Study on pulsed-discharge devices by using pulse-forming-network modules toward intense X-ray source

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Abstract. A pulsed-power generator with a high rate of current rise was studied toward generating intense X-ray source from an X-pinch plasmas. The pulsed-power generator consists of 48 pulse-forming-network (PFN) modules with a three-stage of LC ladder circuit. To evaluate the rate of current rise for the pulsed-power generator, we demonstrated the short circuit experiments with low operation voltage. The rate of current rise depends on the number of PFN modules due to the decrease of inductance of PFN. The rate of current rise for 48 PFN modules at 10 kV of an operation voltage is estimated to be 0.1 kA/ns. To predict the rate of current rise for the requirement to obtain the intense X-ray from the X-pinch, the circuit simulation was demonstrated. The results indicated that the operation voltage requires over 70 kV for the rate of current rise of 1 kA/ns.

1. Introduction

An X-ray source generated by a compact pulsed-power device is an important tool for observing an interior of dense plasma such as warm dense matter (WDM), a lithography, and so on [1, 2, 3, 4, 5]. An X-pinch plasma [6, 7, 8], which is several thin wires crossed a load, is one of the intense X-ray source with the small source size. When the pulsed-power discharge occurs, the metallic thin wires are ablated and the large currents concentrate in the crossing point. The Lorentz force drives the implosion of the ablated wires, due to the interaction of the large currents and the generated magnetic field. However, to obtain the X-ray source for the X-pinch plasma, a rate of current rise of the pulsed-power generator is required to be 1 kA/ns, i.e. 100 kA of current and 100 ns of current rising time [9, 10, 11, 12]. To achieve the required high rate of current rise for generating X-pinch plasma, the pulsed-power generators have the pulse compression system and/or the relatively high voltage system [9, 13, 14]. However, the huge pulsed-power generators are difficult to use the applications such as the plasma diagnostics. To realize the tabletop X-pinch system, the inductance and the operation voltage are key issue to reduce the size of the system.

To generate X-ray source by using X-pinch system, a pulse forming network (PFN) module was used, having the advantages of holding high peak currents, ease of fabrication, and so on [15]. From a previous study [5, 16, 17], we have optimized the circuit topology of the PFN

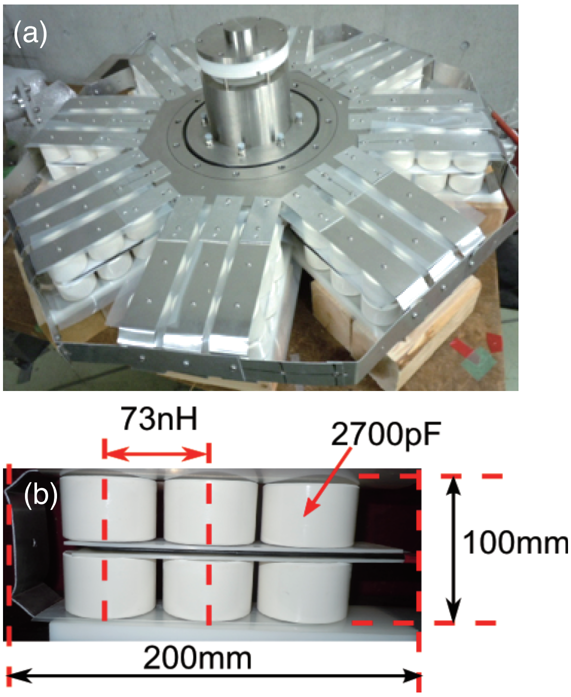

Figure 1. Photograph of X-ray source obtained by the X-pinch driven by the PFN modules. (a) overview of the X-pinch device, (b) modules of PFN.

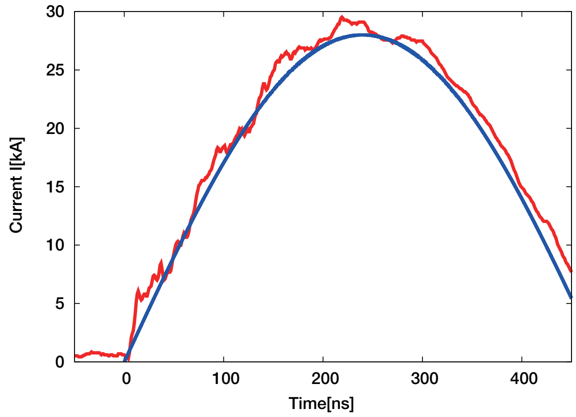

Figure 2. Typical current waveform at 10 kV of the operation voltage and the obtained fitting current waveform from the circuit simulation by ATP-EMTP[18].

module through circuit simulations. The results indicated that a module as three stage LC-ladder of PFN was suitable for the X-pinch light source. The number of module has also been estimated to be 48 with the 25 nH of the circuit inductance [17]. However, from the previous experimental results, the circuit inductance of the X-pinch system was estimated to be 60 nH. Thus, we should understand the X-pinch system to obtain 1 kA/ns of the rate of current rise.

In this study, we have evaluated the rate of current rise of the X-pinch system by using a PFN module from experimental observation and numerical estimation. To understand the behavior of the rate of current rise, the dependence on the number of PFN modules and the required operation voltage are evaluated.

2. Experimental Setup

Figure 1 is a photograph of X-ray source obtained by the X-pinch driven by the PFN modules. In order to reduce the inductance of the X-pinch system, the PFN modules were coaxially arranged in octagon plates, in which 48 PFN modules can be connected to drive the X-pinch. The PFN module as shown in Fig. 1(b) consists of a three-stage of LC ladder circuit. To obtain the high rate of current rise and the sufficient input energy for X-pinch, the capacitance and the inductance are considered. The inductance of the PFN module is determined by the size of capacitor. To reduce the inductance, the smaller ceramic and high-voltage capacitor is selected to be 2700 pF. The conductors of the PFN module makes the inductance. The inductance of the PFN modules are estimated to be 73 nH from the theoretical evaluation. The discharge gap switch, which is a self-breakdown due to the applied voltage, consists of the center of X-pinch system as shown in Fig. 1(a). From the previous experimental evaluation, the total inductance of the X-pinch system is estimated to be 60 nH.

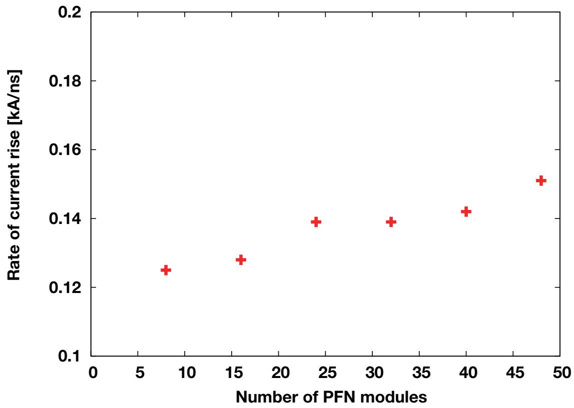

Figure 3. Rate of current rise as a function of the number of PFN modules with 10 kV of the operation voltage.

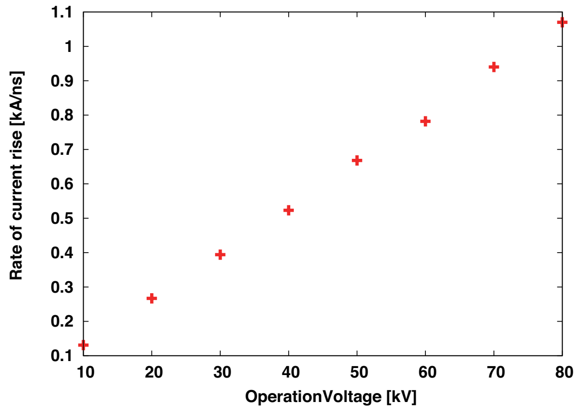

Figure 4. Numerical evaluation of the rate of current rise as a function of the required operation voltage with 48 of PFN modules.

Figure 2 shows the typical current waveform at 10 kV of the operation voltage and the obtained fitting current waveform from the circuit simulation by the Alternative Transients Program-Electromagnetic Transients Program (ATP-EMTP) [18]. The experimentally obtained peak current and rise time were estimated to be 30 kA and 200 ns, respectively. From these evaluations, the rate of current rise is estimated to be 0.15 kA/ns. To understand the X-pinch system, we evaluate the rate of current rise dependence on the number of PFN modules and the required operation voltage.

3. Experimental results and Discussions

Figure 3 is the rate of current rise as a function of the number of PFN modules with 10 kV of the operation voltage. The PFN modules for the X-pinch system arranges the co-axial symmetry for each experiments. The result indicates that the number of PFN modules depends on the rate of current rise. The improvement of the rate of current rise for the increase of the PFN modules is the reduction of inductance due to the parallel connection of PFN modules. Additionally, the rate of current rise increases from the peak current because of the increase of the capacitance of PFN modules.

Figure 4 is the numerical evaluation of the rate of current rise as a function of the required operation voltage with 48 of PFN modules. The results indicate that the increase of the operation voltage is almost linearly the increase of the rate of current rise. To obtain the X-ray from the X-pinch, the required operation voltage for ensured to the rate of current rise is estimated to be about 70 kV. Therefore, we should take care the insulation of the X-pinch system.

From the these results, to construct the table-top X-pinch system, we should consider to reduce the inductance of the X-pinch system, that is, the operation voltage decreases. Thus, the structure of the gap switch and the size of the X-pinch system will be considered to decrease the inductance of the X-pinch system.

4. Concluding Remarks

The pulsed-power generator with a high rate of current rise was studied toward generating intense X-ray source from an X-pinch plasmas. The pulsed-power generator consists of 48 PFN modules with a three-stage of LC ladder circuit. To evaluate the rate of current rise for the pulsed-power generator, we demonstrated the short circuit experiments with low operation voltage. The rate of current rise depends on the number of PFN modules due to the decrease of inductance of

PFN. The rate of current rise for 48 PFN modules at 10 kV of an operation voltage is estimated to be 0.1 kA/ns. To predict the rate of current rise for the requirement to obtain the intense X-ray from the X-pinch, the circuit simulation was demonstrated. The results indicated that the operation voltage requires over 70 kV for the rate of current rise of 1 kA/ns.

To demonstrate the table-top X-pinch system, we will consider the structure of the gap switch and the size of the X-pinch system to reduce the operation voltage.

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