NEW BEAM ARRIVAL TIME MONITOR USED IN A TIME-OF-FLIGHT INJECTOR MEASUREMENT

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Abstract

At FLASH, an optical synchronisation system with femtosecond stability is now being installed and commissioned. The pulses from an erbium-doped fibre laser, distributed in length-stabilised fibres to various end-stations are used to detect the electron bunch arrival time using electro-optical modulators. To determine variations of the arrival time caused by phase changes of the RF gun or by timing changes of the photo-injector laser, a beam arrival time monitor has been installed after the first acceleration section, prior to the bunch compressor. The monitor provides futher insight into the accelerator subsystem performance and stability and opens up the opportunity for a robust fast feedback stabilisation.

INTRODUCTION

FLASH (Free electron LASer in Hamburg) is a FEL user faclility generating laser pulses based on the SASE process with fundamental wavelengths ranging from 6.5 to 48 nm and with typical durations of few 10 fs. In order to improve the resolution of pump-probe experiments, precise information about the timing of both the FEL light pulses and pulses from external lasers are required.
The main issue of the optical synchronisation system now being developed at FLASH is to measure and reduce the relative timing jitter between various subsystems of the FEL facility. For this purpose, as first proposed at MIT[1], ultra-short laser pulses are distributed along the linac via length stabilised optical fibres to different end-stations.
Up to now, several subcomponents of the optical synchronisation infrastructure at FLASH are already installed and commissioned [2].

Electron bunches generated by photoemission in the RF gun are accelerated in the first acceleration module (ACC1) up to 135 MeV before they enter the first longitudinal bunch compressing magnetic chicane. Lately, a Beam Arrival Time Monitor (BAM) has been installed directly before the first bunch compressor. The accumulated beam arrival time jitter up this point in the linac results from arrival time variations of the photo cathode laser pulses and from phase variations of the RF gun while phase as well as amplitude changes of ACC1 have no significant influence. The latter has deep impact on the arrival time further downstream because of the large longitudinal dispersion R_{56} = 186.1 mm of the first bunch compressor. With the BAM installed after ACC1, we were able to measure for the first time the influence of phase changes in both the photoinjector laser and the RF gun directly before the electron bunches enter the dispersive section.

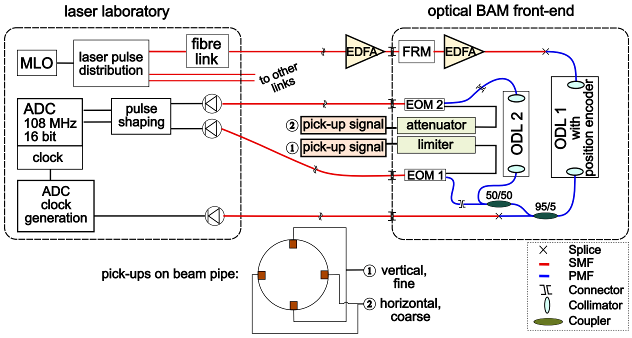

Figure 1: Schematic design of the BAM system used at FLASH.

BEAM ARRIVAL TIME MONITOR

The BAM utilises a Mach-Zehnder type electro-optical interferometry scheme which is described in detail in [3, 4]. Compared to the first two BAMs, which have been installed earlier downstream of the second bunch compressor, the BAM directly after ACC1 has a new design. Major changes are special linear motor stages, which are suited for high duty cycles, a home built polarisation maintaining (PM) optical delay line (ODL) and an active temperature regulation via Peltier elements. A schematic layout of the BAM optical front-end in principle and its connection to the synchronisation system is shown in Fig. 1. The BAM measures the arrival time of the electron bunches relative to a time reference given by laser pulses from a Master Laser Oscillator (MLO). These laser pulses are supplied via an actively length-stabilised, dispersion-compensated fibre link. This avoids additional sources of timing jitter. Occasional slow polarisation changes of the laser pulses are compensated in the fibre link facility, using quarter and half waveplates. The BAM front-end is located in the linac

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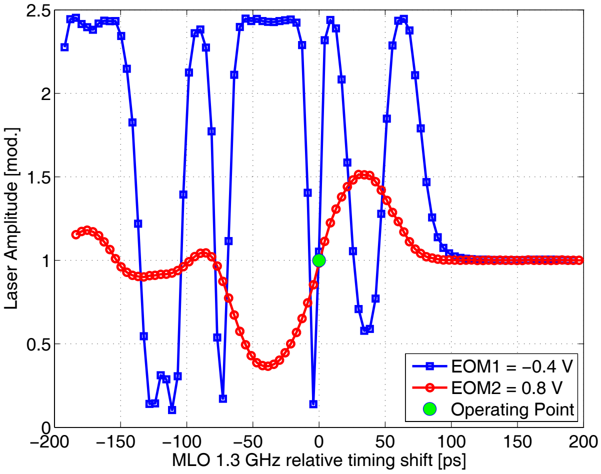

Figure 2: Scan of the fine and coarse BAM signals while shifting the timing of the optical 1.3 GHz clock signal generated from reference laser pulses of the MLO.

tunnel close to the beam pick-up electrodes in order to reduce drifts as well as the attenuation of high frequency components of the RF signal. A traversing electron bunch induces a voltage signal in the beam pick-up which has a bandwidth of several 10 GHz. The shape of the signal is determined by the charge distribution of the electron bunch folded with the beam pick-up response. The pick-up consists of four button-type electrodes positioned on the vertical and horizontal planes of the beam pipe. Due to this design and by the combination of the signals from two outputs on opposite sides of the pick-up, the orbit dependence of the arrival time measurement is reduced [5].

Before the PM fibre section of the optical front-end, the laser pulses are amplified before and after a Faraday Rotating Mirror (FRM) which reflects 50% of the laser pulses back to the fibre link stabilisation unit. The transmitted laser pulses are fed through the first of the two motorised ODL which uses the linear position encoder (Heidenhain LC483). The latter allows for reading out the absolute position over a 110 mm range with an absolute accuray of 3 μm and a resolution on short distances of a few nm. After the ODL, 5% of the reference laser pulse energy is coupled out to generate a clock signal for the fast ADCs. The remaining pulse energy is allocated in equal parts to the first electro-optical modulator (EOM) and through another motorised ODL to the second EOM. Inside those electro-optical devices the laser amplitude is modulated by the fast transient voltage signal from the beam pick-ups. Thus the arrival time is encoded onto the laser pulses. By use of the ODLs, the timing of the reference pulses is adjusted such that the pulses sample the pick-up signal at its zero-crossing. This operating point guarantees a reduced bunch charge dependency and ensures maximum achievable sensitivity. The modulated laser pulses are sent to an electronic read-out system outside the linac tunnel where the pulse energy is detected with a photodetector and digitised with a fast ADC. The baseline and the laser amplitude are sampled by different ADC channels with a data acquisition rate of 108 MHz. The BAM acquistion scheme normalises the laser intensity to a previous laser pulse in order to reduce the influence of opportunistic changes of the RF signal and bias voltages, temperature induced amplitude variations of the EOM and polarisation changes along the link.

The optical BAM front-end makes use of two detection channels with differing resolution. In the first channel the power of the combined RF signals from the vertical plane of the beam pick-up is limited before being applied to EOM 1 (see Fig. 1) and the timing of the laser pulses is adjusted by ODL 1. With the obtained information on the relative beam arrival time and the absolute ODL position, the absolute beam arrival time is calculated. The resolution of this measurement is limited by the dynamic range of EOM 1, which is determined by measuring the rate of laser amplitude modulation while changing the timing of the reference laser pulses relative to the voltage transient's zero-crossing. Because the maximum timing shift, which can be achieved using ODL 1 is 363 ps, outside this range the phase of the laser pulses is adjusted by shifting the phase of the 1.3 GHz clock signal of the MLO and by adjusting the RF cable lenghts.

Figure 2 shows a scan of the laser amplitude modulation rate of the EOMs for a relative timing shift of ± 200 ps related to the operating point, where the modulation factor equals 1. At this point the EOM signal has a linear slope within a range of about 4 ps, defining the dynamic range of the fine channel. The oscillating structure, the so called over-rotation, is a characteristic of the EOMs and happens when the modulation voltage excesses ±5 V. To keep the ODL in the dynamic range of the fine channel, a feedback loop regulates the motor position of ODL 1 around the optimum operating point.

If by fast or large changes of the FLASH machine parameters the timing shift of the RF signal overruns the dynamic range of the fine channel, the point of zero-crossing of the voltage transient can be retrieved by using the second channel. Here, the power of the combined RF signals from the horizontal plane of the beam pick-up is attenuated by 26 dB before being applied to EOM 2, while the laser pulse timing is adjusted once by use of ODL 2. The modulation depth of the laser amplitude is relatively small compared to the fine channel, but the linear slope around modulation factor 1 covers a range of 65 ps (see Fig. 1). This coarse timing information is relevant for the exception handling of integrated feed-back loops, e.g the motor feed-back of ODL 1.

MEASUREMENTS

By use of the BAM, the arrival time of individual bunches of a macro pulse can be measured, thus the timing information will be used to establish intra-train feedback loops on machine parameters, in this case, the injector laser phase or the RF gun phase. This requires detailed information on the dependence of the arrival time on those parameters.

Calibration

The left picture of Fig. 3 shows an example of the BAM calibration. The calibration factor is determined by changing the ODL 1 motor position stepwise by a certain amount and reading out the corresponding rate of laser amplitude modulation.

Using the Heidenhain encoder to determine the absolute motor positon, a dependency of about 22 fs per percent amplitude modulation has been measured. As can be seen in the right picture of Fig. 3, the mean value of this factor from different calibrations varies not significantly over a couple of days. The calibration changes with charge and applied EOM bias voltage. Together with the measured laser amplitude jitter (< 0.3 %) of the unperturbed laser pulses, the resolution of the BAM is estimated to below 6 fs.

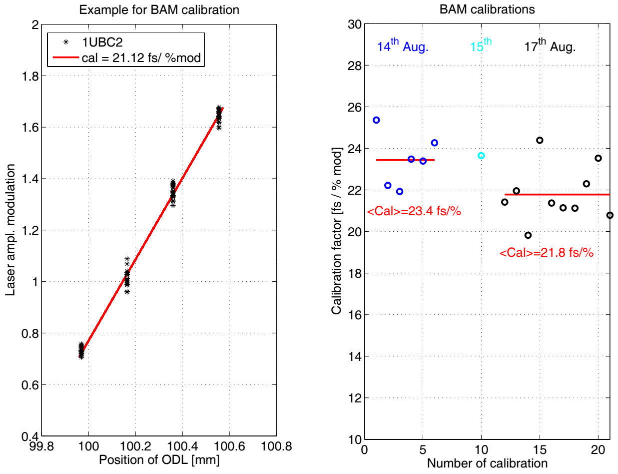

Figure 3: Calibration of the ODL motor stage of the fine BAM channel (left). Variation of the calibration factor over 21 calibrations (right).

Long Term Beam Arrival Time Measurements

The upper part of Fig. 4 shows a long term drift measurement of the beam arrival time, directly before the first bunch compressor. The raw data consists of the mean values of the bunch arrival times within each macro pulse. Averaged over 100 macro pulses, the beam arrival time shows a peak-to-peak variation of 880 fs. The gap within the measured data occured due to technical problems at the photo injector laser. During an interval of approximately 3 hours, the FEL operation was interrupted. As a positive outcome of this short shut-down, it should be emphasised, that the beam arrival time did not change significantly when the machine was in full operation again. The source of the superimposed oscillation is not detected yet, although it is likely to be correlated with oscillations of the temperature regulation of the injector laser facility. The lower part of Fig. 4 shows the rms arrival time jitter over a sliding window of 100 macro pulses. The mean rms jitter amounts to 86.2 fs, only. After the 3 hour shut-down, a decreasing trend of the calculated jitter is clearly visible.

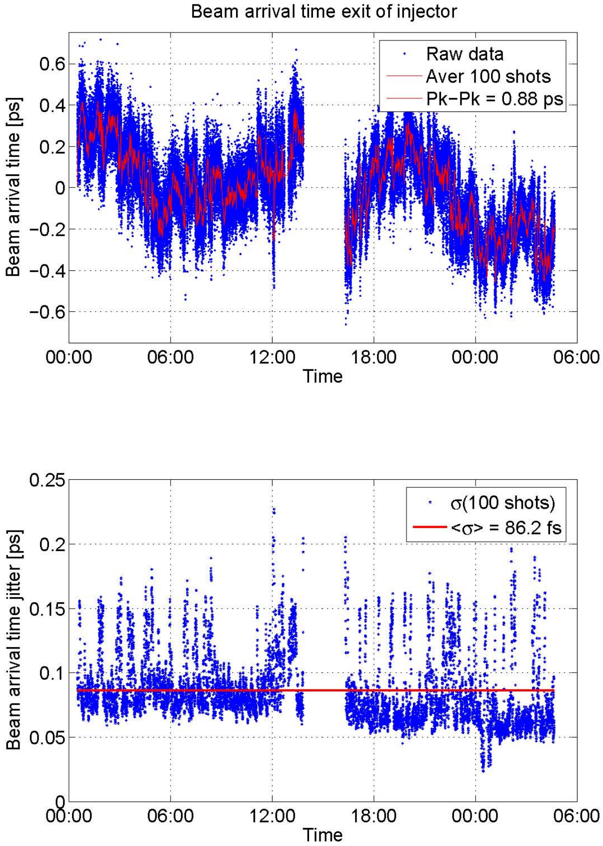

Figure 4: Longterm drift measurement of the beam arrival time before the entrance of the first bunch compressor

The beam arrival time jitter exhibits large, randomly distributed spikes. The origin of these short-term variations is unknown and needs further investigations. In spite of the magnitude of every spike the beam arrival time jitter returns to approximately the primary value.

Impact of Phase Variations on the Beam Arrival Time

With the BAM installed after ACC1 we were able to measure for the first time the influence of phase changes in both the photoinjector laser and the RF gun for electron bunches entering the dispersive section. The accumulated timing change of the electron beam δt_{beam} is given by

$$\delta t_{beam} = G_{gun} * \delta t_{gun} + G_{laser} * \delta t_{laser} \qquad (1)$$

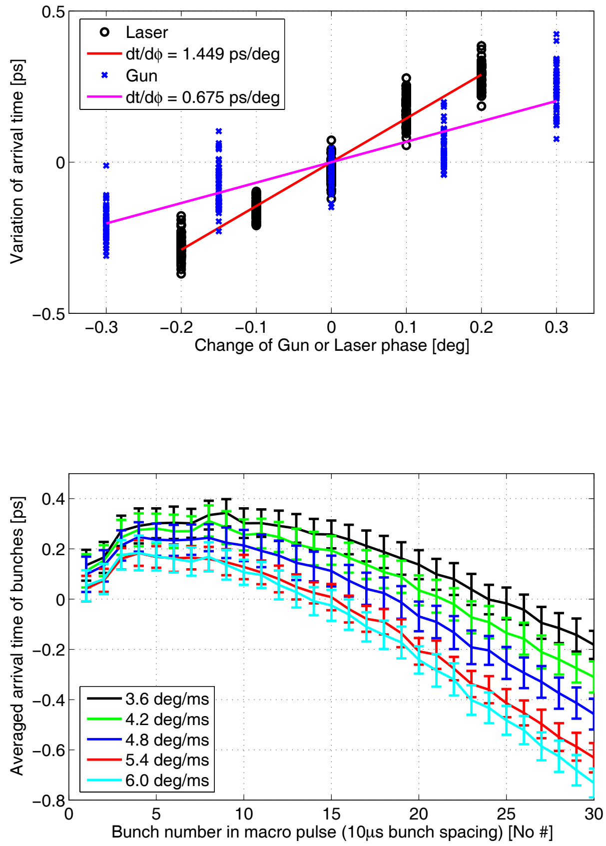

Figure 5: Measured variation of arrival time depending on phase changes in the injector section (upper picture). Averaged bunch arrival time for different values of the RF gun phase slope after filling.(lower picture)

where the factors G_i define the fractional part of timing change from the RF gun and photo-injector laser, and vary with the gun operation phase (laser phase fixed). Since the timing change of both components must cause a timing shift of the beam by equal amount, both factors G_i have to add up to unity. This condition is equivalent to the statement, that the timing changes per degree phase change have to add up to 2.14 ps/deg, where the individual timing changes are given by

$$\delta t_{gun} = \frac{\delta\phi_{gun}}{\omega_{RF}} \quad \text{and} \quad \delta t_{laser} = \frac{\delta\phi_{laser}}{\omega_{RF}} . \qquad (2)$$

The upper part of Fig. 5 shows two measurements of the rate of beam arrival time change, averaged over the macro pulses, for phase changes in the photo-injector. First, the photocathode laser phase was changed by an maximum amount of ±0.2 deg and was set back to the initial value after the measurement. Hereafter, the RF gun phase was changed by an amount of ±0.3 deg. In both cases, a linear fit is applied to the data. The slopes of the measured arrival time variations add up to 2.12 ps/deg, which is less then 1 % deviation from the expected value of 2.14 ps/deg. The lower picture of Fig. 5 shows five consecutive measurements of the averaged arrival times for all bunches of a macro pulse. Between each measurement the phase slope of the RF gun was changed from the initial value of 4.8 deg/ms in steps of 0.4 degrees within a range of 2.4 deg/ms. Clearly, this parameter has a pronounced effect on the slope of the macro pulse bunch arrival time. The maximum timing difference, as measured at bunch number 30, amounts to approximately 0.52 ps. Since the macro pulse has a duration of 300 μs, the maximum range of 2.4 deg/ms accords to a phase shift of 0.7 deg. By multiplying this value with $\delta t/\delta\phi$ = 0.68 ps/deg, as measured for the RF gun, the calculated timing change is 0.49 ps, which matches the measured timing difference of about 0.52 ps. The change of the arrival time of individual bunches in the macro pulse is most likely caused by an imperfect performance of the RF gun regulation during a heating cycle of the copper cavity. To apply adaptive feed-forward algorithms or fast intra-train beam based feedback on the gun phase, in addition, the information on the arrival time of the photo-injector laser pulses determined by use of optical cross-correlation is required.

SUMMARY AND OUTLOOK

A new BAM was successively installed and commissioned at FLASH. It shows an excellent performance without major operation problems. The BAM opens the opportunity for detailed investigations of the photo-injector, concerning the dependency of the beam arrival time on the performance of photocathode laser and RF gun. In the near future, this will be used to set up an intra-train feedback system on the gun phase. This requires a separate monitor setup to control the photo-injector laser, based on optical cross-correlation.

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