# START-TO-END ERROR STUDIES FOR FLUTE

M. Weber*, A.-S. Müller, S. Naknaimueang, M. Schuh, M. Schwarz, P. Wesolowski
KIT, Karlsruhe, Germany

## *Abstract*

FLUTE, a new linac based test facility and THz source, is currently under construction at the Karlsruhe Institute of Technology (KIT) in collaboration with DESY and PSI. With a repetition rate of 10 Hz, electron bunches with charges from 1 pC to 3 nC will be accelerated up to 40-50 MeV and then compressed longitudinally in a magnetic chicane to generate intense coherent THz radiation. Since the stability and repeatability of longitudinal bunch profiles are essential for optimum compression and THz radiation properties, simulation-based start-to-end error studies using the tracking code ASTRA have been performed to determine the influence of the machine elements on the bunches. Thus, critical parameters are identified and their respective tolerance ranges defined. In this contribution a summary of the error studies will be given.

## INTRODUCTION

The "Ferninfrarot Linac- Und Test-Experiment" (FLUTE) [1], [2] is a new compact linear accelerator facility, aimed at the generation of coherent THz radiation with fs electron bunches. Additionally, it will serve as a test stand for the study of different generation mechanisms of THz radiation (CSR, CTR and CER) as well as for the development of diagnostics for the ultra-short bunches.

Figure 1 shows the baseline design of FLUTE. In a 3 GHz RF photo gun the initial bunches with charges from 1 pC to 3 nC are generated and accelerated to about 7 MeV. In order to compensate the strong space charge forces acting within the bunches at low energy, a solenoid is used for transverse focusing right after the gun. A travelling wave linac accelerates the bunches to their final energy of 40-50 MeV. In addition, a negative correlated energy spread is induced to longitudinally compress the bunches in the D-shaped bunch compressor (chicane). To control and optimize the transverse bunch size, a focusing quadrupole doublet is used before the chicane.

## BEAM DYNAMICS SIMULATIONS

For the design of FLUTE and the optimization of the machine parameters, different simulation tools including the tracking code ASTRA [3] have been used [4] in order to get a minimum RMS bunch length after compression. For the error studies the tracking has been done with ASTRA for the entire machine. Table 1 shows the current design values for the machine parameters applied in the simulations. Depending on the bunch charge, RMS bunch lengths between 220 fs (3 nC) and 5 fs (1 pC) after compression can be achieved. CSR effects inside the chicane are neglected in this case. Simulations including CSR effects result in bunch lengths of about 270 fs for the 3 nC bunches, while for 1 pC CSR leads to about 5% longer bunches. Especially in this highly sensitive low charge regime further optimization is ongoing.

Table 1: Design Values for the FLUTE Machine Parameters used in the ASTRA Simulations

| Parameter | Unit | Value |
|---|---|---|
| Bunch charge | nC | 0.001 - 3 |
| Laser spot size (RMS) | mm | 0.5 - 2.25 |
| Laser pulse length (RMS) | ps | 0.5 - 4 |
| Gun peak field | MV/m | 120 |
| Solenoid peak field | T | 0.14 - 0.18 |
| Linac peak field | MV/m | 10 |
| Quadrupole strength | $\mathrm{m}^{-2}$ | 11.88 - 12 |
| Dipole bending radius | m | 1.12 - 1.006 |

## ERROR STUDIES

A solid understanding of the influence of the machine parameters on the 3D bunch shape is a prerequisite for a stable operation with ultra-short bunches. These parameters include the ones shown in Table 1, as well as the alignment of the different machine components. Two simulation procedures have been applied. On the one hand, systematic scans of individual machine parameters have been performed. On the other hand, randomly generated deviations have been added on the design values of these parameters. This has been done for each machine component separately, as well as for the whole machine at once. The errors follow a Gaussian distribution and each entry in the distribution corresponds to one simulation run. For that purpose an internal routine included in ASTRA has been used. Observing the distribution of the output bunch parameters (such as RMS bunch length and transverse bunch size) after multiple simulation runs then gives information about the average influence of the errors on the bunch. Table 2 shows the RMS values for the error distributions on the considered machine parameter values. A cut-off after three sigma has been made, meaning that deviations of the input values do not exceed this range. So values that are too far off from the design value of the respective machine parameter (with probabilities below 0.3%) are avoided within the random distributions.

Regarding the laser, errors have been added on the laser pulse length, timing offset (jitter), spot size and position at the cathode, as well as on the bunch charge (laser amplitude). Out of these, the timing offset has the strongest influence on the bunch profiles. Figure 2 shows a systematic scan of the laser timing between ±500 fs and the impact on the bunch

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* manuel.weber@partner.kit.edu

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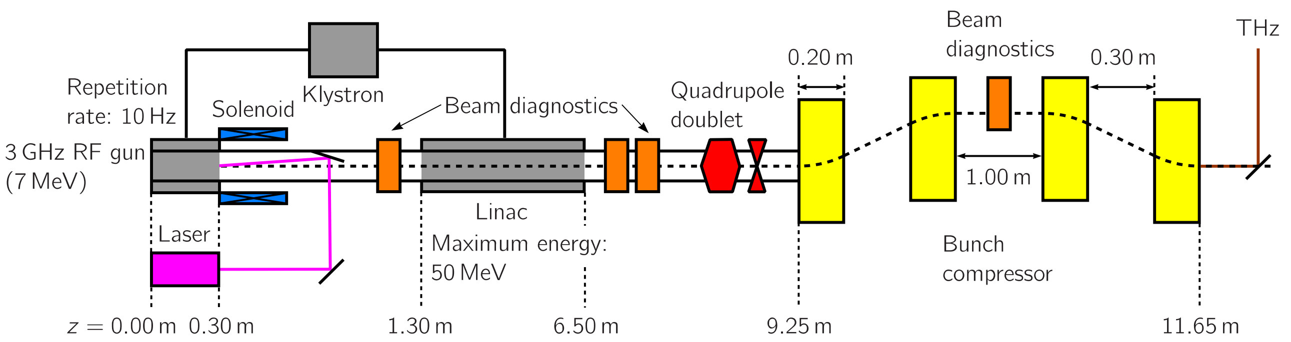

Figure 1: Baseline layout of FLUTE as used for the error studies. The initial bunches are generated in an RF photo gun, accelerated to 40-50 MeV in the linac and then longitudinally compressed in a four dipole chicane. Gun and linac are powered both by the same klystron.

Table 2: RMS Values for the Gaussian Distributed Errors (added on the design value of the respective machine parameter)

| Parameter | Unit | Value |
|---|---|---|
| Bunch charge | % | 0.25 |
| Laser spot size | % | 1 |
| Laser pulse length | % | 0.1 |
| Laser timing | ps | 0.5 |
| Phase (laser, gun, linac) | degree | 0.1 |
| Peak field (gun, solenoid, linac, chicane) | % | 0.1 |
| Position of machine component | mm | 0.25 |
| Rotation of machine component | mrad | 0.5 |

length after compression for a 1 pC bunch. A 500 fs timing offset equals a phase error of

$$\phi(t) = \omega t = 2\pi \times 3\ \text{GHz} \times 500\ \text{fs} \approx 0.5^\circ \tag{1}$$

in gun and linac. So the electrons gain a different amount of energy compared to the case without jitter. This leads to a deviation of mean energy and energy spread of the bunch and disturbs the optimum bunch compression in the chicane.

In Fig. 3, Gaussian distributed errors have been added on all machine parameters simultaneously in 150 simulation runs (this number has been chosen concerning reasonable computation times since one simulation run takes more than two hours). Although the overall fluctuations increase, the effect of the laser timing offset on lengthening the bunch can still be observed. Also, the horizontal RMS bunch size after compression is strongly affected (see Fig. 4). Particles travelling off axis through the linac are influenced by transverse components of the accelerating RF wave. This has a focusing or defocusing effect on the bunch, depending on the linac phase. So the bunch size increases or decreases, while in both cases the RMS bunch length grows.

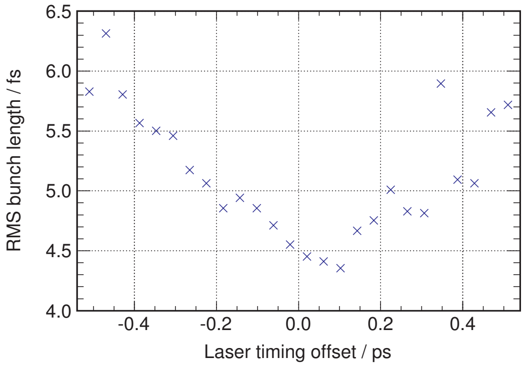

Figure 2: Systematic scan of the laser timing offset for a 1 pC bunch. Timing deviations lead to longer bunches after compression. A stability of ±200 fs is required to keep the fluctuations in bunch length in the range of 0.5 fs.

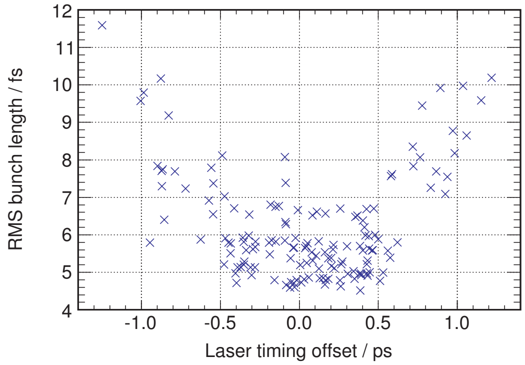

Figure 3: Influence of the laser timing on the RMS bunch length after compression. Gaussian distributed errors are added on all machine parameters simultaneously (1 pC, 150 simulations). Compared to Fig. 2 there is still a correlation between laser timing and compressed bunch length.

Further start-to-end simulations concerning the deviations on the values of gun, solenoid, linac, quadrupole doublet and bunch compressor parameters as listed in Table 2 have been performed. The histograms in Fig. 5 and Fig. 6 show the effect of all errors on bunch length and horizontal bunch size for a 1 pC bunch along the machine axis (after 150 simulation runs). The overall relative fluctuations in bunch length around the mean rise from about 5% before compression to about 20% after compression. Looking at the impact of

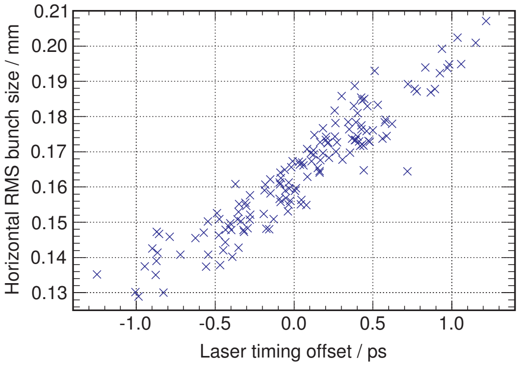

Figure 4: Impact of the laser timing on the horizontal RMS bunch size after compression. Similar to Fig. 3, Gaussian distributed errors are added on all machine parameters simultaneously (1 pC bunch). Transverse components of the accelerating RF wave inside the linac are focusing or defocusing the bunch, depending on the phase. Due to the timing-related phase errors, this has the effect of increasing or decreasing transverse bunch sizes.

the deviations on the horizontal bunch size, the maximum fluctuations around the mean are in the order of 10%. For higher bunch charges up to 3 nC, the relative fluctuations in bunch length before compression are in the same order of magnitude as for 1 pC. After compression the fluctuations are decreasing with higher charges. Because of the very short RMS lengths of the 1 pC bunches, small variations in absolute numbers lead to large deviations in relative numbers. Concerning this sensitive case, also numerical influences on the bunch parameter fluctuations are currently under investigation.

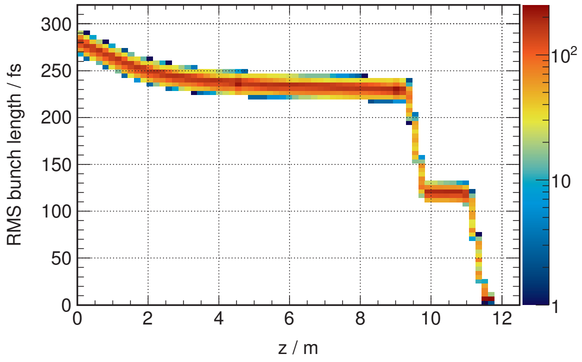

Figure 5: Histogram of the RMS value of the bunch length along the machine axis (1 pC, 150 simulations). Gaussian distributed errors have been added on all machine parameters simultaneously. Fluctuations around the mean value rise from about 5% before compression to about 20% after compression.

## SUMMARY

FLUTE, a new accelerator test facility, is currently under construction at KIT. Simulation-based error studies using the tracking code ASTRA have been performed. The laser timing jitter is identified as the most crucial machine parameter in terms of influencing bunch length and bunch size after compression. Its deviations should be kept below ±200 fs. In this case the RMS compressed bunch length (5 fs, 1 pC bunch charge) fluctuates about 0.5 fs. The average fluctuations increase to about 1 fs when adding Gaussian distributed errors on all machine parameters simultaneously. These parameters include the alignment of the FLUTE machine components, as well as electric and magnetic peak fields and the phases in gun and linac. In general, alignment errors should not exceed 0.25 mm in position and 0.5 mrad in rotation, which is possible with present machining precision. The same applies for deviations up to 0.1% of the electric and magnetic peak fields. The jitter of gun and linac phases should not be larger than 0.1°. The overall relative fluctuations of bunch size and bunch length after compression then amount to about 10-20% for the 1 pC bunches (which is the most sensitive case). The relative fluctuations for higher charges are decreasing due to the larger absolute values of their bunch parameters.

In the next steps the influence of CSR effects inside the chicane will be included in the error studies, especially for the higher charges. Also the impact of the errors on the generated THz radiation will be investigated.

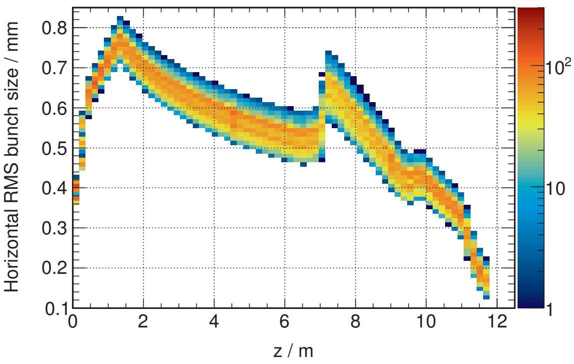

Figure 6: Histogram of horizontal RMS bunch size along the machine axis after 150 simulations with Gaussian distributed errors (1 pC). After compression fluctuations around the mean rise to about 10%.

## REFERENCES

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