Investigation of the effect of short term gain fluctuations of the SiPM's on the muon precession frequency

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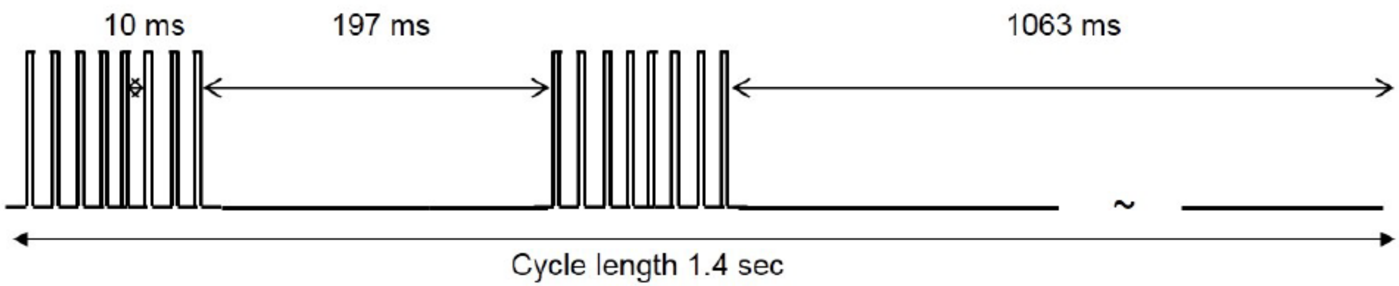
Outline

- Brief discussion of the laser calibration procedure.
- Results of the simulation of Gain Fluctuations using Bias Voltage sagging
- Effects of Laser pulses on this
- Conclusion

Summary of Calibration procedure

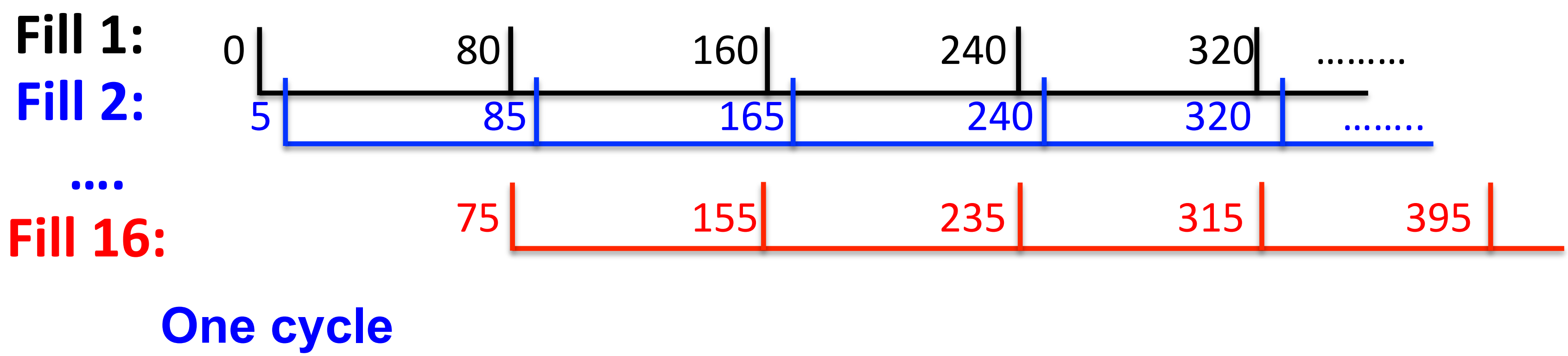
- **Goal** of the Calibration laser system:
  - Monitor the short-term Gain (i.e. within 700 μs fill)
  - Fluctuations at sub per mill level (0.04% statistical+0.01% systematics)



- **Basics**:

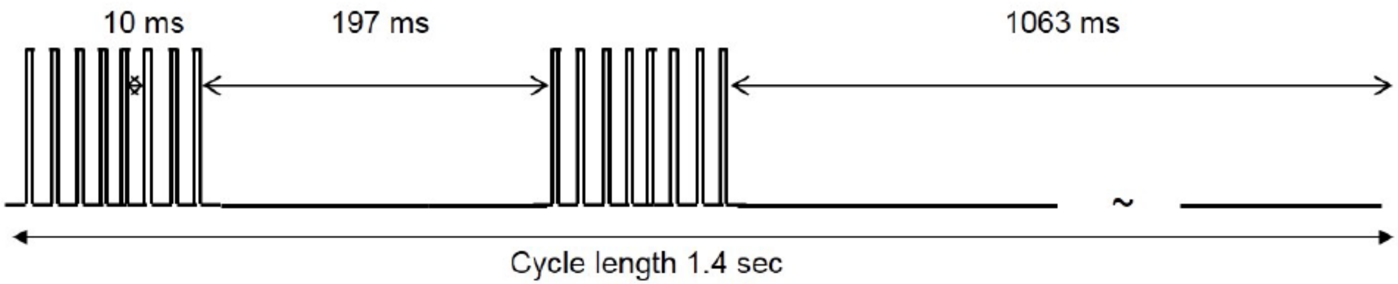
1. In-Fill calibration for short term effects on G(t)
2. Out-of-fill calibration for stability checks

In-fill Calibration: pulsing laser with μ beam



- Short term gain fluctuations (Bias Voltage (BV) sagging) – pulse laser + μ beam. Summary of procedure:
  - 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 with μ beam

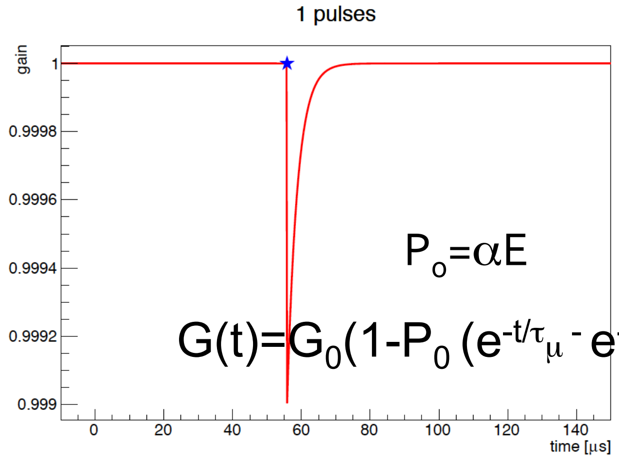


- Pulsing the laser for a dedicated time in the day (like 2 hours in the morning) **assumes** that the laser calibration runs represent the gain fluctuations of the entire day.

- 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 characteristics (Intensity, etc...) for the entire day.

BV Sagging effect

- Gain is the convolution of single energy drop with the time distribution of the positrons and recovery time based on the bias voltage of the SiPM's
- It depends on the rate and intensity of the pulses (positron/laser)



$P_o = \alpha E$

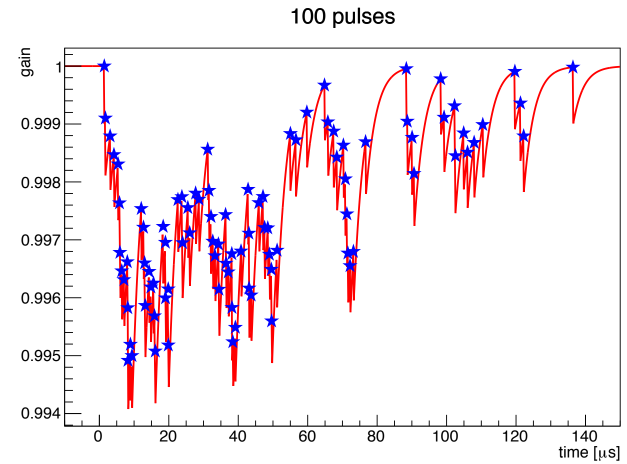
$G(t) = G_0(1 - P_0\,(e^{-t/\tau_\mu} - e^{-t/\tau_r}))$

P_o is gain drop, depends on the e^+ energy

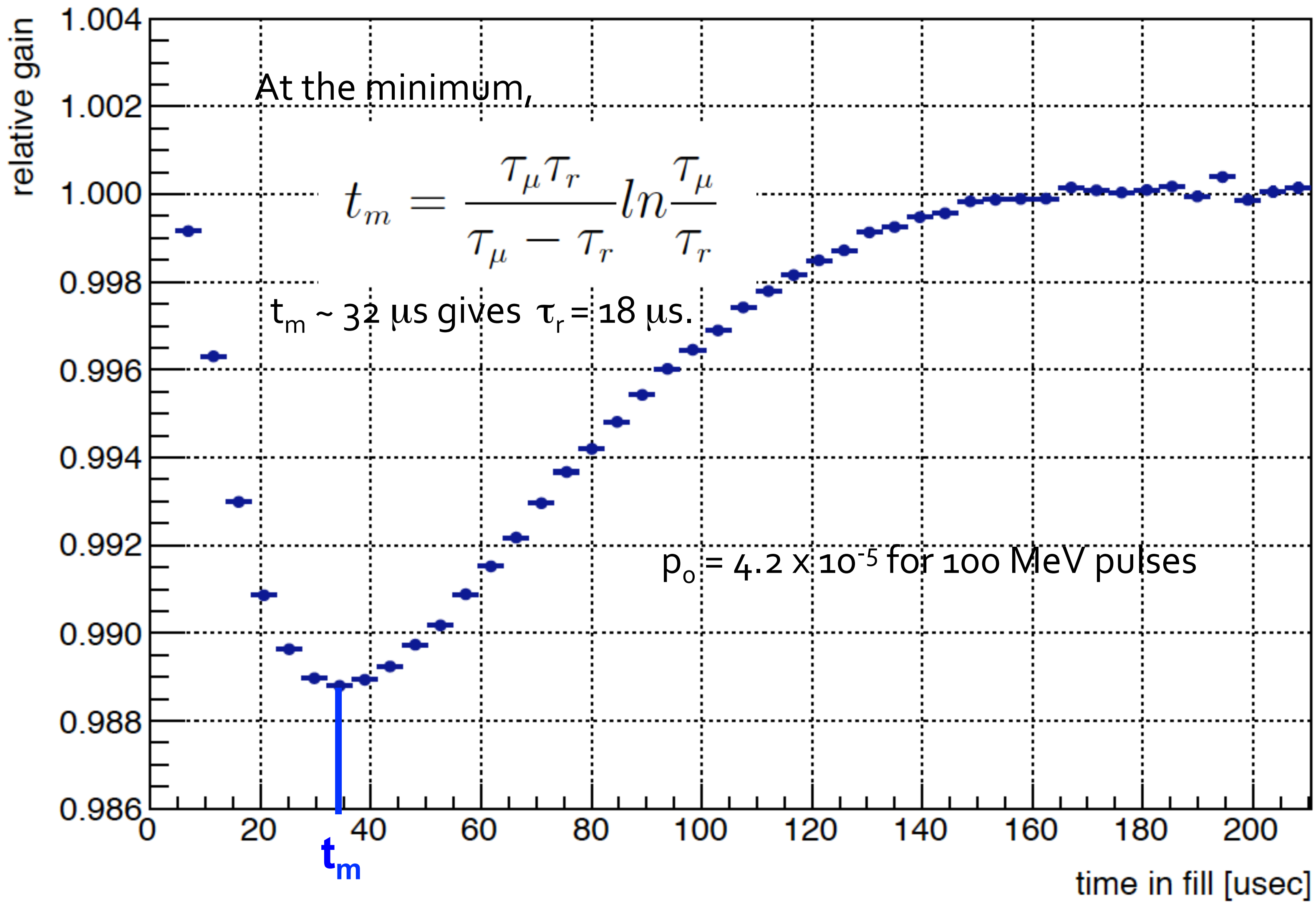
Simulation: Exponential decay for e^+ (or laser pulse). The cumulative gain (for n_o pulses) can be written as

$$\frac{G(t>0)}{G_0} = 1 - \alpha E n_0 \left(e^{-t/\tau_\mu} - e^{-t/\tau_r}\right)$$

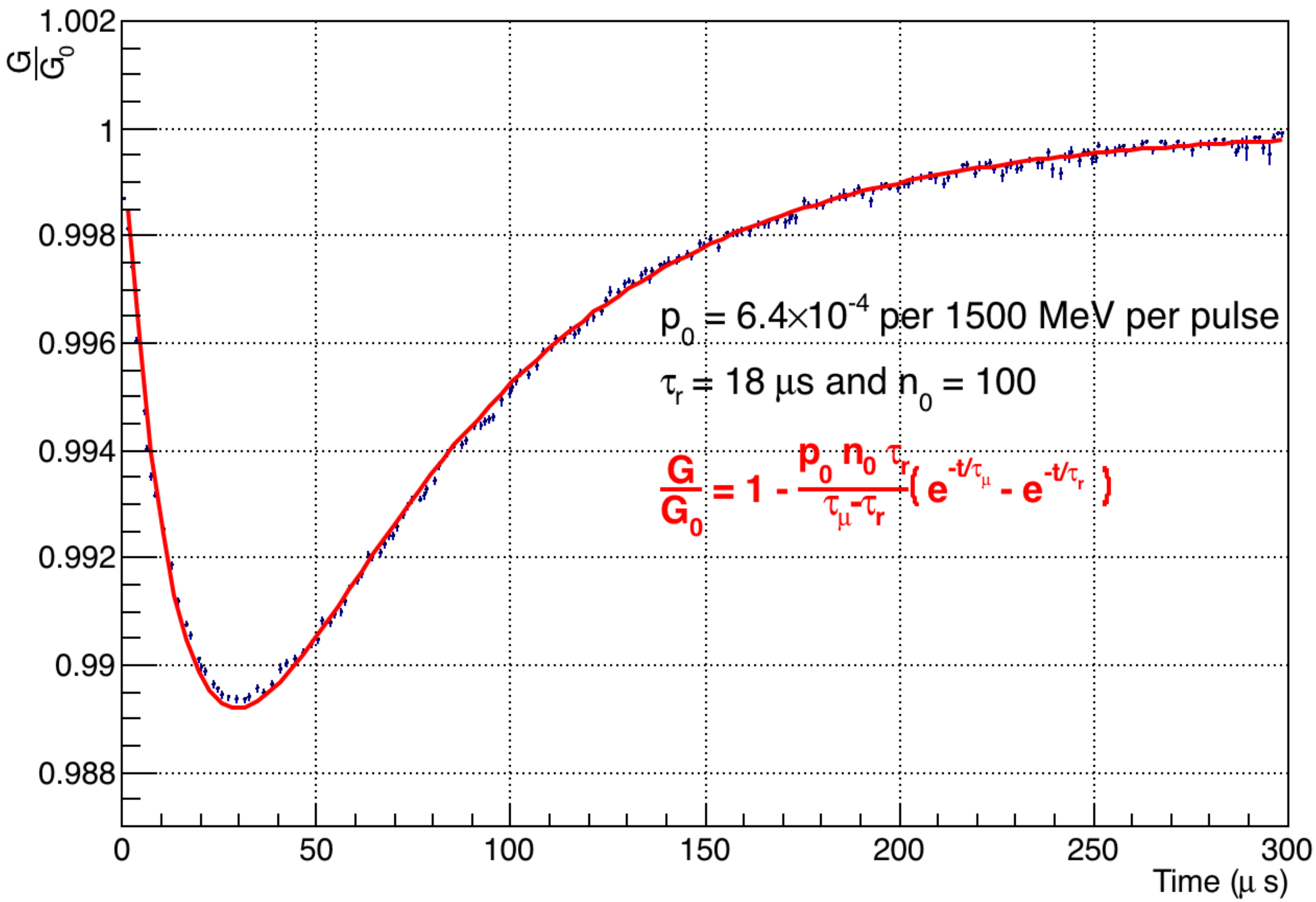
$$\alpha = \frac{\tau_\mu \tau_r}{\tau_\mu - \tau_r}$$



JINST SiPM Function for 1500 PE

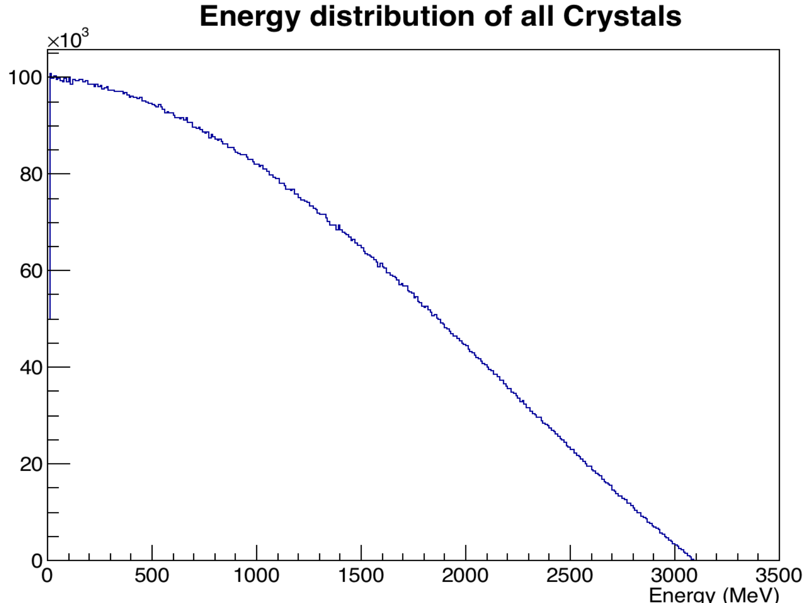


Simulated SiPM Function for 1500 PE

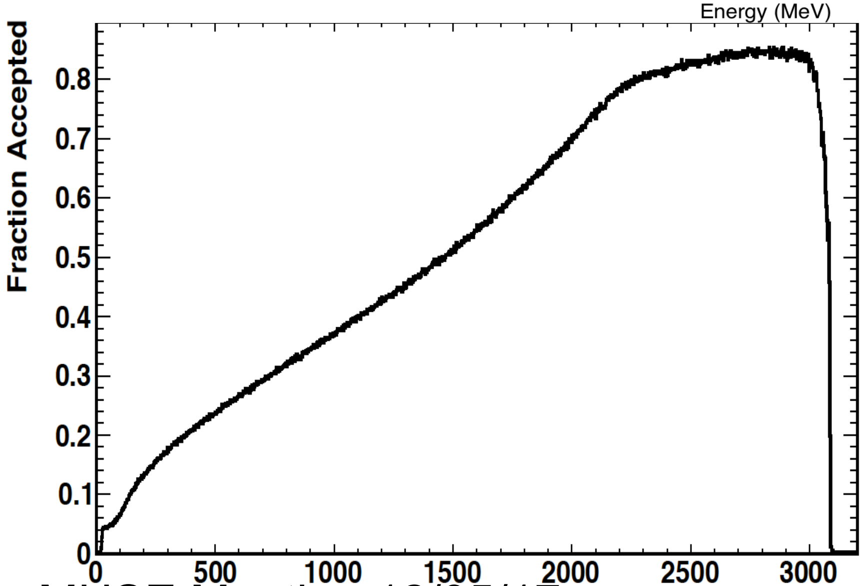


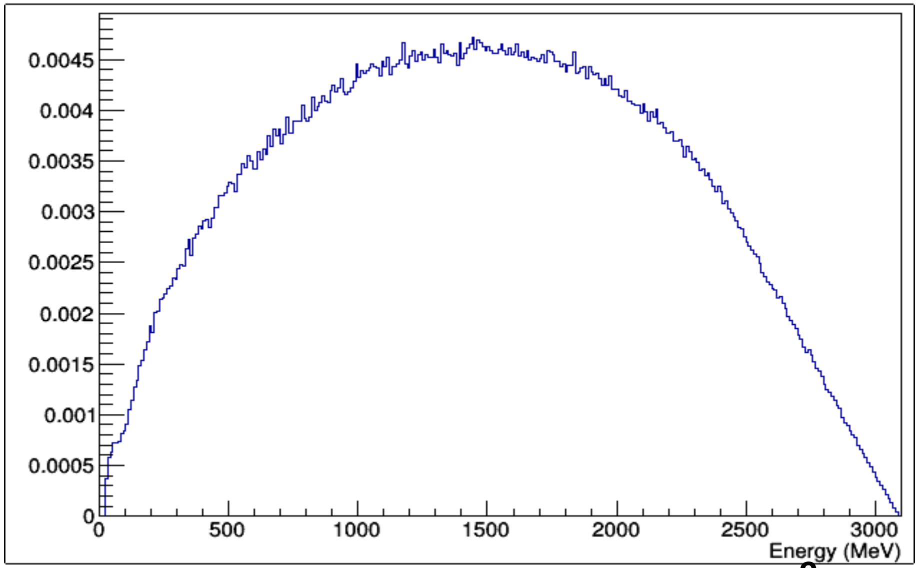
Simulation done with 100 muons and constant energy drop for 1500 PE

Energy Distribution



SiPM gain depends on the energy of the positrons and the energy of the Laser also changes the bias. Normalized total energy distribution of positrons (top) along with detector acceptance (left bottom) gives the probability distribution (right bottom) .



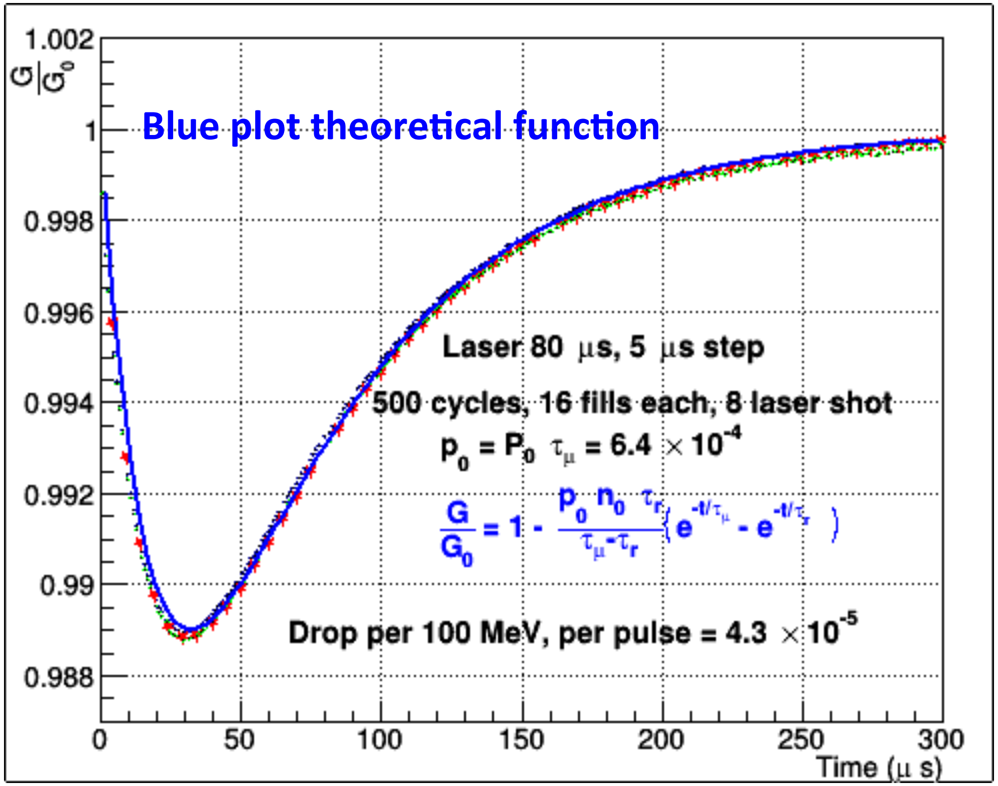


Special Cases for Simulation Studies

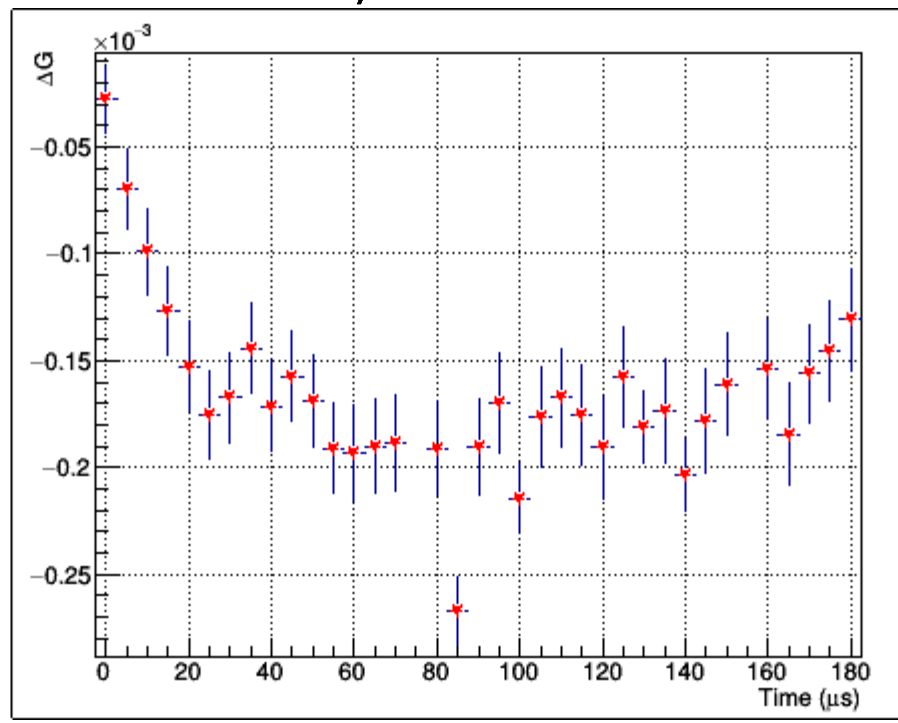
Unless mentioned in these studies we have 100 pulses (positron pulses) in a fill. I reran the simulation with 2000 cycles as the energy distribution takes long. I plan to study the following cases (p_o is the gain drop for one pulse corresponding to an energy of 1500 MeV or 1500 PE):

- Muons + laser rate corresponding to 80 μs interval, 5 μs step and $p_o = 6.4 \times 10^{-4}$, 8 lasers and 16 fills
- Muons + laser rate corresponding to 320 μs interval, 5 μs step and $p_o = 6.4 \times 10^{-4}$, 2 lasers and 64 fills

Laser Shots with 80 μs rate

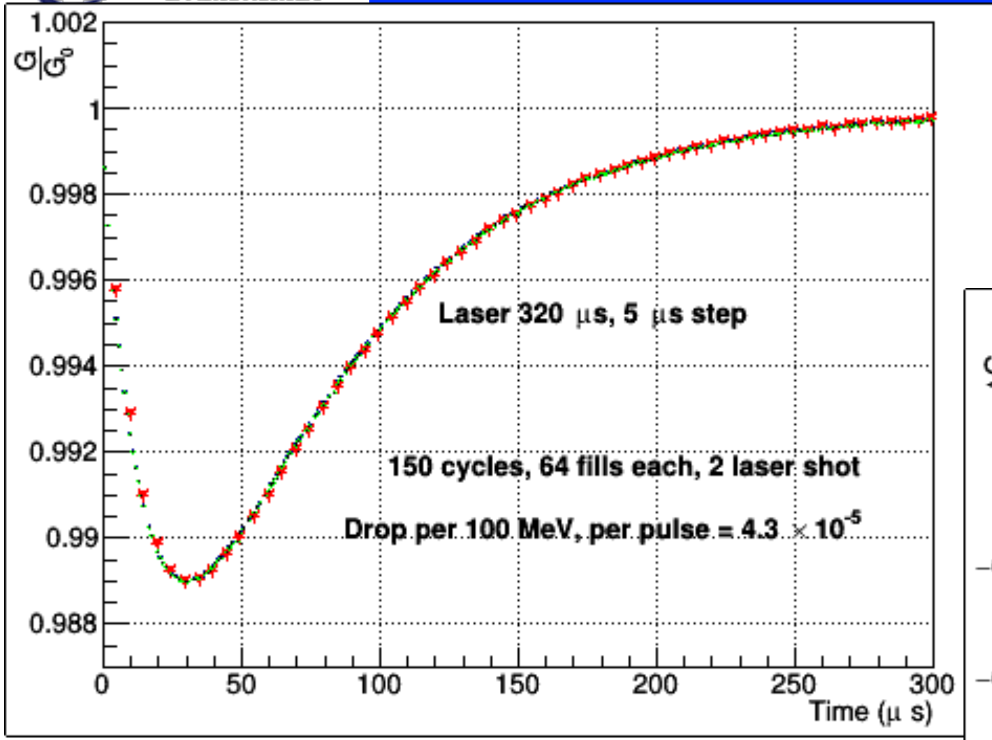


Difference of Laser and Muons Only

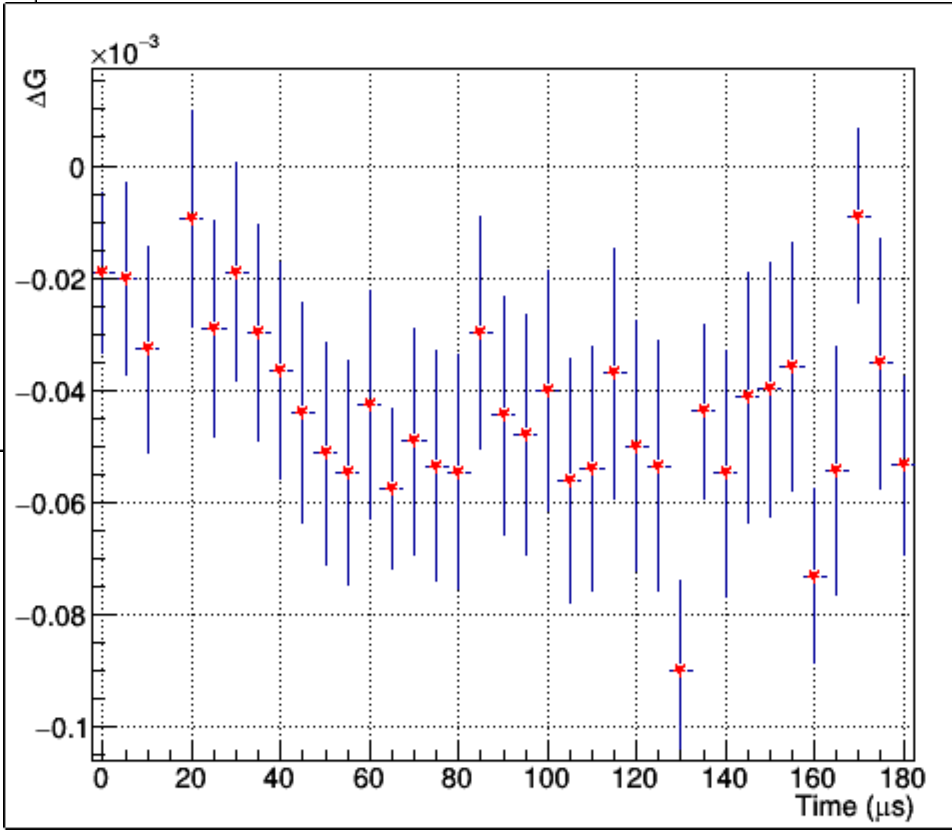


The laser shots at 2 GeV contribute to a larger drop in gain. This explains the negative values.

Laser Shots with 320 μs rate



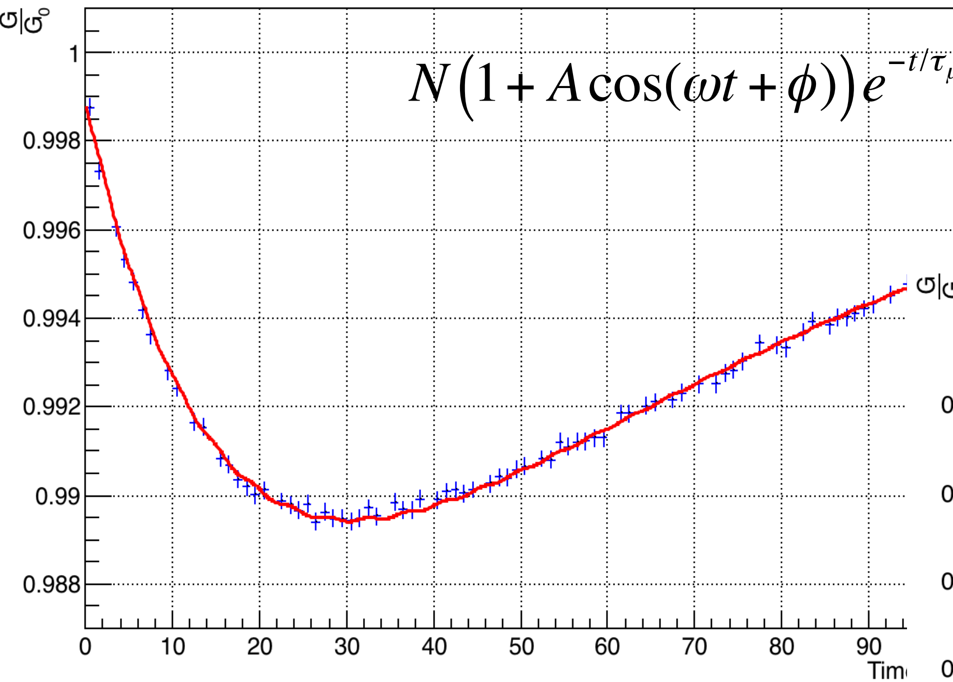
Difference of Laser and Muons Only



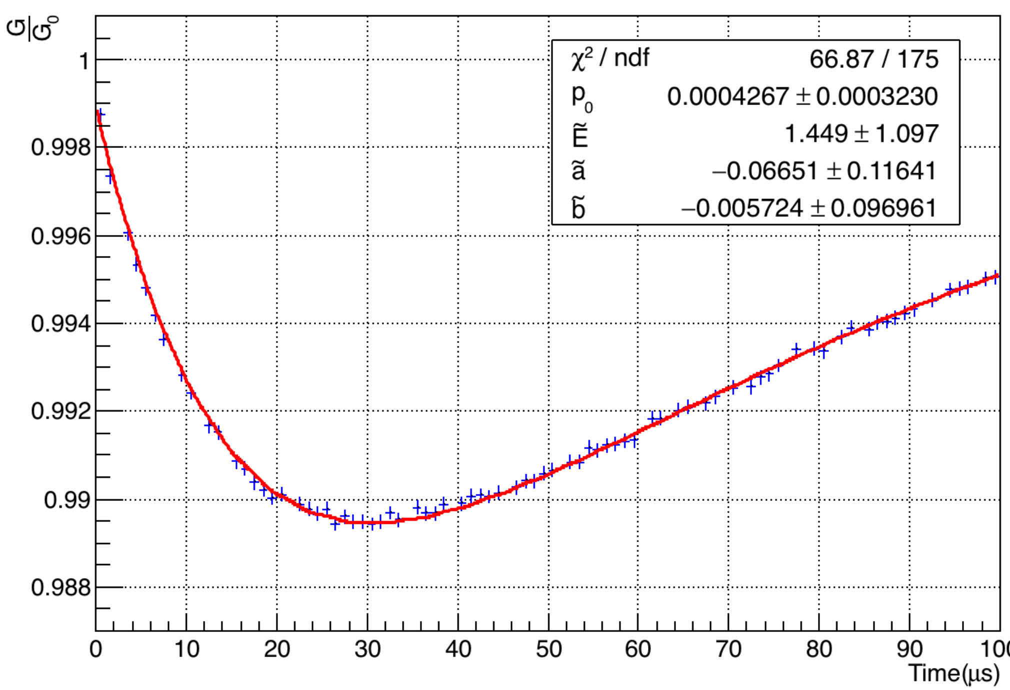
Gain with Wiggles

Used averages found overlaid (left) and fitted (right)fig. Not enough stats.

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

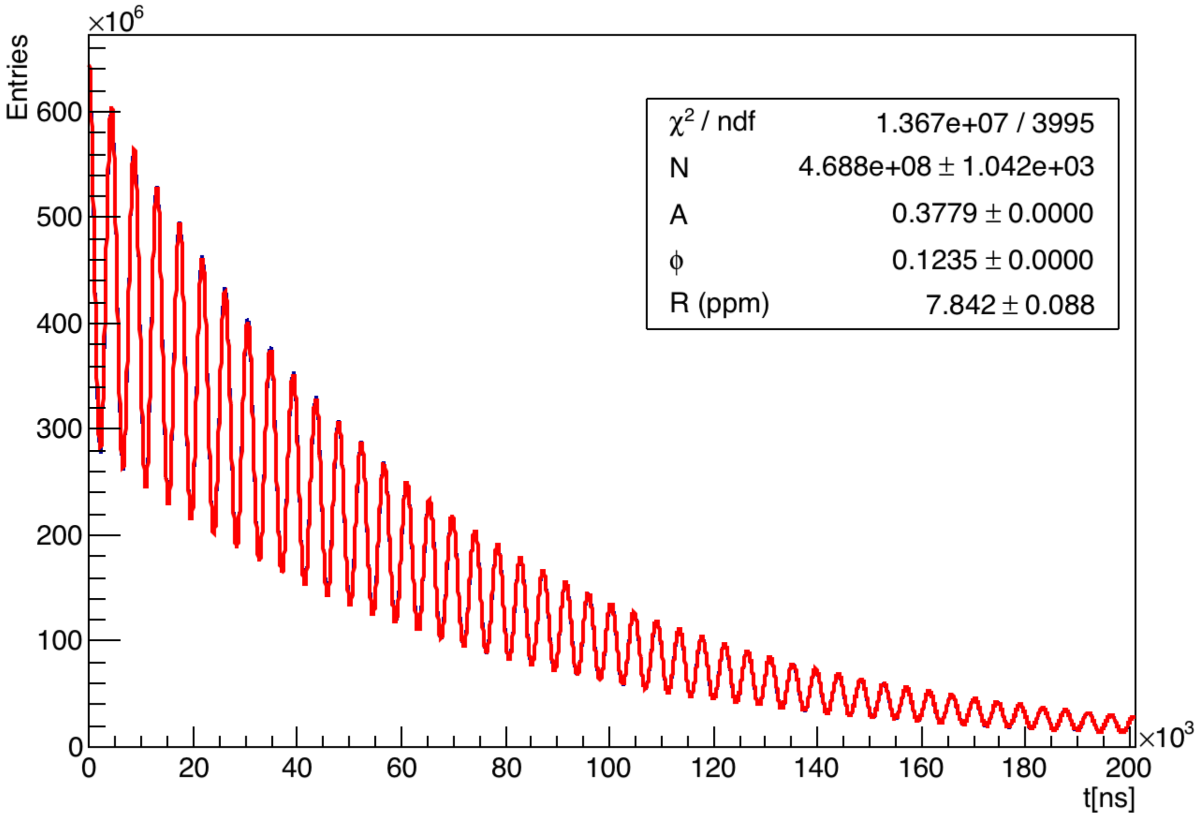


$$N\left(1 + A\cos(\omega t + \phi)\right)e^{-t/\tau_\mu} = e^{-t/\tau_\mu}(N + a\cos\omega t + b\sin\omega t)$$



Effect on Precession Frequency

Using this gain on the wiggle plot finally to see how it effects ω_a



$$N\left(1+A\cos(\omega t+\phi)\right)e^{-t/\tau_\mu} = e^{-t/\tau_\mu}\left(N+a\cos\omega t+b\sin\omega t\right)$$

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 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 the order of10^{-5} at 320 μs separation.
- There is a very large effect in $\Delta\omega_a \sim 7.8$ ppm which must to taken care of or corrected with lasers (work in progress)

THANK YOU!!!

BACK-UP SLIDES

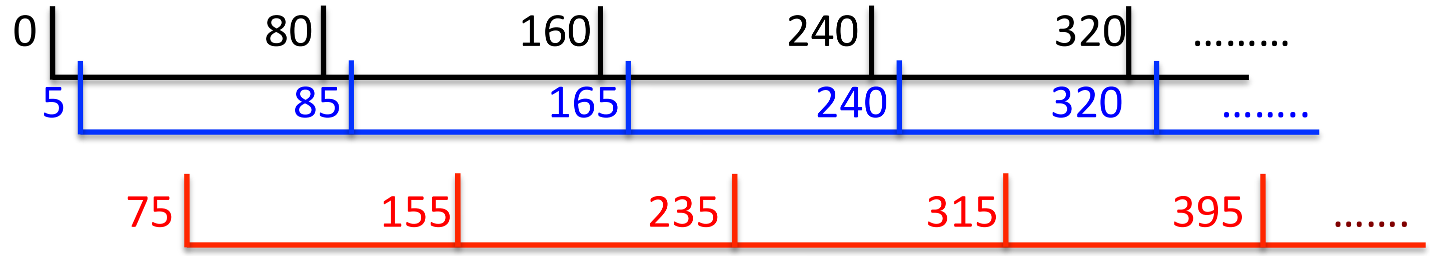
Calibration procedure

- 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

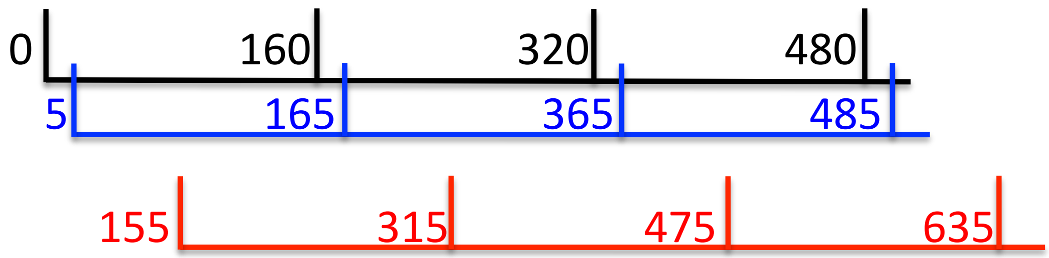
8 Laser shots with 80 ms time interval (corresponding to 12.5 kHz) – 2000 cycles

Fill 1:
Fill 2:
....
Fill 16:



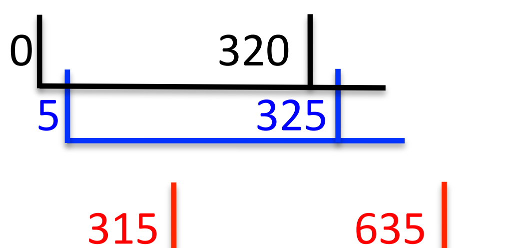
4 Laser shots with 160 ms 1000 cycles

Fill 1:
Fill 2:
....
Fill 32:



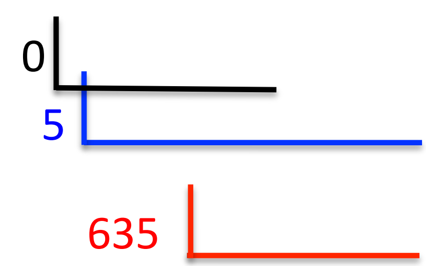
2 Laser shots with 320 ms 500 cycles

Fill 1:
Fill 2:
....
Fill 64:



1 Laser shot with 640 ms 250 cycles

Fill 1:
Fill 2:
....
Fill 64:



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:

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

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:

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

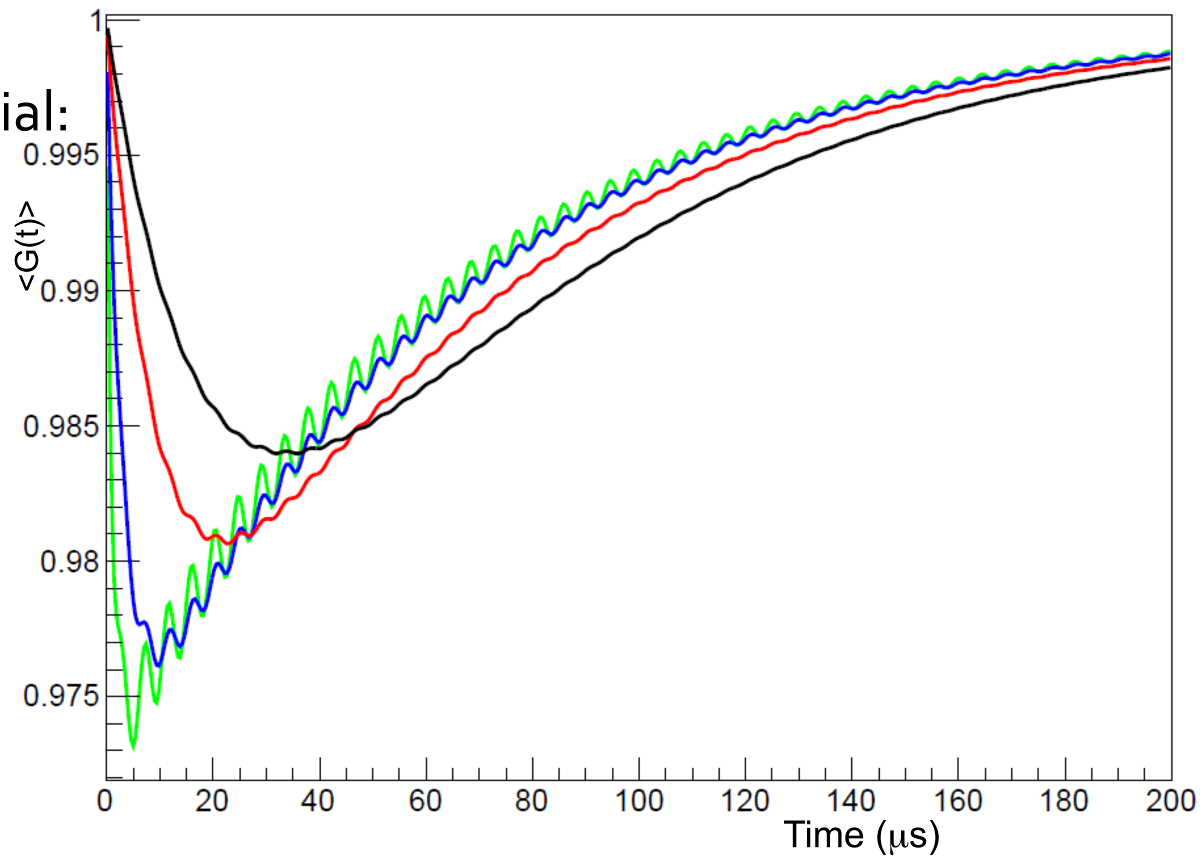
Examples with 1 exponential:

1 μsec

3 μsec

10 μsec

20 μsec



Gain with Wiggles

The actual positron distribution is given by,

$$N\left(1+A\cos(\omega t+\phi)\right)e^{-t/\tau_\mu} = e^{-t/\tau_\mu}(N + a\cos\omega t + b\sin\omega t)$$

Using average values of N, a and b for a fill we get the the average gain,

$$< G(t) >= 1 - n_0 \alpha E(\tilde{N} S_N + \tilde{a} S_a + \tilde{b} S_b)$$

The average values of N, a and b evaluated analytically including the acceptance shown in the plots