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Nuclear Instruments and Methods in Physics Research A 445 (2000) 324–328

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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Evanescent-wave acceleration of femtosecond electron bunches

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Abstract

A 150-fs 800-nm 1-μJ laser was used to excited surface plasmons in the Kretschmann geometry in a 500-Å silver film. Multiphoton excitation results in the emission of femtosecond electron bunches (40 fC) as had been seen before. The electron beam is highly directional and perpendicular to the prism surface. A time-of-flight setup has been used to measure the kinetic-energy distribution of the photoelectrons. Surprisingly, we find that this distribution extends to energies as high as 40 eV. Theoretical calculations show that these high energies may be due to acceleration in the evanescent laser field that extends from the silver film out into the vacuum. These results suggest that femtosecond pulses with more energy per pulse or longer wavelength may be used to accelerate electrons to the keV or even MeV level.

PACS: 41.75.jv; 78.47. + p; 79.60. − i

Keywords: Surface plasmons; Ultrafast electron acceleration

The generation of femtosecond electron pulses is of great interest because of their possible application in miniature free-electron lasers, wake-field accelerators, femtosecond X-ray-pulse generation and time-resolved electron-diffraction experiments. A lot of attention in recent years has been focused on the generation and acceleration of photoelectrons using high-power femtosecond lasers. A number of schemes based on plasma waves have been developed to accelerate electrons using high-power lasers with the objective of building the next generation of high gradient accelerators. Because laser light is a transverse electromagnetic wave, the acceleration is also transverse unless complicated schemes are devised using two-wave cavities or waveguides to produce a light gradient field. Energy transfer from a transverse electromagnetic field to the electrons cannot take place to the first order. Furthermore, electron guns based on the photoelectric effect are usually based on DC electric fields or electric fields in RF cavities. These photoinjectors are usually limited to the acceleration of picosecond electron bunches.

Here, we present a novel scheme combining the femtosecond electron-bunch-generation process with acceleration. The femtosecond electron bunches are generated by multiphoton excitation of surface plasmons (SPs) in a thin metal film in the

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0168-9002/00/$ - see front matter
PII: S0168-9002(00)00136-4

Kretschmann geometry [1]. Because of this arrangement, an evanescent electromagnetic field is produced, which extends into the vacuum. Experimentally the evanescent field is found to accelerate the electrons away from the metal film producing an electron beam directed perpendicular to the surface. A theoretical analysis shows that, although the electromagnetic field oscillates at 400-THz, the evanescent field results in a repulsive ponderomotive potential that pushes charged particles away from the surface. This is similar to a proposed laser-based electron-mirror scheme [2].

The laser system used in the experiments is a 25-W argon-ion laser pumping a Ti:sapphire-based oscillator and regenerative amplifier. The 150-fs pulses produced have a 250-kHz repetition frequency resulting in 600-mW average power at 800 nm. The power used in the experiments could be adjusted using a motorized half-wave retardation plate and a polarizer. Approximately 500-Å thick films of gold and silver were vacuum deposited on one face of 15-mm side-length BK7 right-angle prisms. The laser beam entered the prism from the rear (see Fig. 1) in order to excite SPs in the metal film in the Kretschmann geometry [1]. The experiments were performed in a vacuum chamber at a pressure of 10^{-5}–10^{-7} Torr. The prism was mounted on the outside of the vacuum chamber with an o-ring and hole permitting the electrons to travel into the interior. Maximum electron emission was observed for an internal angle of incidence of $41.3^0/42.4^0$ in silver/gold roughly consistent with the known refractive indices of the prism material and the metals at 800 nm. No electron emission was detectable for angles away from the SP resonance angle or for s-polarized laser light.

In experiments measuring the average photocurrent, copper collector plates have been used as electron detectors. The current flowing from the collector to the prism is measured using lock-in detection. In order to measure the energy distribution of the electrons, a multichannel-array plate (MCP, Galileo, AP-TOF-18) placed at a distance of 32.5 cm fitted with an acceleration grid has been used. The potential difference between the prism and the grid was typically between zero and a few tens of volts. The potential difference between the grid and the MCP was 600 V in order to improve the detection yield for low-energy electrons.

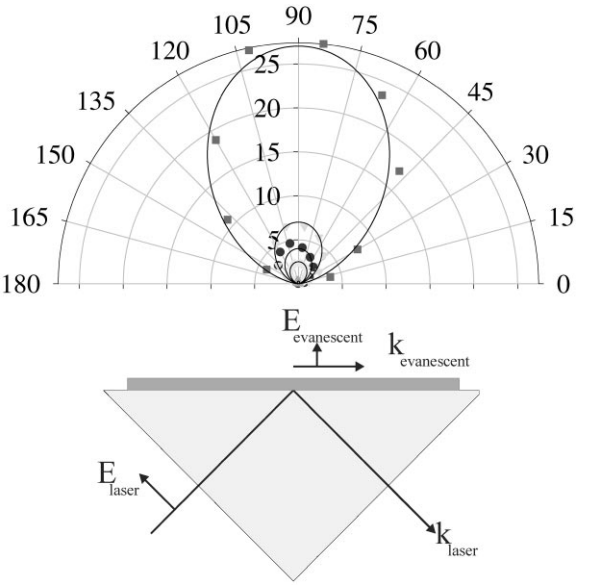

Fig. 1. (Bottom) Schematic of the prism and ~ 500 Å layer of gold used in the experiments. Surface plasmons are excited in the Kretschmann configuration, resulting in the emission of electrons. (Top) Measured angular distribution of electrons emitted from a gold film as a function of applied bias voltage. In all cases, the distribution fits to a $\cos^2\vartheta$ function.

Fig. 2 shows the measured photoelectron current as a function of incident laser power. At zero bias voltage between prism and collector, the current increases as the fifth power of the incident laser power. This is higher than the second- or third-order dependence that has been previously reported for silver and gold surfaces[1,3,4], but to be expected considering an amplified laser has been used in our experiments. When a reverse bias is applied, the current is reduced and the power dependence becomes of higher order.

The top part of Fig. 1 shows the angular distribution of the photoelectrons measured with an array detector consisting of 10 copper collector strips. This distribution fits reasonably well to a $\cos^2\vartheta$ function and is independent of the applied bias (within the signal-to-noise ratio). Such a directional distribution is unexpected. The incoming laser field interacts with the metal–surface excitations to form a mixed excitation called "surface plasmon." As

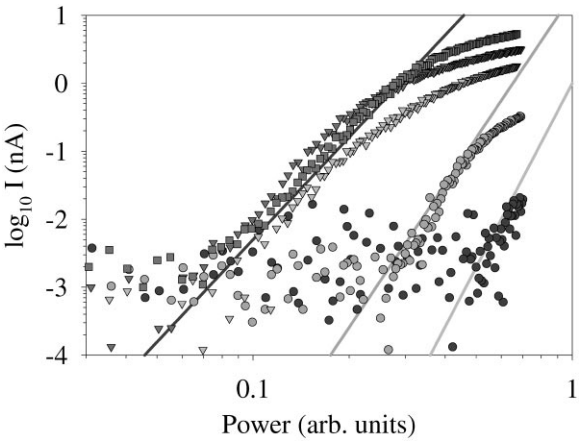

Fig. 2. Dependence of the measured photocurrent from gold on incident laser power. The data were measured with a DC bias between the prism and the detector of (l.t.r.) + 50, + 10, 0, − 10 and − 30 V. The lines show fifth-, seventh- and ninth-order power dependencies.

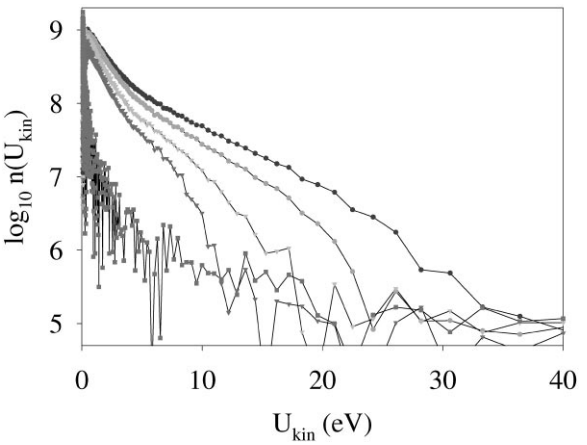

Fig. 3. Kinetic energy distribution of the photoelectrons from a gold film measured as a function of incident power. The incident powers were 0.7, 4.2, 5.5, 8.3 and 21 GW/cm^2.

a result, the electromagnetic field is enhanced by a factor of 10–100 depending on the metal used [1] and may be strong enough to cause multiphoton excitation of electrons. Because of the boundary conditions, the SP electric field must be perpendicular to the film and its wavevector in the plane of the film. Therefore, when the electrons are excited, they will acquire a momentum directed in the plane of the film. Thus, one would expect the electrons to travel through the film, rather than come out of it. In fact, in experiments in which SPs were excited with a low power laser [5], it has been observed that SPs have a 13-μm mean-free path in the metal film.

There are numerous studies of the lifetimes of electrons and plasmons, which show that in metals the *energy* relaxation time is on the order of a few picoseconds (i.e., much slower than the laser pulse) and the *momentum* relaxation time is ~ 40 fs (or faster at higher energies). Therefore, when the electrons are excited above the work function of the metal, they should emerge from the film with a randomized orientational distribution. This, however, is inconsistent with the observed directionality of the emitted electron beam. Therefore, there must be another process pushing the electrons away from the surface.

Fig. 3 shows the measured kinetic-energy distribution of photoelectrons emitted from a gold film. For the lowest power density (0.7 GW/cm^2), it is found that the distribution has a width (HWHM) of ~ 0.2 eV. The reason for this narrow width (as compared to what might be expected from a Fermi–Dirac distribution) is that the SP resonance selects electrons with a narrow range of momenta. At higher power densities, however, the distribution broadens rapidly and there appears to be a cutoff frequency. This cutoff frequency is about 30 eV above the work function of the metal (corresponding to ~ 23 photons) for 21 GW/cm^2. These high kinetic energies cannot be due to multiphoton absorption because in that case one would expect to observe a series of peaks in the spectrum separated by 1.5 eV.

Both the directionality of the electron beam and the unexpectedly large kinetic energies observed suggest that there is a force at work accelerating the electrons away from the prism surface. It is possible that a nonlinearity in the film causes optical rectification of the incoming laser beam resulting in an (essentially) DC field. However, such a field is expected to be extremely weak. The 800-nm laser hitting the metal film at the back of the prism in the Kretschmann geometry will produce an evanescent

field in the vacuum. Using our laser parameters (~ 1 μJ/pulse, 150 fs, beam waist 100 μm) one calculates a field strength of 8 10^8 V/m. Excitation of SPs is known [1] to result in an enhancement of 10–100 depending on the metal used. Therefore, the electric field on the surface of the metal is $\sim 10^{10}$–10^{11} V/m. Such a large field may well be responsible for the acceleration effects observed in the experiments.

If the field strength on the prism surface is $E_0(t)$, the field as a function of position x away from the surface is $E(x,t) = E_0(t)\cos(\omega t)e^{-x/\lambda}$. The Lorentz force on the electrons is $F(x,t) = eE(x,t)$, resulting in the nonlinear differential equation

$$\ddot{x} = f\cos(\omega t)e^{-x/\lambda}, \quad f \equiv eE_0/m \tag{1}$$

where e is the electron charge, m the electron mass, ω the angular frequency of the laser field and λ its wavelength.

The equation of motion for the electron in the field of a laser has been solved numerically using the Verlet algorithm [6]. Because the laser frequency is high ($\omega = 2.4$ PHz rad, corresponding to a period of 2.7 fs), one has to choose the time step sufficiently small. A 20-as time step has been used and the simulation was typically performed for 200–3000 fs. In the simulations, the kinetic energy oscillates strongly as a function of time and therefore great care has to be exercised to avoid edge effects. The simulation results indicated that the *spatial* oscillations induced by the laser field typically have very small amplitude compared to the overall motion of the electron.

From the numerical simulations it follows that the coordinate x has a slow component with a fast oscillatory component superimposed onto it. The electron coordinate can be written as [7] $x(t) = X(t) + \xi(t)$, where X is the slow coordinate and ξ is the fast coordinate. The oscillatory part of the equation of motion is

$$\ddot{\xi} = f\cos(\omega t)e^{-x/\lambda} \tag{2}$$

which is easily solved. If the solution for $\xi(t)$ is inserted back into Eq. (1), averaging over the fast coordinate results in an equation of motion for the slow coordinate only:

$$m\ddot{X} = \frac{dU}{dX}, \quad U = U_{\text{final}}e^{2X/\lambda}, \quad U_{\text{final}} = \frac{e^2E_0^2}{4m\omega^2}. \tag{3}$$

Here U is the ponderomotive potential. The electron thus gains energy U_{final} if the field remains on infinitely long. If E_0 is assumed constant, Eq. (3) can be solved analytically by straightforward integration, resulting in an expression giving the kinetic energy of the electron as a function of interaction time.

To calculate an energy-distribution function for the photoelectrons, it is assumed that the laser pulse is square and the probability of photoelectron production is constant during this pulse. Thus, electrons created at the beginning of the pulse will be accelerated for the entire duration of the pulse, whereas electrons created at the end of the pulse will not be accelerated at all. This results in a distribution of energies. Fig. 4 shows the calculated kinetic-energy distributions for a series of surface electric-field strengths relevant to our experiments. These distributions reproduce the observed cutoff energy although the unrealistic assumption of a square pulse resulted in a much sharper cutoff than that measured in the experiment. For the parameters used in Fig. 4, the cutoff energy scales quadratically with the laser intensity. If the laser intensity or the pulse duration is increased, the kinetic energy will saturate and the final kinetic energy will scale as U_{final}.

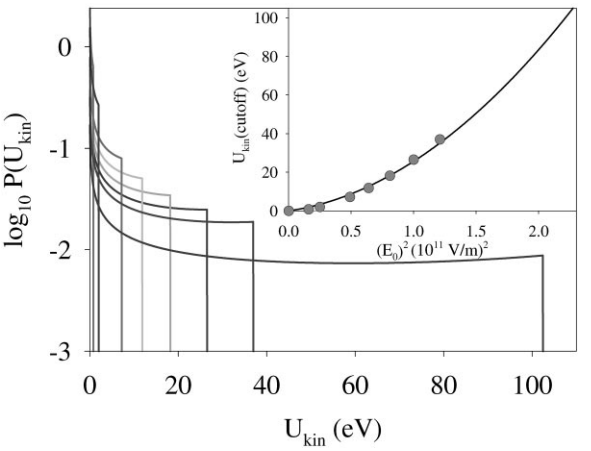

Fig. 4. Theoretical probability distribution function of photoemitted electrons. The calculation was performed with zero initial kinetic energy, $\lambda = 800$ nm, $\tau_{\text{pulse}} = 100$ fs and $E_0 = 0.4$, 0.5, 0.7, 0.8, 0.9, 1, 1.1 and 1.5 10^{11} V/m. The cutoff energy scales quadratically with the laser intensity at low power, linear at high power.

In our experiments, we are limited to peak power densities of $\sim 10\,\mathrm{GW/cm^2}$ and a wavelength of 800 nm. Using the theory, one can extrapolate the results to other regimes. At both low- and high-power density, the final kinetic energy scales as the inverse of ω^2. Therefore, one could obtain much higher energies by using infrared femtosecond laser pulses. Clearly, if a high-power source of single-cycle THz pulses [8] such as those produced by TOPS [9] were available, this would result in the most efficient acceleration (and a breakdown of the approximation leading to Eq. (3)). With higher-energy laser pulses, one could produce electrons with relativistic energies. Our (nonrelativistic) simulations carried out with a surface field two orders of magnitude larger than that used in our experiments, show that the electrons are accelerated to 500 keV in a mere 10 fs. In practice, this could be achieved with a 20-fs 6-μJ pulse with all the other parameters (wavelength, beam waist) kept the same. Modifying the above theory for relativistic effects would be relatively straightforward [2].

The experiments and theory presented here show that evanescent fields produced by amplified femtosecond laser pulses can be used very effectively to accelerate electrons. The relatively long pulse and low energy produced by our laser system limited the maximum observed kinetic energy to ~ 30 eV. However, little technical advancement would be required to be able to accelerate electrons to relativistic energies. This acceleration would be extremely fast (10 fs) thereby eliminating space-charge effects. Such extremely short electron bunches would be of immense value to, for example, time-resolved electron diffraction studies [10].

We gratefully acknowledge the financial support from the Royal Society and EPSRC, and technical support from Andrew Hughes. J.Z. gratefully acknowledges financial support from an Overseas Research Students Award Scheme.

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