Laser-induced emission of strong electron pulses in the nanosecond range

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Abstract

The light of a Q-switched ruby laser (2.5 joule, 17 nsec) is focussed on a tantalum target. Strong electron pulses up to one kiloampere are extracted from the surface. The pulse length in the nanosecond range can be determined by the length of a delay line used as voltage source for the extracting voltage. In additional experiments we identified the charge carriers in the negative pulse to be really free electrons.

Introduction

Accelerators for relativistic electron rings are a new type of machine with which it is hoped to get higher ion energies than those hitherto reached with ordinary accelerators /1/. At the beginning of the accelerating process electrons from a linear accelerator in the MeV range are shot into a magnetic field. These electrons are trapped in a ring. It is electron rings with 10^{13} to 10^{14} electrons that are of interest. These rings can be filled in one or many turns. Therefore, it is necessary to have an electron source for the accelerator that can deliver current pulses of the order of a few hundred to a few thousand amperes in the nanosecond range. One of the most important requirements in this electron source is very small emittance. The value of this quantity is of the order of 200 mrad·cm in ordinary sources with currents up to some hundreds of amperes. It would be very convenient to reduce this value to one or two orders of magnitude. One possibility of keeping the emittance low is to make the electron source as punctiform as possible. The focal point of a laser beam has, in practice, an area of 10^{-2} to 10^{-4} cm^2. If it is possible to produce an electron current pulse of the required magnitude and pulse length by focussing the light of a laser beam on a target surface, this electron source should be very suitable for electron ring accelerators.

Electron emission from a solid surface by interaction with a high power laser beam is described in a number of publications. These can be divided into three groups. Firstly, emission by the nonlinear photoeffect /2,3/. The electron currents are of the order of microamperes. Secondly, thermal emission from a solid surface /4-19/. The power density of the focussed laser beam is about $10^7 W/cm^2$. The measured currents are of the order of up to 100 milliamperes. The current pulse coincides with the laser pulse. The authors interpret this current in terms of the thermal emission of electrons from the surface. The Richardson-Dushman equation is used to calculate the surface temperature. Thirdly, electron emission from a laser-produced plasma /20-24/. The power density of the focused laser beam is about 10^{10}W/cm^{2}. The electron currents range from one ampere to several thousand amperes. The results of some experiments are not free of contradictions. In similar experiments the measured currents differ by several orders of magnitude.

We tried to build a punctiform electron source that might be suitable for an electron ring accelerator if the emittance can be kept low enough. In a first experiment we observed in the recorded probe current, extracted by an applied voltage, a negative electron peak followed by a stronger current across the expanding plasma cloud produced when the laser beam hits the target. In an improved experimental setup the electron pulse was separated. To date we have succeeded in getting an electron pulse in the nanosecond range with an amplitude of about 10^{3} amperes. The charge carries in the negative pulse have subsequently been identified as really free electrons.

First experiments

We started with the experimental setup shown in fig. 1a. The cathode of our circuit was a tantalum plate on which we focussed a ruby laser beam. The focal length of the lens was 15 cm. The output energy was attenuated with filters to 0.1 joule and the half-width of the laser pulse was 17 nsec (about 6 MW). The anode of our circuit was grounded by a 0.5 Ω coaxial resistor. The voltage drop across this resistor was measured by a Tektronix 519. The voltage source was a low-inductance capacitor of 60 nF. The capacitor was charged to 1 kV. The cathode - to - anode distance was 4 cm.

The measured pulse can be seen in fig. 1b. The main part of the current pulse consists of a damped oscillation in front of which a small negative pulse can be seen. The laser pulse coincides with the beginning of this small negative pulse. For the oscillogram we have the following explanation: The first small negative pulse is produced by electrons emitted by the cathode when the laser beam hits the surface of the tantalum target. With a time delay the expanding tantalum plasma reaches the anode and produces a short circuit between the cathode and anode. The capacitor is discharged across this plasma cloud by a damped oscillation. The oscillation frequency is about 1.3 Mc. With a capacitance of 60 nF this corresponds to a circuit inductance of about 250 nHy. This value agrees well with the estimated data in the circuit. If one computes the velocity with which the plasma expands away from the target surface according to fig. 1b one get velocities up to $10^7 \frac{\text{cm}}{\text{sec.}}$. That means a few keV of energy for the tantalum ions. This energy seems very high, but has also been measured by other authors /25-31/. The reason for this high ion energy is not known.

As was pointed out in the introduction, we are only interested in the electron pulse emitted by the cathode. It was therefore

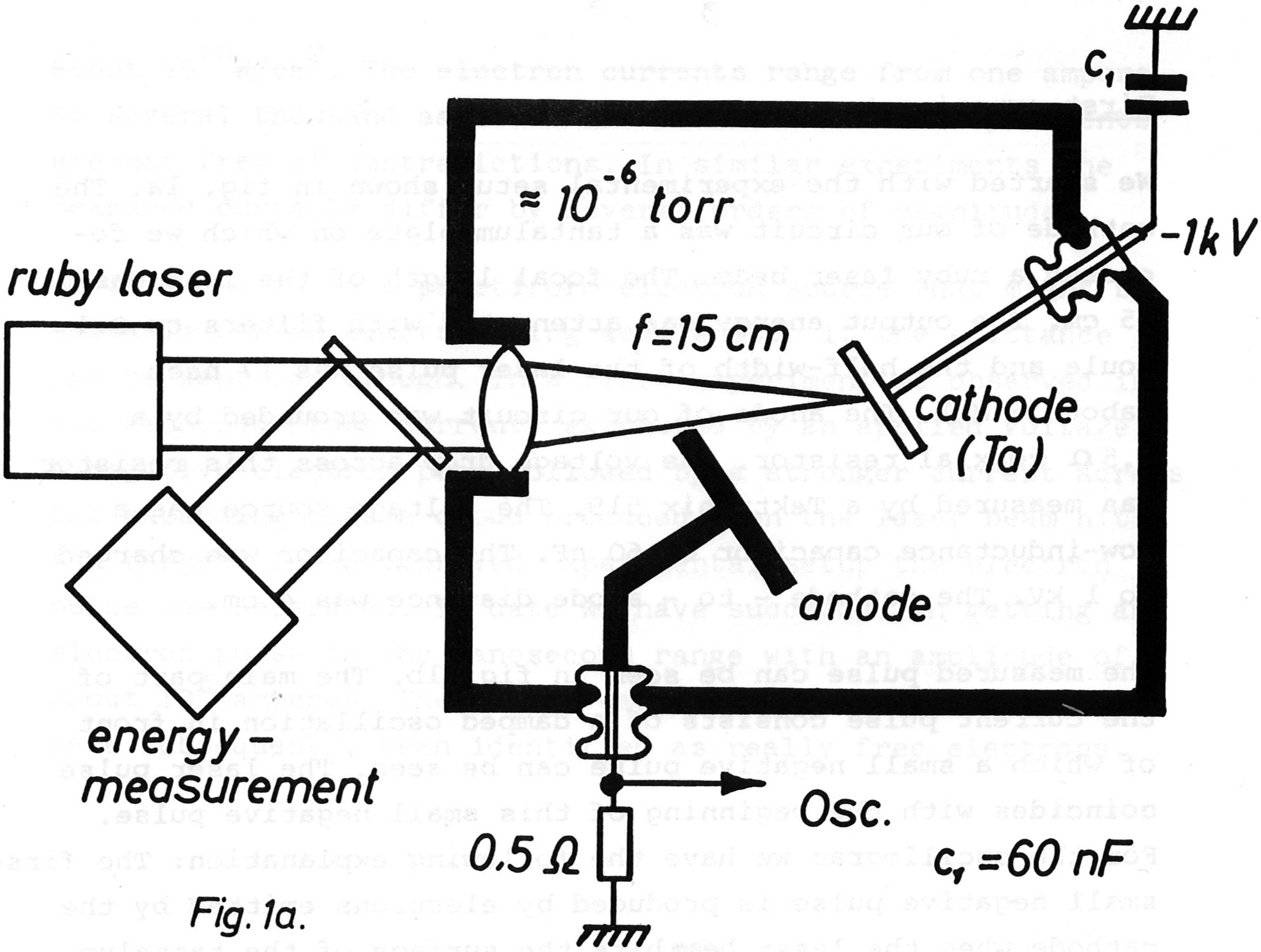


Fig. 1a.

C₁ – charging voltage 1 kV

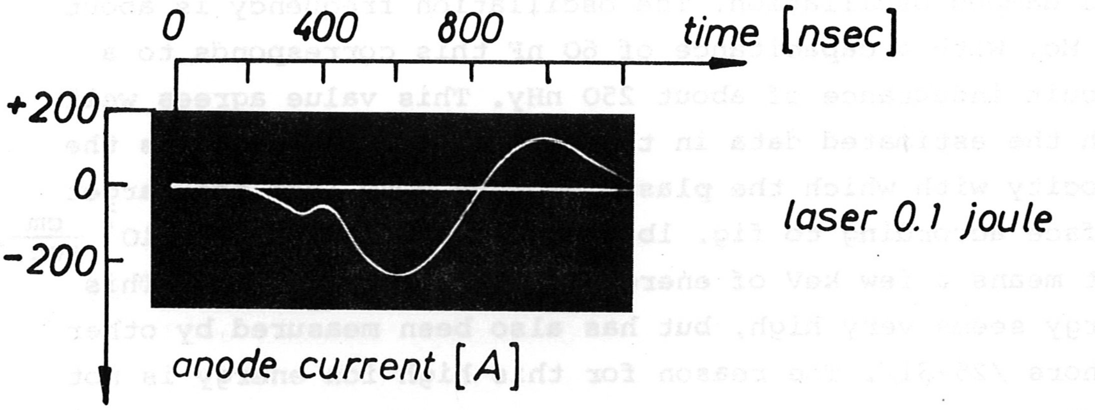


Fig. 1b

Fig. 1 a) Experimental setup of the first experiment

1b) Current pulse

decided to replace the capacitor by another circuit which allows the voltage between the cathode and the anode to be switched off before the expanding plasma cloud from the target has reached the anode.

Improved experimental setup

The improved experimental setup can be seen in fig.2. The capacitor of fig. 1a is now replaced by a coaxial line with a characteristic impedance of 26 Ω . At one end the inner conductor of the line is connected to the cathode. The outer conductor is grounded. At the other end we installed a series connection of a 26 Ω load and a laser-triggered spark gap. The spark gap is triggered by part of the laser energy without a time delay ($<$ 5 nsec) when the energy level of the laser is high enough. This happens at the time when the laser beam hits the target and the electrons are emitted from the cathode. Now the line is terminated at this end by a load equal to its characteristic impedance. An electric pulse travels along the line and discharges it. When the pulse arrives at the other end the high voltage (30 kV) at the cathode is switched off. In this way the time between the ignition of the spark gap and the voltage breakdown at the cathode is determined by the delay time of the line and can be appointed by the length of the line (about 20 cm per nsec). The current at the anode is measured by the voltage drop across a 0.5 Ω coaxial resistor and recorded by a Tektronix 519 with an input impedance of 125 Ω. The 0.5 Ω resistor consists of 20 coaxially arranged composition resistors of 10 Ω. In each composition resistor the skin depth is large compared with the linear dimensions. As in the first experimental setup,the cathode was a thick plate of tantalum and the basic pressure in the vacuum chamber was about 10^{-6} torr.We used a two stage Q-switched ruby laser with an energy up to 2.5 joule and a half width of the laser pulse of 17 nsec. The beam divergence was 5 mrad and the focal length of the focussing lens was 15 cm. Therefore, the focal spot has a radius of 7.5 x 10^{-2} cm.

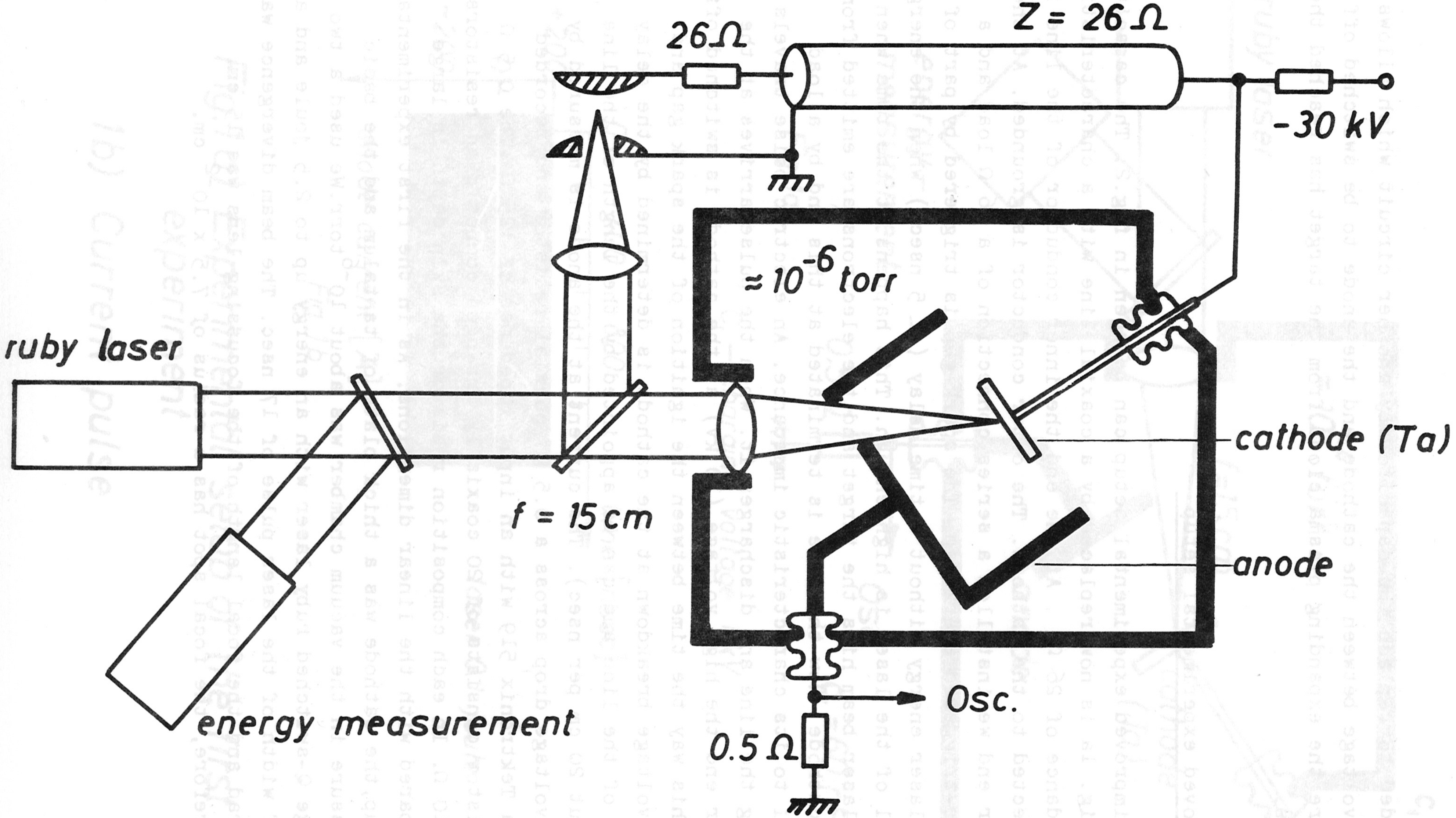


Fig. 2 Jmproved experimental setup

Results

Our experimental results can be divided into two groups, one of low and one of high power density in the laser focus. In both cases the laser energy used was of the same order. The difference between the two cases was the area of the focal spot. The high power density was of the order of 10^{10} W/cm^2 (radius of the focal spot about $7x10^{-2}$cm), and the low power density was about one order of magnitude lower. In fig. 3 two characteristic electron pulses are shown for the low power regime. The length of the line in this case was 5.5 m. This means a time delay of about 30 nsec. The measured pulse length is 40 nsec because the spark gap has a time delay of 10 nsec. The reason is that the energy level of the triggering laser beam was too low for switching without time delay. The charging voltage of the line was -30 kV. The cathode-anode voltage is equal to the charging voltage of the line minus the voltage drop across the internal resistance of the line. The electron current versus the laser energy on the target is shown in fig. 4. The electron current does not depend strongly on the charging voltage of the line, as can be seen from the measured values with a higher charging voltage (34 kV). These points are within the spread of the points for 30 kV. In our experimental setup the maximum possible voltage was 34 kV. This value is very low compared with the approximately 2 MV planned for the final electron source. Therefore, we did not measure the current dependence versus the charging voltage in this low voltage regime.

Characteristic current pulses for the high power regime are shown in fig.5. In fig. 5a and 5b the line length is 5.5 m and in fig. 5c it is 16 m. These pictures show the effect of the line length on the pulse duration. In fig. 5a and 5b the half width of the current pulse is about 45 nsec and in fig. 5c about 110 nsec. The charging voltage of the line is again -30 kV. As shown in fig. 6, the electron current in the high power regime is of the order of a few hundred amperes. With rising current the gradient of the curve becomes lower. We suppose that one reason for this effect is the voltage drop across the inner impedance of the line, which lowers the chathode-anode voltage. With the same laser energy, but with

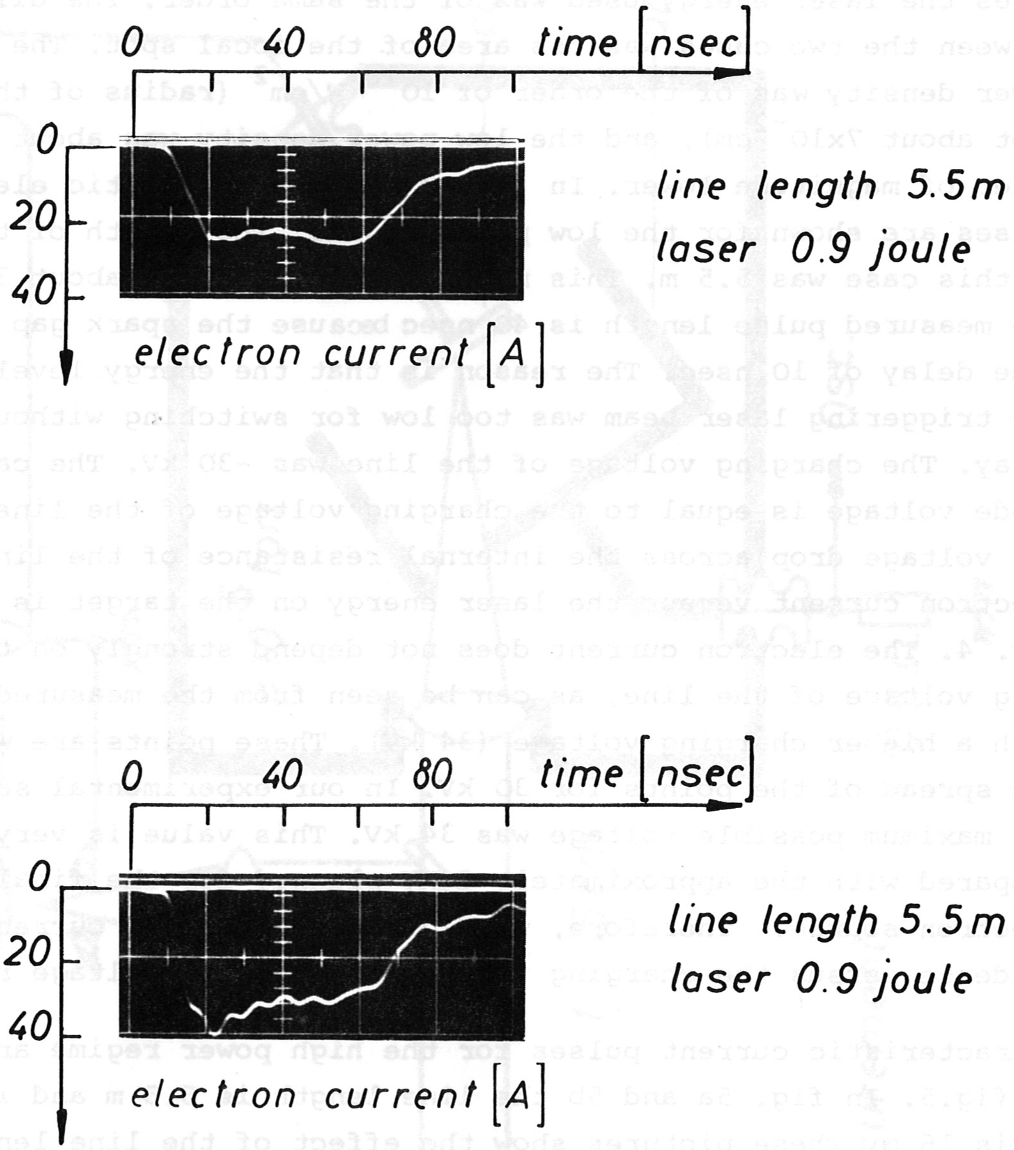


Fig. 3 Electron pulses in the low power regime

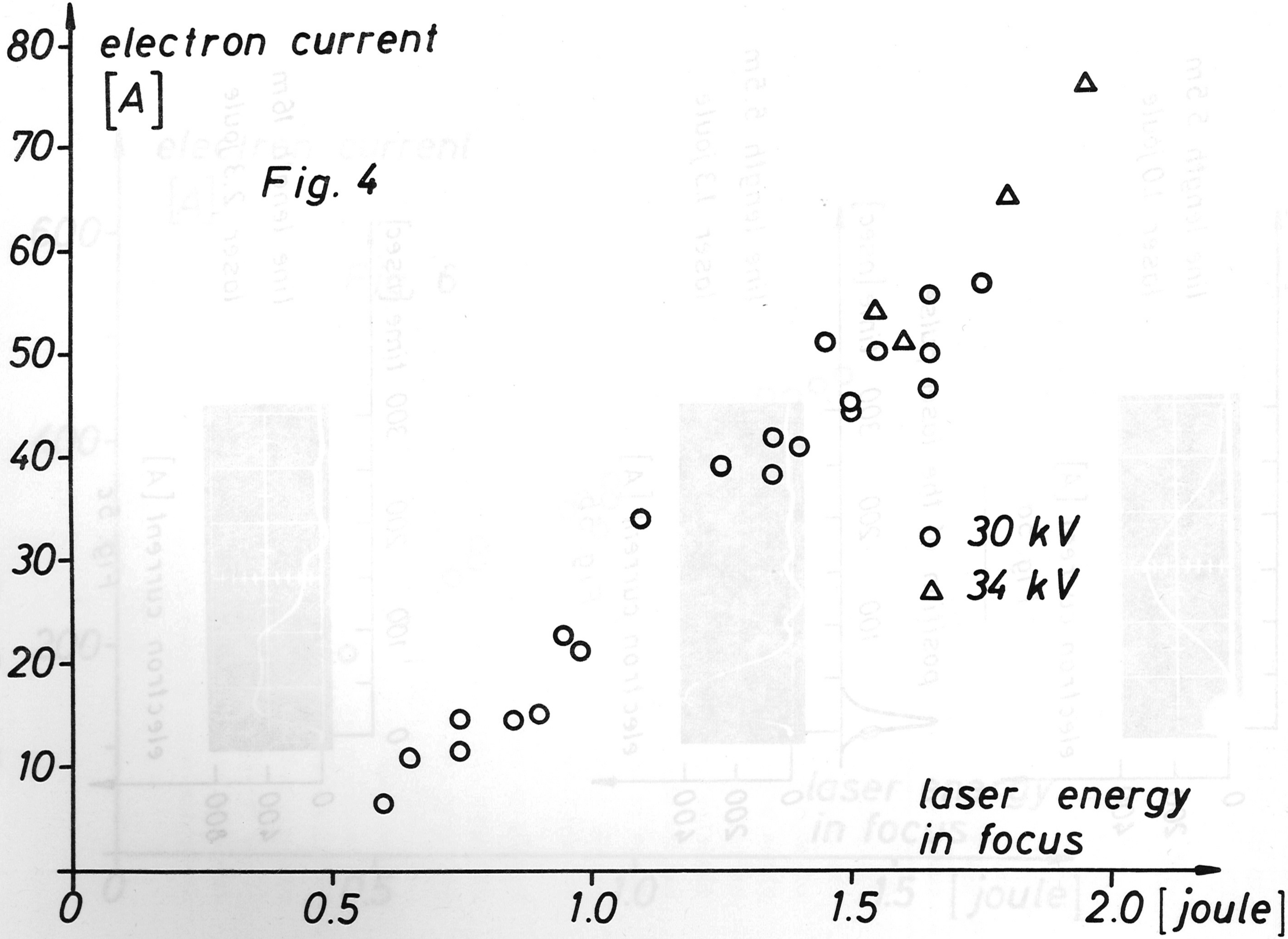
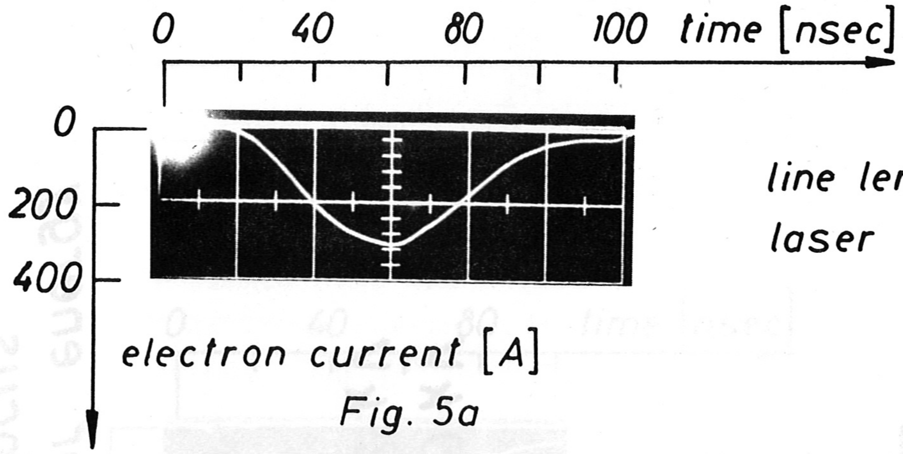


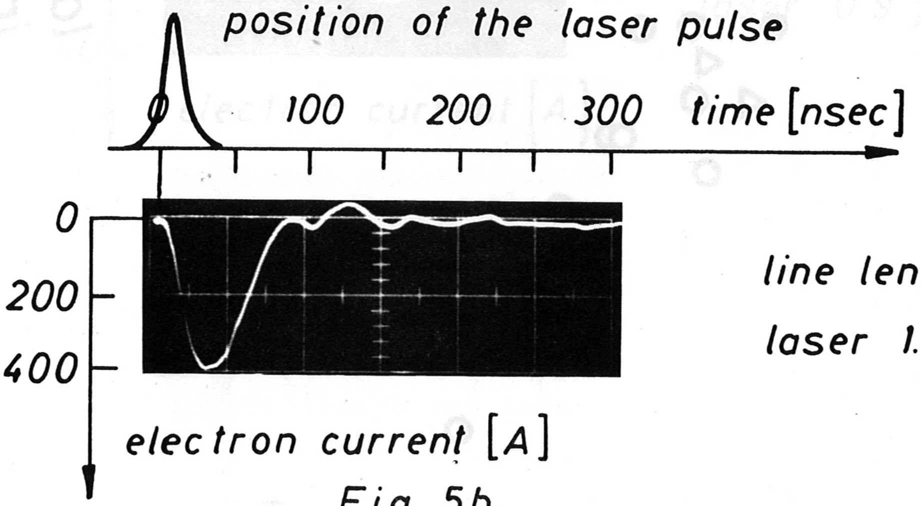
Fig. 4

electron current [A]
80
70
60
50
40
30
20
10
0
0.5
1.0
1.5
2.0 [joule]
laser energy in focus
○ 30 kV
△ 34 kV



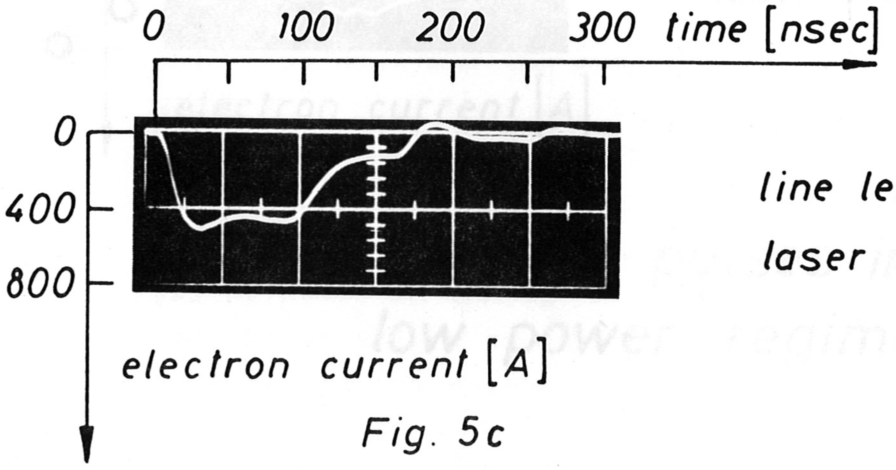
line length 5.5m
laser 1.0 joule

Fig. 5a



line length 5.5m
laser 1.3 joule

Fig. 5b



line length 16m
laser 2.3 joule

Fig. 5c

Fig. 5 Electron pulses in the high power regime

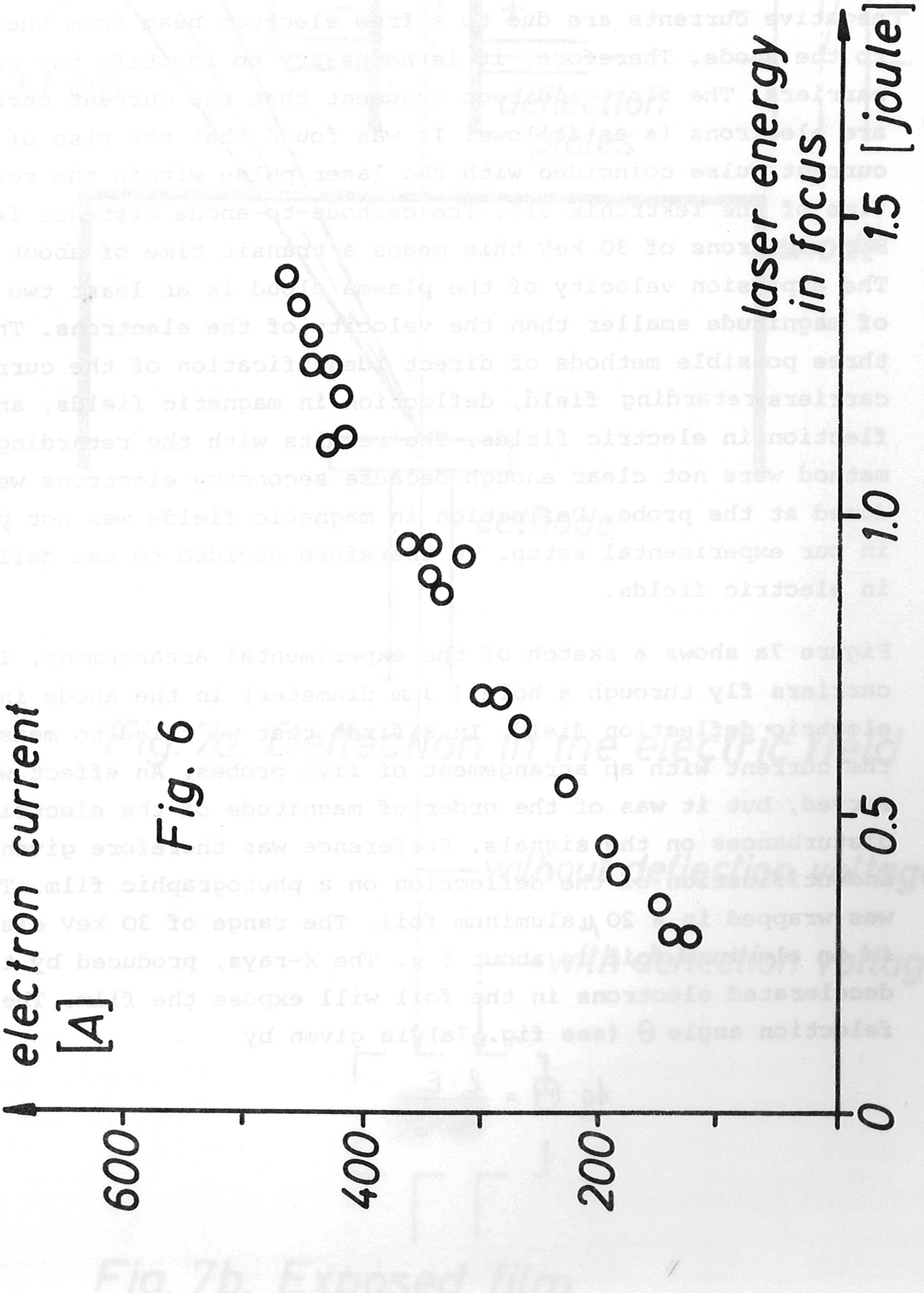

electron current [A]
600
400
200
0
0.5
1.0
1.5 [joule]
laser energy in focus

Fig. 6

extremly good focusing, we reached pulses with amplitude of up to 1000 ampers.

Identification of the current carriers

It is not evident from the very beginning that the measured negative currents are due to a free electron beam from the cathode to the anode. Therefore, it is necessary to identify the current carriers. The first indirect argument that the current carriers are electrons is as follows: It was found that the rise of the current pulse coincided with the laser pulse within the resolving time of the Tektronix 519. The cathode-to-anode distance is 4cm. For electrons of 30 keV this means a transit time of about 0.8 nsec. The expansion velocity of the plasma cloud is at least two orders of magnitude smaller than the velocity of the electrons. There are three possible methods of direct identification of the current carriers;retarding field, deflection in magnetic fields, and deflection in electric fields. The results with the retarding field method were not clear enough because secondary electrons were produced at the probe. Deflection in magnetic fields was not possible in our experimental setup. We therefore decided to use deflection in electric fields.

Figure 7a shows a sketch of the experimental arrangement. The charge carriers fly through a hole (3mm diameter) in the anode into the electric deflection field. In a first test we tried to measure the current with an arrangement of five probes. An effect was observed, but it was of the order of magnitude of the electric disturbances on the signals. Preference was therefore given to indentification of the deflection on a photographic film. The film was wrapped in a 20 μ aluminum foil. The range of 30 keV electrons in an aluminum foil is about 5 μ. The X-rays, produced by the decelerated electrons in the foil will expose the film. The defelection angle Θ (see fig. 7a) is given by

$$tg\, \Theta = \frac{l \cdot E}{2\, U_B}$$

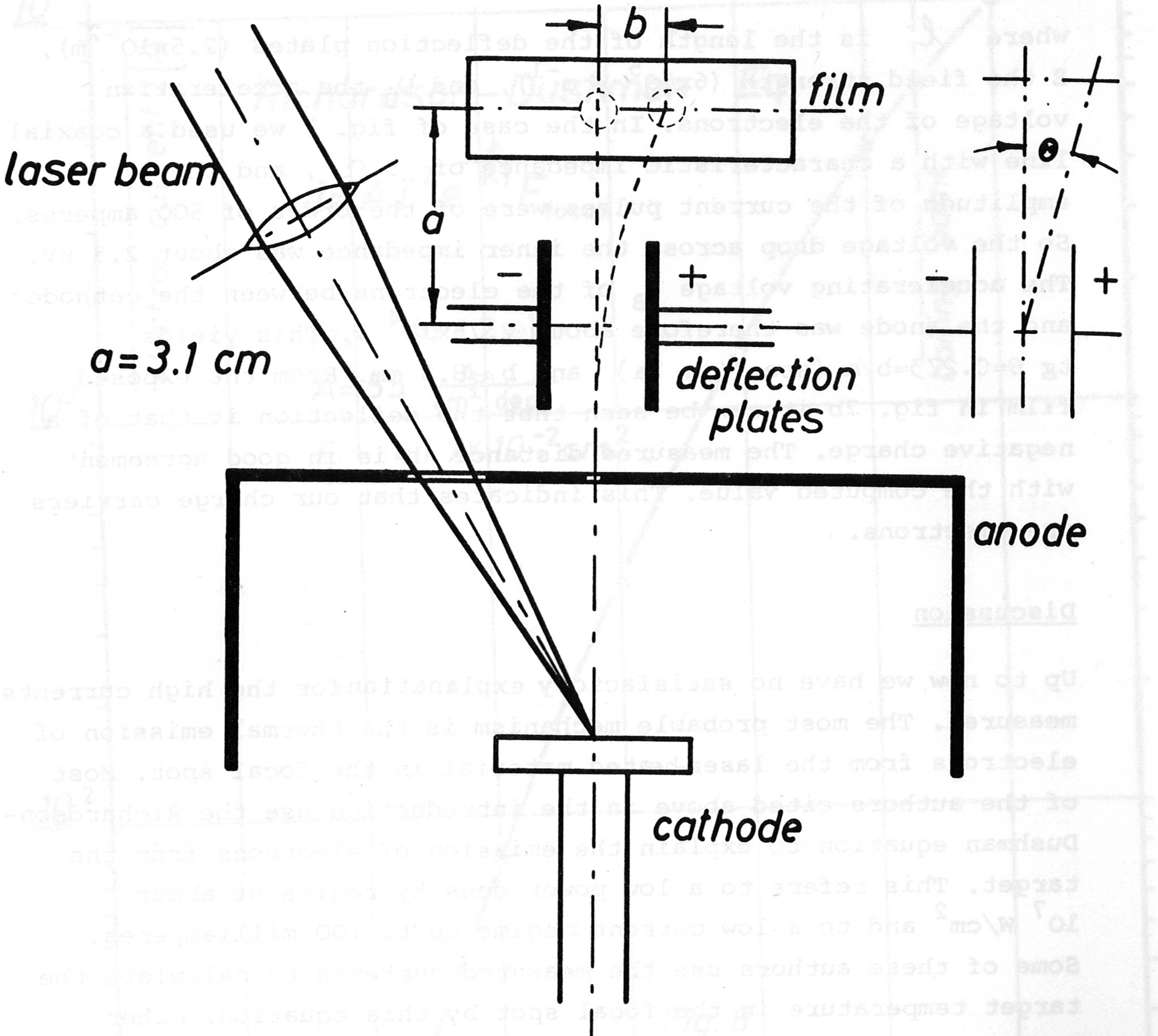


Fig. 7a. Deflection in the electric field

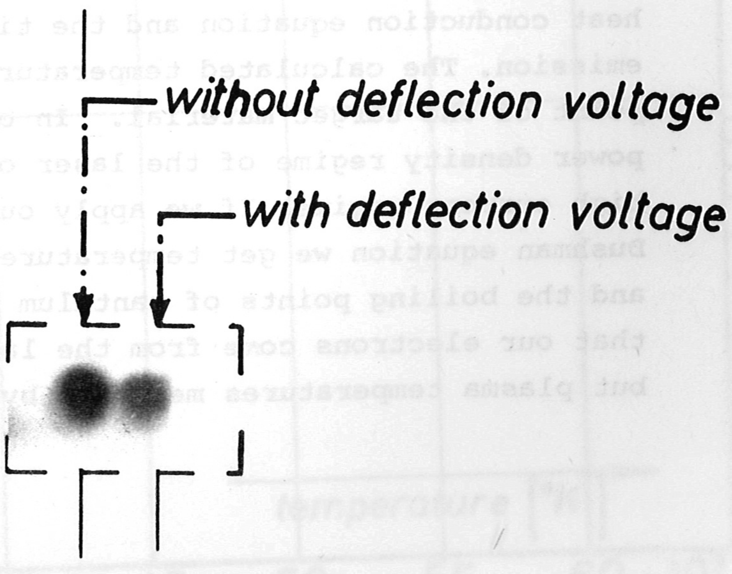


Fig. 7b. Exposed film

where ℓ is the length of the deflection plates (2.5×10^{-2}m), E the field strength (6×10^{5} V·m^{-1}), and U_B the acceleration voltage of the electrons. In the case of fig. 7 we used a coaxial line with a characteristic impedance of 5 Ω, and the amplitude of the current pulses were of the order of 500 amperes. So the voltage drop across the inner impedance was about 2.5 kV. The accelerating voltage U_B of the electrons between the cathode and the anode was therefore about 2.75×10^{4} V. This yields $\mathrm{tg}\ \Theta=0.273=b/a$ (see fig. 7a) and $b\approx8.5$ mm. From the exposed film in fig. 7b it can be seen that the deflection is that of a negative charge. The measured distance b is in good agreement with the computed value. This indicates that our charge carriers are electrons.

Discussion

Up to now we have no satisfactory explanation for the high currents measured. The most probable mechanism is the thermal emission of electrons from the laser-heated material in the focal spot. Most of the authors cited above in the introduction use the Richardson-Dushman equation to explain the emission of electrons from the target. This refers to a low power density regime of about 10^{7} W/cm^{2} and to a low current regime up to 100 milliamperes. Some of these authors use the measured currents to calculate the target temperature in the focal spot by this equation. Other authors compute from the energy dissipated in the focal spot the time dependence of the focal temperature with the aid of the heat conduction equation and the time dependence of the electron emission. The calculated temperatures are lower than the melting point of the target material. In our case we are in a high power density regime of the laser of about 10^{10} W/cm^{2} and in a high current regime. If we apply our results to the Richardson-Dushman equation we get temperatures (fig.8) between the melting and the boiling points of tantalum (about 5×10^{3} ^{o}K). We think that our electrons come from the laser-produced tantalum plasma, but plasma temperatures measured by other methods in similar ex-

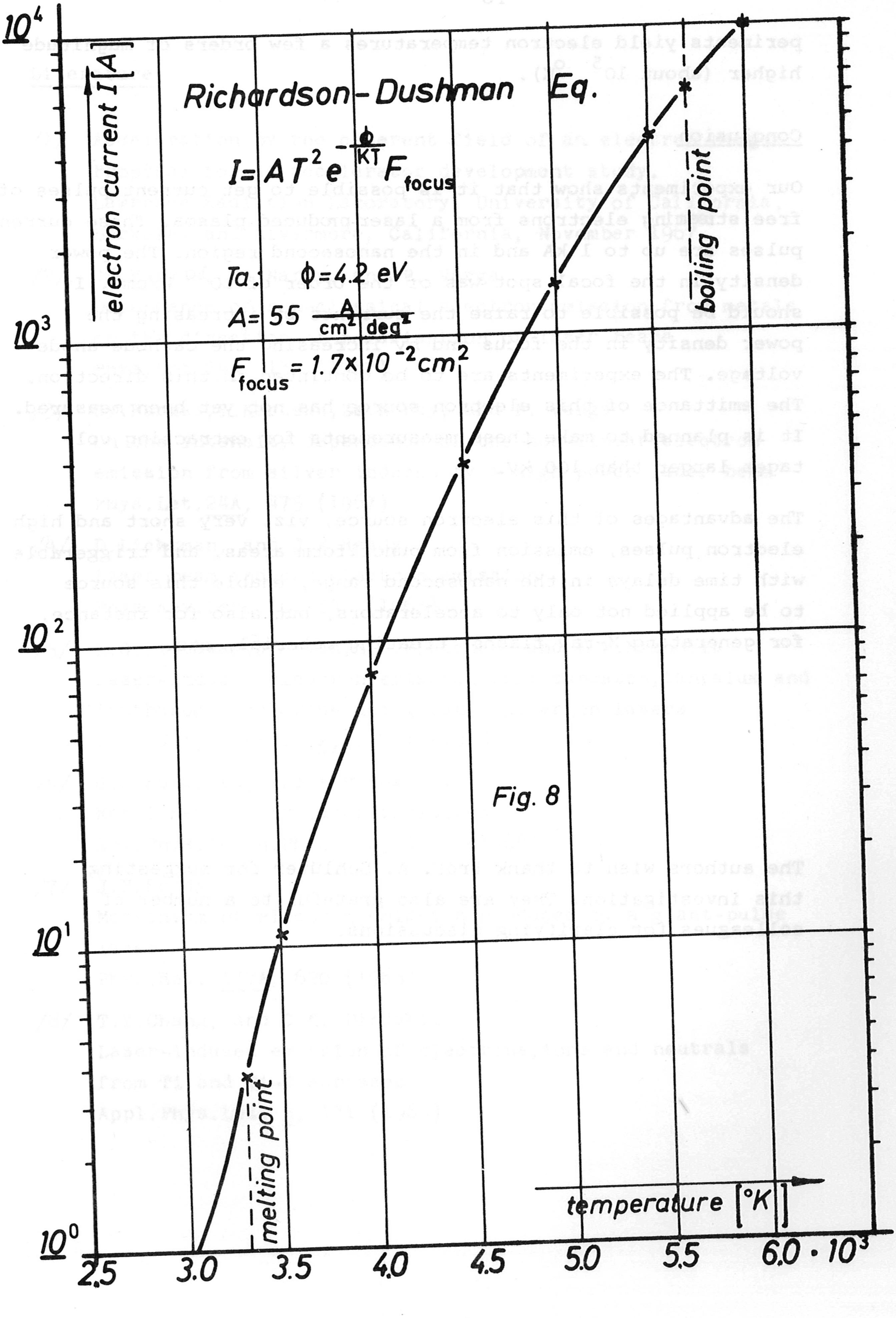

Richardson-Dushman Eq.
$I = A T^2 e^{-\frac{\phi}{KT}} F_{focus}$
Ta: $\phi = 4.2$ eV
$A = 55 \frac{A}{cm^2 deg^2}$
$F_{focus} = 1.7 \times 10^{-2} cm^2$
electron current I [A]
10^4
10^3
10^2
10^1
10^0
boiling point
melting point
temperature [°K]
2.5
3.0
3.5
4.0
4.5
5.0
5.5
$6.0 \cdot 10^3$

Fig. 8

periments yield electron temperatures a few orders of magnitude higher (about 10^5 °K).

Conclusion

Our experiments show that it is possible to get current pulses of free streaming electrons from a laser-produced plasma. These current pulses are up to 1 kA and in the nanosecond region. The power density in the focal spot was of the order of 10^{10} W/cm^2. It should be possible to raise the currents by increasing the power density in the focus and by increasing the cathode-anode voltage. The experiments are to be continued in this direction. The emittance of this electron source has not yet been measured. It is planned to make these measurements for extracting voltages larger than 100 kV.

The advantages of this electron source, viz. very short and high electron pulses, emission from punctiform areas, and triggerable with time delays in the nanosecond range, enable this source to be applied not only to accelerators, but also for instance, for generating X-ray flashs, treating material, etc.

The authors wish to thank Prof. A. Schlüter for suggesting this investigation. They are also grateful to a number of colleagues for clarifying discussions.

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