IL NUOVO CIMENTO Vol. 32 C, N. 3-4 Maggio-Agosto 2009
DOI 10.1393/ncc/i2009-10482-8

Colloquia: IFAE 2009

Laser-plasma acceleration with self-injection: A test experiment for the sub-PW FLAME laser system at LNF-Frascati

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(ricevuto il 19 Settembre 2009; pubblicato online il 24 Novembre 2009)

Summary. — Laser-driven plasma acceleration is now being considered world-wide as a promising technique for the development of a new class of particle accelerators. The INFN-PLASMONX project aims at exploring this scenario using ultra-short laser pulses of the 0.3 PW, Ti:Sa laser system FLAME (Frascati Laser for Acceleration and Multidisciplinary Experiments). A self-injection test experiment (SITE) is being designed and set up to study electron acceleration at the sub GeV energy level. In this paper we describe the planned experiment, including the numerical modelling, the main plasma diagnostics and the electron spectrometer.

PACS `52.50.Jm` – Plasma production and heating by laser beams (laser-foil, laser-cluster, etc.).
PACS `52.38.Kd` – Laser-plasma acceleration of electrons and ions.

1. – Introduction

In the past decade, terawatt, table top laser systems based upon chirped pulse amplification [1] have been successfully used in many laboratories world-wide to explore the laser-matter interaction regime in the ultra-short, ultraintense domain for novel X-ray and γ-ray sources, laser-driven acceleration, inertial fusion energy research through the interaction with gas and solid targets [2,3]. These results are now providing a strong motivation for the development of new laser infrastructures like HiPER [4] and ELI [5]. The perspective of a practical exploitation of laser-driven acceleration for the future generation of particle accelerators is giving thrust to the development of integrated LINAC and

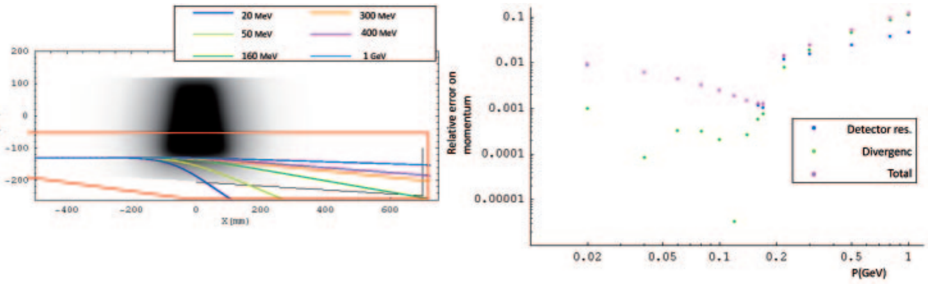

Fig. 1. – (Colour on-line) Left: working principle of the of the SITE spectrometer. The black area represents the area with magnetic field directed orthogonally to the picture. Also shown are the trajectories of the particles (colour lines), the locations of the position detectors (black lines), and the contour of the vacuum chamber (red line). Right: expected resolution showing the error originting from the position resolution of the detector and the error due to the beam divergence.

FEL laboratories. The PLASMONX project [6] aims at exploiting the FLAME laser system and the 150 MeV SPARC [7] LINAC to explore laser-driven particle acceleration in both the self-injection and the external injection scheme. In view of this, a self-injection test experiment (SITE) has been planned to establish the performance of the FLAME laser system and to assess the degree of control of critical laser parameters. In this paper we give an brief overview of the FLAME laboratory followed by a description of the experimental set-up planned for the SITE experiment, with a focus on optical diagnostics and the electron spectrometer for detection of the accelerated electrons. Then we give a summary of the numerical simulations carried out to design the SITE experiment on the basis of the expected laser specifications.

2. – The layout of the experiment

The experiment is under construction at the FLAME laboratory and the set-up is similar to the one used in a previous, pilot experiment carried out recently at the ILIL-IPCF lab [8] and developed in previous extensive experimental campaigns [9-12]. The FLAME laser (Amplitude Tech.) is based upon a Ti:Sa, chirped pulse amplification (CPA) system that will deliver 20 fs, 800 nm, up to 300 TW, laser pulses with a 10 Hz repetition rate at a fundamental wavelength of 800 nm. The system features a high, sub-ns contrast ratio ($> 10^{10}$) and has a fully remotely controlled operation mode. In the experiment, the main laser pulse is focused onto a gas-jet target using an F/10 off-axis parabola at a maximum intensity above $5 \times 10^{19}\,\mathrm{W/cm^2}$. Several optical and high-energy diagnostics including Thomson scattering, optical interferometry [13], scintillators coupled to photomultipliers, a phosphor screen (LANEX) and custom dose sensitive, radiochromic film stacks [14] are under implementation to investigate laser-target interaction and the accelerated electrons. A detailed characterization of the accelerated electron bunch will be carried out by means of a custom-designed magnetic electron spectrometer (see fig. 1).

According to the requirements of the SITE experiment, the spectrometer must be capable of measuring the spectrum of tens of millions of particles arriving simultaneously spread over three order of magnitudes in energy (10 MeV to 1 GeV) with a divergence of a few mrad, originating from a point-like spot located more than a meter before the region with magnetic field. Figure 1 shows the optimal set-up achieved with an existing

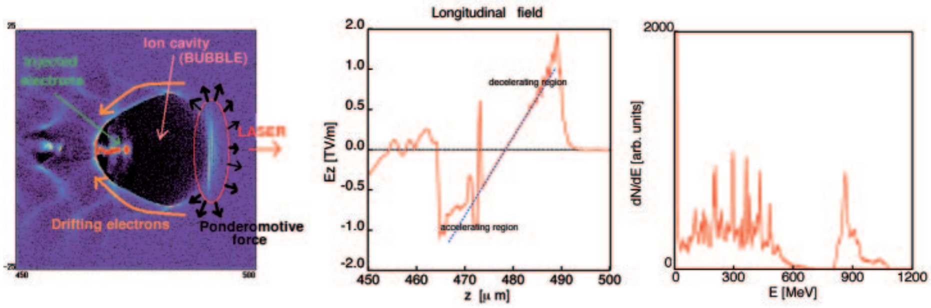

Fig. 2. – The bubble regime. Left: plot of the electron density; middle: line-out of the longitudinal field along the bubble axis. Right: energy spectrum of the accelerated electrons as obtained from the 3D PIC simulation for the SITE after a propagation of 4 mm inside the gas-jet.

magnet, spare of the DAΦNE accelerator and with a maximum magnetic field of 0.5 T. The design of the position detector and its electronics is driven by the large number of electrons impacting at the same time and the need to operate in vacuum. The detectors are therefore made of about 900 scintillating fibers with 1 mm diameter read by five multichannel photomultipliers. This ensures a resolution of better than 1 mm in the whole detector. The relative error of the spectrometer is expected to be better than 1% in the sub 200 MeV range. At higher energies the error increases reaching the value of approximately 10% at 1 GeV as shown in fig. 1 (right). The use of a slit at the entrance of the spectrometer is also planned to reduce the angular acceptance of the spectrometer and improve the resolution at high energy.

3. – The design of the SITE experiment: numerical modelling

The self-injection test experiment at FLAME aims at generating GeV-class electron bunches from laser-plasma interaction using a gas-jet of a few millimeters, working in the so-called bubble regime [15,16]. In the bubble regime, see fig. 2 (left), a short ($c\tau < \lambda_p/2$) and intense ($a_0 > 2$) laser pulse expels the plasma electrons outward creating a bare ion column.

The blown-out electrons form a narrow sheath outside the ion channel and the space charge generated by the charge separation pulls the electrons back creating a bubble-like wake. For sufficiently high laser intensities ($a_0 > 4$) electrons at the back of the bubble can be injected in the cavity and were the longitudinal accelerating field is of the order of $\sim 100\sqrt{n(\mathrm{cm}^{-3})}$ V/m as shown in fig. 2 (middle). The FLAME laser meets both the two conditions of short pulse length and high intensity. As a consequence when the laser pulse impinges onto the gas-jet it promptly excites (without significant pulse evolution) a bubble wake where electrons are readily injected and so the entire gas-jet length can be utilized for the acceleration process. In order to have a "controlled" acceleration mechanism, which ensures a better final bunch quality, the plasma and laser parameters must be chosen according to the phenomenological theory described in [17]. A possible working point for the SITE is described in table I. In this case, following [17], we expect to obtain a quasi-monochromatic (few % momentum spread) bunch with a charge of ~ 0.6 nC and an energy of approximately 1.0 GeV after 4 mm (dephasing length). The acceleration process has been investigated also through 3D PIC simulations performed with the fully self-consistent, relativistic, electromagnetic PIC code ALaDyn [18,19]. The

TABLE I. – *A possible working point of the test experiment on laser-acceleration at FLAME.*

$L_{\text{gas jet}}$ (mm)	n_p (e/cm^3)	τ (fs)	I_0 (W/cm^2)	w_0 (μm)
4	$3 \cdot 10^{18}$	30	$5.2 \cdot 10^{19}$	16

results are summarized in fig. 2 (right plot). At the end of the simulation we obtained a bunch with an energy of 0.9 GeV and a momentum spread (rms) of 3.3%, the charge is 0.6 nC, the bunch length is 1.8 μm (the average current is $\sim$ 50 kA) and the beam divergence (rms) is 2.8 mrad. The results are in good agreement with [17].

4. – Conclusions

The first GeV scale national experiment on laser-driven electron acceleration with self-injection (SITE) is being planned in the commissioning phase of the FLAME laboratory at LNF. This follows a recent successful > 10 MeV scale, pilot experiment completed at ILIL-CNR. These activities, carried out within the PLASMONX Collaboration, are a precursor to the wider programme that also includes the combined use of the SPARC linac and the FLAME laser for alternative schemes of injection and X-ray generation with the Thomson scattering scheme.

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This work was supported by the INFN Project PLASMONX, by the MIUR funded FIRB-SPARX project and by the MIUR-PRIN project "Studio della Generazione e della propagazione di elettroni rapidi [...]". We acknowledge the support of the CINECA computing center for the 3D runs (grant: "Simulazioni PIC 3D per l'accelerazione laser-plasma").

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