Thin Film Cathode for a Hollow Beam Gun

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ABSTRACT

For the new *Resonant Wake Field Transformer* concept, at present in development at DESY and Darmstadt as a candidate for a future linear accelerator, a new kind of Hollow Beam Gun is necessary. This concept requires a hollow electron beam of 10 cm in diameter with a current of 50 A and a pulse length of 180 ns. Using the generalized Richardson effect, the gun is driven by a pulsed laser. The required pulse length of the electron emission exceeds the laser pulse length. One way of achieving this is to insulate the cathode thermally in such a way, that the cathode temperature and the thermionic emission decrease slowly after the end of the laser pulse. A thin tantalum surface of some ten nanometers thickness on a ceramic substratum serves as a cathode. In a first experiment with a 10 ns laser pulse and a tantalum layer of about 100 nm, electron emission of 20 ns has been measured. The layout of the gun, calculations about the thermic behaviour of the cathode and results of the measurements are presented.

INTRODUCTION

The principle of the wake field acceleration mechanism [1], the *Wake Field Transformer* experiment at DESY [2,3] and the *Resonant Wake Field Transformer (RWT) - Collider* [9] have been described in detail in other papers. For the *RWT - Collider* a train of 90 hollow electron bunches at a frequency of 500 MHz is needed as a driver beam. The bunches must have a diameter of 100 mm and a charge of 100 nC per bunch. Therefore the gun must provide a current pulse with a length of at least 180 nsec and a current of 50 Ampere.

For the hollow beam gun a laser driven gun with a tantalum cathode was chosen. The light of a short-pulse, high-power laser is absorbed inside a very thin layer of the cathode. The emission mechanism is explained by the generalized Richardson effect. Two possibilities have been investigated to reach long current pulses with a hollow beam gun.

The pulse of the laser, which has a length of 10 ns, is divided by a beam splitter so that half of the intensity is sent into an optical delay line. If the circumference of the delay line corresponds to the pulslength, the intensity of the outgoing pulse decreases nearly quadratically and compensates the temperture decrease on the cathode surface.

Another possibility is the use of thin film cathodes. A thermally insulating ceramic substratum is coated with a tantalum film of a few hundred nanometers thickness. If the surface is heated by a laser pulse, thermal diffusion can only take place within the tantalum layer and not backwards into the substratum. The temperature on the surface rises fast compared to the length of the laser pulse, but decreases much slower, depending on the thickness of the layer. This corresponds to a delayed thermionic emission of electrons from the surface. Measurements have shown, that current pulses twice as long as the laser pulse can be reached by these methods.

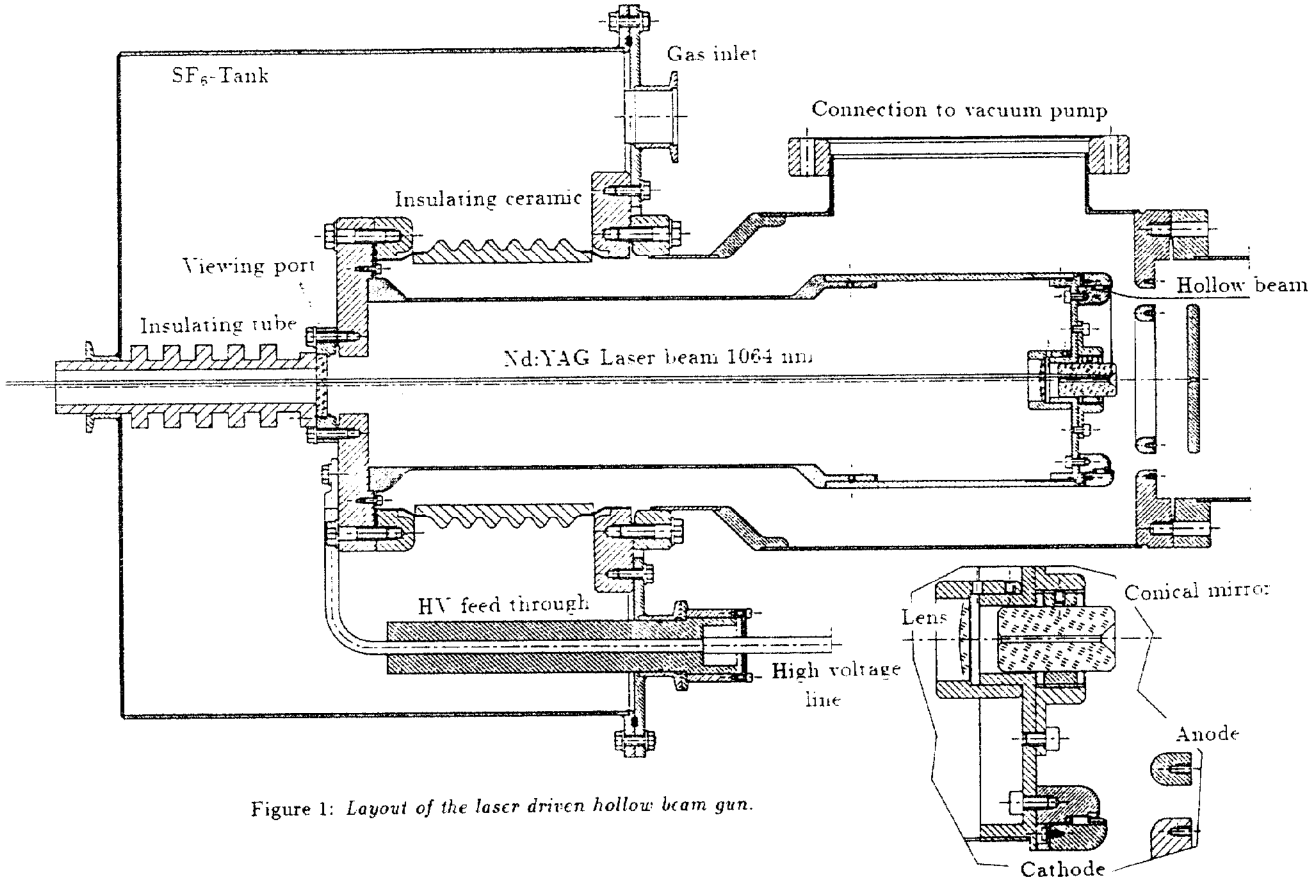

Figure 1: *Layout of the laser driven hollow beam gun.*

1 LAYOUT OF THE GUN

The layout 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 yields pulses with a length of 10 ns and a maximum energy of 900 mJ. The laser beam has a donut profile of 8 mm outer diameter with a 4 mm hole in the center.

The pulse of the laser can be divided by a beam splitter so that half of the intensity is sent into an optical delay line. If the circumference of the delay line corresponds to the pulse length, the intensity of the outgoing pulse decreases nearly quadratically. Figure 2 shows a schematic view of the optical delay line.

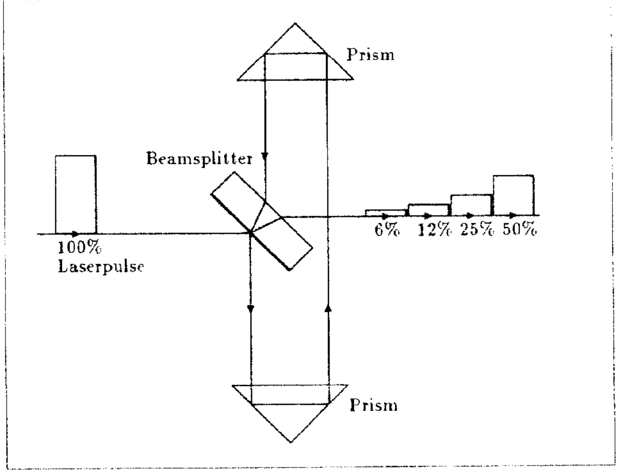

Figure 2: *Pulse lengthening by an optical delay line. The light pulse of a laser is split and part of the pulse is delayed. The light is reflected by two prisms and coupled out by the beamsplitter.*

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 the cathode ring 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 consists of a ceramic ring, coated with a tantalum film of about 100 nm thickness. The reasons for choosing this material are the high vaporizing point of tantalum ($\sim$ 5700 K) and the well known method of evaporation. The entire gun is embedded in a solenoid field (field strength $\sim$ 0.2 T). The cathode ring is held by an inner ring made of stainless steel and surrounded by an iron ring. These rings form the magnetic and electric fields, so that they are parallel at the cathode surface. Fig. 3 shows the magnetic field lines and the electric equipotential lines between the electrodes, calculated by PROFI [7], and the emitted hollow electron beam, calculated by TBCI-SF [8]. Ceramic was chosen as the substratum for the cathode, because a thermally insulating, but mechanically stable material is required to produce a ring of 110 mm diameter, but only 1.5 mm thickness. The ring has to be as thin as possible to get the magnetic field lines at the inner cicumference, i.e. the emission surface, nearly perpendicular to the surface.

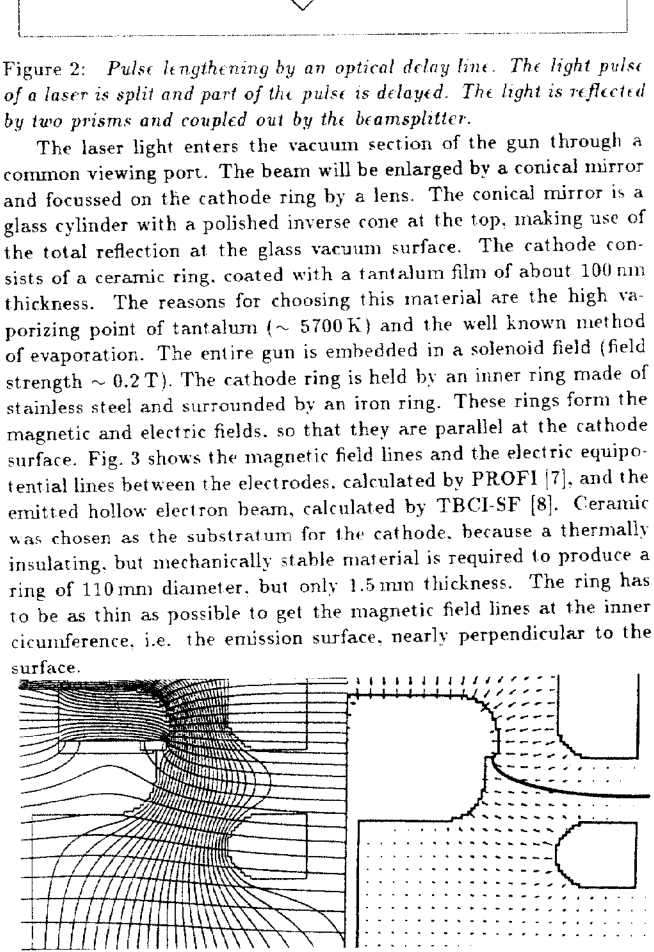

Figure 3: *Magnetic field lines and electric equipotential lines between the electrodes, calculated by PROFI, and the emitted hollow electron beam, calculated by TBCI-SF.*

The electrons are extracted from the tantalum film at the inner surface of the ceramic ring via heating and photoeffect. These electrons are accelerated by the high voltage and follow the magnetic field lines through a slot hole in the anode.

2 PRINCIPLE OF LASER GENERATED ELECTRON EMISSION

The special property of the laser driven hollow beam gun is that the work function of the cathode material (Ta: ϕ_A = 4.12 eV) is much higher than the photon energy of the laser light ($\hbar\omega$ = 1.165 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 Temperature Calculations The heating of a metallic surface by a pulsed laser has been described elsewere [5,6]. Here we want to use these methods for calculating the heating of thin metallic films, irradiated by a pulsed laser at the surface ($z = 0$). Solving the classical heat diffusion equation leads to the following formula for the temperature T in the depth z at the time t:

$$T(z,t) = T_0 + \frac{(1-R)}{\sqrt{\pi\gamma c_v \rho}} I_0 \int_0^t h(t-\tau)\frac{1}{\sqrt{\tau}} \int_0^\infty e^{-(z-\Xi)^2/(4\kappa\tau)} e^{-\Xi/\xi} d\tau d\Xi \,, \tag{1}$$

where T_0 is the initial temperature, γ the thermal conductivity, c_v the specific heat capicity, ρ the specific mass, $\kappa = \gamma/(c_v\rho)$, R the optical reflection of the metallic surface and ξ the penetration depth of the laser light into the metal. Numerical integration of this formula allows the calculation of the temperature at different depths and times. Fig. 4 shows the temperature vs. time for different depth, calculated for a semi-infinite tantalum block and a gaussian laser pulse.

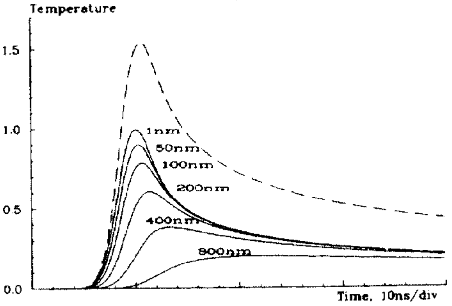

Figure 4: *Temperature vs. time for different depth, calculated for a semi-infinite tantalum block and a gaussian laser pulse. Dashed curve: Surface temperature for a 100 nm tantalum film on an Al_2O_3 substratum.*

To estimate the temperature of a thin film, a very simple model was used: The temperature was calculated for a semi-infinite block and the temperature changes for the points behind the back surface of the film were reflected at the back surface (Reflection factor R_b), added to the temperature in the film and reflected at the front surface (Reflection factor R_f = 1.0). The reflection factor $R_b = 1 - (a_{Ta}/a_{Al_2O_3}) = 0.64$ is given by the ratio of the thermal diffusion coefficients a of tantalum and ceramic. The dashed curve in fig. 4 shows the surface temperature for a 100 nm tantalum film on an Al_2O_3 substratum. The temperature maximum is higher and wider than the maximum for the thick cathode.

2.2 Generalized Richardson Equation For electrons, emitted from a laser illuminated metal surface, the current density of the thermionic emission and the thermionic supported photoelectric emission is given by the generalized Richardson equation

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

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, I the absorbed laser intensity, n is the number of photons of energie $\hbar\omega$ absorbed by one electron and N the largest integer less than $\phi_A/\hbar\omega$, if ϕ_A is the workfunction of the metal. 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

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

and for $n = 0$ the expression is the well known Richardson-Dushman equation.

3 EXPERIMENTAL RESULTS

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 with a 1.5 mm thick tantalum cathode and without laser pulse lengthening is shown in fig. 5 for a cathode voltage of 80 kV and a laser energy of 385 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 also shown in fig. 5. The measured current pulse shape is nearly in agreement with the calculated pulse shape.

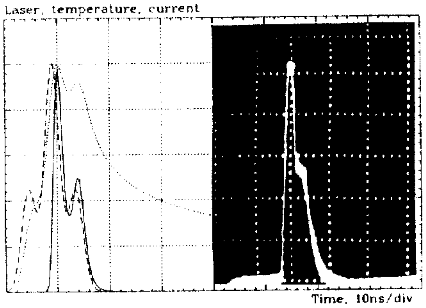

Figure 5: *Calculated surface temperature (dotted) for a semi-infinite tantalum cathode, longitudinal current distribution (solid) for a given laser pulse (dashed) and measured longitudinal current distribution of the hollow beam for a cathode voltage of 80 kV and a laser energy of 385 mJ per pulse. Pulse length 10 ns.*

To get longer current pulses, the optical delay line (see fig. 2) was set up. As the laser pulse consists of three separeted maxima (see fig. 5), the circumference of the delay line was chosen so that the last maximum of the direct pulse coincids with the first maximum of the delayed pulse. The theoretical efficiency of the delay line, which gives an intensity of 25 % for the delayed pulse, was not reached in practice. Fig. 6 shows, for an intensity of 21 % in the delayed pulse, the calculated current pulse and the measured current for a cathode voltage of 80 kV and a laser energy of 455 mJ per pulse, agreeing reasonably well with the calculations.

Without the optical delay line, the gun produces currents up to 73 A at a cathode voltage of 140 kV and a laser energy of 620 mJ per pulse. When using the delay line, the current is limited by the damage threshold of the beam splitter. At laser energies of 500 mJ/pulse the beam splitter was damaged. This gives an energy of 250 mJ for the direct pulse and therefore currents of a few Amperes only. With optical elements of higher quality, both the efficency and the damage threshold of the delay line could be raised.

A further increase in the current pulse length can be achieved by combining the optical delay line with the tantalum coated ceramic cathode. Fig. 7 shows a typical current pulse, measured with both methods of pulse lengthening, and the corresponding calculated pulse form. Obviously the pulse length was increased and the pulse shape changed from a needle (fig. 5) over a triangular (fig. 6) to a rectangular shape.

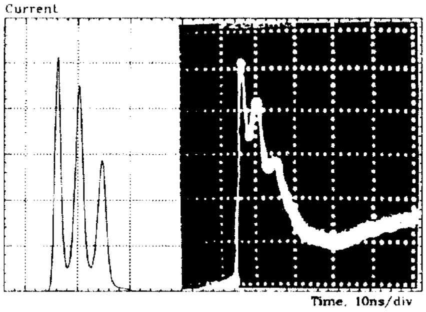

Figure 6: *Measured current pulse and calculated current distribution for a 1.5 mm thick cathode and an optical delay line with an intensity of 21 % in the delayed pulse. Pulse length 15 ns.*

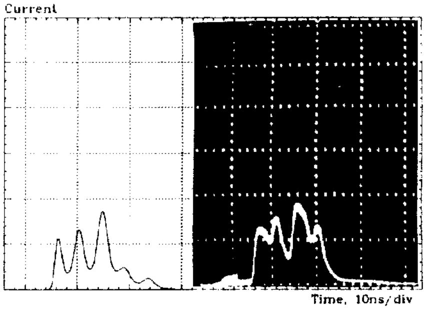

Figure 7: *Measured current pulse and calculated current distribution for a 100 nm film cathode and an optical delay line. Pulse length 20 ns.*

SUMMARY

A laser driven hollow beam gun with a pulse length exceeding the length of the driving laser pulse was investigated. The emission mechanism of the gun is explained by the generalized Richardson effect. At a cathode voltage of 140 kV, the gun produces a hollow beam of 10 cm diameter with a space charge limited current of 73 A over a pulse length of a few nanoseconds. Lengthening the laser pulse and the use of a thin film cathode leads to a pulse length of up to 20 ns with a current of some Amperes. The current is limited by the damage threshold of optical elements in the laser pulse delay line. With optical elements of better quality, higher currents should be obtained.

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