PROGRESS ON THE GENERATION OF UNDULATOR RADIATION IN THE UV FROM A PLASMA-BASED ELECTRON BEAM

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Abstract

Recently, at the Laboratoire d'Optique Appliquée (LOA), progresses have been made for the development of 5th generation light sources based on laser-plasma-accelerator. Electron beam from 100 to 150 MeV was generated at the interaction of a 1 Joule, 30 fs laser focused on a 3 mm long He gas target at an electron density of about $5*10^{18}$ cm^{-3}. Then, the electron beam was focused with a quadrupoles triplet inside a 60 cm long undulator composed of 34 periods of 18 mm. In these conditions, synchrotron radiation light was measured from 450 nm to 230 nm. This constitutes a promising first step in the view of realizing FEL based on plasma acceleration in future.

INTRODUCTION

Synchrotron radiation (SR) and Free-electron laser (FEL) generation processes are well known and understood since many decades. Nowadays, the facilities, which are using these conventional sources, are at the top of the art. Yet, due to the relatively low electric fields (about 30 MV/m) obtained in the classical accelerating structures, huge and high cost installations are necessary.

Advances on laser-plasma acceleration [1-8], in which accelerating fields up to 100 GV/m are created, have motivated the study of the feasibility of synchrotron radiation generation from undulator, in view of realizing a compact FEL. In fact, the number of FEL across the world is rather limited, even if increasing notably recently, and the demand of beam time coming from the user community is highly increasing. Moreover, FEL based on linear accelerator technologies have very limited number of beam lines. As a consequence, performing plasma-based FEL from table-top laser would represent a significant advance and allow to multiply significantly the number of accessible beam lines for studying physics, chemistry and biology.

Actually, this purpose seems quite far from today, but things have to start one day in order to understand better the actual level of possibilities, what has to be improved and in which direction we have to push forward in the coming years. Is the plasma-based electron acceleration mature for this area of activity?

This explains why in LOA, and in other groups all around the world [9-14], in view of getting experience on the way to generate plasma-based FEL, we decided, as a first step, to build a setup for generating synchrotron radiation from electrons wiggling in an undulator [15] and generated in the classical bubble regime.

EXPERIMENTAL SET-UP

The experiment (fig. 1) has been performed with the “salle jaune” Ti: Sa laser facility in LOA. This laser delivers linearly polarized pulses at 800 nm with more than 1 Joule energy, about 30 fs pulse duration and at a maximum of 10 Hz repetition rate. The electrons are generated by focusing the 55 mm aperture laser light with a 1 m length spherical mirror into a supersonic gas target. This latter is a 3 mm long pulsed jet filled with helium gas at pressure about 7 Bars leading to an electron density about $5*10^{18}$ cm^{-3}.

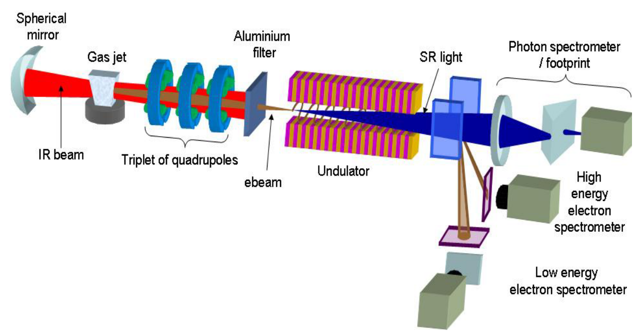

Figure 1: Layout of the experimental setup at LOA for generating synchrotron radiation from laser-plasma acceleration.

With the following conditions, 30 TW pulses focused in a 20 microns (FWHM) spot, the intensity reaches more than $1*10^{18}$ W.cm^{-2} in the gas target, creating a plasma after the ionisation of the gas by the front part of the pulse. In this plasma, the ponderomotive force of the ultra-short laser pushes electrons outward, separates them from the ions and so creates a longitudinal electric field which velocity is close to the speed of light. With these typical electron densities the electric field of the so called “Wakefield” can reach more than 100 GV/m in accelerating structures. After being injected in the wakefield, a few electrons can be accelerated up to energies up to 1 GeV. The regime in which electrons are simply self-injected and accelerated inside the structures is called the “bubble regime”. The experiment was performed in this regime.

After the laser-plasma acceleration, the relativistic electrons pass trough a triplet of specially-designed

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quadrupoles, which aim at focusing the electron beam in the undulator in order to get high electron density while wiggling inside the gain medium. Just before the undulator entrance, a notable degradation of the electron beam quality can be introduced due to the presence of thick aluminium foil. This latter is installed for blocking the highly intense pump laser and the electrons have to pass through this filter in the actual geometry. The undulator is 60 cm long, i.e. based on 34 periods of 18 mm spatial period SmCo magnets with a deflection parameter estimated close to 1.

Finally, the detecting part (fig. 1) is based mainly on three spectrometers. First, a system, developed by the LLR, for measuring very precisely electrons in low and high energy range (more than 200 MeV) is implemented. Second, a photon spectrometer for UV-visible light, composed of a MgF_2 lens with 25 cm focal length, a SiO_2 prism and a CCD camera for detecting X-rays (Princeton 2048*2048, 13*13 microns) is installed to evaluate the synchrotron radiation light. The prism can be removed to measure the SR spatial distributions.

Table 1: Main Laser, Plasma and Undulator Parameters Used During the Experiment

Laser/plasma parameters	Unit	Value
Energy	J	1
Pulse duration	fs	30
Focal length	m	1
Aperture	mm	55
Target length	mm	3
Electron density	cm^{-3}	$5*10^{18}$

Undulator parameters	Unit	Value
Magnet		SmCo
Deflection parameter		1.05
Magnetic gap	mm	3.5-8
Spatial period	mm	18,2
Number of periods		34
Number of sections		1
Peak magnetic field at 4 mm	T	0.6

SPATIAL PROPERTIES AND ESTIMATION OF NUMBER OF PHOTONS

At first, it was decided for increasing the chance to observe SR in single shot to work in the visible-UV range, where optics have theoretically very good transmission. This explains why the photon spectrometer, presented in the last section, is composed of a MgF_2 lens and a prism. As a consequence, with the undulator parameters, we have restricted the electron beam energy to a maximum of 150 MeV in order not to radiate at too short wavelengths for the detecting system.

Fig. 2 (a) presents the footprint of the radiation measured on the CCD camera, which images a position corresponding to 60 cm after the end of the undulator and here for injected electrons with estimated 120 MeV energy. While the vertical spatial distribution is Gaussian, the horizontal one makes appear a more complicated shape composed of two parts: a centre part which seems also Gaussian and a second one of larger size and smaller intensity causing large wings on the distribution. At this step we can assume with relative good confidence that the synchrotron radiation signal correspond to the centre part of the image with double Gaussian spatial distribution. Also important to be noticed, the vertical FWHM divergence of the supposed SR, about 3 mrad, is approximately twice bigger than the horizontal one. This could mean that either the emittance in both directions of the electron beam is notably different or the focusing geometries (positions of focus and beta functions). The second radiation, which origin is not really clear, could be the emission of light caused by the electrons passing through the thick aluminium foil.

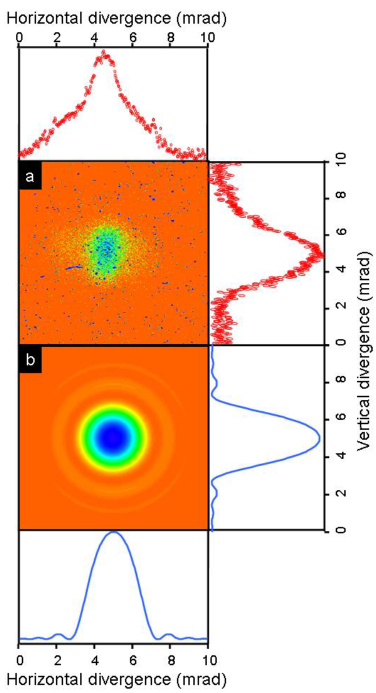

Figure 2: Single shot footprint and corresponding spatial distributions of the radiation measured on the CCD camera. (a) Experimental data. (b) Simulated synchrotron radiation from SRW software [16].

Simulation has been made using the SRW software in order to evaluate the distributions of the SR. Fig 2 (b) shows the SR spatial properties obtained at the same distance of the undulator as in the experiment. For this simulation, 120 MeV electron beam energy, 1 Π mm.mrad emittance for both directions, 1% energy spread and 10 pC charge have been chosen. Compared to Fig. 2 (a), the vertical Gaussian distributions are very similar, while the second part of the horizontal distribution direction is not reproduced. As a consequence, this simulation, which presents a very good agreement with the data, confirms that there is a high probability that the measured signal is a synchrotron radiation generated in the undulator.

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From this same figure and from the following equation (eq. 1), one can deduce a good estimation of the number of photons generated in the undulator.

$$\frac{(Nc^*\Delta H_{FWHM}{}^*\Delta V_{FWHM})^*T_{lens}{}^*G_{CCD}{}^*3.65}{E_{phot}{}^*effq_{CCD}} \sim 3.3\text{-}3.8\ 10^7 \text{ ph/shot} \quad (1)$$

Where Nc is the maximum number of counts on the CCD, $\Delta H, V_{FWHM}$ the width of the horizontal and vertical distributions, T_{lens} the transmission of the lens, G_{CCD} the electronic gain of the CCD, E_{phot} the spectral SR energy estimated from a 120 to 140 MeV electron beam energy, $effq_{CCD}$ the quantum efficiency of the CDD corresponding to E_{phot}.

This value can be compared to the analytical estimation of the SR coming from the following classical formula (eq. 2).

$$\frac{7.28^*(E_{beam})^{2*}Q^*N^*K^2}{\lambda_U{}^*E_{phot}} = 3.7\ 10^7 \text{ ph/shot} \qquad (2)$$

Where E_{beam} is the electron beam energy, Q the charge, N the number of periods and K the deflection parameter.

The two formulas give more or less the same values concluding that estimated parameters are well defined.

SPECTRAL PROPERTIES

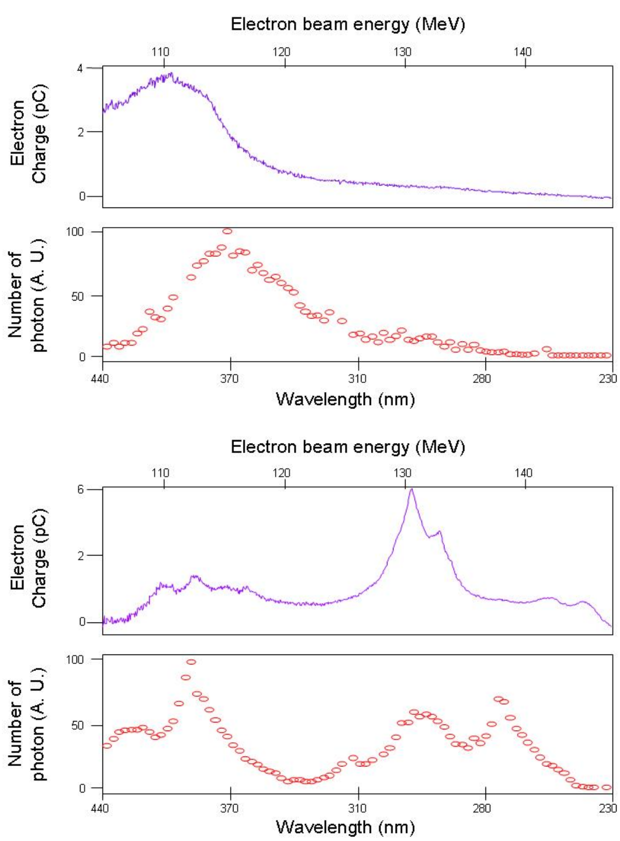

Figure 3: Single shot spectra of photons (red circle) and electrons (violet line) for two different shots.

In order to correctly characterize the emission as a potential SR light, we have measured at the same time the spectra of the laser light and of the electrons. First of all, when electron charge is higher than 1 pC, intense peaks appear in the photon spectrum as in Fig 3, but never below this very clear threshold. Second, when the electron spectrum is composed of multiple peaks, the photon spectrum presents similar distribution, with a relatively nice apparent correlation.

Yet, up to now the laser light spectra are not calibrated. For that, from the position on the CCD camera, one can easily retrieved the corresponding wavelength using the geometrical Descartes laws when passing through the prism.

Then, in order to validate definitively the assertion that this laser light signal is undulator radiation, the energy of the electrons well-focused inside the undulator has been varied. For that, electrons with large energy distributions are generated and then a different current is applied on the triplet of quadrupoles to adapt the focus inside the undulator of the electrons at the desired energy. Fig. 4 presents the evolution of the position on the CCD camera of the experimentally measured laser light as function of the energy varied from 100 MeV to 150 MeV. This “measured spectrum” is compared to a “calculated spectrum”. This latter is obtained by calculating for the different electron energies, the corresponding emitted SR wavelength which could be generated, according to eq. 3.

$$\lambda = \frac{\lambda_U{}^*}{2\gamma^2}\frac{(1+K^2)}{2} \qquad (3)$$

In a second step, the wavelength is transformed into position on the CCD with the Descartes laws. The measured spectrum can be very well fitted by the calculated spectrum if only K equal to 1.5. Yet, this latter was estimated to be equal to 1, constituting a moderate disagreement.

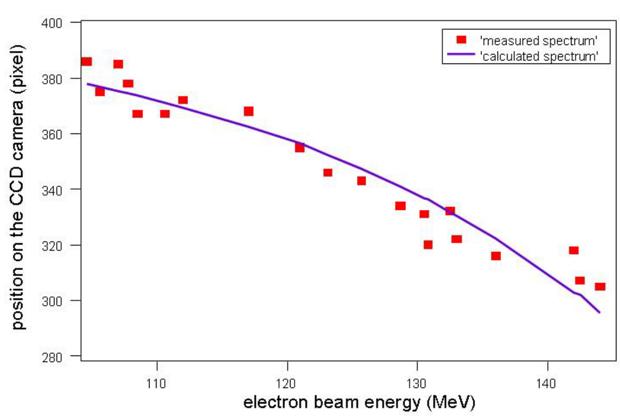

Figure 4: position on the CCD camera of the measured laser light peaks as function of the electron beam energy.

Finally to confirm the relation between position on the CCD and wavelength deduced from the Descartes laws, the position on the CCD camera has been calibrated using Kr and Hg vapour lamps, which radiation peaks are very well known and can be identified in the UV-visible range. This is presented in Fig. 5 and called “calibrated spectrum”. A good agreement is also observed. As a

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consequence we can conclude definitively that the measured signal is synchrotron radiation generated from plasma-based electrons wiggling in undulator.

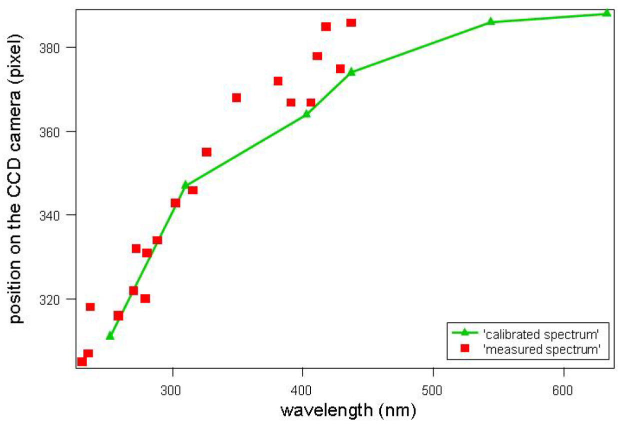

Figure 5: position on the CCD camera of the measured laser light peaks as function of the wavelength.

CONCLUSIONS

In this paper, we have clearly showed that synchrotron radiation was generated from laser-plasma-acceleration electrons introduced in an undulator. Radiations from 440 nm to 230 nm have been observed when changing the energy of the electrons focused inside the undulator from 100 MeV to 150 MeV. Measurements of footprints have shown that the horizontal divergence is twice smaller than the vertical one probably due to different emittances or focussing geometries of the electron beam in both directions. Also the number of photons has been evaluated to be close to $4*10^7$ ph/shot. This remains a low number, which can be explained by the also low electronic charge and large energy spread during the experiment, due to troubles on the laser system at this moment.

For 5^{th} generation light sources, i.e. FEL based on plasma-acceleration, one need considerably smaller energy spread for electrons passing through the quadrupoles to keep emittance and pulse duration at low values. Also, very small pointing variation (work on the stability of the laser in general) is expected to correctly passing through the quadrupoles and undulator and so have stable emission to correctly characterize it. Using longer undulator, stronger K value, increasing charge while keeping other parameters at best is also primordial.

REFERENCES

[1] T. Tajima and J. M. Dawson Phys. Rev. L **43,** 267-270 (1979).
[2] S. Mangles et al. Nature **431,** 535-538 (2004).
[3] C. G. R. Geddes Nature **431,** 538-541 (2004).
[4] J. Faure et al. Nature **431,** 541-544 (2004).
[5] W. P. Leemans et al. Nat. Phys. **2**, 696-699 (2006).
[6] S.P.D Mangles et al. Phys. Rev. L **96,** 215001 (2006).
[7] J. Faure et al. Nature 444, 737-739 (2006)
[8] V. Malka et al. Nat. Phys. 4, 447-453 (2008).
[9] F. Gruner et al. Appl. Phys. B 86 431-435 (2007).
[10] H. P. Schlenvoigt et al. Nat. Phys. **4** 130-133 (2008).
[11] K. Nakajima Nat. Phys. News and views **4** 92-93 (2008).
[12] M. Fuchs et al. Nat. Phys. **5,** 826-829 (2009).
[13] N. Vafaei-Najafabadi and R. Fedosejevs Physcics in Canada **65,** 105-106 (2009).
[14] S. Bajlekov et al. Proc. FEL-08, 163-166 (2008).
[15] R. Bachelard et al. Proc. FEL-09, 138-141 (2009).
[16] O. Chubar, P. Elleaume, Proc. EPAC-98, 1177 (1998).

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