THZ DIAGNOSTIC FOR THE FEMTOSECOND BUNCH SLICING PROJECT AT THE SWISS LIGHT SOURCE

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Abstract

Interaction of electron bunches with a femtosecond Ti:Sa laser beam along a modulator wiggler in the Swiss Light Source (SLS) storage ring results in an energy modulation of the electron beam on the length scale of the laser pulse. While high energy photon pulses (3 - 18 keV, ~ 100 fs long) are produced by an in-vacuum undulator (radiator) and used for time resolved experiments within the SLS femtosecond bunch slicing project, coherent synchrotron radiation (CSR) emitted by the adjacent bending magnet in the THz-regime is used for longitudinal slicing diagnostics and monitoring of slicing efficiency. This paper describes the simulation and layout of the THz-diagnostic beamline and presents first time and spectrally resolved measurements with the longitudinal slicing diagnostics, which has been set-up for the SLS "femto-slicing" project.

INTRODUCTION

The beam slicing method [1] allows the generation of sub-picosecond X-ray pulses in storage rings by resonant interaction of the electron bunches with a laser pulse in the periodic field of a wiggler magnet (modulator). When passing an undulator (radiator), the energy modulated electrons emit X-rays with the same (sub-picosecond) time profile as the laser pulses. A combination of transverse and angular displacement of the off-energy electrons from the core beam along the radiator leads to a subsequent separation of the "femto-slices" and allows the use of the short X-ray pulses through spatial filtering of the core beam by introduction of an aperture in the image plane of the beamline. The beam slicing method has been experimentally demonstrated at the Advanced Light Source (ALS) with bending magnet radiation [2]. A first undulator-based beamline has been successfully commissioned at the BESSY II storage ring, producing soft X-ray pulses between 0.4 and 1.4 keV [3]. In case of the SLS femtosecond bunch slicing project, the electron bunches in the storage ring are energy modulated by a Ti:Sa laser ($\tau \approx 50$ fs FWHM, $P_{pulse} \leq 5$ mJ, $\nu_{rep} = 1$ kHz), resulting in the generation of hard X-ray pulses in the range between 3 and 18 keV using the higher harmonics of an in-vacuum undulator with a period length of $\lambda_U = 19$ mm. An elaborated description of the SLS "femto-slicing" project and the related optics modifications in the storage ring can be found in [4, 5].

THZ SLICING DIAGNOSTICS

Since the radiation intensity from the sliced beam is low compared to the "background" from the core beam (in the order of 10^{-4}), a direct characterization of the slicing efficiency with the X-ray radiation is difficult and can be rather tedious. Particle tracking of the sliced bunch through the storage ring optics indicates however, that the energy modulated electrons form a longitudinal density modulation on the length scale of the laser pulse width [6], leading to the emission of coherent synchrotron radiation (CSR) at the bending magnets downstream of the slicing experiment. Although the number of sliced particles contain only a fraction of the electrons in the core bunch, the quadratic dependence of the coherent emission process dominates the spectral power density of the synchrotron radiation (SR) at wavelengths, which are comparable to and larger than the length scale of the density modulation. Eq. 1 describes this well known effect [7], which is also widely used to measure sub-picosecond electron bunches in linear accelerators [see e.g.: 8, 9, 10].

$$P_{coh}(\omega) \approx \left(N_0 \frac{\tau_L}{\tau_0} \right)^2 p_{inc}(\omega) \left| F(\omega) \right|^2 \qquad (1)$$

In case of the SLS "femto-slicing" experiment, the Ti:Sa laser pulse width is $\tau_L \approx 50$ fs FWHM, while the electron bunch length amounts to $\tau_0 \approx 50$ ps FWHM for a 5 nC bunch charge ($N_0 \approx 3 \cdot 10^{10}$ electrons). The so called bunch form factor $F(\omega)$ is given by the Fourier transform of the longitudinal bunch distribution [11] and accounts for the enhanced SR intensity in the THz regime. The CSR emission generated by the femto slice dominates the incoherent background of the core bunch by 3 - 4 orders of magnitude in the THz range. A simulation of the longitudinal bunch density modulation and the corresponding power spectral density of the SR are shown in Fig. 1 for the 05BE bending magnet of the SLS storage ring, located directly behind the 05L femto-straight.

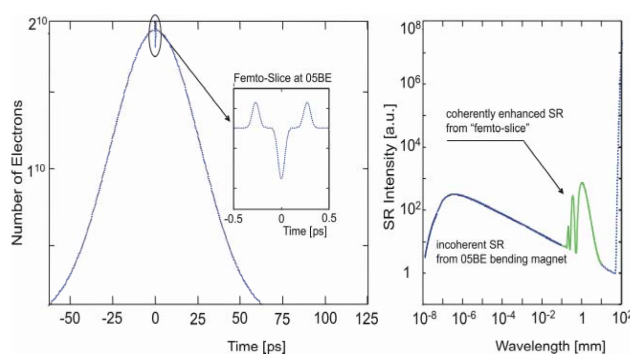

Figure 1: Left: Simulation of the longitudinal distribution of the sliced electron bunch. Particles which gained or lost energy during the laser interaction are piling up in the two humps around the centre dip. Right: SR spectrum of the "femto-sliced" bunch at the 05BE bending magnet showing a coherent enhancement in the THz range.

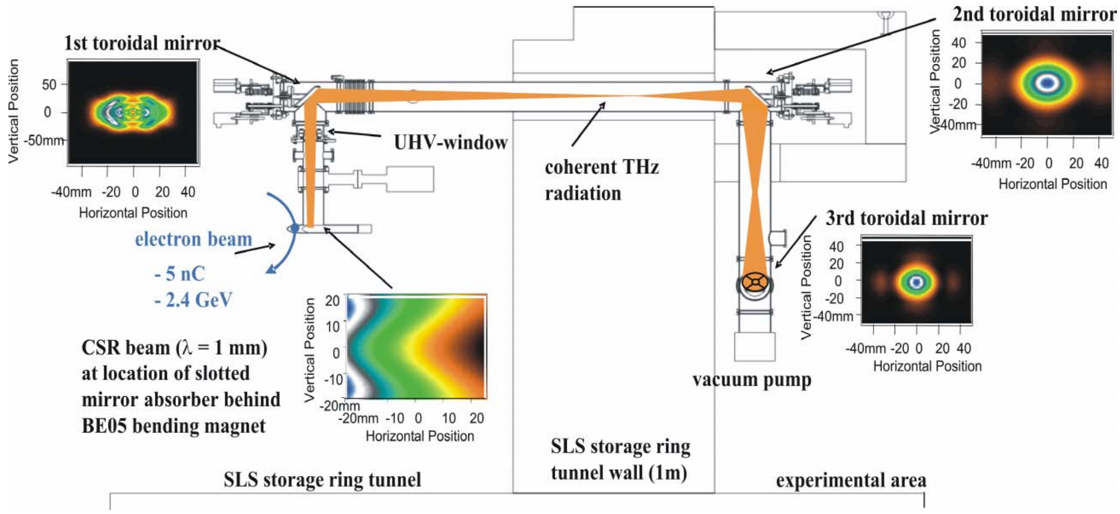

Figure 2: THz transfer line for the SLS "femto-slicing" experiment. The transverse distribution of the synchrotron radiation at λ = 1 mm wavelength as simulated with the SRW code is shown as inlets at the mirror positions. The transfer optics is indicated in orange.

THz Transfer Line

An optical transfer line for visible and long wavelength (THz) SR has been installed between the 05BE bending magnet and the SLS experimental area to allow for longitudinal slicing diagnostics for the "femto-project". The SR is coupled out of the bending magnet and vertically reflected by a water-cooled, slotted Cu absorber, which has been machined to optical quality. A CF63 crystalline quartz window, which is transparent in the visible and for wavelengths $\geq 100\,\mu$m, separates the transfer line from the UHV system of the storage ring. The transfer line is evacuated to pressures of $\leq 10^{-2}$ mbar to avoid water absorption and terminated by a 75 µm thick mylar foil. The optical transfer function has been calculated with the SRW code [12] aiming for lowest possible diffraction losses at long wavelengths. The beam tube diameter has been selected to 150 mm and three toroidal mirrors of 135 mm diameter refocus the SR onto an optical table in the SLS experimental area. The inlets in Fig. 2 show the transverse SR beam distributions at the location of the toroids as simulated by SRW. Diffraction losses through the transfer line are marginal even at wavelengths above 1 mm. Still, absorption in the crystalline quartz UHV-window and the mylar foil at the end of the transfer line have to be regarded, when analyzing the power spectral densities in the CSR (THz) regime.

EXPERIMENTAL SET-UP OF SLICING DIAGNOSTICS AND MEASUREMENTS

Presently, a Martin Puplett interferometer (MPI) has been set-up for longitudinal slicing diagnostics on the optical table in the SLS experimental area (see Fig. 3). The collimated CSR pulse from the THz transfer line is send through the MPI onto an InSb hot electron bolometer [13], which is sensitive in a range from 10 cm^{-1} to about 60 cm^{-1} (3dB cut-off at 35 cm^{-1}).

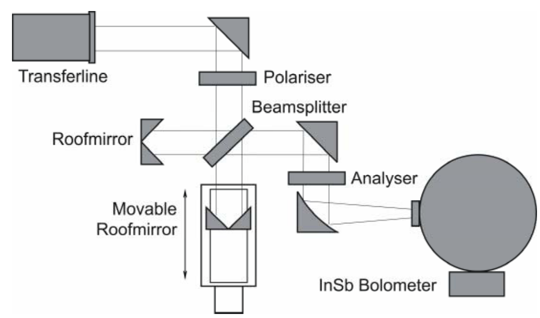

Figure 3: Set-up of the longitudinal slicing diagnostics.

The determination and online monitoring of the slicing efficiency as a function of modulator gap and relative synchronization (overlap) between laser and electron pulse can be accomplished by using the integrated THz signal with one arm of the MPI detuned (see Fig. 4).

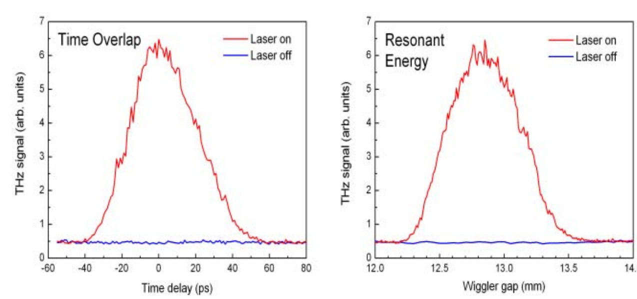

Figure 4: Optimizing of overlap between laser pulse and electron bunch (left) and modulator (wiggler) gap (right) using the integrated THz signal from the InSb bolometer.

Although, the sensitivity range of the InSb detector is not well matched to the CSR emission spectrum of the shortest ("zero" turn) "femto-slice", which can be reaching up to about 200 cm^{-1}, its bandwidth (1.25 MHz) is high enough to resolve single turns and thus the evolution of the "femto-slice" in the storage ring (1 µs revolution time). Fig. 5 shows the InSb bolometer signal recorded for several turns with (red curve) and without (black curve) a "thick grid" high-pass filter with cut-on at 10 cm^{-1}.

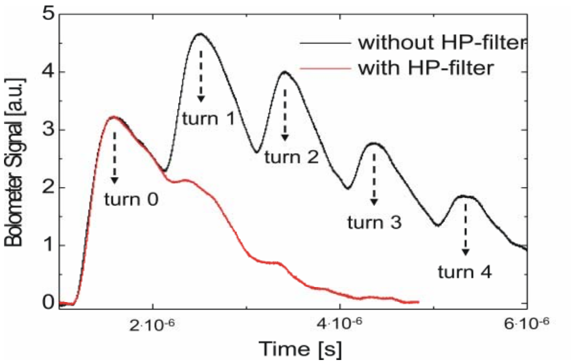

Figure 5: Turn-by-turn THz signal from the InSb bolometer with (red curve) and without (black curve) a "thick grid" high-pass filter (cut-on at 10 cm^{-1}).

The filter suppresses the low frequency components (low wavenumbers resp. long wavelengths) of the CSR spectrum, illustrating that the high frequency components are most dominant for the shortest slicing pulse directly after laser interaction. The subsequent stretching of the sliced pulses during the following turns is due to the non-isochronicity of the storage ring lattice The "dilution time" of the sliced electrons into the core bunch depends on the initial momentum transfer from the slicing laser and the momentum compaction factor of the storage ring. Since the sliced particles have a higher off-energy momentum than the energy spread of the electrons from the core bunch, the humps in the longitudinal bunch distribution (see Fig. 1) smooth out much faster than the stretching and the filling of the centre dip by the core beam electrons occurs. Both effects can be observed qualitatively in the CSR spectrum, which has been recorded with the MPI for the first five turns following the bunch slicing event.

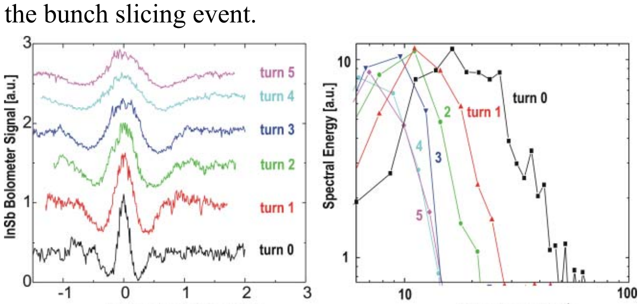

Figure 6: Interferograms (left side) and spectra (right side) taken with the MPI for the first 5 turns after the slicing event (turn 0). Note, that the spectral width of the first turn is restricted by the InSb bolometer response function (3dB cut-off at 35 cm^{-1}).

The rather low CSR spectral intensity at wavenumbers below 5 cm^{-1} is caused by destructive interference of the two humps in the longitudinal electron bunch distribution (see inlet in Fig. 1). The relative increase of the CSR intensity in this spectral range during the following turns is an indication of the fast stretching process of the humps in the longitudinal bunch distribution and the corresponding "dilution" of the off-energy sliced particles into the core bunch [14]. The decreasing spectral width on the other hand corresponds to the stretching and filling of the central hole in the longitudinal electron bunch distribution.

CONCLUSION AND OUTLOOK

The THz diagnostics beamline provides all useful and necessary information to optimize the laser and modulator parameters and to operate the bunch slicing experiment at the SLS storage ring. Moreover, spectrally resolved CSR data, which have been gathered with a MPI in the THz-regime, provides a first understanding of the slicing process and the longitudinal dynamics of the sliced bunches in the SLS storage ring. After further characterization of the THz transfer line, a spatial electro-optical autocorrelation monitor with single-shot capability [10] will be implemented at the slicing source.

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