# ENHANCED COHERENT TERAHERTZ GENERATION IN STORAGE RINGS WITH AN ACTIVE DEMODULATION SECTION

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*Abstract*

Coherent terahertz (THz) radiation sources based on storage rings hold significant promise for generating high-average-power THz radiation, owing to the high revolution frequency of the electron beam. However, the achievable repetition rate is limited by the long time required for the ring damping mechanism to dissipate the phase-space perturbation introduced by the modulation and radiation process. To overcome this bottleneck, we propose a novel scheme incorporating a dedicated demodulation section to enhance the generation of high-repetition-rate coherent THz radiation. In this scheme, after a seed laser imposes an energy modulation and a THz wiggler emits coherent radiation, the electron beam is actively recovered in the demodulation section. This process facilitates rapid beam recovery, allowing the beam to be effectively damped and ultimately reach a new steady state. Simulation results demonstrate that this integrated setup successfully produces coherent THz radiation pulses at a repetition rate of 100 kHz, achieving an average power of 6.2 mW at 10 THz.

## INTRODUCTION

Terahertz radiation is important for spectroscopy, imaging, and materials studies [1, 2]. A persistent challenge is to obtain a source that simultaneously provides useful pulse energy, tunability, and high average power. Storage rings offer an attractive route because the electron beam circulates at MHz revolution frequency and can therefore support high-average-power radiation if the beam perturbation caused by the THz generation process is sufficiently controlled.

Laser-based beam manipulation has already enabled coherent THz generation in several storage rings by imprinting an energy modulation, converting it into microbunching with a chicane, and radiating in a downstream structure [3,4]. The main limitation is that the laser-induced phase-space perturbation must damp before the bunch can be reused efficiently, which typically restricts the per-bunch repetition rate to around 100 Hz and the total rate to the kHz level.

In this work, we introduce an active demodulation stage to suppress the residual energy spread after THz emission and thereby alleviate the damping bottleneck. The proposed scheme reuses the modulation laser after optical transport to a downstream demodulator and applies a phase-reversed interaction to compensate the residual modulation. Three-dimensional time-dependent simulations combined with storage-ring tracking and a longitudinal damping estimate indicate the potential for repetition rates on the order of 100 kHz.

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## PRINCIPLE AND REPETITION-RATE ESTIMATE

The ECTG layout is shown in Fig. 1. It integrates a modulator, a THz radiator, a demodulator, and two chicanes into one straight section. A dual-frequency laser pulse first induces a beat-envelope energy modulation in the electron beam. After the first chicane, this modulation is converted into THz-scale density bunching that drives coherent radiation in the radiator. The same laser pulse is then transported to the demodulator, where a phase-reversed interaction is used to cancel the residual energy modulation after radiation.

This active demodulation is the key difference from conventional laser-modulation THz schemes. Instead of relying entirely on the natural longitudinal damping of the ring to remove beam heating, the present scheme suppresses the residual energy-spread growth immediately after radiation. The remaining beam heating then determines the minimum interval between two manipulation cycles.

Based on the longitudinal damping model, the minimum modulation interval can be expressed as

$$T_{\mathrm{mod,min}} = -\frac{\tau_\epsilon}{2}\ln\left(1-\frac{\Delta\sigma_{\mathrm{heat}}^2}{\sigma_{\delta\,\max}^2-\sigma_{\delta 0}^2}\right), \qquad (1)$$

where $\tau_\epsilon$ is the longitudinal damping time, $\sigma_{\delta 0}$ is the natural energy spread, $\sigma_{\delta\,\max}$ is the allowed upper limit, and $\Delta\sigma_{\mathrm{heat}}$ denotes the equivalent residual energy-spread increment after one cycle. For the HLS-II example, taking $\tau_\epsilon = 10$ ms, $\sigma_{\delta 0} = 5\times10^{-4}$, $\sigma_{\delta\,\max} = 7\times10^{-4}$, and $\Delta\sigma_{\mathrm{heat}} = 1\times10^{-5}$ gives a damping interval of 2329 turns. With 60 filled buckets, the corresponding maximum THz repetition rate reaches about 117 kHz.

Figure 2 shows the sensitivity of the achievable repetition rate to the residual beam heating. In conventional schemes, where the energy-spread increment is typically above $10^{-4}$, the repetition rate remains in the few-kHz range. Once the increment is reduced to the order of $10^{-5}$ through active demodulation, the rate increases by about two orders of magnitude.

From a storage-ring perspective, the benefit of the demodulation section is not limited to lowering the rms energy spread. More importantly, it mitigates the irreversible phase-space distortion left after the radiator, so that the bunch is returned closer to a reusable state immediately after one generation cycle.

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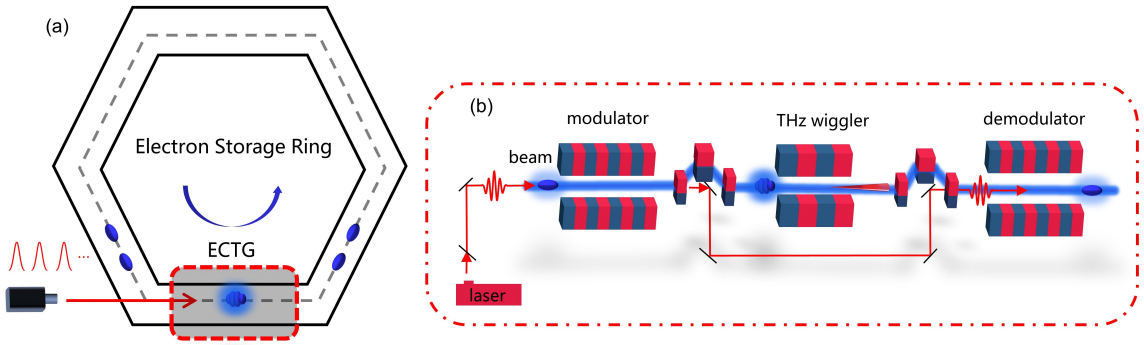



Figure 1: Enhanced coherent THz generation (ECTG) scheme in a storage ring.

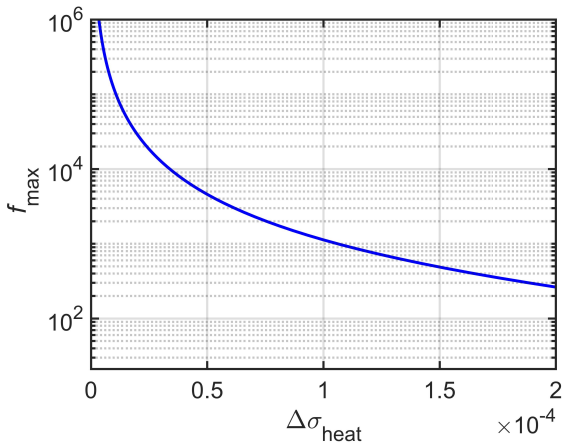



Figure 2: Maximum repetition rate versus residual energy-spread increment per cycle.

Table 1: Main Parameters of the ECTG Example

| Parameter | Value |
|---|---|
| Seed laser wavelength | 800 nm |
| Seed laser beam waist | 874 µm |
| Modulator/demodulator $K$ | 9.8 |
| Modulator/demodulator length (each) | 1.2 m |
| Modulator period length | 8 cm |
| THz wiggler $K$ | 31.28 |
| THz wiggler length | 0.60 m |
| THz wiggler period length | 30 cm |
| Maximum chicane $R_{56}$ | 270 µm |
| Chicane length | 0.40 m |

## SIMULATION RESULTS

To evaluate the scheme under realistic conditions, we use HLS-II parameters as a representative case [5]. The ring energy is 800 MeV, the natural fractional energy spread is $4.7 \times 10^{-4}$, and the rms bunch length is about 50 ps. The complete interaction process is simulated with the three-dimensional, time-dependent code GENESIS 1.3, and the recovered post-demodulation distribution is tracked in the storage-ring lattice with ELEGANT.

The main parameters of the ECTG setup are summarized in Table 1. The total insertion length is limited to 5 m, so the full modulator–radiator–demodulator system can fit into a standard straight section. The radiator parameters correspond to a resonant wavelength of about 30 µm, i.e. 10 THz. The beat laser is centered at 800 nm with a 2 ps envelope duration and about 51 MW peak envelope power, corresponding to roughly 50 µJ pulse energy.

HLS-II is adopted as a representative compact storage ring whose straight-section length, natural energy spread, and longitudinal damping time are suitable for evaluating the feasibility of active demodulation.

Figure 3 presents the simulated longitudinal phase-space evolution through one generation cycle. At the modulator exit, the beat laser produces a nearly sinusoidal energy modulation and increases the relative energy spread to $5.41 \times 10^{-4}$. After the first chicane, this modulation becomes THz-scale density bunching, and the beam emits coherent 10 THz radiation in the radiator with 32 kW peak power.

The radiator must be short enough to preserve the phase-space structure required by the downstream demodulation. After the radiator and compensation chicane, the sinusoidal structure is largely restored, which is essential for the reverse interaction in the demodulator. In the demodulator, the phase-reversed laser suppresses the residual modulation, reducing the relative energy spread to $4.739 \times 10^{-4}$, only $0.39 \times 10^{-5}$ above the initial natural value. Tracking this distribution for 2329 turns indicates recovery toward a state compatible with the next modulation cycle.

## CONCLUSION

A phase-reversed laser interaction can actively suppress the residual energy spread after coherent THz emission in a storage ring and therefore relax the repetition-rate limit imposed by slow natural damping. For the HLS-II example, simulations show coherent 10 THz pulses with 32 kW peak power and 62 nJ pulse energy, while the residual beam heating is low enough to support repetition rates on the order of 100 kHz. This corresponds to an average power of 6.2 mW and suggests a practical path toward higher-average-power THz sources in storage rings.

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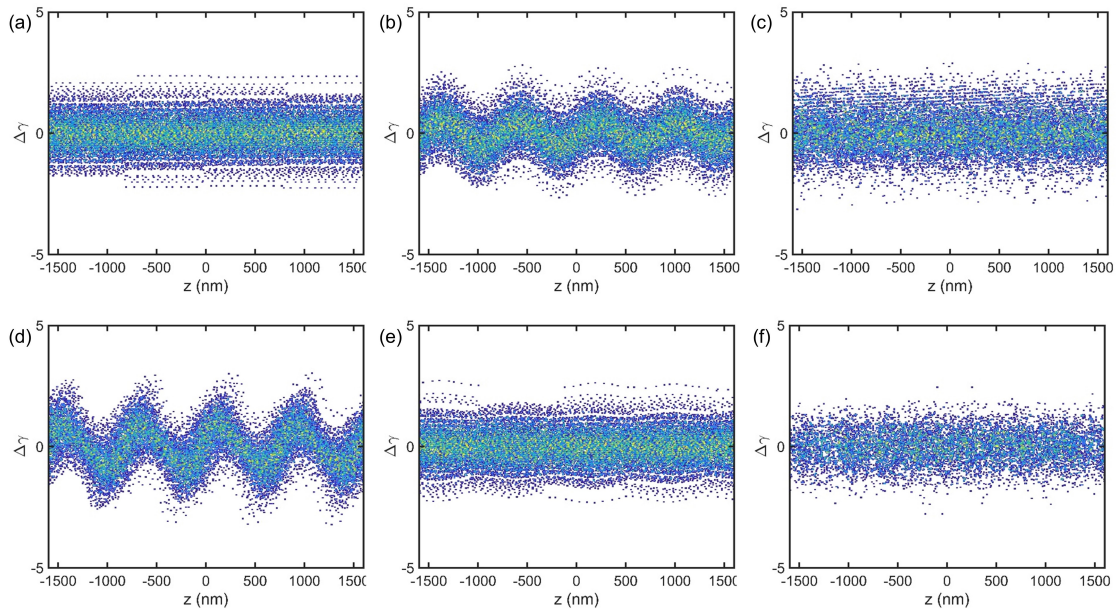



Figure 3: Longitudinal phase-space evolution through one generation cycle.

The results indicate that beam recovery is a key factor for sustainable average output in storage-ring THz sources, and that the proposed ECTG scheme provides a compact implementation of this concept.

## ACKNOWLEDGMENT

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