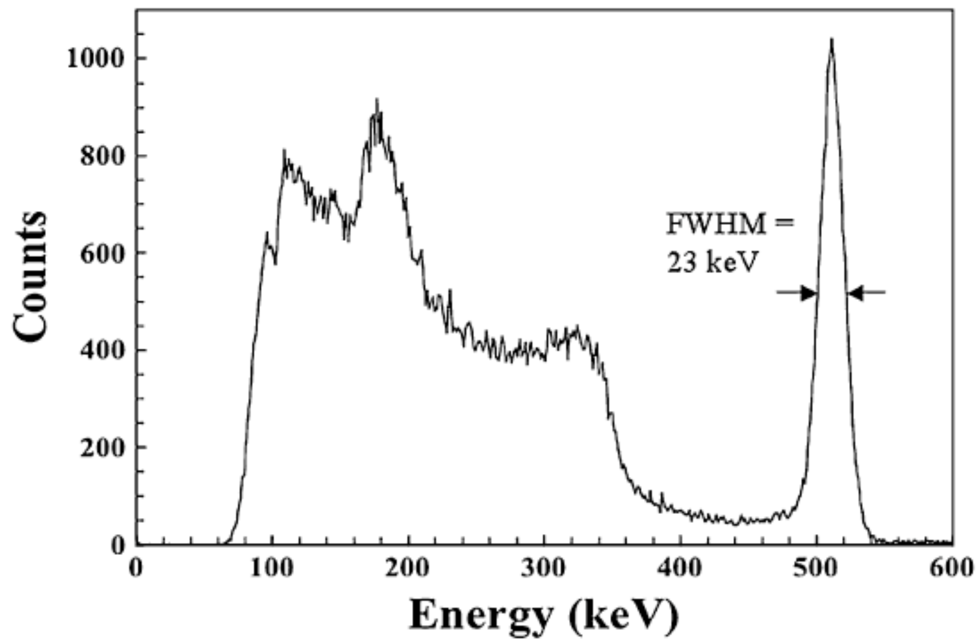


Fig. 3. Energy spectrum measured at 511 keV with the Saint-Gobain 5.0% Ce $LaBr_3$ (4 mm $\times$ 4 mm $\times$ 30 mm) crystal optically coupled to the center of the PMT photocathode. For this pixel, an energy resolution of 23 keV FWHM $(\Delta E/E = 4.5\%)$ was obtained by fitting the photopeak with a Gaussian distribution.