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A simulator for Timepix-like pixel front-ends

Simulation of HR GaAs:Cr Timepix3

R. Ballabriga[2] H. Bromberger[3] M. Campbell[1]
P. Christodoulou[1,2] X. Llopart[2] P. Smolyanskiy[1]
V. Sriskaran[2] L. Tlustos[1,2] *

[1]IEAP, CTU Prague,[2]CERN, [3]DESY

DRD3 Collaboration Week, June 2024

Outline

1. Front-end model
2. Simulation results
   - ToT calibration
   - Timewalk
   - Florescence Photons
   - Ion tracks
   - Pileup
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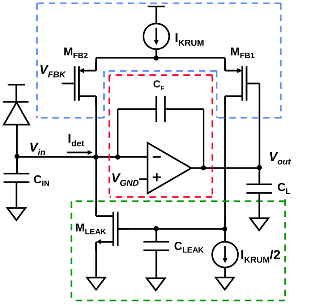
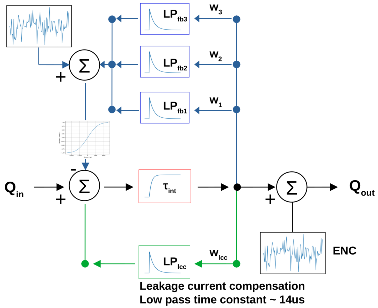
Front-end circuit and model



Schematic of the Timepix3 preamplifier

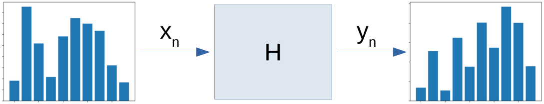


Schematic of the preamplifier model

The integrator and feedback branches are implemented as discrete transfer function

Preamplifier - Discrete Transfer Function

- In the simulation the preamplifier input and output have to be discretized
  - Mapping of discrete input time series to discrete output time series

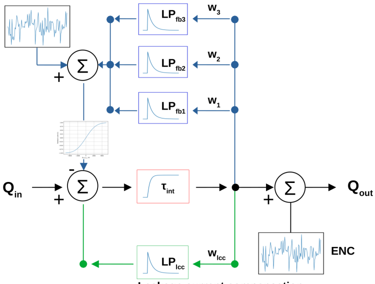


$x(n), y(n)$ sample of input / output taken at time $n\Delta t$

- $H(z) = \frac{\sum_k^M b_k z^{-k}}{\sum_k^N a_k \cdot z^{-k}}$ transfer function in z-domain
- b_n feedforward scaling parameters, a_n feedback scaling parameters

- Load in the x_n and y_n series can be used to switch off computation of inactive branches
  - Reduction of computational load
  - Simulation of large pixel matrix

Timepix3 Pixel Pre-amplifier Model



- Arbitrary number of weighted feedback branches can be specified
- Timepix3: 3 poles in the transfer function -> 3 parallel 1st order Butterworth low-pass filtered feedback loops
- Tanh feedback tapering
- Separate leakage current compensation with a long time constant

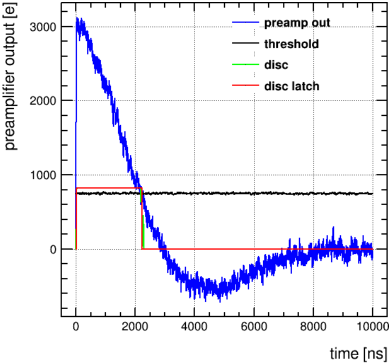
- Improved modeling of low charge input response and pre-amplifier undershoot

Parameter File

(parts of it)


```
.
.
### clock
clock_period = 25ns # ToA clock period
fclock_period = 1.5625ns # fToA clock period
ufclock_period = 195.3ps # ufToA clock period
randomize_event_clock_phase = 1 # random time offset within clock_period
#### Peamplifier
tau_rise = 5.ns # preamplifier integration time
gain = 1.0
gain_dispersion = 0.0perc # gain dispersion across pixel matrix
noise_ENC = 0.0e # preamplifier output noise, typically 60e rms
noise_bw = 1e4Hz 1.0e7Hz # preamplifier output noise bandwidth
#### Feedback
## nonlinear ToT response, eg in https://doi.org/10.1088/1748-0221/13/11/P11014
#fb_ikrum_threshold = 0 200e3 240e3 245e3 555e3 1e6
#fb_ikrum = 1.75e/ns 1.75e/ns 40e/ns 0.5e/ns 0.5e/ns 5e3e/ns
fb_ikrum = 10.e/ns
fb_ikrum_sigma = 0.0e/ns # rms dispersion across pixel matrix
fb_ikrum_enc = 0perc
fb_noise_bw = 1e0Hz 1.0e5Hz # noise bandwidth if alpha_ikrum_noise_enc > 0
fb_tau = 40.0ns 350ns 1.842us
fb_weight = 0.8 1.9 2.15 # relative weights
fb_taper_width = 1000e # krummenacher feedback tapering width
.
```

Pre-amplifier, Discriminator



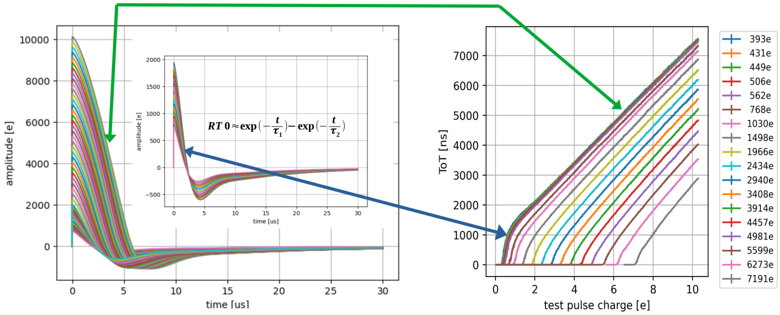
- Separate, band-width filtered Gaussian noise sources for
  - Pre-amplifier ENC
  - Threshold noise
  - Feedback current
- Glitch filtered discriminator with separate rise and fall time constants for ToA/ToT registration

Listmode Output Discriminator Events

idx	row	col	tcc [ns]	rise[ns]	t_fall[ns]	ToT[ns]	clk_r	fclk_r	ufclk_r	clk_f	fclk_f	ufclk_f	peak[e]	t_peak [ns]	input[e]
1	141	135	28.800	45.350	926.050	880.700	2	30	233	38	593	4742	4761.70	92.250	5093.00
1	142	135	29.150	50.750	500.450	449.700	3	33	260	21	321	2563	2158.12	88.550	2401.00
44	128	129	46.250	98.950	127.400	28.450	4	64	507	6	82	653	1057.05	98.950	1230.00
48	129	126	0.550	13.200	1590.400	1577.200	1	9	68	64	1018	8144	9619.42	70.850	9953.00
59	119	131	27.650	43.700	1157.600	1113.900	2	28	224	47	741	5928	6381.32	95.150	6719.00
60	127	126	13.450	27.400	1562.750	1535.350	2	18	141	63	1001	8002	9326.10	84.600	9661.00
70	126	126	17.000	32.150	1320.550	1288.400	2	21	165	53	846	6762	7598.99	86.250	7937.00
70	126	127	18.000	42.400	363.850	321.450	2	28	218	15	233	1864	1713.27	76.800	1928.00

idx	event/primary particle index
row col	pixel address
tcc [ns]	time of first charge arrival to the pixel ~ the charge collection time in the sensor
t_rise[ns]	actual asynchronous disc rise time
t_fall[ns]	actual asynchronous disc fall time
ToT[ns]	actual asynchronous ToT
clk_r	discriminator rise time, sampled with slow clock, usually 40MHz
fclk_r	discriminator rise time, sampled with fast clock, usually 640MHz
uclk_r	discriminator rise time, sampled with ultra fast clock, usually 10.24GHz
clk_f	discriminator fall time, sampled with slow clock
fclk_f	discriminator fall time, sampled with fast clock
ufclk_f	discriminator fall time, sampled with ultra fast clock
peak[e]	maximum pre-amplifier output
t_peak [ns]	pre-amplifier peaking time
input[e]	pixel input charge

Small signal / Feedback saturation



Krummenacher preamplifier has two operational regimes

- Small signal regime: constant return to zero time, responsible for the non-linear bend in ToT/energy calibration $\sim e^{-t/\tau_1} - e^{-t/\tau_2}$
- Saturation regime: constant feedback current, linear region in ToT response
- Shape of the knee mostly governed by feedback taper width (and long time constants in feedback loop)

Timepix3 ToT Calibration, Test-pulse vs Simulation

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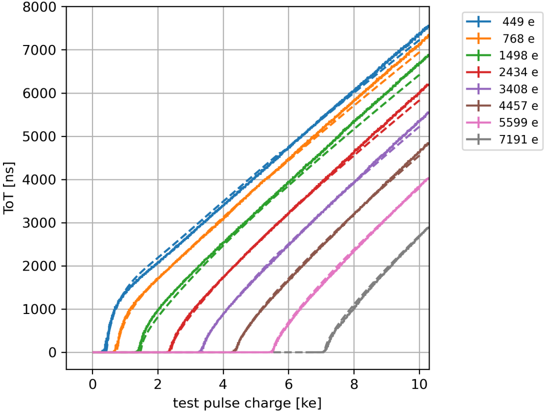
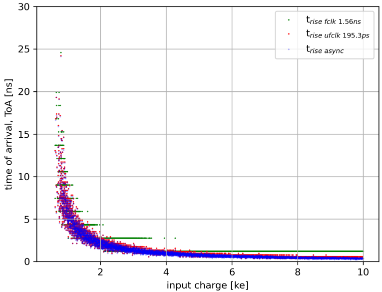


Dashed lines are simulations. The simulated dependence of the Time over Threshold (ToT) on the input charge is in very good agreement with Timepix3 test pulse measurement for a wide range of discriminator threshold settings.

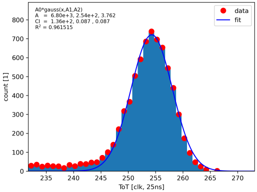
Timepix3(4) Time of Arrival simulation



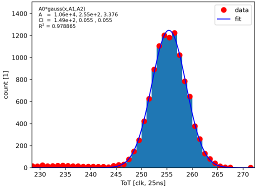
- 3 configurable clock periods
- here 25ns and 1.56ns (Timepix3) and additionally 195.3ps (Timepix4) assuming a main clock of 40 MHz
- 80e- ENC r.m.s, 7e r.m.s threshold noise rms and a peaking time of ~40ns
- ToA corrected for charge induction delays and clock phase offsets

Timepix3 X-Ray fluorescence ^{241}Am

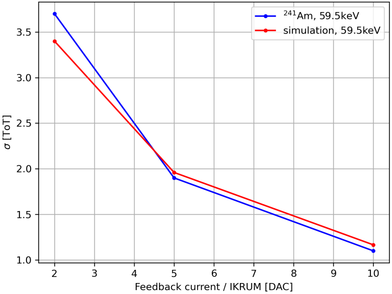
500 μm Si sensor, 55 μm pitch, 200V



Measured 59.5keV with low feedback current (IKRUM 2)



Simulated spectra of mono-energetic 59.5keV photons

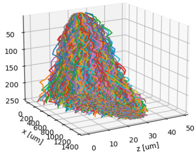


Measured and simulated spectral resolution dependence on the feedback current

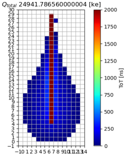
Timepix3, 100MeV alpha 80deg

500 μm p-n Si sensor, 55 μm pitch, 100V

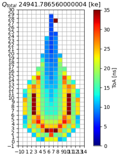
hole packet tracks



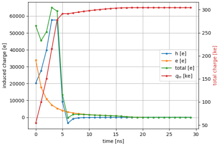
ToT



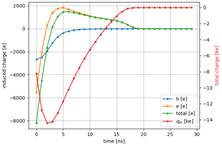
ToA



Induced charge, main track pixel



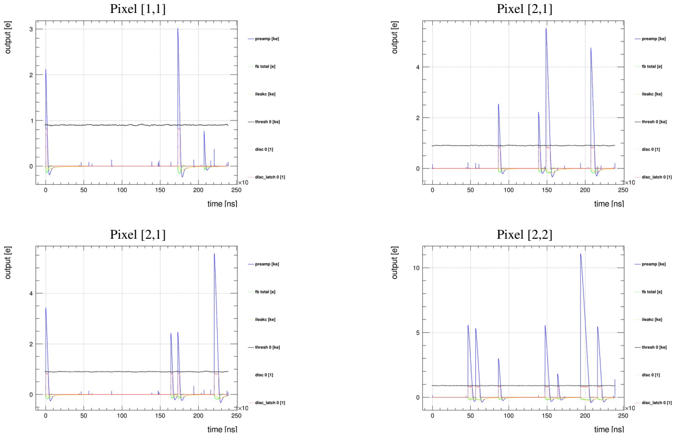
Induced charge, halo pixel, $\Sigma q = 0$



- Random walk diffusion of holes and electrons through weighting field
- Induction calculated for 23x23 pixel neighborhood around charge packet positions
- Halo around the main charge track is artifact due to transient current oscillations in the order shaping time of preamplifier

Cross induction of 20keV electrons

500 μm Si sensor, 55 μm pitch, 200V



- ENC = 0, only threshold noise active
- 20 keV electrons deposited in 250 um sensor depth over 3x3 pixel area
- charge sharing between neighboring pixel
- + cross induction of transient currents -> additional baseline noise

Timepix3, Pre-amplifier undershoot and pileup

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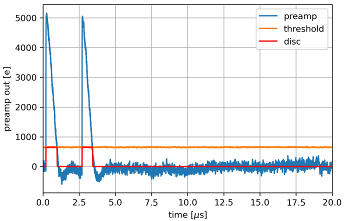
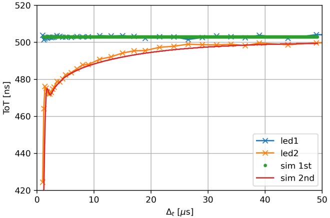
Double LED pulse measurements at DESY showed a reduction of measured ToT for the second LED pulse with decreasing interval between the pulses. This behavior could be reproduced by the simulation and is shown to be consequence of the signal undershoot following a big input charge.

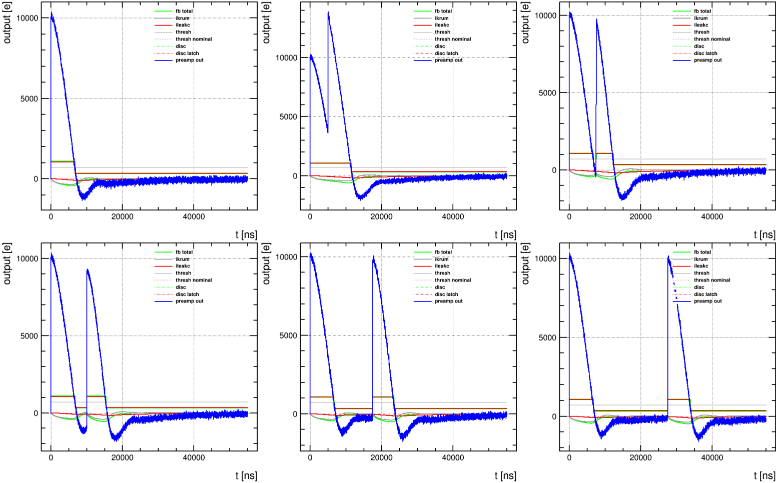


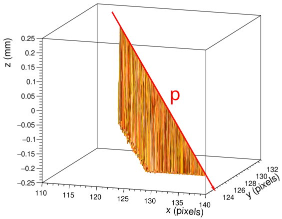
The simulation of two 5ke- input pulses with a delay of 2.5 μs.



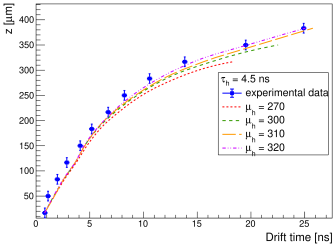
The measured and simulated reduction of the ToT in dependence on the delay of the second pulse with respect to first pulse.

Timepix3, Double 10 ke charge pulse, simulated





125 MeV proton track path, 500 um GaAs:Cr



Drift time(z) in hole collection mode, fixed τ_h = 4.5 ns, various mobilities

Carrier lifetimes and mobilties determined from the dependence of the drift time on interction depth

Drift velocity and CCE for HR GaAs:Cr

Petr Smolyanskiy

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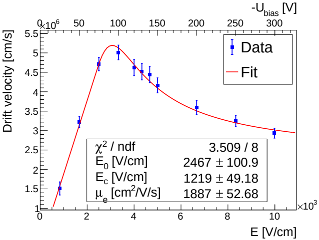
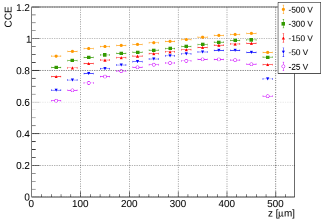
- Drift velocity dependence on the electric field was extracted from the drift time measurements with MIPs.
- It follows Ruch-Kino dependence for n-type GaAs.
- The point with best timing performance is not the point with maximal CCE.
- Determined electron mobility $\mu_e = (2000 \div 6000)$ cm^2/V/s and lifetime $\tau_e = (20 \div 25)$ ns.

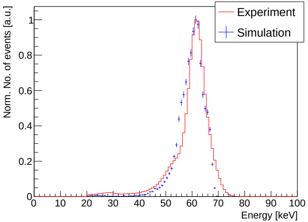


Measured electron drift velocity as a function of the electric field for the 500 μm thick detector.

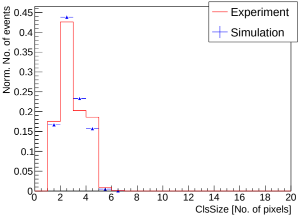


Experimental dependencies of the charge collection efficiency of electrons on the interaction depth z for the 500 μm thick detector (z = 0 corresponds to the pixel side).

- Measured parameters of HR GaAs:Cr were included in the Allpix Squared framework and validation was performed.
- Simulated and measured energy spectra of a ^{241}Am source are consistent (σ/E = 6 %).
- Cluster size spectra are in 2-3 % agreement.



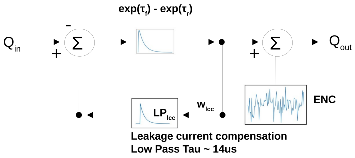
Simulated and experimental energy spectra of the ^{241}Am source.



Comparison of the experimental and simulated distributions of the *cluster size* for irradiation by the ^{241}Am source.

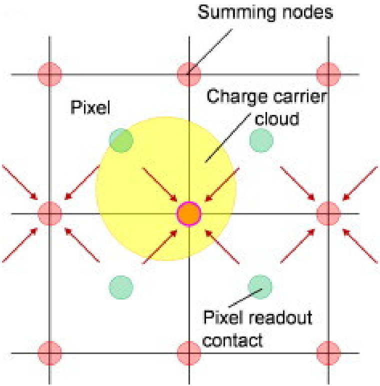
Summary

- A highly configurable front-end model has been develped and tuned to reproduce Timepix3 behavior.
  - is available as plugin for Allpix2
  - can be tuned to other front-ends
  - *note of caution: it is has to be kept in mind that the use of static time constants for the poles in the feed-back path cannot reproduce not all front-end non-linearities.*
- HR GaAs:Cr was added to Allpix2 framework as physical material with corresponding charge transport models.
  - The models were veried with experimental data and the reasonable agreement was demonstrated.
  - Mobility and lifetime of holes in HR GaAs:Cr were estimated using the simulation and experimental data



- Significantly simpler model
- Skipping the first stage in the signal processing chain
- Shaper with fixed return to zero time only, no feedback loops
- Separate leakage current compensation with a long time constant

Medipix3



- Medipix3(4) architecture uses inter-pixel communication
  - preamplifier out summed over 2x2 neighborhood
- Pixel matrix necessary for simulations
- New discriminator model for pile-up tracking (under development)

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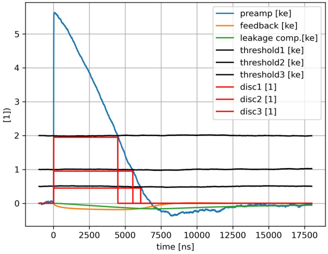
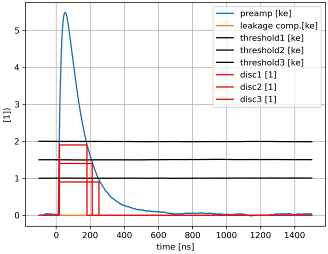
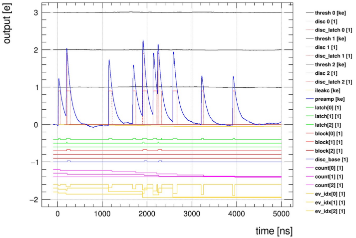
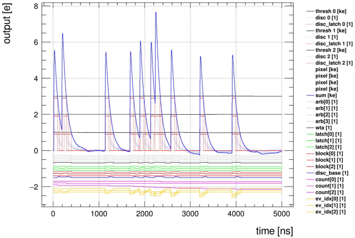
Tpx3 vs Mpx3 Pixel front-end





Medipix3, Poisson interval 500ns





Medipix3, Poisson interval 200ns

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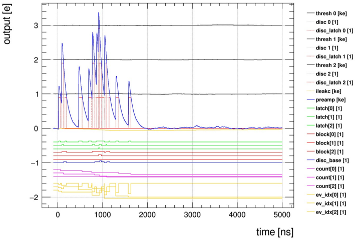
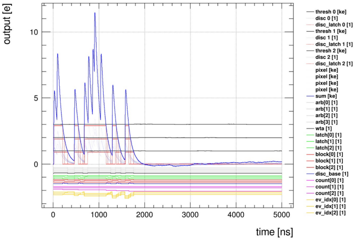
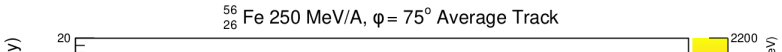
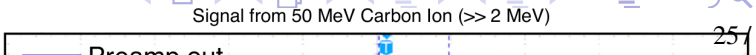


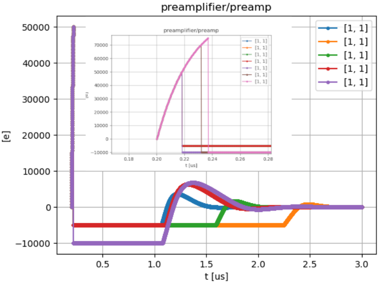


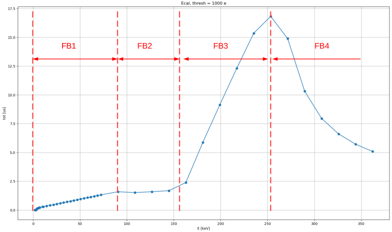
idx	col	row	disc	offs	blck	tcc_ns	t_rise_ns	t_fall_ns	ToT_ns	clk_r	fclk_r	ufclk_r	clk_f	fclk_f	ufclk_f	peak_e	t_peak_ns	input_e
1	2	2	0	0	0	12.2975	20.5495	59.12966	38.58016	1	14	106	3	38	303	1231.31	29.093	1249.85
2	2	2	1	0	0	12.2975	89.881	128.46116	38.58016	4	58	461	6	83	658	2476.09	97.253	1859
2	2	2	0	1	1	83.3867	159.749	194.86316	35.11416	7	103	818	8	125	998	1386.65	159.749	1859
3	2	2	0	0	0	462.0734	466.81	543.86426	77.05426	19	299	2391	22	349	2785	1798.58	477.697	1775
4	2	2	0	0	0	678.2705	683.0071	754.98356	71.97646	28	438	3498	31	484	3866	1737.15	693.504	1562
5	2	2	2	1	0	12.2975	905.2585	932.70656	27.44806	37	580	4636	38	597	4776	3373.84	911.263	5220
6	2	2	1	2	1	859.5089	921.8096	970.98536	49.17576	37	590	4720	39	622	4972	3187.57	921.81	5220
5	2	2	0	1	1	764.7884	855.6029	1036.80146	181.19856	35	548	4381	42	664	5309	3373.84	911.263	5790
8	2	2	1	0	0	1036.646	1071.6047	1090.70426	19.09956	43	686	5487	44	699	5585	2325.53	1071.605	1311
9	2	2	0	0	0	1289.5595	1294.882	1355.92166	61.03966	52	829	6631	55	868	6943	1518.73	1306.551	1302
10	2	2	0	0	0	1570.7915	1577.4811	1626.99806	49.51696	64	1010	8078	66	1042	8331	1378.99	1586.415	1303





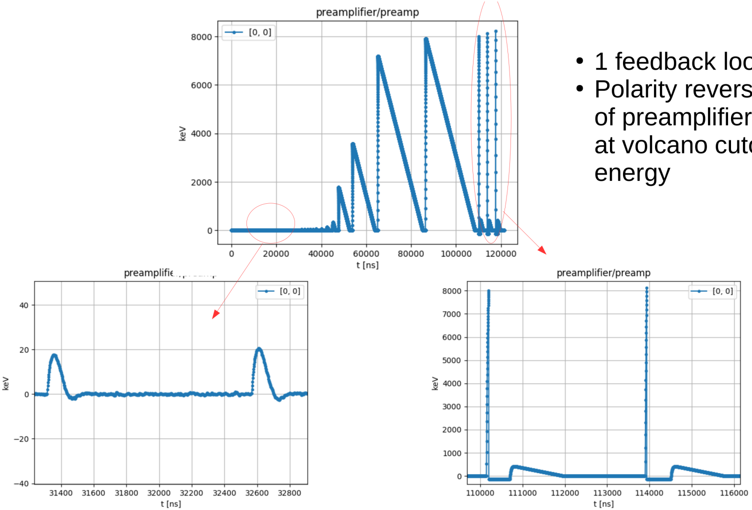
Modeling of Volcano Effect





- Volcano cut-off energy for polarity inversion and undershoot amplitude set via simulation parameters
- Preamplifier overshoot after polarity recovery controlled by differentiator/integrator times and weights
- Measured energy response can be reproduced using 4 feedback loops with limited energy range

“Test Pulse” Energy Calibration



- 1 feedback loop
- Polarity reversal of preamplifier at volcano cutoff energy

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