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An integrated approach to ultraintense laser sciences: The PLASMON-X project

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Abstract. In this paper we discuss recent results in the design configuration and modelling of the PLASMON-X project aimed at the development of an innovative, high-gradient acceleration with super-intense and ultra-short laser pulses, and a tuneable, hard X/γ-ray source, based upon Thomson scattering of optical photons by energetic electrons. Both experiments require very high power, ultra-short laser pulses in combination with very bright and short electron bunches generated either by conventional acceleration (LINAC) or by laser-driven, self injection acceleration in plasmas. The main issues concerning the integrated use of unique laser and linear accelerator installations, and the complementary use of all-optical configurations will be briefly examined.

1 Introduction

In the past decade, terawatt, table top laser systems have been successfully used in many small scale laser facilities world-wide to explore the laser-matter interaction regime in the ultra-short, ultraintense domain and to develop unique investigation techniques. The wealth of new results thus obtained have been further explored and confirmed in larger scale facilities using high energy systems and have generated entirely new fields of research including novel X-ray sources, laser-driven acceleration, fast-ignition for the inertial fusion energy and warm dense matter physics, also through the interaction with solid targets. In Europe, these results are now providing a strong motivation for the development of new laser installations like HiPER and ELI that may finally establish some of these fields as collaborative, long term programmes. At the same time, the growing interest of the particle accelerator community for a practical exploitation of laser-driven acceleration for the future generation of particle accelerators and the strong convergence of the synchrotron radiation and X-ray free-electron laser community on femtosecond, high field physics, is giving thrust to the installation of medium and high energy laser systems integrated in LINAC and FEL laboratories. This opportunity is now becoming a reality that calls for significant resources and expertise that, once again, have their breeding grounds in the small scale laser laboratories.

The PLASMON-X project [1] is an example of this convergence. The 10 Hz, 300 TW TiSa laser system and the 10 Hz, 150 MeV SPARC [2,3] linear accelerator are now well into the construction phase and additional R&D on ultra-fast electron-photon synchronization is being planned. The set of experiments identified for the first phase of operation of the installation include laser-driven acceleration of self-injected as well as externally injected electron bunches, Thomson scattering for production of tunable, hard X-rays for bio-medical applications and FEL laser seeding. All these experiments have now been under extensive modelling and test experiments are already in progress at collaborating small-scale laboratories. In this paper we briefly describe the baseline configuration of the main experimental set up and summarize recent results on the modelling of the experiments.

2 Background and current status

2.1 Laser driven acceleration

After the first pioneering experiments on plasma acceleration carried out in the early eighties, impressive progress in the field of laser-driven acceleration is being achieved today, following the advent of the ultra-short pulse lasers and the Chirped Pulse Amplification (CPA) technique [4]. In fact, thanks to CPA, pulses of a few joules in tens of femtoseconds, at a repetition rate of 10 Hz can now be produced and used. Recently, very encouraging results have been achieved concerning the energy and the quality of the electron bunches by laser-driven acceleration mechanisms [5–8]. More recently this scheme has been widely studied experimentally and electron energies above 100 MeV, with high degree on monochromativity have been achieved and reproduced in a number of laboratories world-wide while in some cases, energies above 1 GeV have been reached [9].

These experiments strongly suggest that a prototype of a fully laser-plasma driven photo-injector can be conceived provided that a control of the laser and plasma performances is implemented in the experimental configuration. In fact, in the general case of acceleration of externally injected electrons, the idea is to inject electron bunches produced by an external source in the electron plasma wave in such a way that the electron bunch experiences an accelerating field and its energy is thus increased. In our case the external source of electron bunches will be either a conventional RF accelerator or a laser-plasma injector. In view of this, a particular attention has been devoted in the recent PLASMON-X project activity to perform basic experiments [10–14] aimed at finalizing the design of a relatively flexible laser system capable of driving a prototype that may also act as an external laser-plasma injector.

2.2 Bright X/γ ray sources

Ultrashort, intense laser pulses offer unique opportunities to activate novel regimes of X-ray generation processes [15]. Thomson Scattering from free electrons is a pure electro-dynamic process in which each particle radiates while interacting with an electromagnetic wave. Thomson scattering of a laser pulse by energetic counter-propagating electrons has been proposed since 1963 [16,17] as a quasi monochromatic and polarized photons source. The development of ultra intense CPA laser systems significantly renewed the interest in the Thomson scattering process. Recently TS in the linear regime has also been used to get the angular distribution of a monochromatic electron bunch [18]. Moreover, experimental methods have been recently proposed to measure the length of a monochromatic electron bunch [19] and to measure the energy spectrum of a single bunch eventually characterized by a wide energy spread or alternatively to measure the angular distribution of a single bunch with a known energy spectrum [20]. These new experimental methods are based on X-ray detectors having both a good spectral and angular resolution (cooled CCD camera used in the single photon counting regime) [21].

In the basic configuration, a relativistic electron bunch generated by a standard RF accelerator is driven in the laser focal spot where the X-ray scattering process takes place. Laser Wake Field Acceleration (LWFA) can be a valid alternative to conventional RF accelerators, provided that the bunch quality is good enough. Advantages of LWFA accelerators relies essentially in the potential compactness of source but also in a higher flexibility on the energy of the e-beam (that can presently be accelerated in the energy range from few MeV's up to one GeV). Moreover, the e-beams produced by LWFA accelerators can be extremely short (less than 1 fs), thus opening new horizons in the development of ultrashort (US) X-ray sources. In the following we briefly summarize the expected performances of a TS source driven by the conventional RF accelerator, with emphasis of flux/monochromaticity/shortness of the source. We will also show the summary results of a preliminary study of a TS source driven by a LWFA.

3 Experiment description

3.1 LASER set up

The FLAME laser for the PLASMON-X project is a CPA system that will deliver < 20 fs, 800 nm, up to 300 TW, laser pulses with a 10 Hz repetition rate. The system features a high, sub-ns contrast ratio ($>10^{10}$) and has a fully remotely controlled operation mode. In view of the above discussed requirements for prototyping of a laser-based electron photo-injector, the laser system will provide shot by shot monitoring of both temporal and spatial properties of the laser pulse. Spatial characterization will be performed in the near and in the far field, using an equivalent plane monitor. Temporal characterization will be performed using two kinds of diagnostics. The first one will operate on a multiple-shot base while the second will operate in a single-shot regime. The multiple-shot diagnostics will offer the advantage of a better performance in view of a fine tuning of the laser parameters during setup. A third order autocorrelator will instead be used to monitor the contrast ratio. Also an interferometric second order autocorrelator will be set up to monitor the oscillator behaviour. The shot by shot performance of the laser system will be monitored using a second order single-shot autocorrelator.

As anticipated above synchronisation of the FLAME laser system with the LINAC will be required. In the existing set-up, the CPA laser driving the LINAC photoinjector is already synchronized with an external radiofrequency, by changing dynamically the length of the oscillator cavity. The final result is a jitter between the radiofrequency and the laser pulse of less than 1 ps. This jitter is still much higher than that required in the case of acceleration of externally injected electrons. This issue is presently under investigation and a preliminary characterisation of the sub-picosecond jitter of the LINAC bunches has already been carried out. Based on this characterisation, a dedicated synchronization system is being studied which is based upon an electro-optics approach [22].

3.2 LINAC set up

The SPARC LINAC presently under installation at INFN-LNF will provide an ultra-bright electron beam at 150 MeV kinetic energy [3]. For the plasma acceleration experiment ultra-short (compressed) bunches will be required, while the Thomson source needs very small energy spread beams to avoid chromatic aberrations in the final focus system where the beam is focused down to sub-10 μm spot sizes to collide with the laser beam. The LINAC is expected to deliver bunches of up to 1.1 nC of charge, rms normalized projected emittance smaller than 2mm·mrad, rms energy spread smaller than 0.2% with rms bunch length of about 2–3 ps (uncompressed bunch). The compressed bunch will feature a charge 25 pC at an energy of up to 100 MeV and a bunch length down to sub-ps regime. The electron bunches will exit the photo-injector with 1 ps time jitter with respect to the laser pulses. This value of the jitter is compatible with a correct space-time overlap of the colliding electron and laser pulses in the final focus region of the Thomson source for mono-chromatic X-ray production as far as the electron bunch is the standard uncompressed beam delivered by the SPARC photo-injector. On the contrary, for the interaction of ultra-short pulses (rms length smaller than 0.5 ps) there is the need to improve the synchronization level between the two beams.

3.3 Laser driven acceleration experiments

In this section we describe the conceptual experiments that will be carried out with the FLAME laser system for production and acceleration of high quality electron beams. The key parameters here are energy gain and energy spread. In particular, different ways of reducing the energy spread are being investigated world-wide, both theoretically and experimentally.

3.3.1 Self injection in LWFA

In the scheme proposed in [23], the production of high-quality electron beams in LWFA is achieved via activation of a controlled longitudinal non-linear wave-breaking induced by a suitably chosen electron density profile characterized by a downward step-like feature along the laser propagation direction. The initial plasma density profile consists of a smooth rising edge and a first plateau where an high amplitude plasma wave is excited. Next, a density downramp makes a transition to a second, lower density plateau. According to both 1D analytical results and 2.5D numerical simulations, a partial break of the wave crests at the transition (downramp) can occur which injects the electrons in the appropriate phase of the plasma wave excited in the second plateau (accelerating region). The physical picture here is that, as the plasma density decreases in the direction of the pulse propagation, the wave number increases with time. The resulting decrease of the phase velocity at the interface between two uniform density regions makes the wave break, even when its initial amplitude is below the nonlinear wave-breaking threshold. As a result of the break at the interface between the two regions, fast electrons from the wave crest are trapped by the wave and accelerated into the lower density region where the wake field remains regular. PIC simulations indeed show that this approach successfully generates mono-energetic electron bunches [24]. Figure 1 (left) shows the energy spectrum of the electrons produced by such an acceleration scheme as calculated by PIC simulations [24]. In the simulations an electron density profile was considered consisting of two regions with a sharp transition as shown in Figure 1 (right).

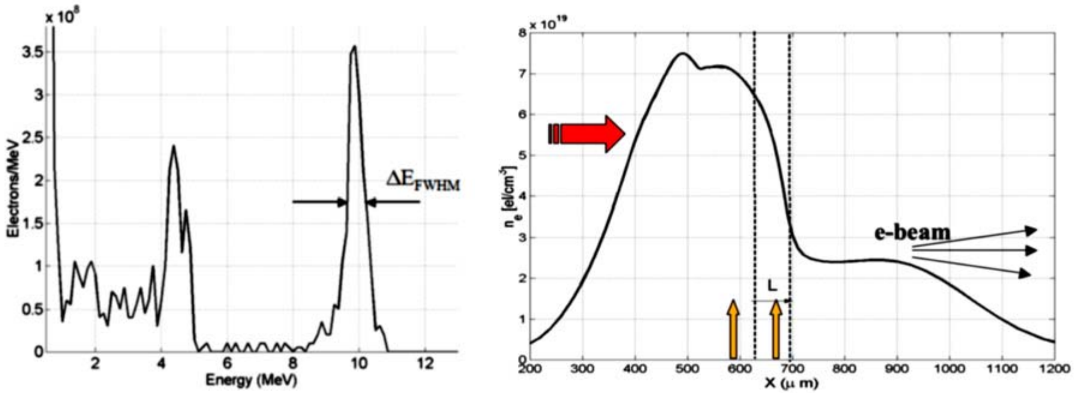

Fig. 1. (Left) energy spectrum of the accelerated electrons in pre-formed plasma with a sharp density depletion like the one shown on the right, generated by 2-dimensional hydrodynamic simulation of laser explosion of a two-foil target as shown by the yellow arrows. The red arrow indicates the direction of propagation of the laser pulse.

After a smooth vacuum-plasma transition, the longitudinal profile of the electron density reaches a first plateau ($n_e = 2.1\,10^{19}\,cm^{-3}$) and then it decreases abruptly with a scale length of $L = 2\,\mu m$ to a second plateau ($n_e = 1.1\,10^{19}\,cm^{-3}$). In this simulation, a $1\,\mu m$ wavelength laser pulse, with a Gaussian envelope (waist $w = 20\,\mu m$, time duration $t_{FWHM} = 17\,fs$) has an intensity of $I = 2.5 \times 10^{18}\,W/cm^2$. From the plot of Figure 1 (left) we can see that, selecting the electrons with energy exceeding 7 MeV, the resulting bunch of $N_e \approx 10^8$ electrons with energy $E \approx 10\,MeV$ is characterized by an energy spread of less than 5%, with transverse and longitudinal sizes of $1\,\mu m$ and $0.5\,\mu m$ respectively.

The schemes discussed so far concern the possibility of producing high energy, high quality electron bunches, starting from plasma electrons, i.e. without external injection. In the following section we analyze the case of laser-driven acceleration of externally injected electrons. A basic requirement for a successful acceleration of externally injected electrons produced by the LINAC is that the bunch length is small compared with the wavelength of the electron plasma wave excited by the laser wakefield. In contrast, as reported above, the shortest length of the LINAC bunch is expected to be in the sub-ps range. This sets a severe restriction to the upper limit of the working point of the wavelength of the epw and, consequently to the maximun electron density for LWFA. Improvement of this condition requires an additional manipulation of the LINAC electron bunch that can be performed either via conventional bunching techniques or by novel techniques based upon bunch propagation in plasmas. In the following section we briefly discuss the working principle of a plasma based acceleration technique, a comprehensive description of which will be reported elsewhere.

3.3.2 External bunch quality control: Compression

A similar scheme as that used above [23] can be adopted to tackle the issue of bunch compression in plasmas when dealing with external injection. Compression schemes based upon the above principle are being investigated to improve the matching conditions of LWFA at higher electron densities. In this scheme, the electron bunch is set to propagate initially in a low density plasma so that its length is much smaller than the plasma wavelength and its velocity is smaller than the phase velocity of the wave. The bunch is injected close to the node of the plasma wave where the transverse forces are focusing. The gradient of the longitudinal force induces a longitudinal bunch compression. Particles do accumulate close to the trapping point. Figure 2 shows the results of a numerical simulation carried out using a 2D-cylindrical fluid code for the cold plasma in the quasi-static approximation. The code includes fully relativistic, nonlinear, space charge and beam-loading effects and uses an optimised mesh size depending on the local pulse waist and plasma density. In the code, a 10 pC, 10 MeV electron bunch with a 60 μm full longitudinal size is injected in the node of the plasma wave generated by a 50 fs laser pulse in a plasma with a density of $5 \cdot 10^{16}\,\mathrm{cm}^{-3}$.

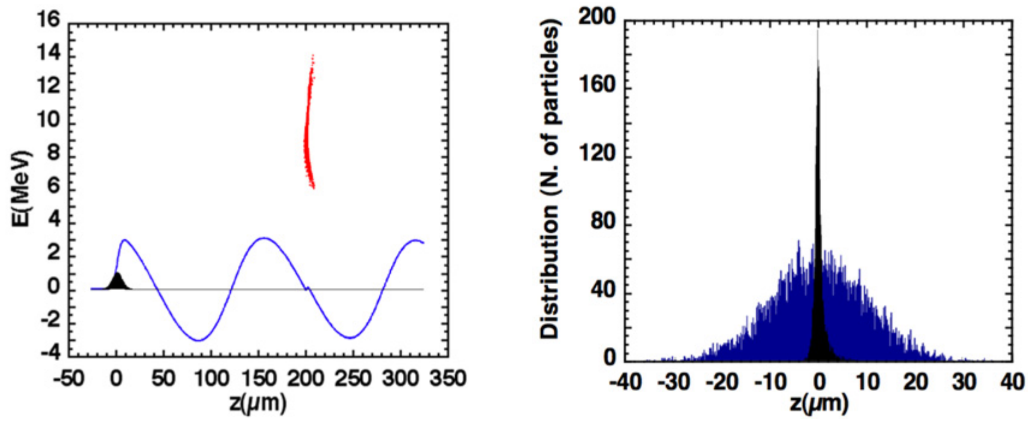

Fig. 2. Numerical simulation of bunch compression in an electron plasma wave. (Left) the electron bunch after compression around the node of the longitudinal field of the epw. (Right) comparison between the initial longitudinal bunch distribution and the same distribution after compression.

The plots of Figure 2 clearly show that effective beam compression can be obtained in this scheme with the bunch being compressed by a factor of 10, from the initial 60 μm full size (10 μm rms) down to 7 μm full size (1 micron rms). These parameters set the conditions for the second accelerating stage. Accurate modellino of the second stage is still in progress. Here we point out that with the bunch length after compression, the accelerating stage can be designed with a relatively high plasma densities in the range 1–$5 \cdot 10^{17}\,\mathrm{cm}^{-3}$. The accelerating plasma wave has therefore a wavelength shorter than 100 micron, enabling us to reach a gain of 1 GeV in 10 cm plasma size limiting the final energy spread to few percent. In practical terms, in the case of a 50 μm waist size pulse, this condition implies guiding the laser pulse over 10 Rayleigh lengths, possibly with additional control of the phase velocity of the accelerating wave (via channel tapering). This is a significant progress of the external injection scheme originally planned which required a plasma density well below 10^{17} cm^{-3}.

3.4 The thomson scattering source

The PLASMON-X approach to a Thomson scattering source includes a configuration based upon the use of the LINAC electron bunches and a more advanced configuration based upon the use of self-injected, Laser Wakefield accelerated electron bunches. The first configuration has been investigated and modelled in several different operating modes, including the *High-Flux-Moderate-Monochromaticity (HFM2) mode* and the *Short and Monochromatic (SM) operating mode*. A detailed description of these two regimes, was obtained with the aid of a Monte Carlo code named "*Thomson Scattering Simulation Tools*", $(\text{TS})^2$ [25], which accounts for the actual focusing of the laser beam with the possibility of implementing propagation up to multiple Rayleigh length *via* pulse guiding. The code also includes full treatment for non-linear effects (multi-photon absorption), an accurate description of the electron bunch emittance effects and non perfect pulse-bunch overlapping. A full account of the modelling of the first configuration is given elsewhere [26].

3.4.1 All-optical TS source

In the second configuration, Laser Wakefield Accelerated electron bunches with controlled injection are used as an alternative to conventional LINAC accelerated electron bunches. As already discussed above, injection by longitudinal nonlinear breaking of the wave at a density down-ramp is one of the most promising way of achieving e-beams having *both* low energy spread and low transverse emittance. Simulations of the LWFA process were performed with the fully self-consistent Particle-In-Cell (PIC) code VORPAL [27] in the 2.5D (3D in the fields, 2D in the coordinates) configuration. A full description of the numerical design of this configuration is reported in [26]. Here we summarise the final result obtained in the case of application to the expected performances of the FLAME laser system.

Optimisation of the parameters of the FLAME laser was carried out assuming a splitting of the main laser pulse in two counter-propagating pulses, a 0.8 J pulse driving the e-beam and a 5 J producing TS. The 0.8 J laser pulse is focused in a beam waist of 12 μm FWHM at an intensity of $7 \cdot 10^{18}$ W/cm^2. The plasma is assumed to have a density of initial plateau of $4 \cdot 10^{19}$ cm^{-3} and a density of the exiting plateau of $4 \cdot 10^{19}$ cm^{-3} with a down-ramp density scalelength of 5 μm and a wavelength of the electron plasma wave of 5 μm. Particle-in-cell simulations show that after an acceleration length of about 200 μm, an electron beam charge of $Q \cong 20$ pC with a mean energy of about 32 MeV with energy spread of 10% (rms), a longitudinal rms size $\sigma_L = 0.27\,\mu$m, transverse rms size $\sigma_T = 0.47\,\mu$m and transverse normalized emittance $\varepsilon_\perp = 0.23$ mm $\cdot$ mrad. In the simulations with the TS code, these electrons were set to undergo head-on collision with the 5J counter-propagating pulses focused to a 15 μm FWHM focal spot. The 5J pulses were assumed to be only partially compressed down to the 5 ps pulse duration to limit non-linearities in the TS process. Simulations show that the energy spread of the scattered X-ray radiation is as small as $(\Delta\omega_F/\omega_F)_{\min} \approx 0.5$ (25% rms).

In summary, the head-on collision of the 20pC e-bunch and the 5J in 5 ps laser pulse focused in a 15 μm of waist can produce a 1 fs-long X-ray pulse of mean energy 20 keV in the fundamental and energy spread of 25% rms with total flux $N_{\gamma US} = 4 \cdot 10^7$ photons/shot (i.e. $4 \cdot 10^8$photons/s @10 Hz). The duration of the scattered radiation is remarkably small, being less than 1 fs. This result, still under further validation with a fully 3D configuration, is a unique result that strongly suggests the possibility of achieving a unique, ultra-short, hard X-ray source.

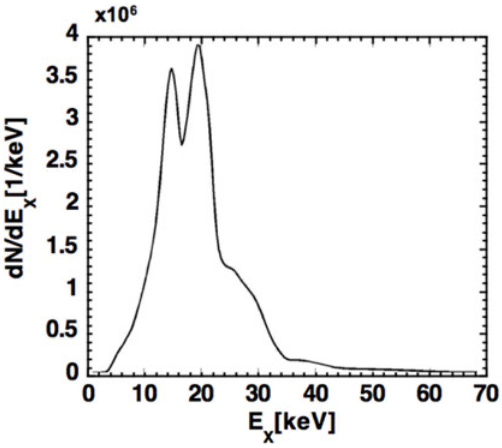

Fig. 3. Spectrum of the TS radiation of the ultra-short source in the case of a normalized acceptance angle of 0.5 deg.

4 Conclusions

Laser-driven acceleration is now emerging worldwide as a mature approach to particle acceleration. The idea of embedding a highly advanced laser laboratory in a LINAC dedicated laboratory is pursued as a necessary step in order to perform a wide range of novel experiments based upon the combined use of high quality electron bunches and ultraintense, short laser pulses for demonstration of high quality acceleration of externally injected bunches and for generation of tunable hard X-ray radiation. At the same time, the most recent progress of control of laser driven acceleration opens the way to complementary, all-optical schemes for X-ray generation that offer the opportunity of unique performances in terms of ultra-short pulse duration.

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