OPERATION OF THE FLASH PHOTOINJECTOR LASER SYSTEM

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

Abstract

The photoinjector of FLASH uses an RF-gun equipped with Cesium telluride photocathode illuminated by appropriate UV laser pulses as a source of ultra-bright electron beams. The superconducting accelerator of FLASH is able to accelerate thousands of electron bunches per second in a burst mode. This puts special demands on the design of the electron source, especially the laser system. The fully diode pumped laser system is based on Nd:YLF and produces a train of 2400 UV-pulses in a burst of 0.8 ms length with a repetition rate of 5 Hz and 800 pulses with 10 Hz. The single pulse energy is up to 45 μJ per pulse at 262 nm. The laser uses a pulsed oscillator synchronized to the master RF with a stability of better than 200 fs (rms) in arrival time at the RF gun. Special care has been taken to produce a uniform and stable pulse train in terms of pulse energy, shape, and phase. Since FLASH is a free-electron laser user facility, the laser is designed to operate for more than 8000 h per year without operator intervention and little maintenance. We report on operational experience with the new system brought in operation in spring 2010.

INTRODUCTION

Since 2005 the free-electron laser FLASH at DESY, Germany operates as a user facility providing laser-like radiation from the VUV to the soft X-ray wavelength regime with an extraordinary high peak brilliance of 10^{29} to 10^{31} B[1].[1] One specialty of FLASH is, that it uses L-band superconducting TESLA-type accelerating technology. The acceleration is driven by long RF-pulses with a length of 1.5 ms, with a usable flat part of 0.8 ms. The repetition rate of 10 Hz, the RF frequency is 1.3 GHz. With 6 TESLA- and 1 XFEL-type 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 with a repetition rate of 10 Hz. The accelerator is designed to compensate beam loading for currents in the train of up to 9 mA, for instance, a 3 MHz train with a single bunch charge of 3 nC.

FLASH is a SASE free-electron laser and requires an excellent beam quality, which is achieved with an injector based on a laser driven L-band RF-gun.[2]

THE ELECTRON SOURCE

The RF-gun is operated with a 5 MW, 1.3 GHz klystron at a repetition rate of 10 Hz. The RF pulse length is with up to 900 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.[3, 4] The bunch charge required for FLASH is in the range of a few 100 pC to a bit more than 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 severe complication for the laser system is, that it has to provide the same burst structure in the UV as required for the electron beam. The picosecond long pulses must be synchronized to the RF of the accelerator to substantially better than 1 ps.

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

THE LASER SYSTEM

The new laser system is described in detail in [7]. The system consists 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 to the UV wavelength of 262 nm. The pulse energy can be adjusted with a remote controlled attenuator. The laser is imaged onto the cathode of the RF-gun. The transverse size of the laser is adjusted with a motorized iris. The laser has a pulse picker which is used by the operator to chose

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* siegfried.schreiber@desy.de

[1] the unit of brilliance is B= $\mathrm{photons/s/mrad^2/mm^2/(0.1\%bw)}$.

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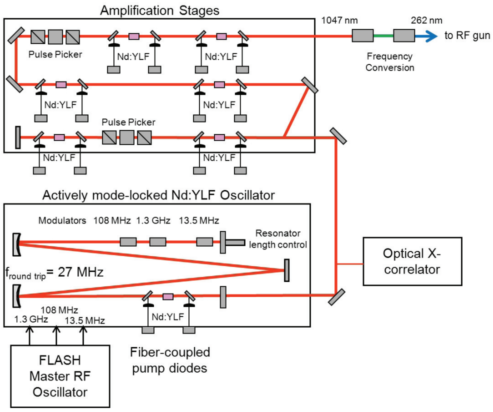

Figure 1: Schematic overview of the laser system.

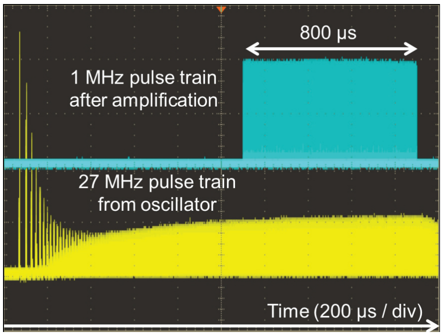

Figure 2: Oscilloscope traces of the laser pulse train of the oscillator (yellow trace), and after final amplification (blue) measured with photodiodes.

the number of laser pulses 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.

Laser Oscillator

The laser oscillator is an actively mode-locked and pulsed oscillator. The round trip time corresponds to 27.08 MHz, the 48th 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. The lasing element is 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, as it is shown in Fig. 2, yellow trace. A modulator operated at the frequency of the accelerator RF of 1.3 GHz 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 [8] of FLASH.

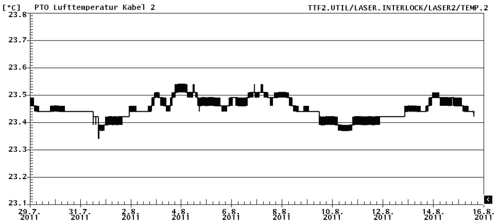

Figure 3: Air temperature at the laser oscillator for a period of 18 days. The average temperature is 23.4°C with an rms fluctuation of 0.04°C.

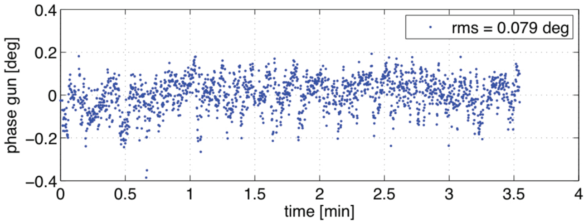

Figure 4: Short term measurement of the relative phase of the laser pulses in respect to the 1.3 GHz RF of the RF-gun. The stability is 0.08° of RF (rms) corresponding to 170 fs rms jitter.

An optical balanced cross correlator has been set-up [9] to monitor the phase of the laser oscillator pulses in respect to the FLASH fiber based synchronization system.[10] 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) (Fig. 3), also the humidity is constant within 10 % (pp).

The successful stabilization of the oscillator in terms of arrival time to better than 200 fs (rms) in respect to the RF of the RF-gun and the accelerator is an important feature to reliably drive the photoinjector of FLASH for long term runs without operator intervention.

By optically cross-correlating the pulses from two laser oscillators we have found that the timing jitter is well below 0.2 ps (rms). The laser data are confirmed by a measurement of the relative phase jitter between the laser pulses and the accelerating field of the RF-gun. See reference [11] for details on the technique applied. The measured short term phase jitter is less than 0.1 dg of 1.3 GHz (rms) (Fig. 4) corresponding to 200 fs rms jitter of arrival time at the RF-gun. This synchronization accuracy is sufficient for a stable operation of the FEL in terms of arrival time jitter.

Amplification

Because the oscillator is operated in pulsed mode, the single pulse energy is already by an order of magnitude higher compared to typical cw oscillators. 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. In a similar way as the oscillator, the amplifiers use Nd:YLF and are again

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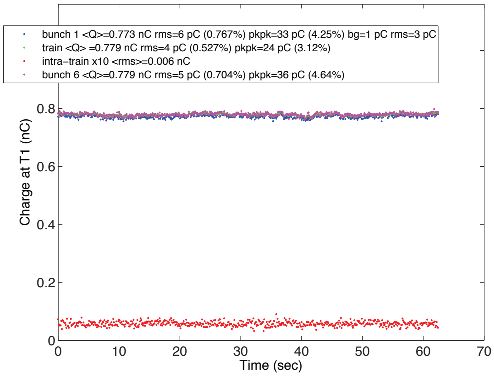

Figure 5: Measured charge at the exit of the RF-gun. Shown is the charge of bunches 1 and 6 (blue, magenta) and also averaged over the train (green). The intra train rms jitter is shown in red with a magnification of 10. The rms stability of a single bunch from shot to shot is better than 1 %.

end-pumped by two fiber-coupled laser diodes each. One advantage of the fiber solution is an easy replacement of the pump fibers. No realignment is required.

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 and a repetition rate of 10 Hz (see Fig. 6 magenta trace). 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 used for emergency switch off in case of beam losses and to limit the number of electron bunches for certain operation modes. 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.

Harmonic Generation Issues

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 1 % (rms). Figure 5 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.

Table 1: Laser Parameters for the Two Main Operation Modes. Some parameters are adjustable and are set according to the requirements for the specific experiment.

	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	200 fs (rms)	
longitudinal shape	Gaussian	
micro pulse length	6.5±0.1 ps (sigma)	
transverse profile	flat	
spot size on cathode	1 mm diam.*	
*adjustable **1 MHz, 500, 250, 200, 100, 50, 40 kHz		

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 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. Absorption of UV in the BBO crystal may lead to a change of the temperature along the laser beam path. The temperature feedback control is able to recover the initial temperature in about 200 s, which is large compared to the duration of the pulse train of 0.8 ms. Because, the laser pulse is with about 15 ps FWHH rather long, a potential change of the laser pulse shape due to a detuned BBO may lead to a change in arrival time at the RF-gun of a few picoseconds.

This has a severe impact on the properties of the electron bunches, since the bunch compression scheme of FLASH relies on a stable arrival time in a sub-picosecond scale, and also on space charge effects which have a square dependence of the charge. This leads to complications for the operation of the accelerator. The protection system of FLASH often triggers emergency switch offs or cuts the number of pulses in the train to a safe value when for instance beam losses occur. See next section for details. After such an event, the load on the BBO changes so that the beam conditions change for the subsequent trains. Since instabilities in laser pulses may trigger further losses or instabilities in the electron beam, this eventually leads to complete beam loss. Operation experience has shown, that once all systems running stable, laser and accelerator, the beam is for many hours in the machine without trips. Investigation are on the way to further understand and improve the conversion process. Further more, pulse picker in the UV after the conversion are in preparation to overcome this issue.

BUNCH TRAIN PATTERN AND MACHINE PROTECTION

An important feature of the laser system is the flexibility in the micro-pulse repetition rate. For certain user experiments, especially when time of flight instruments are

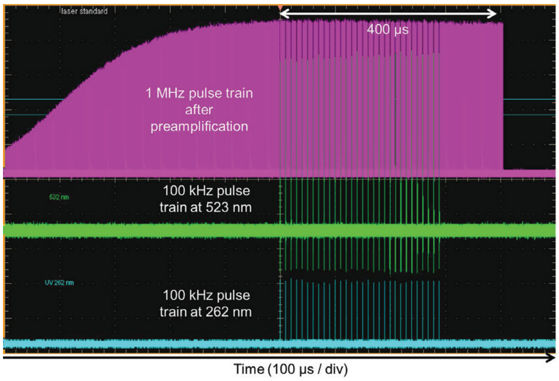

Figure 6: Example of a 100 kHz pulse train, in the green (green trace) and UV wavelength (blue trace). The cyan trace shows the pulse train after preamplification (1 MHz train).

involved, larger bunch spacing than the nominal 1 μs is required. A FPGA based controller is used to provide an easy interface for the operators to change the bunch spacing by acting on the 2nd Pockels cell. Within the base frequency of the FLASH timing system of 9.03 MHz, the intra-train spacing can be chosen freely. Besides the nominal 1 MHz, often bunch spacings of 3 MHz, 500 kHz, 250, 200, 100, 50, 40 kHz are used. Figure 6 shows an example of a 100 kHz pulse train. The controller is at the same time the interface between the machine protection system (MPS) and the laser. Depending on machine operating modes or component failures, the controller is able to block the Pockels cell with a latency of 3 μs, thus inhibiting the generation of electron beams. The latency is mainly due to the length of the accelerator (about 250 m). The MPS also restricts the number of pulses and the total charge emitted by the RF-gun to save values. For instance, when view screens at beam energies above 150 MeV are inserted, the number of bunches per train is limited to 2 (single pulse mode). Tuning of the beam is usually done in the short pulse mode, where a maximum of 30 bunches with not more than 30 nC of charge are allowed. In these cases, the number of triggers to the second Pockels-cell is limited. Also small but permanent losses for instance in the undulator sections may trigger a switch-off signal blocking the laser beam by a laser shutter.

Reliability

The pump diode lasers are running since their installation for more than 10.000 h continuously without any failure or visible degradation. The whole laser system is remarkably robust and needs only little maintenance. The water cooling system for various components needs regular maintenance in intervals of a couple of months, sometimes optical components need replacement, like the conversion crystals. The overall experience is extremely positive, the total downtime contributed to the laser system has been almost zero, except for a failure of the water system flow meters. In the last user run from Sept 2, 2010 up to July 25, 2011, the laser system accounted for a total down time of 9.3 hours only.

For a safe operation of the laser, important operating conditions are surveyed by an SPS based system. For instance, the system issues warnings and interlocks on overtemperature, water flow interruptions and so on. The overall system is controlled with a VME-crate based cpu integrated into the FLASH control system providing an interface to the operators. The cpu reads important laser parameters and drives for instance slow feedbacks on a shot to shot bases.

CONCLUSION

The photoinjector laser system has been upgraded to a fully diode pumped system. The upgraded system has been put into operation at FLASH in Spring 2010 providing beam since then without interruption. The stability and reliability of the system is extremely satisfactory, maintenance a routine task.

ACKNOWLEDGMENT

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