Testifying experiment of the multi-pulse phenomena of capillary discharge soft-X-ray laser

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Received September 14, 2007

In a capillary discharge experiment for the neon-like argon lasing, we have proposed an experimental scheme to verify that the multi-spike of X-ray diode (XRD) signal is a multi-pulse laser or is a reflection of the laser pulse in the XRD. The ceramic capillary has an inner diameter of 3 mm and a length of 200 mm. At the gas pressure of 28 Pa and discharge current of 27 kA, stable lasing has been realized. The experimental results prove that the multi-spike of XRD signal is a reflection of the electromagnetic signal produced by the laser pulse in the XRD. The improved electrocircuit scheme of the XRD to minimize the reflection phenomena is also found.

OCIS codes: 140.7240, 350.5400, 340.7480.

Since the first demonstration of large laser amplification at 46.9 nm in Ar plasma pumped by a Z-pinch capillary discharge, conducted by Rocca *et al.* in 1994[1], the capillary-discharge scheme becomes, to date, one of the most successful excitation schemes for tabletop soft-X-ray laser. After that, successful experiments in a capillary discharge were also reported by other groups[2−4]. In this X-ray pumping scheme, a high pulse current flowing through a capillary channel compresses the preionized plasma column towards the capillary axis, heating the plasma, and increasing the electron density. When the particular plasma conditions (electron temperature of $60-80$ eV, electron density of $0.2\times10^{19}-2\times10^{19}$ cm^{-3}[2], and plasma diameter less than 100 μm[3]) are reached during the plasma compression, laser amplification can be obtained.

In the experiments of two groups, the multi-spike phenomena were detected by a vacuum photodiode or X-ray diode (XRD)[2,4], but the explanation of this phenomenon is extremely different. Niimi *et al.* considered that it indicated multi-pulse laser output, while Tomassetti *et al.* counted it as a reflection of the electromagnetic signal produced by the laser pulse in the XRD. In 2004, we realized soft X-ray laser output at 46.9 nm of the neon-like argon by using capillary discharge[5]. In experiments, we also observed the multi-spike signal of XRD. In order to testify the cause of this phenomenon, we conducted an experiment and proved that the multi-spike of XRD signal is a reflection of the laser pulse in the XRD. We also improved the electrocircuit scheme of the XRD for reduction of the reflection phenomena.

The detailed description of our experimental device can be found elsewhere[6,7]. The radiation signals are measured by using a fast vacuum XRD having a photocathode coated with a gold layer and a wire mesh anode. The distance between the photocathode and the anode is 2 mm and a voltage of −600 V with respect to the grounded anode is applied. The schematic diagram of XRD electrocircuit is shown in Fig. 1. This design has an advantage that the circuit of power supply and the circuit of detection use a same coaxial cable, which is the only coaxial cable connected with the photocathode of XRD, so the design of XRD can be simplified greatly.

In the experiment, we observed soft-X-ray laser output at 46.9 nm of the neon-like argon. Experimental parameters are: Ar pressure 28 Pa, capillary length 200 mm, and main current pulse amplitude about 34 kA.

Figure 2 shows the typical waveforms of the experiments with a laser output. The intense spike in the trace

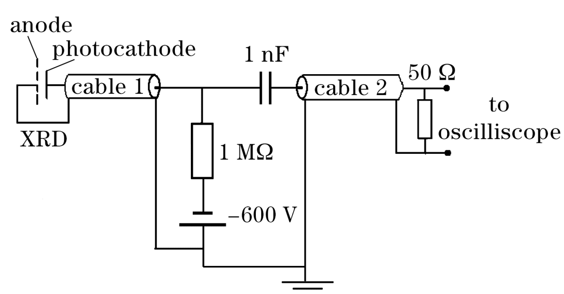

Fig. 1. Schematic diagram of XRD.

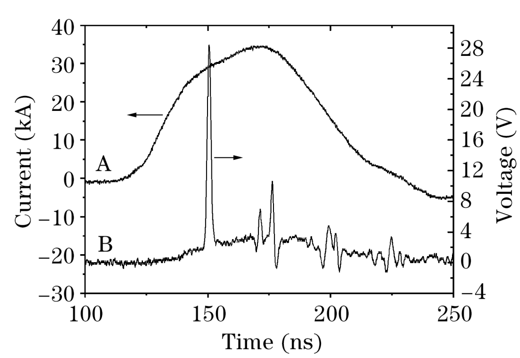

Fig. 2. Measured multi-pulse signal of XRD. The length of coaxial cable connected to XRD is 2.42 m, and that to oscilloscope is 1.93 m. The amplitude of discharge current is 35 kA.

B is a laser emission at the wavelength of 46.9 nm. In Fig. 2, one can see the phenomenon of multi-spike of XRD signals. There are still two evident spikes after the first laser spike. The cause of this phenomenon may be the multi-pulse laser output or the reflection of the electromagnetic signal produced by the laser pulse. In order to testify the real cause, in experiment we observed the variety of this phenomenon, adjusting the lengths of the coaxial cables connected to XRD and oscilloscope respectively. Figures 2 − 4 show the experimental results.

When the lengths of the coaxial cables connected to XRD and oscilloscope are 2.42 and 1.93 m, it can be seen from Fig. 2 that the intervals between the first spike and the second, the third spikes are 20.8 and 25.8 ns, respectively. Then we change the length of the coaxial cable connected to XRD to 4.42 m and keep the other cable unchanged. Figure 3 shows that the interval between the first and the third spikes changes to 45.8 ns, meanwhile, the interval between the first and the second spikes remains 20.8 ns. Similarly, when we change the length of the coaxial cable connected to oscilloscope to 4.1 m and keep the other cable unchanged, the results shown in Fig. 4 are obtained. We can see that the interval between the first and the second spikes changes to 43.6 ns, meanwhile, the interval between the first and the third spikes remains 25.8 ns. So naturally, we can suppose the phenomenon of multi-spike is caused by a reflection of the electromagnetic signal produced by the laser pulse, because the intervals between the first spike and the second, the third spikes regularly change according to various lengths of the coaxial cable connected to oscilloscope and XRD. We calculate the velocity of transmission in coaxial cable by the experimental data for further proving this supposition. The results are as follows. For 2.42-m coaxial cable the velocity is 0.188 m/ns, for 4.1-m cable it is 0.188 m/ns, for 4.42-m cable it is 0.192 m/ns, and for 1.93-m cable it is 0.186 m/ns. We can consider that the velocities are the same with taking experimental error into account. For such reason, we testify that the cause of the multi-spike of XRD signal is the reflection of the laser pulse in the XRD.

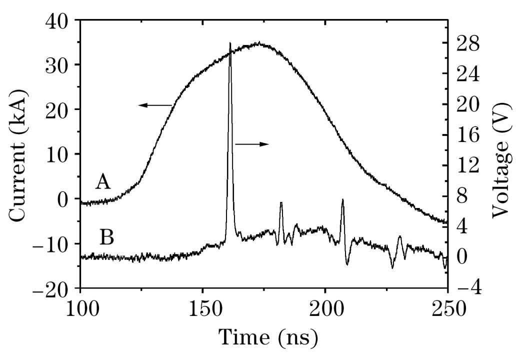

Fig. 3. Measured multi-pulse signal of XRD. The length of coaxial cable connected to XRD is 4.42 m, and that to oscilloscope is 1.93 m. The amplitude of discharge current is 35 kA.

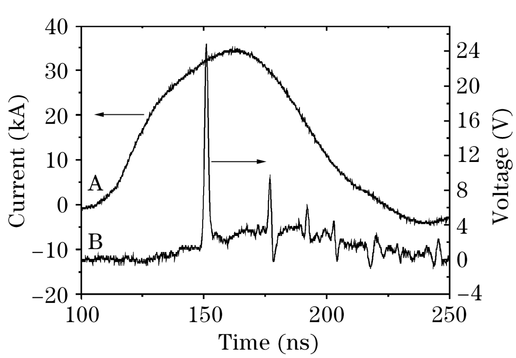

Fig. 4. Measured multi-pulse signal of XRD. The length of coaxial cable connected to XRD is 2.42 m, and that to oscilloscope is 4.1 m. The amplitude of discharge current is 35 kA.

Through the experiments, we have proved that the two reflected spikes are caused by the two coaxial cables used in the electrocircuit of XRD. This indicates the disadvantage of this kind of XRD design, in which the signal of laser pulse must be reflected for two times. Moreover, it is impossible to achieve the match of impedance for all these two coaxial cables, because for the cable connected with XRD the match impedance is a fixed value that is equal to the equivalent impedance of circuit of power supply and detection. So this design cannot avoid the reflected spikes. For reduction of the reflection phenomena, we present another design of XRD and the schematic diagram is shown in Fig. 5. In this design, the circuit of power supply is connected with the anode of XRD and the circuit of detection is connected with the photocathode of XRD, so the two circuits are separated. Thus the XRD only needs one coaxial cable to connect with oscilloscope. This in turn can reduce the reflection phenomena to one reflection spike and further minimize the amplitude of reflection spike by making the impedance of circuit of detection to match with that of coaxial cable.

The experimental results of the new designed XRD are presented in Fig. 6. In this figure, we can see only one

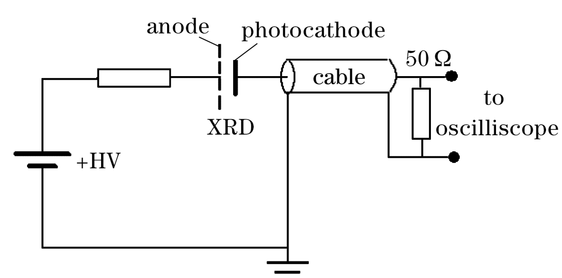

Fig. 5. Schematic diagram of the new designed XRD.

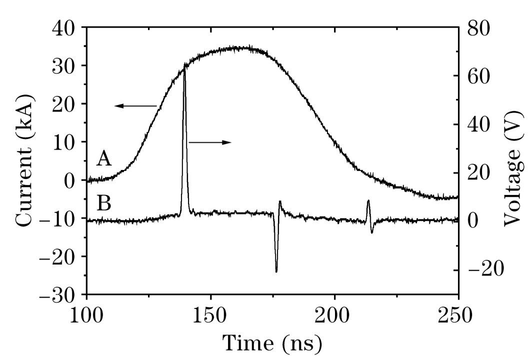

Fig. 6. Measured multi-pulse signal of the new designed XRD. The length of coaxial cable connected to XRD is 3.5 m, and the amplitude of discharge current is 35 kA.

reflection laser spike of XRD signal. Moreover, this result also proves that new designed XRD has an increased detection capability, because under the same experimental condition of 35-kA discharge current, the ratio of amplitude of laser spike to that of background light is about 16, which is significantly higher than the value of about 7.5 by using the old XRD. Besides these phenomena, the signal of XRD also shows that the reflection spike is always contrary to the laser spike. This result generates from the reason that the impedance of circuit of detection does not match with that of coaxial cable.

In summary, in experiment of capillary discharge soft-X-ray laser, the phenomenon of multi-spike of XRD signal was observed. For pursuing the cause of this phenomenon, we proposed a scheme of experiment, in which the multi-spike signal was studied through changing the length of coaxial cables connected with the XRD and oscilloscope. The experimental results proved that all the two spikes after the laser spike of XRD signal are caused by the reflection of electromagnetic signal in coaxial cable. In order to reduce this phenomenon, we suggest using another design of XRD that only needs one coaxial cable. This design can reduce the number of reflection spikes and increase the detection efficiency significantly.

This work was supported by the "863" Project of China (No. 863-804-7-10) and the National Natural Science Foundation of China (No. 60608007). B. Luan's e-mail address is luanbh119@126.com.

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