ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2025-MOPB105

SIMULATION AND OPTIMIZATION OF A SUB-THz CHERENKOV FEL AT AREAL

Karel Peetermans*[1], Alberto Bacci[2], Marcello Rossetti Conti[2], Klaus Floettmann[1], Armen Grigoryan[3],
Bagrat Grigoryan[3], Mikayel Ivanyan[3], Francois Lemery[1]
[1]Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany
[2]Istituto Nazionale di Fisica Nucleare INFN, Milan, Italy
[3]CANDLE Synchrotron Research Institute, Yerevan, Armenia

Abstract

We present optimized start-to-end simulation results of the Cherenkov free electron laser using a simple configuration consisting of an RF gun, focusing solenoid and a dielectric-lined waveguide. For optimization of the system, the genetic optimization algorithm GIOTTO is applied to refine both the waveguide and accelerator variables. Assuming an initial beam energy of 4 MeV with a bunch charge of 300 pC, the optimized parameters produce energy outputs exceeding 20 µJ for a frequency of 100 GHz.

INTRODUCTION

At low energies, self-imparted energy modulations from self-wakes produce significant velocity differences which can lead to compression [1, 2]. It is therefore intuitive to consider extending the length of the waveguide to produce spontaneous stimulated amplified emission (SASE). This concept is not new, and has been previously studied with old microtron devices [3, 4]. More recently a renewed interest has been made [5, 6] using significantly brighter beams generated from modern radiofrequency powered photoguns.

We thoroughly investigate the Cherenkov free electron laser (CFEL) using optimized start-to-end simulations and find interesting and relevant energy and power levels which can be realized on a compact footprint, enabling the production of high-power sub-THz radiation.

THEORY

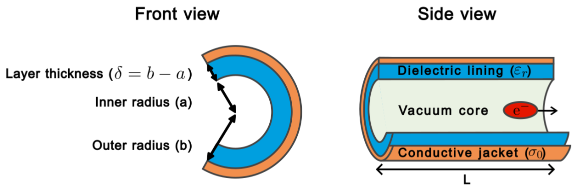

Figure 1: Sketch of a DLW and its parameters.

In a dielectric lined waveguide (DLW), see Fig. 1, the FEL process can be initiated by the self wake generated by the electron bunch. The dielectric lining allows resonant modes with a phase velocity slow enough to match the particle velocity. The wake extends a distance behind the electron bunch, characterised by the group velocity v_g of the waveguide mode and the particle velocity v_p. The wake length is then $L_w(z) = z/v_g - z/v_p$ with z the distance that the electrons has traveled inside the waveguide. The strength of the wake is characterised by the loss factor per unit length κ in the equation $w(s) = 2\kappa \cos(\omega_0 s/t)$. In this work, the loss factor, as shown in Fig. 2, is calculated using the simulation code ECHO1D [7, 8] to find results that hold in the low-frequency, thick-layer regime. The results are shown in function of the dimensionless parameter $U = a\omega_0/c\gamma$, which expresses how relativistic the bunch is compared to the resonant angular frequency ω_0 in the limit $\gamma \to \infty$ [5]. The actual frequency ω_r that is excited by a bunch with finite energy is typically higher than ω_0 and increases with γ.

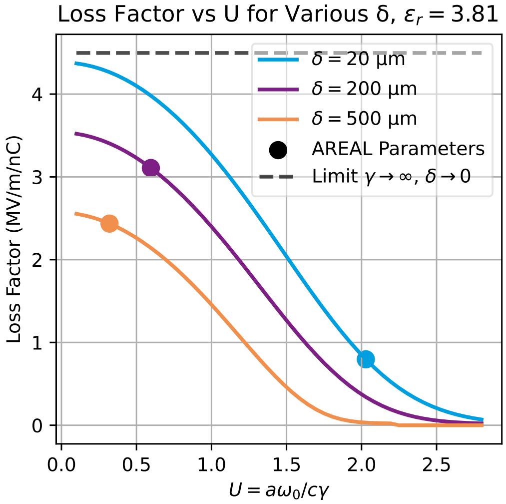

Figure 2: Loss factor of the fundamental mode as a function of the dimensionless parameter $U = a\omega_0/c\gamma$. The trend is shown for different thicknesses of the dielectric layer. The dashed black line shows the limit for $\delta \to 0$ and $\gamma \to \infty$.

ASTRA SIMULATIONS

Multiphysics simulations starting at the cathode were performed using the simulation code ASTRA [9]. Starting from steady-state wake found using ECHO1D, the effect of a wake kick is implemented into ASTRA. The code convolves the Green's function with the charge density and evaluates the longitudinal wake force. Therefore, to simulate the effect of a beam travelling through the DLW for an extended period of time, the wake kicks are applied every centimeter to pro-

---

* karel.peetermans@desy.de

duce a semi-continuous self-wake effect. Further reducing the wake step-size slows down simulation speed while not noticeably affecting the beam dynamics.

A sketch of the beamline is shown in Fig. 3. The emphasis is on simplicity: for this scheme to work, no booster is required and one solenoid suffices as the sole focusing element. The distances, RF fields and laser pulse characteristics were modeled after the AREAL linac situated at the CANDLE SRI in Yerevan, Armenia.

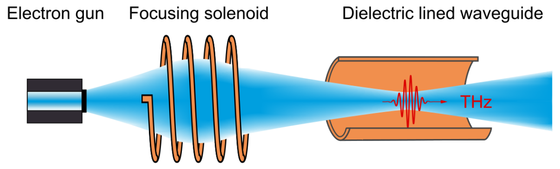

Figure 3: Sketch of the simplified beamline.

To determine the optimal DLW for a potential experiment, the thickness of the dielectric layer is varied while keeping other parameters constant. ASTRA does not output the electric field that is produced during the FEL process. Instead, the field's energy can be estimated from the energy loss of the electron bunch to the wakefield $\mathscr{E}_{\text{rad}}$. This must be equal to $\mathscr{E}_{\text{rad}} = E_{\text{lost, total}} - E_{\text{lost, kinetic}}$, with $E_{\text{lost, kinetic}}$ the energy lost by particles hitting the aperture. The radiated energy along the DLW is shown in Fig. 4.

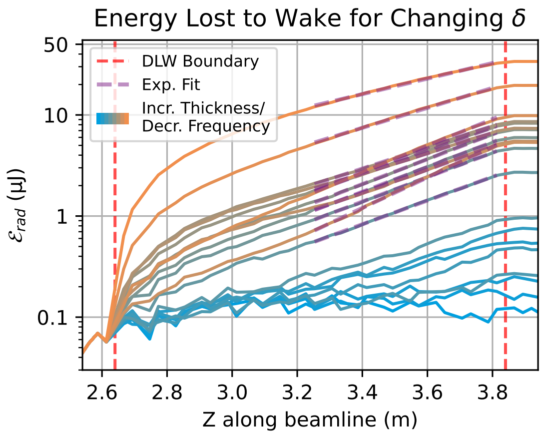

Figure 4: Radiated energy along the DLW from the ASTRA parameter scan, keeping $a = 2$ mm constant. The thickness ranges from 30 µm–700 µm, corresponding to a color change from blue to orange in the plot.

In the log-scale three different regimes can be distinguished. At low frequencies, the bunch is short enough to superradiantly produce light. The wakeforces cause the bunch to longitudinally compress itself into a single microbunch. The exponential energy gain regime is only observed at intermediate frequencies, translating to linear behaviour in the log-scale plot. Here, the particles reorder themselves into micro-bunches separated by the resonant wavelength, after which they lase semi-coherently, and exponential gain is observed. The final regime is characterised by frequencies that are too high for the electrons to couple to significantly because of the large waveguide aperture. No significant micro-bunching occurs and the exponential gain regime is not reached. Figure 5 shows the total net energy radiated when the beam leaves the DLW. Overlayed in the same plot is the gain length as it is found by the fit shown in Fig. 4.

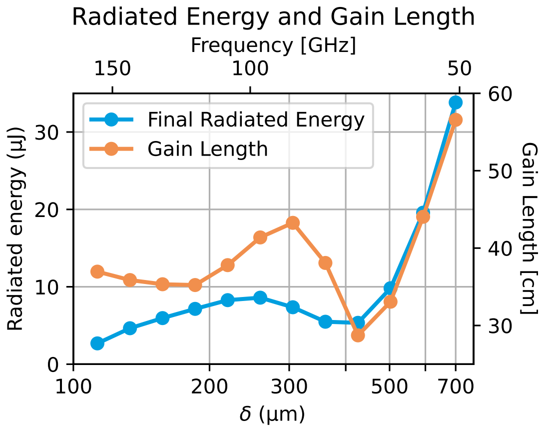

Figure 5: Final radiated energy and fitted gain length from the ASTRA parameter scan. The final energy depends strongly on the initial form factor.

MULTI-OBJECTIVE GENETIC OPTIMIZATIONS WITH GIOTTO

To achieve the highest THz energy possible, the multi-objective genetic optimization algorithm GIOTTO was applied to the AREAL beamline [10, 11]. In this study, the parameters of the DLW as well as the solenoid and gun RF phase were varied. GIOTTO works by iterating over so-called populations, where every gene represents a parameter of the beamline. Within one population are many chromosomes that all have slightly different genes. The program selects the best chromosomes and, by genetic rules, moves on to the next generation, which consists of the best chromosome (inherited) and new ones with different local parameter mixing and random small variations. This continues for many generations until a stable "best-case" is found or the user stops the program. GIOTTO determines the best chromosome in a population based on a user-defined goal function that it tries to maximize.

Two goal functions are taken into consideration in this work. The first one, G_1 corresponding to Run 1, focuses on increasing radiated energy as well as energy spread, while trying to keep particle losses to around 10%. The second function, G_2 corresponding to Run 2, only takes into account total energy radiated with no regard for particle losses. The specific mathematical forms of the goal functions are based on Lorentzian distributions with their maximum at the goal-value of a given parameters. The parameter evolution is shown in Table 1. In both cases, the layer thickness ends around $\delta = 200$ µm, which is commonly available for towerdrawn fused silica waveguides. The frequency produced by the optimized waveguides is approximately 110 GHz.

Table 1: Initial and Final Parameters of the Two GIOTTO Optimizations

Parameter	Start	Run 1	Run 2
a [mm]	2.00	2.04	1.63
δ [µm]	222.7	207.7	212.7
DLW Length [m]	1.20	1.13	1.41
DLW Start [m]	2.640	2.625	2.51
Sol. Strength [T]	0.1966	0.1963	0.1985
Gun Phase [°]	-2.00	-4.45	-3.97
$\mathscr{E}_{\text{rad}}$ [µJ]	9.67	12.40	21.69
Surviving particles	83.6%	83.2%	39.6%

A finite element particle-in-cell solver, ECHO2DPIC, was used to validate the results from ASTRA. The ASTRA particle distribution is extracted before the waveguide entrance and subsequently tracked through the DLW in ECHO2D, allowing the direct measurement of the radiated fields. The instantaneous power $S(t)$ and total pulse energy $\mathscr{E}_{\text{rad}}$ are found by integrating the Poynting-vector as shown in [12].

As visible in Figs. 6 and 7, the power does not reach saturation in the classical sense, instead the power plateaus due to particle losses. For Run 1, the beam loses about 17% while for Run 2, 60% is lost. Finally, a simulation is performed of the beam distribution after bending by 90 deg in the AREAL spectrometer placed behind the DLW. Figure 8 shows the phase space before and after, indicating that this can be a useful diagnostic tool to assess the energy modulation.

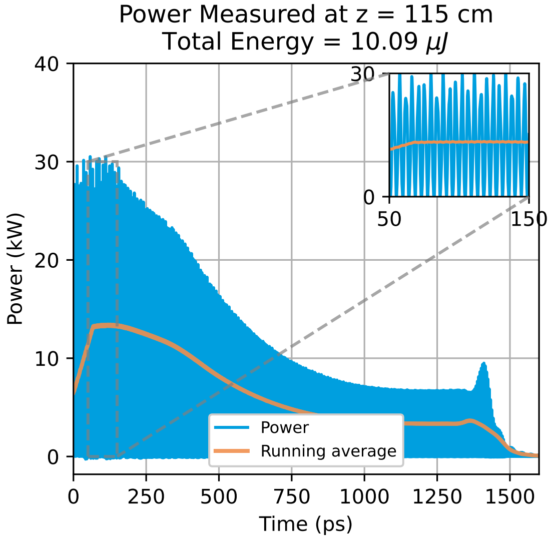

Figure 6: Pulse power measured in ECHO2D. The simulation parameters match the final parameters of Run 1.

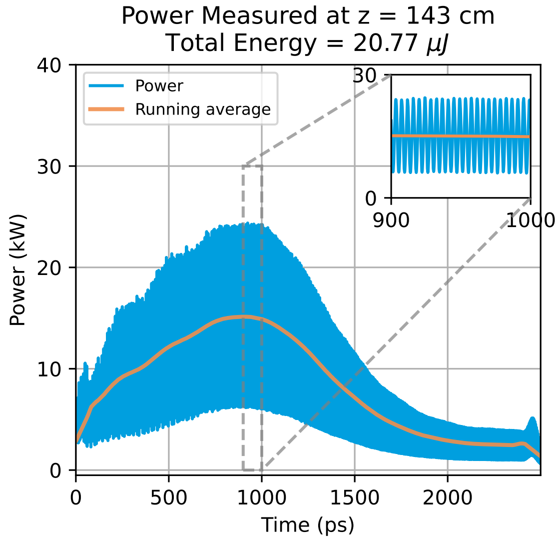

Figure 7: Pulse power measured in ECHO2D. The simulation parameters match the final parameters of Run 2.

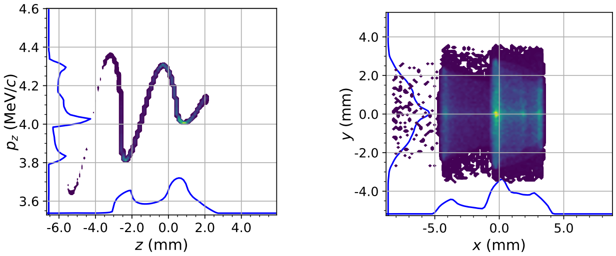

Figure 8: Left: z-p_z phase space after DLW exit, right: x-y phase space after 90 deg right-hand bend. Higher energy particles have positive x.

CONCLUSION

A robust simulation framework was presented to develop a high-energy, accelerator-driven THz source. ASTRA simulations were matched to the results of the ECHO2D particle-in-cell solver. This allows relatively fast optimization using the genetic algorithm GIOTTO, leading to impressive increases in energy compared to the initial parameter set.

Experimental challenges include beam alignment over the relatively long DLW, which may be addressed by adding steering coils before the DLW entrance. Scanning their strength will allow electron beam transmission to be maximised even further. Furthermore, a linac with a lower emittance gun and a solenoid closer to the cathode could allow for a smaller focus to be maintained over a longer distance. If the radius can be reduced down to $a = 0.5$ mm, a frequency of 1 THz can be reached.

ACKNOWLEDGEMENTS

This work was supported by funds of the European XFEL R&D program.

REFERENCES

[1] F. Lemery *et al.*, “Experimental Demonstration of Ballistic Bunching with Dielectric-Lined Waveguides at Pitz”, in *Proc. IPAC’17*, Copenhagen, Denmark, May 2017, pp. 2857–2860. `doi:10.18429/JACoW-IPAC2017-WEPAB122`

[2] F. Lemery *et al.*, “Passive ballistic microbunching of nonultra-relativistic electron bunches using electromagnetic wakefields in dielectric-lined waveguides”, *Phys. Rev. Lett.*, vol. 122, no. 4, p. 044801, Jan. 2019. `doi:10.1103/PhysRevLett.122.044801`

[3] F. Ciocci *et al.*, “Observation of coherent millimeter and submillimeter emission from a microtron-driven Cherenkov free-electron laser”, *Phys. Rev. Lett.*, vol. 66, no. 6, pp. 699–702, Feb. 1991. `doi:10.1103/PhysRevLett.66.699`

[4] F. Ciocci, G. Dattoli, A. Doria, G. Schettini, A. Torre, and J. E. Walsh, “Spontaneous Emission in Cerenkov FEL Devices: a Preliminary Theoretical Analysis”, *Il Nuovo Cimento D*, vol. 10, no. 1, pp. 1–20, 1988. `doi:10.1007/BF02450085`

[5] G. Stupakov, “Using pipe with corrugated walls for a subterahertz free electron laser”, *Phys. Rev. Spec. Top. Accel. Beams*, vol. 18, no. 3, 2015. `doi:10.1103/PhysRevSTAB.18.030709`

[6] W. Li, S. Jiang, Z. He, Q. Jia, L. Wang, and Y. Lu, “Proposal and numerical studies of a terahertz Cherenkov free electron laser driven by a non-ultra relativistic bunched electron beam”, *Nucl. Instrum. Methods Phys. Res. A: Accel. Spectrom. Detect. Assoc. Equip.*, vol. 931, 2019. `doi:10.1016/j.nima.2019.04.029`

[7] I. Zagorodnov and T. Weiland, “TE/TM field solver for particle beam simulations without numerical Cherenkov radiation”, *Phys. Rev. Spec. Top. Accel. Beams*, vol. 8, no. 4, 2005. `doi:10.1103/PhysRevSTAB.8.042001`

[8] I. Zagorodnov, ECHO2D - Version 3.5. `https://echo4d.de/download/echo2d/`

[9] *ASTRA A Space Tracking Algorithm*, Klaus Floettmann, 2017. `https://www.desy.de/~mpyflo/Astra_manual/Astra-Manual_V3.2.pdf`

[10] A. Bacci, V. Petrillo, and M. R. Conti, “GIOTTO: A Genetic Code for Demanding Beam-dynamics Optimizations”, in *Proc. IPAC’16*, May 2016, pp. 3073–3075. `doi:10.18429/JACoW-IPAC2016-WEPOY039`

[11] M. Rossetti Conti *et al.*, “New approach to space charge dominated beamline design”, *Phys. Rev. Accel. Beams*, vol. 26, no. 9, p. 094201, Sep. 2023. `doi:10.1103/PhysRevAccelBeams.26.094201`

[12] KL.F. Bane and G. Stupakov, “Terahertz radiation from a pipe with small corrugations”, *Nucl. Instrum. Methods Phys. Res. A: Accel. Spectrom. Detect. Assoc. Equip.*, vol. 677, pp. 67–73, 2012. `doi:10.1016/j.nima.2012.02.028`