LCWS2023 2023-05-17

Accelerator: Particle Sources

Beam loading compensation on the booster linac

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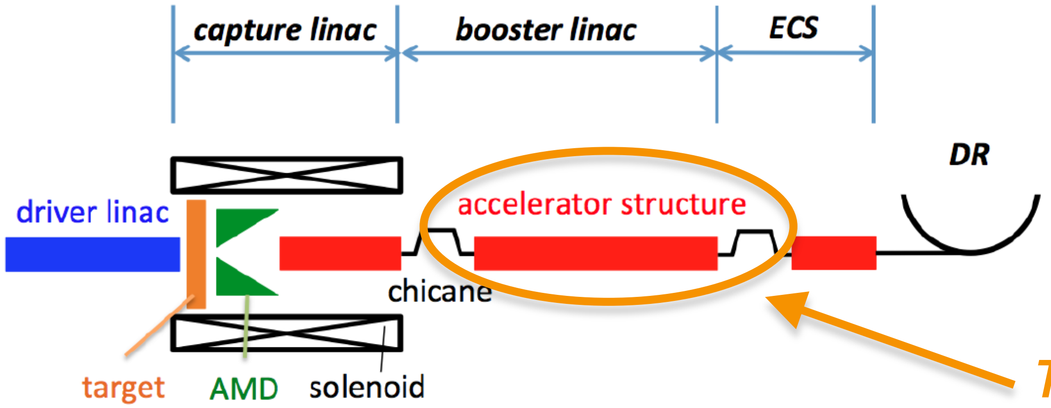
Research Purpose & Method

- In order to accelerate uniformly a multi-bunch positron beam, we studied beam loading compensation with amplitude modulation (AM) on the positron booster, traveling wave (TW) cavity.
- We derived an analytical formula expressing the temporal evolution of TW cavity voltage.
- Evaluated the compensation method including the pulse gap.
- Considered the klystron bandwidth.

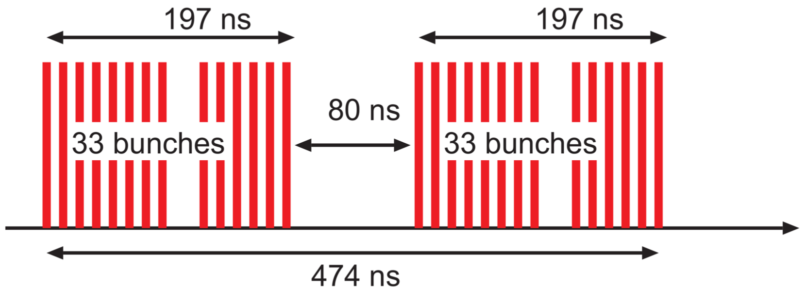
ILC electron-driven positron source



Yuji Seimiya et al., doi:10.1093/ptep/ptv136

The main subject of this study

Time structure of 1 pulse

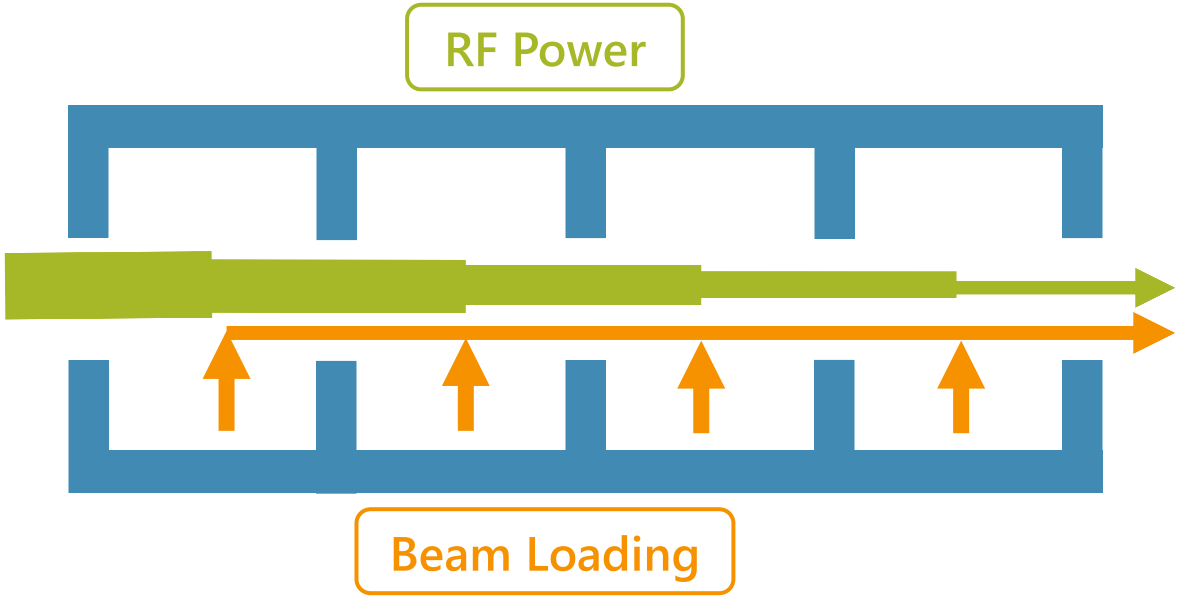


M. Kuriki, doi:10.18429/JACoW-IPAC2018-MOPMF076

- Total is 1320 bunches
- 1 pulse with 2 mini trains consisting of 33 bunches

Booster TW accelerator tubes

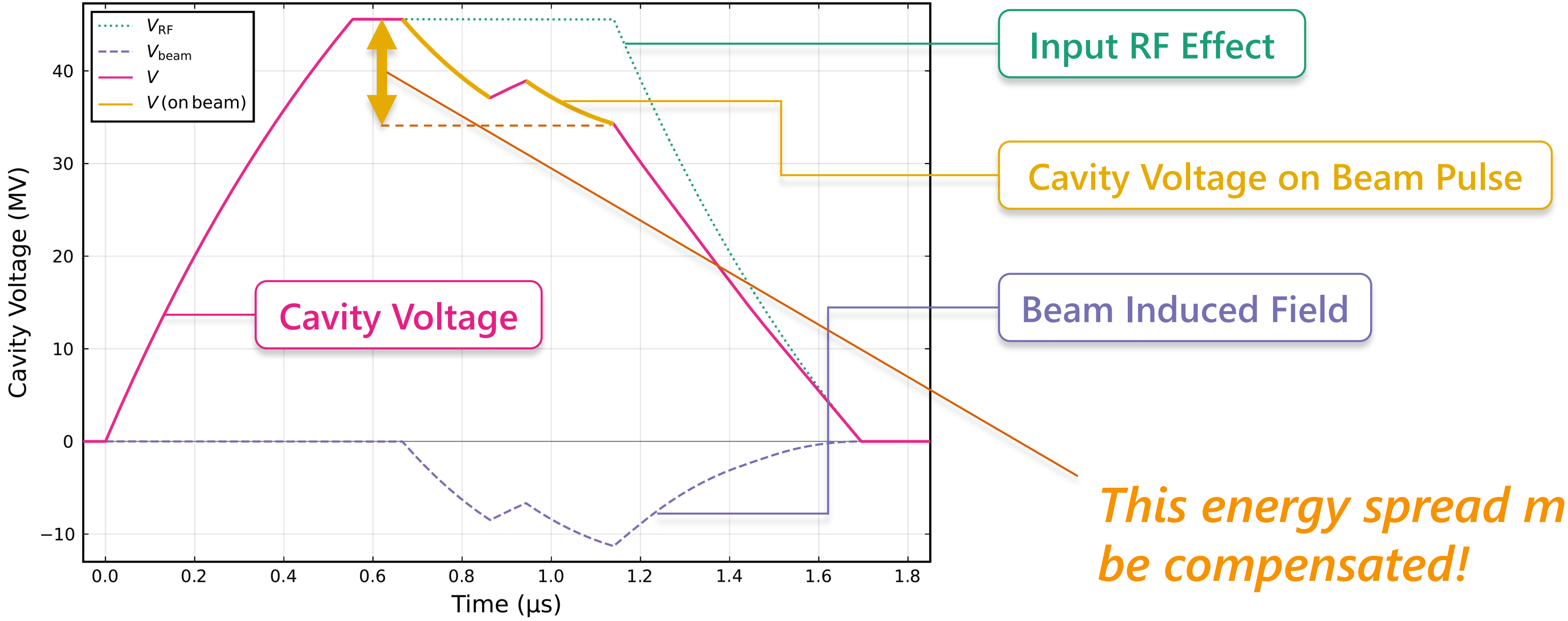
- The positron booster uses a constant-gradient TW tube (L-Band and S-Band).
- Power from the RF input travels at a group velocity v_g to downstream.
- Beam loading is induced in each cell and propagate to downstream in the same way.



Parameter	L-band	S-band	unit
Shunt impedance	46.5	55.1	M/m
Length	2.19	2.15	m
Aperture (2a)	35.0 39.4	24.3-20.3	mm
Attenuation τ	0.261	0.333	
Filling time t_f	1.28	0.55	μs

If no beam loading compensation

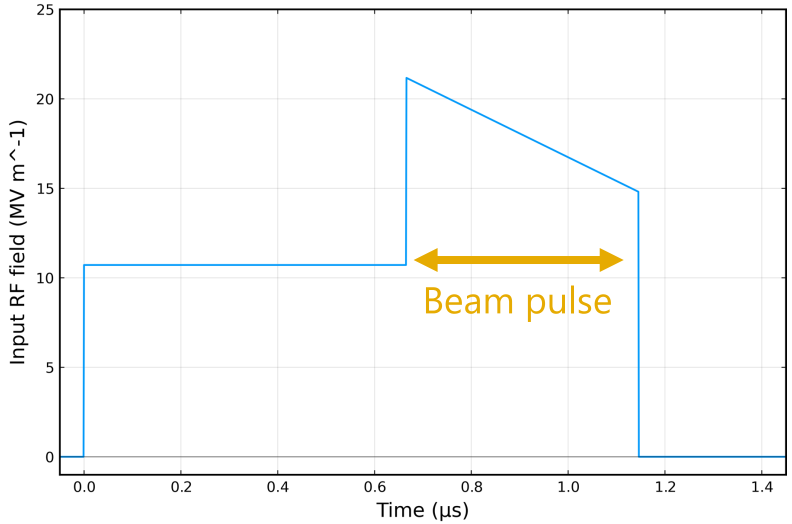
The cavity voltage evolution with the beam loading



This energy spread must be compensated!

After filling time, RF power builds up, but when beam pulses are is injected, the accelerating electric field drops due to beam loading.

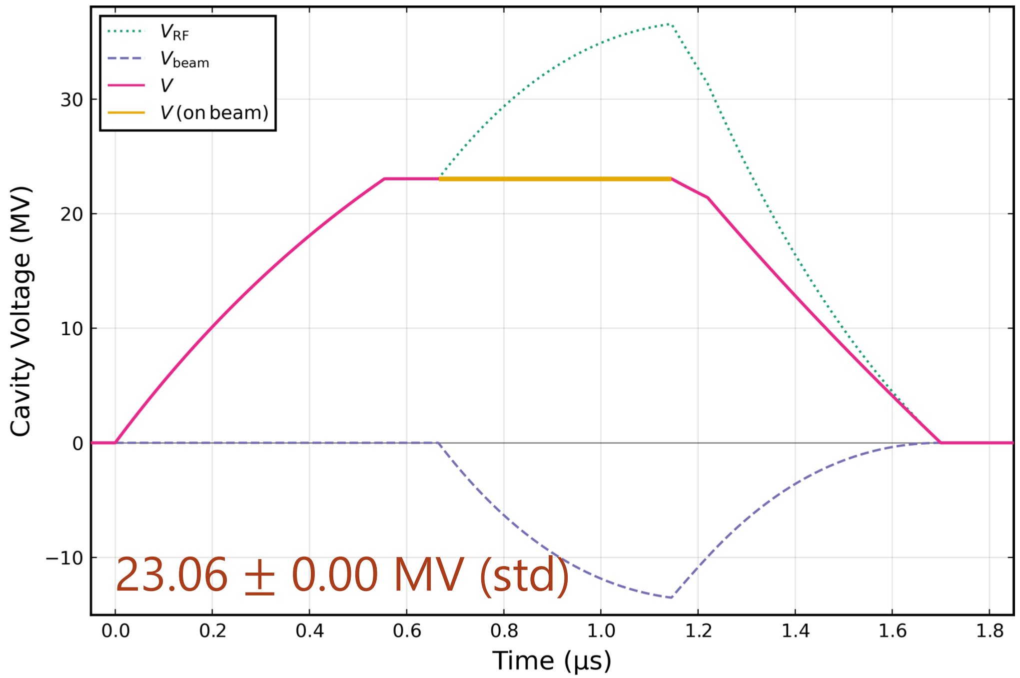
Perfect beam loading compensation with trapezoidal pulse



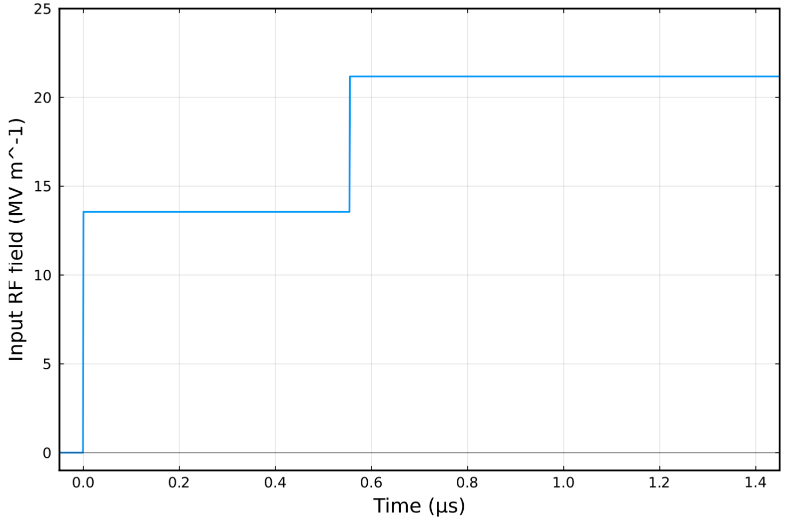
Input RF field

$$E_{\mathrm{in}}(t) = E_0(u(t) - u(t - t_{\mathrm{RF}_1})) + (at + b)(u(t - t_{\mathrm{RF}_1}) - u(t - t_{\mathrm{RF}_2}))$$

- The effect of beam loading can be fully compensated by canceling it with RF input of the trapezoidal pulse.
- However, considering the bandwidth of the klystron, it cannot be fully compensated.
- In addition, since the peak electric field is determined by the maximum power, so the acceleration electric field is suppressed.



Two-component amplitude modulation

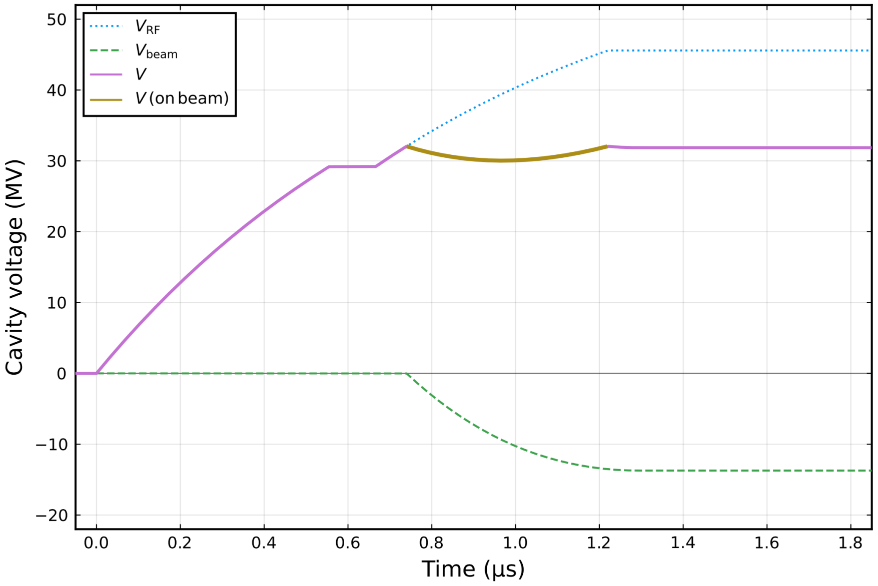


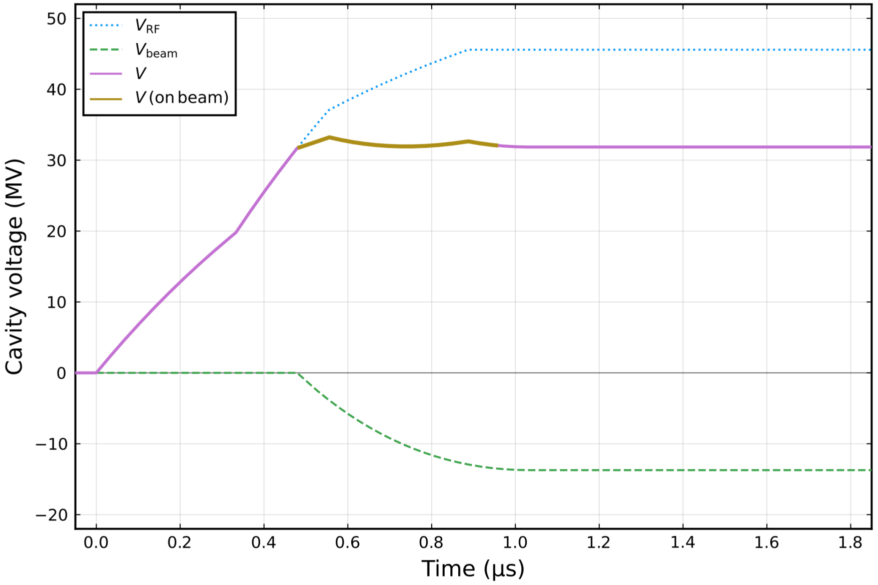
Cavity voltage

$$V_{\mathrm{cavity}}(t) = V_{\mathrm{cavity}_{\mathrm{RF}_0}}(t) + V_{\mathrm{cavity}_{\mathrm{RF}_1}}(t) + V_{\mathrm{cavity}_{\mathrm{beam}}}(t)$$

$$V_{\mathrm{cavity}_{\mathrm{RF}_0}}(t) := \frac{E_0 L}{1 - e^{-\frac{\omega}{Q} t_f}} \left(\left(1 - e^{-\frac{\omega}{Q} t}\right) u(t) - \left(1 - e^{-\frac{\omega}{Q}(t - t_f)}\right) e^{-\frac{\omega}{Q} t_f} u(t - t_f) \right)$$

$$V_{\mathrm{cavity}_{\mathrm{RF}_1}}(t) := \frac{E_1 L}{1 - e^{-\frac{\omega}{Q} t_f}} \left(\left(1 - e^{-\frac{\omega}{Q}(t - t_{\mathrm{RF}_1})}\right) u(t - t_{\mathrm{RF}_1}) - \left(1 - e^{-\frac{\omega}{Q}(t - t_{\mathrm{RF}_1} - t_f)}\right) e^{-\frac{\omega}{Q} t_f} u(t - t_{\mathrm{RF}_1} - t_f) \right)$$



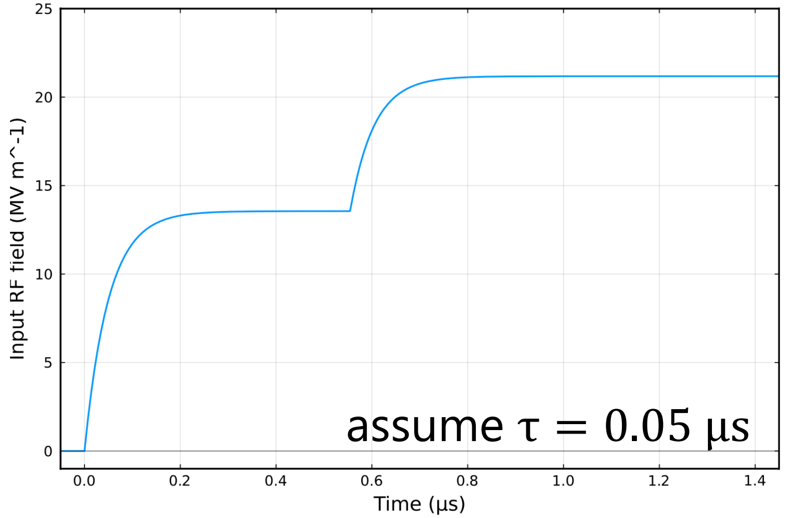


Two-component amplitude modulation

When included klystron bandwidth

Input RF field

$$E_{\text{in}}(t) = E_0\left(1-e^{-\frac{t}{\tau}}\right)u(t) + E_1\left(1-e^{-\frac{t-t_{\text{RF}_1}}{\tau}}\right)u(t-t_{\text{RF}_1})$$



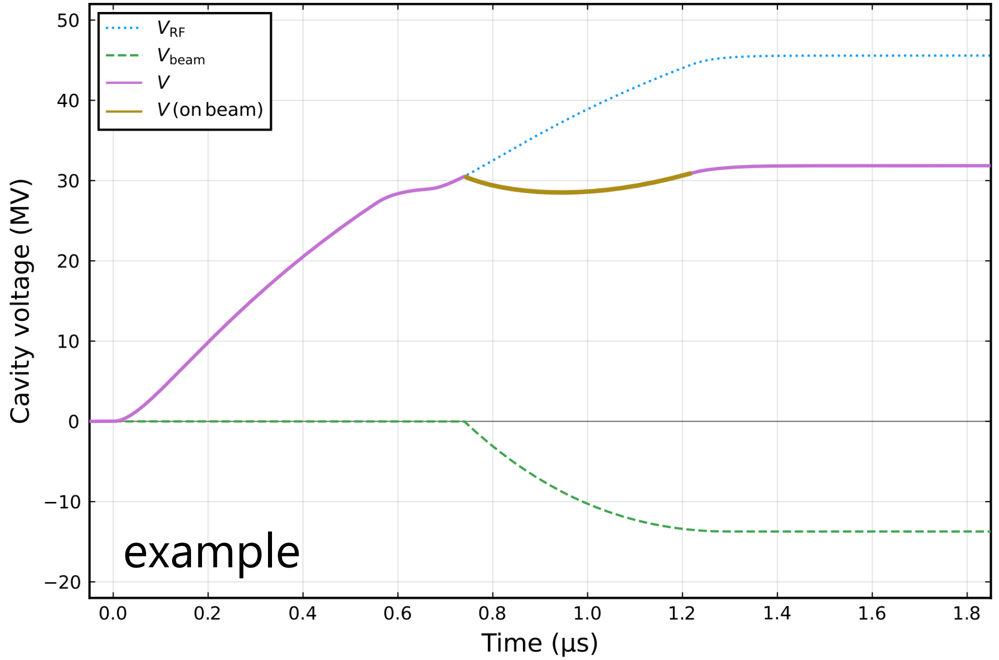
Cavity voltage

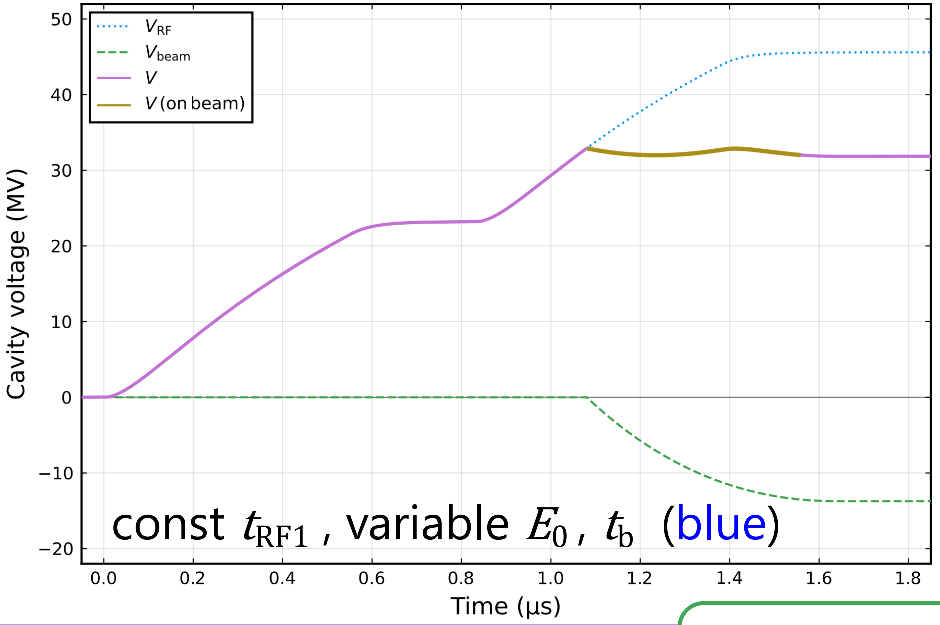
$$V_{\text{cavity}}(t) = V_{\text{cavity}_{\text{RF}_0}}(t) + V_{\text{cavity}_{\text{RF}_1}}(t) + V_{\text{cavity}_{\text{beam}}}(t)$$

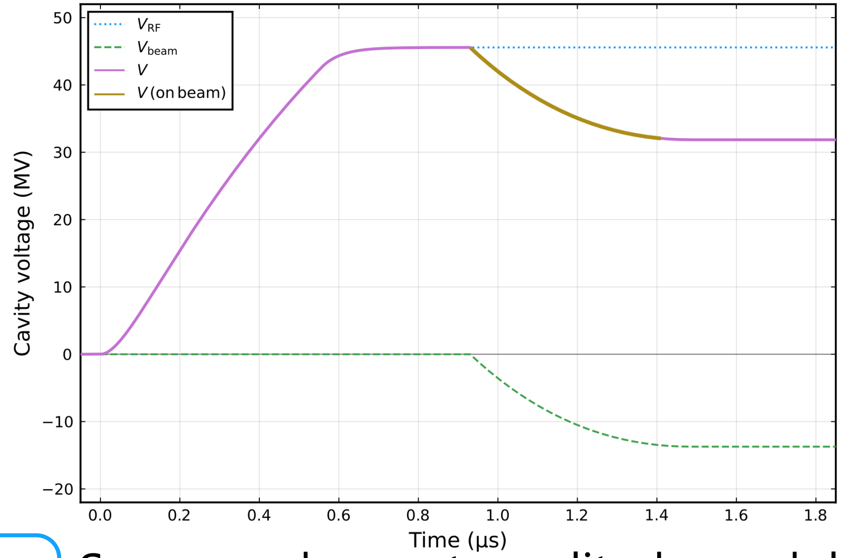
$$V_{\text{cavity}_{\text{RF}_0}}(t) := \frac{E_0 L}{1-e^{-\frac{\omega}{Q}t_f}}\left(\left(1-\frac{1}{1-\frac{\omega}{Q}\tau}\left(e^{-\frac{\omega}{Q}t}-\frac{\omega}{Q}\tau e^{-\frac{t}{\tau}}\right)\right)u(t) - \left(1-\frac{1}{1-\frac{\omega}{Q}\tau}\left(e^{-\frac{\omega}{Q}(t-t_f)}-\frac{\omega}{Q}\tau e^{-\frac{t-t_f}{\tau}}\right)\right)e^{-\frac{\omega}{Q}t_f}u(t-t_f)\right)$$

$$V_{\text{cavity}_{\text{RF}_1}}(t) := \frac{E_1 L}{1-e^{-\frac{\omega}{Q}t_f}}\left(\left(1-\frac{1}{1-\frac{\omega}{Q}\tau}\left(e^{-\frac{\omega}{Q}(t-t_{\text{RF}_1})}-\frac{\omega}{Q}\tau e^{-\frac{t-t_{\text{RF}_1}}{\tau}}\right)\right)u(t-t_{\text{RF}_1}) - \left(1-\frac{1}{1-\frac{\omega}{Q}\tau}\left(e^{-\frac{\omega}{Q}(t-t_{\text{RF}_1}-t_f)}-\frac{\omega}{Q}\tau e^{-\frac{t-t_{\text{RF}_1}-t_f}{\tau}}\right)\right)e^{-\frac{\omega}{Q}t_f}u(t-t_{\text{RF}_1}-t_f)\right)$$

$$V_{\text{cavity}_{\text{beam}}}(t) := -\frac{\frac{1}{2}r_0 I_0 L}{1-e^{-\frac{\omega}{Q}t_f}}\left(\left(1-e^{-\frac{\omega}{Q}(t-t_b)}-\frac{\omega}{Q}(t-t_b)e^{-\frac{\omega}{Q}t_f}\right)u(t-t_b) - \left(\left(1-e^{-\frac{\omega}{Q}(t-t_b-t_f)}\right)e^{-\frac{\omega}{Q}t_f}-\frac{\omega}{Q}(t-t_b-t_f)e^{-\frac{\omega}{Q}t_f}\right)u(t-t_b-t_f)\right)$$



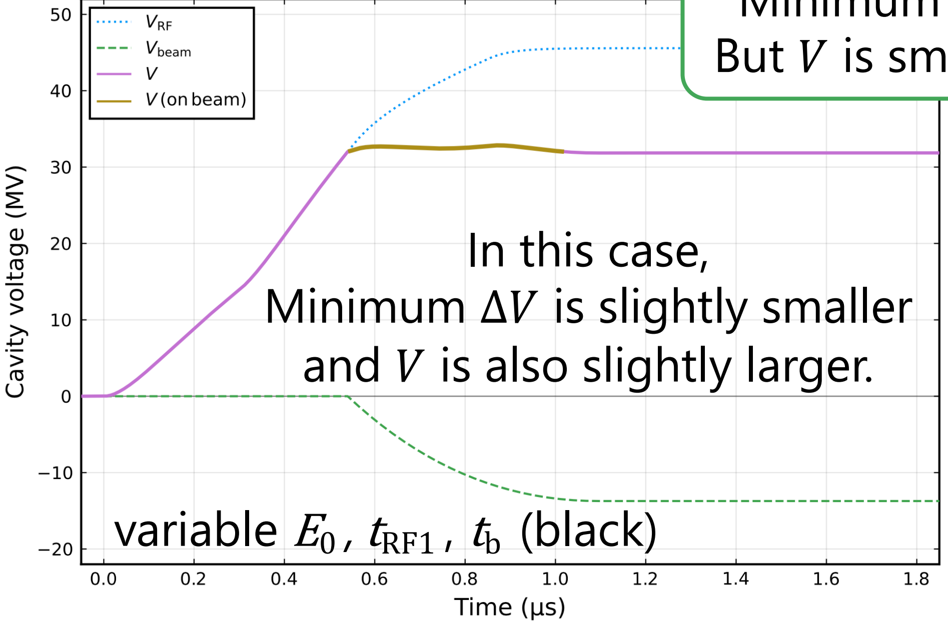




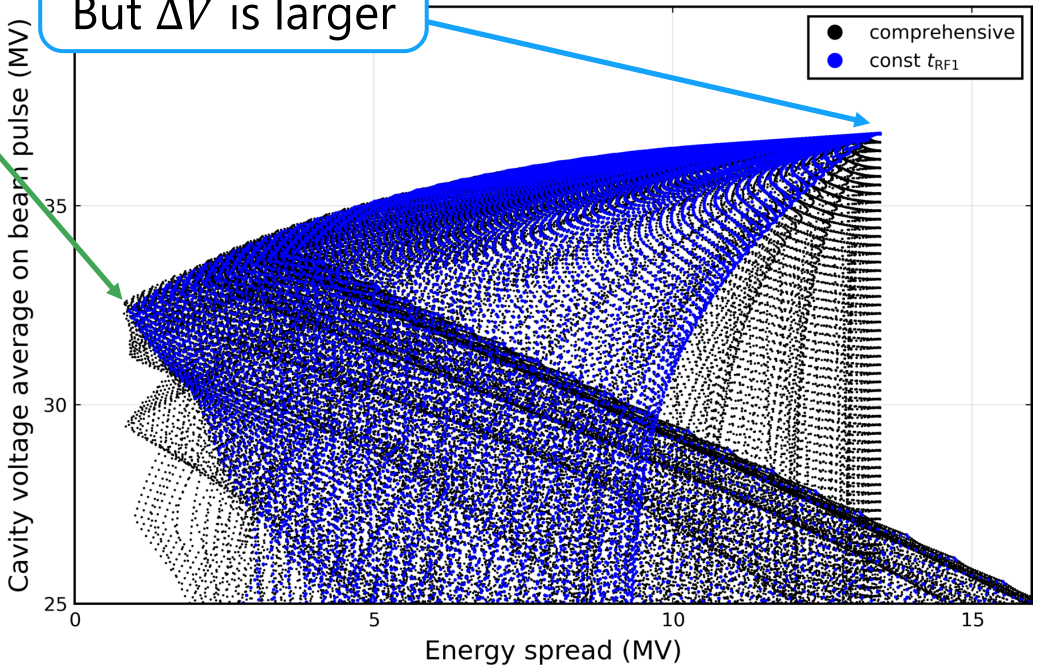
Same as when not amplitude modulated

Minimum ΔV
But V is smaller

Maximum V
But ΔV is larger



In this case,
Minimum ΔV is slightly smaller
and V is also slightly larger.

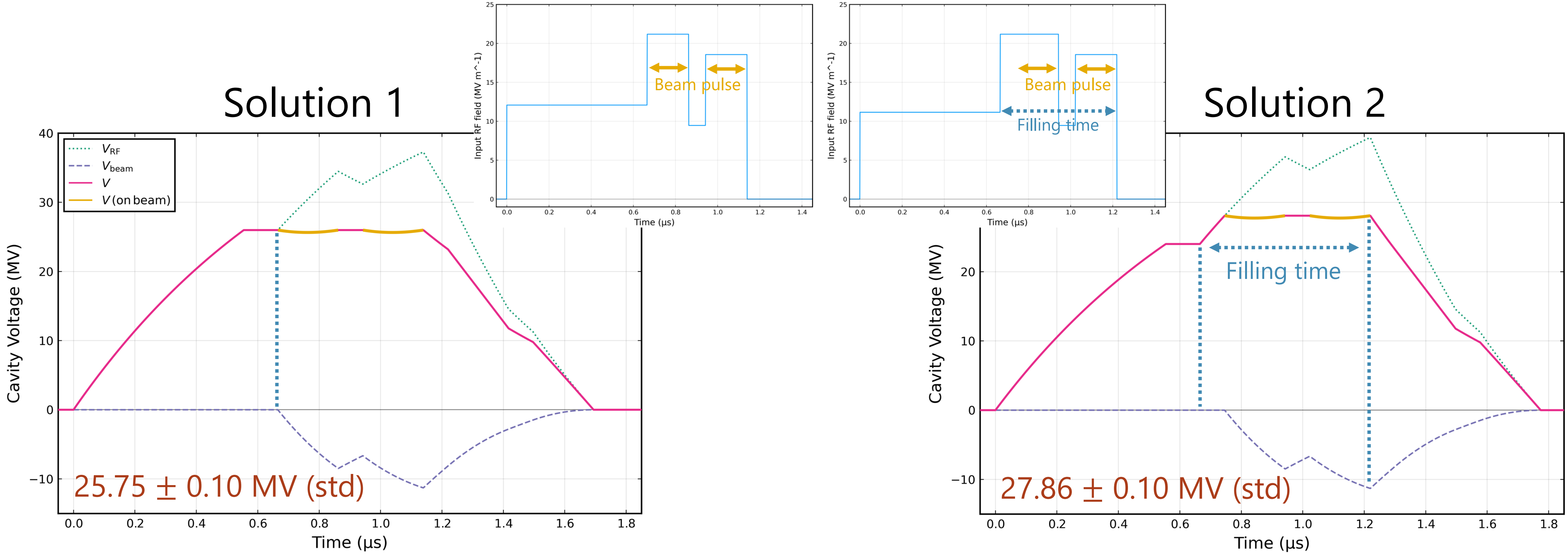


The energy spread (peak-to-peak) is 1.8 % of the voltage ratio.

acceleration voltage and energy spread

Consider the pulse gap of the beam

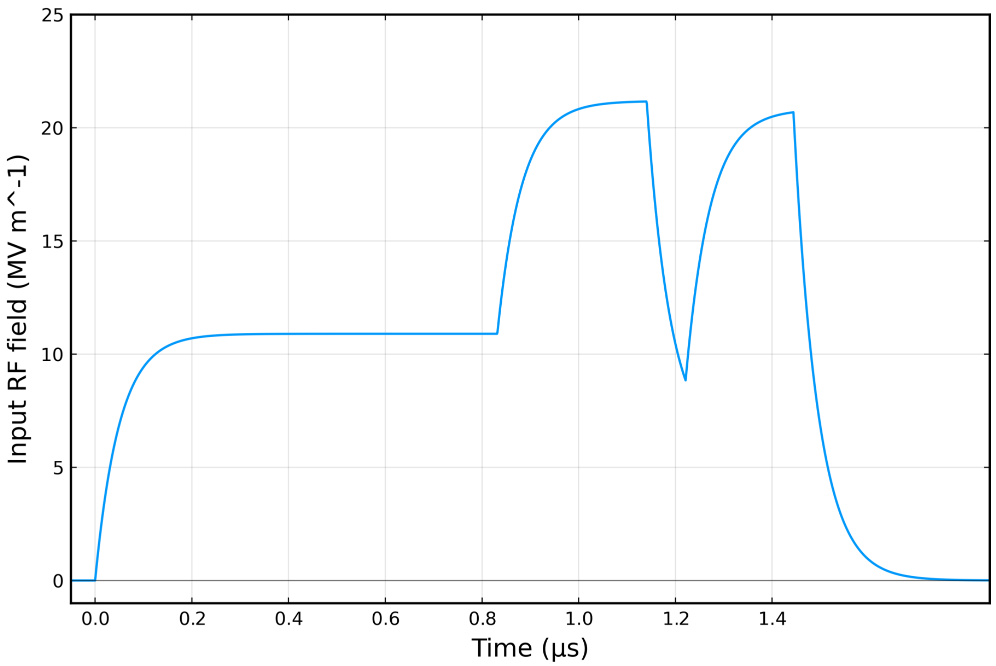
Solution 1: The first AM is synchronized with the beam acceleration start.
Solution 2: The end of beam acceleration is synchronized with the point in time when the filling time has elapsed since the first AM modulation.



Solution 2 is higher voltage!

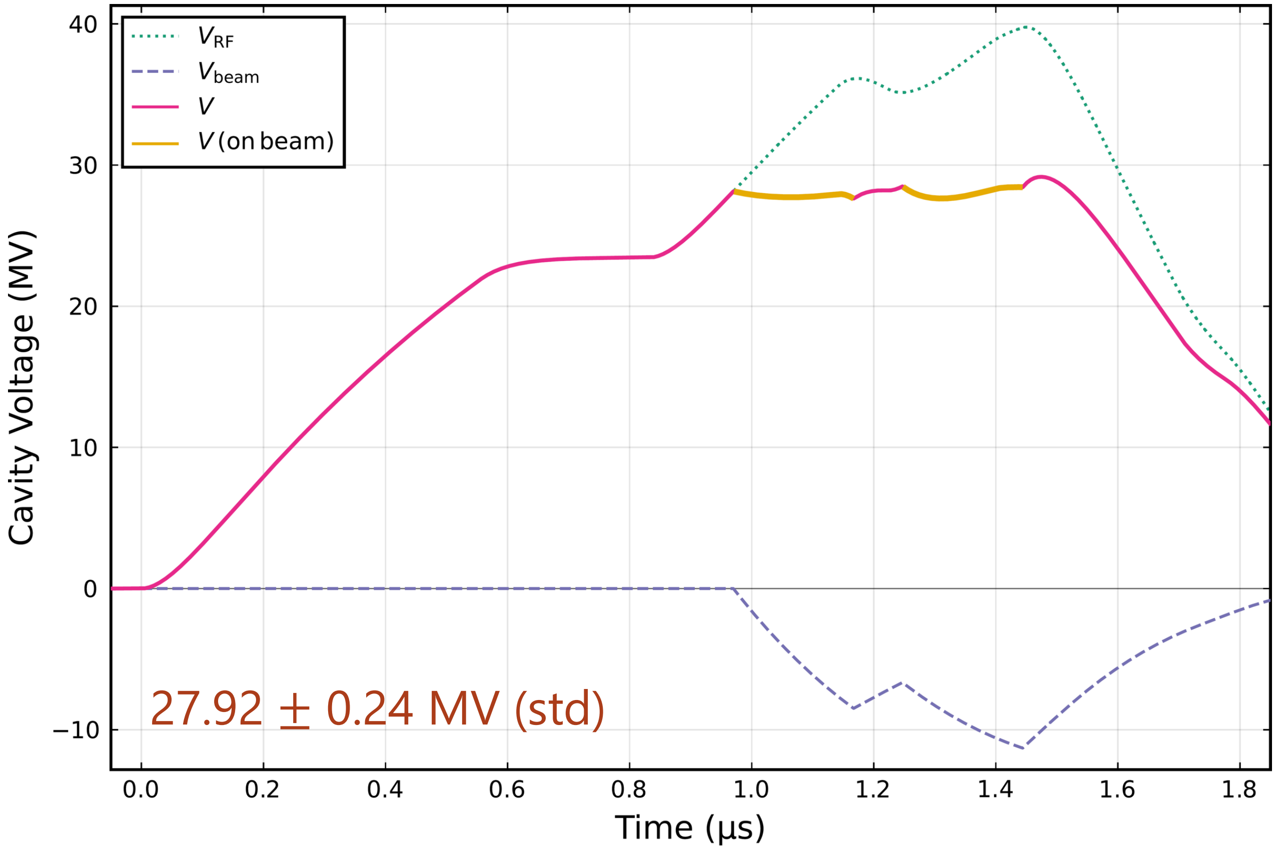
Include klystron bandwidth

Input RF field



assume $\tau = 0.05$ μs

A numerical example based on the solution 2



Note: this is not a fully optimized example.

Conclusions

- We have studied the beam loading compensation with various conditions.
- At a constant beam current, the acceleration voltage can be increased if a wide energy spread is allowed. Conversely, if the energy spread is reduced, the average acceleration voltage is reduced.
- With the trapezoidal AM, the transient beam loading can be perfectly compensated, but the average gradient is suppressed.
- With the two-component AM, the average gradient is recovered, but the small variation is appeared.
- If we include the pulse gap, the performance is almost same, but we need a complicated AM.
- If we include the klystron bandwidth, the same method is applicable.

Future Plans

- Evaluate the energy variation for each bunch.
- Draw the pareto front (energy spread vs. average energy) for various conditions.