FIRST LASING BELOW 7 nm WAVELENGTH AT FLASH/DESY, HAMBURG

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For the FLASH Team

Abstract
In the autumn of 2007, the Free-Electron Laser in Hamburg at DESY, FLASH, has been upgraded by installation of a 6th superconducting accelerator module to reach an electron energy of 1 GeV. Within a few weeks after successful commissioning, FLASH achieved lasing at 6.5 nm, the design wavelength specified some 14 years ago. User operation is regularly running at wavelengths down to 7 nm. 3rd and 5th harmonics have been observed and used for science experiments.

INTRODUCTION

The Free-Electron Laser in Hamburg (FLASH) at DESY, Hamburg, Germany, is the first FEL running in the VUV wavelength regime and the first FEL user facility for wavelengths far below the visible. It is based on a superconducting linear accelerator developed within the international TESLA collaboration [1,2], it employs a high-gain FEL [3-6], and it makes use of the Self-Amplified Spontaneous Emission (SASE) mode [3,6]. The over-all layout is sketched in Fig. 1.

Form the very beginning, FLASH was considered a prototype for an FEL user facility operating in the Angstrom regime. This device, the European XFEL laboratory, is now under way. The conceptual similarity is also seen from Table 1 indicating key design parameters of both FLASH and the XFEL. The major differences are the beam energy at which compression takes place and the final beam energy. This concept makes it possible to perform almost all critical tests at FLASH before they will be implemented into the XFEL. Only those subsystems will be replaced at the XFEL which do not perform in a satisfactory way at FLASH. The other key decision was to get scientific users involved as soon as possible.

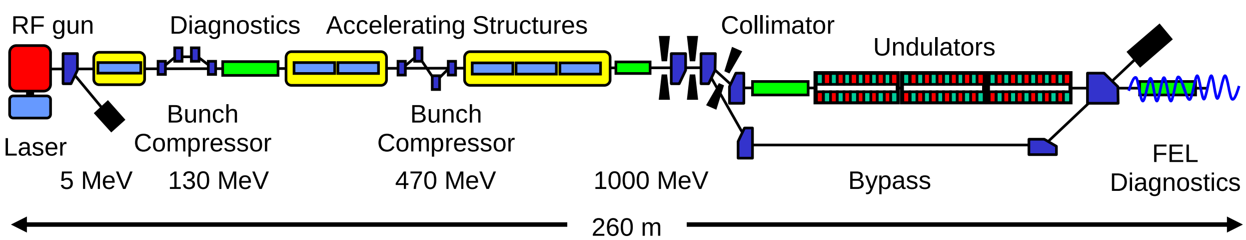

Figure 1: Schematic of the present layout of FLASH. The concept is based on a high-gain SASE FEL driven by a superconducting linear accelerator. Note the conceptual similarity with the European XFEL project for which FLASH can be considered a prototype, the basic difference being only the energy level at which bunch compressors and undulators are installed.

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

FEL PERFORMANCE BELOW 7 nm

After commissioning of the new accelerator module in Sept. 2007, lasing at 6.5 nm has been achieved on Oct. 5th, 2007. Since then, FLASH is running mainly for users at wavelengths down to 7 nm. Radiation pulse energies exceeding 40 µJ have been observed. Also the 2nd, 3rd, and 5th harmonics have been seen, and applied by users. A typical single-shot spectrum of the fundamental within the regime of exponential growth is seen in Fig. 2. According to preliminary analysis, the spectral line width is larger than what would be expected from the gain length. Beam dynamics calculations indicate that this might be due to the energy chirp within the electron bunch. The steady development of FLASH towards smaller and smaller wavelengths is shown in Fig. 3.

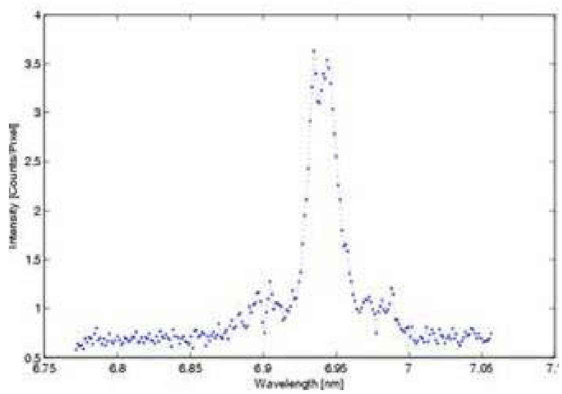

Figure 2: Single-shot spectrum of FEL radiation below 7 nm (fundamental harmonics) at FLASH, DESY.

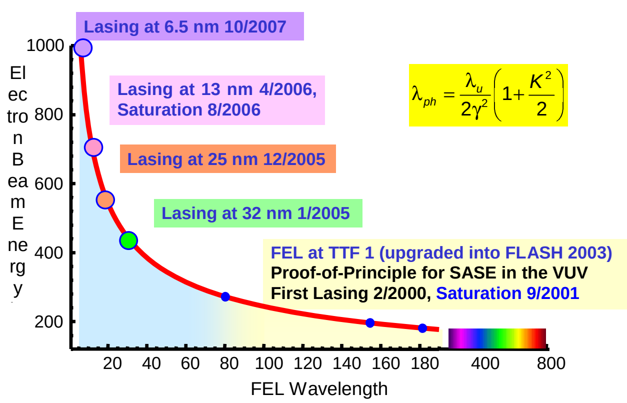

Figure 3: Progress at DESY operating FLASH at smaller and smaller wavelengths.

FLASH is capable of running at long bunch trains. Fig. 4 illustrates the averaged spectrum achieved at 7 nm wavelength with trains consisting of 100 bunches. Comparing with a single-shot spectrum (lower part of Fig. 4), the averaged spectrum indicates that there is some energy variation along the bunch train. This is subject of further investigations and improvements. More details on FLAS user operation are given in Ref. [7].

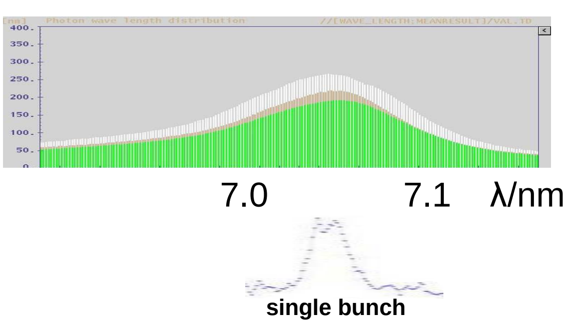

Figure 4: The average wavelength spectrum of a bunch train consisting of 100 bunches, lasing at approx. 7 nm (top), exhibits a much wider spectral range than a single pulse spectrum shown in the lower part.

RADIATION PULSE DURATION

The duration of radiation pulses would be best inferred from direct, time domain measurements. Such measurements are not yet available, although progress is under way, see e.g. Ref. [8]. However, quite reasonable estimates are also possible from frequency domain measurements. Assuming transverse coherence and a smooth longitudinal distribution (e.g. flat-top) within the lasing part of the electron bunch, statistical analysis of the SASE process [9] predicts that the duration of the radiation pulse T_{rad} is related to the FWHM frequency width of individual spikes $\Delta\omega_{\text{spike}}$ observed within the single-shot spectra according to

$$T_{rad} \cong 2\pi / \Delta\omega_{\text{spike}} \ .$$

This kind of analysis can be complemented and cross-checked by estimating the number of longitudinal modes *M* being present in each single shot. This number can be estimated from either the mean number of spikes within each single-shot spectrum or from analysis of the intensity fluctuations of SASE pulses [9]. Note that there is another cross-check from the expectation that both methods should result in the same number for *M*.

Form such kind of analysis the preliminary estimate of the pulse length at 7 nm wavelength is between 5 and 15 fs FWHM.

PEAK BRILLIANCE

The peak brilliance B_{peak} is the figure of merit for many experiments. For incoherent sources like storage rings, it is calculated according to:

$$B_{peak} = \frac{\Phi}{4\pi^2 \Sigma_x \Sigma_{\theta x} \Sigma_y \Sigma_{\theta y}} \qquad (1)$$

Here, the $\sum$'s indicate the convoluted transverse size and divergence of electrons and radiation according to

$$\Sigma_x = \sqrt{\sigma_{x,ph}^2 + \sigma_{x,e}^2} \ \text{, etc.}$$

Φ is the peak spectral flux, calculated from

$$\Phi = \frac{(\text{number of photons})}{(\text{pulse duration}) \cdot (\text{spectral width})} \ .$$

The spectral width is taken in 0.1% units.

For a transversely coherent source like FLASH (which is a good approximation according to double slit diffraction experiments), Eq. (1) is reduced to

$$B_{FEL} = \frac{4\Phi}{\lambda_{rad}^2} \ ,$$

where λ_{rad} is the radiation wavelength.

Based on this analysis, the peak brilliance of FLASH has been estimated and plotted in Fig. 5. It is seen that 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.

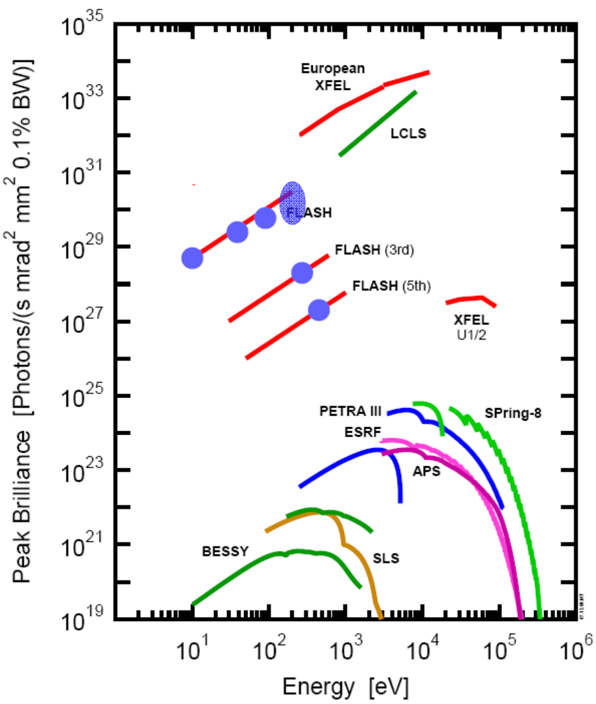

Figure 5: Design peak spectral brilliance of SASE FELs in comparison with state-of-the-art synchrotron radiation sources. The large dots mark the experimental results from FLASH, DESY, Hamburg.

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, developed and fabricated at FNAL, has been successfully cryo-tested.
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 [10].

In addition, work on a proposal is under way aiming at a major extension of FLASH by a new FEL beam line to be installed into a new tunnel, and at a second hall for user experiments.

CONCLUSION

Work on FLASH and its predecessors called TTF FEL1 and TTF FEL2 went a long way taking more than a decade to finally demonstrate lasing and laser saturation at its design wavelength of 6.5 nm, and to demonstrate the usefulness of SASE FELs for a wide range of scientific experiments at VUV and soft X-ray wavelengths. In doing so it simultaneously paved the way towards Angstrom FELs.

ACKNOWLEDGEMENT

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