

Active demodulation for high-repetition-rate coherent terahertz generation in storage rings

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Coherent terahertz (THz) sources based on storage rings offer a compelling pathway to high-average-power radiation, leveraging the high revolution frequency of the electron beam. However, current achievable repetition rates are severely constrained by the radiation damping required to dissipate phase-space perturbations introduced during generation. To address this challenge, we propose a novel scheme incorporating an active demodulation mechanism. This method utilizes a phase-reversed laser interaction to actively compensate for the laser-induced energy modulation immediately following the radiation emission. By rapidly restoring the beam quality rather than waiting for natural radiation damping, the recovery time is significantly shortened. Simulations based on HLS-II, combined with an analytical damping estimate, suggest the feasibility of coherent 10 THz generation at repetition rates on the order of 100 kHz, corresponding to an average power of 6.2 mW.

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I. INTRODUCTION

Terahertz (THz) radiation, occupying a unique region of the electromagnetic spectrum between microwaves and infrared light, has emerged as a powerful tool for fundamental research and technological applications [1,2]. Its significance stems from distinctive properties: nonionizing photon energies coinciding with vibrational and rotational modes of molecules and the ability to penetrate various nonpolar materials. These characteristics have positioned THz radiation as a critical probe in diverse fields, including condensed matter physics, biochemistry, medical imaging, and next-generation wireless communications [3–7]. The ongoing expansion of these applications, however, is critically constrained by the availability of high-performance, coherent THz sources that can simultaneously deliver high average power, broad spectral tunability, and practical facility requirements.

In response to this demand, several competing technologies for coherent THz generation have been developed, each presenting a different set of compromises [8–12]. Tabletop sources, particularly those based on optical rectification (OR) in nonlinear crystals, can

generate ultrashort, intense THz pulses with peak electric fields of 0.1–1 MV/cm, which have been instrumental in pioneering strong-field THz nonlinear spectroscopy [8,9]. Nevertheless, thermal effects become prohibitive at high repetition rates, imposing a strict ceiling on the average power, which typically saturates at the milliwatt-to-tens-of-milliwatt level [13,14]. Quantum cascade lasers (QCLs) offer a compact semiconductor alternative for both continuous-wave and pulsed operation; they are hampered by narrow spectral coverage [10] and low output power, which is typically restricted to the submilliwatt level at room temperature [15].

At the large-scale facility end of the spectrum, terahertz free-electron lasers (THz FELs) deliver unparalleled peak power, with single-pulse energy reaching several hundred microjoules [11,12]. However, high-pulse-energy THz FELs are often limited in repetition rate, while high-average-power superconducting facilities can solve this problem but involve immense capital and operational costs. This restricts their widespread deployment to only a limited number of large-scale research facilities. Recent dedicated single-pass THz FELs have demonstrated pulse energies above 0.1 mJ near 3 THz, together with pulse-train structures compatible with MHz-class XFEL operation [16], highlighting their potential for high-peak- and high-average-power THz generation. The present storage-ring-based scheme provides a complementary approach by reusing the circulating electron beam to enhance the repetition rate without requiring a dedicated accelerator facility.

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In this context, storage-ring-based coherent radiation sources present a compelling alternative pathway, leveraging the high revolution frequency ($\sim$ MHz) of relativistic electron bunches to potentially achieve high-average-power THz radiation. Realizing this potential necessitates the production of electron bunches compressed to the picosecond or even subpicosecond scale to enable efficient coherent emission at THz frequencies. A well-established method to achieve such ultrashort bunches is operating the storage rings in a low momentum compaction factor (low- α) lattice [17,18]. This low- α mode of operation has been successfully implemented at facilities like Diamond and SOLEIL light sources to generate stable coherent synchrotron radiation (CSR) [19,20]. Nevertheless, this approach is fundamentally constrained by severe longitudinal instabilities, specifically the CSR-driven microbunching instability, which is triggered by the coherent radiation at short bunch lengths [17]. This instability imposes a stringent lower limit on the achievable bunch length, ultimately confining efficient and stable CSR operation primarily to the millimeter-wave and low-frequency THz range.

Beam manipulation techniques via laser-electron interaction [21], pioneered in the field of FELs, bring new possibilities for advanced THz sources based on storage rings. This technique can be applied to the THz region by seeding the electron bunches with an external laser. Notably, several facilities [22–29] have utilized laser-electron interactions within an undulator to imprint an energy modulation on a localized slice of the electron bunch. This energy modulation is then converted into a density modulation (microbunching) in a subsequent dispersive section, driving the emission of intense coherent THz radiation.

However, the achievable repetition rate is fundamentally constrained by the storage ring's longitudinal damping time. Since the laser-induced phase-space perturbation

requires a recovery period of typically ~ 10 ms, the modulation rate is restricted to approximately 100 Hz per bunch. Even by distributing the process across multiple bunches, the aggregate repetition rate remains limited to the kHz level. Although recent studies utilizing self-modulation mechanisms have successfully demonstrated high-power coherent radiation at repetition rates approaching 10 kHz [30], the significant energy modulation still necessitates a long recovery period, constraining further improvements. This remains several orders of magnitude below the electron beam's intrinsic MHz revolution frequency, which represents a severe underutilization of the source's inherent capacity for high-average-power radiation.

In this paper, we propose a novel scheme to alleviate the repetition-rate bottleneck in storage-ring-based coherent THz sources by introducing an active demodulation section. By applying a phase-reversed laser interaction to suppress the residual energy spread immediately after radiation, the proposed method mitigates the limitation imposed by the ring's slow natural damping. Simulation results show that the active demodulation scheme can effectively reduce the residual beam heating after radiation. Combined with an analytical longitudinal damping estimate, these results suggest that coherent THz pulse generation at repetition rates on the order of 100 kHz, corresponding to an average power of 6.2 mW, may be feasible in principle. This approach therefore provides a potential route toward better utilizing the intrinsic capability of storage rings for high-repetition-rate, high-average-power THz radiation.

II. PRINCIPLE

The entire scheme for ECTG is illustrated in Fig. 1. It comprises a modulator, a radiator (THz wiggler), a demodulator, and two chicanes, all integrated within a single straight section of the storage ring. Instead of

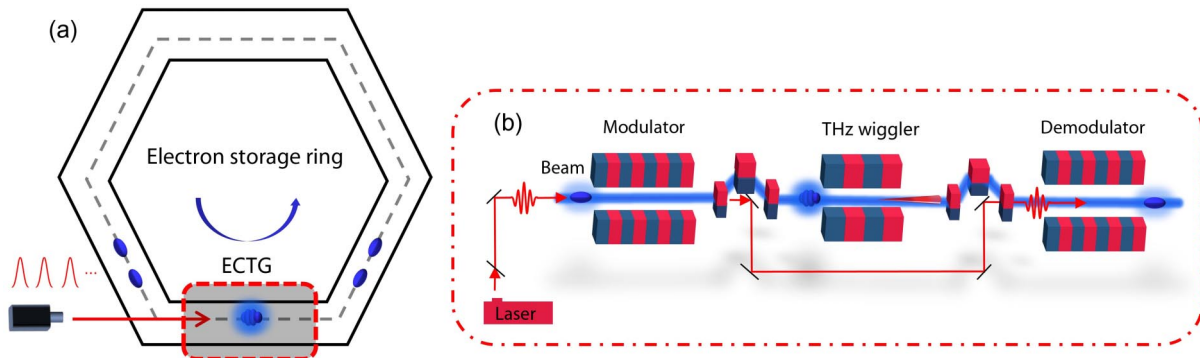


FIG. 1. The Scheme for generating enhanced coherent THz radiation in storage rings. The electron beam undergoes sequential stages of energy modulation, density modulation, radiation emission, and active demodulation within the enhanced coherent THz pulse generation (ECTG) structure. Upon exiting the ECTG structure, the electron beam's microbunching is significantly suppressed, and the beam recovers via damping toward equilibrium in the ring. (b) Detailed layout of the ECTG integrated into a single straight section.

splitting the beam, the scheme employs a sequential interaction configuration where the same temporally beating laser pulse drives both the modulation and demodulation sections. The beating pulse is generated by splitting a broadband, linearly chirped pulse into two delayed replicas and recombining them. The laser pulse exiting the modulator is extracted and transported downstream to the demodulator, where it interacts with the electron beam a second time to cancel the energy modulation. The process begins as the beating laser pulse imprints a periodic energy modulation on the electron beam in the modulator [31]. The first chicane then converts this energy modulation into a density modulation (microbunching), which subsequently drives the emission of intense coherent THz radiation in the THz wiggler. Following radiation, the beam passes through a second chicane and the demodulation section, which actively compensates for the phase-space perturbation from the prior modulation and radiation. This crucial step effectively restores the beam quality, allowing it to promptly recover a steady state and sustain the cyclic generation of high-repetition-rate THz pulses.

The two delayed replicas have the same center wavelength and optical spectrum. Because the common source pulse is linearly chirped, the two replicas have different instantaneous frequencies at the same time within their temporal overlap, producing a tunable THz beating pattern [31]. The resonant laser-electron interaction within the modulator therefore imposes an optical-scale sinusoidal energy modulation whose amplitude follows a picosecond beating envelope. This induced THz-scale periodic structure in the electron beam's energy distribution is critical for enabling the emission of intense coherent radiation at the corresponding terahertz frequency upon subsequent bunching [23,32].

For the radiator, a short-period THz wiggler was employed in preference to a standard bending magnet. While a bending magnet can efficiently generate coherent THz synchrotron radiation, it induces significant transverse-longitudinal phase-space coupling. Such coupling would severely compromise the subsequent demodulation process. In contrast, the wiggler configuration minimizes phase-space distortion, thereby maintaining the reversibility required for effective demodulation, without sacrificing THz radiation intensity.

Following the generation of intense THz pulses in the wiggler, the electron beam enters a dedicated demodulation section designed to compensate for the phase-space perturbations accumulated during the preceding modulation and radiation stages. This section consists of a magnetic chicane and an undulator. The chicane is configured to provide a negative R56 value, which is achieved by integrating quadrupole magnets with the standard chicane structure (not explicitly shown) to cancel the net longitudinal dispersion imparted by the upstream

modules as shown in Eq. (1). The undulator is identical in design to the modulator but is operated with the seeding laser phase-shifted by π , thereby effectively reversing the energy modulation.

$$R_{56,c2} = -(R_{56,\text{mod}} + R_{56,c1} + R_{56,\text{wig}}). \quad (1)$$

It is important to acknowledge that the imprinted beam structure is partially degraded during the coherent radiation process within the wiggler. This degradation arises from the stochastic nature of spontaneous photon emission and nonlinear energy exchange during the FEL interaction, a process that is intrinsically irreversible and cannot be fully compensated by downstream manipulation. Consequently, the radiator length is minimized to limit phase-space distortion. Following interaction with the phase-reversed laser in the demodulator, the electron beam energy spread is significantly suppressed. As the beam continues to circulate, natural synchrotron damping restores it to its initial equilibrium, completing the sequential process of modulation, radiation, demodulation, and damping. This strategy intentionally accepts a modest reduction in single-pulse peak power to enable a substantial increase in repetition rate and the attainment of a stable operational equilibrium.

After the demodulation section, the energy spread of the electron beam is not perfectly restored to its initial value. Instead, it undergoes a cyclic process of excitation (from modulation and radiation), active compensation via demodulation, and radiative damping within the storage ring, eventually converging to a new steady state. The temporal evolution of the beam energy spread in the storage ring is governed by the following expression [33]:

$$\frac{d\sigma_\delta^2}{dt} = -\frac{2}{\tau_e}(\sigma_\delta^2 - \sigma_{\delta 0}^2), \quad (2)$$

where σ_δ is the relative energy spread, $\sigma_{\delta 0}$ is the natural equilibrium energy spread, and τ_e is the longitudinal damping time.

A periodic energy modulation is applied to the electron beam circulating in the storage ring, with a period of $T_{\text{mod}} = N_{\text{mod}} T_0$, where N_{mod} denotes the number of revolution turns per modulation cycle and T_0 is the revolution period. At the end of each modulation event, an instantaneous increase in energy spread is imparted to the beam, introducing an energy spread increment of $\Delta\sigma_{\text{heat}}^2 = \sigma_{\delta,\text{after}}^2 - \sigma_{\delta,\text{before}}^2$. Between consecutive modulation events, the beam experiences radiation damping, driving the energy spread toward its natural equilibrium value. Consequently, the time evolution of the variance $\sigma^2(t)$ can be expressed as:

$$\sigma^2(t) = \sigma_{\delta 0}^2 + (\sigma_{\text{after}}^2 - \sigma_{\delta 0}^2)e^{-2t/\tau_e}, \quad (3)$$

where t represents the time elapsed since the last modulation event.

In the steady-state regime, the beam satisfies the periodicity condition $\sigma_{n+1}^2 = \sigma_n^2$. Solving for the steady-state energy spread variance immediately before and after modulation yields:

$$\sigma_{\delta, \text{before}}^2 = \sigma_{\delta 0}^2 + \frac{\Delta\sigma_{\text{heat}}^2 \exp(-2T_{\text{mod}}/\tau_e)}{1 - \exp(-2T_{\text{mod}}/\tau_e)}, \quad (4)$$

$$\sigma_{\delta, \text{after}}^2 = \sigma_{\delta 0}^2 + \frac{\Delta\sigma_{\text{heat}}^2}{1 - \exp(-2T_{\text{mod}}/\tau_e)}. \quad (5)$$

Under repeated modulation and radiation damping, the energy spread approaches a periodic steady state. Here, $T_{\text{mod min}}$ does not represent a dynamical-stability threshold. Instead, it is defined as the shortest modulation period for which the energy spread immediately after modulation remains below the maximum allowable value, $\sigma_{\text{after}} \leq \sigma_{\delta \text{max}}$. This limiting period is given by:

$$T_{\text{mod min}} = -\frac{\tau_e}{2} \ln \left(1 - \frac{\Delta\sigma_{\text{heat}}^2}{\sigma_{\delta \text{max}}^2 - \sigma_{\delta 0}^2} \right). \quad (6)$$

Figure 2 illustrates the time evolution of the beam energy spread in the storage ring based on this model. For the analytical derivation, the beam heating is quantified by the increment of the energy spread variance, $\Delta\sigma_{\delta, \text{heat}}^2$. For convenience, in the following discussion and in Fig. 3, we also refer to the equivalent residual energy spread increment. The initial natural energy spread is set to

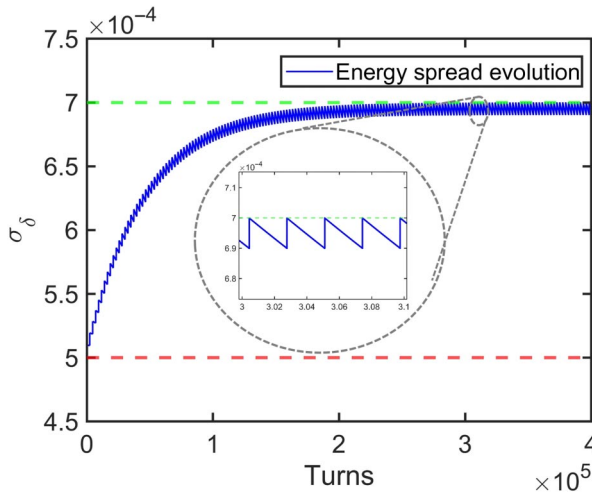


FIG. 2. Time evolution of the beam energy spread σ_{δ} as a function of revolution turns in the storage ring. The dashed red and green lines represent the natural equilibrium energy spread $\sigma_{\delta 0}$ and the predefined upper limit $\sigma_{\delta \text{max}}$, respectively. The inset displays a magnified view of the steady-state sawtooth oscillation caused by the periodic heating-and-damping process.

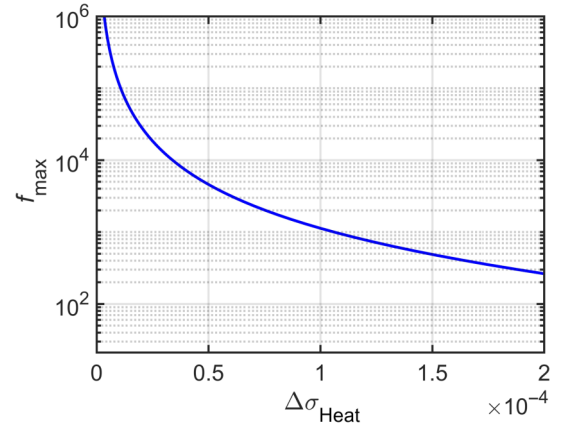


FIG. 3. Calculated maximum radiation repetition rate as a function of the residual energy spread increment per manipulation cycle $\Delta\sigma_{\text{heat}}$.

$\sigma_{\delta} = 5 \times 10^{-4}$, with a predefined upper limit of $\sigma_{\delta \text{max}} = 7 \times 10^{-4}$. The longitudinal damping time is 10 ms, and the revolution period is 0.22 μs . Assuming a residual energy spread increment of $\Delta\sigma_{\text{heat}} = 1 \times 10^{-5}$ per modulation event, the analytical result gives a minimum modulation interval of $N_{\text{mod min}} = 2329$ turns, as determined by the condition $\sigma_{\text{after}} \leq \sigma_{\delta \text{max}}$ in the periodic steady state. With a fill pattern of 60 buckets filled in the ring, the maximum achievable THz repetition rate is calculated to be $f \approx 117$ kHz. This rate could be further increased by reducing the energy spread increment per event or by installing a damping wiggler to shorten the longitudinal damping time. It is worth noting that, in such a high-repetition-rate regime, the limitation on the pulse repetition rate may shift from beam dynamics to the available power of the seed laser system.

Furthermore, an analysis of the maximum achievable modulation repetition rate under different energy spread increments $\Delta\sigma_{\text{heat}}$ is presented in Fig. 3, with all other parameters consistent with those mentioned above. The results demonstrate a steep inverse dependence of the maximum repetition rate on the energy spread increment. Specifically, in conventional schemes where the incremental energy spread typically exceeds 1×10^{-4} , the repetition rate is confined to the few-kHz level. However, by actively demodulating the beam to suppress the increment to the level of $\sim 1 \times 10^{-5}$, the achievable repetition rate increases by 2 orders of magnitude, exceeding 100 kHz. This dramatic sensitivity underscores that the active suppression of beam heating is the decisive factor in unlocking high-repetition-rate operation.

III. SIMULATION RESULTS

To assess the feasibility of the proposed scheme under realistic conditions, we adopt the parameters of the HLS-II storage ring [34] as a representative case. The ring operates

at a beam energy of 800 MeV, with a natural fractional energy spread of $\sigma_\delta = 4.7 \times 10^{-4}$ and a typical rms bunch length of $\sigma_b = 50$ ps. Although this beam energy is substantially higher than the range usually regarded as optimal for THz generation under the FEL resonance condition, which typically lies in the 20–100 MeV regime, it is representative of many second- and third-generation storage rings operating from several hundred MeV to a few GeV. Demonstrating the viability of the scheme under such nonoptimal conditions therefore highlights its broader applicability. In addition, dedicated operation at lower beam energies could further extend the accessible THz frequency range and provide additional flexibility for future optimization.

The nominal element lengths give a total insertion length of approximately 3.8 m. We therefore regard 5 m as a compact design target rather than a demonstrated engineering constraint.

The insertion layout shown in Fig. 1 includes the principal functional elements of the proposed scheme. The dispersive-section lengths used in the present model are nominal values, while the final insertion length will be determined through detailed optimization of the dispersive sections, transverse matching optics, and realistic magnet dimensions. A length of 5 m is adopted as the target for the compact layout.

For clarity, the radiator strength is quoted in terms of the conventional undulator parameter, $K = 31.28$, which corresponds to the planar-undulator input parameter $a_w = 22.12$ used in GENESIS. Together with $\lambda_w = 0.30$ m and $\gamma = 1565.6$, this yields a resonant wavelength of approximately 30 μm , corresponding to 10 THz.

The modulation is driven by a temporally beating laser pulse generated by recombining two delayed replicas of the same linearly chirped broadband pulse centered at 800 nm. The two replicas have the same optical spectrum, while their relative delay produces an instantaneous frequency difference of 10 THz within the temporal overlap region.

The common broadband pulse must support a frequency span of at least 10 THz, corresponding near 800 nm to a lower-bound wavelength bandwidth of approximately 21.3 nm. A larger usable bandwidth may be required, depending on the chirp rate, relative delay, and required overlap duration. If the lower-bound frequency span is treated as the FWHM bandwidth of a transform-limited Gaussian pulse, the corresponding pulse duration is no longer than approximately 44.1 fs.

The quoted duration of 2 ps refers to the stretched beating envelope at the laser-electron interaction point. The quoted peak power of 51 MW denotes the maximum instantaneous power of the beating profile, and the corresponding pulse energy is approximately 0.05 mJ.

The simulated insertion consists of a modulator, a first dispersive section, a two-period THz wiggler, a second

TABLE I. Main parameters of ECTG.

Parameters	Values
Seed laser	
Wavelength	800 nm
Beam waist	874 μm
Modulator and demodulator	
K	9.8
Length (each)	1.2 m
Period length	8 cm
THz wiggler	
K	31.28
Length	60 cm
Period length	30 cm
Chicane	
Max R_{56}	270 μm
Length	40 cm

dispersive section, and a demodulator. The laser-induced modulation, coherent THz emission in the wiggler, and active demodulation are simulated sequentially using the three-dimensional, time-dependent free-electron laser code GENESIS 1.3 [35]. The particle distribution is transferred between the three interaction stages so that the energy modulation, microbunching, coherent THz emission, and residual longitudinal correlations are retained. The two dispersive sections are represented by their longitudinal transfer coefficients, with $|R_{56}| \leq 270 \mu\text{m}$. The postdemodulation particle distribution is subsequently transferred to ELEGANT and tracked through the storage-ring lattice for 2329 turns. The relevant parameters are listed in Table I.

The present simulations represent the two chicanes through their longitudinal transfer coefficients and do not explicitly include CSR or a complete transverse matching lattice. For a representative compact chicane providing $|R_{56}| = 270 \mu\text{m}$, a one-dimensional CSR estimate gives an induced rms relative energy spread of approximately 1.5×10^{-7} per chicane [36]. Including the 10 THz density modulation gives a conservative relative energy variation below 5×10^{-6} , still well below the initial rms energy spread of 4.7×10^{-4} . CSR is therefore not expected to alter the main conclusions, although detailed start-to-end tracking will be required for an experimental implementation [37].

Based on the nominal component lengths adopted in the present conceptual layout, the two modulators, two dispersive sections, and the THz radiator have a combined length of approximately 3.8 m, leaving a nominal space of approximately 1.2 m within the targeted 5 m insertion for transverse matching, diagnostics, and optical components. The final space allocation will depend on the detailed magnet and matching design.

The modulation process is driven by the temporally beating laser pulse described above. Under this condition, the laser-induced energy spread remains sufficiently small for high-repetition-rate operation. As shown in Fig. 4(b), the interaction generates a nearly sinusoidal energy modulation in the longitudinal phase space, increasing the relative energy spread to 5.41×10^{-4} . After passing through the first dispersive chicane, this energy modulation is converted into density modulation at the beat-frequency period. The bunched beam then enters the radiator and emits coherent THz radiation at 10 THz with a peak power of 32 kW.

During radiation, the electron beam phase space is distorted, as expected from the FEL interaction. Figure 4(c) shows the longitudinal phase space at the radiator exit, where the strong longitudinal dispersion shears the beam distribution into a bandlike structure. After passing through the second chicane designed to cancel the net dispersion, the nearly sinusoidal energy modulation is largely restored, as shown in Fig. 4(d). This preservation of the fine phase-space structure is essential for effective demodulation and is primarily enabled by the minimized radiator length of only two periods, which limits irreversible phase-space mixing while still providing sufficient THz radiation power.

The beam then enters the demodulation section, where the residual energy modulation is compensated by a phase-reversed laser pulse. As a result, the relative energy spread is reduced to 4.74×10^{-4} at the demodulator exit, which is only 0.4×10^{-5} above the initial natural value. The corresponding longitudinal phase space is shown in Fig. 4(e), demonstrating a substantial suppression of the residual energy spread growth. To examine the subsequent recovery in the storage ring, the postdemodulation beam distribution is tracked through the ring lattice for 2329 turns in ELEGANT, and the recovered beam state is shown in Fig. 4(f). Together with the residual postdemodulation beam heating and the longitudinal damping estimate discussed above, these results suggest that repetition rates on the order of 100 kHz may be feasible in principle. This estimate is based on a single-cycle GENESIS simulation, multiturn ELEGANT tracking, and a reduced periodic heating-and-damping model.

The optimization of the radiator length constitutes a critical trade-off in the proposed scheme because the phase-space perturbation induced during radiation directly affects the subsequent demodulation process. Although increasing the number of wiggler periods can enhance the THz peak power, it also introduces stronger nonlinear distortion and phase-space folding, which may preclude

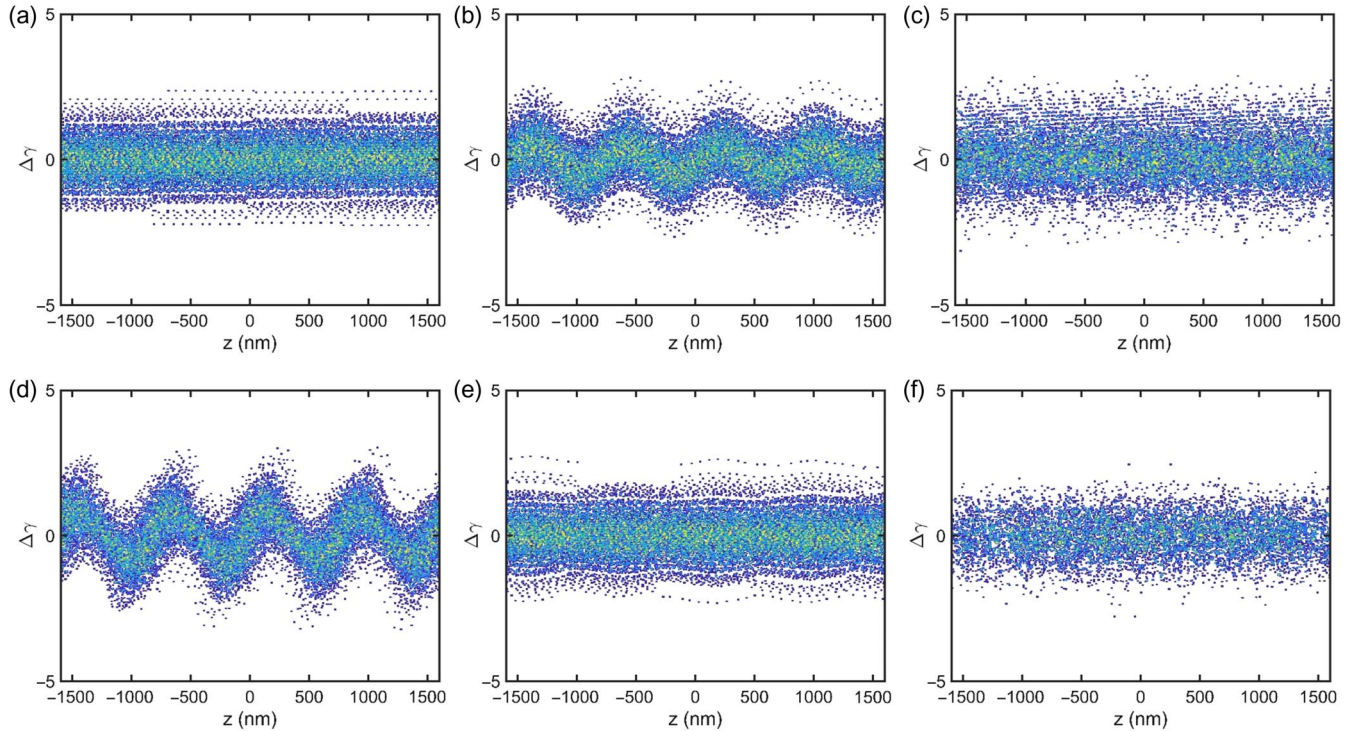


FIG. 4. Evolution of the electron beam longitudinal phase space at the optical wavelength scale throughout one generation cycle. (a) Initial equilibrium phase space. (b) At the exit of the modulator, showing the imprinted sinusoidal energy modulation. (c) At the exit of the radiator, where the phase space is sheared by longitudinal dispersion. (d) At the entrance of the demodulator, after dispersion cancellation, showing the recovery of the nearly sinusoidal structure. (e) At the exit of the demodulator, showing the suppression of the residual energy spread by active demodulation. (f) Recovered beam state after 2329 turns in the storage-ring lattice, obtained by tracking the postdemodulation beam distribution in ELEGANT.

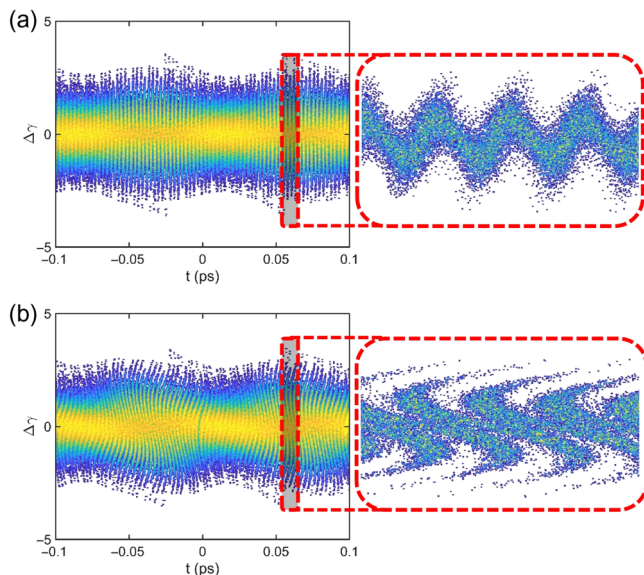


FIG. 5. Longitudinal phase-space distributions of the electron beam after the radiator and dispersion compensation. The left panels show the macroscopic distribution on a picosecond scale, while the right panels (red dashed frames) present the magnified view of the local fine structure. (a) Result for a two-period wiggler, where the beam retains a quasi-sinusoidal energy modulation suitable for demodulation. (b) Result for a 10-period wiggler, where severe phase-space distortion and folding prevent effective phase-space restoration.

efficient recovery of the beam. Figure 5 compares the longitudinal phase-space distributions after the radiator and dispersion compensation for wiggler lengths of 2 and 10 periods. With only two periods, the beam largely preserves a quasi-sinusoidal energy modulation, which is a prerequisite for successful demodulation. In contrast, for a 10-period radiator, the phase space becomes strongly distorted and the sinusoidal structure is washed out, rendering the laser-based demodulation ineffective for recovering the initial steady state.

To maintain compatibility with repetition rates on the order of 100 kHz, the laser parameters are chosen under realistic average-power constraints. The selected beat laser has a peak envelope power of 51 MW, a pulse duration of 2 ps, and a corresponding pulse energy of approximately 50 μ J. Because the same beating pulse is transported sequentially from the modulator to the demodulator, the laser power is not doubled for the two interactions. At 100 kHz, the corresponding average power is approximately 5 W at the interaction point. Broadband optical parametric chirped-pulse amplification (OPCPA) systems operating at 100 kHz have demonstrated average powers of 22.5 and 88.6 W [38,39], indicating that the required pulse parameters are within the range of present high-average-power laser technology. The source power must additionally account for losses associated with pulse stretching, splitting and recombination, and optical transport. The

laser-field evolution in the modulator is calculated self-consistently by GENESIS. Under the parameters considered here, the relative laser-energy depletion is approximately 4×10^{-4} , and the associated changes in the laser power are negligible. The demodulation calculation therefore uses an ideal phase-reversed copy of the input field. Optical losses, dispersion, and phase errors introduced by the external transport line are not included in the present model and should be considered in a detailed experimental design. In addition, the central frequency of the emitted THz radiation remains tunable and is jointly determined by the beat frequency of the seed laser and the magnetic parameters of the wiggler.

The recovered beam state shown in Fig. 4(f) is obtained by tracking the postdemodulation beam distribution through the storage-ring lattice for 2329 turns in ELEGANT, indicating that the beam can recover to conditions compatible with the next radiation cycle. The overall performance of the proposed demodulation scheme depends on the phase matching between the modulation and demodulation lasers, the cancellation of the net longitudinal dispersion, and the degree of nonlinear phase-space distortion introduced in the radiator. In the nominal configuration, the demodulation-laser phase differs by π from the modulation-laser phase.

An additional three-dimensional, time-dependent GENESIS scan was performed by varying only the demodulation-laser phase. The exact π phase reversal reduces the relative energy spread to 4.74×10^{-4} , close to the initial value of 4.70×10^{-4} . A phase error of 0.1π already leaves a residual modulation, and larger phase errors progressively reduce the demodulation efficiency. Because $\Delta\phi = 2\pi\delta L/\lambda_0$, an experimental implementation requires subwavelength optical-path stability and active phase stabilization. A fully closed-loop simulation with repeated GENESIS-ring-GENESIS coupling over many cycles remains beyond the scope of the present proof-of-principle study and will be pursued in future work.

IV. CONCLUSION

In summary, we have proposed a scheme for generating high-repetition-rate coherent THz radiation in storage rings by incorporating an active phase-space demodulation stage. Building upon beat-frequency laser-induced coherent THz emission, the proposed scheme actively suppresses the residual energy spread after radiation and thereby alleviates the repetition-rate limitation imposed by slow natural radiation damping. Numerical simulations based on HLS-II parameters show that the scheme can generate coherent THz pulses centered at 10 THz with a peak power of 32 kW and a pulse energy of 62 nJ. Combined with the residual postdemodulation beam heating and the longitudinal damping estimate, these results suggest that repetition rates on the order of 100 kHz,

corresponding to an average power of 6.2 mW, may be feasible in principle.

In addition, the radiation frequency is tunable within the 5–30 THz range by adjusting the laser beat frequency and the wiggler parameters. The proposed scheme is also compatible with damping wigglers, which may provide a further route toward higher average power [40]. Overall, this work offers a promising approach for overcoming repetition-rate limitations in storage-ring-based coherent THz sources and may be useful for the development of high-average-power THz user facilities.

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DATA AVAILABILITY

The data that support the findings of this article are openly available.

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