Improvement of the atmospheric discharge laser-triggered ability using multiple pulses from a kilohertz KrF laser

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The potential ability of lasers to control lightning can be improved by using a train of pulses with submillisecond separations. Laser-triggered experiments in a small-scale (10-mm gap) atmospheric discharge facility show that the triggering is dramatically enhanced when a five-pulse train of sub-Joule energy is used instead of a single pulse. This effect increases rapidly as the pulse interval is reduced. It appears that at a submillisecond pulse interval, sufficient positive and negative ions survive in subsequent pulses, thus enabling easy deionization. Hence, significant plasma buildup occurs from one pulse to the next. However, this persistence of ions would appear to imply that the rate of recombination (effectively a charge transfer between ions) is considerably lower than previously believed. © 2005 American Institute of Physics. [DOI: 10.1063/1.2009076]

I. INTRODUCTION

An electric power failure occurring, even for a short duration, under a high demand for electric power can have a major impact on modern society. Since lightning is one of the major causes of accidents in power transmission lines, it is very important to protect electrical equipment from lightning bolts. The advancement of laser technology has led to the construction of a high-energy, high-efficiency laser, which can be employed in lightning diversion techniques. Laser-triggered lightning is an epoch-making protective technique for preventing damage from lightning. This technique is based on the concept that a lightning discharge can be triggered along a conducting path between the clouds and the ground by using a laser beam. The key problem to be resolved for a laser-triggered lightning is to develop a method to create a plasma channel with a length greater than 100 m, a required plasma density of $10^{13}$ cm$^{-3}$, and a lifetime of the order of milliseconds. It was calculated that the plasma density of $10^{13}$ cm$^{-3}$ is progressed to an upward leader from a laser-produced plasma. Hence, it is considered that the triggering ability for lightning discharge is enhanced when the plasma density is $10^{13}$ cm$^{-3}$.

During the 1990s, several researchers were engaged in developing a strongly ionized plasma method utilizing high-energy CO$_2$ lasers. In 1997, a research conducted by Japanese scientists culminated in an encouraging report of lightning triggered in real conditions with kilojoule CO$_2$ lasers. A high plasma density greater than $10^{15}$ cm$^{-3}$ successfully triggered a lightning discharge. The lightning discharge could not be guided sufficiently because of the ionization caused by the optically induced electron avalanche breakdown mechanism; the CO$_2$ lasers produced a discontinuous chain of high-density plasma beads and the plasma lifetime was very short. Moreover, a large amount of laser energy is required to produce a long plasma chain. Hence, a weakly ionized plasma channel produced by an ultraviolet laser has been adopted for the laser-triggered lightning method. Weakly ionized plasma has the advantage of possessing a guiding ability because of its long continuous plasma channel through multiphoton ionization with pulses of relatively low energy delivered by compact systems. However, a triggering ability is not expected to be found because one pulse of an excimer laser has an energy less than 1 J, and the produced plasma has a very low density of $10^{12}$ cm$^{-3}$. To date, almost all excimer lasers were used in single-shot operations and a small laser energy of the order of millijoules was used for the weakly ionized plasma channel method. Thus, it has been very difficult to enhance plasma density of $10^{13}$ cm$^{-3}$.

We have been studying the enhancement of weakly ionized plasma density using an excimer laser with a high repetition rate of the order of kilohertz. Thus far, the accumulation effect of charged particles was confirmed in the case of a laser repetition rate of the order of kilohertz. Therefore, in this study, the effect of triggered discharge was evaluated by utilizing the accumulation effect of charged particles generated by a KrF excimer laser with a high repetition rate of the order of kilohertz.

II. EXPERIMENTAL PROCEDURE

We used a pulsed KrF excimer laser with a maximum repetition rate of 2 kHz. The laser energy of one pulse was 20 mJ and the pulse width was 30 ns. Hence, the laser power was calculated to be 0.67 MW. Spherical electrodes made of stainless steel were set into an acrylic container; the distance between the electrodes was 10 mm. After evacuating the container, dry air was filled at atmospheric pressure. The flow rate of air was maintained at 1 l/min throughout the experiment. The KrF excimer laser beam was focused using a quartz lens with a focal length of 250 mm and injected into the container perpendicular to the axis of the electrodes through a quartz window. The breakdown of the air by the laser produced a plasma channel. A high-voltage negative impulse with a rise time of 10 μs and a half-decay time of
1 ms was applied to the spherical electrodes. The impulse voltage was applied to the electrodes at a delay time varying from a few nanoseconds to a few milliseconds after the KrF excimer laser was irradiated in the container at five pulses ranging from a laser repetition rate of 1–2 kHz. The triggering of a discharge between the electrodes is confirmed by two different methods—natural eye observation and a change of wave form on the oscilloscope. The 50% breakdown voltage for dry air is measured using the up-down methods\(^{12}\) in the case of a 1 ms delay time.

In order to evaluate the trigger effect quantitatively, we measured the particle density produced by a pulsed KrF excimer laser. The experimental setup is shown in Fig. 1. An XeCl-excimer-laser-pumped dye laser is used as the probe light source. The wavelength of the dye laser was set to 565 nm because the cross section of the negative ions of oxygen was saturated at \(6 \times 10^{-18} \text{ cm}^2\) from 350 to 620 nm laser wavelength.\(^{13}\)

The laser energy of one pulse was 5 \(\mu\)J and the pulse width was 5 ns. After evacuating the container, dry air was filled at atmospheric pressure. The flow rate of air was maintained at 1 l/min throughout the experiment. The KrF excimer laser beam was focused using a quartz lens of 2000 mm focal length. The dye laser was injected into the container through a quartz window at a delay time varying from a few nanoseconds to a few milliseconds after the KrF excimer laser was irradiated into the container at five pulses varying from a repetition rate of 1- to 2-kHz laser. A signal before the absorption, \(I_0\), and one after the absorption \(I\) were detected simultaneously by two photodetectors and recorded as two wave forms by the oscilloscope. The density of the charged particles was obtained as follows:

\[
N = \ln(I/I_0)/\sigma Z, \tag{1}
\]

where \(N\) denotes the density of the charged particles, \(I_0\) denotes a signal value before the absorption, \(I\) denotes a signal value after the absorption, \(\sigma\) denotes the photodetachment cross section of the negative ion of oxygen (using the value of \(\sigma=6.0 \times 10^{-18} \text{ cm}^2\) at 565 nm),\(^{13}\) and \(Z\) denotes the length of the laser plasma. The section lengths of the laser beam at the container incident inlet and outlet are calculated to be 20 and 10 mm, respectively, using the values of 5-mrad beam divergence of the KrF excimer laser and 2000 mm focal length of a quartz lens. The effective calibers of the container width was 5 ns. After evacuating the container, dry air was filled at atmospheric pressure. The flow rate of air was maintained at 1 l/min throughout the experiment. The KrF excimer laser was irradiated 30 times.

FIG. 1. Schematic diagram of the experimental setup.

FIG. 2. Reduction rate for different repetition rates in the case of a 1 ms delay time.

are 30 mm; hence, the laser beam was approximately collimated until the 1000-mm lateral value of the container was passed. Therefore, the value of \(Z\) used is 1000 mm. The resolution of the plasma density measured by means of laser absorption is greater than \(10^{13} \text{ cm}^{-3}\) due to the photodetachment cross section of the negative ion of the oxygen (6 \(\times 10^{-18} \text{ cm}^2\)) and the length of the laser plasma (1000 mm).

III. RESULTS

A. Characteristics of triggered discharge

The reduction rate for different repetition rates is shown in Fig. 2. The reduction rate \(V_p\) is defined as follows:

\[
V_p = (V_{SBD} - V_{50\%})/V_{SBD} \times 100,
\]

where \(V_{SBD}\) is the self-breakdown voltage and \(V_{50\%}\) is the 50% breakdown voltage. In this experiment, a \(V_{SBD}\) of 30 kV/cm is maintained between the electrodes. \(V_{50\%}\) is 23, 18, and 15 kV in the case of 1-, 1.5-, and 2-kHz laser repetition rates, respectively. The standard deviation of the breakdown voltage is 0.5 kV when the laser was irradiated 30 times. \(V_p\) drastically increases with a laser repetition rate greater than 1 kHz. The maximum value is 50% in the case of 2 kHz. This value is five times greater than that with a laser repetition rate less than 1 kHz. It is comparable to the reduction rate using an ultrashort laser.\(^{14-17}\) This result confirms that a 1-kHz repetition rate of the laser operation contributes to the enhancement of the triggered discharge.

B. Evaluation of charged particles density

1. The experimental results

The data obtained using the laser absorption and effect of the triggering in the case of a laser repetition rate of 2 kHz is shown in Fig. 3. An error bar is inserted in the data to account for the lateral scattering from produced plasma. The probability of the triggered discharge when the laser is irradiated 30 times at every delay time is calculated. Weakly ionized plasma produced using a KrF excimer laser with a high repetition rate of the order of kilohertz maintains a plasma density of the order of \(10^{13} \text{ cm}^{-3}\) until a few milliseconds after irradiating with the laser. The probability of a triggered discharge is more than 50% when the plasma density has been maintained at a value greater than \(10^{13} \text{ cm}^{-3}\).
However, the probability drastically decreases when the plasma density is less than $10^{13}$ cm$^{-3}$. It is clarified that the effect of triggered discharge is enhanced when the plasma density is greater than $10^{13}$ cm$^{-3}$.

2. The calculation results

The rate equations were calculated to clarify the decay of the plasma. The rate equations are as follows:

$$
\frac{dn_e}{dt} = n_T Z_i - \gamma n_e - \beta n_e n^+ - n_e v_d^{-}/\lambda,
$$

(2)

$$
\frac{dn^+}{dt} = n_T Z_i - R n^+ n^- - \beta n^+ n_e - n^+ v_d^{-}/\lambda,
$$

(3)

$$
\frac{dn^-}{dt} = \gamma n_e - R n^+ n^- - n^- v_d^{-}/\lambda,
$$

(4)

where $n_e$, $n^+$, and $n^-$ denotes the electron, positive-ion, and negative-ion densities, respectively. The constants for air in the equations are obtained from the constants for N$_2$ and O$_2$ by considering the ratio of N$_2$ and O$_2$ (N$_2$: 80%, O$_2$: 20%) in air. The total number density is $n_T = n(N_2) + n(O_2)$. The quantity $\gamma = \alpha_1 n(O_2)^2 + \alpha_2 n(N_2)(O_2)$ denotes the effective attachment constant, which is dependent on the oxygen concentration. $\beta$ denotes the recombination rate between the positive ion and the electron. $R$ denotes the recombination rate between the positive and negative ions. $\lambda$ denotes the scaling length approximately equal to the distance over which the charged particles must drift to be removed from the area under analysis. $v_d^e$, $v_d^+$, and $v_d^-$ represent the drift velocity of the electron, positive ion, and negative ion in an applied electric field, respectively. The quantity $Z_i$ gives the natural background ionization rate. The rate constants for processes leading to the decay of laser-generated plasma in atmospheric air are shown in Table I. The comparison of the measured values in the cases of laser repetition rates of 2 kHz and 1 Hz with the calculated values of the temporal evolution of the density of charged particles are shown in Table I and Fig. 4, respectively. The data for the 1-Hz repetition rate shown in the figure were included in the reference data. The calculated plasma density, consisting of the negative and positive ions, had decreased by approximately four orders of magnitude as a result of the recombination from the initial values at a few milliseconds after irradiating of the laser and the simulation results correspond to the data for the 1-Hz repetition rate. However, the simulation results do not correspond with the data for 2-kHz repetition rate.

<table>
<thead>
<tr>
<th>Process</th>
<th>Rate constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron attachment</td>
<td>$\alpha_1 = 1.34 \times 10^{-30}$ cm$^3$ s$^{-1}$</td>
</tr>
<tr>
<td>Ion-electron recombination</td>
<td>$\beta_1 = 2.99 \times 10^{-7}$ cm$^3$ s$^{-1}$</td>
</tr>
<tr>
<td>Ion-ion recombination</td>
<td>$R_1 = 2.77 \times 10^{-7}$ cm$^3$ s$^{-1}$</td>
</tr>
</tbody>
</table>

The comparison of these results of the improved calculation with the data obtained using laser absorption in the case of a laser repetition rate of 2 kHz is shown in Fig. 5. Hence, the rate equations were calculated using the value $\xi \sim 10^{-13}$ cm$^3$/s instead of the coefficient of the ion-ion recombination $10^{-7}$ cm$^3$/s shown in Table I. The decay process of this plasma channel corresponds approximately with the improved calculation results. It is considered that the rate of ion recombination in air is much lower than those presently used to be $10^{-7}$ cm$^3$/s.

IV. DISCUSSION

The density of a weakly ionized plasma channel is enhanced by one order of magnitude compared with the typical...
density of $10^{12}$ cm$^{-3}$ by utilizing an accumulation effect of charged particles. The mechanism of the accumulation effect is considered to be the following: First, nitrogen molecules or atoms in dry air are ionized by the first laser pulse. The produced electrons attach to oxygen molecules or atoms and produce negative ions of oxygen. The negative ions have a longer lifetime, of the order of milliseconds, than electrons and survive until the next laser pulse is irradiated. Subsequently, photodetachments by the next laser pulse occur according to the following:

$$O_2^- + h\nu \rightarrow O_2 + e,$$

(5)

$$O^- + h\nu \rightarrow O + e,$$

(6)

where $h$ denotes the Planck’s constant and $\nu$ denotes the frequency of laser light. Equations (5) and (6) show the effect of the negative ions of oxygen. The condition $h\nu > e$ is also necessary for the photodetachment, where $e$ is the electron affinity. Here, $e$ of the negative ion of the oxygen molecule and that of the oxygen atom are 0.44 and 1.46 eV, respectively.\textsuperscript{12} The photon energy of the KrF excimer laser ($\lambda=248$ nm) is approximately 5 eV. Therefore, the energy of one photon of the KrF excimer laser can induce the photodetachment of the negative ion of oxygen.

The decay time constant of charged particles by the recombination process $t_r$ was obtained as follows:

$$t_r = 1/\alpha n_i,$$

(7)

where $\alpha$ denotes the coefficient of recombination and $n_i$ denotes the density of charged particles produced by one laser pulse. In this case, $\alpha$ was of the order of $10^{-11}$ cm$^3$/s from the data in Fig. 5. The density of charged particles produced by the KrF excimer laser was estimated to be $n_i > 10^{14}$ cm$^{-3}$.$^{10}$ Hence, the value of $t_r$ was less than 1 ms. Therefore, since the negative ions of oxygen and charged particles remain in the laser-irradiated volume until the next laser pulse, charged particles are supplied by the photodetachment of these negative ions and accumulate with time, leading to the enhancement of the plasma density of $10^{13}$ cm$^{-3}$. Further, the plasma has a long lifetime of the order of milliseconds when the time interval of laser pulses is less than 1 ms at a laser operation repetition rate greater than 1 kHz. It is very important to increase the plasma density in order to enhance the effect of triggered discharge.

V. CONCLUSIONS

The effect of triggered discharge is improved by using a KrF excimer laser with a high repetition rate of the order of kilohertz. The plasma density was achieved to be $10^{13}$ cm$^{-3}$. This led to an effective 50% reduction in the self-breakdown voltage. Hence, an excimer laser with a high repetition rate of the order of kilohertz is achieved with the plasma condition for laser-triggered lightning.

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FIG. 5. Comparison of a measured value in the case of a laser repetition rate of the order of kilohertz with the calculation of the temporal evolution of the density of charged particles.

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