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Rise Time and Recovery of GaAs Photoconductive Semiconductor Switches*

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ABSTRACT

Fast rise time applications have encouraged us to look at the rise time dependences of lock-on switching. Our tests have shown rise time and delay effects which decrease dramatically with increasing electric field across the switch and/or optical energy used in activating lock-on. Interest in high repetition rate photoconductive semiconductor switches (PCSS), which require very little trigger energy (our 1.5-cm long switches have been triggered with as little as 20 μJ), has also led us to investigate recovery from lock-on. Several circuits have been used to induce fast recovery, the fastest being 30 ns. The most reliable circuit produced a 4-pulse burst of +/- 10-kV pulses at 7 MHz with 100-μJ trigger energy per pulse.

INTRODUCTION

Experiments with large lateral PCSS for high power, short pulse applications have led to an investigation of some of the characteristics of a high gain switching mode called lock-on. At low fields, the absorbed light (visible to near infra red) used to activate a PCSS is converted to photocurrent with a quantum efficiency of essentially 100%. One electron hole pair is created per each photon absorbed by the semiconductor[1]. At moderately high fields, above 3.5-8.5 kV/cm (depending upon the specific growth process, compensation levels, and contaminates), GaAs exhibits a gain mechanism whereby as many as 1000 electron hole pairs have been produced per absorbed photon. Furthermore, whereas low field carrier recombination causes the PCSS to recover its "off" state resistance in a few nanoseconds after the end of the optical pulse, at high fields the switch "locks on"; i.e., retains its low, "on" state resistance until the field is reduced. Both initiation of switching and the extended low resistance state require either carrier generation and/or longer carrier recombination lifetimes at high fields. Presently, no single physical phenomenon appears to explain all of the data which characterize the lock-on switching mode.[2]

Certainly, a high gain switching mode with an extended on-state is of interest for closing switch applications with low light level triggering. This is the subject of another paper at this conference.[3] Applications for sub-nanosecond rise time high power switching have focused attention to the rise time of the lock-on mode and its dependence on the electric field and optical trigger energy. A close examination of the rise time to lock-on near the electrical and optical thresholds has revealed not only changes in rise time but also a delay between the optical trigger pulse and the initiation of the low resistance "on" state which depends dramatically on electric field and optical trigger energy. These rise time and delay effects are being studied in order to help characterize the lock-on effect and may bear directly on the processes which explain switch recovery. Fast recovery of these switches at low fields, which is important for switching applications at high frequencies (10 MHz), has stimulated the investigation of high field, low light level triggering followed by temporary low field induced recovery.

These two switching characteristics of the lock-on switching mode, rise time and recovery, are the topic of this paper.

LOCK-ON THRESHOLDS

Some of the important differences between linear and lock-on PCSS are illustrated in Figures 1 and 2. In both examples, a 50 Ω transmission line is charged to 19.5 kV and switched with a PCSS through a 38-Ω load. In Figure 1, the switch is triggered below the optical threshold for lock-on at this voltage. The current waveform, 1(a), mimics the laser intensity, 1(b), illustrating linear switching with a light pulse that is long (8 ns) compared to the recombination lifetime of the carriers (1.5 ns). In Figure 2, the optical threshold for lock-on is exceeded and a much higher and longer current pulse is observed, 2(a) and 2(c). The voltage drop across the switch shows no evidence of switching below optical threshold. However, in the lock-on mode, the switch voltage, 2(d), drops to 10 kV (6.7 kV/cm) after some overshoot which is not due to the diagnostics.

In general, lock-on occurs whenever both the optical and electrical thresholds are exceeded. At higher electric fields, less optical intensity is required to trigger lock-on, i.e. the optical threshold decreases. At higher optical intensities, the electric field threshold approaches the "lock-on" field from above. (The lock-on field is defined as the "on" state field sustained by the switch after triggering into lock-on.) These and other characteristics of lock-on have been discussed previously.[4-10]

RISE TIME AND DELAY

Variations in rise time and a small delay to lock-on are evident in the voltage and current waveforms of Figure 3. These examples are for a 3.34-cm long Cr:GaAs PCSS with an 8-kV/cm lock-on field in the circuit described above. The shots were taken just above the optical and electrical thresholds to lock-on. All were optically triggered at the same point in time on the graph. Rise times in this Figure range from 3 to 6 ns and the delays range from 3 to 20 ns.

In these waveforms, linear switching accounts for less than 5% of the initial voltage which implies a switch resistance of greater than 1000 Ω before lock-on. After lock-on, the switch voltage is 60% of the initial voltage which implies a switch resistance of 75 Ω and therefore a carrier gain of greater than 13. The waveforms also show marked oscillations which are often, but not always, characteristic of switching near the thresholds to lock-on. They apparently depend on stray inductance in the switch chamber, structure in the laser pulse, and the recombination lifetime of the switch, but further investigation is needed.

At high optical trigger energies, the rise time of the lock-on current pulse is approximately equal to the width of the optical trigger pulse. Figure 4 shows results of triggering a 1.5-cm long Cr:GaAs PCSS at moderate fields with a 200-ps wide, 20 mJ laser pulse, 4(a). At 12 kV, 4(b), the switch current rises in 200 ps, reaches 150 A, and falls in 1.5 ns due to its characteristics carrier recombination lifetime. At 30 kV, 4(c), the switch current still rises in 200 ps, but now the current reaches 230 A and stays on until the circuit energy is expended.

At very low optical trigger energies, lock-on will not occur until the initial switch field is significantly higher than the lock-on field. Figure 5 is an example where a switch is being triggered at very low light levels and with just enough field to trigger lock-on. Notice the 240-ns delay between optical triggering (at time = 0) and eventual lock-on. Despite this long delay, the rise time in the lock-on pulse is still only 3.6 ns.

Since this switch is in a 50-Ω system, a 10% to 90% rise time in the current means that the switch impedance goes roughly from 450 Ω to 5.5 Ω. If one assumes exponential carrier generation, then this implies an exponential time constant of 3.6/ln(82) = 0.82 ns. In the time between the optical trigger and the lock-on pulse, the resistance of the switch would have decreased by exp(240/0.82) = 8×10^{126}. Clearly, carrier generation is not exponential from the time of triggering to the lock-on pulse. The mechanism which allows the switch to "remember" that it was triggered for several hundred nanoseconds and eventually lock-on in a few nanoseconds remains to be determined.

Figure 6 shows delay times for a 1.5-cm long Cr:GaAs switch being triggered at very low light levels (20 μJ) over a range of moderate to high fields. Above 40 kV, no delay is evident with the 2-ns resolution system which was being used. However, in the range from 19 to 40 kV, delays up to 750 ns were observed. At the lower end of the range, several tests were recorded in which lock-on was not triggered. These tests may represent delay times longer than the charging pulse width (1.5 μs). One of the high field tests is shown in Figure 7. The first part of the current waveform on the most sensitive scale, 7(a), follows the shape of the optical trigger, 7(b), which was produced by a semiconductor laser diode array with a relatively slow rise time. The 10% to 90% rise in current to lock-on, 7(c), is only 2 ns, even though the optical rise time is 21 ns.

A more precise study of the delay between optical triggering and a high gain switching mode in a vertical PCSS is presented by Falk.[11] In his analysis over a range of shorter time delays, the data is fit by assuming a linear dependence on the carrier density in the carrier generation rate (which leads to a term in the rate equation which goes as the square of the carrier density). This leads to "bi-molecular" instead of exponential growth and accommodates the delays recorded with his vertical switch over a range of optical trigger energies. Qualitatively, this type of carrier growth is slower than exponential at low carrier density and approaches exponential growth as the carrier density increases. Such a carrier density dependence may explain the long delays and short rise times for the shots described in Figures 6 and 7. However, a field dependence must also be included to explain the field effect described in Figure 6. Experiments are under way to obtain sufficient data to characterize this dependence.

SWITCH RECOVERY

In order to take advantage of the high gain switching for high repetition rate applications, a way to induce fast recovery following lock-on must be found. Reducing the field across the switch temporarily after triggering it into lock-on should allow normal carrier recombination to dominate if the semiconductor has no "memory" of the lock-on effect. At low fields, our switches recover in a few nanoseconds, Figure 4(b). Three circuits are being explored to test this scheme for inducing fast recovery from lock-on.

The first circuit (Figure 8) uses a transmission line in parallel with the load to reflect a pulse onto the switch and reduce its voltage drop for 20 ns. Recovery was observed when the switch current went to zero before the full voltage returned across the switch. A relatively long voltage pulse is produced at the load because it sees multiple reflections from the transmission line after the PCSS closes. Recovery was always observed provided the optical trigger energy was above 1.5 mJ. Lock-on could be triggered down to 0.5 mJ, but the switch did not recover when it was triggered between 0.5 mJ and 1.5 mJ.

The second circuit (Figure 9) uses a transmission line in series with the load to block the current after it is charged and to force the voltage across the switch to drop. A second PCSS, also operating in the lock-on mode, is used to discharge the transmission line and produce a pulse of the opposite polarity on the load. The fastest recovery observed was 30 ns after a 25-ns wide pulse was provided to the load (producing a 110-ns period for the complete bipolar waveform). Recovery in this time interval did not always occur, so tests were performed with delays out to 75-ns. Although somewhat more reliable operation was achieved at longer times, the improvement was not consistent with the model of exponential carrier recombination at low fields. Perhaps this circuit does not lower the field sufficiently to induce low field recovery, because the lock-on voltage drop still remains across the switch when the transmission line is charged. Alternatively, the lock-on effect may produce some longer-lived carriers which recombine slowly even at low fields. The longest burst of pulses produced using this circuit is shown in Figure 9. After the fourth pulse, the charging switch had not recovered when the discharging switch was triggered. When this happens, both switches form a path to ground which bypasses the load. All of the energy in the circuit is dissipated in the switches, and at fields of interest they are destroyed.

The third circuit (Figure 10) is probably the simplest, but it was not tested immediately because it appears to be the slowest method of inducing recovery. In this circuit, an inductor is used to limit the recharge current until the switch has recovered. If the transmission line is matched to the switch lock-on resistance (voltage dependent) plus the load resistance, all of the energy from the transmission line will be dissipated when the switch is triggered. A sufficiently large inductor will allow the PCSS to recover before the transmission line is recharged. Unfortunately, with a simple inductor, the full voltage is approached gradually late in time. A saturable inductor might improve the circuit, but the fastest approach would be to use several of these circuits in parallel. Each switch could be fired successively after the previous switch has recovered, before the transmission line of the previous switch could be fully recharged. This circuit is under construction and will be tested in the near future. Its maximum rep rate will be limited by the switch recovery time.

CONCLUSION

Data have been presented on the rise time and recovery from a high gain, optically activated switching mode called lock-on. Measurements on the delay between low light level triggering and eventual switching indicate the need for a model with an electric field dependence and more than simple exponential carrier growth. Circuits to test recovery and their results were summarized. More experiments on the initiation of and recovery from lock-on are needed to characterize this process.

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FIGURE CAPTIONS

Figure 1. Linear PCSS switching. The top waveform (a) shows the light intensity used to activate a 1.5-cm long GaAs PCSS. Although the switch voltage was 19 kV, only a few amps was produced in the short current pulse (b) because the optical trigger energy is very weak (less than 300 μJ).

Figure 2. Lock-on switching. Waveforms **a** and **c** show the current produced by a 1.5-cm long GaAs PCSS in lock-on. The most sensitive trace (a) exhibits similar shape to the laser pulse (b) before it goes off scale when lock-on is initiated. The voltage across the switch (d) was initially 19 kV and settled to 8.5 kV during lock-on. This laser pulse (b) was only 1.5 times brighter than the laser pulse in the previous Figure 1(a). However, the current produced in this shot was 100 times greater than the shot shown in Figure 1.

Figure 3. Just above the optical and electrical thresholds to lock-on, these traces show the currents (a) and voltages (b) on four different shots at approximately the same initial voltages and optical trigger energies. In this regime one observes a wide variation in rise times and delays to lock-on.

Figure 4. Short, high energy laser pulses (a) were used in this example to produce linear switching at 12 kV (b) and lock-on (c) switching at 30 kV with a 1.5-cm long Cr:GaAs PCSS. The laser pulse width and current rise times are about 200 ps.

Figure 5. At low light levels, there can be a significant delay between the optical trigger pulse and lock-on switching. Shown here is the current produced by a 3.34-cm long GaAs PCSS when charged to 43 kV. A 500-ps wide laser pulse triggered the switch at time zero. After a 240-ns delay, lock-on occurs with a 3.6-ns rise time.

Figure 6. At very low light levels, lock-on is only initiated at voltages well above the lock-on voltage. This Figure shows the delays between optical triggering and the initiation of lock-on for shots using only 20 μJ of optical trigger energy. Points above the graph represent shots at voltages where lock-on was not initiated.

Figure 7. Switch current is shown for one of the shots from the previous Figure with no delay. The most sensitive trace (a) initially shows a shape similar to the linear current from a previous linear shot (b). The full current is shown in trace c.

Figure 8. Recovery from lock-on using a parallel transmission line circuit. The solid line is the voltage across the PCSS (left axis), and the dotted line is the current through the PCSS (right axis). After being triggered into lock-on at 10 ns, the switch sees a reflection from the transmission line at 35 ns which reduces its voltage below lock-on. Recovery of the switch is demonstrated as its current drops to zero by 50 ns. Late time plateaus in the voltage waveform are produced by the intentional miss-match between the load and the transmission line.

Figure 9. Recovery from lock-on using a series transmission line circuit. A short burst of pulses was produced by this circuit. Both switches are used to charge and discharge the transmission line repetitively at 5 MHz. The top trace shows the voltage produced across the load. The bottom trace shows the recharge current which is passed through PCSS 2. On the fourth repetition, PCSS 1 fails to recover its resistance before PCSS 2 is triggered.

Figure 10. This circuit uses inductively limited recharging current to give the switches some time to recover at low fields. Since inductive recharging slows as it approaches full voltage, the duty cycle of a single charge line and switch would be low. Saturable inductors and/or multiple charge lines and switches will be used to achieve the fastest repetition rate possible.

Figures for

"Rise Time & Recovery of GaAs PCSS"

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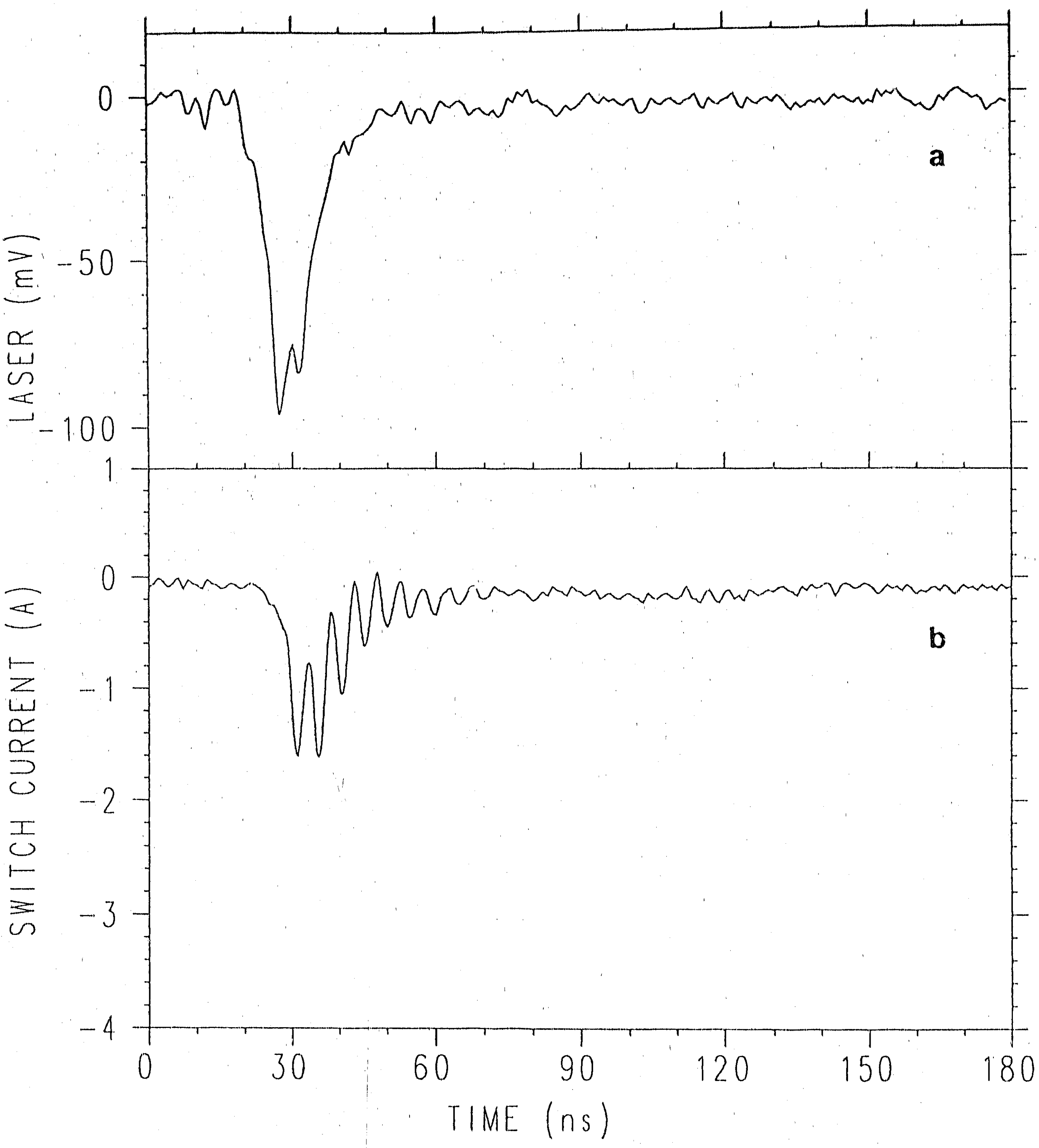


0
-50
-100
1
LASER (mV)
a
0
-1
-2
-3
-4
SWITCH CURRENT (A)
b
0
30
60
90
120
150
180
TIME (ns)

Figure 1.

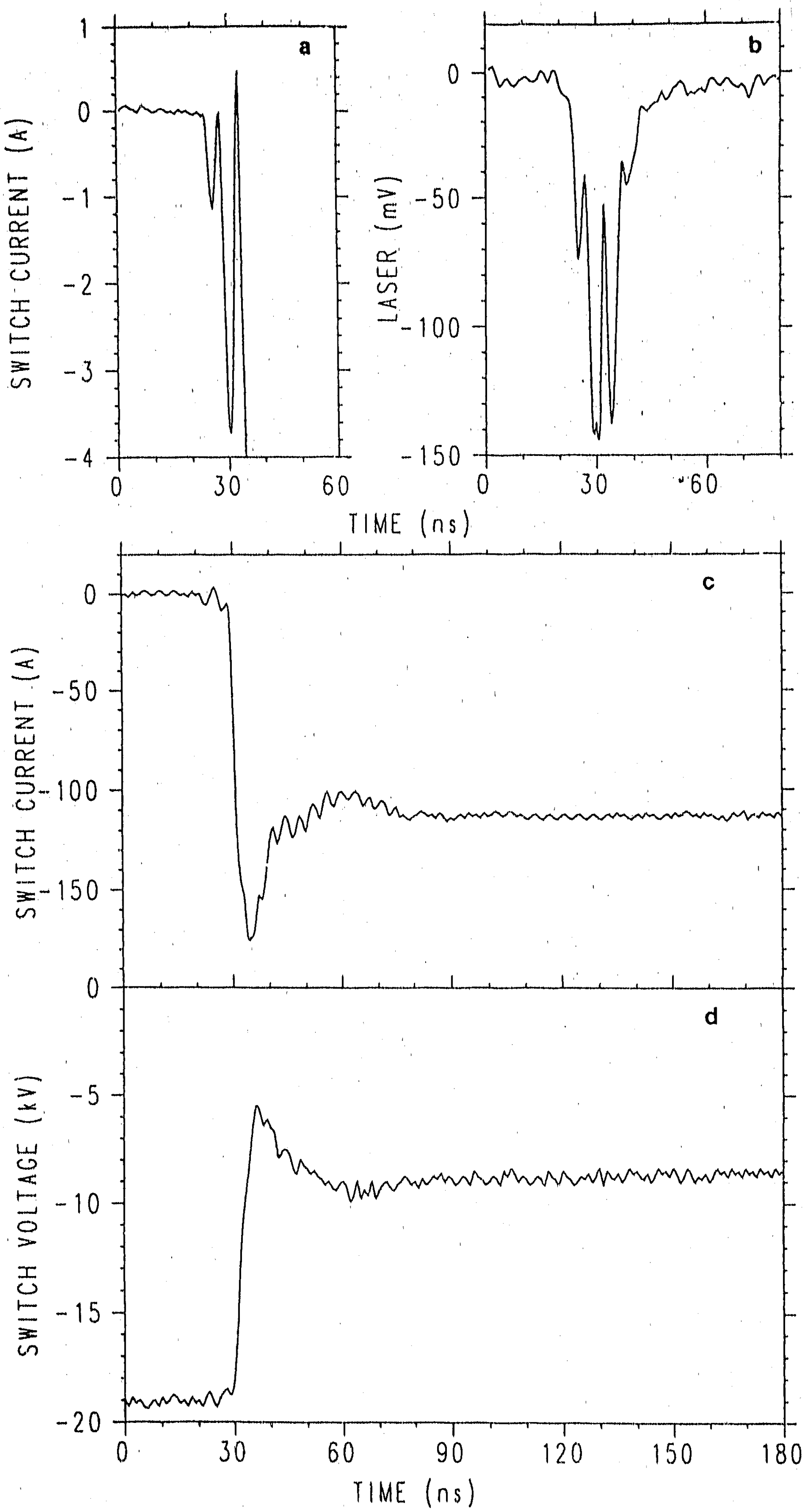
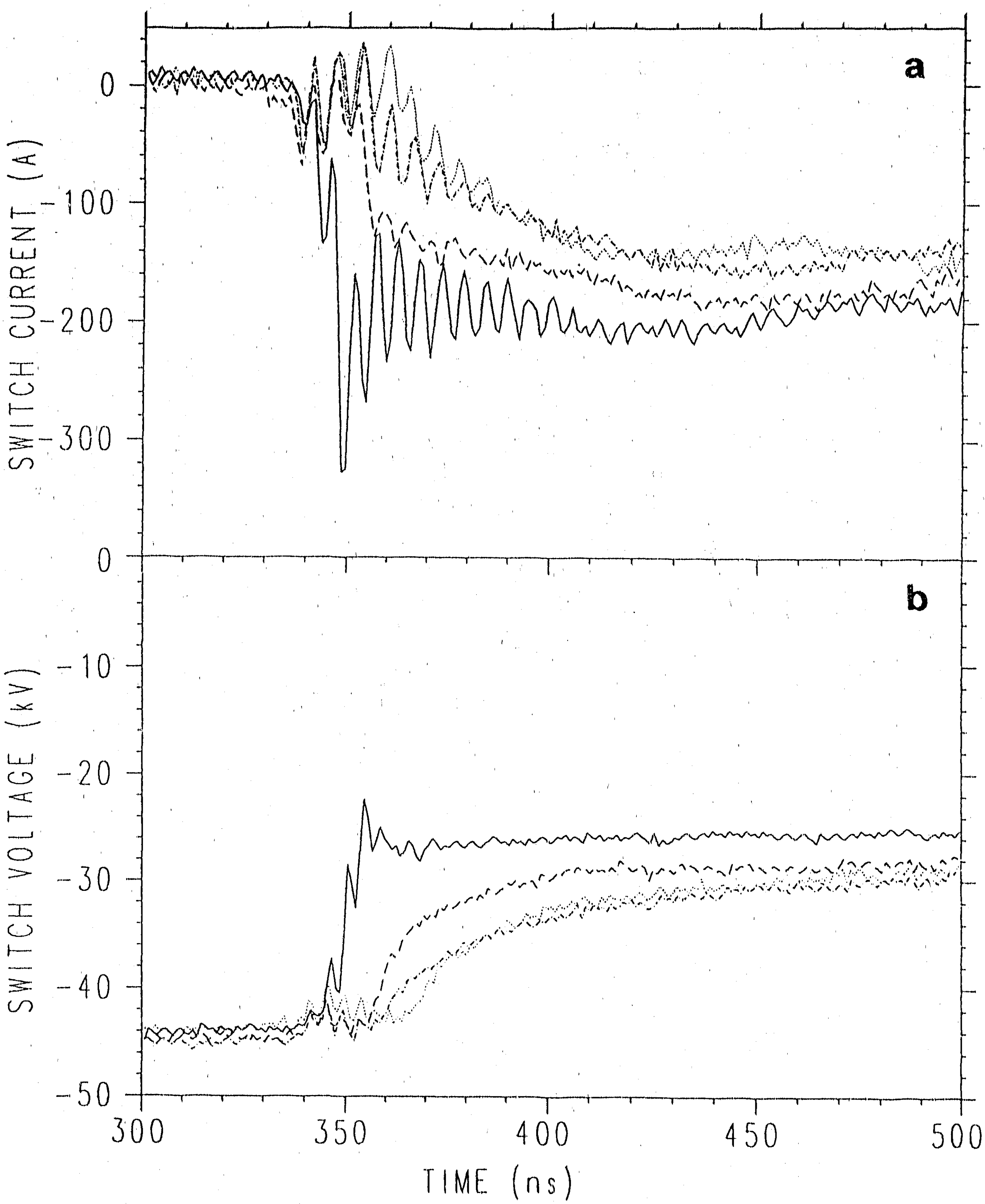

a
b
c
d
SWITCH CURRENT (A)
LASER (mV)
SWITCH CURRENT (A)
SWITCH VOLTAGE (kV)
TIME (ns)
TIME (ns)

Figure 2.


a
b
0
-100
-200
-300
SWITCH CURRENT (A)
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-30
-40
-50
SWITCH VOLTAGE (kV)
300
350
400
450
500
TIME (ns)

Figure 3

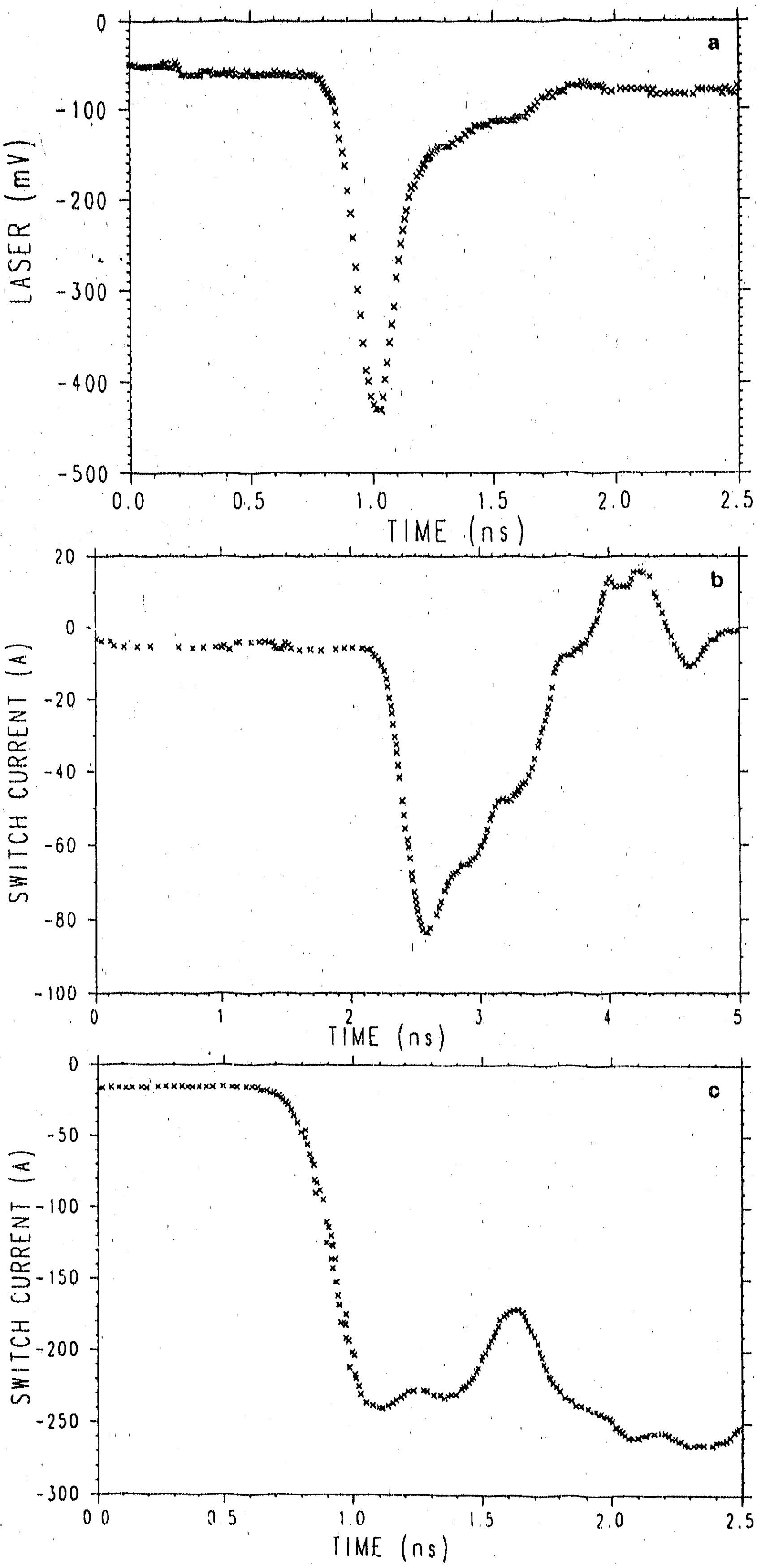
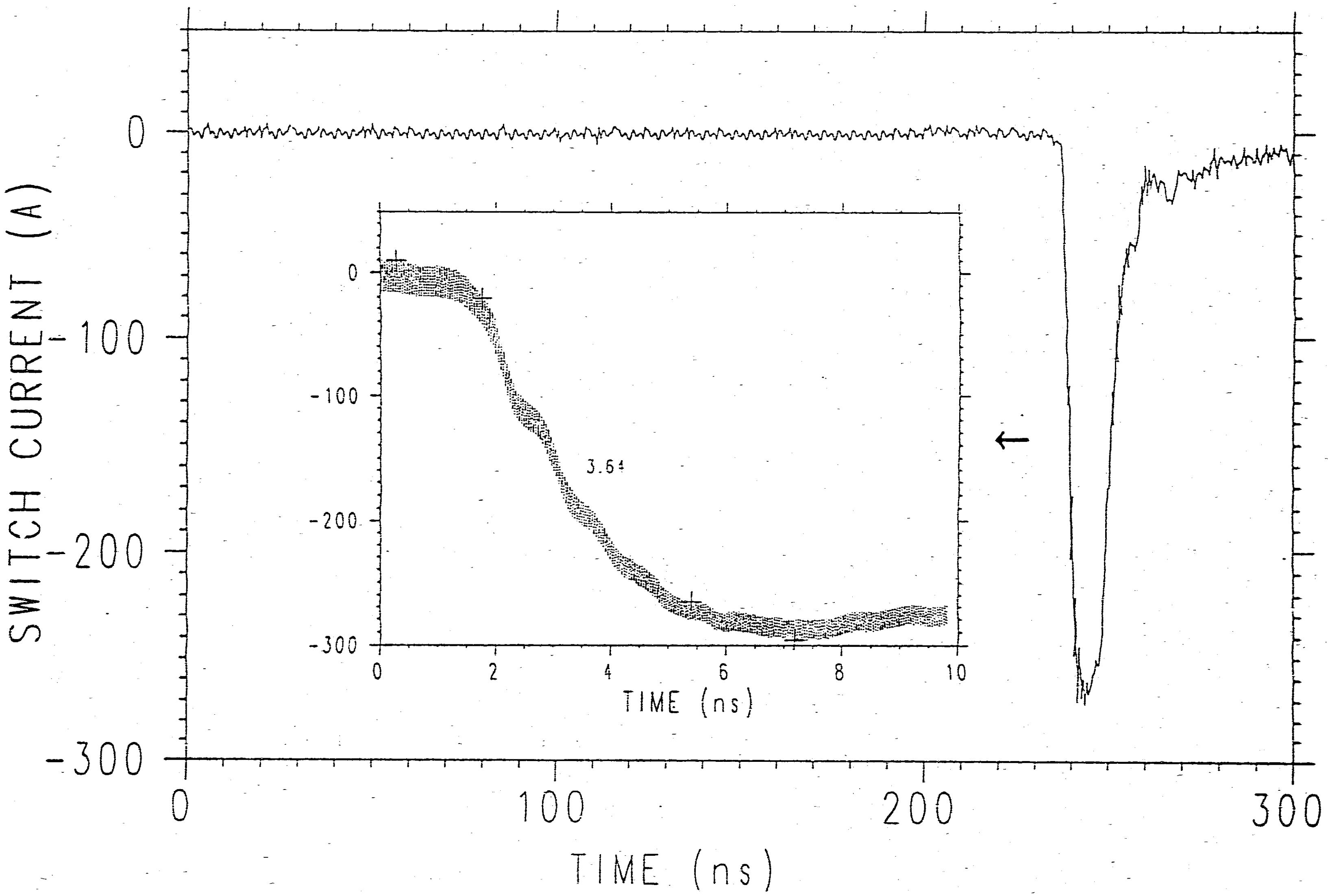

a
LASER (mV)
0
-100
-200
-300
-400
-500
0.0
0.5
1.0
1.5
2.0
2.5
TIME (ns)
b
SWITCH CURRENT (A)
20
0
-20
-40
-60
-80
-100
0
1
2
3
4
5
TIME (ns)
c
SWITCH CURRENT (A)
0
-50
-100
-150
-200
-250
-300
0.0
0.5
1.0
1.5
2.0
2.5
TIME (ns)

Figure 4


SWITCH CURRENT (A)
0
-100
-200
-300
0
100
200
300
TIME (ns)
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-100
-200
-300
0
2
4
6
8
10
TIME (ns)
3.64

Fig. 5

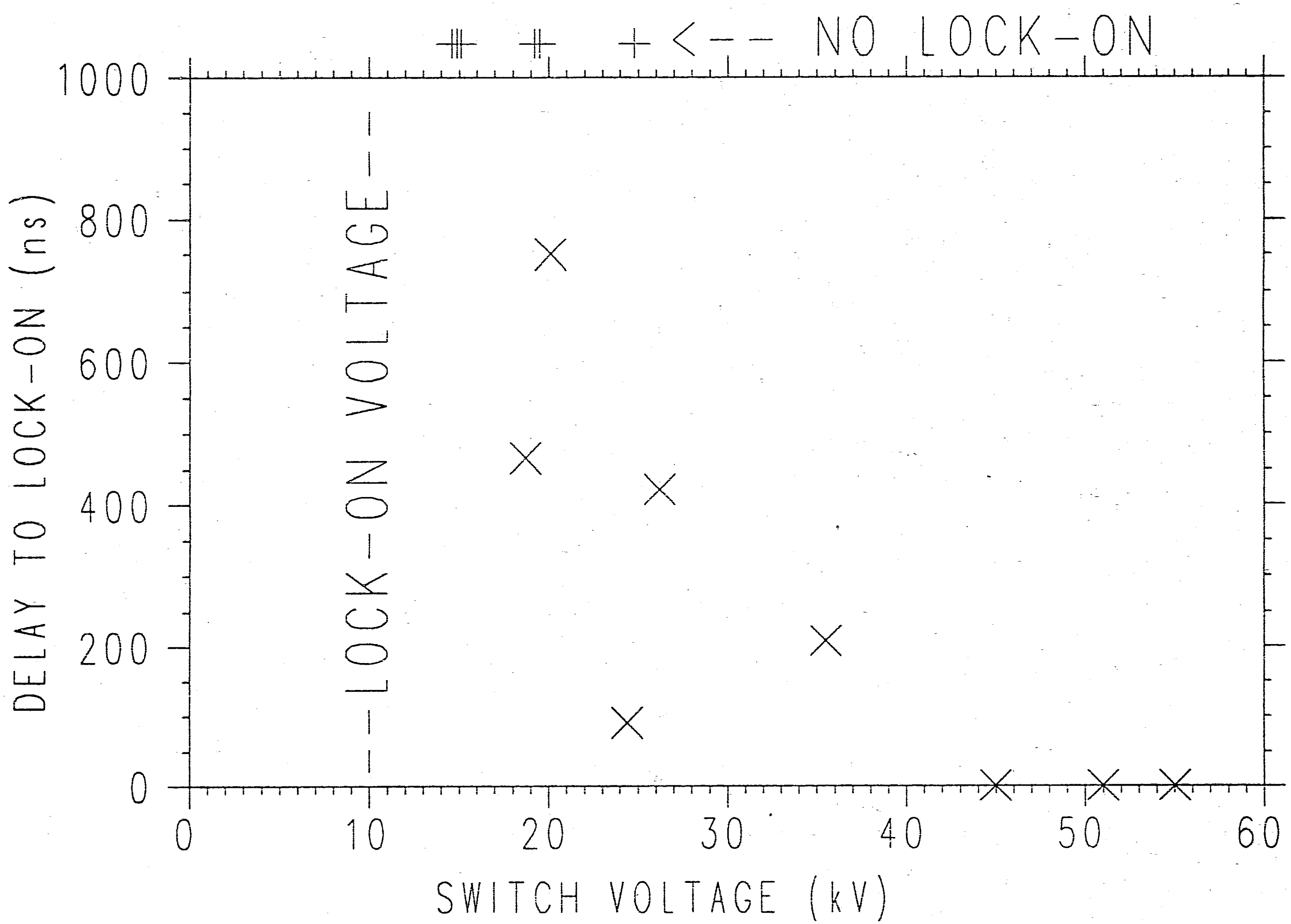
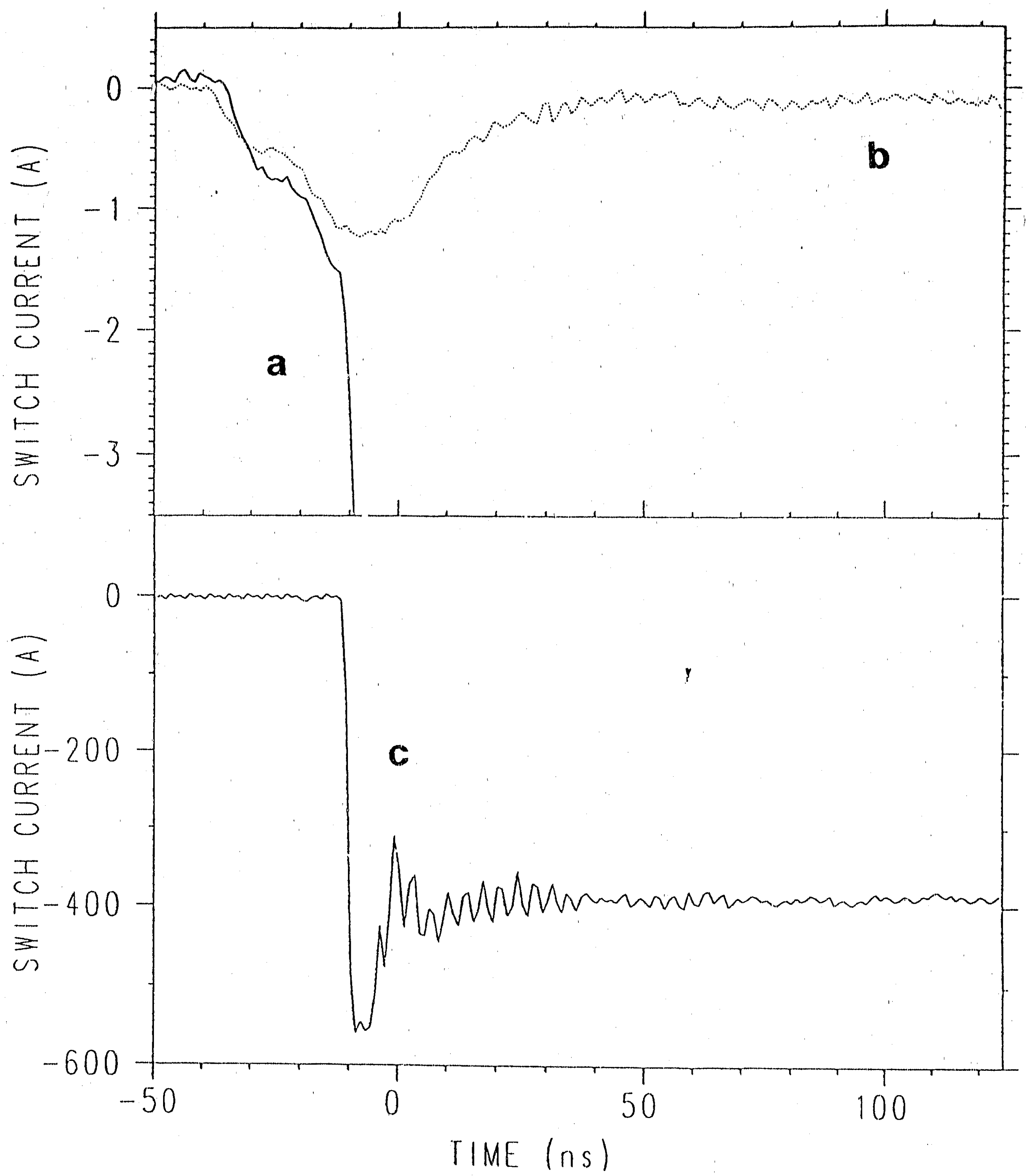

+<-- NO LOCK-ON
LOCK-ON VOLTAGE
DELAY TO LOCK-ON (ns)
1000
800
600
400
200
0
0
10
20
30
40
50
60
SWITCH VOLTAGE (kV)

Fig. 6



SWITCH CURRENT (A)
0
-1
-2
-3
a
b
SWITCH CURRENT (A)
0
-200
-400
-600
c
-50
0
50
100
TIME (ns)

Fig. 7

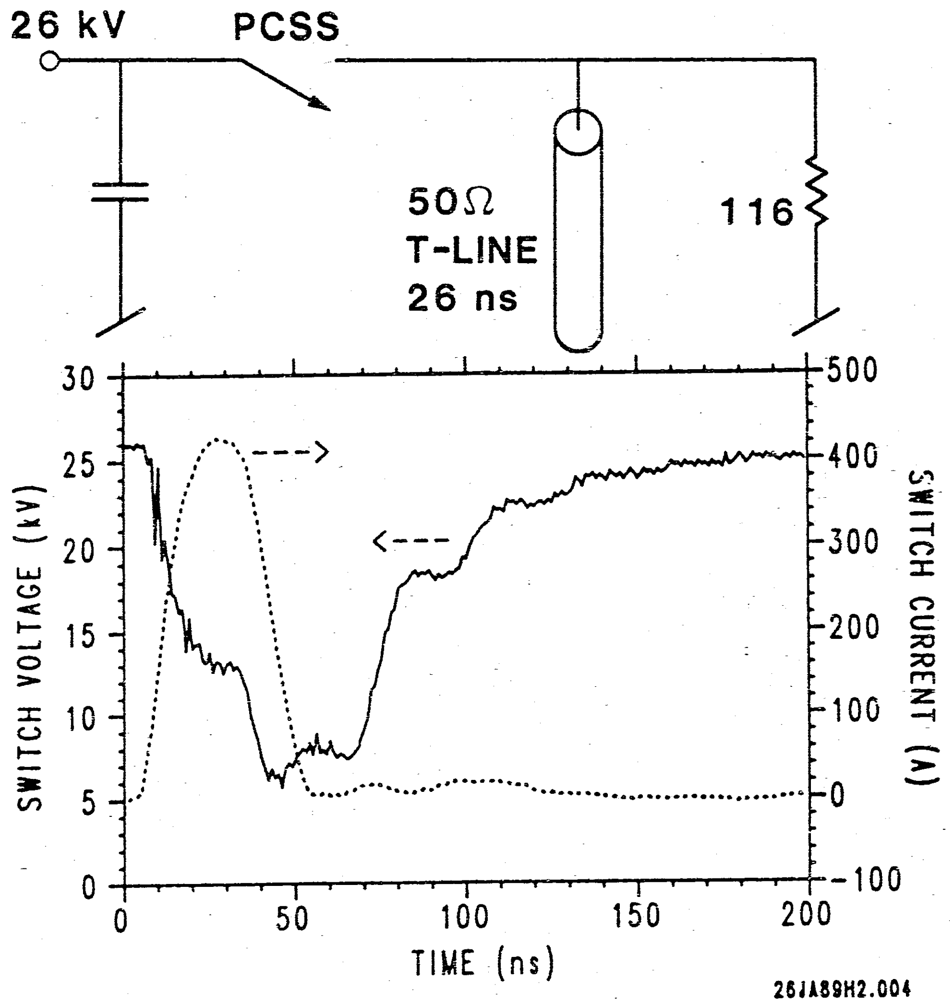

26 kV
PCSS
50Ω
T-LINE
26 ns
116
SWITCH VOLTAGE (kV)
SWITCH CURRENT (A)
TIME (ns)
0
5
10
15
20
25
30
-100
0
100
200
300
400
500
0
50
100
150
200
26JA89H2.004

Figure 8

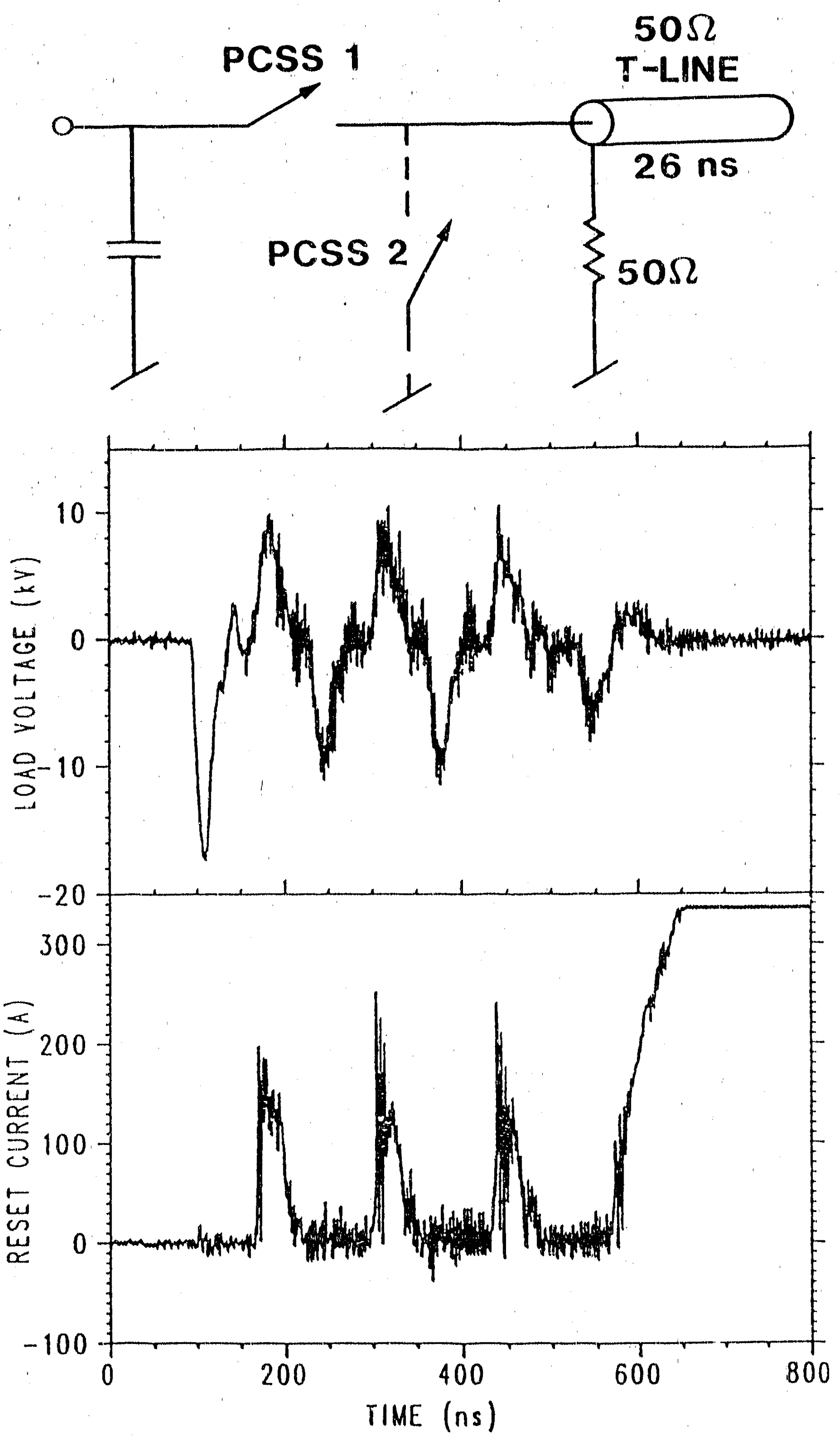

50Ω
T-LINE
PCSS 1
26 ns
PCSS 2
50Ω
LOAD VOLTAGE (kV)
10
0
-10
-20
RESET CURRENT (A)
300
200
100
0
-100
0
200
400
600
800
TIME (ns)

Figure 9

INDUCTIVELY LIMITED RECOVERY

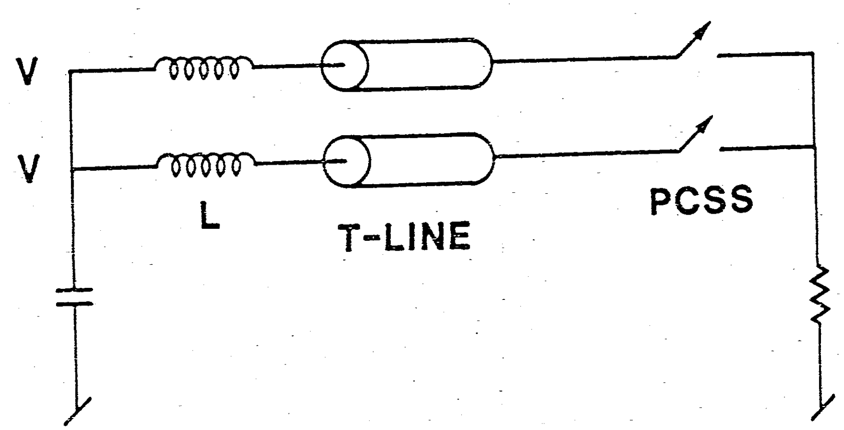


Figure 10

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