BEAM DYNAMICS INVESTIGATIONS ACCOMPANYING THE FLUTE FACILITY UPGRADE

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Abstract

The Ferninfrarot Linac- und Test-Experiment (FLUTE) facility at the Karlsruhe Institute of Technology (KIT) is designed to deliver ultra-short electron bunches offering a broad range of beam parameters for diverse applications and to provide coherent radiation in light pulses spanning the terahertz and far-infrared spectral range. Beyond its current role as a versatile accelerator test facility, FLUTE is intended to become one of the injectors for the Very Large Acceptance-compact Storage Ring (VLA-cSR), presently under construction at KIT within the cSTART project (compact Storage Ring for Accelerator Research and Technology). To fulfill these future roles, FLUTE will undergo a reconstruction and a partial upgrade during the cSTART construction phase. This contribution outlines the planned modifications to the future FLUTE accelerator test facility and presents results from accompanying beam dynamics simulations.

FLUTE FACILITY

FLUTE [1] consists of a low-energy section starting with the photo-injector, which contains a solenoid, diagnostics as well as a spectrometer dipole magnet leading to a side arm with a short beam line and an in-air experimental section. The beam energy here is typically between 5 and 5.5 MeV. The traveling wave linac with a length of 5.3 m is equipped to accelerate the beam up to 90 MeV [2]. The high energy-section contains further diagnostic, a quadrupole triplet and a chicane for longitudinal bunch compression. The high-energy section ends with a second in-air experimental section [3] followed by a Faraday cup and beam dump.

For the construction of the Very Large Acceptance - compact Storage Ring (VLA-cSR) of cSTART on a level 3.3 m above FLUTE [4] in autumn of 2026, FLUTE was temporally deconstructed at the end of March 2026 to protect the components and provide space for construction works in the experimental hall. Reconstruction is planned to start in 2027, as soon as the construction progress at cSTART allows.

For reconstruction, the FLUTE layout is adapted to the additional operation task as an injector for cSTART. The main boundary condition is the transition point to the injection line (FLUTE-IL), which transfers electron bunches into the VLA-cSR. The layout of FLUTE used in this contribution represents the status as of today while the final layout is still under development with some variations in the amount of diagnostics and number of quadrupoles being discussed.

One important change from the previous layout to the new layout is the move of the split-ring resonator (SRR) [5], a THz-streaking longitudinal bunch profile diagnostic, from the low energy section to the high energy section after the bunch compressor. In the course of this, some surrounding valves, one BPM, one corrector and a single quadrupole, currently used to focus the beam into the SRR, will also be removed from the low energy section. This significantly shortens the low energy section and reduces the distance from the electron gun to the linac entrance from 3.2 to ≈1.6 m.

After the linac, the existing quadrupole triplet will be exchanged with two doublets, one after the linac and the other after the chicane to improve the control of the transverse beam properties and match the beam to the FLUTE-IL.

The section after the chicane will continue to contain a chamber for in-vacuum electro-optical spectral decoding [6] as well as a thin aluminum foil for the extraction of transition radiation [7]. Upgraded, the section will also contain two vacuum chambers dedicated to in-vacuum experiments. One will be used for the SRR. The other is intended for the extraction of the THz radiation generated in the superconducting THz-undulator [8] (SCUF) which is delivered and planned to be included. At a distance of 15.95 m from the cathode is the transition point to the FLUTE-IL to cSTART.

Different operation modes are planned to cover the different tasks of FLUTE:

- For the injection of a short bunches into cSTART, FLUTE has to deliver a bunch with the correct longitudinal chirp to the entrance of the FLUTE-IL, in which the bunch will be shortened by the present R_{56} [9, 10].
- For the generation of intense THz radiation [7], FLUTE has to deliver short bunches on the femtosecond scale.
- For ultra-high dose-rate (UHDR) experiments [3, 11, 12] bunch charges in the order of 300 pC are needed.

All operation modes are planned to be usable over the whole range of possible beam energies from approx. 10 MeV up to approx. 90 MeV.

SIMULATIONS

For the different operation modes, tracking simulations with a combination of ASTRA [13] and OCELOT [14] have been conducted. ASTRA is used until after the linac, considering the space charge effect. The tracking through the chicane is done with Ocelot and includes additionally the effects of coherent synchrotron radiation (CSR). For the search for the configurations resulting in the shortest bunch length, an optimization algorithm based on parallel Bayesian optimization [15] was employed. The targeted beam energy was included in the optimization function. The optimizer could vary, within given bounds, the gun RF phase and power, the solenoid strength, the RF phase and power in the linac as well as the strength of the chicane. The transverse optics

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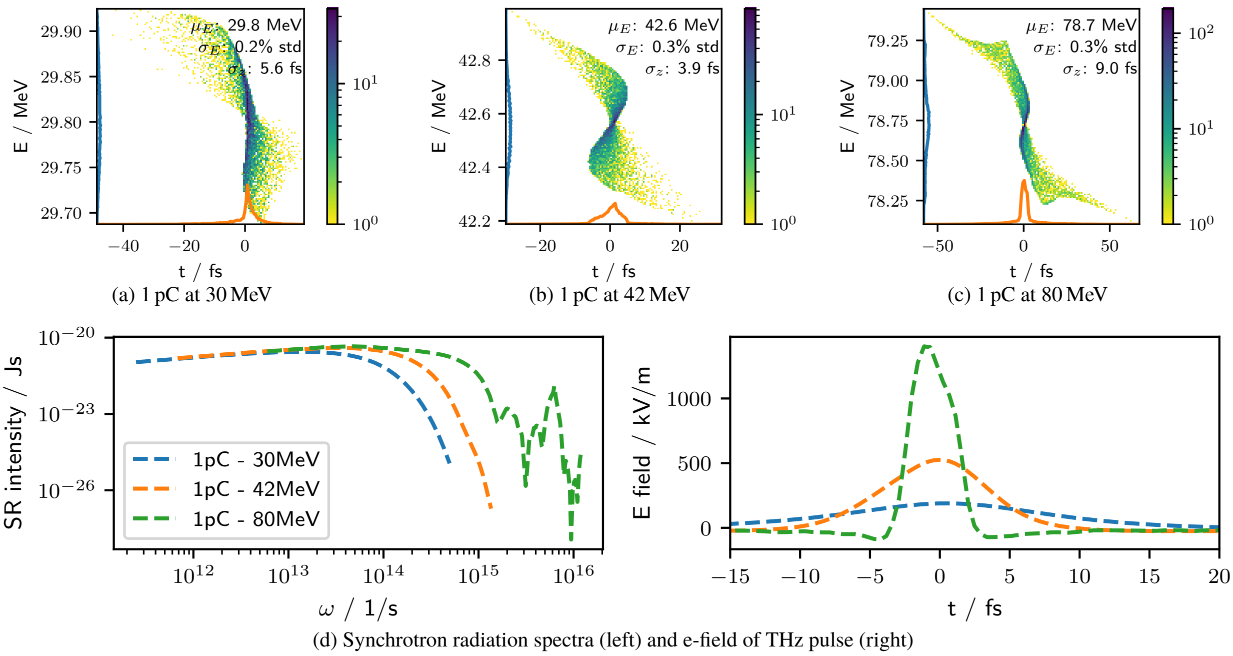

Figure 1: Optimization results for short bunch length: (a)-(c) Charge distribution in the longitudinal phase space for three beam energies. (d) The synchrotron radiation spectra (left) and e-field of THz pulse (right) calculated based on the longitudinal bunch profile.

was roughly adjusted before the optimization and manually fine-tuned afterwards.

RESULTS

In the following, simulations for the different modes are presented, starting with optics for bunch compression at different energies, then an example for injection in cSTART and ending with examples for high bunch charges.

With the optimizer, operation parameters to reach bunch length of a few femtosecond were searched at a bunch charge of 1 pC for three example beam energies (30 MeV, 42 MeV and 80 MeV). Figure 1 shows the final longitudinal phase space with the final RMS bunch length of 5.6 fs (30 MeV), 3.9 fs (42 MeV) and 9.0 fs (80 MeV) as well as the calculated synchrotron radiation spectra and the temporal shape of the calculated THz pulses [15]. More complex considerations on the calculation of the emitted radiation can be found in [16]. Even though the linac and its RF system is designed to accelerate the beam up to 90 MeV, this is only reached at on-crest operation, which does not provide the required energy chirp to shorten the bunches in the chicane afterwards. Therefore, 80 MeV was chosen as target for high energy short bunches. Furthermore, the dipole fields are limited to 0.22 T which corresponds to a maximum bending angle of ≈ 9.5° at 80 MeV. The shown result uses a bending angle of 8.3°.

The transverse optics can be adjusted by the two quadrupole doublets. The dipole magnets in the chicane have a strong vertical quadrupole component (edge focusing) affecting the transverse optics. Therefore, it is, for example, necessary to adjust the quadrupoles after each change in the chicane. Figure 2 shows the beta functions (starting after linac) for two different sets of quadrupole strengths. The final beta functions ranging from around one meter to more than 100 m are examples for which values can be reached. The corresponding final bunch sizes are 0.08 mm and 0.80 mm (Fig. 3). For both settings the quadrupole strength were below 1 T/m, well below their maximum strength of 3 T/m. For 80 MeV, the beta functions for the optimized short bunch settings are shown in Fig. 4. Also here, the quadrupole strength is with ≈ 1.0 T/m well within the feasible range.

For the injection of short bunches into cSTART, the one difference is that the other flank of the RF in the linac is chosen. This way the energy chirp is of opposite sign and the bunch is lengthened in the chicane with the shortening

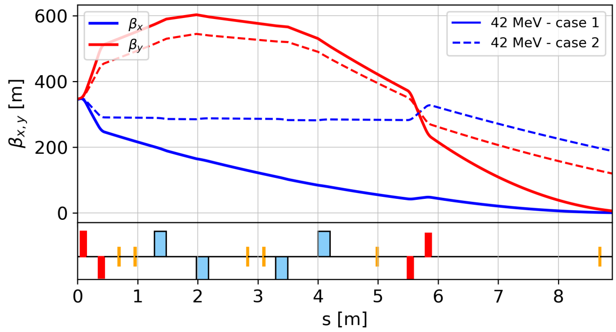

Figure 2: Beta functions after the linac (0 m in the plot corresponds to 7.05 m in FLUTE) at 42 MeV for two example sets of quadrupole parameters. Case 1: focused resulting in β_x=1.6 m, α_x=1.8, β_y=0.3 m, α_x=0.9. Case 2: example for bigger final sizes with β_x=188 m, α_x=20, β_y=119 m, α_x=19.

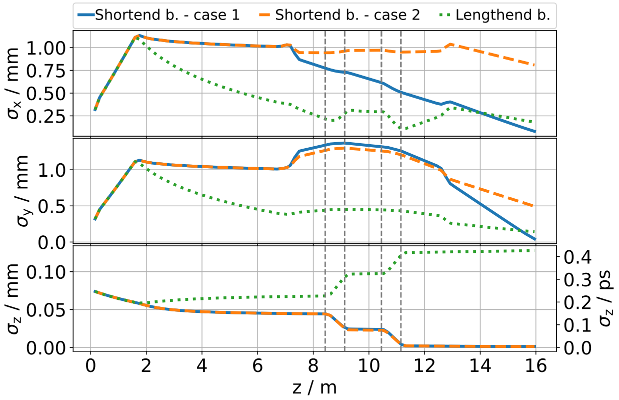

Figure 3: Bunch sizes along FLUTE (1 pC, 42 MeV) for (blue stars) bunch shortening, (orange crosses) same with different quadrupole strengths (Fig. 2 case 1 and 2) and (green points) bunch lengthening (that will be shortened in FLUTE-IL). The vertical lines show the position of the chicane dipoles.

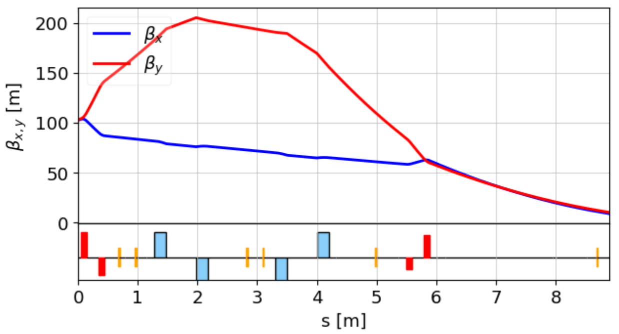

Figure 4: One example of beta functions after the linac (0 m in the plot corresponds to 7.05 m in FLUTE) at 80 MeV with final values of β_x=5.9 m, α_x=1.8, β_y=1.75 m, α_x=0.4 at the end of FLUTE.

happening in the FLUTE-IL shortly before the injection point in the VLA-cSR. For more details see [10]. Using the same operation parameters as used for the short bunch at 42 MeV (Fig. 1b) and only switching the RF phase to the other side of the crest results in the charge distribution in the longitudinal phase space at the transfer point as shown in Fig. 5. The corresponding bunch sizes along FLUTE are displayed in Fig. 3 for both signs of the chirp. The different effect by the chicane can be seen clearly on the bunch length.

The conditions for high charge operations differ slightly. To avoid or reduce the impact on the cathode surface from high intensity laser pulses, the transverse laser spot size is increased by moving the last focusing lens out of focus. Furthermore, the length of the laser pulse can be adjusted by inserting different pieces of quartz rods. This additionally reduces the effect of transverse blow-up due to space charge. In the simulations pulse length of 0.7 ps, 1 ps, or 4.5 ps were used. While the optimizer was able to find settings for 300 pC resulting in ≈ 40 fs, it does not consider the transverse beam sizes and these settings resulted in different positions along FLUTE in sizes of about 10 mm, as it

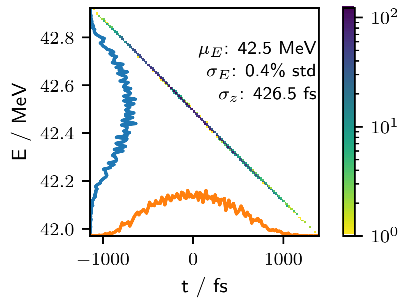

Figure 5: Charge distribution in longitudinal phase space using the opposite phase of linac RF than for compression (see Fig. 1b) for injection into cSTART via FLUTE-IL

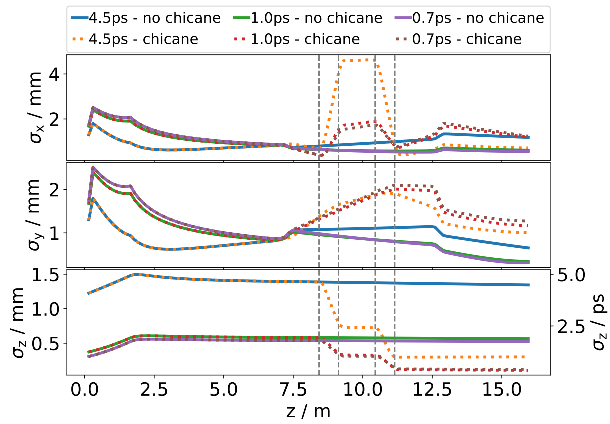

Figure 6: Different operation parameters for 300 pC. The laser pulse length is varied from 0.7 ps to 4.5 ps reducing the transverse size increase in the low energy section. Options with and without the chicane (set to a moderate shortening) are shown.

chose a lower solenoid strength. For possible applications of the high charge operation, such as UHDR experiment, bunch length of a few hundred femtoseconds are sufficient. Therefore, operation parameters where chosen which result only in a moderate bunch length compression. The resulting transverse bunch sizes stay below 3 mm (with one exception in the chicane) and examples are shown in Fig. 6 with and without the chicane tuned in. The final bunch lengths range from 4.5 ps down to 350 fs which covers the area of interest for UHDR experiments. Transverse beam sizes at the in-air experimental section could be varied from sub-mm up to several millimeters.

CONCLUSION

First, preliminary beam dynamics simulation for a potential layout of FLUTE after the upgrade were conducted. All planed operation modes showed the capability to deliver the required beam properties for the three main use cases of FLUTE: injection into cSTART, ultra-short bunches for THz generation as well as higher bunch charges for UHDR operation.

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