SUB-PICOSECOND X-RAY SOURCE FEMTO AT SLS

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Abstract

The FEMTO source at the SLS (Swiss Light Source) employs laser/e-beam slicing to produce sub-picosecond X-ray pulses for time resolved pump/probe experiments. The final design of the source and first commissioning results are presented.

In this paper we focus on the modifications of the SLS storage ring, a complementary paper [1] covers the laser system and experimental aspects.

INTRODUCTION

An electron beam oscillating in the periodic magnetic field of a wiggler may resonantly interact with a laser beam, leading to an energy modulation (positive or negative) of some of the electrons. Based on this mechanism, a source of sub-picosecond X-rays can be built using available short pulse lasers (<100 fs) for modulation of correspondingly thin slices of the relativistic electron beam (some GeV) circulating in a light source storage ring.

The energy modulation has to be sufficiently large (about five times the electron beam's rms energy spread) for transverse (angular or spatial) separation of the modulated slices from the core beam by means of a dispersive element. This requires a rather high laser pulse energy (some mJ) and limits the application to an electron energy of a few GeV.

In a subsequent undulator or bending magnet, the two slices of electrons of opposite energy modulation and the core beam will emit X-rays into different directions, and thus the short radiation pulse from the slices can be extracted while the core beam radiation is blocked.

This so-called "slicing technique" was first demonstrated at a bending magnet at ALS [2] and then implemented at BESSY to generate sub-ps soft X-rays (1–2 keV) of variable polarization in an undulator [3]. The SLS-FEMTO source [4] currently under commissioning at the μXAS beamline of the SLS storage ring (2.4 GeV) will produce X-rays in the range 3–18 keV based on the high harmonic (11^{th}/13^{th}) operation of a short period in-vacuum undulator.

LAYOUT OF SLS-FEMTO

The SLS storage ring is a 12-TBA lattice of 288 m circumference, providing 5 nm·rad natural emittance at an energy of 2.4 GeV and a maximum beam current of 400 mA [5].

The FEMTO installation shown in figure 1 is located in one of the three 11 m long straight sections. It consists of the modulator wiggler, where the laser interacts with the beam, and the radiator undulator, where the sliced beam emits the X-rays. A magnetic chicane is required to translate the energy modulation into transverse separation. Additional vertical focusing is required to reduce the beam height inside the radiator (which is an in-vacuum undulator of 5 mm minimum full gap) and also inside the modulator to maintain the vertical acceptance and therefore the beam lifetime [6].

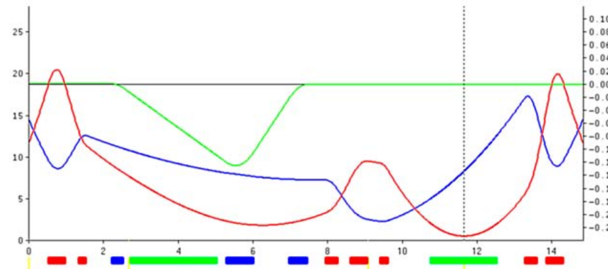

Figure 1: SLS-FEMTO insertion for laser slicing. Line-up: quad doublet, modulator wiggler bracketed by dispersive chicane consisting of three dipoles, quad triplet, radiator undulator, quad doublet. β_x blue, β_y red (left scale, in meter), dispersion green (right scale, in meter).

DESIGN STRATEGY

The FEMTO installation had to be transparent to the storage ring. In particular, the breaking of ring periodicity must not spoil the carefully balanced sextupole pattern [7] in order to maintain the dynamic acceptances. Thus the optical functions at all sextupoles and the horizontal phase advance must not be changed. Increase of the vertical phase advance is inevitable to provide the required focus inside the radiator, however, if the increase amounts to exactly $\Delta\mu_y = \pi$ (or $\Delta\nu_y = 0.5$ in tune) the sextupole pattern is not disturbed, since all resonances driven by regular sextupoles contain only even multiples of ν_y. This kind of tune matching referred to as "pi-trick" was previously applied at the ALS [2].

At least six quadrupoles are needed to fulfill the constraints on the periodic continuation of the ring optics (β_x, α_x, β_y, α_y) and on the betatron phase advances ($\Delta\mu_x = 0$, $\Delta\mu_y = \pi$). Dispersion matching is not required since the chicane represents a closed dispersion bump. A seventh quadrupole allows to provide the vertical focus ($\alpha_y = 0$) in the center of the radiator in order to maximize the vertical acceptance and to protect the undulator from radiation damage.

In principle, the chicane may bracket either the modulator or the radiator. Bracketing the modulator provides an angle or a displacement of its intense photon beam (12 kW !) in order to guide it away and block it. This also facilitates guiding the laser beam to overlap with the electron beam. Furthermore, having the radiator in a dispersion free region avoids dispersive beam widening in the radiator which would aggravate separation of the slice X-rays from the core beam. To have the modulator instead of the radiator inside the chicane is therefore the preferable solution. The drawback however is an increase of the electron beam emittance.

The chicane could be vertical or horizontal. The type of separation could be either spatial, followed by a point-to-point imaging X-ray optics, or angular and large enough for the beams to separate while propagating to the experimental station.

First designs envisaged a vertical spatial separation [4], to exploit the small vertical beam size for using a rather small chicane, however no feasible solution could be found for blocking the modulator beam. Furthermore there have been concerns that imperfections of the X-ray optical elements would increase the background X-rays from the core beam contributing to the sliced beam signal.

A vertical angular separation of sufficient magnitude to separate the sliced beam's X-rays from the tails of the core beam was also not feasible due to the increase of the vertical emittance.

Therefore a large angular horizontal sepeartion was chosen, using a rather large chicane. For an optics layout as shown in Figure 1, the angular separation of the sliced beam from the core beam at the radiator centre approximately scales as [8]

$$\pm x'_u \;\propto\; \phi_1 \sqrt{\beta_{xw}}\,\frac{\Delta E}{E}, \tag{1}$$

where ϕ_1 is the deflection angle of the first chicane magnet, and $\Delta E/E$ the energy modulation. Indices w and u refer to modulator wiggler and radiator undulator.

The number of wiggler periods N_w should match the number of optical cycles which is given by the ratio of laser pulse length to wavelength λ_L.

The resonance condition results in an approximate constraint

$$\lambda_w^3\,\hat{B}^2 \;\propto\; \lambda_L, \tag{2}$$

where λ_w and $\hat{B}$ are period length and peak field of the wiggler.

The increase of the storage ring emittance due to the modulator wiggler scales as

$$\Delta\varepsilon_w \;\propto\; N_w \lambda_w \phi_1^2 \beta_{xw} \hat{B}^3. \tag{3}$$

The scaling relations 1 and 3 reveal a close correlation between beam separation and emittance increase and call for a laser providing the largest energy modulation (i.e. high pulse energy) at the lowest wavelength. Based on these contradicting requirements the best available laser system has to be selected. Relations 2 and 3 exhibit a $\Delta\varepsilon_w \propto \hat{B}^{7/3}$ scaling if the resonance condition is fulfilled. The emittance increase thus is minimized by reducing the modulator's peak field while increasing the period length, and with it the total length $N_w\lambda_w$, as much as the available space permits.

SLS-FEMTO PARAMETERS

The laser system generating 50 fs (FWHM) pulses of 2.5 (max. 5.2 mJ) at a wavelength of $\lambda_L = 805$ nm provides an energy modulation of $\pm(13\ldots 20)$ MeV ($\Delta E/E > 5.4\cdot 10^{-3} \approx 6\sigma_{\Delta E/E}$ at 2.4 GeV). The modulator wiggler is a hybrid device with $N_w = 17$ periods, a period length of $\lambda_w = 138$ mm and a peak field of $\hat{B} = 2.1$ T. The effective field $B_{\rm eff}$ amounts to 1.98 T since the field shape $B(s)$ is between sinusoidal and rectangular. The radiator is of same type like other in-vacuum undulators at SLS ($B_{\rm eff} = 0.94$ T, gap 5 mm, $\lambda_u = 19$ mm, $N_u = 96$). The chicane magnet deflection angles amount to $2.36\,°$, $-7.42°$, $5.06°$.

With a peak current of almost 100 A in the bunches circulating in the storage ring, the expected sliced flux at 8 keV at the sample is 10^4 ph/s/0.01% BW (Si crystal monochromator) and 10^6 ph/s/1.5% BW (multilayer monochromator). The spatial and angular separation of the slice beams at the radiator center amounts to $x_u \approx \pm 2$ mm, $x'_u \approx \pm 0.5$ mrad, thus at the slit system installed at the μXAS beamline in 15 m distance from the radiator, they will be separated from the core beam by $\approx \pm 10$ mm. Spectrum calculations including all possible background contributions (X-rays from the up- and downstream bending magnets, from the chicane dipole magnets and from the modulator) show that X-rays emitted from the slice beams with energy modulation $\Delta E/E \geq 0.5\%$ can be well separated by the slit system.

STORAGE RING MODIFICATION

The rather large deflection angles of the chicane dipoles to generate sufficient dispersion for separation, affects the parameters of the storage ring: The equilibrium emittance of 5.0 nm·rad is raised to 5.5 nm·rad by the chicane alone and further to 7.2 nm·rad when closing the modulator wiggler. The machine circumference is increased by 7.3 mm, corresponding to a detuning of -12.7 kHz of the 500 MHz RF. The working point ν_x/ν_y is shifted from 20.42/8.19 to 20.42/8.**6**9 due to the "pi-trick".

The Fast Orbit Feedback (FOFB) [9] had to be extended from 72 to 73 BPMs and correctors to cover the additional vertical phase advance and define the beam position in the radiator. Additional BPMs and correctors were installed at the modulator and undulator to apply feed forward corrections when moving the gaps. By these means, the photon beam from the undulator can be stabilized to 0.3 μm and 0.2 μrad. For the modulator, in addition a local tune feed forward scheme using the quadrupoles in the FEMTO straight is employed, since closing the gap shifts the vertical tune by $\Delta\nu_y = +0.02$.

Coherent synchrotron radiation (CSR) in the THz spectral range, measured with an InSb-bolometer, is used as online diagnostics to optimize the interaction between laser and electron beam [10]. The CSR is due to longitudinal charge density modulation on the $100\ \mu$m length scale and is extracted at the first bending magnet of the arc following the FEMTO-insertion, where the sliced beams of opposite energy modulation have acquired a temporal separation of ± 200 fs due to energy dependant pathlength differences.

OPERATIONAL EXPERIENCE

Restart of the modified SLS storage ring for normal user operation and early FEMTO commissioning took place in April/May 2006. The shift of the radio frequency by -12.7 kHz required careful retuning of the cavity higher order modes which had been shifted correspondingly. The peak bending magnet current of the booster synchrotron [11] operating at the same RF as the ring had to be lowered, because due to the lower frequency the beam circulates on an orbit correponding to a 0.5% higher energy in the booster. The linac [12] could handle the frequency shift of -77 KHz at 3 GHz without major problems.

Closing the modulator did not affect the injection efficiency and beam lifetime, indicating that the dynamic multipoles from the horizontal field roll-off do not significantly affect the dynamic aperture of the storage ring.

FEMTO operation started at very low current (1 mA) to allow passage of the wiggler light out to a diagnostics station in order to optimize the the overlap of the laser and the electron beam. Successful overlap is demonstrated by the THz-signal of CSR as shown in Figure 2.

Once the THz-signal was detected, the beam current could be increased to nominal values (up to 400 mA) after blocking the high intensity modulator beam by a water-cooled absorber.

The usual filling pattern of the SLS is a total current of 350 mA in a train of 390 bunches in 480 available buckets, leaving a gap of 180 ns length. A single bunch of 5 mA, 20 ns ahead of the train, is used for the laser slicing. Streak camera measurements had shown a peak current of about 80 A even with the 3^{rd} harmonic cavities (for Landau damping of multi-bunch instabilities and lifetime increase by bunch lengthening) in operation. With orbit and tune feed forward on the wiggler gap and with the global fast orbit feedback (100 Hz) in operation, ongoing FEMTO-commissioning affects other synchrotron radiation users only little by the reduced brightness due to the increase of emittance.

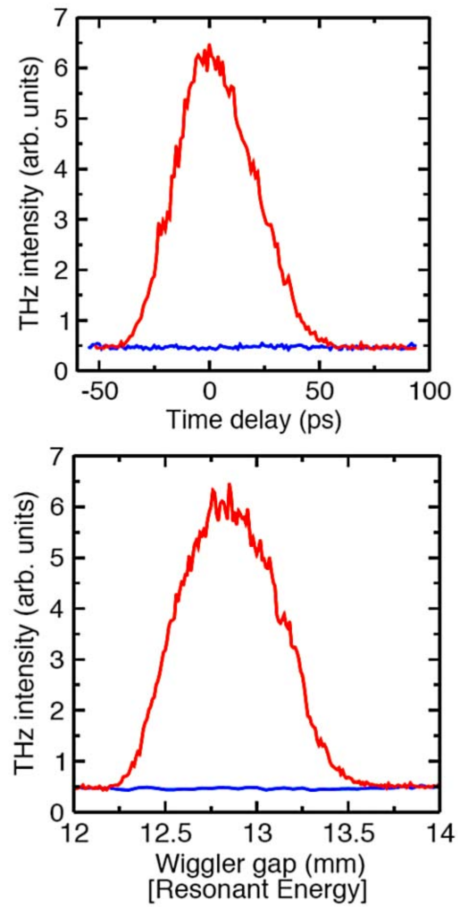

Figure 2: Measured THz-signal as function of laser pulse delay (top) and resonant energy (wiggler gap, bottom) for laser on (red) and off (blue).

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