RESULTS FROM FLASH

J. Rossbach, Universität Hamburg and DESY, 22603 Hamburg, Germany
for the FLASH team

Abstract

After a brief introduction to the basic idea of SASE FELs and its present state of realization, the latest results from the VUV-FEL at DESY, now called FLASH, are reported. The paper presents an overview of the facility and measurements of the internal electron bunch structure taken at ~20 fs resolution. Considerable agreement with numerical beam dynamics simulation is found, indicating that electron beam dynamics in the femtosecond domain, heavily affected by coherent synchrotron radiation and Coulomb forces, is well under control, both theoretically and experimentally. FEL lasing at wavelengths down to 13 nm is reported, with radiation pulses as short as 25 fs. Both spectra and brilliance are in agreement with expectations.

INTRODUCTION

Over the past 30 years, the synchrotron radiation has been developed into a most powerful research tool with applications in many different fields of science ranging from physics, chemistry and biology to material sciences, geophysics and medical diagnostics. Rapid progress was driven by improvements in the technology of electron storage rings and undulators thus providing increasingly brilliant sources of synchrotron radiation. The radiation generated in these devices is based on spontaneous radiation of many electrons uncorrelated in space and time. As a consequence, the radiation power scales linearly with the number N_e of electrons, and the radiation exhibits only limited coherence in space and time.

In order to increase the power and the coherence of the radiation one has to force the electrons to emit coherently by compressing them into a length small compared to the wavelength of the radiation. Passing such a "point-like" bunch of relativistic energy electrons through an undulator would cause a dramatic boost of the radiation power P_{rad} $\sim N_e^2$ with N_e the number of electrons in the bunch. Such a tight compression on an entire bunch is not possible for wavelengths in the nanometer regime. However, if one succeeds to arrange a large number of "point-like" bunchlets longitudinally into a periodic array, with the periodicity given by the wavelength of radiation, one obtains indeed coherent radiation of these bunchlets with the additional advantage of compressing all the radiation into a narrow forward cone. The principle of the Free-Electron Laser (FEL) [1] is based on this idea.

In an FEL, the density of an electron bunch is modulated with the periodicity of the radiation wavelength λ_{ph} by a resonant process taking place in the combined presence of the periodic transverse magnetic field of an undulator and the electromagnetic radiation generated in this same magnet. The wavelength λ_{ph} of the first harmonic of the FEL radiation is related to the period length λ_u of a planar undulator by

$$\lambda_{ph} = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right), \qquad (1)$$

where $\gamma=E/(m_ec^2)$ is the relativistic factor of the electrons, and $K=eB_u\lambda_u/2\pi m_ec$ is the "undulator parameter" with B_u being the peak magnetic field in the undulator. Eq. (1) exhibits two main advantages of the free-electron laser: the free tunability of the wavelength by changing E or B_u and the possibility of achieving very short wavelengths by using ultra-relativistic electrons.

For most FELs presently in operation [2], the electron beam quality and the undulator length result in a gain in radiation power of up to a few 100% per undulator passage, making it necessary to use an optical cavity and a synchronized multi-bunch electron beam to build up high brightness upon several round-trips of the radiation in the cavity.

If one aims at very short wavelengths, where good mirrors are unavailable, high-gain FEL amplification [3,4] up to laser saturation is required within a single passage of the electron beam. This requires extreme parameters of the electron beam and a long undulator. In this mode, the radiation power $P(z)$ is expected to grow exponentially with the distance z along the undulator.

In order to become independent of the availability of a seed laser providing the input power at the desired wavelength, the spontaneous undulator radiation from the first part of the undulator can be used as an input signal to the amplification process. Since a decade, FELs based on this Self-Amplified-Spontaneous Emission (SASE) principle [5] are considered the most promising candidates for extremely brilliant, coherent light sources with wavelengths down to the Angström regime [6-9].

A key quantity relevant for the technical realization is the undulator length required to reach laser power saturation. It can be expressed by the power e-folding length L_g called gain length, given by

$$L_g = \frac{1}{\sqrt{3}}\left[\frac{2mc}{\mu_0 e}\frac{\gamma^3\sigma_r^2\lambda_u}{K^2\hat{I}}\right]^{1/3}$$

in 1D theory [4]. It is seen, that with increasing beam energy γ (i.e. decreasing wavelength λ_{ph}) it becomes more and more difficult to achieve saturation within an acceptable undulator length. Only to some extent this tendency can be compensated by a small transverse electron beam size σ_r and a large peak current $\hat{I}$ inside the bunch. In conjunction with further technical challenges, it was thus the objective of worldwide R&D during the past decades to demonstrate SASE FELs at

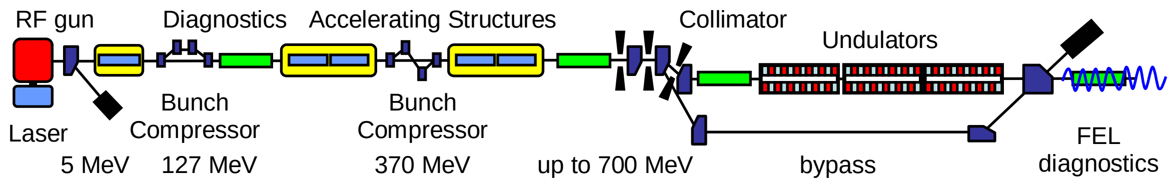

Figure 2: Schematic layout of the *F*ree-Electron *Las*er in *H*amburg, FLASH at DESY.

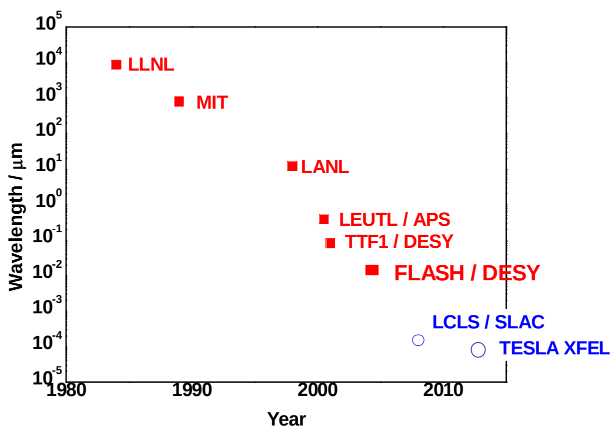

Figure 1: Progress on wavelengths achieved at SASE FELs vs year of 1st operation. Red squares: Successful demonstration, in most cases reaching laser saturation; Blue dots: Projects under way.

smaller and smaller wavelengths. An incomplete illustration of this process is shown in Figure 1.
FLASH is based on the TESLA Test Facility (TTF), a superconducting linear accelerator constructed within the TESLA collaboration [10]. It was built in basically two stages: TTF1 FEL reached FEL gain saturation at wavelengths between 80 and 120 nm in 2001 [11,12]. In a second phase, the linac was upgraded and the undulator was extended to 30 m length. This device, designed for ultimately 1 GeV beam energy and 6 nm wavelength, was called VUV-FEL. In April, 2006, it was
renamed as FLASH (*F*ree-Electron *Las*er in *H*amburg).

The installation has three key missions:

- FEL user operation.
- FEL studies to improve the performance of FLASH, and to learn about short-wavelength FELs in general.
- Studies on high-gradient superconducting linac technology ("TESLA Technology").

FLASH LAYOUT

A schematic layout of FLASH is shown in Figure 2. The electron bunches are produced in a laser-driven photoinjector [13-15] and accelerated to up to 700 MeV. Bunch charges between 0.5 and 1.5 nC are used.

At intermediate energies of 125 MeV and 380 MeV the electron bunches are longitudinally compressed in magnetic chicanes [16-18], thereby increasing the peak current from initially 50-80 A to approximately 1-2 kA as required for FEL operation. The 30 m long undulator [19] consists of NdFeB permanent magnets with a fixed gap of 12 mm, a period length of $\lambda_u = 27.3\mathrm{mm}$ and a peak magnetic field $B_u = 0.47$ T .

ELECTRON BEAM PARAMETERS

Longitudinal Phase Space

The electron bunches are generated from a Cs_2Te cathode illuminated by a Gaussian shaped UV laser pulse with 4 ps rms duration, generated in a mode-locked solid-state laser system (Nd:YLF) synchronized with the rf. Since the bunch length extends over a non-negligible fraction of the the rf wavelength of 23 cm, the particles in the bunch acquire a position-dependent momentum variation during the acceleration. See Figure 3.

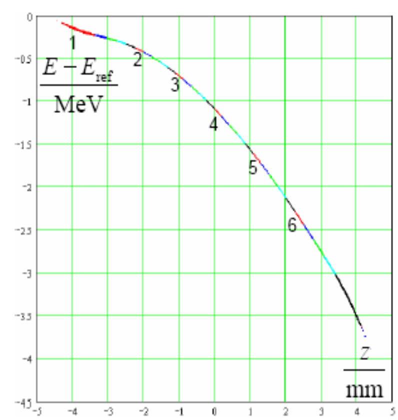

Figure 3: Longitudinal momentum distribution in front of the first bunch compressor. Different slices of the bunch are colour coded for easier identification of what happens during stage of compression.

This energy-position correlation is utilized, and optimized, to reduce the bunch length in two "bunch compressors", consisting of two magnetic chicanes. Figure 4 illustrates the longitudinal phase space distribution 1 m after the exit of the first bunch compressor predicted by numerical simulation. It is seen that the phase space distribution is distorted at the head of the bunch due to combined interaction of the electrons with space charge Coulomb forces and coherent synchrotron radiation (csr) generated in the bending magnets of the chicane. For details on beam dynamics simulation in presence of csr, see Ref. [18].

This interaction becomes even more pronounced during final compression. Figure 5 shows the calculated longitudinal phase space distribution in front of the undulator. csr effects are very pronounced in the head of the bunch, which is the only part of the bunch achieving high enough peak current as to expect FEL gain saturation.

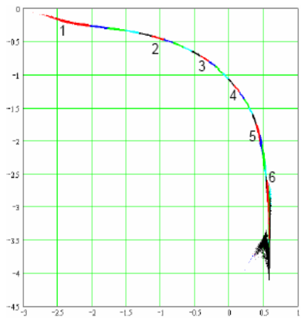

Figure 4: Longitudinal momentum distribution 1 m after the first bunch compressor. The head of the bunch is to the right.

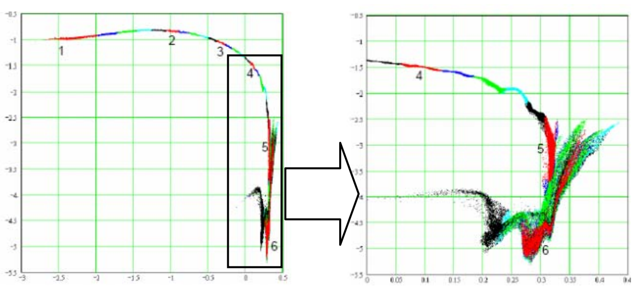

Figure 5: Longitudinal momentum distribution on front of the undulator. The plot on the r.h.s. shows the head of the bunch zoomed.

Csr effects do not only distort the momentum distribution but also the transverse phase space. As a consequence, not all the particles within the head of the bunch have an emittance sufficiently small for lasing. Figure 6 indicates the current distribution resulting from Figure 5 (colours representing the respective particles in Figure 5). The black curve indicates *that* fraction of the particles located within an emittance smaller than the tolerable one ($\varepsilon^{n}_{x,y} \le 3\cdot 10^{-6}\pi\text{m}$). This part of the bunch achieves a peak current of 1400 A and is only approx. 60 fs (FWHM) long. According to FEL simulation [17], such a beam would generate a radiation pulse approx. 30 fs (FWHM) in length, which agrees nicely with the pulse length measured at FLASH (see below).

Various techniques have been established at DESY to determine the longitudinal bunch current profile experimentally [20-22]. One of the most powerful ones makes use of a transverse deflecting mode cavity resonator ("LOLA")[23,24]. LOLA's capability of resolving very detailed longitudinal features of the bunch is illustrated in Figure 7.

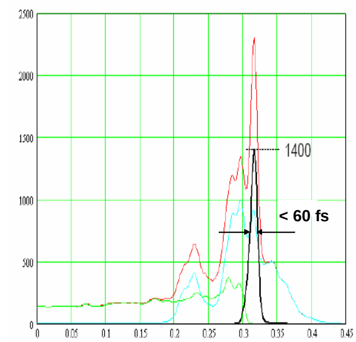

Figure 6: Predicted current distribution in front of the undulator according to beam dynamics calculations.

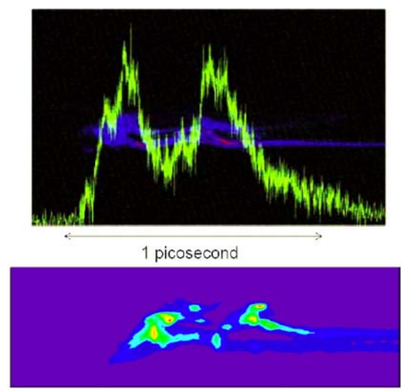

Figure 7: Longitudinal charge distribution within a single electron bunch of FLASH at DESY. Upper part: Image of the bunch on an observation screen, located downstream of the transverse mode cavity LOLA streaking the bunch transversely by a time dependent electro-magnetic field. The horizontal direction corresponds to the time. Only the part containing the spike at the head of the bunch is shown. The (green) solid curve shows the charge density profile projected onto the longitudinal position, i.e. the current profile. In this particular setting of bunch compression parameters, the spike is actually split into two parts approx. 300 fs apart, each part being shorter than 120 fs /(FWHM). The lower part of the figure shows the prediction of numerical beam dynamics simulation.

According to theory, csr plays an important role in beam dynamics, but one would like to disentangle also experimentally to what extent the momentum distribution is distorted by csr, and to what extent by Coulomb forces. This is illustrated in Figure 8, showing the momentum distribution inside the bunch measured with LOLA (followed by a dispersive section) [21]. With only little bunch compression, there is no distortion of the momentum distribution. However, if the bunch is over-compressed such that the bunch is small only inside the chicane, but long outside, there is a considerable momentum shift of the bunch centroid, again in agreement with simulations. As the bunch is long outside the chicane, this effect can indeed only be attributed to csr.

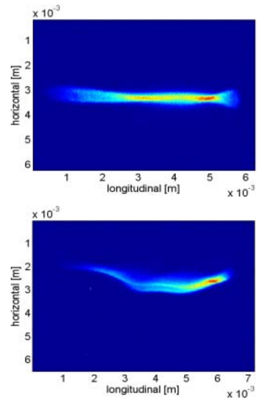

Figure 8: Measured momentum distribution without (top) and with (bottom) strong csr forces being present.

Synchronizsation on the fs level

The radiation pulses length being in the 30 fs range, it is important for users to have the pulses arriving at a time jitter well below 100 fs with respect to a reference clock that can be used for a pump-probe set-up. Techniques are under development with this goal [25-27], involving electro-optical detection of bunch arrival time, a stabilized optical fibre transmission line and an optical-only master clock system. Presently, a bunch–to-bunch time arrival stability of 200 fs rms has been verified.

PHOTON BEAM PARAMETERS

Lasing at 32 nm is illustrated by the spectrum shown in Figure 9. The observed energy of individual pulses is up to 130 µJ, with a length of (25 ± 5)fs. Thus, the peak power exceeds 4 GW. Also, considerable radiation power is observed at the 2nd and 3rd harmonics, indicating that the FEL is operating in the saturation regime.

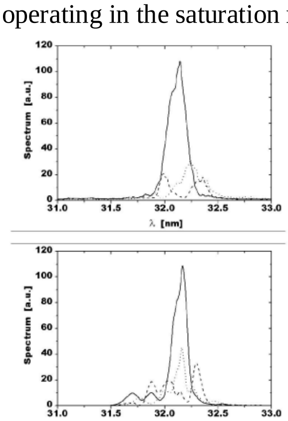

Figure 9. Top: Three different single-shot wavelength spectra of FEL radiation pulses at 32 nm wavelength measured at FLASH. A pulse length of ~25 fs can be inferred from the width of individual spikes in the spectrum [28]. Bottom: Predicted spectrum for three different electron statistics seeds [17]. Note that the number of spikes in the spectrum is in average equal to the number of spikes (coherent wave packets) in the time domain.

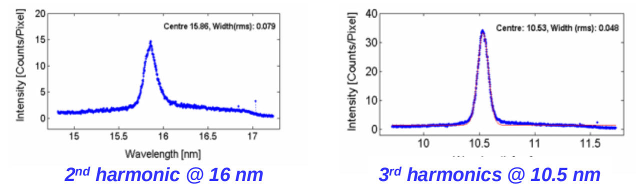

Figure 10. Second and third harmonics spectra averaged over 4000 radiation pulses.

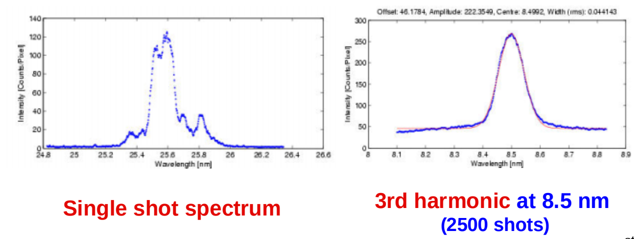

Figure 11. Single shot spectrum at 25 nm wavelength (1st harmonics) (left), and corresponding 3rd harmonics spectrum (right).

Correspondingly, Figure 11 shows a single shot spectrum at 25 nm, together with its 3rd harmonics spectrum, averaged over 2500 shots.

A large degree of >80% transverse coherence can be concluded from double-slit diffraction measurements, illustrated in Figure 12 for a slit distance of 0.15 mm.

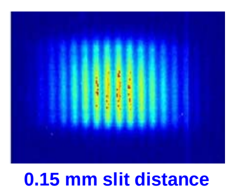

Figure 12. Double-slit diffraction pattern taken at 25 nm wavelength.

Most recently, at 690 MeV electron energy, FLASH succeeded in lasing at 13 nm (1st harmonics, see Figure 13), with pulse energies exceeding 30 µJ. From the numbers quoted, the peak brilliance achieved at FLASH is estimated at

$5 \cdot 10^{29}$ photons/(s $\cdot$ mrad^2 $\cdot$ mm^2 $\cdot$ 0.1%BW), with an estimated uncertainty of a factor of two. As indicated in Figure 14, this brilliance exceeds the state-of-the-art of synchrotron radiation sources by some eight orders of magnitude, and is in reasonable agreement with the expected performance.

The FEL radiation as described above is routinely delivered to scientific users. So far, 16 teams of users have been supplied with FEL beam at various wavelengths.

CONCLUSION

FEL lasing at wavelengths down to 13 nm in the first harmonics has been demonstrated at FLASH, and is being delivered routinely to users. Pulses are as short as 25 fs, and the peak brilliance exceeds all existing sources at this wavelength by orders of magnitude. Electron beam dynamics is well under control on the fs level. This achievement, both in terms of FEL physics and accelerator technology, provides a solid basis for future FEL projects, in particular for the planned European XFEL laboratory which is based on the same technology.

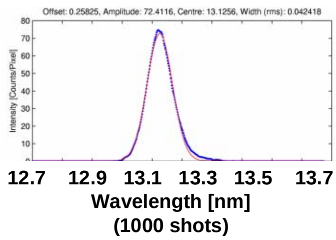

Figure 13. Averaged spectrum of 1000 pulses at FLASH tuned for 1st harmonics at 13 nm wavelength.

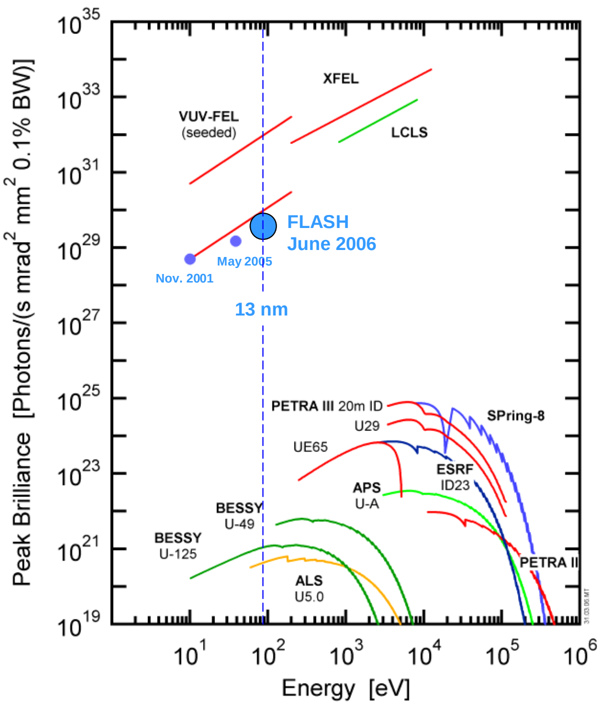

Figure 14. Peak brilliance demonstrated at FLASH (dots), compared with expected values (solid line), with values of some FELs under construction (LCLS) or proposed (European XFEL), and with values of state-of-the-art synchrotron radiation sources.

REFERENCES

[1] J.M.J. Madey, J Appl. Phys. **42**, 1906 (1971)

[2] W.B. Colson, B.W. Williams, Proc. 26th Intl. FEL Conf, Trieste, Italy, 706 (2000)

[3] K.J. Kim, Phys. Rev. Lett. **57,** 1871 (1986)

[4] E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov, *The Physics of Free-Electron Lasers* (Springer, 1999) and references therein

[5] A.M. Kondratenko, E.L. Saldin, Part. Accelerators **10**, 207 (1980)

[6] H. Winick et al., Proc. PAC, Washington and SLAC-PUB-6185 (1993)

[7] R. Brinkmann, et al., Nucl. Instr. Meth. **A 393**, 86 (1997)

[8] TESLA Technical Design Report, edited by F. Richard et al., DESY 2001-011 and http://tesla.desy.de

[9] For an overview, see C. Pellegrini, this conference FRYBPA01

[10] The TTF FEL team, DESY Print TESLA-FEL 2002-01 (2002)

[11] V. Ayvazyan et al., Phys. Rev. Lett. **88**, No.10 (2002)

[12] V. Ayvazyan, et al., Eur. Phys. J. **D 20**, 149 (2002)

[13] M. Krasilnikov et al., Proc. EPAC 2004 Conf., 260 (2004)

[14] S. Schreiber, Proc. EPAC 2004 Conf., 351 (2004)

[15] K. Flöttmann, Ph. Piot, Proc. EPAC 2002 Conf., 1798 (2002)

[16] T. Limberg et al., Proc. EPAC 2002 Conf., 811 (2002)

[17] E.L. Saldin et al., DESY Print TESLA-FEL 2004-06 (2004)

[18] M. Dohlus, this conference WEYFI01

[19] J. Pflüger, Nucl. Instrum. Meth **A** 445, 366 (2000)

[20] H. Schlarb, this conference, THXPA03

[21] M. Roehrs, this conference, MOPCH014

[22] H. Delsim-Hashemi, this conference, MOPCH016

[23] P. Krejcik, et al., Proc. 2003 Part. Acc. Conf, 423 (2003)

[24] R. Akre et al., Proc. EPAC 2002 Conf. (2002)

[25] B. Steffen, et al., this conference, TUPCH027

[26] A. Winter, et al., this conference, TUPCH028

[27] F. Löhl, this conference, THOBFI01

[28] V. Ayvazyan, et al., Eur. Phys. J. **D 37**, 297 (2006)