GENERATION OF FEMTOSECOND X-RAY PULSES AND OTHER LASER-ELECTRON BEAM EXPERIMENTS AT DELTA

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Abstract

A novel technique for generating sub-picosecond x-ray pulses, based on the interaction of an electron beam with a co-propagating femtosecond laser, is proposed to be applied at DELTA/Dortmund. Simulations show that a brilliance of 10^8 photons/s per mm^2, mrad^2 and 0.1% bandwidth can be achieved. The pulse duration is of the order of 100 fs rms. Additionally, other experiments using laser pulses in combination with the DELTA storage ring beam can be envisioned.

1 INTRODUCTION

High-brilliance synchrotron radiation sources are the most powerful tools for probing the atomic structure of matter in the VUV or x-ray regime. Their time resolution, however, is limited to $>$10 ps. The study of ultrafast atomic phenomena in physics, chemistry and biology still relies largely on the well established technology of optical laser pulses below 100 fs duration.

A promising approach to combine short pulse length and short wavelength is to combine the two technologies of femtosecond lasers and synchrotron light sources as proposed by [1] and currently tested at the Advanced Light Source (ALS) in Berkeley [2].

The application of this method at BESSY-II, a 3rd generation synchrotron light source currently being commissioned in Berlin [3], has been described in [4]. However, there are several advantages in performing first tests at the DELTA storage ring of the University of Dortmund [5]. In contrast to a purely user-oriented facility, DELTA is partly dedicated to accelerator-physics experiments. The storage ring is already in operation and, as will be shown below, its insertion devices are suitable for sub-picosecond pulse generation without major modifications of hardware or storage ring optics.

2 GENERATION OF ULTRASHORT X-RAY PULSES

The principle of short x-ray-pulse generation as proposed by [1] is sketched in figure 1. A short laser pulse of wavelength λ_L co-propagates with an electron bunch of Lorentz factor γ in an undulator (interaction region) of period length λ_u. If the undulator parameter K satisfies the condition

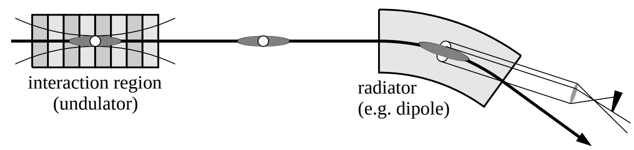

Figure 1: Principle of the generation of short x-ray pulses.

$$\left(1+\frac{K^2}{2}\right)\lambda_u = 2\gamma^2\lambda_L, \tag{1}$$

the laser produces a short region within the bunch, where electrons have gained or lost energy, depending on their position relative to the laser wave. A transverse displacement of these energy-modulated electrons by dispersion in a second magnetic device (radiator) allows to separate the short component from the synchrotron radiation of the other electrons. The radiator may be a dipole magnet or a second undulator. Since the non-isochronicity of the storage ring would destroy the time structure of the energy modulated electrons, the radiator should be close to the interaction region.

The maximum energy modulation ΔE is given by [1]

$$(\Delta E)^2 = 4\pi\alpha\cdot\epsilon\cdot A_L\cdot E_L \tag{2}$$

where E_L is the photon energy, A_L is the energy content of a laser pulse, and $\alpha = 1/137$. The undulator properties are contained in

$$\epsilon = \frac{K^2/2}{1+K^2/2}\cdot\min\left(\frac{M_U}{M_L},1\right). \tag{3}$$

Here, M_U is the number of undulator periods and M_L is the number of wavelengths within the (fwhm) length of the laser pulse.

The rate of short-pulse photons depends strongly on ΔE. For the separation to be feasible, the energy modulation must be significantly larger than the natural energy spread. On the other hand, increasing ΔE at a given average laser power P_L reduces the repetition rate of the short pulses $f = P_L/A_L \sim (\Delta E)^{-2}$.

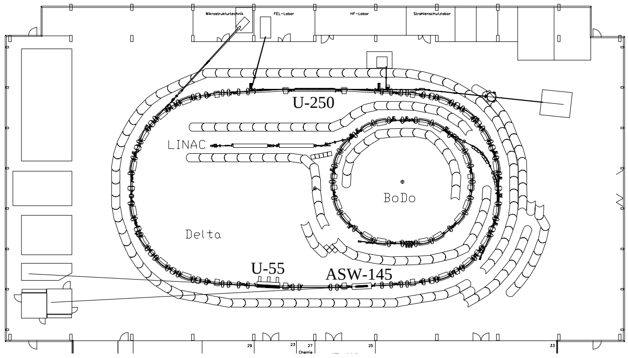

Figure 2: DELTA at the University of Dortmund.

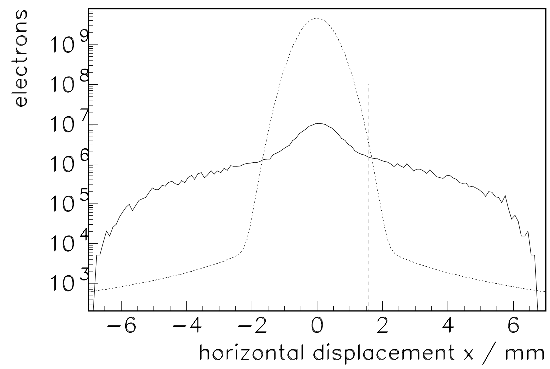

Figure 3: Horizontal beam profile (dotted) and distribution of energy-modulated electrons (solid line) in the U-55.

Table 1: DELTA insertion device parameters.

	U-250	ASW-145	U-55
number of periods	19	9	49
period length	250 mm	145 mm	55 mm
max. value of K	3.07	37	3.49

3 APPLICATION AT DELTA

Figure 2 gives an overview of the DELTA facility, consisting of an injector linac, a booster sychrotron (BoDo) and the storage ring. Also shown is the position of the already installed FEL-undulator U-250, the superconducting wiggler ASW-145, and the U-55 undulator to be installed later this year. Their basic properties are given in table 1.

DELTA is designed for electron energies ranging from about 300 MeV to 1500 MeV. Under the assumption of a Ti:sapphire laser system with chirped pulse amplification [6] and $\lambda_L = 800$ nm, the U-55 fulfills equation 1 only for $\gamma \leq 494$ (i.e. electron energy ≤ 252 MeV) and cannot easily be used as interaction region. The other options are:

- Using the U-250 as interaction region at a beam energy ≤ 482 MeV and one of the subsequent dipole magnets as radiator. Clearly, the brilliance of the pulses from dipole magnets will not allow more than a proof-of-principle experiment.
- Using the ASW-145 as interaction region with some flexibility in the beam energy and the U-55 as radiator. The comparatively high brilliance compensates for the fact that the process of energy modulation is not very efficient due to the low M_U (cf. equations 2 and 3).

In a simulation of the interaction process in both cases, electrons were represented by macroparticles at position (x, y, z, t) and transverse velocity $x'(t)$. Their energy change due to the interaction with the laser field $\mathcal{E}(x, y, z, t)$

$$\Delta E = -e\,c \int x'(\tau)\ \mathcal{E}(x, y, z, \tau)\ d\tau \qquad (4)$$

was integrated in small time steps. The energy-modulated macroparticles were transported through the magnetic lattice to determine their horizontal and time displacement at the position of the radiator. The amount of synchrotron radiation emitted by electrons exceeding a certain transverse displacement was evaluated by standard methods.

Figure 3 shows the transverse distribution of energy-modulated electrons at the center of the U-55. In this example, the ASW-145 was set to $K = 4.1$ and the corresponding beam energy was 472 MeV. Using the program ZAP [7], the estimated horizontal emittance at 20 mA per bunch was $1.4 \cdot 10^{-8}$ radm, the energy spread was 0.003 and the bunch length was 95 ps rms. A 1 W laser of 100 fs (fwhm) pulse duration was assumed with only 10% of its power acting on the electron bunch and 90% lost elsewhere. The dotted curve in figure 3 represents the profile of the other electrons including non-Gaussian tails from residual-gas interaction [8]. A threshold was set such that the background rate was ten times lower than the rate of short-pulse electrons (at 1.6 mm in figure 3).

Figure 4 shows some properties of electrons above the threshold as function of the laser pulse energy. The maximum rate is $8 \cdot 10^9$ electrons/s for 0.2 mJ laser pulses and a repetition rate of 500 Hz. The drop of the rate at larger pulse energy reflects the decreasing repetition rate, whereas below 0.1 mJ the desired signal/background ratio of 10 is not achievable. With increasing pulse energy, the electron distribution broadens in energy and therefore in x, x' and time. At the maximum of the electron rate, the duration of the synchrotron radiation pulse is about 100 fs rms.

The brilliance of the short synchrotron radiation component can be estimated from the electron rate and distribution in (x, x'), considering the properties of the radiator and the diffraction limit. It is shown in figure 5 for the combination of ASW-145 and U-55 as well as for the U-250 with a dipole as radiator. The maximum achievable brilliance is of the order of 10^8 photons/s per mm^2, mrad^2 and 0.1% bandwidth, decreasing with increasing laser-pulse energy.

A possible way to measure the x-ray pulse duration directly would be the observation the ponderomotoric shift of a K-edge due to the laser field as function of the relative delay between laser and x-ray pulse [9].

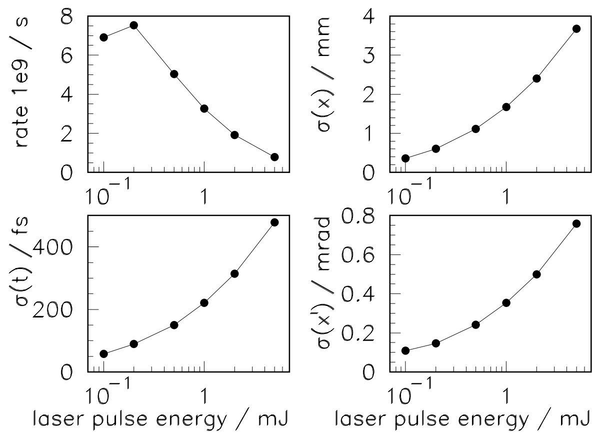

Figure 4: Electron rate and rms width in x, x' and time.

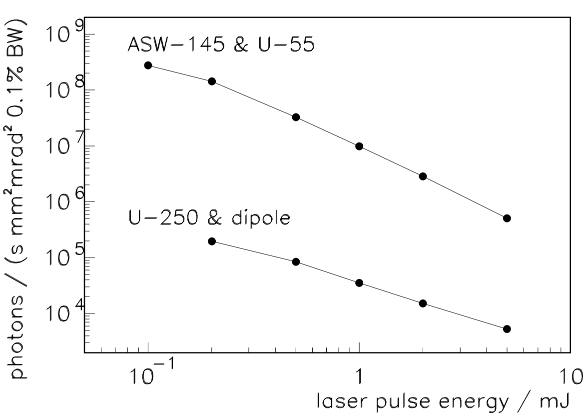

Figure 5: Short-pulse brilliance as function of laser energy.

4 OTHER LASER-E$^-$ EXPERIMENTS

Besides the generation of sub-picosecond x-ray pulses, one can envision a rich physics program of other laser-electron-beam experiments at the DELTA facility. They all take advantage of the extraordinary qualities of the new generation of lasers with high peak power, like the ones being developed and operated at the Max Born Institite (MBI) in Berlin.

By Compton conversion of light both from an external laser and by intracavity Compton backscattering of free-electron-laser (FEL) photons from the electron beam, tunable beams of unpolarized and polarized (>85%) monochromatic x-rays and γ-rays can be generated. Of particular interest are nuclear-astrophysics applications of highly collimated, low-background, monochromatic γ-rays. At very low energies or nuclear cross-sections, respectively, also the high intracavity peak power of the FEL radiation, which is naturally synchronized and aligned with the e$^-$ beam, will be used. One example is the measurement of the α yields from photofission of light nuclei, in particular of ^{16}O, which is the reverse of the "helium-burning" process ^{12}C(α,γ)^{16}O, a key reaction in nuclear synthesis of red-giant stars.

A laser can also be used for electron beam diagnostics, i.e. measurements of beam parameters like emittance, bunch length, absolute energy and polarization, and to test the acceleration of electrons by the "Inverse FEL" principle.

Another accelerator-physics application may be stimulated radiation damping of the beam emittance on a fast time scale by the interaction of electrons with a counter-streaming intense transverse laser field, counterbalancing intrabeam scattering (first tests at about 300 MeV).

Installing an optical Fabry-Perot resonator inside the storage ring for recirculating a laser pulse would allow for repeated interaction with the electron bunches.

Furthermore, experiments of the interaction between the electron beam and a well-focussed strong axial electric laser field (TEM10 mode) are envisioned, injecting laser pulses collinearly with the electron bunches, with and without the superposition of a magnetic undulator field.

5 CONCLUSIONS

The DELTA storage ring at the University of Dortmund and its insertion devices are ideally suited to test a novel technique for generating sub-picosecond x-ray pulses. The required femtosecond laser system may serve other purposes as well. It can be used to produce γ-rays for various applications and to perform innovative accelerator-physics experiments.

6 ACKNOWLEDGEMENTS

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