STATUS OF THE FREE–ELECTRON LASER FLASH AT DESY

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Abstract

The free–electron laser facility FLASH at DESY has been upgraded in 2010. Now, FLASH delivers an electron beam energy up to 1.25 GeV. The longitudinal phase–space is linearized by 3.9 GHz superconducting cavities. The facility delivers to users ultra–short laser like radiation pulses in the range of less than 50 fs to 200 fs in the soft X–ray wavelength range from 45 down to 4.1 nm. FLASH provides hundreds to thousands pulses per second to users with unprecedented peak brilliance. FLASH will be upgraded with a second undulator beam line and an additional experimental hall. Construction starts Autumn 2011. We summarize the operational status of the ongoing 3-rd user period.

Table 1: FLASH parameters 2011

e^- :			
emittance	$\beta\gamma\varepsilon_{x,y}$		
(1 nC, on–crest, 90% rms)		1.4	mm mrad
charge		0.15 - 1.5	nC
beam energy		375 - 1250	MeV
bunches / train		1 - 500	
bunch spacing		1 - 25	μs
train repetition frequency		10	Hz
γ :			
wavelength (fundamental)		4.1 - 45	nm
average single pulse energy		10 - 400	μJ
pulse duration (fwhm)		50 - 200	fs
spectral width (fwhm)		0.7 - 2.0	%
peak power		1 - 3	GW
peak brilliance		10^{29} - 10^{31}	(+)
average brilliance		10^{17} - 10^{21}	(+)

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

INTRODUCTION

FLASH is a superconducting linac with an RF photo cathode gun driving a SASE FEL in the XUV and soft–X–ray regime. During the shutdown of 2009/2010 FLASH was upgraded in several major aspects: A new XFEL–type acceleration module, a 3-rd harmonic module, and the hardware for higher harmonic generation (HHG) seeding (sFLASH) have been installed, the RF stations and the beam diagnostics have been upgraded. Moreover, during the last year the low level RF controls have been significantly refined.

In the last 12 months more than 200 days were devoted to user operation. By now, the experiments carried out at FLASH have resulted in 150 publications, many of them in highly ranked journals.[1]

We summarize here the present status of the upgraded FLASH facility, highlight the key achievements of the present run period and briefly touch upcoming upgrades. Part of the material presented here has been already discussed in proceedings of previous conferences [2, 3].

THE FLASH LINAC

FLASH consists of a 256 m long electron linac followed by a photon transport line equipped with photon diagnostics and 5 experimental beam lines for users. A schematic layout is shown in Fig. 1, and some of its key parameters are listed in Tab. 1.

Electron bunches are generated by photo emission induced by UV laser pulses of 262 nm wavelength on a Cs_2Te cathode at the end of a normalconducting 1.5 cell 1.3 GHz copper cavity [4, 5]. The laser spot on the cathode is transversely approximately flat and has a typical diameter of 1 mm (0.7 mm - 3 mm). It is longitudinally approximately Gaussian with a σ of 6.5 ps. All RF stations are pulsed with 10 Hz and a design flat top for beam operation of 800 μs. The current laser is capable of producing 800 pulses at 1MHz per RF pulse in 10 Hz operation. Several bunch frequencies from 1 MHz down to 40 kHz can be provided. During early recommissioning in spring 2010 the RF coupler window of the gun was exchanged due to an increasing trip rate. After 4 weeks of conditioning the gun was operational again at a pulse length of 150 μs and since than has steadily increased to recently 550 μs allowing for about 500 bunches per RF pulse.

FLASH has seven 1.3 GHz (L–band) modules with 8 nine–cell niobium cavities each. Their theoretical maximum energy gain per module ranges from 180 MeV (older modules) to 240 MeV (latest XFEL prototype). Additionally a superconducting 3.9GHz 3-rd harmonic module with 4 cavities produced at Fermilab has been installed during the upgrade. It is driven by a custom–made klystron and modulator.

The bunches are compressed in two stages. Each stage consists in off–crest operated RF inducing an energy chirp along the bunch and an adjacent magnetic dipole chicane which compresses the charge density through path length differences in the dispersive structure. The 1-st chicane is a 4–dipole (D) chicane and is located directly after the 1-st L–band module and the 3-rd harmonic module. It is typically operated at 150 MeV with a bend angle of 18° and an R_{56} of 181 mm. The 2-nd chicane is a 6–dipole (S) chicane adjacent to the 3-rd L–band module at $\approx$ 450 MeV

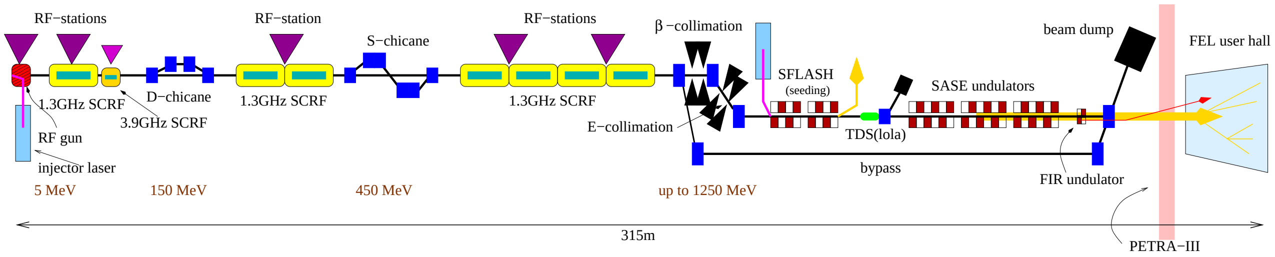

Figure 1: Overview of FLASH from the RF photo cathode gun (left) to the experimental hall (right).

with 4.65° and $R_{56} = 73$ mm.

After the last module beams can be provided with energies between about 375 MeV and 1250 MeV. Downstream of the last module FLASH has a transverse collimation section and a dispersive "dog–leg" for energy collimation upstream of the undulators.

During the 2009/2010 upgrade hardware for seeding with a HHG source was installed (sFLASH)[6]. One bunch per RF–pulse can be seeded in 4 tunable (variable gap) undulators. Between sFLASH and the main undulators a vertically deflecting traveling wave RF structure, originally manufactured at SLAC, and called LOLA is installed, followed by a switchable dispersive arm (horizontal dipole) equipped with a screen (OTR or YAG) to image the streaked bunch. LOLA maps the longitudinal phase space into transverse configuration space and is therefore our key diagnostic to evaluate the result of bunch compression and beam transport — including all collective effects. Unfortunately the dipole deflects the beam out of the undulator beam line and thus LOLA cannot be used parasitically in user operation.

The SASE FEL radiation is produced by six 4.5 m long fixed gap undulators (permanent NdFeB magnets, period 27.3 mm, $K = 1.23$). A planar electromagnetic undulator is placed downstream the SASE undulators to produce radiation in the THz range. The electron beam is then separated from the photons and sent to a dump. The FEL radiation is passed through a beam line equipped with photon diagnostics and (during user operation) through the crossing with PETRA–III into the FLASH experimental hall.

USER OPERATION MODES

The FLASH experimental hall has 5 separate beam lines of which one at a time can be served with FEL radiation. Typically two beam lines have experiments ready for beam at the same time and the beam is then switched in 12h or 24h blocks. It is possible to have "secondary" experiments use the spent beam of the "primary" experiment at each beam line. User requests are quite variable concerning radiation wavelength, bunch train structure, photon pulse length, energy and bandwidth, bunch–by–bunch stability, etc. Typical FEL parameters are listed in Tab. 1. Tab. 1 gives approximate boundaries on the *individual* FEL parameters, but does not imply that all *combinations* of parameters inside their individual boundaries are operationally feasible. About half the scheduled shifts request single bunch operation, the 2-nd half request multi bunch trains with variable patterns. Little more than a quarter of the experiments in this run period required ultra short pulses ($\leq$ 50 fs (fwhm)), more than 50% between 50 fs and 100 fs, but only less than a 5-th of the experiments did not critically rely on the FEL pulse lengths.

During the first 7 blocks of this run period 76% of the time FEL radiation was delivered to the users, 19% was used for tuning, 1% for scheduled maintenance and 4% of the time the machine was down because of technical problems. The average up–time has therefore increased to 96%, comapred to 87% and 93% for the 1-st and 2-nd run period.

LASING AT 4.12 NM

With the new 7-th superconducting accelerating module beam energies of up to 1.25GeV have been achieved. On the September 25-th 2010 a wavelength of about 4.12 nm has been measured with a spectrometer upstream the first photon transport mirror. The pulse energy was about 60 μJ. This wavelength is in the so called "water window", below the carbon K–absorption edge of 4.4 nm and above the Oxygen K–edge at 2.3 nm. Water is transparent for soft X–ray inside the "water window" while carbon is still absorbing. Reaching the "water window" is therefore considered extremely valuable for viewing bio–molecules dissolved in water. However, most of the mirrors in the photon beam lines are carbon coated and thus may be damaged by FEL radiation below 4.4 nm. In Spring 2011 an in–house experiment using nickel coated mirrors has been performed. The machine now routinely operates at wavelengths below 7 nm ($E_e \geq 950$ MeV).

OPERATIONAL ASPECTS

Key ingredients to stable multi bunch operation are accuracy, reproducibility and stability of the RF pulse flat tops. The effective amplitude and phase of the accelerating field given by the vector sum over all the cavities driven by one klystron is regulated by field programmable gate array based low level RF controllers. In the last year the regulation was updated and improved and now includes an adaptive output rotation matrix, adaptive feed–forward, and beam loading compensation, both acting on the set point table, and a fast feedback. Moreover it allows the inclusion of (fast) beam based feedbacks to stabilize compression and energy gain over a bunch train, and reduce the photon arrival time jitter at the user experiments [8, 9]. In addition to the RF controller based bunch–by–bunch features 5 slow feedbacks can be used to compensate for drifts in amplitude and phase of the RF upstream of the 1-st chicane, between the 1-st and 2-nd chicane, and energy after the last modules. While these slow feedbacks are still stand alone clients they will soon be integrated into a (coupled) 5×5 feedback server.

Another major aspect of stable and reliable operation is stability and reproducibility of the short–term time–averaged bunch trajectory (falsely but conveniently called "orbit"). An intrinsic problem of linacs is that the energy profile, apart from some specially featured loations, is only approximately known and even only approximately reproducible. We are in the process of commissioning a server based "orbit" feedback system based on a combination of measured and theoretical response matrices.

LINEARIZED BUNCH COMPRESSION

One of the major achievements of the upgrade was the installation and commissioning of the 3-rd harmonic module produced by Fermilab. In order to reduce space charge effects in the low energy regime the bunches must be generated significantly longer, i.e. with less peak current, at the cathode than needed for the SASE process in the undulators. The long bunches sample the non–linearity of the sinusoidal RF wave which leads to a longitudinal phase space density with "banana shaped" fundamental structure. Strong compression then generates strongly spiked charge densities. The spike potentially destroys the transverse emittance and slice energy spread of the remnant of the bunch and the spike centroid typically does not coincide with the beam centroid. Thus only the spike — which carries only about 10% of the charge – lases, and is almost impossible to tune in a systematic way. The non–linear effects can to a great extent be compensated employing an additional higher harmonic RF component. The 3-rd harmonic system of FLASH was installed right after the first superconducting module. It is capable of providing a total energy "gain" of 20 MeV but is operated typically close to anti–on–crest (deceleration mode). With the 3-rd harmonic in operation the fundamental structure of the longtidinal phase space density is much closer to a linearly energy–chirped (extremely thin) ellipse. Thus a larger portion of the bunch finally lases, the overall properties of the phase space distribution are much better behaved, in particular the beam core is the lasing part. In summary the 3-rd harmonic module improves the operability of the machine significantly.

The transverse deflecting structure LOLA, described above, complements the potential of the 3-rd harmonic module by allowing to actually measure the longitudinal phase space density right before the SASE undulators. The measurements are not only used for empirical tuning but also used as input for numerical start to end simulations to refine the theoretical model of the machine [10].

While the closer–to–linear compression with the 3-rd harmonic RF component improves the operability and enhances the potential pulse energy it also potentially lengthens the FEL pulse. Since a longitudinally larger fraction of the bunch reaches the required peak current at reasonable slice energy spread and transverse emittance, the lasing part is simply longer. However, by reducing the bunch charge and at the same time increasing the compression factor it is possible to shorten the lasing part of the bunch — at the expense of reducing the pulse energy. Unfortunately reliable photon pulse length measurements are difficult, rare and tedious. Moreover the current FLASH diagnostics is not well suited for charges below 0.3 nC. So far FLASH has successfully produced and verified FEL pulses with about 40 - 60 fs length by compressing bunches of 0.25 down to 0.15 nC.

OUTLOOK : FLASH2

In mid September 2011 civil construction will start for the FLASH2 [11] extension to FLASH. When FLASH2 is fully assembled (end 2013), there will be a fast switch yard (fast flat–top kicker and Lambertson Septum) after the last accelerating module, capable of switching between the existing (FLASH) and the new (FLASH2) FEL in about 50 μs, i.e. within a short fraction of the RF pulse. Both FELs will be served with 10 Hz and independent variable bunch patterns. The FLASH2 FEL consists of an additional "dog–leg" for beam transport and collimation a variable gap undulator, a separate beam dump, a photon beam line equipped with diagnostics and an additional experimental hall to double the number of experimental beam lines. There will be a 2-nd injector laser to accommodate for the independent beam patterns and intensities. The complete timing system and a large fraction of the control and diagnostics systems will be upgraded to cope with the "split train" structure.

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