FACILITY FOR COHERENT THZ AND FIR RADIATION

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Abstract

Linac based THz sources are increasingly becoming the method of choice for a variety of research fields, justifying the increasing demand for high repetition rate THz FEL facilities world wide. In particular, pump and probe experiments with THz and FIR radiation are of major interest for the user community. In this paper, we propose a facility which accommodates an SRF-linac driven cw THz-FEL in combination with an FIR undulator which utilizes the micro-bunched beam. The layout permits almost perfect synchronization between pump and probe pulse as well as nearly independently tunable THz and FIR radiation.

INTRODUCTION

In recent years several accelerator based facilities for THz radiation started to operate. In order to extend the capability of these facilities toward pump-probe experiments a second radiation source synchronized on the femto-second level to the THz source is desirable. The second source could be an external conventional laser system. This option, however, requires complex synchronization of the accelerator based source and the laser. In this report we discuss a way to generate two frequencies from the same electron-beam, such that the synchronization is inherently given.

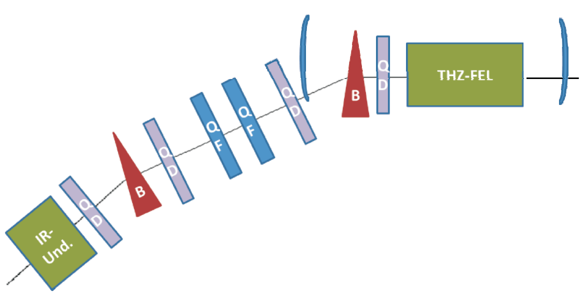

Figure 1: The geometry.

We base our proposal on a 10 MeV electron beam with a typical charge on the order of 300 pC that drives a conventional FEL in oscillator configuration with a frequency of 1 THz. The micro-bunching introduced in the oscillator is converted in a short beam line to a comb-like bunch with a spiked longitudinal distribution capable of generating high harmonics in a second undulator. In the remainder of the report we discuss first the conceptual design, followed by a numerical simulations and concluding remarks.

CONCEPTUAL

Initially we intended to consider an electron beam that had acquired a longitudinal correlation in a buncher cavity, bunch it in an oscillator with a transverse-gradient undulator and then compress it in order to up-convert the micro-bunching to higher frequencies. This proved to be impossible, because the typical momentum spreads generated in THz oscillator destroyed the delicate structures in phase-space. In the process, however, we developed methods to analyze the propagation of distribution functions that proved useful in the analysis of even the simpler setup, we eventually had to settle for.

We started by considering a distribution in longitudinal phase space z_b, δ_b after the initial buncher given by

$$\Psi_b(z_b,\delta_b) = \frac{1}{2\pi\sigma_z\sigma_\delta} \times \exp\left[-\frac{1}{2}\left\{\left(\frac{1}{\sigma_z^2}+\frac{h^2}{\sigma_\delta^2}\right)z_b^2 - 2\frac{h}{\sigma_\delta^2}z_b\delta_b + \frac{\delta_b^2}{\sigma_\delta^2}\right\}\right] \quad (1)$$

where σ_z is the initial bunch length and σ_δ the initial relative momentum spread. The parameter h is the conventional chirp parameter $(dE/dz)/E_0$ of a buncher system, where dE/dz denotes the energy gain per unit length and E_0 the average energy of the beam, 10 MeV in our case.

After modulating the energy in the THz oscillator $\delta_u = \delta_b + a\cos(k_t z_b)$ with amplitude a and wavenumber k_t corresponding to 1 THz we get the distribution function

$$\Psi_u(z_u,\delta_u) = \int d\delta_b \int dz_b \Psi_b(z_b,\delta_b)\, \delta(z_u - z_b)\delta\left(\delta_u - \delta_b - a\cos(k_t z_u)\right) \quad (2)$$

and after ensuring that the Jacobian is unity and doing the integrals we obtain $\Psi_u(z_u,\delta_u)$. We can apply the same method for the propagation through the beam line with a given R_{56} and finally get the distribution function immediately upstream of the second undulator $\Psi_f(z_f,\delta_f)$ as

$$\begin{aligned}\Psi_f(z_f,\delta_f) = {} & \frac{1}{2\pi\sigma_z\sigma_\delta} \\ & \exp\left[-\frac{1}{2}\left\{\left(\frac{1}{\sigma_z^2}+\frac{h^2}{\sigma_\delta^2}\right)[z_f - R_{56}\delta_f]^2\right.\right. \\ & -2\frac{h}{\sigma_\delta^2}[z_f - R_{56}\delta_f](\delta_f - a\cos(k_t[z_f - R_{56}\delta_f])) \\ & \left.\left.+\frac{(\delta_f - a\cos(k_t[z_f - R_{56}\delta_f]))^2}{\sigma_\delta^2}\right\}\right]. \end{aligned} \quad (3)$$

This expression is easily coded in Matlab to produce contour plots of phase space and projections onto the longitudinal axis. The algorithm is extremely rapid. Each run only takes a few second and allows convenient parameter variations.

Playing with the parameters for chirp h, bunching amplitude a and R_{56} of the beam line resulted in the comb-like

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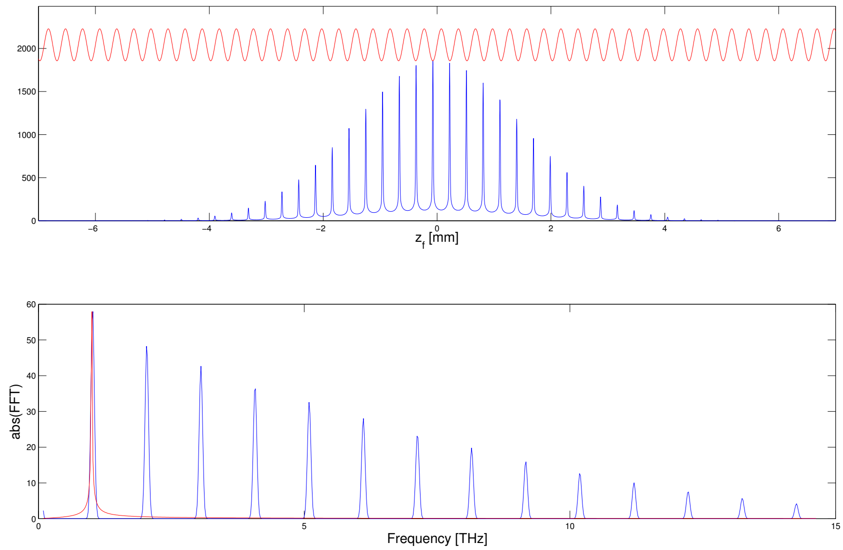

Figure 2: The final longitudinal distribution for a bunching system that is optimally set up according to the parameters given in the main text.

beam shown in the upper graph in Fig. 2. There we show a bunch with initial bunch length $\sigma_z = 1.5\,\mathrm{mm}$, momentum spread $\sigma_\delta = 10^{-3}$ propagated through a system with $h = 2.7/\mathrm{m}$, $a = 0.01, R_{56} = -4.8\,\mathrm{mm}$. Note that we also show a 1 THz oscillation in red for comparison. The bottom graph shows the Fourier-transform of the comb-like bunch with harmonics extending way above the tenth harmonics. We need to point out that the modulation amplitude is rather large compared to the incoherent momentum spread.

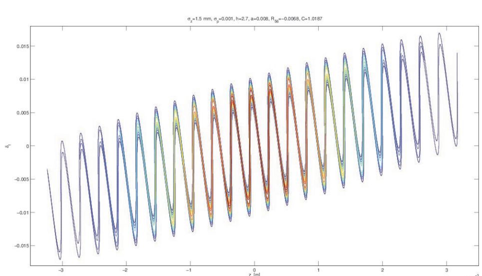

Figure 3: A contour plot of the longitudinal distribution corresponding to Fig. 2. Note that the left slopes of the distribution is rather steep resulting in high harmonics.

The optimum set of parameters to produce the most pronounced comb-like bunch can be understood intuitively by requiring that the modulation in phase space, as shown in Fig. 3 is distorted in such a way in the beam line that one side of the sine-like modulation becomes vertical. A simple linearized model leads to the relation $0 = 1 + R_{56}(h + k_t a)$ which resembles the requirement for maximum compression, but here the chirp is replaced by the chirp h and the slope of the modulation in the FEL $k_t a$. It turns out that with our chosen parameters $k_t a$ is much larger than any reasonable h, such that an initial chirp will only affect the results in a minor way.

NUMERICAL

We tested the feasibility of the scheme with $h = 0$ by simulating the THz oscillator with an optical cavity length of 8.042 m, an undulator with 30 periods of 10 cm each and $K_{rms} = 1.14$ with FELO [1]. For the simulations we assumed the same beam parameters as in the previous section and equal horizontal and vertical normalized emittances of 5 mm mrad.

We found that in saturation the output power reached about 13 MW as shown in Fig. 4 and the modulation amplitude reached 2.6 % after an initial transient of about 300 pulses as

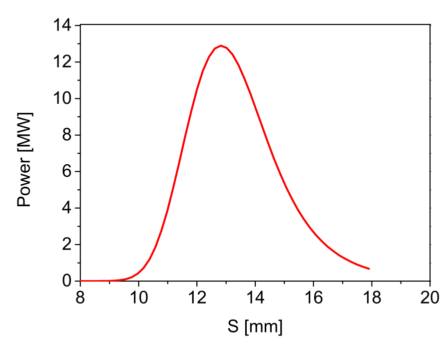

Figure 4: The radiation profile of the THz-FEL after 300 passes is shown

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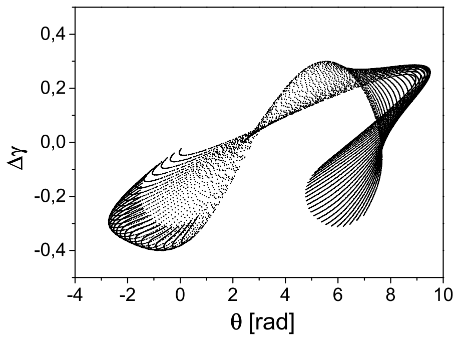

Figure 5: The energy deviation of electrons is plotted against electron phases. Phase space plots for each slice are overlaid on top of each other. There are 30 slices of 300 μm each.

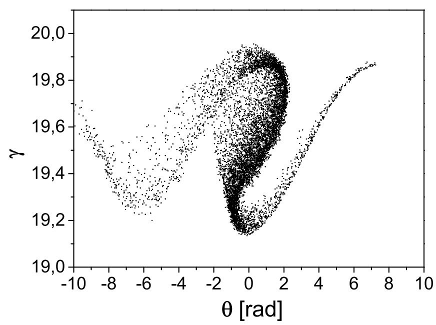

Figure 6: The electron energies as a function of electron phases is plotted for the central slice.

shown in Fig. 5. The gain settles to 15 % in the steady state. Since FELO is a one-dimensional code we verified the three-dimensional behavior of the system and in particular the micro-bunching of the electron beam using Genesis [2] while utilizing the THz photon intensity obtained in the previous FELO runs as well as the same electron beam parameters.

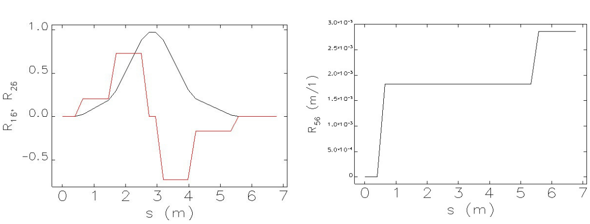

Figure 7: The dispersion and R_{56} for the beam line between the undulators.

Since the optimized THz-FEL saturates, the maximum bunching for the fundamental wavelength is already achieved at the exit of the THz-FEL. Figure 6 shows the longitudinal phase space of the central slice at the undulator exit. The imprinted energy modulation as well as the nonlinear shape of it, typical for saturation behavior, are clearly visible. Generally, in an FEL the maximum bunching of higher harmonics is reached before the fundamental bunching saturates. Thus, the harmonics for which we are aiming in this study are somewhat over-bunched. Therefore it is crucial to adjust the bunching, following the discussion in the previous section, before the entrance of the second undulator which is tuned to the sixth harmonics. For this, we designed a simple beam line consisting of two identical weak dipole magnets and six small quadrupole magnets. The dipoles bend about 12 degree each in the same direction, while the quadrupoles take care of beam size and dispersion compensation. The R_{16}, R_{26}, and R_{56} of the beam line are depicted in Fig. 7. We expect a negligible incoherent synchrotron radiation from this beam line, however, there still might be a small contribution of coherent synchrotron radiation as the current profile is not smooth as discussed below.

For the simulation we modeled an electron distribution suitable for the code elegant [3] corresponding to the distribution obtained from GENESIS and propagated it through the beam line to the entrance of the second undulator. The longitudinal current profile at this position is shown in Fig. 8, while its corresponding spectrum is depicted in Fig. 9. The amount of micro-bunching which can be expected after the

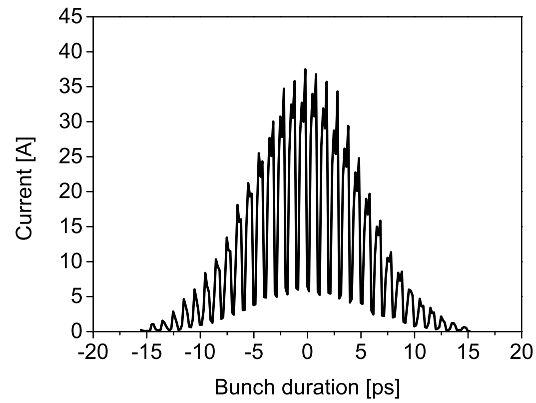

Figure 8: The longitudinal current distribution propagated to the entrance of the second undulator.

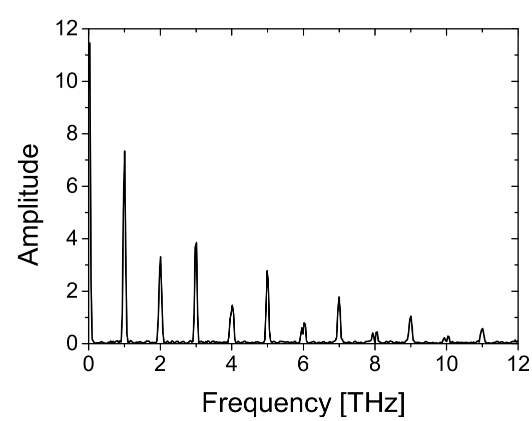

Figure 9: The spectrum corresponding to Fig. 8 obtained by Fourier-transformation.

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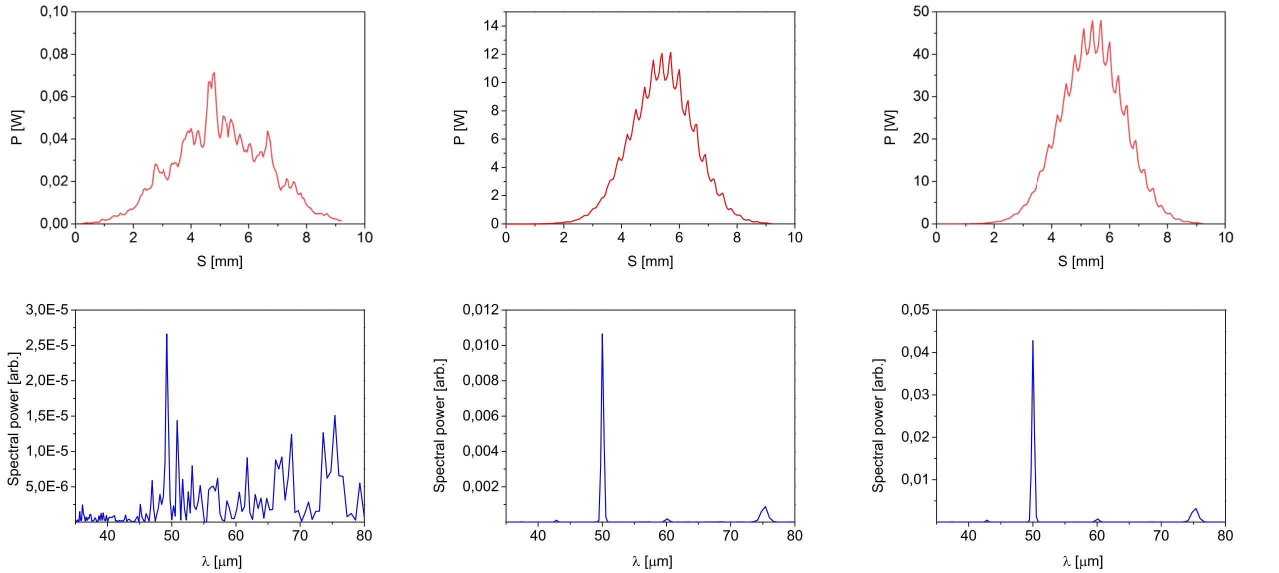

Figure 10: The output power profile (top row) and spectrum (bottom) from the second undulator that is driven by the current distribution from Fig. 8 with zero (left), 0.5 % (center), and 1 % (right) micro-bunching.

passage through the beam line depends on the effect of coherent synchrotron radiation and space charge forces. These effects need to be studied in full 3D and are subject to future studies. From our simple tracking simulations, we expect a maximum bunching of about 2 %. Assuming that the bunching will smear out, due the effects mentioned above, we perform simulations for initial micro-bunching of 0.5 % and 1 %. This longitudinal electron beam distribution is used as input to GENESIS simulations of the second undulator with 20 periods of 2.4 cm each and $K_{rms} = 0.76$. This corresponds to a resonant frequency of 6 THz or equivalently $\lambda = 50\,\mu$m. We find that the initial bunching is crucial. In spite of the current profile with higher spikes, significant radiation output can only be achieved with an initial micro-bunching. Figure 10 demonstrates the effect of micro-bunching clearly. Dependent on the initial micro-bunching we obtain radiation with a peak power of 12 W to 45 W. Even if we do not expect to initiate the FEL process, we think that using GENESIS is justified as we study coherent emission of micro-bunched beam.

CONCLUSIONS

We discussed a scheme where the micro-bunching generated in a THz oscillator is preserved and optimized in a simple beam line to provide a comb-like longitudinal current distribution. This is used in a second undulator tuned to harmonics to generate radiation at the harmonic that is inherently synchronized with the THz radiation from the first undulator. The expected FIR peak output power of 12 W to 45 W is comparable to IR peak output powers from storage rings operating with similar bunch charges but at considerably higher energies.

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