NEW IDEA FOR LASER PRODUCTION OF VERY HIGH ELECTRON DENSITIES

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ABSTRACT

We present the basic concepts of a new arrangement for high intensity electron emission from metal photocathode It conjugates the actions of two lasers : the first is a low frequency (e.g. CO_2 or FIR laser) with relatively high intensity (> 10 MW/cm^2) at grazing incidence on a surface to enhance the potential energy of the electrons in the conduction band and then the effective photoelectric quantum efficiency ; the second is a visible or near-UV pulsed laser with a lower peak intensity (≈ 50 kW/cm^2) producing a high photoelectron density. This arrangement could also give us some better understanding of the basic interaction phenomena of a high intensity electromagnetic wave with a solid.

1. INTRODUCTION

Our object is to produce a very high density electron beam by laser action on a solid target. Such electron beams find their applications in different domains as Free-Electron Laser (F.E.L.) for instance

High-current photocathodes yielding current densities larger than 1 A/cm^2 have several advantages over conventional thermal and field emitters : (1) the electron beam intensity can be modulated by modulation of the light source ; (2) the beam can be shaped by patterning the photocathode ; (3) the energy spread of the electron beam can be reduced by selecting the wavelength of the incident light[1] ; (4) as radiation sources can operate at high average power, it is then possible that beams show high luminosity (B_n > 10^{10} A/(m^2 rad^2))[2,3]. Increasing the brightness of the high current electron beam used in FEL amplifiers, increases markedly the amplifier gain and the energy conversion efficiency[4].

In the next section, we give principal reasons of our choice of metallic photocathodes connected to laser interaction effects. The quantum efficiency of classical photoelectric emission is reviewed in Section 3. Arguments to achieve conditions for a very high current density production are presented in Section 4. In Section 5, principles of a new idea of photoelectron emission assisted by two lasers (PEAL) are described and a new experimental arrangement is proposed

2. CHOICE OF PHOTOCATHODE

The following factors have to be considered when a photoelectron source is made : (1) cathode life ; (2) operational environment; (3) performance of the cathode and (4) cathode

replacement Points (1), (2) and (3) are inter related and the cleanliness of the system is very important[5]. The problem of photocathode lifetime is bound to the optimal conditions. These conditions are directly dependent on the temporal and energetic characteristics of the light source and on the limits of damage due to interaction between the beam and the cathode surface, and they are critical with a high power laser as light source

The laser damage intensity I_D, or fluence F_D, depends on numerous parameters : (1) geometrical (rugosity) and chemical (adsorbed atoms or molecules) surface states ; (2) laser frequency ω (it seems that I_D is higher when ω is reduced) ; (3) laser pulse duration τ_p (for nanosecond and subnanosecond pulses, I_D is proportional to $\sim \tau_p^{1/2}$); (4) the angle of incidence of the laser beam and (5) the spot dimension S (I_D is lowered when S increases). However, precise limits for laser damage on material are not well-known. Only hypothesis is possible on the real maximal values of I_D. As a FEL oscillator requires a train of high density electron bunches, with high peak current (i_K > 100 A) and a low transverse beam emittance, this implies lighting the cathode by a train of high peak intensity laser pulses with approximatively the same temporal characteristics, i.e. τ_p < 200 ps and pulse repetition rate R_p = 100 MHz. In such conditions, a large part of the absorbed laser energy is converted to heat, which causes a rapid rise of the surface temperature and then the appearance of damages[6]

The cleanliness of the system is another drastic condition. Photocathodes with adsorbed atoms such as Cs or Na offer the great advantage of smaller work functions, but the action of a high power laser on the surface amplifies the scattering of these atoms outside the material, polluting the high vacuum chamber. Moreover, the adsorbate's migration modifies the quantum yield

From this point of view, pure metal photocathodes present obvious advantages. Also, the preparation of high-yielding semi-conductor photocathode needs, generally, a sophisticated and expensive technology, while the preparation of a pure metal target is much more simple

Finally, metal disposes of a large reserve of electrons in the conduction band ($\simeq 10^{22}$ cm ^{3}) greater by a factor $\simeq 10^{4}$ 10^{5} than semi-conductors and presents an opportunity for the production of very high electron density.

3. EFFICIENCY OF PHOTOELECTRIC EMISSION

To avoid melting and damage to the cathode surface, it seems reasonable to limit the peak intensity of each micro-pulse to a relatively low value, typically 0.5 - 1 MW/cm^2, mainly when a very high-frequency repetition, short laser pulse, train is considered. Calculations[7] of temperature variations on the tungsten surface for a pulsed laser train of 530 nm wavelength and 1 µs duration, composed of micro-pulses with peak intensity I_ω = 50 kW/cm^2, duration τ_p = 35 ps and a repetition rate R_p = 3 GHz, indicate a rise of temperature from 300 K to 1500 K in less than 1 minute.

For many conductors, the damage intensity I_D is certainly lower than the intensity I_ω needed to entirely remove the electrons from the conduction band. However we note some results inconsistent with this assertion. The saturation phenomena takes place at intensity $I_\omega < I_D$ [8].

The photoelectric quantum yield for metal photocathode being limited to about $\eta_\omega = 10^{-2}$ 10^{-3}, it is then evident from Figure 1 that peak current intensity can only be in the order of $i_k = 100$ A/cm^2 for $I_\omega = 50$ kW/cm^2

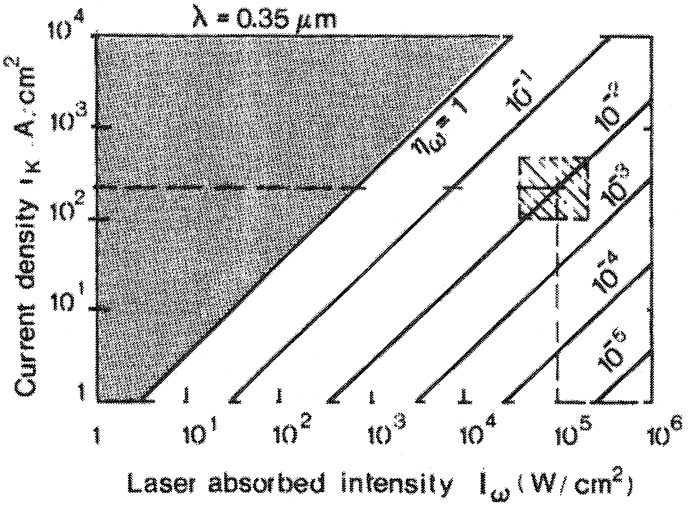

Fig 1 Photocurrent density versus laser absorbed intensity and quantum yield η_ω for $\lambda = 0.35$ μm

From the classical expression for photoelectric quantum yield :

$$\eta_\omega = \frac{h\omega}{e} \frac{i_k}{I_\omega} \qquad (1)$$

we observe that i_k depends essentially on two physical parameters : the absorbed laser intensity and the quantum yield. e is the electron charge and h_ω the photon energy Then, production of higher current density from a metal photocathode without increasing the peak laser intensity needs the creation of new electronic conditions at the surface. Compared to the classical approach, these conditions will correspond to a non linear photoelectric behaviour of the material. To summarize, the idea is to look for such conditions that metal offers a photoelectric quantum efficiency as high as semi conductor yield, while conserving its higher laser damage limit.

4 ACHIEVEMENT FOR VERY HIGH INTENSITY PHOTOELECTRON EMISSION

From simplified electronic representation of a metal, electrons with low potential energy are weakly bound and occupy approximatively all the levels below the Fermi level in the conduction band In the absence of any external field or thermal excitation, the surface

constitutes for the electrons an impassable border From the Einstein condition, in mono photo electric effect, electrons are removed from the metal only if the photon energy is greater than the work function ϕ, defined as the difference between the Fermi energy and the poten tial energy of the surface Application of a sufficiently high electrical field on the ca thode from an external anode can lower the potential barrier and electrons leave the metal by "tunnelling" through the barrier Knownas "field emission", the current density is however limited to less than 100 A/cm^2 because of electrical break down.

So, the principal conditions to achieve very high intensity photoelectron emission from metal are: (1) to apply an external electrical field with an amplitude sufficient to drag away the electrons when they leave the surface; (2) to obtain a higher photoelectric quantum yield. As η_ω depends on the height of the potential barrier, this condition will be realized only if the apparent amplitude and width of this barrier are lowered. An equivalent situa tion could be realized by transfer of conduction electrons in higher energy levels ; (3) to increase the coupling between the incident laser beam and the surface In the limit of field break down, this requires the choice of a convenient roughness to reduce the optical reflectivity

Recent experiments of CO_2 laser action on gold photocathode by Chin and Farkas[9,10] show the possibility of modifying the energy distribution of conduction electrons and also the potential barrier at the surface, so that emission of relatively high current density becomes possible although the frequency of a CO_2 laser is theoretically not well adapted These results can be interpreted by early theories of Keldysh[11] and Bunkin[12], who studied the influence on atoms and solids of a high amplitude e.m field with frequency $\omega < \phi/h$

The main results of the Keldysh theory may be summarized essentially in the form of very general closed formulae obtained from the ionization probability for an atom and which is a function of the atomic and laser characteristics, plus a useful parameter of both defi- ned as :

$$\gamma = \omega/\omega_S \tag{2}$$

with

$$\omega_S = \frac{eE_L}{\sqrt{2m_e \bar{I}_0}} \tag{3}$$

where E_L is the laser electric field strength, I_0 is the ionization potential of the atom ($I_0 = \phi$ for a solid) and m is the effective mass of the electron γ furnishes the per- turbation criterion condition

$$\frac{2\Delta}{\bar{I}_0} \sim \gamma^2 \tag{4}$$

where

$$\Delta \equiv e^2 E_L^2/4m\omega^2 \tag{5}$$

is the average oscillation electron energy in the laser field γ may also be expressed as

$$\gamma = \tau/T \ , \tag{6}$$

T being the laser period and τ the "tunnelling time" through the potential barrier

Then two extreme cases corresponding to very different values of laser intensity I_ω have to be considered :

(1) for $\gamma \gg 1$ (or $\tau \gg T$), we obtain the formulae of the perturbation theory which are characteristic for multiphoton effect or quantum limit . Then the number of electrons is :

$$N_e \propto |E_L|^{2n_o} \propto I_\omega^{n_o} \ , \tag{7}$$

$n_o = (I_0/\hbar\omega + 1)$ is the minimum photon number necessary for ionization
(2) for $\gamma \ll 1$ (or $\tau \ll T$), the probability of ionization furnished automatically the formula of the non-perturbative theory in the classical limit of "optical tunnelling"

$$N_e \propto f(E_L) \exp (\ -cst/E_L) \tag{8}$$

$f(E_L)$ depends on light polarization only As recalled by Farkas[13], in a recent review paper, to achieve the tunnelling condition corresponding to higher current density i_k, we have either to increase I_ω, that is to say E_L, or to decrease ω as follows from the $\gamma < 1$ condition (Figure 2). As I_ω is increasing during the laser pulse, if the frequency ω is high, multiphoton ionization may first saturate before the appearence of tunnelling[13,14]. Then the use of ultra short laser pulses of low ω(e.g. CO_2 of FIR lasers) may only insure the $\gamma < 1$ tunnelling condition during the whole pulse.

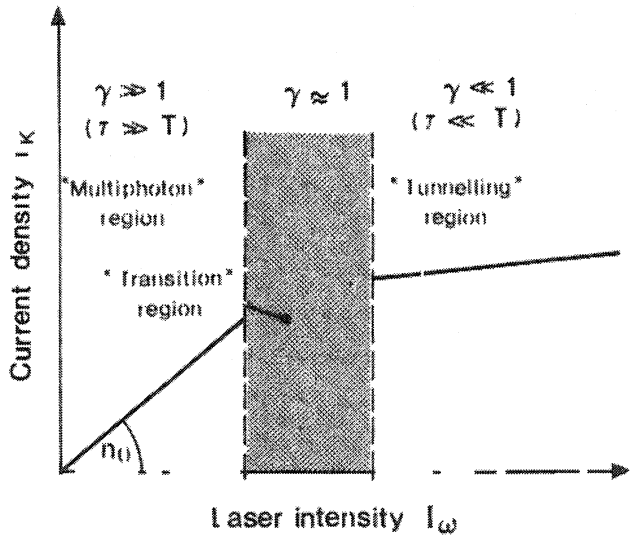

Fig 2 Definitions of laser assisted "multiphoton" and "tunnelling" photoelectron emission characterized by γ and n_o, in the plane i_k versus $I_\omega \propto |E_L|^2$ τ is the tunnelling time and T the period of incident radiation.

When a high intensity and low frequency, linearly polarized, short pulsed, laser impinges on the metal surface, with a near grazing incidence, so $E_{//}$ is normal to the surface, the effective work function seems to be reduced during the time of the pulse. The potential barrier is sufficiently narrowed to further "tunnelling" of the electron as described in Figure 3. To characterize this situation, Farkas introduces the new idea of "dynamical tunnelling". The value of dynamic scale parameter $\gamma'(t)$ deduced from experiments is much smaller than the one calculated from Eq. (2) and Eq. (3) ($\gamma'(t) \approx 0.08 << 1$ compared to static $\gamma = 6.68$). We will note that in the region of the top of the potential barriet for an atomic system, and probably for solid, the width is estimated to be about 20 Å, while "tunnelling time", for electrons with sufficient kinetic energy is $\approx 10^{-16}$ s[15].

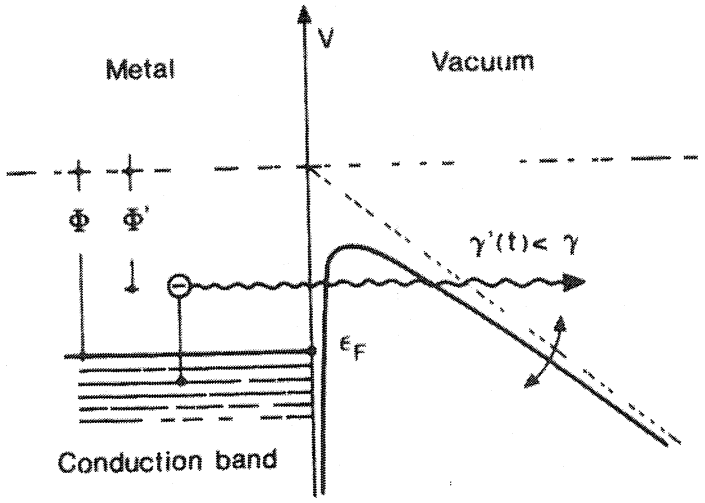

Fig. 3 Illustration of the laser assisted tunnelling electron emission[13]

The electric field of a laser is :

$$\vec{E}_L = -\nabla V - \partial\vec{A}/\partial t \qquad (9)$$

where V is the scalar potential and $\vec{A}$ the vector potential $\nabla V \equiv 0$ in medium free of charges only. When electrons are just out of the surface, they are subjected to the action of $\vec{E}_{//}$ which, alternatively during each half period ($T/2 = \Pi/\omega$), lowers and increases the potential barrier, inducing periodic modulation of the tunnelling. This view of the problem is also supported by Jones and Reiss[16] : as noted by Vaidyanathan and Guenther[17], an interesting consequence of low frequency, high power, pulsed, laser interaction would be an increase of the conduction electron potential energy when the intensity of radiation rises, as :

$$\Delta E_c = E_c(A) - E_c(0) = \frac{e^2}{4 m_c} \frac{A^2(t)}{c^2} \qquad (10)$$

where m_c is the effective mass of the conduction electrons Their theory forecasts that the energy of valence electrons remains the free-field value. This theory is supported by experimen

tal data on semi conductors. To support again this opinion, we refer to the prediction and the observation before the advent of lasers[18] of the bunching of emitted electrons at frequencies ω, 2ω, 3ω . . due to the simultaneous application on the cathode of a static field with amplitude just above the threshold of "field effect" emission, and an r.f. electromagnetic wave with frequency ω. Finally, we keep in mind that the action length of linearly polarized laser electric field in a material is evaluated by most authors as $\approx \lambda/2$. This value is always higher than the energy absorption depth of IR laser beam.

5. PHOTOELECTRON EMISSION ASSISTED BY TWO LASERS (PEAL)

From Section 4, the use of low frequency and high intensity pulsed laser, at grazing incidence on a surface of metal, seems to be able to lower the potential barrier and, we hope, to increase the potential energy of electrons in the conduction band and so enhance tunnelling effect. But, the production of very high electron densities by this single process is not realistic. It can only be an efficient assistance in creating conditions for a "super emission" of electrons.

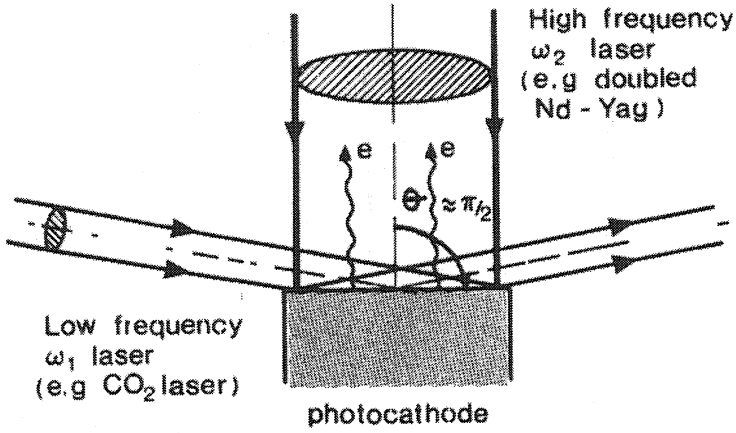

Fig. 4 Diagram of arrangement for laser induced photoelectron emission assisted by a low frequency laser (PEAL)

So the basis of the new system is described in Figure 4. Two lasers are used simultaneously, each one having a well-defined role to assist the production of high current densities. The first laser, working in a wave-coupling mode, will be a low frequency and relatively high intensity laser (e.g. CO_2 or FIR laser, $I_\omega > 10$ MW/cm^2) impinging on the photocathode surface at near grazing angle ($\approx \pi/2$), while the second laser will be a visible or near-UV pulsed laser (e.g. doubled-frequency Nd Yag laser $\omega_2 \approx 530$ nm, or XeCl excimer laser $\omega_2 \approx 308$ nm) with a lower peak intensity ($I_{\omega_2} \approx 50$ kW/cm^2) and subnanosecond pulse duration at normal incidence and acting by photoelectric effect. The pulse duration τ_M of the first laser will be adapted to the length of the electron burst (1 100 µs) while the pulse duration τ_{p_2} and the repetition rate of the second laser will be adjusted to the working frequency of the accelerator or the FEL[19].

The low frequency laser lowers the effective work function, raising the energy levels of the electrons at the surface. In this way, it assists the photoelectric process produced by the second laser, increasing the quantum efficiency of the surface Then, the peak intensity of the second, higher frequency, laser can be limited to a reasonably mean value, far less than the damage intensity As described in Figure 5, a greater electron density being involved with the second laser, the quantum yield of photoelectric effect and the emitted current density i_k would be enhanced i_k is then supposed to be more than 100 A/cm^2 and, by adjusting all parameters of both lasers, may reach the band of kA/cm^2

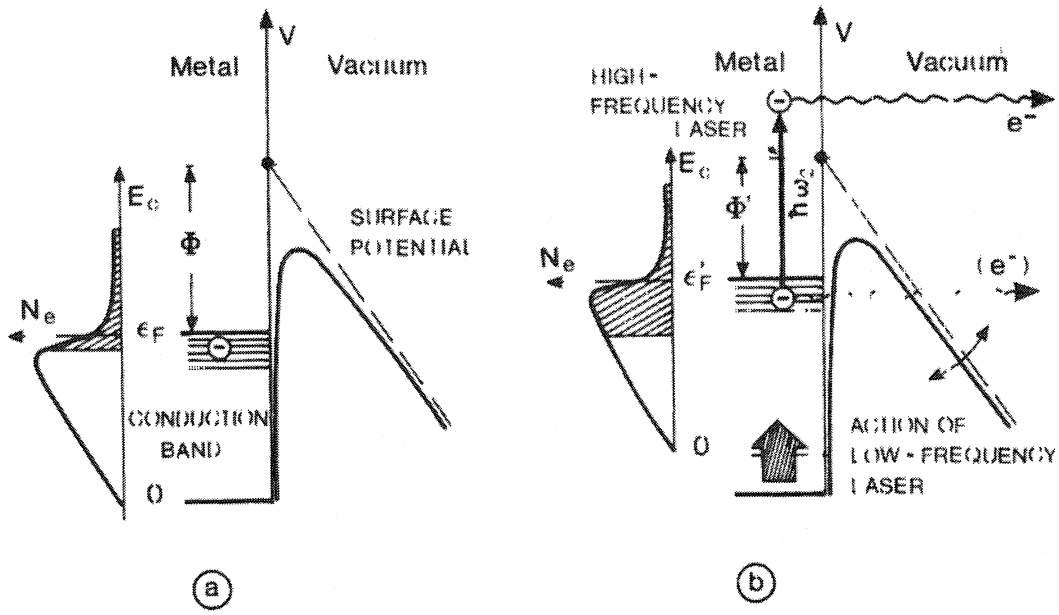

Fig. 5 Representation of conduction electron potential energy E_c and density N_e in a metal:
(a) without laser field,
(b) when high frequency laser induced photoelectron emission is assisted by a low frequency laser.

6 CONCLUSION

We propose to improve the energetic performance of an electron source using a laser on a metallic photocathode, by use of a second laser of lower frequency, at grazing incidence, to assist the classical photoelectric emission. From arguments developed in this paper, we think that it is possible to enhance significantly the current density while conserving a very low beam emittance. But this method could also give us some better understanding of the basic interaction phenomena of a high intensity electromagnetic wave with the elementary constituents of a solid and it could be possible to test a model of the photoelectric effect and to specify the relative importance of processes governing the electron production. Then, frequencies and intensities of the two lasers used in a PEAL injector could be adjusted to produce a higher conversion efficiency

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