A robust and powerful green light photoemission source: The ferroelectric ceramics

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The photoemission characteristics of ceramic disks of lead zirconate titanate lanthanum doped (PLZT), have been investigated. We observe 1 nC of extracted charge under an accelerating field of 20 kV/cm in poor vacuum conditions. The emission is clearly limited by space charge effects. The extrapolated quantum efficiency results in $\approx 10^{-6}$. The yield of a PLZT ceramic in the ferroelectric state and its slope versus light intensity have turned out higher than those of antiferroelectric ceramic. Samples in different experimental configurations have shown different nonlinear yields. © *1999 American Institute of Physics.* [S0003-6951(99)03504-4]

In recent years the photoemission from ferroelectric materials has been the object of deep investigation at CERN.[1–8] The reasonably good emissivity at wavelength varying from green to ultraviolet (UV), coupled to robustness made this ferroelectric lead zirconate titanate lanthanum doped (referred as PLZT) ceramic a real subject of research for an efficient and robust photocathode for switched power linac,[9] next generation of accelerators,[10,11] ultrashort x-ray sources.

A nonlinear behavior of the extraction efficiency in terms of the laser intensity has been reported in Refs. 4–7. It has also been shown that the nonlinearity is stronger at lower laser frequencies. This behavior suggests the possibility of getting efficient electron extraction even at the second harmonic of neodimium yttrium–aluminum–garnet (YAG) laser. These results and a proposed modelization[12] suggested the investigation of the emission in the visible range.

The sketch of the experimental setup is shown in Fig. 1. A frequency doubled Nd-YAG laser provides light at $\lambda = 532$ nm with a pulse length of 25 ps. The cathode is illuminated over an area of about $10\,\text{mm}^2$ with an elliptic spot size. The incidence angle is around 60°.

The cathode is set in front of a flat anode, at a distance of about 3 mm. The charge is collected by a coaxial copper anode (Faraday cup) matched with a 50 Ω cable. The Faraday cup is directly connected to a 200 MHz bandwidth oscilloscope. The minimum detectable charge, tested with a gold cathode, is approximately 0.1 pC. The working pressure is maintained by a dry turbo pump at approximately $2-3 \times 10^{-5}$ mbar.

The experiment has been carried out with PLZT having composition 8/65/35 and 4/95/5, where the numbers refer to lanthanum (in relation to lead), zirconium, and titanium relative atom percentage. The ceramic of 8/65/35 is in ferroelectric phase at room temperature, while the 4/95/5 is in antiferroelectric phase, but it undergoes a transition from antiferro to ferroelectric phase under the action of a suitable electric field.[13] The cathodes are disks of 16 mm diameter and 1 mm thickness, coated by a uniform metallic film on the back surface and by a grating interconnected by an external ring or by the external ring only on the front surface, see Fig.1. The cathode is held in place by a metal ring connected to the rear surface. The whole assembly is set at a negative voltage (with respect to the grounded anode) which ranged from zero up to 7 kV, for a maximum gradient of 20 kV/cm. The whole holder assembly can rotate about the vertical axis so that the angle of incidence can be varied.

The emitted charge has been measured as a function of laser energy and accelerating voltage. For each pulse the

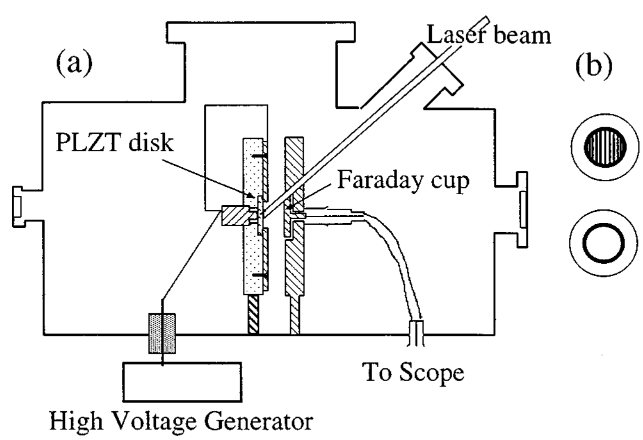

FIG. 1. (a) Sketch of the experimental apparatus used in the photoemission experiments, (b) sketch of the cathode with the two types of electroding at the front surface. The laser is a Quantel YG501 Nd-YAG laser. A Drytel turbo pump keeps the vacuum at about $2-3\times10^{-5}$ mbar.

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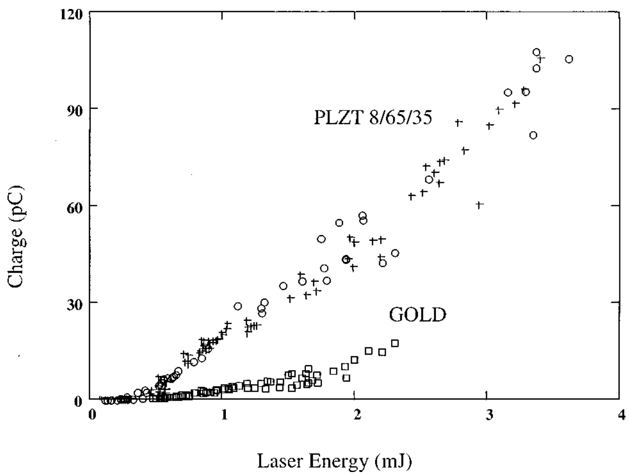

FIG. 2. Emitted charge vs laser energy for an unprepoled PLZT 8/65/35 gridded sample. The circles and crosses refer, respectively, to 3.5 and 7.0 kV of accelerating voltage. The squares refers to emission from gold at 3.5 kV.

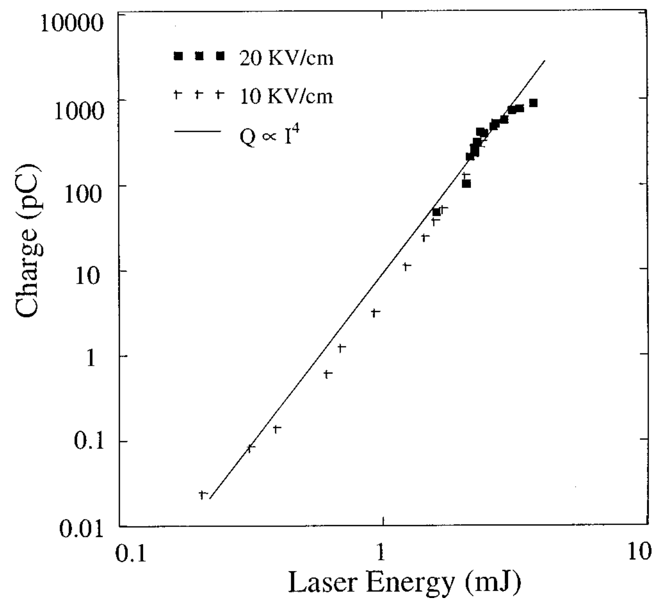

FIG. 4. Emitted charge vs laser energy for PLZT 8/65/35 without the front grid. The continuous line is a fit with $Q\alpha I^4$ scaling law. Data have been obtained at two different accelerating voltages: 10 (crosses) and 20 kV/cm (squares).

laser intensity and the relative emitted current have been recorded and integrated. The charge emission as a function of the laser energy at an accelerating field of 10 and 20 kV/cm for a gridded unprepoled PLZT 8/65/35 sample is shown in Figs. 2 and 3.

The emitted charge versus laser energy is almost linear with a threshold at 0.2 mJ. Energies lower than this value provided charges below the observable limit. The absence of a substantial difference between the data sets corresponding to 10 and 20 kV/cm of accelerating voltage indicates that no space charge effects are present up to 100 pC of extracted charge. In Fig. 3, the extraction efficiency is shown. The data from gold display the typical two photons linear efficiency growth with the laser energy. The situation is more structured in the PLZT case where we have an evident jump in the efficiency around 0.5–0.7 mJ. In these conditions efficiencies in the range $\approx 0.5\times 10^{-7}$ have been observed.

A sample with the same composition but without the metallic grid on the front surface [see Fig. 1(b)] has provided the data shown in Fig. 4. The accelerating gradient was 10 kV/cm for laser energies up to 4 mJ (crosses) and 20 kV/cm for higher laser energies. The experimental data are compared with a $Q\propto I^4$ scaling law. Notwithstanding the doubled accelerating gradient, at high laser intensities we have a clear yield limitation due to space charge effects. This has also been observed from the time resolved current wave forms that were temporally dispersed when charges in excess of 0.3 nC were extracted. The quantum efficiency at 3.3 mJ of laser energy is 1.4×10^{-7} and grows rapidly with the laser power due to the nonlinearity of the emission process. The maximum charge extracted is 0.9 nC. Extrapolating from the curve of Fig. 4, e.g., assuming an accelerating field high enough to avoid saturation effects, the emitted charge at 5 mJ of laser light would exceed 5 nC. The value of quantum efficiency is in this case in the 10^{-6} range. The illuminated area is about 10 mm^2, if the electron pulse length is equal to the light pulse length ($\approx$25 ps) we would have a current density of 2 kA/cm^2. The laser power is well below the damage threshold. The great increase in the line slope passing from a gridded to a bare cathode, probably indicates that the sample polarization is affecting the emission process. The grid is indeed partially shielding the sample from the accelerating field.

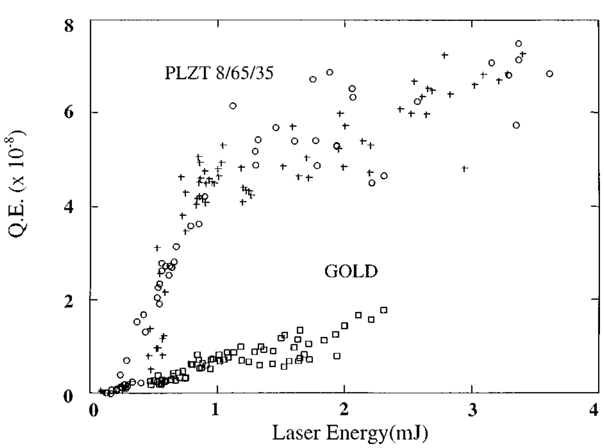

FIG. 3. Quantum efficiency (electrons/photons) vs laser energy for an unprepoled PLZT 8/65/35 gridded sample. The circles and crosses refer, respectively to 3.5 and 7.0 kV of accelerating voltage. The squares refers to emission from gold at 3.5 kV.

We have also investigated the emission from PLZT 4/95/5. This sample was unelectroded on the front side and under the action of the external accelerating field. As previously remarked this composition provides samples in antiferroelectric state at room temperature. In Fig. 5, it is shown the charge yield obtained at different accelerating voltages. The data have been acquired in the following chronological order: 3.5, 5.0, 5 (repeated), 7, and 3.5 kV (repeated). In each sequence at fixed voltage a scan of the yield varying the laser energy from low to high values has been done.

It is evident that the charge yield is strongly affected by the accelerating voltage, that is again an indication of the influence of the sample polarization state on the electron emission process. The difference of the two series of data at 3.5 kV (the first and the last set of measures) evidences a hysteretical behavior. The laser excitation process alone is

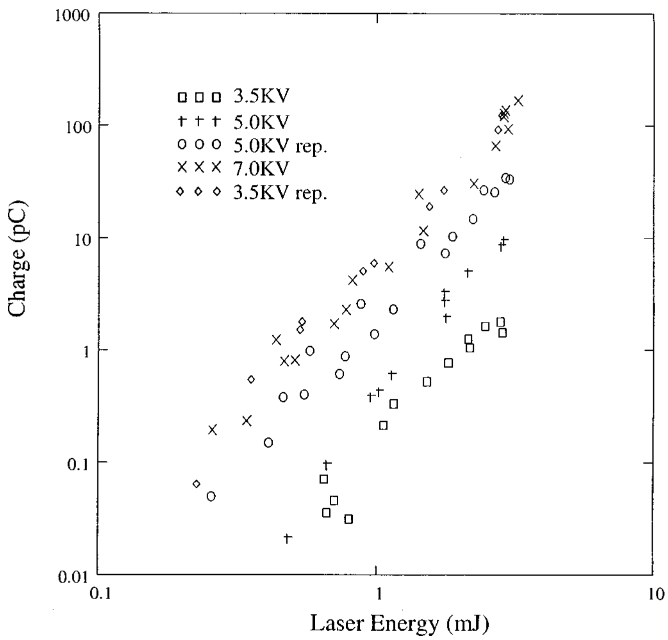

FIG. 5. Emitted charge vs laser energy for PLZT 4/95/5 without the front grid. Data have been acquired in the following chronological order: 3.5, 5, 5 (repeated), 7, and 3.5 kV (repeated).

also inducing an efficiency growth, as it is shown by the two series of data taken at 5 kV, one right after the other. The emission has increased by a factor 5 without any change of the supplied voltage. The charge emission versus the laser energy scales in this case with a $Q=\alpha\times I^{2-2,5}$ law.

The hysteretical behavior is confirmed by the data displayed in Fig. 6. We have heated for 1 h at 250 °C the sample that provided the data shown in Fig. 5. This procedure should have resembled the original sample polarization conditions by inducing a paraelectric transition. After cooling we have measured the yield by keeping constant as much as possible the laser energy and by changing the accelerating voltage. We first raised the voltage up to 7 kV and then we reduced it down to 0 to close the loop. In Fig. 6 we have displayed the yield divided by the squared laser energy versus the applied voltage. This allowed to reduce the scatter due to laser energy fluctuations. The yield first grows with the voltage but then remains unchanged when the voltage is reduced down to 3.5 kV. Beyond this value it goes to zero linearly while the voltage goes to zero as well. Charges extracted below 100–200 V were affected by space charge limitation, as was observed by the time resolved current wave forms.

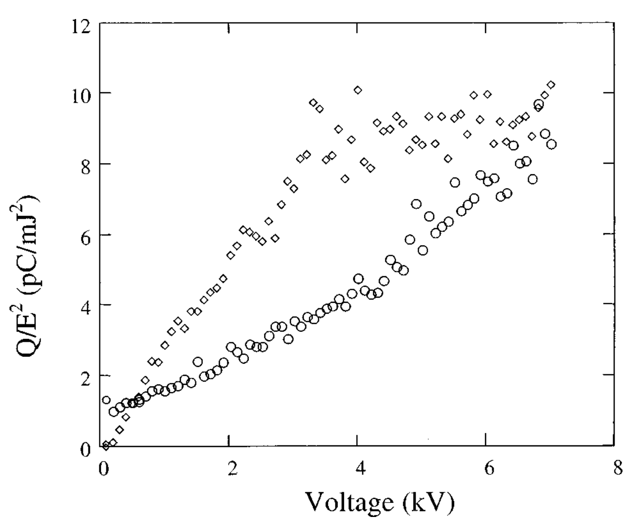

FIG. 6. Charge normalized to squared laser energy vs accelerating voltage for PLZT 4/95/5. The data have been acquired starting at zero voltage. The yield first grows with the voltage up to 7 kV (circles), it remains unchanged when the voltage is reduced down to 3.5 kV and then goes to zero linearly when the voltage goes to zero as well (diamonds).

In conclusion, a new efficient configuration for ferroelectric photocathodes has been investigated. The characteristics of these cathodes, are: (a) strong robustness, they work in any kind of vacuum showing a long life; (b) they do not require any particular processing; (c) they can be operated with green light. The nonlinear extraction efficiency together with the high damage threshold suggest that quantum efficiencies larger than 10^{-6} can be obtained.

In our experimental conditions the emission could be due to the combination of many effects: multiphoton absorption, thermally assisted multiphoton absorption,[14] coherent harmonic generation and one photon absorption, and Auger electron emission. More investigation is required to select and refine a correct model.

In the next future the extracted electron beam will be characterized in terms of time structure. If the electron pulse duration is strictly related to the laser pulse duration, these cathodes promise to deliver current densities larger than 1 kA/cm^2 and to be valid competitors of both metallic and alkali cathodes.

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