X-γ ray sources based on electron laser-plasma acceleration

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Abstract

The high field gradients, attained in the electron Laser Plasma Acceleration, open the way for the realization of compact secondary sources of X-γ rays. In particular, the Thomson Backscattering and the Betatron Radiation in the so called bubble regime are presented as good candidate in this sense.

Introduction

The propagation of the super-intense and ultra-short laser pulses in plasmas in the so called ‘‘bubble regime’’ is one of the most interesting acceleration scheme, due to the high energy and relatively low energy spread that can be obtained. In this physical process the accelerated electrons, moving along a region depleted by the electron density, suffer a restoring force towards the bubble axis due to the unbalanced positive ion charges. The transverse electric field due to space charge separation induces an oscillatory motion on the electrons. The transversal oscillation of the relativistic electron accelerated in the bubble produces an intense X-ray emission along the same direction of the laser pulse and the accelerated electrons. The so called Betatron Radiation [1,2] shows several analogies to the Synchrotron Radiation [3–5]. Another interesting physical phenomenon is produced when high energy plasma-accelerated electrons interact by Thomson Backscattering with a fraction of the same laser pulse exploited to accelerate them. This all-optical scattering configuration could be a promising candidate for the generation of quasi-monochromatic and high-collimated X-γ ray beams [6], resulting competitive with more conventional Thomson Scattering sources, in which laser pulses are made to interact with electrons bunches accelerated in a LINAC. In this article we consider the experimental potential offered by the infrastructures of the National Laboratories in Frascati (LNF) of the Istituto Nazionale di Fisica Nucleare (INFN), relative to the study of the physical phenomena mentioned above and in particular the experimental parameters characteristic of the laser **FLAME** (**F**rascati **L**aser for **A**cceleration and **M**ultidisciplinary **E**xperiments) of the INFN Strategic Project **PLASMONX** (**PLAS**ma acceleration and **MOM**ocrhomatic **X** ray production) [7] and the LINAC of the project **SPARC** (**S**orgente **P**ulsata **A**uto-amplificata di **R**adiazione **C**oerente) [8] both operating at LNF. **FLAME** is a 300 TW Ti:Sapphire laser (emission wavelength λ_0=0.8μm), with which several hundred MeV electrons have been already accelerated in bubble regime [9] . The **SPARC** LINAC can deliver up to 1nC electron bunches with energies up to 200 MeV. Most of the experiments programme relies on the synchronisation of the FLAME laser system with the SPARC LINAC and, in particular, with the LINAC photoinjector laser system. This can be done either using an electro-optics based approach or optically.

Thomson Scattering based X-ray source

Thomson Scattering from free electrons is a pure electrodynamic process in which each particle radiates while interacting with an electromagnetic wave. From the quantum mechanical point of view Thomson scattering 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), Thomson scattering is the limit of Compton scattering in which the wavelength λ_X of the scattered photon observed in the particle's rest frame is much larger than the Compton wavelength $\lambda_c = h/mc$ of the electron. Since $\lambda_c/\lambda_X \ll 1$, the Thomson scattering process can be fully described within classical electrodynamics both in the linear and nonlinear (i.e. when the electron absorbs more than one photon) regimes. Thomson scattering of a laser pulse by energetic counter propagating electrons has been proposed since 1963 [10,11] as a quasi monochromatic and polarized photons source. With the development of ultra intense CPA laser systems the interest on this process dramatically renewed and the Thomson scattering process of photons of ultra intense laser pulses onto relativistic electron bunches can now be employed as a bright source of energetic photons from UV to γ rays and atto-second sources in the full nonlinear regime. Recently TS in the linear regime has also been used to get the angular distribution of a monochromatic electron bunch. Moreover, experimental methods have been recently proposed to measure the length of a monochromatic electron bunch 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 [12]. 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).The three main parameters of the Thomson scattering of a laser pulse by a free electron are the particle energy γ_0, the laser pulse peak normalized amplitude $a_0 = 8.5\times10^{-10}\sqrt{I\lambda^2}$ (where I is in W/cm^2 and λ in μm) and the angle α_L between the propagation directions of the pulse and the electron. The pulse amplitude a_0 controls the momentum transferred from the laser pulse to the electron, i.e. the number of photons of the pulse absorbed by the electron. If $a_0 \ll 1$ only one photon is absorbed and the resulting electron motion always admits a reference frame in which the quivering is non-relativistic (linear Thomson scattering). For an electron initially moving with $\gamma_0 \gg 1$ the resulting scattered radiation is spectrally shifted at a peak wavelength

$$\lambda_X = \lambda \frac{1-\beta\cos\theta}{1-\beta\cos\alpha_L}$$

and emitted forward with respect to the electron initial motion within a cone of aperture $1/\gamma_0$ (see Figure 1).

Among the possible interaction geometries, the case of *backscattering* ($\alpha L = \pi$) is the most suitable for at least three aspects: i) it produces radiation with the highest energy $h\nu_X \approx 4\gamma_0^2 h\nu_0$, where $h\nu_0$ is the energy of laser photons ii) it allows the highest overlap of the electron beam and the pulse and iii) it minimizes spurious effects induced by the transverse ponderomotive forces of the laser pulse.

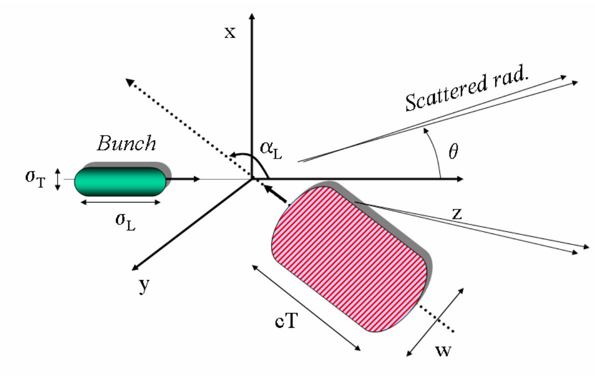


Figure 1. Thomson scattering geometry. The scattered radiation is emitted along the z axis, in a small cone of aperture $1/\gamma_0$. When $\alpha_L = \pi$ the backscattering geometry occurs.

A Thomson scattering source is presently under development at Frascati National Laboratory of INFN. A complete simulation of the source including the electron beam, laser beam, Thomson interaction and X-ray imaging has been performed. The X-rays are generated in the energy range suitable for mammography and used to generate images of a mammographic phantom [13]. As a result of the optimization process, a laser pulse of waist size w_0=15µm and duration T=6ps, with intensity I=2.3x10^{17}W/cm^2, corresponding to a_0=0.33 is made to collide with the electron bunch. The main parameters of the electron bunch were : energy 30MeV, charge 1nC, 8-10µm transversal size, 4mm longitudinal size. The backscattered radiation is collected within a cone of aperture θ_M=8mrad, yielding a flux of 1.5x10^8 photon/shot with an energy spead of 20% FWHM. In Figure 2 the spectrum of the collected radiation is reported.

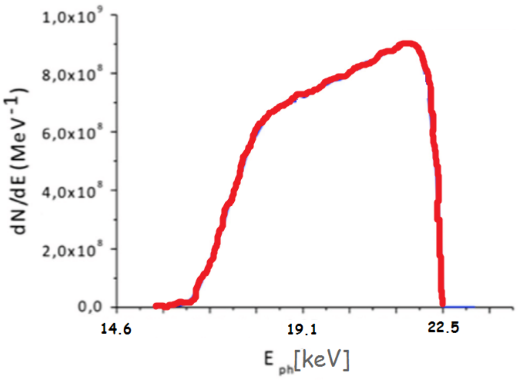
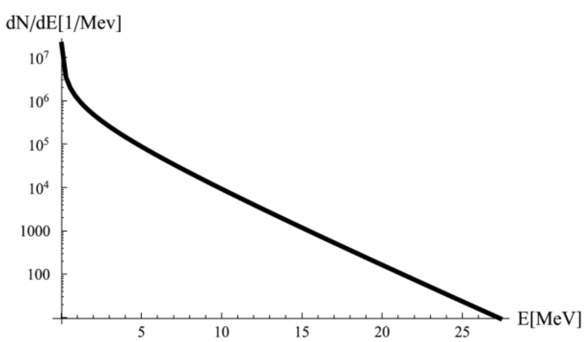


Figure 2. Spectrum of the collected radiation.

All-optical Thomson Backscattering

In the frame of the laser-plasma acceleration an all-optical Thomson X-γ ray source could be thought. This scheme provides that the laser, split into two beams, is exploited as photon source as well as to accelerate the electrons in a plasma. In Figure 3 we consider laser beam exploited in the scattering process with Ti: Sapphire laser emission wavelength λ=0.8µm; τ=30 fs pulse duration, w_0 =30µm beam waist at the focus, E_L= 3J energy per single laser pulse. A second laser beam with almost the same properties of the first is utilized to accelerate electrons in a plasma. We choose typical gettable parameters for the electron bunch in such a setting of laser-plasma acceleration. The electron bunch angular divergence will be θ_e=5 mrad , each bunch will carry about N_e=1.25x10^{9}electrons of τ_e= 50 fs time duration, and 500 MeV of energy with 1% energy spread. We can see that the spectrum is quite broad: this is due to the fact that the relativistic laser intensity I=3.5x10^{18}W/cm^2 stimulates the emission of the upper harmonics and meanwhile the big electron divergence θ_e determines the overlapping of the single harmonic emissions. Also is worth noting the fact that the emitted radiation field dimension is ruled by the geometrical divergence of the electron bunch, and that the laser polarisation plays an important role in modeling its shape. In any case the all-optical Thomson Backscattering makes possible the generation of high-collimated and brilliant γ-ray beams.



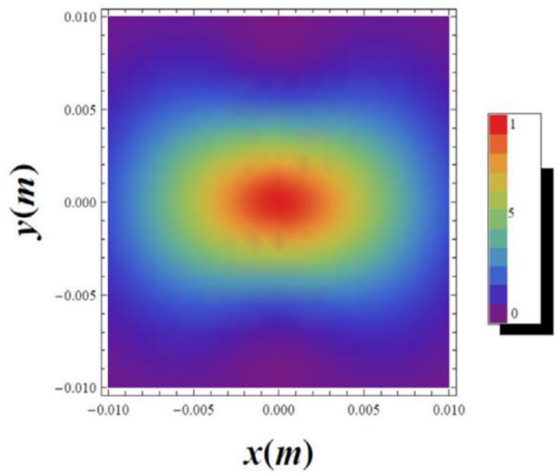


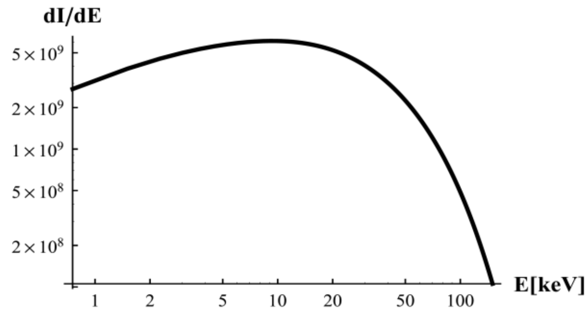
Figure 3. Spectral (up) and spatial (down) distribution of the Thomson radiation detected at 1 m from the interaction point (scattered laser pulse duration τ= 30 fs, laser intensity I=3.5x10^{18}W/cm^2, electron bunch duration τ_e= 50 fs; 500 MeV emitting electrons). Thomson spectrum: the radiation is detected over the whole cone of emission. The total number of radiated photons is about N_{tot}=1.85x10^7. Such a wide spectrum due to the overlapping of upper harmonic contributions. Red stands for ≈1.85x10^7 photons/cm^2; we notice that the angular divergence is bigger than 1/γ_0, because the electron bunch angular divergence θ_e is larger than 1/γ_0. The elongated shape is due to the laser polarisation.

Betatron Radiation

In order to find innovative X-γ ray sources the eyes must be laid on the Betatron Radiation in plasmas. The electron motion inside the low electron density region in the wake of the super intense and ultra-short laser pulse (bubble regime) corresponds at a first order to $r(z) = r_b \cos(k_b z)$ where z is the laser-bubble propagation axis, r_β the betatron oscillationamplitude and k_β the betatron wavenumber. The betatron frequency is related to the plasma frequency by the following relation: $w_b = \frac{w_p}{\sqrt{2g_0}}$, with γ_0 the electron Lorentz factor. The radiation emitted by the electrons shows a divergence ≈$k_\beta r_\beta$ with a strength parameter K= γ_0 $k_\beta r_\beta$. For K <<1 the radiation detected in the laboratory frame should be

$$\omega_f = 2\frac{\gamma_0^2 \omega_\beta}{\left(1+\frac{K^2}{2}\right)}$$

which corresponds to the betatron frequency, Doppler shifted in the laboratory reference frame. For K > 1 the amplitude of the electron transversal motion increases, the plasma channel acts as a wiggler and high harmonics are radiated in a broad frequency band centered at $w_c = \frac{3K^3}{4} w_f$. Fig. 4 shows a calculation corresponding to a 100 pC electron bunch, with 1% energy spread at about 1 GeV, accelerated by a 30 fs laser pulse focused at I=10^{19}W/cm^2, in a 1.2x10^{18}cm^{-3} electron plasma density over a ≈13 mm acceleration length. In order to calculate the betatron spectra and the radiation distribution, the tracking of the electron trajectories inside the bubble is performed, including also the longitudinal acceleration in the wakefield. The average betatron amplitude results r_b≈3µm. The equation of motion exploited are the same showed in [14]. The critical energy is about 100 keV and the radiation is high collimated in a narrow cone, giving to the Betatron Radiation its particular brilliance property. The shape of the radiation field spot strongly depends on the trajectories of the electrons in the bubble and on the initial coordinates and momenta at the injection into the bubble [15]. Here is considered a circular initial distribution for the electrons at the entrance of the bubble. The Betatron Radiation is clearly a good candidate for the X-ray phase contrast imaging [16]. The usability of the Betatron Radiation for high brilliance and polarizable γ-ray source has also been shown [17].



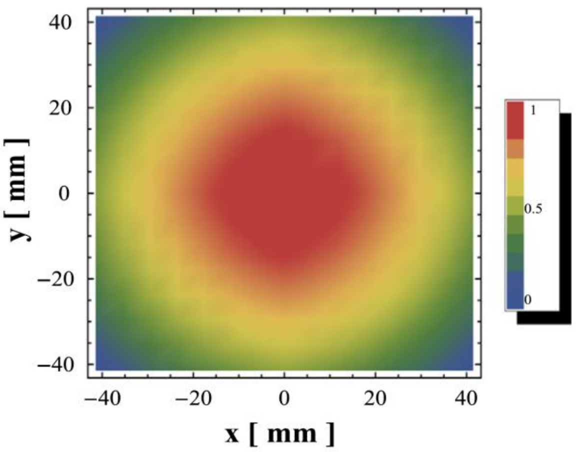


Figure 4. Spectral (up) and spatial (down) distribution of the Betatron Radiation detected at 1 m from the interaction point (LASER intensity ≈10^{19} Wcm^{-2}, plasma electron density 1.2x10^{18}cm^{-3}; ≈1 GeV emitting electrons, L_{acc} ≈13 mm). The critical energy is about 100 keV, showing the possibility to obtain many X-ray photons, nearly one per electron inside the bunch. The angular dimension of the spatial distribution is related to the product $k_\beta r_\beta \approx 0.14$ rad. Red stands for ≈70 μJ/cm^2. Very high brightness levels can be reached by the Betatron Radiation beams.

Conclusions

With the maximum achievable energies in laser-plasma acceleration experiments to date, namely few GeV, one could think to produce Betatron Radiation with critical energies of some MeV as well as Thomson Backscattering radiation of several tens of MeV,opening new frontiers to the technology of the γ-ray sources.

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