Electron Emission from Ferroelectric Cathodes Excited by Picosecond Laser Pulses with Long Wavelengths

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Abstract

The efficiency of laser-induced electron emission from ferroelectric (FE) cathodes grows significantly when the pulse length of the incident laser pulse is shortened. A tenfold increase of emitted charge was observed with PZT 95/5 FE cathodes illuminated by 40 ps long laser pulses of 532 nm wavelength compared with irradiation by 5 ns pulses with the same pulse energy and wavelength. Irradiation with 40 ps long double laser pulses spaced by 1 ns resulted in the same emission of double electron pulses as that found with double laser pulses spaced by 1 s. The efficiency of laser-induced emission from FE cathodes also strongly increases with incident laser energy density at constant laser pulse length. Enhancements of emission efficiency, though far less important, were also measured for angles of the incident laser beam different from 0°. Transient enhancement of 'basic' laser-induced FE emission by previous polarization switching and subsequent surface charge refreshment was observed in the visible and infrared wavelength region. Thick FE disks are easy-to-handle candidates for reliable photocathodes, especially in RF-driven electron guns operating at high repetition rates and at high average power density conditions.

1 INTRODUCTION

Cathodes made from FE material, excited by fast HV pulses, are most probably the easiest way of producing electron beams for a large range of applications, but why are FE photocathodes (pc's) interesting? Conventional semiconductor pc's have a high quantum efficiency, but generally need a very good vacuum, and cannot be transported through air. At high average power levels of incident light their reliability is very poor. Metallic pc's are very resistant and less sensitive to poor vacuum. However, their quantum efficiency is low, and their use is restricted to wavelengths in the UV region. With the limited R&D on FE pc's carried out up to now [1–7], it has been demonstrated that certain FE materials have significantly higher electron yields than metallic pc's, and their long-term emission properties remain unchanged at incident laser power density levels under which conventional semiconductor pc's would be destroyed immediately. Moreover, FE pc's can be transported and stored for years under atmospheric pressure and operated in gas or plasma environments.

The mechanisms of laser-induced electron emission from FE are complex and differ strongly from conventional photoemission. Nevertheless, at the very start it was assumed that FE pc's would offer interesting electron yields at laser wavelengths in the visible and IR regions. The results of the R&D presented in this paper confirm this assumption. Several techniques can be used to enhance the emission efficiency of FE pc's. Electron beam densities which are at the limit of what todays laser-driven electron guns may digest, can be generated with high reliabilty and long lifetime under illumination from lasers at long wavelengths, and with the average power levels available in the near future.

2 TEST SET-UPS

FE cathodes have been investigated at the LAL/Orsay and at CERN with the same vacuum tank, but with two different Nd:YAG lasers: the LAL laser has a 40 ps and the CERN laser a 5 ns pulse length. Both laser systems can operate with 1064, 532, 355, and 266 nm wavelength. The laser spot diameter was varied between 2 and 6 mm. In most experiments an extraction voltage of 30 kV was applied corresponding to an extraction field of 3 MV/m. The incidence angle of the laser beam on the cathode surface could be varied between 0° and 50°. Simultaneous polarization switching of the FE pc and laser-induced emission was not possible. The vacuum, in which the tests were carried out, was in the range from 10^{-5} to 10^{-7} mbar. Joulemeters and fast photodiodes were used for the diagnostics of the laser beam and charge collectors connected to oscilloscopes of 1 GHz bandwidth for the electron beam.

3 MEASUREMENTS

In conventional photoemission, quantum efficiency does not depend strongly on the pulse length of the incident light. In contrast, we measured a more than one order of magnitude increase of emission efficiency for FE pc's, when going from 5 ns to 40 ps laser pulse length. Figure 1 illustrates the efficiency of a PZT 95/5 cathode doted with 2% Cr_2O_3 for the two pulse lengths with the wavelength as the parameter. This enhancement increases with wavelength and disappears almost fully at 266 nm. It is independent of other enhancement effects which are described below, and predicts emission efficiencies of the same order of magnitude at all wavelengths for even shorter pulse length.

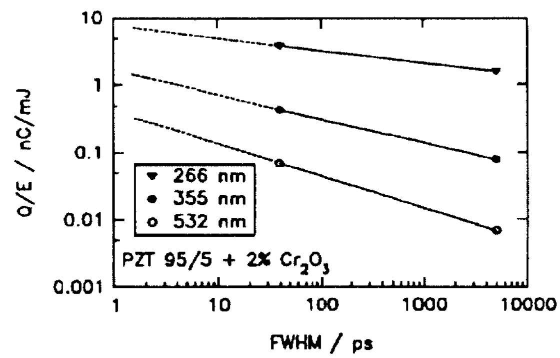

Figure 1: Emission efficiency for different wavelengths as a function of laser pulse length.

Several FE cathodes were irradiated with 40 ps long double laser pulses spaced by 1 ns. The waveforms of emitted current and the amounts of emitted charge did not differ from those obtained with a double pulse with a spacing of 1 s. Hence, there is no indication for saturation or charge recovery effects within this range of time.

Another strong influence on the emission efficiency, Q/E = charge/laser energy, of FE pc's is exerted by the incident laser beam energy density. Figures 2a and 2b show Q/E as a function of laser energy density for 40 ps and 5 ns pulse length at 266, 355, and 532 nm. The same PZT 95/5 cathode doted with 2% Cr_2O_3 was used with the different lasers. This enhancement effect becomes smaller for shorter wavelengths especially with 40 ps laser pulses. The space charge limit for 30 kV extraction potential shown in Fig. 2a, which is not reached with 5 ns pulses in the range shown in Fig. 2b, limits the intensity of the laser-induced emission. With other FE materials, such as PLZT's, similar characteristics were measured.

Figure 3 shows an efficiency plot as a function of laser power density for a PZT 95/5 pc doted with 2% Cr_2O_3. The two groups of measured data correspond to the laser pulse lengths of 40 ps and 5 ns. The efficiency growth with power density is less than linear.

With metallic pc's a strong emission dependence on the angle of incident laser light was reported [8]. A similar, but weaker effect was measured with a PLZT 2/94.5/5 pc at LAL under irradiation with laser light of 532 nm and 40 ps pulse length. The emitted charge rises by 40% when increasing the laser beam incidence angle from 0° to 50°. The resulting increase of emission efficiency by increasing the angle is plotted in Fig. 4. With different FE pc's never more than 50% enhancement of emission, and sometimes no enhancement at all, was observed.

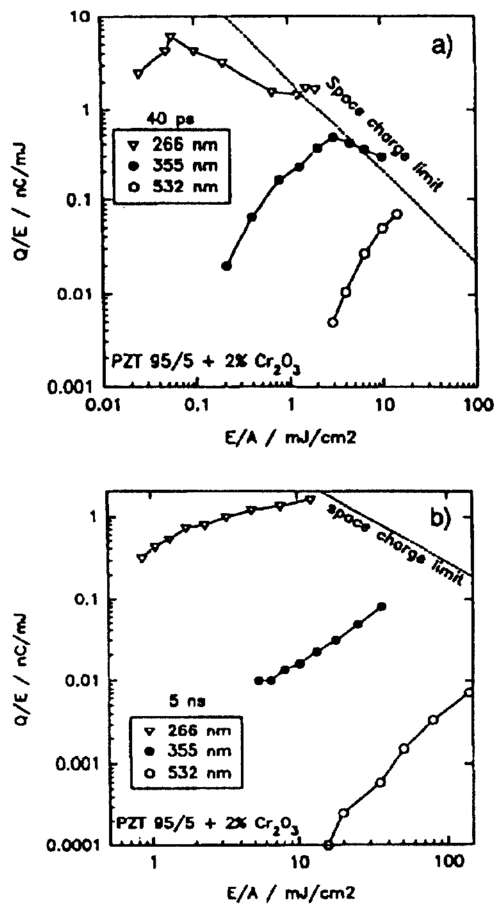

Figure 2: Emission efficiency as a function of laser pulse energy density for three different wavelengths at (a) 40 ps and (b) 5 ns laser pulse duration.

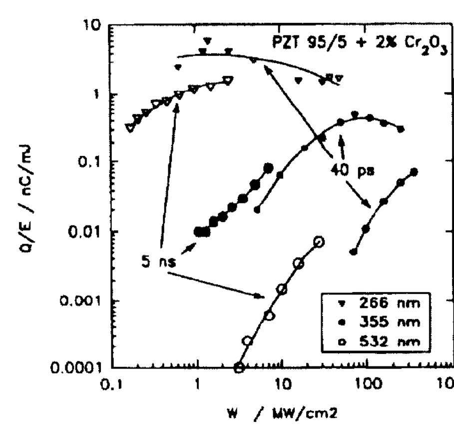

Figure 3: Emission efficiency as a function of laser pulse power density for three different wavelengths including measurements with 40 ps and 5 ns laser pulse length.

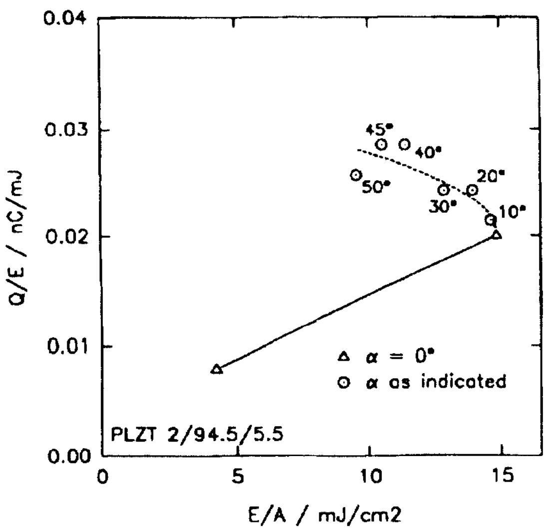

Figure 4: Emission efficiency of a PLZT 2/94.5/5.5 pc irradiated with 40 ps laser pulses of 532 nm wavelength and 7 kV extraction potential as a function of energy density at different incidence angles (0° = perpendicular incidence).

At picosecond pulse length, enhancement effects induced by FE polarization switching as reported in Ref. [2] were also observed. Transient amplified emission of charge densities, which can be achieved under normal (non-switching) conditions only at UV wavelengths, was observed in the IR region. By irradiating a PLZT 2/94.5/5.5 pc with 40 ps laser pulses at 1064 nm and power densities of several hundreds of $\mu J/cm^2$, enhanced emitted charge densities of almost 1 nC/cm^2 were measured. During laser-induced emission experiments with FE pc's it was recognized that the application of d.c. extraction eliminates the polarization switching capability of the FE pc in the region of the laser spot. The transient enhancement, which grows with increasing wavelength, can only be applied at very low d.c. extraction potentials [2], or together with pulsed or RF extraction fields.

4 DISCUSSION OF RESULTS

The 'basic' laser-induced emission efficiency of FE pc's is surpassing that of metallic pc's by at least one order of magnitude. Semi-conductor pc's offer much higher efficiencies, but in a high-power environment and without excellent vacuum their lifetime, is very short. With respect to reliabilty and lifetime, FE pc's beat even metallic pc's, and they work well in a gas or plasma atmosphere. The experimental results in this paper show that several methods allow the emission efficiency of FE pc's to be increased considerably. The possibilities of enhancement are especially strong and manifold in the visible and IR region, where they are most welcome.

The enhancement of FE pc emission and the performance optimization may not only be achieved by properly choosing average and peak laser power density with respect to the destruction threshold, but also by optimizing the FE material composition, the strength of spontaneous polarization, internal phase distribution, grain and domain sizes, porosity, light absorption and reflection properties, cathode thickness and surface structure, prepoling and electroding procedures. The results of the investigations reported above will permit the extrapolation of pc performance with the FE materials at present being studied with respect to available short-pulse lasers. They will also encourage R&D to produce even better FE pc's and their application in laser-driven electron guns.

5 CONCLUSIONS

Ferroelectric photocathodes are becoming increasingly useful for the electron guns of free electron lasers and of future high-power and high repetition rate linear colliders. R&D based on the results obtained may lead to performance optimization, which will well match the proven robustness and reliability of ferroelectric cathodes.

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