

# Characteristics of the Long Duration Pulses in a Shunt Linear Voltage Regulator<sup>☆</sup>

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## Abstract

Shunt linear voltage regulators are still used in situations where other kinds of regulators are not advised. This paper explores a mechanism liable to induce long duration pulses ( $\sim 100 \mu\text{s}$ ) in these devices, which is eventually demonstrated using a pulsed laser facility. Data issued from these tests helps to understand how the electrical network parameters as well as the non-idealities of the devices affect the characteristics of the transients. Finally, this phenomenon is investigated in similar structures with identical purpose.

*Keywords:* Laser tests, long duration pulses, peak detector effect, power electronics, single event transients, shunt voltage regulators

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## 1. Introduction

The family of linear voltage regulators (or simply references, if the device is not designed to provide a high output current) is classically divided into two large subfamilies: Series and shunt regulators. The second family, on which this work focuses, are devices that set an accurate voltage value in a specific node of the circuit working *in parallel* with the load. It is recommended for low power systems, also if the power supply is higher than 40 V, and, finally, is useful when negative, limiting or floating references are required [1]. A typical example is the Zener diode (Fig. 1a). The Zener diode sets the output near its breakdown voltage,  $V_Z$ . Thus, the power supply provides a constant quiescent current,  $I_S \approx \frac{V_{CC} - V_Z}{R_S}$ , independent of the load characteristics. The excess of current,  $I_P = I_S - I_O > 0$ , is drained by the diode. However, in case of needing an accurate value of the output voltage, the simple Zener diode must be discarded in benefit of structures such as that shown in Fig. 1b. In this case, an operational amplifier (op amp) sets the output voltage to  $(1 + k) \cdot V_{REF}$ . Typically,  $V_{REF}$  is the output of a band-gap cell, a Zener diode, etc. Another function of the op amp is biasing the base of a PNP bipolar transistor to drain the excess of current. A PMOS transistor can replace the PNP one [2] as well as an NPN or NMOS transistor [3]. In this case, the op amp inputs must swap their roles to avoid positive feedback.

Voltage regulators have been tested in radiation environments investigating the effects of the accumulated damage or single event effects, as a recent review paper has summarised [4], to be used in harsh environments such as space or accelerators [5, 6, 7]. In particular, shunt linear voltage regulators have been tested in radiation facilities,

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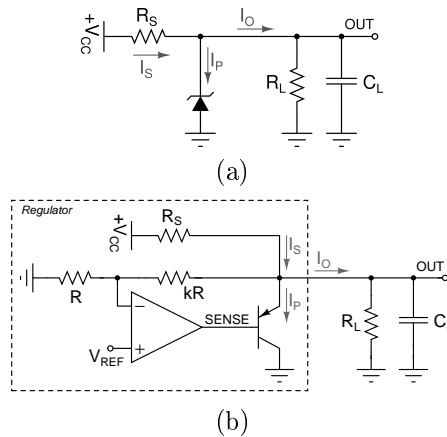


Figure 1: Several kinds of shunt linear voltage regulators: A simple Zener diode (a) and a more accurate version based on an op amp (b).

26 sometimes focusing on total ionizing dose [8, 9, 10, 11], sometimes on the single event transients (SETs) in these  
 27 devices [3, 12, 13]. A recent paper [3] has investigated the characteristics of the SETs in a COTS (Commercial-  
 28 off the shelf) shunt regulator, the LM4050, and successfully associated the transient duration with the dynamical  
 29 parameters. Unlike the *series* linear voltage regulators, the influence of the external configuration devices on the  
 30 transients of *shunt* regulators has not deeply studied. A common practice is to add a bypass capacitor to the output  
 31 of the voltage regulator ( $C_L$  in Fig. 1a-b) with several purposes: removal of high-frequency noise, stabilization of  
 32 the circuits, reservoir of current, etc. Other papers have shown that, contrary to the first impression, this extra  
 33 device can make the transients more dangerous in *series* linear regulators [14, 15]. In shunt regulators, long duration  
 34 pulses (LDPs) might occur due to a similar mechanism: Let us suppose that, due to the impact of an energetic  
 35 heavy ion, a negative transient appears at the output of the op amp, called SENSE in Fig. 1b. As the transistor is  
 36 in common-collector configuration, the output voltage,  $V_O$  tries to follow the evolution of  $V_{SNS}$  so a negative peak  
 37 occurs at the regulator output. Then, the op amp quickly reacts since  $V_- = \frac{V_O(t)}{1+k} < V_+ = V_{REF}$ , quitting the  
 38 linear zone and jumping to positive saturation.

39 If the capacitor were not present, the transient would vanish after a few microseconds since, in its trip to the  
 40 positive saturation state, the output of the op amp grows so much that  $V_- > V_+$ . Negative feedback acts so the  
 41 output voltage starts decreasing and softly returns to the stable DC value. However, the presence of the capacitor,  
 42 which was efficiently discharged by the transistor but can be charged again only by  $I_S$ , freezes the output voltage  
 43 so the op amp eventually reaches the positive saturation state. Then, the transistor stays cut off and the circuit  
 44 behaves like a classical RC network. Fig. 2 shows the expected behaviour of the transients according a SPICE  
 45 simulation and explains why these transients are so long and intrinsically bipolar. Also, characteristic times and  
 46 voltages are defined therein. This transient was simulated injecting 3 pC in a transistor, called Q09, inside the op  
 47 amp gain stage. More details about the simulation can be found in Section 3.

48 This phenomenon is just a modification of the “peak detector effect”, observed in series linear voltage regulators  
 49 and references [14, 15]. Some characteristics of the transients can be easily deduced. First of all, when the pass  
 50 transistor goes to OFF state, the network becomes a typical RC network (From C to E in Fig. 2). Calling

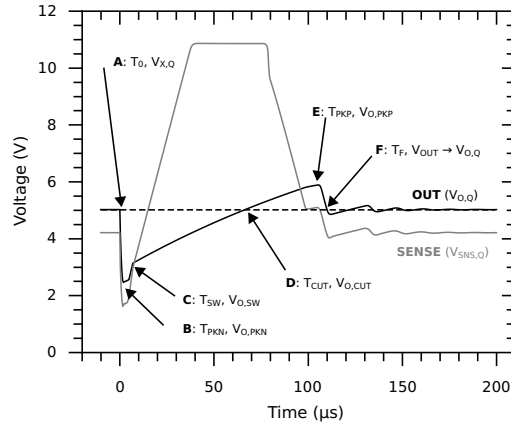


Figure 2: Predicted behaviour of a long duration pulse in shunt voltage regulators. After the transient trigger (A), the OUT & SENSE voltages reaches the minimum (B). However, due to the fact that  $V_+ - V_- > 0$ , the SENSE voltage,  $V_{SNS}$ , goes to the positive saturation voltage switching off the transistor in such a way that the capacitor recovery becomes that of a typical RC network (C). Much later, the output voltage goes beyond the DC value (D),  $V_+ - V_- < 0$  so the op amp returns to the linear zone. Meanwhile, the output voltage goes on increasing and reaches a top peak value (E) before returning to the DC output voltage (F).

51  $V_{O,SW} \equiv V_O(t = T_{SW})$  (C in Fig. 2), the final value would be

$$V_O(t \rightarrow \infty) = V_\infty = \frac{R_L^*}{R_L^* + R_S} \cdot V_{CC}, \quad (1)$$

52  $R_L^*$  being  $R_L / [(1 + k) \cdot R]$ . Then, the temporal evolution is:

$$V_O(t) = V_\infty + [V_{O,SW} - V_\infty] \cdot \exp\left(-\frac{t - T_{SW}}{\tau}\right) \quad (2)$$

53 with

$$\tau = (R_L^* // R_S) \cdot C_L. \quad (3)$$

54 From now on,  $\tau$  will be called “*theoretical discharge time*”. Finally, another interesting characteristic of the transients  
 55 is the size of the negative peak,  $V_{O,PKN}$ . A simple way to determine the parameters that affect the value of this  
 56 parameter is the following. Once the transient starts, the external PNP/PMOS transistor is set on a low-impedance  
 57 state. Let us suppose that the transistor collector/drain current is limited to  $I_{P,MAX}$  due to non-ideal effects such  
 58 as collector/drain resistance, base resistance, high current injection, etc. If the transient reaches its lowest value at  
 59  $t = T_{PKN}$  and provided that the transistor is discharging a capacitor, it is very easy to deduce that

$$|V_{O,PKN} - V_{O,Q}| \approx C_L^{-1} \cdot T_{PKN} \cdot I_{P,MAX} \quad (4)$$

60 In other words, the negative peak transient should be inversely proportional to the capacitor value. A similar  
 61 conclusion, using more sophisticated models, was deduced and experimentally observed in series linear regulators  
 62 [15].

## 63 2. Experimental set-up

64 In order to verify that the hypothetical LDPs actually occur in shunt linear voltage regulators, the network in  
 65 Fig. 1b was built using an LM124A, the behaviour of which is well known, as its core. This amplifier was fed back  
 66 with an 2N2907A PNP transistor and resistors of 100 & 33 kΩ (DC Gain  $\approx 4$ ). The rest of parameters were variable

Table 1: Top and bottom values of the circuit parameters.

Parameter	Bottom	Top
$V_{REF}$	0.75 V	1.50 V
$V_O$	3.0 V	6.0 V
$V_{CC}$	10 V	16 V
$R_S$	220 $\Omega$	390 $\Omega$
$R_L$	680 $\Omega$	2.7 k $\Omega$
$C_L$	220 nF	4.7 $\mu$ F

67 (Table 1). In the second round of experiments, the PNP transistor was replaced by a BS250, a silicon DMOS-PFET  
68 for high-speed switching applications. Unlike typical integrated shunt regulators, the op amp was biased by the  
69 power supply and not by its own output. Otherwise, the structure would not have worked.

70 Heavy-ion facilities have been traditionally the place where electronic devices are tested for SET sensitivity.  
71 However, it is widely accepted that a pulsed laser is a good tool to test bipolar technologies since the elements  
72 are much bigger than the typical spot size [16]. The possible LDPs associated with the shunt voltage regulators  
73 were investigated at the UCM laser facility [17]. In this facility, a 60-fs pulsed laser was used to induce SETs in  
74 the op amp. Its wavelength was set to 800 nm (spot size  $\sim 1 \mu\text{m}$ ) and the energy to 60 pJ (absorption coefficient,  
75  $\sim 0.085 \mu\text{m}^{-1}$ , penetration depth,  $\sim 11.8 \mu\text{m}$  [16]). It is interesting to correlate this energy with the equivalent  
76 LET of an ion. In 2000, a work by McMorro [18] calculated that, in many not very integrated technologies and  
77 with single photon absorption, 1 pJ  $\sim 3 \text{ MeV}\cdot\text{mg}\cdot\text{cm}^{-2}$ . This ratio has been confirmed by more recent works [14].  
78 In conclusion, the equivalent laser LET is in the order of 180  $\text{MeV}\cdot\text{mg}\cdot\text{cm}^{-2}$ . This value is not realistic but offers  
79 the chance to obtain repeatable transients on the oscilloscope screen. Let us bear in mind that the main purpose of  
80 the paper is to investigate how external devices affect the characteristics of the transients. Therefore, a repeatable  
81 transient is mandatory to draw any conclusion.

82 The LM124A, in ceramic package, was mechanically decapsulated to reach the internal components. Namely,  
83 the laser was focused on the collector-base junction of a transistor inside the common-collector / common-emitter  
84 gain stage. This 60- $\mu\text{m}$  wide vertical NPN transistor is called Q12 in the manufacturer's datasheet but Q09 in some  
85 scientific works [15, 19, 20, 21]. Transients originating here are sudden negative peaks.

86 The main circuit signals ( $V_{OUT}$ ,  $V_{SNS}$ ,  $V_{CC}$ ) were captured with a Yokogawa DLM6000 oscilloscope triggered  
87 by a logic signal coming from the laser system. These analogue signals were numerically treated with an 11<sup>th</sup>- order  
88 Savitzky-Golay filter to remove quantization and high-frequency noise. Every time that the signals were recorded,  
89 the oscilloscope stored 2500 samples of each, of which  $\sim 250$  were taken before the laser arrival. These subset of  
90 samples were used to compute the mean DC values of those signals,  $V_{O,Q}$ ,  $V_{SNS,Q}$  &  $V_{CC,Q}$ . Besides, the error of  
91 every signal was calculated as the maximum of *a*) the instrumental error of the oscilloscope ( $\pm 20 \text{ mV}$ ) and *b*) 1.98  
92 times the standard deviation of the subsets of 250 samples, (Confidence of 95% in Gaussian distributions). The  
93 error margin of any parameter derived from these signals is calculated from these original values ( $\Delta V_O$ ,  $\Delta V_{SNS}$   
94 &  $\Delta V_{CC}$ ) according to the theory of propagation of uncertainty. Every signal was measured 5 times to verify the  
95 consistence of the measurements.

### 96 3. Simulations in SPICE

97 LDPs were also investigated using SPICE simulations. The LM124A was simulated with a SPICE micromodel  
 98 developed with the following three assumptions: First, the internal topology was that shown in a paper by Savage  
 99 *et al.* [19]; second, the SPICE transistors parameters were obtained from state-of-the-art tables, such as those found  
 100 in [22]; Third, the area of the transistor inside the bias mirrors were scaled to obtain the currents shown by the  
 101 manufacturer in the LM124A datasheet.

102 Transients are emulated using piecewise current sources with a duration in the order of 1 ps, much smaller  
 103 than the device response time. This micromodel has several drawbacks. For instance, there is not any difference  
 104 between vertical and lateral transistors. Besides, as the sizes of the transistors are not those of the actual device,  
 105 the injected charge should not be extrapolated from simulations to actual transients. However, the micromodel is  
 106 accurate enough to predict the way in which the feedback network or loads affect the shape of the SETs. Indeed,  
 107 it has been successfully used by the authors in the study of SETs in structures containing an LM124A [15, 20].

108 Finally, the SPICE engine was the NGSpice v. 25, a GNU fork<sup>1</sup> of the original Berkeley Spice 3f5. Fig. 2, which  
 109 illustrates the LDP parameters, was obtained with this SPICE micromodel.

### 110 4. Results

111 First of all, there was not any significant difference between the behaviour of the PNP and the PMOS versions.  
 112 In both cases, the shape of the *OUT* signal was similar to that Fig. 2. Minor differences are in the shape of *SNS*  
 113 signal without influence on the shape of *OUT* at any rate. Therefore, redundant information is removed and only  
 114 results on the PNP version will be reported unless otherwise noted.

115 The first step in this work is to verify that the expected LDPs do occur. An example is Fig. 3a-c, which were  
 116 registered using a 2N2907A as pass transistor with different values of  $C_L$  and other passive components shown in  
 117 the caption. One can see that the shape of the transients reminds of those predicted in Fig. 2. Inside the graphs,  
 118 the supposed-to-be exponential zone was fitted to a function with a final value of 7.59 V, predicted by Eq. 1 with  
 119 the parameters in the caption of Fig. 3. From these fits, one can extract the value of the experimental characteristic  
 120 time,  $\tau_{EXP}$ , which must be equal to  $\tau$ , obtained from Eq. 3. These procedure was repeated in all of the hundreds of  
 121 measurements recorded at the laser facility. Sometimes, an anomalously large value of error appears due to one of  
 122 these two reasons: First, the spontaneous appearance of oscillations, with an amplitude of 50-150 mV, superposed  
 123 to the DC value (E. g., 3a). Second, the error increases if the exponential zone is too flat (E. g., Fig. 3c). Both  
 124 values of  $\tau$  are compared in Fig. 4 and the results of the linear fit shown in Table 2. Parameters corresponding to  
 125 the linear fit of the 4.7- $\mu$ F capacitor have wide error margins due to the worse quality of the original data, calculated  
 126 from exponential curves like that of 3c. Ideally, the predicted slope in the linear fits is 1 and the only divergence  
 127 should be attributed to the tolerance of the discrete devices. Resistor can be easily measured with the 4-wire  
 128 technique to refine the calculation of  $\tau$  so any remaining divergence must be related to the capacitor. According to  
 129 the manufacturers, the tolerance of these devices is  $\pm 10 - 20\%$ , too small to explain some values of B in Table 2.

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<sup>1</sup><http://ngspice.sourceforge.net/>

Table 2: Results of fitting Fig. 4 to  $\tau_{EXP} = A + B \cdot \tau$ .  $r$  is the Pearson's correlation coefficient.

Sample	A	B	$r^2$
220 nF	$-0.3 \pm 0.3$	$1.04 \pm 0.02$	0.999
470 nF	$-1.9 \pm 0.7$	$0.88 \pm 0.02$	0.999
1.0 $\mu$ F	$-3.4 \pm 1.6$	$0.87 \pm 0.02$	0.999
2.2 $\mu$ F	$-18 \pm 10$	$0.90 \pm 0.02$	0.996
4.7 $\mu$ F	$-18 \pm 34$	$0.69 \pm 0.06$	0.964

Table 3:  $V_{PKN}$  vs.  $V_{O,Q}$  ( $V_{CC} = 12$  V,  $C_L = 1$   $\mu$ F,  $R_S = 389$   $\Omega$ ,  $R_L^* = 672$   $\Omega$ )

$V_{O,Q}$	$V_{O,Q} - V_{PKN}$
$2.94 \pm 0.21$ V	$0.47 \pm 0.29$ V
$3.98 \pm 0.05$ V	$1.24 \pm 0.13$ V
$4.95 \pm 0.07$ V	$1.40 \pm 0.13$ V
$5.94 \pm 0.02$ V	$1.41 \pm 0.04$ V

130 This phenomenon will be discussed in Section 5.1. Now, other characteristics such as the negative & positive peaks  
 131 and the transient duration will be studied.

#### 132 4.1. Negative peak

133 According to Eq. 4, the size of the negative peak,  $|V_{O,PKN} - V_{O,Q}|$  is proportional to  $C_L^{-1}$ . Fig. 5 shows that  
 134 the negative peak of actual transients seem to follow a hyperbolic trend with the exceptions of the 2.2- $\mu$ F and,  
 135 more clearly, the 4.7- $\mu$ F capacitors. Just like the strange behaviour during the discharge interval, this anomaly will  
 136 be explained in the discussion regarding the non-idealities of the capacitor. Another important conclusion to be  
 137 drawn from this graph is that dots corresponding to different combinations of  $R_L$  &  $R_S$  are pretty close to each  
 138 other. Therefore, the dependence of  $V_{O,PKN}$  on these parameters, if any, is negligible compared to that on  $C_L$ .

139 Apart from the capacitor value, the only parameter that the negative peak voltage depends on is the DC output  
 140 voltage. In fact, the negative peak voltage decreases with  $V_{O,Q}$  (Table 3). In the case of the PMOS transistors,  
 141 transients were even absent if  $V_{O,Q} \leq 4.0$  V. However, behind this behaviour there is a very simple reason: The op  
 142 amp output is too close to the negative saturation voltage and has no margin to fall down. Therefore, the capacitor  
 143 cannot be efficiently drained and the negative peak voltage is smaller. A simple reconnection of the op amp negative  
 144 power supply from ground to  $-5$  V makes the transients with  $V_{O,Q} = 3$  V as large as those with  $V_{O,Q} = 6$  V.

#### 145 4.2. Positive peak size

146 A simple way of estimating the size of the positive peak consists in accepting that higher values of  $\frac{dV_O}{dt}$  at  $t = T_D$   
 147 lead to higher values of  $V_{O,PKP}$ . Differentiating Eq. 2 and taking into account that  $V_O(T_D) = V_\infty + [V_{O,SW} - V_\infty] \cdot$   
 148  $\exp\left(\frac{T_D - T_{SW}}{\tau}\right) = V_{O,Q}$ , it is easy to demonstrate that

$$\frac{dV_O}{dt} \Big|_{t=T_D} = \frac{V_\infty - V_{O,Q}}{\tau} \quad (5)$$

149 In other words, positive peaks increase with  $\tau^{-1} = \frac{1}{C_L \cdot (R_S // R_L^*)}$  and  $\frac{R_L^*}{R_L^* + R_S} V_{CC} - V_{O,Q}$ . Fig. 6 demonstrates  
 150 that both parameters affect the size of the positive peak as predicted by this simple approach.

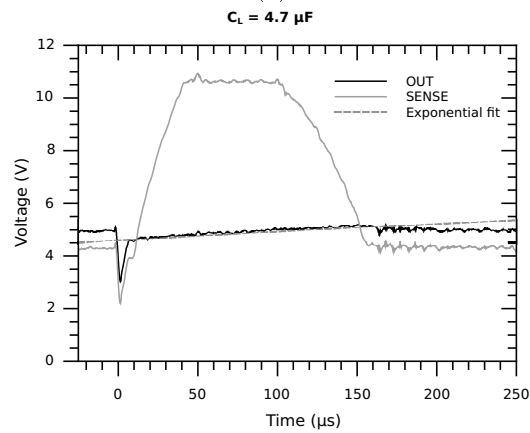
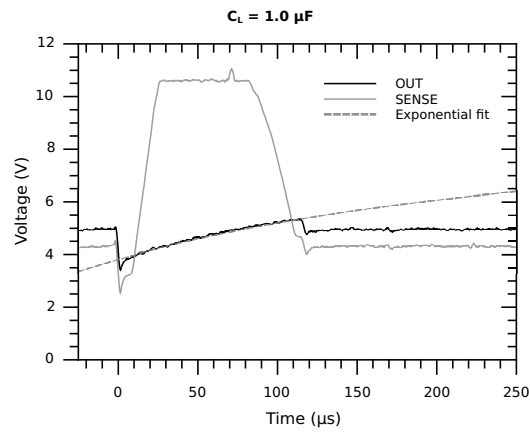
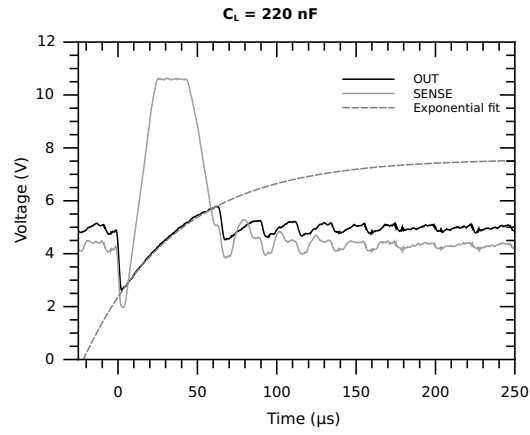


Figure 3: Experimental measurements of long duration pulses with  $V_O = 5 \text{ V}$ ,  $V_{CC} = 12 \text{ V}$ ,  $R_S = 389 \Omega$ , and  $R_L^* = 672 \Omega$ . The dashed line is the exponential fit of the transient while the transistor is cut off.

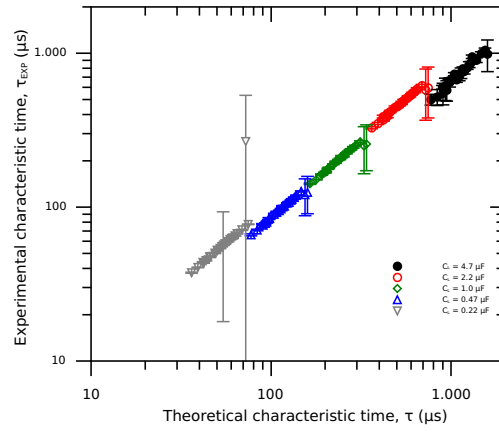


Figure 4: Experimental vs. theoretical values of  $\tau$  obtained from actual measurements. Each color is associated with a capacitor value. Every set of data is obtained varying  $R_L$  &  $R_S$  so there are 25 dots in each set. The largest error bars are related to small oscillations or to very flat exponential stages. Axis are in logarithm format in order to show the whole population of dots so the graph is slightly distorted.

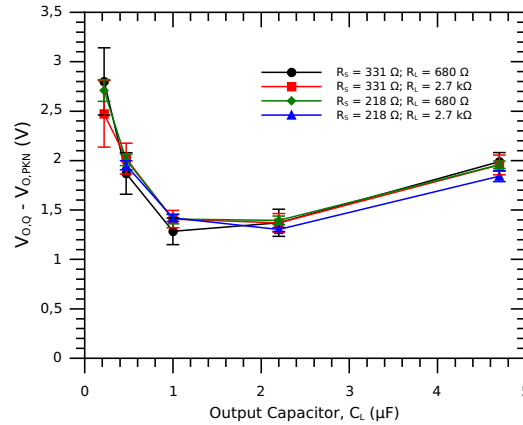
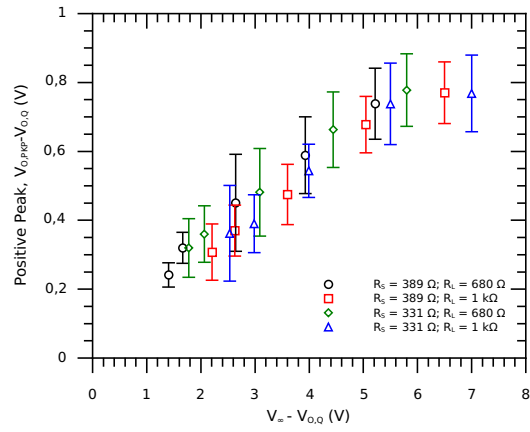
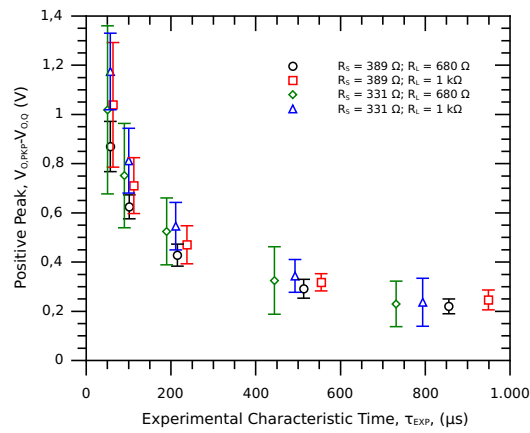


Figure 5: Evolution of the negative peak voltage in proportion to the output capacitor value with different values of network resistors in actual measurements ( $V_{CC} = 12 V$ ,  $V_O = 5 V$ ).





(a)



(b)

Figure 6: Dependence of  $V_{O,PKP}$  on the parameters on the electrical network in actual measurements. In the first graph (a),  $V_O = 5V$ ,  $10V < V_{CC} < 16V$  and  $C_L = 1 \mu F$ . In the second one (b), the experimental characteristic time changes with  $C_L$  and  $R_S$  &  $R_L$  ( $V_O = 5V$ ,  $V_{CC} = 12V$ ).

### 151 4.3. Transient duration

152 The most significant characteristic of the long duration pulses is that they are much longer than other SETs.  
 153 The definition of duration in these transients is difficult. Sometimes, the transient does not fall smoothly to the  
 154 DC value but shows a sort of damped oscillation. Therefore, for the sake of simplicity, the transient duration was  
 155 defined as the first time that the output signal crosses the DC output voltage after the positive peak (**F** in Fig. 2).  
 156 Recorded transients lasted for 40-160  $\mu\text{s}$  and, in general, the duration increases with  $\tau$  (Fig. 3).

## 157 5. Discussion

158 In the previous section, it was demonstrated that long duration pulses can occur in shunt voltage regulators. This  
 159 phenomenon is intrinsically related to the electric topology so it should be expected not only in those regulators  
 160 built with discrete devices but those built in integrated circuits. However, there are some points such as the  
 161 characteristic time anomaly, the strange behaviour of the negative pulse, etc., that must be carefully studied.  
 162 Besides, it is interesting to determine if the LDPs also occur in other topologies of shunt voltage regulators.

### 163 5.1. Non-idealities of the capacitors and pass transistors

164 In the experiments, commercial capacitors were used to investigate the long duration pulses. The smallest  
 165 capacitor (220 nF) was made in polyester and the rest of devices were Al-electrolytic capacitors. These are extremely  
 166 non-linear and dependent on the frequency [23]. Their characteristics were measured with an Agilent 4294A LCR  
 167 impedance meter (Fig. 7) and are very useful to explain the odd characteristic of some transients.

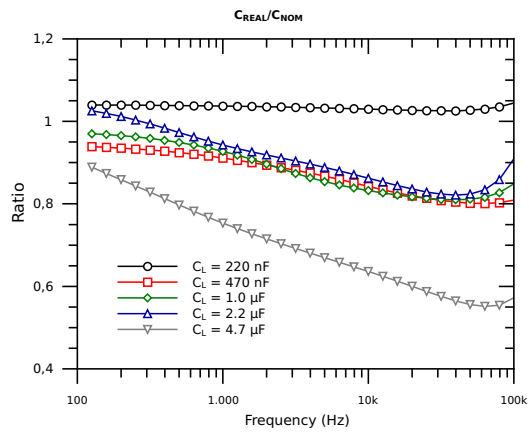
168 First of all, let us remember that the Laplace transform of Eq. 2 is

$$V_O(s) = \frac{V_\infty}{s} + \frac{V_{O,SW} - V_\infty}{s + \tau^{-1}} \quad (6)$$

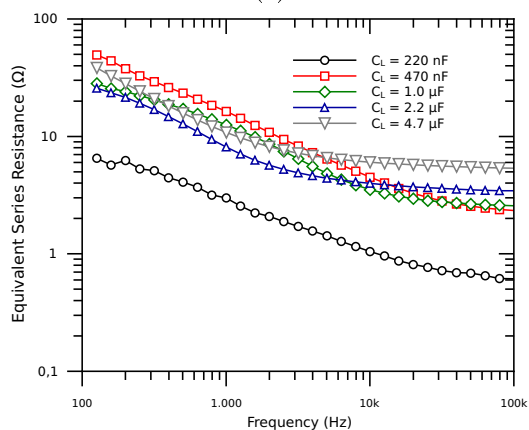
169 An exponential phase factor related to the delay,  $T_{SW}$ , has been removed for the sake of clarity. Eq. 6 offers two  
 170 readings: a) There is a peak at  $s = 0$  that quickly vanishes as  $s \rightarrow \infty$ . b) the frequency spectrum is almost constant  
 171 and not negligible for any component below  $s \sim \tau^{-1}$ . Typically,  $\tau \sim 0.04 - 1$  ms in most of the transients (Fig.  
 172 4) so it is sensible to use the capacitance value on the order of 1-10 kHz instead of using the DC nominal value to  
 173 refine the calculation of  $\tau_{EXP}$ .  $C_L$  values in this frequency range (Fig. 7a) are much closer than the nominal ones  
 174 to those values issued from the experimental discharge time of the RC network (Table 2).

175 In the laboratory, it was determined that the highest collector current of the 2N2907 sample was  $\sim 600$  mA.  
 176 Besides, we observed that, typically, the negative peak was reached  $1.8 \pm 0.7 \mu\text{s}$  after the beginning of the SET.  
 177 Therefore, according to Eq. 4,  $|V_{O,PKN} - V_{O,Q}|$  must be between the hyperbolae  $0.66 \cdot 10^{-6} \cdot C_L^{-1}$  &  $1.5 \cdot 10^{-6} \cdot C_L^{-1}$ .  
 178 In Fig. 5, samples corresponding to  $C_L = 0.22, 0.47$  &  $1.0 \mu\text{F}$  follow this prediction but those related to the larger  
 179 values show peaks much larger than expected. Fig. 7b helps to explain this anomaly. Both capacitors are also  
 180 characterized by having a high ESR value. Recently, Allen *et al.* discovered the influence of the capacitor ESR value  
 181 on the size of the transients in *series* voltage regulators [24]. Basically, the higher value of ESR at high frequency,  
 182 the larger the size of the transients. Therefore, a similar behaviour might be expected in *shunt* voltage regulators.

183 Fig. 8 shows the simulation of the negative transient after injecting 5 pC in Q09 of the LM124-like SPICE  
 184 micromodel. This simulation confirms the previous assumption since, in the inset of the graph, one can see that the



(a)



(b)

Figure 7: Characteristics of the actual capacitors as a function of the work frequency. The normalized capacitance (a) and the equivalent series resistance, ESR (b).

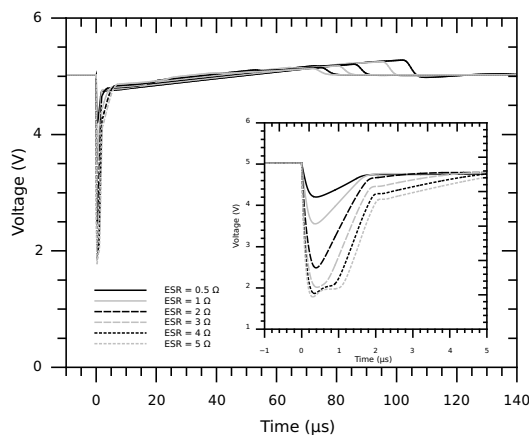


Figure 8: SPICE simulation of the effects of ESR in the shape of the transients ( $C_L = 4.7$   $\mu$ F,  $R_L = 1$  k $\Omega$ ,  $R_S = 220$   $\Omega$ ,  $V_{CC} = 12$  V,  $V_O = 5$  V).

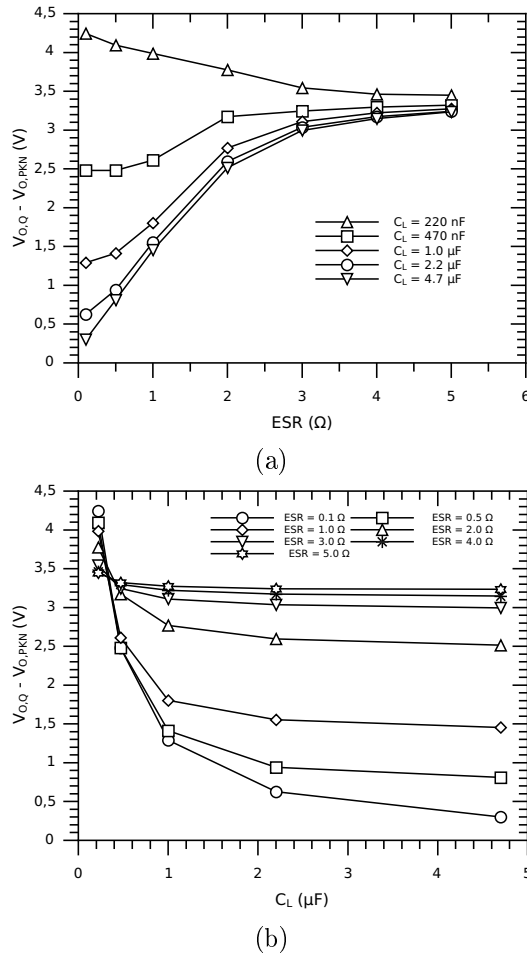


Figure 9: Evolution of the negative peak voltage with the ESR value for different values of  $C_L$  in SPICE simulations (a). In the second graph,  $C_L$  is used as X-variable and ERS as parameter ( $R_L = 1\text{ k}\Omega$ ,  $R_S = 220\ \Omega$ ,  $V_{CC} = 12\text{ V}$ ,  $V_O = 5\text{ V}$ ).

185 peak voltage grows very quickly with the ESR value. This behaviour is summarised in Fig. 9a-b. In the case of the  
 186 largest capacitors, an ESR value in the order of  $5\ \Omega$  makes the voltage several times higher than expected with an  
 187 ideal capacitor. Another conclusion of Fig. 9b is that, for the lowest value of ESR, the values of  $|V_{O,PKN} - V_{O,Q}|$   
 188 are distributed following a hyperbola accounting for the predictions of Eq. 4. Finally, it is important to remark  
 189 that the influence of ESR on  $|V_{O,PKN} - V_{O,Q}|$  is identical to the one reported by Allen *et al.* in *series* voltage  
 190 regulators [24]. In other words, it does not matter if the regulator belongs to the shunt or series families.

191 Besides, an interesting property of the simulated transients can be observed in Fig. 8b: The ESR value has  
 192 influence on  $V_{O,SW}$ . In this simulation, one can realise that the value of  $|V_{O,Q} - V_{O,SW}|$  falls as the ESR value  
 193 increases. However, this is not a general trend since, in other simulation, the behaviour is just the contrary. Further  
 194 work is necessary in this research line since the value of  $V_{O,SW}$  determines the size and duration of the LDP.

195 As the ESR is a parameter that shifts as the capacitor ages [25], these results also make one think that transients  
 196 in voltage regulator designed to work for a long time in radiation environments will change as years go by due to  
 197 the ESR drift.

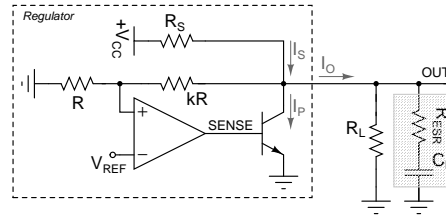


Figure 10: Shunt voltage regulator with an NPN as pass transistor. The parasitic ESR has been added to the output capacitor.

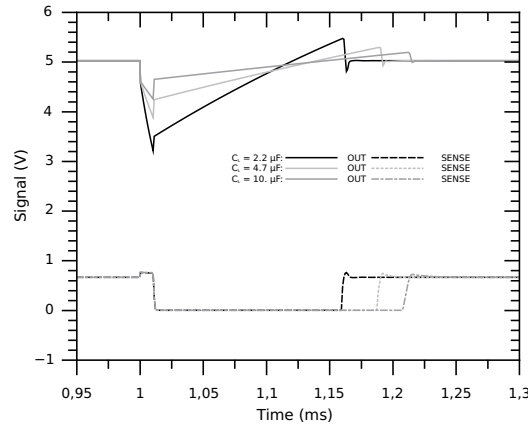


Figure 11: SPICE simulation of the structure of Fig. 10 with an 2N2222A,  $R_L = 1\text{ k}\Omega$ ,  $R_S = 220\ \Omega$ , and different values of the output capacitor. An ESR of  $1\ \Omega$  was added to stabilise the system.

## 198 5.2. Other topologies

199 The structure shown in Fig. 1 is only one of the possible topologies to build shunt voltage regulators. However,  
 200 there are other structures that can be also used to design blocks with similar features. A choice is replacing the  
 201 PNP (PMOS) by an NPN (NMOS) transistor and changing the feedback loop to stabilize the device (Fig. 10).  
 202 Apparently, this topology is sensitive to *positive* peaks at the op amp output, SENSE. A positive peak activates the  
 203 NPN BE-junction leading to a sudden increase of  $I_P$ , which discharges the capacitor. In consequence,  $V_{OUT}$  &  $V_+$   
 204 decrease and the op amp reacts going to negative saturation, cutting off the pass transistor. Thus, the capacitor  
 205 can be charged only with the help of  $I_S$ , just like the structure of Fig. 1.

206 Unfortunately, this structure could not be tested in the laser facility since despite the fact of trying several  
 207 devices, the regulator based on an LM124A was unstable. Fortunately, SPICE simulations were stable and the  
 208 phenomenon could be investigated (Fig. 11). In this case, single events were simulated injecting charge in QR1, an  
 209 open-base NPN transistor working as a resistor in the gain stage of the LM124A [19, 20]. As expected, the LDPs  
 210 occur and the shape and other characteristics of the output voltage are similar to those of the PNP version of the  
 211 shunt voltage regulator.

212 Another point to deal with is the fact that, in integrated circuits, the positive power supply of the op amps is  
 213 usually connected to the regulator output. Thus, the shunt voltage regulator becomes a two-terminal device. Let us  
 214 bear in mind that, in our experiments, the positive power supply was independent of the output of the device. This  
 215 strategy is not unusual and has been explored by other authors [13]. In the structure of Fig. 10, this detail lacks  
 216 importance as the op amp output falls down to the other power supply, ground. In the case of the PNP regulator,

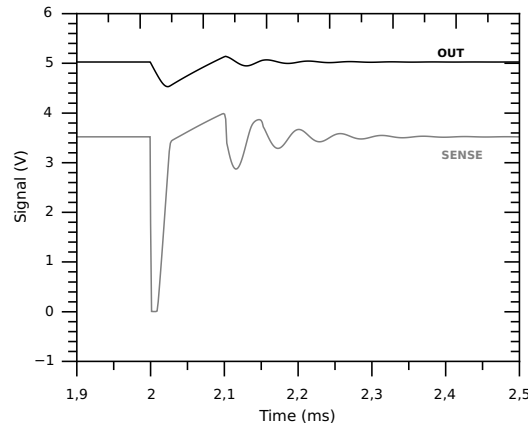


Figure 12: SPICE simulation of the structure of Fig. 1 with a PMOS transistor and the op amp biased by the output itself. Parameters concerning the simulation:  $V_{CC} = 24\text{ V}$ ,  $R_L = 10\text{ k}\Omega$ ,  $R_S = 2.2\text{ k}\Omega$ ,  $C_L = 0.47\text{ }\mu\text{F}$ ,  $ESR = 1\text{ }\Omega$ . The PMOS transistor model, in a 350-nm technology, was downloaded from <http://www.mosis.org> and simulated with  $W = 0.35\text{ }\mu\text{m}$  and  $L = 350\text{ }\mu\text{m}$ .

217 a problem appears: the LM124A is not rail-to-rail so the output voltage cannot be large enough to cut off the PNP  
 218 transistor in Fig. 1. On the contrary, the PMOS solution does not share this drawback and the LM124A can switch  
 219 off the PMOS transistor. Fig. 12 corresponds to a SPICE simulation of the structure, demonstrating that LDPs  
 220 can occur even with the op amp biased by the regulator output. Curiously, simulations show that transients are  
 221 usually longer for this configuration. This is due to the fact that, in many op amps, the frequency response worsens  
 222 as the power supply value decreases [26], slowing down the op amp recovery.

## 223 6. Conclusion

224 In this paper, long duration pulses related to the presence of external output capacitors have been found in shunt  
 225 voltage regulators. These pulses were observed in SPICE simulations and in laser tests and can be expected if the  
 226 regulator is exposed to heavy-ion radiation. In spite of the fact that the experiments were performed in blocks built  
 227 with discrete devices, this family of single event transients is intrinsically related to the topology of the electrical  
 228 network so they can occur in integrated regulators.

229 These transients are always bipolar: A sharp negative spike, the size of which strongly depends not only on the  
 230 value of the output capacitor but also on other parameters such as the equivalent series resistance at high frequency.  
 231 Later, there is a positive peak the size of which is mostly related to the values of the passive discrete devices such  
 232 as the capacitor, load & source resistors, etc. In between, there is an interval during which the capacitor is slowly  
 233 recharged. The duration of this stage depends not only on the values of the network resistors and output capacitor  
 234 but also on the value of the equivalent series resistance of the capacitor, which affects the voltage at which the  
 235 exponential decay starts. In general, the duration of the transient is on the order of 0.1 ms and, more or less, can  
 236 be related to the value of the characteristic time of the circuit,  $\tau$ .

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