Train of ultrashort UV pulses produces plasma channel

Andrey Ionin, Sergey Kudryashov, Aleksey Levchenko, Leonid Seleznev, Aleksey Shutov, Dmitry Sinitsyn, Igor Smetanin, Elena Sunchugasheva, Nikolay Ustinovsky, and Vladimir Zvorykin

Non-self-sustained electric discharge and electric breakdown were triggered and guided by a train of picosecond pulses overlapped with a long free-running pulse at the same frequency.

Plasma channels produced by laser radiation in atmospheric air or certain other gases are of great interest for many fundamental problems and technical applications, such as laser-driven acceleration and guiding of electrons, which may be used for triggering and diverting lightning, and directing microwave radiation to overcome its original divergence. Early experiments with carbon dioxide (CO$_2$) laser pulses of microsecond length showed that the dense plasma produced via avalanche ionization was opaque, and this limited the length and continuity of the channel. In contrast, approaches based on the use of UV or femtosecond laser pulses can produce long-distance partially ionized tracks in air (or other gases) due to multiphoton ionization, either with or without filamentation (thread-like structures) of radiation. Primary photoelectrons quickly recombine with positive ions and attach to molecular oxygen (for about ~10–50ns), and so we expect an additional influence of a longer laser pulse to be sustaining the electron density for much longer.

There are several experimental and theoretical papers in which combinations of single femtosecond and single nanosecond pulses resulted in plasma revival and improved triggering and guiding of electric discharges. However, they have dealt with UV pulses but with near-IR femtosecond and visible or IR nanosecond pulses. Applying a long train of ultrashort UV laser pulses or combining such a train with a long UV pulse seems to be the most attractive for creating and sustaining plasma channels because the quantum energy (~5eV) is far higher and the self-focusing critical power is about two orders lower than for IR pulses. As a result, fewer quanta are needed to ionize the gas, and less power is needed to work in filamentation mode.

Figure 1. Output UV laser pulse (upper traces) and photocurrent response (lower traces) for (a) a sequence of ultra-short pulses (USPs) following with period of 5ns and (b) with period of 17ns, and (c) for free-running lasing (without USPs). Laser pulse signals appear with a ~5ns delay because of a time delay between electronic signals.
We modified a hybrid titanium:sapphire–krypton fluoride (KrF) laser system\textsuperscript{10} that emitted a single subpicosecond terawatt pulse\textsuperscript{11} so that it produced combined ultrashort and long UV laser pulses.\textsuperscript{12} A single UV ultrashort pulse (USP) of 0.5mJ energy and 100fs duration at wavelength $\lambda=248\text{nm}$ or a train of such pulses a tenth of a microsecond long with a period of 5ns was injected into the e-beam pumped KrF laser amplifier equipped with a confocal unstable cavity. This cavity, which has a double-pass time of 17ns, was formed by a rear concave high-reflectivity mirror and a partially transparent convex output mirror. The foci of the concave and convex mirrors were matched. The multi-pass amplification of the injected USP (or injected train of USPs with period of 5ns) in this cavity and free-running lasing of the KrF laser with this cavity meant that the laser system emitted a train of ultrashort picosecond (because of group velocity dispersion in optical windows) UV pulses superimposed over a KrF laser pulse lasting tens of nanoseconds. The output signal period was 17ns for single pulse injection or 5ns for USP train injection. The total energy of the combined laser pulse depended on the reflectivity of the output mirror, and it was varied between 10 and 30J. We estimated the maximum peak power of UV USPs in the train as 0.2TW.

UV radiation was focused by a concave mirror in between ring electrodes situated 20cm from each other and through the high-voltage ring electrode along the inter-electrode gap, where it produced a plasma channel. We applied high voltage between the electrodes. The UV USPs triggered and sustained a non-self-sustained electric discharge, the voltage not being enough for electrical breakdown (a self-sustained discharge) of the inter-electrode gap. Photocurrent signals corresponding to injection of the single USP and USP train together with laser pulses are presented in Figure 1. (It should be noted that the laser pulse signals appear with a $\sim5\text{ns}$ delay because of a time delay between electronic signals.)

The photocurrent signal of Figure 1(a) consists of a sequence of short current pulses of $\sim2\text{ns}$ length following with period of $\sim5\text{ns}$. These short pulses were followed by period of 17ns when a single USP was injected: see Figure 1(b). Comparing laser and current signals in Figure 1(b), one can see that the photocurrent amplitude is close to zero at the start of the free-running UV pulse and sharply increases for the USP. When focusing only the smooth free-running laser pulse with the same energy (under blocked USP injection), the photocurrent amplitude was only around 1% of that obtained for the single ultrashort laser pulse: see Figure 1(c). This difference in photocurrent amplitudes is connected with the nonlinear dependence of air ionization on the laser intensity. For more frequently modulated UV laser pulses, a quasi-steady baseline in the photocurrent response, which increases in time, is more pronounced compared with rarely modulated laser pulses: compare Figure 1(a) and (c). This USP train effect demonstrates how electrons accumulate in the plasma channel.

The ability to form long conductive plasma channels and sustain them over tens of nanoseconds with a train of UV laser pulses gives us an opportunity to efficiently trigger and guide electrical breakdown across a long air gap. We used another scheme to carry out initial experiments on triggering and guiding electric breakdown across a short inter-electrode gap. We focused pulsed UV radiation along the inter-electrode gap between electrodes 10mm in diameter: see Figure 2(a). In this way, we demonstrated that with an applied voltage of 50kV, a free-running UV pulse triggered electric breakdown across an inter-electrode gap 4.0cm in length, with self-sustained discharge starting $\sim5\mu\text{s}$ after the laser pulse and its trajectory independent of the laser beam: see Figure 2(b and d). At the same high voltage and laser output energy, a train of UV USPs combined with

\textit{Figure 2.} (a) Electrodes. (b) Self-sustained discharge triggered by a free-running UV pulse. (c) Self-sustained discharge triggered and guided by a train of UV USPs combined with a long UV pulse. (d) Oscilloscope traces of the self-sustained discharge, 1, and laser pulse, 2, from the discharge shown in (b). Oscilloscope traces of the self-sustained discharge, 1, and laser pulse, 2, and plasma emission, 3, from (c). The breakdown time delay relative to the laser pulse is at least two orders of magnitude shorter than in (d).
a long UV pulse triggered and guided electric breakdown along the laser beam across a distance of 7.0cm with the breakdown time-delay relative to the laser pulse at least two orders of magnitude shorter than in former case: see Figure 2(c and e).

In summary, we demonstrated that a train of UV USPs produced plasma channels of much higher conductivity, triggering a longer electric discharge and guiding it along the laser beam, when compared to free-running long pulse of the same energy and duration. The next step for our research seems to be additional plasma channel heating by long-pulse IR (carbon monoxide or CO₂) laser radiation to increase the electric field/gas density ratio due to plasma expansion.

Author Information

Andrey Ionin, Sergey Kudryashov, Aleksey Levchenko, Leonid Seleznev, Aleksey Shutov, Dmitry Sinitsyn, Igor Smetanin, Elena Sunchugasheva, Nikolay Ustinovsky, and Vladimir Zvorykin
Lebedev Physical Institute of the Russian Academy of Sciences
Moscow, Russia

References