SPOTLIGHT ON

Towards the generation of femtosecond pulses at SOLEIL*

In a 3rd generation light source, the photon pulse length, in usual operation, allows dynamic phenomena to be studied on the scale of a few tens of picoseconds. However, thanks to a new technique called "slicing", it is becoming possible to produce sub-picosecond pulses short enough to probe ultra-fast dynamic structures.

SOLEIL is a 3rd generation synchrotron light source producing photon beams of very high brilliance, from infrared (IR) to hard X-rays. This radiation is emitted in very short pulses which duration is determined by that of the electron bunches circulating in the storage ring. For reasons intrinsic to the dynamics of electrons in storage rings, it is very difficult, under normal operating conditions, to obtain electron bunches with temporal widths below 30 picoseconds (ps = 10^{-12} sec) FWHM (1). Although the corresponding photon pulse durations, can be used to study a large number of dynamic phenomena, they are still too long to probe ultra-fast dynamic structures such as chemical reactions, phase transitions, rapid structural changes in crystals and other intra-atomic phenomena that occur on the 100 femtosecond scale (fs = 10^{-15} sec). Unlike the 3rd generation sources, the 4th generation ones, such as free-electron lasers based on linear accelerators, are capable of producing fs pulses. However, a recent technique called "slicing" enables to generate sub-picosecond pulses on storage rings.

The principle of the Slicing

A powerful and ultra short laser pulse (~50 fs - FWHM) co-propagates with an electron bunch (30 ps of duration) oscillating in the periodic magnetic field of a wiggler (called "modulator") (Figure 1). The electrons that are affected by the electromagnetic field of the laser change energy, since inside the wiggler their velocity acquires a transverse component parallel to the laser's electric field: some electrons gain and others lose energy. This concern only the electrons which are entering the wiggler at the same time as the laser pulse (in the 50 fs «slice»).

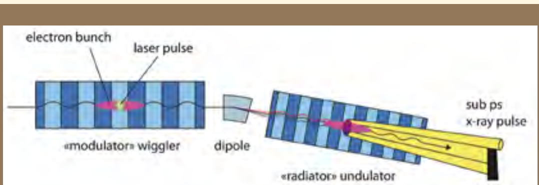

Figure 1: Sketch showing the principle of bunch slicing to generate femtosecond pulses of synchrotron radiation. From S. Khan, EPAC 2002.

The laser-electron interaction is maximum when the central wavelength of the spontaneous emission from an electron passing the wiggler λ_{rs} satisfies the following resonance condition:

$$\lambda_{rs} = \lambda_L = \frac{\lambda_w}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

where λ_L is the laser wavelength, γ is the Lorentz factor, λ_w is the wiggler period and K its deflection parameter.

When this electron bunch then passes through a dispersive magnetic field (bending magnet) or a zone where the dispersion function is non-zero, the energy modulation generated inside the wiggler translates itself into a spatial or angular separation: the sliced electrons and those of the core bunch not having undergone the laser action have different trajectories. Thus one can spatially separate the radiation produced by these different electrons in a «radiator» that can be a bending magnet or an undulator (Figure 1).
This technique, which has been validated experimentally for the first time at ALS (Berkeley, USA), is currently operated on sources such as BESSYII (Germany), SLS (Switzerland), the new ALS project and on UVSOR (Japan). However, as the laser-electron interaction involves only a small part of the electron beam, the photon flux coming from the slice is consequently much lower than the one produced by the whole electron beam. The values reported from the experiments cited above are around 10^5 photons/s/0.1% b.w(2) for pulse durations between 150 and 200 fs FWHM.
The SOLEIL Femto-Slicing project differs from the projects cited above by at least three major points of view:
• several beamlines (instead of a single one) will be able to use these ultrashort pulses simultaneously. CRISTAL (4 to 30 keV) and TEMPO (50 eV to 1.5 keV) will be the first two beamlines. They are respectively interested in sub-picosecond diffraction and time-resolved photoelectron spectroscopy. Later, the DEIMOS and GALAXIES beamlines would also benefit from these ultra short pulses. Thus fs pulses will be produced at SOLEIL covering the soft and hard X-rays energy range.
• the geometric separation between the slice and the core is generated without using any extra magnetic element. The scheme takes advantage from the linear optics of the ring that has a natural non-zero horizontal dispersion in all straight sections.
• the radiation emitted by the modulator will be routinely and independently used as a source for a dedicated beamline, the PUMA beamline (for the study of ancient materials).

The modulator

The magnetic and geometric parameters for the choice of the wiggler (modulator) must take into account some

Breaking news

*** This ambitious project is not being funded by SOLEIL at present, the Council gathered on March 2, 2011, having asked that outside funding be found to carry it out.**

constraints. The wiggler must emit radiation at the same wavelength as the laser (800 nm), the total radiated power must be below the limit set by the front-end of the beamline and the performance of the ring, in terms of emittance and beam lifetime, must be preserved. In addition, the wiggler must yield a high photon flux up to 50 keV to satisfy the PUMA beamline specifications. The magnetic studies, in one hand, and beam dynamics, on the other, have converged on to a wiggler with 20 magnetic periods of 164 mm, a length of 3.28 m and a maximum magnetic field of 1.63 T. The power emitted is 20 kW.

Figure 2: Diagram showing the location of the Femto-Slicing laser hutch, of the wiggler modulator, of the TEMPO and CRISTAL beamlines and of the HHG and PLEIADES experimental hutches.

The laser

The laser must be able to deliver ultra short pulses and an energy output large enough to ensure an effective separation between the slice and the core. Moreover, since the frequency of the electron bunches is very high (352 MHz) and the expected flux of fs pulses is rather low, it is important that the repetition frequency of the laser is as high as possible. Table 1 summarizes the main specifications of the selected laser system.

The Femto-slicing laser system hutch will be located in the inner service area of the synchrotron. The stability criteria of the laser required the replacement of the existing 20 cm thin slab which rested directly on a raft, unlike the storage ring tunnel that is resting on piles. Part of the existing slab was cut, removed and replaced by a thicker and more stable slab. The operation took place during the machine shut down of January 2011.

Table 1: Main characteristics of the laser system at SOLEIL

Central wavelength (nm)	800 Titanium :Sapphire
Minimum pulse duration (FWHM) (fs)	30
Output energy 800nm (mJ)	5
Repetition frequency (kHz)	10

Transport of the laser beam

The laser beam will be propagated under vacuum from the exit of the hutch to its injection point into the wiggler. It must therefore cross the inner radiation shielding wall of the storage ring and a dedicated shield of the penetration is of course foreseen. To enable the laser beam entering the ring vacuum, a new bending magnet vacuum chamber is under construction. Studies concerning the transport of the laser beam, its alignment and focusing towards the wiggler are also underway. In addition, the laser beam must be matched temporally, spectrally and spatially to the electron beam in the wiggler. For this, an IR diagnostics beamline will be installed at the 0° output of the wiggler, inside the tunnel.

The laser beam and the synchrotron radiation from the wiggler at 800 nm will be extracted at very low current, using a retractable mirror, and then transported to a diagnostic station to make temporal, spectral and spatial measurements. To measure and optimize in real time the efficiency of the slicing at high current, an indirect method will be used, the analysis of Coherent Synchrotron Radiation (CSR) in the THz range generated from the bending magnets of the ring. The intensity of the CSR is directly related to the efficiency of the energy modulation in the wiggler. The extraction of THz radiation will be carried out at the bending magnet exit of the Machine Diagnostics beamline MSRV (Mirror Synchrotron Radiation in the Visible) which will be optimized for this purpose.

Use of femtosecond radiation

Slicing experiment will be performed with a 10 mA electron bunch, with the storage ring topped up in either single bunch mode, in 8-bunch mode to 90 mA, or in hybrid mode at 390 mA + 10 mA. Performance in terms of photon flux must be calculated accurately including all the contributing factors. However, initial calculations give sample fluxes between 10^6 and 10^7 photons/s/0.1% b.w. The duration of the photon pulse emitted in each of the radiators will be longer than the duration of the laser pulse, due to the effect of slippage (electrons drift with respect to the wavelength of light in the wiggler) and due to the effects of the emittance and energy dispersion of the electron beam during its transport from the modulator to the radiators.

The total duration of the pulse expected at CRISTAL and TEMPO beamlines is given in Table 2, taking into account the different uncorrelated contributions.

Table 2: Total pulse durations (FWHM in fs)

Radiator	Laser	Slippage	Emittance	Energy Dispersion	Total
CRISTAL	50	53	54	52	104
TEMPO	50	53	47	117	145

Synchronization

As the experiments on TEMPO and CRISTAL beamlines will be of «pump-probe» type (stimulation of a sample by a laser beam, prior to analysis by the photon fs beam), this will require synchronization between the stimulating lasers pulses and the slicing laser pulse with an accuracy of a few tens of fs. Given the large distances between the different systems (~ 50 m) this remains one of the major difficulties to overcome. Several options are under consideration.

Other uses for laser slicing

The laser for the slicing has outstanding characteristics in terms of power and repetition rate, making it a very interesting tool for complementary applications when not being used for slicing:

- experiments on the PLEIADES beamline, coupling synchrotron radiation with the laser for spectroscopy experiments in strong fields
- experiments without synchrotron radiation, through generating high order harmonics in gases (HHG) for experiments in dilute phase and for imaging.

The Femto-Slicing project requires development and equipment that are under the responsibility of the Sources & Accelerators and Experiments Divisions. Amor Nadji is the project leader on the Machine side and Jan Luning is the project leader on the Experiments side, responsible for the scientific coordination of the project. They are assisted by Marie-Emmanuelle Couprie and Pascale Prigent, respectively.

1 FWHM: full width at half maximum
2 b.w.: bandwidth

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