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UV-SOFT X-RAY BETATRON RADIATION CHARACTERIZATION FROM LASER-PLASMA WAKEFIELD ACCELERATION

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Abstract

The spontaneous emission of radiation from relativistic electrons within a plasma channel is called betatron radiation and holds great potential to become a compact X-ray source in the future. We present an analysis of the performance of a broad secondary radiation source based on a high-gradient laser-plasma wakefield electron accelerator. The purpose of this study is to assess the possibility of having a new source for non-destructive X-ray phase contrast imaging and tomography of heterogeneous materials. We report a preliminary studies of UV and soft X-ray generation via betatron oscillations in a plasma, and in particular, the measurement of the radiation spectrum emitted from the electron beam is analyzed using a grazing incidence monochromator at the Centro de Laseres Pulsados Ultraintensos (CLPU).

INTRODUCTION

Starting from the idea proposed by Tajima and Dawson [1], who first suggested accelerating electrons produced by the interaction of a laser with a plasma, there have been many advances in laser wakefield acceleration (LWFA) over the years. These advances are largely due to significant progress in laser technology, which has made it possible to achieve ultrashort pulses (femtoseconds). Today, LWFA is not only used as a compact acceleration technique but also as a photon source [2, 3]. The radiation emitted, known as betatron radiation, is sometimes referred to as synchrotron-like [4] and has been extensively studied over the years. In the coming years, it is proposed to become a valid alternative to well-established light sources, as X-ray sources based on plasma accelerators promise to become compact, economically accessible sources. Their advantage lies in the shortness of the pulses produced, which fall within the femtosecond range, opening up possibilities for ultrafast photon science, along with applications in medicine, biology, and industry.

BETATRON RADIATION

Betatron radiation results from the oscillations of electrons within the ion bubble in plasma acceleration, such as Fig. 1. A high-intensity femtosecond laser is fired into a gas jet or gas cell below critical density. The laser's ponderomotive force causes the removal of electrons from a region known as the bubble region or blowout regime. This regime is achieved when the waist w_0 of the focused laser pulse matches the plasma ($k_p w_0 = 2\sqrt{a_0}$), with $k_p = \omega_p/c$ and the pulse duration approximately half a plasma wavelength ($c\tau \approx \lambda_p/2$). Additionally, the laser intensity must be sufficiently high ($a_0 > 2$) to expel most of the electrons from the focal spot [5].

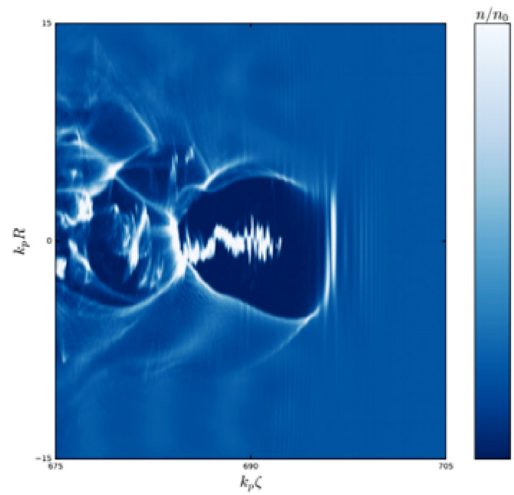

Figure 1: PIC simulation representing the electron oscillation in blow out regime.

The oscillation of the electrons is the main emission process and can be compared to what occurs in wigglers (K > 1) or undulators (K < 1), although in the case of betatron radiation it is not possible to distinguish between these regimes, a parameter called the betatron strength parameter $K_\beta = r(t)\gamma(t)k_\beta(t)$ can be defined, where $r_\beta(t) = \sqrt{x_\beta^2 + y_\beta^2}$ represents the amplitude of the electron oscillations. Thus, the ion cavity acts as an undulator or wiggler with a period $\lambda_\beta = \lambda_p/2\gamma^2$ and strength parameter K_β.

EXPERIMENTAL SETUP

A self-injection experiment was conducted at the Centro de Laseres Pulsados Ultraintensos (CLPU) in Spain using the VEGA II laser system. The characteristics of the laser

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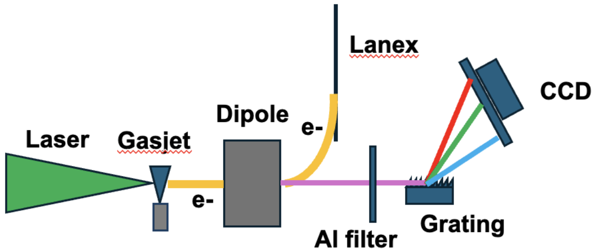

Figure 2: Simplified diagram of the experiment setup. In green the 800 nm and 30 fs laser that affects the He gas, in yellow the electrons that come out of the LWFA, in gray the dipole that deviates the trajectory of the electrons on a scintillator screen (lanex), while the photons continue forward generated in the plasma until reaching the detector. A 150-nm aluminum filter was placed to eliminate primary laser residue.

are summarized in Table 1. The primary laser pulse featured 4 J of energy, delivered in a 30 fs (FWHM) over a 10 µm diameter. The laser was directed at a helium gas-jet target. The electron density of the created plasma was determined to be 4.5×10^{19} cm^{-3} using a Mach-Zehnder interferometer. The spot size of the electron beam and their energy was captured using a motorized scintillator screen (LANEX), while the spectrum was measured with a CCD camera. The measurement of the EUV spectrum required the use of a grazing incidence spectrometer and a CCD camera, while for the measurement of the X-ray range, we operated without a spectrometer, using only the CCD camera in single photon counting mode. The general setup of the experiment is shown in Fig. 2.

MEASUREMENTS

Below we show the different measurements carried out, and the importance of these measurements for the complete characterization of the beam.

Divergence Measurements

The measurement of the divergence of the electron beam is made by removing the dipole from the path of the electrons, so that they continue straight and end up on a scintillator screen (Lanex). The divergence is defined as the beam size over the distance from the capillary exit to the Lanex screen. In this case, the horizontal divergence is $\theta_x = 3$ mrad and the vertical divergence is $\theta_y = 3.4$ mrad (Fig. 3). From the knowledge of $\theta_{x,y}$, it is possible to determine the average

Table 1: Laser Parameters of VEGA II at CLPU

Peak power	200 TW
Energy/shot	4 J
Duration pulse	30 fs
Rep.Rate	10 Hz
Central wavelength	800 nm

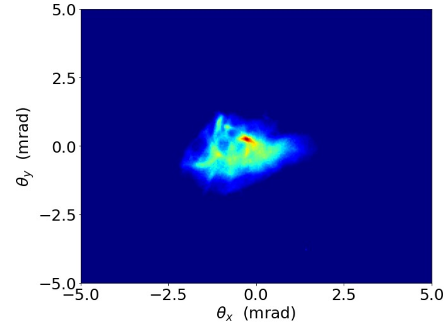

Figure 3: Electron beam spot on the lanex screen, plotted in divergence units.

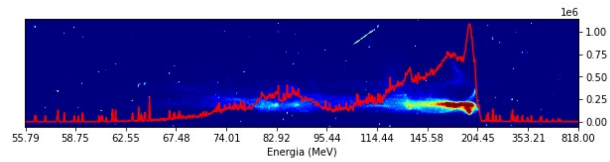

Figure 4: Electron beam energy on the lanex screen.

oscillation amplitude of the electrons r_β because if we assume that the electrons are in the wiggler regime (K>1), then the radiation is confined in a angle $\theta_{x,y} = K_{\beta x,y}/\gamma$, and we remember that the oscillation amplitude is incorporated in $K_\beta = r(t)\gamma(t)k_\beta(t)$. To determine γ, we need to measure the energy of the electrons.

Electron Energy Measurements

To measure the energy of the electrons, a dipole of 11 cm × 12 cm and a magnetic field of 1 T, was inserted into the trajectory of the electrons. The less energetic electrons are deflected more, the more energetic ones are deflected less, and then always end up on the lanex, as shown in Fig. 4. In our case the average energy of the beam is around 200 MeV. We can therefore say that $\overline{\gamma} = \overline{E}/E_0 = 391$.

EUV Spectrum Measurements

To measure the energy spectrum in UEV we used a grazing incidence monochromator, with Rowland geometry (McPhearson). In this setup the dipole remains in the path of the electrons, while the lanex screen is moved out. The grating used is 600 g/mm, and the calibration of the wavelengths (1–35 nm) was done both with the help of Zemax Optic Studio and with a mercury lamp. The used camera was a Great Eyes 1024×256, with an image area of 26.6 mm × 6.7 mm, a pixel size of 26 µm × 26 µm, operated at a pixel readout frequency of 500 kHz and a temperature of the sensor equal to -40 C. Before the CCD a 150 nm aluminum foil is in the line of the photons, to stop primary laser residue. For the reconstruction of the spectrum, the deconvolution with the quantum efficiency of the camera, with the efficiency of the grating, and of the aluminum filter was then taken into account. The result obtained is the left part of the spectrum shown in the Fig. 5 up to approximately 1 keV.

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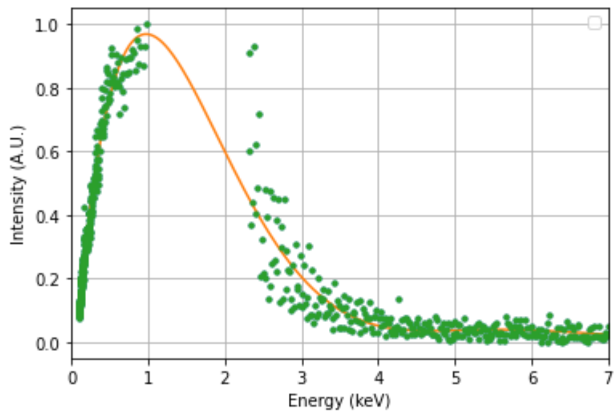

Figure 5: Energy spectrum of betatron radiation. The part between 1 and 2.5 keV was interpolated as the measurement was too affected by noise.

Xray Spectrum Measurements

For the measurement in the X-ray range, the dipole remains in place, the Lanex screen is moved out, and the monochromator is also removed, as the measurement is made directly from the CCD camera using the single photon counting technique. This technique involves placing the detector in a position to receive a low photon flux, either by positioning the CCD camera far from the source or by limiting exposure times. Once the image is obtained, single photon counting is confirmed if the illuminated pixels are sparsely distributed on the screen, and then a histogram of pixel intensities is created. The CCD camera has been previously calibrated with a known source. To obtain the energy spectrum, the histogram signal is deconvolved with the camera's quantum efficiency and the aluminum foil placed before the sensor. Figure 5 illustrates that we get the right part of the spectrum in the 2–7-keV range.

CONCLUSION

This proceeding briefly reports on an LWFA experiment conducted at CLPU (Spain), where betatron radiation was studied. It demonstrates one of the techniques for characterizing the betatron radiation spectrum, using two different methods to measure two different parts of the spectrum. The EUV part requires a grazing incidence spectrometer, while single photon counting allows direct measurement of the spectrum in the X-ray range. However, in our case, there is a limitation from 1 to 2.5 keV due to the thermal noise being higher than the signal we want to measure.

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