Laser-Plasma Acceleration and Radiation Sources for Applications

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Laser-plasma acceleration is now established for a variety of applications while secondary sources are being developed and experimental exploration of electrodynamics in the strong field regime in starting. An overview of the field will be given along with a discussion on perspectives for possible future development of high average power, all-optical radiation sources.

I. Introduction

The recent progress of high power laser technology initiated by the introduction of the Chirped Pulse Amplification (CPA) concept [1] is now leading to the realization of new large laser systems within the framework of the Extreme Light Infrastructure (ELI) that, by the end of this decade, will start paving the way to the exploration of new physical domains, approaching the regime of electron-positron pair creation and the possibility to reach the critical field of quantum electrodynamics [2]. At the same time, the control of ultra-high gradient plasma acceleration [3] is being pursued and advanced schemes are being proposed for the future TeV linear collider [4]. Meanwhile, existing laser-plasma accelerating scheme are being considered for the development of novel radiation sources. All-optical, laser-based bremsstrahlung X-ray and γ-ray sources have already been explored and successfully tested using self-injection electron bunches showing high efficiency and potential for laboratory applications [5, 6]. New sources have been developed [7] based upon the use of high energy LINACS and high power lasers or free electron lasers [8] to generate γ-rays via Thomson/Compton scattering. In this scenario, the use of laser-plasma accelerated electrons is also being explored and is regarded as a possible way to make nuclear sources far more accessible than current Linac based sources.

II. Laser-plasma sources

Since the initial experiments, laser-plasma acceleration has seen dramatic advances and laser-accelerated electrons can now exceed 1GeV with energy spread well below 10%, with record values close to 1% [9]. New schemes are being proposed to control injection and optimize acceleration, to further improve the quality of laser-accelerated electrons. Indeed, even at a smaller laboratory scale, laser-plasma acceleration is now sufficiently mature to be considered as reliable alternative to the RF LINACs used in radiotherapy. Given the much higher accelerating field compared to RF machines, electron bunches with high energies can be easily achieved, representing a new option in radiotherapy and other medical practices. Radiobiology with this new class of sources is now in progress to study the biological response and to assess the potential of such new sources for radiotherapy and diagnostics. In view of this, a table-top laser-driven electron gun has been developed at ILIL at INO-CNR (Pisa) and is currently being used for a range of applications including electron microradiography and comparative dosimeter with standard electron sources in the sub 10 MeV electron energy region.

As for higher energy applications, a widely used scheme is based upon the so-called bubble regime [10], a basic self-injection scheme that can be implemented to achieve reproducible accelerated bunches from a simple experimental configuration. In this scheme, electron bunches are generated from laser-plasma interaction with a gas-jet of a few millimeters. In this regime, a short ($c\tau < \lambda_p /2$, λ_p being the electron plasma wavelength) and intense ($a_0 > 2$, $a_0 = 8.5\text{x}10^{-10}\ (I\,\lambda^2)^{1/2}$ being the laser pulse normalized amplitude where λ is the laser wavelength in μm and I is the laser intensity in W/cm^2) laser pulse rapidly ionizes the gas [11] and expels the plasma electrons outward creating a bare ion bubble. For sufficiently high laser intensities ($a_0 \geq$ 3-4), electrons at the back of the bubble can be injected in the cavity, where the longitudinal accelerating field $E \approx 100\ (\Delta n\ [\text{cm}^{-3}])^{1/2}$V/m, where Δn is the amplitude of the local electron density depression in the wake. The FLAME laser at LNF (Frascati) meets both conditions of short pulse duration and high intensity required to achieve this condition [12] and experimental runs [13] dedicated to laser-plasma acceleration experiment with self-injection [14] have already been performed recently in view of the development of a γ-ray source based upon Thomson back-scattering.

III. Thomson scattering

Thomson scattering (TS) from free electrons is a pure electrodynamics process in which each particle radiates while interacting with an electromagnetic wave. TS of a laser pulse by energetic counter-propagating electrons was initially proposed in 1963 [15, 16] as a quasi monochromatic and polarized photon source. From the quantum-mechanical point of view TS is a limiting case of the process of emission of a photon by an electron absorbing one or more photons from an external field, in which the energy of the scattered radiation is negligible with respect to the electron's energy. If the particle absorbs only one photon by the field (the linear or non relativistic quivering regime), TS is the limit of Compton scattering. With the development of ultra intense lasers the interest on this process has grown and the process is now being exploited as a bright source of energetic photons from UV to γ-rays [17]. The three main parameters of the Thomson scattering of a laser pulse by a free electron are the particle energy γ_0, the angle α_L between the propagation directions of the pulse and the electron and the laser pulse normalized amplitude a_0. If $a_0 \ll 1$ only one photon is absorbed and the quivering is non-relativistic (linear Thomson scattering). Among the possible interaction geometries, the case of backscattering is the most suitable for a source as it produces radiation with the highest energy, $E_{Back} \approx 4\gamma^2 E_0$, where E_0 is the energy of laser photons.

IV. Towards High Field Effects

In the general description, the emission of radiation by the accelerated particle gives rise to a back-reaction, the so-called Radiation Reaction (RR) [18]. It can be shown that radiation dominates when the motion of the particle changes appreciably in a time $t = 10^{-24}$ s or over a distance $ct = 10^{-13}$ cm, i.e. a distance comparable with the classical electron radius. These considerations lead to the conclusion that accessing a radiation-dominated regime in the laboratory is extremely challenging. Ultra-intense, femtosecond laser pulses are regarded as a possible tool to enter this regime and may lead to an experimental test of current available theoretical and numerical models. In fact, according to recent models [19], experimental evidence of RR effects can be obtained in Thomson scattering configurations at relatively laser intensities not far from the maximum intensities available from PW-class laser systems. In addition, other models [20] predict laser pulse intensification and shortening in a self-injection laser wakefield acceleration configuration which could enhance the effect and make RR observable at existing laser facilities. In view of this, feasibility studies towards the experimental realization may be already investigated, starting from a dedicated, start-to-end simulation of the entire interaction configuration. Moreover, from an experimental viewpoint, control of the laser-plasma acceleration process is necessary to establish parameters of the accelerated electron bunch to be included in the simulations. From the modelling viewpoint, we study laser-plasma acceleration using advanced 3D GPU particle in cell code. In fact, computer architectures based upon graphical processing units (GPU) provide much faster simulations [21] than previous CPU based architectures. This leads to reasonable execution time of full 3D simulations and therefore a more reliable technical design of the laser-plasma electron source. Concerning the modelling of radiation effects, the approach uses numerical tools capable of describing the dynamics of electron beam acceleration and interaction with the counter-propagating pulse in a realistic geometry and incorporating RR effects. Numerical efficiency is critical for such simulations (which require large supercomputers) because in a PIC code the run time mostly depends on the calculation of particle acceleration, hence on details of the force term. Our numerical implementation proved to be efficient enough to allow fully three-dimensional simulations and was thus suitable for full-scale simulations [22]. A similar approach is being followed for the full modelling of the radiation source at FLAME.

V. High Average Power Sources

As a final remark we point out that the practical use of laser-driven electron and γ-ray sources will require the development of high-efficiency and high-repetition rate laser systems for pumping ultra short lasers currently based on Ti:Sa amplifiers. This problem can be solved by adopting the so-called Diode Pumping Solid State Laser (DPSSL) technology, instead of flash-lamps. In fact, it is well known that laser diodes can provide a "selective pumping", leading to and increase of efficiency of up to two orders of magnitude. After the first attempt to DPSSL was the MERCURY project of the LLNL (USA), which delivered 70 J at 10 Hz, new projects have been established at LULI[23] and at RAL [24] within the HiPER programme and in the LASERLAB Joint Research Activities named HAPPIE and EUROLITE. Within this framework, we are developing an optical cavity based on Yb for a high energy amplifier to be used to pump future high-rep rate Ti:Sa PW scale systems.

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