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# High Gain GaAs Switches for Impulse Sources; Measurement of the Speed of Current Filaments†

G. M. Loubriel, F. J. Zutavern, M. W. O'Malley, R. R. Gallegos, W. D. Helgeson, H. P. Hjalmarson, A. G. Baca and T. A. Plut

Sandia National Laboratories, MS 1153, Albuquerque, NM 87185-1153, (505) 845-7096

## Abstract

A high peak power impulse pulser that is controlled with high gain, optically triggered GaAs Photoconductive Semiconductor Switches (PCSS) has been constructed and tested. The system has a short 50 Ω line that is charged to 100 kV and discharged through the switch when the switch is triggered with as little as 90 nJ of laser energy. We have demonstrated that the GaAs switches can be used to produce either a monocycle or a monopulse with a period or total duration of about 3 ns. For the monopulse, the voltage switched was above 100 kV, producing a peak power of about 48 MW to the 30 Ω load at a burst repetition rate of 1 kHz. The laser that is used is a small laser diode array whose output is delivered through a fiber to the switch. The current in the system has rise times of 430 ps and a pulse width of 1.4 ns when two laser diode arrays are used to trigger the switch. The small trigger energy and switch jitter are due to a high gain switching mechanism in GaAs. This experiment also shows a relationship between the rise time of the voltage across the switch and the required trigger energy and switch jitter. Because the jitter is small, we can trigger two current filaments simultaneously.

The time evolution of the current filaments in an optically triggered, high gain GaAs switch was studied by recording the infrared photoluminescence from the filaments. When the system is triggered with two laser diode arrays that are activated within 1 ns of each other, two current filaments are observed. By delaying one laser with respect to the other, the evolution of the filament was recorded in a time resolved fashion. The filament that is triggered first crosses the switch, the voltage drops and the other filament ceases to grow. By varying the delay between the trigger lasers, the tip velocity is measured to be up to $5.9 \pm 1 \times 10^9$ cm/s. This speed is 600 times larger than the peak drift velocity of carriers in GaAs. This observation supports switching models that rely on carrier generation at the tip of the filament. The filaments speed up as they cross the switch: for one voltage range initial speeds were $0.7 \pm 1 \times 10^9$ cm/s and final speeds exceed $5.5 \pm 1 \times 10^9$ cm/s.

## Introduction

This research has focused on optically triggered, high gain GaAs switches for high speed, high power electronics and optoelectronics. The practical significance of this high gain switching mode is that the switches can be activated with very low energy optical triggers.[1] For example, this work will show that a 90 nJ optical pulse has triggered switches that have delivered 48 MW in a 30-50 Ω system, and previously we have switched 6 MW for ~100 ns in a 0.25 Ω system.[2] The GaAs switches used in this experiment are lateral switches: they have two contacts on one side of a wafer separated by an insulating region of intrinsic material. At electric fields below 4 kV/cm, the GaAs switches are activated by the creation of, at most, one electron hole pair per photon absorbed. This linear mode demands high laser power, and after the light is extinguished, the carrier density decays in 1- 10 ns. At higher electric fields these switches behave very differently. The high field induces carrier multiplication so that the amount of light required is reduced by as much as five orders of magnitude[1,2]. This high gain mode is characterized by fast current rise times (~200 ps) and filamentary currents with densities of several MA/cm$^2$ and diameters of 15- 300 μm (from the photographs of recombination radiation). In the "on" state there is a characteristic, constant field across the switch called the lock-on field. The switch current is circuit-limited provided the circuit maintains the lock-on field.[2] As the field increases, the switch risetime decreases and the trigger energy is reduced.[2] During high gain switching the switches emit bandgap radiation. When this radiation is imaged, filaments are observed, even if the triggering radiation is uniform.[3,4] Table 1 shows the results from this experiment and the best results that we have achieved (in other work) with the high gain GaAs switches when triggered with either compact laser diode arrays or with flashlamp-pumped lasers. The work of many others has been presented at various conferences.[5]

| | This Exp. | Other* |
|---|---|---|
| Switch Voltage (kV) | 100 | 155 |
| Switch Current (kA) | 1.3 | 5.2 |
| Peak Power (MW) | 48 | 120 |
| Rise time (ps) | 430 | 430 |
| R-M-S jitter (ps) | 150 | 150 |
| Optical Trigger Energy (nJ) | 180 | 90 |
| Repetition Rate (Hz) | 1,000 | 1,000 |
| Electric Field (kV/cm) | 67 | 100 |
| Device Lifetime (No. pulses) | NA | 4,000,000 |

* Not all the results are simultaneous.

Table I. Results of tests with high gain GaAs switches. The first column is this work only, the second column includes results of previous tests.

## Experimental Setup

The circuit that was used in these tests is shown in Figure 1. It operated in bursts of up to 5 pulses at a repetition rate of 1 kHz. We charged a nominally 1.0 ns long, 47 Ω, parallel plate transmission line to voltages of about 100 kV. This line is discharged with either one or two switches into a 30 Ω load. We measured the voltage on the transmission line and the current through the load. A typical transmission line voltage waveform is shown in Figure 2. The voltage on the line, shown at 100 ns/div., rose to a peak value with a charge time of 210 ns. At this point the laser activated the switch and the line voltage dropped. If only one switch was triggered, the resulting load voltage was a monopulse. If both switches were triggered simultaneously the load current was a monocycle (bipolar pulse). The switches were fabricated from undoped GaAs with Ni-Ge-Au-Ni-Au metallization. Their insulating region separating the two contacts was 1.5 cm, the total contact width was 7.6 cm. Because of the high electric fields the switches were immersed in a dielectric liquid (Fluorinert®). To avoid corona and breakdown, the transmission line was in $SF_6$ gas.

For most of the experiment two laser diode arrays were used to trigger the switches. Each consisted of three laser diodes coupled to a 400 μm fiber optic. Each array delivered 90 nJ in 4.2 ns at 876 and 857 nm to a spot near the negative high voltage (100 kV) side of the switch. For other tests, these same laser diode arrays were configured to produce a longer pulse (20 ns) with larger energy (1.8 μJ) and power (90 W).

All the monitors were calibrated. The calibration of the low bandwidth voltage monitor was straightforward. The actual dynamic resistance of the load was measured to be 30 Ω. The peak power is then 48 MW. Using the charge voltage of 100 kV and an estimate of the switch voltage drop of 9 to 6 kV, the peak power is 42 to 45 MW for the 30 Ω load.

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## DISCLAIMER

## Impulse Source

In the first set of tests both laser diode arrays were used to activate one switch and obtain a monopulse. The highest current measured with this system is shown in Figure 3. The width of the current pulse and its peak value depend on the time delay between when the two laser diodes are triggered. When both diodes are triggered to produce simultaneous current pulses, the current is largest and the current pulse width is smallest. The highest current was 1.26 kA with a rise time of 430 ps and a pulse width of 1.4 ns. The peak power is 48 MW. With one laser diode activating one switch the current is about 1.1 kA with a rise time of about 770 ps and a pulse width of 1.8 -1.9 ns.

The difference in current waveforms when we use one laser versus two may be due to two different reasons: a difference in the switch inductance and a the dynamics of the high gain process. Our circuit simulations show that the current risetime for a total inductance of 18 nH would be about 430 ps with a width of 1.3 ns. An inductance of 40 nH results in a rise time of 740 ps with a width of 1.6 ns. Thus it may be possible that one filament with an inductance of 40 nH results in one current waveform and two filaments with about half the inductance create a faster current pulse with a faster rise and smaller width. The problem with this scenario is that the inductance we expect, based on the pictures of the filaments that gave rise to these current waveforms, is much smaller: 4 nH. Thus, other factors contribute to the different waveforms. One possibility is that the gain in one filament may be affected by the presence of the other filament resulting in a faster process: the lower current density in each filament may allow it to create more carriers, especially if there is an upper bound in the carrier density. Another possibility is that both filaments are generating carriers and thus the time required for their combined resistance to drop is reduced by a factor of two.

The second set of tests utilized both laser diodes, each triggering one switch, to produce a monocycle. Figure 4 shows the current waveform. In theory, with ideal switching, the monocycle should be composed of two monopulses of opposite polarity each with half the pulse width. Thus, we expect a monocycle composed of a negative and positive pulses with a width (each) of 0.9 ns. What we observe is a width of 1.0 ns for the negative pulse and 1.3 ns for the positive pulse. The reason for this is a timing error of about 200 ps. The minimum width should occur when both switches are triggered simultaneously. It is very important to trigger both switches at the same time to obtain full voltage and to obtain the proper waveform. In our tests, the switch jitter did not allow us to always reproduce the monocycle.

Low jitter triggering at 90 to 180 nJ of optical energy depends on the rise time of the pulse charging (voltage) waveform. We tested this effect in a experiment where the first to last timing spread was recorded for different voltage rise times (210, 590, and 865 ns) and different laser energies (90 nJ and 1.8 μJ). Neither laser energy triggered the switch with the 865 ns rise time. The 90 nJ did not trigger the switch when the voltage rise time was 590 ns. The 1.8 μJ did trigger the switch when the rise time was 590 ns but only about half the time. The first to last timing spread was 6 ns for one ten pulse sequence and up to 100 ns in others. For the 213 ns rise time both laser energies resulted in timing spreads of < 1 ns. The experiment shows a relationship between the rise time of the voltage across the switch, the required trigger energy, and switch jitter. This is opposite to the switch rise time for linear photoconductivity where the drop in switch resistance is dependent only on the laser pulse and the carrier lifetime. Note that the dielectric relaxation time, $\rho\varepsilon$, is 11.6 μs. Thus, these effects are occurring at times that are much shorter than the relaxation time. It may be possible that the effect that we observe is related to trap filling in the GaAs because trap filling affects the electric field distribution.

## Switch Longevity

Given that the high gain switches are capable of producing this type of current pulses, it is important to understand the mechanisms that damage the switches to be able to predict their longevity. The mechanisms that may result in damage to the PCSS are many. Initiation of the final breakdown appears to come from regions near the contacts which have been significantly damaged during previous pulses.

To test for switch longevity we have performed extensive switch longevity tests using the circuit shown in Figure 5. The pulsed power source charged a 50 Ω coaxial cable to 1.7 or 3.3 kV in 100 ns to 1μs. This was discharged by the switch (1 mm long by 5 mm wide) into a 50 Ω load producing a current pulse of 10.5 or 23 A with a duration of 3.5 ns. The system had a switch voltage monitor and a current viewing resistor. Figure 6 shows representative voltage and current waveforms. To trigger the switches we used a laser diode array with a pulse duration of 40 ns and a total energy of about 1 μJ. Many different metallizations and switch geometries were tested to determine the wear mechanism and the best contact metallization. The switches have lasted up to 4 million pulses under these conditions. This is in contrast to previous tests with a different circuit where similar switches lasted 50,000 pulses. The increase in longevity was accomplished, mainly, by improving the driving circuit: the new circuit eliminates bleed through of current after the line is discharged. Tests were also carried out with a pulse duration of 30 ns (at 1.7 kV charge, 10.5A). These switches were not taken to failure but the switch wear after 100,000 pulses is small indicating that the switches will last for at least five times further. Although these tests were carried out at 100 Hz, another test showed no large increase in switch wear at a repetition rate of 400 Hz. Further tests for longevity are being carried out to understand the effect of pulse duration, contact metallizations, risetime of the charging pulse, laser energy and pulse width, and switch geometry .

## Filament Speed

To measure the propagation velocity of the filaments we set up a system where two filaments could be triggered and imaged.[6] Two laser diode arrays were used to trigger the switch. Each consisted of three laser diodes coupled to a 400 μm fiber optic whose output was a 4.2 ns pulse with 90 nJ of energy at 876 and 857 nm. Current filaments from over 1,000 pulses were recorded on video tapes. In all these pictures the bottom of the picture shows the cathode (high voltage) side of the switch. If one fiber is triggered much earlier than the other, only one filament is observed (Figure 7a). In this case, the filament that is created first crosses the switch prior to the second laser pulse and thus the second laser pulse only shows as a dot. Figures 7b to 7d show that we are able to freeze a filament in transit if the delay between the lasers is varied. The first filament closes the switch and reduces the voltage so that the filament that is triggered later stops growing. We have also carried out this experiment using a mode locked laser to trigger both filaments, varying the delay between the triggers by adjusting the light's (532 nm) path length. In this latter case we have more control on the delay and we were able to investigate a wider range of delays and voltages.

Using the delays in the triggering of the lasers and the lengths of the filaments, it is possible to obtain their velocities. Using the laser diodes for triggers at 100 kV charge we measure $2.0 \pm 1.0 \times 10^9$ cm/s with an uncertainty that depends on our estimate of where the filament ends and the jitter in the system. This velocity is 4 times smaller than the speed of light in GaAs, about 100 times larger than the room temperature peak drift velocity of electrons in GaAs ($2.2 \times 10^7$ cm/s at 3.2 kV/cm), and 200 times larger than the high field saturation velocity ($10^7$ cm/s). The speed of the filaments is not necessarily constant as the filament crosses the insulating region. This measurement is the average speed between 200 -400 ps after the filament starts. The fact that the filament is moving faster than the free carriers in GaAs implies that carriers are being created at or ahead of the filament. We cannot determine if carriers are created by the enhanced field, or recombination radiation from the filament, or if both are required.

Using the mode locked laser we have investigated a voltage range from about 60 kV to 110 kV and we varied the delay in steps of 100 ps. With the increased accuracy we are able to determine that the filaments speed up as they cross the gap. For example, at about 105 kV, the first length we measure is 6.3 mm. Adding delays of 100 ps at a time, the length increases to 7.0 mm, 9.5 mm, and 15.0 mm. This results in speeds of 0.7 cm/ns, 2.5 cm/ns, and >5.5 cm/ns. While the uncertainty in the speed is large (± 1 cm/ns) this acceleration was observed for all the voltages studied. Figure 8 shows this last data although the filament that crosses the gap fully is not shown. The highest speed we measured was 5.9 cm/ns, for voltages of about 115 kV.

Another observation is that the filaments which have partially crossed the switch are dim compared to those that have crossed. These pictures are open shutter pictures and the carrier lifetime is long compared to the filament crossing time or the current pulse duration. The data are consistent with an increase in the carrier density after a filament crosses the switch. Furthermore, we have varied the position of the laser beams. In one particular case the filaments were triggered in the middle of the insulating region and resulted in filaments going both ways towards the contacts. This is shown in figure 9.

The current waveform was monitored as the delay between the filaments was varied. The width of the current pulse and its peak value depend on the delay. With one filament the current is about 1.1 kA and the current pulse width is 1.8 -1.9 ns. With two filaments the current is slightly larger and the current pulse width is smaller. The highest current was 1.26 kA with a width of 1.4 ns. This waveform with the highest current is shown in figure 3 and corresponds to the infrared emission shown in Fig. 10d. The activation delay between the application of the laser pulses and the current rise was not measured. In previous studies, under similar conditions, delays of a few nanoseconds were measured.[2]

Several theoretical models have been proposed to explain high gain switching in GaAs. The only ones that result in fast filament velocities are labeled "streamer" models. They require field enhancement for band to band impact ionization. Carriers are created in the high field at the tip of the filament. In one case[7] the initial enhanced field is assumed and filament propagation is demonstrated giving speeds of 6.6 -11.4 x $10^7$ cm/s for enhanced fields of 371 -421 kV/cm. In the other model[8], creation of a non-uniform distribution of carriers by the Franz-Keldysh effect, field enhancement, and impact ionization lead to filament formation and propagation. This model calculates a filament velocity of 5.2 x $10^8$ cm/s. This model predicts that the filament will originate from the electrode which is not illuminated, in disagreement with our data. Further theoretical work[9] has shown that the filament may originate in the contact that was illuminated provided that the optically created carriers create a significant field enhancement at that contact.

A new model relies on optically-triggered impact ionization to explain filaments and their propagation.[10] Field enhancements do not have a significant role in this model which predicts that filaments propagate as a shock wave with a velocity that can exceed the saturated carrier drift velocity.

## Conclusion

This study has shown that it is possible to obtain high peak power (48 MW) impulses in a system with an impedance of 30- 50 Ω using laser diode triggered PCSS operated in the high gain mode. The system was operated at a burst repetition rate of 1 kHz. The system is very small because laser diode arrays of very small energy output (90 nJ) were utilized to trigger the switches. The ability of the laser diodes to trigger the switches was enhanced by fast (210 ns) charging of the transmission line which the switch discharges. An added benefit of the faster charging was a small switch jitter (150 ps). The small jitter may allow the use of these pulsers in transmitter arrays.

Pictures of the time evolution of current filaments during optically triggered, high gain switching in GaAs were presented. The tip velocity is measured to accelerate from 0.7 cm/ns when it starts to 5.5 cm/ns when it reaches its full length. This speed is much larger than the saturation drift velocity and is close to the speed of light (8 cm/ns) in the GaAs. This result rules out models which assume that filament propagation proceeds at the saturated drift velocity of charged carriers. The experiment also suggests significant current growth after the filament has crossed the insulating region.

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## Figures

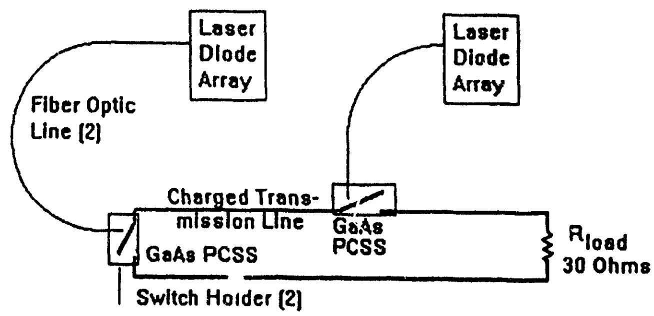


Figure 1. Schematic of the circuit that was used in these experiments. A short (1 ns), 47 Ω transmission line (the charge line) was charged to high voltage at a burst repetition rate of 1 kHz. Two switches were used on either side of the line to discharge the line into a 30 Ω load.

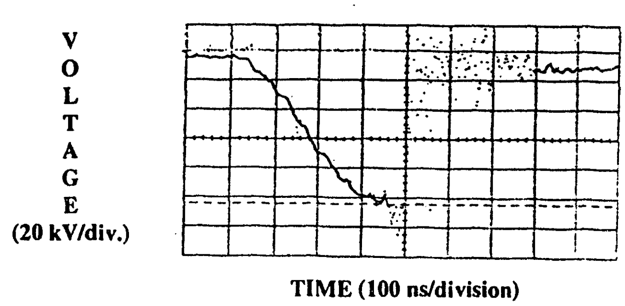


Figure 2. The voltage on the charge line. The waveform is displayed at 20 kV/div. (0 is one division from the top) and at 100 ns/div. The charge time is 210 ns and the peak voltage is 100 kV. When the voltage reaches its peak value of 100 kV the laser diode arrays triggers the switch (at the center of the waveform) discharging the line.

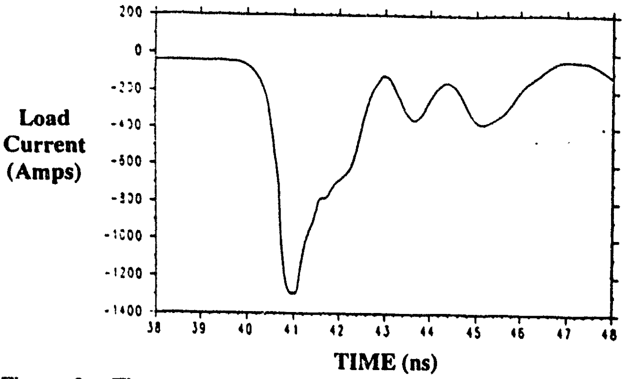


Figure 3. The current through the 30 Ω load when both laser diodes illuminate one switch: 1.26 kA peak (48 MW), 430 ps rise, 1.4 ns wide.

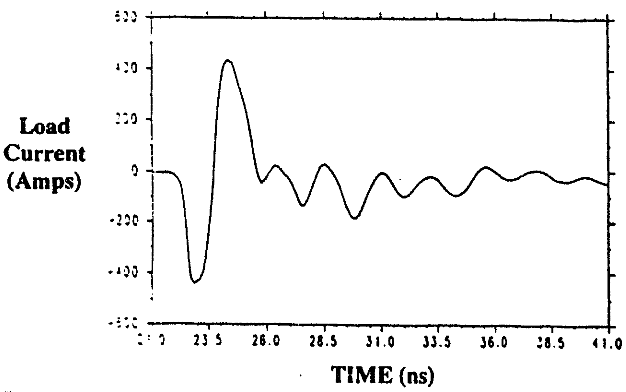


Figure 4. The current through the 30 Ω load when each of the two laser diodes is used to trigger one switch.

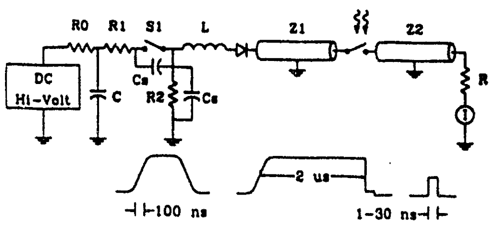


Figure 5. Circuit used for testing the longevity of high gain GaAs switches. With this circuit over 4,000,000 pulses were obtained.

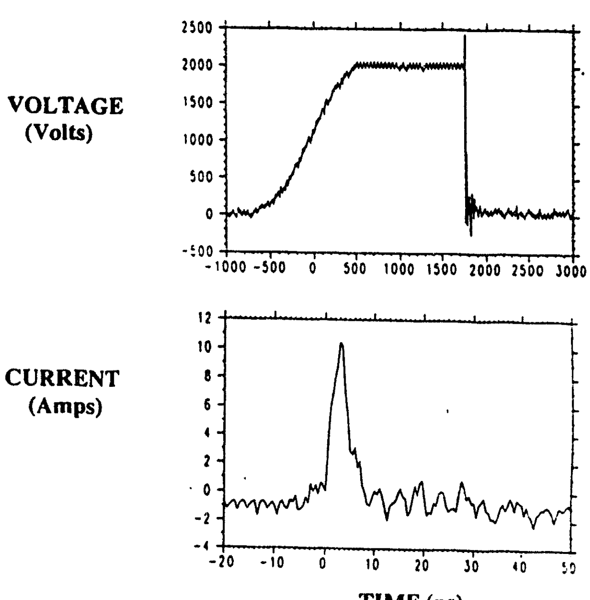


Figure 6. Voltage and current waveforms for testing switch longevity.

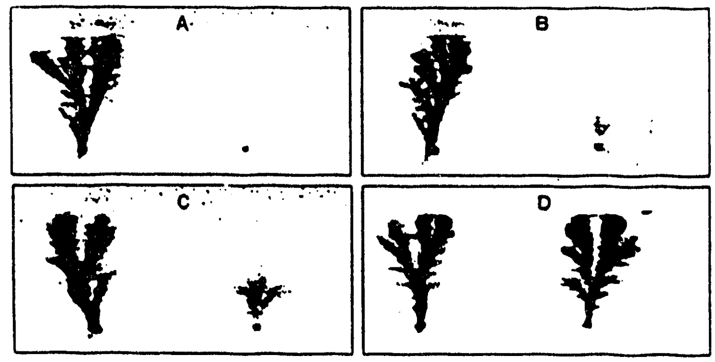


Figure 7. The infrared emission from the filaments (in black). Fig. a shows the emission when the laser on the left is turned on earlier than the laser on the right. Here the filament on the left closes the switch and when the light from the fiber on the right strikes the switch, the voltage is low and there is no filament formation. In Fig. b the delay between the pulses is 200 ps smaller than in a. In Fig. c the delay is 200 ps smaller than in b and the filament on the right is longer. Fig. d shows two filaments that are equally strong. The distance between the contacts is 1.5 cm which is the length of the filaments.

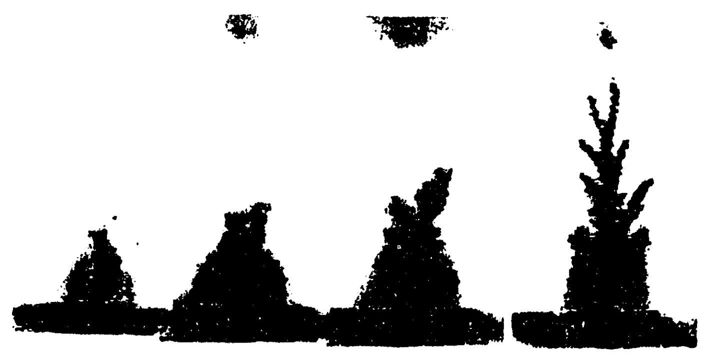

Figure 8. The infrared emission from the filaments with time steps of 100 ps. The delay between the trigger for the first filament (not shown) and that of the second (shown) varies from 600 ps (left) to 300 ps (right). This shows how the filament accelerates as it crosses the insulating region.

Figure 9. In this case the filament on the right was triggered in the middle of the gap. The filament on the left was triggered 600 ps later.

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