OPERATION OF FLASH AT 6.5 nm WAVELENGTH

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Abstract

FLASH, the Free-Electron Laser at DESY, Germany has been upgraded in 2007. A sixth accelerating module with eight 9-cell superconducting cavities of the TESLA type has been installed. In addition, another module has been replaced and tuners of a third module have been repaired. In September 2007, a beam energy of 1 GeV has been achieved for the first time, followed by lasing at 6.5 nm shortly after. With this remarkable achievement, the initial design goals of the FEL in terms of beam energy and wavelength have been reached.

INTRODUCTION

The Free-Electron Laser FLASH at DESY is the first user facility for VUV and soft X-ray laser like radiation using the SASE scheme. Since summer 2005, it provides coherent femtosecond light pulses to user experiments with an impressive brilliance.

FLASH is based on the TTF-FEL [1], which was in operation until end 2002 lasing in the range of 80 to 120 nm [2, 3]. The TTF-FEL has been completely redesigned to meet the demands on beam energy and beam properties for lasing down to 6.5 nm. A first stage has been brought into operation in 2004. The accelerator has now been completed in 2007 with an additional accelerating module to reach an electron beam energy of 1 GeV required for 6.5 nm operation.

Highlights of FLASH have been first lasing at a wavelength of 32 nm in January 2005 [4], and later on, saturation and full characterization of the FEL radiation at 13.7 nm in 2006 [5]. The SASE process also generates higher harmonics radiation. In saturation, the radiation contains mainly odd harmonics. As an example, we observed while lasing at the fundamental wavelength of 13.7 nm the third, fifths, and seventh harmonics with a considerable fraction of the fundamental energy, about 0.5 % for the third, less for the higher harmonics.[5]

Figure 1 gives a schematic overview of the present configuration of the linac. Table 1 summarizes the present beam and FEL performance. For a more detailed discussion of parameter choices refer to [6].

Injector

The injector has been successfully commissioned in the first half of 2004.[7] It generates trains of electron bunches with a charge of 0.5 to 1 nC each. The bunch train length of 800 μm and the repetition rate of 5 Hz are adapted to the superconducting TESLA accelerating structures. The normalized transverse projected emittance measured in the injector at 127 MeV meets the design with 1.5 to 2 μm rad. [8] Important for the lasing process however is the emittance of the lasing spike, which is estimated by the analysis of the FEL radiation properties to be between 1 and 2 μm rad. This empirical result is supported by measurements with the deflecting cavity LOLA.[9]

The laser driven RF gun is a 1.5 cell L-band cavity (1.3 GHz). The RF gun is operated with an RF power of 3.5 MW (a maximum of 44 MV/m on the cathode) and an RF pulse length of up to 0.9 ms. A low level RF system based on FPGA controllers with a small latency (150 ns) reads the forward and reflected power from the gun, builds the vector sum and regulates the RF power and phase.[11] The rms phase stability achieved is a remarkable 0.1° of 1.3 GHz or 300 fs in time. The amplitude stability is within 0.1 %.

Table 1: Present parameters of FLASH.

Electron beam		
Energy	MeV	370 - 1000
Peak current	kA	1 - 2
Emittance, norm. (x,y)	μm rad	1.5 - 2
Nb. of bunches/train		1 - 800
bunch train length	ms	up to 0.8
Rep. rate	Hz	5
ΔE (rms)	keV	300
Undulator		
Period	cm	2.73
Gap	mm	12
Peak magnetic Field	T	0.48
K		1.23
total length	m	27.3
FEL radiation		
Wavelength	nm	47 - 6.5
Average pulse energy typ.	μJ	30 - 50
Average pulse energy, max.	μJ	100
Bandwidth (fwhm)	%	0.5 - 1.0
Pulse duration (fwhm)	fs	10 - 50
Peak Power	GW	5
Average Power	mW	100
Peak spectral Brilliance	B *	$\approx 10^{29}$ - $\approx 10^{30}$

* photons/s/mrad^2/mm^2/(0.1 % bw)

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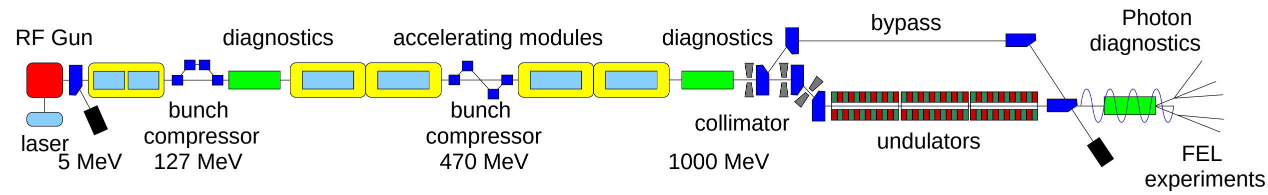

Figure 1: Schematic overview of the FLASH linac (not to scale). Beam direction is from left to right, the total length including the experimental hall is 315 m.

A Cs_2Te photocathode is inserted into the RF gun backplane via a load-lock system and can be changed if required. The cathode quantum efficiency (for UV light) is initially high (more than 10 %). Depending on the vacuum condition, the lifetime of the cathodes vary. For instance, Cathode # 24.3 has been in operation for 5 months from Dec 2007 to April 2008 (details in [12]).

The photocathode laser system is based on a mode-locked pulse train oscillator synchronized to the 1.3 GHz RF of the accelerator. The phase stability is better than an equivalent of 200 fs. A chain of linear Nd:YLF amplifiers provides enough energy to convert the initial infrared wavelength into UV (262 nm, up to 25 μJ per pulse). The system produces pulse trains with up to 800 μs length at a repetition rate of up to 10 Hz. The pulse spacing is usually 1 μs (1 MHz) and can be varied to a certain extend: several other frequencies like 500 kHz, 250 kHz, and 100 kHz have been realized.[10]

Acceleration

A complete TESLA module with eight accelerating structures boosts the beam energy to 127 MeV before the first bunch compressor. The first four cavities are operated with a moderate accelerating gradient of 12 MV/m to reduce space charge effect due to pondoromotive focusing. With the FPGA based feedback system, phase and amplitude of the accelerating structures is regulated.[13] An excellent energy stability $\delta E/E$ of $1.6 \cdot 10^{-4}$ rms (at 127 MeV) has been measured. The arrival time jitter of the electron beam and thus the FEL radiation at the experiment is dominated by the already very small energy variation and is measured to be in the order of 200 fs rms.[14]

Two TESLA accelerating modules (ACC2, ACC3) increase the energy to 470 MeV before the second bunch compressor, three modules (ACC4, ACC5, and ACC6) boost to the energy required for the specific wavelength of FEL radiation. In summer 2007, two new modules have been installed: module 7 replacing module $3^\star$ at position ACC3 and the new module 6 at ACC6. The performance of the new modules is excellent: an average gradient of 25 MV/m is exceeded for both, four cavities in module 6 even reach more than 30 MV/m. Figure 2 shows an overview of usable gradients of modules operated at TTF1 and FLASH.

The red bars show the gradients achieved by the sum of the performance of individual cavities, the blue bars show the achieved gradients in the accelerator. In the linac, with the exception of module 6, the weakest cavity determines the average module gradient. Module 6 is equipped with a newly developed waveguide system which allows to adjust RF power of individual cavities according to their performance.[15]

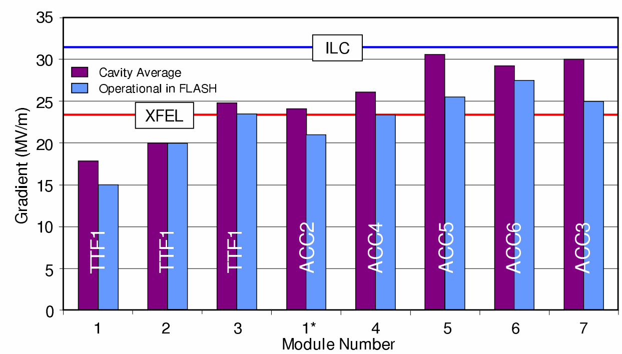

Figure 2: Operable accelerating gradients of modules operated at TTF-FEL (modules 1, 2, and 3) and which are installed in FLASH. The red bars show the gradients achieved by the sum of the performance of individual cavities, the blue bars show the achieved gradients in the accelerator. In the linac, with the exception of module 6, the weakest cavity determines the average module gradient. The goals for the XFEL and ILC project are indicated.

In September 2007, the commissioning of the accelerator section took place. The energy gain of all individual cavities has been measured with beam. After optimizing the phasing between modules and the phases and gradients of all individual cavities, the final goal of an energy of 1 GeV has been reached. The beam energy has been measured with the dipole spectrometer and has been verified by RF power measurements and - most important - by the measurement of the spectrum of the spontaneous undulator radiation. The spectra peak at a wavelength of 6.3 nm corresponding to 1 GeV beam energy.

LASING AT 6.5nm

October 5^{th}, 2007, shortly after the successful commissioning of the accelerator, SASE FEL radiation at 6.5 nm has been observed for the first time - a new world record. Figure 3 shows the spectrum of the SASE radiation peaking at 6.5 nm. The wavelength corresponds to a beam energy of 980 MeV. The off-crest acceleration required by the bunch compression scheme reduces the beam energy by about 20 MeV.

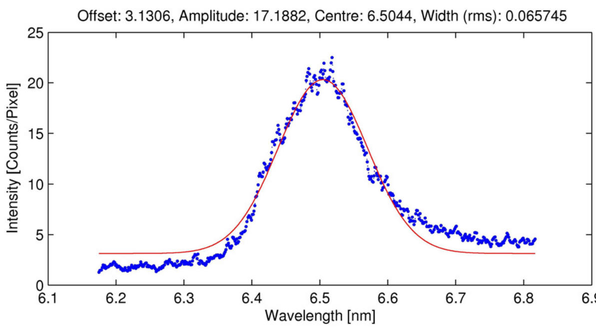

Figure 3: Spectrum of the SASE FEL radiation peaking at 6.5 nm generated at FLASH for the first time – a new world record.

Further optimization of the lasing process lead to the measurements of the gain curve and a preliminary estimate of the peak brilliance in the order of $\approx 10^{29}$ - $\approx 10^{30}$ photons/s/mrad^2/mm^2/(0.1 % bw). From the number of observed lasing modes with an extrapolation from the 13.7 nm data [5] we can estimate the FEL pulse width to be in the order of 10 fs. First experiments have already been successfully performed with a train of bunches at a wavelength of 7 nm (see figure 4).

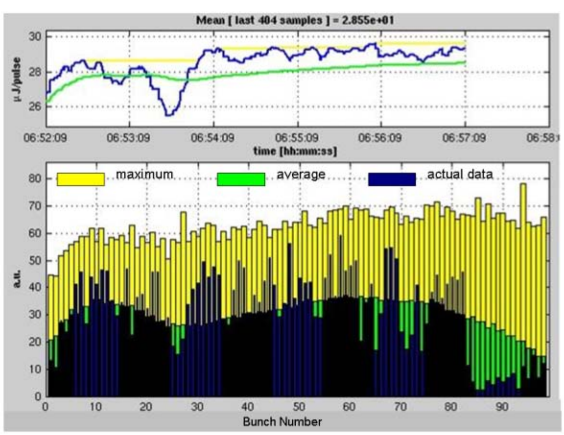

Figure 4: Lasing at 7 nm with a bunch train of 100 bunches at 500 kHz. The gas monitor detector [16] measures the relative energy of individual pulses (lower plot) and with the ion signal a calibrated energy per single pulse (upper plot).

SUMMARY AND OUTLOOK

After the shutdown in 2007, a sixth accelerating module has been installed. The design electron beam energy of 1 GeV has been achieved in September 2007. Shortly after, lasing at 6.5 nm has been observed - a new world record for SASE FEL radiation. This important milestone is a major achievement in the effort of the realization of an FEL at DESY. Meanwhile, many user experiments have been successfully performed with a wavelength down to 7 nm including harmonics down to 1.6 nm.

ACKNOWLEDGMENT

On behalf of the FLASH group, we would like to thank all colleagues from DESY and the collaborating institutes for their enthusiastic commitment in the development, operation, and maintenance of the machine.

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