APPLICATIONS OF TIME-OF-FLIGHT MEASUREMENTS AT FLASH

M. Kollewe, K. Flöttmann, DESY, Hamburg, Germany

Abstract

The linear **F***ree-Electron*-**Las***er in* **H***amburg*, FLASH [3] produces short laser pulses in the vacuum ultra-violet. A two-stage bunch compression yields the required peak-current of ≈ 2.5 kA. This compression process will be improved, when a further RF module operating at the third harmonic RF frequency of 3.9 GHz will have been installed. It allows to optimize the longitudinal bunch charge distribution [4]. To measure the compression parameters and adjust the third harmonic cavity operation, FLASH is equipped with sensors for measuring the bunch Time-Of-Flight (TOF) through the compressors. Temperature, bunch charge and beam position influence the TOF measurements. The TOF setup was used to determine *on-crest* angles of acceleration and to measure the *longitudinal transfer map coefficients* R_{56} and T_{566} of one compressor. The measured R_{56} agrees with design values [5], the measurements of T_{566} have to be improved to achieve a higher accuracy.

INTRODUCTION

As a smaller prototype of the European XFEL, FLASH has been build and commissioned at DESY by an international collaboration. It consists of a 255 m long linear electron accelerator with an undulator arrangement (see Fig. 1), and produces short pulses of radiation in the vacuum ultra-violet by the so-called Self-Amplified Spontaneous Emission (SASE) process. In January 2005 first lasing for the current machine configuration took place, since spring 2005 it is placed at the users disposal.

Fig. 1 shows a sketch of the FLASH linac. To generate the laser pulses bunches of electrons are produced by an electron *gun*, and then compressed in longitudinal direction. For the measurements presented here typical FLASH operation values were selected. The bunches carry ≈ 1 nC charge and are produced with a frequency of 1 MHz. 10 bunches form a *macropulse*, the macropulse frequency is 5 Hz. The electrons are accelerated to 130 MeV by the gun and first module (on-crest) and enter the first bunch compressor. The final energy is currently ≈ 450 MeV achieved by 5 modules. Two magnetic bunch compressors reduce the bunch length from 2.5 mm to 50 μm - 100 μm. In that way, the necessary peak current of about 2.5 kA is reached.

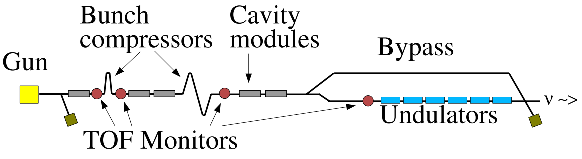

Figure 1: Sketch of the FLASH linac. Four monitors are mounted to measure the Time-Of-Flight.

To examine the compression process four TOF monitors are installed at the accelerator. Each pair of two successive detectors covers a beamline section with variable electron path length (i.e. the bunch compressors and the collimator section upstream of the undulators). They measure the time of bunch passages relative to an oscillating reference signal. Differences of bunch passage times at different linac locations yield TOF values. The measurements can be used to determine 'on-crest' RF-phases of an accelerating module, i.e. the RF-phases for which maximum energy gain for beam or dark current takes place, or to characterize or adjust bunch compression parameters, such as the longitudinal transfer map coefficients or in the future the gradient and phase of the *third harmonic* cavity.

Such a cavity will be mounted between the first module and the first bunch compressor. Model calculations show its effect when it is properly operated (see Fig. 2): The charge density gets higher, the bunch length is shortened and the charge density is smoother.

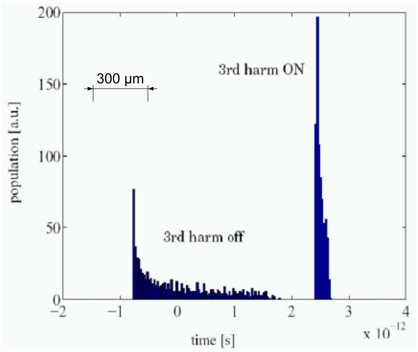

Figure 2: Effect of the 'third harmonic section' operation on the longitudinal bunch charge distribution [4].

TOF measurements allow to characterize the compression process [2] and were successfully applied for that purpose at Jefferson Lab [7].

MEASUREMENT PRINCIPLE

One of the TOF-detectors is shown in Fig. 3. It consists of a ring antenna of 40 mm diameter mounted in the center of a stainless-steel flange. On one side it is terminated, the other side forms the plug for the signal cable. The center of the antenna corresponds to the beam center, when the detector is mounted in the beamline (see Fig. 3, right). The electrode is aligned with the vacuum chamber wall.

An electron bunch passing one of the TOF-monitors evokes a voltage burst within the antenna. This burst is led to an RF analog electronics which compares the time of the surge with a stable reference oscillation. A further analog mixing results in the real (Q) and imaginary (I) component of the difference vector between voltage surge and reference oscillation. I and Q are then processed by the FLASH control system DOOCS [1]. The angle or phase ϕ of the difference vector is calculated by $\phi = \arctan(I/Q)$.

As an example Fig. 4 shows the signal I of the most upstream monitor. It is a sum of two contributions. A $\approx$ 90 μs wide signal, caused by dark current, is superimposed by the beam signal with its maximum at $\approx$ 710 μs. Due to restrictions of the analog electronics single bunches can not be separated, only the macropulse signal can be seen as one maximum. Beam and dark current signals can easily be separated by substraction.

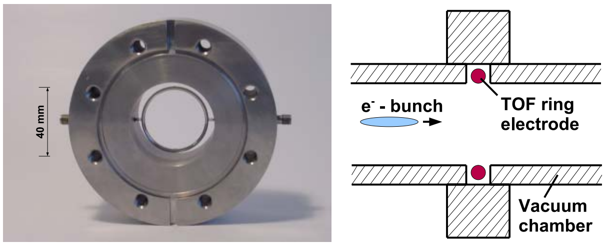

Figure 3: Left: View of a dismantled TOF monitor. The center of the ring is the nominal beam position. Right: Cross-section in beam direction plane.

Different sensitivity measurements show that the TOF-monitor signals are however influenced by parameters not directly related to the TOF. Long-term tests with a stable reference signal showed that the measured bunch arrival time can vary by ± 10 ps (= 5 deg) over a couple of days. This is probably caused by *temperature variations* of the analog electronics. Independend laboratory examinations showed that a temperature change of 1 °C results in 2.1 ps change of measured bunch arrival time.

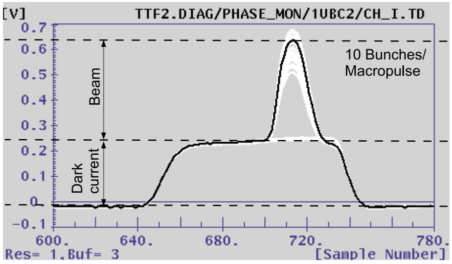

Figure 4: Example of the RF-electronics output signal, digitized with 1 MHz (sample points on abscissa)

.

To test the influence of the *charge per bunch*, variations of it were done while the bunch passage time at one monitor was recorded. A pronounced sensitivity of Δt = 57 ps/nC was found, but differential measurements with two monitors compensate for this effect (see Fig. 6).

When the *transverse beam position* is varied the bunch arrival time measured by a TOF monitor varies by 4.2 ps/mm. These influences need to be investigated.

ON-CREST PHASE DETERMINATION

The electron bunches are accelerated by the cosinusoidal electric field in the superconducting cavities. If the bunches pass the cavities when the electric field has reached its maximum the so called 'on-crest' phase of the electric field is realized. Then, the maximum energy gain takes place, the path length trough a bunch compressor is minimized and thus, the TOF through the bunch compressor reaches a minimum. This depedencies can be used to find the on-crest phase of the electric field by minimizing the TOF through a bunch compressor.

Since the dark current is subject to the same impacts as the beam, its on-crest phase can be measured in the same way as described above. Fig. 5 shows the *dark current* arrival time at the TOF monitor downstream of the first bunch compressor, expressed as the reference oscillation phase, as a function of the accelerating RF field phase of the first cavity module. A clear maximum can be seen when the dark current gains maximum energy.

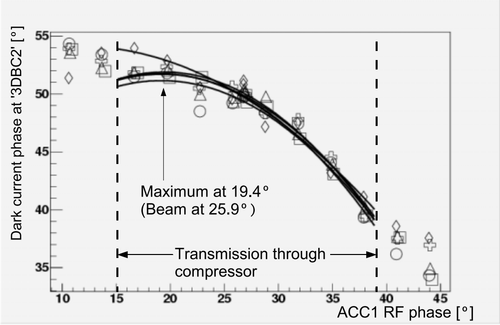

Figure 5: Dark current phase in relation to the reference signal phase. It reaches a maximum when the dark current is 'on-crest'. Four scans with same conditions are shown.

A determination of the *beam* on-crest phase is illustrated in Fig. 6. The upper curves show the bunch passage times for *one* monitor and different bunch charges, while in the lower curves the differences of two monitors (= the TOF) prove that the influence of bunch charge is compensated.

DETERMINATION OF LONGITUDINAL TRANSFER MAP COEFFICIENTS

At FLASH a *magnetic* bunch compression scheme is realized. First, an energy variation, correlated with the longitudinal bunch axis, is impressed on the electron packet by *off-crest* acceleration, i.e. the electron bunch enters the accelerating field before the field has reached its maximum.

In the bunch compressor, the electron momentum is left unattached but the electron position is changed, since electrons with lower energies (at the 'head' of the bunch) travel on longer trajectories. If z_f is the coordinate of an electron in the *longitudinal phase space* downstream of the compressor and z_m upstream of it, the electron transfer along the bunch axis is approximated by

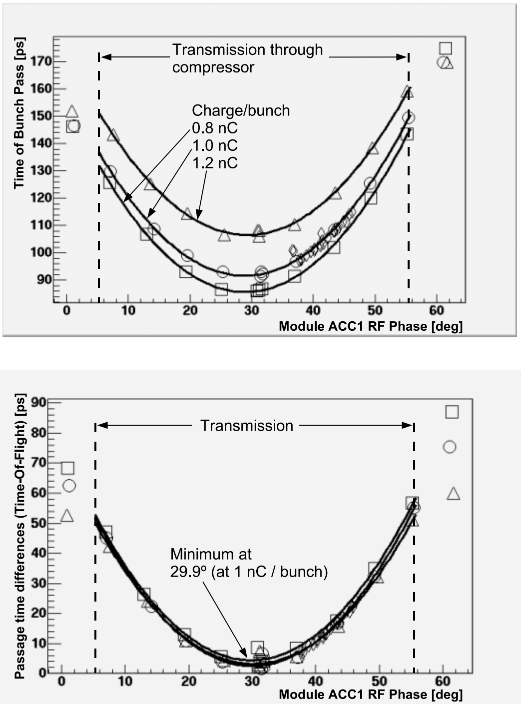

Figure 6: a) Time of bunch passage as function of RF field phase for one monitor downstream of first bunch compressor. b) As a) but time differences (TOF) of two monitors.

$$z_f = z_m + R_{56}\,\delta + T_{566}\,\delta^2, \tag{1}$$

with the longitudinal transfer map coefficients R_{56} and T_{566}. The momentum is expressed as normalized offset around a reference value p_0, $\delta = (p - p_0)/p_0$. See also [6].

During the measurements $z_f - z_m$ was measured by the TOF monitors while δ was varied by changing the phase of the accelerating RF field in the most upstream module. In that way, the $z_f - z_m$ dependence on δ could be measured at different sample points and R_{56} and T_{566} were calculated by fitting the $z_f - z_m$ versus δ curve. This was done two times with the same conditions (see Fig. 7).

Table 1 compares the results of the first measurements of R_{56} and T_{566} with design values. The agreement of the measured and calculated R_{56} is acceptable for a first attempt, while measured and calculated values for T_{566} do not agree. Steering effects during the scans in combination with the beam position sensitivity of the TOF monitors probably cause this inaccuracies and have to be addressed.

Table 1: Transfer map coefficients of flash FLASH bunch compressor. (Design values from [5].)

	Design value	Scan 1	Scan 2
R_{56} [mm]	-181	-176	-163
T_{566} [mm]	295	479	119

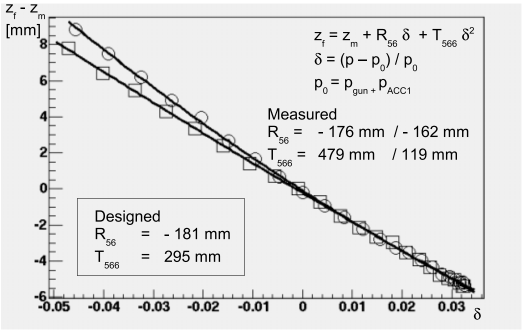

Figure 7: Determinations of longitudinal transfer map coefficients of first bunch compressor (two RF phase scans).

CONCLUSION

First measurements with the TOF system at FLASH were successfully performed. A better understanding of disturbing effects and error sources is required to improve the accuracy of the transfer coefficient measurements.

ACKNOWLEDGEMENTS

We like to thank Mr. Matthiesen from DESY/MSK for support during the setup commissioning and operation.

REFERENCES

[1] DOOCS, http://doocs.desy.de

[2] M. Ferarrio, K. Flttmann, B. Grigoryan, T. Limberg, Ph. Piot, "Conceptual Design of the TESLA XFEL Photoinjector", TESLA FEL Report 2001-03.

[3] FLASH, http://flash.desy.de

[4] K. Floettmann, T. Limberg, Ph. Piot, "Generation of Ultrashort Electron Bunches by cancellation of nonlinear distortions in the longitudinal phase space", TESLA FEL Report 2001-06.

[5] The TESLA Test Facility FEL team, "SASE FEL at the TESLA Facility, Phase2", TESLA FEL Report 2002-01.

[6] P. Piot, "State-Of-The-Art Electron Bunch Compression", LINAC'04, Lübeck/Germany, August 2004, p. 528.

[7] P. Piot and D. R. Douglas and G. A. Krafft, "Longitudinal phase space manipulation in energy recovering linac-driven free-electron lasers", PHYS.REV.ST ACCEL.BEAMS, 6, p. 30702, http://www.citebase.org