OPTIMIZATION OF BEAM OPTICS PARAMETERS OF THE LINAC-BASED TERAHERTZ SOURCE FLUTE

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Abstract

FLUTE is a compact accelerator-based THz source in the final design phase at the Karlsruhe Institute of Technology (KIT) in cooperation with Paul Scherrer Institute (PSI), Switzerland. The design is based on a 7 MeV photo-injector gun, S-band linac with a maximum energy of 50 MeV and a bunch compressor. In this paper simulations of the beam dynamics in FLUTE for various bunch charges and laser parameters are presented. The results for bunch charges of up to 3 nC are compared to bunch charge as low as 1 pC in order to analyze the effect of space charge forces and coherent synchrotron radiation (CSR). Those effects were simulated with ASTRA [1] and CSRtrack [2].

THE LAYOUT OF FLUTE

For the simulations the following preliminary layout of FLUTE is shown in Fig. 1 [3]. The $2\frac{1}{2}$ cell rf gun [4] produces a pulsed beam with an energy of 7 MeV.

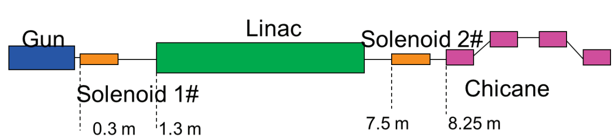

Figure 1: layout of FLUTE

We plan to use a Ti:Sapphire laser which allows to change both laser pulse length and laser intensity. The output pulse length can be varied between 1 and 4 ps. In the commissioning phase a Cu cathode will be used. Gun and linac will be operated together at 2.9985 MHz by one 45 MW klystron. The rf power is split between gun and linac in such a way that phase and power can be adjusted individually in the two power lines. The rf pulse length is 3 μs.

OPTIMIZATION OF BEAM PARAMETERS

The simulations for the chicane were performed using the codes ASTRA and CSRtrack, as well as a simple transfer matrix method. ASTRA was used for tracking the beam in the gun and the linac. The chicane was pre-optimized using the transfer matrix method. The beam dynamics in the compressor was simulated under consideration of CSR effects with the code CSRtrack and with ASTRA.

Space Charge Effects in the Gun

The electron transverse beam size at the exit of the first solenoid depends on the laser spot size and is strongly influenced by the space charge effects in the gun. Fig. 2 shows the optimized beam size for a bunch charge of 3 nC and a laser pulse length of 4 ps. In order to minimize the electron beam size the laser transverse dimension should be about 2.25 mm (rms) for 3 nC.

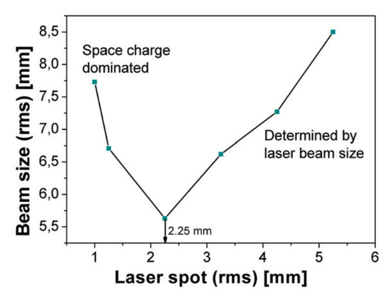

Figure 2: Optimized electron spot size vs laser spot size at the exit of the first solenoid after the gun. Below the laser spot size of 2.25 mm the beam size is increased by space charge effects (bunch charge 3 nC, laser pulse length 4 ps).

Fig. 3 shows the rms electron transverse beam size in the entire machine for a laser spot size of 2.25 mm when the magnets in the chicane are switched off. For keeping the rf-nonlinearities low the beam is kept small under given bunch charge and layout constrains. The beam has a focus in the linac and is made parallel after the structure using a solenoid (Fig. 1 and 3) or a quadrupole doublet or triplet.

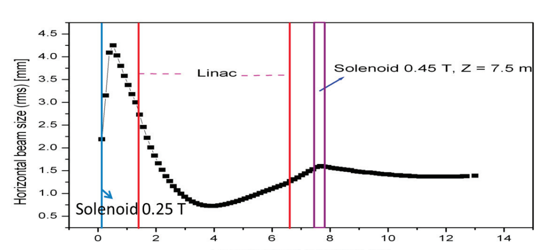

Figure 3: rms electron transverse beam size in FLUTE calculated with ASTRA between gun and chicane: bunch charge is 3 nC, laser pulse length 4 ps. Chicane magnets are set to zero current.

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Laser Parameters for Different Bunch Charges

For different bunch charges the following parameters have to be optimized:

- laser spot size at the cathode
- laser pulse length
- rf initial phase at gun and linac
- strength of the solenoids

After optimizing these parameters the smallest achievable beam size for different beam charges is listed in Table 1.

Table 1: Optimum laser parameters (smallest transverse beam size and shortest bunch length after the gun)

Charge	Laser spot (rms)	laser pulse length (rms)
3 nC	2.25 mm	4 ps
1 nC	1.5 mm	3 ps
100 pC	0.5 mm	2 ps
1 pC	0.05 mm	1 ps

Fig. 4 demonstrates as an example the effect of space charge forces in the gun and linac. For a bunch charge of 1 pC the laser pulse length is varied between 1 and 4 ps. The strength of the solenoids are identical as in Fig. 3.

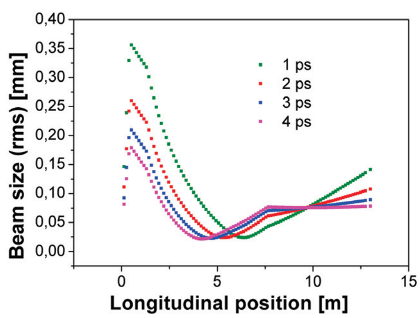

Figure 4: The rms transverse beam size for different laser pulse lengths. The bunch charge is 1 pC. Chicane magnets are switched off. The laser spot size at the cathode (0.05 mm rms) and solenoid (0.45 T) parameters are identical for all curves.

CALCULATION OF BUNCH LENGTH AFTER COMPRESSION

Transfer Matrix Method

The path length difference between the length of the dispersive trajectory in the chicane compared with the length of an undeflected beam is given by [5]:

$$\Delta S = 2[\frac{2L_B\theta}{\sin\theta} + \frac{L_D}{\cos\theta} - 2L_B - L_D] \qquad (1)$$

where L_B is effective magnet length (0.5 m), θ is the bending angle in each magnet and L_D is drift between bending magnet 1 and 2 as well as 3 and 4. The distance between the second and the third magnet is 1 m. The transfer matrix element R_{56} of a chicane shown in Fig. 1 is given by

$$R_{56} = [\frac{4L_B(\theta - \tan\theta)}{\sin\theta} - \frac{2L_D\tan^2\theta}{\cos\theta}] \qquad (2)$$

and is independent on the distance between the second and the third magnet.

Fig. 5 shows the bunch chirp and longitudinal bunch profile using Eq. 2. This equation does not take space charge forces and CSR effects in the chicane into account.

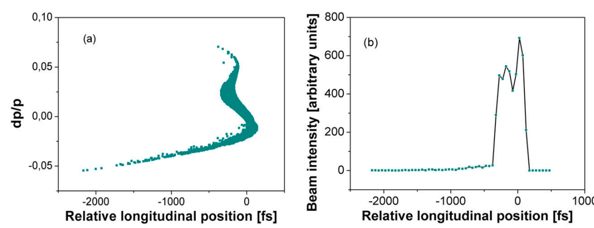

Figure 5: Compression of a 3 nC bunch calculated by a transfer matrix method (R_{56}= -40 mm, bending radius is 3.4 m) (a) phase-space plot (b) bunch shape, the final rms longitudinal bunch length is 213 fs.

Simulations with ASTRA

Simulations with the ASTRA code (Fig. 6 and Fig. 7) show that including the space charge forces in the chicane changes the bunch shape slightly. This results in a bunch elongation from 213 fs to 250 fs (compare with Fig. 5).

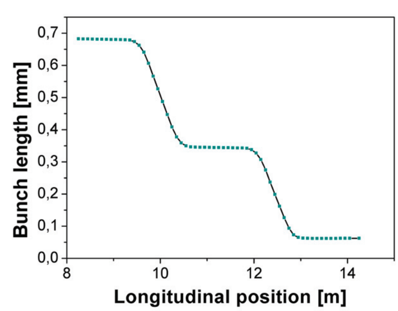

Figure 6: The development of the longitudinal bunch length in the bunch compressor tracked using a 3D space charge routine of ASTRA.

Simulations with the Code CSRtrack

The development of the beam in the gun and the linac is simulated with the code ASTRA up to the entrance of the first magnet of the compressor. A conversion program was developed which translates the ASTRA output file into a CSRtrack input file. The beam is tracked through the compressor by taking into account not only space charge

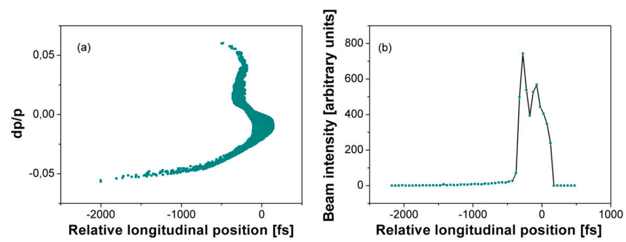

Figure 7: Simulations with ASTRA including the effect of space charge in the compressor: The phase space plot in (a) is similar to Fig. 5(a) and (b). The final rms longitudinal bunch length is 250 fs.

effects but also the action of the emitted CSR on the beam (see Fig 8).

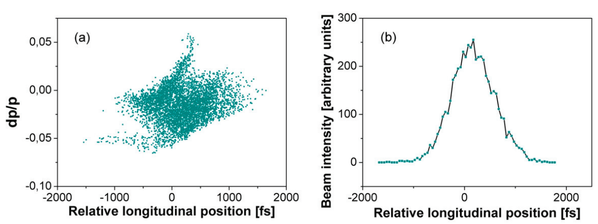

Figure 8: Influence of coherent synchrotron radiation and space charge effects on the final bunch shape. (a) phase space plot and (b) bunch shape, the final rms longitudinal bunch length is 419 fs

The bunch charge is 3 nC, the laser pulse length is 4 ps. CSRtrack predicts that the rms bunch length is 419 fs about a factor of two larger compared to Fig. 5 and Fig. 7. This discrepancy might be due to the influence of CSR effect. Reducing the value of the bunch charge to 100 pC (laser pulse 4 ps, the laser spot size on the cathode optimized) reduces the longitudinal quantity to about 163 fs (rms) for the transfer matrix method, 172 fs for the ASTRA simulation and 173 fs for the CSRtrack code. The simulations show that CSR effects might dominate the value of the longitudinal bunch length at high bunch charges.

INFLUENCE OF THE LASER PULSE LENGTH ON THE COMPRESSED ELECTRON BUNCH

The bunch compression was calculated in the previous sections for a laser pulse length of 4 ps. Reducing the laser pulse length can reduce the final electron bunch length at lower currents as shown in Table 2 and Table 3 (calculated with CSRtrack code). Table 2 shows the length of the compressed electron pulse for 100 pC as a function of the laser pulse length. A reasonable compression down to 51 fs can be achieved. Table 3 shows the minimum bunch lengths for various bunch charges. In a lower charge regime a substantially smaller beam at the cathode can be used which results in a much better compression.

Table 2: Compressed bunch length as a function of bunch charge 100 pC for various laser pulse lengths

Laser pulse length (rms)	bending radius	bunch length (rms)
1 ps	3.5 m	54 fs
2 ps	3.8 m	51 fs
3 ps	3.8 m	106 fs
4 ps	3.9 m	169 fs

Table 3: Compressed bunch length as a function of bunch charge for various laser pulse lengths

charge	laser pulse (rms)	bunch length (rms)
3 nC	4 ps	419 fs
1 nC	3 ps	143 fs
0.1 nC	2 ps	51 fs
0.001 nC	1 ps	15 fs

SUMMARY

The beam parameters such as the final longitudinal bunch length and transverse beam size are mainly limited by the space charge effects in the rf-gun and CSR effects in the bunch compressor. At the end of the chicane at 41 MeV a bunch length of 419 fs (rms) can be achieved at 3 nC bunch charge whereas operating at 100 pC results in a compression down to 51 fs (rms). A complementary paper [6] shows simulations of the expected THz-radiation spectra for the various operational modes.

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