

Capacitive-Load Pulsing: Rise Time, Slew Rate, and Power

Why a fast voltage edge into a capacitor demands large peak current, what sets the achievable rise time, and how average power scales with capacitance, voltage, and repetition rate. A first-principles guide for Pockels cells, deflection plates, and other capacitive loads.



TECHNICAL NOTE · DEI PULSERS (DIRECTED ENERGY DIVISION)

1 The Governing Equation

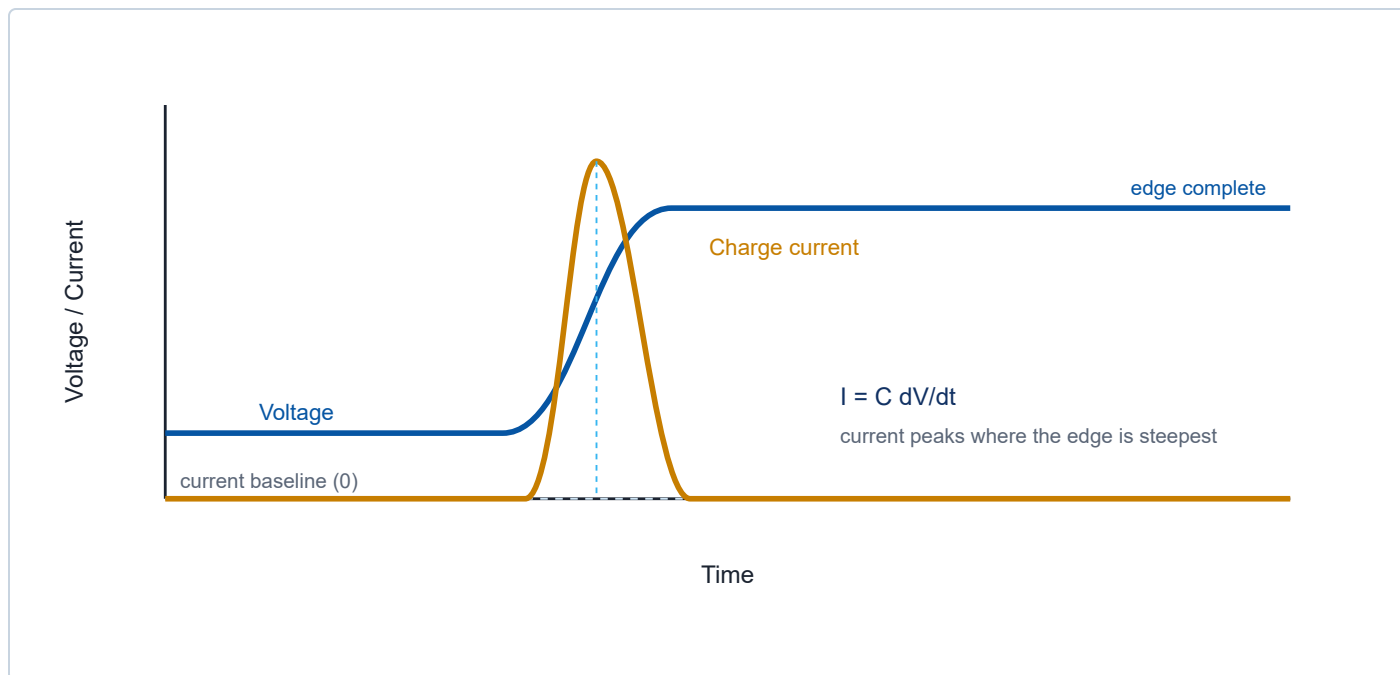
Almost every difficulty in driving a Pockels cell, a deflection plate, an extraction grid, or any other capacitive load traces back to one relation. A capacitor does not respond to voltage. It responds to the rate of change of voltage. The current that flows into a capacitor is set by how fast you move its voltage, written plainly as $I = C \text{ times } dV/dt$: current equals capacitance times the rate of change of voltage.

The terms: **I** is the instantaneous current the source must deliver, in amperes. **C** is the load capacitance, in farads, fixed by the device and its wiring. **dV/dt** is the slew rate, the rate at which the output voltage changes, in volts per second. When the voltage is flat, dV/dt is zero and no current flows into an ideal capacitor. When the voltage is moving, the source has to supply current in proportion to both the capacitance and the speed of the change.

2 Why a Fast Edge Demands Big Current

The consequence of $I = C \text{ times } dV/dt$ is direct: a faster edge into the same capacitor demands proportionally more current. Halve the rise time and you double the slew rate, so you double the peak charging current the driver must source. The capacitance has not changed. Only the speed has, and current tracks speed.

This is why capacitive-load pulsing is harder than driving a resistor. A resistive load draws a current set by Ohm's law and the voltage level. A capacitive load draws a current set by the steepness of the edge, and a square pulse with sharp transitions is the steepest edge you can ask for. The current does not flow during the flat top. It flows in a burst concentrated on each transition, where the voltage is changing fastest (Figure 1).



SCHEMATIC **Figure 1.** The charging current (amber) follows the slope of the voltage, not its level. It peaks during the steepest part of the rising edge (blue) and falls to zero once the voltage is flat.

3 Slew-Rate Limits

Every driver can only source and sink so much peak current. That ceiling is a hard physical limit set by the output devices, and it caps how fast the output can slew into a given capacitance. Rearrange the governing equation and the limit becomes plain: $dV/dt = I_{\text{peak}} / C$. The maximum slew rate equals the maximum peak current the driver can deliver, divided by the load capacitance.

This sets the achievable rise time on any given load. For a voltage swing of ΔV , the time to cross it is roughly $t_{\text{rise}} \sim C \times \Delta V / I_{\text{peak}}$. A bigger swing or a bigger capacitance takes longer at a fixed current, and the only way to recover the speed is to deliver more current. A generator rated for a fast edge into a small capacitance will not hold that edge into a much larger one, because the current ceiling has not moved. This is why a rise-time specification carries its load: the PVX-4141 is rated at 25 ns or less into 50 pF at 3,500 V. The figure that matters for a design is rise time into your capacitance, at your voltage.

4 RC and Cabling Effects

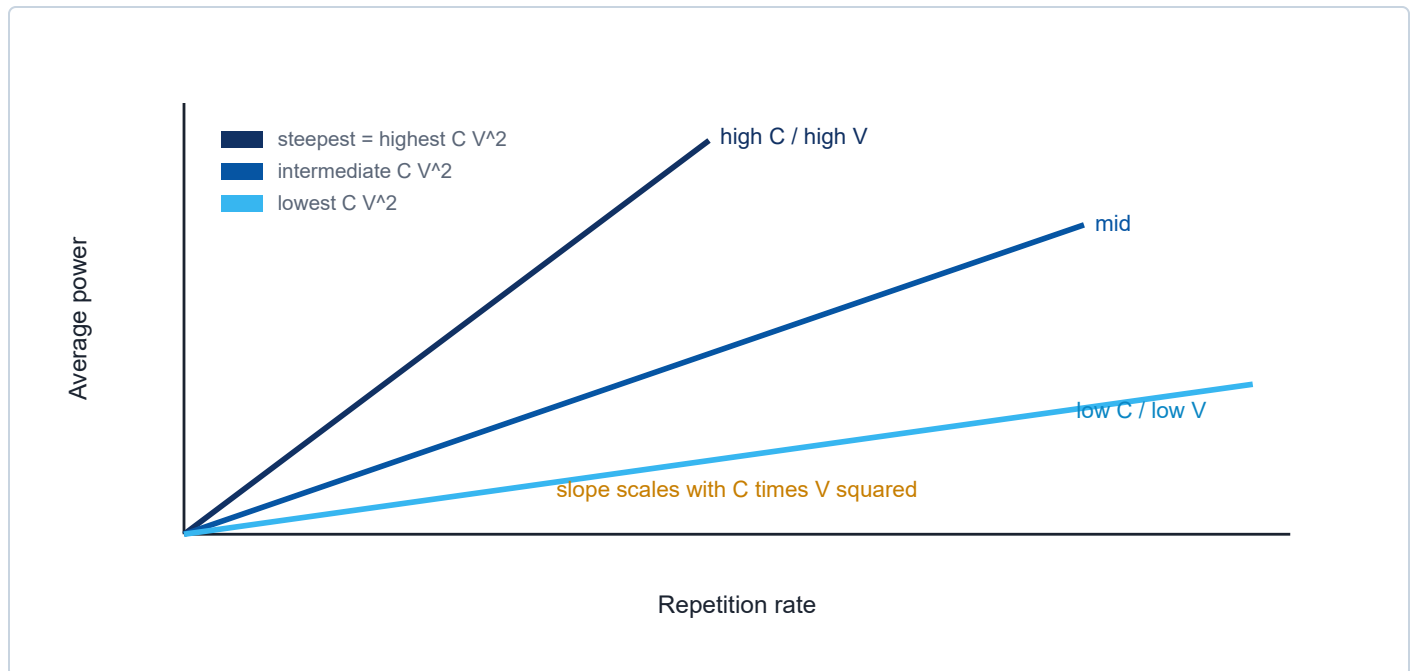
The driver is not the only thing between the source and the load. The output resistance of the generator, plus the series resistance of the cable and any source-termination resistor, forms an RC time constant with the load capacitance. That time constant, $\tau = R \times C$, rounds the corners of the edge no matter how hard the driver pushes. An ideal step filtered through an RC network arrives as an exponential, with a ten-to-ninety-percent rise time on the order of $2.2 \times R \times C$.

Cabling makes this worse in two ways. Every length of coax adds its own capacitance in parallel with the load, on the order of tens of picofarads per foot, so a long run can rival the device you are trying to drive. That added capacitance then combines with the series resistance to lengthen τ . The guidance is direct: keep the load close, keep the leads short, and treat the cable capacitance as part of the load you must charge. A clean fast edge at the generator output can still arrive soft at the device if the path between them is long.

5 The Average-Power Budget

Peak current sets whether you can make the edge. Average power sets whether you can sustain it. Each time the load is charged from zero to V , it stores $E = (1/2) C V^2$, and charging it from a fixed supply through any resistance dissipates another $(1/2) C V^2$ in that resistance. On the falling edge the stored energy is dissipated as the load discharges. One full charge plus discharge therefore dissipates $C V^2$ per cycle, independent of the resistance values in the path.

Run that cycle at a repetition rate f and the average power is $P = C V^2 f$. This is the formula the PVX datasheets use for power dissipation into a capacitive load, with C the sum of the load, the cable, and the pulser's internal capacitance (about 120 pF on the PVX-4141). The split between the driver and any series resistance depends on their resistances; the total does not. Average power scales with capacitance, with the **square** of voltage, and linearly with repetition rate (Figure 2). Double the voltage and the power quadruples. Double the rep rate and it doubles. This is why a pulser comfortable at a low rep rate reaches its thermal limit when the rate rises, even though nothing about the single-pulse shape has changed.



SCHEMATIC Figure 2. Average power rises linearly with repetition rate, and the slope of each line is C times V squared. A higher-capacitance or higher-voltage load (navy) reaches a given power budget at a far lower rep rate than a light load (sky).

6 Overshoot, Ringing, and Damping

Real wiring has inductance. The load capacitance combines with the inductance of the leads and the internal current path to form an LC resonant circuit, and an underdamped LC circuit overshoots and rings when you hit it with a fast edge. The faster the edge, the more energy you dump into that resonance, so the speed you want for performance is the speed that excites the ringing.

The control is damping. A small series resistance, sized against the LC, brings the response toward critical damping and trades a little edge speed for a clean settle with controlled overshoot. For a series RLC, critical damping occurs at $R = 2 \sqrt{L / C}$: 100 nH of lead inductance into 100 pF gives $2 \sqrt{1000} \approx 63$ ohms. Too little resistance leaves the output ringing past the device's safe limits. Too much softens the edge through the RC effect of the previous section. The value is set by the lead inductance and the load capacitance together, not either alone.

7 The Half-Bridge Totem-Pole Advantage

A capacitor has to be charged on the rising edge and actively discharged on the falling edge. A simple driver that switches the load high and then relies on a passive pull-down resistor to bring it low will charge fast but fall slowly, because the resistor can only sink the current the RC time constant allows. The falling edge ends up far softer than the rising edge, and the asymmetry shows up directly in the optical or beam response.

A half-bridge totem-pole arrangement solves this with two switches, an upper device and a lower device. The upper switch actively sources current to charge the load on the rising edge. The lower switch actively sinks current to discharge it on the falling edge. Both edges are driven into the capacitance instead of one being driven and the other left to coast. The result is symmetric rise and fall times and a falling edge as fast as the rising edge: the PVX datasheets specify one rise-and-fall figure for both edges (25 ns or less on the PVX-4141). For Pockels-cell switching and other loads where the falling edge closes the event, that active sink sets the speed of the closing edge.

8 A Worked Numeric Example

The numbers below are a worked example, chosen to show the arithmetic. They are not a product specification. Suppose you drive a 100 pF load, a Pockels cell plus its cable, from 0 to 2000 V, and you want the edge to complete in 50 ns.

Slew rate. The voltage changes by 2000 V in 50 ns. So $dV/dt = 2000 \text{ V} / 50 \text{ ns} = 4 \times 10^{10} \text{ V/s}$, which is 40 V/ns. That is the rate the output has to move during the edge.

Peak current. Apply the governing equation. $I = C \times dV/dt = 100\text{e-}12 \text{ F} \times 4\text{e}10 \text{ V/s} = 4 \text{ A}$. For a linear 50 ns ramp into 100 pF at 2000 V the driver sources 4 amperes throughout the edge; an S-shaped edge of the same duration peaks higher. If you wanted the edge twice as fast, at 25 ns, you would need 8 amperes, because the current scales directly with the slew rate.

Energy per edge. Each full charge stores $E = (1/2) C V^2 = 0.5 \times 100\text{e-}12 \times 2000^2$. Working it through: 2000 squared is 4e6, times 100e-12 is 4e-4, times one half is 2e-4 joules, which is 0.2 mJ per charge.

Average power. Run that at a 10 kHz repetition rate. The stored energy alone gives $0.2 \text{ mJ} \times 10,000 = 2 \text{ W}$. A full charge and discharge dissipates twice the stored energy, $C V^2 = 0.4 \text{ mJ}$ per cycle, so the dissipation is $C V^2 f = 4 \text{ W}$. Hold the rep rate and double the voltage to 4000 V, and both figures quadruple: 8 W for the stored-energy term and 16 W for the full cycle.

From example to specification

The numbers above are round values chosen to show the arithmetic. For a given model, the datasheet's rise time, reference load, internal capacitance, and maximum average power set the limits: the PVX-4141, for example, is rated at 25 ns or less into 50 pF at 3,500 V, with about 120 pF internal capacitance and 100 W maximum average power.

9 Relationship Summary

The table collects the first-order relations in one place. Read them as scaling laws that tell you which way a number moves when you change the load, the voltage, the speed, or the rep rate. They set the shape of the design problem before any specific model enters the picture.

Table 1.

Quantity	Relation	Note
Peak current	$I = C \, dV/dt$	Scales with capacitance and slew rate; sets the driver demand.

Quantity	Relation	Note
Slew rate	$dV/dt = I_{\text{peak}} / C$	Capped by the driver's peak current into the load capacitance.
Rise time	$t_{\text{rise}} \sim C \Delta V / I_{\text{peak}}$	Longer for bigger swing or bigger C at fixed current.
Energy per edge	$E \sim (1/2) C V^2$	Stored on charge, dissipated on discharge.
Average power	$P \sim C V^2 f$	Scales with C, the square of V, and linearly with rep rate.

Read as first-order

Peak-current and rise-time relations are first-order; exact values depend on waveform and damping. For a switched charge and discharge, $P = C V^2 f$ is the total dissipation; the split between driver and series resistance depends on their resistances. For capacitive-load pulsers in the DEI line, see the PVX-4141 (3,500 V), the PVX-4110 (10,000 V), the PVX-4000-2kV (bipolar, 2,000 V), and the PVM-4210 (dual output, 950 V per channel). For model selection, see Choosing a Pulse Generator, and for the photonics case, Driving Laser Diodes.

10 Talk to an Engineer

The physics on this page narrows the field, but the last step is matching it to your real capacitance, voltage, edge, and duty cycle. That is where a worked budget against a real datasheet replaces the scaling laws. The DEI capacitive-load pulsers, including the PVX-4141, the PVX-4110, and the PVX-4000, span a range of these tradeoffs, and the right choice depends on which term in $I = C \text{ times } dV/dt$ and $P = C V^2 f$ binds.

For help choosing, contact a BNC applications engineer at info@berkeleynucleonics.com or 800-234-7858.

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Technical Note

DEI Pulsers (Directed Energy Division)