STUDY OF HIGH HARMONIC GENERATION AT SYNCHROTRON SOLEIL USING ECHO ENABLING TECHNIQUE

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Abstract

SOLEIL group is presently evaluating various ways to produce ultra-short x-ray pulses at the synchrotron SOLEIL. As a possibility we consider implementation of the echo enabling harmonic generation (EEHG) technique recently proposed for free electron laser [1]. We show that a slight modification of the slicing scheme previously used at ALS [2], BESSY [3] and SLS [4] will enable generation of ultra-short pulses of coherent synchrotron radiation (CSR) in a storage ring at high harmonic. In the synchrotron SOLEIL, the two laser/electrons interactions will take place in two out of vacuum wigglers of period 150 mm, and x-ray will be emitted in an APPLE-II type undulator with a period of 44mm or 80 mm in the beamline TEMPO.

INTRODUCTION

A schematic for the implantation of the "standard" slicing [5] at SOLEIL is shown in Fig. 1. The main parameters are given in Table 1. The laser-electron beam interaction takes place in the out of vacuum wiggler, called a modulator, located in the middle of the section 6. The separation is then performed thanks to the dispersion of the SOLEIL lattice. The sliced radiation is intended presently to be exploited on CRISTAL beamline using an in vacuum undulator located in the short straight section 6, and on TEMPO beamline using two APPLE-II undulators located in the medium section number 8 [6, 7].

In this proposal we consider adding a second modulator to produce coherent harmonic emission from the radiator undulator instead of spontaneous emission thanks to a highly efficient up-conversion of the modulation frequency.

MODELLING

We first study the longitudinal properties of the electron bunch while neglecting the transverse dependence. As for the EEHG modelling, we follow the electron bunch density $f$ in the longitudinal phase space $(z, p)$, with $z$ the longitudinal coordinate normalised by $\sigma_z$ and $p$ the energy difference with respect to $E_0$ and normalised by $\sigma_E$. As an initial condition, we consider a gaussian distribution in function of $p$ and along $z$, the electron bunch density is supposed to be uniform at the scale of the laser length, as $f(p) = N_0 \sqrt{2\pi} e^{-p^2/2}$, with $N_0$ the number of electrons per unit of length. After the first modulator, the electron energy is modulated at the laser wavelength $\lambda_L$ along the RMS laser pulse length $\sigma_{L1}$: $p = p + A_1 e^{-z^2 / (2\sigma_{L1}^2)} \cos(2\pi / \lambda_L)$, with $A_1$ the modulation amplitude in energy spread unit. The electron bunch then passes in a storage ring section, where it experiences dispersion as the path taken by the electrons depends of their interaction with the magnetic field. After the second modulator, the electron energy is again modulated at the laser wavelength $\lambda_L$ along the RMS laser pulse length $\sigma_{L2}$: $p = p + A_2 e^{-z^2 / (2\sigma_{L2}^2)} \cos(2\pi / \lambda_L)$, with $A_2$ the modulation amplitude in energy spread unit.

Table 1: Synchrotron SOLEIL and laser parameters used in our study

<table>
<thead>
<tr>
<th>Component</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron bunch</td>
<td>Nominal energy $E_0$</td>
<td>GeV</td>
</tr>
<tr>
<td></td>
<td>Energy spread $\sigma_E$</td>
<td>MeV</td>
</tr>
<tr>
<td></td>
<td>Bunch length $\sigma_z$</td>
<td>mm</td>
</tr>
<tr>
<td>Modulators</td>
<td>Period length</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>Length</td>
<td>m</td>
</tr>
<tr>
<td>Radiator U20 CRISTAL</td>
<td>Energy range</td>
<td>keV</td>
</tr>
<tr>
<td></td>
<td>Maximum magnetic field $B_z$</td>
<td>T</td>
</tr>
<tr>
<td>HU44/HU80 TEMPO</td>
<td>Energy range</td>
<td>eV</td>
</tr>
<tr>
<td></td>
<td>HU44 maximum magnetic field $B_{x, z}$</td>
<td>T</td>
</tr>
<tr>
<td></td>
<td>HU80 maximum magnetic field $B_{x, z}$</td>
<td>T</td>
</tr>
<tr>
<td>Laser</td>
<td>Wavelength $\lambda_L$</td>
<td>nm</td>
</tr>
<tr>
<td></td>
<td>Pulse energy</td>
<td>mJ</td>
</tr>
<tr>
<td></td>
<td>Minimum length (FWHM)</td>
<td>fs</td>
</tr>
</tbody>
</table>

Figure 1: Implementation of the slicing operation at SOLEIL. Laser-electron beam interaction occurring in the section 06-M, and femtosecond radiation being collected in the CRISTAL and in the TEMPO beamline.
energy. After the dispersive section the longitudinal coordinate becomes $z = z + pR_{56}^1 \sigma_E / (E_0 \sigma_z)$, with $R_{56}^1$ the coefficient of the transport matrix of the storage ring section considered. Then the electron bunch is re-submitted to a laser interaction in a second modulator, the coordinate $p$ becomes: $p = p + A_2 e^{-z^2/(2\sigma_{l2}^2)} \cos(2\pi/\lambda_L + \Phi)$, with $A_2$ the energy modulation amplitude in unit of $\sigma_E$, $\sigma_{l2}$ the RMS laser pulse length in unit of $\sigma_z$ and $\Phi$ the phase difference between the two laser signals ($\Phi$ is fixed at 0). The electron bunch then passes in an adaptive dispersion section, whose strength is characterised by the $R_{56}^2$ value. The longitudinal coordinate $z$ becomes: $z = z + pR_{56}^2 \sigma_E / (E_0 \sigma_z)$. At this point, with an appropriate set of parameters, the longitudinal charge distribution can be modulated at a harmonic number $k$ of the laser wavelength [1, 8]. In case of periodic distribution, the modulation amplitude is characterised by the so-called bunching factor [1, 8] $b(k)$:

$$b(k) = \frac{1}{N_0} |\langle \rho(z) e^{-ikz\sigma_z 2\pi/\lambda_L} \rangle|,$$

(1)

with $\rho(z) = \int_{-\infty}^{\infty} f(z,p) dp$, and $\langle \rangle$ the average over the coordinate $z$. In the case of infinite laser pulse lengths, an optimised bunching factor is given by [8]:

$$b(k) = |J_{k+1}[kA_2 B_2] J_k[A_1(B_1-kB_2)] \times e^{-\frac{1}{2}([B_1-kB_2]^2)}|,$$

(2)

with $A_1, A_2, B_{56}, B_{56}^2$. Besides, a numerical macroparticle code enables to take into account the laser pulse lengths $\sigma_{l1}, \sigma_{l2}$, a limitation of the energy modulation amplitude (the values of $A_1$ and $A_2$ have been limited to 5) and the energy spread $\Delta \sigma_E$ introduced by Incoherent Synchrotron Radiation (ISR) when the electron bunch radiates in bending magnets, $\Delta \sigma_E^2 = \frac{5\alpha_0 (hc)^2}{48\lambda_0 R^2 \gamma^7}$ [9], with $\alpha_f$ the fine structure constant, $h$ the Planck constant, $c$ the light velocity, $L$ the magnet length, $R$ the bending radius, and $\gamma$ the normalised energy. In the SOLEIL case, $L = 1$ m and $R = 5.39$ m, so $\Delta \sigma_E = 4.5 \times 10^{-3} \sigma_E$.

**TEMPO BEAMLINE**

In the TEMPO beamline, radiation can be produced between 27.6 nm and 0.8 nm, i.e. the harmonic number $k$ of the Ti:Sa wavelength stands between 29 and 967. According to the free space available in the straight sections, the second modulator can be located either on the section 7M or on the section 8M (cf. Fig.1). However, the echo scheme needs the second dispersion strength $R_{56}^2$ to be small and thus, this implies that the second modulator cannot be placed on the section 7M. In the case of the second modulator placed in 8M, the coefficient $R_{56}^1$ is of -1.46 cm. This value is rather important and implies that the energy modulated electrons are extended over a long range in the longitudinal coordinate, compared to the laser pulse length (Fig. 2). Thus, with a 5 mJ laser pulse, either a small number of electrons have their energy changed by the second modulator, either the peak laser power is weak. Furthermore, a strong $R_{56}^2$ value induced a very fine structure (Fig.2b) which is more sensible to noise introduced by ISR.

![Figure 2: Longitudinal phase space of the electron-bunch after the first dispersive section, a) on the scale of the laser pulse length, b) on the scale of the laser wavelength. Parameters: $A_1 = 5, R_{56}^2 = -1.46$ cm.](image)

To overcome these difficulties, the machine optics is modified to get a value of $R_{56}^1$ smaller, using a so-called low momentum compaction factor configuration. In the case of a momentum compaction factor of $\alpha_0/\gamma$, with $\alpha_0$ the nominal value ($\alpha_0 = 4.4 \times 10^{-4}$), the coefficient $R_{56}^1$ is of -2.26 mm. An example of longitudinal phase space after the second dispersive section, in an $\alpha_0/\gamma$ configuration, is shown Fig. 3.

![Figure 3: Longitudinal phase space of the electron-bunch after the second dispersive section, a) at the scale of the laser pulse lengths and b) at the scale of the laser wavelength. Parameters: $A_1 = 5, A_2 = 1.9, R_{56}^1 = -2.26$ mm, $R_{56}^2 = -74$ mm, $\sigma_{l1} = 1.21 \times 10^{-3}$, $\sigma_{l2} = 4.84 \times 10^{-3}$.](image)
are four bending magnets. In the numerical code, energy spread from ISR is added at each of them.

Figure 4: Dashed line: \( R_{56}^1 \) values between the section M6 and the section M8. Full line: associated storage ring synoptic.

In order to know at which wavelength, coherent emission is possible, the bunching factor \( b \) in function of the harmonic number \( k \) of the laser wavelength is calculated. A first approach is done in calculating the bunching factor with the equation (1). However, further investigations will be devoted to take into account that the longitudinal charge distribution \( \rho(z) \) is not periodic because of \( \sigma_{L1}, \sigma_{L2} \).

Fig. 5 shows the bunching factor versus the harmonic number for a low-\( \alpha \) configuration \( \alpha_0/7 \). The bunching factor decreases smoothly towards a cut-off which arrives when \( A_2 \) reaches the fixed limited value of 5. In this configuration, the cutoff appears for a harmonic number of about 80, which corresponds to a wavelength of 10 nm.

Figure 5: Bunching factor \( b(k) \) in function of the harmonic number \( k \) calculated with a numerical code over 50 laser wavelengths \((-25\lambda_L/\sigma_z < z < +25\lambda_L/\sigma_z)\). Fixed parameters: \( A_1 = 5, \ R_{56}^1 = -2.26 \text{ mm}, \ \sigma_{L1} = 1.21 \times 10^{-3}, \ \sigma_{L2} = 4.84 \times 10^{-3} \).

**CONCLUSION**

A method to generate coherent synchrotron radiation at high harmonics in a storage ring using an echo scheme has been proposed. This method includes the specificities of the slicing and the EEHG. The study presented here concerns the longitudinal modulation of the electron bunch induced by the two laser-electron interactions and two dispersive sections. In the future, transverse dynamics will be investigated. The application on the synchrotron SOLEIL shows that it seems possible to have coherent radiation on the TEMPO beamline, configuring the storage ring in low-\( \alpha \) mode.

We would like to thank P. Brunelle for low-\( \alpha \) storage ring calculations.

**REFERENCES**


[7] A. Nadji et. al., this proceeding
