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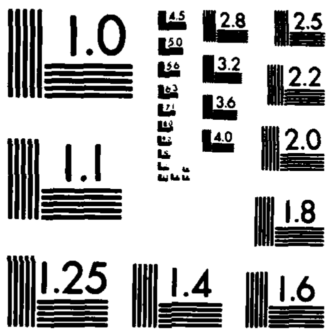

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A MINIATURE NANOSECOND ELECTRON BEAM GENERATOR

by

Xie Xiaoxiang, Wang Ruging, et al

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A MINIATURE NANOSECOND ELECTRON BEAM GENERATOR

Xie Xiaoxiang, Wang Reqing, Sha Guohe, Zhang Cunhao*

The construction of a miniature nanosecond electron beam generator suitable for laser related kinetics studies is presented. The peak current of the electron beam measured behind a 6-mm-diameter electron beam window is 7 amperes. The pulse duration (FW HM) is 6 - 8 nanoseconds and the maximum electron energy is about 107 keV.

I. INTRODUCTION

With the development of electron-beam initiated chemical lasers and electron-beam pumped molecular lasers,a large amount of research on the dynamic processes of producing lasers have been conductrd both theoretically and experimentally. The method of using high energy electron beams of short impulses as tools for studying the rapid dynamic processes of those two types of laser devices has become very important in recent years [1-4].

To study the dynamic processes in an electron-beam initiated laser, a pulsed HF chemical laser device is designed and built based on the works of Brau, et al [5] and after many tests and improvements. Its high voltage pulse is produced by a spiral generator. When the input voltage of the spiral generator is 15.7 kV, the electron beam generator produces electron beam pulses with peak current of about 7 amperes. The maximum energy of the electron is about 107 keV and the pulse duration (F WHM) is 6-8 nanoseconds.

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II. THE SPIRAL GENERATOR

Electromagnetic wave U is allowed to propagate through a transmission line with wave resistance Z_r. If it meets another conducting line with wave resistance Z_t, U_r will experience some reflection at the junction of the two conducting lines. The coefficient of reflection β is

$$\beta = \frac{Z_t - Z_r}{Z_t + Z_r} \tag{1}$$

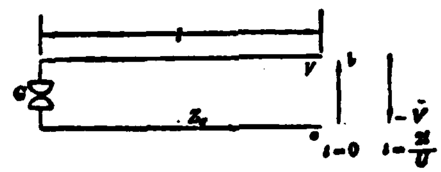

Figure 1. The transmission line

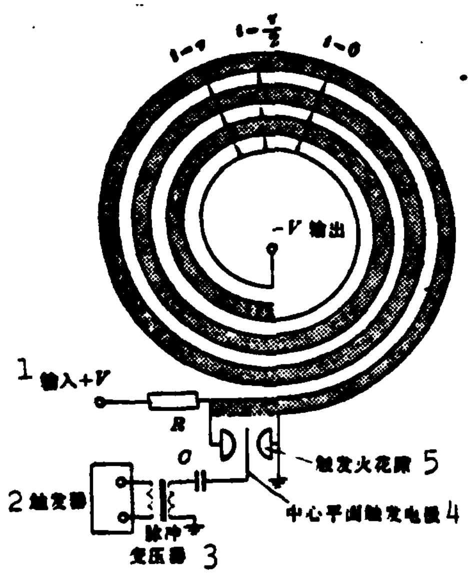

Figure 2. Schematic diagram of the spiral generator (The shaded region is the active line and the unshaded region is the passive line).
1--input; 2--trigger; 3--pulse transformer; 4--mid-planar initiation pole; 5--initiation spark gap

when $Z_f = 0$, $\beta=-1$. U_r will be reflected completely at the junction point and will change its polarity. When $Z_f = \infty$, $\beta = 1$. U_r will be reflected completely but will not change its polarity. For the case shown in Figure 1, the transmission line is connected to a spark gap switch G on one end, and to an open circuit on the other. Let v be the propagation speed of the wave in the transmission line, and l be the length of the transmission line. The transmission line is charged to voltage V before G is closed (t = 0). This is indicated at the open circuit end by the positive vector V. When G is closed, a voltage wave with a polarity opposite to that of V is formed at G and is propagated toward the open circuit end. This wave will eliminate the original charged vector V and will nullify the voltage as it travels through the line. When it reaches the open circuit end ($t = l/v$) where $Z_f = \infty$, it is reflected completely without changing polarity and will propagate back to the switch G. By this time, the transmission line has been recharged, thus acquiring a negative vector - V. The voltage vector is then reversed due to the reflection of the wave. This is the simple principle of vector (reversal).

The spiral generator is constructed upon the vector (reversal) principle proposed by Fitch, et al [7] in 1964. Its structure is a Blumlein transmission line consisting of a metal band and an intermediate band coiled into a spiral shape as shown in Figure 2.

Each layer of the spiral generator is composed of an active line and a passive line. The outermost layer is connected to the spark gap switch. The generator is charged to a voltage of V_o by a direct current power source through the resistor R. When the switch is open, the electric vectors in the active line and the passive line cancel each other. When t = 0, the switch conducts, based on the vector reversal principle, a voltage wave of reversed polarity starts to propagate toward the inner layers along the active line, eliminating the voltage vector in the active line and producing a current at the same time. The electrostatic energy in the generator is thus transformed into electromagnetic energy. At $t = \tau/2$ (τ is the transient time of generator voltage), the voltage wave reaches the open circuit end at the innermost layer and is reflected with reversed pole. A voltage opposite to the initially charged voltage is then established, and the current becomes zero.

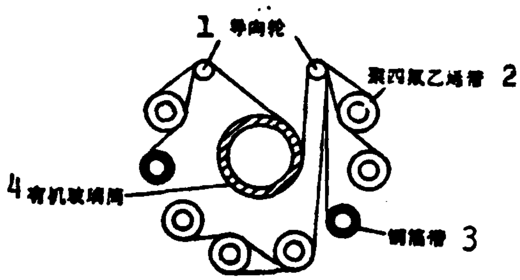

Figure 3. Hand-driven coiling machine
1--guiding wheel; 2--$C_2H_4F_4$ band; 3--copper band; 4--organic glass tube

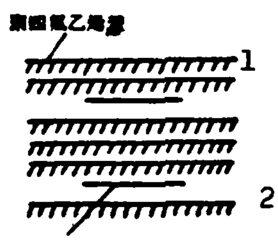

Figure 4. Cross-section of the transmitting line of the TIV generator (thickness of the $C_2H_4F_4$ band is 0.10 mm, thickness of the copper band is 0.05 cm).
1--$C_2H_4F_4$ band; 2--copper band

At $t = \tau$, the wave returns to the switch. The voltage vectors in the active line and the passive line are aligned in the same direction and hence, the output voltage reaches the maximum value. Let n be the number of coils of the generator; then the output voltage V is

$$V = -2nV_0 \qquad (2)$$

and the voltage duration τ of the generator is

$$\tau = \frac{2\pi n D}{v} \qquad (3)$$

where D is the mean diameter of the generator, v is the propagation speed of the wave in the medium. When the voltage is increasing, the whole generator is equivalent to a set of cylindrical capacitors in series. Hence, the effective output capacity of the generator is

$$C = \frac{\pi D W \epsilon}{2nt} \qquad (4)$$

where w, t and ε are, respectively, the width of the transmission line center conductor, the thickness and the dielectric constant of the dielectric medium.

In fact, since layers of the generator are kept in contact by means of a conducting band, the electric vector in the passive line cannot remain fixed and hence, the output voltage cannot reach the value given by equation (2). Furthermore, the inductance in the spark gap switch and the resistance and the losses between the layers of the generator also cause the actual result to be far less than the theoretical value given by equation (2). For instance, the voltage multiplication efficiency η of a 25-coil generator is only 17--30% of the theoretical value.

A 9-cm wide $C_2H_4H_4$ band is used as the insulation medium for the transmitting line. The conducting medium is a 0.05 cm-thick, 2.5 cm-wide copper band. These bands are coiled around the shaft of separate hand-driven machines, and then are coiled together on a 14-cm diameter organic glass tube, as shown in Figure 3. The cross-section of the transmitting line of the TIV generator is illustrated in Figure 4. The medium thickness and the coil number of the TIII generator are slightly different; otherwise, the two generators are basically similar.

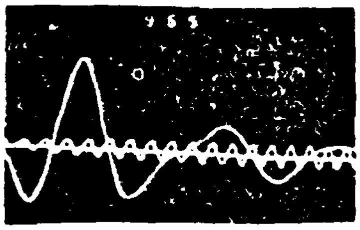

Figure 5. Output voltage wave form of the spiral generator peak voltage value (negative peak: 146 kV)

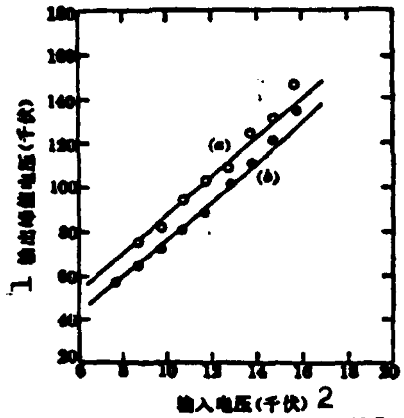

Figure 6. Output voltage curve of the spiral generator

0--TIV generator; 0--TIII generator.
1--output voltage peak value (kV);
2--input voltage (kV)

During the testing process of the generator, leakage at the surface of the medium often occurs, especially at the inner layers. In order to avoid this phenomenon, the generator is immersed in the oil tank of the transformer and is evacuated for 50 hours to drive out all the gas in the layers. This process has been proven to be effective in preventing leakage (see Figure 7).

The two conductor bands of the generator are connected separately on the two poles of the spark gap switch (as shown in Figure 2). The distance between the poles of the spark gap at normal operation condition is 8 mm. This initiating pulse signal which is produced by a hydrogen valve flow pipe passes through the transformer and a 1000 micro-micro Faraday to the mid planar pole. The peak value of the initiation pulse voltage is higher than 7 kV, ensuring effective initiation.

The output voltage of the generator is measured by resistance-type potential meter. Figure 5 shows the wave form of the voltage recorded on an OK-19 high voltage oscilloscope. The relation between the peak value of the output voltage and the input voltage is basically linear. But for high input voltage, the voltage multiplication efficiency of the generator improves. It is obvious from Figure 6 that the efficiency of the TIV generator is higher than that of the TIII generator.

The electron gun

The voltage pulse produced by the spiral generator passes through the spark gap and reaches the cathode of the electric gun, as shown in Figure 7. The electron gun is a vacuum tube with a cold cathode, which is a carbon rod of 3.6 mm diameter supported on a copper base of 25 mm diameter and extends about 20 mm. The tip of the carbon rod is rounded off.

The anode is an iron ne. with a hole-gap efficiency of 77%. The electron beam passes through the anode net, an 8 mm long fieldless region and a 6 mm diameter, 25 μ thick aluminum plate to the measuring chamber. The cathode tube reaches a vacuum of 9×10^{-6} Pa during the operation.

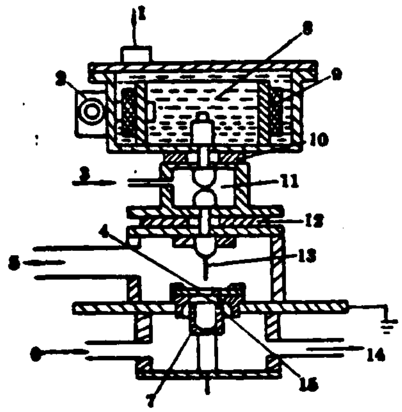

Figure 7. Structure of an electron beam generator.
1--to vacuum; 2--initiation spark gap; 3--nitrogen gas; 4--anode; 5--to vacuum; 6--oxygen; 7--Faraday cup; 8--transformer oil tank; 9--coil generator; 10,12--insulation layers; 11--spark gap; 13--cathode; 14--outlet; 15--aluminum block

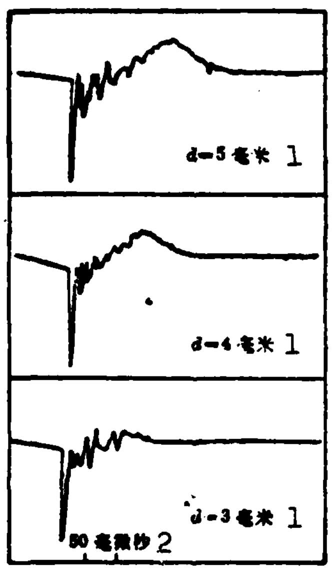

Figure 8. Cathode voltage of the electric gun.
Input voltage: 14.7 kV, pressure in the spark gap: 3-6 atm.
1--mm; 2--nanosecond

Experiments show that, if the spark gap is not added to the cathode, the peak value of the cathqde voltage can only reach about 80 kV. This is because the cathode is initiated before the voltage peak value is reached, producing a relatively weak electron beam signal behind the aluminum plate. The spark gap is hence indispensible for producing high energy nanosecond electron beam pulses. The spark gap is 1 cm wide and is filled with nitrogen gas at 3.0-3.4 atmospheric pressure. Within this pressure range, the voltage across the gap is generally higher than 100 kV.

IV. CALIBRATION AND MEASUREMENT OF THE ELECTRON BEAM GENERATOR

In the vacuum tube, the current density is restricted by the space charge. For one-dimensional condition, the current density J according to the Child-Langmuir law [8] is

$$J = (2.3\times10^{-6})\frac{V^{3/2}}{d^2} \qquad (5)$$

where d is the distance between the anode and cathode. From equation (5) the impedence of the vacuum tube can be obtained as

$$Z = K\frac{d^2}{\sqrt{V}} \qquad (6)$$

where K is a constant.

For effective transfer of energy from the high voltage generator to the electron gun, the impedence of the vacuum tube must be adjusted to match the performance of the generator. It can be seen from equation (6) that the impedence Z of the vacuum tube is a function of d. During calibration, the TIV generator is used as the high voltage pulse source. Under the operating condition of an output voltage peak value of V = 146 kV, the gas pressure in the spark gap is kept constant while the interval d is varied. From the cathode voltage signal recorded by the OK-19 high voltage oscilloscope (Figure 8), it is observed that when d = 5, 4, 3 mm, the positive peak of the voltage signal decreases accordingly. This indicates that the reflected voltage also decreases. When d = 3 mm, the positive peak practically disappears. The peak value of the voltage in the tube is about 107 kV.

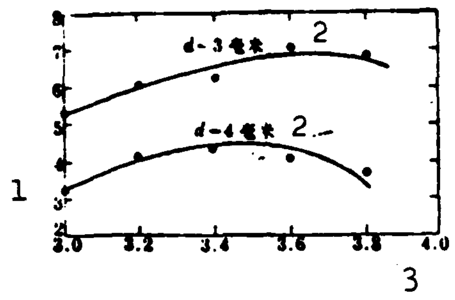

Figure 9. Relation between the peak current value of the electron beam and the spark gap pressure
input voltage: 15.7 kV,
generator: TIV

1--peak current of electron beam (A);
2--mm; 3--atmospheres

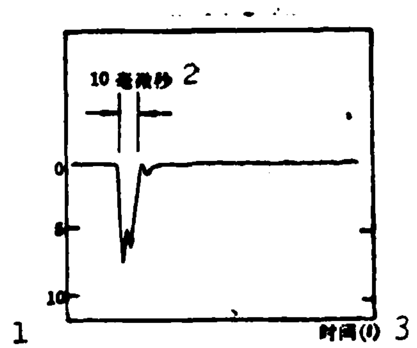

Figure 10. Current signal of the electron beam

1--peak current of electron beam (A);
2--nanosecond; 3--time

The gas pressure P in the spark gap has a significant influence on the voltage of the electron gun. If P is adjusted such that the releasing voltage is close to the peak value of the output voltage V of the spiral generator, then the voltage in the vacuum tube is the greatest. Both an excess or an insufficient pressure would cause a lower voltage. A Faraday cup is placed in the detection chamber of the electron beam device to collect the electrons passing through the aluminum block. A 75 ohm-resistor is connected in series with the Faraday cup calibration loop and the OK-19 high voltage oscilloscope is used to detect the current signal of the electron beam. The detection chamber is evacuated to prevent the effect of air on the dispersion of electrons and the back flow of the ions. The variation of the electron beam current with P and d is observed by varying P and d, respectively, while keeping the output voltage peak value at a constant of V = 146 kV. The experimental results agree with the above analysis almost perfectly. Figure 9 presents the relation between the peak value of the electron gun current with P for d = 3, 4 mm. As the interval d decreases, the peak value of the current increases, but the electron energy decreases slightly. This result also shows the effect of interval d on the impedence. Figure 10 shows the current signal of the electron beam. For P = 3.6 atmospheres and d = 3 mm, the peak current value of the electron beam is 7.1 amperes and the pulse duration (FWHM) is 8 nanoseconds.

To measure the dispersion of the electrons, a blue film which can detect radiation (Hewlett-Packard Avisco Cellophane) is placed behind the anode. The relative distribution of electron beam current on the anode is recorded by "exposing" the film to the electron beam, and then by measuring the distribution of transmissivity of the film with 6328Å He-Ne laser. Figure 11(b) shows that although the distribution range is large, most of the electrons cluster in a disk of 2 cm diameter. Figure 11(a) shows the dispersion of the electrons at the cathode.

5. Conclusion

1. Fitch, et al did not explain completely the appearance of positive peaks in the output voltage signal and the reason why the

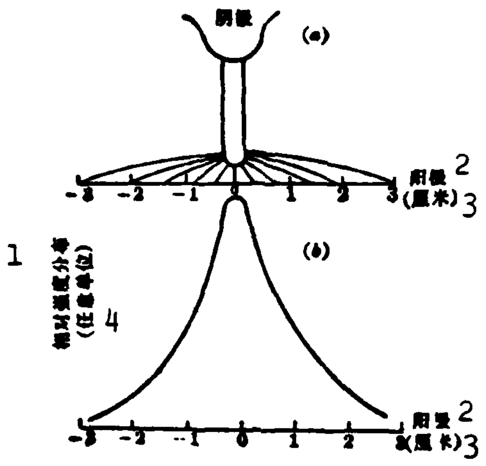

Figure 11. Distribution of the current intensity of the electron beam

1--distribution of relative intensity; 2--anode; 3--cm; 4--arbitrary units positive peak magnitude is much larger than the first negative peak. From our experimental results, we suspect that the signal in Figure 5 is the superposed result of the signals of the active and the passive lines. If the two signals can be separated by some mathematical method, the mechanism of the formation of high voltage pulse in the spiral generator can be analyzed in more detail.

2. By changing the pole of the input voltage, the releasing voltage of the spark gap is raised (such that no release appears at the first peak). The second positive peak can then be employed to obtain a higher voltage-multiplication efficiency.

3. Appropriate dilation of the diameter of the electron beam window can increase the magnitude of the output current of the electron beam significantly.

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