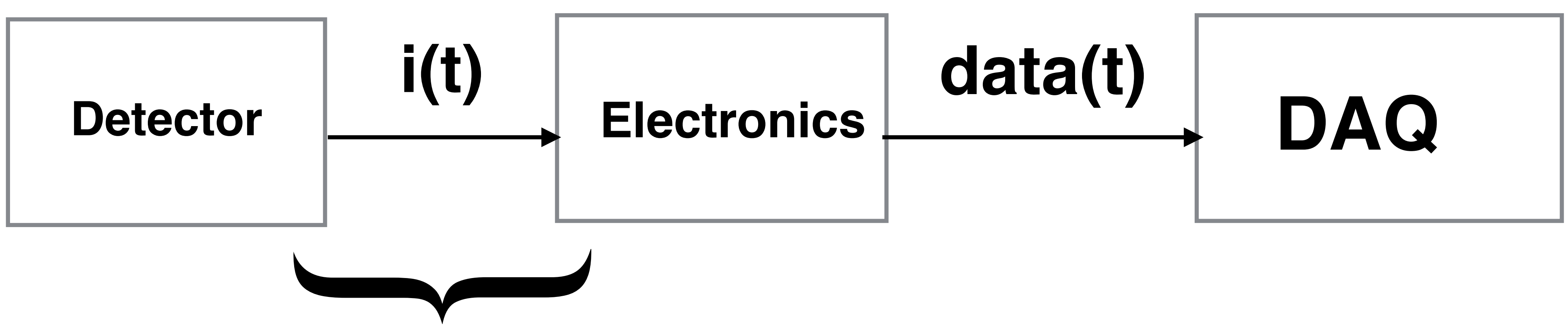
Requirements

MVD
12/15/2016

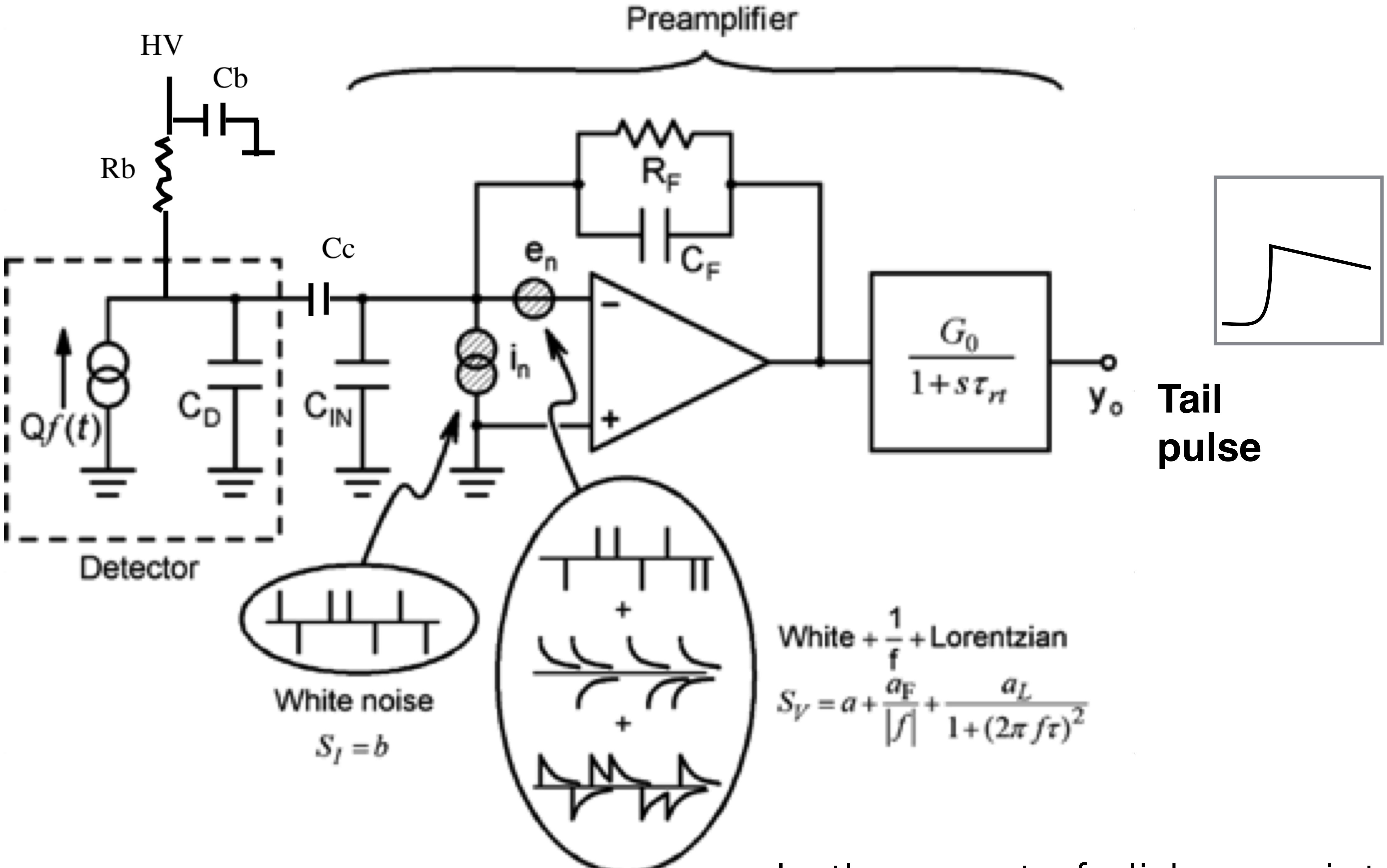
There are many absolute numbers in this presentation. Currents, voltages, charge, counts, etc. Mistakes are possible. Please check and correct.

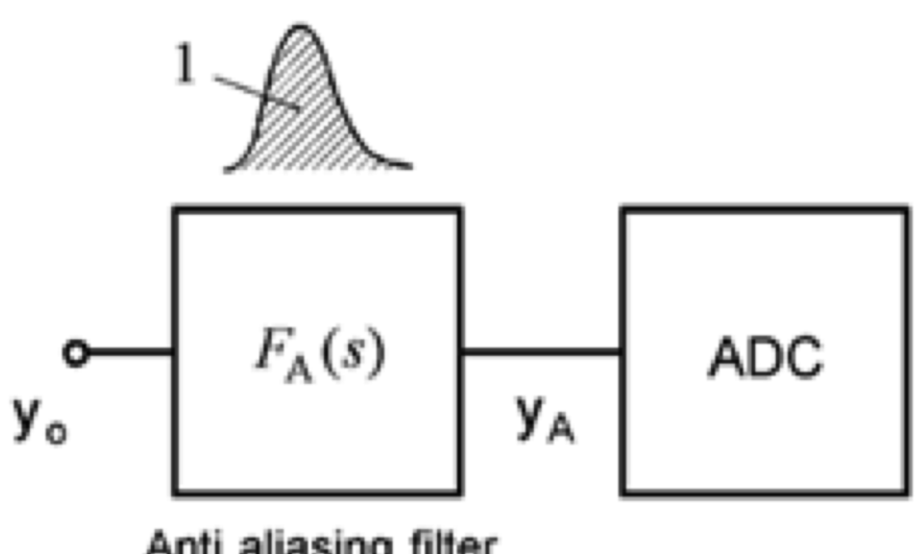
Preamble

- Cold electronics specifications are reasonably well known and settled by the experts.
- There is no attempt to reinvent anything here, but to document the minimum functions that are needed.
- We also want to create record/create the needed terminology.



DUNE's technological goal is to integrate the detector and the electronics. Although these are all divided in components, it makes no sense to consider the requirements separately. Modern technical management emphasizes focus on integration. The output of the system are time ordered integers: {1,20, 34,0,200,1000,2000,200,..}





In these set of slides we intend to analyze the functioning and requirements of the electronics and readout for a LAR TPC. This is done at a high level with a lot of pedagogy.

- The final goal is to produce a simulation of signal +noise through the system. For both induction or a collection signal.
- The signal+noise waveform (in time domain) will be analyzed to reconstruct the input current pulse.
- Based on the quality of the reconstruction, we produce requirements on the noise components, gain, shaping, sampling time, dynamic range and resolution.
- The idea is to do this calculation from basic principles as much as possible.

Team

3D calculation of i(t)

Brett,
Yichen, Bo,

Experience from microboone analysis/simulation

Xin, Chao, Jyoti,

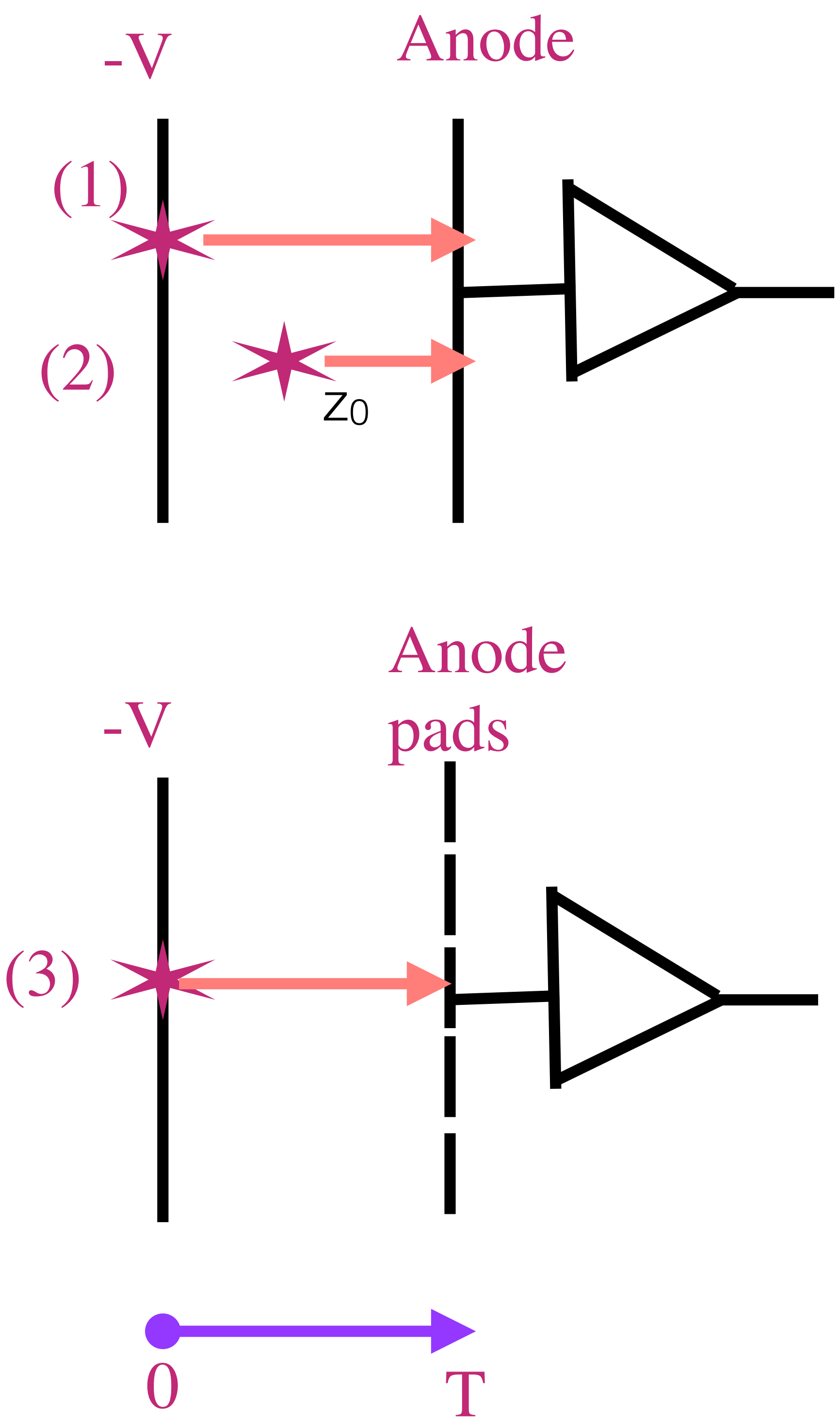
Requirements

MWorcester, MVD,
Hucheng,

Documentation, analysis

Specific design answers from BNL-ID

Induced current basics



Here Assume T is very small

Drift Field $E = -\nabla\varphi$

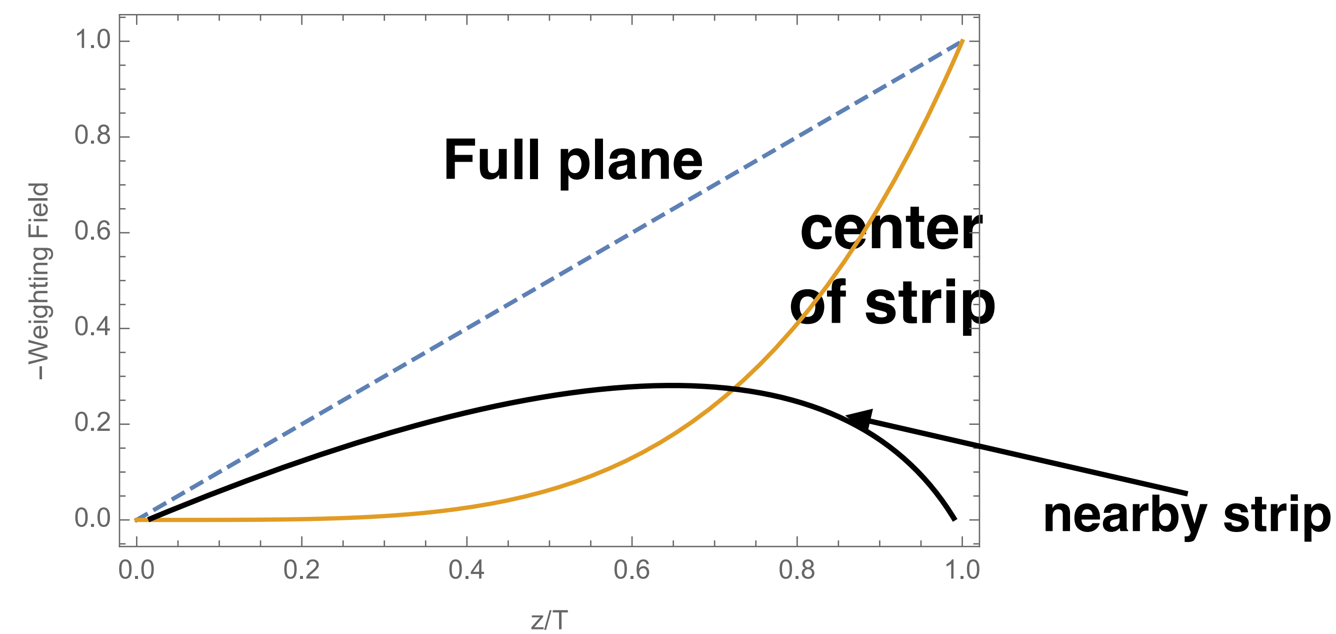
$$\varphi = -V(z/T)$$

$$\vec{E} = \hat{z}(V/T)$$

Shockley-Ramo.

$\vec{\mathrm{E}}_{sr}$ = weighting field

$$i = q\vec{v} \bullet \vec{E}_{sr} \text{ or } Q = q\Delta\varphi_{sr}$$



$$(1)\ Q = -ne \bullet (\varphi_{sr}(T) - \varphi_{sr}(0)) = -ne$$

$$(2)\ Q = -ne(\varphi_{sr}(T) - \varphi_{sr}(z_0)) + ne(\varphi_{sr}(0) - \varphi_{sr}(z_0))$$

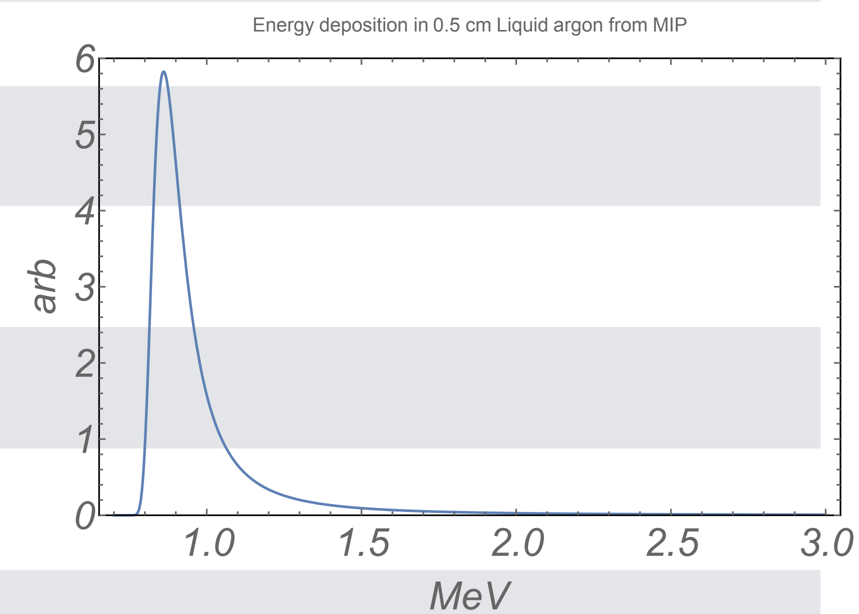
$= -ne$ If ions move, otherwise smaller.

$(3)\ Q = -ne,$ but most of the charge will arrive in a short time close to the pad.

- DUNE geometry is much more complicated including wire grids and multiple planes.
- A catalog of induced current shapes will be used when we finish the 3D calculations.
- **For the moment, let’s assume that the entire charge is collected in a very short time and derive appropriate requirements.**
- These are in spreadsheets at dcdb-1807

Basic detector parameters

wire pitch	0.5	cm	
Most probable energy loss for 0.5 cm thick	0.83	MeV	This calculation comes from the landau distribution for 0.5 cm. It is not dedx.
liquid argon pair threshold	23.6	eV	
electrons per MIP	35169.49153		
recombination at 500 V/cm	0.7		
drift length	3.6	m	
drift velocity	1.6	m/ms	
electron lifetime (requirement)	3	ms	
charge at the wires from far end for 1 MIP	11629.02403		



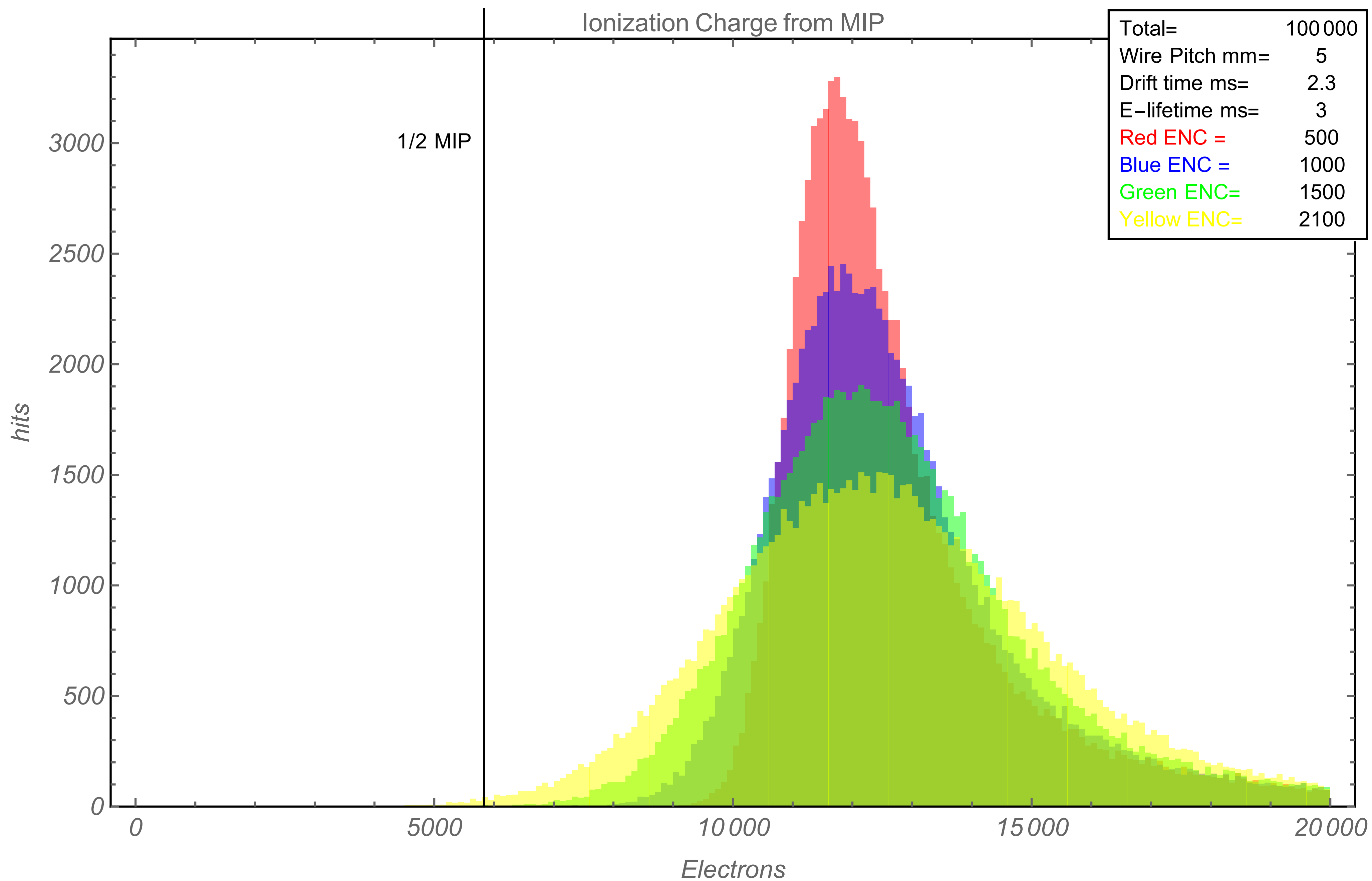
What level of noise in electrons can we tolerate to make the 1 MIP charge detectable ? What is the appropriate level of detectability ?

Some definitions and assumptions

- Equivalent noise charge is the amount of charge when deposited instantly at the input of the preamp produces the RMS voltage at the output.
- We are going to use this ENC to be the same as the noise on the signal charge. This is o.k. as long as all other sources of uncertainty are small.
- This is not true for induction wires. We will for the moment assume that induction wires require 1/2 of the noise of collection.
- We assume that for analysis we will impose some threshold to select good hits. This is set to be ~1/2 MIP or ~0.41 MeV. We also try an alternative of 5 sigma in noise.
- We now require that noise does not cause MIP hits to be lost below threshold at rate >0.001. No more than 1/1000 of the hits can be lost.
- Another requirement is that the total data does not exceed some limit, but we will not deal with this here.

Minimum ionizing particle is assumed to be 500 MeV/c muon for these calculations.

1 MIP at far end with noise



Noise level for collection based on 100k events

For 0.5 cm wire pitch consider collection only	ENC	hits lost below 5*noise	hits lost below 1/2 MIP	fraction lost below 5*noise	fraction lost below 1/2MIP
	1100	0	0	0	0
	1200	0	0	0	0
	1300	10	0	0.00001	0
Level where noise starts cutting into signal	1500	260	2	0.0026	0.00002
	1700	2261	33	0.02261	0.00033
	1900	8844	81	0.08844	0.00081
	2100	20006	216	0.2	0.00261

5 σ

The collection wires for 0.5 cm pitch are tolerant of noise up to ~1300-1400 electrons equivalent. Therefore using our rule we need noise level of <700 for induction. But this needs more analysis when we refine the model and add the pulse shape to the analysis. Also notice that it is dependent on the electron lifetime that can be achieved.

Dynamic range and resolution

- Here we continue to consider the collection wires which are expected to have the best performance for charge measurement.
- **Definition: Dynamic range is the largest amount of charge that can be measured without saturation.**
- Resolution: has three components
  - Resolution due to RMS noise
  - ADC fluctuation (the ADC distribution for a given voltage has a nonzero sigma. This is set to 2.9 ADC counts.)
  - ADC bin width. (this is sometimes referred to as digitization noise).
  - I find the idea of effective number of ADC bits (ENOB) and digitization noise to be unnecessarily confusing and not needed.
- What Physics should set the dynamic range and resolution ? Next slide

Physics for dynamic range and resolution

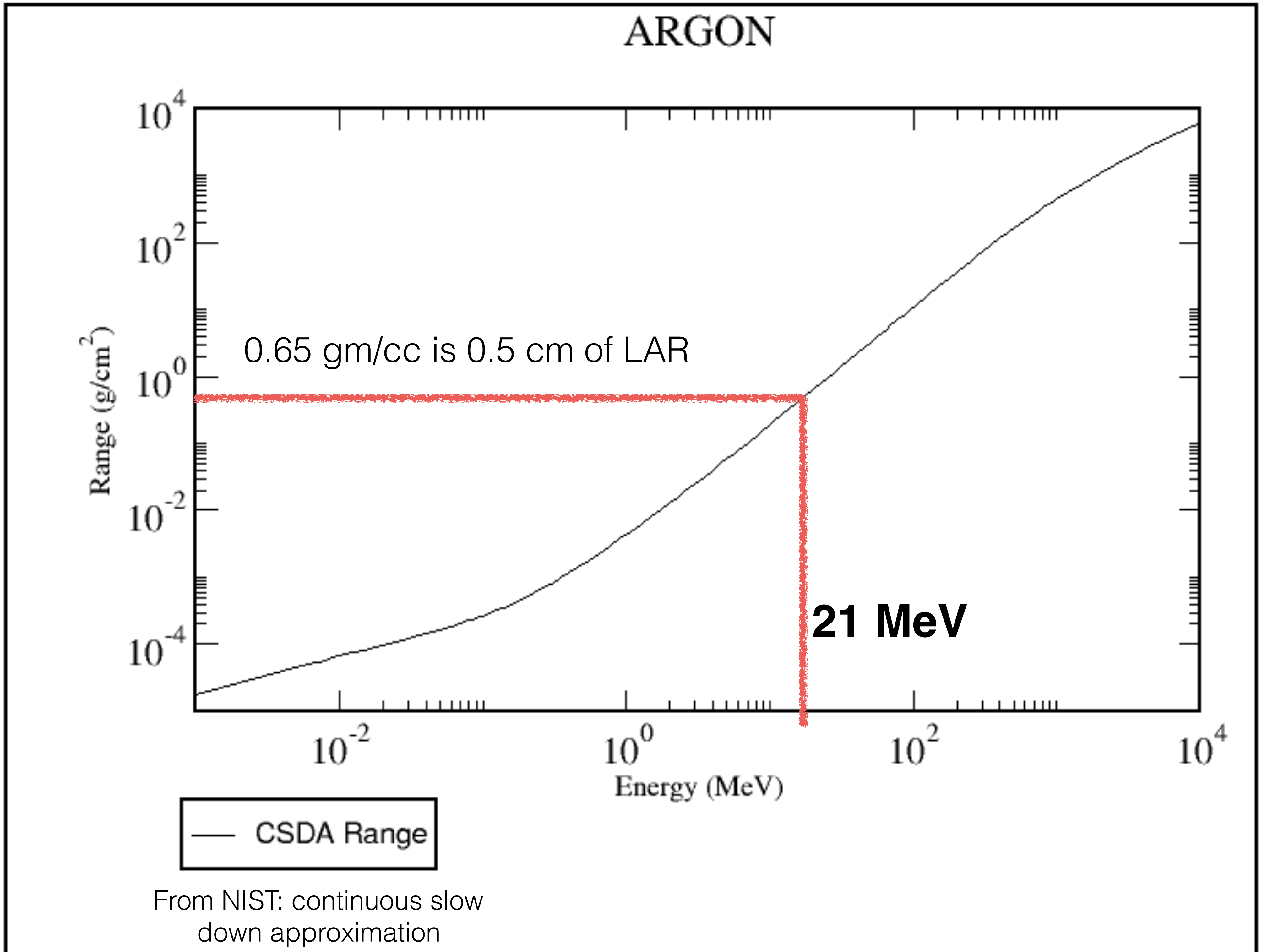
- Dynamic range: maximum visible energy in a single voxel divided by minimum visible energy that can be measured.
  - The maximum number of protons that stop < 0.5 cm. These might be produced at a neutrino vertex. This number is not known well, but it would be prudent to assume it is ~4-5.
  - A long MIP track that runs along a wire before scattering. What is the maximum such track that can be accommodated ?
- Minimum energy/energy per count or Resolution:
  - Measurement of MIP charge with <few percent. (current high level requirement is 1% which does not seem reasonable even if we decide to use it for global calibration.)
  - Good separation of 1 MIP and 2 MIP signals. (seems reasonable.) <=
  - Resolution on the low energy photons from supernova neutrino detection. But we have no clue how these are distributed and how they are to be used in analysis.

Dynamic range top end calculation

Max output voltage for 180 nm ASIC (V)	1.6			
Baseline (V)	0.2			
Electrons/fc	6250		Energy of protons range of 0.5 cm	21 MeV
Near end MIP charge per 0.5 cm	24000		recombination factor	0.25
Far end MIP charge per 0.5 cm	11600		Proton charge in electrons	222457
Gain Settings mV/fc	4.7	***7.8***	14	25
Range in number of electrons	1860000	***1120000***	625000	350000
Range in MIPs (at near end)	75	***45***	25	14
Range in Length of MIP track (cm)	38	***23***	13	7
Mean scattering distance (cm)	1.7	***0.8***	0.33	0.14
Number of 0.5 cm range protons	8.4	***5.0***	2.8	1.6

This is where we plan to run

With this gain and the maximum voltage, the requirement appears to be satisfied


ARGON
Range (g/cm^2)
Energy (MeV)
0.65 gm/cc is 0.5 cm of LAR
21 MeV
CSDA Range
From NIST: continuous slow down approximation

Resolution calculation I

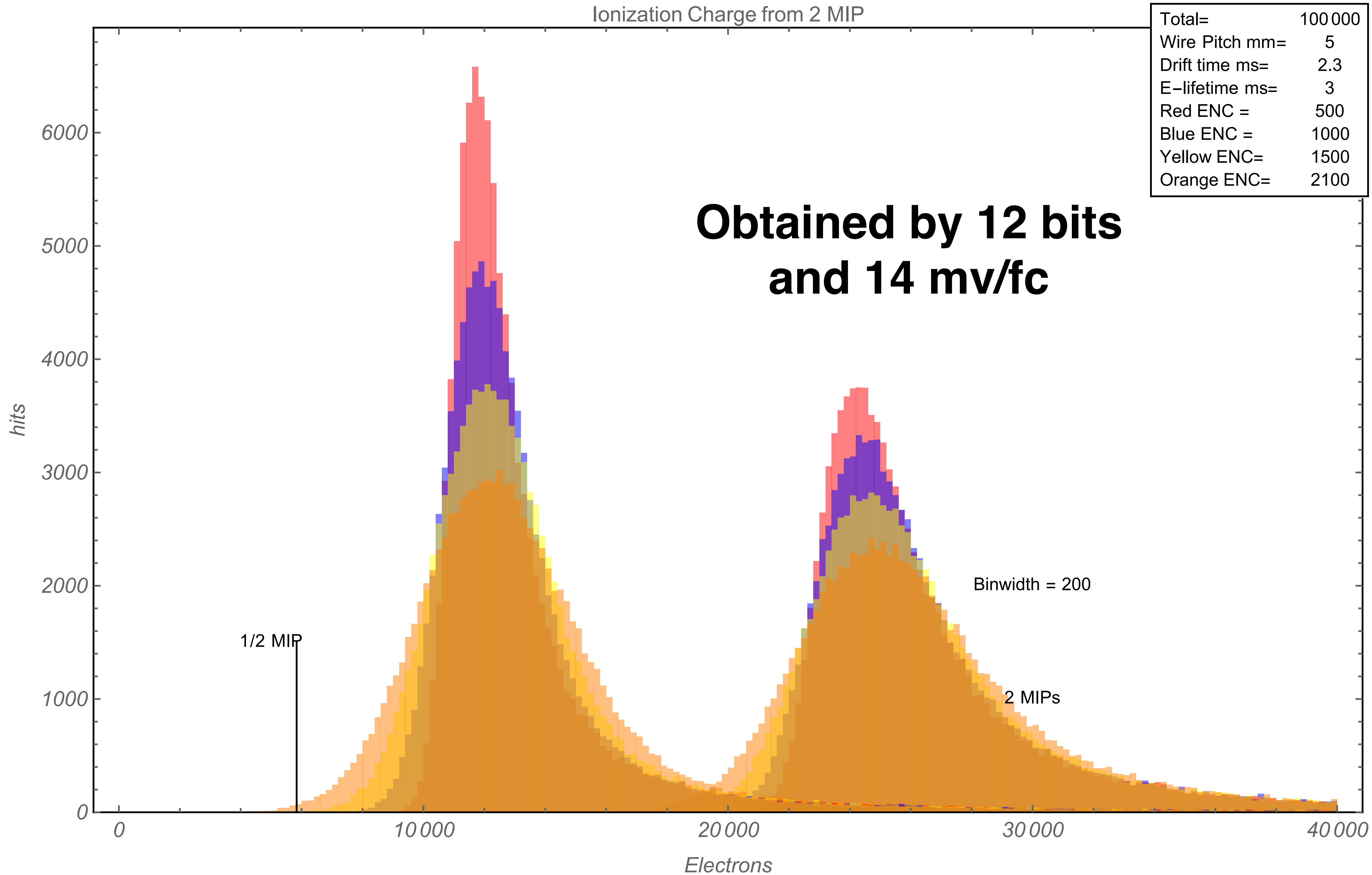
maximum Voltage	1.6			
Baseline	0.2			
ADC bits	12	10	8	6
Counts	4096	1024	256	64
Bsseline in ADC counts	500	125	31.25	7.8
ADC range	3596	899	224	56
Volts/count	0.000389	0.00156	0.00623	0.025

This is independent of the gain.

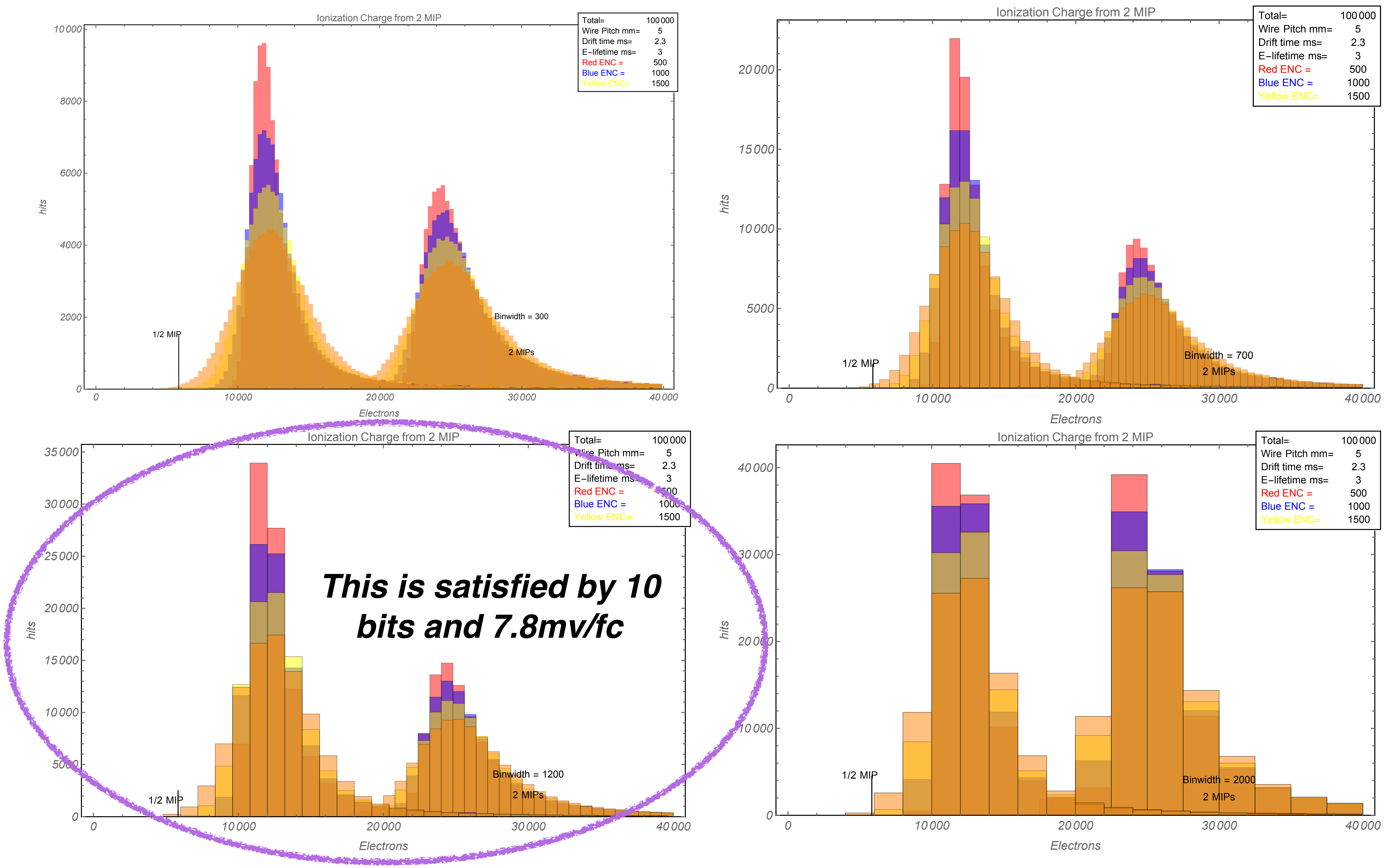
Resolution calculation II

ADC bits	Gain ->	4.7mv/fc	7.8mv/fc	14mv/fc	25mv/fc
12	fc/count	0.083	0.050	0.028	0.016
	e/count	517	311	174	97
	counts/MIP	22.5	37.3	66.9	119.5
	MIP bit res.	0.044	0.027	0.015	0.0084
10	fc/count	0.33	*0.20*	*0.11*	0.062
	e/count	2071	*1248*	*695*	389
	counts/MIP	5.6	*9.3*	*16.7*	29.8
	MIP bit res.	0.17	*0.11*	*0.060*	0.033
8	fc/count	1.32	0.80	0.44	0.24
	e/count	8283	4991	2781	1557
	counts/MIP	1.4	2.3	4.2	7.5
	MIP bit res.	0.7	0.42	0.24	0.13
6	fc/count	5.3	3.2	1.8	1.0
	e/count	33133	19965	11123	6229
	counts/MIP	0.35	0.58	1.04	1.86
	MIP bit res.	2.85	1.72	0.96	0.53

1% resolution for 1 MIP is not possible without high gain and 12 bits. The indicated solution with 10 bit ADC seems adequate, but our choice is in the box. Induction wires need pulse shape analysis, but >10 bits is certainly needed. Dual 8 bit ADC solution is also possible with each working at different gain.


Ionization Charge from 2 MIP
Total= 100 000
Wire Pitch mm= 5
Drift time ms= 2.3
E−lifetime ms= 3
Red ENC = 500
Blue ENC = 1000
Yellow ENC= 1500
Orange ENC= 2100
Obtained by 12 bits
and 14 mv/fc
Binwidth = 200
1/2 MIP
2 MIPs
hits
Electrons
0
10 000
20 000
30 000
40 000
1000
2000
3000
4000
5000
6000

1 MIP/2 MIP separation



Summary of first order requirements.

- The noise level from the front end should be sufficiently low so that the ionization from a 1 MIP particle at the longest drift distance is not lost below threshold (with rate of >1/1000) on the collection or induction wires.
  - If threshold is >1/2 MIP the noise level (given the current parameters of the detector and expected electron lifetime) for collection ~1400 ENC and induction ~700 ENC.

- The maximum of the dynamic range should accommodate the expected amount of charge from heavily ionizing particles at the vertex of an accelerator neutrino event.
- The maximum of the dynamic range should also accommodate tracks that could be 10-20 cm long and stay within a given cell.
  - If we expect a few protons from the neutrino-argon reaction, then gain setting of 7 - 14 mV/fc is sufficient given the maximum expected output from the preamplifier (0.2 to 1.6 V)

- The ADC resolution should be good enough to a. measure 1 MIP energy deposition with <10% resolution for each channel, and b. to adequately separate 1 MIP and 2 MIP energy deposition.
  - A >10 bit ADC with a gain factor of 7-14 mv/fc is found to be sufficient to satisfy the requirement.

Until now we have ignored the time domain nature of the pulse. We need to understand how the measurement is done over time to get a better picture.

First we start on the filters that create a shaped pulse that can be digitized.

Analysis Methods

Measurements are usually done in the time domain, and so simulation must recreate time domain waveforms with appropriate sampling.

Signals are usually transients. A signal current is a pulse that exists at t >0, gets amplified and shaped so that it can be sampled. This analysis is best done by Laplace transforms which deal with t>0 and puts results in s-space.

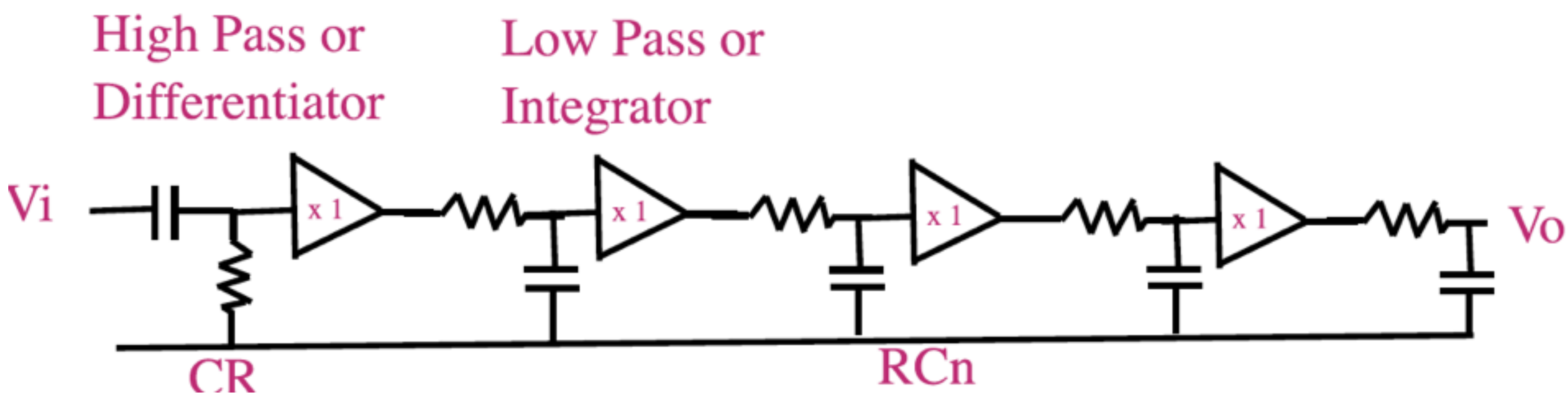
Noise is a continuous process that extends for all time. It is normal to analyze this with Fourier transforms and plot the power in frequency space.

$$If\ \ f(t) = 0\ \ for\ t < 0\ and$$

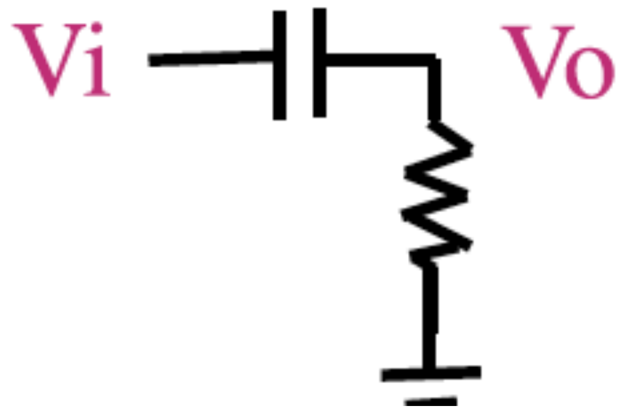
$$\int_0^\infty |\,f(t)\,|\,dt < \infty\ then\ F_{fou}(\omega) = F_{Lap}(s \to i\omega)$$

This must be used with care. It is not correct for a step function or for a cosine.

We first try to understand the filters. what is a CR-RC^4 filter ? This is just a brief intro.



Purpose is to create a Gaussian shaped pulse from a step voltage. The height of the pulse should be the voltage step. The peak of the pulse is given by the peaking time which is n X τ=RC = 1/γ



High pass, differentiator

$$V_o(t) + Q/C = V_i(t)$$

$$\frac{dV_o(t)}{dt} + i/C = \frac{dV_i(t)}{dt}$$

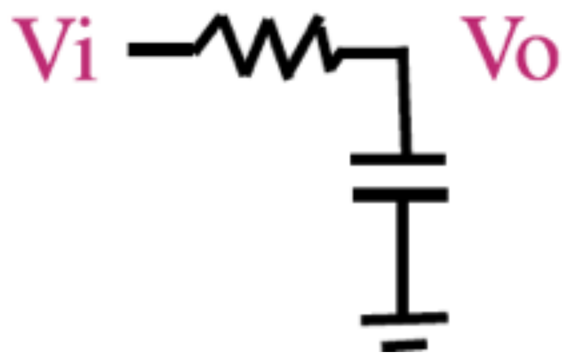
Use Laplace Transforms to solve for t ≥ 0

$$L[V(t)] = V(s), \;\; L[V'(t)] = sV(s)$$

$$sV_o(s) + V_o(s)/RC = sV_i(s)$$

$$V_o(s) = V_i(s) \times \frac{s}{s + 1/\tau}$$

For any V_i, we can calculate the Laplace transform, multiply by the filter transfer function, and invert.



Low pass, integrator

$$V_o(s) = V_i(s) \times \frac{1}{s + 1/\tau}$$

And for a CR-RC^4 we can just multiply the transfer functions.

$$V_o(s) = V_i(s) \times \frac{s}{s + 1/\tau} \times \frac{1}{(s + 1/\tau)^4}$$

This can be inverted to obtain time domain pulse for some V_i. For a step pulse:

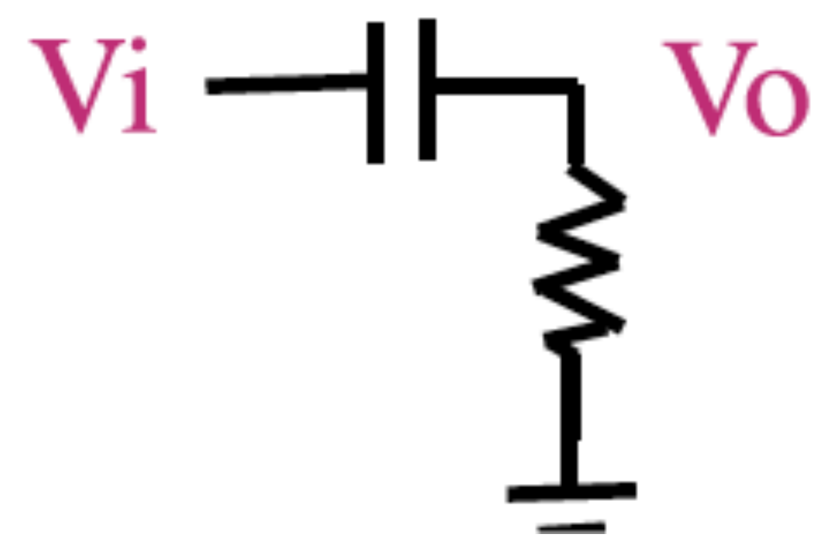
$$V_i(s) = 1/s$$

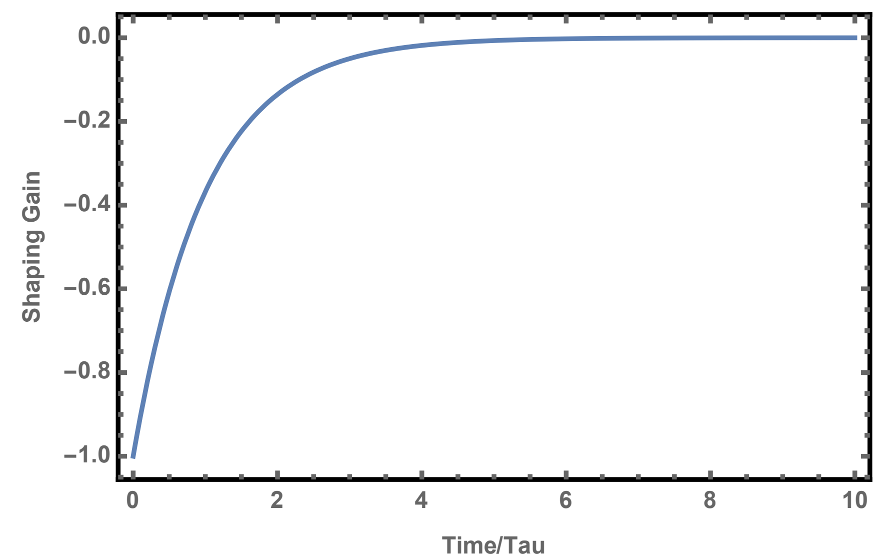
$$V_o(t) = \frac{t^4}{4!} e^{-t/\tau}$$

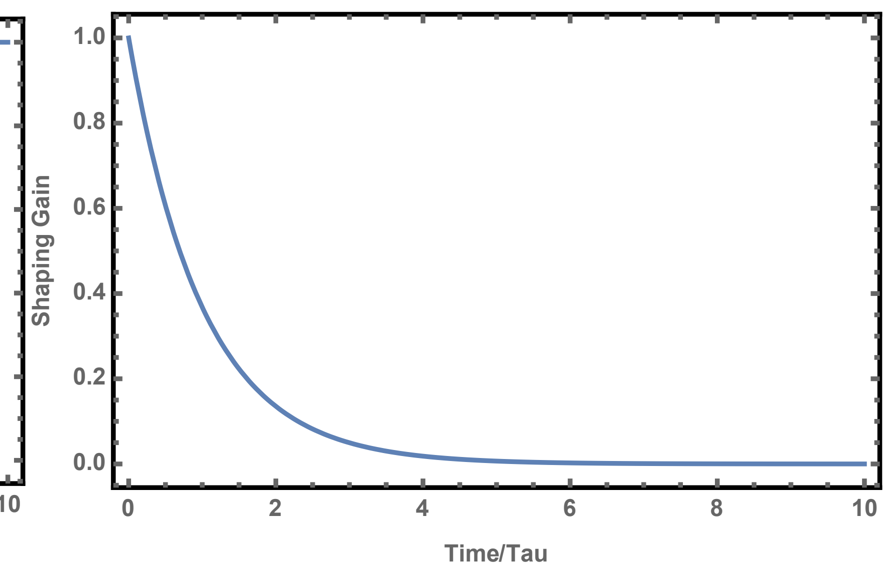
Set RC = 1

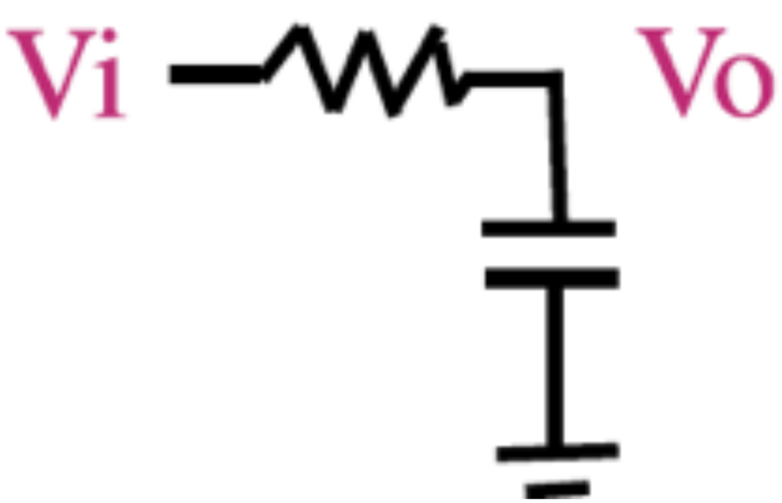
Output if Input is delta(t)

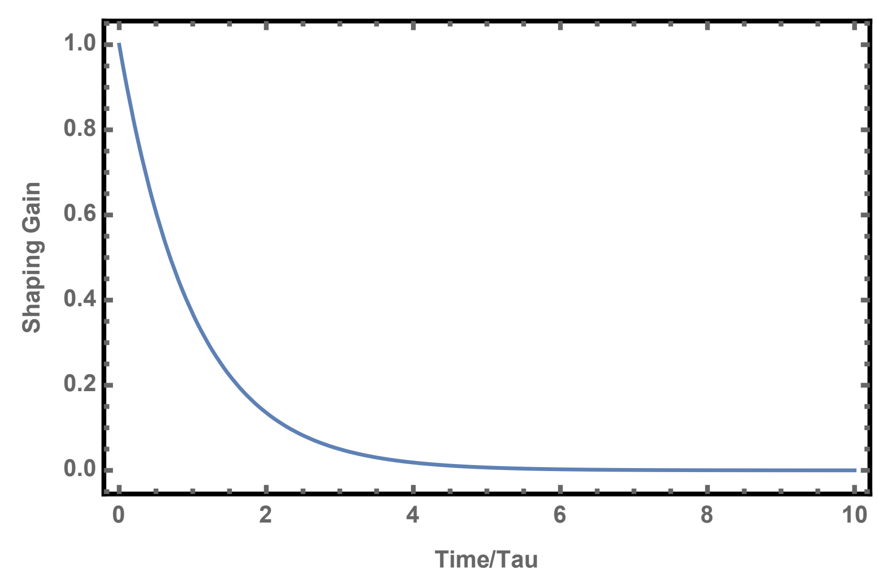
Output if Input is Step function u(t) = 1 for t>0

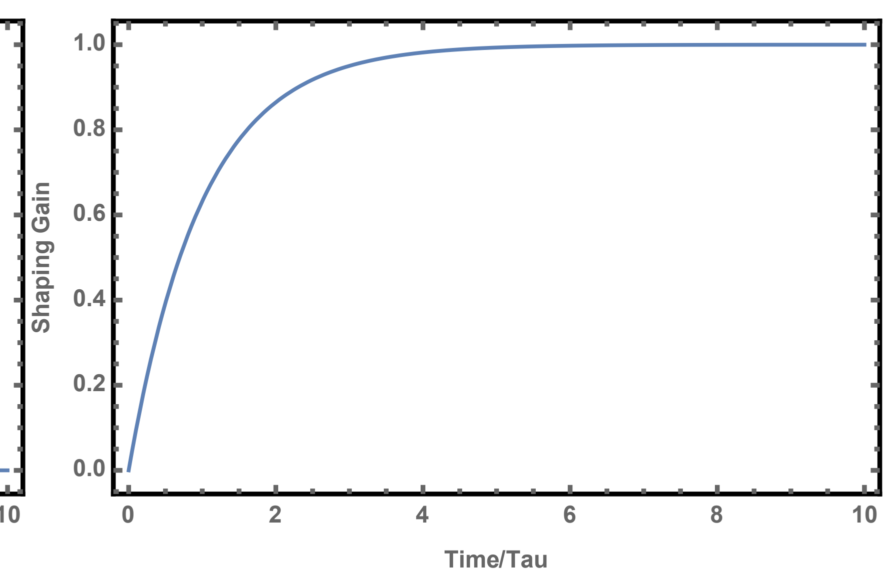






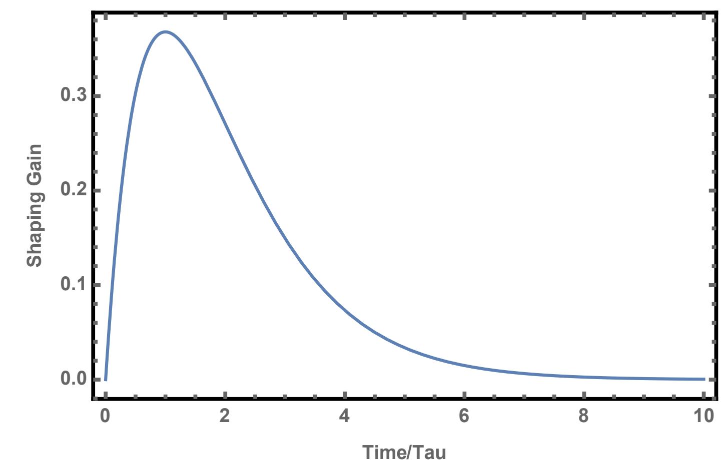




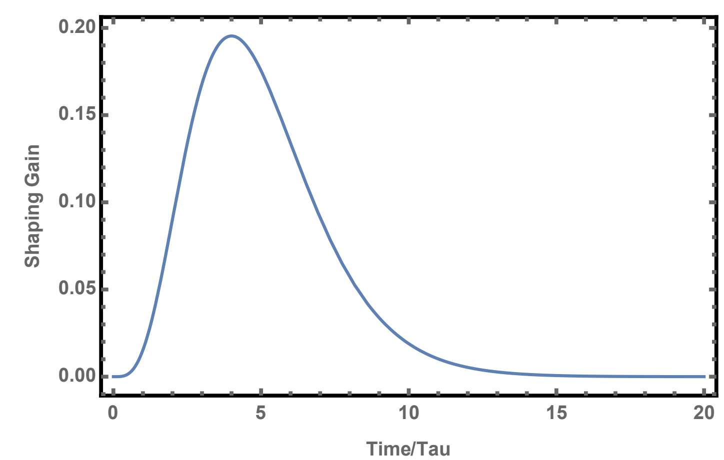


The ideal preamp produces a step function called a “tail pulse”. This step must be shaped.

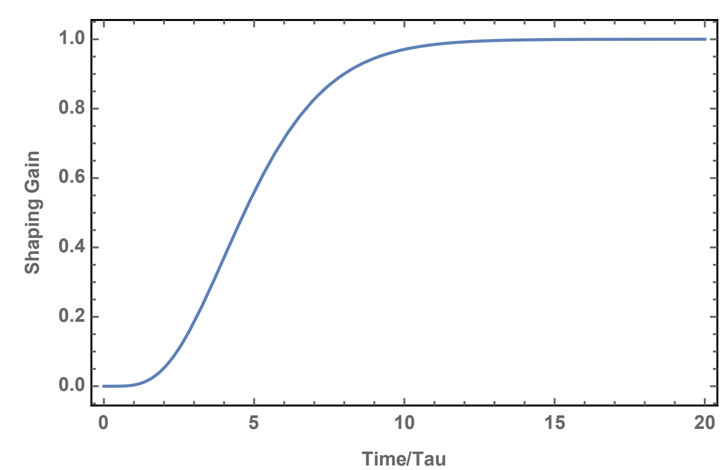
Input is step function with a CR-RC filter. Peak is at time $=1*\tau$



Input is step function with a CR-RC^4 filter. Peak is at time $=4*\tau$



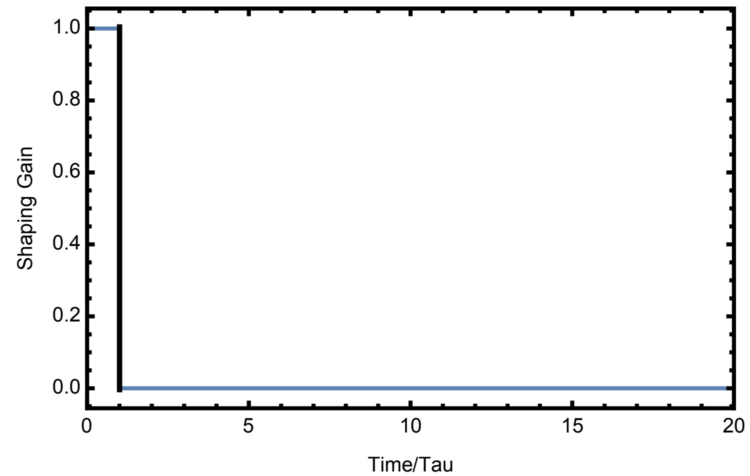
Input is step function with a RC^5 filter. For such a filter there is no low frequency cutoff.



Our pulses can be long or who short, and so this is what we want

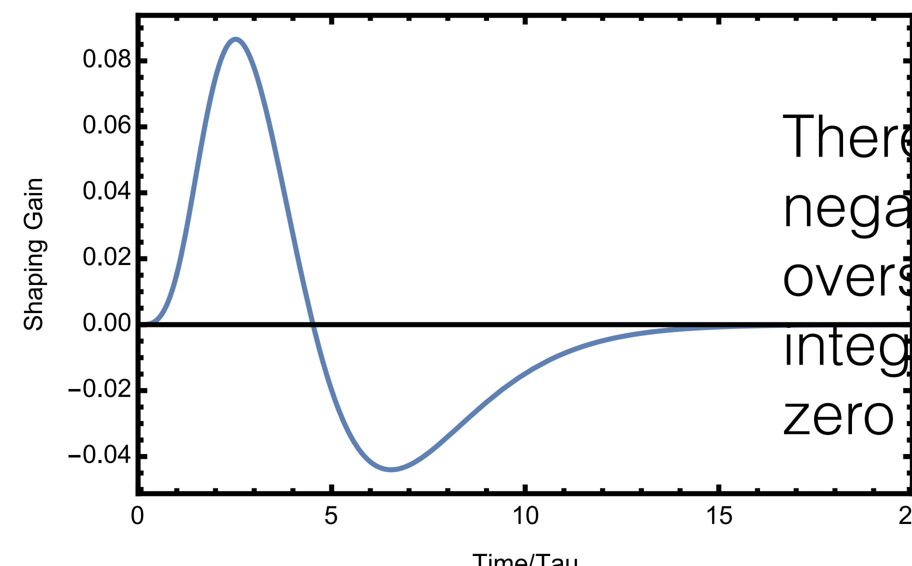
The real input pulses are pulses with some widths. Or they have a long shaping time to bring them back to baseline.

Input



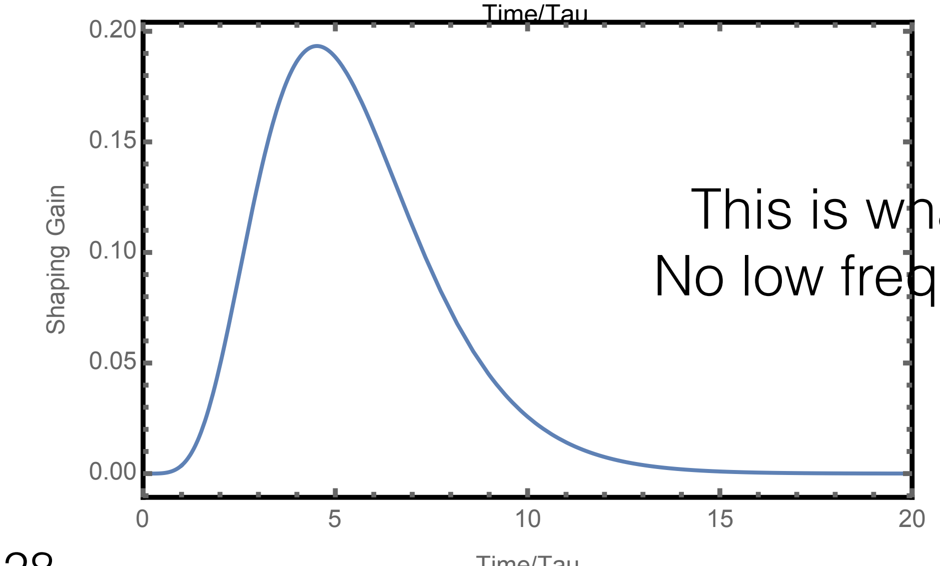
1 mu-sec square pulse

Output after CR-RC4



There will be a negative overshoot and the integral will be zero

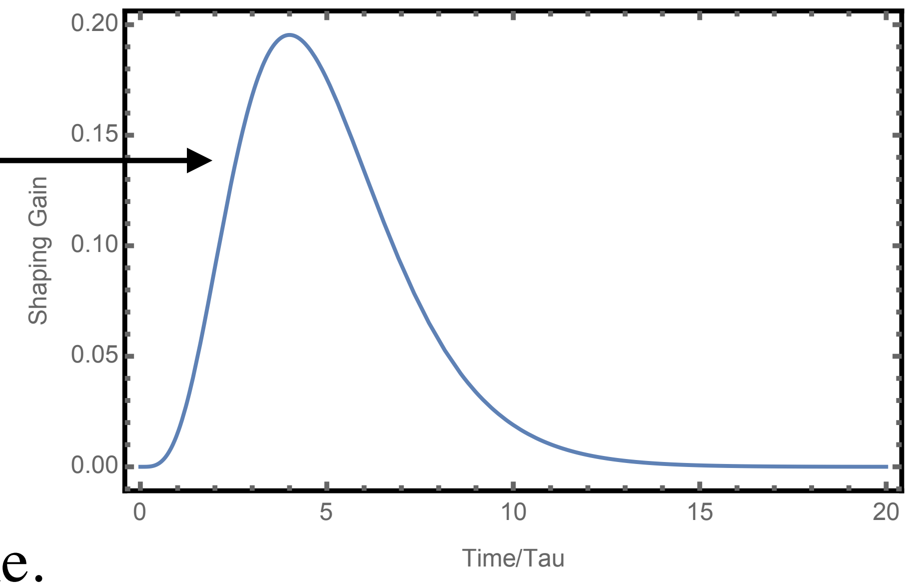
Output after RC5



This is what we want.
No low frequency cutoff.

More about poles, let's start with a 5th order shaper

$$F(s) = \frac{1}{(s+a)^5} \to f(t) = \frac{t^4}{4!} e^{-at}$$



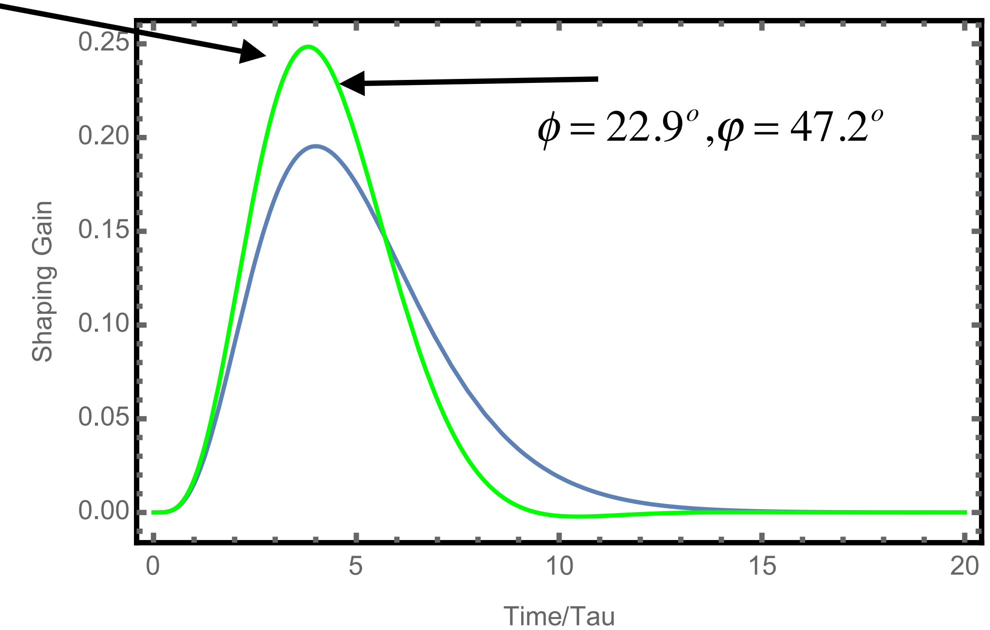
This has a maximum at $t = 4/a$

$$f(4/a) = \frac{32}{3}\frac{e^{-4}}{a^4} = \frac{0.195}{a^4}$$

$f(15/a) \approx 0.6 * 10^{-3} \cdots$ It takes 15 times to restore baseline.

$$F(s) = \frac{1}{(s+a)((s+a\cos(\phi))^2 + a^2\sin^2(\phi))((s+a\cos(\varphi))^2 + a^2\sin^2(\varphi))}$$

$$\to f(t) = Ae^{-at} + \sum_{i=2,3} B_i e^{-r_i t}\cos(c_i t + \gamma_i)$$



Complex poles allows the baseline to be restored much faster.

In addition, we adjust the amplitude to obtain the same peak for any value of shaping time.

Ohkawa,Yoshizawa,Husimi, NIM 138, 85-92, 1976

General characteristics of a filter that preserves the integral.

- Because of the undershoot we cannot use the CR-RC4 type filter for a liquid argon TPC. The current pulses have lengths from 1 micros to >100 micros. The output pulse must produce a voltage that follows the input pulse shape.

Assume that input is $f(t)$ and $L[f(t)] = F(s)$

Assume shaping transfer function is T(s).

The input has finite integral Q = $\int_{0-}^{\infty} f(t)\,dt$

$$L[\int_{0-}^{t} f(x)dx] = \frac{1}{s}F(s)$$

$$Q = \lim_{t\to\infty}\int_{0-}^{t} f(x)dx = \lim_{s\to 0} s\times\frac{1}{s}F(s)$$

$$Q = \lim_{s\to 0} F(s)$$

If the pulse goes through a filter

$$f_{out}(t) = L^{-1}[F(s)\times T(s)]$$

$$\int_{0-}^{\infty} f_{out}(t)\,dt = \lim_{s\to 0} F(s)\cdot T(s)$$

To preserve the integral regardless of pulse width, $T(0)$ must be >0

This is the same as the area theorem in Fourier transforms.

Our Shaping function is not a CR-RC^4 filter. (Don't worry about how it is implemented yet)

$$F(s) = \frac{G}{(s+p)\bullet((s+\alpha)^2+\beta^2)\bullet((s+a)^2+b^2)}$$

$$T = shaping\ time: 0.5, 1.0, 1.5, 2.0\ micro\sec$$

$$g = gain: 4.7, 7.8, 14, 25(mV/fc)\ or\ (\times 10^{12} V/C)$$

$$cT = 1/1.996$$

$$cA = 2.7433/(cT.T)^4$$

$$p = 1.477/(cT.T)$$

$$\alpha = 1.417/(cT.T)$$

$$\beta = 0.598/(cT.T)$$

$$a = 1.204/(cT.T)$$

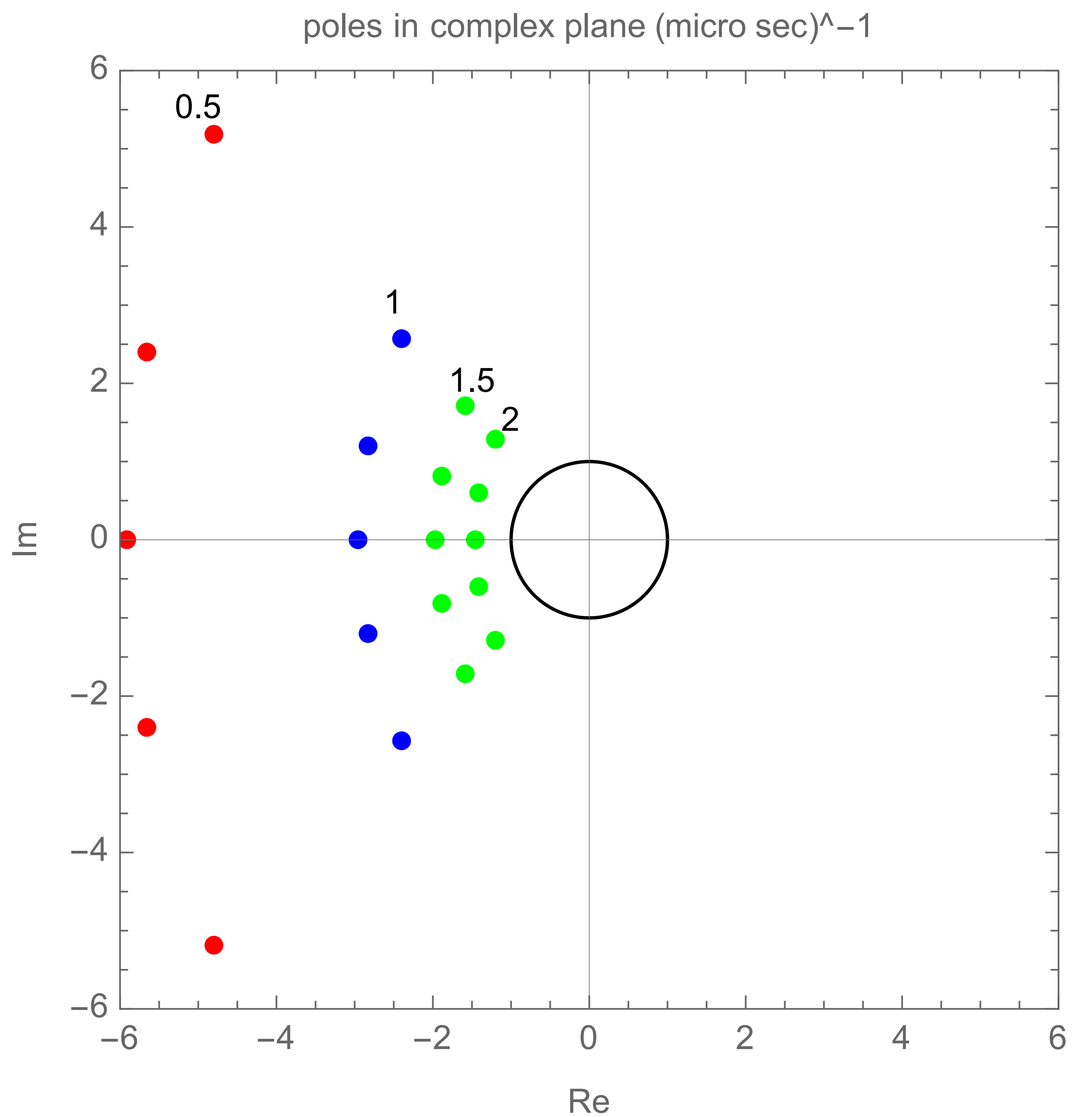
$$b = 1.299/(cT.T)$$

$$G = g\bullet cA\bullet 10: \frac{mV}{fc} Hz^4\ or\ 10^{12}\frac{V}{C} Hz^4$$

$F(s)$ has units of $\frac{V}{C\bullet Hz}$

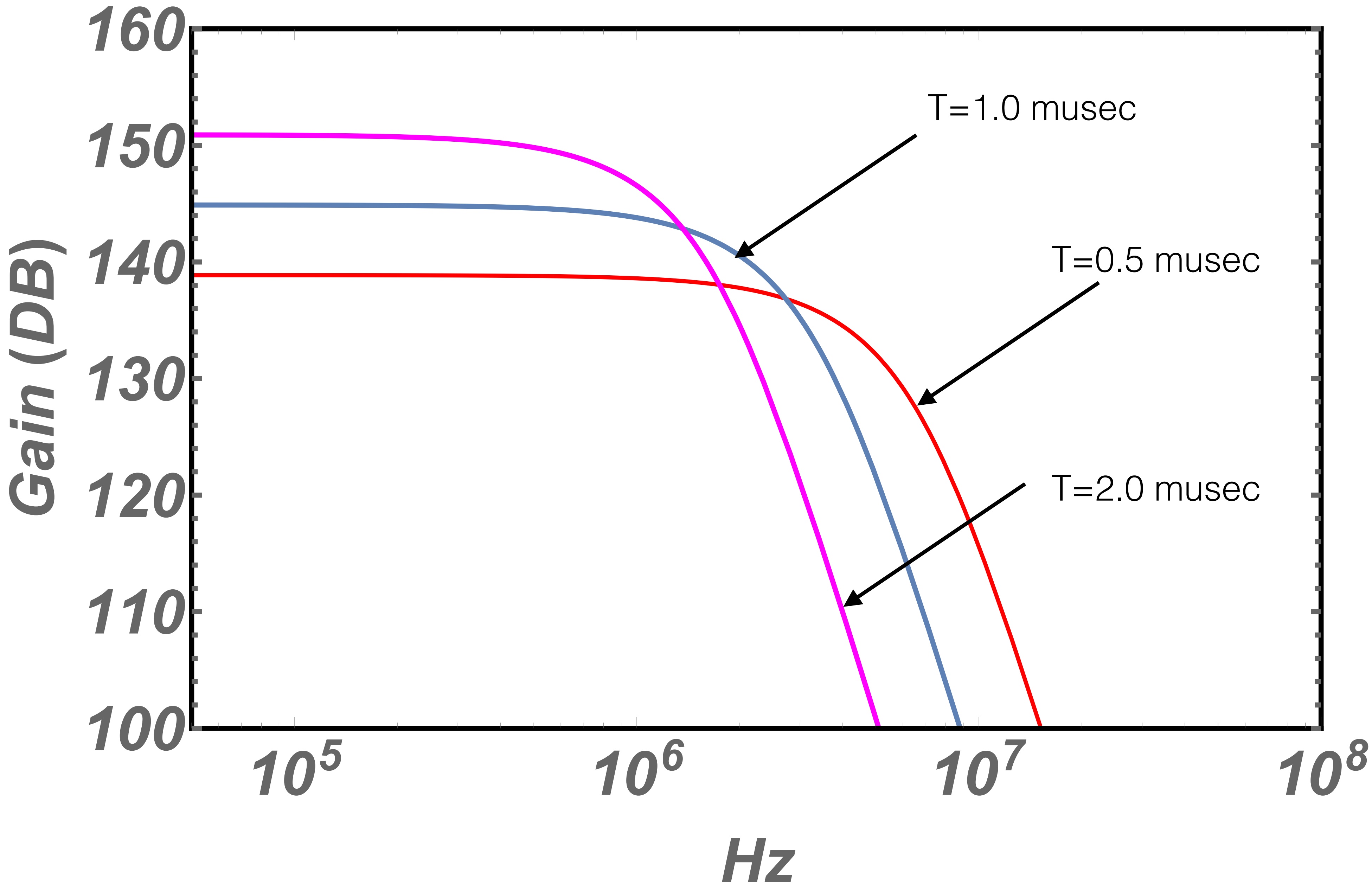
Notice that the gain is adjusted as $1/T^4$ so that the maximum is indep. of T.

Poles

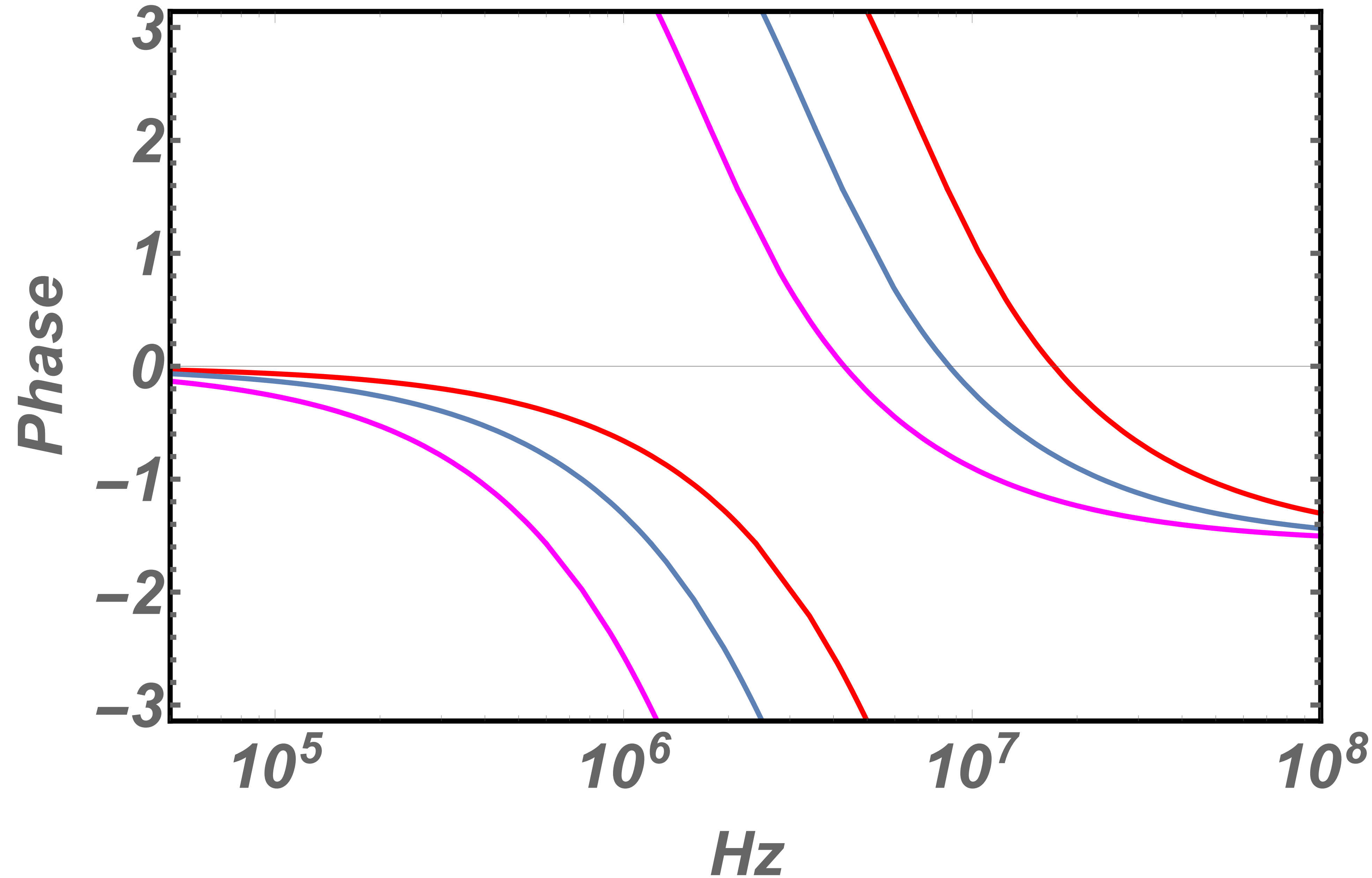


All the poles are on the left and F(0) is finite. To avoid confusion this means that the Fourier transform can be obtained by the substitution $s \rightarrow i\omega$.

Frequency Response



Phase plot



We use a 5th order filter that has no high pass filter.

$$F(s) = \frac{G}{(s+p) \bullet ((s+\alpha)^2 + \beta^2) \bullet ((s+a)^2 + b^2)}$$

Define for convenience $\quad Q(s,a,b) = ((s+a)^2 + b^2)$

First convert above to

$$F(s) = \frac{A}{(s+p)} + \frac{Bs}{((s+\alpha)^2 + \beta^2)} + \frac{C}{((s+\alpha)^2 + \beta^2)} + \frac{Ds}{((s+a)^2 + b^2)} + \frac{E}{((s+a)^2 + b^2)}$$

$$A=\frac{G}{Q(-p,a,b)\bullet Q(-p,\alpha,\beta)}$$

$$B=\frac{G(-a^2-b^2-2ap+4a\alpha+2p\alpha-3\alpha^2+\beta^2)}{Q(-p,\alpha,\beta).[(b^2+(a-\alpha)^2)^2+2(a-b-\alpha)(a+b-\alpha)\beta^2+\beta^4]}$$

$$C=\frac{G(a^2p+b^2p-2a^2\alpha-2b^2\alpha-4ap\alpha+6a\alpha^2+3p\alpha^2-4\alpha^3-2a\beta^2-p\beta^2+4\alpha\beta^2)}{Q(-p,\alpha,\beta).[(b^2+(a-\alpha)^2)^2+2(a-b-\alpha)(a+b-\alpha)\beta^2+\beta^4]}$$

$$D=\frac{-G(3a^2-b^2-2ap-4a\alpha+2p\alpha+\alpha^2+\beta^2)}{Q(-p,a,b).[(b^2+(a-\alpha)^2)^2+2(a-b-\alpha)(a+b-\alpha)\beta^2+\beta^4]}$$

$$E=\frac{-G(4a^3-4ab^2-3a^2p+b^2p-6a^2\alpha+2b^2\alpha+4ap\alpha+2a\alpha^2-p\alpha^2+2a\beta^2-p\beta^2)}{Q(-p,a,b).[(b^2+(a-\alpha)^2)^2+2(a-b-\alpha)(a+b-\alpha)\beta^2+\beta^4]}$$

$$F(s)=\frac{A}{(s+p)}+\frac{Bs}{((s+\alpha)^2+\beta^2)}+\frac{C}{((s+\alpha)^2+\beta^2)}$$
$$+\frac{Ds}{((s+a)^2+b^2)}+\frac{E}{((s+a)^2+b^2)}$$

Slight rearrangement

$$F(s)=\frac{A}{(s+p)}+\frac{B(s+\alpha)}{((s+\alpha)^2+\beta^2)}+\frac{(C-B\alpha)(1/\beta)\times\beta}{((s+\alpha)^2+\beta^2)}$$
$$+\frac{D(s+a)}{((s+a)^2+b^2)}+\frac{(E-Da)(1/b)\times b}{((s+a)^2+b^2)}$$

$$F(s) = \frac{A}{(s+p)} + \frac{B(s+\alpha)}{((s+\alpha)^2 + \beta^2)} + \frac{(C - B\alpha)(1/\beta)\times\beta}{((s+\alpha)^2+\beta^2)}$$
$$+\frac{D(s+a)}{((s+a)^2+b^2)} + \frac{(E-Da)(1/b)\times b}{((s+a)^2+b^2)}$$

Invert to time space

$$f(t) = A\cdot e^{-pt} + B\cdot e^{-\alpha t}\,\mathrm{Cos}(\beta t) + (C - B\alpha)(1/\beta)\cdot e^{-\alpha t}\,\mathrm{Sin}(\beta t)$$
$$+D\cdot e^{-at}\,\mathrm{Cos}(bt) + (E - Da)(1/b)\cdot e^{-at}\,\mathrm{Sin}(bt)$$

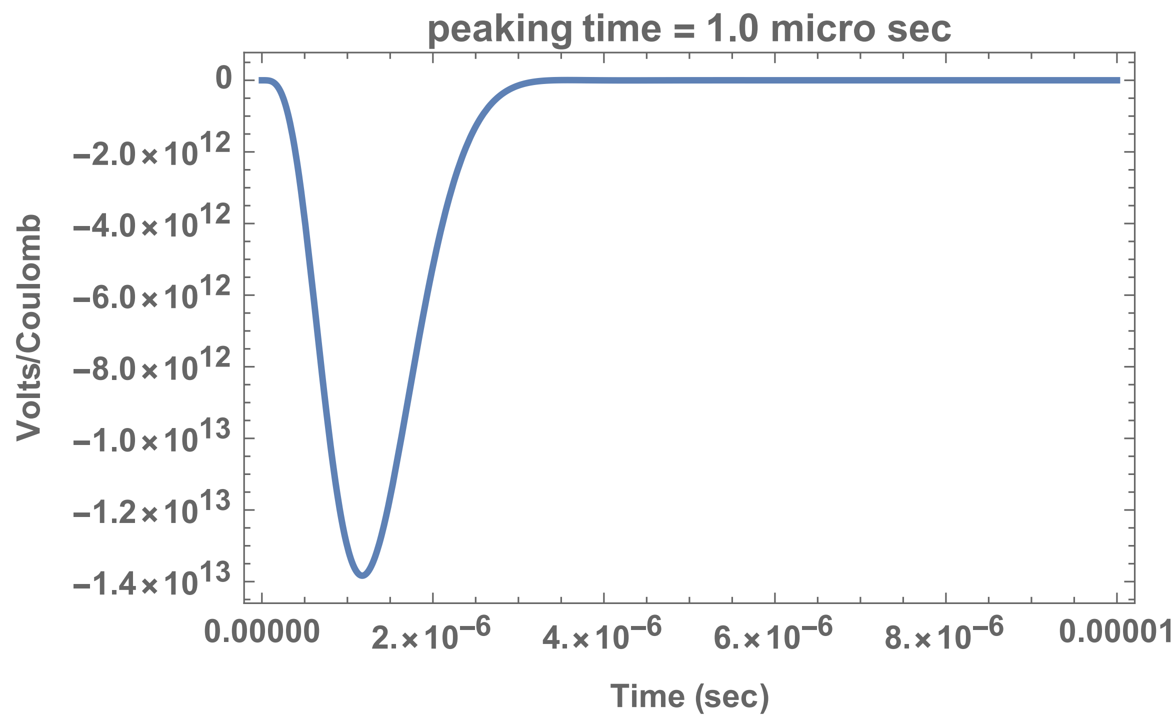
f(t) has units of gain only (V/C)

Shaping Time	0.5 micro sec	1.0 micro sec	1.5 micro sec	2.0 micro sec
p(MHz)	5.89618	2.94809	1.96539	1.47405
α(Mhz)	5.65666	2.82833	1.88555	1.41417
β(MHz)	2.38722	1.19361	0.795739	0.596804
a(Mhz)	4.80637	2.40318	1.60212	1.20159
b(Mhz)	5.18561	2.5928	1.72854	1.2964
G/g/10 10^{24} (Hz^4)	696.683	43.5427	8.60103	2.72142
A/g(unitless)	4.31054	4.31054	4.31054	4.31054
B/g(unitless)	-5.24039	-5.24039	-5.24039	-5.24039
C/g* T(unitless)	-13.0014	-13.0014	-13.0014	-13.0014
D/g(unitless)	0.929848	0.929848	0.929848	0.929848
E/g * T(unitless)	0.535356	0.535356	0.535356	0.535356

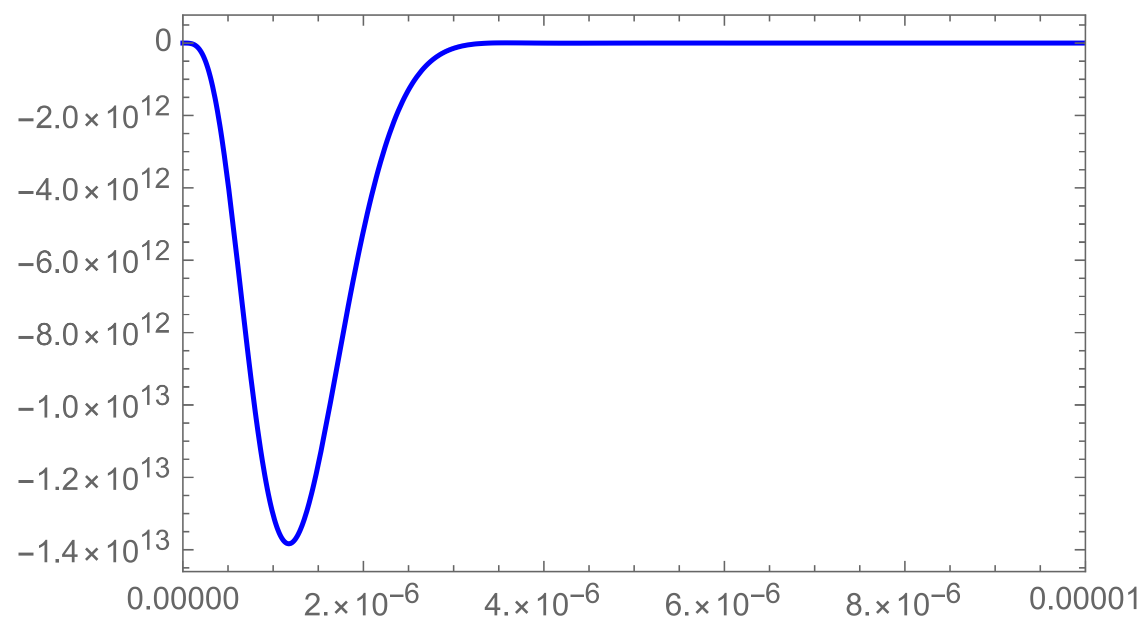
Phases complex poles:
22.88 deg, 47.17 deg

T0 = 1 microsec

Calculated numerically as inverse of F[s]

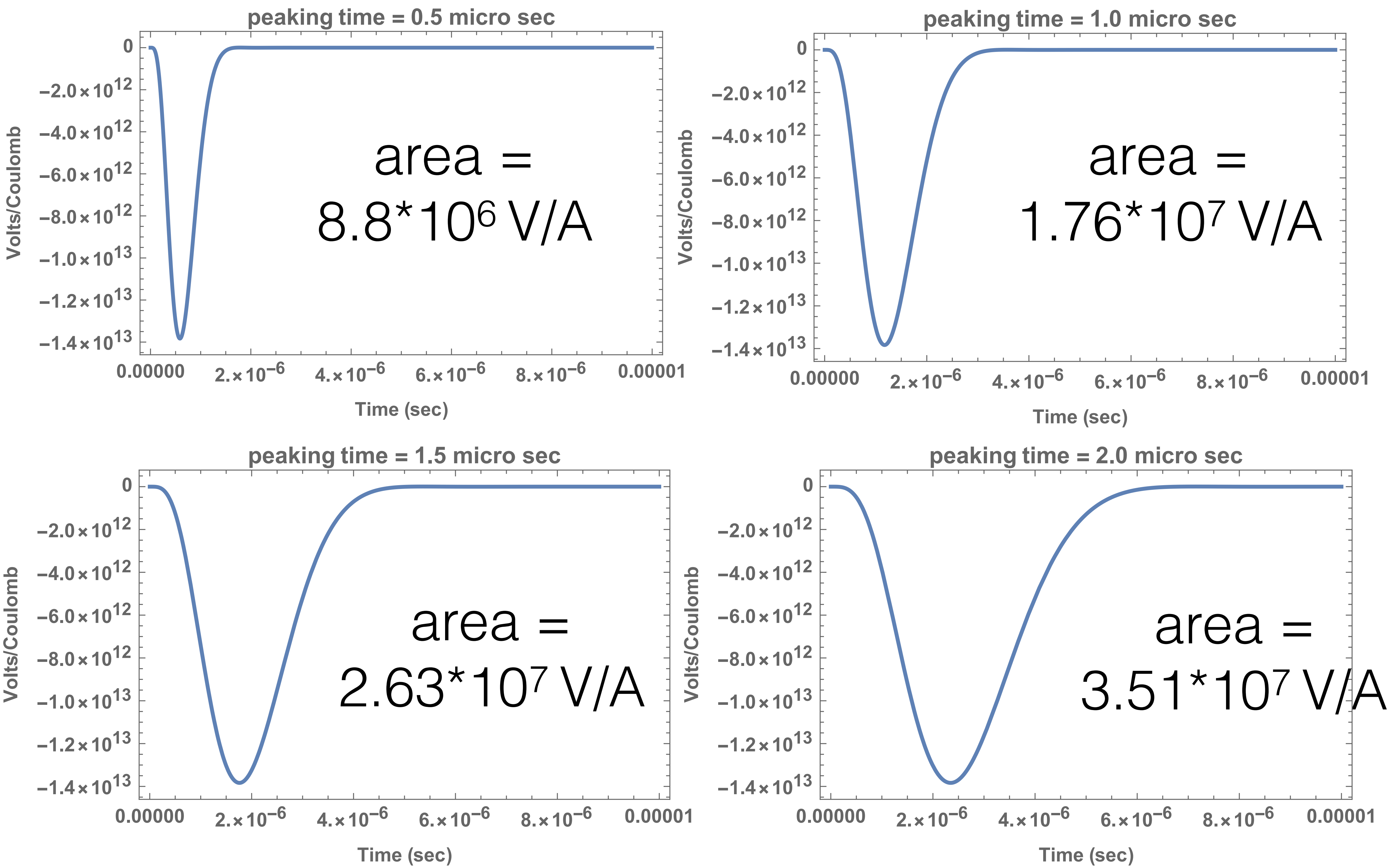


f[t] plotted from formula

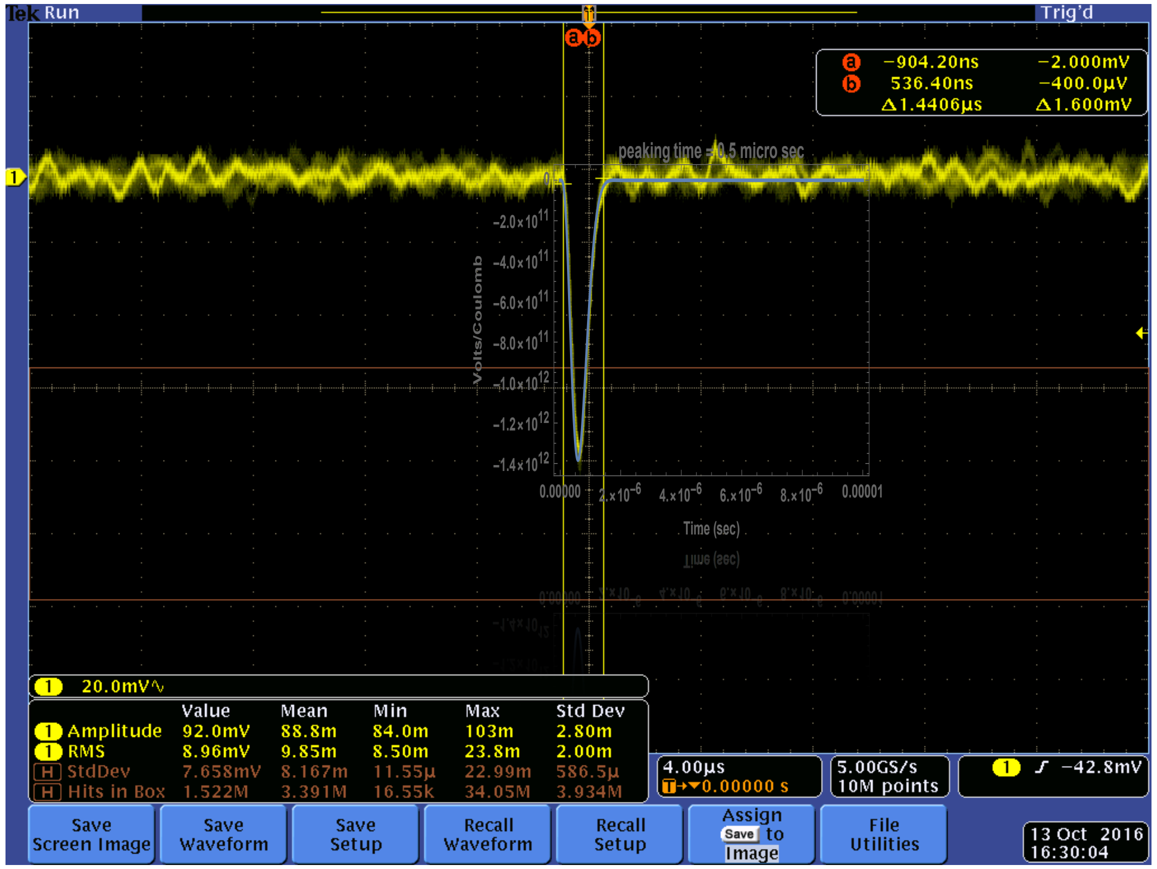


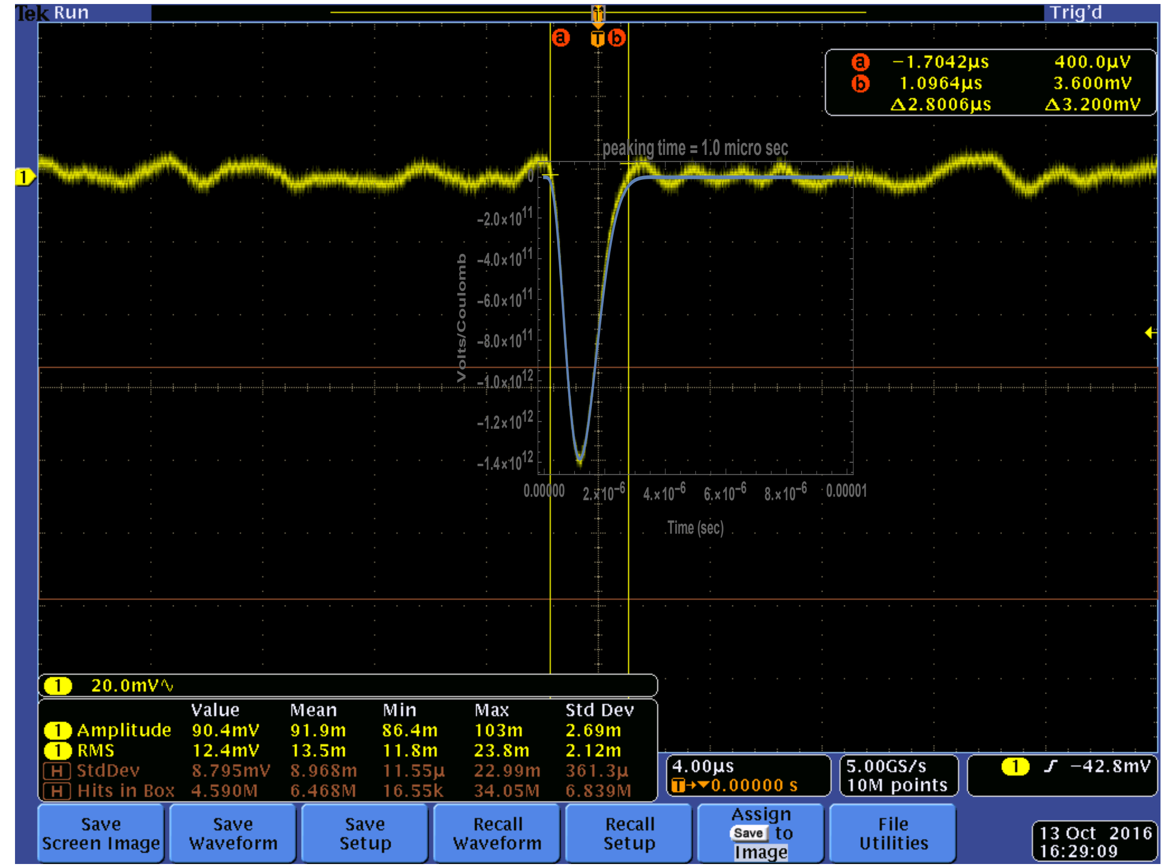
Plots are identical

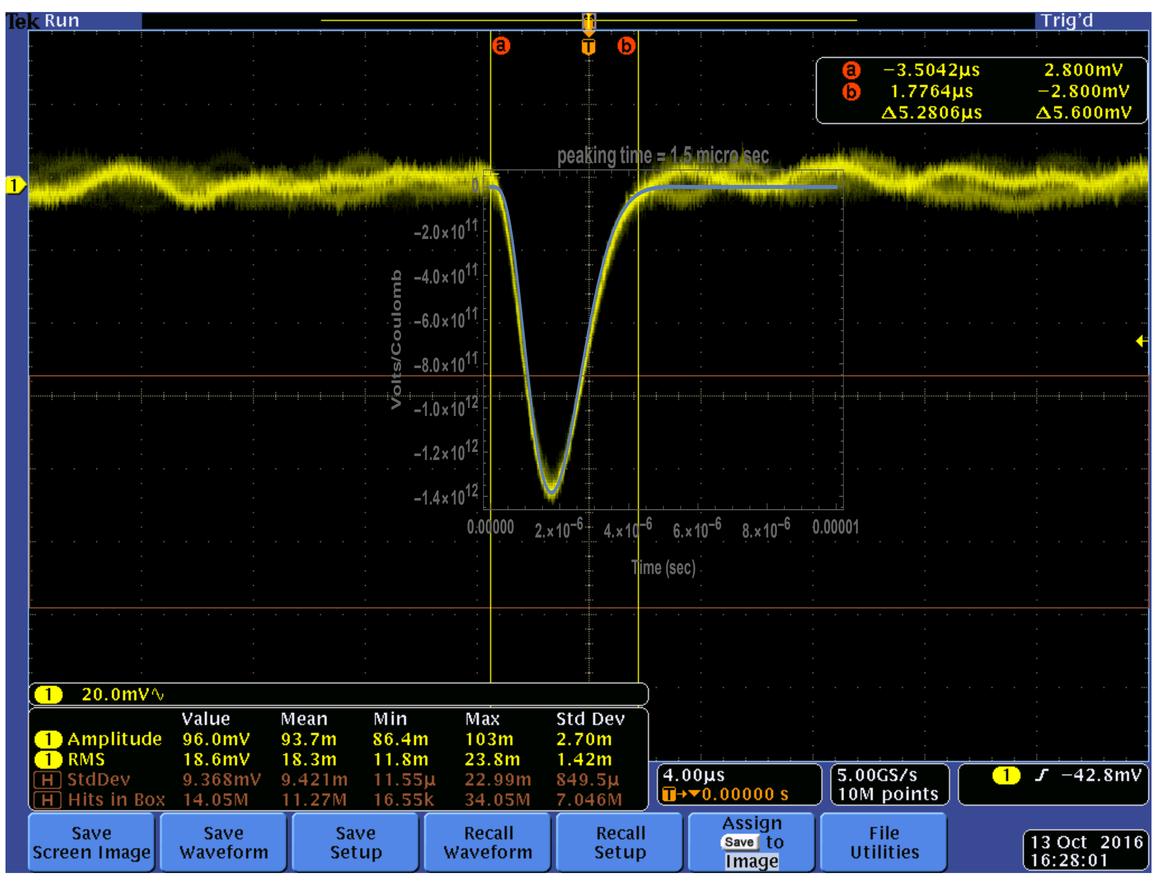
Response to a delta function of charge with gain = 14 mv/fc

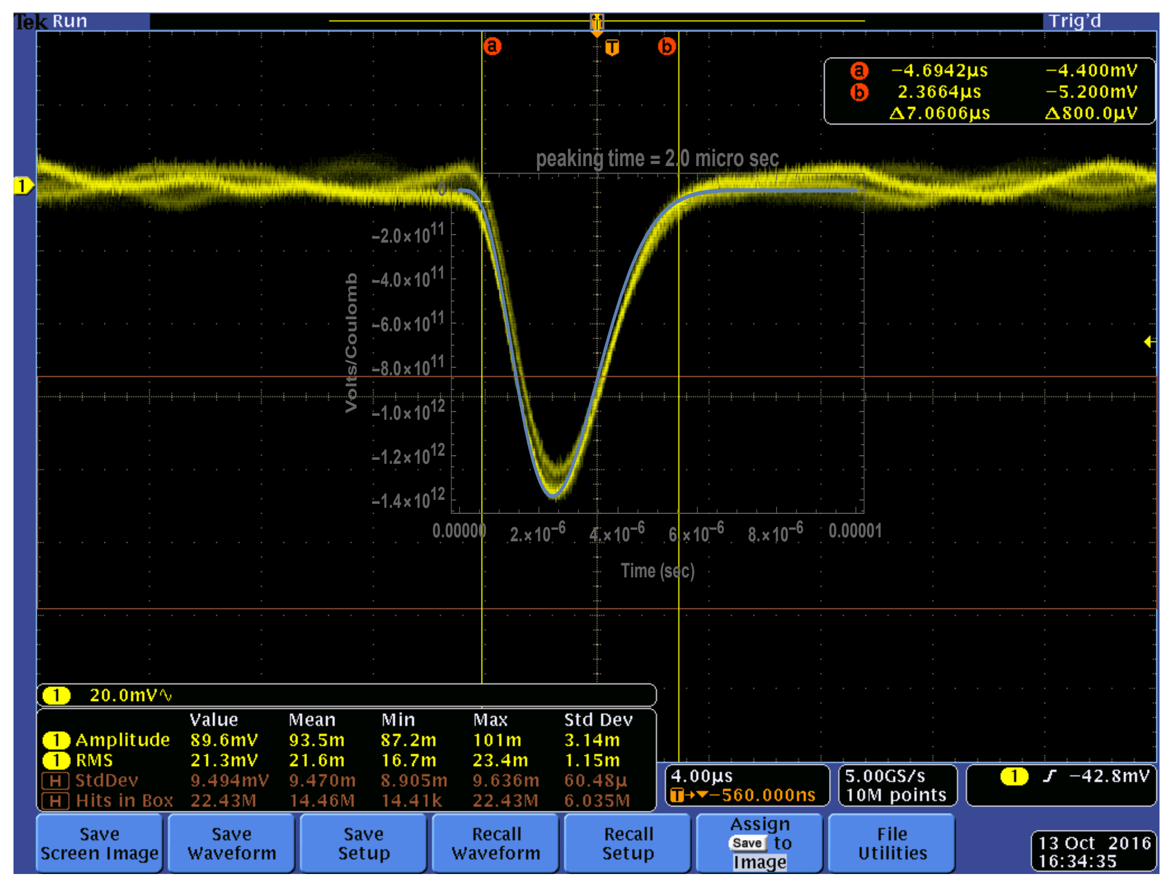


The peak of voltage = g (mv/fc)*Q (fc) for any shaping time.
Integral is designed to be proportional to shaping time.







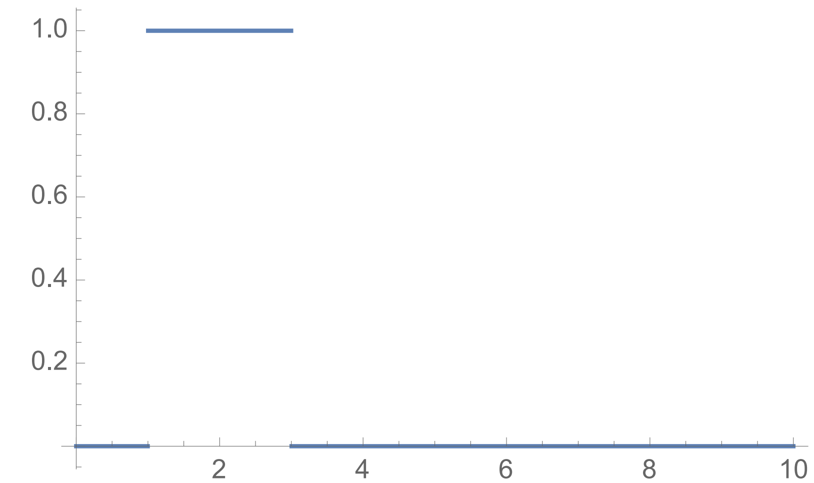


The measured pulses can be fit with the shaping function to extract the actual peaking time. The ratios should be checked to see if the channel parameters are correct.

What happens to square pulses that go through the filter ?

A step function normalized to Q

$$g(t)=\frac{Q}{t_2-t_1}\times(u(t-t_1)-u(t-t_2))$$



$$G(s)=\frac{Q}{t_2-t_1}\times\frac{(e^{-t_1 s}-e^{-t_2 s})}{s}$$

$$L[g(t)\otimes f(t)]=G(s)\cdot F(s)$$

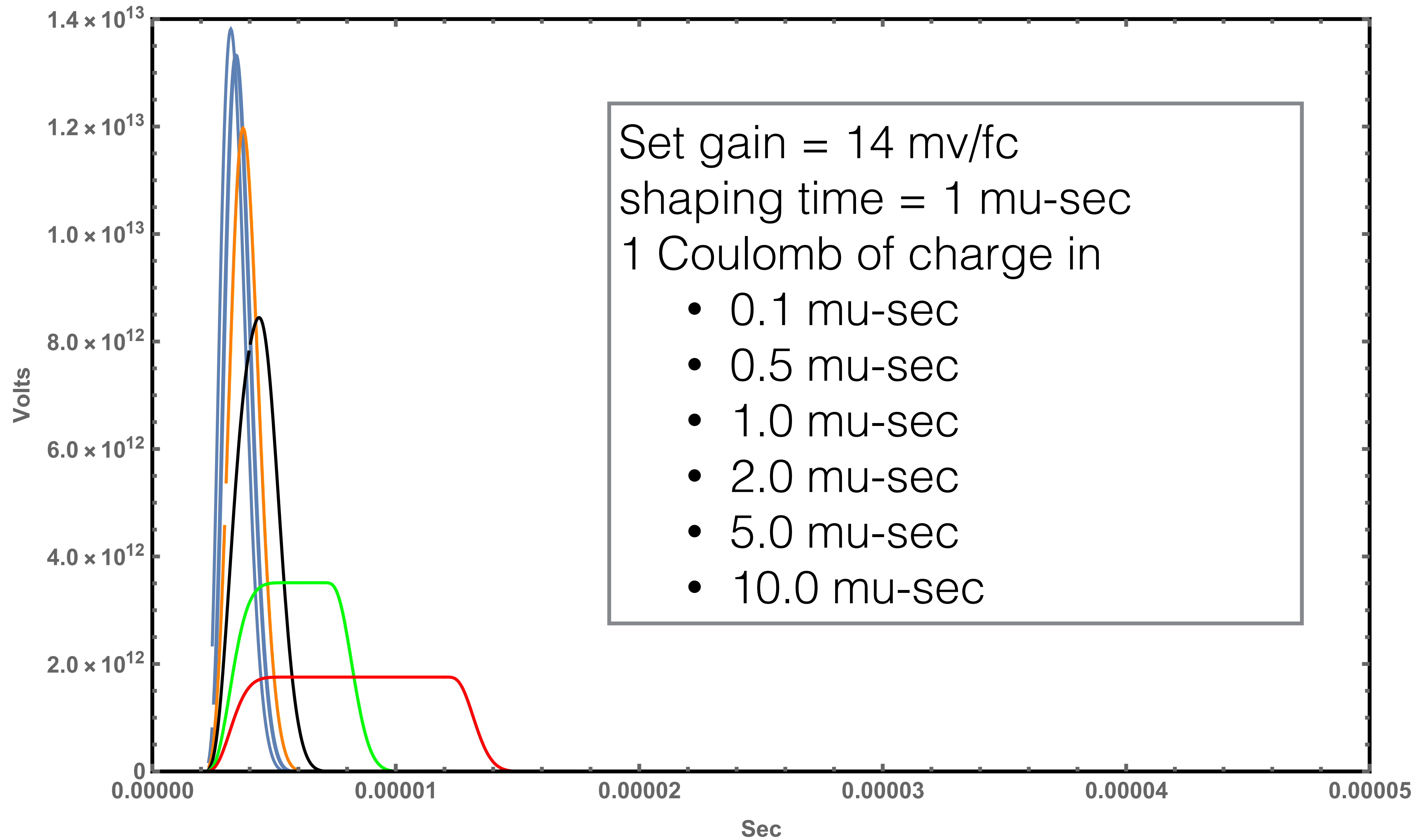
The integral of the convolution will be

$$\lim_{s\to 0}G(s)\cdot F(s)=Q\times\frac{G}{p(\alpha^2+\beta^2)(a^2+b^2)}$$

$$=g(mV/fc)*Q(fc)*T_{shp}(\mu s)*1.25399$$

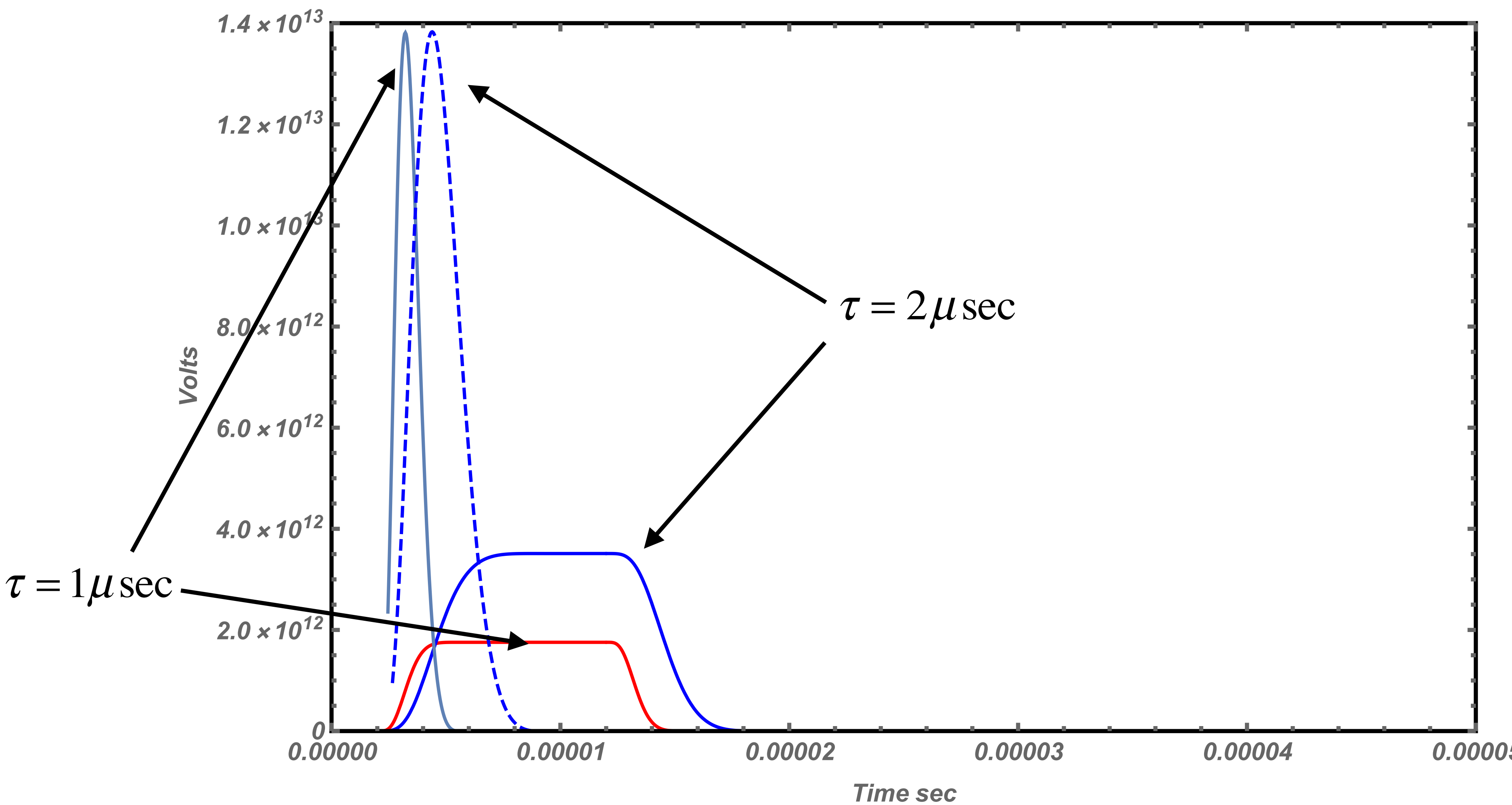
This is independent of the pulse g(t) shape (width or start).

Response to wide pulses



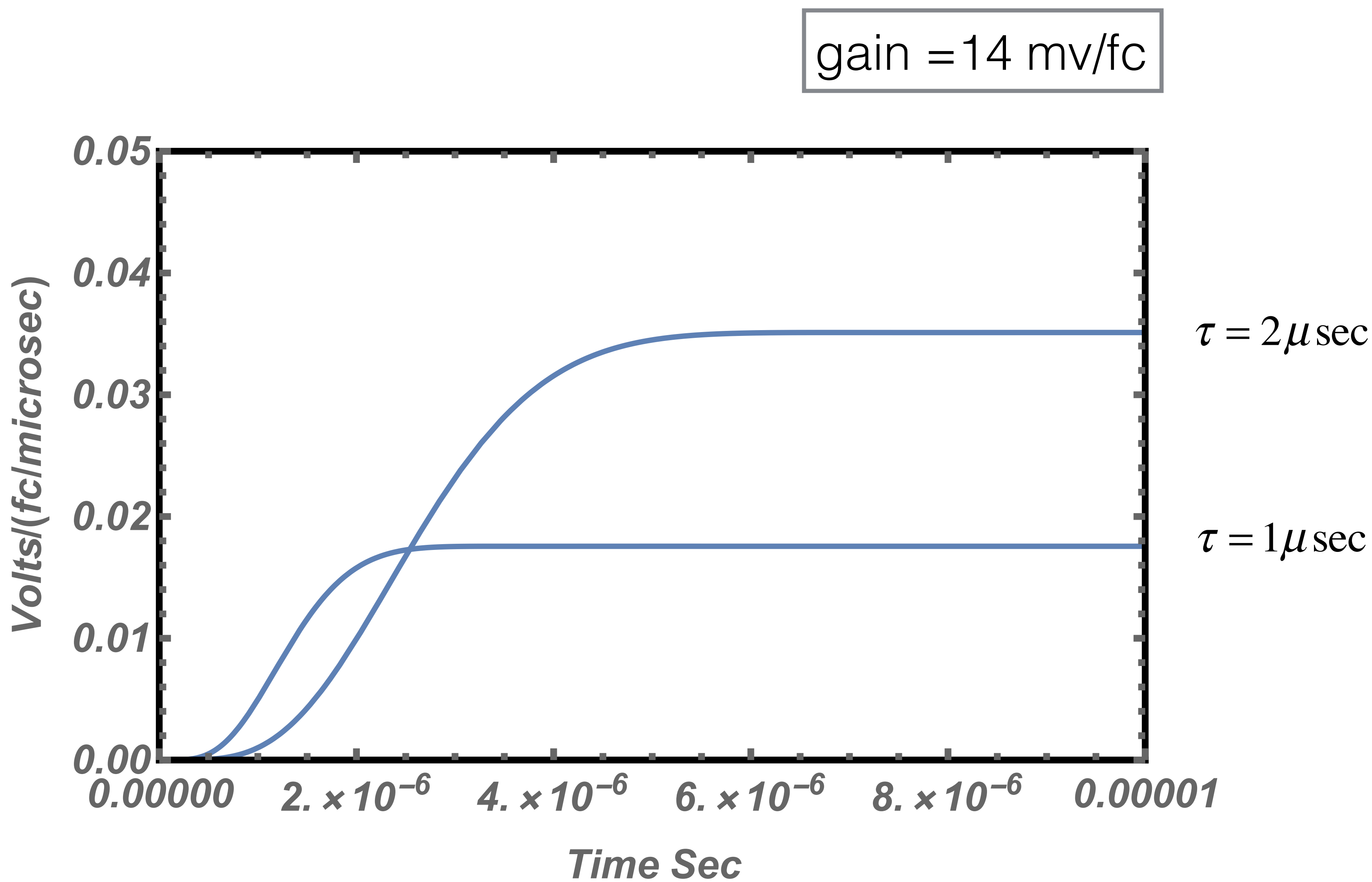
The integral of these pulses is exactly the same for each pulse width. For a delta pulse the peak will rise to Voltage = (gain*total charge).

Finite pulse width and shaping time



Pulse widths of 0.1 and 10 micro-sec

Response to a DC pulse



Summary

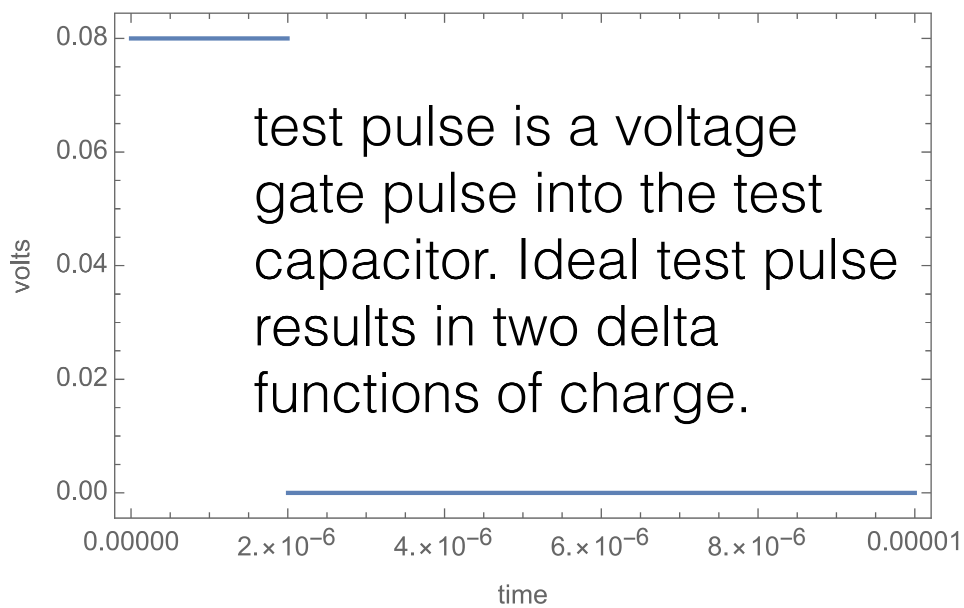
1. For a delta pulse of fixed charge, the amplitude of the output is the same for any shaping time.

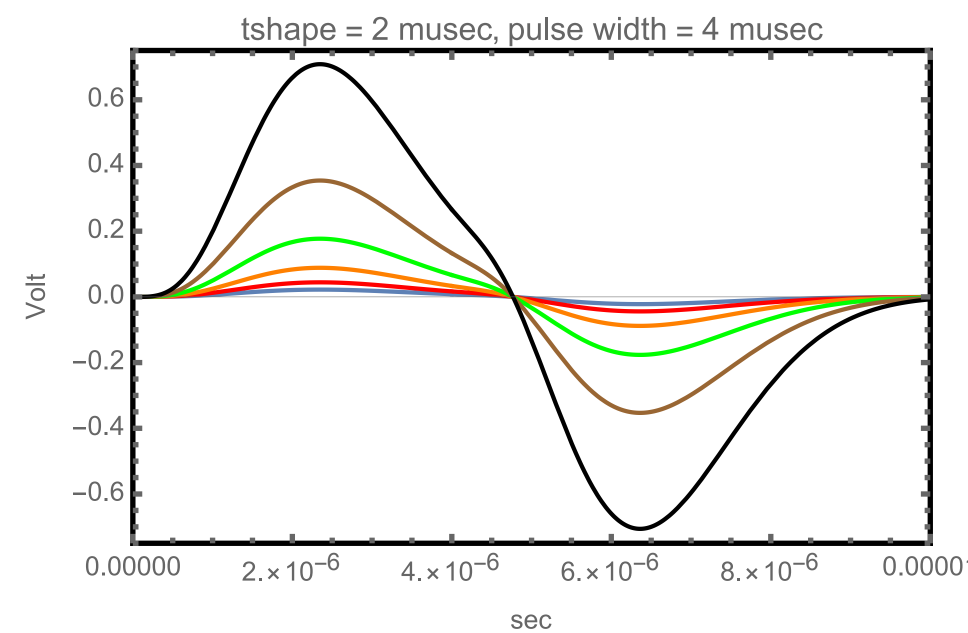
2. For a pulse of any width, the area of the output pulse is in ratio of the shaping time.

3. For a pulse of finite width, the amplitude with change with shaping time respecting rule #2.

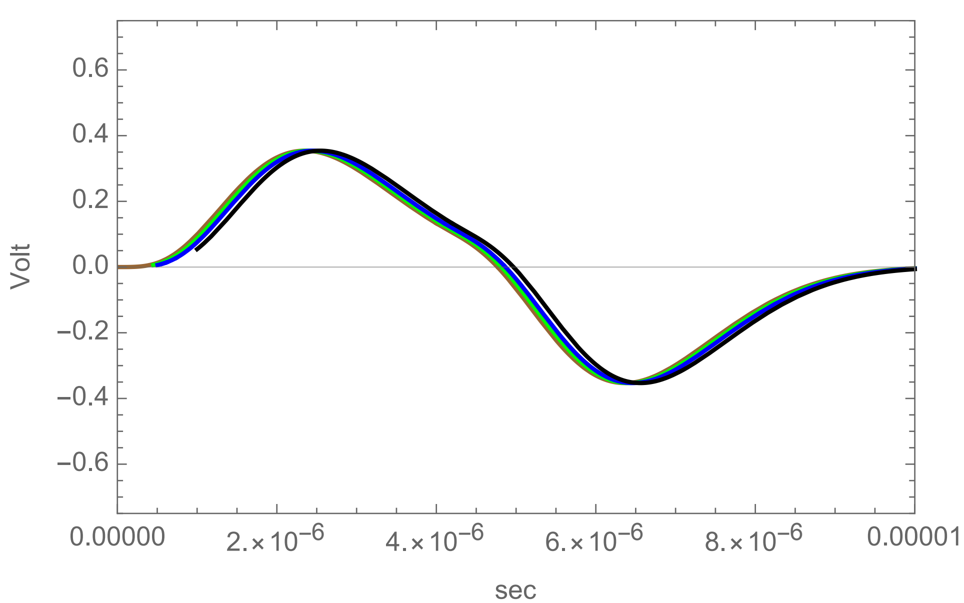
4. For a DC step pulse, the amplitude reached will be in ratio of the shaping time.

What happens to a test pulse to the calibration capacitor ?





Voltage steps: 0.008, 0.016, 0.032, 0.064, 0.128, 0.256

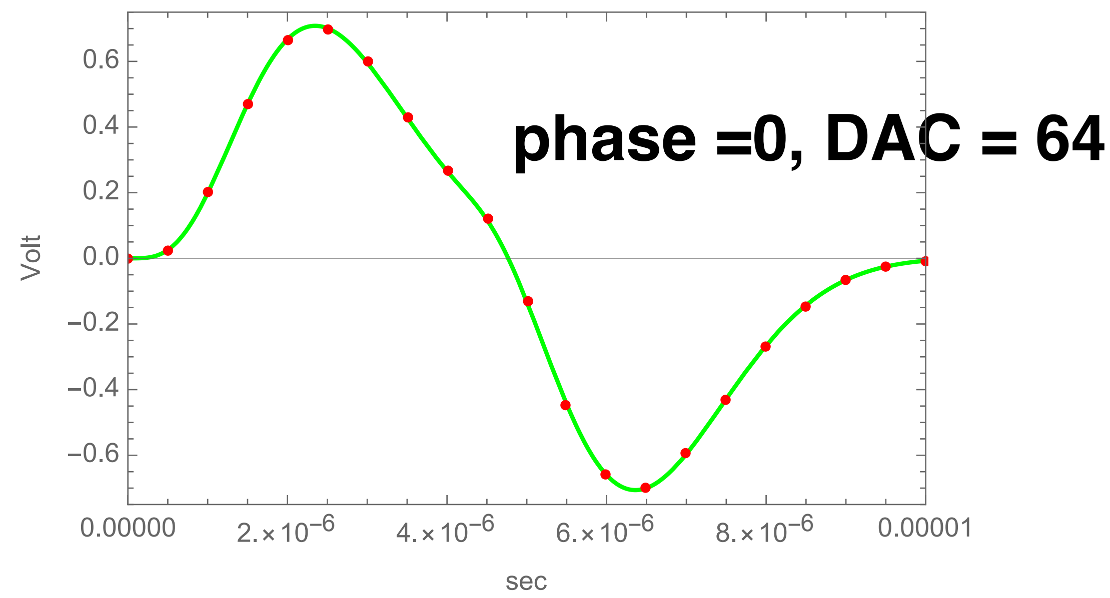


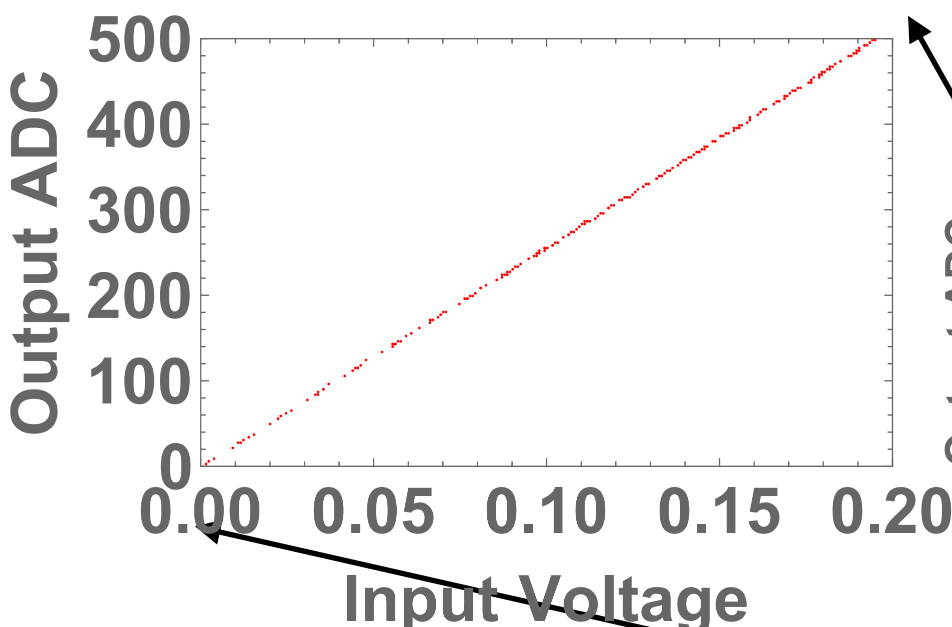
Time steps: 0, 50, 100, 200, nsec

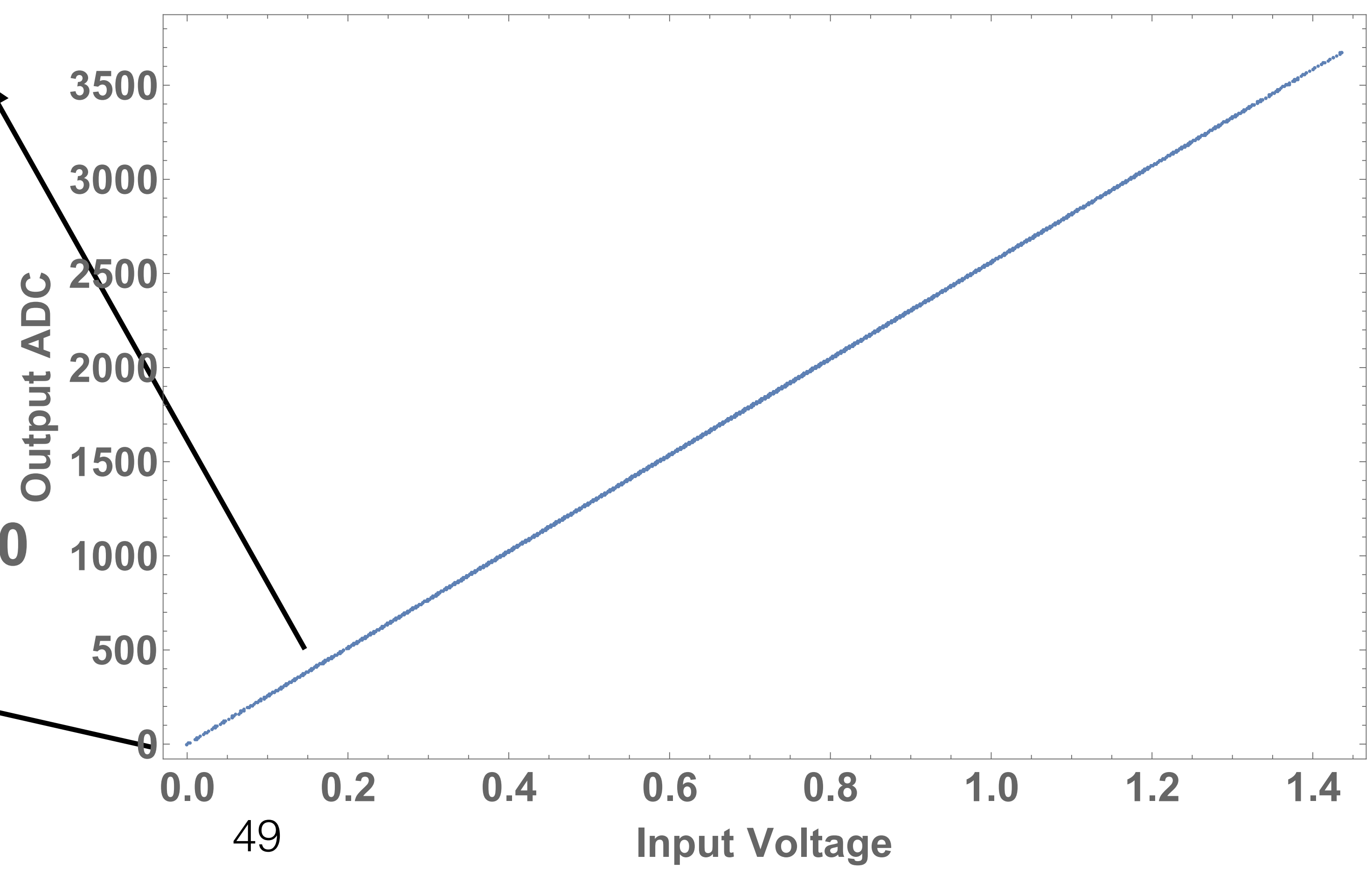
- A square test pulse results in a bipolar output pulse. test capacitance ~ 200 fF
- By changing voltages (with 6 bit DAC), and time shift it is possible to scan the ADC voltage range.
- For proper ADC calibration the pulse shape must be well understood.
- How many different voltage measurements can be made with this technique ?

Calculation of possible voltages for calibration given perfect knowledge of the pulse shape.

- **Assumptions**
- **0.004 volts/DAC count**
- **gain setting 14 mv/fc**
- **Max +-0.72 V=2.8*testV**
- **Shaping time of 2 musec**
- **pulse width of 4 muse**
- **2 MHz sampling**
- **5 phases: 0, 50, 100, 150, 200 nsec.**







Questions to create calibration requirement

- How well is the test capacitor known for each channel ? Stability also.
- How well is the pulse shape known for each channel ?
- Is the pulse shape completely described by a single parameter ?
- What is the maximum voltage range of the DAC that supplies the test pulse ? How many volts per step ?
- Internal DAC: 18mV/step => max of 1.152 V
- FPGA DAC: 19mV/step => max of 1.216 V
- What is the resolution with which time shifts can be made to shift the pulse across ADC time bins? (50 ns/step with 256 steps => max 12.8 mu-sec)
- How granular does the ADC calibration need to be ?

Review calibration steps.

Signal sequence

$$dE/dx\,(MeV/cm) \xrightarrow{\substack{Ionization\\ Saturation\\ \mathrm{Re}comb.}} Q\,(fC) \xrightarrow{\substack{Drift\\ Diffusion}} Q_{APA}(fC)$$

$$I_{APA}(fC/\mu\mathrm{sec}) \xrightarrow{\substack{Field\ Effect\\ Induction}} I_{wire}(fC/\mu\mathrm{sec}) \xrightarrow{\substack{\mathrm{Wire}\\ \mathrm{capacitance}}} I_{gate}(fC/\mu\mathrm{sec})$$

$$\xrightarrow{Gain/Shape} V_{ADC}(t) \xrightarrow{\substack{ADC\\ calibration}} ADC(t_i)$$

Test pulse sequence

$$V_{Pulse}(dac, twid) \xrightarrow{\substack{DACcalib\\ risetime\\ falltime\\ test\ capacitor}} Q_{pulse}(t_1, t_2)$$

$$\xrightarrow{Gain/Shape} V_{testout}(t_i) \xrightarrow{ADCcalib} ADC(t_i)$$

Notice that Vpulse from DAC needs to be known as well as the test capacitor. And shape needs to be known to calibration the ADC.

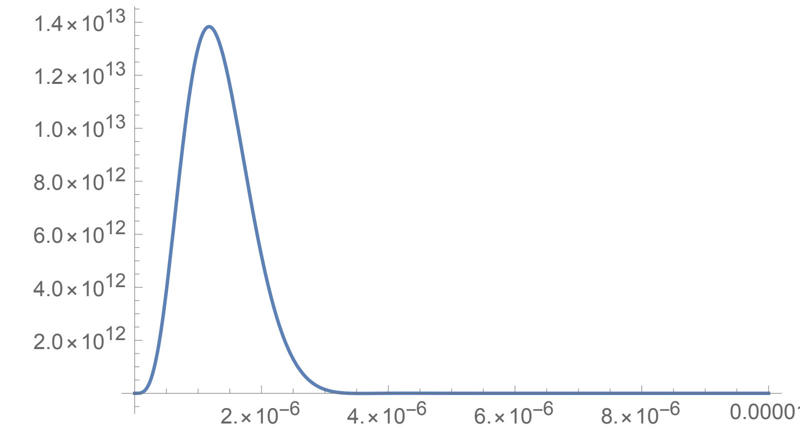
Summary

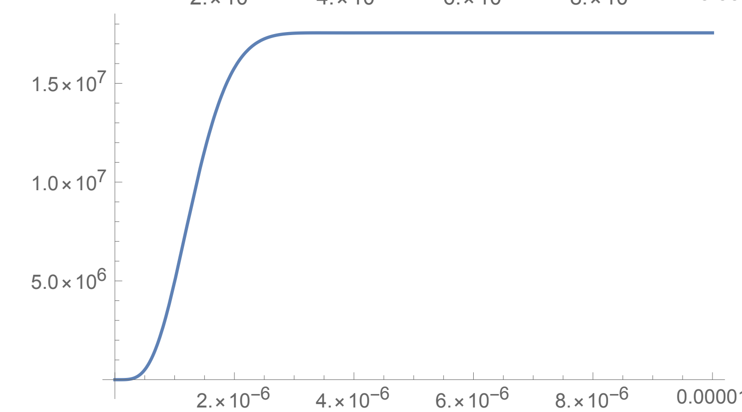
- The pre-amplier and the shaped pulse should have the following features
  - Independent gain and shaping time settings.
  - The gain settings should allow
    - Resolution and dynamic range as specified.
    - High and low gain settings for special calibrations.
    - Current choices: 4.7, 7.8, 14, 25 mv/fc
  - Shaping time settings should allow
    - Optimum noise performance given the expected signal including diffusion, induction.
    - Special calibration settings for fast and long shaping times.
    - Well known pulse shape to calibrate the ADC.

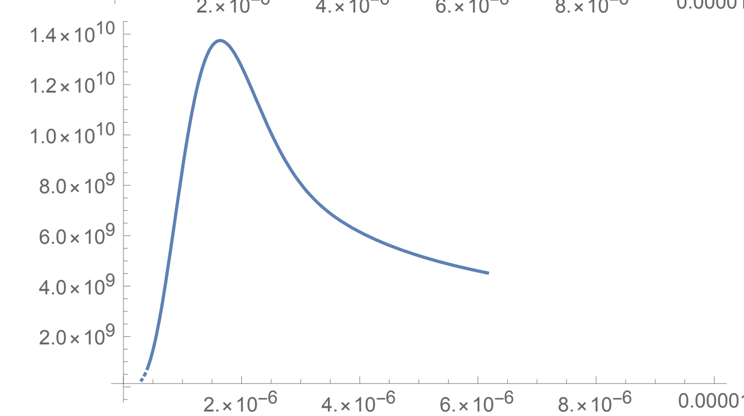
More functions (needed for noise analysis)

Noise type	Time domain	S-domain
Series white	delta(t-t$_i$)	Exp[-st$_i$]
parallel white	u(t-t$_i$)	Exp[-st$_i$]
1/f	1/Sqrt[t-t$_i$].u(t-t$_i$)	Sqrt(π)Exp[-st$_i$]/Sqrt[s]

After Shaper







We need these functions for the analysis of noise which will be the next topic.