Hollow Beam Gun for the Wake Field Transformer Experiment at DESY

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ABSTRACT

Most of the future accelerator concepts require new types of electron guns. A short pulse high current electron gun is needed for wake field accelerators. A group at DESY is investigating the possibility of accelerating particles with a high gradient in a *Wake Field Transformer*. This paper will focus on the hollow beam gun developed for this experiment. A laser driven gun was chosen which uses the general Richardson effect. The theory of this effect is described and compared with experimental results. At a cathode voltage of nearly 100 kV, the gun produces a hollow beam of 10 cm diameter with a space charge limited current of about 100 A over a pulse length of a few nanoseconds.

INTRODUCTION

The principle of the wake field acceleration mechanism [1] and the *Wake Field Transformer* experiment at DESY [2,3] have been described in detail in other papers.

For the hollow beam gun a laser driven gun with a tantalum cathode was chosen. The photon energy of the laser light is much lower than the work function of the cathode material. The emission mechanism is explained by the generalized Richardson effect. The light of a short pulse high power laser is absorbed inside a very thin layer of the cathode. Thus, since the surface temperature increases, thermionic emission and thermionic supported photoelectric emission is possible. The calculations of the surface temperature by solving the heat diffusion equation and of the extracted electron current by using the generalized Richardson equation are compared with experimental results. The characteristics of the hollow beam gun were measured and are compared with calculations of the limit of emission by space charge effect in the gun.

1 LAYOUT OF THE GUN

A perspective drawing of the hollow beam gun is shown in Fig. 1. A Nd:YAG laser (wave length 1.064 μm) is used as light source. It consists of a Q-switched oscillator with an unstable resonator and an amplifier and it yields pulses with a length of 10 ns and a maximum energy of 900 mJ. The laser beam has a donut profil of 8 mm outer diameter with a 4 mm hole in the center.

The laser light enters the vacuum section of the gun through a common viewing port. The beam will be enlarged by a conical mirror and focussed on a ring at the conical tantalum cathode by a lens. The conical mirror is a glass cylinder with a polished inverse cone at the top, making use of the total reflection at the glass vacuum surface. The cathode was manufactured out of a 0.5 mm thick tantalum plate. The reasons for choosing this material are the high vaporizing point of tantalum ($\sim$ 5700 K) and the relatively ease of machining which is similar to stainless steel. The electrons are extracted from the metal via heating and photoeffect. These electrons are accelerated by the high voltage and follow the magnetic field lines. The entire gun is embedded in a solenoid field (field strength $\sim$ 0.2 T), which guides the electrons through a slot hole in the anode. In order to reach the design value of 150 kV for the pulsed cathode voltage the insulating ceramic of the gun is surrounded by an insulating gas for which

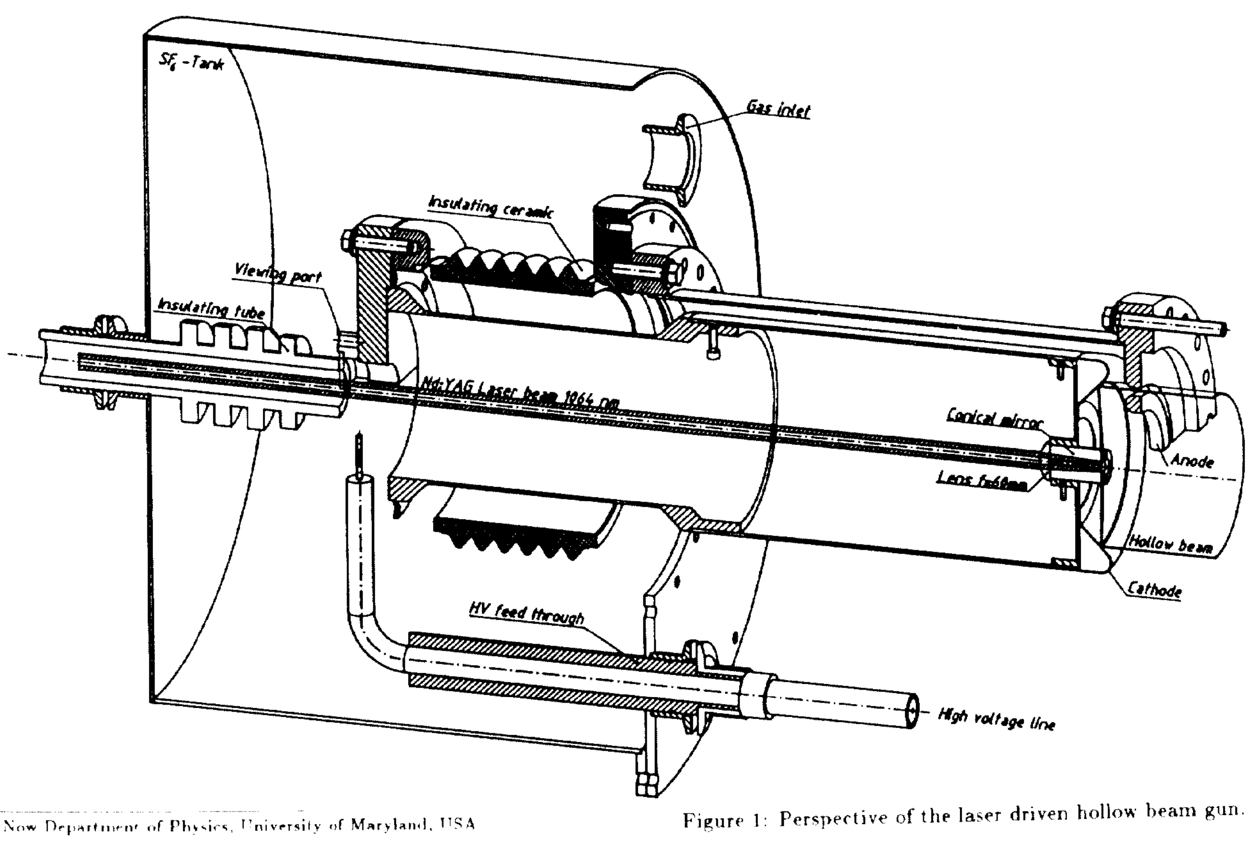

Figure 1: Perspective of the laser driven hollow beam gun.

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SF_6-gas is used. Since the high power laser light must not penetrate the gas, because otherwise glass surfaces would be etched, it travels in air inside an insulating tube (see Fig. 1). The peak value of the pulsed high voltage is limited by the minimum cathode anode distance of 1 cm and additionally reduced by switching on the solenoid field. During firing the gun for some nanoseconds the voltage depends on the capacity close to the cathode. In order to achieve high currents we have provided a coaxial stucture with a low impedance ($Z = 9\,\Omega$) compared to the load impedance. The advantage of a coaxial device is a constant cathode voltage over twice of the travelling time on the tube.

2 PRINCIPLE OF LASER GENERATED ELECTRON EMISSION

The characteristic of the laser driven hollow beam gun is that the work function of the used cathode material (Ta: $\phi_A = 4.12\,\mathrm{eV}$) is much higher than the photon energy of the laser light ($\hbar\omega = 1.165\,\mathrm{eV}$). Thus common photoelectric emission is not possible. But in our arrangement the parameters of the Nd:YAG laser are sufficient for heating the cathode surface. If the illuminated area at the cathode is small enough, the temperature can cross the melting point (Ta: $3269\,K$). Significant thermionic emission and thermionic supported photoelectric emission is possible.

2.1 Surface Temperature Calculations Inside a metallic plate the energy of a nanosecond light pulse will be nearly immediately transfered to the lattice and classical heat diffusion calculation can be used.

The temperature of a laser irradiated cathode can be calculated by solving the homogeneous heat diffusion equation with constant coefficients. We assume that the specific heat capicity c_v, the thermal conductivity γ and the optical reflection R of the metallic surface are independent of the temperature and we neglect the penetration of the light into the metallic plate. For a rectangular laser pulse of the length t_p we get the equation for the surface temperature [5]

$$\hat{T}_s = T_0 + 2(1 - R)I_0\sqrt{\frac{t_p}{\pi\gamma c_v\rho}}. \tag{1}$$

where T_0 is the initial temperature and ρ the specific mass. For nanosecond laser pulses the transversal heat diffusion can be neglected. Assuming an absorbed laser intensity of $50\,\mathrm{MW/cm^2}$ and a pulse length of 3.5 ns from this relationship we obtain a maximum surface temperature difference $\Delta T_s = \hat{T}_s - T_0 = 2887\,\mathrm{K}$ for a tantalum plate.

2.2 Generalized Richardson Equation In a simple model at a metal surface a potential step of the height ϕ_A over the Fermi energy E_F prevents the electrons from leaving the solid. At high temperatures electrons occupy energy levels above the Fermi energy and some electrons are able to overcome the potential step and to leave the solid. Additionally the electrons can absorb the photon energy $\hbar\omega$ of penetrating light. The condition for electrons leaving the metal is for the thermionic emission and for the thermionic supported photoelectric emission

$$\frac{m_0}{2}v_\perp^2 + n\,\hbar\omega > E_F + \phi_A \qquad n = 1,\ldots,N+1,$$

where m_0 is the rest mass of an electron, $v_\perp$ the thermionic velocity of an electron normal to the surface of the cathode and N the largest integer less than $\phi_A/\hbar\omega$, and n is the number of photons absorbed by one electron. This condition together with the Pauli principle and Fermi statistics leads to the generalized Richardson equation for the current density

$$j = \sum_{n=0}^{N+1} j_n, \tag{2}$$

with

$$j_n = A\,T_s^2 a_n\,I^n \int_o^\infty \ln(1 + e^{\delta_n - x})\,dx; \quad \delta_n = \frac{\phi_A - n\,\hbar\omega}{k_B T_s}. \tag{3}$$

where A is the Richardson constant and $I = (1 - R)I_0 h(t)$ the absorbed laser intensity. j_0 represents the pure thermionic emission, for $n > 0$, j_n represents the n-photon photoelectric emission and a_n are the appropriate coefficients related to the matrix element of quantum n-photon process. At typical temperatures and for $n \leq N$ the exponential term of the integral is much less than one and the current density is approximately

$$j_n = A\,T_s^2 a_n\,I^n e^{\delta_n} \qquad n = 1,\ldots,N. \tag{4}$$

and for $n = 0$ the expression is the well known Richardson-Dushman equation. At sufficiently high temperatures the thermionic emission dominates the current density. If we use the parameters from section 2.1 we can expect a pure thermionic current density of $180\,\mathrm{A/cm^2}$ at a cathode surface temperature of 3200 K.

2.3 Characteristics of a Gun The dependence of the space charge limited current on the applied voltage for different cathode surface temperatures (i.e. laser energies per pulse) will be called the characteristics of a gun. For sufficiently high emission at the total active cathode surface the dependence of the beam current I on the applied voltage U is represented by the Child-Langmuir law

$$I = pU^{3/2}, \tag{5}$$

where p is the perveance of a gun, which is a geometric factor. For a thin hollow electron beam the perveance of the gun is approximately

$$p = 1.4\frac{\mu A}{V^{\frac{3}{2}}}\;\frac{A}{d^2}\;\sqrt{2d/\Delta}, \tag{6}$$

where A is the emission surface at the cathode, d the anode cathode distance and Δ the wall thickness of the hollow beam. Assuming a thickness of 0.5 mm we will expect a space charge limited current of 85 A at a cathode voltage of 50 kV for an anode cathode distance of 1.5 cm and 440 A at 150 kV.

At high voltage the current depends on the emission. The dependence of the beam current on the voltage can be derived from the Schottky effect and is for thermionic emission and thermionic supported photoelectric emission

$$I = I_s e^{a_0\sqrt{U}}. \tag{7}$$

The crossing between these two regions will be approximately described by [5]

$$I = I_0\left\{1 - \left[1 - \left(\frac{U}{U_0}\right)^{1.5}\right]^2\right\}. \tag{8}$$

This expression is only valid for a hollow beam gun.

3 EXPERIMENTAL RESULTS

3.1 Longitudinal Current Distribution In the drift space behind the gun a gap monitor [4] was installed to measure the longitudinal current distribution of the hollow electron beam. A typical current versus time measured by the gap monitor is shown in Fig. 2 for a cathode voltage of 60 kV and a laser energy of 350 mJ per pulse. At these parameter values the hollow beam gun is working in the emission limited region and it is possible to compare the measured pulse shape with theoretical calculations. The calculated surface temperature and current are shown in Fig. 3. The measured current pulse shape is nearly in agreement with the calculated pulse shape. The difference between the pulse shapes can be explained by linear theory for the calculation of the surface temperature (1). Particularly the reflection R depends strongly on the temperature. But from the comparision of the calculated pulse shape with the measured pulse shape it is not possible to decide whether a thermionic emission or a thermionic supported photoelectric emission is the major component of the laser driven current.

3.2 Characteristics of the Hollow Beam Gun The characteristics of the hollow beam gun are shown in Fig. 4. The points represent the measured current from the cathode. The curves are fitted theoretical

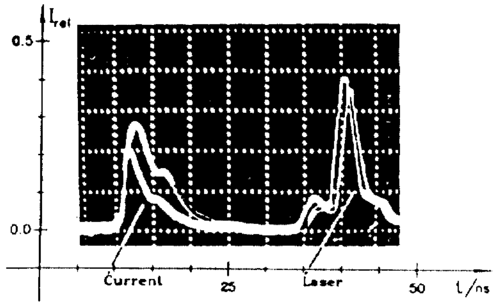

Figure 2: Measured longitudinal current distribution of the hollow beam for a cathode voltage of 60 kV and a laser energy of 350 mJ per pulse.

This photograf shows two subsequent pulses due to the long exposure time.

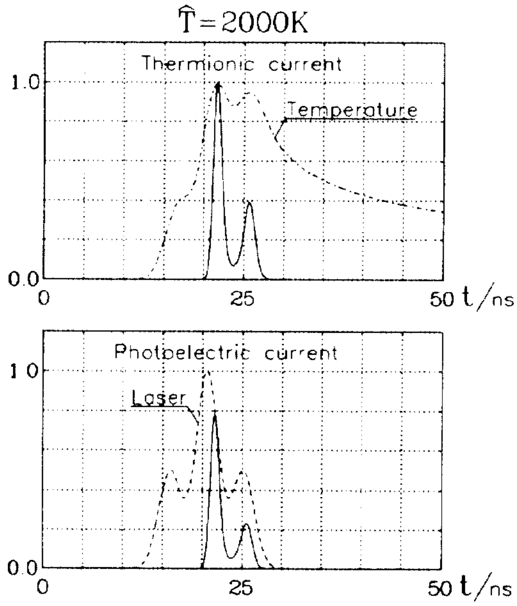

Figure 3: Calculated surface temperature at the cathode and longitudinal current distribution for a given laser pulse.

The surface temperature (dash-dotted line) is calculated for a given time dependence of the laser intensity (dashed line) and normalized to the maximum surface temperature (1). The upper solid curve is showing the thermionic current distribution, the lower solid curve is showing the thermionic supported photoelectric current.

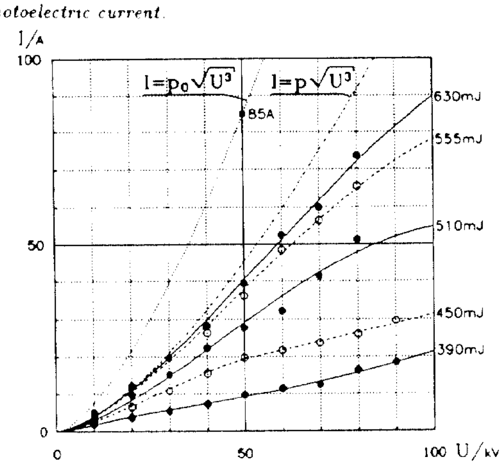

Figure 4: Characteristics of the hollow beam gun for different energies per laser pulse.

The points represent experimental results. The curves (solid and dashed lines) are the fitted theoretical values given by Equation (7) and Equation (8). The dash-dotted line is the space charge limited current with a perveance $p = 4.1\,\mu A/V^{1.5}$. The dotted curve is the theoretical space charge limited current of the gun for a hollow beam thickness $\Delta = 0.5$ mm

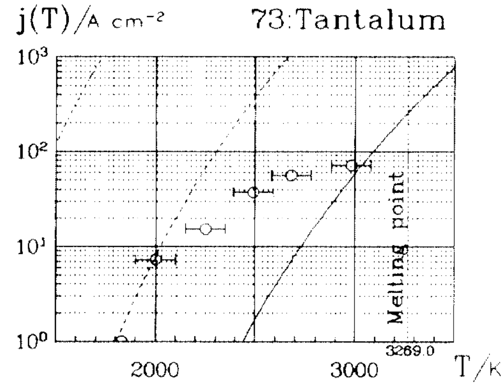

Figure 5: Measured current density of a tantalum cathode versus the calculated surface temperature.

values given by Equation (8). For laser energies of less equal 450 mJ per pulse the gun current is limited by the emission. Due to this reason these curves are fitted theoretical values given by Equation (7) for higher cathode voltages. The perveance of the hollow beam gun is $p = 4.1\,\mu A/V^{1.5}$ which is derived from the parameter values of the fitted curve for the maximum laser energy per pulse. For a hollow beam thickness of 0.5 mm the theoretical calculated perveance is $p_0 = 7.6\,\mu A/V^{1.5}$. Thus the illuminated thickness on the cathode is much lower.

The maximum current density for the different laser energies can be taken from the fitted curves. These values, without consideration of the Schottky effect, versus the calculated surface temperature are shown in Fig. 5. The solid curve is the thermionic current density and the dashed curve the thermionic supported photoellectric current density for tantalum with a work function $\phi_A = 4.12$ eV and a Richardson constant $A = 55\,A\ cm^{-2}\,K^{-2}$ and Nd:YAG laser light with a photon energy $\hbar\omega = 1.165$ eV. From the comparison it follows that for lower temperatures the photoelectric emission is the major component of the laser driven current and for higher temperatures it is the thermionic emission.

SUMMARY

A laser driven hollow beam gun was developed for the Wake Field Transformer experiment at DESY. The main property of the gun is that the work function of the cathode material is much higher than the photon energy of the used laser light. In this case the emission mechanism is explained by the generalized Richardson effect. Thermionic emission is the major component of the laser driven current. At a cathode voltage of nearly 100 kV, the gun produces a hollow beam of 10 cm diameter with a space charge limited current of about 100 A over a pulse length of a few nanoseconds. The voltage is limited by vacuum break down between cathode and anode. If the pulse length of the voltage would be shortened an increase of the peak value should be possible and therefore an enhancement of the space charge limited current by a factor of two to three should be obtained.

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