# OPTIMIZATION OF THz RADIATION PULSES AT FLUTE

M. Yan*, A.-S. Müller, M. J. Nasse, M. Schuh, M. Schwarz
Karlsruhe Institute of Technology, Karlsruhe, Germany

*Abstract*

The accelerator test facility FLUTE (Ferninfrarot Linac Und Test Experiment) will allow research and development in electron accelerator technology as well as photon science. Electron bunches of durations in the femtosecond range will be provided to generate intense THz radiation. Start-to-end simulation of the accelerator has been performed with the bunch length as the optimization objective. Based on the resulting charge distribution the expected THz field properties can be calculated. In this paper we combine the two tools and present first results.

## INTRODUCTION

The accelerator test facility FLUTE is currently under construction at KIT in collaboration with PSI (Villigen, Switzerland) and DESY (Hamburg, Germany). Its aims range from investigation of space charge and coherent radiation induced effects, bunch compression studies, to systematic comparison of simulation code with measurement results [1, 2]. Furthermore, it will serve as a test bench for advanced diagnostics and instrumentation. The generated intense THz radiation will be used for various experiments, for example to study the radiative impact on relevant biomedical tissue.

The schematic layout of FLUTE is shown in Fig. 1. The total length of the accelerator is ~15 m. In the RF photo cathode gun, electrons are generated and accelerated to an energy of ~7 MeV. A solenoid focuses the electron bunch before it being accelerated by the main *S*-band linac accelerating structure to the energy of ~41 MeV. After a matching section with a quadrupole triplet, the electron bunch is longitudinally compressed in a magnetic bunch compressor consisting of four dipole magnets. Coherent synchrotron radiation (CSR) generated from the fourth dipole magnet and coherent transition radiation (CTR) emitted by a screen directly downstream of the bunch compressor will be used as THz radiation sources for experiments.

The design parameters at the time, which are summarized in Table 1, are obtained based on particle tracking simulations with a parameter scan method. The focus of the optimization was on the electron beam parameters. Based on the development in numerical calculation of the THz radiation pulse from an electron bunch with arbitrary current distribution [3], we combine the accelerator tracking tool with the computation of the THz radiation field and thus make the direct optimization of the THz parameters possible. Furthermore, we implement a genetic algorithm, which improves dramatically the efficiency and performance of the optimization. In this paper, we present the optimization procedure and the first results obtained with this method.

* minjie.yan@kit.edu

Table 1: Main FLUTE Parameters from Simulation

| Parameter | Value | Unit |
|---|---|---|
| Final electron energy | ~41 | MeV |
| Electron bunch charge | ~1–3000 | pC |
| Final electron bunch length (rms) | ~1–300 | fs |
| Pulse repetition rate | 10 | Hz |
| Energy / THz pulse | up to ~3 | mJ |
| Power / THz pulse | up to ~5 | GW |

## OPTIMIZATION PROCEDURE

Start-to-end (S2E) simulations are performed to optimize the electron and photon parameters: the electrons are tracked from the cathode to the exit of the bunch compressor using the code ASTRA [4]; the output particle distributions from ASTRA are then forwarded into a program to compute the electric field of the THz radiation generated by the electron bunch.

Calculation of the THz radiation field is based on the method presented in Ref. [3]. The electric field $E(t)$ of the emitted THz pulse is given by

$$E(t) = 2\,N_e\,\mathrm{Re}\left[\mathrm{e}^{-\mathrm{i}\phi}\int_0^\infty \tilde{\varrho}(\omega)\,\tilde{E}_0(\omega)\mathrm{e}^{-\mathrm{i}\,\omega\,t}\,\mathrm{d}\omega\right], \quad (1)$$

where $E_0$ denotes the electric field of a single particle, $\varrho$ the (normalized) particle density, $N_e$ the number of electrons in the bunch, and $\phi$ is an undetermined phase that is set to zero in the following. A tilde above a symbol denotes its Fourier transform. For the single particle spectrum $\tilde{E}_0$ we use synchrotron radiation [5] and transition radiation [6]. The integral in Eq. (1) is solved numerically with the method presented in Ref. [3].

Table 2: Most Important Genetic Algorithm Parameters

| Parameter | Value |
|---|---|
| Size population | 30 |
| Population initialization | latin hypercube sampling |
| Fitness scaling | rank |
| Selection | stochastic uniform |
| Mutation operator | adapt feasible |
| Crossover operator | uniform |

The work flow of the optimization procedure is illustrated in Fig. 2. Either the rms electron bunch length or the peak THz field (from CSR or CTR source) from the S2E simulation can be chosen as the objective for the optimizer. The input variables for the optimizer are the accelerator operating parameters: phase and amplitude of both the gun and the




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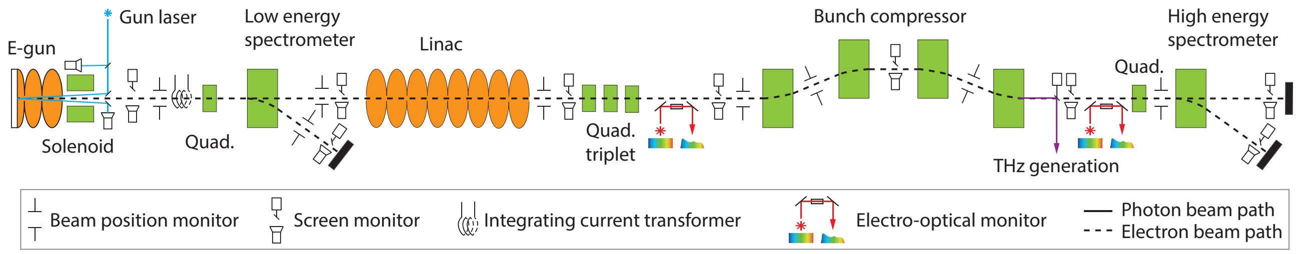


Figure 1: Schematic layout of FLUTE including various diagnostics elements. RF components are marked in orange and magnets in green. Not to scale.

linac, focal length of the solenoid and quadrupoles, strength of the bunch compressor magnets.

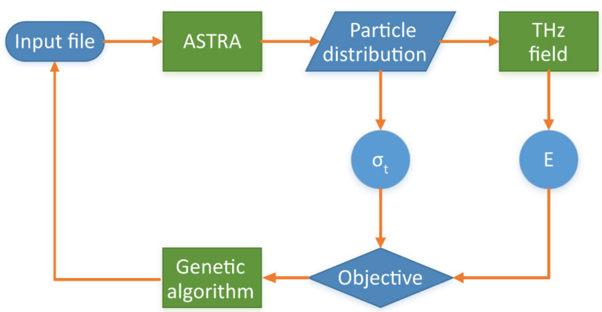


Figure 2: Work flow of the optimization. The simulation and computation programs are denoted in green, the input and output parameters in blue.

The optimizer employs the genetic algorithm method, of which the most important parameters are summarized in Table 2. The populations are initialized using the latin hypercube sampling of the input parameters in their search space. After the fitnesses of the objective function being scaled according to their rank, the populations are operated with stochastic uniform selection, adapt feasible mutation and uniform crossover to produce the next generation. Each generation contains 30 populations.

## FIRST RESULTS

A first attempt with the above described optimization method was to minimize the rms electron bunch length for the case of 1 pC charge. The gun laser has an rms pulse length of 700 fs and a transverse rms beam size of 0.85 mm. The number of macro particles was chosen to be 10k, which reduces dramatically the computation time of ASTRA tracking while still being sufficient to represent the beam dynamics along the accelerator.

Figure 3 shows the evolution of the minimum and mean rms bunch length in each generation. It can be seen that genetic algorithm efficiently reduces the mean bunch length from 1 ps to below 100 fs already after 3 generations. An optimized value of 3.2 fs for the rms bunch length is found after 20 generations. The accordingly optimized accelerator working point is summarized in Table 3.

In order to validate the accuracy of the simulation results, the start-to-end simulation was repeated with the optimized

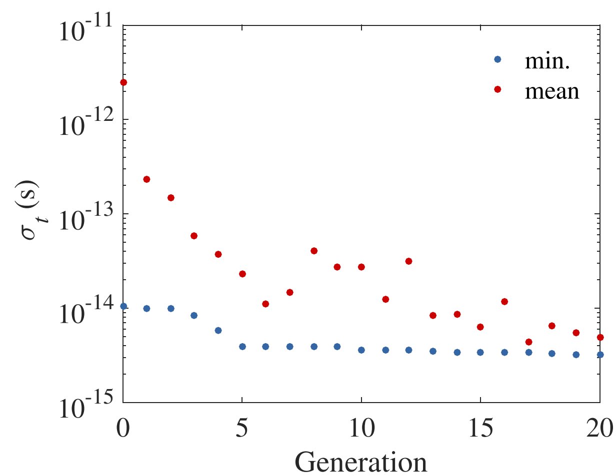


Figure 3: Evolution of the minimum (blue) and mean (red) rms bunch length during the optimization procedure using genetic algorithm.

Table 3: Optimized Accelerator Operating Parameters

| **Parameter** | **Value** |
|---|---|
| Gun max. gradient | −118.45 MV/m |
| Gun phase | −29.87° |
| Solenoid | 0.10 T |
| Linac max. gradient | 11.54 MV/m |
| Linac phase | −40.34° |
| BC bending radius | 1.62 m |

accelerator parameters with 100k macro particles (the computation time increases by more than one order of magnitude). The longitudinal phase space of the final electron bunch at the exit of the bunch compressor is shown in Fig. 4, where the colour code depicts the density of the particle distribution. It should be noted that the impact of CSR on the electron beam dynamics in the bunch compressor is negligible at this low charge of 1 pC.

Compared to the previous design with electron bunch parameters of 5 fs and 41 MeV [7], our new optimization procedure obtains an improved solution that provides shorter bunch length while retaining the electron energy. The new compression scheme leads to a more localized concentration of the electrons.

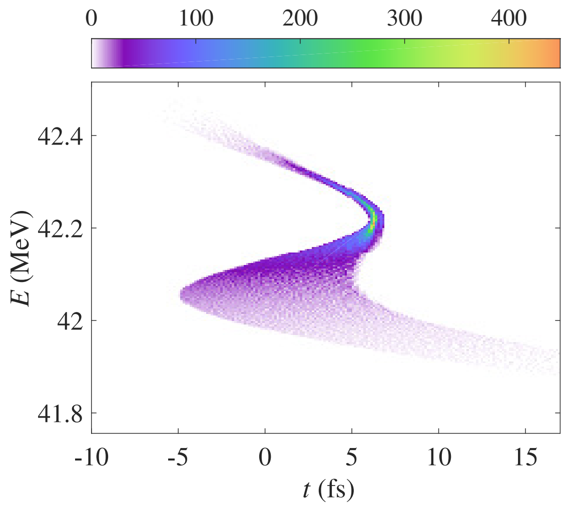


Figure 4: Longitudinal phase space of the electron bunch optimized with the genetic algorithm. The rms bunch length is $\sigma_t = 3.2\,\text{fs}$.

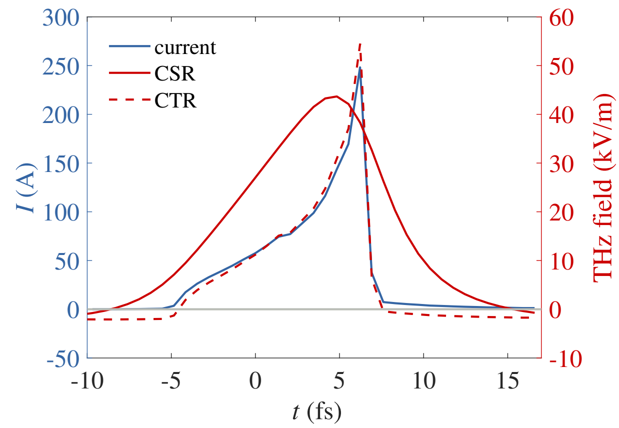


Figure 5: Bunch current profile (blue solid) of the optimized electron distribution (cf. Fig. 4) and the resulting electric THz fields of CSR (red solid) and CTR (red dashed).

The current profile of the electron bunch (blue solid) is displayed in Fig. 5. The rms bunch length is determined to be $\sigma_t = 3.2\,\text{fs}$, and a high peak current of $\sim 250\,\text{A}$ can be reached. The resulting electric fields of CSR and CTR are compared and shown in Fig. 5 as the red solid and dashed curves, respectively.

Both pulses display a "half-cycle" shape because we set $\phi = 0$, but notice the long negative tails, required to make the time integral vanish [8]. The different pulse shapes result from an interplay between the bunch length $\sigma_t$ and the typical frequency of the spectrum $\tilde{E}_0$ [9]. For the optimal machine parameters, the critical frequency of synchrotron radiation $\omega_c = 1.6 \times 10^{14}\,\text{s}^{-1}$ is about half of the inverse bunch length $1/\sigma_t = 3.1 \times 10^{14}\,\text{s}^{-1}$. This means that the electron bunch radiates CSR almost fully coherently as a single particle of charge 1 pC. Almost all structural information is lost and the pulse duration is about $\pm 1/\omega_c = \pm 6.4\,\text{fs}$. Further decreasing the bunch length would, thus, neither significantly decrease the pulse duration nor the peak electric field. Contrary to CSR, the spectrum of transition radiation $\tilde{E}_0$ is almost flat without any characteristic frequency. Thus, pulse shape is dominated by the bunch shape [9], which can be seen in Fig. 5. Any manipulation of the bunch profile would directly carry over to the CTR pulse shape.

Another optimization with the peak THz field from CSR source as the objective leads to very similar accelerator parameters and thus the same longitudinal phase space of the final electron bunch. It further confirms that when the bunch is extremely short, the whole bunch radiates CSR almost fully coherently.

During the many optimization runs, multiple local optima of accelerator working points that provide electron bunch with rms bunch length of $\sim 5\,\text{fs}$ have been found. The flexibility of the machine settings will ease the bunch compression procedure. Optimization of the THz radiation field of CTR source is still ongoing.

## SUMMARY AND OUTLOOK

We have combined the electron particle tracking tool with the calculation of the THz radiation fields, and integrated the S2E simulations into a genetic algorithm optimizer. This method has efficiently found optimized accelerator operating parameters with targets as minimum bunch length and maximum THz radiation field. The optimized rms bunch length has been further reduced to 3.2 fs compared to our previous design value. We plan to include more accelerator parameters in the optimization procedure to exploit the possibility of FLUTE. Furthermore, this method could be extended with a multi-objective genetic algorithm for problems with multiple (contradicting) objectives. Implementation of this method on clusters is foreseen to speed up the time-consuming S2E simulations.

## REFERENCES


[1] M. J. Nasse *et al.*, Rev. of Sci. Instrum. **84**, 022705 (2013).

[2] M. J. Nasse *et al.*, in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, paper TUPWA042, pp. 1506–1508.

[3] M. Schwarz *et al.*, in *Proc. IPAC'14*, Dresden, Germany, June 2014, paper MOPRO067, pp. 234–236.

[4] K. Flöttmann, "ASTRA: A Space Charge Tracking Algorithm", `http://www.desy.de/~mpyflo`.

[5] J.D. Jackson, *Classical Electrodynamics*, John Wiley & Sons, 1999.

[6] S. Casalbuoni et al., TESLA-Report 2005-05 (2005).

[7] M. Weber *et al.*, in *Proc. FEL'14*, Basel, Switzerland, August 2014, paper THP004, pp. 682–684.

[8] K.-J. Kim *et al.*, Phys. Rev. Lett. **84**, p. 3210 (2000).

[9] M. Schwarz *et al.*, in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, paper MOPHA043, pp. 885–887.



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