FLUTE, A LINAC BASED THz SOURCE

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Abstract

We propose a versatile THz source named FLUTE (Ferninfrarot Linac- Und Test-Experiment) based on a 30 - 50 MeV S-band linac with bunch compressor, that aims at not only producing high field THz pulses but also at serving as a test facility to study accelerator physics issues. This source is an important step towards the planned ultra-broadband THz to mid infrared user facility TBONE. Special emphasis is put on studies of bunch compression as a function of bunch charge (0.1-5 nC) and of different generation mechanisms of coherent radiation (CSR, CER, CTR). This paper describes the design and layout of the proposed FLUTE machine and presents results of beam dynamic calculations with the tracking programs ASTRA and CSRtrack. In addition, calculations for the achievable peak electrical field and spectral characteristics for one version of the FLUTE layout are shown.

THE CONCEPT OF FLUTE

KIT (Karlsruhe Institute of Technology) has a long tradition in generating [1] and using [2] coherent IR and THz radiation. The coherent radiation is produced with the storage ring ANKA operating in the so-called low alpha mode: sub-picosecond electron bunches are produced by reducing the momentum compaction factor α of the stored beam. The sub-picosecond long bunches emit coherent synchrotron radiation.

Recently, PSI and KIT discussed the possibility to build a compact linac-based coherent THz source named FLUTE. Built at KIT, it could eventually be used later for pump-probe experiments at the SwissFEL [3] while KIT develops TBONE [4], a THz source based on a superconducting linac.

The general parameter list for FLUTE is

max. repetition rate:	100 Hz
pulse length:	0.2-1 ps
max. pulse charge:	5 nC
max. beam energy:	50 MeV

The general layout of FLUTE is shown in fig. 1. With an RF laser gun operating at 3 GHz a single bunch with a bunch charge of up to 5 nC is produced. The bunch is accelerated in the 2 ½ cell gun to 7 MeV.

After a beam diagnostic area the beam enters a 3 GHz linac and is accelerated to about 45 MeV out of crest. The bunch, originally several ps long, is afterward compressed in a bunch-compressor to about 300 fs. Different compressor layouts, e.g. with a two or a four magnet chicane, will be investigated. In the following, the four magnet version will be discussed.

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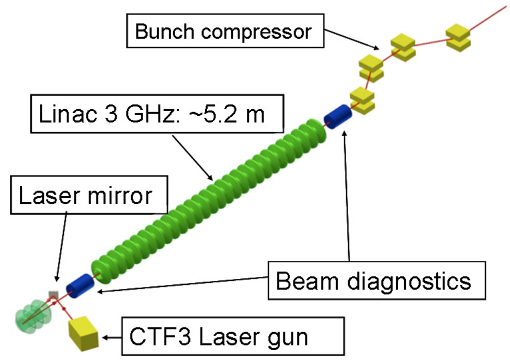

Figure 1: The concept of FLUTE with a 2 ½ cell RF photo-gun and 3 GHz linear accelerator followed by a bunch compressor. The total length of FLUTE is about 12 m.

The source of the coherent radiation can be either the synchrotron radiation at the last bending magnet, edge radiation or transition radiation from a foil. The different source mechanisms will be studied for the FLUTE beam in theory and experiment.

TECHNICAL LAYOUT OF FLUTE

The photo-injector foreseen for FLUTE is the CTF3 gun developed for the CLIC test facility [5]. The electron beam is accelerated in the electron gun to 7 MeV.

The gun cavity is powered by a 2 μs long pulse from a klystron. The estimated 45 MW power from this klystron is split: 22 MW are sent to the gun and 20 MW to the 5.2 m long S-band linac with 156 cells. The maximum energy of the linac is 50 MeV. For the gun a Ti:Sapphire laser is foreseen with a pulse length of 1 to 4 ps, an energy per pulse of 200 μJ, and a repetition rate of up to 100 Hz. With these parameters the CTF3 gun reaches gradients of up to 100 MV/m. The bunch charge can be as high as 5 nC, using large laser spot size of up to 10 mm full width.

BEAM SIMULATIONS

The particles emitted in the 2½ cell laser gun were tracked with ASTRA [6] through the linac and with CSRtrack [7] through the bunch compressor. The bunch is ac-

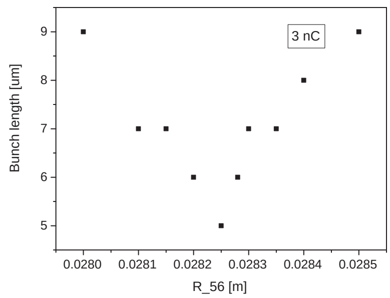

Figure 2: Bunch length (rms) in dependence of R_{56} for a charge of 3 nC. The shortest bunch length is at R_{56} =0.02825 m.

celerated in the linac 20 degree off crest. ASTRA calculates the rms bunch length Δs_i and the momentum spread $\Delta p/p$ at the end of the linac. The following equation gives a rough estimation of the final bunch length Δs_f after the chicane:

$$\Delta s_f = \Delta s_i + R_{56}\frac{\Delta p}{p}, \tag{1}$$

$$R_{56} = \frac{4L_B(\Theta - \tan\Theta)}{\sin\Theta} - \frac{2L_D.\tan^2\Theta}{\cos\Theta}. \tag{2}$$

Eq. (2) shows the dependence of R_{56} as a function of the deflecting angle Θ in the compressor magnet, the length of the magnet L_B, and the drift space L_D for the bunch compressor. The optimized chicane was found with $L_B = L_D = 0.5$ m and a total length of 4 m. The optimum choice of bending radius, derived from Θ and L_B, differs for each bunch current and has to be adapted. Fig. 2 shows the results for a bunch charge of 3 nC and an energy of 41 MeV.

Since Eq. (1) does not take into account space charge and CSR effects in the chicane, the selection of bending radius to achieve maximum compression is followed by a full simulation of the chicane in CSRtrack.

Fig. 3 shows the minimum achievable bunch length obtained from this procedure as a function of bunch charge. It is clearly visible, that the higher charge has less compression than the lower charge. Above 3 nC, the coherent synchrotron radiation effect has a strong influence on the bunch length.

Fig. 4 shows the longitudinal charge profile at the end of the optimized bunch compressor for bunch charges 0.1 nC and 3 nC, respectively. The number of particles rises exponentially to a maximum value followed by a sharp drop. The widening due to space charges is clearly visible. For the calculation of the peak electric field it is convenient to approximate the profiles by Gaussians. However, for the calculation of the spectral power we use the more accurate approximation by a saw-tooth. The CSR spectrum is proportional to the square of the number of particles N_e in the bunch and the form factor $F(\omega)$, which is the Fourier transform of the particle distribution function. Since the form factor of a saw-tooth like bunch falls off only as ω^{-4}, in contrast to the exponential decrease for a Gaussian bunch, the CSR spectrum extends to higher frequencies.

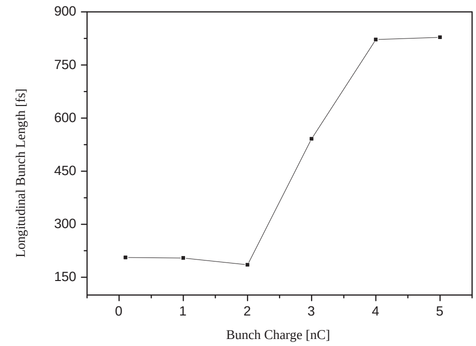

Figure 3: Relation between compressed bunch (rms) and bunch charge.

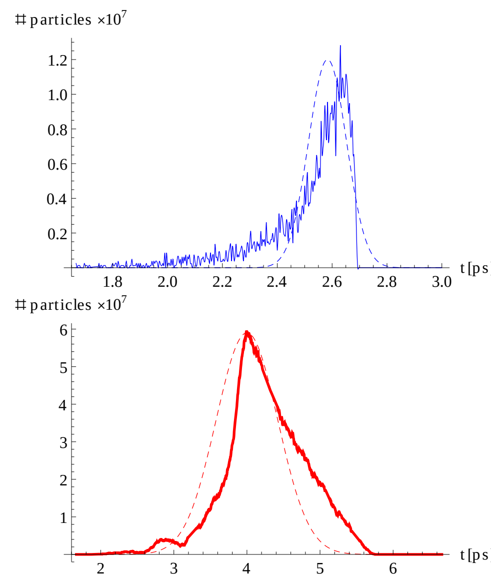

Figure 4: Longitudinal charge profile for bunches with total charge of 0.1 nC (blue) and 3 nC (red). Dashed curves are Gaussian approximations with the same total charge and $\sigma = 0.1$ ps (blue) and $\sigma = 0.6$ ps (red).

SPECTRUM AND FIELD STRENGTH

Fig. 5 shows the calculated CSR power spectra emitted by the 3 nC and 100 pC bunches. As expected for small frequencies, the CSR is enhanced by a factor N_e compared to the incoherent radiation. The spectral suppression due to the form factor sets in at frequencies above $c/l_{\text{bunch}} \sim 0.4$ THz and 1.5 THz. Because of the above mentioned slow decrease of the form factor, the coherent radiation dominates the spectrum up to frequencies of 100 THz. If the bunches were of a Gaussian shape instead, the incoherent spectrum would become dominant already at frequencies of 10 THz, as shown by the dashed curve in fig. 5.

Since the number of particles in the 3 nC bunch is 30 times higher than that of the 100 pC bunch, the coherent power is about 900 times higher for frequencies below 0.1 THz, where the form factors are very close to unity. However, the bunch length of the 3 nC bunch is longer and the drop is not as sharp as that of the 100 pC bunch (see

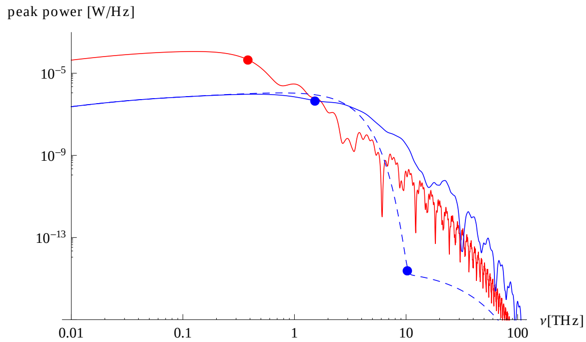

Figure 5: Power spectrum of the 3 nC (red) and 100 pC (blue) bunch. The points mark the power at frequencies corresponding to the bunch lengths (0.4 THz and 1.5T Hz). The dashed curve depicts the spectrum of the Gaussian approximation of the 100 pC bunch with $\sigma = 10$ THz.

fig. 4). This implies that the form factor suppression sets in earlier (at 0.4 THz) and is steeper, and the coherent powers become comparable at 1 THz.

The time dependence of the electric field, resulting from coherent synchrotron radiation, is of interest in pump-probe experiments. Following [8], we calculate the time dependence of the electric field $E(t)$ emitted by a bunch with charge distribution $\rho(x)$ as

$$E(t) \sim \cos\phi \mathrm{Re} A(t) + \sin\phi \mathrm{Im} A(t)\,,$$
$$A(t) \equiv \int_0^\infty \mathrm{d}\omega \int_{-\infty}^{\infty} \mathrm{d}x s(\omega)\rho(x)\mathrm{e}^{-\mathrm{i}\omega(t-x/c)}\,.$$

Here, $s(\omega) \propto \omega^{1/6}$ is the low frequency synchrotron radiation spectrum. The tunable phase ϕ depends on the machine parameters, and is determined by the local acceleration process of the emitting electrons. To perform the integrations analytically, we approximated the saw-tooth like bunch profile by three line segments. The resulting pulse shape for 100 pC is shown in fig. 6. To obtain the asymmetric pulse we chose $\phi = 325\,\mathrm{deg}$. The marked points on the t-axis correspond to the $t-$values of the points we used in the approximation of ρ. The cusps at these points are artifacts of this approximation. Notice that the field is sizable only during times corresponding to the bunch length.

To obtain the peak electric field E_0, we use the following equation, valid for a Gaussian bunch shape,

$$E_0^2\epsilon_0 c S \approx \frac{Wc}{3.8\sigma}\,, \tag{3}$$

where W is the total pulse energy radiated into the area S. Thus, we determine the peak field strength to be 3.012×10^8 V/m and 7.495×10^7 V/m for the 3 nC and 100 pC bunch, respectively.

It is remarkable, that even though the power ratio is 900, the electric fields for the two situations differ only by a factor of 4. Fig. 7 shows the dependence of the peak electric field on bunch length and charge for Gaussian bunch shapes. The regions of constant field for different charge/length combinations are clearly visible.

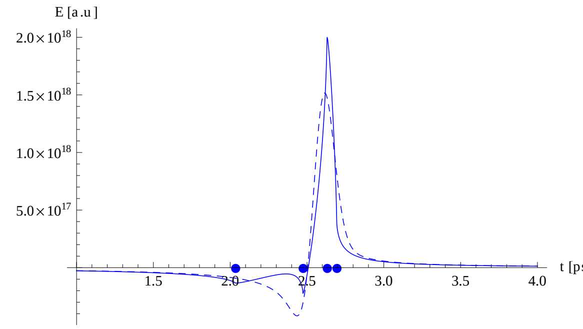

Figure 6: Pulse shape of the electric fields emitted by the 100 pc bunch with $\phi = 325\,\mathrm{deg}$. For the cusps see text. The dashed curve shows the field for the Gaussian approximation.

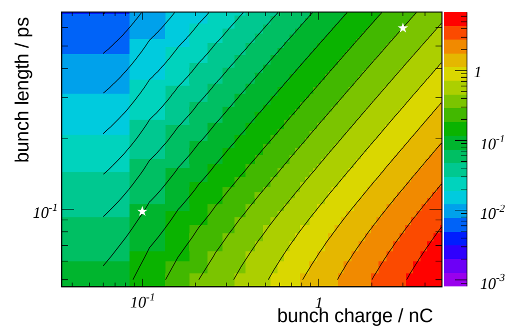

Figure 7: Strength of the electric field in GV/m (color) for Gaussian bunches according to Eq. (3). The markers denote the fields for the Gauss equivalent bunches of Fig. 4.

SUMMARY

FLUTE is a planed compact linear accelerator for the production of broadband coherent THz radiation with high peak fields. We presented the basic machine setup and performed simulations, showing that FLUTE can provide broadband THz radiation with peak field strengths of the order of 3×10^8 V/m.

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