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DEVELOPMENT OF HIGH CURRENT ELECTRON SOURCE USING PHOTOEMISSION FROM METALS WITH ULTRASHORT LASER PULSES*

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Development of High Current Electron Source Using Photoemission from Metals with Ultrashort Laser Pulses

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ABSTRACT

We summarize the studies of photoemission from metal photocathodes using picosecond pulses in the UV (4.66 eV) wavelength and femtosecond laser pulses in the visible (2 eV) wavelengths. To achieve high current density yield from metal photocathodes, multiphoton photoemission using femtosecond laser pulses are suggested. Electron yield improvement incorporating surface photoemission and surface plasmon resonance in metals and metal films are demonstrated. We examine the possibility of the nonlinear photoemission process overtaking the linear process, and identity some possible complexity. To extract the large amount of electrons free of space charge, a pulsed high voltage is designed; the results of the preliminary test are presented. Finally, for the first time, the width of the electron temporal profiles are measured, ultilizing the nonlinear photoelectric effect, to below 100 fsec time regime. The results indicated that the electron pulse duration follows the laser pulses and are not limited by the material.

I. Introduction

The urge of using high power ultrafast lasers to extract electrons from metal photocathodes achieving 100 kA/cm^2 in an area of 1 cm^2 has invoked fundamental studies of electron extraction mechanisms. In this workshop, we examine the possibility of using photoemission from metals to achieve the required current density demanded from the 1 Å free-electon laser (FEL). To reach the stringent requirements, metal photocathodes are used to generate the short electron pulse with high current density. In the next section, we will summary the past studies of linear photoemission from metal photocathodes using picosecond UV laser pulses. In section III, we explore the multiphoton photoemission using femtosecond laser pulses in the visible wavelength regime. The advantage and disadvantage of the nonlinear photoemission are compared. Section IV describes the pulsed high voltage extraction scheme attempted to overcome the space charge regime. Finally, section V forms the conclusion.

II. Linear Photoemission with 4.66 eV Photons

Because the work functions of most metal photocathodes used in this study are below 4.66 eV, the energy of one photon is enough to extract one electron from the metal surface (hence linear photoemission). The laser source is a 10 Hz Nd:YAG laser, actively and passive mode-locked with an AO modulator and absorber laser dye, respectively. After amplifying the infrared laser pulses to an energy of 25 mJ using a regenerative amplifier, it is frequency quadrupled to the wavelength of 266 nm with an energy output of 1.5 mJ per pulse in a 10 psec pulse duration. Figure 1 shows the experimental setup. The typical electron yield from an activated yttrium photocathode is shown in Figure 2. Charge density as large as 200 nC/cm^2 (20 kA/cm^2 in 10 ps pulse) has been obtained but is still space-charge limited under a DC extraction voltage of 10 KV/mm. The activation was done by scanning the metal photocathode with the UV laser at a relatively high laser intensity so that surface contamination can be removed. Because true vacuum condition can never be achieved in an experimental cell, monolayer of residual contaminant will form on the metal surface and lowers the quantum efficiency. In an experiment, we monitor the change of the quantum efficiency as a function of time after the photocathode surface has been activated. The results are presented in Figure 3. Quantum efficiency improves from 10^{-6} to 5×10^{-4} after it has been activated, and decreases to $\sim 2 \times 10^{-4}$ in a period of 120 hours exposure to a vacuum of 10^{-8} torr.

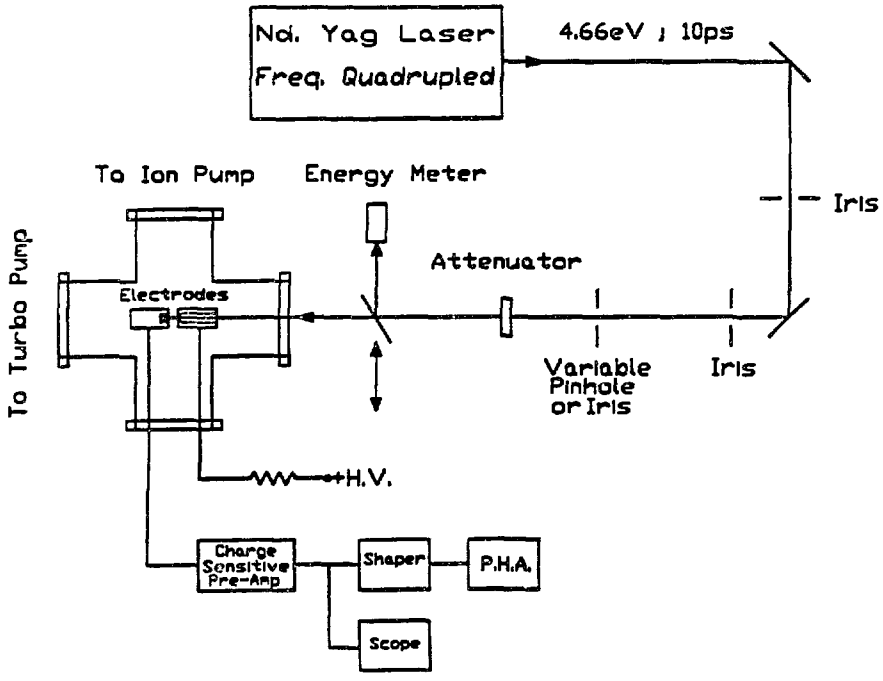


Figure 1. Experimental setup for the linear photoemission.

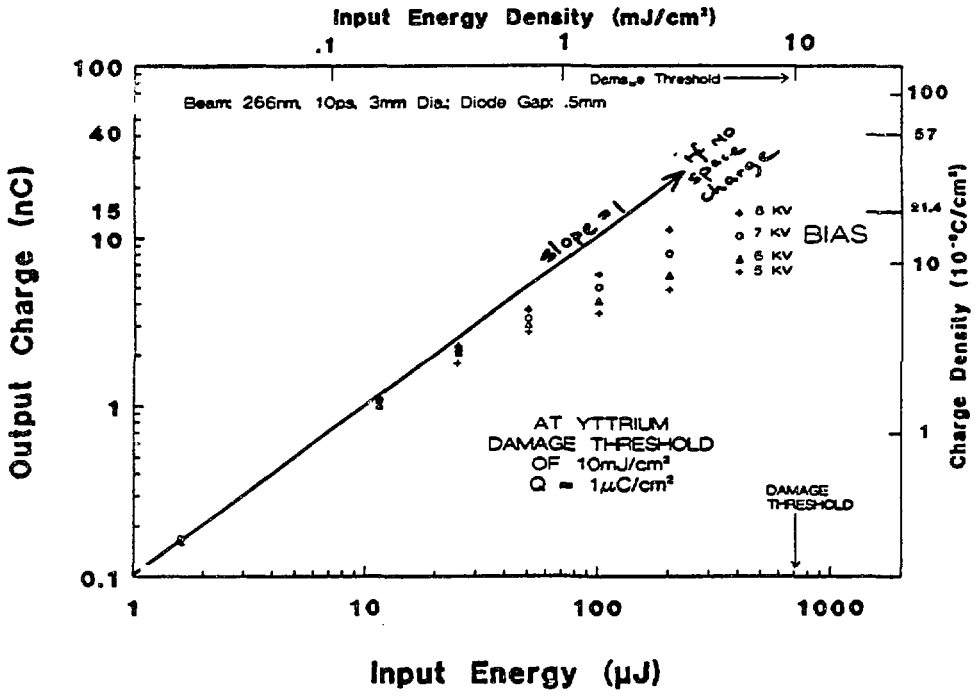


Figure 2. Electron yield of an activated yttrium photocathode.

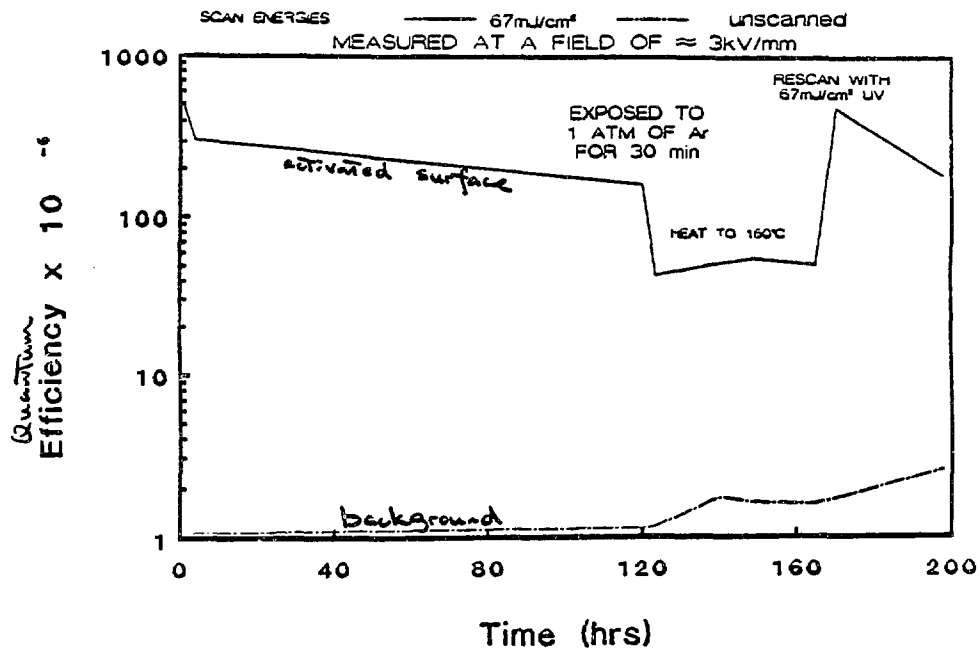


Figure 3. Lifetime of the activated yttrium photocathode due to monolayer gas formation and exposure to Ar gas.

Introduction of 1 atm of Ar or N_2 gas quenches the quantum efficiency to $\sim 5 \times 10^{-5}$ but is recoverable after re-activated with the UV laser. The results indicated that, at a vacuum condition of 10^{-8} torr, the usable lifetime of the photocathode is ~4 days after UV activation. The lowering of the quantum efficiency is most likely due to the formation of monolayer gas on the photocathode alone.

III. Multiphoton Photoemission with 2 eV photons

Our interest in the multiphoton photoelectric emission [1-2] is to examine the possibliity of nonlinear photoemission overtaking the linear photoemission process so that a higher quantum efficiency and higher brightness electron source can be obtained from metal photoinjectors. Because the quantum efficiency increases as P^{n-1} incident laser power, where n is the order of the multiphoton process, therefore, higher electron yield can possibly be obtained from multiphoton photoemission without damaging the photocathode. Figure 4 compares the case of linear versus nonlinear photoemission from different metal photocathodes that we have investigated. For the same laser power density, the nonlinear photoemission will overtake the linear case at 5×10^9 W/cm^2.

Recent investigations of electron emission using the surface photoelectric effect [3] has proven that electron yield can be improved by a decade or more with *p*-polarized light. Figure 5 shows this polarization improvement by sending a laser beam with different polarization angles. A factor of 10 increase of electron yield has obtained by varying the input polarization from *s* to *p*.

Further improvement of electron yield can be achieved through surface plasmon excitation on the metal surface. The basic excitation method is presented in FIgure 6. A thin metal film is evaporated on the back of the hypotenuse side of a prism, a laser beam is illuminated from the back of the prism to the metal film. By varying the input angle of incidence, the surface plasmon can be realized by an abrupt change of reflectivity. The special excitation geometry allows the coupling of the photon field to the surface plasmon (SP) field by matching the momentum wave vectors of the photon and the SP. [4] In our experiment, we employed the SP and the nonlinear photoemission to examine the electron emission process, the enhancement due to SP field, [5] and the electron pulse duration. Figure 7 shows the experimental setup of the nonlinear SP enhanced multiphoton photoemission. With a single laser beam, the polarization dependence and the order of the nonlinearity can be investigated. Using two laser beams arranged in a pump-probe like geometry, the electron pulse duration can be obtained when both beams

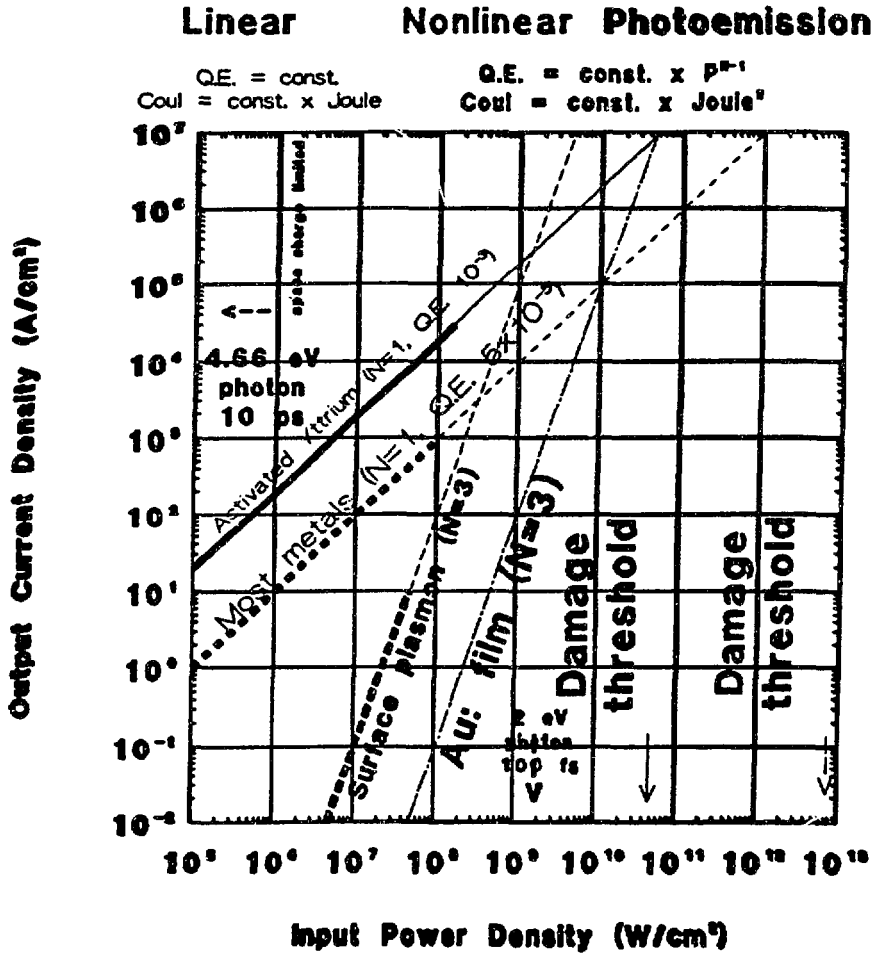


Figure 4. Comparison of linear vs. nonlinear photoemission from difference metal photocathodes.

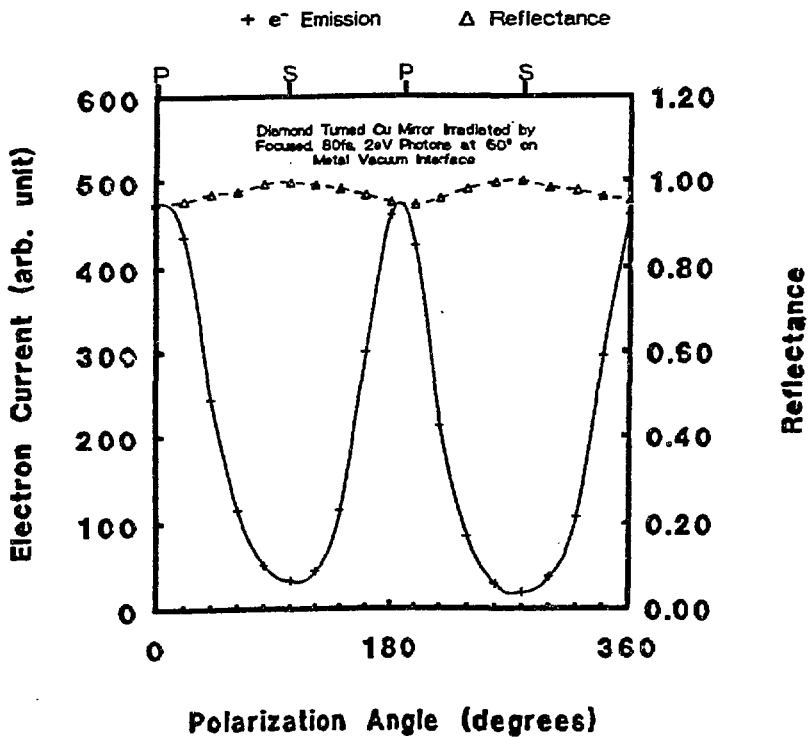


Figure 5. Polarization dependence of electron emission on a Cu metal photocathode.

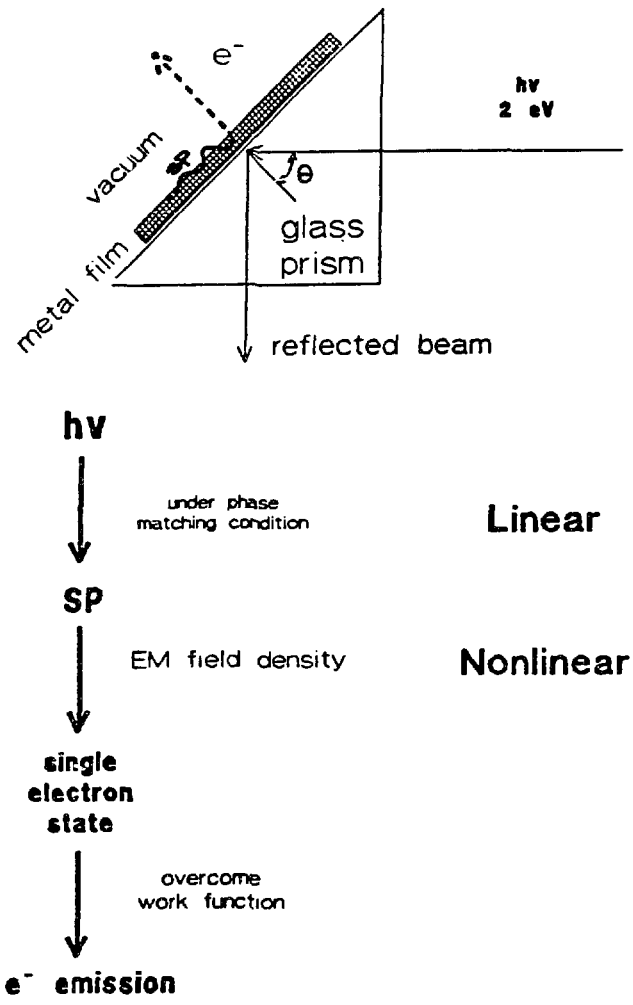


Figure 6. Schematic of the surface plasmon mediated electron emission.

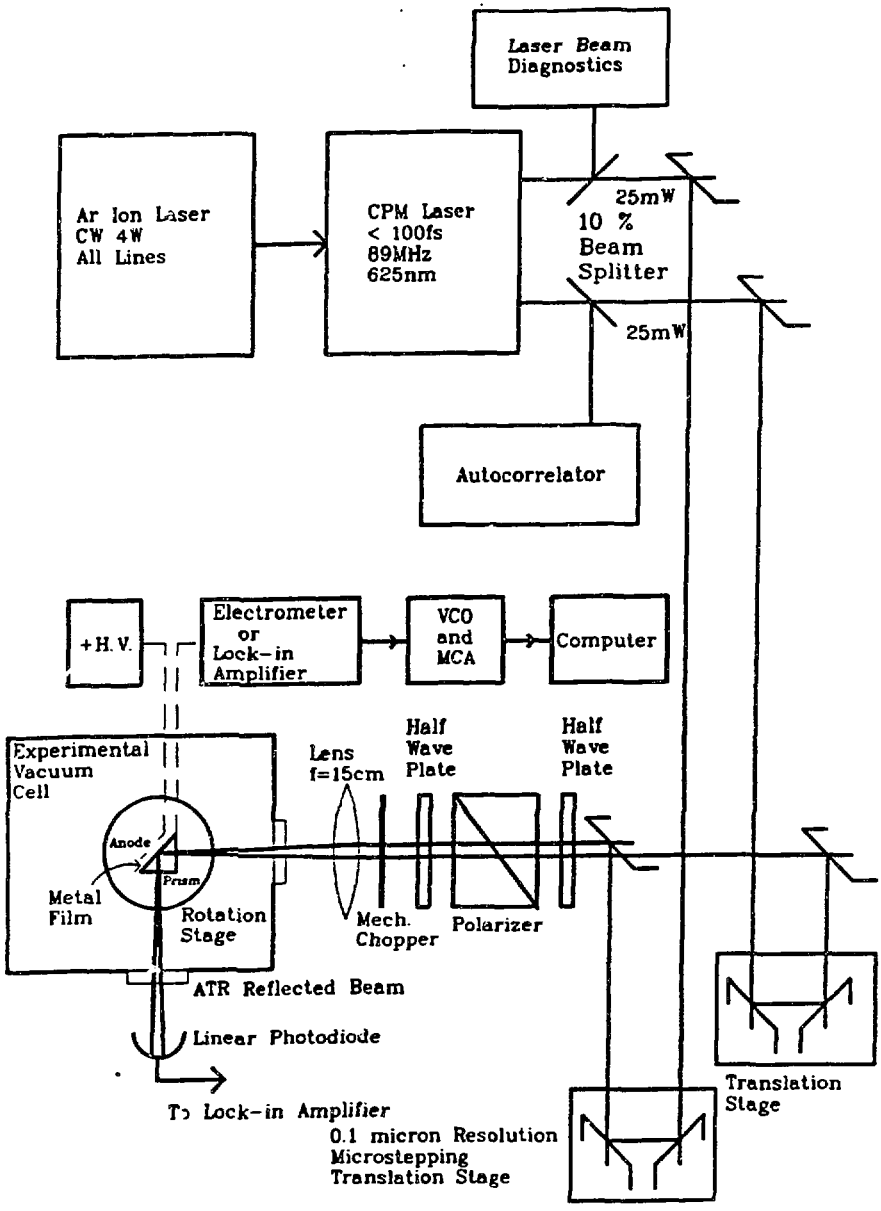


Figure 7. Experimental setup for the nonlinear photoemission and the surface plasmon mediated electron emission.

overlap spatially and temporally on the surface of the photocathode. The theoretical calculated reflectance and the normalized electron yield of each metal films (Ag, Au, Cu, and Al) using Fresnal coefficients are depicted in Figure 8. The SP excitations are predicted at the incidence angle of the minimum reflectance. However, base on this theoretical calculation, the electron emission peaks do not maximize at the reflectivity minima, suggesting that electron emits as a result of the high optical field created by the SP rather than the high absorption. Figure 9 shows the results of the experiment using a 100 fs colliding-pulse mode-locked ring laser. The reflectance minima and the electron yield maxima of all films compare favorably with the calculation except Al. The results also indicated that electron emission due to s-polarization is significantly lower than the p-polarization in this excitation geometry, as predicted by theory. Finally, to confirm the multiphoton process, Figure 10 shows the log-log plots of input laser power vs. output electron current from each metal film. 3-photon processes are found in Au, Cu, and Al films, while Ag has a 2-photon process. Several order of magnitudes of electron yield enhancement are found when SPs are resonantly excited in the metal films. These enhancements are in fair agreement with the SP optical field density calculation.

The electron pulse duration are measured on these metal films utilizing the multiphoton photoelectric effect. Unlike semiconductor photocathodes, [6] the temporal response of a metal photocathode is believed to be limited only by the existence of surface states and the transit time for the electrons to diffuse to the metal surface. Real time measurement of the electron pulse duration become almost impossible in the femtosecond regime. However, using nonlinear photoelectric effect, the correlated electron from two laser beams gives directly the electron pulse duration. Figure 11 shows the results of this measurement. The electron temporal profiles strikingly resemble that of the laser autocorrelations for all 4 films. The multiphoton electron emission from Au, Cu, and Al are 3rd order process, therefore, the intrinsic electron temporal profile should be narrower than the laser autocorrelation by a factor of $\sqrt{\frac{3}{2}}$. However, for the bulk metal photocathodes (Figure 12), the agreements are better. More studies are needed to fully understand this discrepancy.

One consequency of using ultrashort laser pulses to investigate laser interaction with metal is the generation of hot electrons on the metal surface. [7] This hot electrons can be model by heat diffusion through two coupled differential equations, Figure 13 illustrates the picturial representation of the model and the equations. When the temperature of

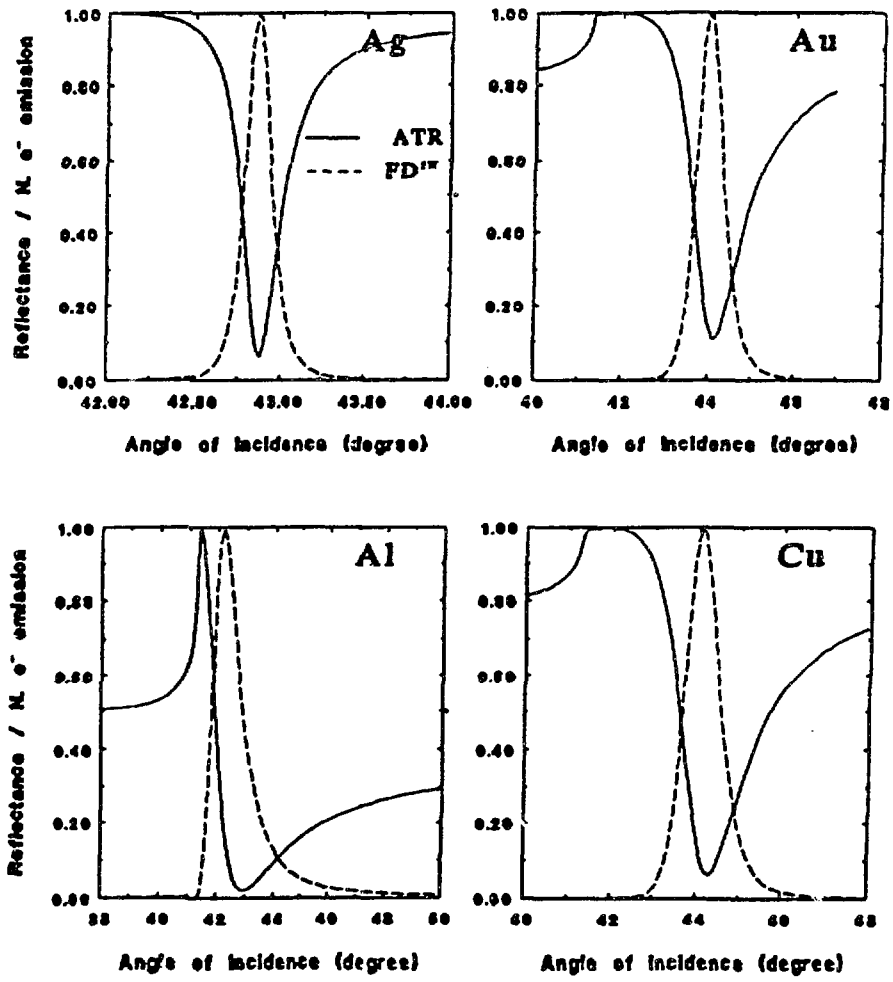


Figure 8. Theoretical calculations of reflectance and multiphoton electron emission with surface plasmon excitation.

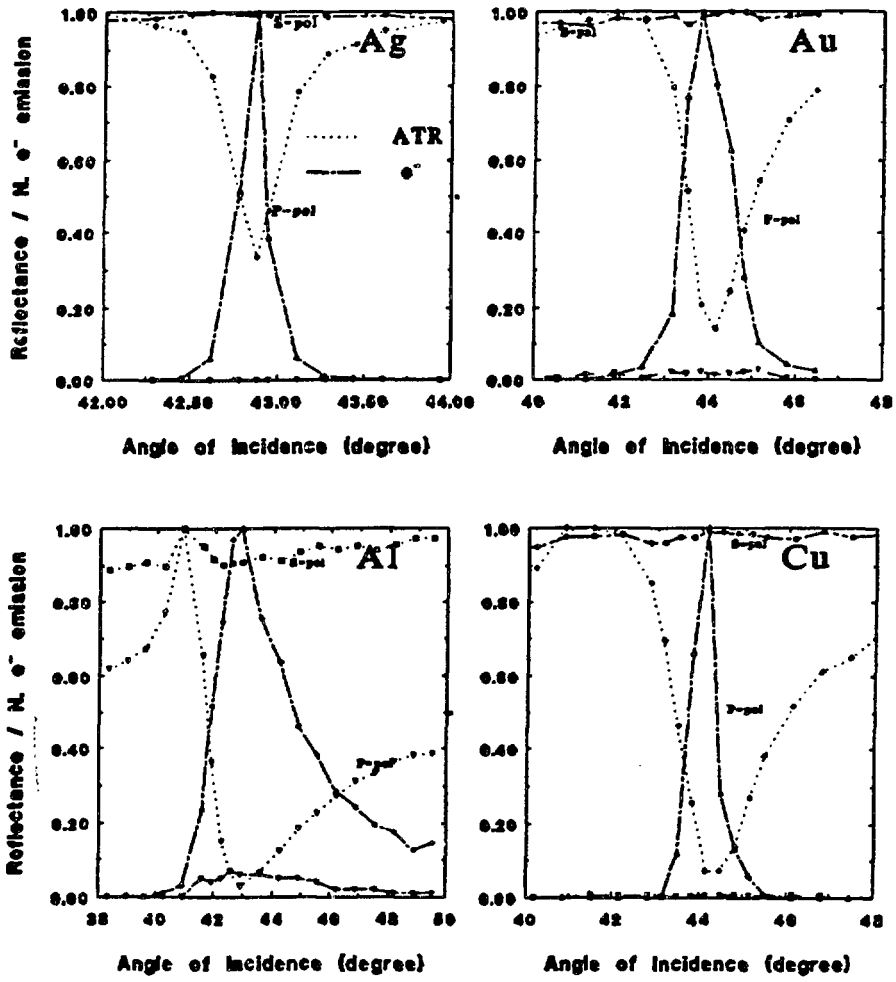


Figure 9. Experimental measurements of p and s-polarized reflectance and multiphoton electron emission with surface plasmon.

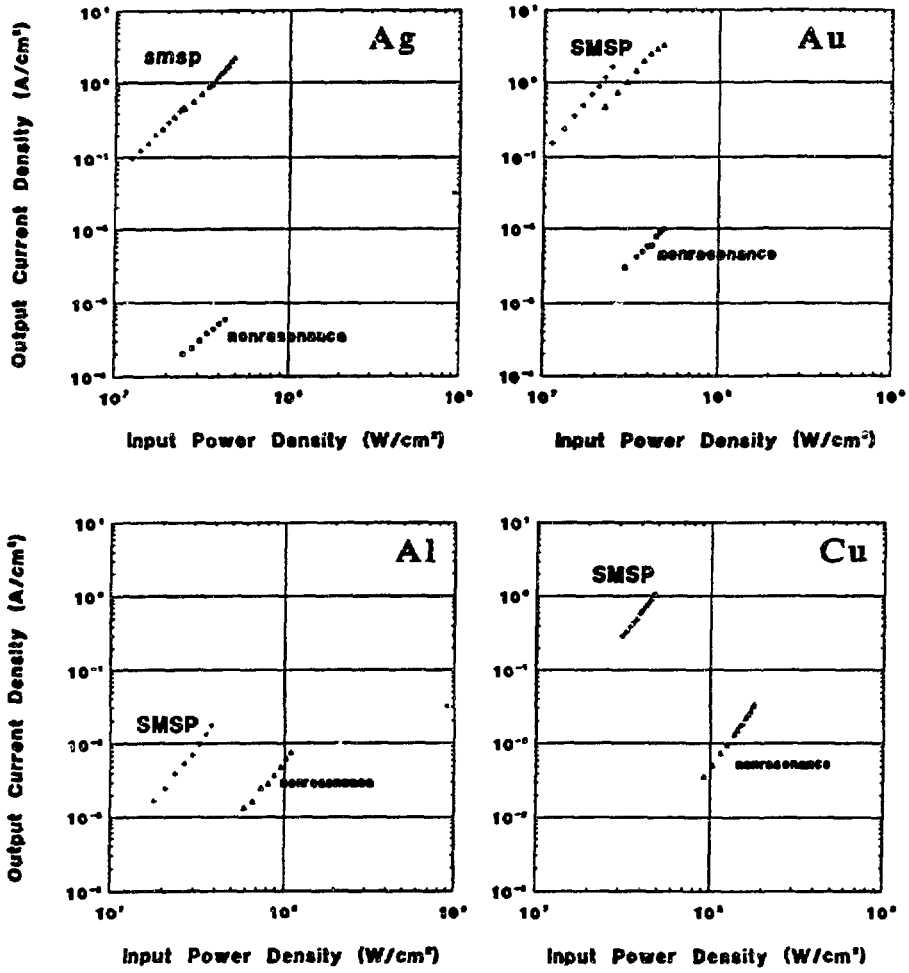


Figure 10. Experimental measurements of the multiphoton photoemission for Ag, Au, Cu, and Al thin films using surface plasmon excitation.

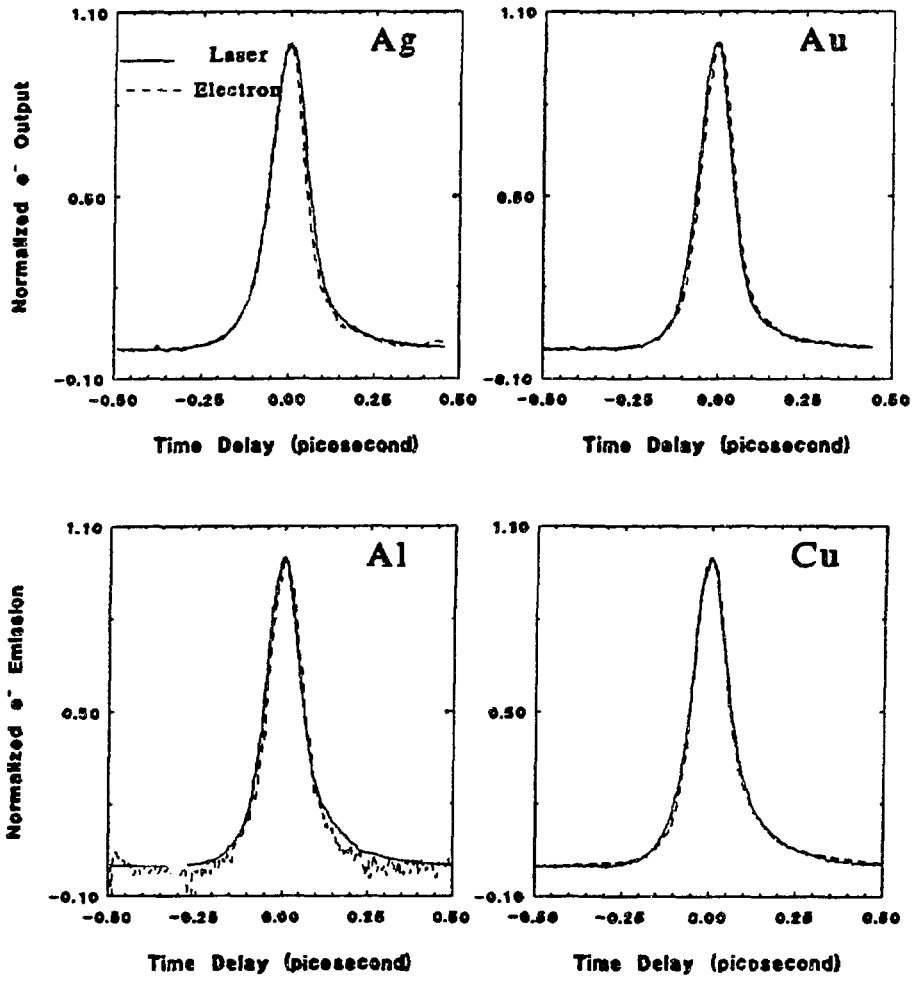


Figure 11. Experimental measurements of the electron and laser pulse durations using nonlinear photoemission and second harmonic generation techniques, respectively, from thin metal films.

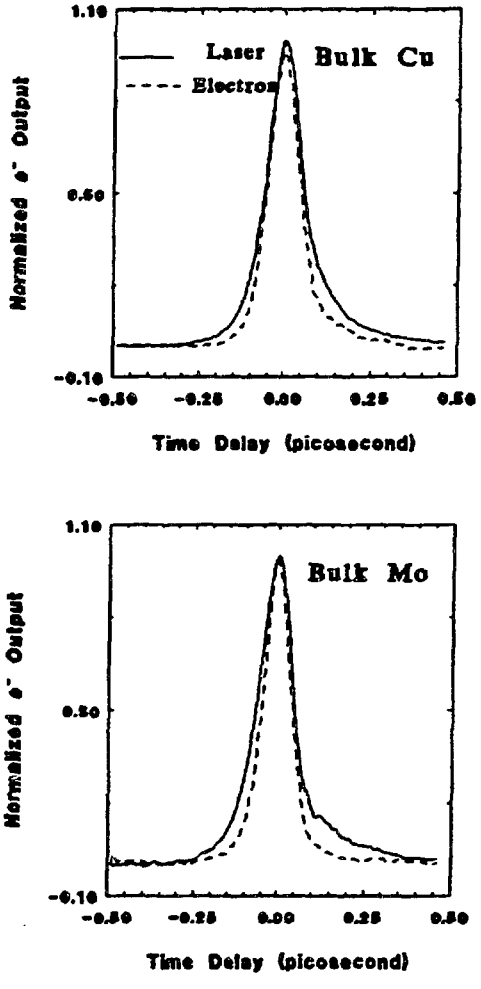
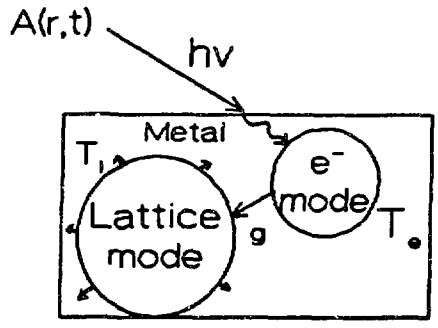


Figure 12. Experimental measurements of the electron and laser pulse durations using nonlinear photoemission and second harmonic generation techniques, respectively, from bulk metals.

For Laser Pulse Duration ≤ Electron-Phonon Relaxation Time (<25 ps)



$$C_e(T_e)\frac{\partial T_e}{\partial t} = K\nabla^2 T_e - g(T_e - T_i) + A(r,t) - [L(r,t)]$$

$$C_i\frac{\partial T_i}{\partial t} = g(T_e - T_i)$$

C_e = Electronic heat capacity = γT_e
C_i = Lattice heat capacity
K = Thermal conductivity
$A(r,t)$ = Heat source term representing laser
$L(r,t)$ = Heat carry away by plasmons
m = Electron mass
N = Conduction electron density
v_s = Velocity of sound in metal
τ_{ep} = Electron – phonon collision time
T_d = Debye temperature
g = Electron – phonon coupling parameter

$$= \frac{\pi^2 m N v_s^2}{\partial \tau_{ep} T_i}\left(\frac{T_e}{T_i}\right)^4 \int_0^{T_e/T_d}\left[x^4(e^x - 1)^{-1}dx\right]$$

Figure 13. Model of the hot electrons in metal.

the electrons are out equilibrium with the lattice phonons, significant electron temperature is generated which might degrade the emitted electron energy and momemtum. However, the advantage being lower the lattice temperature so that damage threshold can be improved. With a computer program, we have numerically calculated the electron and lattice temperatures by solving the coupled differential equations shown in Figure 13. A representative result from Cu using 10 ps and 100 fs laser pulses are shown in Figure 14. With 15 GW/cm^2 of laser power, the higher electron temperature obtained is ~ 0.1 eV for a 10 ps laser pulse and ~ 0.05 eV for the 100 fs pulse. These temperatures are tolerable in a typical RF photoinjector. The lattice temperatures, however, are significantly lower when ultrashort laser pulses are used. Therefore, damage of metal photocathode can be avoided.

IV. High Voltage Extraction Schemes

Using laser triggered photoinjectors, high brightness electron source can be designed, however, the space-charge effect must be overcome before higher than 20kA/cm^2 of electron current can be obtained. One traditional approach to overcome the space-charge is by using high voltage pulse extraction method. Figure 15 (a) and (b) show the schemetics of a 3-laser-beam and a 2-laser-beam triggered electron gun and high voltage pulsing system that we attempted to use. To prevent breakdown effect and minimize the electrical jitter to below 1 ns, careful intergration of the system is necessary. Figure 15 (c) shows a preliminary test of the laser triggered Marx generator output. A 50 kV pulse with 13 ns duration in a jitter of $\leq$ 1ns has obtained. Complete test of the high voltage system are in progress. Other electron extraction scheme under consideration are magnetically guide the electrons to a Faraday cup for evaluations, and shaping of the cathode geometry.

V. Conclusion

In conclusion, linear photoemission are reviewed. To obtain higher electron current density from metal photocathodes, nonlinear photoemission are sugggested. Electron yield enhancement has been observed with a p-polarized laser source using surface photoelectric effect.

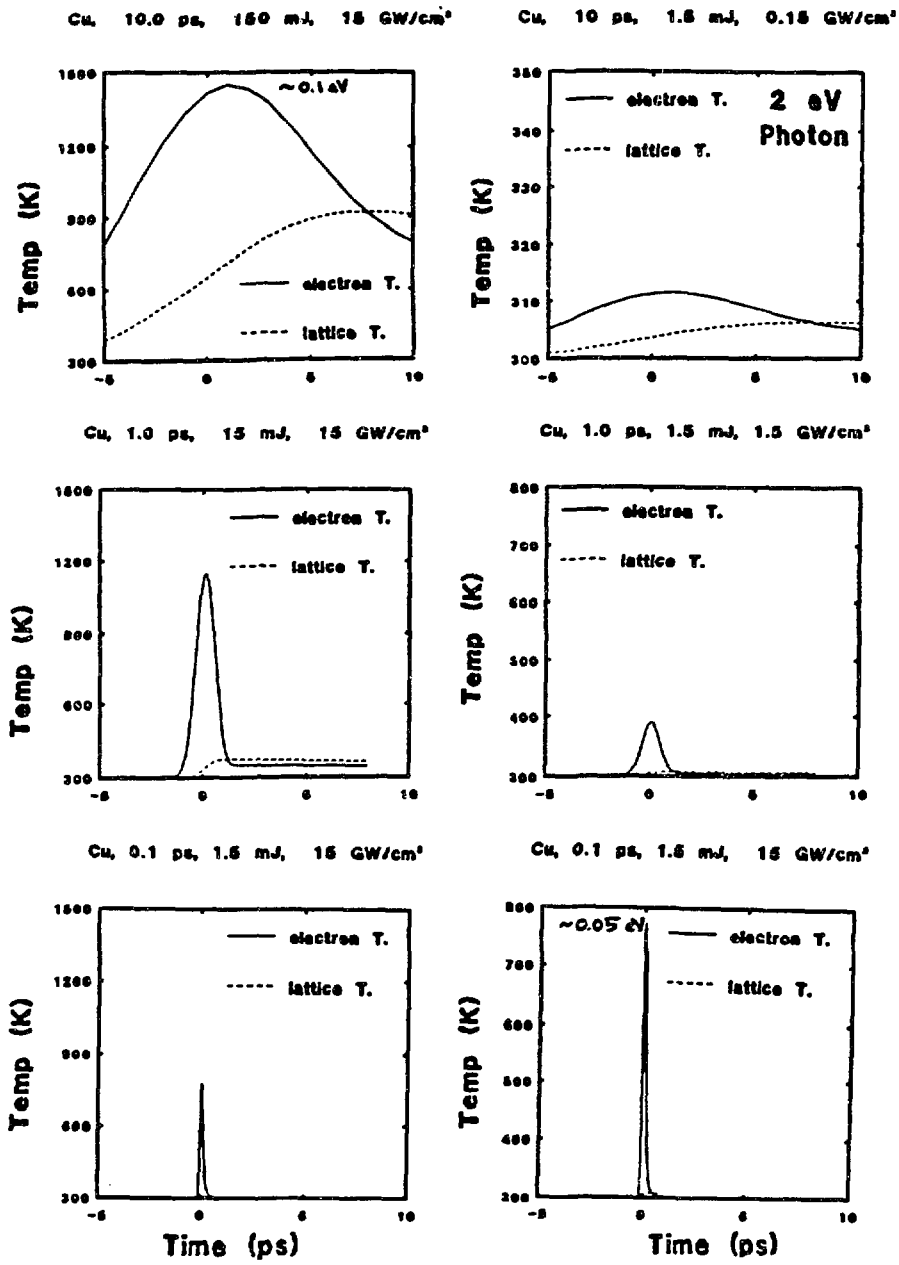
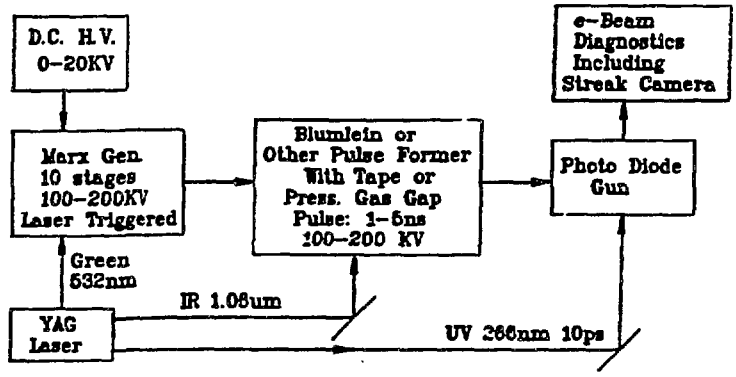
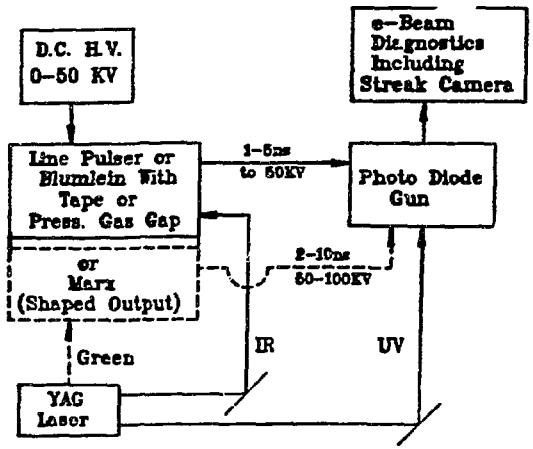


Figure 14. Nonequilibrium between electron and lattice temperatures with various incident laser pulse durations and energies on Cu surface.

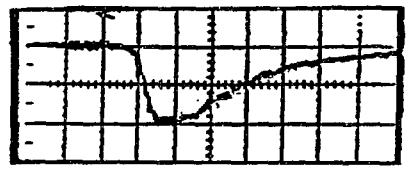
a) 3 Beam Laser; Total Delay ~10ns



b) 2 Beam Laser; Delay: Line Pulser<5ns or Marx<10ns



c)



50 KV Marx Pulse Into 50 Ohms
5ns/div. ; 25KV/div.

Figure 15. (a)-(b) Schematics of the laser triggered electron gun and high voltage pulsing systems. (c) High voltage pulse output of the laser triggered Marx generator.

Further electron enhancement using surface plasmon resonant excitation has been demonstrated. Quantum efficiency of 10^{-7}, 8×10^{-7}, 0.5×10^{-7}, and 1.6×10^{-9} are obtained from SP mediated electron emission from Ag, Au, Cu, and Al films, respectively, at the input power density of $50 MW/cm^2$. Based on a theoretical investigation, we found the nature of the enhancement favors the localized SMSP field calculations using the Fresnel coefficients than the absorption relied on the reflectivity measurements. By monitoring the electron current and the reflectivity simultaneously, we have shown that electron emission peaked at a slightly different incident angle than that registered by the ATR spectra, which were predicted by the SMSP field calculations. We have also demonstrated the electron pulse duration measurement in the femtosecond time regime using the nonlinear photoelectric effect. The electron pulses duration are found only limited by the laser. However, the width of the electron pulses fail to narrow commensurating with a higher order autocorrelation.

In the SMSP enhanced electron scheme, the electrons are possibly ejected in a forward direction with respect to the laser beam, thereby, reducing the possible interaction of the electrons with the intense photon field and consequently suppressing electron momentum broadening.[8] The upper limit of the peak electron current density, however, is governed by the damage threshold of the thin metal films, which can be improved using an ultrashort laser source.

Acknowledgements

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