FLUTE: A VERSATILE LINAC-BASED THz SOURCE GENERATING ULTRA-SHORT PULSES

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Abstract

FLUTE is a linac-based accelerator test facility and a THz source currently being constructed at KIT with an electron beam energy of $\sim 41\,\mathrm{MeV}$. It is designed to cover a large charge range from a few pC to $\sim 3\,\mathrm{nC}$. FLUTE is optimized to provide ultra-short electron bunches with an RMS length down to a few fs. In this contribution, we focus on the layout of the machine from the RF gun & gun laser over the linac and the compressor to the THz beamline for the generation of coherent synchrotron, transition and edge radiation (CSR, CTR, CER).

INTRODUCTION

There are a lot of scientific experiments that require the use of THz radiation [1, 2]. For many experiments (e.g., [3]), difficult-to-generate short THz pulses (sub-ps) with tunable shape and high peak fields in the MV/cm range are mandatory [1, 2]. One class of THz sources capable of generating such pulses is based on electron accelerators.

The Karlsruhe Institute of Technology (KIT), in collaboration with PSI and DESY, is currently developing and constructing a flexible linac-based test-stand for the generation of high peak field, short THz pulses. Named FLUTE (*Ferninfrarot Linac- Und Test-Experiment*—farinfrared linac- and test-experiment) it pursues the following objectives:

- Study space charge and CSR-induced effects and instabilities
- Systematic bunch compression studies
- Test bench for the development of new diagnostics and instrumentation
- Compare in theory and experiment different coherent radiation generation mechanisms (CSR, CTR, CER)
- Injector test stand for laser wakefield accelerators
- Experiments with THz pulses, e.g., pump-probe, new materials, ...
- Study for future compact, broadband accelerator-based THz user-facilities

FLUTE LAYOUT

The baseline layout of FLUTE [4] is shown in Fig. 1. The electrons are generated from a photoinjector radio-frequency (RF) gun, originally built for the CERN CLIC test facility (CTF) to deliver very high charges, and accelerated to an energy of $\sim 7\,\mathrm{MeV}$. The peak accelerating gradient of this 2 1/2-cell gun is around 120 MV/m. We plan to initially equip the gun with a Cu cathode because this material is relatively easy to handle. At a later phase, we will use a material providing a higher quantum efficiency like $\mathrm{Cs_2Te}$. We have evaluated several different laser systems for the gun and currently plan to use a commercial Ti:Sa laser equipped with a regenerative amplifier delivering $\sim 120\,\mathrm{fs}$ pulses with an energy of $\sim 5\,\mathrm{mJ}$. The UV light ($< 270\,\mathrm{nm}$) required for the photocathode will be produced by a third harmonic generation unit from the laser fundamental wavelength of $\sim 800\,\mathrm{nm}$. Subsequently, a pulse picker will reduce the repetition rate of the laser (kHz) to the mains-synchronized repetition rate of FLUTE ($\sim 10\,\mathrm{Hz}$). We plan to use a pulse stretcher to obtain laser pulses in the 1–4 ps range (RMS—root mean square). A fast feedback system regulating the oscillator cavity length will make sure that the laser is synchronized with the 36th subharmonic (83.278 MHz) of the master clock at 2.998 GHz. The RF system of the gun and the linac (both normal-conducting European S-band) are also triggered by the master clock. Right after the gun cavities a solenoid will be installed to focus the electrons transversally, which are not yet ultra-relativistic at this point.

The electron bunch will then be accelerated by a 156-cell traveling wave DESY linac II structure to an energy of $\sim 41\,\mathrm{MeV}$. The linac has a length of 5.2 m. Both the gun and linac cavities will be powered by one 45 MW klystron. A tunable power splitter and phase shifter will allow us to tune power and phase of both RF components independently.

Subsequently, a quadrupole doublet refocuses the electron beam, which then enters a 4-magnet D-shaped chicane compressing the bunch longitudinally. A skew quadrupole between chicane magnets 2 and 3, together with a screen at the end of the bunch compressor, will be used to measure the longitudinal phase space parameters.

After the chicane, when the bunch is shortest, we will install a THz port equipped with a screen-changer. The changer is planned to contain a thin metal foil to generate CTR as well as a set of solid mirrors with various holes to

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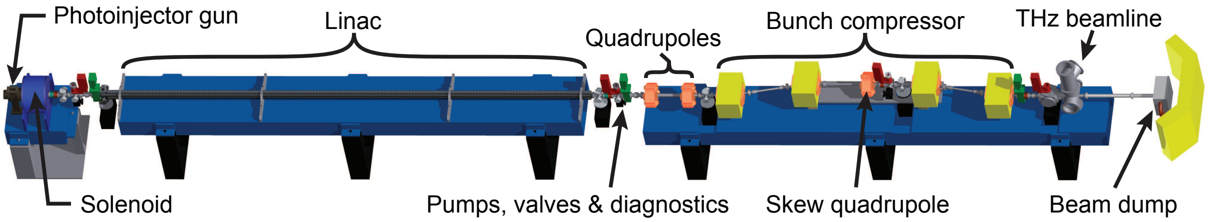

Figure 1: Sketch of the FLUTE layout. Total length of the machine is around 15 m.

allow the passage of the electron bunch and the collection of CSR and CER from the 4th chicane magnet. This way one single THz beamline can collect the radiation from all three generation mechanisms (CSR, CER, and CTR), so that we can compare the three radiation schemes with each other and with simulation results.

Finally, the electrons are guided into the beam dump, mainly consisting of a water-cooled aluminum block and lead bricks. Apart from the baseline layout presented here, other layout options including an additional buncher cavity are studied [5]. Furthermore, at a later phase, we consider to generate x-rays from a Compton backscattering setup. The x-rays and/or visible light pulses from the fs gun laser could be used for scientific experiments such as pump-probe or 2D spectroscopy.

SIMULATION RESULTS

The design of FLUTE was optimized with mainly two simulation programs [6]: ASTRA was used from the gun to the end of the linac as there space charge effects are dominant. In the chicane, especially at the end, where the bunch becomes short, CSR-induced effects become important and have to be taken into account. Therefore, we used CSRtrack for this part of FLUTE. The parameters optimized with this chain of programs achieve the shortest RMS bunch length and are summarized in Table 1. They are the basis for the following plots.

Additionally, we have developed a set of tools based on analytical calculations to quickly compute expected spectra and THz pulses from the simulation output. This will, in the near future, permit us to optimize for other parameters than the RMS bunch length, such as the spectrum of the emitted radiation, peak fields, etc.

Figure 2 shows the results of the simulated longitudinal bunch profile at the end of the bunch compressor for 100 pC and 3 nC. In these simulations we do not take possible damping effects due to a finite THz beamline diameter into account. The bunch lengths obtained for these two cases are 67 and 270 fs RMS, respectively. At a later phase we will experiment with lower bunch charges down to 1 pC to explore the limits of achievable bunch lengths below 10 fs.

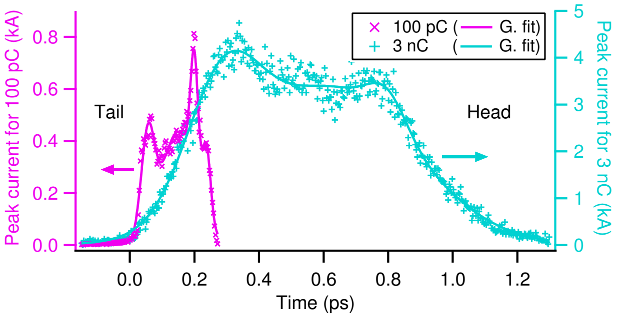

Figure 2: Longitudinal bunch current profile after the chicane for two charge values. Markers denote the histogram results from the simulation programs and continuous lines correspond to multi-gaussian fits (RMS bunch lengths: 67 fs for 100 pC, 270 fs for 3 nC). Parameters see Table 1.

To calculate the coherent spectra, we fit a multi-peak Gaussian to the simulated longitudinal bunch profiles (Fig. 2), which allows us to compute the form factor analytically. Based on this we then compute the coherent spectra shown in Fig. 3. The small modulations on the spectra are due to the substructure visible on the charge profile. The spectral intensity is about $(3\,\mathrm{nC}/100\,\mathrm{pC})^2 = 900$ times stronger for the higher charge bunch for frequencies below ~ 0.1 THz, as expected for coherent radiation. At ~ 50 THz and ~ 10 THz the coherent components become negligible and merge with the incoherent spectrum. The difference is due to the different bunch lengths. If a drop to the 0.1%-level is taken as a reference value (assumed dynamic detector range) for comparison, the CSR spectral limits are at ~ 25 THz and ~ 4 THz for the 100 pC and 3 nC cases, respectively. The first case covers the range of

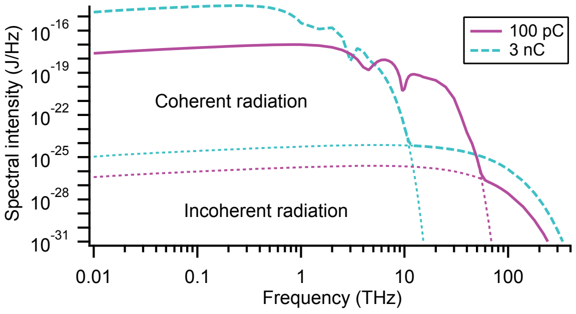

Figure 3: Spectra of the coherent and incoherent components (dotted lines) of the synchrotron radiation for 100 pC and 3 nC. The thick lines correspond to the total emitted radiation.

Table 1: Baseline design parameters of FLUTE (RMS bunch length L_{RMS}, bending radius r_{bend}, dipole magnetic field B, momentum compaction R_{56}). The chicane dipole magnet length L_b is 0.2 m and the drift space D between chicane dipole 1 & 2 and 3 & 4 is 0.3 m for all cases.

Charge [nC]	Laser spot ø (RMS) [mm]	Laser pulse (RMS) [ps]	L_{RMS} before linac [ps]	Average energy [MeV]	r_{bend} [m]	B [T]	$-R_{56}$ [mm]	L_{RMS} after chicane [fs]
3	4.50	4	2.43	40.79	1.006	0.135	36.1	270
2	3.00	4	2.45	40.76	1.058	0.128	32.5	224
1	3.00	3	1.81	40.72	1.032	0.132	34.2	146
0.1	1.00	2	1.20	40.68	1.108	0.124	29.5	67
0.001	1.00	1	0.57	40.66	1.135	0.119	28.1	13

up to ~ 10 THz particularly, which is particularly important for biomedical experiments [1].

The results presented in Fig. 4 compare the various THz generation schemes (CSR, CTR, and CER) for 3 nC. Our calculations indicate that CSR yields a higher spectral intensity while the other two mechanisms have very similar, but lower intensity. The drop of the CTR spectrum for low frequencies is due to the finite size (6 cm diameter) metal foil used for the computation, causing a frequency cut-off. The instantaneous generation mechanism of CTR and CER assumed in the model leads to the constant intensity visible in the spectrum at higher frequencies.

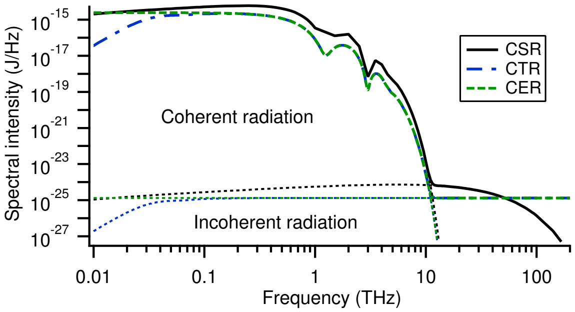

Figure 4: Comparison of spectra from CSR, CTR, and CER for a bunch charge of 3 nC. Thin lines illustrate the incoherent components, whereas the thick lines correspond to the total emitted radiation.

The THz pulse can also be calculated analytically from the Gaussian multi-peak fit to the charge profile [7] (Fig. 5). To be closer to experimental conditions it is assumed here that the field collected at a distance of 1 m from the source is focused to a disc of 1 mm radius. Electric and magnetic field strengths of several MV/cm and a few tesla can be reached for sub-ps pulses. These values are well suited for switching experiments (e.g., [3]).

SUMMARY

A new linac-based THz source named FLUTE is currently being constructed at KIT. This 41 MeV machine is designed to offer a wide bunch charge range from the pC to the nC regime with a repetition rate of ~ 10 Hz. It is therefore very well suited to systematically study various accelerator physics questions, from optimal parameter sets and compression layouts for short but intense THz peak fields to CSR-induced effects and instabilities. Simulations show that the current layout design can achieve bunch lengths from 270 to 13 fs and field strengths of several MV/cm up to ~ 25 − 33 THz, dependent on the bunch charge.

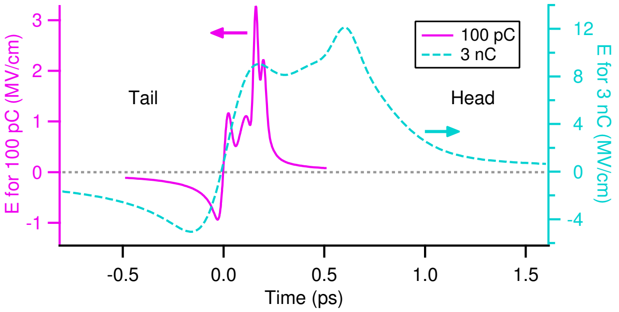

Figure 5: THz pulse (electric field component) calculated from the Gaussian multi-peak fit of the longitudinal current profile (see Fig. 2). It is assumed that the pulse is focused to a disc with a radius of 1 mm at a distance of 1 m from the source.

ACKNOWLEDGMENT

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