ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOMS022

DETAILED ANALYSIS OF TRANSVERSE EMITTANCE OF THE FLUTE ELECTRON BUNCH

T. Schmelzer*, E. Bründermann, M.J. Nasse, R. Ruprecht, J. Schäfer, M. Schuh, N.J. Smale, P. Wesolowski and A.-S. Müller, Karlsruhe Institute of Technology, Karlsruhe, Germany

Abstract

The compact and versatile linear accelerator-based test facility FLUTE (Ferninfrarot Linac- Und Test-Experiment) is operated at KIT. Its primary goal is to serve as a platform for a variety of accelerator R&D studies like the generation of strong ultra-short terahertz pulses. The amplitude of the generated coherent THz pulses is proportional to the square number of particles in the bunch. With the transverse emittance a measure for the transverse particle density can be determined. It is therefore a vital parameter in the optimization for operation. In a systematic study, the transverse emittance of the electron beam was measured in the FLUTE injector. A detailed analysis considers different influences such as the bunch charge and compares this with particle tracking simulations carried out with ASTRA. In this contribution, the key findings of this analysis are discussed.

INTRODUCTION

The electron bunch at the Ferninfrarot Linac- und Test-Experiment (FLUTE) is generated with a photoinjector system [1]. A Ti:Sa laser system together with a 2.5 cell S-band cavity are used to accelerate the electron bunch up to 7 MeV bunch energy. In the first section, i.e., the low energy section, several diagnostic systems are installed to monitor the electron bunch parameters, which includes the bunch charge measured with an integrated current transformer (ICT) [2]. An experiment chamber in the low energy section allows to use the electron bunch for first experiments, e.g., the split-ring-resonator (SRR) experiment [3]. After the diagnostics a linear accelerator structure will be connected to increase the electron energy up to 41 MeV for short-bunch R&D. The characterization of the electron beam parameters is crucial for optimizing the beam for various experiments. One important parameter is the transverse bunch emittance, which can be measured at FLUTE via a quadrupole scan. For a detailed analysis the uncertainties from several parameters were measured and included in the simulations performed with ASTRA [4].

MEASUREMENTS

The transverse emittance was evaluated at the quadrupole position (1.45 m from the cathode surface), using the quadrupole scan technique described in [5]. Several bunch parameters influence the transverse emittance, such as the bunch energy and charge. Any parameter fluctuation during the quadrupole scan increases the uncertainty of the emittance result. For a detailed analysis the settings and fluctuations of the bunch parameters are needed and are listed in Table 1 together with the machine settings. The RF phase was adjusted to the highest energy gain at the beginning of the measurement.

Table 1: Emittance Measurement Settings

Property	Value	Unit
RF power input	10.345 ± 0.02	MW
RF phase[1]	0 ± 0.4	°
Laser pulse energy	24.5 ± 1.6	µJ
Laser spot width (rms)	0.21 ± 0.01	mm
Mean solenoid strength	151.6 ± 0.4	mT
Mean bunch energy	5.817 ± 0.003	MeV
Mean bunch charge	16.4 ± 1.5	pC

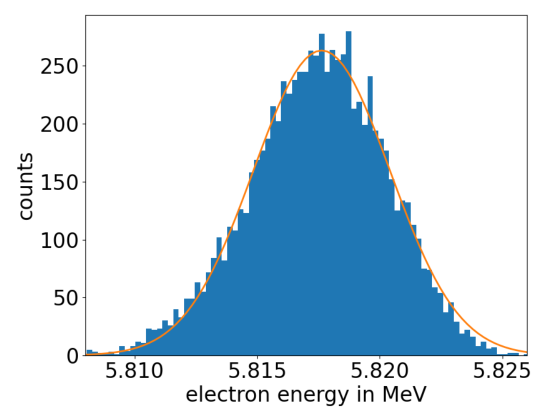

Figure 1: Fluctuation of mean bunch energy (data in counts in blue, Gaussian fit as solid line in orange).

At the low-energy spectrometer the bunch energy was measured for two hours using the profile monitor system, 2.86 m after the cathode [2]. The fluctuations of the mean bunch energy for the recorded 8000 shots are shown in Fig. 1. The slightly skewed Gaussian distribution is a result of the RF phase fluctuation and the used on-crest working point. Here, positive and negative phase fluctuations both result in a decrease of the mean bunch energy. Considering the uncertainty of one σ the bunch energy achieves a stability of 0.05%.

The bunch charge influences the transverse emittance due to space charge effects. During the quadrupole scan the bunch charge was monitored with the non-destructive measurement system Turbo-ICT from Bergoz [2]. With

* thiemo.schmelzer@kit.edu

[1] relative value; zero set to highest electron energy gain

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOMS022

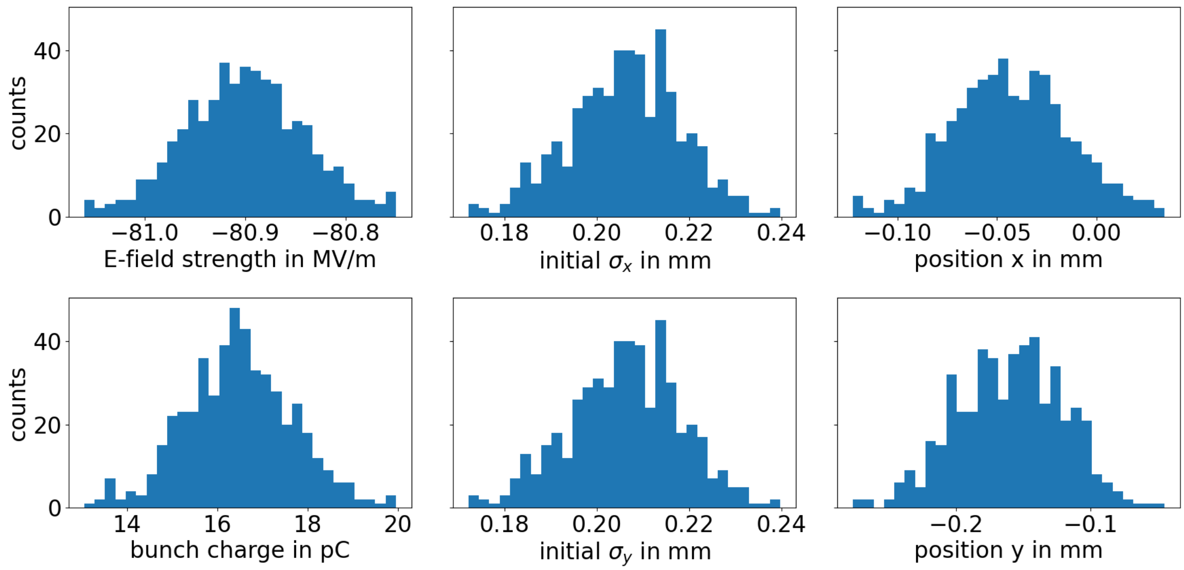

Figure 2: Generated input values for error simulations. A total of 500 simulations were performed.

the ultraviolet laser beam positioned at the cathode center, the measurement of the bunch charge revealed a significant fluctuation of 9.3%. As main factor the laser pulse power fluctuations could be identified, with previously measured fluctuations of 7%.

Quadrupole Scanning Tool

For the quadrupole scan an automated system was developed in Python, which performs the scanning and data acquisition. In this tool, the scan range and step size can be adjusted. This opens the opportunity to perform a detailed measurement with small step size or a fast scan, resulting in a coarse result. At FLUTE the current gun has a significant amount of dark current present, which is influenced by the quadrupole field. Therefore, a background subtraction for the electron profile measurement is part of the automation. As an additional option the number of data points per scanning steps can be adjusted.

In the measurements presented in this paper, the quadrupole current is scanned from −2.9 A to 3 A with a step size of 0.1 A. This corresponds to a change of the quadrupole strength k of 0.52 m^{-2} per step. At each position 30 images of the resulting electron bunch profile were recorded. With the repetition rate of 5 Hz, these settings resulted in a total scanning time of approximately one hour.

SIMULATIONS

The measured machine parameters were used to simulate the transverse emittance of the electron bunch with ASTRA. As input the initial electron bunch parameters are needed, this includes the 3D bunch size and bunch charge. Here, the measurements of the laser profile on the cathode surface and the charge values from the Turbo-ICT were used. For the laser pulse length a calculated value of 1.7 ps (rms) was used. In addition the E-field strength of the gun cavity used in the simulation was adjusted to match the measured mean energy with a comparable RF phase.

For a better understanding of the influences, an error study was performed with 500 simulations. In each simulation one set of six input parameters were used, generated within the measured fluctuation range and using a Gaussian distribution. The investigated input parameters were: the bunch charge, the E-field strength, the laser spot size and position on the cathode surface (each separated in x and y components). These generated values are shown in Fig. 2.

RESULTS

Within the same order of magnitude, the results for simulation and measurement diverge noticeably, including the uncertainty. In Table 2 these results are listed. The simulation overestimates the transverse emittance compared to the measurement, while the uncertainty for the latter is about a factor of five higher than the simulated results.

Investigating the correlation to the input parameter, shown in Fig. 3 for the horizontal emittance, further reveals a strong influence of the bunch charge on the simulated transverse emittance, with a correlation coefficient of 0.86. The introduced uncertainties in the error study only showed one additional and significant correlation to the laser spot size. For the horizontal component ϵ_x, the vertical bunch size σ_y is correlated with a coefficient of 0.48. In the vertical plane this correlation swaps, where ϵ_y is correlated to σ_x with a coefficient of 0.59. This 90 degree rotation is introduced by the solenoid after the cavity. Within the measured fluctuations the other input parameters do not show any influence towards the transverse emittance.

In addition to the measured parameters, the laser pulse length influences the transverse emittance, which is shown

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOMS022

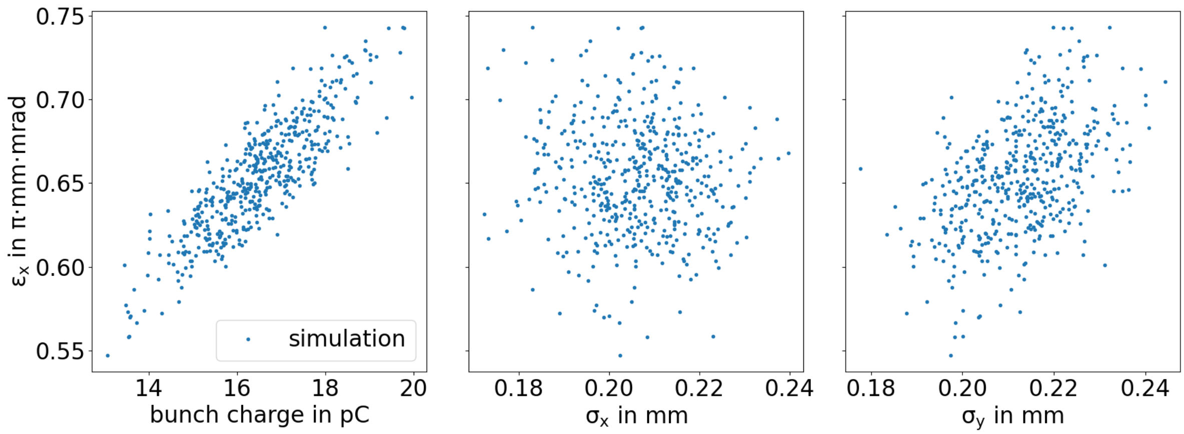

Figure 3: Simulated horizontal emittance correlated to input parameters at cathode center.

Table 2: Results for the Center Cathode Position

Property	Unit	Simulated	Measured
ϵ_x	π mm mrad	0.65 ± 0.03	0.29 ± 0.11
ϵ_y	π mm mrad	0.58 ± 0.03	0.39 ± 0.15

in Fig. 4. For the error study a calculated value for the pulse length was used. A deviation towards longer laser pulses in the measurement could contribute significantly to the higher emittance values observed in the simulation.

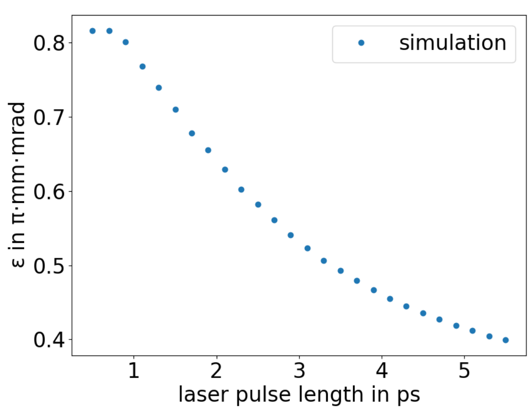

Figure 4: Influence of laser pulse length on ϵ.

SUMMARY

Introducing a versatile scanning tool, a detailed quadrupole scan was performed to investigate the transverse emittance and the influences of the beam parameters. With a model of the first section of FLUTE, particle tracking simulations were performed as error study. This enables the analysis of important parameters that influence the transverse emittance. The precise determination of the laser pulse length can contribute to explain the offset seen between measurement and simulation. Further improvements of the laser system, including the shaping of the 3D-laser pulse with a spatial light modulator are ongoing [6]. According to the error study, the derived emittance value is strongly influ-enced by the bunch charge, where further measurements might benefit from a reduction of the laser power-induced fluctuation.

ACKNOWLEDGEMENTS

The authors like to thank Igor Kriznar from Paradigma-Tech, Senzana, Slovenia for the valuable support on the control system for the FLUTE project. T. Schmelzer ac-knowledges the support by the DFG-funded doctoral School “Karlsruhe School of Elementary and Astroparticle Physics: Science and Technology”

REFERENCES

[1] M. J. Nasse *et al.*, “Status of the Accelerator Physics Test Facility FLUTE”, in *Proc. 6th Int. Particle Accelerator Conf. (IPAC’15)*, Richmond, VA, USA, May 2015, pp. 1506–1508. doi:10.18429/JACoW-IPAC2015-TUPWA042

[2] T. Schmelzer *et al.*, “Diagnostics and First Beam Measurements at FLUTE”, in *Proc. 10th Int. Particle Accelerator Conf. (IPAC’19)*, Melbourne, Australia, May 2019, pp. 2484–2486. doi:10.18429/JACoW-IPAC2019-WEPGW010

[3] J. Schäfer *et al.*, “Split Ring Resonator Experiment - Simulation Results”, in *Proc. 12th Int. Particle Accelerator Conf. (IPAC’21)*, Campinas, Brazil, May 2021, pp. 888–891. doi:10.18429/JACoW-IPAC2021-MOPAB280

[4] K. Floettmann, ”ASTRA: A Space Charge Tracking Algorithm”, 2017; http://www.desy.de/~mpyflo/Astra_manual/Astra-Manual_V3.2.pdf

[5] T. Schmelzer *et al.*, “Systematic Beam Parameter Studies at the Injector Section of FLUTE”, in *Proc. 12th Int. Particle Accelerator Conf. (IPAC’21)*, Campinas, Brazil, May 2021, pp. 2837–2839. doi:10.18429/JACoW-IPAC2021-WEPAB103

[6] M. Nabinger *et al.*, “Transverse and longitudinal modulation of photoinjection pulses at FLUTE”, in *Proc. 13th International Particle Accelerator Conf. (IPAC’22)*, Bangkok, Thailand, Jun. 2022, paper TUPOPT068, this conference.