

# INNOVATIVE SINGLE-SHOT DIAGNOSTICS FOR ELECTRONS FROM LASER WAKEFIELD ACCELERATION AT FLAME

F.G. Bisesto\*, M.P. Anania, E. Chiadroni, A. Curcio,  
M. Ferrario, R. Pompili, INFN-LNF, Via Enrico Fermi 40, 00044 Frascati, Italy  
A. Cianchi, University of Rome Tor Vergata, 00133 Rome, Italy  
A. Zigler, Racah Institute of Physics, Hebrew University, 91904 Jerusalem, Israel

## Abstract

Plasma wakefield acceleration is the most promising acceleration technique known nowadays, able to provide very high accelerating fields ( $> 100$  GV/m), enabling acceleration of electrons to GeV energy in few centimeters. Here we present all the plasma related activities currently underway at SPARC\_LAB exploiting the high power laser FLAME. In particular, we will give an overview of the single shot diagnostics employed: Electro Optic Sampling (EOS) for temporal measurement and Optical Transition Radiation (OTR) for an innovative one shot emittance measurements. In detail, the EOS technique has been employed to measure for the first time the longitudinal profile of electric field of fast electrons escaping from a solid target, driving the ions and protons acceleration, and to study the impact of using different target shapes. Moreover, a novel scheme for one shot emittance measurements based on OTR, developed and tested at SPARC\_LAB LINAC, used in an experiment on electrons from laser wakefield acceleration still undergoing, will be shown.

## INTRODUCTION

The fast development in the laser field during the past decade has provided high power multi-TW system at femtosecond level. The availability of such systems has allowed to study the interaction between ultra intense ( $> 10^{19} W/cm^2$ ) lasers with matter in different fields: astrophysics in laboratory [1], high energy density experiments [2], electromagnetic wave sources [3] and novel schemes for particle acceleration [4–8]. Particular attention has been given to the latter since the possibility to have a table-top accelerator, exploiting relative small and cheap systems, results very fascinating. Nevertheless, the produced particle (electrons and ions) beams suffer of shot-to-shot instabilities and the physical mechanism is not yet well clear, especially concerning the interaction with solid targets for ion acceleration. In this context, the need for single shot diagnostics to be employed in laser-plasma experiments is crucial in order to achieve a better control.

The plasma related activities currently underway at SPARC\_LAB exploiting the high power laser FLAME are moving in this direction.

In this work, an overview of the developed single shot diagnostics will be given. In detail, we are focusing on a temporal diagnostics based on Electro Optic Sampling

(EOS), to study the emission of fast electrons from thin solid targets responsible of ion and proton acceleration, and on a scheme for single shot emittance measurements based on OTR (Optical Transition Radiation).

## EOS DIAGNOSTICS FOR FS RESOLUTION TEMPORAL MEASUREMENTS ON FAST ELECTRONS

Ion acceleration from thin foils irradiated by high-intensity short-pulse lasers is one of the most interesting aspect in this research field since it produces a large amount of particles with energies in multi-MeV range [9, 10]. According to the established theoretical models [11], the process starts when some electrons, directly accelerated by the laser, penetrate the target. The majority of them spread and dissipate energy inside of it while the hot component of these electrons is able to reach the target rear side and is released in vacuum [12]. The most energetic electrons escape, leaving behind an electrostatic potential, set up by the unbalanced positive charge left on target, that locks the majority of them near the target [13]. Such potential generates an electric field that ionizes and accelerates surface ions in a process called Target Normal Sheath Acceleration [14] (TNSA).

So far only indirect evidences of the escaping electrons have been detected by measuring the radiated electromagnetic pulses [15, 16] and magnetic fields [17]. Here we report direct and temporally resolved measurements of fast electrons by means of a temporal diagnostics based on EOS [18].

## Experimental Setup and Results

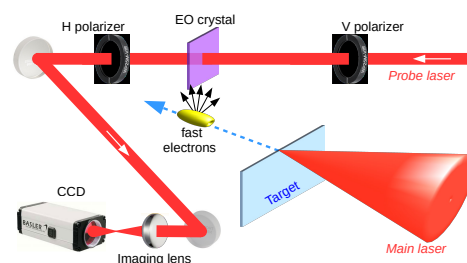


Figure 1: Setup of the experiment. The FLAME laser is focused on a metallic target from where fast electrons can escape. The EOS system, based on a  $500\mu m$  thick ZnTe crystal placed 1 mm downstream the target, allows to measure the temporal profile of the emitted electrons by means of an ancillary laser beam probing the local birefringence induced by the electric field.

\* fabrizio.giuseppe.bisesto@lnf.infn.it

The experiment has been carried out with the FLAME laser at the SPARC\_LAB test-facility [19] using the setup in Fig. 1. FLAME consists in a 130 TW Ti:Sapphire laser system delivering 35fs (FWHM), up to 4J pulses at 800nm central wavelength and 10Hz repetition rate. The laser beam was focused by a  $f/10$  off-axis parabolic mirror with focal length  $f = 1\text{m}$ . The  $1/e^2$  diameter of the laser spot on target was approximately  $60\mu\text{m}$ , corresponding to a peak intensity of about  $10^{19}\text{W}/\text{cm}^2$ . Exploiting such an intense laser pulse, fast electrons are produced by irradiating the tip (about  $10\mu\text{m}$  thick) of a stainless steel wedged target. The diagnostics is based on a  $500\mu\text{m}$  thick ZnTe EO crystal, placed  $1\text{mm}$  downstream the target. The longitudinal profile of the electric field carried by fast electrons is encoded into the transversal plane of a probe laser following the EOS spatial scheme [21]. The probe laser employed to detect the EO signal (35fs FWHM pulse duration) is directly split from the FLAME laser, ensuring a jitter-free synchronization. The synchronization of the main and probe lasers in correspondence of the EOS crystal is obtained by means of an  $\alpha$ -cut BBO crystal. The time overlapping, i.e. our reference time, is then retrieved by looking for the light from sum frequency generation (SFG).

Once calibrated for time of flight measurements in order to retrieve the electron energy [20], we studied the influence of target shape by testing planar, blade and tip targets [22]. We changed the position of the laser on the target at each shot. In the case of the planar foil target, the resulting snapshot in Fig. 2(a,d) shows the presence of a first emitted bunch with approximately 1.2 nC charge and 7 MeV energy followed by a second broadened structure carrying a larger amount of particles (about 3 nC). For the wedged target, the snapshot in Fig. 2(b,e) shows a similar structure. The first bunch now carries a larger amount of electrons (2 nC) at the same energy (7 MeV) while the charge in the second bunch is strongly reduced to 0.3 nC. Electron bunches coming from the tip target are shown in Fig. 2(c,f). In this case the interaction with the laser produced a much larger number of released electrons (about 7 nC) at higher energies (about 12 MeV).

In conclusion, we measured for the first time the temporal profile of the electric field carried by fast electrons, related to the ion acceleration in high intensity laser and solid target interactions. Afterwards, we used our diagnostics to test the influence of target shape. In detail, the results provide a direct evidence of charge and energy boost when using sharp tips. Therefore a consequently field enhancement for ion and proton acceleration has been measured.

## SINGLE SHOT EMITTANCE MEASUREMENTS BASED ON INCOHERENT OTR

Electron beams from plasma accelerators are characterized by relatively large energy spread (around 5% rms) and suffer shot to shot instabilities. These points make the common diagnostics tools for emittance measurements almost not useful. The quadrupole scan technique [23], for example,

is a multi-shot technique and it is very sensitive to energy spread [24].

A solution under studying at SPARC\_LAB comes from Optical Transition Radiation (OTR). [25]. The main features of OTR can be found analysing its angular distribution by looking at in the focal plane of a lens. Indeed, it shows a strong dependence from the particle energy: the characteristic lobes (Fig. 3) are peaked at  $1/\gamma$ , where  $\gamma$  is the relativistic Lorentz factor. Furthermore, from [27], it can be found that beam divergence affects the incoherent OTR angular distribution. Figure 3 shows the comparison between the line profiles of the angular distributions with and without taking into account the beam angular divergence: the former has a central minimum different from 0. Using the information coming from the beam image and the OTR angular distribution, both values of beam dimension and divergence can be obtained with a single shot. A first scheme based on OTR [26] provided an emittance measurement only in a beam waist where the correlation term between divergence and beam size is zero. However, for its own nature the plasma acceleration has strong shot-to-shot fluctuations and a beam waist cannot be guaranteed. Therefore, in order to fully measure the emittance, it is necessary to measure the correlation term as well. The idea developed in this work is to use a microlens array that allows to correlate the beam divergence with the spatial position by analysing the OTR angular distribution of each microlens.

### *Experimental Setup*

In Fig. 4 the layout of our experimental setup for single shot emittance measurement is shown. The OTR emitted by a silicon aluminated screen is sent to two different arms through a 90:10 beam splitter: the reflected radiation is used for transverse dimension diagnostics, in combination with a high quantum efficiency Hamamatsu Orca II camera, equipped with a Nikon  $f = 180\text{mm}$  focal length F/2.8; the transmitted part passes through a  $400\text{mm}$  focal length achromatic doublet which makes a 1:1 replica of OTR source in its imaging plane where a microlens array ( $10\text{mm} \times 10\text{mm}$ ,  $300\mu\text{m}$  pitch,  $18.7\text{mm}$  focal length plano-convex lenses) takes place. Its focal plane is duplicated by a  $50\text{mm}$  focal length achromatic doublet imaged on an intensified camera (Hamamatsu Orca IV). The whole setup has been extensively simulated by means of Zemax, an optical and illumination design software, in order to evaluate any possible aberrations affecting the measure. In Fig. 5 a qualitatively comparison between simulation and experimental results is reported. The experiment has been performed with the SPARC\_LAB photoinjector [19], using  $200\text{pC}$  bunch charge at  $125\text{MeV}$ . Unfortunately, the maximum energy achievable in this run was limited by the use of only two of the three accelerating sections and the minimum detectable angular divergence was equal to  $500\mu\text{rad}$ , while our electron beam had  $250\mu\text{rad}$  [27]. Even though we did not measure the emittance, this preliminary result demonstrates that it is possible to produce the OTR angular distribution from different part of the beam image.

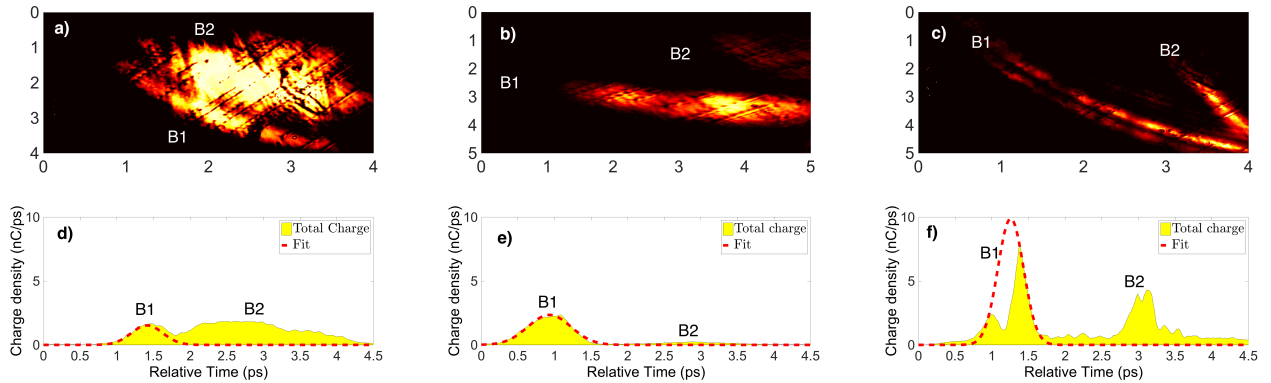


Figure 2: Snapshots with different target shapes. Signatures of the escaping electrons from (a) planar, (b) wedged and (c) tipped targets. The emitted charges are, respectively, (a) 1.2nC (B1) and 3nC (B2); (b) 2nC (B1) and 0.3nC (B2); (c) 7nC (B1) and 3nC (B2). The gaussian envelopes represent the extrapolated charge profiles of each bunch. (d-f) Corresponding longitudinal charge profiles.

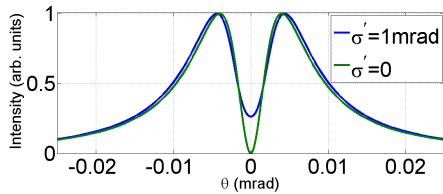


Figure 3: Incoherent OTR angular distribution line profile with (red) and without (blue) angular divergence for a 125MeV electron beam. The effect due to 1mrad beam divergence is the increase of the central minimum.

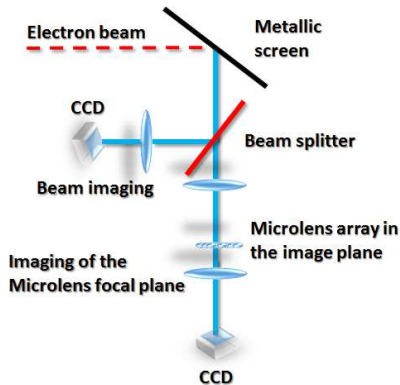


Figure 4: Single shot emittance measurement setup: one arm is for transversal size diagnostics, the other is dedicated to correlation term measurement by means of microlens array. [27]

## CONCLUSIONS

In this work, we presented the development of two single shot diagnostics for ultraintense laser-plasma interaction experiments. A setup based on Electro Optical Sampling has been realized in order to measure for the first time the longitudinal profile of fast electron electric field escaping from a solid target during the interaction with a high inten-

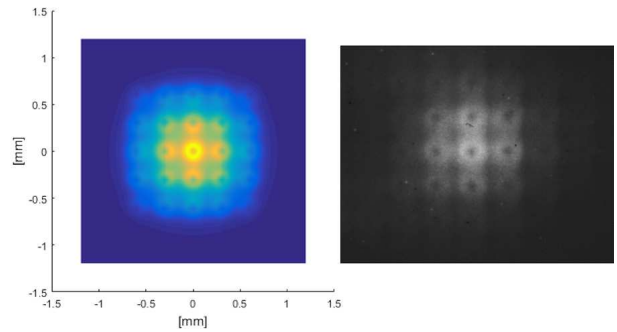


Figure 5: Comparison between a simulation made by means of Zemax (on the left) and a typical experimental measurement (on the right). [27]

sity laser pulse. With such a diagnostics, we have measured a significant increase in the charge and energy of the escaping electrons (corresponding to an increase in the potential barrier) for sharp structured targets. These results can be used as a guideline in order to achieve higher energies for positively charged ions with respect to what is currently obtained through conventional laser acceleration schemes. Moreover a new scheme for single shot emittance measurements has been proposed. It relies on the characterization of incoherent optical transition radiation. Using a microlens array it is possible to retrieve the correlation term between beam divergence and spatial position. This allows to measure the emittance in one shot. This kind of diagnostics represents a very useful tool to fully characterize an electron beam from LWFA despite its typical shot-to-shot instabilities and relative large energy spread. Some preliminary results obtained with the SPARC\_LAB LINAC have been reported, while a measurement on a plasma-accelerated electron beam at FLAME Facility is still under design, both with a self-injection and external injection [28] scheme.

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