Ablation characteristics of hybrid target materials for laser triggered vacuum switches

Chen Hui$^{1,2,3,4}$

1 The State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science and Technology Wuhan Hubei 430074 P.R.China
2 Hubei Collaborative Innovation Center for High-efficiency Utilization of Solar Energy, Hubei University of technology, Wuhan, 430068, P. R. China
3 Hubei Key Laboratory for High-efficiency Utilization of Solar Energy and Operation Control of Energy Storage System, Hubei University of technology, Wuhan, 430068, P. R. China
4 E-mail: 992424568@qq.com

Abstract. The key difference of laser triggered vacuum switch (LTVS) and electrical triggered vacuum switch (ETVS) is the different triggered way, because the initial plasmas were generated by laser irradiation target material of LTVS, which generates different impact on the triggered characteristics of LTVS with different target materials. There are three laser wavelength (1064nm, 532nm and 266nm) which are tested the triggered characteristics of target materials, with decreased conduction time delay under the condition of increasing laser energy.

1. Introduction
Laser Triggered Vacuum Switch (LTVS) is an advanced pulse power control device with a unique triggering mode, to protect it from electromagnetic interference [1, 2]. Because of vacuum state of the switch, it has the advantages of high withstand voltage and high arc extinguishing speed. In 1987, PJ Brannon and DF Cowgill first selected Ti with a diameter of 8 μm and KCl with a diameter of 300 μm as mixed target materials [3]. The designed switching pattern is planar, the gap distance is 0.5 mm, and the withstand voltage is 6 kV [4, 5]. Experiments have proved that the mixed target material of LTVS has the advantages of short delay and low laser energy required, compared with previous LTVS [6-8].

The LTVCs designed in this paper increases the gap distance in order to reach 30kV withstand voltage [9]. At the same time, the structure of the switch is improved, and the electrode structure is multi-rod type. This can effectively avoid the erosion of the discharge arc on the electrode, and increase the service life of the switch. The triggering characteristics of the three metal elements, which are Cu, Al and Ti as target materials, were compared in the experiment, pure KCl and KCl/Ti also included.

2. Experiment device
The experimental device multi-bar LTVC structure is shown in figure 1. The target material, which is indicated in part number 6 of figure 1, is fixed at the cathode position, the laser incident window and
the target material are coaxial, and the diameter of the anode through hole is slightly larger than the diameter of the cathode through hole, which is favorable for the laser irradiation target. The internal vacuum degree of the switch is maintained at 1×10^{-5}\text{Pa}.

![Figure 1. Six-gap rod electrode LTVS.](image)

1- Insulating shell, 2- Metal shield, 3- Quartz window, 4- Anode, 5- Cathode, 6- Trigger material, 7- Discharge gap.

The basic optical path diagram used in the experiment is shown in figure 2. The laser uses a lamp-pumped Q-switched Nd: YAG laser. The wavelength of the laser light is 1064 nm, and 532 nm or 266 nm laser can be obtained through the frequency doubler. The focal length is 200mm, and the photodetector model is the THORLABS DET10A/M silicon detector. The oscilloscope model is the Agilent DSO-X3104A.

![Figure 2. The basic diagram of the optical path.](image)

In figure 3, the circuit diagram of experiment is shown. This circuit consists of three parts: charging circuit, discharge circuit, and protection circuit. The power supply is charged by the voltage regulator, transformer, protection resistor R1 and silicon stack D1 to the storage capacitor C1; the storage capacitor C1 releases electric energy via the dummy loads R2 and LTVS; when the switch does not work normally, the storage capacitor C1 passes through the water resistor R3 release electrical energy. The high voltage meter reads the voltage across the storage capacitor voltage C1. The switching voltage waveform is measured by the TEKP6015 high voltage probe [10].

![Figure 3. Experimental circuit diagram.](image)
3. Experiment and Result Analysis

Table 1 shows the three wavelengths and their maximum output energy tables, and table 2 shows the characteristics of the target materials. In table 2, the work functions of copper and aluminium are all less than the single photon energy of the 266 nm laser, which is prone to photoelectric effects.

| Wavelength(nm) | Photon energy(eV) | Maximum output laser energy(mJ) |
|----------------|-------------------|---------------------------------|
| 1064           | 1.165             | 210                             |
| 532            | 2.33              | 100                             |
| 266            | 4.66              | 40                              |

**Table 2. Target material properties.**

| Target Material | Work Function(eV) | Reflection coefficient(1064nm) | Reflection coefficient(532nm) | Reflection coefficient(266nm) |
|-----------------|-------------------|--------------------------------|--------------------------------|-------------------------------|
| Graphite        | 5.00              | 0.50                           | 0.30                           | 0.40                          |
| Nickel          | 4.84              | 0.73                           | 0.60                           | 0.43                          |
| Molybdenum      | 4.60              | 0.70                           | 0.58                           | 0.66                          |
| Tungsten        | 4.54              | 0.60                           | 0.49                           | 0.46                          |
| Copper          | 4.50              | 0.97                           | 0.92                           | 0.35                          |
| Titanium        | 4.33              | 0.55                           | 0.49                           | 0.26                          |
| Aluminium       | 4.28              | 0.96                           | 0.92                           | 0.93                          |
| Silver          | 4.26              | 0.98                           | 0.92                           | 0.25                          |

3.1. The triggering characteristics of target material under 1064nm laser

When the laser wavelength is 1064nm, as shown in figure 4, is the conduction delay of different target materials, in which the conduction time of graphite is relatively minimum, the triggering characteristics are better. The minimum conduction time delay is 3μs, and the corresponding laser energy is 43.5mJ. With the same laser energy, the conduction time delay of graphite is much smaller than that of other target materials. In this case, the conduction time delay of titanium is the longest, the minimum conduction time delay is 9μs, and the corresponding laser energy is 43.5mJ. Each target material has a laser trigger energy threshold, as shown in table 3.

**Figure 4.** Conduction delay of the different target materials in 1064nm laser.

| Target Material | Laser trigger energy threshold (mJ) |
|-----------------|------------------------------------|
| Graphite        | 12.5                               |
| Nickel          | 16                                 |
| Molybdenum      | 15                                 |
| Tungsten        | 17                                 |
| Copper          | 20                                 |
| Titanium        | 32.5                               |
| Aluminium       | 9                                  |
| Silver          | 18                                 |
3.2. Triggering characteristics of target material under 532nm laser
When the laser wavelength is 532nm, as shown in figure 5, the conduction delays of different target materials, the graphite conduction delay is the lowest under the same laser energy, the laser energy is 41mJ, and the conduction delay of the switch is 7 μs. The on-time delay of other target materials is basically maintained at 10μs~11μs, and the conduction time delay of nickel is basically constant. Under the same laser energy, the conduction time delay is basically the largest. However, when the laser energy is 11.5mJ~29.5mJ, the conduction delay decreases with the increase of the laser energy. When the laser energy is 29.5mJ~39.5mJ, the conduction delay increases with the laser energy. At this wavelength, the laser triggered energy threshold for each target material is shown in table 4.

![Figure 5. Conduction delay of the different target materials in 532nm laser.](image)

**Table 4. Laser trigger energy threshold in 532nm laser.**

| Target Material | Laser trigger energy threshold (mJ) |
|-----------------|------------------------------------|
| Graphite        | 10                                 |
| Nickel          | 22                                 |
| Molybdenum      | 19                                 |
| Tungsten        | 16                                 |
| Copper          | 15                                 |
| Titanium        | 30                                 |
| Aluminium       | 14                                 |
| Silver          | 11.5                               |

3.3. Triggering characteristics of target material under 266nm laser
When the laser wavelength is 266 nm, as shown in figure 6, the conduction delays of different target materials, and the conduction time delay of aluminium is the smallest under the same laser energy condition. At this wavelength, the laser trigger energy threshold of each target material, as shown in table 5, is compared with the other two waveforms. Under the irradiation of the 266 nm laser, the required laser trigger energy threshold is the lowest. The delay is relatively longer than the 1064 nm laser and shorter than the 532 nm laser [11].

![Figure 6. Conduction delay of the different target materials in 266nm laser.](image)
4. Target material trigger characteristics analysis

Through the triggering characteristics of the target material under three laser wavelengths (1064 nm, 532 nm, and 266 nm), the overall on-time delay decreases as the laser energy increases.

For the above eight target materials, the relevant triggering mechanism is not very clear under the irradiation of three wavelengths of laser light. When the laser wavelength is 266 nm, the photoelectric effect may be the most important conduction mechanism, because the energy of a single photon is larger than that of the six materials, except graphite and nickel. Although a single photon can ionize six of these materials, if the laser energy does not reach a certain level, it is difficult to generate enough initial plasma and the switch cannot be turned on. Therefore, the energy threshold of the 266 nm laser is lower than that of the other two wavelength lasers. However, the on-time delay of these materials is larger than that of aluminium under the photoelectric effect of a single photon. The atomic weight of each material is different, and there are trace amounts of gas in the target material when the laser is irradiated multiple times. In the target material, gas adsorbed on the target material is ionized by the laser. When the laser wavelength is 532nm or 1064nm, the photon effect of a single photon is difficult to ionize the target material. The conduction mechanism at this time is multiphoton ionization, when the target material is irradiated by a 532nm laser, two photons are simultaneously absorbed. However, with the increase of the number of absorbed photons, the turn-on delay of the switch should be correspondingly increased. However, under the irradiation of the 1064 nm laser, the turn-on delay of the switch is the shortest. When the laser wavelength is 322nm or 1064nm, the threshold of the laser energy is relatively high, indicating that the generation of the initial plasma is related to the surface temperature of the target material, and the conduction of the switch conduction is effected by the laser of these two wavelengths. The mechanism is laser ablation or thermionic emission.

The relationship between the reflection coefficient and the turn-on delay of the switch is also not very clear. When the laser wavelength is 532 nm or 1064 nm, the reflection coefficient of graphite is the smallest and the turn-on delay is minimal. However, the reflection coefficient of titanium is relatively smaller than the remaining six materials, with the longest conduction delay. When the laser wavelength is 266 nm, the reflection coefficient of aluminium is the highest, with the smallest conduction delay.

5. Conclusions

Through the analysis of the above experimental results, which can be considered to select the laser-triggered wavelength and target material, the wavelength of the laser is chosen 1064nm and 266nm. 532nm laser is not selected is for similar triggering characteristic but larger conduction delay I comparing with 1064nm. 266nm laser is selected for lower laser energy threshold, which is advantageous to the miniaturized optimization design of the laser. The target material is combined with graphite, copper and aluminium. The reason is that the conduction delay is minimum under the irradiation of 1064 nm laser. Furthermore, aluminium is for smallest conduction delay under the irradiation of 266 nm laser. Triggering characteristics of copper is almost between graphite and

### Table 5. Laser trigger energy threshold in 266nm laser.

| Target Material | Laser trigger energy threshold (mJ) |
|-----------------|-----------------------------------|
| Graphite        | 7                                 |
| Nickel          | 9                                 |
| Molybdenum      | 7.5                               |
| Tungsten        | 9                                 |
| Copper          | 10                                |
| Titanium        | 22                                |
| Aluminium       | 6.5                               |
| Silver          | 8                                 |

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aluminium under those two laser wavelengths, and it takes half proportion of material in the main electrode of the switch in reality.

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