The Plasma Channel Evolution Characteristics of Pulsed Flashlamps Working in an Array

JIA Shenli (贾中利)¹, LI Rui (李瑞)¹, LIU Jianjun (刘建军)², LI Xingwen (李兴文)¹, SONG Xiaochuan (宋晓川)¹, LI Haibing (李海兵)²

¹State Key Laboratory of Electrical Insulation and Power Equipment, Xi’an Jiaotong University, Xi’an 710049, China
²Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China

Abstract This work is devoted to the study of plasma channel evolution characteristics in pulsed xenon flashlamps working in an array. Influencing factors on the plasma channel evolution process are studied, including pre-ionization pulse and neighbor flashlamps. It has been found that neighbor flashlamps affect the plasma channel by shaping the electric potential distribution, rather than by Lorentz force. Branching is observed in the plasma channels of the flashlamps in the middle of the array. Inconsistency also exists in the plasma channels of these flashlamps in different tests. The branching and inconsistency are both caused by the unique electric field distribution in these flashlamps. Besides, the pre-ionization pulse can help the main pulse plasma channel to develop more smoothly and faster, which will weaken the shock wave and benefit the mechanical strength of the flashlamp.

Keywords: xenon flashlamps, plasma channel, inertial confined fusion

PACS: 52.80.Mg

DOI: 10.1088/1009-0630/15/7/07

1 Introduction

Pulsed xenon flashlamps are widely used as radiation sources for pumping solid state lasers because of their high intensity, efficiency, and convenience in operation [1]. Pulsed xenon flashlamps are key optical components in laser inertia confined fusion (ICF) facilities. Although diode pumping sources are much more efficient, most existing laser ICF facilities and those currently under construction still have flashlamps as their pumping sources, including NIF and NOVA in the USA [2], LMJ in France, and LUCH in Russia [3]. The formation and evolution characteristics of the plasma in a flashlamp are important to its performance since the plasma is the origin of radiation. Plasma induced erosion of the flashlamp tube will deteriorate its transparency. Damage to the electrode seals and tube caused by the plasma and shockwaves leads to the weakening of the flashlamp’s mechanical strength [4]. These factors are known as primary failure mechanisms in flashlamps. Up to now a lot of work has been done to optimize the flashlamps in terms of mechanical, electrical and optical performance [5~8]. However, there is still a shortage of knowledge in the characteristics of the plasma in flashlamps, especially when the flashlamps are working in a parallel array for practical pumping. Therefore the present work aims to study the plasma channel evolution characteristics in the flashlamps working in array. The influence of neighbor flashlamps and pre-ionization pulse is studied, and it is found that: the neighbor flashlamps affect the plasma channel pattern by shaping the electric potential distribution, rather than by Lorentz force. The unique electric field distribution in flashlamps located in the middle of the array leads to plasma channel branching and inconsistency in the plasma channel pattern in different tests. Besides, the pre-ionization pulse is found to be helpful for the plasma channel of the main pulse to develop more smoothly and faster, which will mitigate the shockwave and benefit the mechanical strength of the flashlamp.

2 Experiment

2.1 Experimental setup

The overall experimental setup is illustrated in Fig. 1. There is an energy storage unit consisting of two parts in parallel, a pre-ionization capacitor in series with an ignitron to produce the pre-ionization pulse, and a main capacitor bank in series with an ignitron and a pulse shaping inductor to produce the main pulse. The energy storage unit is connected in series with the flashlamp load, which is in parallel with a crowbar diode. The capacitor utilized in the experiment is 4 μF in capacitance, and the main capacitor bank consists of 19 capacitors in parallel. The combination of the main capacitor bank and a 40 μH inductor can generate a discharge pulse with 510 μs pulse width (10%-10% in the power pulse).
A phantom V10 CCD camera is utilized to record the plasma channel evolution process with an exposure time of 2 µs. This exposure time is short enough to capture the evolution of the discharge as the widths of pre-ionization and main pulses are both of the order of tens or hundreds of micro seconds. Because of the strong brightness of the flashlamps, filters are used to protect the camera. During the test the pre-ionization ignitron is triggered at the same time as the CCD camera, then after certain time delay the main ignitron is triggered to generate the main pulse.

2.2 Layout of the flashlamps

The flashlamps used in the study have a length of 450 mm and an internal diameter of 48 mm. In the test, six flashlamps are connected in series to comprise an array, and their layout is shown in Fig. 2.

In Fig. 2, the arrows indicate the current direction. The flashlamp terminal with a plus sign ‘+’ indicates the wire-in terminal which has the maximum electric potential and the terminal with a minus sign ‘−’ indicates the grounded terminal. The gap between adjacent flashlamps is 45 mm. There is a steel installation frame on both sides of the flashlamp array and it is connected to the ground. There are totally ten slots in the installation frame. Each flashlamp is numbered and the dashed region indicates the vacant slots.

3 Results and discussion

3.1 The influence of neighbor flashlamps

Fig. 3 shows the plasma channels during the pre-ionization pulses. It should be noted that the plasma channel evolution characteristics in the pre-ionization pulse are similar to those in the main pulse. However, the energy dissipated in the pre-ionization pulse is much smaller than in the main pulse, leading to more lucid plasma channel patterns. Therefore the pre-ionization results are listed here for analyzing the influence of neighbor flashlamps.

Since the capacity of the CCD camera is limited, in order to capture the plasma channel in the whole flashlamp, an image for each flashlamp in the array is recorded in different tests and the results are shown in Fig. 3(a). In order to capture the plasma channels in different flashlamps at the same instant, only the lower region of the flashlamp array can be recorded and the results are shown in Fig. 3(b). Fig. 3(d) shows the typical current and voltage traces during the pre-ionization pulse.

In Fig. 3(a) the image for flashlamp 6 is recorded when it works in the layout shown in Fig. 2(b) (referred to as layout (b)). By using this layout, the influence of the grounded frame on flashlamp 6 can be removed. Except for this, other images are all recorded when the flashlamps work in the layout shown in Fig. 2(a) (referred to as layout (a)).

When layout (a) is used, in flashlamp 1, the plasma channel develops along the right-hand side for the most part, as illustrated in Fig. 3(a) and (b). In the lower part of flashlamp 6, the plasma channel develops along the right-hand side, as illustrated in Fig. 3(b). In the flashlamps between flashlamp 1 and flashlamp 6, the plasma channel tends to develop along different a side near each terminal except for flashlamp 4, in which the plasma channel develops on the right-hand side in the whole lamp. The cause for such a phenomenon can be explained as follows.

Let us assume that the electric potential at the wire-in terminal is $\Phi_6$ and the electric potential at each joint terminal is respectively $\Phi_1 \sim \Phi_5$, as illustrated in Fig. 2(a). Then near the lower terminal of flashlamp 1, the electric potential difference $\Delta \Phi$ between flashlamp 1 and flashlamp 2 is $\Phi_2$ on the right-hand side, while on the left-hand side $\Delta \Phi$ between flashlamp 1 and the left grounding frame is near zero. Therefore in the lower part of flashlamp 1 the electric field strength on the right-hand side will definitely be larger. As we know, the plasma channel tends to develop in the region with higher electric field, because higher electric field leads to stronger acceleration of the electrons, which will further cause electrical breakdown and the formation of plasma $[9,10]$. Therefore the plasma channel in the lower part of flashlamp 1 will develop on the right-hand side. In the region near the upper terminal of flashlamp 1,
$\Delta \Phi$ between it and flashlamp 2 is zero while the $\Delta \Phi$ between it and the grounding frame is $\Phi_1$. Therefore the greater electric field will locate on the left-hand side and a branching in the plasma channel will emerge in the flashlamp. However, the distance between flashlamp 1 and the frame is much larger than the gap between flashlamp 1 and flashlamp 2, therefore the branching occurs close to the upper terminal of flashlamp 1, as illustrated in Fig. 3(a) and (b).

For flashlamp 6, near the upper terminal, $\Delta \Phi$ between it and the right grounding frame is $\Phi_5$, and $\Delta \Phi$ between it and flashlamp 5 is zero, whereas near the lower terminal, $\Delta \Phi$ between flashlamp 6 and the frame is $\Phi_6$, and $\Delta \Phi$ between it and flashlamp 5 is $(\Phi_6 - \Phi_5)$. Therefore in flashlamp 6, the electric field strength on the right-hand side will always be larger than that on the left, and the plasma channel should also develop on the right side. Fig. 3(b) confirms this supposition in the lower part of the flashlamp 6, but unfortunately the image for the upper part of flashlamp 6 in layout (a) was not recorded in the test.

For the flashlamps between flashlamp 1 and flashlamp 6, the electric field will locate on different sides near different terminals. Take flashlamp 2 for example, near the upper terminal, $\Delta \Phi$ on the left-hand side is zero while on the right-hand side it is $(\Phi_3 - \Phi_1)$, whereas near the lower terminal, $\Delta \Phi$ is $\Phi_2$ on the left-hand side and zero on the right-hand side. Therefore the plasma channel will develop along the right-hand side in the upper region and along the left-hand side in the lower region. If the applied voltage is uniformly distributed among the six flashlamps, then a branching point will occur just in the middle of the flashlamp. The plasma channels’ images of flashlamp 2, flashlamp 3, and flashlamp 5 are consistent with this situation.

However, if the plasma channel happens to form firstly near one terminal only, which is very likely, there is a possibility that the whole plasma channel will develop along the side of the first emerging plasma, and no branching will be observed in this case. This effect can lead to inconsistency in plasma channel patterns in different tests. Taking flashlamp 5 for example, clear inconsistency can be observed between plasma channels in different tests in Fig. 3(c).

In order to further confirm the effect that the electric field exerts on the plasma channels, layout (b) is used to remove the influence of the right-hand grounding frame on flashlamp 6. Then in Fig 3(a) we can see that the plasma channel in flashlamp 6 becomes quite different from that in layout (a). This is caused by a totally different electric field distribution in flashlamp 6. In layout (b), near the lower terminal the electric potential differences on both sides are zero, whereas near the upper terminal, $\Delta \Phi$ between flashlamp 6 and the left grounding frame is $\Phi_5$, and $\Delta \Phi$ between flashlamp 6 and flashlamp 1 is $(\Phi_6 - \Phi_1)$, which is smaller than on the left-hand side. However, the distance between flashlamp 6 and the frame is much larger than that between it and flashlamp 5, and the larger distance compromises the greater electric potential gap. Therefore near the upper terminal of flashlamp 6, it is hard to tell on which side the electric field is greater. Under the influence of such electric field distribution, the plasma channel will not follow a specific path, but distribute randomly in the whole flashlamp, as illustrated in Fig. 3(a).

From the above discussion, we can draw a conclusion that neighbor flashlamps affect the plasma channel pattern by shaping the electric potential distribution, rather than by Lorentz force. Due to Lorentz force, in layout (a) the plasma channel in flashlamp 6 will develop on the left-hand side (the current directions in flashlamp 6 and flashlamp 5 are opposite and the Lorentz force tends to draw the plasma channels towards each other). Besides, in order to improve the consistency of the plasma channel pattern in different shots, external trigger components are needed to reshape the electric potential distribution.
3.2 The influence of pre-ionization pulse

Fig. 4(a) shows typical current and voltage curves of the main pulse with or without the pre-ionization. From this figure one can see that without pre-ionization, there is a spike at the start of the voltage curve. If pre-ionization is added before the main pulse, the voltage spike will transfer to start the pre-ionization pulse, and in the main pulse, the voltage curve becomes much smoother. This voltage spike corresponds to the formation of a plasma channel and the accompanied shockwave. In the pre-ionization pulse, the energy is much smaller than in the main pulse, and the generated shockwave will have less power. Therefore, by adding a pre-ionization pulse, the shockwave produced by the initial expansion of the plasma channel can be weakened, benefitting the structural strength of the flashlamp. Fig. 4(b) illustrates the differences between plasma channels with or without pre-ionization. It is shown that the plasma channel of the main pulse with pre-ionization is wider than that without it, at a corresponding moment. This effect is most obvious in the early phase of the plasma channel (before 238 µs). It indicates that the pre-ionization pulse can help the plasma channel of the main pulse to develop more smoothly and faster, which confirms the above conclusion that addition of a pre-ionization pulse can weaken the shockwave.

Fig.4 (a) Typical current and voltage traces of the main pulse with or without the pre-ionization pulse, (b) Plasma channel images of the main pulse with or without the pre-ionization (color online)

4 Conclusion

In this work, the plasma channel evolution characteristics in a pulsed xenon flashlamp working in an array are studied. The influence of neighbor flashlamps and pre-ionization pulse is analyzed, and the following conclusion can be drawn.

The neighbor flashlamps affect the plasma channel pattern by shaping the electric potential distribution, rather than by Lorentz force.

For the flashlamps in the middle of the array, branching can be observed in the plasma channels, and inconsistency exists in the plasma channels in different tests. The branching and inconsistency are caused by the unique electric field distribution in these flashlamps. In order to improve the consistency, external trigger components are needed to reshape the electric potential distribution.

The pre-ionization pulse can help the plasma channel of the main pulse to develop more smoothly and faster, which will weaken the shockwave and benefit the mechanical strength of the flashlamp.

References


(Manuscript received 7 November 2011)
(Manuscript accepted 24 January 2013)
E-mail address of corresponding author LI Rui: lirui.cn@msn.cn