Control of undulator radiation using a Laser Plasma Acceleration Source

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Abstract. Spontaneous undulator radiation emission, after the COXINEL line using a Laser Plasma acceleration (LPA) source, has been observed. The line enables to manipulate the electron beam phase space such as emittance, dispersion and energy spread along a 10 m long transport. The large divergence is handled at a very early stage to mitigate the chromatic emittance, using high gradient permanent magnet based quadrupoles mounted on translation tables. The operating energy is between 161-180 MeV focused in a 2-m long cryo-ready undulator with a period of 18 mm emitting light in the Ultra-Violet range. The spectral flux is characterized using a spectrometer. The wavelength is tuned by either changing the electron beam energy or by adjusting the undulator gap. The radiation pattern signature is illustrated alongside its dependence on the energy spread that is modified by introducing a slit in a magnetic chicane where a small relative bandwidth of 5% has been achieved.

1. Introduction

Accelerator based light sources [1] are presently experiencing a vibrant development, enabling to transform the world’s understanding with light by uncovering phenomena occurring at the quantum level. Storage ring based facilities are the typical sources for the generation of high brilliance X-ray undulator radiation that address the 21st century societal challenges. Undulator radiation presents specific angular-spectral distributions and polarization properties [2, 3, 4, 5, 6, 7] with a rather small relative spectral bandwidth. However, electron beam properties (energy spread and emittance) can affect the interference process, broaden the line and reduce accordingly the photon beam brilliance.

Moreover, with the advent of Free Electron Lasers (FELs) [8], the X-ray sources [9] have been increased by orders of magnitude in terms of brilliance opening the path for deciphering unexplored ultra-fast phenomena with unprecedented time resolution. Because of the recent advances of Laser Plasma Acceleration [10, 11, 12], it is of great interest to explore whether they can drive an undulator radiation source or an FEL. If successfull, it would make the accelerator light sources more compact. In such accelerator, a high-power and ultra-short laser beam focused into a gas target resonantly drives a plasma wave traveling with a velocity close to the speed of light, which can trap and accelerate electrons from the ambient plasma [13, 14]. LPA delivers
few GeV electron beams [15, 16] within centimeter accelerating distance with low emittance [17], few-femtosecond bunch duration [18], quasi-monochromatic energy [19] and high charge [20, 21].

2. COXINEL setup

The experiment aims at controlling and transporting electron beams produced by an LPA source to demonstrate FEL amplification at 200 nm and 40 nm [22, 23, 24]. The key concept relies on an innovative electron beam longitudinal and transverse manipulation along the transport line towards the undulator. The line have been designed by SOLEIL and installed at Laboratoire d’Optique Appliquée with the 30 TW laser of Salle Jaune for baseline reference parameters given in Table 1. Table 1 presents the average electron beam parameters measured compared to the baseline reference case. The real beam quality is quite different from the baseline reference case, where the energy spread is one order of magnitude higher and divergence is larger by a factor of 2.

![Figure 1. COXINEL line sheme. laser hutch (grey), gas jet (orange), permanent magnet based quadrupoles (QUAPEVAs) (green), electro-magnet dipoles (red), electro-magnet quadrupoles (blue), undulator (blue and red), lens (purple), UV spectrometer (light grey).](image)

The COXINEL transport line [25], as shown in Fig. 1, starts with a triplet of high variable gradient permanent magnet based quadrupoles (QUAPEVAs) [26, 27, 28] that strongly focuses the LPA electron beam and permits to handle the divergence. The electron beam is then sent through a four-dipole-magnet chicane enabling to reduce the slice energy spread and lengthening the electron bunch accordingly. The presence of a variable width slit in the middle of the chicane enables to select an energy range of interest [29, 30]. A second set of quadrupoles placed after the chicane ensures that the transverse beam size is minimized at the undulator center. The commissioned undulator is a hybrid cryo-ready undulator (operates at room and cryogenic temperature), consisting of 107 number of 18 mm periods [31, 32, 33], Pr$_2$Fe$_{14}$B magnets and Vanadium Permendur poles. The in-vacuum girders, that hold the assembly of magnets, are separated by an adjustable gap allowing for wavelength tunability. The measured peak field $B_{\text{peak}}$ versus gap $g$ (between 5 mm and 10 mm) is fitted with:

$$B_{\text{peak}} = 3.37 \exp \left( -4.34 \frac{g}{\lambda_u} + 1.12 \left( \frac{g}{\lambda_u} \right)^2 \right)$$

(1)

The radiation is focused at the entrance slit of the spectrometer with a CaF$_2$ lens (eSource Optics CF5025LCX) with a schematic view presented in Fig. 1. Due to the chromatic dispersion of the CaF$_2$ [34], the conversion from observation angle to position on the CCD of the spectrometer includes chromatic aberration effect. By using ray optics approach to apply the chromatic effects of the lens considering the far-field radiation and by taking into account the spectrometer magnification $G$, the vertical displacement of the CCD $H$, the vertical axis of the observed image on the CCD camera can be expressed as [35]:

$$z_c = G \times \left( D \theta_0 + h \right) \cdot \left( 1 - \frac{d}{f(\lambda)} \right) + \theta_0 d + H,$$

(2)

where $D$ ($d$ respectively) is the distance of the lens from the undulator center (spectrometer entrance slit), $\theta_0$ being the angle of the emitted radiation, $h$ the vertical offset of the lens w.r.t. the optical axis and $f(\lambda)$ the focal length.
Table 1. Beam parameters at the generation point in the gas jet. Divergence, beam size and beam length in rms. Emittance value is deduced from simulations.

| Parameters                  | RUN4  | RUN5  | Baseline | Unit   |
|-----------------------------|-------|-------|----------|--------|
| Energy                      | 176   | 161   | 200      | MeV    |
| Charge density              | 1     | 1     | 5        | pC     |
| Normalized emittance        | 1     | 1     | 1        | mm.mrad|
| Energy spread               | > 10  | > 10  | 1        | %      |
| Vertical Divergence         | 2     | 2     | 1        | mrad   |
| Horizontal Divergence       | 3     | 3     | 1        | mrad   |

3. Photon beam measurement

The radiation emitted by relativistic electrons of Lorentz factor $\gamma$ traversing an undulator interferes from one period $\lambda_u$ to another, leading to a spectrum of sharp lines at the fundamental wavelength $\lambda$ expressed as:

$$\lambda = \frac{\lambda_u}{2 \gamma^2} \left[ 1 + \frac{K_u^2}{2} + \gamma^2 \theta^2 \right]$$

with $K_u$ the deflection parameter proportional to the period and field and $\theta$ the observation angle. Figure 2 presents a single shot measurement of the spatio-spectra distribution. The image exhibits the distinguished moon-shape type pattern of undulator radiation, resulting from the off-axis emission red shift. The image analysis starts with removing the high pixels and background noise of the CCD camera (b) from the raw data (a). Then a median filter is applied (c) followed by adding the spectrometer calibration (grating reflectivity and CCD quantum efficiency) (d). The defined triangular shape, instead of the typical parabolic shape caused by the $\gamma^2 \theta^2$ term in Eq. (3), is due to the chromatic effects of the lens. Thus by using Eqs. (2) and (3), a theoretical fit is added to the image (dashed curve).

![Figure 2](image-url)

4. Wavelength tunability

The undulator radiation tunability, one of the major undulator properties, has been explored at COXINEL. The radiated wavelength is independently varied either by changing the undulator...
gap or the electron beam energy. Figure 3 shows the measured spatio-spectral distribution for different undulator gaps during RUN4. The smaller the gap, the larger the wavelength.

Figure 3. Spatio-spectral profile single shots measurements for different undulator gaps: (a) 4.5 mm, (b) 4.7 mm, (c) 5.0 mm. Shots taken from RUN4 for an electron slit of 3 mm.

The resonant wavelength is measured by doing a cut at the center of the spatio-spectral profile and taking the wavelength at which the intensity is peaked. Figure 4 displays the resonant wavelength measured during RUN4 (a) and RUN5 (b) as a function of the undulator gap. The behaviour shows a good agreement with the theoretical curves (dashed) using the measured magnetic field gap dependence especially during RUN5 (blue), where the generated electron beam had better qualities. In the case of RUN4 (red), the measurements drift from the theoretical value at gaps >6 mm, due to the degradation of the laser at the end of the day that reduced the electron beam energy. In summary, a wavelength tunability around 120 nm is achieved. Such an undulator wavelength control corresponds to what is currently achieved with conventional accelerators.

Figure 4. Wavelength tunability by undulator gap and energy change. (a) Measurements during RUN4 where the (red) and (green) correspond to two consecutive days. (b) Measurements during RUN5 (blue). (Dashed) theoretical values using the measured field.

5. Spectral bandwidth control

Figure 5-(a,b,c) shows the undulator spatio-spectral patterns, with the corresponding appended on-axis spectra, measured while shaping the beam parameters during RUN4 as the electron slit in the middle of the chicane is varied. As the slit is closed, the electron beam energy spread is reduced [35]. The relative bandwidth measured is reduced from 14% down to 8% when closing the slit from 4 mm to 2 mm. The electron beam parameters deduced from the measured distribution and transported along the line are used for the undulator radiation modeling using SRW code [36] in the far-field region as shown in Fig. 5-right. A so-called slicing method is used, where radiation of each electron energy slice is computed separately with its corresponding parameters (divergence and size), and then all the spectra are added up taking into account the slice energy distributions.
Figure 5. Single shot measured spatio-spectral distributions during RUN4 for a 5 mm undulator gap while varying the electron slit width: 4 (a), 3 (b), 2 (c) with a 2.2 mm spectrometer entrance slit. Simulated spectra using SRW for a magnetic field of 1.11 T, with beam parameters taken from the simulations of the corresponding electron beam distribution transported along the line. White curves: on-axis spectral flux at $z=H$.

Figure 6 presents the relative bandwidth of all the shots measured during RUN4 (red) and RUN5 (blue) for different electron slit cases. Simulations (cyan) are compared to the measurements of RUN5 and show a good agreement. A minimum relative bandwidth of 5% is achieved with a 1 mm slit case.

6. Conclusion
Laser plasma acceleration based undulator radiation have been measured after the successful transport of highly divergent electron beams from source to undulator. Thanks to the adjustable gap of the undulator, we have achieved a wavelength tunability of $\sim 100$ nm. We even went further to try and control the spectral purity of the radiation, by inserting an electron collimator at the center of the chicane to select a smaller range of energies, where the spectral relative bandwidth is reduced down to 5%. These measurements provide a clear characterization of the spontaneous emission of undulator radiation, as a necessary step towards an FEL effect.

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