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].

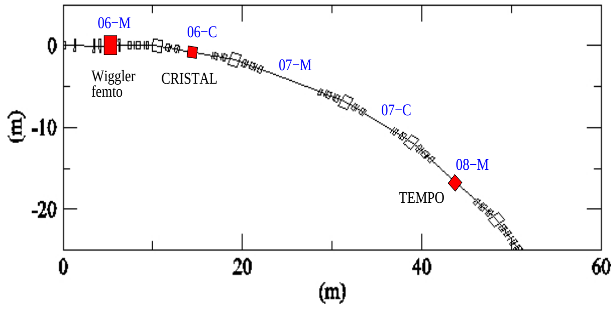

Figure 1: Implementation of the slicing operation at SOLEIL. Laser-electron beam interaction occurring in the section 06-M, and femtosecond radiation being collected in the CRISTAL and in the TEMPO beamline.

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

Component	**Unit**	**Value**
Electron bunch		
Nominal energy E_0	GeV	2.75
Energy spread σ_E	MeV	2.79
Bunch length σ_z	mm	10.5
Modulators		
Period length	mm	150
Length	m	3
Radiator		
U20 CRISTAL		
Energy range	keV	4 - 30
Maximum magnetic field B_z	T	1.03
HU44/HU80 TEMPO		
Energy range	eV	45-1 500
HU44 maximum magnetic field B_x, B_z	T	0.41, 0.64
HU80 maximum magnetic field B_x, B_z	T	0.76, 0.85
laser		
Wavelength λ_L	nm	800
Pulse energy	mJ	5
Minimum length (FWHM)	fs	30

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 σ_z and p the energy difference with respect to E_0 and normalised by σ_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 $f(p) = \frac{N_0}{\sqrt{2\pi}} e^{-p^2/2}$, with N_0 the number of electrons per unit of length. After the first modulator, the electron energy is modulated at the laser wavelength λ_L along the RMS laser pulse length σ_{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 energy. After the dispersive section the longitudinal coordinate becomes $z = z + pR^1_{56}\sigma_E/(E_0\sigma_z)$, with R^1_{56} 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: $p = p + A_2 e^{-z^2/(2\sigma^2_{L2})}\cos(2\pi/\lambda_L + \Phi)$, with A_2 the energy modulation amplitude in unit of σ_E, σ_{L2} the RMS laser pulse length in unit of σ_z and Φ the phase difference between the two laser signals (Φ is fixed at 0). The electron bunch then passes in an adaptive dispersion section, whose strength is characterised by the R^2_{56} value. The longitudinal coordinate z becomes: $z = z + pR^2_{56}\sigma_E/(E_0\sigma_z)$. 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] $b(k)$:

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

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

$$b(k) = |J_{k+1}[kA_2B_2]J_1[A_1(B_1-kB_2)]\times e^{-\frac{1}{2}[B_1-kB_2]^2}|, \qquad (2)$$

with $B_i = R^i_{56}\frac{2\pi}{\lambda_L}\sigma_E/E_0$ and J_k the Bessel function of order k. This formula has been used to fix the parameters $A_1, A_2, R^1_{56}, R^2_{56}$. Besides, a numerical macroparticule code enables to take into account the laser pulse lengths σ_{L1}, σ_{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, $\Delta\sigma^2_E = \frac{55\alpha_f(\hbar c)^2}{48\sqrt{3}}\frac{L}{R^3}\gamma^7$ [9], with α_f the fine structure constant, $\hbar$ the Planck constant, c the light velocity, L the magnet length, R the bending radius, and γ 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^2_{56} 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^1_{56} 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^1_{56} value induced a very fine structure (Fig.2b) which is more sensible to noise introduced by ISR.

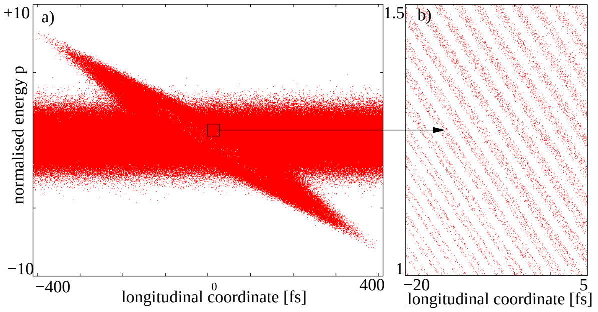

Figure 2: Longitudinal phase space of the electron-bunch after the first dispersive section, a) on the scale of the laser pulse length, b) on the scale of the laser wavelength. Parameters: $A_1 = 5$, $R^1_{56} = -1.46$ cm.

To overcome these difficulties, the machine optics is modified to get a value of R^1_{56} smaller, using a so-called low momentum compaction factor configuration. In the case of a momentum compaction factor of $\alpha_0/7$, with α_0 the nominal value ($\alpha_0 = 4.4\times10^{-4}$), the coefficient R^1_{56} is of -2.26 mm. An example of longitudinal phase space after the second dispersive section, in an $\alpha_0/7$ configuration, is shown Fig. 3.

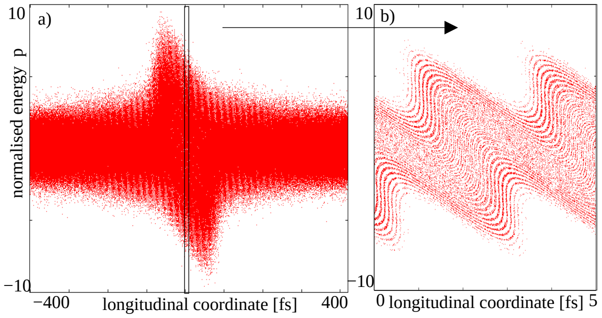

Figure 3: Longitudinal phase space of the electron-bunch after the second dispersive section, a) at the scale of the laser pulse lengths and b) at the scale of the laser wavelength. Parameters: $A_1 = 5$, $A_2 = 1.9$, $R^1_{56} = -2.26$ mm, $R^2_{56} = -74$ μm, $\sigma_{L1} = 1.21 \times 10^{-3}$, $\sigma_{L2} = 4.84 \times 10^{-3}$.

An example of the R^1_{56} values between the two modulators is shown Fig. 4. Between the two modulators, there are four bending magnets. In the numerical code, energy spread from ISR is added at each of them.

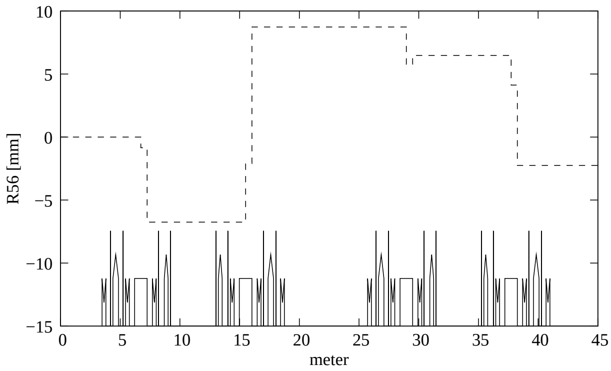

Figure 4: Dashed line : R^1_{56} values between the section M6 and the section M8. Full line: associated storage ring synoptic.

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 σ_{L1}, σ_{L2}. Fig. 5 shows the bunching factor versus the harmonic number for a low-α 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.

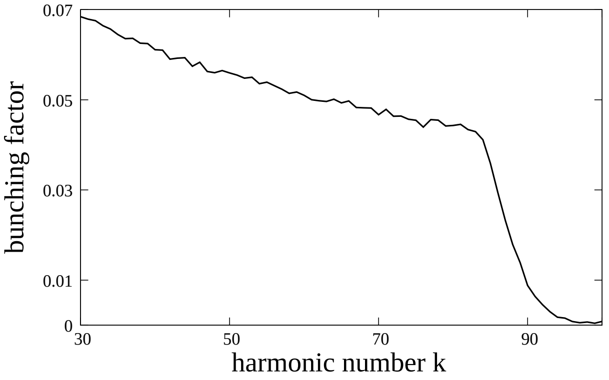

Figure 5: Bunching factor b(k) in function of the harmonic number k calculated with a numerical code over 50 laser wavelengths ($-25\lambda_L/\sigma_z < z < +25\lambda_L/\sigma_z$). Fixed parameters: $A_1 = 5$, $R^1_{56} = -2.26$ mm, $\sigma_{L1} = 1.21 \times 10^{-3}$, $\sigma_{L2} = 4.84 \times 10^{-3}$.

CRISTAL BEAMLINE

The possibility to get coherent radiation on the CRISTAL beamline has also been investigated. Only free space is available in the section 06-M, that is in the same straight section that the femto wiggler (Fig. 1). The required very high harmonic number ($k > 2580$) implies a strong dispersive section, which can be difficult to construct in a straight section. Concerning the electron-bunch density, as also discussed for the TEMPO beamline, a strong longitudinal dispersion implies that either only a small part of electrons are in interaction with the second laser pulse, or either the second laser power peak is weak. Furthermore it also implies that the internal structure is very fine so very sensitive to noise. For these reasons, it seems not possible to obtain coherent radiation on the CRISTAL beamline with this scheme.

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.

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REFERENCES

[1] G. Stupakov, “Using the Beam-Echo Effect for Generation of Short-Wavelength Radiation”, Phys. Rev. Lett. 102 (2009), 074801

[2] R. W. Schoenlein. et. al. , “Generation of Femtosecond Pulses of Synchrotron Radiation”, Science 287 (2000), 2237

[3] S. Khan et. al., “Femtosecond Undulator Radiation from Sliced Electron Bunches”, Phys. Rev. Lett. 97 (2006), 074801

[4] P. Beaud et. al. “Spatiotemporal Stability of a Femtosecond Hard–X-Ray Undulator Source Studied by Control of Coherent Optical Phonons”, Phys. Rev. Lett. 99 (2007) 174801

[5] A. A. Zholents and M. S. Zolotorev, “Femtosecond X-Ray Pulses of Synchrotron Radiation”, Phys. Rev. Lett. 76 (1996) 912

[6] A. Nadji et. al. “Femto-second electron beam slicing project at SOLEIL”, EPAC'04 (2004) 2332.

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

[8] D. Xiang and G. Stupakov, “Echo-enabled harmonic generation free electron laser”, Phys. Rev. ST Accel. Beams 12 (2009), 030702

[9] A. W. Chao and M. Tigner, “Handbook of Accelerator Physics and Engineering”, World Scientific (2006)