LAYOUT OF A FEMTOSECOND X-RAY SOURCE AT BESSY II *

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Abstract

The generation of femtosecond x-ray pulses with circular polarization is planned at BESSY II. The paper describes the underlying principle (”femtoslicing”), its technical implementation, and the expected output, based on simulations and measurements.

INTRODUCTION

Probing structural changes and magnetic phenomena on a sub-picosecond time scale with x-rays is a new and exciting scientific field, initiated by the advent of femtosecond lasers and techniques to convert ultrashort visible pulses into x-rays. Compared to other approaches such as harmonic generation or plasma sources, the generation of ultrashort synchrotron radiation pulses described below offers a wider range of photon energies, better tunability in energy and polarization, and a larger brightness in the x-ray regime. This technique, now dubbed ”femtoslicing”, was proposed [1] and experimentally demonstrated [2] at the Advanced Light Source in Berkeley. The principle is to modulate the energy of electrons by the field of a femtosecond laser pulse co-propagating with an electron bunch in a wiggler (”modulator”). Off-energy electrons are then transversely displaced using a dispersive magnetic field to extract the short component of radiation emitted in a subsequent undulator (”radiator”).

A user facility to produce x-ray pulses of 50 fs duration with linear and circular polarization is under construction at BESSY II in Berlin. Pilot experiments will concentrate on circular magnetic dichroism to probe element-specific spin and orbital properties of magnetic materials with unprecedented time resolution. Furthermore, the interaction of femtosecond laser pulses and electron bunches will provide a unique opportunity to gain experience in view of BESSY’s soft-x-ray FEL project [3]. The energy-modulation process is the basis of FEL-seeding schemes such as high-gain harmonic generation [4] or sideband seeding [5]. Other hot topics are electron-laser synchronization and femtosecond diagnostics for electrons and photons.

TECHNICAL IMPLEMENTATION

All major hardware components described in this paragraph are underway and will be installed in a shutdown period early in 2004. The layout of the femtosecond facility is based on the following considerations:

Minimum pulse duration: In order to preserve the temporal characteristics of the laser pulse in the electron distribution, the modulator and radiator should be placed in the same straight section. A scheme with two straight sections would not only use more space, but would require to operate the storage ring in a special isochronous mode.

Minimum background: As discussed in a previous paper [6], mirrors to create an image of the source for short-pulse separation may cause intolerably large background due to non-specular reflection. If, on the other hand, the energy-modulated electrons are displaced from the core bunch by a sufficiently large angle such that their respective radiation cones do not overlap, the short pulse can be separated just by an aperture. This angle should be at least 1 mrad which – assuming an energy modulation of 1% of the beam energy – implies a 100 mrad bending magnet between modulator and radiator.

Minimum impact on the storage ring: The previous considerations suggest to place two undulators and a dipole magnet of 100 mrad bending angle in a straight section of 5.4 m length, where the dipole must be part of a closed orbit bump. In the layout shown in figure 1, the bump is formed by three dipoles, all within the straight section. Other schemes involving the adjacent achromats would strongly break the symmetry of the storage ring and would make its circumference incompatible with the synchrotron.

The Laser System

The obvious choice for a laser with pulses of 30-50 fs duration is a Ti:sapphire system with chirped pulse amplification, operating at 800 nm wavelength. Analytical estimates and simulations suggest a pulse energy of 2-3 mJ, allowing for losses between laser and interaction region, moderate deviations from the diffraction limit ($M^2 < 1.5$), and for extracting a pulse of 0.1 mJ that is naturally synchronized with the short x-ray pulse for pump-probe applications. The repetition rate should be as high as possible, only limited by N/τ, where N is the number of electron bunches and τ is the decay time of the energy modulation (8 ms for BESSY II). The laser system will comprise an oscillator and two amplifier stages. In the first stage, liquid-nitrogen cooling of the Ti:sapphire crystal allows in principle to extend the repetition rate to the 10 kHz regime [7]. The second stage is required to produce multi-mJ pulses and will initially operate at 1 kHz [8].

* Funded by the Bundesministerium für Bildung und Forschung and by the Land Berlin. Contact: Shaukat.Khan@bessy.de

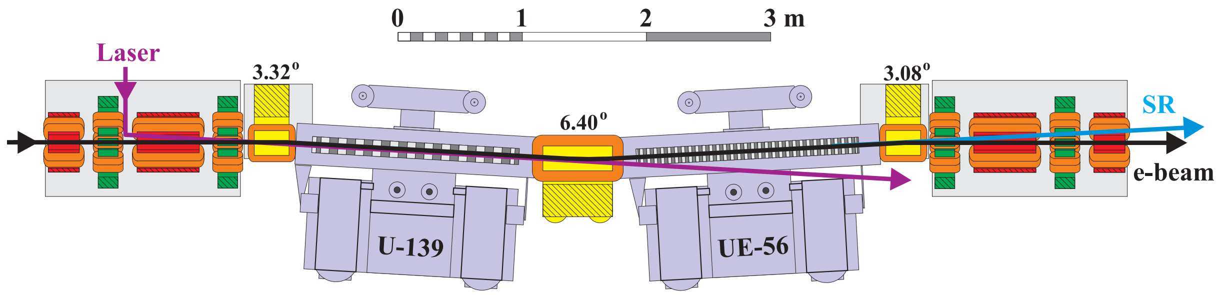

Figure 1: The magnetic system of the femtosecond facility, comprising two undulators (U-139 and UE-56) and three dipole magnets (yellow). Also shown are adjacent quadrupole (red) and sextupole (green) magnets.

Magnetic Components

For resonant laser-electron interaction, the modulator has to operate at the laser wavelength i.e. 800 nm. The U-139 is a planar wiggler with a period length of 139 mm and 10 full periods plus endpoles. The amplitudes of the first and third harmonic of the magnetic field are 1.4 T and 0.2 T, respectively.

In view of magnetic dichroism studies with variable polarization, the radiator (UE-56) is an apple-type elliptical undulator with a period length of 56 mm and 30 periods [9]. In March 2003, the original UE-56 double undulator was removed and its downstream part reinstalled on a new support structure.

Angular separation is provided by a 0.56 m long C-shaped dipole magnet with a bending angle of 112 mrad ($6.4°$). Together with two 0.28 m long dipoles, it forms a closed orbit bump. A moderate bending radius of 5 m (with a field of 1.13 T at 1.7 GeV) leaves ample margin to operate the storage ring at higher beam energy.

Vacuum System

The vacuum chambers will be replaced over a length of 9 m. The undulator chambers with a vertical aperture of 11 mm are fabricated by extrusion and subsequent machining of aluminium [10]. Other chambers with vertical apertures ranging from 11 mm to 35 mm are made of stainless steel. Carefully designed absorbers account for synchrotron radiation from the dipole magnets and the U-139 wiggler.

The laser beam enters through a window 2.3 m upstream of the U-139 center. Laser and wiggler radiation travel through a narrow pipe to a mirror chamber 3.9 m downstream of the U-139 center. Here, two mirrors extract the laser pulses as well as the near-visible part of the U-139 spectrum for diagnostics purposes. Synchrotron radiation from the UE-56 radiator exits at an angle of 3.08° with respect to the straight section axis.

Diagnostics

Beam position monitors at either end of both undulators help to keep the electron beam position fixed while the laser can be adjusted using remotely controlled mirrors. The laser-electron interaction requires spectral, transverse and longitudinal overlap of laser pulses and spontaneous U-139 radiation. Once its x-ray part with 1-2 kW average power is removed by water-cooled mirrors, the U-139 radiation can be analyzed by the same instruments as the laser using e.g. a CCD camera, photo diodes, or a spectrometer.

Energy modulation can be detected and optimized by monitoring coherent infrared radiation a few meters downstream of the modulator. When the path length differences of energy-modulated electrons exceed the laser pulse length, they leave a hole in the longitudinal electron distribution, which is gradually filled by other electrons over $\sim 1/4$ of the ring circumference. This hole, being equivalent to a bunch of ~ 20 μm length, will emit coherent radiation at wavenumbers of 10-50 cm^{-1}. Here, BESSY can rely on its expertise from low-momentum-compaction studies [11].

Frontend and Beamlines

The orbit bump requires a 3.08° shift of the UE-56 frontend and two existing beamlines, one with a plane-grating monochromator (PGM), the other with a spherical-grating monochromator. The PGM beamline will be modified to improve the focus at the experiment, and a second branch will be added for femtosecond applications, where a coarser grating will be used to reduce pulse lengthening at the expense of energy resolution.

EXPERIMENTAL STUDIES

In order to verify the angular separation concept, the angular characteristics of radiation from the UE-56 undulator were studied experimentally and by simulation using the code WAVE [12]. An aperture 12 m downstream of the source with no optical elements inbetween was moved across the radiation distribution while monitoring the intensity at 708 eV behind the PGM monochromator with a GaAs photodiode. In order to cover a large angular range, the electron beam was moved by angular orbit bumps in 0.2 mrad steps. Previous results [6] were limited by noise at $3 \cdot 10^{-5}$ of the distribution maximum, while the noise floor of the measurement shown in figure 2 is at 10^{-7}. The data closely resemble the predicted distribution (solid line), a convolution of the calculated single-electron radiation characteristics and the electron distribution, assuming a Gaussian core with tails from scattering processes. As a consequence of the angular bumps, radiation from the adjacent dipole magnets appeared below 10^{-6} (not shown in the figure). In the femtosecond facility, dipole radiation background will be avoided by an appropriate choice of the electron orbit.

EXPECTED PERFORMANCE

A simulation with 10^5 pseudo-electrons in the laser field, radiating according to their angle, energy and arrival time in the radiator, yields the broad distribution shown in figure 2 (dashed) from which the short pulse will be selected by an aperture. Its photon yield, signal-to-background ratio, spectrum and pulse duration can be estimated, depending in detail on many parameters – electron bunch and laser properties, background assumptions, settings of the undulator, monchromator and aperture. As an order of magnitude, 10^6 photons per second and 0.1% bandwidth can be expected to enter the beamline, if the laser repetition rate is 1 kHz. The measured angular distribution suggests a signal-to-background ratio better than 10. Thanks to the proximity of the radiator to the modulator, the pulse duration will be ~ 50 fs (fwhm).

Since the modulator is in a dispersive region, the longitudinal offset of energy-modulated electrons does not just increase with distance s from the modulator, but is, in fact, a complicated function of s. As shown in figure 3, an electron with $\Delta E/E = 0.01$ is almost isochronous in the next straight section ($s = 15$ m) and crosses the nominal orbit at a large angle, allowing for angular separation of short x-ray pulses. One straight section further away ($s = 30$ m), the angle of the electron trajectory is small, but the horizontal displacement is large. For femtosecond applications, the longitudinal deviation (0.33 ps) can be reduced by manipulating the momentum compaction of the ring. In addition, it is conceivable to tune the undulator in this straight section (U-125) to the second or third harmonic of the U-139 and test high-gain harmonic generation.

ACKNOWLEDGEMENTS

Fruitful discussions with P. Heimann, R. Schoenlein, A. Zholents (LBNL, Berkeley), R. Abela and G. Ingold (SLS, Villigen) are gratefully acknowledged.

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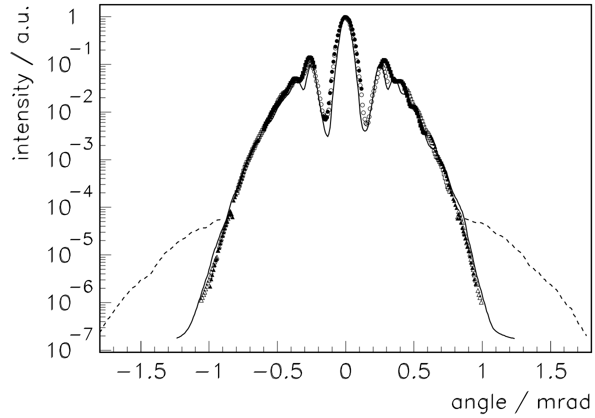

Figure 2: Measured (points) and calculated (solid line) angular distribution of UE-56 radiation at 708 eV. Also shown is the calculated short-pulse component (dashed lines).

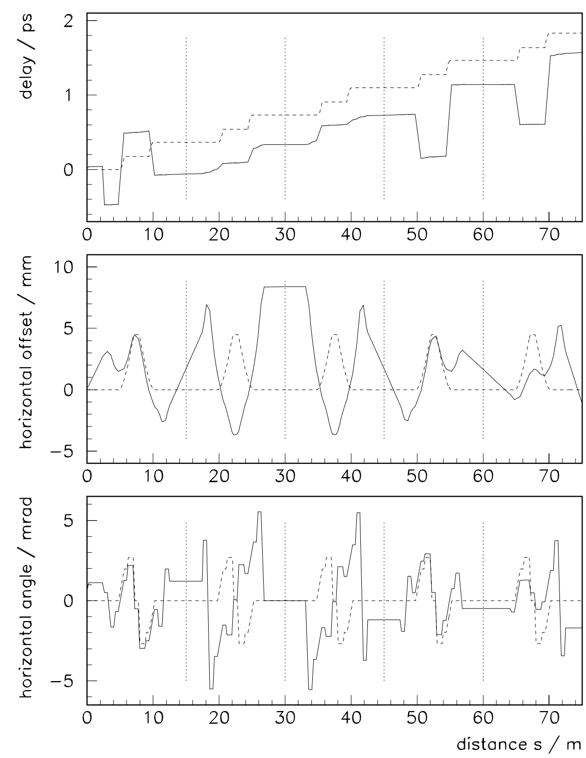

Figure 3: Calculated delay, horizontal offset and angle for an electron with energy deviation $\Delta E/E = 0.01$ as function of distance from the modulator. For comparison, the dashed lines show the same functions for a modulator in a dispersion-free region. Each vertical line marks the center of a straight section.

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