RF BUNCH COMPRESSION STUDIES FOR FLUTE

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Abstract

FLUTE is a planned 40 to 50 MeV accelerator test facility consisting, in the first phase, of an electron gun with an output energy of about 7 MeV, a traveling wave linac and a magnet chicane bunch compressor. The machine will serve as a source of intense THz radiation using coherent synchrotron radiation (CSR), coherent transition radiation (CTR), and coherent edge radiation (CER) as generation mechanisms. It is planned to operate the machine in the charge regime from a few pC up to several nC in order to study bunch compression schemes as well as the THz radiation generation. In this contribution the effect of velocity bunching by using a dedicated buncher cavity at low energy and operating the linac off-crest is studied in order to deliver RMS bunch lengths in the femtosecond range at low charge.

INTRODUCTION

The "Ferninfrarot Linac und Test Experiment" (FLUTE) is an accelerator R&D facility currently under construction at KIT. Its purpose is to produce short bunches for the generation of coherent THz emission which is discussed in detail in [1, 2]. Beam dynamics studies for the high charge regime are presented in a separate contribution in this conference proceedings [3].

Short bunches are generally produced using a magnetic bunch compression chicane, for example four dipole magnets with a D-shape beam passage. In order to compress the beam an electron bunch with a linear energy chirp is required. Then the path length difference of particles with different energy is utilized to reduce the bunch length inside the bunch compressor. Looking at the transfer matrix of the complete chicane the element R_{56} describes the compression process and is derived as

$$R_{56} = -2\left(\frac{L_\mathrm{b}}{R_0}\right)^2\left(\frac{2}{3}L_\mathrm{b} + L_\mathrm{d}\right) \qquad (1)$$

where L_b is the effective length of the dipole bending magnet, L_d the drift length between the first and second as well as third and the forth dipole bending magnet, and R_0 the bending radius of reference particle with the momentum p_0. Using equation (1) the longitudinal position s_a of a particle after the chicane with respect to the reference particle can be computed as

$$s_\mathrm{a} = s_\mathrm{b} - R_{56}\frac{\Delta p}{p_0}, \qquad (2)$$

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where s_b is the longitudinal position in the bunch before the chicane and $\Delta p/p_0$ the relative momentum deviation. For a given particle distribution with an RMS bunch length σ_z and an RMS momentum spread p_RMS that is dominated by the correlated energy spread the optimum compression in terms of R_{56} can be computed as

$$R_{56,\mathrm{opt}} = \frac{\sigma_z}{\left|\frac{p_\mathrm{RMS}-\bar{p}}{\bar{p}}\right|}, \qquad (3)$$

where $\bar{p}$ is the mean of the momentum distribution. Formula (3) will be used in the following to estimate the potential of a magnetic bunch compressor neglecting effects such as space charge and CSR.

At moderate energy bunch compression can also be obtained by using a cavity operated $-90°$ off-crest, a so called buncher cavity, and drift space afterwards. In the buncher cavity the head particles are decelerated and the tail particles accelerated. Due to velocity differences of the head and tail particles the bunch length decreases in the following drift space until a minimum is reached and increases again afterwards. By placing the next accelerating structure at the position of the minimum bunch length the short bunch length can be conserved.

In the following two different scenarios, referred to as Buncher I and Buncher II, including a buncher cavity between gun and linac are evaluated and compared to the FLUTE baseline design [1, 2] as illustrated in Fig. 1.

SIMULATION SCENARIOS

The buncher cavity is a four cell standing structure, as it is operated at REGAE [4]. It is placed at 1.3 m - the linac position in the baseline design. In scenario Buncher I the linac and all subsequent components are shifted 2 m downstream. In scenario Buncher II the linac is placed at 7.3 m where the bunches are shortest after the buncher cavity. A further compression after the linac using a magnetic chicane is not possible in this scenario because the required energy chirp is not present anymore. The bunch length evolution of the different scenarios along the machine with deactivated chicane is simulated with ASTRA [5] and shown in Fig. 2.

All beam dynamics simulations from the cathode to the end of the linac are carried out with ASTRA using 5000 macro particles and the rotation symmetric space charge routine. For simplicity only the solenoid after the gun is used for focusing and no further focusing elements after the linac. With this the transverse beam size is kept below 1.5 mm along the machine for all simulations and results

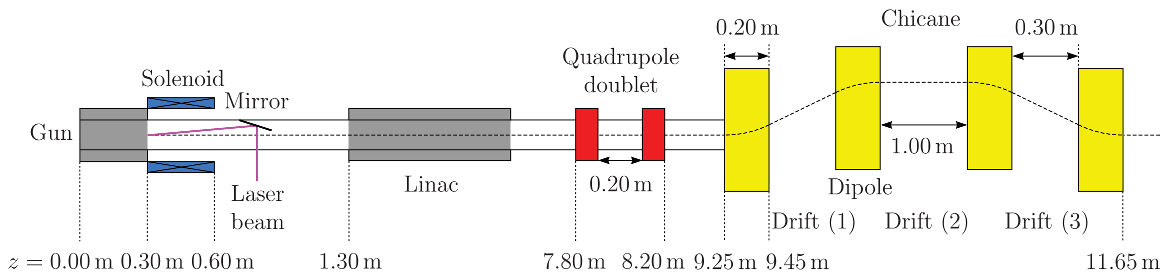

Figure 1: FLUTE baseline layout. In the Buncher scenarios the buncher cavity is placed at 1.3 m and all components are shifted downstream by 2 m or 5 m respectively.

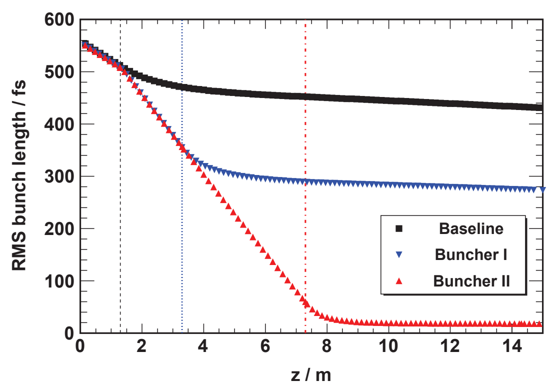

Figure 2: RMS bunch length evolution along the machine with deactivated magnetic bunch compressor simulated with ASTRA for the baseline design and the two buncher options. The vertical lines indicate the linac entrance in the different scenarios.

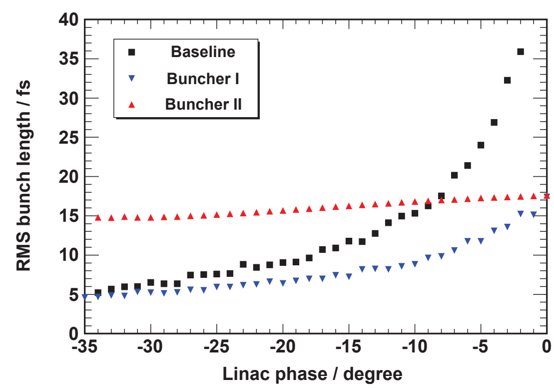

Figure 3: Compressed RMS bunch length vs. the linac phase using a peak E-field of 10 MV/m. Far off-crest there is no difference between the baseline and Buncher I. Buncher II shows higher values for all phases.

Table 1: ASTRA Simulation Input Parameters

Parameter	Unit	Value
Bunch charge	pC	1
Laser spot size (rms radius)	mm	0.5
Laser pulse length (rms)	ps	1
Gun peak field	MV/m	120
Gun phase ϕ_{gun}	degree	-22
Solenoid B-field	T	0.18 - 0.19
Buncher position	m	1.3
Buncher peak field	MV/m	25
Buncher phase ϕ_{buncher}	degree	-90
Linac position	m	1.3 / 3.3 / 7.3†
Linac accelerating peak field	MV/m	10
Linac phase ϕ_{acc}	degree	-31

†Baseline / Buncher I / Buncher II

in a transverse emittance after the linac of about 0.2 πmm mrad without optimizing it. All ASTRA simulation input parameters are summarized in Table 1. For the scenario baseline and Buncher I the bunch compression in the magnetic chicane is computed analytically using equations (3) and (1) for a fast evaluation and optimization. Additional 1D CSRtrack [6] simulations are carried out where space charge and CSR effects are taken into account.

SIMULATION RESULTS

Figure 3 shows the compressed RMS bunch length as function of the ϕ_{acc}. The RMS bunch length decreases with increasing $|\phi_{\text{acc}}|$ for all scenarios. On-crest the scenario Buncher I and Buncher II give the shortest RMS bunch length. Far off-crest the results of baseline and Buncher I merge and the smallest RMS bunch length is about 5 fs for both cases. Scenario Buncher II shows larger values for all off-crest phases. The bunch compression factor in the chicane increases from 8 to 85 for the baseline and from 18 to 60 for Buncher I. After the linac the bunches are about a factor 1.6 shorter in the scenario Buncher I compared to the baseline.

The output energy drops from 47 MeV to 40 MeV. Going further off-crest would reduce the beam energy significantly. This should be avoided to ensure sufficient overlap of the bunch spectrum with the synchrotron spectrum. Hence, the accelerating peak field is increased from 10 MV/m to 15 MV/m and the result is shown in Fig. 4. There the RMS bunch length after the linac for the baseline layout decreases with the phase from 490 fs to 390 fs. In scenario Buncher I the bunches are about a factor 1.5 shorter after the linac. The RMS bunch length is reduced in the chicane up to a factor of 120 in the baseline and 90 in Buncher I. At $\phi_{\text{acc}} = -58°$ the output energy drops below 40 MeV and the RMS bunch length is about 3 fs after the

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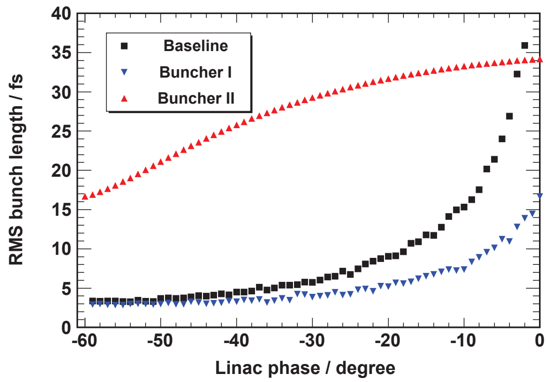

Figure 4: Compressed RMS bunch length vs. the linac phase using a peak E-field of 15 MV/m. Far off-crest there is no difference between the baseline and Buncher I.

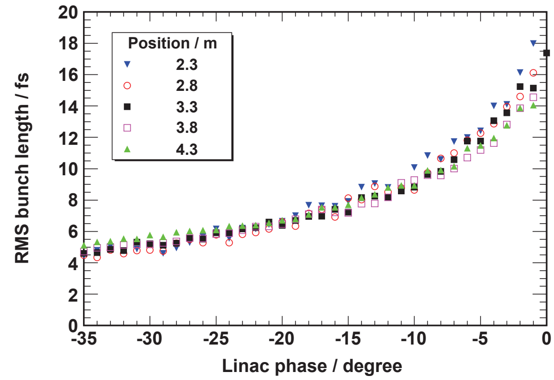

Figure 5: Compressed RMS bunch length vs. the linac phase for different linac positions.

Table 2: CSRtrack Simulation Results

Input parameter	Unit	Baseline	Buncher I
Ref. momentum p_0	MeV/c	40.3	40.0
RMS $\Delta p/p$	%	0.90	0.73
RMS bunch length	fs	345.54	239.97
Bending radius R_0	m	1.805	1.960
Output			
RMS bunch length	fs	11.89	6.36

chicane for the baseline and the Buncher I. These two cases are simulated with CSRtrack and summarized in Table 2. When taking non-linear beam dynamics, space charge and CSR effects into account, the simulated RMS bunch length increases significantly compared to the simple calculation using R_{56}. The effect is larger for the baseline where a higher compression in the chicane is needed.

The influence of the drift space between buncher cavity and linac in scenario Buncher I is evaluated as well. The linac position is scanned from 2.3 m to 4.3 m in steps of 0.5 m and the resulting compressed RMS bunch length as function of the linac phase is illustrated in Fig. 5. The RMS bunch length after the linac decreases from 350 fs to 200 fs when increasing the drift space. This difference is compensated by the chicane using a different setting for the dipole bending radius R_0.

DISCUSSION AND OUTLOOK

The simulations show the possibility of generating pC electron bunches with an RMS bunch length below 10 fs at 40 MeV. In scenario Buncher II the bunches are longer and more space than in the other scenarios is required which is an crucial issue. Because of space limitations the overall machine length has to be below 20 m. Furthermore only CTR can be used if no additional bending magnet as radiator is installed which requires additional space and influences the RMS bunch length. Comparing the two Buncher scenarios there is a clear preference for using both a buncher cavity together with a magnetic chicane over using a buncher cavity only.

The results obtained simulating the magnetic bunch compressor with a simple transfer matrix method two regimes can be identified. Operating the linac on-crest leads to a higher output energy and the buncher cavity can reduce the RMS bunch length by more than a factor of two. In the other regime the linac is operated far off-crest and acts as a long buncher cavity. There the resulting RMS bunch length is about the same but the results from CSRtrack differ by almost a factor two. This leads to the conclusion that detailed studies of the bunch compression chicane including non linear effects are required for the final optimization. The next steps will be to include CSRtrack simulations directly in the optimization process or improve the used analytic approach.

An issue which has not be addressed here is the stability and reproducibility of femto-second electron bunches. Start to end simulations including alignment errors as well as dynamic errors of different components such as for example RF, laser, power supplies, or synchronization have been started with the goal to identify critical parameters. For scenario Buncher II alignment and dynamic errors are studied with ASTRA. First results show an increase of the average RMS bunch length to 21 ± 7 fs.

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