SIMULATING THE BUNCH STRUCTURE IN THE THz SOURCE FLUTE

S. Naknaimueang*, E. Huttel, S. Marsching, A-S. Müller, M. J. Nasse, R. Rossmanith, R. Ruprecht, M. Schreck, M. Schuh, M. Schwarz, M. Weber, P. Wesolowski, KIT, Karlsruhe, Germany
M. Schmelling, MPI-K, Heidelberg, Germany

Abstract

FLUTE is a linac-based THz source under construction at KIT, operating at a beam energy of 40 to 50 MeV in a wide bunch charge range. In the first phase it consists of a laser driven rf-gun, a linac, and a magnetic bunch compressor. The high current density combined with the relatively low energy of FLUTE leads to complex strong self-field and beam-radiation field interactions, which are the limiting factors for the bunch compression efficiency. The results of numerical studies are presented in this paper.

INTRODUCTION

FLUTE is a compact linac-based THz source with a relatively low beam energy of 40 MeV [1]. The machine layout of FLUTE is shown in Fig. 1. A 2 1/2 cell photo-injector gun [2, 3] produces single electron bunches with an energy of 7 MeV. The bunch is further accelerated by a 3 GHz traveling wave linac to an energy of around 40 MeV. Afterwards, the beam enters the bunch compressor.

Bunches with the maximum charge of 3 nC can be compressed to a length of less than 300 fs (RMS). With this compressed bunch coherent synchrotron radiation (CSR) up to a few THz can be produced. Space charge and self forces due to CSR limit the final bunch length.

For the simulation results presented in this paper the program ASTRA [4] was used for simulations from the cathode to the entrance of the bunch compressor and CSRtrack [5] for simulations in the bunch compressor. CSRtrack has several beam self-interaction routines as, e.g.

(a) without space charge and CSR effects,

(b) with space charge and CSR effects in the so-called 1D version where the particle coordinates are projected on the z-axis, and

(c) the so-called 3D version, which considers the transverse extensions of the beam.

In this paper it is shown that for a low energy/high current beam (as in FLUTE) 1D and 3D simulations produce different results. In the following the results of the 1D and the 3D calculations are compared.

MACHINE LAYOUT FOR BUNCH LENGTH MINIMIZATION

In a first step the main parameters of the machine are optimized in order to obtain a minimum bunch length for different bunch charges. The optimum linac phase for the bunch is 31° off-crest and the length of each bending magnet in the bunch compressor is 20 cm [6]. The distance between the first two and the last two dipole magnets of the compressor is 30 cm and the distance between the second and the third dipole magnet is 1 m (see Fig. 1). For these machine parameters, in a second step, the parameters depending on the bunch charge were optimized: the transverse laser beam size, the laser pulse length, and the bending radius r_{bend} of the bunch compressor magnets. The parameters are listed in Table 1.

Table 1: Optimum machine parameters for different bunch charges. For both the laser spot size and the laser pulse length the respective RMS values are given

Bunch charge [nC]	Laser spot size [mm]	Laser pulse length [ps]	r_{bend} [m]
3	2.25	4	1.006
2	1.50	4	1.058
1	1.50	3	1.032
0.1	0.50	2	1.108
0.001	0.50	1	1.135

CSRTRACK SIMULATION RESULTS

Table 2 summarizes the RMS compressed bunch length from 1D and 3D CSRtrack calculations.

The 1D and 3D simulation show very similar results for 3 nC until the beam enters the final magnet of the bunch compressor (Fig. 2). Before this point, the beam is not short enough to produce significant CSR and experience space charge effects.

Table 2: RMS compressed bunch length from 1D and 3D CSRtrack calculations ("initial": before the compressor, "final": after the compressor)

Bunch charge [nC]	L_{rms} [ps] (initial)	L_{rms} [fs] 1D (final)	L_{rms} [fs] 3D (final)
3	2.24	199	270
2	2.25	157	224
1	1.65	114	146
0.1	1.05	52	67
0.001	1.05	13	14

The RMS bunch lengths after compression are 199 fs and

* somprasong.naknaimueang@kit.edu

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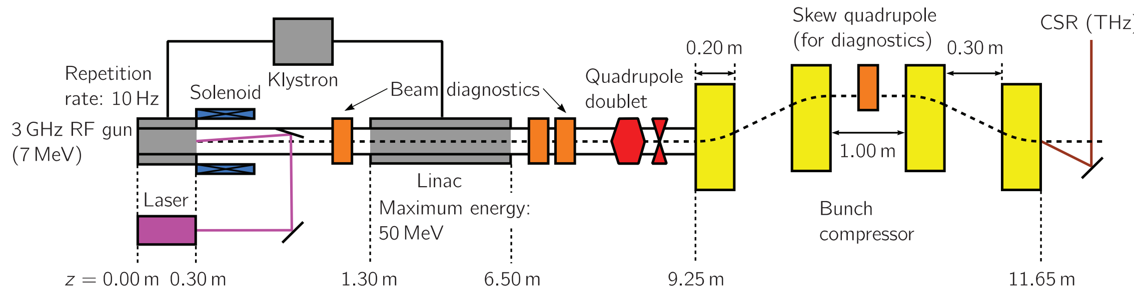

Figure 1: Layout of FLUTE.

270 fs for the 1D and 3D simulations, respectively. For smaller bunch charges the difference in the bunch length from the two simulations is smaller (Fig. 3).

Fig. 3 shows the longitudinal phase space distributions and bunch profiles for a bunch charge of 1 pC. The achieved bunch lengths are more similar than for the 3 nC simulations shown in Fig. 2.

In Fig. 4, the energy of the beam was increased from 40 MeV to a hypothetical value of 300 MeV and dipole magnet field strengths readjusted to the latter energy. The 1D and 3D simulations show similar results. Since bunch profiles calculated without space and CSR effects have similar shapes, we conclude that the influence of these effects almost disappears for 3 nC at these energies.

The simulations also show that CSR and space charge effects can be reduced by increasing the transverse beam size. This is shown in Fig. 5. For a 3 nC beam an increase of the transverse beam size by a factor of 5 compared to Fig. 2 results in a similar bunch length in the 1D and 3D simulations.

In Fig. 5 the transverse dimensions of the bunch are increased by changing the quadrupole strength. Fig. 6 shows that the result of this concept is limited by the nonlinearities of the compressor. With small transverse bunch dimensions CSR and space charge effects make the bunch longer. With increasing transverse beam size the bunch length goes through a minimum and increases due to nonlinearities of the compression scheme for larger bunch dimensions.

CONCLUSION

The intermediate beam energy at FLUTE limits the maximum bunch charge 3 nC. Results for the 1D and 3D op-

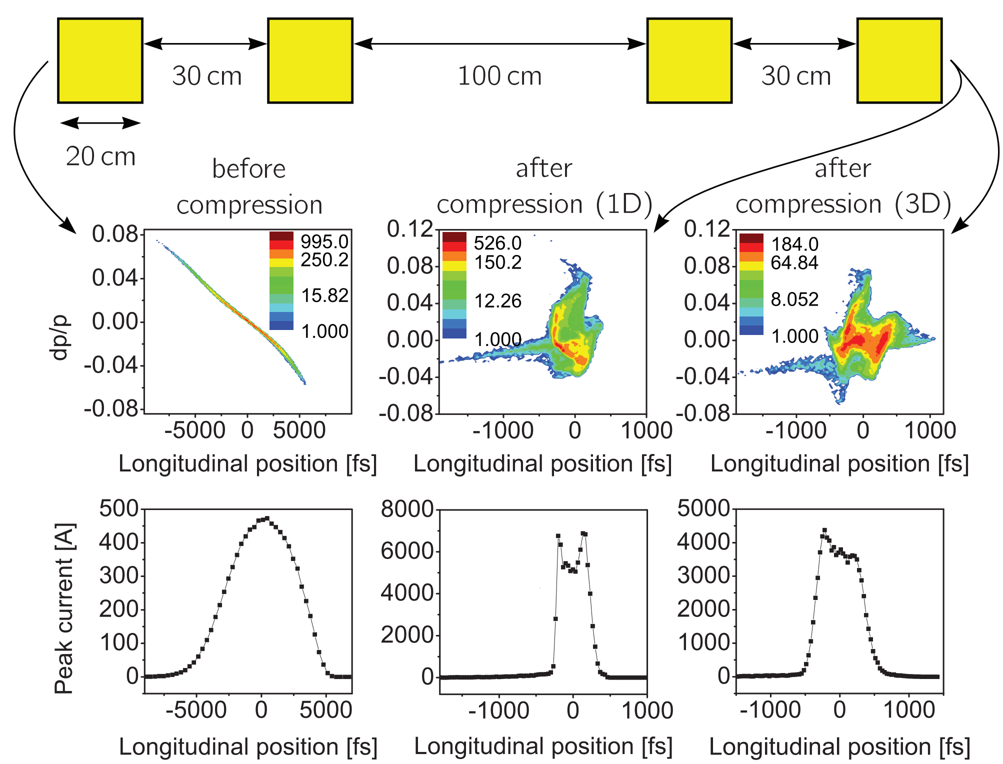

Figure 2: Longitudinal phase space distributions and bunch profiles for a bunch charge of 3 nC before and after compression using 1D ($L_{\rm rms} = 199$ fs) and 3D simulations ($L_{\rm rms} = 270$ fs).

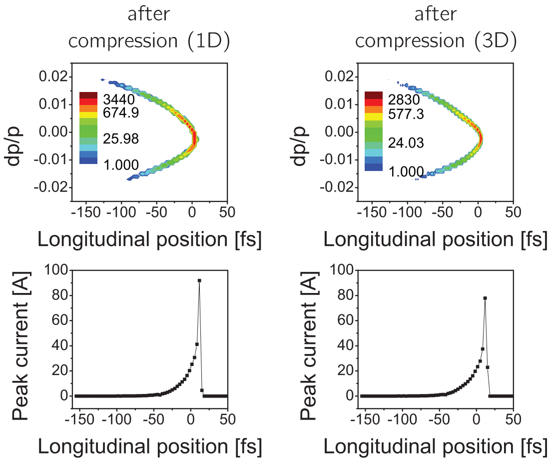

Figure 3: Longitudinal phase space distributions and bunch profiles for a bunch charge of 1 pC after compression using 1D ($L_{\mathrm{rms}} = 13$ fs) and 3D ($L_{\mathrm{rms}} = 14$ fs) simulations. The achieved bunch lengths are more similar to each other than in case of the 3 nC (shown in Fig. 2).

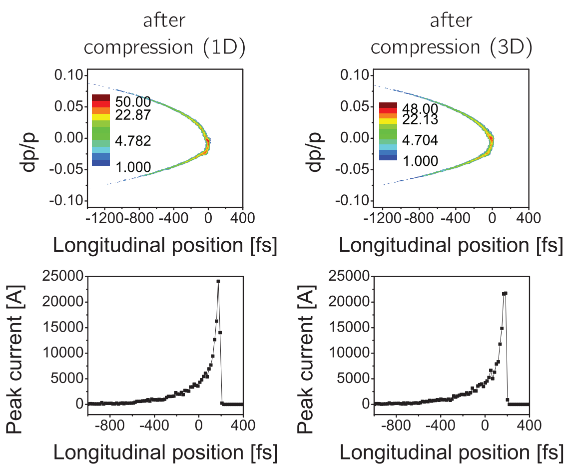

Figure 4: Longitudinal phase space distributions and bunch profiles for a bunch charge of 3 nC after compression. The bunch energy is increased from 40 MeV (Fig. 2) to hypothetical 300 MeV with the dipole field adjusted accordingly.

tions of CSRtrack give slightly different bunch profiles. Those differences converge at lower charge densities or larger beam energies. To understand more about the influence of CSR and space charge effects to the compressed bunch, further investigations are planned.

ACKNOWLEDGMENT

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REFERENCES

[1] M. J. Nasse et al., "FLUTE: A versatile linac-based THz source," Rev. Sci. Instrum. **84**, 022705 (2013).

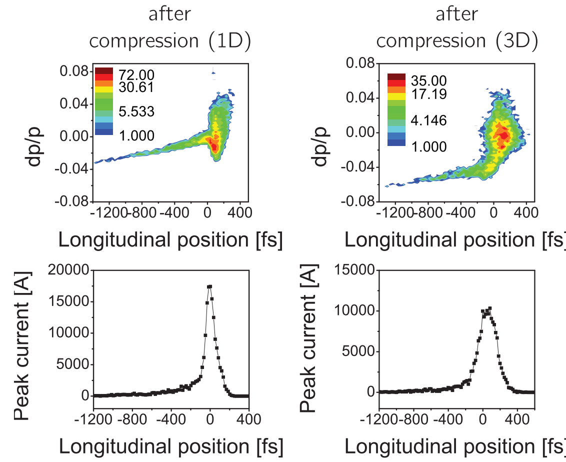

Figure 5: Longitudinal phase space distributions and bunch profiles for a bunch charge of 3 nC after compression. The transverse beam size is increased by a factor of 5 compared to Fig. 2. The difference between the 1D and 3D simulations is significantly smaller.

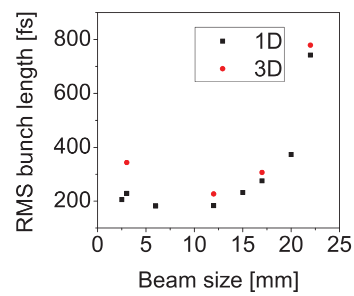

Figure 6: Compressed bunch length as a function of transverse beam size for a bunch charge of 3 nC and an energy of 40.8 MeV. For reasons of demonstration the space charge density was artificially decreased by expanding the transverse beam size far beyond the design values. Results for 1D and 3D options converge at lower charge densities, i.e. bigger beam sizes.

[2] R. Bossart et al., "A 3 GHz photoelectron gun for high beam intensity," Nucl. Instrum. Meth. A **375** (1996) ABS7.

[3] H. H. Braun, "Experimental results and technical results and development at CTF II," EPAC 2000, Vienna, Austria, June 2000, FRXE02, p. 48, `http://accelconf.web.cern.ch/AccelConf/e00/PAPERS/FRXE02.pdf`

[4] K. Floettmann, "ASTRA — A Space Charge Tracking Algorithm, Version 3.0" (2013), `http://www.desy.de/~mpyflo`

[5] M. Dohlus and T. Limberg, "CSRtrack" (2013), `http://www.desy.de/xfel-beam/csrtrack`

[6] S. Naknaimueang et al. "FLUTE, a compact accelerator-based source for coherent THz radiation," FEL 2012, Nara, Japan, August 2012.

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