Algorithm for Longitudinal Profile Diagnostics of the Electron Beam for the FLASH Linear Accelerator in Hamburg

Jan Wychowaniak

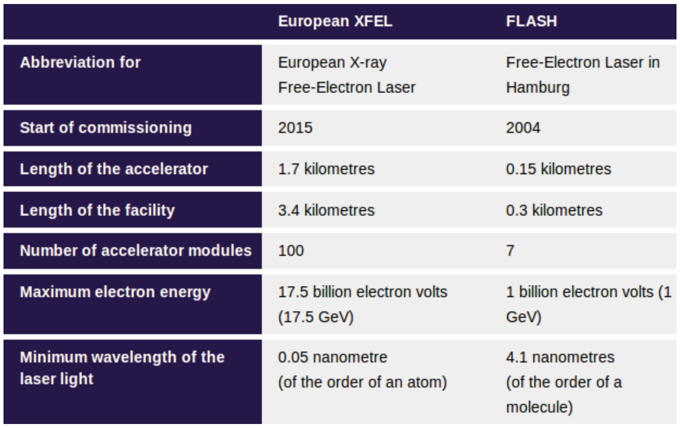
Abstract—**The lasing process taking place in a free electron laser based on the Self-Amplification Spontaneous Emission (SASE) is generated by high-brightness electron beams passing through an undulator system. There exist strict quality requirements that must be met by the electron bunches constituting the beam in order for the SASE phenomena to appear.**

This paper describes selected diagnostic installations supervising the longitudinal electron bunch profile parameters for the electron beams in the Free Electron Laser in Hamburg (FLASH) at the Deutsches Elektronen-Synchrotron (DESY) and focuses on software delivered for processing of the acquired diagnostic data.

***Index Terms*—DESY, FLASH, XFEL, electron beam diagnostics, image data processing, cameras.**

I. INTRODUCTION

DESY, located in Hamburg, Germany, belongs to the world's leading high energy physics centers. It constructs and operates large particle accelerators, which help to investigate matter and explore photon science and particle physics. The European X-ray Free Electron Laser (XFEL), a 3.4-kilometre-long facility currently under construction at DESY, will generate extremely intense X-ray pulses that will enable completely new experimentation areas (Fig. 1). The FLASH, currently operating smaller accelerator, is capable of producing femtosecond laser pulses with a rate of thousands per second. It is also a test facility for solutions to be used for construction of XFEL [1]. Its layout is presented in Fig. 2.



	European XFEL	FLASH
Abbreviation for	European X-ray Free-Electron Laser	Free-Electron Laser in Hamburg
Start of commissioning	2015	2004
Length of the accelerator	1.7 kilometres	0.15 kilometres
Length of the facility	3.4 kilometres	0.3 kilometres
Number of accelerator modules	100	7
Maximum electron energy	17.5 billion electron volts (17.5 GeV)	1 billion electron volts (1 GeV)
Minimum wavelength of the laser light	0.05 nanometre (of the order of an atom)	4.1 nanometres (of the order of a molecule)

Fig. 1. The XFEL and FLASH lasers in numbers.

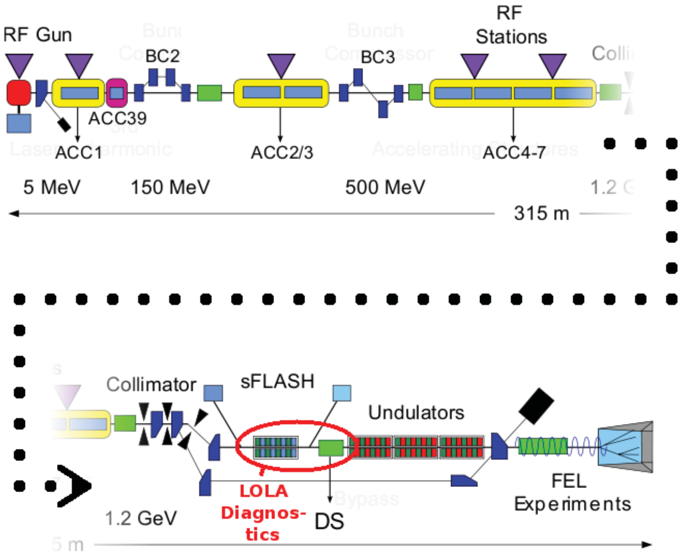


Fig. 2. The FLASH layout.

It has been since 2005, that FLASH is available for experiments to the photon science user community. The accelerator is known for being the first soft X-ray free-electron laser in the world [2].

It is capable of producing an electron beam of energy reaching the level of 1.25 Gigaelectron volts (GeV). The superconducting cavities contribute to the process of shaping the electron bunches in a way that high intensity of the laser light is achieved. Such an energy level gives the possibility of reaching a wavelength of 4.12 nanometres. As a result, the accelerator is capable of generating laser light in the so-called water window with the fundamental wavelength, where water becomes transparent for light, completely giving up on its absorbtion. This opens up the possibility to investigate biological and other aqueous solutions-based samples [2].

II. LONGITUDINAL BUNCH PROFILE OBSERVATIONS

The principle of operation of the FLASH laser is based on a physical phenomena introduced as the SASE - a result of passage of accelerated electrons through the undulator section of the accelerator tunnel. The basic, high-level mechanism of SASE is relatively simple to comprehend. During the operation of the machine the electrons of the electron bunches move through its undulator section, traveling with relativistic velocity. There, they are subject to the Lorentz force introduced by the magnetic field produced by the undulator.

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As a result, the electrons are accelerated perpendicularly to the direction of their propagation [3].

They start propagating along a sinusoidal path, emitting synchrotron radiation in a shape resembling a narrow cone expanding in the forward direction of the electrons movement (Fig. 3).

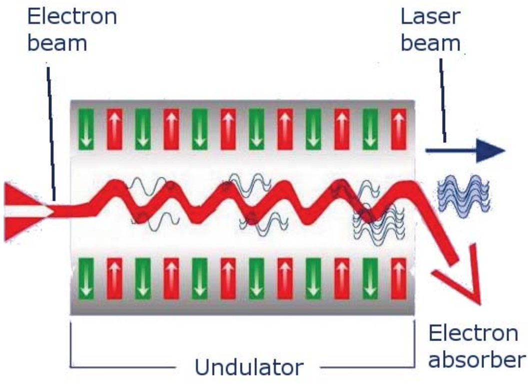


Fig. 3. An illustration of the SASE phenomena within the undulator of a linear laser.

Hence, the radiation resulting from the electrons moving along the individual magnetic periods tends to overlap. The electron bunch passing the undulator, as the oscillations grow, tends to interact with its own electromagnetic field. Electrons that happen to be in phase with the wave of the electromagnetic field experience a deceleration (retardation), and the opposite phase electrons acquire energy (accelerate). Hence, increasing percentage of electrons starts to emit in phase, which results in coherent radiation (Fig. 4).

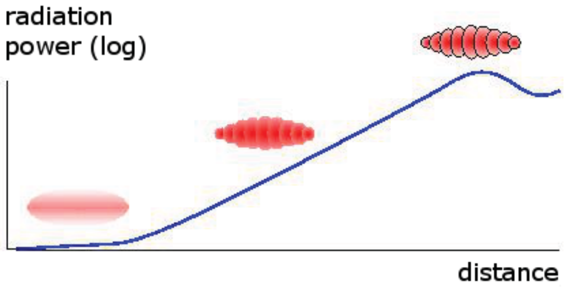
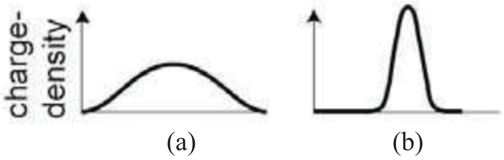


Fig. 4. A relation of the radiation intensity to the distance the electrons travel through an undulator.



(a) (b)

Fig. 5. An electron bunch parameters visualisation before (a) and after (b) compression.

In order for SASE to be triggered, electron bunches of high peak current and low energy spread are required. Specialised electron bunch diagnostic equipment needs to be used in order to ensure the required beam parameters [1, 4].

The desired shape of an electron bunch can be achieved by its longitudinal compression (results as of Fig. 5), performed by dedicated magnetic chicanes, after electron bunches are accelerated to high energies. The longitudinal charge distribution of a bunch reflects the quality of the compression process, and via this, the peak current and the energy spread of a bunch. It is therefore critical for this characteristic to meet certain requirements. It can be measured by dedicated diagnostic setups based on charge-coupled device (CCD) cameras. Data from the cameras provide the possibility to study the longitudinal profile of a bunch. The TDS setup (LOLA, Fig. 1f), installed in the FLASH tunnel, is an example of such equipment.

III. THE TDS SETUP

On its way through the accelerator tunnel, an electron beam passes through an installation referred to as the transverse deflecting structure (TDS), a waveguide fulfilling a task of producing a transverse charge distribution of the electron beam out of its longitudinal charge distribution. The transverse charge distribution can be measured with a help of a setup composed of an imaging screen and a camera system, the longitudinal charge distribution can be later reconstructed from the result. After a beam passes the TDS, it encounters a fast kicker magnet capable of deflecting a single electron bunch out of a bunch train and driving it sideways towards a so called non-dispersive section with a screen and a camera system. There the longitudinal beam profile can be obtained online during the SASE operation [1, 5].

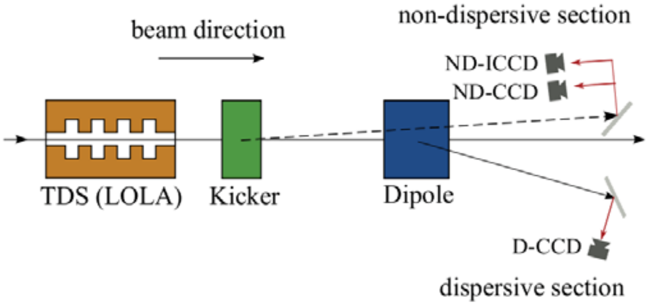


Fig. 6. The TDS experiment diagram.

There is also a dipole magnet on the path, capable of driving the entire bunch train towards another camera-equipped installation, referred to as the dispersive section. The dispersive section is proven to yield more reliable charge measurement results, therefore it may serve as a reference for the results from the non-dispersive section. The electron bunch out of a bunch train (or the whole train itself) can be deflected towards either the non-dispersive or the dispersive section, depending on whether the fast kicker or the dipole magnet is turned on. When the fast kicker magnet is on, and a single bunch is deflected, the remaining bunch train is usable in the usual way and can normally drive the FEL lasing process. Sample electron bunch image data from the TDS setup is depicted in Fig. 7.

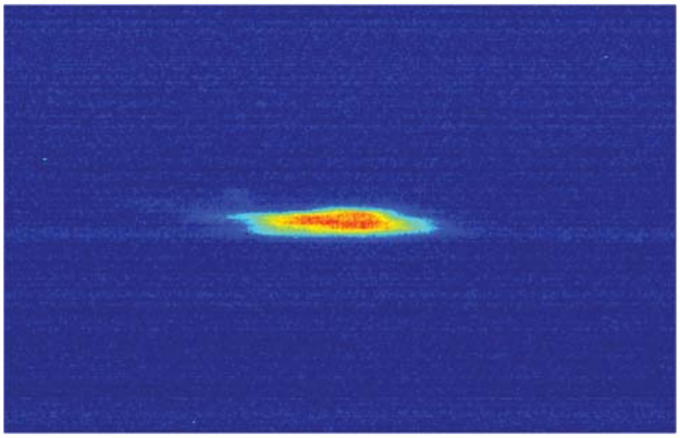


Fig. 7. A visualization of exemplary raw image data from the TDS.

IV. IDENTIFIED PROBLEMS

Currently there exists a software layer of the described setups, responsible for image data processing, realized in a form of Matlab scripts. Such approach, however, is problematic for multiple reasons. The scripts originate from specialists in physics-related areas, who designed the diagnostic setups, but have limited knowledge in field of software engineering. This causes severe inconveniences during further development and maintenance of the software.

Apart from this, the aforementioned software development approach provides no support for handling exceptional conditions possible during the laser operation. And those may be plenty, as in case of any sophisticated hardware infrastructure, and the risk of their occurrence is substantial. The reliability of measurements is heavily dependent of correctness of operation of other hardware components, as well as depends on appropriate recognition of conditions produced by those. No support for these factors is a serious disadvantage of control implemented by the means of Matlab code.

Also there is currently a lack of convenient interface to the diagnostic setups for the laser operators. Only higher specialised diagnostic staff is able to operate those, which severely limits the benefits from the measurement capabilities they offer.

Finally, the Matlab software for the experiments is usable only on-demand. This is in contrast to the vision of constant on-line operation, which would yield incomparably more comprehensive measurements, and thus is required, but is not possible with Matlab.

V. PROPOSED SOLUTION

The work backing this paper is aimed at providing solutions to the problems identified above, and from there to proceed further towards development of the measurements software. The camera data processing logic outlined in Matlab scripts was inspiration and basis for interpretation to a C++ form in order to prepare extended algorithms for longitudinal profile extraction, calculation of compressed bunch lengths and providing statistics for charge distribution. This form is also structured in a way that yields significant improvement of maintainability and further extendibility.

What is more, such form of this software makes it capable of being plugged into the laser control system (described later), which results in series of advantages.

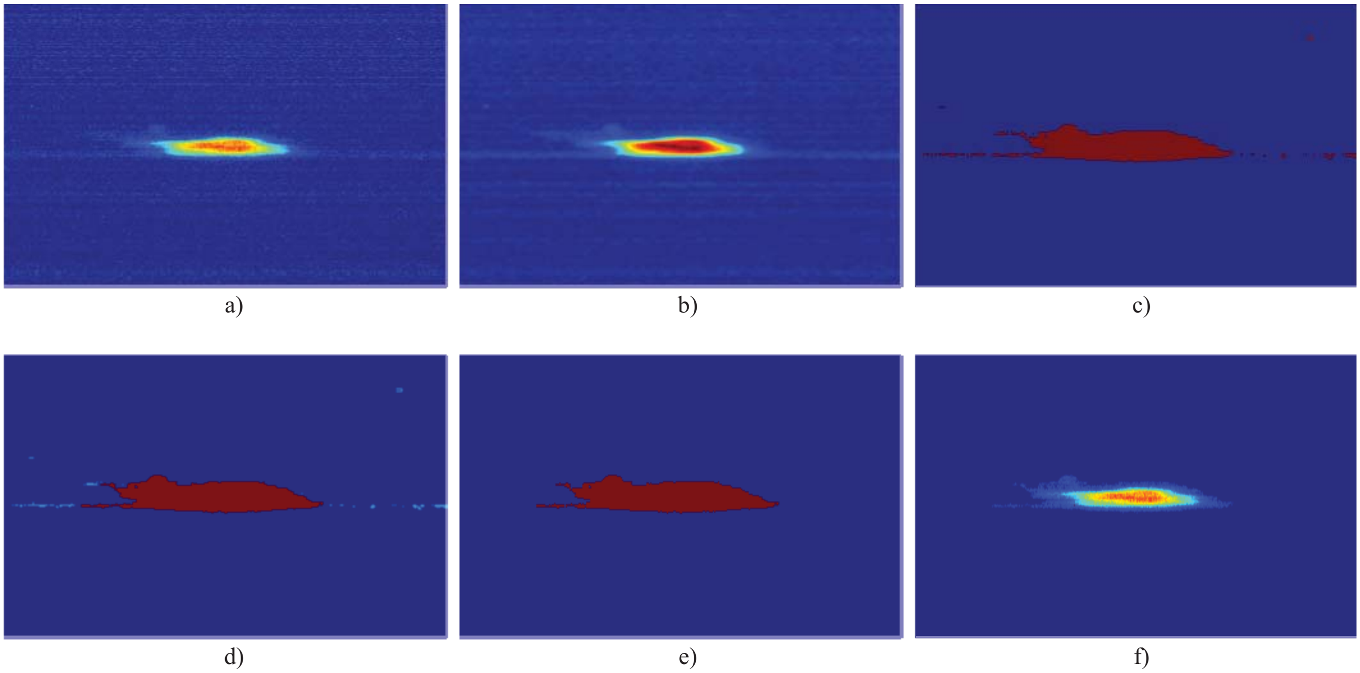
In particular, as an element of the control system, it can exchange information with a rich set of other diagnostic hardware of different kinds in order to build information regarding the machine status. This brings the possibility to detect and react to potential erroneous conditions of the machine operation that would be able to invalidate the measurement results. By the means of the control system the software also went into the so much required continuous operation mode, which provides constant supervision over the bunch profile parameters.

As of this moment, the possibility to communicate with other hardware in order to collect machine status is researched in order to provide routines for detection and reaction to the machine problems that may occur. Providing such routines would also result in automation of many activities related to configuration and operation of the setups, which would make using them and their measurements more approachable to a regular laser operator.

The following is a brief draft of the idea of how a raw CCD camera image can be processed to a form allowing for study of the profile of a single electron bunch.

Fig. 8a shows a single raw bunch image taken from the TDS setup. The relevant element of the visual data is only the one containing the actual electron bunch, referred to as the region of interest (ROI), and its position in the image needs to be determined in order to be extracted from the image. The first required step of this process is passing it through a blurring filter, which makes the image looking smoother (Fig. 8b). Then, the mean noise intensity of the image needs to be estimated. It is later used for setting all the pixels of value smaller than a particular threshold value, based on the mean noise intensity, to zero, and setting the remaining pixels to one (Fig. 8c). As a result of this step, the image may be composed of a group of isolated areas, one of which corresponds to the bunch. The bunch is assumed to be in the area that contains the brightest pixel (Fig. 8d). This area is assumed to be the ROI, all the other areas are zeroed out (Fig. 8e), and pixels inside the ROI are restored to their original values from before step c) (Fig. 8f). The image of the clean bunch, extracted from the original image, is used to obtain the longitudinal bunch profile, which, calibrated from image pixels to meaningful units (Fig. 9), can be further studied for desired parameters as a next step (Fig. 10).

For the developed software to be actually put into operation, it needs to be plugged into the control system of the laser. DESY developed their custom control system for the purposes of performing control and supervision activities over the laser components, called the Distributed Object Oriented Control System (DOOCS) [7].


a) b) c)

d) e) f)

Fig. 8. Searching for the ROI as a part of obtaining the longitudinal bunch profile.

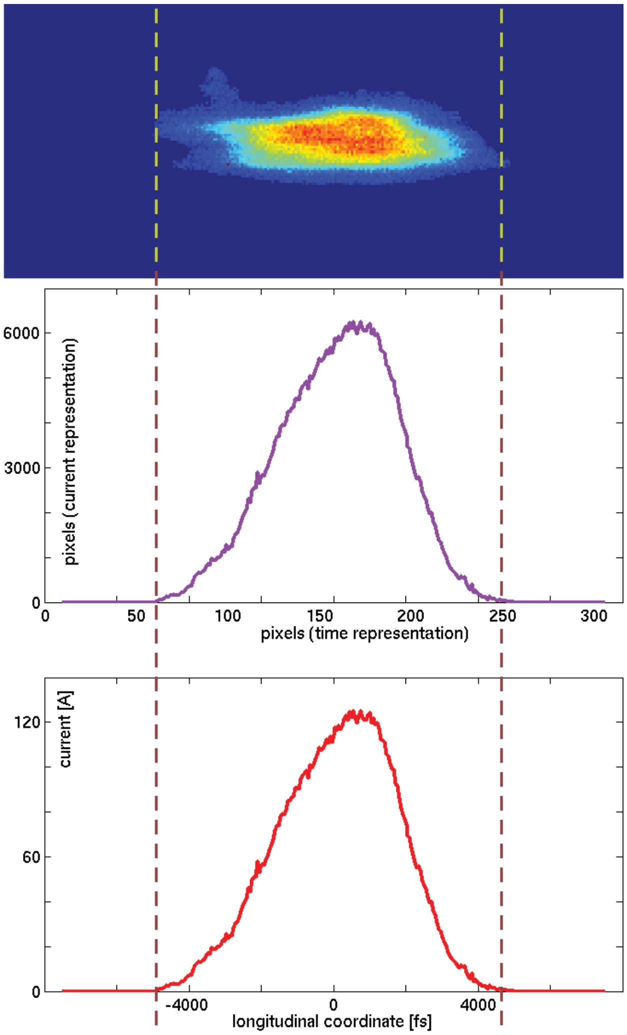


Fig. 9. A profile from longitudinal bunch profile measurements.

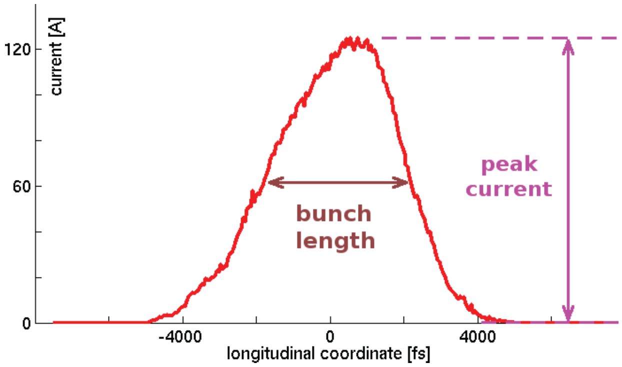


Fig. 10. A profile from longitudinal bunch profile measurements, with desired parameters indicated.

VI. CONCLUSIONS AND FURTHER DEVELOPMENT PLANS

The above outlined path for determining ROI from a bunch picture was developed is tested with the TDS experiment, but can be applied to images with ROIs of arbitrary shape. This makes the developed software easily adaptable for other visual data based experiments, which forms a foundation for a more generic beam-related image processing library, which can be taken advantage of when designing future beam diagnostic experiments.

Such code, apart from providing remedy to the problems identified above, would also bring significant software reliability and reduce the possibility of implementation error occurrence for beam diagnostic experiments, both currently existing and anticipated for the future. This would significantly facilitate measurements of critical electron bunch parameters (the longitudinal charge distribution being a good example), thus contributing to better beam quality supervision and improved reliability of the laser as a whole.

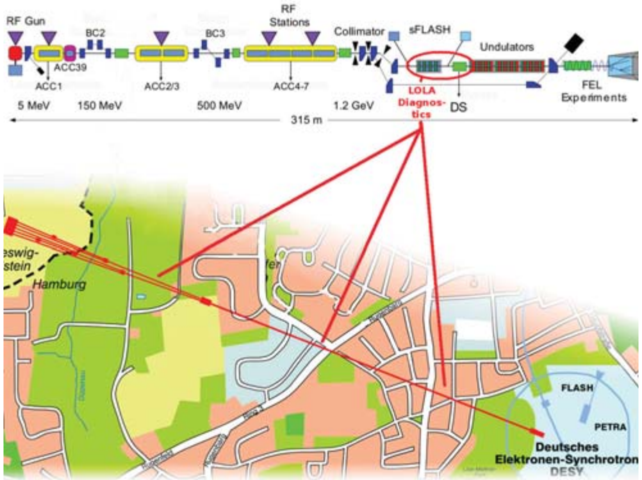


Fig. 11. Multiple TDS setups in XFEL.

As compared to FLASH, the issue becomes even more relevant in the context of XFEL, as it will be larger and more complicated in design (Fig. 11). Therefore more beam diagnostics stations are expected to be installed there, which will make the role and the use of the proposed software even more significant and intensive.

Rerefences

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