Demonstration of Rapid Electrical Recovery in Repetitive Operation of a Counter-Facing Plasma-Focus Device

Tatsuya SODEKODA[1,2], Hajime KUWABARA[2], Masashi MASUDA[1] and Kazuhiko HORIOKA[1]

[1] *Department of Energy Sciences, Tokyo Institute of Technology, Midori-Ku, Yokohama 226-8502, Japan*

[2] *Research Laboratory, IHI Corporation, Isogo-Ku, Yokohama 235-8501, Japan*

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Two plasma-focus electrodes, consisting of a pair of counter-facing center electrodes surrounded by six outer electrodes, can sustain a long-life, high-energy-density (HED) plasma initiated by laser-triggered multi-channel discharges. With the goal of making a high-average-power plasma device, we investigated the repetition rate of this device. Double-pulse experiments showed that when the device was driven with positive polarity, in which the center electrodes were biased at a positive voltage, the time required for the device to return to a non-conducting state was less than 100 μs, regardless of the operating voltage. The device thus has a repetition rate of more than 10 kHz.

Keywords: plasma focus, multi-channel electrode, pulsed discharge, electric recovery, lithium plasma

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HED plasmas can be sources of bright X-rays, energetic particles, and/or high neutron fluxes. Recently, radiation from an HED plasma in the extreme ultraviolet (EUV) region has been used as a light source for next-generation photo-lithography. To be cost-effective, such a light source must have a high repetition rate.

Plasma-focus devices have been used for more than 50 years to produce HED plasmas. Compared to other methods, they have many advantages, such as small size, simple configurations, and low cost. However, they have not been used as industrial HED plasma sources because up to now they have had low average power output due to short lifetime and low repetition rates of HED plasma. In order to increase the average power of such a device, a high repetition rate is essential. A counter-facing plasma focus (CFPF) system has been proposed [1] to solve these issues.

A schematic diagram of the CFPF device we have studied is shown in Fig. 1. The cylindrically symmetric device is based on a counter-facing pair of electrodes. We have found that this plasma-focus device can sustain plasma lifetimes up to 2 μs, an order of magnitude longer than that attainable with conventional plasma-focus devices. After preliminary experiments, the geometry of the device was modified to include two counter-facing sets of six laser-triggered focusing electrodes, as shown in Fig. 1 [2, 3], to improve the uniformity of the plasma discharge.

When the repetition rate of the plasma device exceeds its recovery rate, its operation is degraded by the delay in returning to a non-conducting state, disturbing its subsequent operation. Although we have achieved quasi-continuous operation of the present device at 1 kHz using a repetitively pulsed driver [3], the limit to the repetition rate has not been previously established, due to limitations of the power supply.

To determine the limiting repetition rate of the CFPF device, we investigated its rate of recovery to a non-conducting state using a double-pulse driver. Figure 2 shows a schematic diagram of this driver. We investigated the recovery rate of the device in order to determine the maximum repetition rate. Each half of the device consists of six outer electrodes surrounding an inner electrode that contains the plasma source material. The operational principle of the CFPF device is as follows: First, a charging voltage was applied between the inner and the outer electrodes through inductively isolated 2 × 6-channel pulsed power circuits. When lithium, used as the source material for these experiments, was ablated by a pulsed laser, the re-

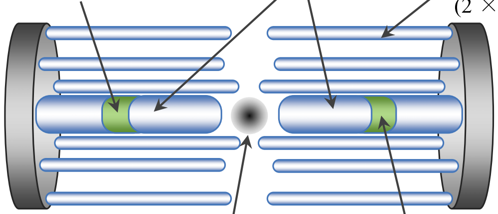

Fig. 1 Schematic of the electrode arrangement in a counter-facing plasma-focus device.

author's e-mail: tatsuya_sodekoda@ihi.co.jp

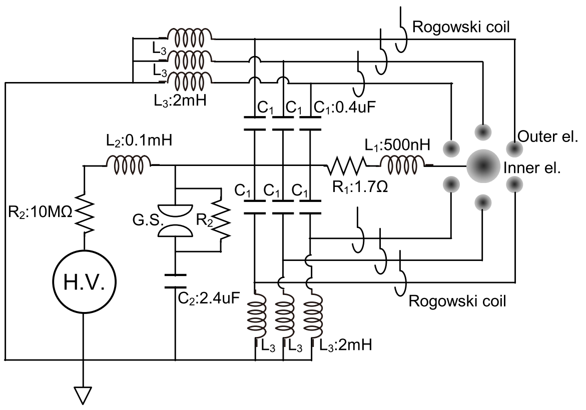

Fig. 2 Electrical circuit employed for operation of a multi-channel plasma-focus device in double-pulse experiments.

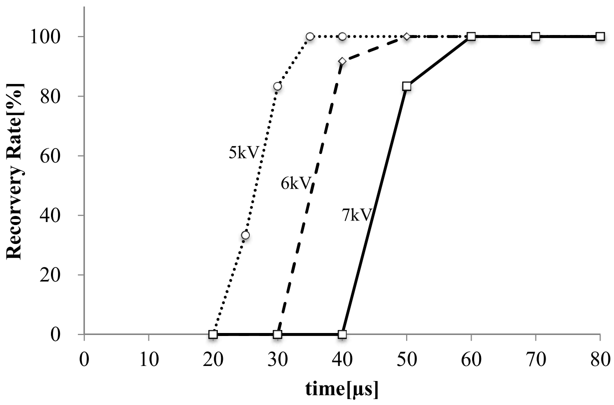

Fig. 3 Recovery rate of the electrode gaps versus time delay before voltage application in the second pulse.

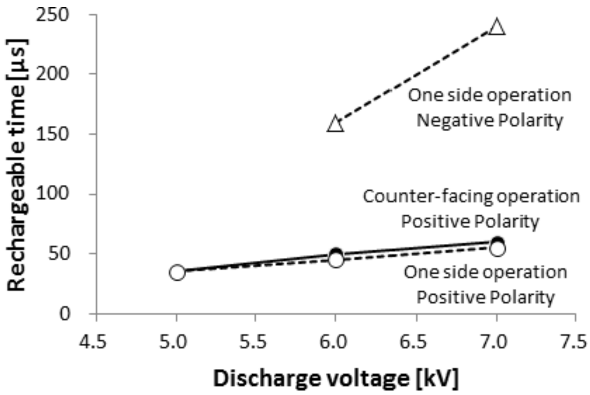

Fig. 4 Recharge time for subsequent operation.

sulting lithium plasma triggered a multi-channel discharge. Using this laser-trigger method, ring-shaped source plasmas were generated simultaneously on both sides of the device. The initial plasma rings were accelerated by electromagnetic forces toward the center of the device. The accelerated plasma rings collided and combined at the midpoint gap space between the two inner electrodes. The plasma was thermalized and compressed inward by the multi-channel discharge currents [2]. As long as the currents and the plasma remained stable, the HED plasma was maintained, and EUV light emission was sustained.

As shown in Fig. 2, an extra charging circuit composed of capacitor C_2 and a gap switch (G.S.) was incorporated to drive the second pulse in the double-pulse experiment. The second pulse was applied after a specified delay, and the voltages between the electrodes were measured to investigate recovery of the non-conducting state. The capacitors C_1 ($0.4\,\mu F \times 12$) were placed between the inner and the outer electrodes of the plasma device, and identical high voltages were applied by the high-voltage generator (H.V.). A quasi-sinusoidal current, with half-period 2 μs, was driven by the LCR circuits through the damping resistor (1.7 Ω). The applied charging voltages ranged from 5 to 7 kV, which corresponded to peak currents ranging from 1.5 to 2.5 kA/channel.

Figure 3 shows the recovery rate of the device, which we define as the ratio of the number of successful recharges to the total trial times, plotted as a function of the delay time before the application of the second pulse. As shown, the recovery rate depends slightly on the charging voltage. When the delay time was more than 60 μs, the non-conducting state was fully recovered, and the device able to be recharged successfully for the second pulse discharge. The recharge time is thus the minimum period required to clear the residual effects of the first pulse.

The recharge time is shown in Fig. 4 as a function of the applied voltage. Here we define the recharge time as that for which the capacitors can be recharged with 100% probability before application of the second discharge pulse. As shown in the figure, when the device was driven with positive polarity, the electrodes could be recharged within 100 μs, regardless of the applied voltage. The longer recovery time for the case of negative polarity is probably due to vaporization caused by cathode arcs at the tops of the center electrodes.

Although the recovery time depends slightly on the operating voltage, we have confirmed that the CFPF device can achieve a repetition rate of more than 10 kHz. Probably, the fast recovery rate is owing to the plasma supply through the laser ablation and the high vacuum conductance of the outer electrodes. Triggering the device by laser ablation enables us to control the amount of source plasma produced. Also the residual time of byproducts accompanied by the pulsed discharge should be reduced by the transparent outer electrodes for the vacuum pumping.

In summary, we evaluated maximum repetition rate of the CFPF device by means of double-pulse experiments. Our results show that the device can be operated up to at least 10 kHz. Since the device can maintain an HED state of plasma for an order-of-magnitude longer time than can be achieved by conventional plasma-focus devices [2], these results mean that the device can significantly increase the average output power for applications [3].

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