

COMMISSIONING RESULTS FROM THE BESSY II FEMTOSLICING SOURCE *

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Abstract

At the BESSY II storage ring, a femtosecond x-ray source with tunable polarization and excellent signal-to-background ratio has been constructed and commissioned in 2004. This source is based on laser-induced energy modulation ("femtosing") and subsequent angular separation of the short-pulse x-rays emitted by an elliptical undulator.

INTRODUCTION

Probing atomic motion and magnetic phenomena on a sub-picosecond time scale with x-rays offers exciting scientific opportunities [1]. At the BESSY II 1.7-GeV storage ring, x-ray pulses of 100 fs (fwhm) duration with linear and circular polarization are produced by "femtosing", a technique proposed [2] and experimentally demonstrated [3] at the Advanced Light Source (ALS) in Berkeley. The principle is sketched in Fig. 1: A femtosecond laser pulse copropagates with an electron bunch in an undulator (the "modulator"), causing an oscillatory energy modulation of electrons in the short overlap region. The off-energy electrons are transversely displaced by dispersive elements in order to extract the short component of radiation emitted in a subsequent device (the "radiator"). Following the pioneering experiment at the ALS, the BESSY installation is the second femtoslicing facility worldwide and the first to use an undulator as radiator, which is placed in the same straight section as the modulator to minimize path length differences between them. The angular separation scheme [4] allows to extract the short radiation component without imaging the source, thus avoiding diffuse scattering background from mirrors.

Figure 2 shows a part of the BESSY II floorplan, where the features related to femtoslicing are highlighted. A Ti:sapphire laser system [5] provides 800-nm pulses up to 2.8 mJ at a repetition rate of 1 kHz (alternatively 1.8 mJ at 2 kHz) with a pulse duration of ≥ 30 fs (fwhm). The facility was completed in April 2004 [6] after installing three additional bend magnets, the modulator U139 (a planar undulator with 10 periods of 139 mm length), the radiator UE56 (an elliptical undulator with 30 periods of 56 mm length) and replacing 9 m of storage ring vacuum chambers. Two x-ray beamlines were relocated, a third beamline added, and a beamline for THz radiation [7] was constructed.

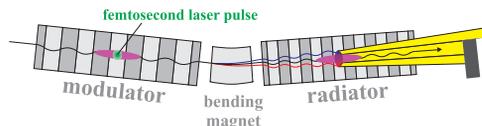


Figure 1: The principle of short-pulse generation by laser-induced energy modulation of electrons with subsequent angular separation.

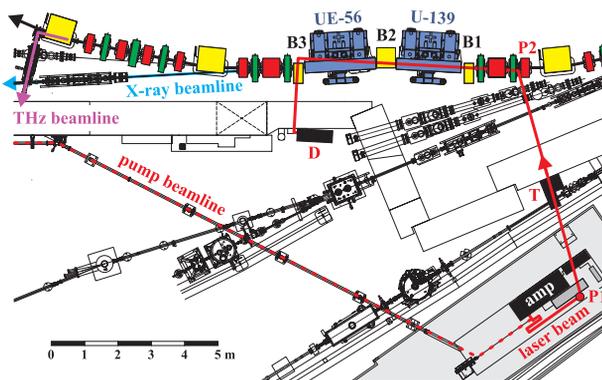


Figure 2: Part of the BESSY II storage ring with dipole (yellow), quadrupole (red) and sextupole magnets (green). An orbit bump (B1-B2-B3) encloses the modulator (U139) and radiator (UE56). A hutch (gray) contains a Ti:sapphire oscillator and amplifier (amp). Laser pulses (solid red line) are focused by a telescope (T) and terminate at a diagnostics station (D), pump pulses (dotted red line) are directed to the experiment at the x-ray beamline (blue). The energy modulation is monitored by THz radiation (magenta).

DIAGNOSTICS AND CONTROL

With the electron beam position fixed and its temporal structure given by the rf system, laser-electron overlap is established by moving the laser beam transversely and synchronizing the Ti:sapphire oscillator with the rf master clock. The laser passes an upward periscope (P1 in Fig. 2), a 2-lens telescope (T), and a downward periscope (P2). The upper mirrors of both periscopes are under computer control, where minimum backlash ($< 10 \mu\text{rad}$) is important to reproduce the settings and to apply automated optimization routines. Laser and U139 radiation are both directed to a diagnostics station (D in Fig. 2) by water-cooled copper mirrors. With the first mirror at 8° incidence to distribute the power load over a large surface, the overlap can be monitored during normal user operation at full beam current.

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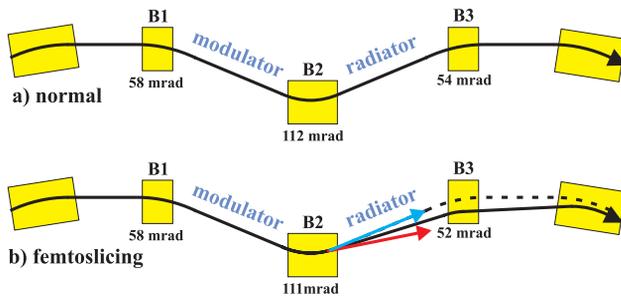


Figure 3: Sketch of the electron orbit for (a) normal operation and for (b) femtoslicing, where low-energy electrons (blue arrow) are aligned with the radiator axis and radiation from the bend magnets B2 and B3 misses the beamline.

Using two CCD cameras with telescopes of different focal length and an avalanche photodiode (APD) connected to a 2-GHz oscilloscope, the transverse overlap is established within $20\ \mu\text{m}$ and the temporal overlap within 100 ps. The signature of energy modulation, a far-IR (THz) signal at the laser repetition frequency, is typically found within minutes and can be optimized by further longitudinal and transverse adjustment. Coherent THz radiation is caused by a short dip and two side bumps in the longitudinal electron profile due to energy-dependent path length differences between modulator and THz beamline. It is detected by a He-cooled InSb bolometer and monitored by a FFT analyzer or by a lock-in amplifier tuned to a harmonic of the laser repetition frequency [7, 8].

In order to inspect position, size and divergence of the laser waist, the beam can be sent back to the laser hutch after passing the telescope. The laser pulse duration is measured using a SPIDER [9].

The transverse displacement of energy-modulated electrons is detectable in the pinhole image of a bend magnet source. Quantitatively, it is determined by moving a scraper towards the beam while recording the beam lifetime with a calibrated photodiode [10].

Once the energy modulation is sufficient to detect short-pulse photons in the x-ray beamline, their signal can be used to further optimize the relevant parameters: magnetic gap of the modulator, laser beam position and angle, position of the focus, laser power and longitudinal chirp.

COMMISSIONING EXPERIENCE

Commissioning of the facility proceeded in several steps. At first, the storage ring with the new permanent orbit bump was re-commissioned, and the transmission of the laser beam through the vacuum vessel was ensured. Next, the spatial and temporal overlap of laser pulses and electron bunches was established and optimized using the THz signal, where the first laser-induced energy modulation was observed in April 2004. The modulation amplitude was determined in scraper experiments. During summer 2004, radiation in the x-ray beamline was studied first by time-

integrated measurements using a GaAs diode, then by time-resolved measurements with an APD, where the amplified signal was synchronized with the laser pulses and accumulated by a digital oscilloscope. For these measurements, the electron orbit has to be modified such that low-energy electrons are aligned with the radiator axis and the x-ray beamline (see Fig. 3). This was done either during user operation with a single bunch (typically 4 mA) added to the 250 mA multibunch pattern, or in dedicated shifts with one or five bunches on top of a 10-20 mA multibunch fill. In view of x-ray magnetic circular dichroism (XMCD) studies, the 3rd harmonic of the radiator and the plane-grating monochromator [11] were tuned to the vicinity of the $L_{2,3}$ edges of Fe (721 and 708 eV) or Ni (871 and 853 eV). The APPLE-type UE56 [12] allows to select the polarization state by a longitudinal shift of the magnetic half-structure, which was either 13 mm or 25 mm (for elliptical polarization with a horizontal or vertical linear contribution, respectively), or 28 mm (for vertical linear polarization). Finally, short-pulse x-rays passing a magnetized Fe or Ni sample were studied, measuring the absorption spectrum and investigating their polarization state with XMCD.

During several hundred hours of laser-electron interaction, there were few hardware failures. The most serious ones concerned the in-vacuum dielectric mirrors of the periscope P2. After an operation time of the order of 100 h, the lower 1-inch mirror, exposed to $0.02\ \text{J}/\text{cm}^2$ per pulse (peak power $0.5\ \text{TW}/\text{cm}^2$, assuming a Gaussian profile) showed slight ablation and carbon deposits and was replaced by a Ag mirror which no further incident. The upper 2-inch mirror with lower exposure and 1.4 m above the storage ring plane (making radiation effects unlikely) showed similar damage, which occurred once more after replacing it by another dielectric mirror.

RESULTS

The THz signal is the prime diagnostics tool for everyday operation of the femtoslicing source, and is discussed in detail in a separate paper [8].

Examples of scraper experiments, probing the transverse distribution of electrons after laser-induced energy modulation, are given in [6] and [13]. A sufficient modulation amplitude ($\Delta E/E > 0.8\%$) was obtained, but the required laser power was significantly larger than expected from analytical estimates or simulations. This may be due to insufficient overlap, transverse vibrations or temporal jitter, loss of laser power on the way to the modulator, or optical aberrations.

Figure 4 illustrates the angular separation scheme, showing the angular distribution calculated [14] and measured at 708 eV with vertical linear polarization without (solid line) and with energy modulation (dashed line), where the short-pulse component can be extracted by an aperture. As shown in Fig. 5 for two examples, signal and background depend on the angle selected by the setting of bend magnet B2 and fine-tuned by the aperture position.

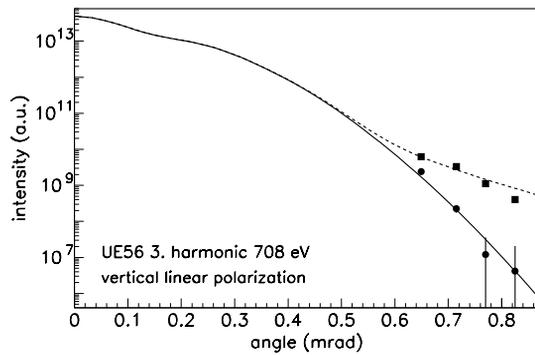


Figure 4: Calculated (lines) and measured (dots) angular distribution of synchrotron radiation at 708 eV with vertical linear polarization with and without energy modulation.

Turn-by-turn observation of the radiation from bunches interacting with the laser (Figure 6, left) reveals a structure consistent with the betatron and synchrotron motion of electrons having lost energy in a dispersive region. After ≥ 1 ms (Figure 6, right), this structure is no longer visible and the signal – still containing small remnants of the interaction – decays exponentially with a time constant of 5 ms. This measurement was performed with 5 bunches interacting in turn with the laser. After 1 ms, the background from the preceding interaction is much smaller than the longitudinal and transverse damping times (8 and 16 ms, respectively) would suggest, because the betatron phase is randomized after $> 10^4$ cycles. This would not be the case for energy modulation in a dispersion-free section, where only synchrotron motion with < 10 cycles/ms would be excited. As a consequence, only one bunch with enhanced charge is used in most experiments, and the radiation from that bunch one turn ahead of the next interaction is measured to quantify the background.

Providing circular polarization for XMCD studies is yet another challenge, since the polarization depends on the angle of photons relative to their respective source electron. For horizontal-elliptical polarization (shifting the UE56 magnetic half-structure by 13 mm), the angular distribution is rather broad. The helicity reverses at 0.6 mrad and will be different for signal and background. For vertical-elliptical polarization (shift 25 mm), the separation task is facilitated by a narrower angular distribution, but the helicity changes sign at 0.2 mrad and the short-pulse component contains contributions of opposite helicity. The resulting degree of polarization depends on the modulation amplitude and must be carefully checked.

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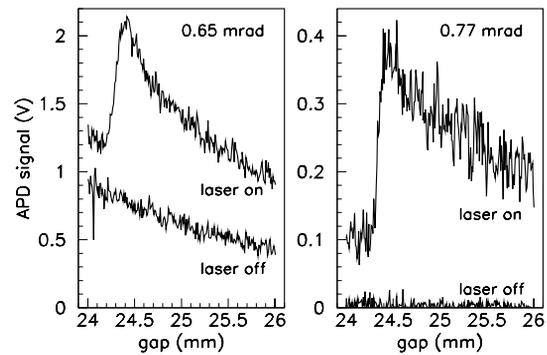


Figure 5: Femtosecond x-ray signal and background (laser off) at 708 eV as function of the UE56 magnetic gap for two observation angles, scanning the 3rd undulator harmonic.

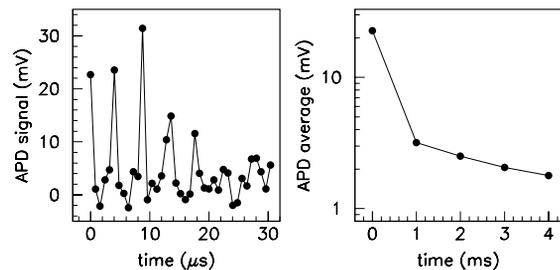


Figure 6: Time-resolved APD signal from successive turns (left) and on the millisecond time scale (right). After 1 ms, the betatron motion is no longer visible and the signal was averaged over several turns.

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