Gain Studies

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Outline

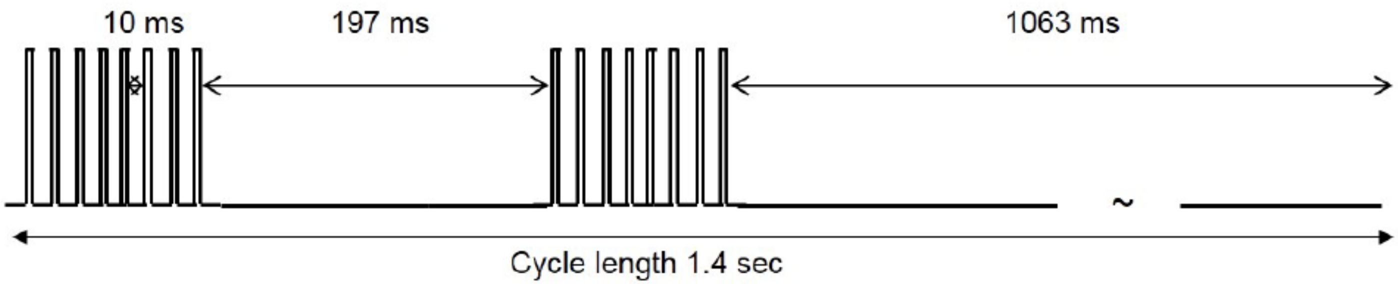
- Recalling the calibration procedure
- Semi-analytical approach of gain fluctuation
- Results on the simulation of Gain Fluctuations using Bias Voltage sagging (Aaron model)
- Effects of Laser pulses
- Conclusion

Reminder on Calibration procedure

- **Goal** of the Calibration laser system:
  - Monitor the short-term Gain (i.e. within 700 μs fill)
  - Fluctuations at sub per mill level (0.04% statistical+0.01% systematics)

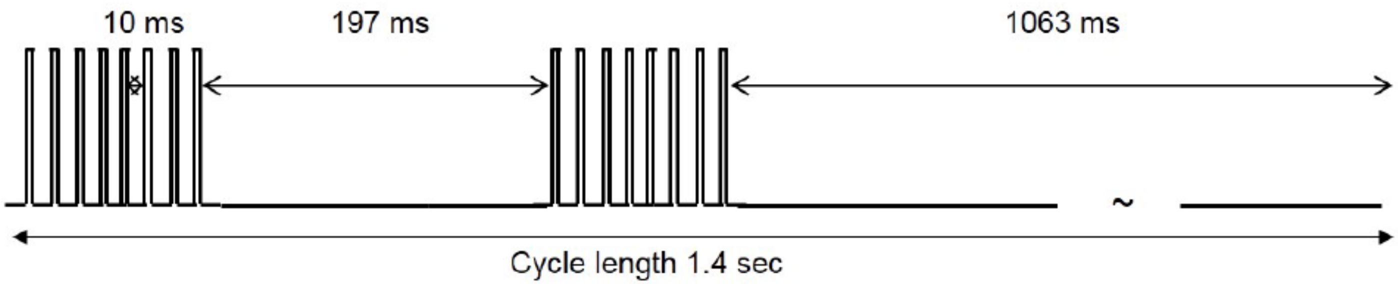
- **Basics**:
  1. In-Fill calibration for short term effects on G(t)
  2. Out-of-fill calibration for stability checks
  3. The short term fluctuations will be mostly driven by the Bias Voltage (BV) sagging

In-fill Calibration: pulsing laser at ~10 kHz with μ beam



- Short term gain fluctuations – we pulse the laser along with μ beam. A recap of the procedure presented several times in the past:
  - In case of 12.5 kHz laser (80 μs) we get ~ 8 points in a fill (700 μs)
  - After each subsequent fill, move offset by 5 μs => 16 fills for a calibration cycle/event = one beam cycle i.e. 1.4 s.
  - Accuracy for the 140 points separated by 5 μs (time bin) – our goal with 2000 cycles / points. This defines a **calibration run (~1-2 h).**

In-fill Calibration: pulsing laser at ~10 kHz with μ beam



- Pulsing the laser for a dedicated time in the day (like 2 hours in the morning) **assumes** that the laser calibration runs represent the gain fluctuations of the entire day.

- A different approach (under study) could be to pulse the laser 1 fill out of XX(10-20) continuously during the day. The calibration runs in this case will be distributed over the whole day and will be a more realistic representative of the muon beam conditions (Intensity, etc...) for the entire day.

- It is important that the laser shouldn't introduce a bias in the gain.

Gain Variation in Fill: semi-analytical approach

The gain function in a fill is:

$$G(t) = 1 - \alpha E \sum_{i=1}^{n_0} \sum_{k=1}^{p} f_k \theta(t - t_i) e^{-(t-t_i)/\tau_k}$$

where,

- n_o pulses in a fill. Times t_i corresponds to the i^{th} pulse, αE = gain drop
- Recovery times are sum of exponentials over k (k>1 includes very small lifetimes too).

  - f_k, τ_κ fraction and recovery time of exponential at k ($\Sigma f_k = 1$)

Average gain by averaging over all t_i and energy.

Average Gain Function

All time averages are the same so:

$$< G(t) >= 1 - n_0\alpha \sum_{k=1}^{p} f_k \int_0^\infty de \int_0^t e w(e,t') e^{-(t-t')/\tau_k} dt'$$

The two integrals are decoupled

Let: $$\tilde{x} = \int_0^\infty e\epsilon(e)x(e)\, de$$

$$S_{N_k}(t) = \int_0^t e^{-(t-t')/\tau_k} e^{-t'/\tau_\mu} dt'$$

$$S_{a_k}(t) = \int_0^t e^{-(t-t')/\tau_k} e^{-t'/\tau_\mu} cos\omega t' dt'$$

$$S_{b_k}(t) = \int_0^t e^{-(t-t')/\tau_k} e^{-t'/\tau_\mu} sin\omega t' dt'$$

Where all time integrals are solved analytically. Here a and b are derived from the decoupled wiggle plot definition

$$\frac{\partial^2 P}{\partial e \partial t} = e^{-\frac{t}{\tau}}(N + a\, cos\, \omega t + b\, sin\, \omega t)$$

Average Gain Function

Finally:

$$< G(t) >= 1 - n_0\alpha \sum_{k=1}^{p} f_k(\tilde{N} S_{N_k}(t) + \tilde{a} S_{a_k}(t) + \tilde{b} S_{b_k}(t))$$

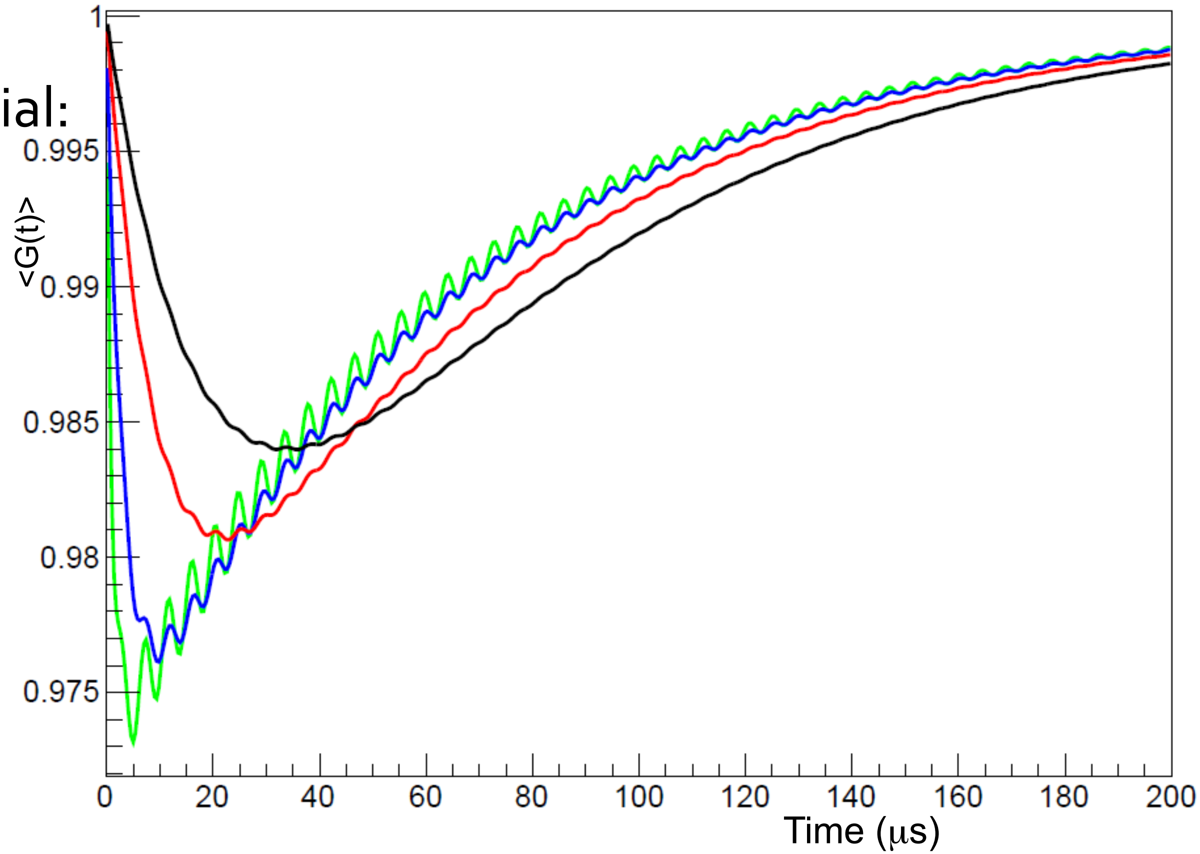
Examples with 1 exponential:

1 μsec

3 μsec

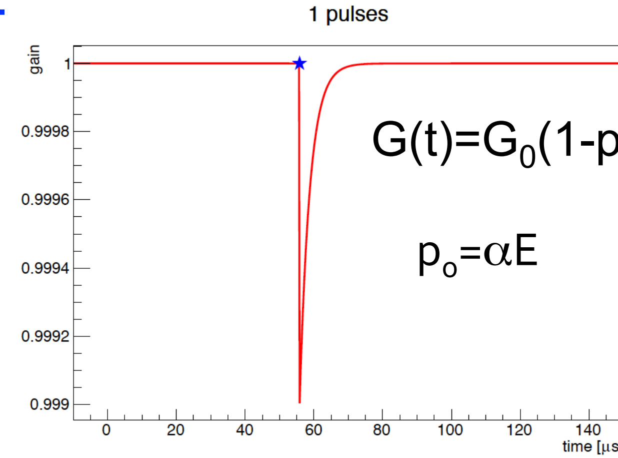
10 μsec

20 μsec



BV Sagging effect

- The BV sagging effect is the convolution of single energy drop with the time distribution of the positrons
- It depends on the rate and intensity of the pulses (positron/laser)

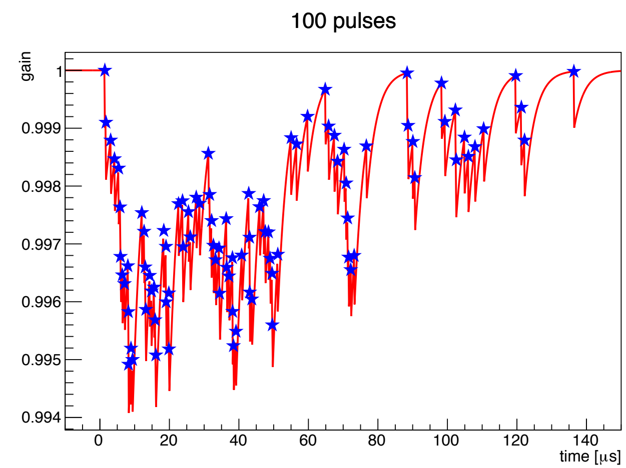


$G(t)=G_0(1-p_0e^{-t/\tau})$

$p_o=\alpha E$

p_o is gain drop, depends on the e^- energy

- Pulsing at too high frequency affects the BV and changes the gain for the following recovering time (~20-60 µs)
- A safer margin of 100 µs between pulses (10 kHz) would allow to neglect the effect due to the previous pulse



BV sagging: Simulation

Simulation uses a simple exponential decay for e^+ (or laser pulse)
The cumulative gain (for n_o pulses) can be written as

$$\frac{G(t)}{G_0} = 1 - p_0 n_0 \frac{\tau_r}{\tau_\mu - \tau_r}\left(e^{-t/\tau_\mu} - e^{-t/\tau_r}\right)$$

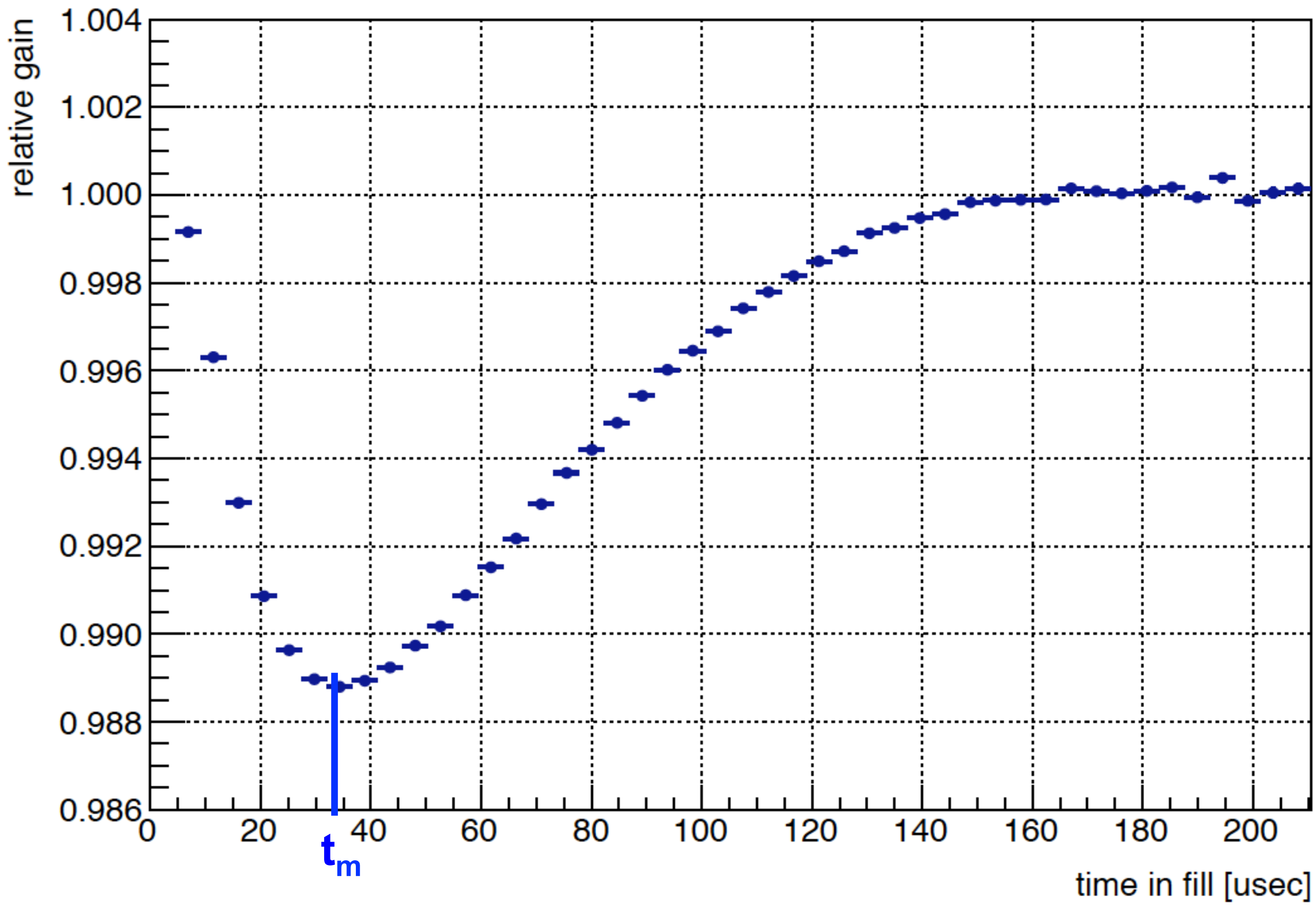
$p_o = 6.4 \times 10^{-4}$ for 1500 PE per pulse for $n_o = 100$ and $t_m \sim 32\ \mu s$ taken from JINST paper.

At the minimum $$t_m = \frac{\tau_\mu \tau_r}{\tau_\mu - \tau_r} ln \frac{\tau_\mu}{\tau_r}$$

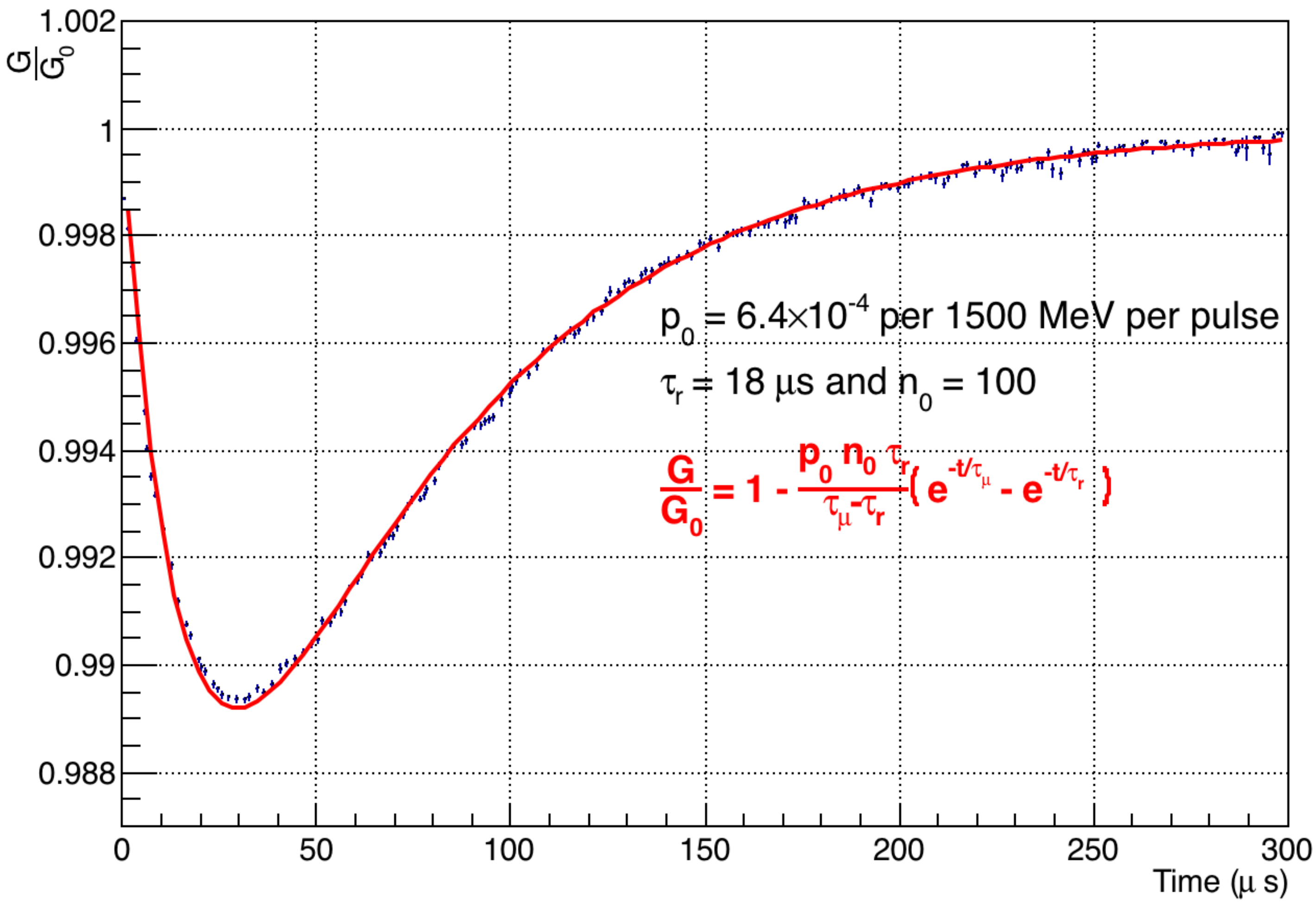
Plugging in the above equation $t_m \sim 32\ \mu s$ gives $t_r = 18\ \mu s$. Used a constant $\alpha = 4.2 \times 10^{-5}$ for 100 MeV pulses which replaces p_o with αE. Also p_o depends on the bias voltage po=dG/CdV

NOTE: I have not used oscillatory effects of ω_a

JINST SiPM Function for 1500 PE



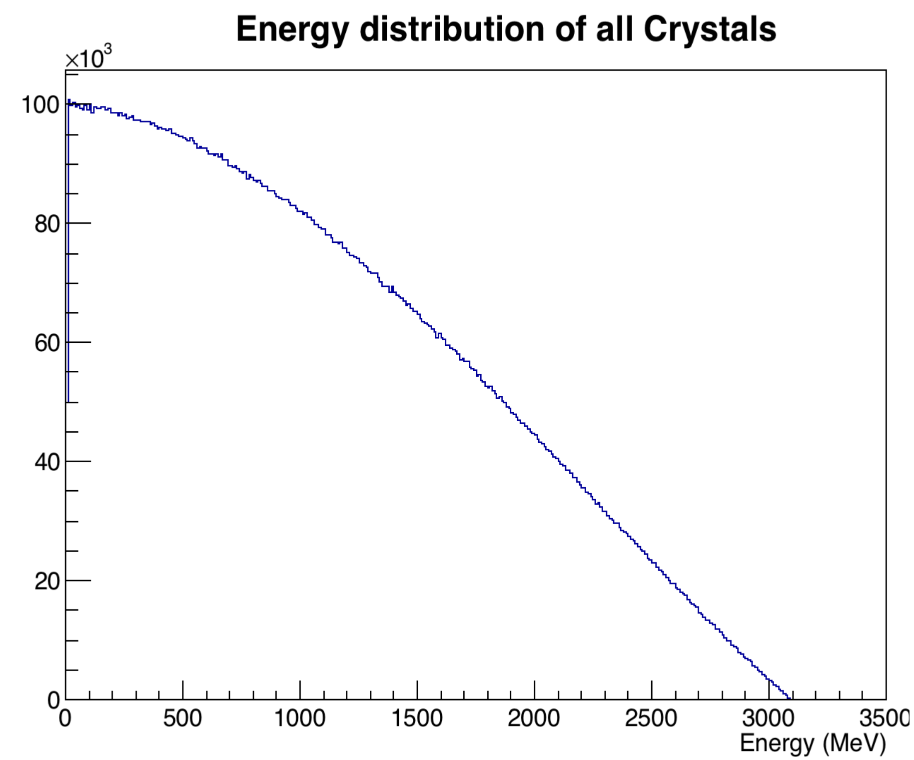
Simulated SiPM Function for 1500 PE

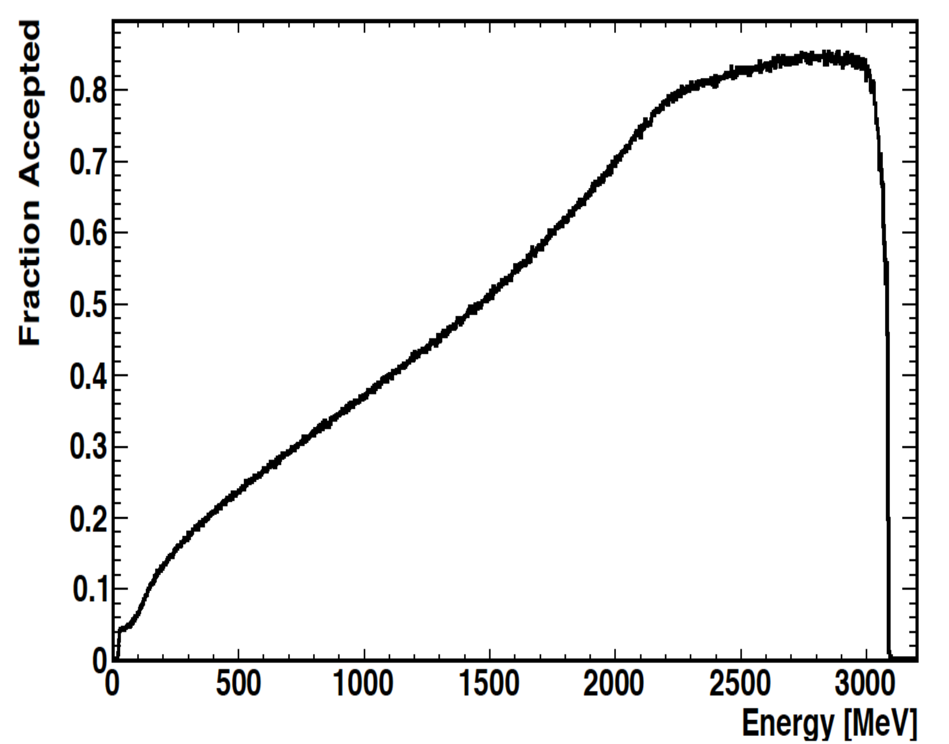


Simulation done with 100 muons and constant energy drop for 1500 PE

Energy Distribution

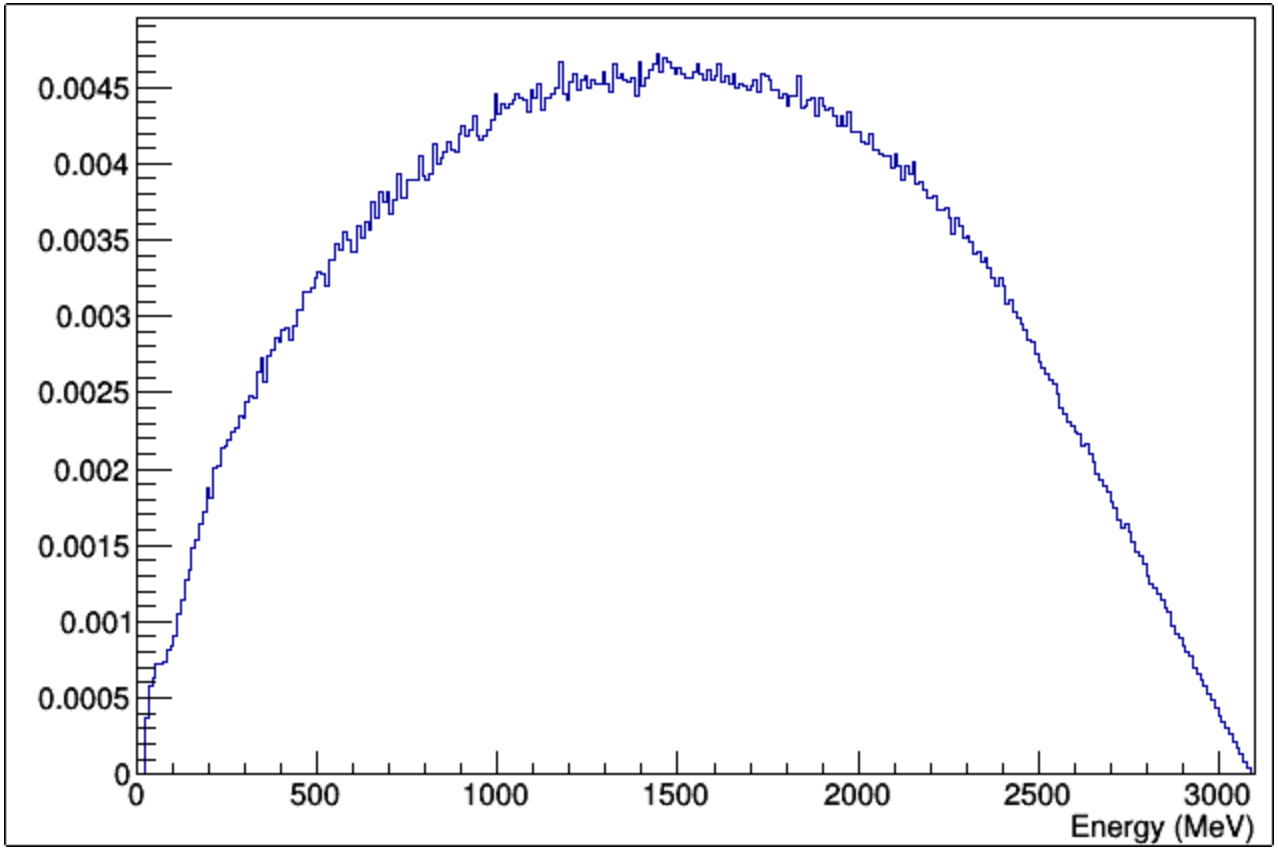
The functional form of the SiPM perturbation in gain depends on the energy of the positrons and the energy of the Laser also changes the bias. Assume 100 positrons hit a crystal with energy given by the plot (total energy distribution of positrons hitting all crystals - left) and the detector acceptance is shown on the right.





Energy Probability Distribution

The final probability distribution of energy (applying detector acceptance) used for our 2000 cycles and all fills for all muons used is shown below.



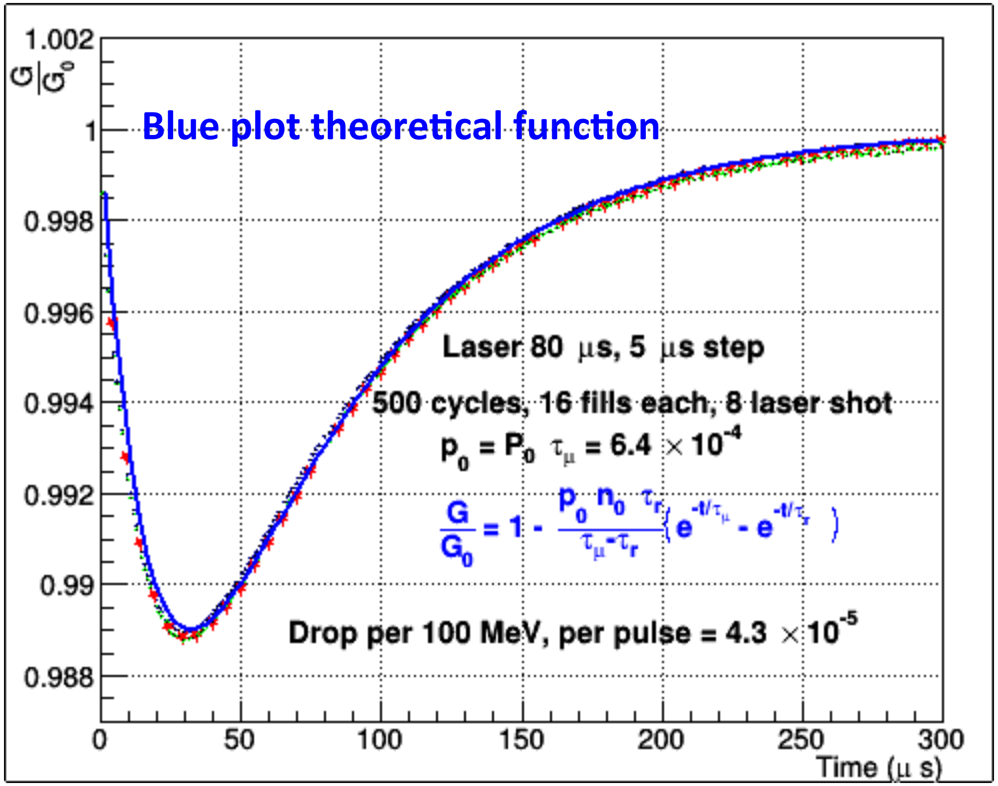
Special Cases for Simulation Studies

Unless mentioned in these studies we have 100 pulses (positron pulses) in a fill. I reran the simulation with 200 cycles as the energy distribution takes long. I studied the following cases:

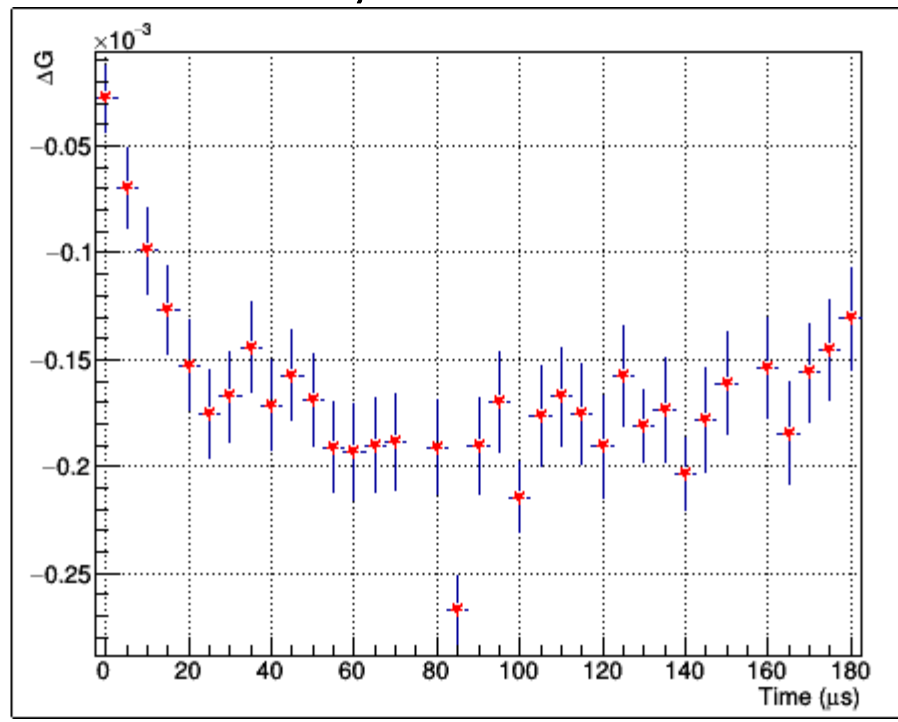
- Muons + laser rate corresponding to 80 μs interval, 5 μs step, 8 laser pulses/fill
- Muons + laser rate corresponding to 160 μs interval, 5 μs step, 4 laser pulses/fill
- Muons + laser rate corresponding to 320 μs interval, 5 μs step, 2 laser pulses/fill
- Muons + laser rate corresponding to 640 μs interval, 5 μs step, 1 laser pulse/fill

The laser shots at 2 GeV ($p_0 = 8.5\text{x } 10^{-4}$)

Laser Shots with 80 μs rate

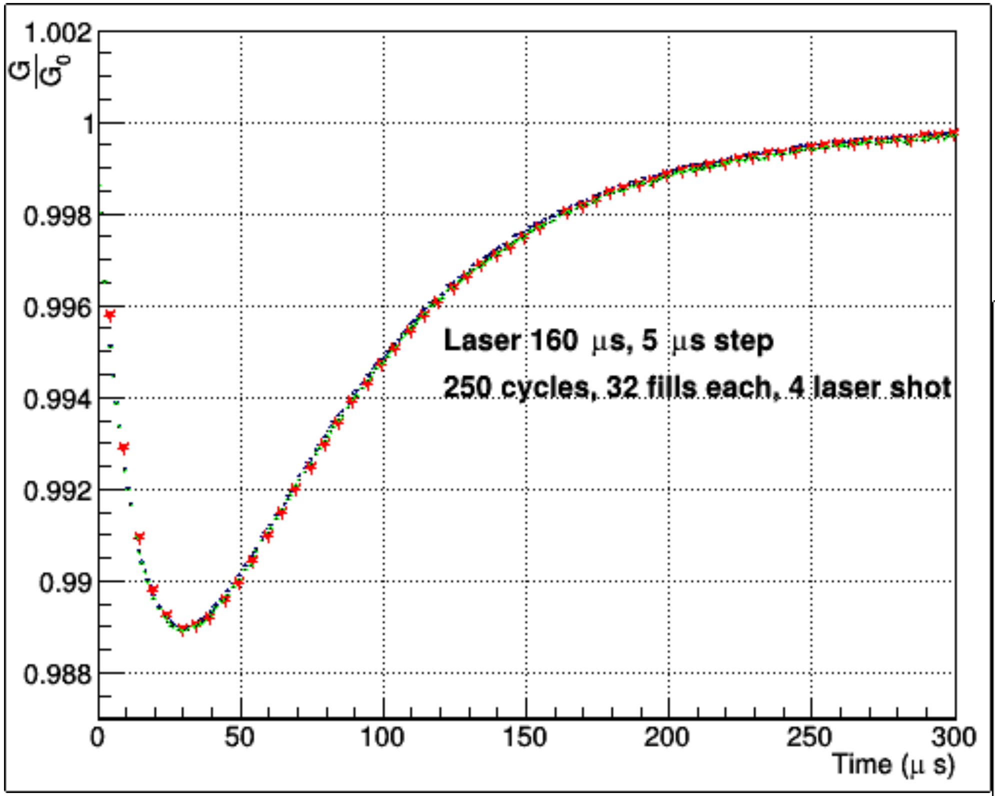


Difference of Laser and Muons Only

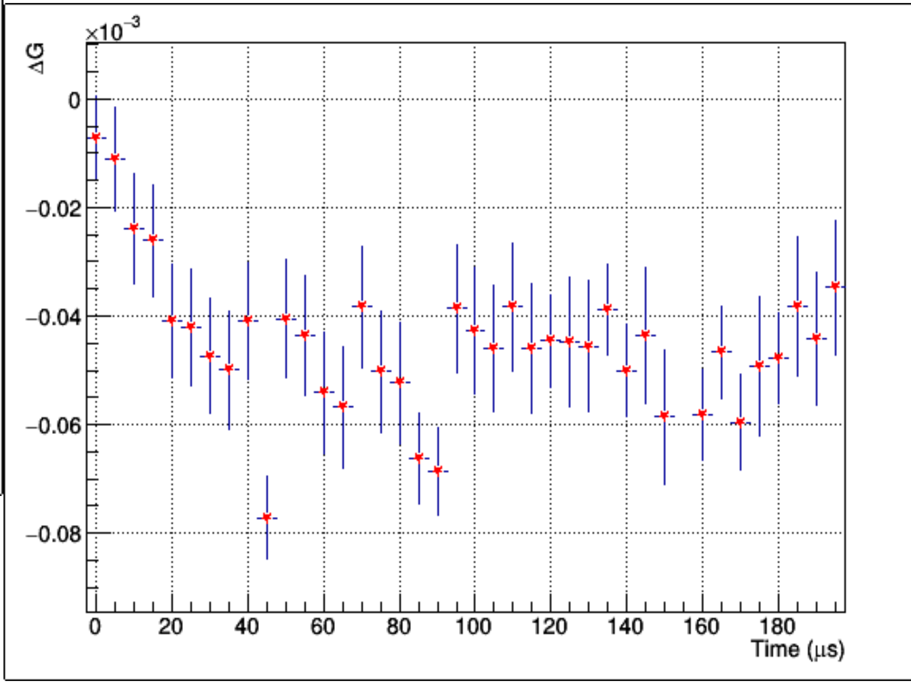


The laser shots at 2 GeV contribute to a larger drop in gain. This explains the negative values.

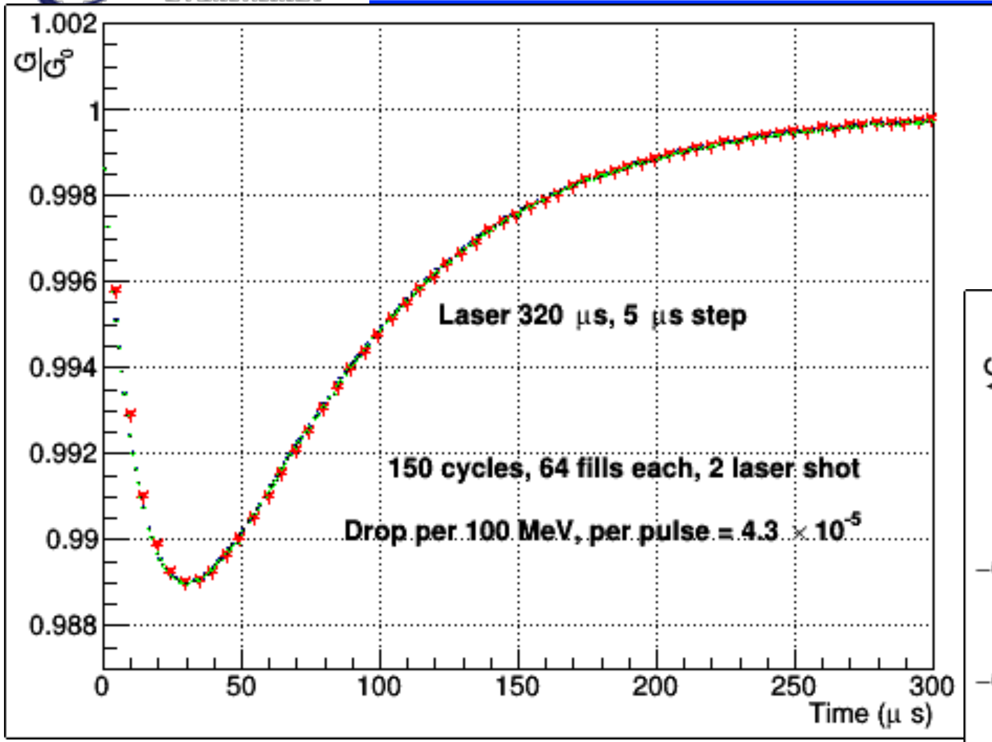
Laser Shots with 160 μs rate



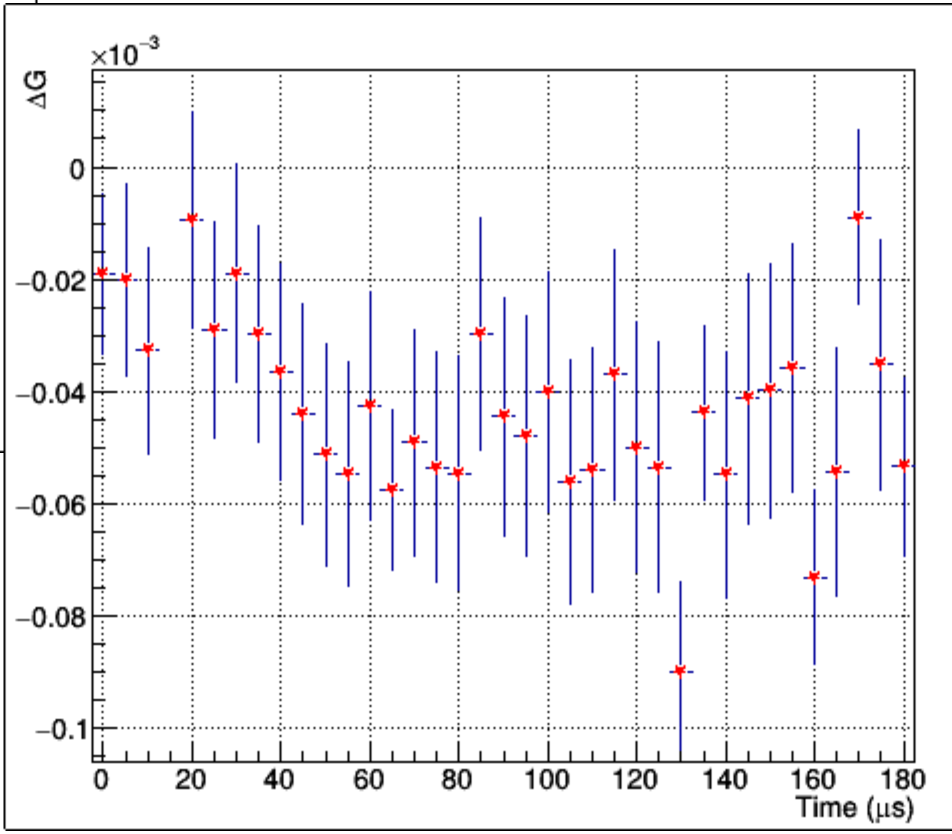
Difference of Laser and Muons Only



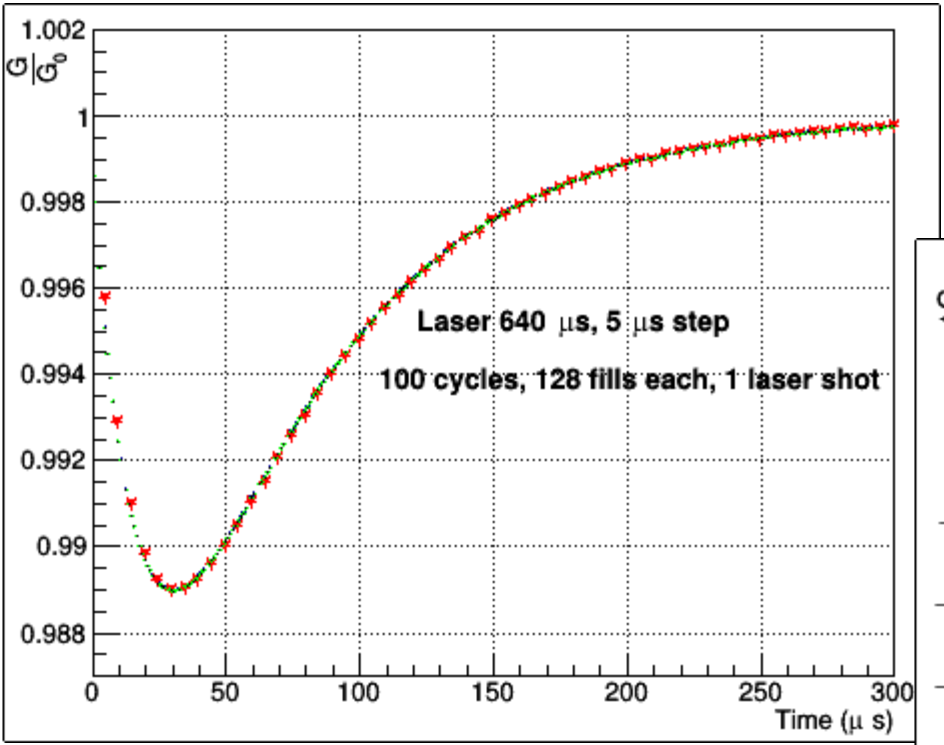
Laser Shots with 320 μs rate



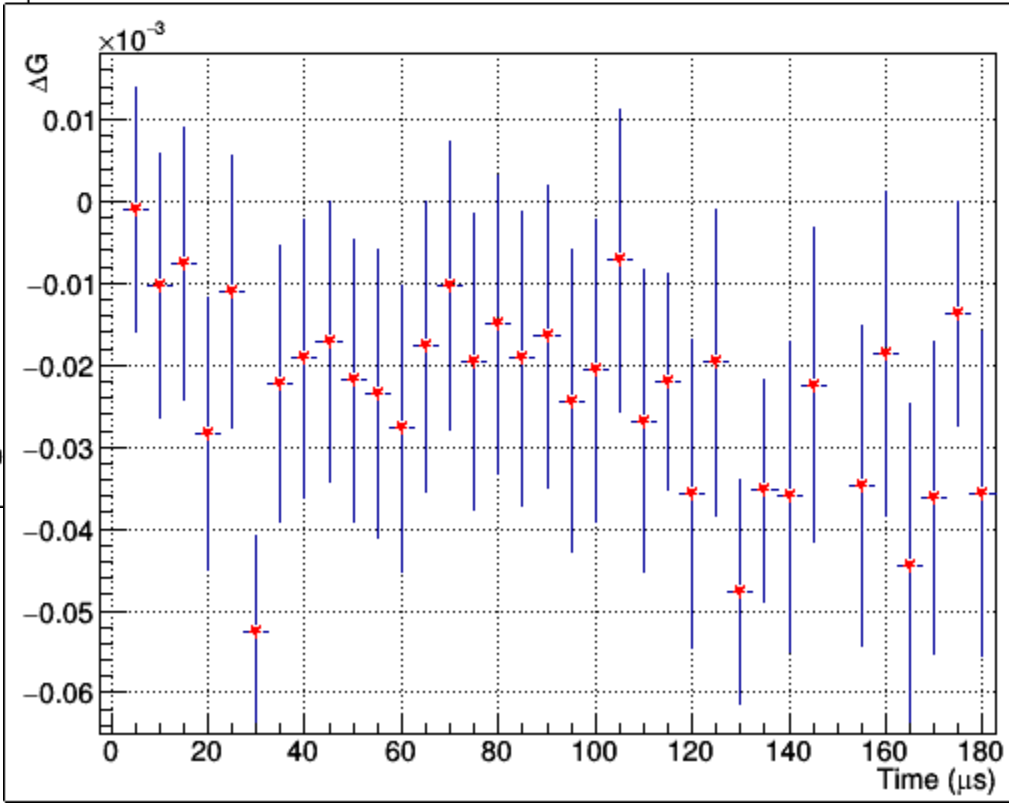
Difference of Laser and Muons Only



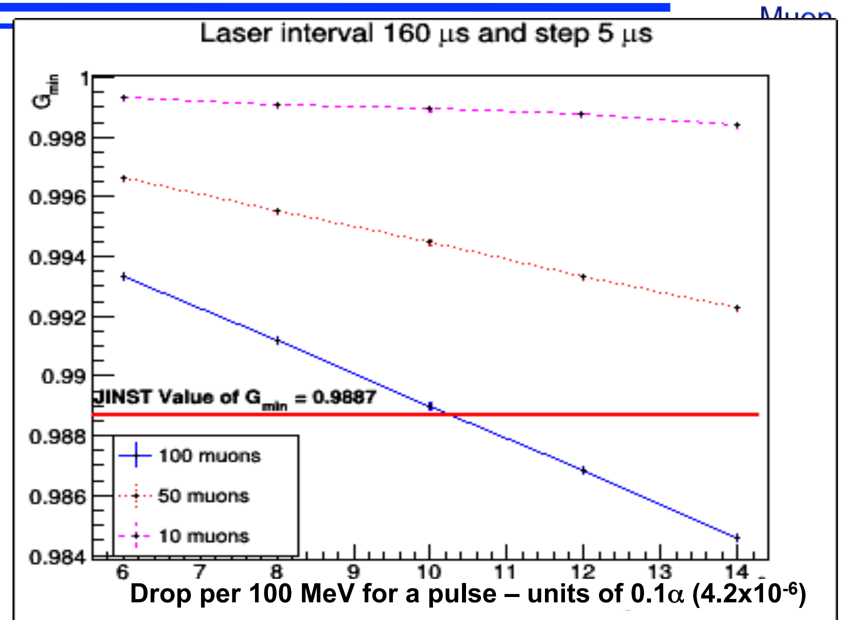
Laser Shots with 640 μs rate

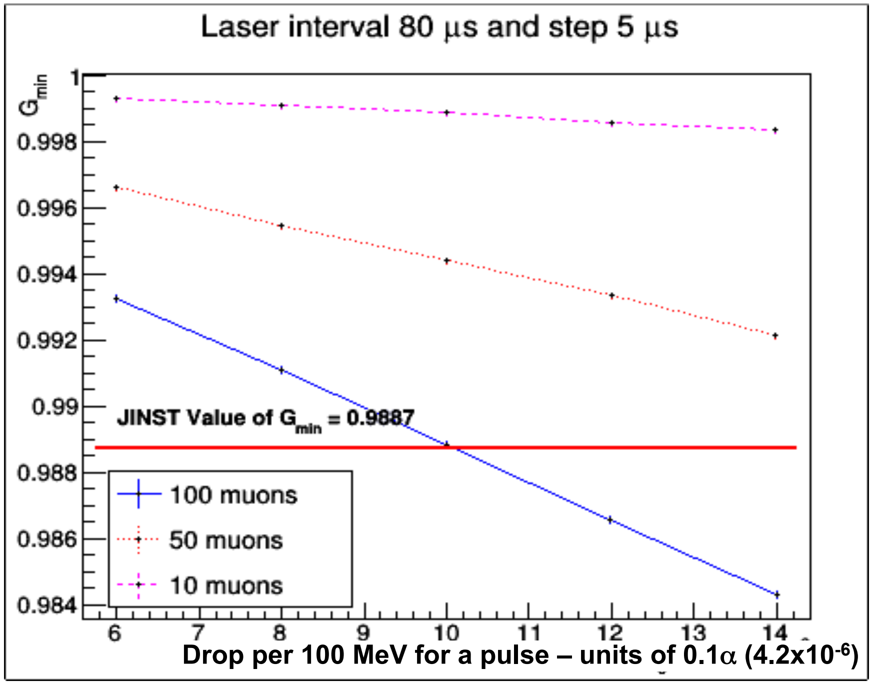


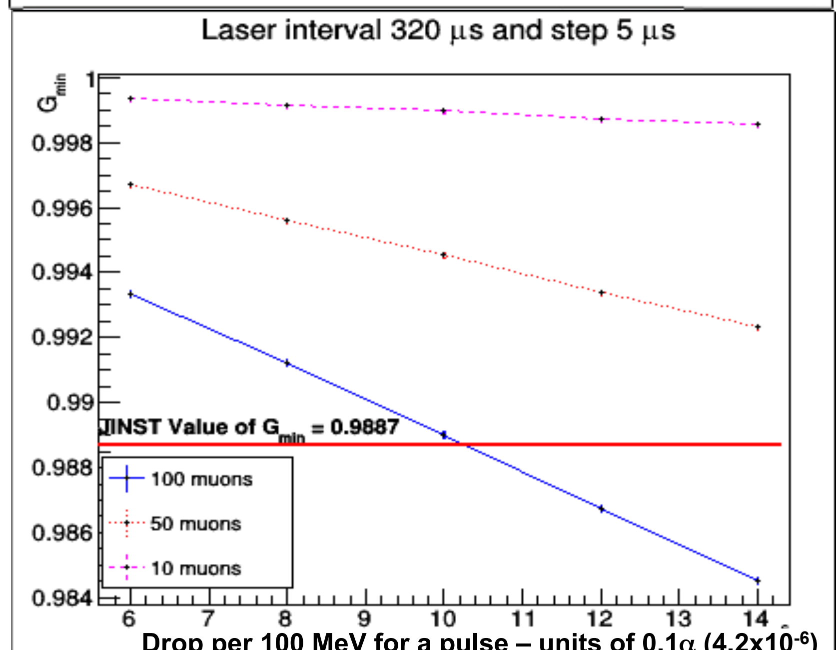
Difference of Laser and Muons Only



Optimizing the Drop in Gain per Pulse and Number of Pulses







Conclusion

- Calibration procedure will mostly be based on in- and out-of fills.
- We concentrate on the in-fill procedure trying to evaluate the effects of the laser pulses on the gain.
- A semi-analytical approach is used to study the shape of average gain within a fill.
- A realistic gain effect was considered (BV) which depends on the number of muons times the energy drop.
- By assuming 100 muons per fill and 4.2×10^{-5} drop @100 MeV we were able to study the effects of the laser pulse on the gain.
- By pulsing the laser at 2 GeV the effect with a repetition gain goes from $\sim10^{-4}$ (at 80 μs separation, 8 pulses per fill) to 2×10^{-5} at 640 μs separation.
- We can refine our studies including more realistic effects, like ω_a, different (short-long) recovering times and correct energy & rate for individual crystals.
- We have a documentation in progress.

BACK-UP SLIDES

Calibration procedure

- Effect of gain fluctuations on the uncertainties and ω_a. Can have infill and out of fill effects (negligibly small as they are due to slow variations). Consider only infill effects. Reduce error due to gain changes to 20 ppb.
- Study and simulate gain fluctuations/stability of SiPMs based on the BV sagging effects studied by Aaron , introducing a perturbation in gain function G(t) = $(G'-G_0)$ where G_0 is the ideal/corrected gain and G' is true gain vs. time due to detector readouts etc.
- A very stable laser calibration system used which monitors the source for stability/fluctuation before calibration which gives G_0 and G' is measured using the above – laser through calorimeters.
- Simulate the effect of laser pulses on this SiPM's gain function.

Special cases – Number of fills and lasers

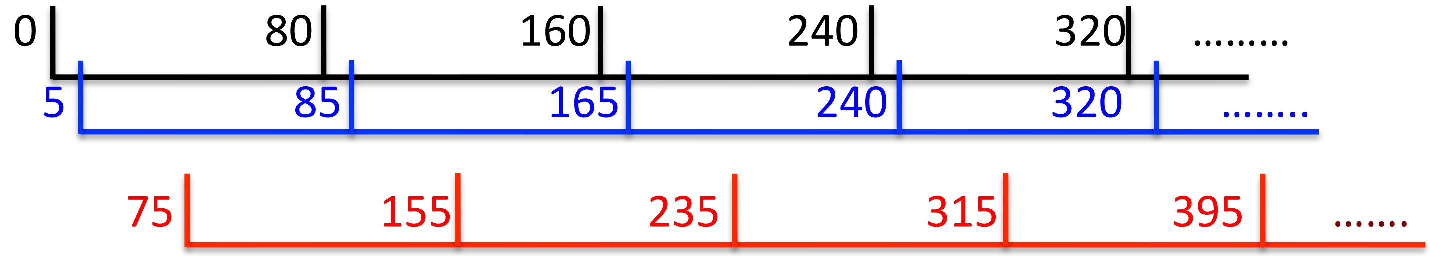
8 Laser shots with 80 ms time interval (corresponding to 12.5 kHz) – 2000 cycles

Fill 1:

Fill 2:

....

Fill 16:



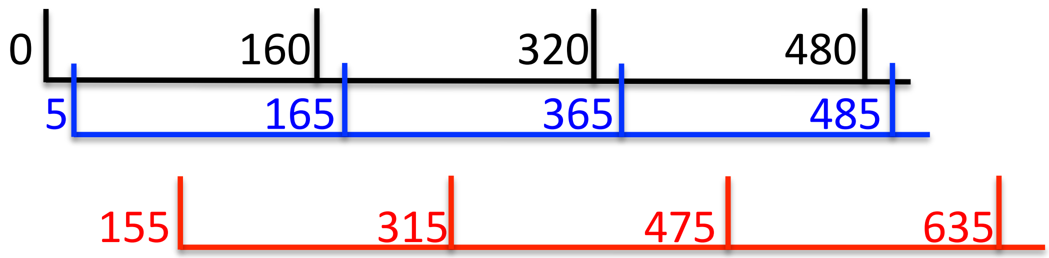
4 Laser shots with 160 ms 1000 cycles

Fill 1:

Fill 2:

....

Fill 32:



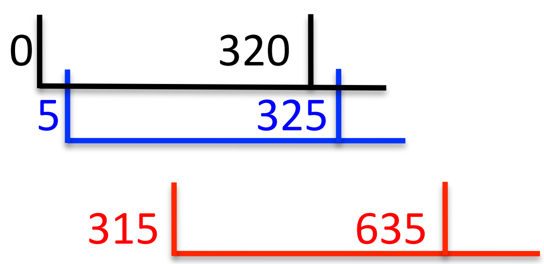
2 Laser shots with 320 ms 500 cycles

Fill 1:

Fill 2:

....

Fill 64:



1 Laser shot with 640 ms 250 cycles

Fill 1:

Fill 2:

....

Fill 64: