DESIGN STUDIES FOR FLUTE, A LINAC-BASED SOURCE OF TERAHERTZ RADIATION

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Abstract

FLUTE is a linac-based THz source with a nominal beam energy of 40-50 MeV, which is presently under construction at KIT and in collaboration with PSI and DESY. FLUTE will be operated in a wide bunch charge range of 1 pC-3 nC. The source will allow studies of different mechanisms of THz radiation generation and will serve as a test facility for related accelerator technology. In this paper the basic layout design of FLUTE is discussed.

INTRODUCTION

Terahertz radiation has recently become an important tool in a variety of applications. The production of high-intensity THz radiation with accelerators is based on the compression of electron bunches to lengths of below one picosecond either in storage rings or in linear accelerators. In linear accelerators two compression schemes are known: compression either by velocity bunching (if the energy of the particles is nonrelativistic) or in a chicane (for relativistic particles). In both cases the particle energy must vary as a function of longitudinal position (chirp). In storage rings a so-called low-alpha optics allows the production of short bunches [1]. The reduction of the bunch length is limited by instabilities of the beam [2].

Recently, a new technique to generate coherent THz radiation based on beams produced by laser wake field accelerators was investigated [3]. The advantage of the THz radiation generated by laser wake field accelerators is that the originally produced electron bunch already has a length of only a few femtoseconds. Therefore bunch compression is not necessary. Nevertheless, reproducibility and stability are still a problem with this technique. An overview of laser-based THz sources can be found in [4].

FLUTE will become a linac-based THz source where various techniques of compressing and measuring short bunches can be tested and optimized. With the basic design of FLUTE (final particle energy of 40 to 50 MeV) bunch lengths between 10 fs to 300 fs with a bunch charge ranging from 1 pC to 3 nC can be obtained. After compression, THz radiation can be produced either by coherent synchrotron radiation, - edge radiation or - transition radiation (CSR, CER, CTR).

BASELINE MACHINE DESIGN

The baseline layout of FLUTE [5–7] is shown in Fig. 1. A 3 GHz laser-driven RF gun produces a bunch with a charge from 1 pC to 3 nC and a bunch length of several picoseconds. Such a bunch is then accelerated to 40-50 MeV and compressed subsequently by a magnetic bunch compressor consisting of four dipole magnets (D-shape chicane).

The beam simulation programs ASTRA [8] and CSRtrack [9] are used to minimize the bunch length for the different bunch charges. Since the beam energy of FLUTE is relatively low, CSR effects determine the length of the compressed bunch. In the gun and linac the particle beam is simulated with ASTRA, whereas in the chicane the 1D and 3D routines of CSRtrack are used to simulate the CSR backreaction on the bunch. The 3D option gives a more reliable result for the RMS compressed bunch length (L_{rms}) for our beam energy (≈ 40 MeV).

Table 1: RMS Compressed Bunch Length for Various Bunch Charges

Charge [nC]	Laser pulse length [ps]	Laser spot size [mm]	$-R_{56}$ [mm]	L_{rms} [fs]
3	4	2.25	36.1	270
2	4	1.50	32.5	224
1	3	1.50	34.2	146
0.1	2	0.50	29.5	67
0.001	1	0.50	28.8	13

The simulations showed that the length of the chicane magnets has little influence on the compression factor. From a technical point of view dipole magnets with a length of 20 cm were chosen. The space between the first two and the last two magnets is 30 cm, respectively. The RMS compressed bunch lengths for various bunch charges are shown in Table 1.

The bunch profiles for a 3 nC bunch after the bunch compressor obtained with 1D and 3D simulations are shown in Fig. 2. For a lower bunch charge (1 pC), the differences between 1D and 3D calculations are presented in Fig. 3. For lower bunch charges CSR effects are significantly smaller and results in fewer differences between the 1D and 3D calculations.

On one hand, the longer the compressed bunch length is,

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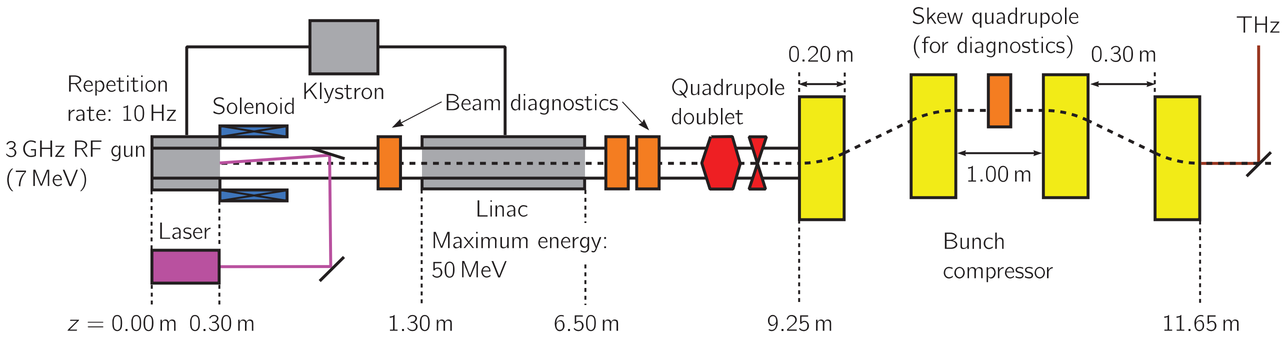

Figure 1: Baseline machine layout.

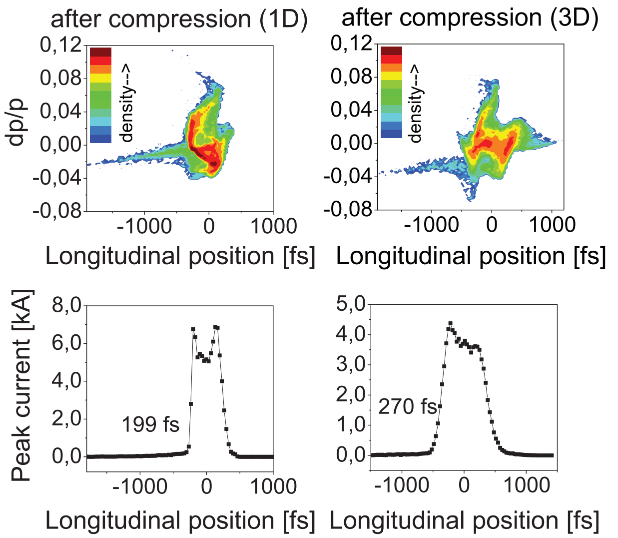

Figure 2: Longitudinal phase space distributions and bunch profiles for a bunch charge of 3 nC. The calculations clearly indicate that in the CSRtrack simulations the central part of the bunch differs 199 fs (1D) vs 270 fs (3D). The lower two curves present the corresponding longitudinal bunch profiles. The beam energy is 40 MeV and the laser pulse length is 4 ps.

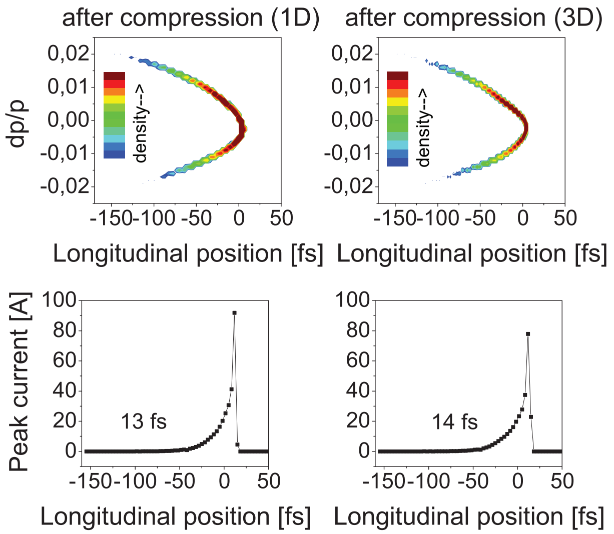

Figure 3: Longitudinal phase space distributions and bunch profiles for a bunch charge of 1 pC after compression simulated using the 1D (13 fs)and 3D (14 fs) CSRtrack routines. The achieved bunch lengths are more similar to each other than in case of the 3 nC bunch. The beam energy is 40 MeV and the laser pulse length is 2 ps.

the smaller is the spectral range of the THz radiation. On the other hand, the intensity of the radiation increases with the bunch charge. However, there is a trade-off between bunch charge and bunch length as higher charges lead to necessarily longer bunches due to space charge effects. The required bunch length can be selected for a given experiment. The THz radiation spectra for 3 nC and 100 pC are shown in Fig 4. The calculation of the spectra can be found in [10].

The calculated spectra for CSR, CER and CTR are shown in Fig. 5 for bunch charges of 0.1 nC and 3 nC.

CSR delivers higher intensities than CER and CTR. The spectral range is similar for the three sources. Only for CTR the intensities at lower frequencies are significantly weaker due to the finite screen size. At a distance of 1 m the spot size of the unfocused beam is about 12 mm if it is assumed that the beam radiates into an angle of $1/\gamma$ (with the Lorentz factor γ). The peak electric field for a 0.1 nC bunch is 2 MV/m and for a 3 nC bunch it is 8 MV/m. Focusing these beams to 1 mm would yield electric fields of 288 MV/m and 1152 MV/m, respectively.

Reduction of CSR Effects at Higher Beam Energies

For a hypothetical energy of 300 MeV calculations with 1D and 3D routines lead to the results shown in Fig. 6. In this case both routines produce the same final bunch profile indicating that the backreaction of CSR is suppressed at higher energies. At a first glance this result seems to be puzzling since the total synchrotron radiation power grows with the fourth power of the Lorentz factor γ. However one has to bear in mind that the CSR spectrum is highly suppressed for frequencies $\omega \gg \omega_b$ [11], where $\omega_b = c/L_{\mathrm{rms}}$

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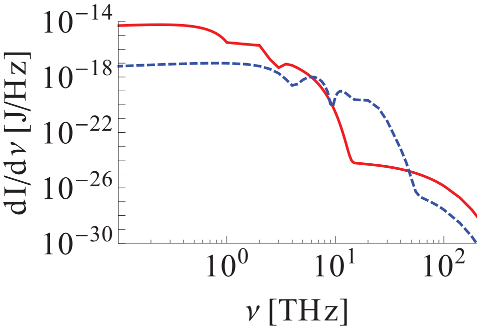

Figure 4: THz sprectrum for a 3 nC (red-solid) and a 100 pC (blue-dashed) bunch. The coherent frequency range for 3 nC is smaller than the range for 100 pC. However, at lower frequencies for 3 nC the intensity of coherent radiation in the THz regime is a factor 900 higher than for 100 pC.

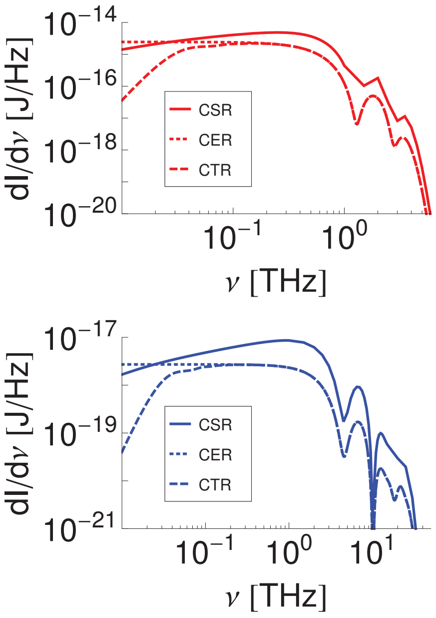

Figure 5: Calculated spectra of CSR, CER, and CTR for a 3 nC (upper) and 0.1 nC (lower) bunch [10].

is the bunch frequency and c the speed of light. Assuming $\omega_b \ll \omega_c$, where ω_c is the critical frequency of synchrotron radiation, it can be proven that the CSR radiation power is, indeed, independent of γ. At FLUTE, this condition is satisfied for charges above 100 pC. Since the momenta of the bunch particles grow with γ the bunch is more stable at higher energies. As a result, CSR backreaction effects then play a minor role. For smaller charges, and shorter bunches, $\omega_b \gg \omega_c$. However, the peak current in this case is about a factor 60 smaller (compare Fig. 2 and 3), leading to a decrease in CSR intensity by a factor of about 10^4.

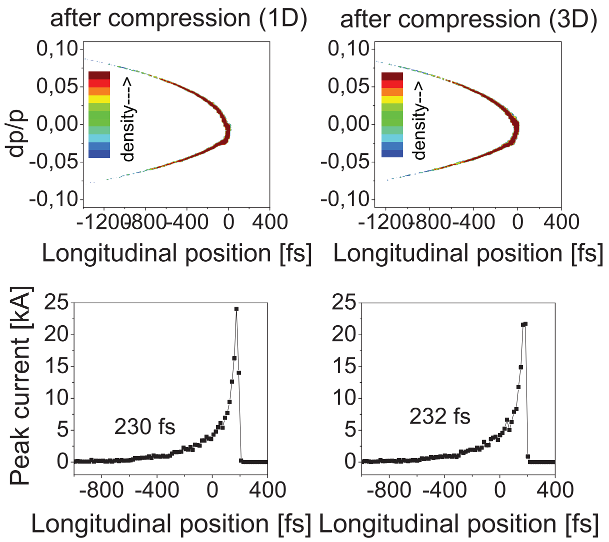

Figure 6: Longitudinal phase space distributions and bunch profiles for a bunch charge of 3 nC after compression using 1D (230 fs) and 3D (232 fs) CSRtrack routines. The hypothetical beam energy is 300 MeV. The laser spot size at the cathode and the laser pulse length are the same as in Fig. 2.

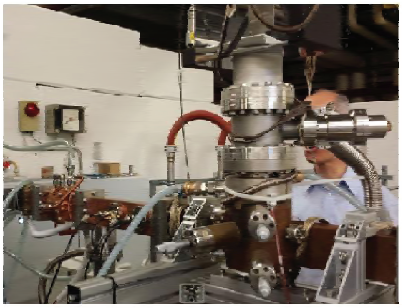

Figure 7: Gun power RF test. For the test the gun is mounted vertically. Each of the 2 1/2 cells can be tuned individually by the three tuners shown in the picture.

GUN TEST

Apart from simulation we have started to perform RF power tests with the FLUTE RF gun. The 3 GHz RF gun with 2 1/2 cells was originally developed by CERN for the CLIC test facility [12]. After bead-pull tests, the RF tests were conducted using an RF setup from Max IV, Sweden installed at ELSA, University of Bonn, Germany (Fig. 7).

As shown in Fig. 8 the RF signal in each of the cells has been measured individually using three pickups. For these measurements RF pulses of up to 2.3 MW and pulse durations of up to 1.2 µs were coupled into the gun cavities.

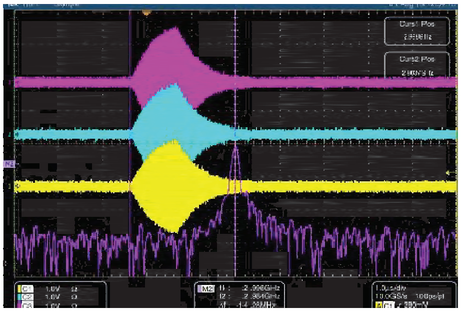

Figure 8: Gun high-power RF test. The graph shows the RF voltage oscillations in each of the 2 1/2 cells as a response to a 2.3 MW 3 GHz pulse.

CONCLUSION

In this paper the baseline design of FLUTE was introduced. The design consists of a gun, an accelerating structure, and a D-shape chicane bunch compressor. The simulation results shown that we can compress electron bunch up to 300 fs. We also presented beam dynamics simulations showing the influence of CSR on bunch compression. CSR effects are dramatically reduced by increasing the beam energy (hypothetical beam energy is 300 MeV). FLUTE will be installed in one of the bunkers of the former KIT cyclotron. At the University of Bonn the gun has recently been tested. An existing RF modulator unit will be modified and the complete RF and laser system should be operable by the middle of next year.

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