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Pulsed current wave shaping with a transmission line by utilizing superposition of a forward and a backward voltage wave for fast capillary Z-pinch discharge

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By using a water transmission line, current wave shaping was demonstrated for a fast capillary Z-pinch discharge recombination soft x-ray laser study. The pulsed power system consists of a water capacitor, a gap switch, a transmission line, and a capillary plasma load. A voltage wave initiated at the water capacitor propagates toward the capillary load through the transmission line. Control of the pulse delay that occurred in the transmission line provides the superposition of the forward and the backward voltage waves effectively in order to perform current wave shaping with higher current amplitude and rapid current decay. © *2010 American Institute of Physics.*
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I. INTRODUCTION

The Z-pinch plasma has been studied and applied to the wide range of fields. It is utilized as a source of strong radiation field for the investigation of inertial confinement fusion,[1] a light source for high-resolution radiography of biological specimens[2] or extreme ultraviolet lithography,[3] a plasma waveguide for ultrashort pulsed laser,[4] and a capillary discharge soft x-ray laser.[5,6] There is a lot of discharge system using different unique geometries for the generation of the fast discharge current with pulse widths of tens to hundreds of nanoseconds.[7–10] In such systems, stray inductance of the load, including a high voltage gap switch and a plasma load, should be kept low in order to obtain higher peak current with shorter pulse width. Especially, for lasing the capillary discharge soft x-ray laser at shorter wavelength, the plasma column is expected to be long enough, tens of centimeters, to obtain larger gain-length product, resulting in an increase in the circuit stray inductance. In addition, to realize the recombination soft x-ray laser at shorter wavelength, rapid current decay is required to cool down the nonequilibrium pinched plasma within a few tens of nanoseconds.[11,12] Furthermore, higher dI/dt is also preferable in order to reduce the amount of ablation materials from the inner wall of the capillary, which realizes the stable ideal snow plow compression.[13]

In order to decrease the inductance of the load, several attractive schemes have been developed such as a laser trigger gap switch with multidischarge channel.[14] However, it is still difficult to reduce the inductance of the dynamic plasma load in which soft x-ray amplification is expected.

In this paper, pulse wave shaping for obtaining higher current amplitude with rapid current decay by using a transmission line is proposed. The forward and backward voltage can be delayed by the transmission line between the gap switch and the capillary plasma, so the waveform of voltage can be controlled to produce the triangular current with high amplitude. Utilizing a superposition of the forward and the reflected voltage waves, the generation of a triangular discharge current with high current amplitude and rapid current decay is demonstrated.

II. EXPERIMENTAL SETUP

Schematic drawing of the experimental setup is shown in Fig. 1. Coaxial discharge system consists of a water capacitor, a gap switch, a transmission line, and a capillary plasma load. The low impedance water transmission line is placed between the high impedance gap switch and the capillary.

The gap switch is pressurized with SF_6 gas to decrease the gap distance to about 3 cm. Furthermore, several insulating barriers are used to prevent the surface discharge in the gap switch and the capillary section. Resulting inductances of the gap switch and the capillary section are about 75 and 50 nH, respectively. Surge impedance of the coaxial water capacitor is 3.8 Ω, and that of inserted transmission line can be varied from 0.5 to 10 Ω by altering the inner conductor diameter. The length of the water capacitor is 40 cm, and that of transmission line can also be changed arbitrarily. The surge impedance and the length of the each section are shown in Table I. A transmission line with surge impedance of 3.0 Ω and length of 25 cm was used in this experiment. Outer diameters of the water capacitor and the transmission line are 100 and 11 cm, respectively. Discharge current in the capillary load was measured by using a pick up coil, which is set at the end of the capillary near the transmission line.

III. PRINCIPLE OF THE WAVE SHAPING AND COMPUTED CURRENT WAVEFORMS

Current waveforms can be computed by the telegraph equation, which is based on the actual experimental setup, in order to find the optimum geometry of the transmission line for capillary discharge soft x-ray laser study. In this study, the length and the surge impedance of the transmission line are varied from 0 to 120 cm and from 0.5 to 10 Ω, respec-

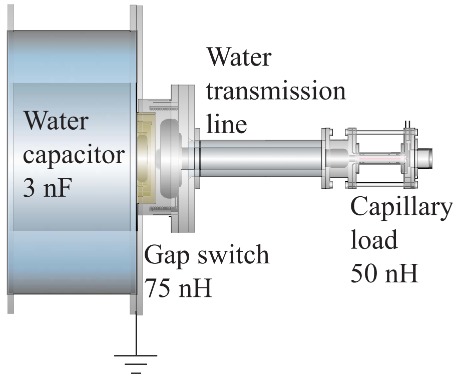

FIG. 1. (Color online) Schematic drawing of a capillary discharge system with a water transmission line.

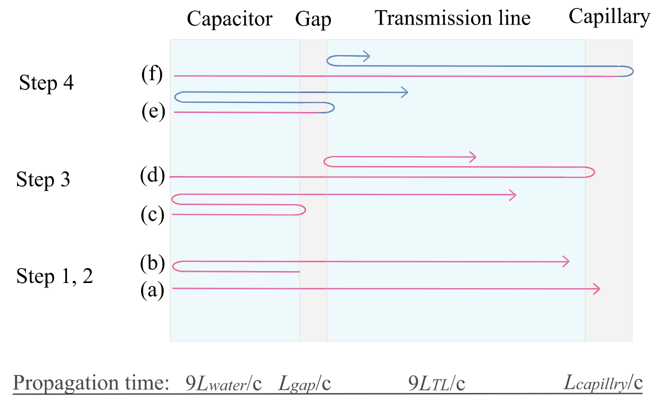

FIG. 2. (Color online) Schematic diagram of pulse forming, where c is the velocity of the light and L is the length of each section.

tively. Time evolution of the voltage in each segment, which has distributed capacitance C and inductance L per unit length, is computed by the telegraph equation as follows:

$$\frac{\partial V}{\partial x} = -L\frac{\partial I}{\partial t} - RI, \tag{1}$$

$$\frac{\partial I}{\partial x} = -C\frac{\partial V}{\partial t}, \tag{2}$$

where R is the series resistance per unit length and V and I are the voltage and current on the transmission line, respectively. Voltage waves calculated by using a 3.0 Ω transmission line with 0, 10, 25, and 60 cm lengths are shown in Fig. 2. The wave shaping is performed along the following steps, and a schematic diagram of pulse forming is shown in Fig. 2. In Fig. 2, c is the velocity of the light and L is the length of each section. In the water capacitor and the transmission line, the voltage waves propagate at a speed of one-ninth of the light speed in vacuum because the relative permittivity of the water is 82.

- Step 1. At first, the water capacitor is charged to 300 kV. When the gap switch is closed, the forward and the backward voltage waves start to propagate toward the capillary load (a) or the opposite end of the water capacitor (b).
- Step 2. The forward voltage wave, generated at the 40 cm length water capacitor, propagates toward the capillary load through the gap switch and the transmission line. These positive forward voltage waves propagate from the water capacitor [(a) and (b)]. At the time of 20–60 ns, this positive voltage wave leads to the increase in the current at the load capillary continuously as shown in the red colored main first cycle of current pulse in the right hand side of Fig. 3.

TABLE I. Surge impedance and length of each section.

	Length (cm)	Surge impedance (Ω/m)
Water capacitor	40	3.8
Gap switch	20	≈100
Transmission line	0–120	0.5–10
Capillary section	15	≈50

- Step 3. While the positive voltage wave, reflected by the high impedance gap switch (c) and the front of capillary (d), propagates toward the end of the water capacitor (c) and gap switch (d), respectively, at the end of the water capacitor and front of the gap switch, the reflected positive voltage wave is reflected again and returns toward the capillary load. These positively reflected voltage waves also increase the amplitude of current pulse of first cycle by superposition at the capillary load.
- Step 4. However, the voltage wave reflected at the front of the low impedance transmission line (e) and at the rear of the short-circuit capillary (f), i.e., earth terminal, changes the polarity, and a negative voltage wave propagates back to the water capacitor. At the high impedance terminal, such as the gap switch (f) or the end of the water capacitor (e), these negative voltage waves are reflected toward the capillary. The superposition of these negative voltage

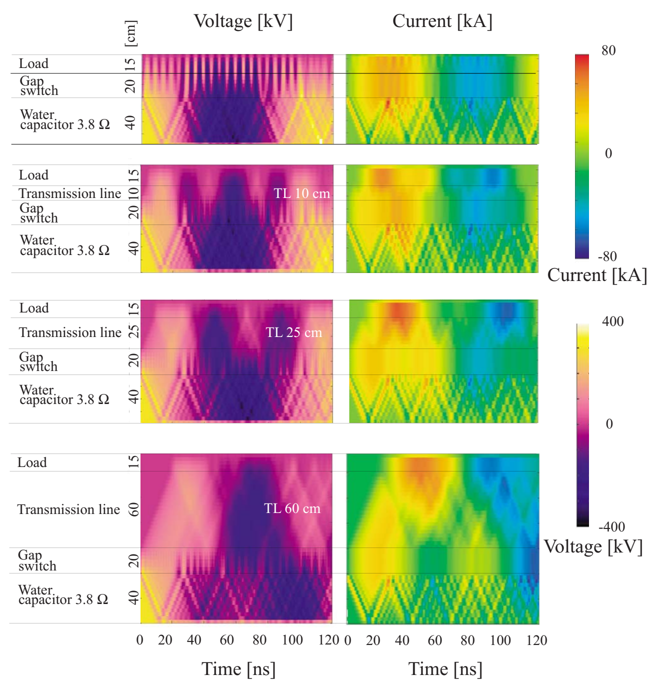

FIG. 3. (Color online) Propagation of voltage and current waves computed by telegraph equation.

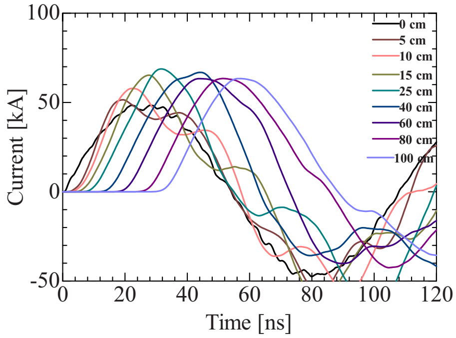

FIG. 4. (Color online) Computed discharge current waveforms in the capillary load obtained by using the transmission lines with various lengths. The surge impedance of the transmission line is fixed to be 3.0 Ω.

waves results in a decrease in the current amplitude at the capillary load.

- Step 5. These reflections and transmissions of the voltage waves repeat. When the amplitude of negative voltage wave at the capillary becomes larger than that of the positive voltage wave, the first cycle of current pulse ends.

Followed by the mechanism mentioned above, by changing the length of the transmission line, it is possible to control the propagation time of the positive voltage waves or the negative voltage waves. If these positive voltage waves were superimposed simultaneously, triangular current pulse with higher peak amplitude could be generated. Otherwise, if propagation times of these positive voltage waves are increased, a wide rectangular current pulse with relatively low peak amplitude could be generated.

Figure 4 shows the current waveforms in front of the capillary computed for transmission lines with various lengths at the capillary load. In Fig. 4, surge impedance is fixed to be 3.0 Ω. The longer the transmission line, the longer the pulse width of a generated current waveform. In the case of using a 25 cm long transmission line, the triangular current waveform with the highest peak amplitude can be generated because a forward wave and a reflected wave are superposed in phase at the center of the pulse.

Computed current waveforms in the capillary load using a transmission line with various surge impedances are shown in Fig. 5. In the computation, surge impedance was varied

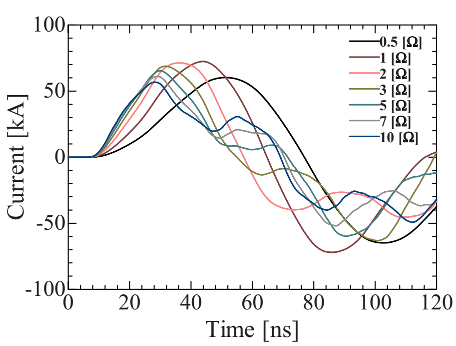

FIG. 5. (Color online) Computed discharge current waveforms in the capillary load obtained by using the transmission lines with various surge impedances. The length of the transmission line is fixed to be 25 cm.

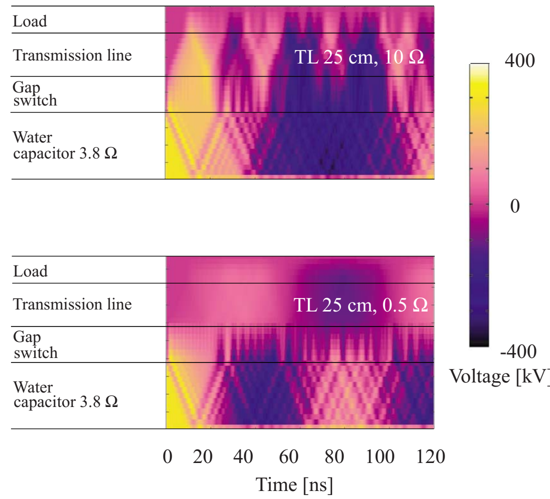

FIG. 6. (Color online) Voltage wave propagation computed with the 25 cm length transmission lines. Upper: with surge impedance of 0.5 Ω. Lower: with surge impedance of 10 Ω.

from 0.5 to 10 Ω, while the length of the transmission line was fixed to be 25 cm.

From the computation results shown in Fig. 5, it can be seen that the larger the surge impedance of the transmission line, the lower the peak amplitude of the current, except in the case of using a 0.5 Ω transmission line. To investigate the discrepancy in the current amplitudes using various surge impedance transmission lines, the computation of the voltage wave is performed for the case of using 0.5 and 10 Ω transmission lines, as shown in Fig. 6. The reason for these discrepancies is as follows. In the case of using the 0.5 Ω transmission line, the amplitude of the positive voltage propagated through the transmission line is smaller than that in the case of using the 10 Ω transmission line. However, with the 0.5 Ω transmission line, the positive voltage wave first reflected at the high impedance capillary load propagates back to the high impedance gap switch from the low impedance transmission line, where the positively reflected voltage wave is generated and propagates toward the capillary load again. It causes the continuous current to increase at the capillary load. However, in the case of using the 10 Ω transmission line, when the positively reflected voltage wave propagates back to the gap switch, because the impedance of the transmission line is larger, a large amount of positive voltage wave can transmit from the high impedance transmission line to the low impedance water capacitor. When these backward positive voltage waves reach the front of the water capacitor from the high impedance gap switch, the voltage wave polarity is changed, and a negative voltage wave begins to propagate toward the capillary load, resulting in the generation of oscillation at the capillary load, which decreases the current at the load.

Pulsed current with the maximum amplitude can be generated by using a 1.0 Ω transmission line. Moreover pulsed current with the shortest pulse width can be generated by using a 3.0 Ω transmission line. The abovementioned computation shows that by using the transmission line with arbitrary surge impedance or line length, it becomes possible to shape arbitrary current waveforms.

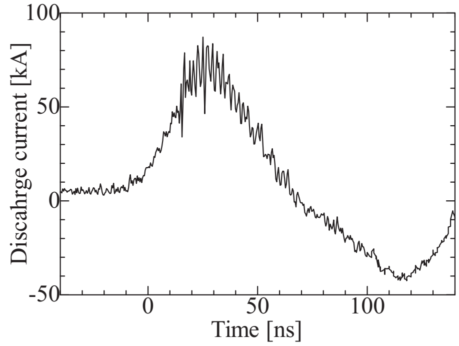

FIG. 7. Experimentally obtained triangular discharge current waveform obtained by using the transmission line with surge impedance of 3.0 Ω and length of 25 cm.

IV. EXPERIMENTAL RESULT

To verify the validity of the current wave shaping scheme, discharge experiment was performed with a water capacitor voltage of 300 kV. In the experiment, alumina capillary with inner diameter of 3 mm and length of 75 mm was filled with 2 Torr nitrogen molecular gas. In this discharge experiment, a transmission line with length of 25 cm and surge impedance of 3.0 Ω was used, which was expected to generate the shortest pulse width and relatively high peak current amplitude as shown in the computation. Capillary plasma was preionized to generate axially uniform plasma by utilizing a *RC* discharge with initial current amplitude of 20 A and a decay time constant of 10 μs. Measured discharge current is shown in Fig. 7, which has a peak current amplitude of about 70 kA. As a result, the experimentally obtained current waveform is quite similar to that calculated by telegraph equation as shown in Fig. 4. However, the pulse width of the experimentally obtained current is slightly longer than that of the simulation result. This discrepancy maybe occurred due to the disagreement of an inductance or a capacitance between the actual and the estimated value. In fast capillary discharge experiment, the inductance and the resistance of the capillary load plasma change due to the plasma implosion. Moreover, electron and ion motions in the gap switch plasma may dynamically change in nanosecond scale. These collective effects are considered to affect the wave shaping. In either case, the generation of the triangular current pulse by control of the incident and reflected waves has been experimentally demonstrated. To generate such a triangular pulse with high peak amplitude, the contribution of the positively reflected voltage wave (b) and (d) in Fig. 2 is considered to be important. The total propagation time of these voltage waves are calculated as

$$t_b \approx 2 \times 9\frac{L_{\mathrm{water}}}{c} + 9\frac{L_{\mathrm{TL}}}{c}, \tag{3}$$

$$t_d \approx 9\frac{L_{\mathrm{water}}}{c} + 3 \times 9\frac{L_{\mathrm{TL}}}{c}. \tag{4}$$

If these propagation times are the same, strong superposition of positive propagation voltage waves at the capillary is possible. With the use of 25 cm transmission line and 40 cm water capacitor, these propagation times becomes the same as follows:

$$t_b \approx t_d \approx 32 \ \text{ns}.$$

Consequently, this coincidence of voltage propagation time results in the generation of triangular pulse with higher peak amplitude.

V. CONCLUSION

By utilizing the transmission line with various lengths, the propagation time through transmission lines can be adjusted in order to control the voltage wave at the capillary plasma load. Taking advantage of the superposition of the positive forward and the backward voltage waves, discharge current wave shaping becomes possible. Based on the computation results obtained by telegraph equation, using the transmission line of 25 cm in length with surge impedance of 3.0 Ω, the generation of the triangular pulsed current, which has a peak amplitude of 70 kA and pulse width of 60 ns, has been demonstrated. This pulsed current shaping scheme can be applied to the compact pulsed power generator for capillary Z-pinch discharge study. Especially, the application of experimentally demonstrated triangular shaped triangular pulse with higher amplitude could be used for rapid cooling of the plasma, which is of potential use for the investigation of recombination soft x-ray laser study.

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