Electron Source from a Laser Plasma Expanding in an Electric Field

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A bright, pulsed and low energy electron source is under development at CENBG[1] in Bordeaux, France, to measure cross sections of nuclear excitation by electron inelastic scattering. This source is based on the extraction of electrons from a laser produced plasma during its expansion in an electric field. PIC simulations are performed and reproduce the measured characteristics of the extracted electrons.

Introduction

Four main mechanisms of nuclear excitation occur in hot and dense plasmas of astrophysical relevance, or produced in inertial fusion experiments [1, 2]. The free electron inelastic scattering (e,e') is one of them, which is particularly weak and poorly described at energies of the order of a few tens to hundreds of keV characteristic of hot and dense plasmas. Significant nuclear excitation rates by (e,e') are nonetheless possible, as the expected electron flux can reach $10^{38}-10^{39}$ m^{-2}s^{-1}keV^{-1} at kinetic energies between 10 and 40 keV in astrophysical plasmas [3]. The evaluation of nuclear excitation rates in these extreme thermodynamic conditions requires the knowledge of the (e,e') cross sections, but calculations give results which vary by several orders of magnitude [4]. New experimental data are thus essential. We propose first cross section measurements of the (e,e') excitation in the case of ^{181}Ta, for which experimental attempts at a detection of excited states in a plasma have been carried out [5]. These measurements require an electron beam with a challenging $10^{13}-10^{14}$ particles per bunch of a few ns duration at a repetition rate of at least 10 Hz and energies between a few tens to one hundred keV. Such a source is being developed at CENBG[1], in Bordeaux, France.

Set-up

To reach the above-mentioned intensities, the source of the electron beam is based on the extraction of electrons from a laser produced plasma, when this plasma expands in an electric field. As illustrated in Fig.1, the plasma is obtained with a 1J, 9 ns Nd-Yag laser pulse focused down to a spot of a few tens of μm in diameter on a solid aluminum target, reaching intensities of 10^{13} W.cm^{-2}. The extraction electric field is set by biasing the target at

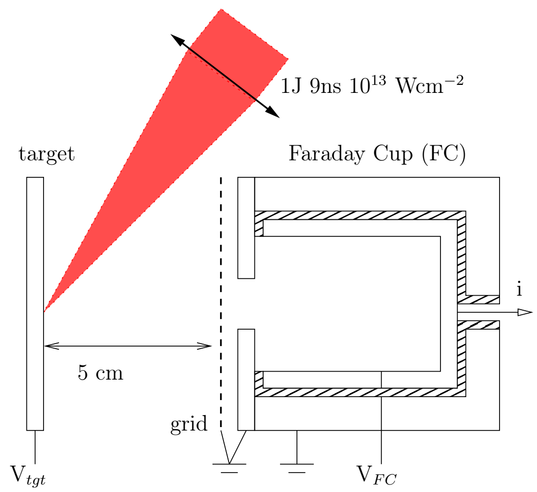

Figure 1: *Set up.*

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a negative V_{tgt} voltage and placing a grounded grid down the expansion path of the plasma, 5 cm away from the target. The extracted electrons are detected with a Faraday Cup (FC), composed of two nested conducting open cylinders. The inner cylinder is 5.6 cm in diameter. The outer cylinder is grounded and placed behind the grid in the beam path, while the inner cylinder can be biased at a negative V_{FC} voltage. The charged particles impinging on the inner cylinder induce a current representative of the total deposited charge.

Figure 2 shows a typical FC signal in volts measured in a 50 Ω load as a function of time, obtained whith $V_{tgt} = -5$ kV and $V_{FC} = 0$ V. The signal is attenuated by a factor of 100, and the origin of time corresponds to the instant of laser-target interaction. A negative first peak can be observed between about 20 and 120 ns, and a larger positive peak at about 300 ns. Turning off V_{tgt} suppresses the first peak, signing the extracted electron contribution. The second peak is the positively charged part of the plasma which reaches the FC after the electron extraction. The 120 ns duration typically corresponds to the time needed for the front edge of the plasma to expand in the 5 cm distance between the target and the grid, as expected from Al plasma dynamics previously characterized [6]. The electron instants of detection can be considered as their instant of extraction, as their flight duration to reach the anode is below 2 ns.

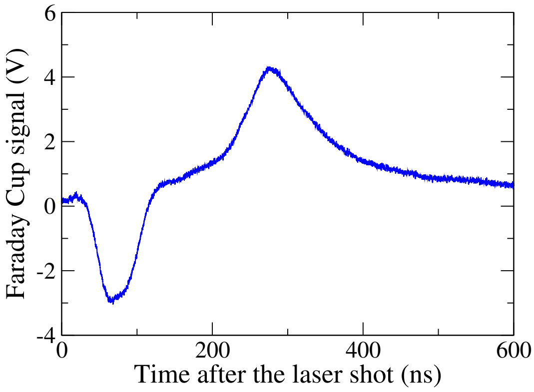

Figure 2: *Typical FC signal vs time.*

Extracted Electron Energy Distributions

When biasing V_{FC} at negative voltages, a repulsive electric field is induced in the FC, which pushes part of the electrons backwards depending on their kinetic energy. Figure 3 illustrates such a selection, as the less energetic electrons are gradually cut at later times when the FC voltage increases, up to a complete disappearance of the electron signal when $|V_{tgt}| \leq |V_{FC}|$. Such V_{FC} scans allow the determination of the energy distributions of the extracted electrons, either for the whole bunch or at different extraction times. The signals are integrated over a chosen time interval, and differences between signals at different V_{FC} values correspond to the number of electrons in the associated energy interval.

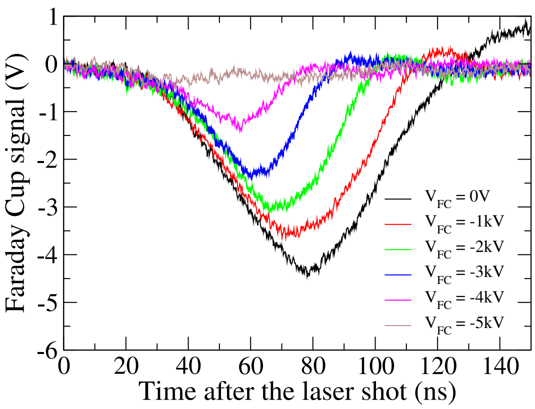

Figure 3: *Effect of* V_{FC} *on the electron signal.*

Figure 4 shows the obtained experimental energy distributions of electrons extracted at different instants after the laser-target interaction when V_{tgt} is at -5 kV. Electrons extracted at increasing times have a mean kinetic energy which decreases from about 4.5 to 1 keV, resulting in a continuous energy distribution for the final total electron bunch over 1 to 5 keV. This decrease in electron mean energy with time suggests a drop in the extracting voltage V_{tgt} with time.

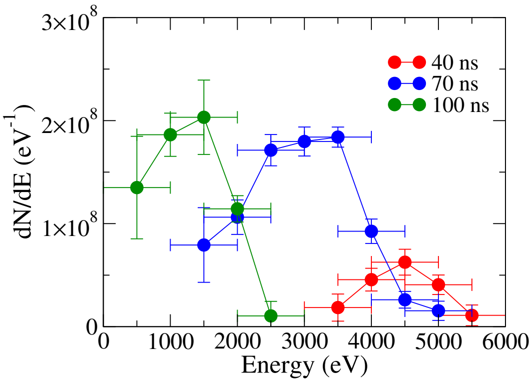

Figure 4: *Electron energy distributions.*

A capacitive voltage divider allows us to monitor the time evolution of the target voltage during the extraction process. This evolution is shown in Fig. 5 as a solid line. The absolute value of the target voltage is initially set at $|V_{tgt}| = 5$ kV and drops down to 1 kV over the 120 ns duration of electron extraction. The measured mean energies of the electrons reaching the anode, which correspond to the mean value and width of the distributions presented in Fig.4, are also shown as a function of time. They seem to follow the target voltage drop except above 100 ns, where they are lower than the target voltage. This observation would indicate that the electrons extracted from the expanding plasma gain energies directly related to the actual target voltage at their instant of extraction.

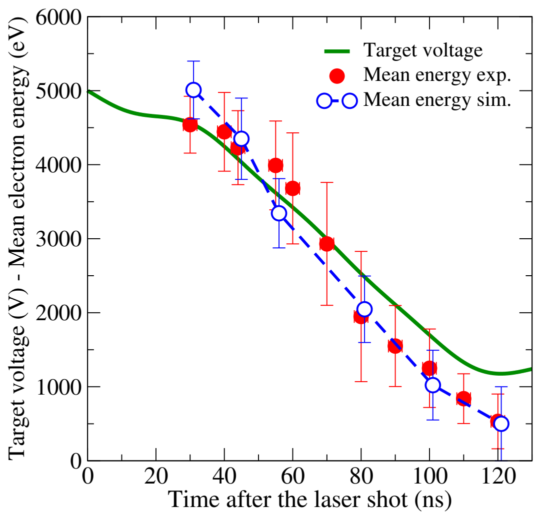

Figure 5: *Electron mean energies vs time.*

Two dimensional particle-in-cell (PIC) simulations were performed with the XOOPIC code [7] to corroborate this observation and to identify the mechanisms of electron extraction at different instants of plasma expansion. The plasma expansion over the 5 cm from target to grid lasts about 120 ns, which is too long to be fully simulated. However, the typical acceleration duration of an electron of a few keV is about one ns. We have therefore considered given times with the longitudinal plasma extension deduced from the ion energy distributions previously characterized [6]. Because of computational limitations, the simulation geometry is simplified to a cylindrical box 5 cm in longitudinal length and 640 μm in transversal radius. One edge of the cylindrical box is biased at the measured target voltage value $V_{tgt}(t)$ at a given time whereas the opposite edge is grounded (anode). The plasma is considered as homogeneous, neutral and composed of electrons and Al ions with an 8+ mean charge deduced from previous works [6]. The density is set at the front edge value also deduced from previously measured absolute ion energy distributions [6]. The electron plasma temperature is below 1 eV. The cell size in z-r coordinates are 50×10 μm^2 and the time step is 10^{-12} s. These characteristics ensure numerical stability governed by the Debye length and the plasma frequency. Simulations are run up to 1 ns after the first electrons reach the anode. The mean energies of the extracted electrons obtained from the simulations are compared to the measured mean energies and the target voltage in Fig. 5. Simulation and experimental data are in good agreement. Due to the Debye length being lower than a few tens of μm, the electric field is screened in the cm large plasma and only the expanding plasma edges are sensitive to the extraction field. Electrons are extracted from the expanding front edge acting as a cathode moving in direction of the anode. Simulations show that during the first 80 ns following the laser shot the rear edge of the plasma is close to the target and the plasma cathode is biased at a voltage close to V_{tgt}. As seen in Fig. 5, the electron mean energies and the target voltage therefore display a similar behavior with time. At later times, the front edge of the plasma gets closer to the anode and the plasma voltage decreases to reach values close to the ground potential, leading to the extraction of electrons with energies lower than 1 keV. Ions are also extracted from the rear edge of the plasma and accelerated towards the target, leading to the drop of V_{tgt}.

Conclusion

An electron source based on the extraction of electrons from a laser plasma produced at 10 Hz and $\sim 10^{13}$ W.cm^{-2} is being developed. Electron bunches containing up to 6×10^{12} particles per bunch are obtained with a continuous energy distribution between 1 and 5 keV. The extraction is based on the biasing of the target forcing the plasma to expand in an electric field. PIC simulations with the XOOPIC code reproduce the extraction dynamics induced by the extraction field which varies with time. The simulated energy distributions of the extracted electrons are in agreement with the experiment. The drop in target voltage which is observed as the plasma expands limits the total number of extracted electrons. A stabilisation of this voltage is being studied and first results show that a factor of 3 can be gained on the number of electrons.

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