ELECTRO-OPTIC ELECTRON BUNCH DIAGNOSTIC AT FLASH USING AN YTTERBIUM FIBER LASER

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Abstract

FLASH (The Free-Electron Laser in Hamburg) is a High-Gain SASE-FEL (Self Amplified Spontaneous Emission) providing ultrashort pulses with a central wavelength of 6.5 to 40 nm. Measuring and controlling the longitudinal shape of the electron bunches can help considerably to understand and to improve the stability of the lasing process. Non-destructive electro-optical (EO) bunch profile diagnostics have proved to work with resolutions down to 100 fs (rms). Bunch arrival time diagnostic works with comparable precision. The electro-optical setup at FLASH relies presently on a Ti:sapphire laser delivering 80 fs pulses with 4 nJ pulse energy. For practical and physical reasons (i.e., space, cost, ability of permanent operation) an alternative, ytterbium fiber laser system has been developed. This laser system is designed to produce pulse energies of 4.5 nJ at a centre wavelength of 1030 nm with a spectral bandwidth of up to 80 nm. Active repetition rate control allows to lock the laser to the accelerator RF or later to an optical synchronisation system [1]. First results from the prototype Yb laser system will be presented.

INTRODUCTION

Free Electron Lasers (FEL) consisting of a linear electron accelerator and an undulator section are of growing interest as they can produce very short pulses of coherent light in a wide wavelength range. FLASH is the first SASE-FEL in the soft x-ray region. For an efficient SASE process, high peak charge densities corresponding to a strong electron bunch compression are crucial. Beside destructive methods of measuring the longitudinal shape of the electron bunch such as the Transverse Deflecting Structure (TDS), non-destructive techniques have been developed. Setups using the electro-optic effect exist for some years at FLASH, they rely on a Ti:sapphire oscillator [2]. The need for a robust, but small system led to the development of a fibre laser. An ytterbium laser has been chosen for its central wavelength. At 1030 nm the match of the phase velocity of the field of the electron bunch and the group velocity of the laser light is very good for the electro-optical Gallium Phosphide (GaP) crystal. Thus, an enhanced signal-to-noise ratio is expected compared to electro-optical experiments using the Ti:sapphire laser.

EXPERIMENTAL SETUP

The existing EO setup using the spectral decoding technique has been upgraded to enable the use of two laser systems in parallel. It now consists of the two laser sources, the laser transfer line from the optics laboratory into the accelerator tunnel including some focusing elements, the electro-optic crystal inside the electron beam pipe and a spectrometer with a camera (Fig. 2). The laser pulse train is generated in the laboratory with either the Ti:sapphire laser or the Yb laser and sent through the laser transfer line, where it is focused onto the EO crystal. After passing the crystal, the laser pulses are reflected out of the vacuum chamber and transported back to the laboratory via optical fibres. For each laser system a separate fibre and spectrometer with an attached camera is used.

The ytterbium fibre laser system fiber

The laser system consists of two main parts, the oscillator itself and an amplifier stage with a pre-chirper (Fig. 1). The oscillator is a stretched-pulse laser with self-starting mode lock from nonlinear polarisation evolution [3]. The repetition rate is 54.1 MHz and matched to be the 24th subharmonic of 1.3 GHz, the driving frequency of the accelerating cavities at FLASH. For synchronisation purposes, the free-running oscillator should have an integrated timing jitter (1 kHz to 40 MHz) of well below 50 fs. Furthermore, the laser has a cavity of variable length which is realised by a motorised delay stage and a fast piezo fibre stretcher.

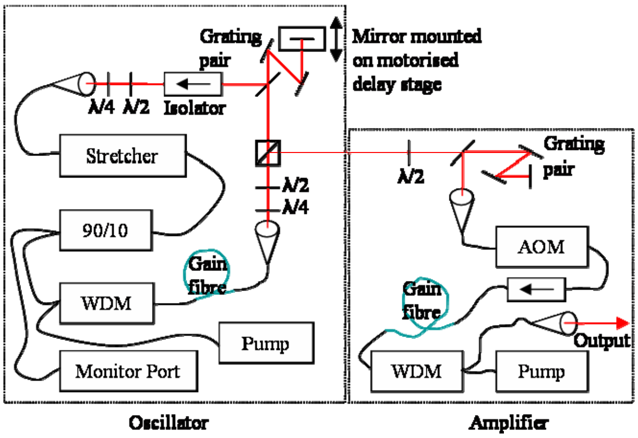

Figure 1: Ytterbium laser system with oscillator, pre-chirper and amplifer.

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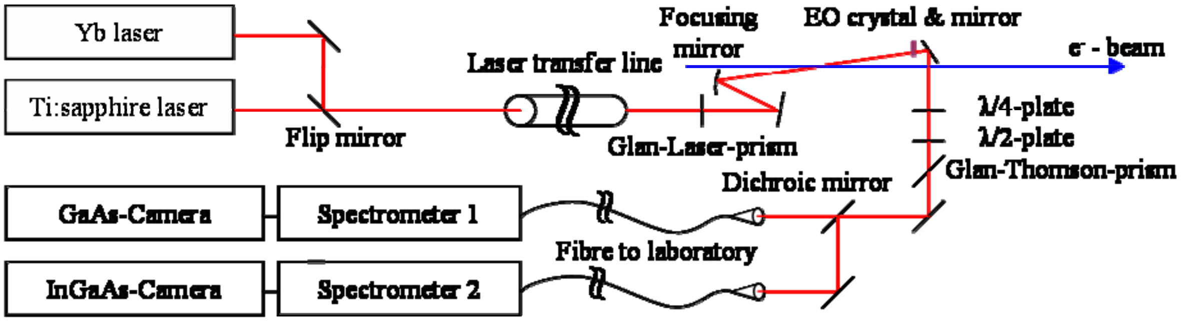

Figure 2: Current EO setup used for spectral decoding with a Ti:sapphire or an Ytterbium fibre laser

The delivered pulse energy is 0.7 nJ and the spectral bandwidth is about 45 nm. The linearly polarised pulses leave the oscillator with a positive chirp and a pulse duration of 1 ps. Before the pulses enter the amplifier they transit a grating compressor. In this overcompensating pre-chirper, the sign of the chirp is turned from positive to negative. After entering the amplifier, the pulses traverse a fibre-coupled acousto-optic modulator (AOM). The spectrometer for the EOSD set-up is equipped with an Andor IDus InGaAs line detector with a minimum exposure time of 1.4 µs. Without gating, about 80 laser pulses would be integrated out of which only one is modulated by the electro-optic effect. The AOM in the amplifier suppresses unwanted pulses and allows to generate a pulse train that is matched to the repetition rate of the electron bunches (1 MHz). The rise time of the AOM is specified to be 7 ns. An extinction of 35 dB is achieved. The pre-chirper is adjusted to reach the maximum bandwidth broadening in the amplifier. The pulse energy behind the amplifer is about 3.5 nJ at a repetition rate of 1 MHz. The pulses leave the amplifier with a positive chirp and a length of 1.2 ps.

Synchronisation of the laser to the MO

The laser has to be synchronised to the local RF master oscillator (MO) of the accelerator to establish perfect temporal overlap of the laser pulse and the electron bunch (fig 3). The oscillator has a fibre-coupled monitor port connected to a 10 GHz InGaAs photodiode. The 24th harmonic of the photodiode signal is filtered out with a 1.3 GHz band pass filter. This signal is amplified and mixed with the 1.3 GHz signal originating from the MO. A low pass filter selects the difference frequency. This error signal is read by a fast sampling ADC and fed into a digital control loop running on a Digital Signal Processor (DSP). The regulation signal is handed to a DAC, amplified with a piezo driver and fed to the piezo fibre stretcher. To account for large deviations and drifts, the DSP controls a motorized delay stage in the laser cavity. As there are 24 different possibilities to lock a 54 MHz oscillator to a 1.3 GHz reference frequency, a slow phase detector is used for bucket detection. It consists of a -20 dB power splitter for the 54 MHz signal from the photodiode and a divider board for the splitted 1.3 GHz signal. The two 54 MHz signals are compared in a phase detector (AD8302) with an output voltage depending on the relative phases. Scanning of the laser pulse with respect to the electron bunch is accomplished with a vector modulator changing the phase of the reference frequency.

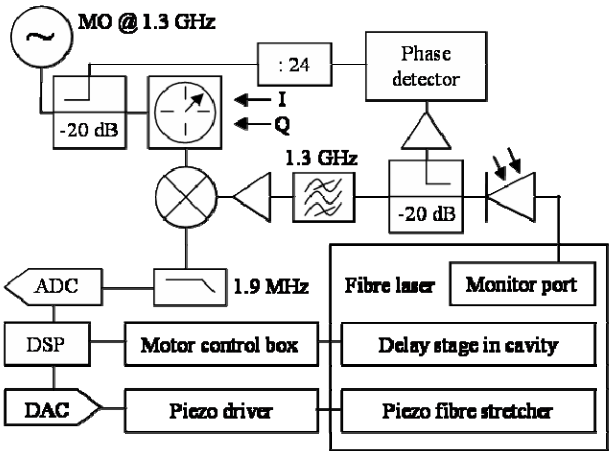

Figure 3: Synchronisation of the laser to the MO

MEASUREMENTS

Phase noise

Phase noise measurements are used as a standard diagnostic tool indicating the correct mode lock state as well as the quality of the RF lock. Measurements were done with an Agilent E5052 Signal Source Analyser (SSA). The phase noise of the free running oscillator in the frequency range above the cut off frequency of the regulation (1 kHz) must be low enough to maintain a stable RF lock. The integrated timing jitter between 1 kHz and 40 MHz was measured to be 16.3 fs (fig. 4 a) with the pulse train exiting the monitor port using a photodiode with a large bandwidth (10 GHz). In the frequency range below 1 kHz the noise performance of the laser oscillator is inferior to that of the RF master oscillator (fig 4 b). To benefit from the low noise of the master oscillator the RF lock is established. With the digital control loop sketched above, an integrated timing jitter of 197.2 fs (10 Hz - 40 MHz) was measured (fig. 4c). This data has been taken from an out-of-loop measurement using the pulse train from the free-space output port of the RF locked laser that was sent to another 10 GHz photodiode connected to a

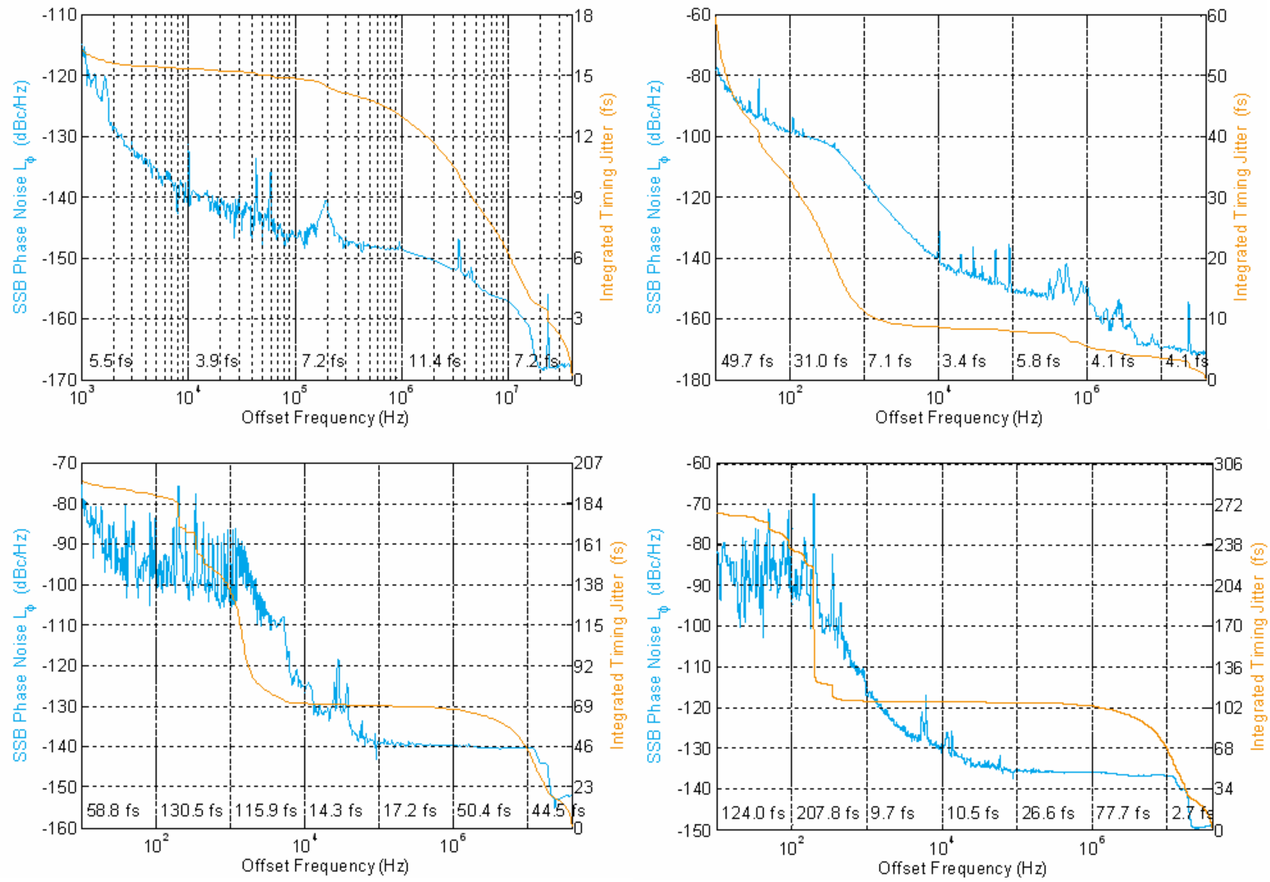

Figure 4. Phase noise measurements. a) free running laser oscillator, int. timing jitter (1 kHz – 40 MHz) 16.3 fs. b) RF master oscillator reference, 10 Hz – 40 MHz int. jitter 60 fs. c) Laser locked to reference. Out-of-loop measurement, int. timing jitter (10 Hz – 40 MHz) 197.2 fs, digital control loop. d) Same as c) but with analogue control loop, int. timing jitter 265 fs.

band pass filter, an RF amplifier and again the SSA. These 197.2 fs integrated timing jitter contain the noise of the RF master oscillator, the high frequency noise of the laser, and the additional phase noise of the digital control loop. Due to software problems, a long-term stable RF lock using the digital control loop has not been established yet. An alternative analogue control loop has been installed. With it, the integrated timing jitter is 265 fs in the same offset frequency range (fig. 4d) and a stable RF lock can be established and maintained for about an hour, which is sufficient for first EO experiments.

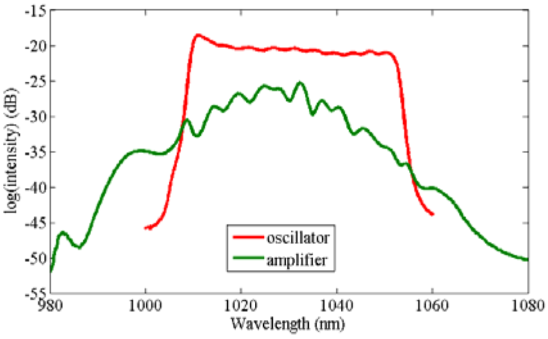

Figure 5: Optical spectra of the laser pulse train of the ytterbium laser oscillator and after amplification.

Optical spectra of the laser and the amplifier

The spectrum of the laser oscillator shown in Fig. 5 has been taken from the pulses leaving the monitor port. It has a bandwidth of 45 nm centred around 1030 nm and is very flat. The flatness of the spectrum of the amplified pulses is reduced while the spectral bandwidth is increased; it is measured to be 70 nm. The reason for the undesired reduction of the flatness as well as the desired spectral broadening is the self-phase modulation in the amplifier that produces new spectral components at the steep sides of the laser pulse.

Polarisation modulation in the EO crystal

For timing search the gating is turned off and the full repetition rate (54.1 MHz) laser is used. The polarisation state of a laser pulse passing through the EO crystal in synchronisation with the electron bunch passing next to the crystal will be modulated. In the Glann-Thomson-prism the polarisation modulation is turned into an amplitude modulation of one pulse out of a pulse train. This can be measured with an InGaAs-photodiode. In Fig. 6, a modulated pulse train can be seen. In this case, the modulation is lowering the amplitude of since the wave

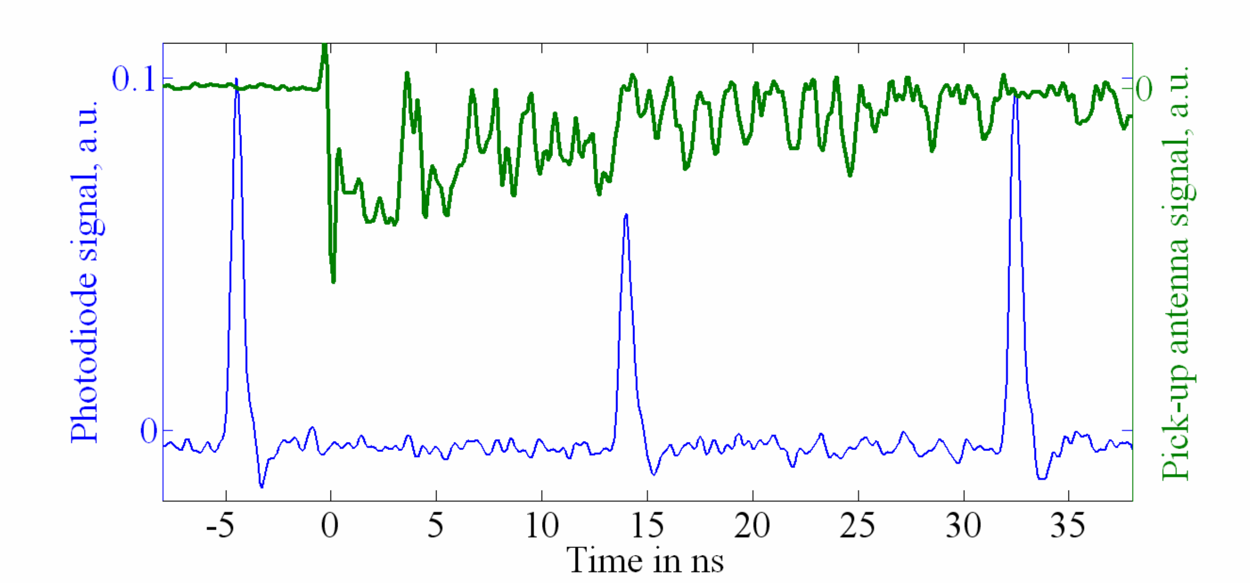

Figure 6: Modulated pulse train out of the EO-crystal.

plates after the vacuum chamber were not set for maximum extinction (crossed polarizer). The signal printed in green is a pulse coming from a pick-up-antenna that is installed outside the electron beam pipe some centimetres before the EO crystal. It is used to find the temporal overlap of the electron beam and the modulated laser pulse. The delay between the pick-up antenna signal and the modulated laser pulse is fixed as long as no cables are changed and the optical path length remains the same.

SUMMARY

A fibre laser system with a broad spectral bandwidth, sufficient pulse energy and a variable gating pattern has been commissioned. A low noise operation state has been found enabling a tight lock to the 1.3 GHz reference frequency. Characterisation of the mode lock state and the RF lock has been carried out. Different control loops were tested with respect to short term and long term stability. The upgrade of the EO setup to two laser systems has been completed such that alternate measurements are now possible. The spatial and temporal overlap of the laser pulse and the electron bunch were established. An amplitude modulation of a laser pulse caused by the electro-optical effect was achieved.

The next step towards a reliable diagnostic tool is taking spectra of the modulated pulse. There will be an arrival time measurement comparing the EO arrival time with the signal of a beam arrival time monitor (BAM). These data will be compared to earlier data taken with the Ti:sapphire system. A structurally engineered version of the new laser system will benefit from the experiences gained with the experimental laser setup.

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