FLUTE, A COMPACT ACCELERATOR-BASED SOURCE FOR COHERENT THZ RADIATION

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Abstract

In this paper beam dynamics simulations of the Linac-based THz source FLUTE (Ferninfrarot Linac- Und Test-Experiment) are presented. The optimization of various machine parameters such as laser spot size, laser pulse length, and lengths of the chicane magnets are discussed. Spectra of the generated coherent THz radiation, which depend on the compressed bunch length and charge, are shown.

INTRODUCTION

FLUTE is designed to be a test bench to answer various accelerator physics questions for future compact broadband accelerator-based THz sources. For example, effective bunch compression as well as THz generation schemes, such as coherent synchrotron, transition, and edge radiation (CSR, CTR, CER), will be implemented and compared, and corresponding diagnostic instrumentation will be studied. Furthermore, experiments using the strong THz pulses will be carried out.

The FLUTE design is a collaboration between PSI and KIT. The installation of FLUTE on the KIT campus is planned to start in 2013. The machine layout is shown in Fig. 1. The main components are a photo rf gun, a 50 MeV linac, a bunch compressor, and finally a beam dump. The pulse repetition rate is 10 Hz. FLUTE is designed to cover a large bunch charge range from 100 pC to 3 nC. The THz spectral range and intensity can be adjusted according to the experimental requirements by modifying both the electron bunch charge and length.

BEAM DYNAMICS SIMULATIONS

For the beam dynamics simulations we used both ASTRA [1] for calculating space charge effects for the entire machine, and CSRtrack [2] for calculating coherent synchrotron as well as space charge effects in the chicane.

Space Charge Effects in the Gun and Linac

We plan to use a Ti:Sa laser system together with a $2\frac{1}{2}$ cell photo-injector gun [3] to produce single electron bunches with an energy of 7 MeV. After this, the bunch is further accelerated by a 3 GHz linac with a maximum energy of 50 MeV.

The transverse beam size throughout the machine is determined by space charge effects in the gun. As shown in Fig. 2 for a bunch charge of 3 nC, the transverse electron beam size is minimal for a certain laser spot size. For smaller laser spot sizes the electron beam size is dominated by space charge effects, whereas for larger laser spots, the beam size is dominated by the laser spot size. The optimum laser spot size for various bunch charges and laser pulse lengths can be found in Table. 1.

Table 1: Optimum laser pulse and spot size for various bunch charges calculated with 3D CSRtrack for chicane magnet length of 30 cm. L_{rms} is RMS bunch length.

Charge	Laser spot	Laser pulse	L_{rms}
3 nC	2.25 mm	4 ps	287 fs
2 nC	1.5 mm	4 ps	235 fs
1 nC	1.5 mm	3 ps	199 fs
0.1 nC	0.5 mm	2 ps	70 fs

Fig. 3 shows the transverse beam size tracked through the machine for the 3 nC case with optimum laser spot size and pulse length (in this plot we have switched the chicane off to verify that the beam remains focused throughout the entire bunch compressor). The largest beam size occurs right after the gun due to the space charge effects and the relatively low energy at this point. The solenoid therefore has to be installed as close as possible to the gun to focus the beam through the linac. A quadrupole doublet after the linac is used to focus the beam through the bunch compressor. A solenoid is used in the first case because it focuses the beam symmetrically, while in the second case the quadrupole doublet allows the independent adjustment of the focusing in both transverse directions. This equips the machine with an additional knob for better beam tuning in and after the chicane.

Table 2: Compressed bunch vs chicane magnet lengths (L_b) for 3 nC calculated with CSRtrack (R_{56} is the momentum compaction, α is the bending angle of the chicane magnets and L_{rms} is RMS bunch length).

L_b	R_{56}	α	L_{rms} (1D)	3D
0.5 m	-36.1 mm	8.35°	184 fs	312 fs
0.3 m	-36.1 mm	9.08°	183 fs	287 fs
0.2 m	-36.1 mm	9.54°	183 fs	274 fs

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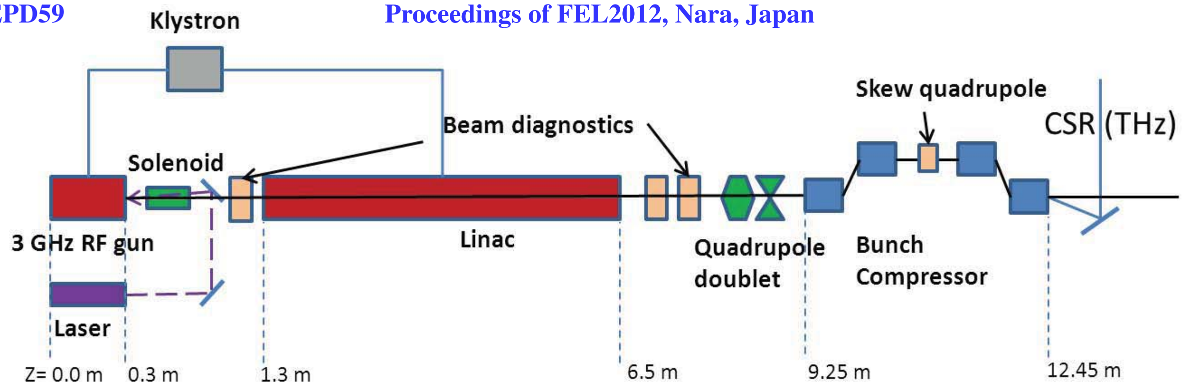

Figure 1: Schematic FLUTE layout (not to scale).

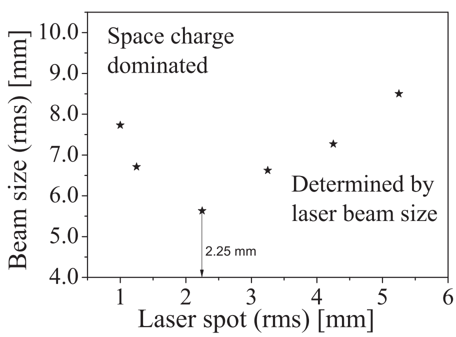

Figure 2: Optimized electron vs laser spot size at the exit of the solenoid after the gun as calculated with ASTRA 3D. For laser spot sizes smaller than 2.25 mm the beam size is increased by space charge effects, for larger spot sizes the beam size is dominated by the laser spot size (bunch charge 3 nC, laser pulse length 4 ps).

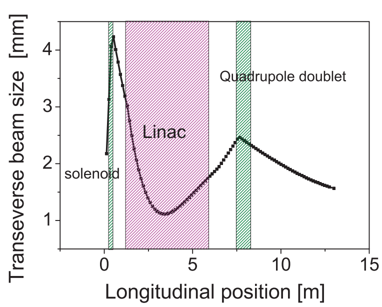

Figure 3: Transverse beam size tracked from cathode through the linac to the end of the chicane (calculated with ASTRA 3D). Chicane magnets are switched off here (bunch charge 3 nC, laser pulse length 4 ps).

Space Charge and Coherent Synchrotron Radiation Effects in the Chicane

For FLUTE, a four magnet chicane will be used in the first phase (see Fig. 1). Chicanes with different magnet lengths were investigated: 0.5, 0.3, and 0.2 m. The bunch length through the chicane was calculated first with the 3D space charge routine of ASTRA (see Fig. 4). For example, for a magnet length of 50 cm, we found an RMS bunch length after the compressor of 250 fs for a 3 nC bunch charge and a 4 ps long laser pulse.

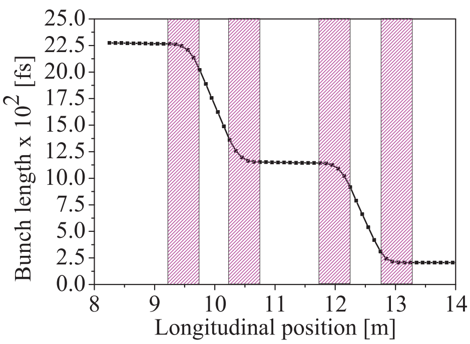

Figure 4: The development of the bunch length tracked through the compressor using ASTRA 3D routines. The shaded parts symbolize the position of the magnets (here 50 cm long).

However, in the chicane coherent radiation effects, which are not taken into account by ASTRA, have a considerable impact on the bunch length. Therefore, in order to study the influence of coherent radiation effects, we employed the 3D routines of CSRtrack (3D CSRtrack). For the same parameters as for the ASTRA calculations (Fig. 4) we obtain an RMS bunch length of 312 fs at the end of the chicane. Here the coherent radiation effects lead to a bunch lengthening of $\sim 25\%$ as compared to the results obtained with ASTRA.

The minimum obtainable compressed bunch length also depends crucially on the RF phase difference between the gun and the linac, as well as between the klystron and the gun laser pulse. The phase stability requirements are discussed in the following. Since 3D CSRtrack calculations are very time consuming, a faster 1D routine of CSRtrack

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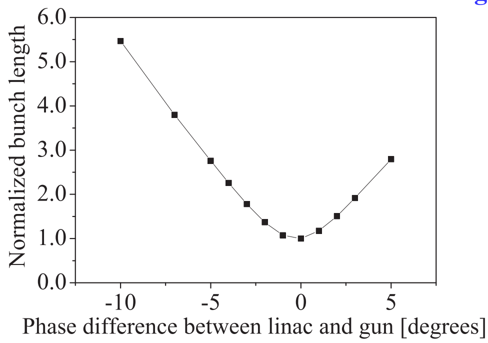

Figure 5: Compressed bunch length as a function of the phase difference between gun and linac cavities calculated with 1D CSRtrack (3 nC charge, 4 ps laser pulse length).

(1D CSRtrack) was used. This routine neglects transverse effects [2] and therefore leads in general to a shorter bunch length especially at a higher beam charge. For instance, for a bunch charge of 3 nC, we find a compressed bunch length of 312 fs with 3D CSRtrack, but only of 184 fs with 1D CSRtrack. Although these values are rather different, we used the 1D CSRtrack code to quickly assess relative performance changes in order to find the optimum. Then the more realistic 3D CSRtrack numbers were calculated around the previously found values.

Fig. 5 shows that the phase difference between the gun and the linac cavities has a relatively strong influence on the compressed bunch length. The simulations indicate that a phase stability around $\pm 1°$ is required. However, since both the gun and the linac cavities are powered by the same klystron, we expect that this condition can be met.

The influence of the phase difference between the RF wave and the laser pulse for the gun is shown in Fig. 6 (here we assume a stable gun–linac phase difference of 0). From this figure we can see that a stability tolerance of $\pm 2°$ has to reached, which is feasible using state-of-the-art components.

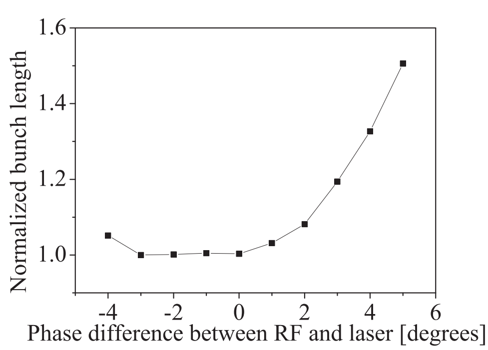

Figure 6: Bunch lengthg as a function of the phase difference between laser pulses and RF signal, calculated with 1D CSRtrack (3 nC, 4 ps laser pulse length).

Summarizing the previous results, Table 2 shows the effect of the chicane magnet lengths on the bunch length as calculated by CSRtrack 1D and 3D with optimized bending angles. From this table a chicane magnet length of 20 cm seems to be optimal, however, practical considerations like fringe fields, which are more relevant for shorter magnets, and field homogeneities lead us to consider the 30 cm magnets for the FLUTE design.

Table 1 summarizes the resulting RMS bunch lengths for various bunch charges together with the corresponding optimized laser pulse length and spot size. The shortest bunch length occurs for the smallest bunch charge, leading to a broader spectrum as laid out in the next section.

MEASUREMENT OF THE ENERGY-SPREAD

Following the proposal [4] a diagnostics section will be installed in the center of the chicane. It is proposed to measure the energy spread of the beam with a skew quadrupole in between chicane magnet 2 and 3 (see Fig. 1). The skew quadrupole introduces a horizontal-to-vertical coupling in the horizontally dispersive section. During a subsequent cancellation of the dispersion the vertical beam profile remains a fingerprint of the horizontal beam density at the position of the skew quadrupole. Since a dispersive section converts a longitudinal energy modulation into a density modulation, this fingerprint reveals the correlated energy distribution along a bunch. The consideration above applies to the horizontal beam profiles, which are dominated by dispersion at the skew quadrupole. This constraint is fulfilled by the FLUTE beam in the low and intermediate bunch charge ranges.

Simulations with the code ASTRA [1] showed, that the temporal bunch structure is clearly visible on a x-y screen in a distance of 1 m after the chicane, when a skew quadrupole with 10 cm length and a focusing strength of $K = 5\,\mathrm{m}^{-2}$ is chosen.

CSR PRODUCTION

The spectral intensity I emitted by a bunch of N particles is given by

$$\left.\frac{\mathrm{d}^2 I}{\mathrm{d}\omega \mathrm{d}\Omega}\right|_{\text{bunch}} = N\left[1 + (N-1)\,F(\omega)\right] \left.\frac{\mathrm{d}^2 I}{\mathrm{d}\omega \mathrm{d}\Omega}\right|_{\text{single}} . \tag{1}$$

This expression can be split into an incoherent part, which is N times the single particle spectrum $\mathrm{d}^2 I/\mathrm{d}\omega\mathrm{d}\Omega|_{\text{single}}$, and a coherent part, which is is proportional to N^2. The latter part can be enhanced by several orders of magnitude compared to the incoherent radiation, provided the form factor $F(\omega)$ is close to unity. Since $F(\omega)$ is related to the Fourier transform of the longitudinal charge distribution, it will drop for wavelengths smaller than the bunch length. To achieve coherent THz radiation, bunch lengths below 1 ps are required.

Figure. 7 shows an example for the longitudinal charge profile of the 3nC bunch at the exit of the fourth chicane

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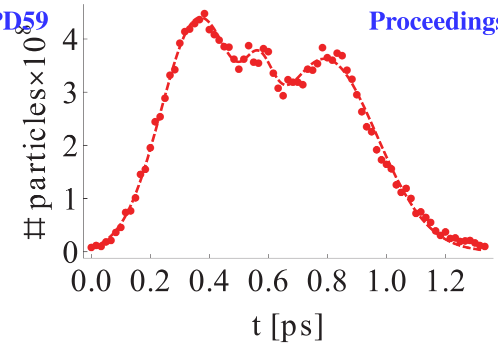

Figure 7: Longitudinal charge profile for a 3 nC bunch at the exit of the fourth chicane magnet. The dashed curve is a Gaussian fit of the data.

magnet obtained for the current simulations using a chicane magnet length of 30 cm. To calculate the form factor, we fit three Gaussians (dashed curve in Fig. 7) to the charge profile. A similar fit is applied to the 100 pC bunch.

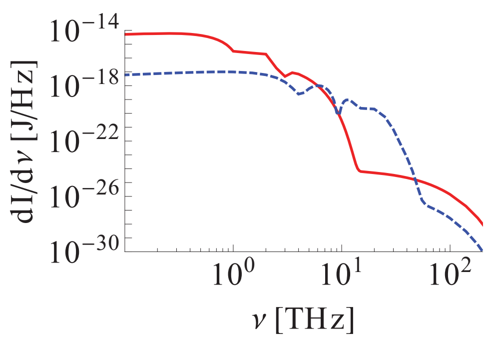

Figure 8: CSR spectrum for the 3 nC (continuous) and 100 pC (dashed) bunches.

Figure. 8 compares the CSR spectra for the two bunches. For frequencies below 1 THz the spectral intensity of the 3 nC bunch is a factor $N_{3\mathrm{nC}}^2/N_{100\mathrm{pC}}^2 = 900$ larger than for the 100 pC bunch, as expected from Eq. 1. At 1 THz, the coherent spectrum decreases for the 3 nC bunch due to the onset of the form factor suppression and drops below the incoherent one at 10 THz. The same happens qualitatively for the 100 pC bunch, but here at frequencies of 3 THz and 50 THz, respectively.

With the longitudinal bunch profile expressed as a sum of Gaussians, the electric field pulse can be calculated analytically [5]. Assuming a focusing onto a 1 mm radius disc, the electric field at a distance of 1 m is shown in Fig. 9. Notice that it can reach maximum values of up to 1 GV/m.

CONCLUSIONS

FLUTE is a coherent THz source in the design phase at KIT. It will generate electron bunches with a charge of up to 3 nC with a repetition rate of 10 Hz. The maximum beam energy will be 41 MeV. The bunch charge is mainly limited by space charge effects in the gun and coherent synchrotron radiation effects in the compressor. After the linac, the 3 nC bunch is compressed to about 310 fs. With lower bunch charges, the bunch can be compressed to less than 100 fs.

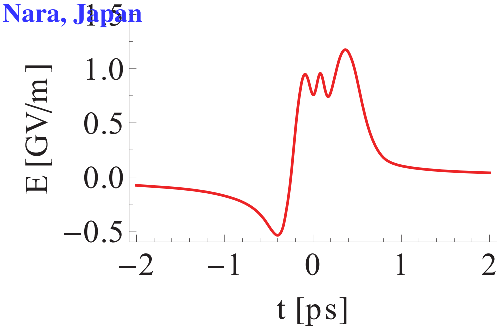

Figure 9: The focused electric field pulse calculated from the 3 nC bunch charge.

As a result, the frequency range of the coherent THz radiation is increased. Changing the laser pulse length allows one to adjust the generated radiation to the requirements of future experiments.

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