FEMTO-SECOND ELECTRON BEAM SLICING PROJECT AT SOLEIL

A. Nadji, O. Chubar, M. Idir, M.-P. Level, A. Loulergue, T. Moreno, L. Nadolski, F. Polack,

SOLEIL, L'Orme des Merisiers, Saint-Aubin BP 48, 91192 Gif-sur-Yvette CEDEX, FRANCE

Abstract

The goal of the slicing project at SOLEIL is to provide 100fs long pulses of soft and hard X-rays with reasonable flux and with a 1-10kHz repetition rate. The slicing principle is based on Zholents and Zoloterev method [1]. The SOLEIL horizontal natural optics enables the sliced pulse to be used on several consecutive straight sections without any modification to the magnet lattice. Feasibility and expected performances on two different beamlines are reported in this paper.

INTRODUCTION

The exciting opportunity of producing photon pulses with temporal width of about 100fs is seized at SOLEIL. Electron-beam slicing method has been proposed in [1], then experimentally demonstrated at the ALS in Berkeley [2] and implemented recently in other third generation light sources (BESSYII [3], SLS [4] and a new project at ALS [5]). This technique uses the interaction inside a wiggler ("modulator"), of a laser beam ultra-short-pulse with an electron bunch, inducing an energy-modulation of the electrons within a short section of that bunch ("slice"). Using dispersing magnetic fields or non-zero dispersion sections, this slice gives two transversely separated satellites which will radiate in an undulator ("radiator") located downstream. At present, it is planned that two beamlines at SOLEIL can profit from the slicing process for time resolved electron spectroscopy and for diffraction in the sub-picosecond time scale. The former, TEMPO, will use an helical undulator (HU80) covering a photon energy range from 200eV to 1000eV and the latter, CRISTAL, using an in-vacuum undulator (U20) in the 4 - 30keV energy range. The main issues to overcome are :

- to minimize the impact on the storage ring performances (symmetry, beam lifetime,…) in one hand and managing engineering problems such as wiggler design, vacuum vessels and power extraction on the other hand,
- to achieve a clear and efficient separation between the "newly created" femtosecond pulse and the electron picosecond pulse for the two beamlines.

LASER–ELECTRON INTERACTION

An important parameter of the slicing project is the laser system, which will be developed and managed by the LOA [6]. The main characteristics of the laser system are the following:

Wavelength λ_L: 800 nm

Energy per pulse A_L: 5 mJ – 10 mJ

Repetition rate f_L: 1 kHz – 10 kHz (100kHz)

Pulse length τ_L: 25 fs to 1 ps (rms)

Part of the laser radiation can also serve for pump-probe experiments. For resonant laser-electron interaction, the modulator has to operate at the laser wavelength (800nm). A wiggler with a period of 130mm and a field of 2.2T is a good candidate. A minimum length of 3m (20 periods) is necessary in order to optimize the energy modulation rate. The corresponding radiated power is about 23kW which is the state of the art for the beamline front ends. With these parameters and adequate focusing for the laser beam, a maximum energy modulation of ±20MeV is expected. However, the calculations were made with a more conservative value of ±14 MeV.

SLICING EFFICIENCY

One major difficulty for such a technique is the small efficiency of the slicing process. Several factors reduce the flux of short pulses compared to the normal beam :

- r_1: ratio between the rms temporal width of the laser pulse (~50fs) and the electron bunch (~24ps in a single bunch of 10mA),
- r_2: ratio between the repetition rate of the laser (~10 kHz) and the revolution frequency (0.8466 MHz)
- r_3: only 20% of the electrons receive the energy modulation and just one half is used [2].

In summary, a total efficiency ($r = r_1r_2r_3$) of 2.5×10^{-6} can be expected corresponding to a flux of about 4×10^7 photons/s/0.1%b.w for 10mA in one bunch. More accurate calculations will be presented later in this paper.

ELECTRON SEPARATION SCHEME

Modulator and radiator location

Basically, the slicing technique can be implemented in two different ways :

- case 1: the modulator and one radiator in the same straight section,
- case 2: the modulator and radiators in different straight sections.

Moreover, to separate the sliced beam from the main (or core) beam, four different schemes are possible: horizontal or vertical and spatial or angular separation.

In order to preserve the temporal characteristics of the sliced beam, the first case with a vertical spatial separation was privileged at the beginning of the study. The modulator and one radiator were placed in one of the four 12m long straight sections [7]. As for all the other straight sections, the horizontal dispersion is non-zero. The vertical dispersion required for the separation is produced with a closed bump in the modulator. The

solution is almost valid in terms of linear and non-linear electron beam dynamics, nevertheless some problems mainly on the technical side have weaken it seriously. In addition, there was an uncertainty on the feasibility of the X-ray optics for such a separation scheme. The same idea in the horizontal plane could not be applied because of the effect of the quite large horizontal dispersion.
Then, we explored the possibilities given by the second case. Such a configuration is sketched in Fig. 1. The modulator is installed in a medium straight section, the radiator 1, U20, is installed in the following short straight section and the radiator 2, HU80, in an other medium straight section.

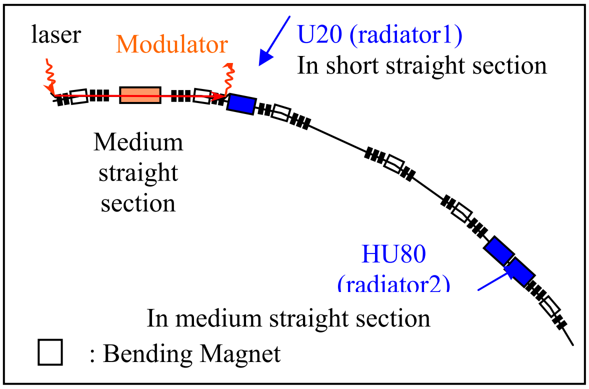

Figure 1: Implementation of the slicing project.

The electrons getting the energy modulation in a non-zero dispersion straight section, start betatron oscillations around a new orbit (behaving like Touschek-scattered particles). A bending magnet of the storage ring which follows the modulator, will produce the horizontal displacement of off-energy electrons. The trajectory of the sliced beam calculated as a function of the storage ring optical functions is given by:

$$D_{eff} = \eta_2 - (\sqrt{\beta_1\beta_2}\,\eta_1' + \alpha_1\sqrt{\frac{\beta_2}{\beta_1}}\,\eta_1)\sin\mu_{12} - \sqrt{\frac{\beta_2}{\beta_1}}\,\eta_1\cos\mu_{12} \qquad (1)$$

The subscript 1 refers to the centre of the modulator and 2, to the centre of the radiator. μ_{12} is the relative phase advance, β and α are the Twiss parameters and, η is the dispersion function. As the modulator is located in a symmetry point, $\alpha_1 = \eta'_1 = 0$, then the expression (1) can be simplified and becomes :

$$D_{eff} = \eta_2 - \eta_1\sqrt{\frac{\beta_2}{\beta_1}}\cos\mu_{12} \qquad (2)$$

the transverse displacement due to betatron oscillations is:

$$\Delta x = D_{eff}\frac{\Delta E}{E_0} \qquad (3)$$

where $\Delta E/E_0$ is the energy deviation. According to [2], a minimum horizontal separation Δx of at least 5 times the beam size is needed to get a good signal to noise ratio. The phase advance μ_{12} corresponds to a high and negative cosine (-0.848) which is very suitable to have a large value of D_{eff}. Fig. 2 shows the values of D_{eff} in different straight sections following the modulator. The large value of D_{eff} (0.53m) in radiator 1 results in Δx = 2.8mm = $7\sigma_x$ where σ_x is the horizontal beam size in a short straight section. This should enable a good horizontal spatial separation for the hard X-rays CRISTAL beamline. Concerning the soft X-rays TEMPO beamline, the second medium straight section downstream the modulator is preferred to the first one. It combines spatial and angular separations, which gives a more favourable separation between the photons of the main beam and those of the sliced beam.

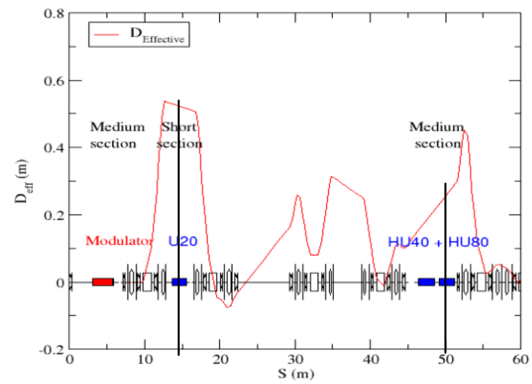

Figure 2: Trajectory of the sliced beam

A 3-dipole chicane bracketing the modulator has been studied in order to improve the separation in the case of TEMPO but the impact on the engineering aspects have been estimated to be prohibitive in comparison with the expected gain.
The natural optics of SOLEIL would then allow the sliced pulse to be used on both beamlines with no modification to the magnet lattice, no extra magnetic elements like chicane or quadrupoles (needed in the first case) and no additional power absorber. Furthermore, the radiation emitted by the modulator can be used by an other beamline.

Sliced bunch time structure

The drawback of such a configuration (modulator and radiators in different straight sections) could be the possible lengthening of the sliced bunch during his travel from the modulator to the radiators. As the horizontal dispersion is non-zero everywhere in the machine, a tracking program has been used in order to calculate accurately the dilution of the short pulse. Lengthening could result from either the natural betatron oscillation (emittance) or the energy modulation. The total effect is given by a quadratic sum. Table 1 shows that in our case, the effect is acceptable for both beamlines.

Table 1: Dilution of the slice (rms values)

Beamline	τ_{Laser} **(fs)**	$\tau_{Emittance}$ **(fs)**	τ_{Energy} **(fs)**	τ_{total} **(fs)**
CRISTAL	50	23	22	60
TEMPO	50	20	50	72

PHOTON PULSES SEPARATION

Computations have been done using SRW code [8]. First, the phase space distribution of electrons was simulated at exit of modulator and propagated through magnet lattice to the radiator. Next, the electric field of spontaneous emission from individual electrons was computed and propagated, using the principles of Fourier optics, through initial optical components of a beamline, up to a given transverse plane. The radiation intensity from different electrons of the slice was then summed-up and compared to the intensity of the electron bunch core emission. It was assumed that the contribution of emission from other "non-sliced" electron bunches was completely suppressed by a chopper and/or a gating detector.

CRISTAL beamline

In the short straight section, the electron beam size is rather large and the divergence is very small. Moreover, the radiated hard X-rays have also a small divergence, so a spatial separation scheme is suitable for this experiment. A good separation of the slice from the core is possible with a simple slit. The results with a 0.5 x 0.5 mm^2 slit set at 15m from the centre of the straight section are shown in Fig.3, for 7keV photons.

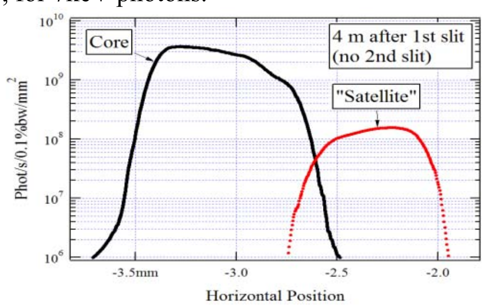

Figure 3: Intensity and separation of the core and the slice

One can see the clear separation between the slice (electrons with –14 < ΔE (MeV) < -7) and the beam core. The expected flux on the sample after a Ge111 double crystal monochromator is ~ 10^7 photons with a spectral resolution of 3300 and a signal/noise > 100.

TEMPO beamline

In the medium straight section where HU40 + HU80 will be installed, the electron beam size is rather small and the divergence is large. Besides, because of lower photon energy of the radiation used at this beamline, the contribution of diffraction is more valuable, compared to the hard X-rays case. Simulation has shown a mixed angular-spatial separation to be a better choice for this beamline. In this separation scheme, a slit and a focusing mirror are placed at a transverse position corresponding to one of the satellites (see Figs. 4, 5). Because of the presence of angular dispersion, the central cone of the core emission goes mainly out of the slit. This minimises contribution of parasitic scattering from the surface of the mirror in the image plane (see Figs. 4, 6).

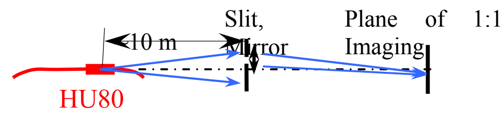

Figure 4: Mixed angular-spatial separation scheme.

The results with a 2 x 1 mm^2 slit set at 10m from the centre of the undulator HU80 are shown in Figs. 5. and 6., for 415eV photons with linear horizontal polarization.The expected flux on the sample is ~ $3x10^6$ photons, with a spectral resolution of around 1500 and signal/noise ~ 10.

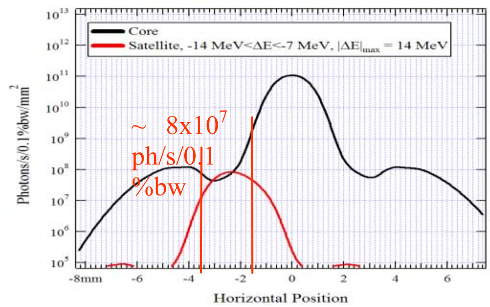

Figure 5: Intensity and separation of the core and the slice emissions for TEMPO experiment, before mirror.

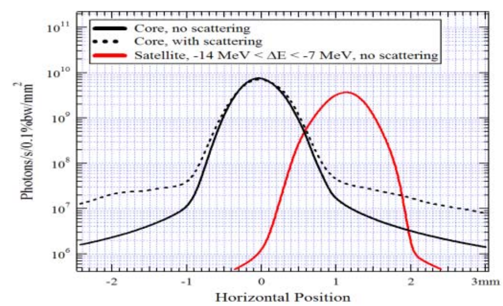

Figure 6: Intensity in the plane of 1:1 imaging. The scattering from mirror surface was simulated by a random phase error, assuming average surface roughness 2.5 Å, slope error 1.5μrad, incidence angle ~1°.

CONCLUSION

Generating femtosecond pulses of both hard and soft X-rays appears to be feasible with a good separation from the main beam and without modification of the storage ring except laser beam injection. Some tracking calculations are being performed in order to estimate the perturbed equilibrium of the sliced bunch due to the laser heating.

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