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SASE free electron lasers as short wavelength coherent sources

From first results at 100 nm to a 1 Å X-ray laser

R. Treusch[a] and J. Feldhaus

Hamburger Synchrotronstrahlungslabor HASYLAB at Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22603 Hamburg, Germany

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Abstract. During the last few years free electron lasers (FELs) based on self-amplified spontaneous emission (SASE) have been demonstrated at wavelengths of 12 μm [1], 830 nm [2], 530 nm [3] and 385 nm [3], and around 100 nm [4]. Recently, saturation has been observed in the vacuum ultraviolet (VUV) spectral region between 82 nm and 125 nm at the TESLA Test Facility (TTF) at DESY. The radiation pulses have been characterized with respect to pulse energy, statistical fluctuations, angular divergence and spectral distribution, both in the linear gain and in the saturation regime of the FEL [5,6]. The results are in good agreement with theoretical simulations, providing a solid basis for other projects aiming at still shorter wavelengths down to the 0.1 nm range [7,8].

PACS. 41.60.Cr Free-electron lasers – 42.25.Fx Diffraction and scattering – 42.25.Kb Coherence – 29.17.+w Electrostatic, collective, and linear accelerators – 41.75.Lx Other advanced accelerator concepts – 36.40.Qv Stability and fragmentation of clusters

1 Introduction

In a SASE FEL, lasing occurs within a single pass of a relativistic, high-quality electron bunch through a long undulator. Starting from shot noise (spontaneous emission) of the electron beam, the radiation power grows exponentially along the undulator [9]. This self-amplification of spontaneous undulator emission is initiated by an increasingly pronounced charge density modulation of the electron bunch. The longitudinal distribution of electrons in the bunch is “cut” into equidistant slices with a separation corresponding to the wavelength of the emitted radiation which causes the modulation. More and more electrons thus begin to radiate in phase, which results in an increasingly coherent superposition of the radiation emitted from the “micro-bunched” electrons. The more intense the electromagnetic field gets, the more pronounced the longitudinal density modulation of the electron bunch becomes and *vice versa*, hence leading to exponential gain of the output radiation intensity. At saturation, typically around 1‰ of the electron beam energy has been transferred into the electromagnetic radiation field, corresponding to a gain between 10^7 and 10^9.

[a] e-mail: rolf.treush@desy.de

2 Experimental results

On February 22, 2000, the FEL at the TESLA Test Facility (TTF) showed first SASE at a radiation wavelength of 109 nm [4]. Since then, the performance of the superconducting linear accelerator and the FEL was continuously optimized yielding saturation of the output radiation in September 2001 [5,6].

A measured gain curve at 98 nm wavelength is shown in Figure 1. The curve was obtained by varying the active undulator length over which the FEL interaction (SASE) took place. This was realized by powering electromagnetic steerers along the undulator to “turn off” the overlap between the electron bunch and the radiation field beyond a certain position and thereby preventing further amplification. The power gain length derived from this curve is 67 cm. The average radiation pulse energy at saturation is 30–100 μJ depending on the tuning of the accelerator. Energy fluctuations from pulse to pulse are observed which are characteristic of SASE. The probability distribution of the measured intensities is in full agreement with theoretical calculations [6,9,10].

The angular divergence of the radiation is significantly smaller than that of the spontaneous undulator radiation indicating a high degree of coherence. This is corroborated by the double slit diffraction pattern depicted in Figure 2. The image was taken from a Ce:YAG screen about 3 m behind the slits which were located 12 m behind the undulator. The high fringe visibility is a clear indication of

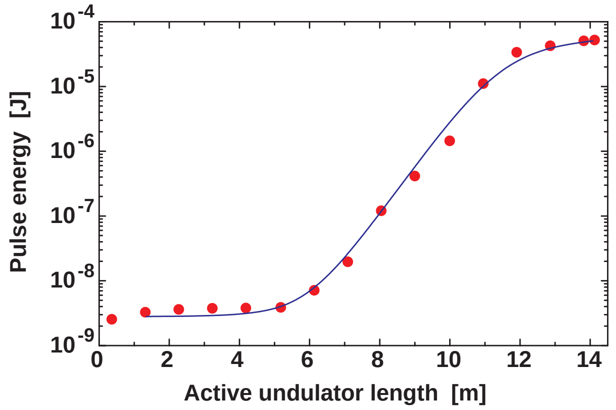

Fig. 1. Average energy of the FEL radiation pulse as a function of the active undulator length (see text). Circles: measurement, line: simulation. For details see [5,6].

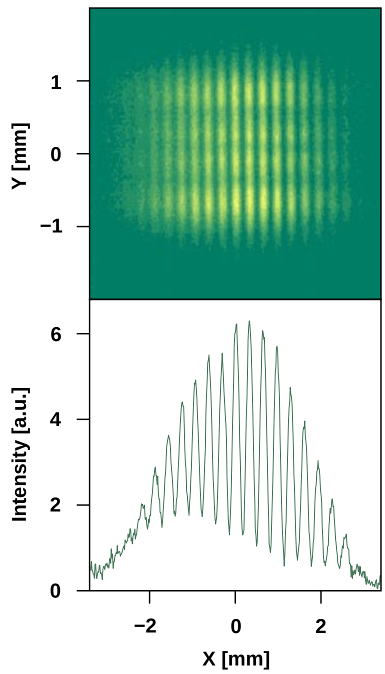

Fig. 2. Top: double slit diffraction pattern of the FEL beam at $\lambda = 95$ nm. Bottom: horizontal cut through the center of the diffraction pattern above. The slits were 2 mm long, 200 μm wide, and 1 mm apart.

almost full transverse coherence of the FEL radiation (a detailed investigation can be found in [11]).

The temporal coherence is only partial, which is reflected by a spectrum with not only one but several lines. The pulse duration could be varied from about 50 fs to 200 fs. It depends sensitively on the electron bunch compression providing the high peak current required for lasing. Figure 3 gives an example of two spectra for different bunch compression settings. Table 1 summarises the parameters of the TTF FEL at saturation.

The GW level VUV pulses have also been used for first exploratory experiments on gases [12] and solids [13] demonstrating the unique properties of the new source.

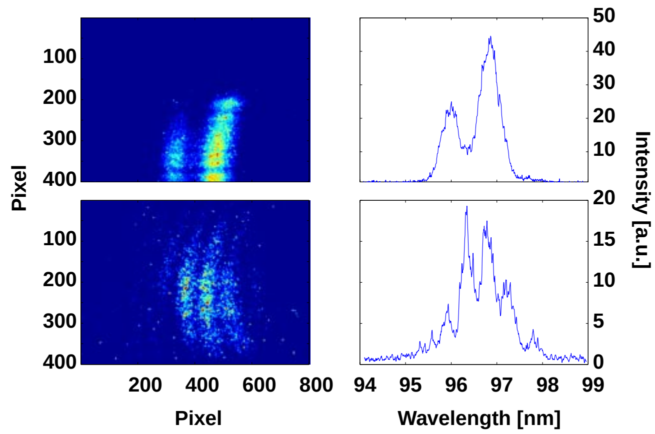

Fig. 3. Single shot FEL spectra for different electron bunch compressor settings. The images on the left were recorded with a gated ICCD camera attached to a 1 m normal incidence monochromator. The spectra on the right are horizontal cuts through the images. The distinct peaks arise from the superposition of several longitudinal modes of the FEL radiation which vary statistically from shot to shot. The width of the spikes is related to the pulse duration [9]. For more details see [6].

Table 1. Measured parameters of the FEL in phase 1 of the TESLA test facility (TTF 1).

wavelength range (with saturation power)	82–125 nm
pulse energy	30–100 μJ
pulse duration (FWHM)	50–200 fs
peak power level	1 GW
average power	up to 5 mW
spectral width (FWHM)	1%
spot size at undulator exit (FWHM)	250 μm
angular divergence (FWHM)	260 μrad
peak brilliance	$\geq 2\times10^{28}$ ⋆

⋆: photons/(s mm^{2}mrad^{2}0.1% bandwidth).

As an example, we show some results from a study of Xe atoms and clusters in the focused FEL beam with power densities up to a few times 10^{13} W/cm^2. While Xe atoms absorb at most one photon and become singly ionized, the absorption in clusters is strongly enhanced (see Fig. 4). At 7×10^{13} W/cm^2 and 98 nm wavelength, each atom in large clusters absorbs up to 400 eV energy on average, which corresponds to about 30 photons. The clusters completely disintegrate in a Coulomb explosion. The current understanding is that the cluster ionization proceeds mainly by thermionic electron emission.

Currently an energy upgrade of the TTF linear accelerator to 1 GeV is being prepared which will make radiation wavelengths down to 6 nm available for users. The design parameters are listed in Table 2.

At the same time other important projects for a VUV FEL user facility (Fig. 5) are in progress such as online photon diagnostics, a synchronised optical laser system for time resolved pump-probe measurements, and a

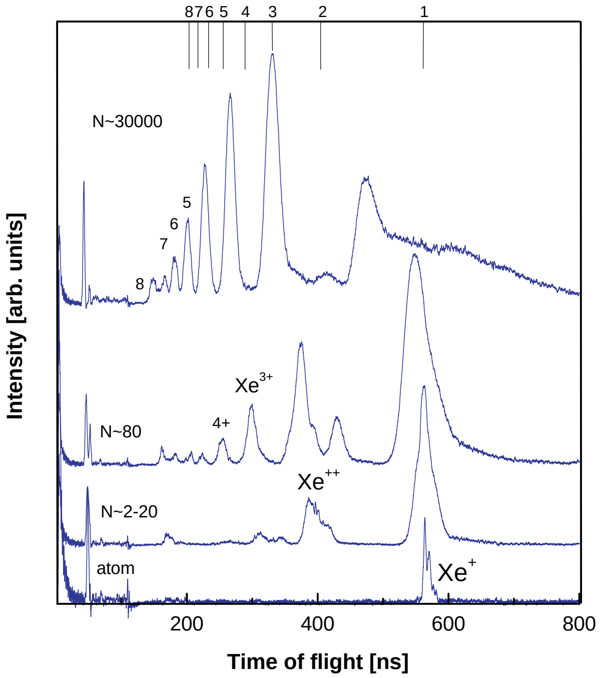

Fig. 4. Time-of-flight (TOF) mass spectra of the ionization products of Xe atoms and clusters after being exposed to 98 nm FEL radiation at an average power density of 2×10^{13} W/cm^2. The atomic spectrum at the bottom exhibits a splitting of the Xe^+-line arising from different isotopes. After irradiation of clusters, highly charged ions are observed. They possess high kinetic energy which is indicated by the shift of the lines with respect to the calculated flight times indicated by the thin vertical lines on the top. N is the number of atoms per cluster. For more details see [12].

Table 2. Design parameters of the FEL in phase 2 of the TESLA test facility (TTF 2).

wavelength range	60–6 nm
photons per pulse	2×10^{14}–2×10^{13}
pulse energy	60–600 μJ
pulse duration (FWHM)	$\leq$ 200 fs
peak power	0.3–2.8 GW
average power	20–40 W
spectral width (FWHM)	$\approx$ 0.5 %
spot size at undulator exit (FWHM)	340–190 μm
angular divergence (FWHM)	107–24 μrad
peak brilliance	2×10^{28}–2×10^{30} $\star$

$\star$: photons/(s mm^{2}mrad^{2}0.1% bandwidth).

two-undulator self-seeding setup to improve the temporal coherence of the radiation [14].

The project review for the first round of research proposals was completed in September 2002. The submitted proposals reflect a broad variety of ground-breaking experiments with the new source, ranging from atomic, molecular and cluster physics, condensed matter physics and plasma physics to chemistry and biology.

Fig. 5. Aerial view of the experimental hall for the FEL User Facility (front, center) and the tunnel for the TTF phase 2 extension behind it (covered with grass). The hall in the upper right corner houses the TTF phase 1 FEL.

3 Summary and outlook

SASE FELs are presently unrivaled radiation sources in a spectral range that is hardly accessible with conventional lasers (the peak intensities of high harmonics generations schemes using conventional table top lasers are exceeded by two to three orders of magnitude). They deliver extremely intense, coherent radiation with short pulse length and a broad wavelength tunability. The VUV FEL at the TESLA Test Facility has successfully demonstrated SASE at wavelengths from 80 to 180 nm and reached saturation from 82 to 125 nm with GW peak power and pulse lengths around 100 fs. Starting in 2004, the phase 2 extension of TTF will deliver FEL radiation down to soft X-rays with a minimum wavelength of about 6 nm in the first harmonic and reaching into the "water window" in the higher harmonics.

The final goal is an X-ray Free Electron Laser (XFEL) laboratory [8,15] which has been proposed in the frame of the TESLA [16] project. A peak brilliance in the order of 10^{34} photons/(s mm^2 mrad^2 0.1%BW) is expected at photon energies from 500 eV to 14.4 keV, *i.e.* at minimum wavelengths around 0.1 nm. A number of experiments located behind several independent FEL undulators will then in parallel be provided with beam. The undulators will be fed with electron bunches by one linear accelerator in an alternating manner via fast switching devices.

References

1. M.J. Hogan *et al.*, Phys. Rev. Lett. **81**, 4867 (1998)
2. A. Tremaine *et al.*, Nucl. Instrum. Meth. A **483**, 24 (2002)
3. S.V. Milton *et al.*, Science **292**, 2037 (2001)
4. J. Andruszkow *et al.*, Phys. Rev. Lett. **85**, 3825 (2000)
5. V. Ayvazyan *et al.*, Phys. Rev. Lett. **88**, 104802 (2002)
6. V. Ayvazyan *et al.*, Eur. Phys. J. D **20**, 149 (2002)
7. M. Cornacchia *et al.*, Linac Coherent Light Source (LCLS) design study report, SLAC-R-521 (1998)
8. TESLA Technical Design Report, Part V: The X-Ray Free Electron Laser, edited by G. Materlik, Th. Tschentscher, DESY 2001-011 available at `http://tesla.desy.de/new_pages/TDR_CD/PartV/fel.html` and `http://tesla.desy.de/new_pages/tdr_update/start.html`
9. E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov, *The Physics of Free Electron Lasers* (Springer, Berlin, 1999) and references therein
10. V. Ayvazyan *et al.*, Study of the statistical properties of the radiation from a VUV SASE FEL operating in the femtosecond regime, *Proceedings of the 24th International Free Electron Laser Conference* (FEL 2002), Argonne, IL, USA, September 2002, to be published in Nucl. Instrum. Meth. A
11. R. Ischebeck *et al.*, Study of the Transverse Coherence at the TTF Free Electron Laser, *Proceedings of the 24th International Free Electron Laser Conference* (FEL 2002), Argonne, IL, USA, September 2002, to be published in Nucl. Instrum. Meth. A
12. H. Wabnitz *et al.*, Nature **420**, 482 (2002)
13. A. Andrejczuk *et al.*, HASYLAB Ann. Rep. **1**, 117 (2001), available at `http://www-hasylab.desy.de/science/annual_reports/2001_report`
14. `http://www-hasylab.desy.de/facility/fel/vuv/projects/`
15. `http://www-hasylab.desy.de/facility/fel`
16. TESLA Technical Design Report, DESY 2001-011/ECFA 2001-209 (2001) and `http://tesla.desy.de`