Detector Electronics II

FADC Optimization

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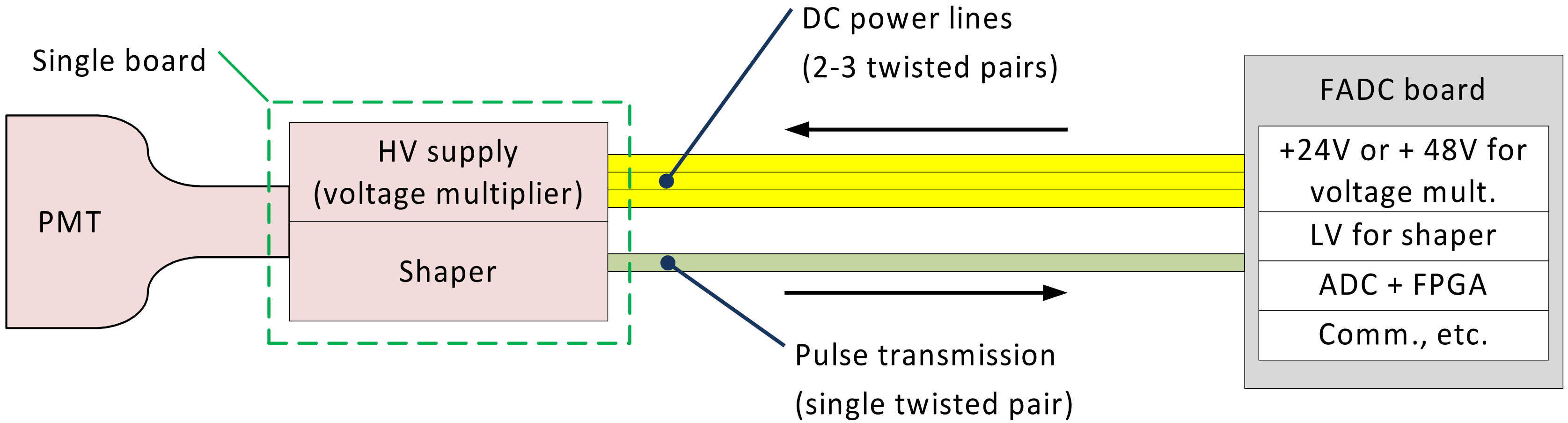
What's in the EoI

- FADC digitization.
- Pulse stretching (i.e. pulse shaping).
- Standard commercial ADC:
  - 12-16 bits, 80-500 MHz.
- FPGA processing to find PMT hits and calculate pulse time and charge.
- 0.1-1250 p.e. dynamic range.
- Distinguish hits that differ by 10s of ns.

Suggested Setup



- HV supply and the shaper on a single board
- HV control link over the DC power line
- Fully differential signal transmission
  - Improved EMI performance
  - Ground is not used in signal transmission
- Use standard UTP telecom cable (4 pairs)
  - Single cable per PMT (no additional HV cable)
  - No HV going through the water

Simulation Purpose

- Get an initial estimate of the performance of the FADC acquisition scheme
- Try to determine optimum shaping, sampling frequency and the number of the ADC bits.
- Investigated parameters:
  - Time resolution
  - Charge resolution
  - Ability to distinguish piled-up pulsed
- What we want:
  - Lowest number of bits, lowest sampling frequency
  - But still meet performance requirements

ADC cost (USD per channel)

Resolution

Sampling Rate (min)

	10 bits	12 bits	14 bits	16 bits
80M	$4 to $8	$7 to $33	$10 to $40	$42 to $58
100M	$6 to $25	$15 to $34	$25 to $58	$57 to $68
125M	$6 to $22	$15 to $35	$21 to $78	$63 to $72
150M	$19 to $21	$19 to $48	$33 to $96	$52 to $79
200M	$25 to $41	$31 to $56	$55 to $110	
250M	$18 to $35	$30 to $65	$37 to $106	$93
300M	$47	$85	$182	$116 to $133
500M		$110 to $193		
1G		$162	$272	

NOTE: This is only an ADC IC cost – it does not include additional analog electronics (anti-aliasing filter, shaper, cables, connectors, etc.)

Source: ANALOG DEVICES, Texas Instruments

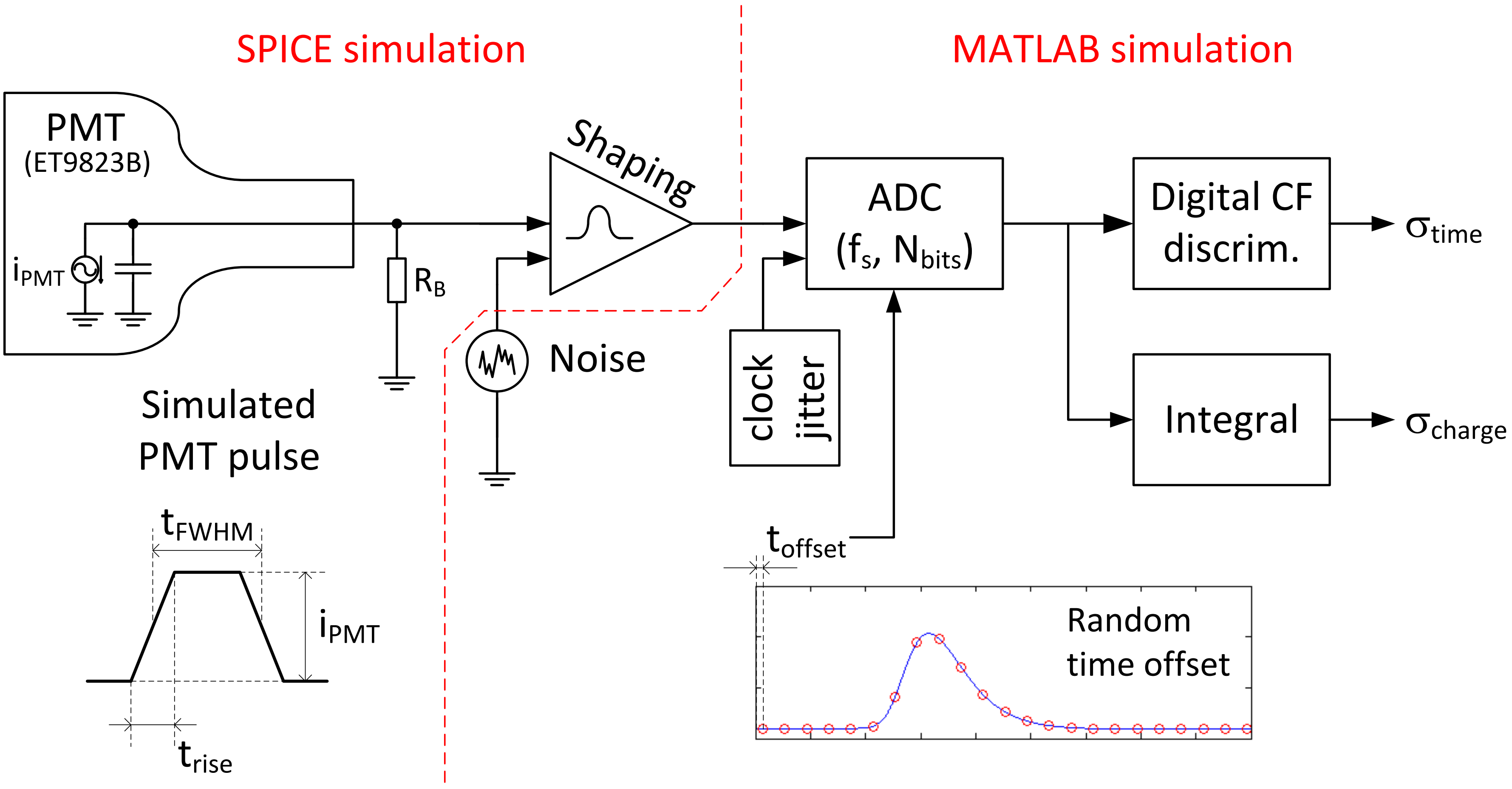
EoI Simulations 1/2

- Dynamic range: 2000 p.e. (to accommodate pulse pile-up)
- Pulse amplitude: 1 p.e. and 10 p.e.
- No PMT randomizations
  - Test only electronics-related errors
- Almost optimum shaping (LT-SPICE simulation)
  - 6^{th} or 7^{th} order RC-integrator
  - Approx. 3.5 samples on the rising edge
  - Use real amplifier models (i.e. apply bandwidth and slew-rate limitations, account for noise)

EoI Simulations 2/2

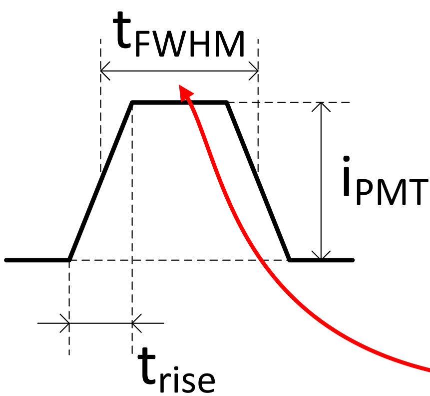
- Simulated parameter sets:
  - Fs = 80 MHz, 125 MHz, 250 MHz
  - Number of bits: 10, 12, 14, 16
- ADC simulation (done in MATLAB):
  - Time-base jitter
  - Random time offset between beginning of the shaper pulse and the phase of the sampling clock
  - Ideal ADC – non-linearity was not simulated (yet)
- Time extraction using a digital constant-fraction discriminator

EoI Simulations – Setup



EoI Simulations – PMT pulse

2000 p.e. → i_{PMT} = 150 mA



Excerpt of the ET9823B datasheet (5” PMT)

pulsed linearity (-5% deviation):			
divider A	mA	50	
divider B	mA	150	
rate effect (I_a for $\Delta g/g=1\%$):	µA	1	
magnetic field sensitivity:			
the field for which the output decreases by 50 %			
most sensitive direction	$T \times 10^{-4}$	0.8	
temperature coefficient:	$\%\ {}^{o}C^{-1}$	± 0.5	
timing:			
multi electron rise time	ns	3.5	
multi electron fwhm	ns	6	
single electron rise time	ns	2.7	
single electron fwhm	ns	3.6	
single electron jitter (fwhm)	ns	2.4	
transit time	ns	55	
anode sensitivity in divider B:			
nominal anode sensitivity	A/lm	5000	
max. rated anode sensitivity	A/lm	10000	
overall V for nominal A/lm	V	2400	3000
overall V for max. rated A/lm	V	2550	
gain at nominal A/lm	$\times 10^6$	80	

Problem of the PMT gain:

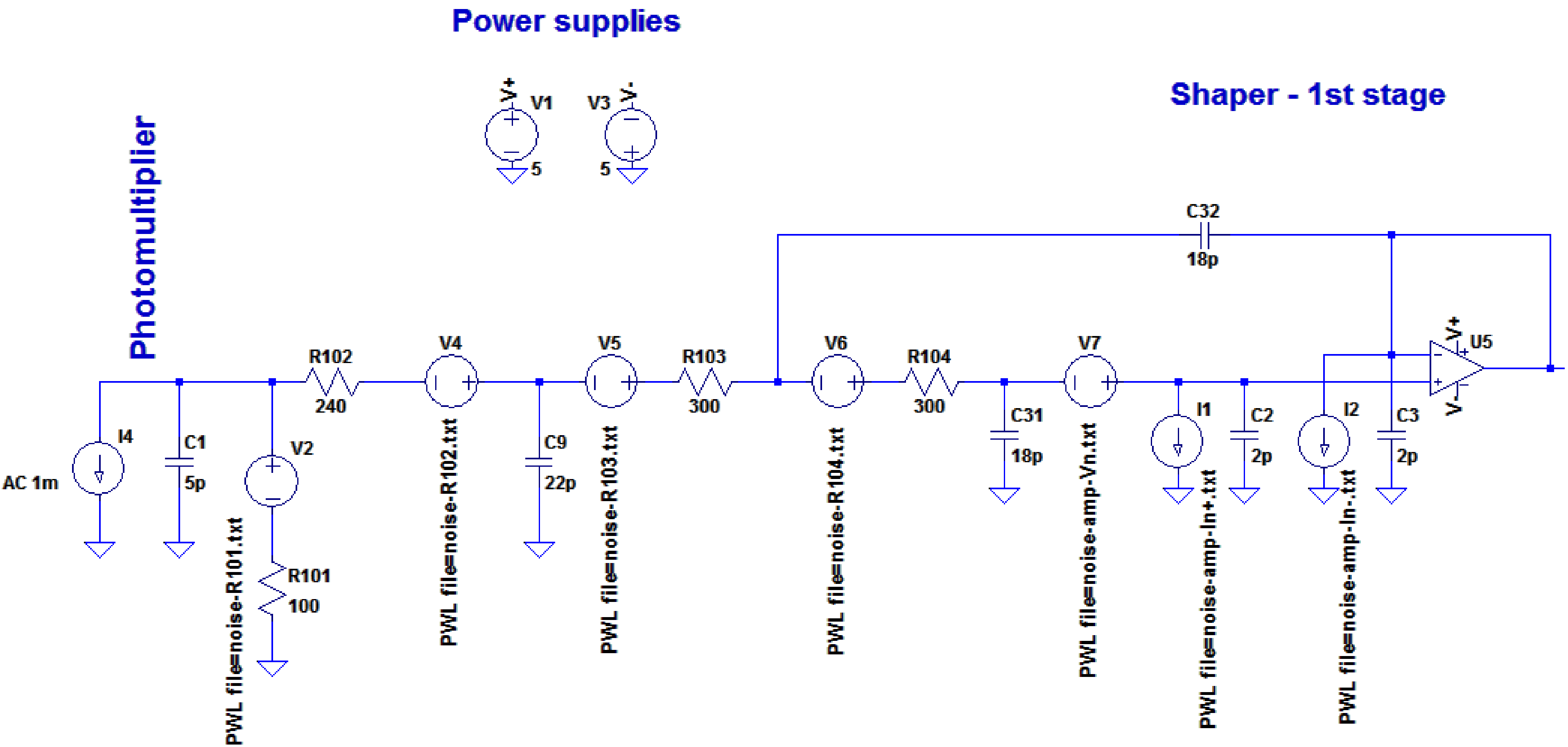
$$q = 150 \cdot 10^{-3} \cdot 6 \cdot 10^{-9} = 9 \cdot 10^{-10} = 900\, pC$$

$$\frac{9 \cdot 10^{-10}}{1.6 \cdot 10^{-19}} = 5.625 \cdot 10^{9} e$$ ➡ 2000 p.e.

1 p.e. ➡ $2.813 \cdot 10^6 e$

Dropping PMT linearity requirement for large pulses is considered.

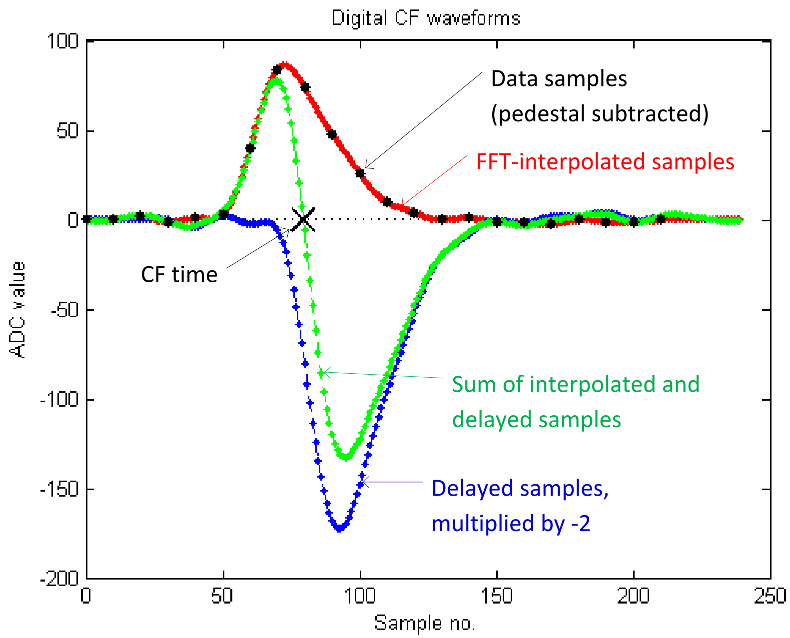
EoI Simulations – Shaper



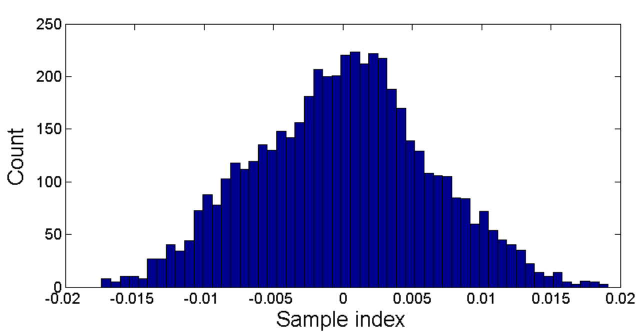
Need to stay within common mode range of the amplifier

EoI Simulations - Time Extraction

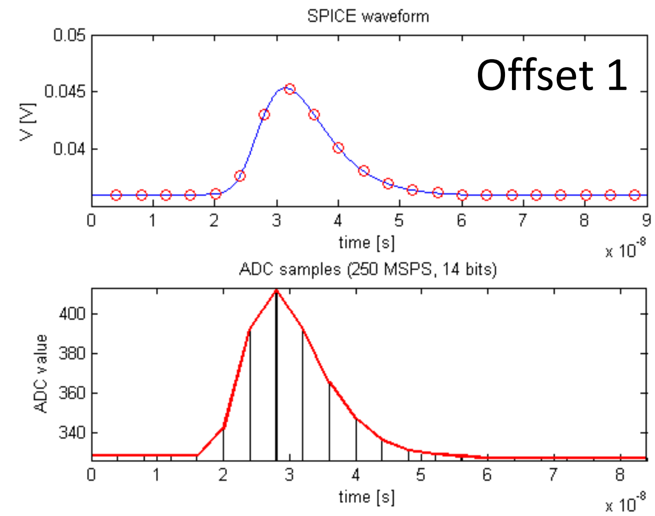
Digital Constant-Fraction

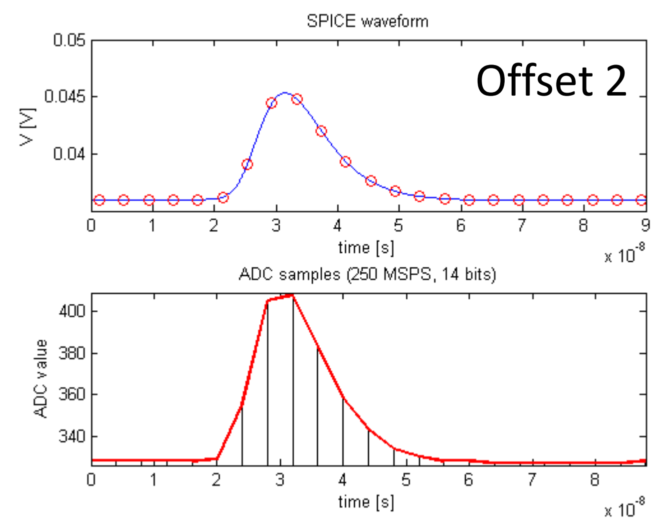


Error distribution due to the time offset

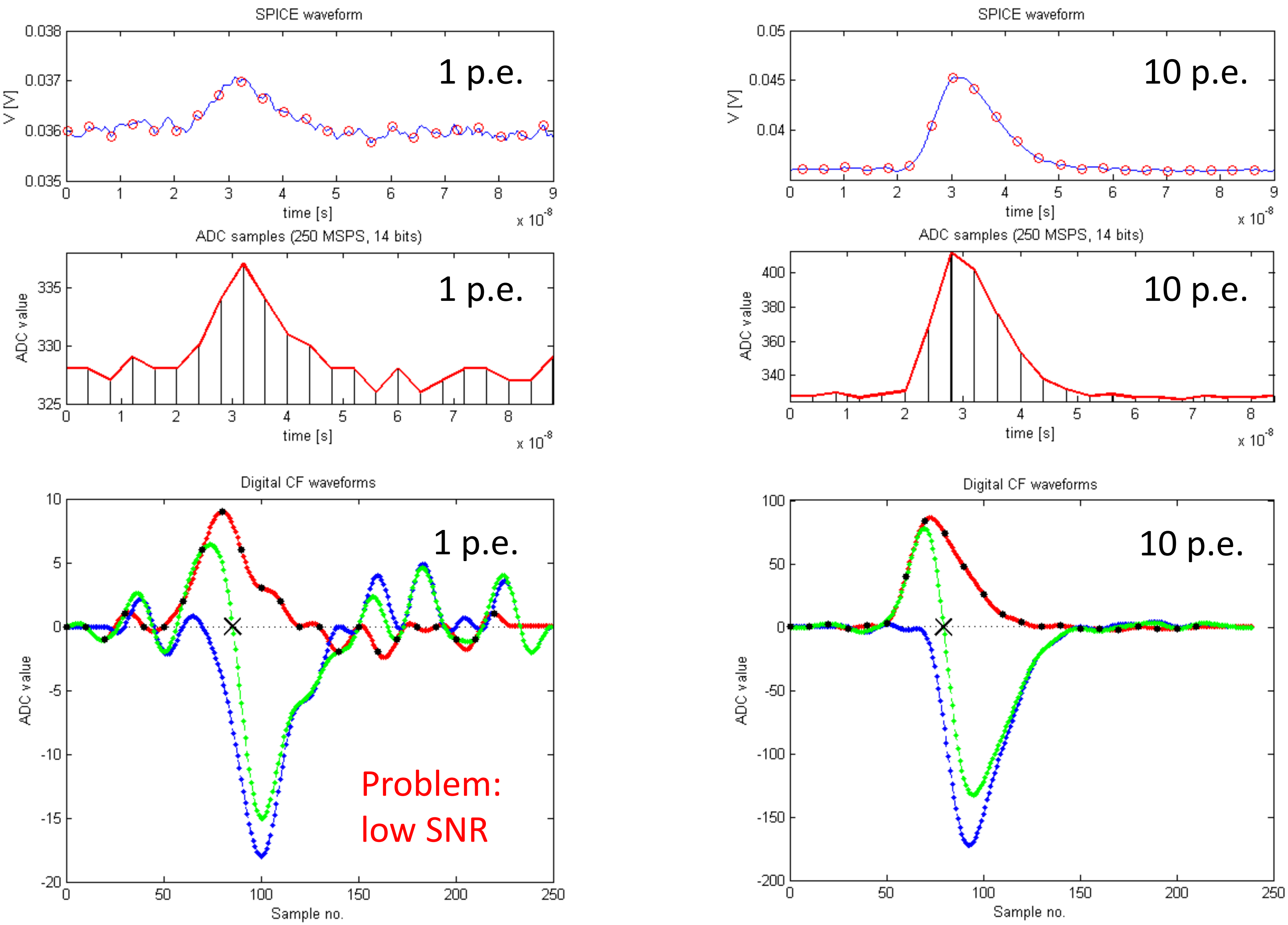


Error due to random time offset between sampling clock and the leading edge



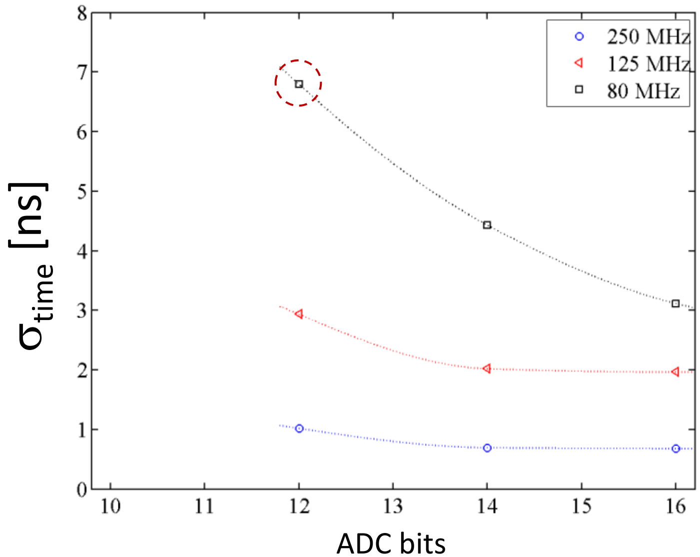


Example waveforms (250 MSPS, 14 bit)

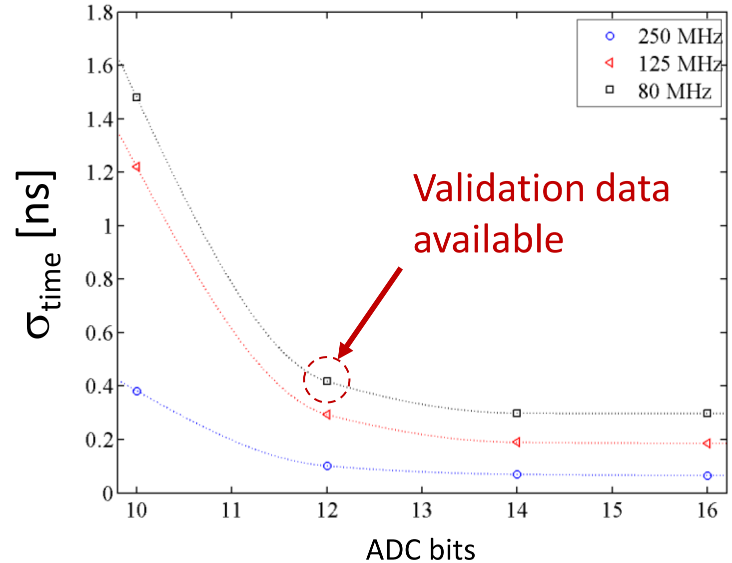


EoI Simulations - Results

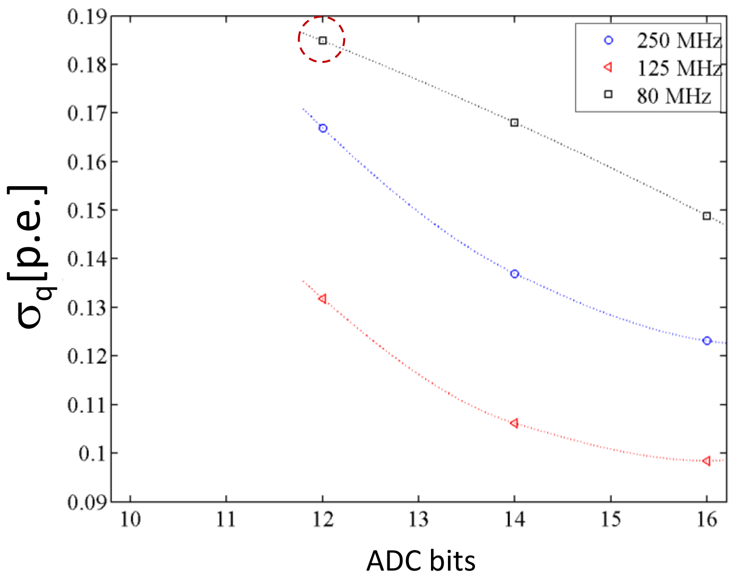
Time resolution vs ADC resolution (q = 1 p.e.)



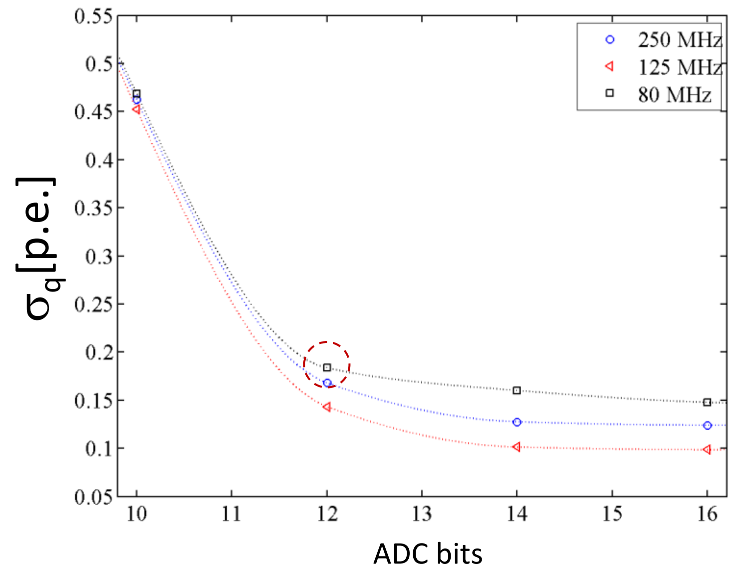
Time resolution vs ADC resolution (q = 10 p.e.)



Charge resolution vs ADC resolution (q = 1 p.e.)



Charge resolution vs ADC resolution (q = 10 p.e.)



EoI Simulations – Conclusions

- Charge resolution is not very sensitive to signal-to-noise ratio – even for noisy signals we get <1 p.e. resolution.
- Time extraction using a digital CF-algorithm is heavily dependent on signal-to-noise ratio.
- **If the model is accurate**, then, **using the assumed methods of signal processing**, a **12-bit 250 MSPS** system should provide sufficient timing performance, i.e. the limiting factor will be the PMT transit time spread.

Improve SNR

- Design all electronics in such a way that we can operate PMT at the highest possible gain.
- Decide whether we need PMT linearity in the full dynamic range.
- Fully understand shaper design.
- IceCube's pulse-compressor?

Optimize algorithms

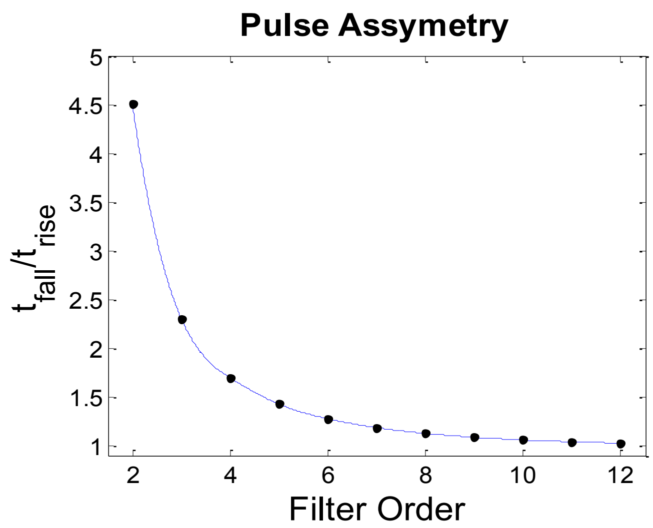
- Try a different algorithm for small pulses – see how radar people do their tricks (matched filtering)
- Optimize shaping, investigate various shaping techniques
- Apply digital filtering of input signal (should improve SNR)

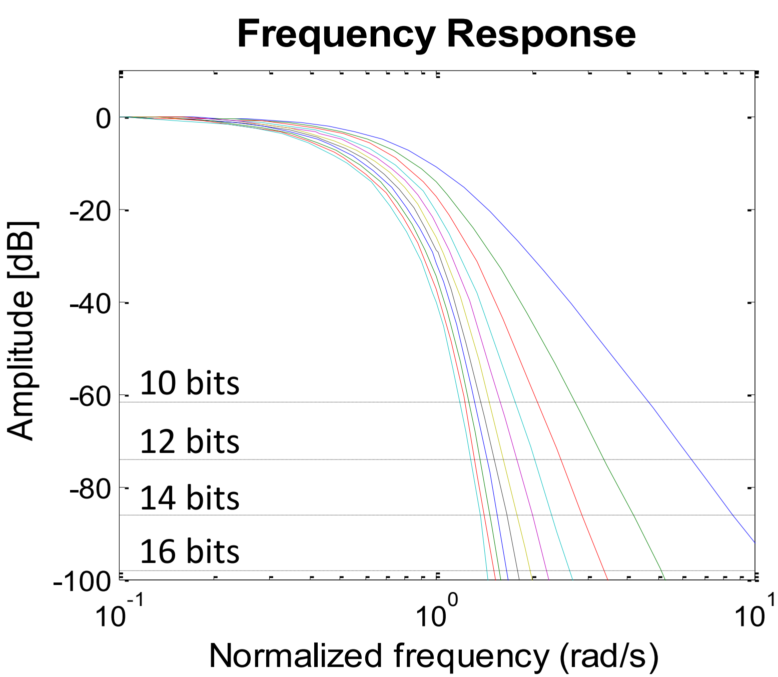
Shaper design 1/2

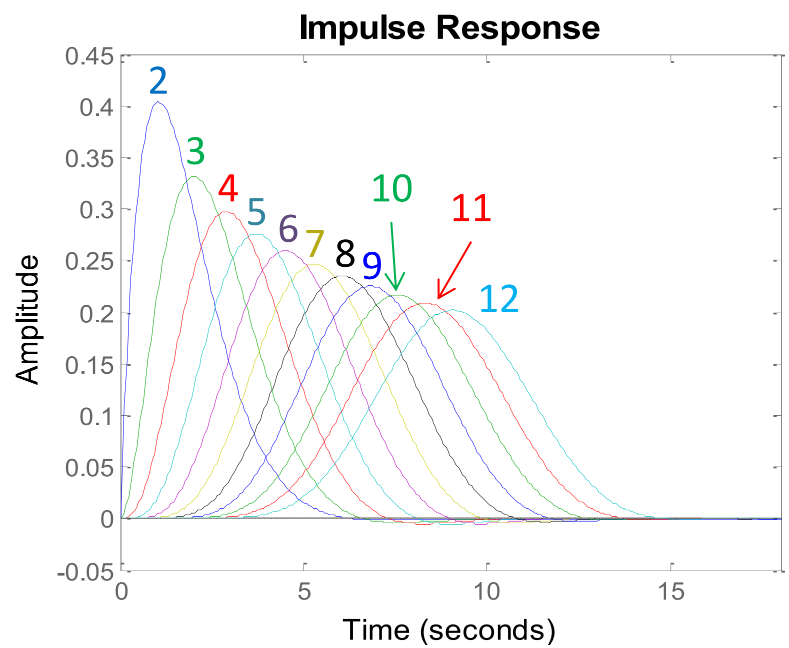
Shaper = low pass filter

- Filter design is a well established theory
- Bessel-type so that there is no ringing
- Amplifier bandwidth should be significantly higher than the stop-band corner frequency.

ADC SNR = (6.02N+1.76) dB

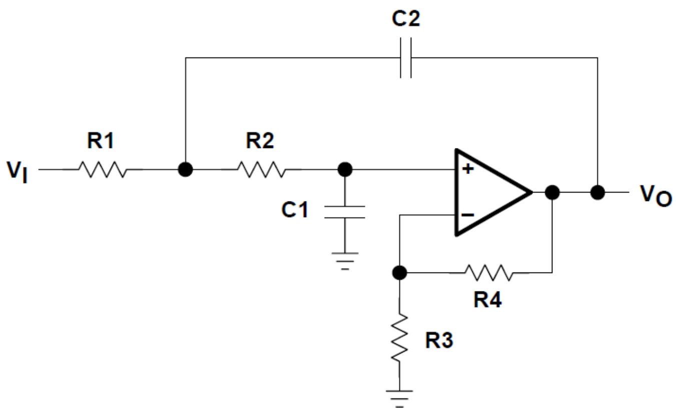




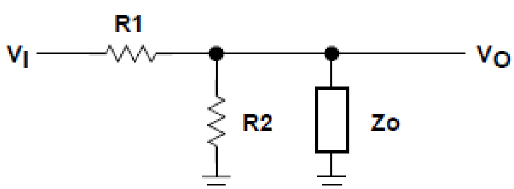


Shaper Design 2/2

Building block – Sallen-Key architecture



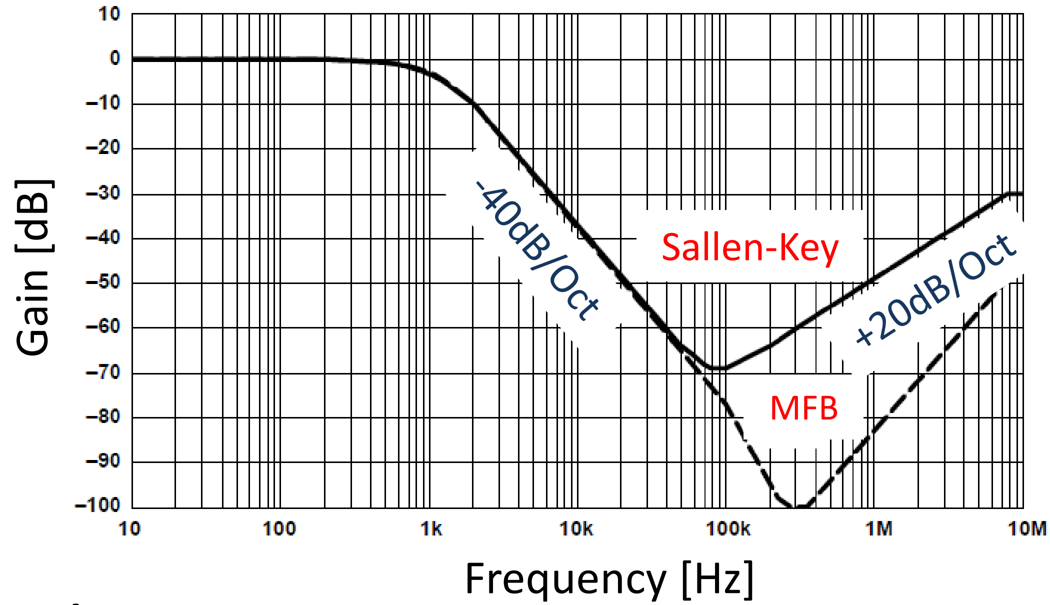
High frequency model



$$Zo = \frac{zo}{1 + a(f)\beta}$$

Source: Texas Instruments, SLOA049B

Frequency response – real 2nd order LP filter



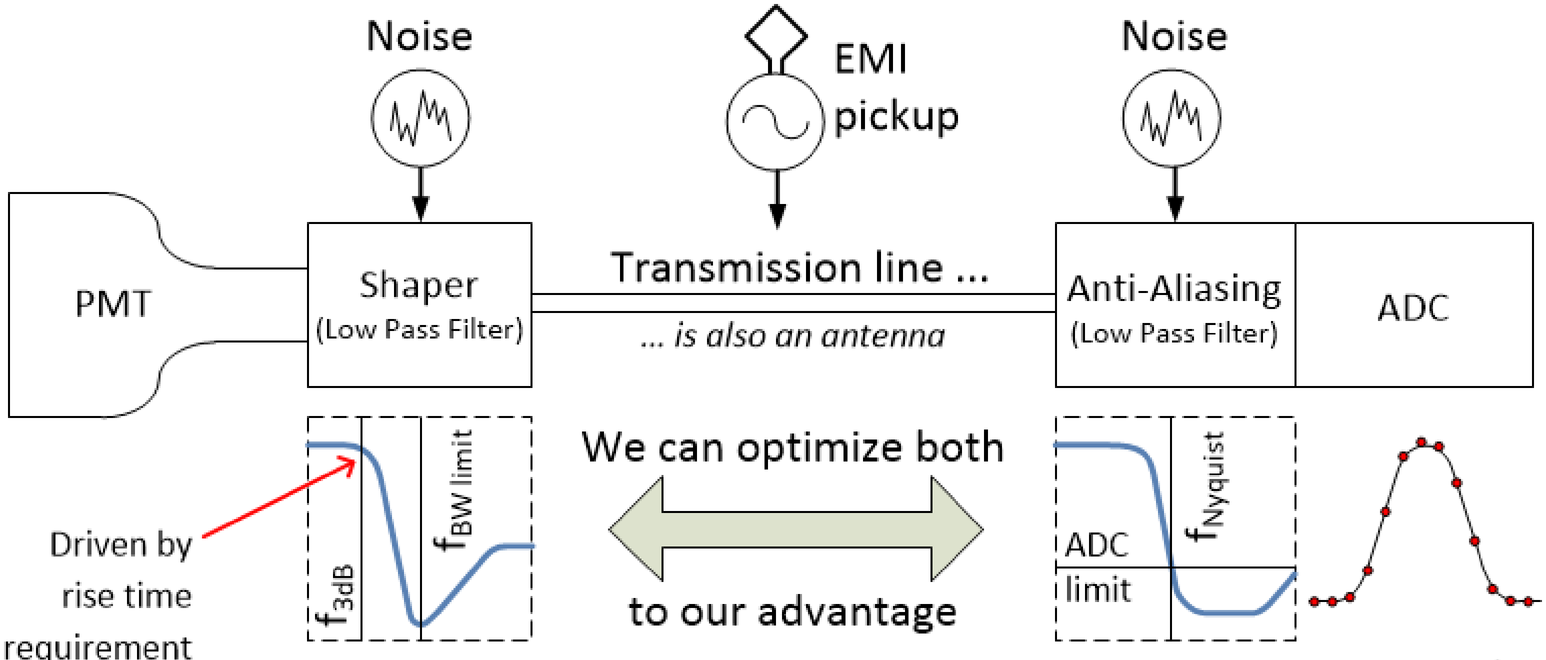
Advantages:

- Does not change pulse polarity
- More dynamic range
  (can use non-symmetric supplies)
- Possibly can use current-feedback op-amps

Disadvantage:

- Undesired stop-band behavior due to amplifier bandwidth limitations

Signal Chain



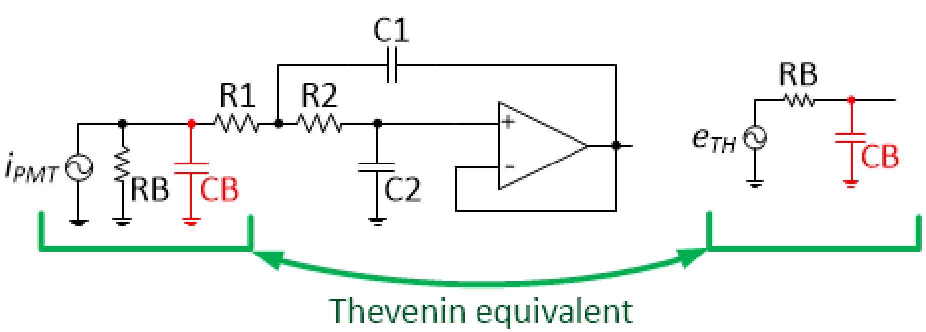
Oversampling

+

Know output from the shaper

Use digital low-pass filtering to remove unwanted signals

Dynamic range issue



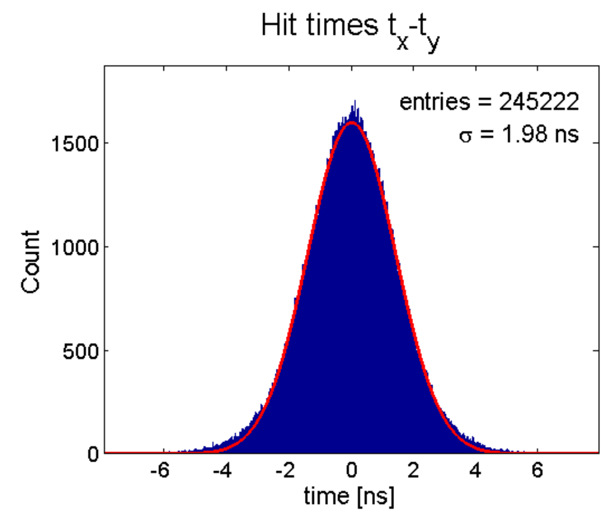
$$v_n = \sqrt{4kTR\Delta f}$$

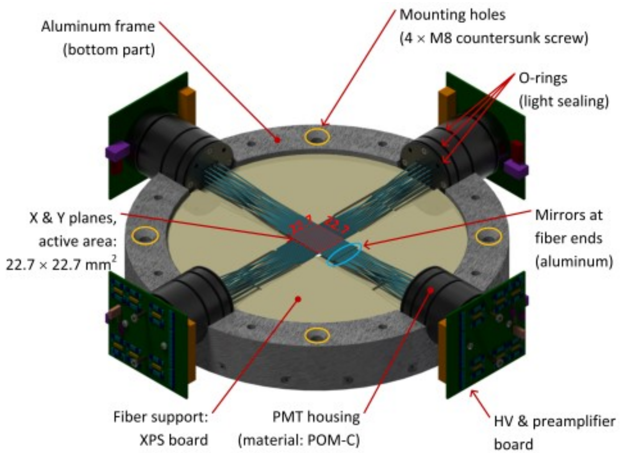
$$\Delta f = \frac{1}{4RC}$$

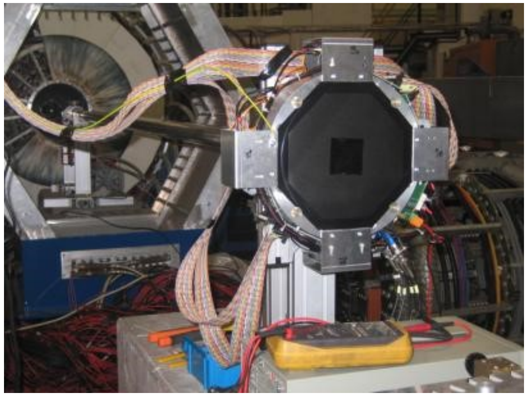
$$v_n = \sqrt{\frac{kT}{C}}$$

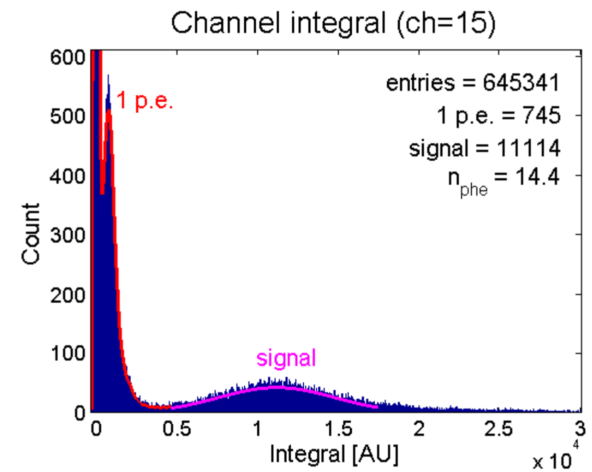
Model Validation 1/2

- Model validation possible using data from beam tests done for the COMPASS experiment.
- Scintillating fiber detector, similar acquisition scheme (Kuraray fibers, H8711-10 PMT, Shaping, ADC $\rightarrow$ 12 bits, 80 MHz).
- Electron beam data available (test done at ELSA, Bonn, February 2014). Further tests in CERN, October 2014.
- 1.98 ns time resolution for a system with an average signal level of 14.4 p.e. and the dynamic range of approx. 60 p.e. !!! – probably due to SNR, investigation is under way.









Model Validation 2/2

- First prototype shaper design under way, to be completed next week (schematic).
  - Three versions – for 100 MHz, 250 MHz and 500 MHz systems.
  - For now single-ended, 50 Ohm input impedance, 50 Ohm output.
- Make tests using shaper prototype and pulse generator (Warsaw + TRIUMF) and various commercial ADC modules.
- Coordinate with Fabrice – more tests with arbitrary waveform generator.

Conclusions & Work Plan

- Achieving desired performance will be a challenge for a single channel system, but we should try to avoid split gain system.
  - There is still some time to try various solutions.
- SNR is a critical issue – needs to be improved in any way possible.
- My plan for the near future:
  - Finish shaper design and send it to Fabrice.
  - Go on holiday ☺
  - Investigate worse than expected time resolution of the SciFi and try to improve it by applying matched filtering algorithms.
  - Add an ADC non-linearity simulation to the model.
  - Run a second set of simulations with improved shaper designs and try time extraction using both the digital constant-fraction algorithm and matched filtering algorithms.
  - Analyze results and decide on optimum pulse shape (i.e. rise time and filter order).
  - Modify shapers for the SciFi before October test to see if the time resolution will improve.
  - Analyze ability to distinguish piled-up pulses.
- At some point, add PMT simulation and time spectrum of arriving photons.