COMMISSIONING AND DIAGNOSTICS DEVELOPMENT FOR THE NEW SHORT-PULSE INJECTOR LASER AT FLASH*

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Abstract

In order to extend the parameter range of FLASH towards shorter electron pulses down to a few femto-second self-amplified stimulated emission (SASE) pulses, shorter bunches with very small charges of a few tens of picocoulombs directly at the photo injector are necessary. To achieve so short bunches at FLASH, a new injector laser delivering pulses of 1 to 5 ps duration has been installed and commissioned. The influence of the laser parameters on the electron beam was studied theoretically. In this paper we discuss the required laser beam diagnostics and present measurements of critical laser and electron beam parameters.

INTRODUCTION

One of the most important characteristics of free electron lasers is the generation of very short light pulses. At the **F**ree Electron **Las**er in **H**amburg (FLASH) current generated electron bunches have a full width at half maximum of about 100 to 400 fs, resulting in a SASE radiation pulse duration below 50 to and up to 200 fs (FWHM) [1].

There are several options to shorten the emitted SASE radiation pulse, one of them is to decrease the electron bunch length. At FLASH this is usually done by two bunch compressors. Using the standard FLASH injector laser with an rms laser pulse length of 6.4 ps one would have to achieve a compression factor of 2000 in order to reach an rms bunch duration of 3 fs [2]. This would require a technically challenging radio-frequency phase stability.

A much more stable method is to use a shorter incident laser pulse. This can only be done by a new photo-injector laser system that is able to provide sub-picosecond laser pulses.

This paper describes the commissioning and developed diagnostics of such a laser system at FLASH.

LASER SYSTEM

For short-pulse operation at FLASH a new photo-injector laser system has been installed and commissioned. The laser system consists of an oscillator[1] and a Yb:YAG amplifier[2] [3].

The oscillator provides 400 fs pulses at 1030 nm with a repetition rate of 54.16 MHz and an average output power of over 163 mW. An acousto-optic modulator (AOM) picks 1 MHz pulses which are amplified up to 10 W average output power, at which one pulse has an energy of about 10 µJ.

While FLASH operates with 10 Hz bunch trains with a duration of 800 µs, the intra-train spacing of the bunches can be as small as 1 MHz. Therefore, laser pulses have to be picked by a second AOM to provide the cathode with a suitable pulse pattern. This second AOM allows for arbitrary pulse picking.

The frequency of the remaining pulses has to be converted into its fourth harmonic to suit the electron's work function at the cathode. This is done by two non-linear crystals, each generating the second harmonic of the incident light.

During the first SASE shift in January 2013 a setup with 2 BBO crystals was used. In order to achieve a high conversion efficiency the laser beam was strongly focussed into both crystals. A high beam divergence at the crystal's position causes leading to increased instabilities in the harmonic generation, which in the end deteriorates the charge stability. With this setup a overall conversion efficiency of about 1 % was achieved.

Before the next measurement shifts the frequency conversion needs to be upgraded to get higher efficiency and stability. A non-critical LBO crystal will convert the light into its second harmonic and a thin BBO crystal generates the fourth harmonic. The design efficiency of this setup is about 10 %.

The converted laser pulse has a duration of about 800 fs. A laser pulse of this length would generate a short bunch at the cathode and depending on the charge a high longitudinal space charge force could appear and therefore would expand rapidly in this direction. To optimise the bunch length at the cathode, one can stretch the laser pulse with an optical stretcher consisting of two transmissive gratings with 4000 lines per cm. With this, we are able to choose an arbitrary pulse length between 1 and 5 ps (fwhm).

To optimise the emission process, we installed a variable telescope followed by an iris with different diameters, called beam shaping aperture, which allows us the choice of a transversal beam size at the cathode. The beam shaping aperture supplies 15 different aperture diameters. With this part of the laser beam line we can choose an optimal laser spot size and profile in order to minimise emittance.

Information about the laser system's snychronisation system can be found in [4].

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[1] Origami 10XP by Onefive (http://www.onefive.com/)

[2] Amphos (http://www.amphos.de/)

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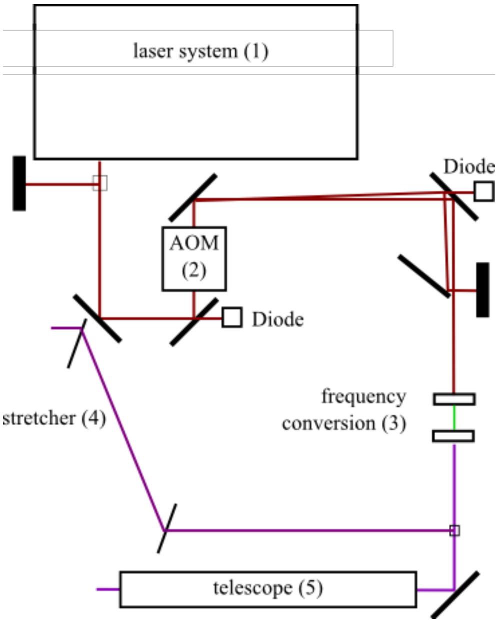

Figure 1: Schematic layout of the setup of laser system.

SIMULATIONS

In order to generate short FEL pulses with a sufficient power we have to minimise emittance. The linear accelerator at FLASH conserves normalized emittance during acceleration and therefore, the initial emittance at the gun needs to be small.

The transverse emittance at the gun mainly consists of three contributions [5]:

$$\epsilon = \sqrt{\epsilon_{rf}^2 + \epsilon_{cath}^2 + \epsilon_{sc}^2} \tag{1}$$

Here, ϵ_{rf} describes the emittance caused by the radio frequency, ϵ_{sc} the emittance contribution caused by space charge forces and ϵ_{cath} emittance contribution of the cathode often called thermal emittance.

While ϵ_{cath} and ϵ_{rf} are functions of the laser pulse dimensions, ϵ_{sc} is a function of the laser pulse shape. The thermal emittance depends on the laser spot size on the cathode and the rf induced emittance on the bunch duration.

The gun itself is accompanied by a focussing magnetic solenoid lens. The solenoid's focussing forces are proportional to the radial distance to the center of the magnet:

$$F(r) \propto r \tag{2}$$

A linear magnetic field can compensate only for linear space charge forces. This is why the radial space charge forces should be linearized. This can be done by achieving a transversal laser profile at the cathode that is referred to as truncated Gaussian [6].

A truncated Gaussian can be modeled using two parameters. The first is the standard deviation of the Gaussian, called σ_{inp}, the other is the cut parameter C_{Cut}. Only the part of the Gaussian within $|r| < C_{Cut} \cdot \sigma_{inp}$ is used. The parts of the Gaussian outside the region are cut away..

Another essential bunch parameter a for stable single-spike operation is the bunch duration. As explained before we need the new photo-injector laser system to produce short electron bunches in order to keep the compression factor reasonably low.

Therefore, when optimising the injector laser parameters a small bunch duration in combination with a reasonable small transverse emittance are the goal bunch parameters.

In order to find the best σ_{inp} and C_{Cut}, simulations using the particle tracking code ASTRA have been performed. Table 1 shows the most important simulation parameters.

Table 1: Important Simulation Parameters

Parameter	**Value**
laser pulse duration (RMS)	1.0 ps
bunch charge	20 pC
macro particles	20 000
gun gradient	50 $\frac{MV}{m}$
laser spot profile	truncated Gaussian
laser spot size (rms)	0.25 - 3.0 mm
aperture size	0.4 - 3.0 mm

Figure 2 shows the outcome of the simulations. Low values of σ_{inp} and especially small beam shaping apertures result in a high bunch length at the entrance of the first accelerating module. With high bunch length the compression factor would stay high which is why we aim to get small bunch length at the injector.

While the bunch length prefers bigger apertures and higher values of σ_{inp}, we get low emittance at the other end of the parameter range. The search for a good working point is therefore a trade off between low emittance and small bunch length. The final decision on the working point is subject to further discussions and measurements, but simulations suggest to choose a small σ_{inp} of about 0.5 to 1 mm with a beam shaping aperture within the same order of magnitude.

Figure 3 shows a Gaussian distribution for one of the parameter sets with low emittance and small bunch length. The distribution clearly shows a truncated Gaussian and not a flat-top.

DIAGNOSTICS

In order to measure the above mentioned laser parameters and correlate those with the corresponding properties of the electron bunch, we designed and started to install new diagnostics.

The laser intensity and transversal stability can be measured with a set of quadrant diodes, for transverse profile measurements a UV camera[3] was installed which is also used as a spectrometer together with a grating.

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[3] A JAI CM-140 GE-UV was used.

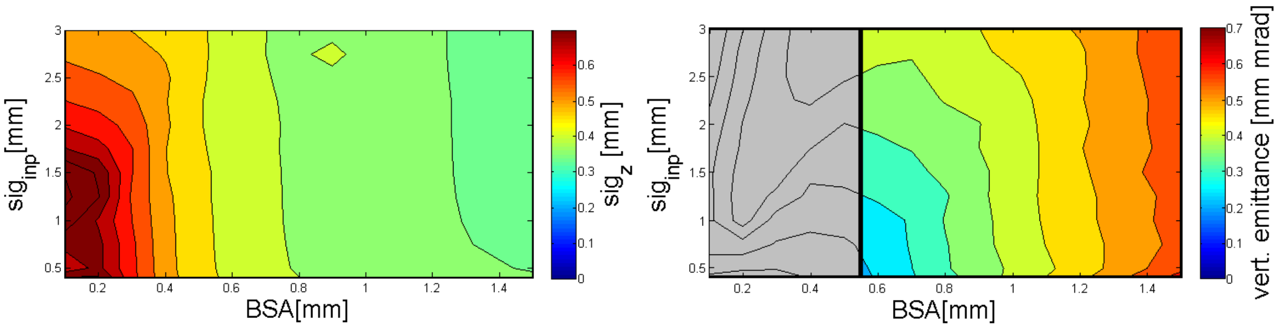

Figure 2: Simulated bunch properties at a grunphase of 0 degrees which corresponds to maximum energy gain. The left graph shows the longitudinal bunch rms length as a function of σ_{inp} and the size of the beam shaping aperture (BSA). The right graph shows the transverse emittance at the entrance of the first acceleration module of FLASH again as a function of the BSA diameter and laser spot size. The light grey area has been excluded because of too long bunches. (In this case a threshold of 0.45 mm as maximum rms bunch length of the the gun was chosen.)

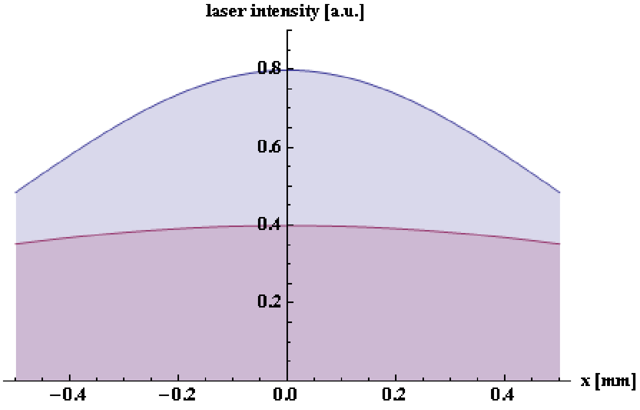

Figure 3: One of the possible transverse laser profiles. The blue curve shows a truncated Gaussian with a σ_{inp} of 0.5 mm and a aperture size of 0.5 mm radius. The violet curve shows a Gaussian with a σ_{inp} of 1.0 mm which is already much closer to a flat-top, but has also bigger emittance.

For laser pulse length measurements a Streak Camera[4] is used.

Spectrometer

The spectrometer was built using the same gratings that are used in the stretcher setup in the laser beam line with 4000 lines per cm. The laser beam is widened before passing through the grating at its blazing angle to illuminate enough lines.

After passing the grating the beam is focussed with a small focal length lens to get a small enough spatial distribution.

Quadrant Diodes

The quadrant diodes[5] have a cutoff frequency of 20 MHz which allows us to observe single pulses within a pulse train and study laser satbilities on a pulse to pulse basis.

The diodes are not set up yet which is why we cannot present stability measurements in this paper.

Stability Measurements

Another way to measure the overall laser stability (in terms of energy and position) is to use the charge stability of the generated electron bunch. To measure charge stability a series of charge measurements is taken, the standard devieation of these measurements then is the charge stability. This is measured using the dark current monitor at FLASH [7]. Measurements and the discussion of those can be found in the next section.

MEASUREMENTS

First measurement shifts have been conducted in September of last and January of this year.

Charge Stability Measurements

During the shift in september the charge stability for the new photo-injector laser was measured at three different gun phases (see figure 4). The charge instabilities have been measured with to 0.43 pC at 32 pC total charge and 15°gun phase, 0.66 pC at 56 pC and 38°and 0.71 pC at 56 pC and 78°.

The uncertainty of the measurements of the dark current monitor is in the order of about 0.8 pC. All measurement results have statsitical errors below 0.8 pC and are limited by the dark current monitor's resolution.

To calculate an upper boundary of the laser amplitude ability we took the measurement on the plateau (78°), which is less influenced by gun phase jitter. On the other hand we can neglect the position instabilities, because of a nearly uniform quantum efficiency around the laser spot position. An upper boundary for the laser's amplitude jitter is then 83 pJ at a total power of 6.5 nJ mostly dominated by the resolution of the dark current monitor.

Figure 4 shows a gun phase scan with the points marked at which the measurements were taken. Figure 5 shows

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[4] FESCA 200, Hamamatsu

[5] S4349, Hamamatsu

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a typical charge stability measurement for the new short-pulse laser at the typical working phase at FLASH.

Figure 5 shows a charge stability measurement of the short-pulse injector laser taken during a shift in September 2012. Here the charge stability is much better than in January 2013 due to the already mentioned frequency conversion setup in January.

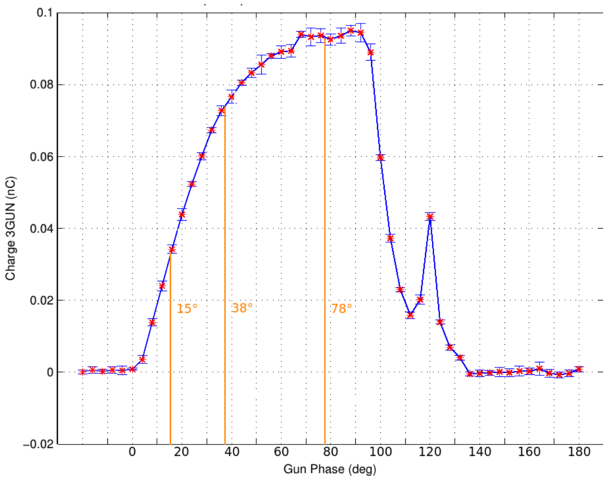

Figure 4: Scan of the charge as a function of the gun phase, made with the new short-pulse injector laser. The three measurement points refered to in the text are marked as orange lines. This scan of the gunphase however does not show the same charge values as given in the table because it was done at a different laser attenuator setting.

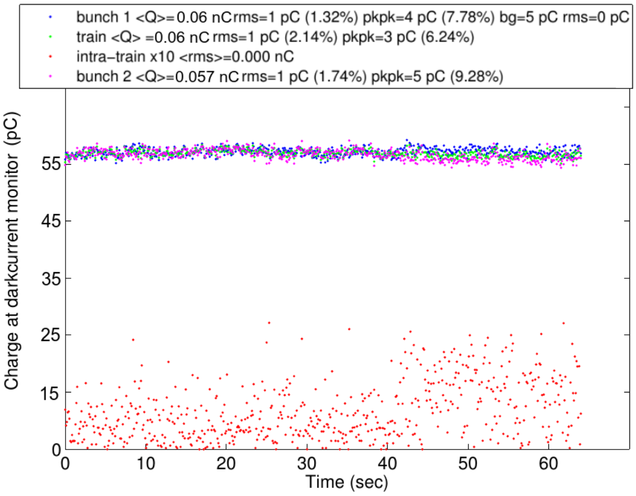

Figure 5: Charge stability measurement of the new photo-injector laser in September 2012 at the gun phase typically used during FLASH operation. The blue and violet points show measurements of single bunches in a two-bunch train. The blue dots are averaged values for the train. The red dots are intra-train jitter measurements multiplied by a factor of 10.

Laser Pulse Duration

The laser pulse duration was measured using a streak camera with a resolution of 500 fs in the UV. Measurements dertemine the laser pulse length without usage of the stretcher to 1.3 ps (FWHM). First SASE in January has been seen using a stretcher setting providing a pulse length of 2.4 ps (FWHM). [2]

Electron Bunch and SASE

In January 2013 first SASE radiation was generated using the new photo-injector laser. The laser pulse was stretched to a pulse duration of 2.4 ± 0.5 ps.

Two setups with a bunch duration of about 35 fs with a bunch charge of 35 pC as well as 80 pC and an electron bunch length of 78 fs successfully generated SASE. Due to the short injector laser only a small compression factor of 25-60 was needed, which significantly improved SASE stability compared to short pulses with the standard injector laser.

For more information about the shifts refer to [2].

OUTLOOK

The new photo-injector laser system for short pulse operation at FLASH should be ready for regular operation by the beginning of next year.

With the setup of the quadrant diodes the diagnostics will be finished which allows for full characterisation of the laser properties and optimisation of the system.

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