FAST COOLING OF BUNCHES IN COMPTON STORAGE RINGS*

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Abstract

We propose an enhancement of laser radiative cooling by utilizing laser pulses of small spatial and temporal dimensions, which interact only with a fraction of an electron bunch circulating in a storage ring. We studied the dynamics of such electron bunch when laser photons scatter off the electrons at a collision point placed in a section with nonzero dispersion. In this case of 'asymmetric cooling', the stationary energy spread is much smaller than under conditions of regular scattering where the laser spot size is larger than the electron beam; and the synchrotron oscillations are damped faster. Coherent oscillations of large amplitude may be damped within one synchrotron period, so that this method can support the rapid successive injection of many bunches in longitudinal phase space for stacking purposes. Results of extensive simulations are presented for the performance optimization of Compton gamma-ray sources and damping rings.

INTRODUCTION

Compton rings, i.e. electron storage rings equipped with laser resonators in which the circulating electron bunches scatter off laser photons, have few, if any, competitors as intensive sources of gamma-ray radiation. In a Compton ring the gamma-ray radiation is generated by electrons of moderate energy. One of the major performance limitations of these sources arises from the large recoils suffered by the electrons when scattering off the laser photons, which causes a large energy spread of the circulating electrons; see [1].

In our previous works we found that small sizes of the laser pulse lead to a reduction of the steady-state emittances by up to a factor of two. In our recent paper [2], a model was studied, both theoretically and with simulations, which considered the interaction of electrons circulating in a Compton ring with laser pulses located in a dispersive section of the ring. In the model investigated it was supposed that only electrons with energy above the synchronous one are exposed to the laser photons. It was shown that under these conditions the energy spread in the bunch may be sufficiently reduced as well as the cooling time.

In the present paper we report further studies on the asymmetric cooling, also taking into account the transverse particle oscillations. The paper covers both theory and extended simulations in the next two sections.

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THEORY

Theoretical Model

The model is based on the following assumptions:

- The collision point (CP) where the laser pulse crosses the trajectory of the electron bunch is set up in a section with nonzero dispersion D: so that the transverse position, x_i, of the i-th electron depends on its relative energy deviation, $\delta \equiv (\gamma_i - \gamma)/\gamma$, from the synchronous particle as $x(\delta) = D\delta +$ betatron osc. terms $= g\delta\beta +$ bet. osc. , where γ_i designates the Lorentz-factor of the i-th electron, and β the betatron function (envelope) at the Compton collision point (CP). The function $g = D/\beta$ is a normalized, dimensionless dispersion.
- The density of the laser radiation at CP can be approximated by a step function: the scattering of laser photons takes place only at $x \geq 0$, see [2].
- Both the synchrotron and betatron oscillations are harmonic; a Maxwellian steady-state distribution is established both for δ^2 and for the squared amplitude of the betatron oscillations.

Schematically the theoretical model with the laser pulses used for the simulations is depicted in Fig. 1. The laser field (gray ellipses) is modeled by an array of individual pulses which are transversely displaced from one another.

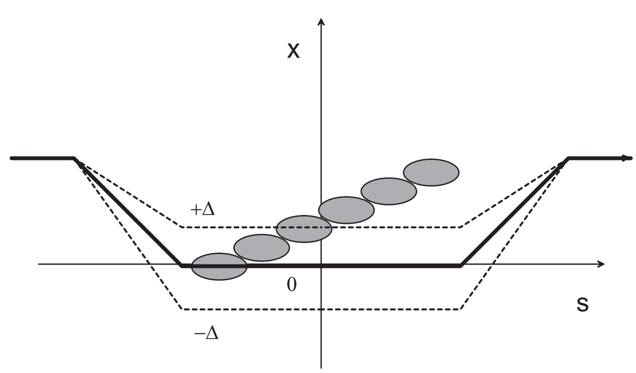

Figure 1: Trajectories at CP with positive ($+\Delta$), negative ($-\Delta$), and zero deviation of electron energy.

Under these assumptions, the average scattering event (the recoil averaged over the Compton spectrum, and over both the synchrotron and betatron phases θ, ψ) contributes to the squared amplitude of synchrotron oscillations, $S \equiv \langle \delta^2 \rangle$, and to the normalized transverse emittance, $\varepsilon = \epsilon/\beta$ as follows:

$$\begin{aligned} \frac{\Delta\varepsilon}{\Delta\tau} &= -\frac{b}{2}\varepsilon + bg\sqrt{2\varepsilon}F_s(G) + \frac{3b^2}{80\gamma^2}\left(1+\frac{14}{3}g^2\gamma^2\right); \\ \frac{\Delta S}{\Delta\tau} &= -bS - b\sqrt{2S}\,F_c(G) + \frac{7b^2}{40}\,. \end{aligned} \quad (1)$$

where $b \approx 4\gamma\gamma_{\rm las}$ is the maximal recoil undergone by the electron scattered off the laser photon, with $\gamma_{\rm las}$ denoting the ratio of the laser photon energy to the electron rest mass, $G \equiv g\sqrt{S/\varepsilon}$, and τ is the time in units of scattering events. The nonlinear functions $F_c(G)$ and $F_s(G)$ coupling the longitudinal and the transverse motions are presented in Fig. 2.

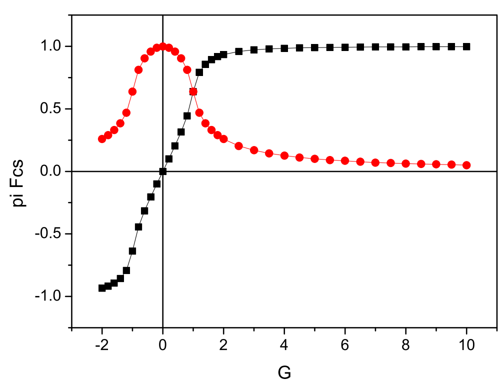

Figure 2: $\pi F_s(G)$ (red) and $\pi F_c(G)$ (black) vs. G.

Steady States

Steady-state moments correspond to zero changes in the average moments (1): $\Delta\varepsilon = 0$, $\Delta S = 0$. Since the energy spread S and the emittance ε are interdependent, the spread depends on the emittance and vice versa, the roots should be attained at the same value of the dispersion g.

In the particular case of zero dispersion, S and ε are independent of each other, and the steady states become [1]:

$$\varepsilon_* = \frac{3}{40}\frac{b}{\gamma^2} \approx \frac{3}{10}\frac{\gamma_{\rm las}}{\gamma}\,, \quad S_* = \frac{7b}{40} \approx \frac{7}{10}\gamma\gamma_{\rm las}\,. \quad (2)$$

A nonzero dispersion at the CP causes the well-known additional excitation proportional to g^2 that significantly builds up the emittance. In addition, a nonzero dispersion at CP together with the asymmetric laser field gives rise to terms proportional to $\sqrt{\varepsilon}$, $\sqrt{S}$ with *opposite signs* for the two planes. This means that only one degree of freedom, i.e., either the longitudinal or one of the two transverse degrees, may be cooled while the other is heated up.

'Decrements'

Compton scattering of electrons induces damping of the synchrotron and betatron oscillations, just like the damping due to emission of regular synchrotron radiation. In the case that the CP lies in a dispersion-free section, $g = 0$, it follows from (1) that the emittance and the squared energy spread behave as

$$\begin{aligned} \varepsilon(\tau) - \varepsilon_* &= (\varepsilon_0 - \varepsilon_*)\exp(-b\tau/2)\,; \\ \langle p^2\rangle(\tau) - \langle p^2\rangle_* &= \left(\langle p^2\rangle_0 - \langle p^2\rangle_*\right)\exp(-b\tau)\,, \end{aligned}$$

i.e. the difference between the initial and the steady-state values decreases exponentially.

However, in the case $g > 0$ the energy spread decreases in time non-exponentially and towards a smaller asymptotic value. Therefore a final spread $\sqrt{<\delta^2>(\tau)}$, above the steady-state value, $\sqrt{<\delta^2>_*}$, is attained in less scatterings, as is illustrated in Fig. 3.

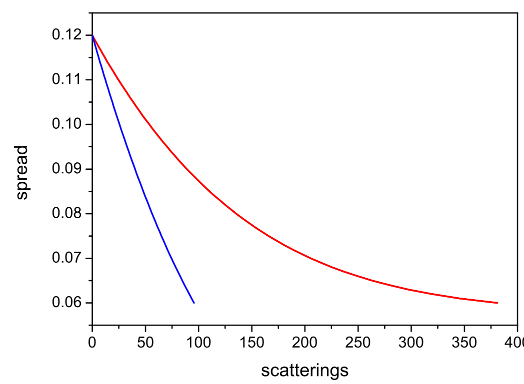

Figure 3: Energy spread vs. number of scattering events, red – non dispersive CP, blue – with a positive dispersion and an asymmetric laser pulse.

The conjugated transverse degree of freedom is cooled more slowly or even heated at $g > 0$, as follows from (1).

SIMULATIONS

Numerical Model

Simulations were performed to validate the principle of asymmetric laser cooling in realistic conditions. The numerical model used for validating the principle of asymmetric laser cooling in [2] was upgraded to include a more refined approximation of the theoretical model: the single laser pulse was replaced with an array of identical pulses of tri-Gaussian density profiles; see Fig. 1. Each individual pulse was displaced vertically by a certain step. The crossing angle between the electron and laser orbits in the (x, z) plane was $8°$, for all pulses.

The following parameters were controlled:

- Dispersion D at CP: the reference orbit horizontal (or vertical) position is $x_0(p) = Dp$.
- Shift of the first laser pulse in x-direction from the reference orbit and displacement of the each pulse with respect to the previous one.

Results

Simulations were done for 1 GeV electrons colliding with 1 eV laser photons. The steady-state emittance and the energy spread for different dispersion values at the CP are presented in Fig. 4.

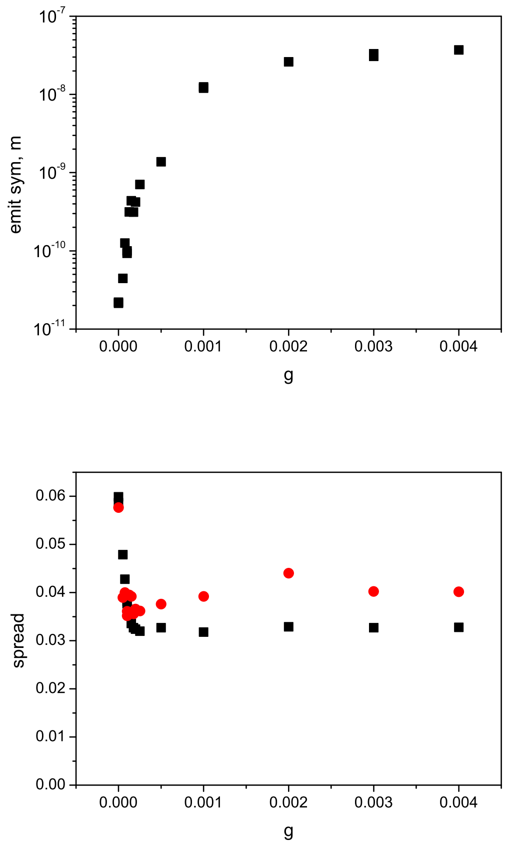

Figure 4: Simulated emittance (top) and spread vs g (black). The red dots represent the theoretical estimation of spread (1) using the emittance from simulations.

The steady-state spread shows a'saturation' at $g \geq 0.0005$ (or $g\gamma \geq 1$), while the emittance saturates later, for larger dispersion.

The simulated behavior of the momentum spread and emittance in time (number of scattering events undergone by the average electron), in Fig. 5, confirms the theoretical predictions of Fig. 3. The initial values for momentum spread and emittance are not exactly the same.

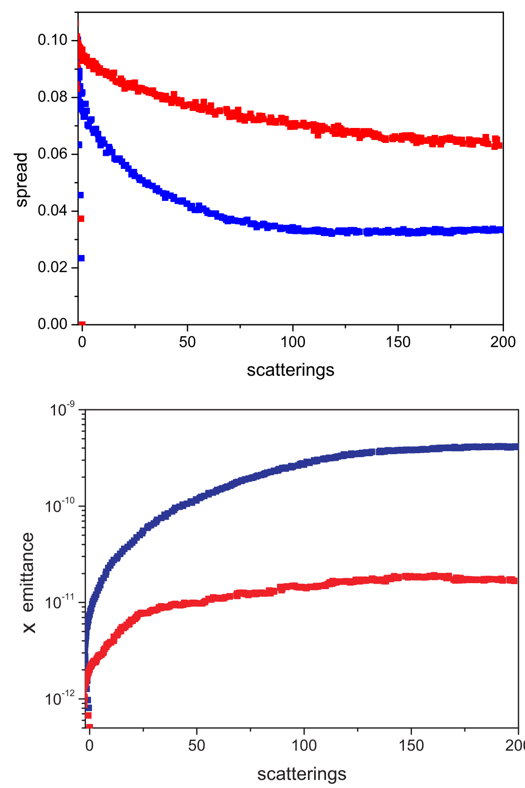

Figure 5: Simulated spread (top) and x-emittance (bottom) vs number of scattering events, red: zero dispersion, blue: $g = 2 \times 10^{-4}$.

CONCLUSIONS

Spatial localization of the laser field allows reducing one of the most performance-limiting parameters of the Compton-ring gamma sources, namely the energy spread of the circulating bunches, as well as a significant decrease in the cooling period for laser-based damping rings.

The construction of a low-energy damping ring with asymmetric laser cooling appears feasible.

The fast cooling through a localized laser field relaxes the requirements on other parameters for ring-based sources of gamma-ray beams, such as energy acceptance and required RF voltage [3]. It also eases the stacking in a positron accumulator ring for a Compton positron source.

The increase of the transverse emittance due to asymmetric cooling may be tolerable since in laser-dominated rings the 'symmetric' steady-state emittance is very small.

The effect considered deserves an experimental study.

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REFERENCES

[1] E. Bulyak, P. Gladkikh, L. Rinolfi, T. Omori, and J. Urakawa. "Beam dynamics in Compton rings with laser cooling", IPAC'10, Kyoto, Japan, May 2010, tupd093.

[2] E. Bulyak, J. Urakawa, and F. Zimmermann. "Asymmetric laser radiant cooling in storage rings", PAC'11, New York, U.S.A., 2011, mop064.

[3] E. Bulyak, P. Gladkikh, M. Kuriki, T. Omori, J. Urakawa, and A. Variola. "Compton gamma-sources: Beam dynamics and performance", PosiPol'07, Orsay, France, 2007.