SIMULTANEOUS OPERATION OF THREE LASER SYSTEMS AT THE FLASH PHOTOINJECTOR

S. Schreiber*, J. Roensch-Schulenburg, B. Steffen, C. Gruen, K. Klose, DESY, Hamburg, Germany

Abstract

The free-electron laser facility FLASH at DESY (Hamburg, Germany) operates two undulator beamlines simultaneously. Both undulator beamlines are driven by a common linear superconducting accelerator with a beam energy of up to 1.25 GeV. The superconducting technology allows the acceleration of trains of several hundred microsecond spaced bunches with a repetition rate of 10 Hz. A fast kickers-septum system is installed to distribute one part of the electron bunch train to FLASH1 and the other part to FLASH2 keeping the full 10 Hz repetition rate for both beamlines. In order to deliver different beam properties to each beamline, the FLASH photoinjector uses two independent laser systems to generate different bunch pattern and bunch charges. One laser serves the FLASH1 beamline, the other the FLASH2 beamline. A third laser with adjus ö laser pulse duration is used to generate ultra-short bunches for single spike lasing.

INTRODUCTION

FLASH [1–3], the free-electron laser (FEL) user facility at DESY (Hamburg) simultaneously operates two undulator beamlines [4–6]. It delivers high brilliance XUV and soft X-ray SASE radiation to photon experiments. FLASH is a user facility since 2005.

FLASH is a linear accelerator with a photoinjector followed by a superconducting linear accelerator. The maximum electron beam energy is 1.25 GeV, allowing SASE lasing down to 4 nm. The FLASH1 undulator beamline is in operation since 2004, the new FLASH2 beamline since 2014.

More details on the FLASH facility and its present status as well as on simultaneous operation of two beamlines can be found in these proceedings [3, 6].

A unique feature of FLASH is its superconducting accelerating technology. It allows to accelerate several thousand electron bunches per second. The bunches come in bursts with a repetition rate of 10 Hz. The maximal burst duration is 0.8 ms, the smallest distance between single bunches is 1 µs allowing a maximum number of 800 bunches per burst or 8000 bunches per second. FLASH has two undulator beamlines: FLASH1 and FLASH2. The burst of electron bunches is shared between them, keeping the 10 Hz repetition rate of the accelerator for each beamline.

An important and unique feature of FLASH is, that beam parameters and bunch pattern can vary for the two undulator beamlines: experiments with different wavelengths, pulse durations, and pulse pattern are possible at the same time.

* siegfried.schreiber@desy.de

The flexibility is realized with three main features. Firstly, variable gap undulators allow to adjust the wavelength for FLASH2 experiments, while the beam energy is determined by the wavelength required for FLASH1 lasing with its fixed gab undulators. Secondly, different photoinjector laser systems operated in parallel allow different charges, different pulse pattern, and to create a variable gap between the sub-bursts for FLASH1 and FLASH2. Thirdly, the low-level RF control of the accelerating structures are able to adjust phases and amplitudes – to a certain extend – independently for both beamlines, thus making different compression schemes possible. For details on FLASH2 photon beam parameters, the reader is referred to [4].

FLASH has three photoinjector lasers. Two lasers provide bursts of laser pulses with high single pulse energy but fixed single pulse duration. A third system has the feature of short and variable pulse duration optimized for high compression for ultra-short single spike SASE photon pulses.

The most promising method to achieve such short pulses is to compress the electron bunch to the femtosecond level. In the most extreme case the lasing part of the bunch is as short as one longitudinal optical mode. These so-called single-spike SASE pulses [7, 8] are bandwidth limited, longitudinally coherent.

In order to mitigate space charge forces, a low bunch charge of 20 pC is applied. It is generated at the gun by a short laser pulse of less than 1 ps (rms), thus substantially reducing the bunch compression factor required for bunch durations of a few femtoseconds only.

THE ELECTRON SOURCE

The electron source of FLASH is a photoinjector based on a normal conducting L-band 1.5 cell RF-gun. The gun is operated with an RF power of 5 MW at 1.3 GHz, corresponding to a maximal accelerating field at the cathode of 52 MV/m. The RF pulse duration is up to 850 µs, sufficient for generation of the required bunch trains of 800 µs duration. The repetition rate is 10 Hz. The beam momentum at the gun exit is 5.6 MeV/c.

As discussed in the introduction, the RF pulse length of the gun is adapted to the high duty cycle of the superconducting accelerator.

FLASH can accelerate many thousands of electron bunches per second. 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. The lifetime is more than 400 days of continuous operation [9]. The bunch charge

ISBN 978-3-95450-134-2

required for FLASH SASE operation is between 20 pC and a bit more than 1 nC. Assuming a very conservative quantum efficiency of the cathode of 0.5 %, a laser pulse energy of not more then 1 µJ on the cathode is sufficient to produce a 1 nC electron bunch. For 8000 bunches per second this corresponds to a reasonable intra train power of 1 W (0.8 ms burst) and an average power of 8 mW at 262 nm.

A challenge for the laser system is its burst mode structure with 0.8 ms long flat bursts of laser pulses. In addition, the picosecond long pulses must be synchronized to the RF of the accelerator to the 100 fs level.

THE LASER SYSTEMS

Laser 1 and Laser 2

The two laser systems [10] described in this section have been installed in 2010 [11] and 2012, and are a substantial upgrade compared to the previous lasers in operation at FLASH and the former TESLA Test facility (TTF) [12, 13]. The lasers have been developed in the Max Born Institute, partially tested at DESY, Zeuthen at PITZ and finally installed at FLASH.

Both lasers are used to drive the FLASH1 and FLASH2 beamlines for user runs. Both lasers can run for either beamline and also on the same beamline simultaneously, and also serve as a backup system for the other.

The layout of both lasers are very similar. Both systems consist of a pulsed laser oscillator with subsequent amplification stages. Figure 1 shows a schematic overview. A recent description of the laser systems can be found in [14], where the upgrade plans now realized have been described. 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 crystal to the UV wavelength of 262 nm. Figure 2 shows an example of a scope trace of laser pulse trains.

The laser is equipped with two Pockels cell based pulse pickers before and after the pre-amplification stages. The one before the preamplifier is operated at a constant 1 MHz, the second just before the last high power amplifiers are used by the operator to control the number and distance of pulses per train – 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.

In addition to the Pockels-cell based pickers in the IR, a new UV pulse picker is being tested based on an acousto-optic modulator [15].

For details on the pulse train oscillator [13] and amplification stages, the reader is referred to [10, 14]. Table 1 summarizes the pulse parameters for the lasers.

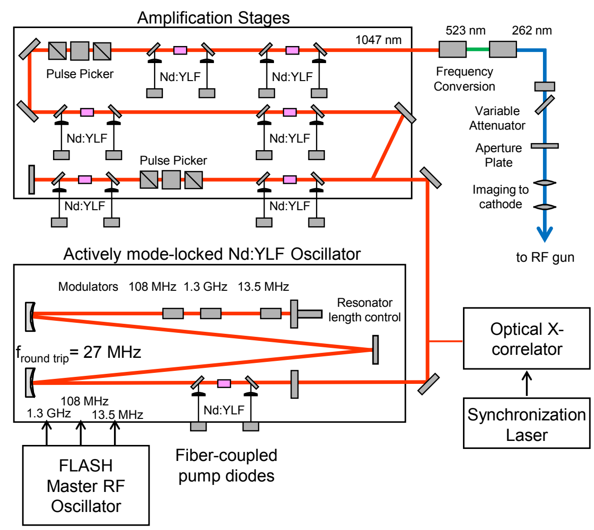

Figure 1: Schematic overview of laser 2 [14]. The oscillator and amplifiers are pulsed with 10 Hz, pulses are a few milliseconds long. The laser 1 amplification stages are very similar. Laser 1 has a shorter oscillator operating at 108 MHz using a 54 MHz AOM and a 1.3 GHz EOM.

Laser 3

Laser 3 has been installed and commissioned in 2013 [16]. The laser system consists of an oscillator [17] and a Yb:YAG amplifier [18]. The oscillator provides 400 fs pulses at 1030 nm with a repetition rate of 54 MHz. An acousto-optic modulator (AOM) picks with 1 MHz before final amplification to nominal 10 W average output power. The single pulse energy is about 10 µJ at 1030 nm. A second AOM picker before wavelength conversion is used by the operator to adjust the number and distance of pulses sent to the RF gun.

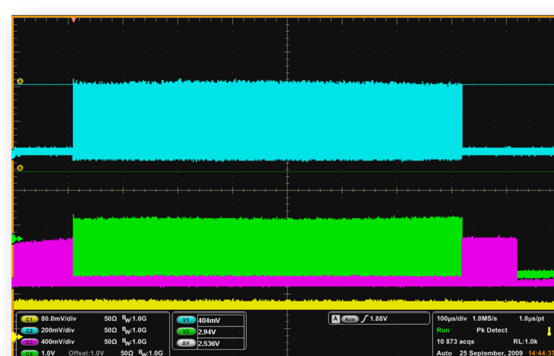

Figure 2: Example of a train of laser pulses [14]. The oscilloscope traces show the pulse train of the 27 MHz oscillator (yellow trace), after preamplification (3 MHz, wavelength 1047 nm, magenta), after conversion to 523 nm (3 MHz, 523 nm, green), and after conversion to the UV (3 MHz, 262 nm, blue). The time scale is 100 µs per division. Neither the 27 MHz nor the 3 MHz pulse structure is not resolved. Usually the laser is operated in the 1 MHz mode.

ISBN 978-3-95450-134-2

Frequency conversion is obtained with an LBO to the green, and with a BBO crystal to the UV (257.5 nm). The efficiency is 10 %; additional losses are due to the pulse stretcher and the transverse beam shaping. Overall, the pulse energy is sufficient for for electron bunch charges up to 200 pC.

Pulse Duration

The lasers do not apply longitudinal beam shaping, thus the longitudinal shape is close to a Gaussian. The duration of the UV-pulse is measured with a streak camera [19]. The measured pulse duration is $\sigma = 4.5 \pm 0.1$ ps for laser 1 and 6.5 ± 0.1 ps for laser 2 (sigma of a Gaussian fit). The pulse duration difference is due to their different laser oscillator.

The special feature of laser 3 is its adjustable pulse duration. The initial 800 fs long UV pulses are stretched by two transmissive gratings with 4000 lines per cm. A pulse duration between $\sigma = 0.8$ and 1.6 ps is adjustable.

Energy Control and Recombination Technique

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 to adjust the electron bunch charge emitted at the cathode.

The attenuators consist of a remote controlled half-wave plate together with Brewster angle polarizer plate.

These type of polarizer plates are also used to combine the three lasers into one common beamline. With a similar technique, pulse stacking [20] and double pulses by the split and delay technique are produced for certain experiments [21]. The Brewster angle polarizer plate is a thin coated fused silica plate oriented at the Brewster angle of 56°, transmitting 94 % of the p-polarization and reflecting 99.7 % of the s-polarization component.

The incoming UV laser pulse is linear polarized. The half-wave plate turns the polarization angle to the desired value while the polarizer transmits the p-polarized state only. For split and delay units, the relative intensities of the transmitted and the reflected beam are also adjusted with a remote controlled half-wave plate.

Combination of two laser pulses into one beamline – either from two laser systems or after the split and delay-unit –, are done in a similar way simply reversing the beam direction. The advantage of Brewster plate polarizers compared to polarizing independent beam splitters is that the recombination avoids the usual 50 % beam loss.

Beamline

Lasers 1 and 2 consequently use relay imaging together with spatial filtering. All amplification stages are imaged to the next amplifier head, and then to the frequency conversion crystals, followed by the last spatial filter in the UV.

The laser beam is then expanded and collimated to overfill a beam shaping aperture (BSA). A set of remotely controlled hard edge apertures of various sizes can be put into the laser beam. Usually an aperture size of 1.2 mm in diameter is used. Finally, the pulse shaping aperture is imaged onto the cathode of the RF-gun. The beam shaping aperture produces a quasi flat truncated Gaussian pulse on the cathode with negligible pointing jitter.

The laser beamline from the BSA to the cathode has a horizontal geometry with a length of about 5 m and traverses the radiation shielding of the accelerator. The beamline is sealed in tubes which are not evacuated. A quartz window separates the laser hutch with the tunnel to avoid air flows in the tubes. Finally, a fused silica vacuum window is followed by an all metal in vacuum mirror with an optically polished surface and and an enhanced UV-reflectivity. The cathode is hit under a small angle of 3°. Using linear translation stages the laser beam can be moved and aligned on the cathode with a precision of better than 10 µm. The laser beam can be deflected to a so-called virtual cathode, a Ce:YAG scintillator screen placed at the exact distance as the photo cathode.

Table 1: Main Parameters for the Photoinjector Laser Systems. Some parameters are adjustable and are set according to the requirements of the specific experiment.

Item	**Laser 1**	**Laser 2**	**Laser 3**
Laser material	Nd:YLF		Yb:YAG
Wavelength	1047 nm		1030 nm
4th harmonic	261.7 nm		257.5 nm
Train repetition rate	10 Hz		
Max. train duration	800 µs		
Intra-train rate	1 MHz (*)		
Pulses per train	1 – 800		
Pulse energy UV	50 µJ		1 µJ
Average power (IR)	2 W		10 W
Arrival time jitter	60 fs (rms)		—
Longitudinal shape	Gaussian		
Pulse duration (σ)	4.5±0.1 ps	6.5±0.1 ps	0.8–1.6 ps
Transverse profile	flat, truncated Gaussian		
Spot size on cathode	1.2 mm diam. ($^+$)		0.8 mm ($^+$)
Charge stability	0.5% rms		1% rms

* also: 500, 250, 200, 100, 50, or 40 kHz; 3 MHz optional
$^+$ truncated Gaussian; 15 different diameters are available

Combining the Lasers into One Beamline for Simultaneous Operation

Figure 3 shows how the laser beams of all three lasers are combined to one beamline. The Brewster plate polarizers are used for this purpose. Laser 1 is s-polarized and reflected by combiner 1 into the beamline of laser 2, which is p-polarized. Laser 3 is injected in a similar way using combiner 2.

Since laser 1 and laser 2 exhibit s- and p-polarization resp., a half wave plate turns the polarization state of both lasers such that both lasers are transmitted by combiner 2. The energy loss for lasers 1 and 2 is acceptable. This would not be the case for laser 3.

Combiner 2 is mounted on a translation stage and can be completely removed from the beamline if required. A

ISBN 978-3-95450-134-2

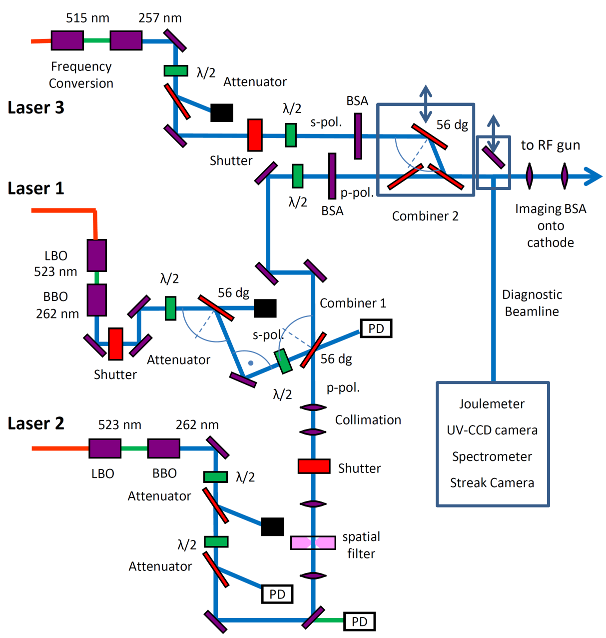

Figure 3: Beamline to combine all three laser systems. See explanations in the text.

second plate compensates the lateral shift of the polarizer plate. Laser 1 and laser 2 have the same beam shaping aperture (BSA), laser 3 has its own. The position of the BSA plates are such, that the aperture is imaged onto the photo cathode.

A diagnostic beamline features various instruments, a joulemeter, a UV enhanced CCD-camera, a spectrometer, and a streak camera.

SIMULTANEOUS OPERATION FLASH1 AND FLASH2

To allow different photon pulse pattern simultaneously for both FLASH undulator beamlines, two laser systems are used to serve FLASH1 and FLASH2. This is usually laser 1 and laser 2.

For operational reasons and the realization of different bunch pattern and charge, using two laser systems is a straightforward solution. An alternative would be to use a flexible pulse picker in the UV as described in [15] controlling the number of pulses, the amplitudes, and the distance independently for both beamlines. Such a pulse picker is in preparation.

As discussed above, FLASH operates with 0.8 ms long RF-pulse. The first part of the RF-pulse is used for FLASH1, the second part for FLASH2 (or vice versa). Between the sub-trains, a gap of 50 µs allows for the transition time of the kicker-septum system and the low level RF system to adjust (see Fig. 4).

For certain experiments, the short pulse laser 3 can be diploid to either of the two beamlines or in parallel with laser 1 or laser 2. This is done for example for experiments to generate ultra-short single-spike SASE pulses [22].

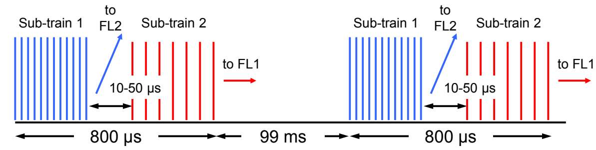

Figure 4: Bunch train sharing between FLASH1 (FL1) and FLASH2 (FL2): one RF pulse (10 Hz repetition rate) is shared by two sub-bunch trains. One train goes to FLASH1, the other is kicked to FLASH2. The sub-trains may have different bunch pattern or charge.

In the near future, FLASH will be equipped with a 3rd beamline, operated simultaneously in a similar way.

CONCLUSION

The three photoinjector laser systems are operated at the same time simultaneously to produce flexible electron bunch pattern for the FLASH beamlines, FLASH1 and FLASH2, and in the future also FLASH3.

ACKNOWLEDGMENT

We like to thank our colleagues from DESY and MBI, Berlin for their valuable and constant support.

REFERENCES

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

[2] K. Tiedtke *et al.*, "The soft x-ray free-electron laser FLASH at DESY: beamlines, diagnostics and end-stations", New J. Phys. **11**, 023029 (2009).

[3] K. Honkavaara *et al.*, "Status of the Soft X-ray User Facility FLASH", in *These Proceedings: Proc. 37th Int. Free-Electron Laser Conf.*, Daejeon, Korea, 2015, MOP014.

[4] B. Faatz *et al.*, "FLASH II: Perspectives and challenges", Nucl. Instr. Meth. A **635**, S2 (2011).

[5] K. Honkavaara *et al.*, "FLASH: First Soft X-ray FEL Operating Two Undulator Beamlines Simultaneously", in *Proc. 36th Int. Free-Electron Laser Conf.*, Basel, Switzerland, 2014, WEB05.

[6] M. Scholz *et al.*, "First Simultaneous Operation of Two SASE Beamlines in FLASH", in *These Proceedings: Proc. 37th Int. Free-Electron Laser Conf.*, Daejeon, Korea, 2015, TUA04.

[7] R. Bonifacio, L. De Salvo, P. Pierini, N. Piovella, and C. Pellegrini, "Spectrum, temporal structure, and fluctuations in a high-gain free-electron laser starting from noise", Phys. Rev. Lett. **73**, 70 (1994).

[8] J.B. Rosenzweig *et al.*, "Generation of ultra-short, high brightness electron beams for single-spike SASE FEL operation", Nucl. Instr. Meth. A **593**, 39 (2008).

[9] S. Schreiber *et al.*, "Lifetime of Cs2Te Cathodes Operated at the FLASH Facility", in *These Proceedings: Proc. 37th Int. Free-Electron Laser Conf.*, Daejeon, Korea, 2015, TUP042.

ISBN 978-3-95450-134-2

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

[11] S. Schreiber *et al.*, "Operation of the FLASH Photoinjector Laser System", in *Proc. 33th Int. Free-Electron Laser Conf.*, Shanghai, China, 2011, p. 507.

[12] 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. Instr. Meth. A **445**, 427 (2000).

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

[14] S. Schreiber *et al.*, "Upgrades of the Photoinjector Laser System at FLASH", in *Proc. 34th Int. Free-Electron Laser Conf.*, Nara, Japan, 2012, p. 385 (WEPD08).

[15] M. Gross *et al.*, "Laser Pulse Train Management with an Acousto-optic Modulator", in *Proc. 34th Int. Free-Electron Laser Conf.*, Nara, Japan, 2012, p. 189 (MOPD61).

[16] T. Plath *et al.*, "Commissioning and Diagnostics Development for the New Short-Pulse Injector Laser at FLASH", in *Proc. 2nd International Beam Instrumentation Conf.*, Oxford, United Kingdom, 2013, p. 353 (TUPC03).

[17] Origami 10XP by Onefive GmbH, Zurich, Switzerland, `http://www.onefive.com`

[18] Amplifer by AMPHOS, Aachen, Germany, `http://www.amphos.de`

[19] Femtosecond streak camera C6138 (FESCA-200), Hamamatsu Photonics K.K., Hamamatsu, Japan.

[20] S. Schreiber, "Pulse Stacker for the Photoinjector Laser System", in *Proc. TESLA Collaboration Meeting*, Zeuthen, Germany, Jan 21-23, 2004, WG3, `http://www-zeuthen.desy.de/tesla2004/agenda_wg3.html`

[21] O. Grimm, K. Klose, and S. Schreiber, "Double-pulse Generation with the FLASH Injector Laser for Pump/Probe Experiments", in *Proc. 10th European Particle Accelerator Conf.*, Edinburgh, Scotland, 2006, p. 3143 (THPCH150).

[22] J. Roensch-Schulenburg *et al.*, "Operation of FLASH with short SASE-FEL Radiation Pulses", in *Proc. 36th Int. Free-Electron Laser Conf.*, Basel, Switzerland, 2014, p. 342 (TUB04).

ISBN 978-3-95450-134-2