

FEMTOSECOND SYNCHROTRON RADIATION PULSES AT BESSY II*

S. Khan, H. A. Dürr, BESSY, Berlin, Germany

Abstract

The bunch-slicing method to generate sub-picosecond pulses at storage-ring based synchrotron radiation sources has received new interest at BESSY II, fueled by user demand and by SASE-FEL studies. This paper describes several design issues of a femtosecond source at BESSY II.

1 INTRODUCTION

Probing atomic motion or magnetic properties with x-rays on a sub-picosecond time scale is a new field with the prospect of exciting scientific opportunities. While contemporary synchrotron radiation sources are limited in pulse duration to tens of picoseconds, x-ray free-electron lasers are expected to deliver pulses shorter than 100 fs by the end of the decade. Apart from laser-based techniques such as higher-harmonic generation or plasma sources, each with their specific merits and shortcomings, a new approach, combining femtosecond lasers with the flexibility of third-generation synchrotron light sources, was proposed [1] and experimentally demonstrated [2] at the Advanced Light Source in Berkeley.

At BESSY II, the interest in implementing this technique, now commonly known as bunch "slicing", is twofold. One motivation is to gain hands-on experience in view of a future soft x-ray FEL currently under study [3]. The other – more immediate – motivation is to study ultrafast magnetic phenomena, which are at the frontier of novel data storage technologies. While the slicing method could provide a time resolution of ~ 50 fs, well-established x-ray techniques such as linear and circular magnetic dichroism or resonant magnetic scattering allow to probe element-specific spin and orbital properties of magnetic materials (see e.g. [4] [5] for details).

The principle of bunch slicing is sketched in figure 1: In the field of a wiggler ("modulator"), a femtosecond laser co-propagating with an electron bunch modifies the electron energy within the overlap region. The change of energy is used to extract the radiation from this short bunch "slice" in a subsequent undulator ("radiator"). Using dispersive magnetic fields, the energy deviation translates itself into a transverse parallel shift (figure 1, top) or angular displacement (bottom) in the radiator.

The technical implementation at BESSY II will be tailored to the scientific case mentioned above, but should be flexible enough to allow other applications. In particular, a free choice of the degree of linear or circular polarization must be ensured, and the separation of the short pulse should be efficient for a wide range of photon energies. The most challenging issue is the temporal resolution

which should not be diluted by the non-isochronicity of the electron optics. Since an electron energy difference of 1% causes a time difference of 400 fs in a BESSY II achromat, optimum time resolution requires modulator and radiator to be placed in the same straight section of 5.4 m length.

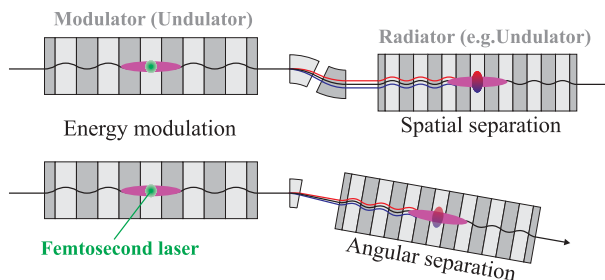


Figure 1: Principle of bunch slicing with spatial and angular separation of energy-modulated electrons.

2 LASER-ELECTRON INTERACTION

Given the requirement of circular polarization, an elliptical undulator like BESSY's UE-56 is the obvious choice for a radiator. Presently, there are two such devices installed, each consisting of two 1.8 m long modules with 30 periods to produce both helicities simultaneously. Replacing an upstream module by a suitable modulator would not only produce x-ray pulses with essentially the same duration as the laser pulses, but would also minimize the costs by using existing hardware and allow operation of the UE-56 downstream module as before.

The modulator, a wiggler with period length λ_U and field parameter K , has to fulfill the resonance condition

$$\lambda_L = \frac{\lambda_U}{2\gamma^2} \left(1 + \frac{K^2}{2} \right) \quad (1)$$

at a beam energy of 1.7 GeV (Lorentz factor $\gamma = 3327$), i.e. the wavelength of its radiation has to be equal to the laser wavelength λ_L . Assuming a Ti:sapphire laser system, the wavelength will be 800 nm or a harmonic thereof. Figure 2 shows the magnetic peak field as function of the period length, that fulfills equation 1 for $\lambda_L = 800$ nm and 400 nm. Also shown are parameters of existing undulators, where the U-125 is a candidate for operation at 400 nm. However, to avoid losses by second-harmonic generation, a magnetic structure of slightly larger peak field is preferred, and a design with 15 periods of 120 mm length is currently pursued, matching the number of optical cycles in the laser pulse.

The amplitude of the energy modulation should be of the order of 1% of the beam energy, which requires a

* Funded by the Bundesministerium für Bildung und Forschung and by the Land Berlin.

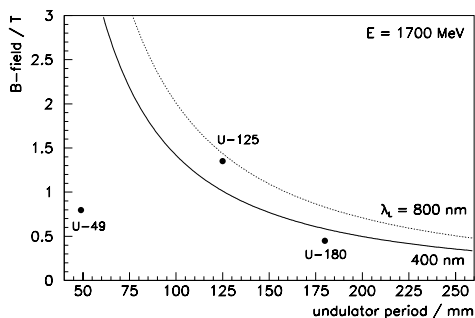


Figure 2: Peak field versus period length of an undulator. The lines represent equation 1 for two values of laser wavelength λ_L and $\gamma = 3327$.

laser pulse energy of at least 1 mJ. Commercially available Ti:sapphire systems deliver pulses of this energy at a repetition rate of 1 kHz, which is far below the ultimate limit of 100 kHz, assuming that each of 400 bunches is reused after 4 ms (half the longitudinal damping time). Other laser requirements include a pulse duration of about 30 fs fwhm, a spatial profile with $M^2 < 1.5$, synchronization with the rf bunch clock on the level of 1 ps, and flexibility in the choice of pulses to be amplified (*not* just synchronized to one bunch). The laser requirements were studied in detailed simulations of the laser-electron interaction. Some results are shown in figure 3, where the rate of modulated electrons above a given energy offset $\Delta E/E$ is used as a figure of merit. The dependence on pulse duration τ_L is flat, since the number of electrons in the slice increases, but the modulation amplitude decreases with τ_L for a given pulse energy. The variation of $\Delta E/E$ in figure 3 (bottom) illustrates, that the required pulse energy is strongly linked to the separation capabilities.

3 SHORT-PULSE SEPARATION

While laser-driven energy modulation has been demonstrated experimentally, sufficient separation of the ultrashort x-ray pulse is another challenging task. The two cases of a transverse displacement shown in figure 1 are discussed in the following paragraphs.

3.1 Spatial Separation

A chicane of two magnets with opposite field between modulator and radiator provides a parallel displacement of off-energy electrons (figure 1, top). This scheme suggests vertical separation since the vertical size of the electron beam is typically one order of magnitude smaller than horizontally.

For BESSY II, a vertical dispersion of 11 mm, produced by two pairs of magnets enclosing the modulator, was considered. There are substantial engineering problems to be solved e.g. the entrance and exit of the laser beam, or the absorption of synchrotron radiation from the modulator and from the chicane magnets.

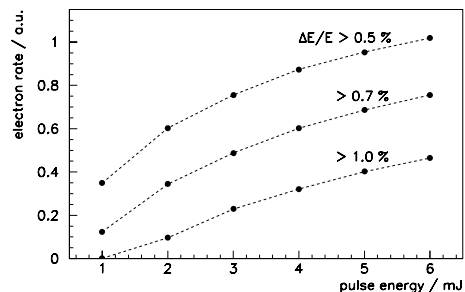
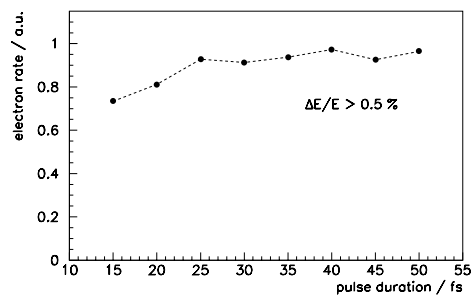


Figure 3: Rate of electrons (in arbitrary units) above a given energy deviation $\Delta E/E$ as function of pulse duration and pulse energy.

For spatial separation, the source must be imaged onto an aperture by a mirror. Distortions of the image are minimized by using a 1:1 magnification. Furthermore, since the sagittal slope error is reduced by a factor of Θ (the angle of incidence) as compared to the meridional error [6], a horizontally deflecting mirror should be used for vertical separation. With this in mind, the image of a Gaussian beam and the energy-modulated bunch slice was calculated applying the code RAY [7] to the output of a simulation of the energy modulation process. The result (figure 4, top) suggests sufficient separation. However, there is strong concern that non-specular reflection due to the mirror's surface roughness may produce intolerable background [8], which – being insignificant for most applications – is not included in the code. Angular separation avoids this uncertainty.

3.2 Angular Separation

A single bending magnet between modulator and radiator produces an angular displacement of off-energy electrons. If the angle is sufficiently large, their radiation can be extracted just by an aperture, and the beamline – not involved in the separation task – requires no special design. Furthermore, since the synchrotron radiation cone is not dominated by the electron beam divergence, this scheme might be employed in the horizontal plane, where the technical problems mentioned above are greatly reduced.

Figure 4 (bottom) shows the angular characteristics of radiation from a Gaussian beam and from the bunch slice, calculated using the code WAVE [9]. Assuming an energy modulation of 1% and a separation by 1 mrad, the horizontal bending angle between modulator and radiator would be 100 mrad. This appears to be technically feasible, but the

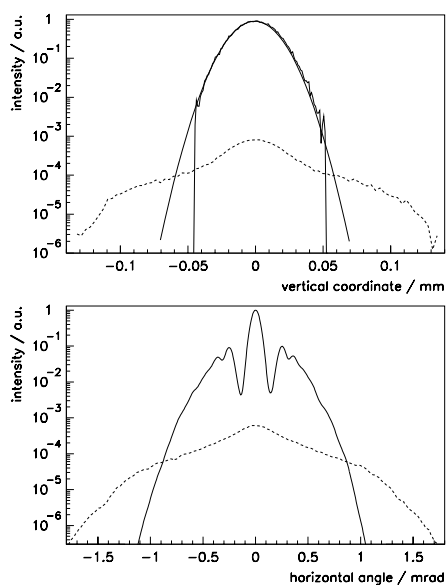


Figure 4: Vertical spatial distribution (top) and horizontal angular distribution (bottom) of radiation from a Gaussian bunch (solid line) and from the energy-modulated bunch slice (dashed line).

approval of this scheme is subject to further studies of radiation characteristics and electron dynamics. The increase of the horizontal emittance is moderate (100 mrad corresponds to half the bending angle of one of the 32 storage ring dipoles), but other effects (e.g. on the dynamic aperture) have to be investigated.

The prediction of angular radiation characteristics on the 10^{-5} level has to be checked carefully. A first measurement [10], shown in figure 5, is compatible with the WAVE simulation over almost five orders of magnitude. A pin-hole 12 m downstream of the source (UE-56) with no optical elements inbetween was moved across the radiation cone while the intensity on the 3rd harmonic at 706 eV was monitored with a GaAs diode at the end of the beamline. In order to increase the angular range, the electron beam was tilted in 0.25 mrad steps (corresponding to different symbols in figure 5). At $3 \cdot 10^{-5}$ of the peak, the noise floor of the detector was reached without observing any background, neither from the bending magnet following the undulator nor from non-Gaussian tails of the electron beam (expected at a 10^{-5} level, see e.g. [11]).

4 OUTLOOK

A femtosecond source at BESSY II, based on the slicing method with a downstream UE-56 module as radiator and a planar undulator in the same straight section as modulator, appears to be feasible. Horizontal angular separation has distinct advantages over a vertical scheme, and the engineering design for the required components is underway. In parallel, the conclusions drawn so far will be substantiated by further simulations and experimental studies.

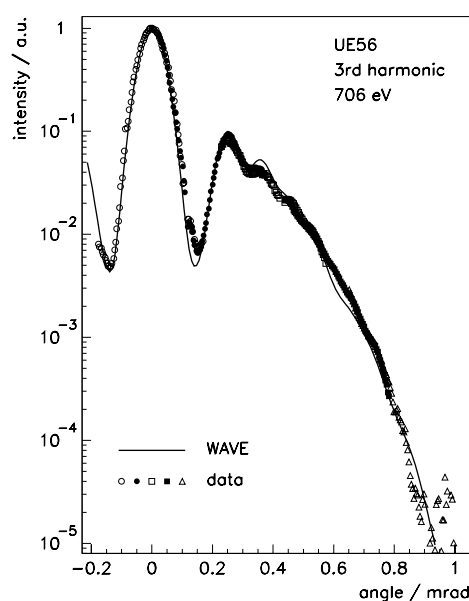


Figure 5: Calculated (solid line) and measured (symbols) [10] horizontal angular distribution of nearly (90%) circularly polarized light of a UE-56 undulator.

5 ACKNOWLEDGEMENTS

The encouragement from the BESSY management and the help from our co-workers, in particular J. Bährdt, H. Bäcker, V. Dürr, K. Holldack, D. Krämer, H.-C. Mertins, W. Peatman, F. Schäfers, M. Scheer and F. Senf, as well as from I. Will (MBI, Berlin) is gratefully acknowledged. We would like to thank P. Heimann, R. Schoenlein and A. Zholents (LBNL, Berkeley) for generously sharing their expertise with us.

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