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FLASH PHOTOINJECTOR LASER SYSTEMS

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Abstract

The free-electron laser facility FLASH at DESY (Hamburg, Germany) operates two undulator beamlines simultaneously for FEL operation and a third for plasma acceleration experiments (FLASHForward). The L-band superconducting technology allows accelerating fields of up to 0.8 ms in length at a repetition rate of 10 Hz (burst mode). A fast kicker-septum system picks one part of the electron bunch train and kicks it to the second beamline such that two beamlines are operated simultaneously with the full repetition rate of 10 Hz. The photoinjector operates three laser systems. They have different pulse duration and transverse shapes and are chosen to serve best for the given user experiment in terms of electron bunch charge, bunch compression, and bunch pattern. It is also possible to operate the laser systems on the same beamline to provide specific double pulses for certain type of experiments.

INTRODUCTION

FLASH, the free-electron laser (FEL) user facility at DESY (Hamburg) [1–3] simultaneously operates two undulator beamlines [4,5]. It delivers high brilliance XUV and soft X-ray SASE radiation to photon experiments. FLASH is a user facility since 2005. [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 duration of 0.8 ms and a repetition rate of 10 Hz. The laser systems of the photoinjector have to produce as many bunches within the burst as possible. For FLASH, the intra-burst repetition rate delivered to user experiments is 1 MHz and lower. Some experiments ask for 100 kHz, photon hungry experiments are able to take higher repetition rates.

An important feature of FLASH is, that one part of the burst is delivered to users at the FLASH1 beamline, the second part to users at the FLASH2 beamline. In order to serve different kind of experiments, the properties of the electron bunches usually differ between the two parts of the burst in charge, duration, and pulse pattern. [7] Therefore, FLASH has three photoinjector lasers running simultaneously on operator chosen beamlines. [8] 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, as an example.

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, with an RF pulse duration of 650 µs at a repetition rate of 10 Hz.

Since FLASH can accelerate many thousands of electron bunches per second with a charge of up to 2 nC, the quantum efficiency of the photocathode must be in the order of a few percent in order to keep the average laser power at an acceptable limit. Cesium telluride has been proven to be a reliable and stable cathode material with a quantum efficiency (QE) well above 5 % for a wavelength in the UV (around 260 nm). The lifetime is much longer than 1000 days of continuous operation. [9] To give an idea of the required laser single pulse energy, as an example, for a bunch charge of 1 nC and a QE of 1 % a single pulse energy of 0.5 µJ is required. For 10,000 bunches per second this corresponds to a reasonable intra-train power of 0.5 W (1 ms burst) and an average power of 5 mW in the UV.

The actual challenge for the laser systems is its burst mode structure with 1 ms long flat bursts of laser pulses. Flat in terms of single pulse energy and arrival time at the RF-gun. A feature is implemented to apply a linear slope over the laser pulse train using the phase of the 1.3 GHz synchronization RF. This is used to compensate possible arrival time slopes in respect the the accelerator due to heating of the BBO crystal along the burst (green to UV conversion). The pulse duration of the laser pulses must be in the order of a few degrees in 1.3 GHz RF phase. An optimum duration for longitudinal Gaussian shaped pulses is $\sigma = 5$ to 10 ps and 1 ps for ultra-short pulse operation.

Since FLASH delivers SASE pulses below 100 fs in duration, the required arrival time stability must be better than 50 fs (rms). This is achieved by synchronizing the laser oscillator with an external ultra-stable 1.3 GHz RF-source. The lasers are cross-correlated with the master laser oscillator of the FLASH synchronization system [10, 11] to measure the stability and to realize a slow feedback to compensate slow drifts.

THE LASER SYSTEMS

Laser 1 and Laser 2

The two laser systems [12] described in this section have been installed in 2010 [13] and 2012, and are a substantial upgrade compared to the previous lasers in operation at FLASH and the former TESLA Test facility (TTF) [14, 15]. The lasers have been developed in the Max Born Institute, Germany partially tested at DESY (Zeuthen, PITZ) and finally installed at FLASH.

The layout of both Laser 1 and Laser 2 are very similar. Both systems consist of a pulsed laser oscillator with subsequent amplification stages. A recent description of the laser systems can be found in [8, 16]. The laser material is Nd:YLF lasing at a wavelength of 1047 nm. Nd:YLF has a high gain and a long upper-state lifetime of 480 µs, and

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exhibits only weak thermal lensing. This makes it suitable to produce pulse trains with milliseconds in duration. After amplification, the wavelength is converted into the UV wavelength of 262 nm in two steps using an LBO and a BBO crystal. Figure 1 shows an example of a scope trace of a laser pulse train (burst). The lasers are equipped with two Pockels cell based pulse pickers before and after the pre-amplification stages. The one before the pre-amplifier 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 lasers do not apply longitudinal beam shaping, the longitudinal shape is close to a Gaussian. The duration of the UV-pulse as measured with a streak camera [17] is $\sigma = 4.5 \pm 0.1$ ps for Laser 1 and 6.5 ± 0.1 ps for Laser 2. The pulse duration difference is due to their different laser oscillator design.

For details on the pulse train oscillator [15] and amplification stages, the reader is referred to [12, 16]. Table 1 summarizes the pulse parameters for the lasers.

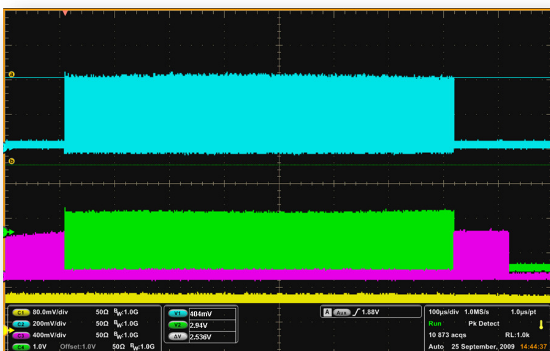

Figure 1: Example of a train of laser pulses taken from [16]. The oscilloscope traces show the pulse train of the 27 MHz oscillator (yellow trace), after pre-amplification (3 MHz, wavelength 1047 nm, magenta), after conversion to 523 nm (green), and to 262 nm (3 MHz, blue). The time scale is 100 µs per division.

Laser 3

Laser 3 has been installed and commissioned in 2013. [18] The laser oscillator [19] provides 400 fs pulses at 1030 nm with a repetition rate of 54 MHz (cw). An acousto-optic modulator (AOM) picks with 1 MHz before final amplification. The Yb:YAG amplifier [20] is designed to achieve 10 W average power, the single pulse energy is up to 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 (up to 1 ms bursts of 1 MHz or less at 10 Hz). Frequency conversion is again obtained with an LBO/BBO crystal pair into the UV (257.5 nm). Overall, the pulse energy is sufficient for electron bunch charges up to 200 pC.

A special feature of Laser 3 is its adjustable pulse duration. The initial 1 ps long UV pulses are compressed or stretched by two transmission gratings with 4000 lines per cm. A pulse duration between $\sigma = 0.8$ and 1.6 ps is adjustable. The pulses are shorter compared to Laser 1 and Laser 2, because in order to generate ultra-short electron bunches, a very short laser pulse duration is required to ease bunch compression in the subsequent bunch compressors of FLASH.

Energy Control

For each laser, 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. The attenuators consist of a remote controlled half-wave plate together with a Brewster angle polarizer plate, which is a thin coated fused silica plate oriented at the Brewster angle of 56°, transmitting 94 % of the p-polarized and reflecting 99.7 % of the s-polarized 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.

With a similar technique, double pulses by a split and delay technique (21 ns distance) are produced for experiments using THz radiation [21]. These type of polarizer plates are also used to combine the three lasers into one common beamline. [8]

Beamline

Lasers 1 and 2 consequently use relay imaging together with spatial filtering. The UV laser beams are expanded and collimated to overfill a beam shaping aperture (BSA). A set of 15 remotely controlled hard edge apertures of various sizes are available; from 0.05 to 2 mm in diameter. The pulse shaping aperture is imaged onto the cathode of the RF-gun. This method produces a quasi flat truncated Gaussian pulse on the cathode with negligible pointing jitter.

The choice of the appropriate aperture for best beam performance has been evaluated and is predefined depending mainly on the charge, but also on the laser used (pulse duration). The laser spot size needs to balance space-charge effects (better for larger spot sizes, longer pulses) and emittance (better at smaller spot sizes). For normal operation (0.3 - 0.4 nC), usually an aperture size of 1.2 mm is used for Laser 1 and Laser 2. Laser 3 is designed for ultra-short pulse operation. The optimization in this case is different. [18] The laser spot diameter for Laser 3 is usually 0.8 mm.

The laser beamline from the BSA to the cathode has a horizontal geometry with a length of about 5 m. A fused silica vacuum window is used 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. It is used

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to adjust the laser on the beam shaping apertures and to keep the laser beam at the cathode center.

Table 1: Main parameters of 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		
Train duration	800 µs		
Intra-train rate	1 MHz (*)		
Pulses per train (at 1 MHz)	1 – 800		
Pulse energy UV	10 µJ		1 µJ
Average power (IR)	2 W		10 W
Arrival time jitter	<50 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 2 shows how the laser beams of all three lasers are combined to one beamline. Brewster plate polarizers as described in the previous section 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 are cross-polarized (s/p), a half wave plate turns the polarization state of both lasers such that both lasers are equally transmitted by combiner 2. The energy loss due this scheme for Lasers 1 and 2 is acceptable. A 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. 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 2 for FLASH1, Laser1 or Laser 3 for FLASH2. Laser 3 is used for ultra-short pulse SASE operation. For operational reasons and the realization of different bunch pattern and charge, using three laser systems is a straightforward solution. As discussed above, FLASH operates with 0.8 ms long RF-pulses. The first part of the RF-pulse is used for FLASH1, the second part for FLASH2 (or vice versa). Between the

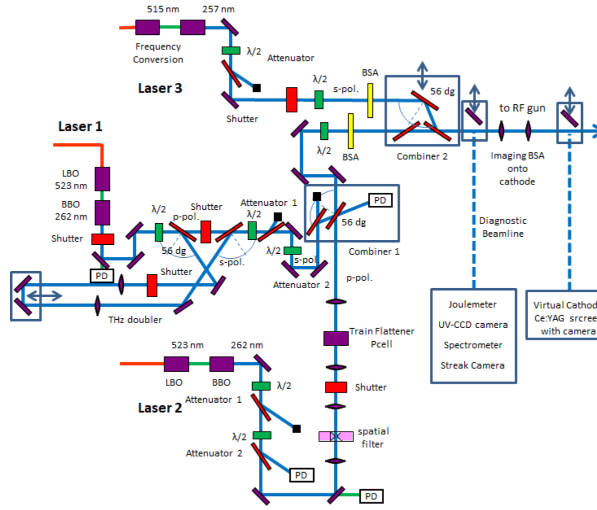

Figure 2: Beamline to combine all three laser systems. See explanations in the text.

sub-trains, a gap of about 50 µs allows for the transition time of the kicker-septum system and the low level RF system to adjust.

The 3rd FLASH beamline, FLASH3 is used for the development of and experiments with a novel plasma wakefield accelerator, FLASHForward. [22]

SUMMARY AND OUTLOOK

The three photoinjector laser systems are operated simultaneously to produce flexible electron bunch pattern for the FLASH beamlines FLASH1, FLASH2, and also FLASH3. The present laser systems are now in continuous operation for more than 10 years with negligible downtime (a few hours in the last years). Nevertheless, the system is aging and requires a refurbishment. Within the present general refurbishment and upgrade process of FLASH, a new modern laser system is being developed in-house. We expect the new system to be ready for operation in 2021.

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