LASERTRON FOR A LINEAR COLLIDER IN TeV REGION

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ABSTRACT

Research and development on a new type of rf source "LASERTRON" have been started for an electron-positron linear collider in the multi-TeV energy region. In the LASERTRON, bunches of electrons are emitted at the photocathode with a mode-locked laser modulated at the microwave frequency. A prototype LASERTRON Mk-I has been developed and the rf power of 1.6 kW has been generated at the frequency of 2884 MHz.

1. INTRODUCTION

A linear collider[1,2) seems to be one of the most appropriate accelerators on the order of 1 x 1 TeV in an electron-positron colliding beam-machine in the future. In the linear collider the particles are accelerated to high energies after passing through the half length of the collider, and they are thrown away after collision. The total length of the linear collider is given by the ratio of the center-of-mass energy and the average accelerating gradient in the linear accelerator . In order to make such large linear accelerators economically feasible, an accelerating gradient greater than 100 MeV/m should be realized. Pulsed rf sources with a peak power of the order of 1 GW are required to generate such high gradients. This rf power is much beyond the level which can be obtained by the conventional technique, and the development of high power rf sources is required.

The LASERTRON[3,4] is a new type of rf source for generating very high peak rf power. Figure 1 shows a conceptual drawing of the LASERTRON. When a photocathode is irradiated by a mode-locked laser modulated at the desired rf frequency, bunches of electrons are emitted from the photocathode during the burst of the laser. The bunches are accelerated by the high voltage applied on the photocathode, and they travel through a cavity gap after passing through an anode. As the electrons are emitted in bunches from the photocathode, the long drift distance required by conventional klystrons for bunching at the relativistic velocity is eliminated. The pulse length of each of the bunches is sufficiently shorter than the rf wavelength, that it is expected to make efficient coupling to the fields in the rf output cavity.

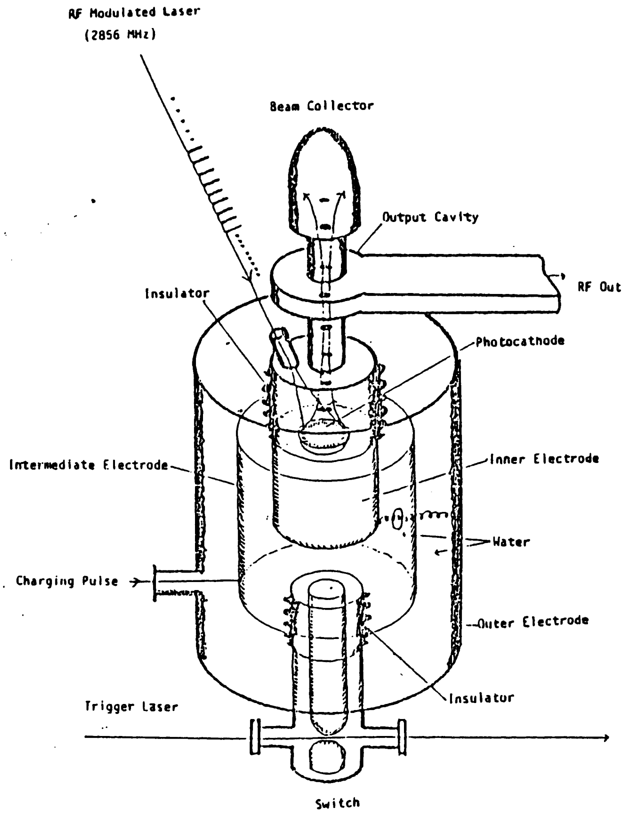


Fig. 1 A conceptual drawing of the LASERTRON.

A prototype LASERTRON Mk-I has been developed, and the rf power of 1.6 kW has been generated by applying the cathode voltage of 30 kV. In order to attain the peak power on the order of 1 GW, many problems over the wide fields in physics and engineering must be solved. Except for the problems in relation to the photocathode material and to the mode-locked laser, the problems seem to be very much like the conventional klystrons. There remains, however, some quite different potential problems on beam dynamics.[5,6]

2. CONVENTIONAL KLYSTRONS

In the conventional klystron , the transit time of electrons between cathode and anode is shorter than the pulse length of the beam, which is generally of the order of 1 μsec. During the beam pulse, electrons are continuously emitted from the thermionic cathode, and then the electrons are filled in a diode during the beam pulse. The current of the beam is limited due to the space-charge effects in a diode. And then the beam current I_0 in the conventional klystron is defined in terms of the applied voltage V_0 and the perveance k as

$$I_0 = k\, V_0^{3/2} \quad . \tag{1}$$

The beam impedance Z_b decreases with square root of the accelerating voltage as

$$Z_b = k^{-1}\, V_0^{-1/2} \quad . \tag{2}$$

The beam power P_b depends on the accelerating voltage and is given by

$$P_b = k\, V_0^{5/2} \quad . \tag{3}$$

The rf power is, therefore, obtained by multiplying the conversion efficiency η_{rf} of the beam power to the rf output as

$$P_{rf} = k\, \eta_{rf}\, V_0^{5/2} \quad . \tag{4}$$

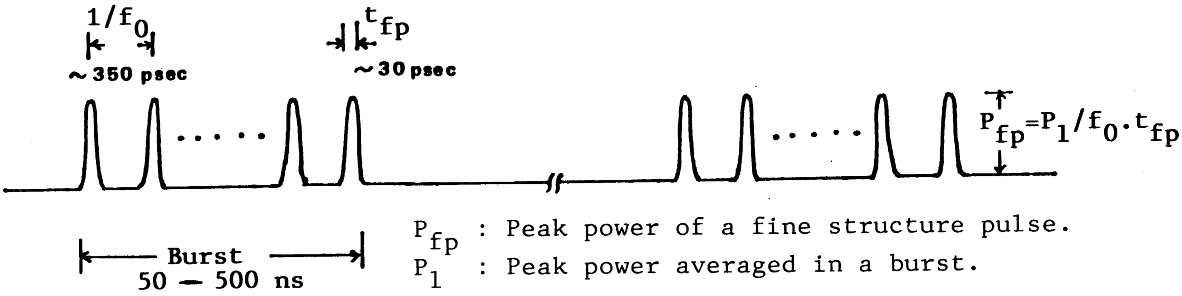
As the perveance k increases, the space-charge effect becomes more severe, which makes it more difficult to obtain the small mono-energetic bunches at the gap of the rf output cavity. The efficiency η_{rf} of the conventional klystrons, therefore, decreases with increasing perveance.7) If an efficiency greater than 60 % is required, the perveance should be less than 2×10^{-6} A / $V^{-3/2}$. When the rf power on the order of 1 GW is to be generated, the applied voltage V_0 should be increased to the range between 1 - 2 MV. At such high beam voltage, more rf input power or a longer drift distance is required to modulate the high-current electron beam.

3. LASERTRONS

In the LASERTRON , the photocathode is irradiated by a mode-locked laser modulated at the rf frequency f_0. As shown in Fig. 2-a, the burst of the laser consists of many fine structure pulses with the time interval of $1/f_0$. The number of photons in a fine structure pulse is given by

$$n_{ph} = \frac{\lambda\, P_1}{h\, C\, f_0} \quad , \tag{5}$$

where P_1 is a peak power averaged in the burst in W, λ is the wavelength of the laser and h is Plank's constant.



P_{fp} : Peak power of a fine structure pulse.
P_l : Peak power averaged in a burst.

Fig. 2-a Laser required for LASERTRON.

The quantum efficiency η_e is not saturated at the laser power required for the LASERTRON , and then the number of electrons generated on the photocathode is proportional to the number of photons. The shape of the bunch might be equal to the shape of the fine structure pulses of the mode-locked laser. The charge Q_e of photoelectrons produced on the photocathode is, therefore, given by,

$$Q_e = e\,\eta_e\,n_{ph}\ . \tag{6}$$

And then the current of the photoelectrons is given by,

$$I_e = f_0\,Q_e\ . \tag{7}$$

However, the number of electrons, which can be accelerated by the applied voltage V_0 between cathode and anode, is limited by space-charge effects. The pulse width of the fine structure pulse of the mode-locked laser is on the order of 10 ps, and then the transit time of electrons between cathode and anode is longer than the pulse width of the bunch. The bunch length is quite shorter than the cathode-anode distance. When a bunch travels through the cathode-anode gap, bunched electrons exist only in a fraction of the space in the cathode-anode gaps as shown in Fig. 2-b. In this respect, the LASERTRON differs entirely from the conventional klystron .

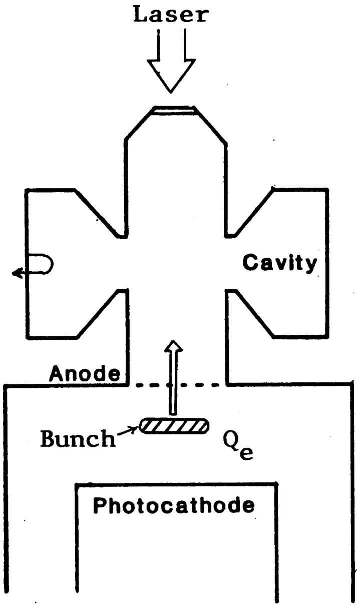


Fig. 2-b Bunch exists in a fraction of the space in the diode.

When the laser power is sufficiently intense, the maximum charge of a bunch is determined not by the charge Q_e but by the limited charge Q_c, which is equal to the surface charge Q_s on the photocathode induced by the applied voltage. The surface charge Q_s is obtained both by the applied voltage V_0 and by the capacitance C between cathode and anode as

$$Q_s = C\ V_0\ . \tag{8}$$

In a planar diode, the capacitance C is obtained by

$$C = \epsilon_0\ S\ /\ d\ , \tag{9}$$

where S is the surface area of the photocathode and d is the distance between anode and cathode.

The bunches are emitted at the repetition rate equal to the rf frequency f_0, so that the average beam current I_0 is also limited by the surface charge Q_s. Therefore, I_0 should be smaller than the limited current I_c, which is given by

$$\begin{aligned} I_c &= f_0\ Q_s \\ &= f_0\ C\ V_0\ . \end{aligned} \tag{10}$$

The limited current I_c is proportional to the applied voltage V_0, and then the beam impedance Z_b is independent of V_0 as

$$\begin{aligned} Z_b &= V_0\ /\ I_c \\ &= 1\ /\ f_0\ C\ . \end{aligned} \tag{11}$$

The beam power P_b is given by

$$P_b = f_0\ C\ V_0^2\ . \tag{12}$$

The rf power is, therefore, obtained by multiplying the conversion efficiency η_{rf} of the beam to the rf power as

$$P_{rf} = f_0\ C\ \eta_{rf}\ V_0^2\ . \tag{13}$$

The rf power depends on V_0^2 in the LASERTRON while on $V_0^{5/2}$ in the klystrons. It is the dependence of rf power on the applied voltage that makes difference between LASERTRONS and klystrons.

4. PROTOTYPE LASERTRON Mk-I

4.1 Mode-Locked Laser System

The laser system consists of a passive and active mode-locked YAG laser. After increasing the laser power by two amplifiers, the wavelength is converted from 1.06 to 0.53 μm with a KD^*P crystal in order to shift the wavelength to the sensitive region of the photocathode material. The pulse width of the burst is 50 ns, and the total energy per burst is 50 μJ. The laser output from the amplifier consists of the fine structure pulses with the frequencies of 169.6 MHz. In order to obtain the frequencies in S-band, an etalon is utilized to multiply the frequency to 2884 MHz, which is 17 times 169.9 MHz. The shape of the each fine structure pulse of the laser is measured by a streak camera and the pulse width is estimated to be 35 ps, while the time interval between pulses is 347 ps. As the peak power averaged in a burst is 1 kW, the peak power of each fine structure pulse is estimated to be about 10 kW.

4.2 LASERTRON Mk-I

Figure 3 shows the crosssectional drawing of the LASERTRON Mk-I. It was fabricated by modifying a photo-diode8) which is commercially obtained for the detection of the light pulse on subnanosecond time scale. The LASERTRON Mk-I consists of an electron gun and a cylindrical rf output cavity.

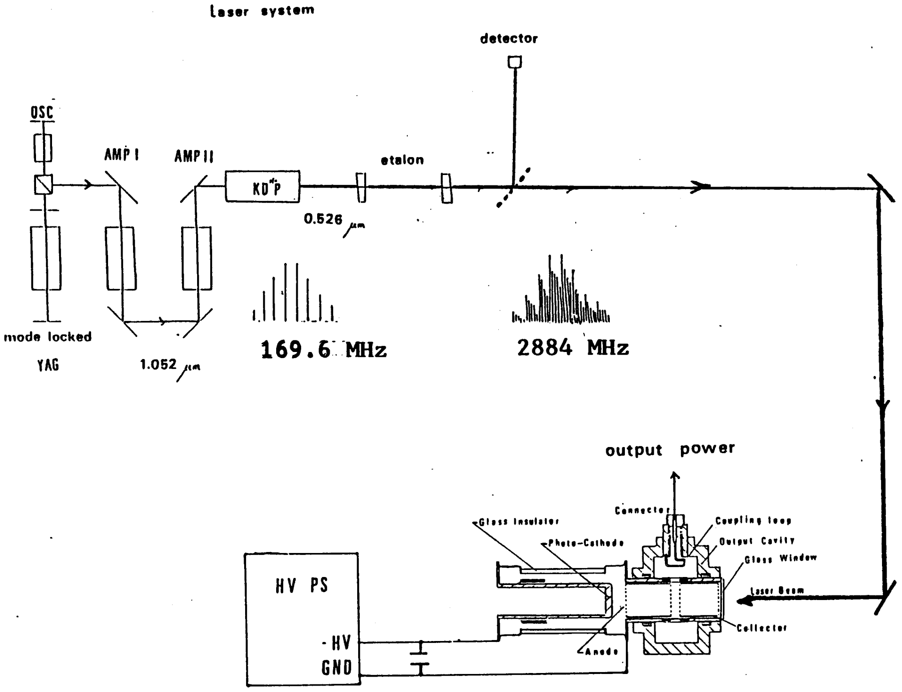


Fig. 3 A crosssectional view of the LASERTRON Mk-I and the experimental arrangement.

The photocathode material is made of bi-alkali and the effective area of the photocathode is 1.33 cm^2. The gap distance between the cathode and the anode mesh is 0.75 cm. The cavity is mounted on a glass tube after chipping off the tube, and then the inside of the cavity is in the atmosphere. The resonant frequency of the cavity is adjusted to the frequency of 2884 MHz, and the rf loss factor Q is estimated to be 75. The rf power is picked up by a coupling loop with the coupling efficiency of 0.3. Two meshes are set at the cavity gap in the drift tube in order to improve the transit angle even if the accelerating voltage is low. The gap distance between these meshes is 5 mm. The beam collector consists of a mesh on the glass window so that the laser light penetrates from the outside of the LASERTRON Mk-I to the photocathode. A high DC-voltage was supplied to the cathode through a charging coaxial-line in order to supply charges with fast time-response.

5. EXPERIMENTAL RESULTS AND DISCUSSIONS

Experiments have been performed with a prototype LASERTRON Mk-I to obtain the fundamental data required for development of next LASERTRON. As a function of applied voltage V_0, the beam current I_0 is shown in Fig. 4 and the rf power P_{rf} is shown in Fig. 5. At the maximum applied voltage of 30 kV, which is the limited voltage due to breakdown, both the beam current I_0 of 10 A and the rf power of 1.6 kW have been observed. The power of the present laser is sufficiently intense since the current of photoelectrons I_e is estimated to be 12 A, which is higher than the maximum beam current of 10 A at 30 kV. If the beam current is lower than I_e, it is expected that the beam current I_0 increases in proportion to the applied voltage V_0 and that the rf power increases with square of the applied voltage. The experimental results show that the rf power increases with $V_0^{2.8}$. It seems that the conversion efficiency η_{rf} depends on the applied voltage V_0, since the transit angle of the bunched beam in the cavity gap depends on the non-relativistic velocity of the bunches.

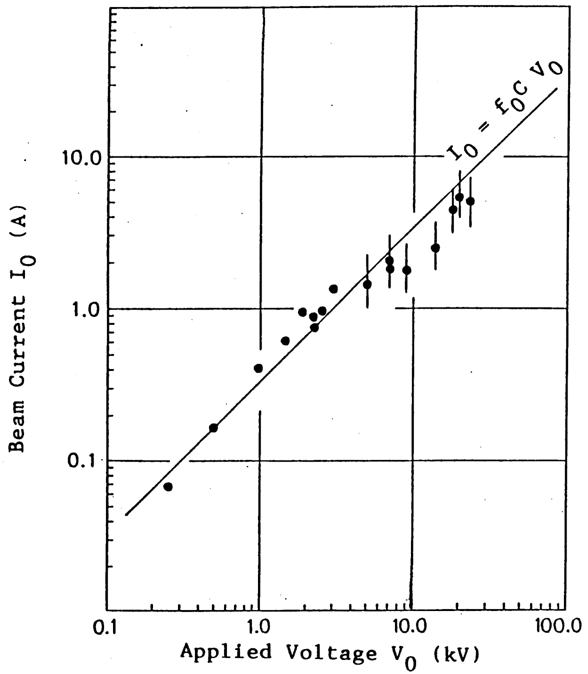


Fig. 4 The average beam current I_0 per burst of laser.

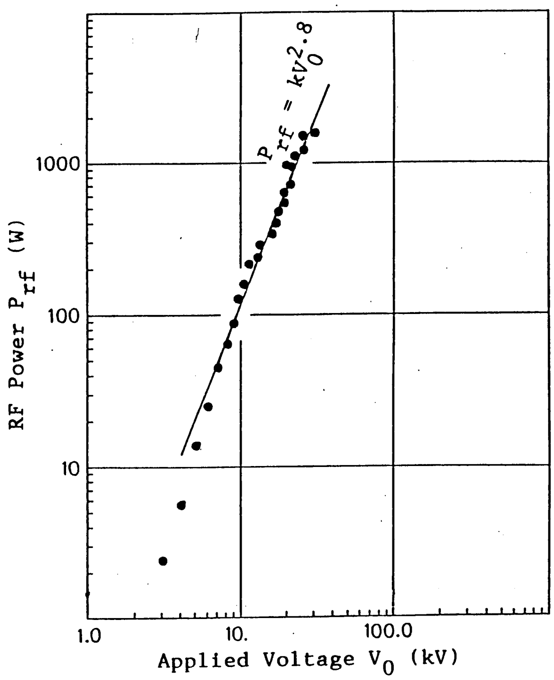


Fig. 5 The rf power as the function of applied voltage.

6. CONCLUSION

An rf power of 1.6 kW has been generated at the rf frequency of 2884 MHz by applying the accelerating voltage of 30 kV. A new prototype of the LASERTRON is now being studied in order to increase the applied voltage. Several kinds of cathode materials with negative electron affinity are also being studied to obtain high current beam and to realize the demountable photocathode gun.

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Discussion

J. Rees, SLAC

At the end of your talk you mentioned plans for a Lasertron Mk II, operating at 300 kV to give a peak power of ~ 50 MW. What are the radio-frequency, pulse length and repetition rate?

Answer

The linear collider group propose a disc and washer accelerating structure operating at 2.8 GHz, so this is the frequency for the lasertron. The pulse length is 70 ns and the repetition rate 200 Hz.

L. Funk, Chalk River

What is the efficiency of your lasertron, and what do you expect will be the upper limit of achievable efficiency?

Answer

We expect about 50%.