YTTERBIUM FIBRE LASER BASED ELECTRO-OPTIC MEASUREMENTS OF THE LONGITUDINAL CHARGE DISTRIBUTION OF ELECTRON BUNCHES AT FLASH

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Abstract

The Free Electron Laser FLASH has been upgraded during winter 2009/10. Amongst other components, a third harmonic module operating at 3.9 GHz (ACC39) has been installed. Together with the energy chirp induced by off-crest operation, it allows for a linearization of the longitudinal phase space, leading to a uniform compression of the electron bunch with final bunch lengths of 150 µm rms. In contrast to the old non-linear compression scheme, peak current and bunch length are extremely sensitive to the phases of ACC39 and ACC1 and have to be monitored continuously. The foreseen bunch length is within the resolution of electro-optic spectral decoding methods. An ytterbium fibre laser system in combination with a 175 µm thick GaP crystal is used to achieve a good match between the electric field phase velocity and the laser pulse group velocity in the electro-optic crystal. This ensures a large modulation of the polarisation of the chirped laser pulse in the EO crystal. The information on the electron bunch length carried by the laser pulse is decoded in a spectrometer and read out with an InGaAs line scan camera.

INTRODUCTION

Free electron lasers were the first and are still the most powerful devices for producing coherent light at short wavelengths. The electron beam quality required for the SASE-process, in which an energy transfer from the electron bunch to the light wave occurs, is high in terms of peak current, emittance and, for seeded operation, timing jitter. These requirements are best met with linear accelerators. Besides standard diagnostics, these accelerators have to be equipped with special diagnostic devices that are capable of measuring all key parameters that need to be controlled for reaching and maintaining stable SASE operation. In the field of longitudinal electron bunch diagnostics, a transverse deflecting structure (TDS) is in operation at FLASH supporting highest resolutions for bunch length measurements. Drawbacks of the TDS are its large size (several meters) and the fact that it is a destructive device, which means, the electron bunch cannot be used for SASE after having passed the TDS setup. An alternative approach is based on electro-optic (EO) methods which can be used in parasitic operation. These systems consist of a laser system with synchronisation electronics, an electro-optic crystal near the electron beam, and a readout section. In this paper we report on the measurements done with a rebuild EO setup at FLASH using an ytterbium doped fibre laser system.

EXPERIMENTAL SETUP

Laser System

The home made laser system consists of an ytterbium doped fibre laser and a fibre amplifier [1]. This 1030 nm laser works in a self-starting mode lock regime via nonlinear polarisation evolution (NPE). The ring oscillator has an actively controlled repetition rate of 54.16 MHz (the 24th sub harmonic of the accelerator driving frequency, 1.3 GHz). It features a fast regulation using a piezo fibre stretcher and a slow drift compensation using a motorised delay stage. The synchronisation electronics as well as the laser system are described in detail in [2]. Pulses leaving the oscillator at the NPE rejection port have pulse energies of about 0.6 nJ, a spectral width of about 30 nm, and a length of about 1 ps. The pulses are not Fourier limited (30 nm spectral bandwidth at 1030 nm central wavelength correspond to less than 100 fs length) but have a linear, positive chirp. In a grating compressor with variable grating distance the pulses are stretched until they have a considerable

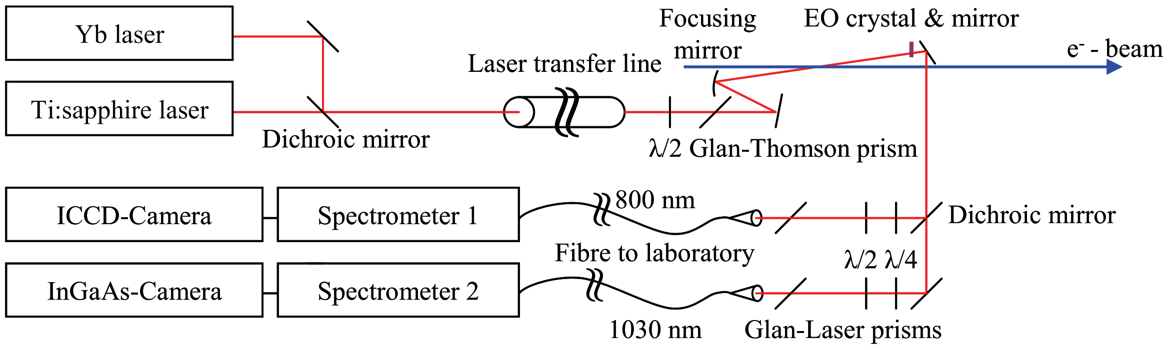

Figure 1: Current EO setup at FLASH at 140 meter.

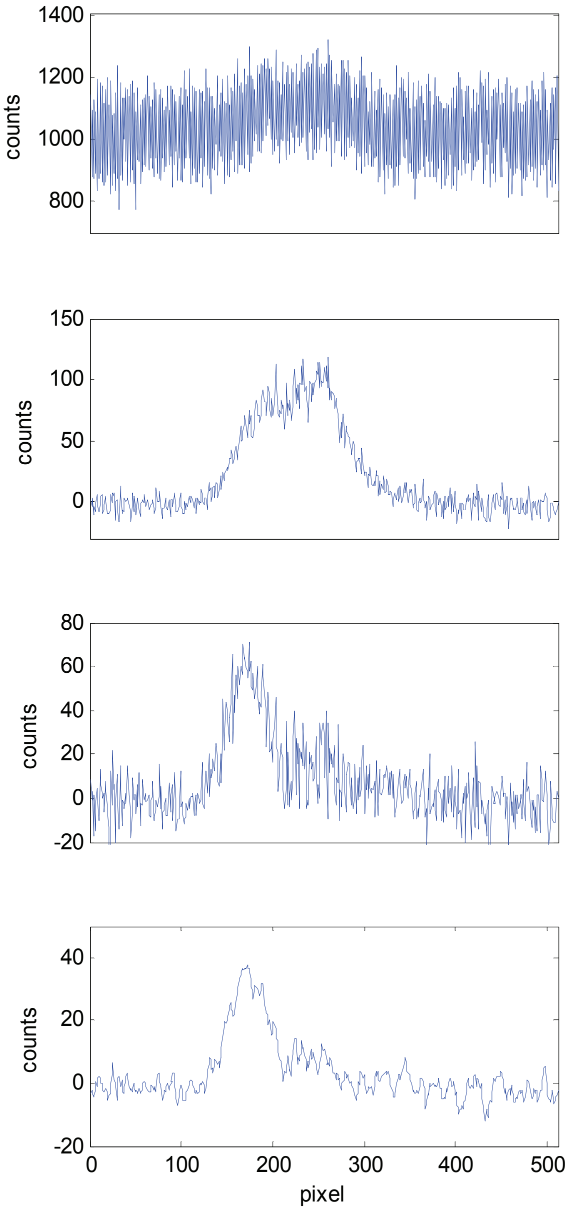

Figure 2: A single shot measurement in crossed polariser setting. From top to bottom: raw data, raw data corrected for camera background, raw data corrected for camera background and ASE spectrum, EO signal (smoothed, 5 pixel moving average).

negative chirp. The pulses enter an ytterbium doped fibre amplifier with a gating device, a fast switching acousto-optic modulator (AOM) with a rise time of 10 ns. After having passed the AOM, the pulses undergo a strong amplification in the gain fibre. At the same time, the pulses become short due to the dispersion of the glass fibre and the resulting high peak intensity leads to self-phase modulation. Thus, new frequency components are produced and the spectrum of the pulses leaving the amplifier is broadened to about 50 nm. The current operating parameters are: pulse repetition rate of 10 Hz, pulse energy above 5 nJ, optical bandwidth 50 nm, pulse length 1.5 ps with a positive chirp. A double pulse operation state of the laser system is prevented by routinely using a 1 GHz oscilloscope, an optical spectrum analyser, a RF spectrum analyser, a signal source analyser for measuring the single sideband noise, and an autocorrelator whenever the oscillator is set to a new mode locked state of operation.

EO Setup

After leaving the amplifier, the optical pulse train is led through a dichroic mirror enabling EO measurements with two different laser systems at one time into the accelerator tunnel via a 16 meter long free space laser transfer line. In the tunnel, the laser beam passes through a polariser ensuring a horizontal polarisation and is then focused onto the electro-optic crystal (GaP, 175 micrometer). The beam is reflected out of the electron beam pipe and passes again a dichroic mirror, before arriving at a lambda-quarter wave plate set for correcting the intrinsic birefringence of the EO crystal. A lambda-half wave plate is used to adjust the extinction rate in the next polariser. Here, a polarisation modulation invoked by the passing electron field is changed to an amplitude modulation in the simultaneously passing laser pulse. The beam is now fed to an optical fibre leading back to the laboratory for spectral analysis. This is done using a spectrometer and an InGaAs line scan camera (see fig. 1).

MEASUREMENTS

Signal Search

Finding the correct timing (i.e. the temporal overlap of the laser pulse propagating through the EO crystal and the THz field travelling with the electron bunch) for the first time has been accomplished by using a photodiode looking at the not gated optical pulse train coming from the EO crystal. When the laser pulse is shifted in time with respect to the electron beam, at some point a modulated pulse should occur. The signal of a pick-up antenna installed some centimetres upstream the EO crystal is taken as a rough estimation and a zero in time. The maximum range that has to be scanned is the pulse repetition time, in this case 18.2 ns, with a step size on the order of the laser pulse length – 1.0 ps. Having found the modulated pulse once, the absolute timing position is fixed within some 10 ps (depending on exact compression parameters of the electron bunch) and can be found using the synchronisation electronics and software. Looking on the pulse train with a photodiode is not necessary after the rough timing has been found.

First Signal

The pulse train is gated and the spectrum of a modulated laser pulse is observed with the line scan camera. The camera itself has a background that varies strongly from pixel to pixel and that has to be subtracted from every spectrum. The remaining signal mainly consists of the spectrum of the ASE light collected by the camera within the exposure time (3 µs, second picture from the top in fig. 2). The ASE spectrum can be isolated by shifting the camera trigger to a place where no laser pulse arrives at the camera so the ASE spectrum can be taken. Typically, the background subtraction together with the ASE correction is conducted before reading out the data for analysis. Only the laser spectrum and its modulation due to the electron bunch field are captured. The lowest trace shows a typical single shot measurement corrected for all backgrounds and smoothed with a 5 pixel moving average in the crossed polariser setting.

Time Axis Calibration

The time axis calibration is done by observing the shift of the EO signal on the camera while scanning the laser with respect to the electron bunch. For every time step, a series of spectra is taken and a Gaussian is fitted to the data. The average place of its maximum is plotted over the corresponding time step (Fig. 3). The time step size was 150 fs to ensure the time step is larger than the expected timing jitter. From the linear component of the fit, a calibration of 20 fs/pixel is calculated. Higher order chirp seems to be present but the linear approximation is used for the following estimates.

Preliminary Results

Fitting a Gaussian to every single shot of a series, the place of the maximum, the width of the signal and its amplitude can be obtained. The FWHM width of the signal is about 45 pixel corresponding to 900 fs. The accelerator operated in SASE mode with a bunch charge of 0.8 nC. Previously made measurements with the TDS indicate bunch lengths between 350 fs FWHM for 0.6 nC and 940 fs FWHM for 1.2 nC. This first preliminary result is already in a reasonable range. The timing jitter is estimated from the standard deviation of the place of the maximum of the subsequent shots. With 20 fs/pixel, we get an rms jitter of about 50 fs. This value is lower than expected as recent BAM measurements show arrival time jitters well above 100 fs [3]. This jitter gives a lower threshold for the possible time step size for scanning the laser with respect to the electron beam (like in fig. 3). For the signal amplitudes we get a variation of about 6 %. To this value contribute different sources, the laser itself has an amplitude jitter but also polarisation changes can occur in the amplifier, the electron bunch charge and the orbit of the beam, and even vibrations of the optomechanical components can occur.

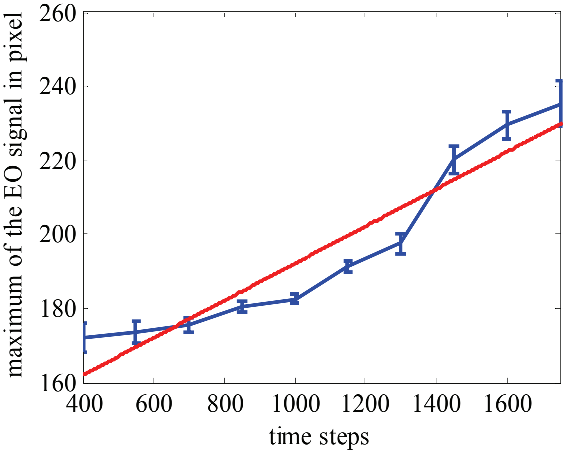

Figure 3: Time axis calibration. The place of the maximum of the averaged EO signal is plotted over the corresponding time steps.

SUMMARY

After rebuilding the setup for electro-optic bunch detection based on an ytterbium fibre laser system after the shutdown of FLASH, first data have been taken. Preliminary results are in expected orders of magnitude concerning the electron bunch width and the timing jitter.

OUTLOOK

Having made the above measurements is only the first step. More systematic studies are needed after refining the setup to yield a significant better signal-to-noise ratio. It then is of interest

- to correlate the arrival time measured with the EO setup with the arrival time measured by a beam arrival time monitor (BAM)
- to compare the width and form of the electron bunch measured with the EO setup with the bunch width and form measured with the TDS
- to perform simultaneous measurements with the two different laser systems on the same bunch
- to conduct measurements together with the ytterbium fibre laser based EO system that is being set up behind the first bunch compressor in the moment.

A significant upgrade will be the implementation of an automated tool for the timing search. It consists of a fast ADC sampling the optical pulse train with 108 MHz with an intrinsically synchronised clock. With it, a continuous timing control is possible. To improve the long-time stability of the laser oscillator, a new version of it featuring an active temperature stabilisation is planned.

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