UPGRADES OF THE PHOTOINJECTOR LASER SYSTEM AT FLASH

S. Schreiber*, M. Gross, C. Grün, O. Hensler, G. Klemz, K. Klose, G. Koss, S. Schulz, T. Schulz,
M. Staack, DESY, Hamburg and Zeuthen, Germany
I. Will, I.H. Templin, H. Willert, MBI, Berlin, Germany

Abstract

The photoinjector of FLASH uses an RF gun equipped with cesium telluride photocathodes illuminated by appropriate UV laser pulses as a source of ultra-bright electron beams. The superconducting accelerator of FLASH is able to accelerate 800 µs long trains of thousands of electron bunches in a burst mode. This puts special demands on the design of the laser system, since it has to produce flat pulse trains with a flexible pattern. The construction of a second undulator beamline FLASH2 has started. The pulse train will be divided into two parts to serve both beamlines simultaneously. Since experiments with the FLASH soft X-ray beam need flexibility, we plan to use two laser systems each serving one beamline. This makes it possible to deliver two trains with different properties in charge, number of bunches, and bunch spacing in the same RF pulse. This also required an upgrade of the laser beamline design. Moreover, we report on recent improvements in arrival time stabilization.

INTRODUCTION

Since 2005, the free-electron laser FLASH at DESY, Germany operates as a user facility providing laser-like radiation pulses from the XUV to the soft X-ray wavelength regime with durations down to a few ten femtoseconds.[1] FLASH uses L-band superconducting TESLA-type accelerating technology. The acceleration is driven by long RF pulses with a length of 1.5 ms, and a usable flat part for acceleration of 0.8 ms. The repetition rate is 10 Hz, the RF frequency 1.3 GHz. With seven accelerating modules installed, the beam energy of FLASH reaches 1.25 GeV.

The high duty cycle is efficiently used by accelerating bursts (or trains) of electron bunches. The standard operation mode is 800 bunches spaced by 1 µs (1 MHz) in a pulse train.

THE ELECTRON SOURCE

The electron source is based on a normal conducting RF-gun operated with a 10 MW, 1.3 GHz klystron at a repetition rate of 10 Hz. The RF pulse length is up to 850 µs, sufficient for generation of the required bunch trains of 800 µs duration.

In order to keep the average power of the laser system reasonably small, a photocathode with a high quantum efficiency is used. Cesium telluride has been proven to be a reliable and stable cathode material with a quantum efficiency above 5 % for a wavelength around 260 nm for a long time of more than 170 days of continuous operation [2, 3]. The bunch charge required for FLASH is up to 1 nC, some experiments require up to 3 nC per bunch. Assuming a very conservative quantum efficiency of the cathode of 0.5 %, a laser pulse energy of not more then 3 µJ on the cathode is sufficient to produce a 3 nC electron bunch. For 800 bunches in 800 µs long trains, this corresponds to a reasonable intra train power of 3 W in the UV (average power 24 mW for 10 Hz).

A challenge for the laser system is, that it has to provide the same flat burst structure in the UV as required for the electron beam. In addition, the picosecond long pulses must be synchronized to the RF of the accelerator to substantially better than 1 ps.

THE LASER SYSTEM

The laser systems [4] described in this report have been installed in 2010 [5] and 2012, and are a substantial upgrade compared to the previous lasers in operation at FLASH and the former TESLA Test facility [6, 7]. The lasers have been developed in the Max Born Institute, tested at DESY (PITZ) and finally installed at FLASH.

Recently, a second laser system has been installed, almost identical to the one in operation, The laser system design is described in detail in [4]. Both systems consist of a pulsed laser oscillator with subsequent amplification stages. Figure 1 shows a schematic overview of the laser. The laser material chosen is Nd:YLF, lasing at a wavelength of 1047 nm. The material has together with a high gain, a long upper-state lifetime of 480 µs, and exhibits only a weak thermal lensing. This makes it suitable to produce pulse trains with milliseconds duration. After amplification, the wavelength is converted in two steps using an LBO and BBO to the UV wavelength of 262 nm. Figure 2 shows examples of pulse trains measured with photodiodes.

The pulse energy is adjusted by two remote controlled attenuators. One attenuator is used by a feedback system to compensate for slow drifts in pulse energy, the other by the operators of FLASH. The laser beam is expanded and collimated to overfill a set of remotely controlled hard edge apertures of various sizes. The chosen aperture corresponding to the required transverse size is imaged onto the cathode of the RF-gun. The nominal laser pulse diameter is 1.2 mm flat-hat.

The laser is equipped with a pulse picker which is used by the operator to chose the number of laser pulses,

* siegfried.schreiber@desy.de

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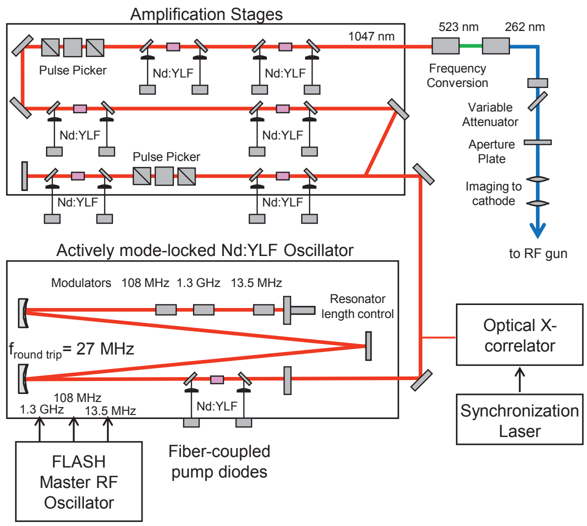

Figure 1: Schematic overview of the laser system. The second new laser has a more modern shorter oscillator operated at 108 MHz.

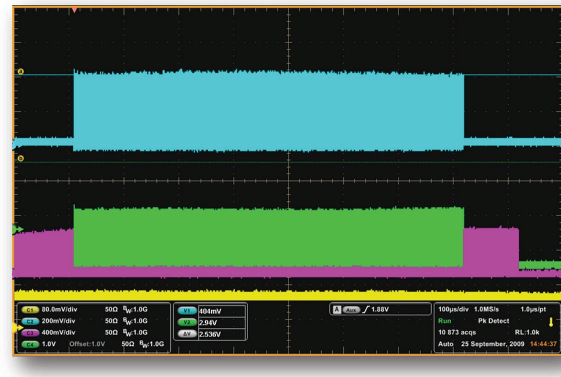

Figure 2: Example of a 3 MHz laser pulse train. The oscilloscope traces show the pulse train of the oscillator (yellow trace), after preamplification (wavelength 1047 nm, magenta), after conversion to 523 nm (green), and after conversion to the UV (262 nm, blue). The time scale is 1 ms (whole range). The train length is 700 µs. The 3 MHz pulse structure is not resolved.

and also the distance between pulses (intra-train repetition rate), according to the requirements determined by the experiment of the facility. The protection system of the accelerator acts on the laser to realize an emergency switch-off of the electron beam. Depending on the operation mode, it is also able to restrict the laser output to a save number of pulses per second.

The installation of the new laser is just being finished. It is planned to set-up the laser beamlines in a way, that they are both transported to the RF-gun simultaneously. This is required for the planned operation of FLASH1 and FLASH2 at the same time [8].

Laser Oscillator

The laser oscillator is an actively mode-locked and pulsed oscillator. The repetition rate is 27.08 MHz, the 48$^{\mathrm{th}}$ subharmonic of the accelerator RF frequency of 1.3 GHz. A large resonator length and thus a large distance of 37 ns between the pulses has been chosen to facilitate the subsequent Pockels-cell drivers for pulse picking. A Nd:YLF rod is end-pumped by two fiber-coupled laser diodes. Mode-locking is achieved with a 13.54 MHz modulator. The oscillator is pulsed with 10 Hz. The initial relaxation oscillations in the pulse train of the oscillator completely settle after 1 ms. A second modulator operates at the frequency of the accelerator RF of 1.3 GHz and provides the required phase stability. A third mode-locker operating at 108 MHz is required for stabilization. All frequencies are locked to the master RF oscillator [9] of the accelerator. The length of the resonator is stabilized with a slow feedback using a Piezo actuator at one of the mirrors. The air temperature at the oscillator is stabilized to 0.04°C (rms), the humidity is constant within 10 % (pp).

An optical balanced cross-correlator has been set-up [10]

Figure 3: Upper plot: Relative arrival time of the laser in respect to the FLASH synchronization laser measured at the exit if the injector laser oscillator using the optical cross-correlator. The data shown are with slow feedback on, over a period of 21 hours. The arrival time jitter over the whole period is $\delta t = 57$ fs (rms). Lower plot: Response of the slow feedback on the relative phase of the 1.3 GHz RF used to synchronize the laser oscillator. The phase has been corrected by a small amount of $\pm$ 0.2°(pp) by the feedback action.

to monitor the phase of the laser oscillator pulses in respect to the FLASH laser-based optical synchronization system. The arrival time is stabilized in a slow feedback loop acting on the phase of the 1.3 GHz RF driving the electro-optical modulator of the laser. A stability of 60 fs (rms) is achieved routinely (Fig. 3).

Amplification

The amplifier chain increases the energy by about four orders of magnitude to a level of 100 to 300 µJ, depending on the operation mode. No stretcher or compressor is used. The Nd:YLF amplifiers are again end-pumped by two fiber-coupled laser diodes each.

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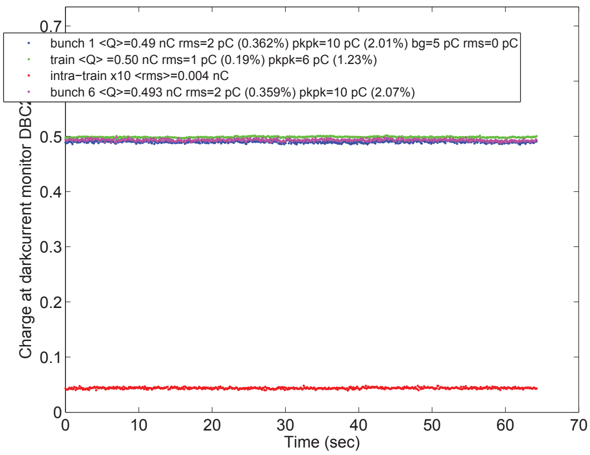

Figure 4: Measured charge in the FLASH accelerator. Shown is the charge of bunches 1 and 6 (blue, magenta) and also averaged over the train (green). The intra train rms jitter is shown in red with a magnification of 10. The rms stability of a single bunch from shot to shot is 0.36 %, and average over the pulse train, 0.19 %. In this example, 1250 bunches per second have been accelerated.

A Pockels cell based pulse picker installed in the preamplification stage runs at 1 MHz forming a pulse train with a length of about 1.5 ms (repetition rate 10 Hz). A second pulse picker installed before the final amplification stages picks only those laser pulses, which the accelerator needs. This pulse picker is controlled by the operator and is also used for emergency switch off. A maximum of 800 pulses with 1 MHz per train at 10 Hz with a single pulse energy of up to 300 µJ or in a second mode, up to 2400 pulses with 3 MHz at 5 Hz and a reduced single pulse energy can be amplified. Table 1 summarizes the pulse parameters for the two main operational modes of the laser.

Charge Stability

The infrared radiation (1047 nm) is frequency doubled twice to the UV (262 nm) with two non-linear crystals, LBO and BBO. The crystals are equipped with a temperature stabilizer and a remote phase matching angle control. After proper adjustment, the single pulse energy jitter is below 0.5% (rms). Figure 4 shows a stability measurement of the electron bunch charge. The charge is stable over several hours with only little or no adjustments for small drifts required. A slow feedback to compensate small long-term drifts acts on a variable attenuator. The attenuator consists of a remote controlled half wave plate together with a polarizer. The polarizer is a thin plate mounted at the Brewster angle (s-polarization is totally reflected). A special coating allows for almost 100% transmission of a p-polarized beam.

Table 1: Laser Parameters for the Two Main Operation Modes. Some Parameters are Adjustable and are Set According to the Requirements of the Specific Experiment. Updated from [5]

	option	
parameter	**1 MHz**	**3 MHz**
laser material	Nd:YLF	
wavelength	1047 nm	
4th harmonic	262 nm	
train repetition rate	10 Hz	5 Hz
max. train length	800 µs	
intra-train rate	up to 1 MHz**	3 MHz
pulses per train	800*	2400*
max. pulse energy UV	45 µJ	15 µJ
max. energy per train	36 mJ	36 mJ
arrival time jitter	60 fs (rms)	
longitudinal shape	Gaussian	
micro pulse length	6.5±0.1 ps (sigma)	
transverse profile	flat	
spot size on cathode	1.2 mm diam.*	
charge stability	0.5% rms	
*adjustable	**1 MHz, 500, 250, 200, 100, 50, 40 kHz	

Pulse Length

The duration of the UV-pulse is 6.5±0.1 ps, measured with a streak camera. The longitudinal shape is Gaussian, no longitudinal pulse shaper is installed.

The duration of the UV pulse is also determined by the pulse shortening due to the nonlinearity of the wavelength conversion process, and saturation effects which lengthen the pulse. These effects lead to a measurable change of the pulse duration and longitudinal shape in dependence on the intensity of the laser pulses [5]. In consequence, a proper adjustment of the BBO phase matching angle is required during machine set-up, since this influences the bunch compression process of the accelerator. Later on, changes in for instance number of pulses per train may require a retuning of the bunch compression and adjustments of the phase of the laser in respect to the RF.

To mitigate this effect, a pulse picker in the UV is being designed. The kicker will allow to operate the BBO at constant power, while the bunch pattern is modeled by the picker. Such a pulse picker based on an acousto-optic modulator has been successfully tested recently [11].

SIMULTANEOUS OPERATION FLASH1 AND FLASH2

FLASH is being upgraded with a second undulator beamline, FLASH2 [12]. The goal is to operate the two undulator beamlines FLASH1 and FLASH2 simultaneously for different kind of experiments. However, since one accelerator drives both beamlines, the beam parameters delivered for FLASH1 and FLASH2 users can not be completely independent from each other. On the other hand, every photon experiment has its own requirements on beam

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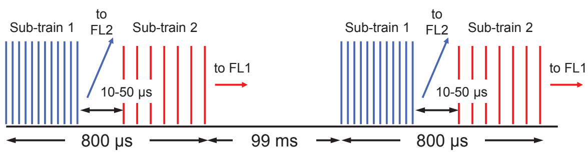

Figure 5: Bunch train sharing between FLASH1 (FL1) and FLASH2 (FL2): one RF pulse is shared by two sub-bunch trains. One train goes to FLASH1, the other is kicked to FLASH2. The sub-trains may have different bunch pattern or energy as indicated.

pattern, photon wavelength, pulse duration, number of pulses etc.

The plan is to share every 0.8 ms long RF-pulse between two bunch trains: one part of the bunch train (sub-train 1) is transported to FLASH1, while the other part (sub-train 2) is deflected by a kicker-septum system to FLASH2 (see Fig. 5).

Both beamlines are served with the same 10 Hz repetition rate. The sub-trains will have a distance as short as possible, between 10 and 50 µs, determined by the kicker response time. The easiest and most straight-forward and also transparent way to realize different bunch patterns for both sub-trains (number of bunches, bunch spacing, bunch charge) is to use two separate injector laser systems.

The UV laser pulse kicker system [11] under development as described in the previous section, will also allow – to a certain extend – a bunch pattern manipulation. With such a laser kicker system, flexible bunch pattern for both beamlines may be realized with one laser only.

A more detailed discussion of simultaneous operation of FLASH1 and FLASH2, including results from performance tests, is in [8].

CONCLUSION

The photoinjector laser system has been upgraded in several places. A second laser system has been installed to serve as a back-up for normal FLASH operation but also to allow sharing of pulse trains within one RF pulse between FLASH1 and the new FLASH2 undulator beamline. Two lasers allow the generation of flexible, independent pulse pattern for each sub-train. In addition, the transport beamline has been upgraded to improve the transverse beam quality using fixed apertures imaged onto the cathode. A laser UV kicker system is being developed to further improve the operability of the laser system. The arrival time of the laser oscillator is stabilized by an optical cross-correlator linked to the FLASH synchronization system. An arrival time stability of 60 fs (rms) is achieved. Further upgrades are planned to improve the stabilization, especially shot-to-shot and intra-bunch train charge and arrival time.

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REFERENCES

[1] W. Ackermann et al., “Operation of a free-electron laser from the extreme ultraviolet to the water window”, Nature Photonics **1** (2007) 336.

[2] S. Schreiber et al., “Photocathodes at FLASH”, Proc. IPAC 2012, New Orleans, USA, p. 625.

[3] S. Lederer et al., “Photocathodes at FLASH”, Proc. FEL 2011, Shanghai, China, p. 511.

[4] I. Will, H. I. Templin, S. Schreiber, and W. Sandner, “Photoinjector drive laser of the FLASH FEL”, Optics Express **19** (2011) 23770.

[5] S. Schreiber et al., ”Operation of the FLASH Photoinjector Laser System”, Proc. FEL 2011, Shanghai, China, p. 507.

[6] S. Schreiber, D. Sertore, I. Will, A. Liero and W. Sandner, “Running experience with the laser system for the RF-gun based injector at the TESLA Test Facility linac,” Nucl. Instrum. Meth. A **445** (2000) 427.

[7] I. Will, G. Koss and I. Templin, “The upgraded photocathode laser of the TESLA Test Facility,” Nucl. Instrum. Meth. A **541** (2005) 467.

[8] B. Faatz et al., “Simultaneous Operation of a Multi Beamline FEL Facility”, this conference, TUPD32.

[9] M. F. Felber et al., “Performance of the New Master Oscillator and Phase Reference System at FLASH,” Proc. PAC2007, Albuquerque, New Mexico, p. 188.

[10] S. Schulz et al., “Precision Synchronization of the FLASH Photoinjector Laser,” Proc. IPAC 2010, Kyoto, Japan, p. 2875.

[11] M. Gross et al., “Laser Pulse Train Management with an Acousto-optic Modulator”, this conference, MOPD61.

[12] K. Honkavaara et al., “Status of the FLASH II Project”, this conference, WEPD07.

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