REVIEW OF DESY FEL ACTIVITIES

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Abstract

Deveolopment, construction and operation of free-electron lasers delivering radiation in the VUV and X-ray regime down to wavelengths in the Ångstrøm range are presently among the key activities at DESY, Hamburg, Germany. The focus is on the Free-electron LASer in Hamburg, FLASH already running for users and on the European free-electron laser laboratory XFEL being under progress within an international collaboration. Both project are tighly related to each other in the sense that, to a large extent, identical concepts and technologies are used such that FLASH can be considered a prototype for the XFEL. The talk reports on the achievements at FLASH and on the status of both projects.

INTRODUCTION

The basic concept of a free-electron laser (FEL) is based on the fact that, according to classical electro-dynamics, a point-like charge $Q = N_e \cdot e$ radiates at a power $P_{rad} \sim N_e^2$, with N_e the number of electrons moving at ultrarelativistic speed and oscillating transversely to its mean direction of motion with an amplitude *a*:

$$P_{rad} = \frac{Q^2 a^2}{4\pi\varepsilon_0 3c^3}\gamma^4 \tag{1}$$

Here $\gamma = E/(m_e c^2)$ is the relativistic factor of the electrons. This is in contrast to spontaneous radiation of electrons in standard synchrotron radiation which scales linearly with N_e since electrons are uncorrelated in space and time.

The problem in making full profit of Eq. (1) is, that it holds only for a point-like charge distribution, and "point-like" refers to an electron bunch length shorter that the wavelength radiated. Aiming at wavelengths well below 1 µm, it becomes obvious that it is technically impossible to generate such electron bunches with charges in the pC to nC range from any existing electron source. The way out is to start with a much longer electron bunch and to find a mechanism cutting the electron bunch longitudinally in thin slices "automatically". The FEL provides such a mechanism. 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 an electromagnetic wave [1-4]. This leads to an exponential growth of radiation power while the electron bunch is passing the long undulator, see Fig. 1. The amplification works only within a small bandwidth around the FEL resonance wavelength:

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

which is identical to the wavelength of spontaneous undulator radiation. Here, λ_u is the undulator wavelength, $K = eB_u\lambda_u/2\pi m_e c$ the "undulator parameter", and B_u the peak magnetic field in the undulator. If the electro-magnetic field in the first part of the FEL undulator is given by the spontaneous undulator radiation, the device is said to operate in the Self-Amplified Spontaneous Radiation (SASE) mode [5] which provides a simple and robust operation at short wavelengths where good sources for external seeding are hardly available.

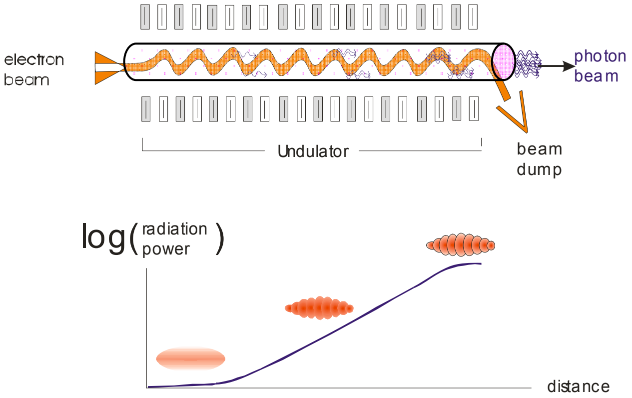

Figure 1: Schematic of a single-pass free-electron laser. Top: Electron beam moving in the alternating field of an undulator, superimposed with an electro-magnetic wave of adequate wavelength. Note that the direction of oscillation is in fact perpendicular to the direction of the magnetic field. Bottom: Exponential growth of radiation power and gradually developing modulation of charge density within the bunch.

In order to achieve a reasonably small e-folding length of the gain process, the bunch must provide a very small emittance and a peak current in the kA range. To this end, magnetic chicanes are inserted at beam energies high enough that space charge forces are sufficiently suppressed by relativistic effects. Meeting the kA peak-current requirement results almost automatically in bunch lengths in the 10-100 fs range. Such bunches generate radiation pulses in the FEL of the same duration or even shorter, which is, besides the spectacular peak brilliance, a feature of outmost importance for many users.

DESIGN FEATURES AND STRATEGY

DESY's involvement in short-wavelength FELs started in 1994 with the approval of the construction of an FEL user facility (now called FLASH) based on an upgrade of

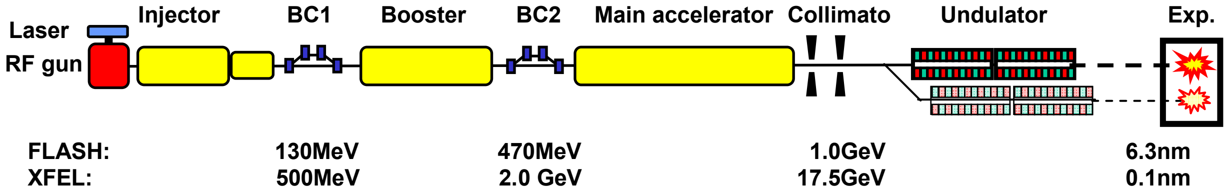

Figure 2: Schematic layout of FLASH and the XFEL, indicating the conceptual similarity of both machines, the basic difference being only the energy level at which bunch compressors and undulators are installed.

the TESLA Test Facility (TTF). It was the strategy to rely on the superconducting accelerator technology developed within the international TESLA collaboration [6,7] because of its intrinsically excellent stability and the large number of bunches that can be accelerated within each RF pulse, providing a good basis for a multi-user facility. The aim was to eventually reach Ångstrøm wavelengths, but to proceed in reasonably ambitious steps towards shorter and shorter wavelengths: 100 nm (TTF1 FEL [8]), 32 nm (TTF2 FEL [9]), 14 nm (FLASH [10]), now 6.5 nm at FLASH and, ultimately, 0.1 nm at XFEL. This progress is illustrated in Fig. 3. The other key decision was to get scientific users involved as soon as possible, in order to achieve experience with user operation on both, the machine and the user sides.

The general layouts of FLASH and the XFEL are in fact quite similar, see Fig. 2. In both cases the longitudinal bunch compression is achieved by two magnetic chicanes. The major difference is the beam energy at which compression takes place and the final beam energy, determining the radiation wavelength according to Eq. (2). Also, most of the beam parameters are very similar, see Table 1.

Table 1: Main Design Parameters of FLASH and the European XFEL.

Parameter	FLASH	XFEL
Norm. emittance x/y	2 µm	1.4 µm
Bunch peak current	2.5 kA	5 kA
Bunch repetition rate	1 (9) MHz	5 MHz
Bunch charge	1 nC	1 nC
Max. beam energy	1 GeV	17.5 GeV
RF	1.3/3.9 GHz	1.3/3.9 GHz
Max. length of bunch train	800 µs	650 µs

This concept makes it possible to perform almost all critical test at FLASH before they will be implemented into the XFEL, including beam dynamics issues, development of sophisticated diagnostics tools, and tests of utility systems. Only those subsystems will be replaced for the XFEL which did not perform in a satisfactory way at FLASH.

RECENT PROGRESS

The progress in terms of achieving FEL gain saturation at short wavelengths is visualized in Fig. 3. During the 2007 summer shut-down, a sixth superconducting accelerator module was installed taking the max. electron energy up to 1 GeV, the original FLASH design value [11]. Only a few weeks after this beam energy was reached, FEL operation in the laser saturation regime was accomplished at wavelengths between 6.5 nm and 7 nm, thus achieving the FLASH design wavelength [11]. 7 nm radiation is now regularly delivered to users. A single-shot spectrum taken below saturation is shown in Fig. 4. From the small number of spikes within the FEL bandwidth, representing the number of longitudinal modes taking part in the gain process, it can be concluded that the radiation pulse is very short, in the 5-15 fs range.

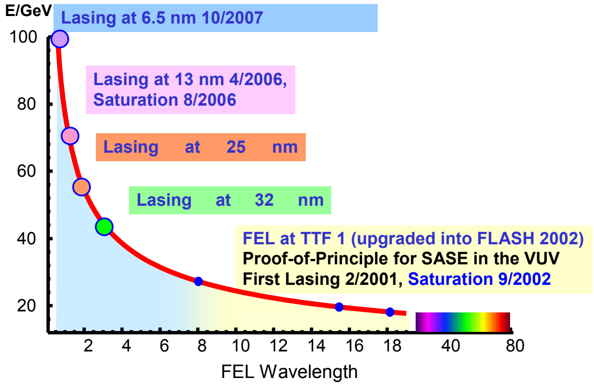

Figure 3: Progess at DESY towards operating the FEL at smaller and smaller wavelengths.

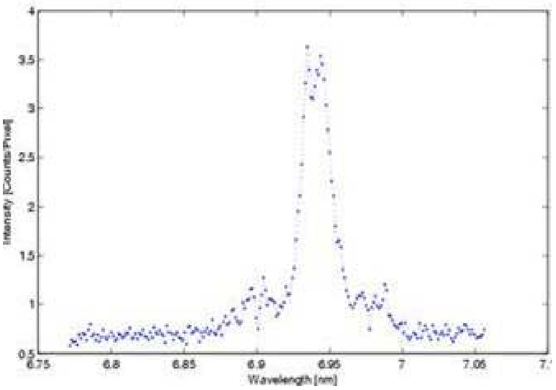

Figure 4: Single-shot spectrum of FEL radiation below 7 nm (fundamental harmonics) at FLASH, DESY.

FLASH now delivers radiation within the entire spectral range it was planned for, at peak brilliance values in agreement (within error bars) with its original design values, see Fig. 5.

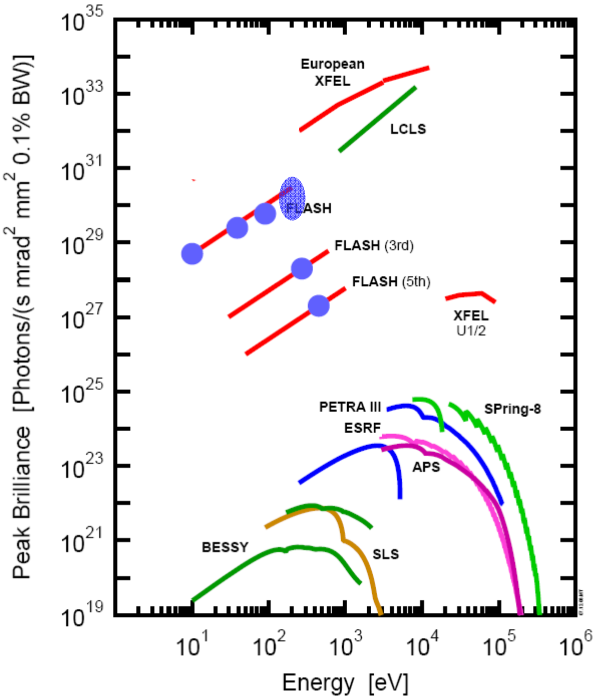

Figure 5: Design peak spectral brilliance of SASE FELs in comparison with state-of-the-art synchrotron radiation sources. The large dots mark the experimental resuls from FLASH, DESY, Hamburg.

Due to its unprecedented radiation quality, FLASH has been used by a large user community, covering a broad range of science issues. During the first round of user experiments which ended March 2007, 18 science projects received beam time, involving more than 200 scientists from 60 institutes and 11 countries. This resulted in publication of more than 25 papers in high level journals [12], and many more are in the pipeline. For the second round, which started after the 2007 shut-down, 32 proposals were accepted (out of 45 submitted), and 377 12-hour shifts will be available during 18 months until spring 2009. Out of these, 316 shifts have been allocated so far, see Table 2.

Table 2: Beam Time Allocation for the Second Round of User Experiments at FLASH

Research field	Number of 12-hour shifts	
	Requested (all 45 prop.)	Allocated
Atoms, Molecules, Ions	247	61
Clusters	71	36
Imaging, Diffraction	90	53
Plasma physics/ warm dense matter	194	56
Solids, Surfaces	214	46
Methods/Technology	157	64

Having established user operation, quite some effort was made to realize FEL operation with long bunch trains. FLASH is presently able to deliver bunch trains up to 800 µs long. Fig. 6 illustrates lasing at 14 nm with 800 bunches running at 1 MHz repetition rate. At 5 Hz RF repetition rate, the avg. electron beam power is 2.7 kW which required installation of a sophisticated machine protection system. Without this there would be considerable danger of undulator damage due to electron halo lost in the vacuum chamber. As seen from Fig. 6, all bunches do lase, but at a different level, with a characteristic profile along the bunch train. This behaviour is subject of further investigations. It is, most likely, partly due to variation of beam energy along the pulse, as suggested by widening of the radiation spectrum. see Fig. 7

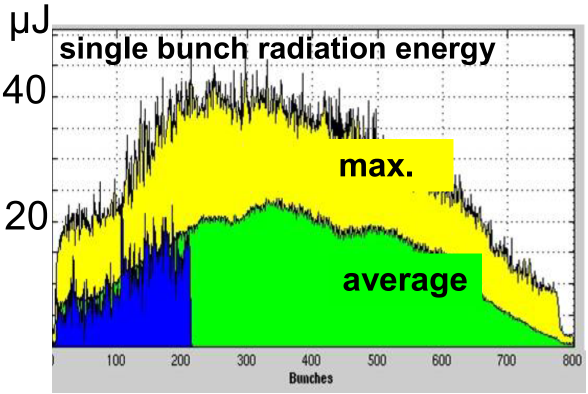

Figure 6: Lasing of a bunch train consisting of 800 bunches at FLASH. Yellow: single shot radiation energy generated by each bunch. Green: average value.

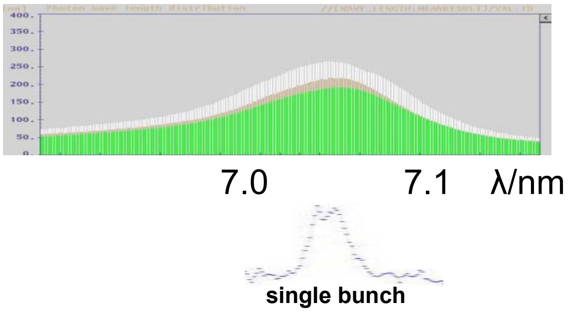

Figure 7: Average wavelength spectrum of a bunch train consisting of 100 bunches, lasing at approx. 7 nm (top), exhibiting a much wider spectral range than a single pulse spectrum shown in the lower part.

Generation of electron bunches at minimum emittance is of outmost importance for all single pass, small-wavelength FELs. DESY runs, within an international collaboration, a dedicated “photo-injector test stand” (PITZ) at its site in Zeuthen. By increasing the electric field on the cathode up to 60 MV/m, an emittance of 0.8 mrad mm (rms, both planes) has be demonstrated for a 1 nC bunch, if only 5% of the beam halo was cut away [13]. This is sufficient for the XFEL. By CO_2 cleaning, the amount of dark current could be drastically reduced.

With the cooperation length of the FEL gain process being in the μm range, it is relevant to know the distribution of electrons within the bunch at μm resolution. A step forward towards this ambitious goal has been made at FLASH by measurement of the 6D phase space distribution of bunches [14] after compression, see Fig. 8, using a transverse RF deflecting resonator [15]. It is seen that the slice emittance is considerably increased where the instantaneous current is large.

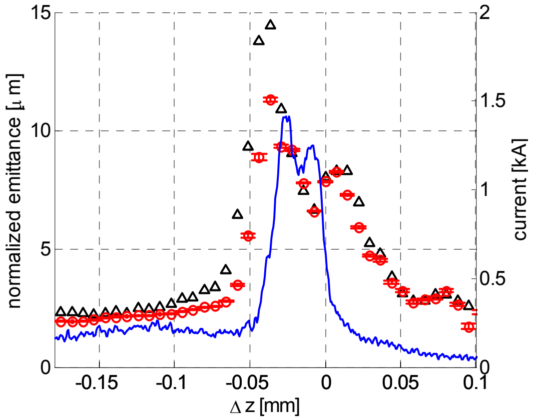

Figure 8: Emittance measurement of slices within the compressed electron bunch (resolution approx. 5 μm) at FLASH (dots) [14]. The slice emittance is considerably increased where the instantaneous current (blue solid line) is large.

Another way of time-domain investigation of the charge profile is given by the “Optical Replica Syntheziser” [16] that has been installed into the FLASH beam line and has observed first signal.

Frequency domain techniques are a complementary diagnostic tool, in particularly when it comes to any longitudinal fine structure inside the bunch. To this end, a broad-band spectrometer has been designed and constructed capable of measuring the coherent infrared radiation generated by single bunches when radiating transition or synchrotron radiation [17]. Fig. 9 illustrates a single-shot spectrum taken from a transition radiation monitor. Besides the peak around 35 μm wavelength that is characteristic for the high-peak-current lasing spike, further coherent radiation is visible below 10 μm indicating that there is quite some substructure on the longitudinal bunch profile. The origin of this is subject of further investigations. Also, a new infrared undulator has been installed at the exit of the FEL undulator at FLASH [18] enabling both more refined investigations on the bunch profile and pump-probe experiments involving both the FEL pulse and an infrared-pulse naturally synchronized to the FEL pulse.

Several scientific applications of the ultra-short radiation pulses call for the possibility to synchronize the arrival time of these pulses with an external laser system (“pump-probe experiments”).at a precision better than the pulse length, i.e. below 10 fs. To this end, an all-optical synchronization system has been developed at FLASH. A key component is a beam arrival time monitor (BAM) based on electro-optical detection which was demonstrated under realistic operation conditions at FLASH to measure the bunch arrival time at a precision better than 7 fs [19]. In a first step, this signal, derived at the end of the compression stages, was transmitted by optical fibre to regulate phase and amplitude of the first accelerator module thus stabilizing the arrival time to better than 40 fs rms, see Fig. 10 [20]. Since parameters of accelerator modules further downstream have also an impact on the beam arrival time, there is headroom for even better stability of arrival time.

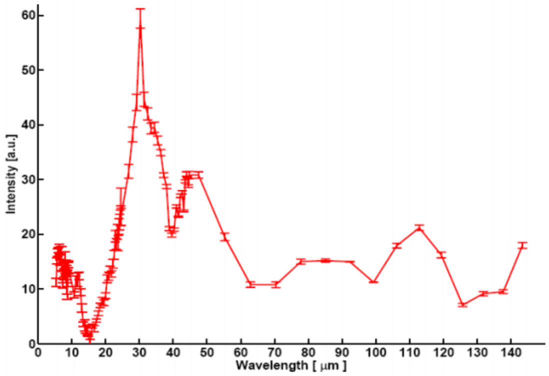

Figure 9: Infrared spectrum taken at FLASH, using a novel broad-band, single shot spectrometer.

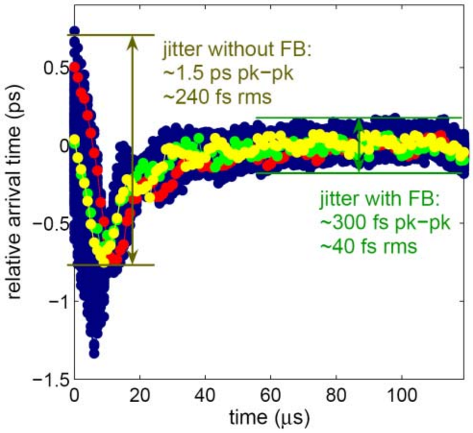

Figure 10: Stabilization of arrival time measured at the end of the FLASH linac by an all-optical feedback loop.

UPGRADE ACTIVITIES AT FLASH

Upgrade activities at FLASH all aim at improving the performance for user. There are essentially three short-term upgrade plans (all approved and scheduled for installation during the 2009 shut-down):

1. By installation of a superconducting 3rd harmonics (3.9 GHz) RF system the nonlinearity in the longitudinal phase space distribution of electrons can be corrected. Then, a larger fraction of the bunch can be compressed to the kA-level, thus increasing both the pulse length and the number of photons per pulse. This system (see Fig. 11), developed and fabricated at FNAL, has been successfully cryo-tested.

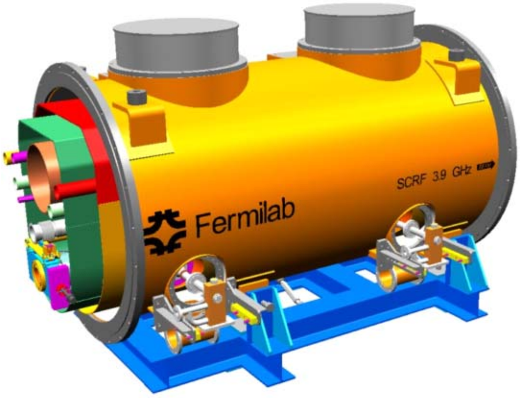

Figure 11: Superconducting 3rd harmonics RF system for linearization of the longitudinal phase space distribution [21].

2. By installation of a 7th accelerator module, higher beam energy and smaller FEL wavelengths will be achieved.
3. It is the hope to improve the energy stability of radiation pulses and their longitudinal coherence by seeding the FEL gain process by a coherent external radiation source. This concept will be tested ("sFLASH") using high laser harmonics at approx. 30 nm generated in a gas cell and a new, 10 m long movable gap undulator [22].

THE EUROPEAN X-RAY LABORATORY

The European Xray FEL company is presently in the process of being funded. The status of financial commitments to this project is illustrated in Fig. 12 (note that contracts are not yet signed, so minor adjustments may occur).

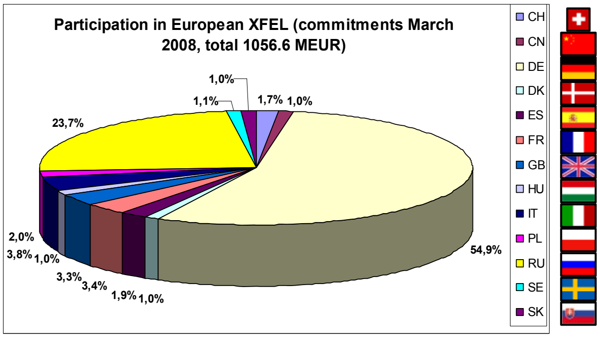

Figure 11: Status of financial commitments made for the European XFEL project [23].

The start-up scenario foresees three FEL beam lines, see Fig. 12. They will cover the wavelength range between 0.1 nm and 1.6 nm (first harmonics).

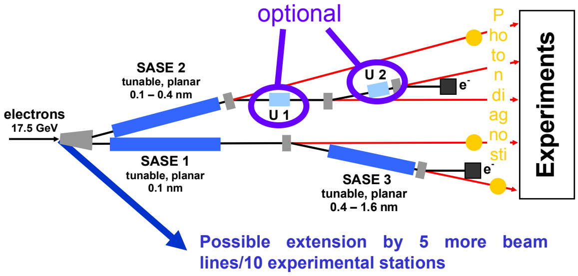

Figure 12: Start-up scenario of the European XFEL.

CONCLUSION

FELs for VUV and X-ray wavelengths have developed into a major technology driver for accelerator R&D. It is very likely that this will remain being so for a number of years to come.

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