DESY 03–091
July 2003

ISSN 0418-9833

Two-color FEL amplifier for femtosecond-resolution pump-probe experiments with GW-scale X-ray and optical pulses

J. Feldhaus [a], M. Körfer [a], T. Möller [a], J. Pflüger [a], E.L. Saldin [a], E.A. Schneidmiller [a], S. Schreiber [a], and M.V. Yurkov [b]

[a] *Deutsches Elektronen-Synchrotron (DESY), Notkestrasse 85, Hamburg, Germany*

[b] *Joint Institute for Nuclear Research, Dubna, 141980 Moscow Region, Russia*

arXiv:physics/0307092 v1 18 Jul 2003

Abstract

Pump-probe experiments combining pulses from a X-ray FEL and an optical femtosecond laser are very attractive for sub-picosecond time-resolved studies. Since the synchronization between the two independent light sources to an accuracy of 100 fs is not yet solved, it is proposed to derive both femtosecond radiation pulses from the same electron bunch but from two insertion devices. This eliminates the need for synchronization and developing a tunable high power femtosecond quantum laser. In the proposed scheme a GW-level soft X-ray pulse is naturally synchronized with a GW-level optical pulse, independent of any jitter in the arrival time of the electron bunches. The concept is based on the generation of optical radiation in a master oscillator-power FEL amplifier (MOPA) configuration. X-ray radiation is generated in an X-ray undulator inserted between the modulator and radiator sections of the optical MOPA scheme. An attractive feature of the FEL amplifier scheme is the absence of any apparent limitations which could prevent operation in the femtosecond regime in a wide (200-900 nm) wavelength range. A commercially available long (nanosecond) pulse dye laser can be used as seed laser.

Preprint submitted to

1 Introduction

Time-resolved experiments are used to monitor time-dependent phenomena. In a typical pump-probe experiment a short probe pulse follows a short pump pulse at some specified delay. The pump pulse triggers the system, for example it heats up the sample and produces a plasma, or it starts a photo-chemical reaction, and the probe pulse causes a signal recorded by a conventional, slow detector which reflects the state of the sample during the brief probing. The experiment must be repeated many times with different delays in order to reconstruct the femtosecond dynamical process. Femtosecond capabilities have been available for some years at visible wavelengths. However, there is a strong interest in extending these techniques to X-ray wavelengths because they allow to probe directly structural changes with atomic resolution.

Recent progress in free electron laser (FEL) techniques have paved the way for the production of GW-level, sub-100 fs, coherent X-ray pulses. This has recently been demonstrated experimentally at the TESLA Test Facility (TTF) at DESY [1], although only at vacuum ultraviolet (VUV) wavelengths down to 80 nm. First user experiments have led to exciting results [2]. A SASE X-ray FEL (SASE stands for self-amplified spontaneous emission) will be commissioned as a user facility in 2004 at DESY, covering the VUV and soft X-ray range down to 6 nm wavelength. The unique properties of this new source are attracting much attention in a wide science community. The short-wavelength, GW-level radiation pulses with sub-100 fs duration are particularly interesting for time-resolved studies of transient structures of matter on the time scale of chemical reactions.

The straightforward approach for pump-probe experiments, the combination of the X-ray FEL with a conventional quantum laser system, is presently being realized at the TESLA Test Facility at DESY [3]. The laser system comprises a seed pulse laser, special synchronization with the accelerator, pulse shaping, and a pump laser together with an optical parametric amplifier (OPA). The laser will initially cover the spectral region between 750 nm and 900 nm and will provide a train of 200 MW-level pulses with 200 fs pulse duration synchronized with the FEL. The main challenges are the development of the high power OPA and the synchronization system. The SASE FEL can produce radiation pulses shorter than 100 fs, hence the synchronization should be at least as good. The main uncertainty is the time jitter of the electron bunches. The latter is produced in the magnetic bunch compressors and is estimated to $\pm$1ps for the expected $\pm$0.1% energy jitter of the electron bunch. At the moment it is not clear by how much this time jitter can be reduced, and where the limits are for the electronic synchronization.

If we consider the standard technique for high-resolution time-resolved measurements, we find that the problem of synchronization of the two optical pulses usually does not exist at all. For very high resolution studies with optical quantum lasers in the femtosecond regime the two optical pulses are always derived from the same laser to ensure perfect synchronization, and the time difference is adjusted by changing the path length through an optical delay line. Pump-probe experiments combining pulses from a X-ray FEL and a quantum laser are more difficult. The synchronization of an independent optical laser with the FEL pulses is the most challenging task of this type of pump-probe technique. Picosecond time resolved work can be performed using known techniques. Sub-picosecond synchronization, on the other hand, needs further development.

The new method proposed in this paper is an attempt to get around the synchronization

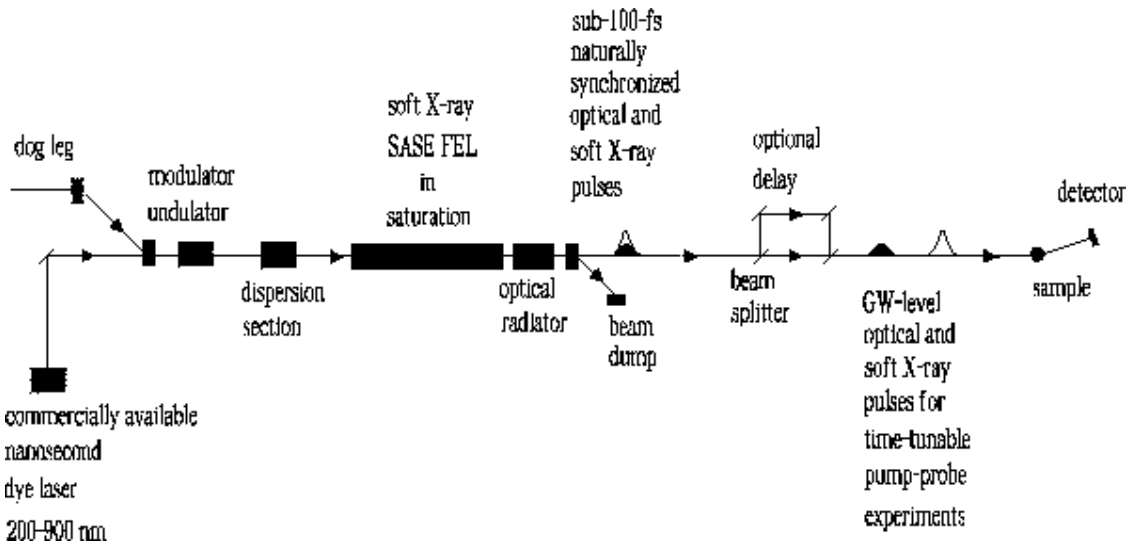

Fig. 1. Scheme for pump-probe experiments employing an optical pulse as a pump and a soft X-ray pulse as a probe or vice versa. A very long laser pulse is used for modulation of the energy and density of the electrons at the optical frequency. Optical photons for pump-probe experiments are generated by an additional insertion device (optical radiator) using the same electron bunch

obstacle by using a two step FEL process, in which two different frequencies (colors) are generated by the same femtosecond electron bunch. This method could be a very interesting alternative to the "independent optical quantum laser- SASE FEL" approach, and it has the further advantage to make a wide frequency range accessible at high peak power and high repetition rates not so easily available from conventional lasers.

The concept of the proposal is schematically illustrated in Fig. 1. Two different frequencies (colors) are generated by the same electron bunch, but in different insertion devices. The optical radiation is generated in a master oscillator-power FEL amplifier (MOPA) configuration. The X-ray radiation is generated in a X-ray undulator inserted between modulator and radiator sections of the optical MOPA scheme. The scheme operates as follows: The electron beam and the optical pulse from the seed laser enter the modulator radiator. Due to the FEL process the electron bunch gains energy modulation at the optical frequency which is then transformed to a density modulation in the dispersion section. The density modulation exiting the modulator (i.e. the energy-modulation undulator and the dispersion section) is about $10 - 20\%$. Thus, the optical seeding signal is imprinted in the electron bunch. Then the electron bunch is directed to the X-ray undulator. The process of amplification of the radiation in the main (soft X-ray) undulator develops in the same way as in the conventional SASE FEL: fluctuations of the electron beam current density serve as input signal. At the chosen level of density modulation the SASE process develops nearly in the same way as with an unmodulated electron beam because of the large ratio of the cooperation length to the optical wavelength [4]. As a result, at the exit of the X-ray undulator the electron bunch produces a GW-level X-ray pulse. A GW-level optical pulse is then produced when the electron bunch passes the optical radiator. The optical radiator is a conventional FEL amplifier seeded by the density modulation in the electron bunch. Although the electron beam leaving the soft X-ray FEL has acquired some additional energy spread, it is still a good "active medium" for an optical radiator at the end. Approximately 20% of density modulation is sufficient to drive the optical FEL amplifier in the nonlinear regime and to produce GW-level optical pulses in a short undulator.

An important feature of the proposed scheme is that the optical radiator uses the spent electron beam. As a result, the optical FEL can operate in saturation mode without interfering with the soft X-ray SASE FEL operation.

We illustrate the two-color FEL amplifier scheme for the parameters of the TESLA Test Facility at DESY. The proposed pump-probe facility has unique features: Both, X-ray and optical pulses, have very high peak power in the GW range. Both wavelengths are continuously and independently tunable in a wide range: $200-900$ nm for the optical pulses, and $6-120$ nm for the X-ray pulses. Both pulses have diffraction limited angular divergence. The spectral width of the optical pulse is transform limited. Finally, the optical and X-ray pulses are precisely synchronized at a femtosecond level, since they both are produced by the same electron pulse, and there are no reasons for any time jitter between them.

2 Two-color FEL amplifier at the TESLA Test Facility

Figure 2 shows the layout of the soft X-ray FEL in the first phase, including the linear accelerator with two magnetic bunch compressors and six undulator modules at the end of the accelerator tunnel. The first goal is to reach saturation in the soft X-ray range with this configuration, using the six undulator modules in SASE mode. In a second step the free space in front of the undulator will be used to build a fully coherent soft X-ray facility based on the two stage self-seeding concept [5].

The two-color FEL amplifier employs additional undulators to generate the second color radiation pulses. It requires free space in front of and behind the main soft X-ray FEL undulator which has already been foreseen at the design stage of the TTF FEL, Phase 2. Figure 3 shows the location of additional hardware components: the seed laser, the modulator undulator, a dispersion section, the main soft X-ray SASE undulator, and the optical undulator. The parameters of the hardware components required for the optical part of the pump-probe facility are listed in Table 1.

A commercially available dye laser, for example, can be used as a seed laser. The typical pulse energy of a dye laser system is in the range of 2 to 10 mJ with a pulse duration of 5–10 ns, and the peak power is in the range of 1 MW which gives us sufficient safety margin for operation of the modulator. The installation of a seed laser is greatly facilitated by the fact that the magnetic chicane of the electron beam collimation system allows to insert a

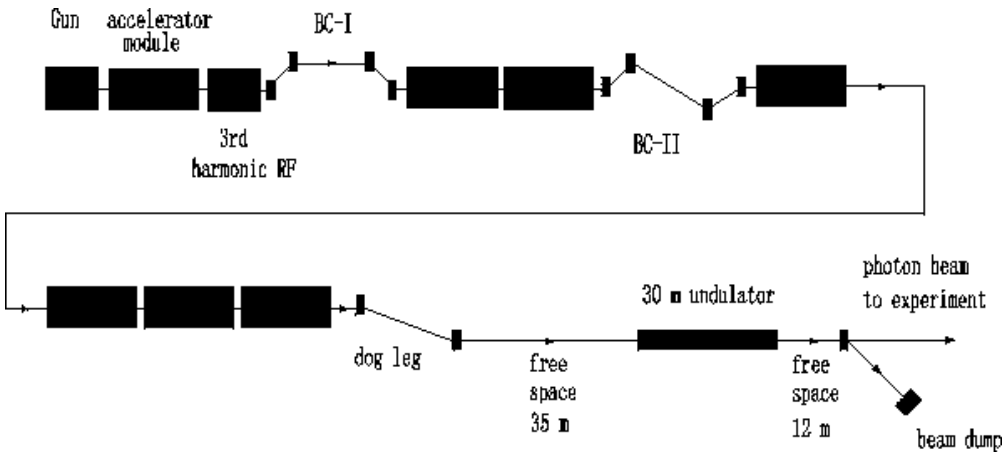

Fig. 2. Schematic layout of the soft X-ray SASE FEL facility

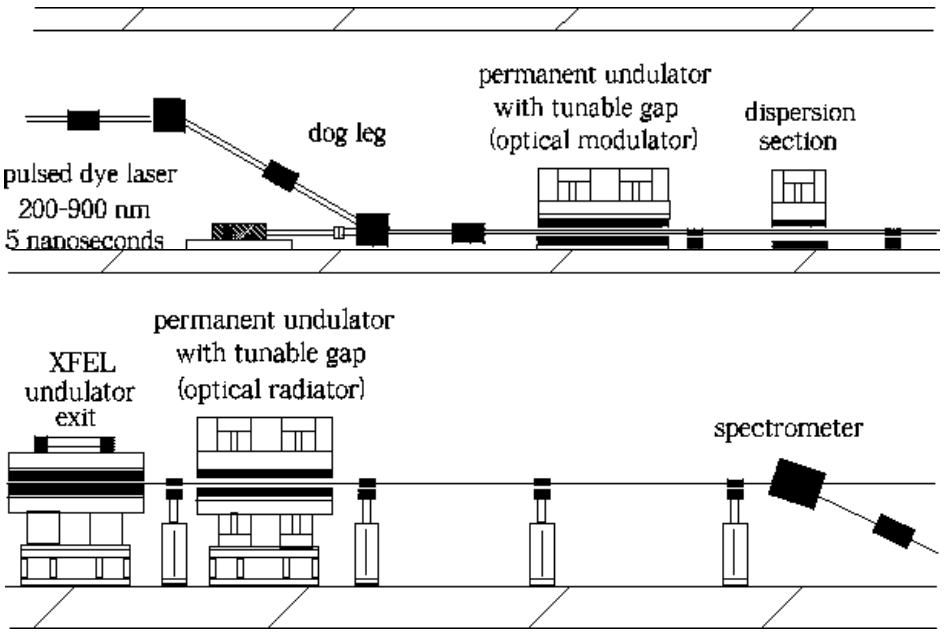

Fig. 3. Side view of the electron beam transport system, showing the location of the seed laser and the modulator (top) and of the optical radiator (bottom)

Table 1
Parameters of the components required for the optical part of the femtosecond pump-probe facility

Seed laser	
Type	dye
Wavelength [nm]	200–900
Pulse duration [ns]	5–10
Pulse energy [mJ]	2–10
Repetition rate [Hz]	10
Undulator	
Number of modules	2
Type	planar
Period [cm]	8.2
Gap [mm]	12–30
Peak field [T]	0.5–1.8
K-value	5–14
Number of periods	55
Length of each module [m]	4.5
Modulator chicane	
Number of dipoles magnets	4
Length of each dipole magnet [m]	0.25
Maximum magnetic field [T]	0.2
Total length of chicane [m]	1.5

view port for the input optical system. Also it is very important, that there is free space downstream of the main undulator (see Fig. 3) available for the optical radiator.

Both modulator and radiator undulators are identical tunable-gap devices similar to those used at DORIS. The dispersion section is composed of four standard bending magnets similar to those used at the HERA storage ring. Therefore, this optical radiation source could be realized at the TESLA Test Facility rather quickly and with minimum cost expenses.

3 Generation of two-color radiation pulses

The principle of two-color femtosecond pulse generation has been sketched briefly in Sections 1 and 2. Here we present a detailed description of the physical processes in both the optical and X-ray undulators. The parameters of the optical part of the facility have been optimized using the time-dependent FEL simulation code FAST [6]. Starting point for the optimization were the parameters of the TESLA Test Facility, Phase 2, given in an update [7] to the original design report [8]. The FEL at DESY will cover the wavelength range from 120 to 6 nm. Two modes of operation are currently foreseen:

(1) femtosecond mode (for $\lambda = 30 - 120$ nm, pulse duration 50-100 fs);
(2) short wavelength mode (for $\lambda = 6 - 30$ nm, pulse duration 200 fs).

The analysis of experimental results obtained at the TTF FEL, Phase 1, showed that the local energy spread is less than 0.2 MeV [9] which is significantly less than the previous project value of 1 MeV. This low value of the local energy spread improves significantly the operation of both the optical and the X-ray FEL and extends the safety margin for operation.

The operation of the two-color femtosecond facility is illustrated for the two modes of FEL operation: short wavelength mode with a bunch shape close to gaussian, and femtosecond mode when the electron bunch has a strongly non-gaussian shape with an intense leading peak [1,7]. We demonstrate that the two-color facility will work effectively in both cases.

3.1 Operation of the optical modulator

The optical modulator consists of three elements: the optical seed laser, the modulator undulator, and the dispersion section. The seed laser pulse interacts with the electron beam in the modulator undulator which is resonant with the laser frequency $\omega_{\rm opt}$, and produces an energy modulation of P_0 in the electron bunch. The amplitude of the induced beam modulation is small, typically of about a percent only. The electron beam then passes through the dispersion section where the energy modulation is converted to a density modulation at the optical wavelength. Optimum parameters of the dispersion section can be calculated in the following way. The phase space distribution of the particles in the first FEL amplifier is described in terms of the distribution function $f(P,\psi)$ written in "energy-phase" variables $P = E - E_0$ and $\psi = k_{\rm w} z + \omega_{\rm opt}(z/c - t)$, where E_0 is the nominal energy of the particle, $k_{\rm w} = 2\pi/\lambda_{\rm w}$ is the undulator wavenumber, and $\omega_{\rm opt}$ is the frequency of the seed radiation. Before entering the first undulator, the electron distribution is assumed to be Gaussian in energy and uniform in phase ψ:

$$f_0(P,\psi) = \frac{1}{\sqrt{2\pi\langle(\Delta E)^2\rangle}} \exp\left(-\frac{P^2}{2\langle(\Delta E)^2\rangle}\right) \ .$$

At the exit of the first undulator the amplitude modulation is very small, and there is an energy modulation $P_0 \sin\psi$ only. Thus, the distribution function at the entrance to the dispersion section is $f_0(P + P_0 \sin\psi)$. After passing through the dispersion section with a dispersion strength $\mathrm{d}\,\psi/\mathrm{d}\,P$, the electrons of phase ψ and energy deviation P will come to

a new phase $\psi + P\,\mathrm{d}\,\psi/\,\mathrm{d}\,P$. Hence, the distribution function becomes

$$f(P,\psi) = f_0\left(P + P_0 \sin\left(\psi - P\frac{\mathrm{d}\,\psi}{\mathrm{d}\,P}\right)\right) \ .$$

The integration of this distribution over energy provides the beam density distribution, and the Fourier expansion of this function gives the harmonic components of the density modulation converted from the energy modulation [10]:

$$I/I_0 = 1 + 2\sum_{n=1}^{\infty} \exp\left[-\frac{n^2}{2}\langle(\Delta E)^2\rangle\left(\frac{\mathrm{d}\,\psi}{\mathrm{d}\,P}\right)^2\right] J_n\left(nP_0\frac{\mathrm{d}\,\psi}{\mathrm{d}\,P}\right)\cos(n\psi) \ .$$

Here J_n is the Bessel function of n-th order. Assuming the argument of the Bessel function to be small, we find that maximum bunching at the fundamental harmonic $(a_1)_{\max} = P_0/\sqrt{2.72\langle(\Delta E)^2\rangle}$ is achieved at $(\mathrm{d}\,\psi/\,\mathrm{d}\,P)_{\max} = 1/\sqrt{\langle(\Delta E)^2\rangle}$.

During the passage through a long main SASE undulator the electron density modulation at the optical wavelength can be suppressed by the longitudinal velocity spread in the electron beam. For effective operation of the optical FEL amplifier the value of the suppression factor should be close to unity. A calculation shows that this should not be a serious limitation in the TTF case.

3.2 Femtosecond mode operation

The femtosecond mode operation is based on the experience obtained during the test runs of the TTF FEL, Phase 1 [1] and it requires one bunch compressor only. An electron bunch with a sharp spike at the head is prepared, with an rms width of about 20 μm and a peak current of about 2 kA. This spike in the bunch generates FEL pulses with a duration below one hundred femtoseconds. An example of the longitudinal phase-space distribution for a compressed beam including the effect of RF curvature is shown in Fig. 4, where the longitudinal bunch charge distribution involves concentration of charges in a small fraction of the bunch length. The longitudinal bunch profile is shown as solid line in Fig. 5. In the femtosecond mode only the first magnetic chicane BC-I will be active, and this will be the default mode of operation for some time until the 3rd harmonic cavity has been installed in the injector (see Fig. 2).

The performance of the two-color facility is illustrated for an optical wavelength of 400 nm and an X-ray wavelength of 30 nm. The bunch profile at the entrance of the undulator is shown as a solid line in Fig. 5. Simulations show that the value of the slice normalized emittance in the leading spike is about 7π mm-mrad. An important feature is a pronounced decrease of the local energy spread in the head of the bunch which can be derived from the phase space distribution (see Fig. 4). It will be shown below that the combination of high peak current and low energy spread in the leading spike will result in significant shortening of both optical and X-ray radiation pulses.

The seed laser pulse interacts with the electron beam in the modulator undulator and produces an energy modulation of about 100 keV in the electron bunch. The amplitude of the induced beam modulation is less than a percent. Then the electron beam passes through the dispersion section where the energy modulation is converted to a density modulation at

the optical wavelength. The grey line in Fig. 5 shows the bunch profile after the dispersion section. The density modulation reaches an amplitude of about 20%. It should be noted that the beam modulation is strongly non-uniform along the bunch. This is a consequence of the strongly varying energy spread along the bunch, since the bunching depends on the ratio of the energy modulation to the local energy spread. In our example the dispersion section is tuned to obtain maximum bunching in the top of the spike. Thus, the seeding is strongly suppressed in the tail of the bunch.

Upon leaving the dispersion section, the electron beam passes the X-ray undulator where it produces X-ray pulses (this process will be described below). The electron bunch leaving the X-ray undulator has a large induced energy spread of about 1 MeV but is still "cold" enough for the generation of optical radiation. Since the bunch is strongly modulated at the optical wavelength $\lambda_{\rm opt}$, it readily starts to produce powerful optical radiation when it

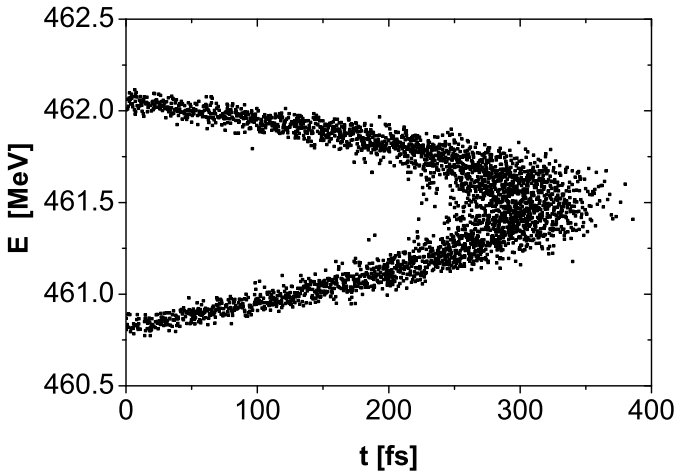

Fig. 4. Phase space distribution of electrons in the femtosecond mode after full compression with the first bunch compressor. The head of the bunch is on the right. The charge of the bunch is 1 nC, the local energy spread is 5 keV at the entrance of the bunch compressor.

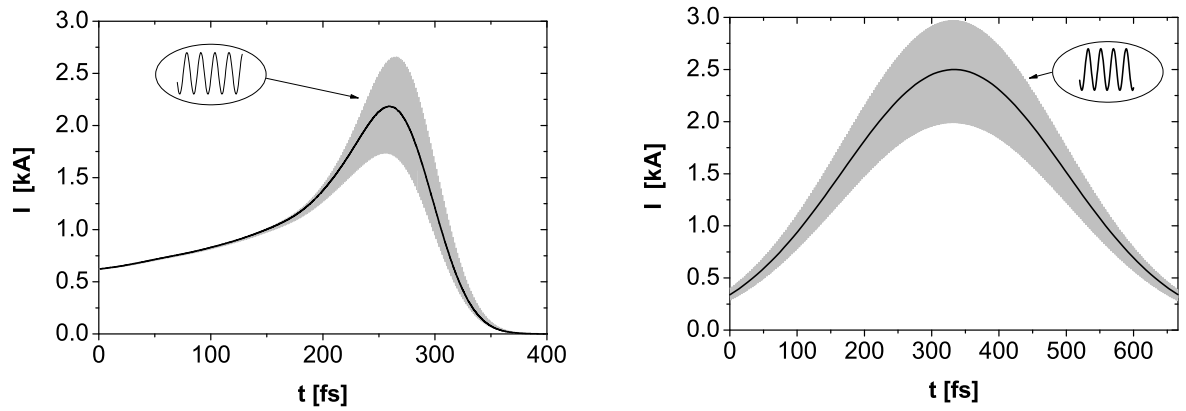

Fig. 5. Current distribution along the bunch after the dispersion section for femtosecond mode operation (left plot) and for short wavelength mode operation (right plot). The bunch is modulated with a period equal to the optical wavelength. The solid lines show the bunch profiles at the entrance to the optical modulator.

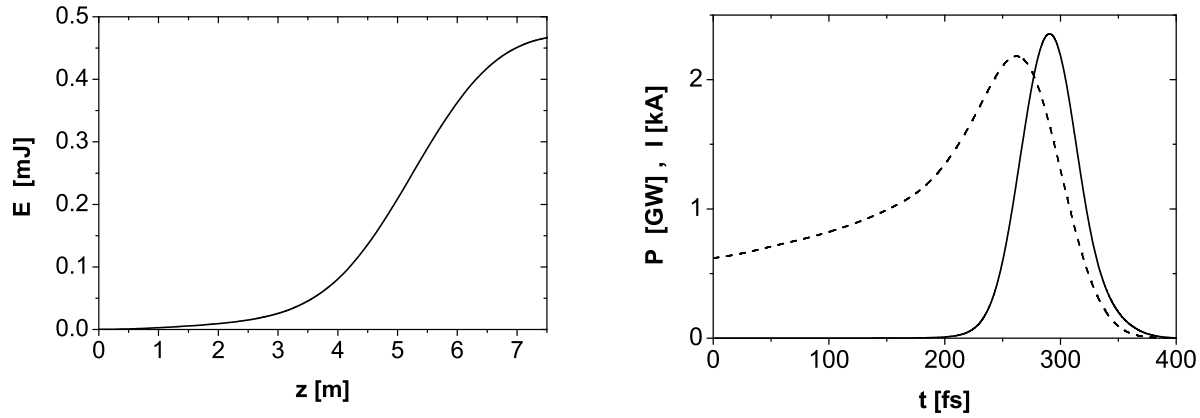

Fig. 6. Radiation energy in the optical pulse versus undulator length (left plot) and time structure of the radiation pulse at the exit of the optical radiator (right plot) in the femtosecond mode for a radiation wavelength of 400 nm. The dashed line indicates the profile of the electron bunch.

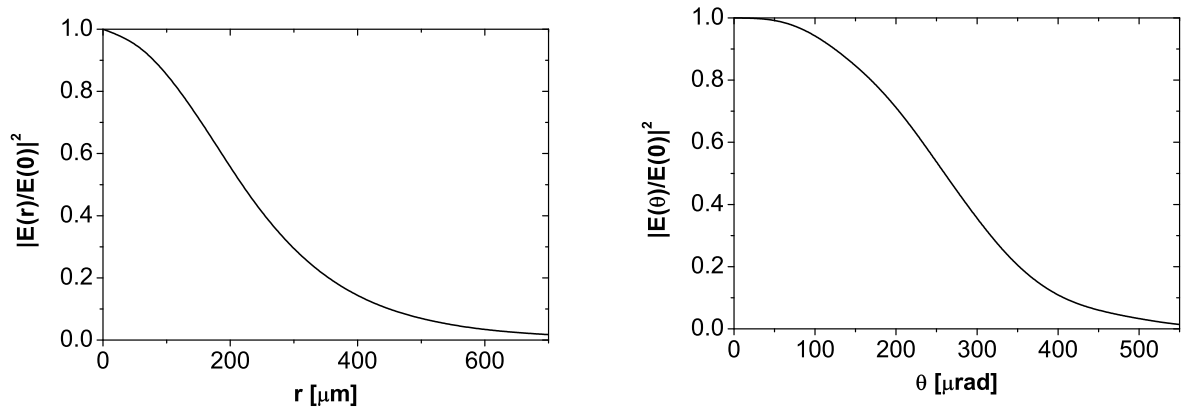

Fig. 7. Radial distribution of the radiation intensity at the undulator exit (left plot) and intensity distribution in the far zone (right plot) for 400 nm wavelength in the femtosecond mode.

enters the optical radiator resonant at $\lambda_{\rm opt}$. The evolution of the radiation energy in the optical radiator is presented in the left plot of Fig. 6. The right plot shows the temporal structure of the optical pulse at the exit of the optical radiator (at z=4.5 m). The dashed curve in this plot presents the electron bunch shape. It is evident that the optical pulse is much shorter than the electron bunch. This is the result of the three factors mentioned above: the strongly non-uniform pulse profile, the decrease of the energy spread in the head of the bunch, and the nonuniform seeding modulation. All these factors lead to a very strong suppression of the lasing properties of the bunch tail. The optical pulse has about 2 GW peak power, 50 fs FWHM pulse width, and about 100 μJ pulse energy. The installation of one additional optical undulator would allow to increase the pulse energy to 500 μJ as it is seen from the left plot in Fig. 6. It should be noted that the optical pulse is completely coherent, and its spectral width is transform-limited. The transverse shape of the radiation pulse at the undulator exit and its intensity distribution in the far zone are shown in Fig. 7.

So far we have considered the chain for producing femtosecond optical pulses. Let us now turn our attention to the SASE process in the X-ray undulator. Although the electron bunch density is strongly modulated (see Fig. 5), the SASE FEL process in the X-ray undulator remains almost the same as for an unmodulated electron beam. This is due to the fact that

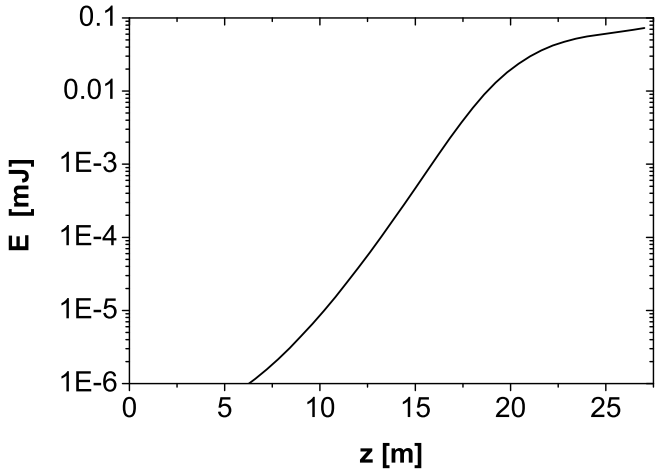

Fig. 8. Radiation energy in the X-ray SASE pulse versus undulator length for the femtosecond mode of operation. The radiation wavelength is 30 nm.

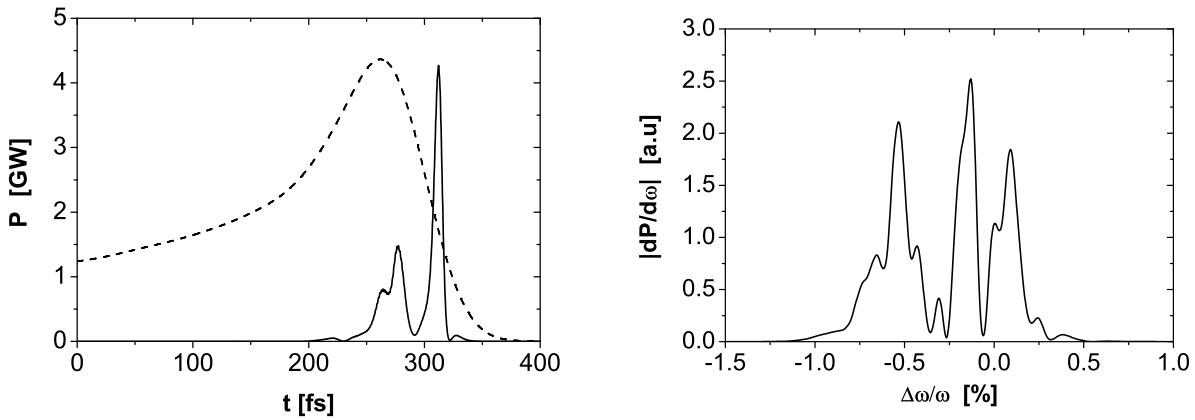

Fig. 9. Time (left plot) and spectral (right plot) structure of the X-ray SASE pulse at the exit of the undulator for the femtosecond mode of operation at a radiation wavelength of 30 nm. The dashed line shows the bunch profile.

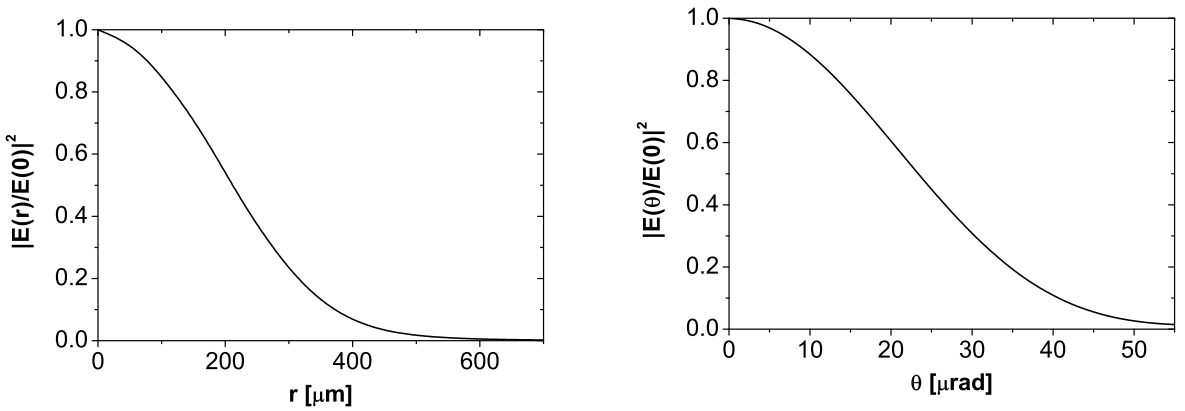

Fig. 10. Radial distribution of the X-ray SASE pulse intensity at the undulator exit (left plot) and intensity distribution in the far zone (right plot) for the femtosecond mode of operation at a radiation wavelength of 30 nm.

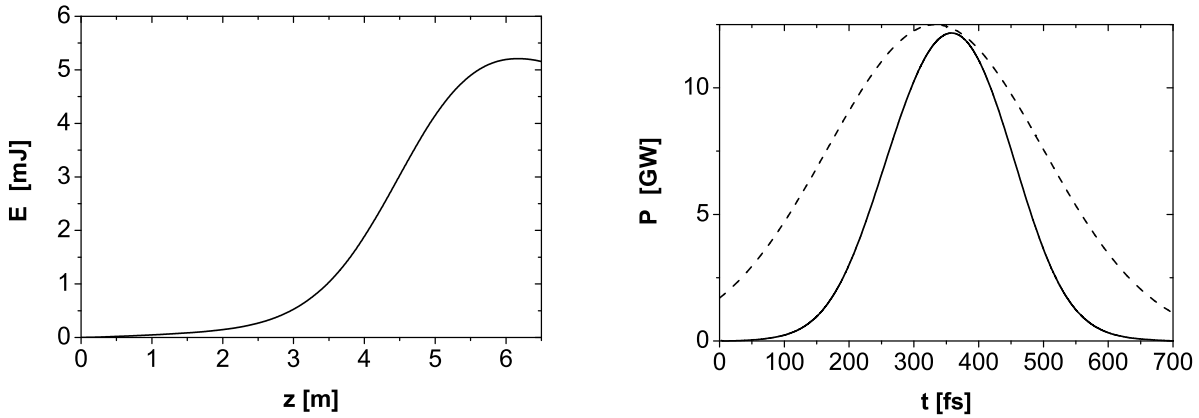

Fig. 11. Radiation energy in the optical pulse versus undulator length (left plot) and time structure of the radiation pulse at the exit of the optical radiator (right plot) in short wavelength mode for 400 nm wavelength. The dashed line shows the bunch profile.

the cooperation length in the X-ray undulator is much longer then the modulation period at the optical wavelength. As a result, averaging of the process takes place. Of course, the output radiation has contents of the sideband harmonic [4], but its contribution to the total radiation energy is tiny, of the order of 10^{-4}. Figure 8 shows the evolution of the energy in the X-ray pulse along the X-ray undulator, and Fig. 9 shows the time and spectral structure of the radiation pulse at the undulator exit. The properties of the radiation pulse are the same as for an unmodulated electron beam [7]. The peak radiation power is in the GW range and the FWHM pulse width is about 50 fs. The transverse shape of the radiation pulse at the undulator exit and its intensity distribution in the far zone are shown in Fig. 10.

These results demonstrate that the two-color scheme for the femtosecond mode of operation is capable to produce 50 fs long, GW-level optical and X-ray pulses which are precisely synchronized at a femtosecond level, since they both are produced by the same electron bunch, and there are no effects which could affect the synchronization.

3.3 Short wavelength mode operation

Operation of the FEL in the short wavelength mode requires the complete chain of the bunch compression scheme (BC-I, BC-II, and the 3rd harmonic RF section of the injector, see Fig. 2). The operating range of the accelerator is from 460 to 1000 MeV electron energy. The longitudinal profile of the electron bunch is shown in Fig. 5. We illustrate the proposed two-color FEL scheme for an X-ray wavelength of 6 nm (i.e. the minimum project value) and an optical wavelength of 400 nm (in the middle of the tuning range). The parameters of the electron beam are: 1 GeV energy, 2500 A peak current, and 2π mm-mrad rms normalized emittance. Recent start-to-end simulations predict a local energy spread less than 0.2 MeV [9]. In the present example we use a value of 0.5 MeV for the local energy spread in order to demonstrate that the proposed pump-probe scheme has sufficient safety margin.

The operation of the two-color scheme is the same as it was described above. The electron beam is modulated in the optical modulator (see Fig. 5). Then it passes through the X-ray undulator and produces GW-level X-ray radiation pulses. Upon leaving the X-ray undulator the beam is directed to the optical radiator and produces GW-level optical pulses. The

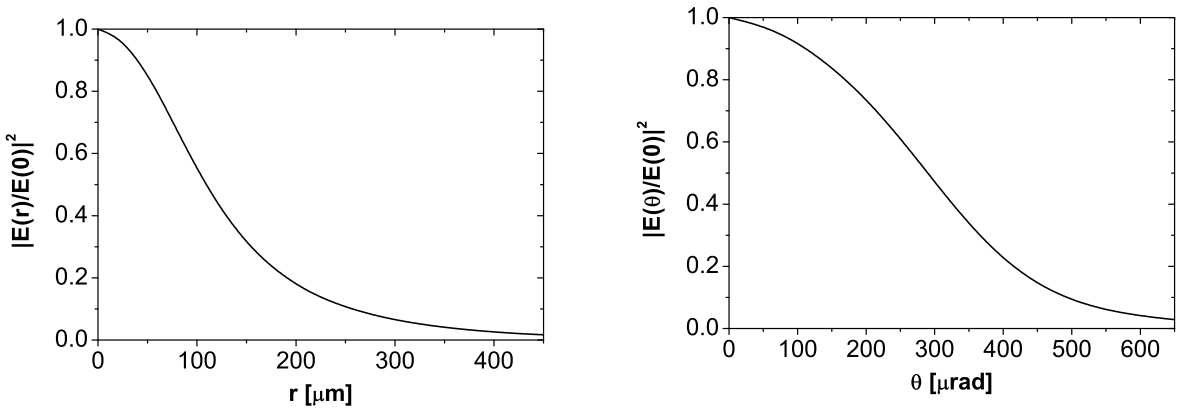

Fig. 12. Radial distribution of the optical pulse intensity at the undulator exit (left plot) and intensity distribution in the far zone (right plot) in short wavelength mode for 400 nm wavelength.

properties of the optical radiation are illustrated with Figs. 11 and 12. The energy of the optical pulse exceeds the mJ level, and the peak radiation power exceeds 10 GW. The FWHM pulse duration is about 150 fs.

The properties of the X-ray pulse are illustrated with Figs. 13, 14, and 15. It is seen that the properties of the X-ray radiation are the same as for an unmodulated electron beam [7]. Thus, we can state that the two-color facility does not interfere with the main modes of FEL operation.

3.4 Pulse separation

We demonstrated that the proposed two-color facility is capable of producing GW-level optical and X-ray pulses which are precisely synchronized at a femtosecond level. These pulses overlap not only longitudinally, but also transversely if the X-ray undulator and the optical radiator are in line. In this case the two beams can be separated for pump-probe experiments by making use of their rather different divergence (see, e.g. Figs. 7 and 10). At some distance from the source the optical beam size will be much larger than that of the X-ray beam such that a mirror with a hole can be used to separate the beams. Another possibility is to tilt the undulator axes by about a mrad. In this case the optical and X-ray pulses are pointing in slightly different directions and can be delivered to the sample via different beamlines. The optical transport line to the sample has to include a variable delay which allows precise tuning over a range of several picoseconds including zero crossing. This is not trivial since only very small deflection angles are possible for the X-ray beam, and there are other geometrical constraints coming from the existing FEL beam distribution system. This needs further work and is beyond the scope of the present paper.

4 Conclusion

A novel two-color FEL amplifier for pump-probe experiments has been described combining sub-100 fs optical and X-ray pulses. The properties of the radiation pulses are summarized in Table 2. The proposed facility has unique features: Both pulses have very high peak power in the GW range. The wavelengths of both radiation sources are continuously

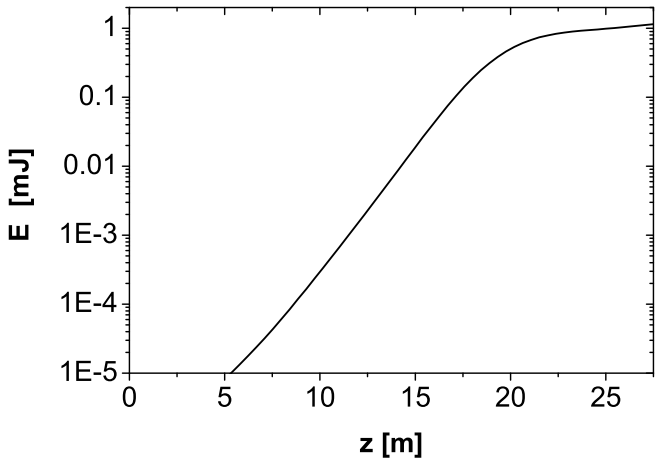

Fig. 13. Radiation energy of the X-ray SASE pulse versus undulator length in the short wavelength mode for a radiation wavelength of 6.4 nm.

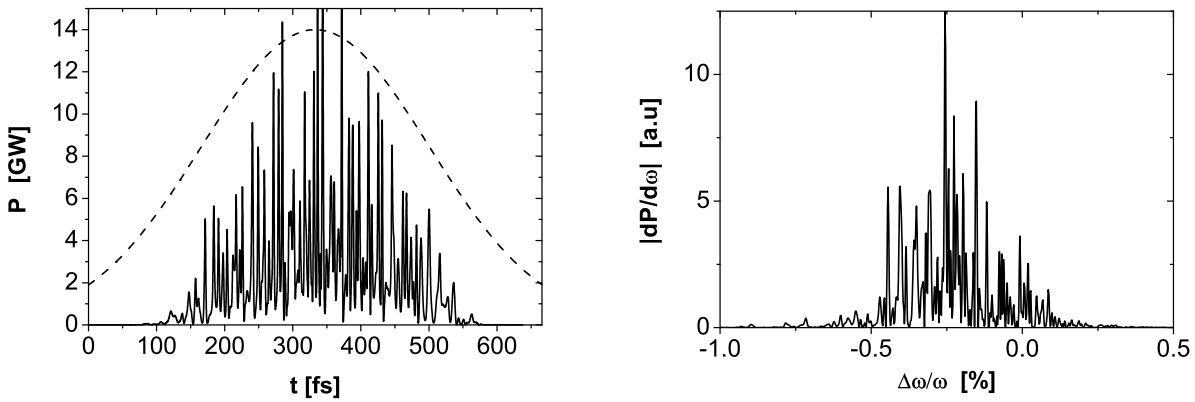

Fig. 14. Time (left plot) and spectral (right plot) structure of the X-ray SASE pulse at the exit of the undulator in the short wavelength mode for a radiation wavelength of 6.4 nm. The dashed line shows the bunch profile.

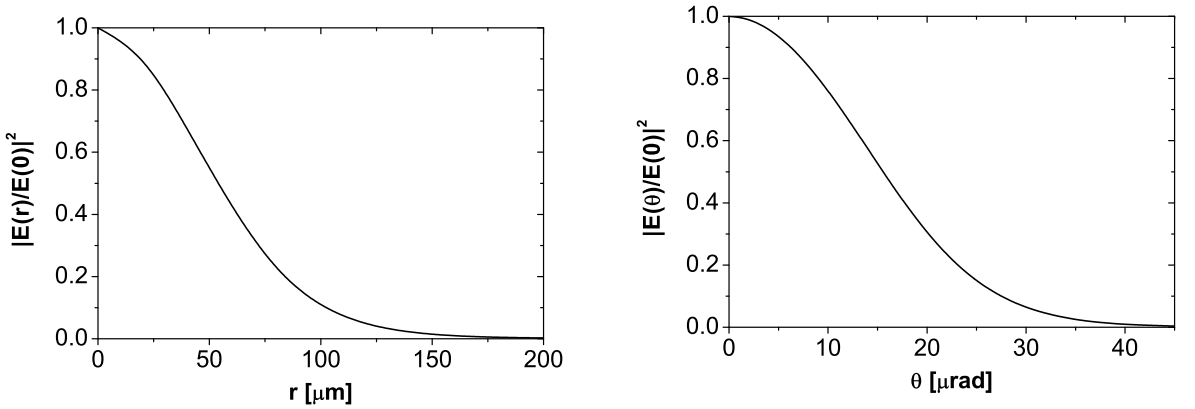

Fig. 15. Radial distribution of the X-ray SASE pulse intensity at the undulator exit (left plot) and its intensity distribution in the far zone (right plot) for the short wavelength mode at a. radiation wavelength of 6.4 nm.

tunable in a wide range: $200 - 900$ nm for the optical pulses, and $6 - 120$ nm for the X-ray pulses. Both pulses have diffraction limited angular divergence. The spectral width of the optical pulse is transform limited. Finally and most important, optical and X-ray pulses are precisely synchronized at a femtosecond level, since they both are produced by the same electron bunch, and there are no reasons for any time jitter between the pulses. Based on these unique features a pump-probe facility could be built with unique possibilities for studying time dependent processes on the time scale of chemical reactions. It is worth to mention that the Nobel prize in chemistry in 1999 was awarded to A. Zewail for pump-probe experiments using a quantum laser (40 fs pulse duration) operating in the visible range. The combination of visible light and X-rays would add the new dimensions of element specificity and direct structural information.

A two-color FEL amplifier could be realized at the TESLA Test Facility rather quickly and with moderate cost expenses for the required components, i.e. a seed laser, two optical undulators, and a dispersion section The tunable-gap optical undulators would be similar to insertion devices used at DORIS. Initially one could use a commercially available long (nanosecond) pulse dye laser with a repetition rate of 10 Hz. This could later be replaced by an OPA laser system similar to the one currently under development at TTF [3] in order to operate the system at the full repetition rate of the LINAC.

Acknowledgments

We thank R. Brinkmann, J. Krzywinski, E.A. Matyushevskiy, J. Rossbach, and M. Tischer for many useful discussions. We thank C. Pagani, J.R. Schneider, D. Trines, and A. Wag-

Table 2
Properties of the radiation pulses of the two-color pump-probe facility

Parameter	Units	Femtosecond mode	Short wavelength mode
Optical pulse			
Wavelength	nm	200-900	
Pulse energy	mJ	0.1–0.5	1–5
Pulse duration (FWHM)	fs	30-100	150
Peak power	GW	2	5–15
Spectrum width		Transform-limited	
Spot size (FWHM)	μm	150–200	80–120
Angular divergence* (FWHM)	μrad	100–500	150–700
Repetition rate	Hz	10 (10^4)	
X-ray SASE pulse			
Wavelength	nm	30–120	6–30
Pulse energy	mJ	0.1	1
Pulse duration (FWHM)	fs	30-100	150
Peak power	GW	2	2
Spectrum width	%	0.4–0.6	0.3–0.6
Spot size (FWHM)	μm	350–1400	140–210
Angular divergence (FWHM)	μrad	40–150	20–70
Repetition rate	Hz	10 (10^4)	

*Diffraction limited

ner for interest in this work.

References

[1] V. Ayvazyan et al., Phys. Rev. Lett. **88**(2002)10482.

[2] H. Wabnitz et al., Nature **420**(2002)482.

[3] "Development of a pump-probe facility with sub-picosecond time resolution combining a high-power optical laser and a soft X-ray free electron laser": Joint DESY (Germany), Forschungszentrum Juelich (Germany), Max-Born Institute Berlin (Germany), Dublin City University (Ireland), MAX-Lab/Lund Laser Centre (Sweden), and CNRS/LURE, Orsay (France) Proposal. Available at DESY by request only.

[4] E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov, Opt. Commun. **205**(2002)385.

[5] J. Feldhaus et al., Opt. Commun. **140**(1997)341.

[6] E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov, Nucl. Instrum. and Methods **A429**(1999)233.

[7] SASE FEL at the TESLA Test Facility, Phase2, TESLA-FEL 2002-01, DESY, Hamburg, Germany.

[8] A VUV Free Electron Laser at the TESLA Test Facility at DESY, Conceptual Design report, Deutsches Elektronen-Synchrotron, DESY, TESLA-FEL 95-03, DESY, Hamburg, Germany.

[9] Ph. Piot, TESLA-FEL 2002-08, DESY, Hamburg, Germany.

[10] P. Czonka, Part. Accel. **8**(1978)225.