EFFECT OF TRANSVERSE COUPLING ON ASYMMETRIC COOLING IN COMPTON RINGS*

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Abstract

Fast cooling of bunches circulating in a Compton ring is achieved by placing the collision point between electron bunches and laser pulses in a dispersive section and by, in addition, introducing a transverse offset between the laser pulse and the electron-beam closed orbit. Growth of the emittance in the dispersive transversal direction due to the additional excitation of betatron oscillations limits this type of cooling. Here we present the results of further studies on the fast cooling process, looking at the effect of the coupling of the transverse (betatron) oscillations. We first show theoretically that the transverse betatron coupling shortens the cooling time and hence reduces the steady-state energy spread of the electron beam, as well as the quantum losses. The theoretical estimates are then validated by simulations. Finally, a proof-of-principle experiment at the KEK ATF Damping Ring is proposed.

INTRODUCTION

Compton rings, i.e. electron storage rings equipped with laser resonators where the circulating electrons scatter off laser-pulse photons, have few if any competitors as sources of intense gamma-ray radiation. In particular, the gamma-ray radiation is generated by electrons of moderate energy.

One of the major performance limitations of these sources arises from large recoils suffered by the electrons when they scatter off the laser photons, which results in a large energy spread of the stored electrons [1].

In our previous studies, we found that lowering the transverse and/or longitudinal sizes of the laser pulse reduces the steady-state emittances by up to a factor of two. Recently [2] we studied a model, both analytically and in simulations, where the interaction of Compton-ring electrons and laser pulses takes place in a dispersive section of the ring. In addition, we assumed that only electrons with an energy higher than the nominal were expose to the laser photons. It was shown that under these conditions both the bunch energy spread and the cooling time can be sufficiently reduced, compared with the case of Compton scattering in a non-dipersive location.

In the present paper, we report further studies on the asymmetric cooling including the effect of betatron coupling. We note that historically betatron coupling in storage rings was studied and used for other applications, e.g. [3]. Our study here covers both analytical treatment and extended simulations.

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ASYMMETRIC COOLING

Earlier we presented a method of asymmetric laser cooling for bunches circulating in Compton rings [2, 4, 5]. This method is based on setting up the collision point (CP) in a dispersive part of rings orbit, with a definite asymmetry of the laser pulse along the direction of dispersion. Considering a semi-infinite laser field (with a pulse overlap range $z \geq 0$ where z denotes the transverse coordinate along the direction of dispersion; x will be used to designate the orthogonal transverse direction) the evolution of the second moments of the electron bunch distribution is described by

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

where $S \equiv \langle p^2\rangle$ is the squared momentum spread, $\varepsilon = \epsilon/\beta$ the normalized transverse emittance (ϵ the natural emittance, β the beta function magnitude at the collision point, CP), $g = D/\beta$ the normalized dispersion at CP (D the natural dispersion at CP), $b \approx 4\gamma\gamma_{\mathrm{las}}$ the maximal recoil undergone by the electron scattered off the laser photon, $G \equiv g\sqrt{S/\varepsilon}$.

The nonlinear functions $F_c(G)$ and $F_s(G)$ coupling the longitudinal and the transversal motions are

$$\begin{aligned}F_s(G) &= \frac{1}{4\pi^2}\int\int_0^{2\pi} \mathrm{d}\psi\mathrm{d}\theta\sin\theta\,\mathrm{H}(\sin\theta + G\cos\psi) ;\\ F_c(G) &= \frac{1}{4\pi^2}\int\int_0^{2\pi} \mathrm{d}\psi\mathrm{d}\theta\cos\psi\,\mathrm{H}(\sin\theta + G\cos\psi) .\end{aligned}$$

where $\mathrm{H}(x)$ denotes the Heaviside unit step function.

Full Coupling of Transverse Emittances

At the (phenomenological) conditions of full coupling, both transverse emittances are equal to each other and therefore equal to half of the total transversal emittance:

$$\epsilon_x = \epsilon_z = \epsilon/2 .\tag{2}$$

Let us rewrite the transverse equation (1) for the coupled emittances multiplied by $\beta_{x,z}$ and suppose $D_x = 0$ (achromatic x plane at CP):

$$\frac{\Delta\epsilon_x}{\Delta\tau} = -\frac{b}{2}\epsilon_x + \frac{3b^2\beta_x}{80\gamma^2} ;\tag{3}$$

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$$\frac{\Delta\epsilon_z}{\Delta\tau} = -\frac{b}{2}\epsilon_z + bD\sqrt{2\epsilon_z/\beta_z}F_s(G) + \frac{3b^2\beta_z}{80\gamma^2}\left[1+\frac{14}{3}g^2\gamma^2\right] .$$

The equation for the sum of the two transverse emittances, $\epsilon \equiv \epsilon_x + \epsilon_z$, in case of full coupling reads

$$\frac{\Delta\epsilon}{\Delta\tau} = -\frac{b}{2}\epsilon + bD\sqrt{\epsilon/\beta_z}F_s(G) + \frac{3b^2}{80}\frac{14}{3\beta_z}D^2 , \quad (4)$$

where we neglected the scattering excitation as being small compared with the dispersive one: $1 \ll \frac{14}{3}g^2\gamma^2$.

Under the condition of large dispersive (z) emittance in a laser-dominated ring, the sum of the transverse emittances approximately equals the dispersive one, $\varepsilon \approx \varepsilon_z$. In this case the excitation term for the vertical emittance in (1) is reduced to half of its uncoupled value:

$$\frac{\Delta\varepsilon}{\Delta\tau} = -\frac{b}{2}\varepsilon + \frac{bg}{2}\sqrt{2\varepsilon}F_s(G) + \frac{7}{80}b^2g^2 . \quad (5)$$

This result simply means that the excitation is distributed equally between the two degrees of freedom. Also it should be noted that the excitation magnitude is inversely proportional to β_z since $g \equiv D/\beta_z$.

Figure 1 presents two sets of the analytic dependence of the spread upon number of scatterings, starting from 10 % spread (cooling), and from zero spread (gamma source mode).

These curves illustrate that coupling of the transverse emittances enhances the asymmetric cooling; also the steady-state spread is lower in the case of coupling.

Simulations for an idealized model without synchrotron radiation, presented in Fig.2, show reasonable agreement with the analytical predictions.

SYNCHROTRON + COMPTON RADIATION

For a realistic case of electron bunches undergoing two independent perturbations — namely, Compton scattering and emission of regular synchrotron radiation — the steady-state emittances (and squared energy spread) become the weighted sum of the partial emittances (or spreads) related to these two effects [1]:

$$\epsilon_* = \frac{\epsilon_C w_C + \epsilon_s w_s}{w_C + w_s} , \quad (6)$$

where $w_{C,s}$ denotes the average energy losses due to the two specific processes (i.e. the partial energy losses).

The theory outlined above corresponds to 'absolute' laser domination, or $w_C \gg w_s$. For typical gamma-ray sources, the synchrotron radiation damping dominates over the effect of Compton scattering for stored laser-pulse energies in optical resonators which are available now and in the near future, but Compton excitation dominates the energy spread, i.e. $S_C w_C > S_s w_s$, due to the large partial spread, $S_C \gg S_s$, even at a low laser power.

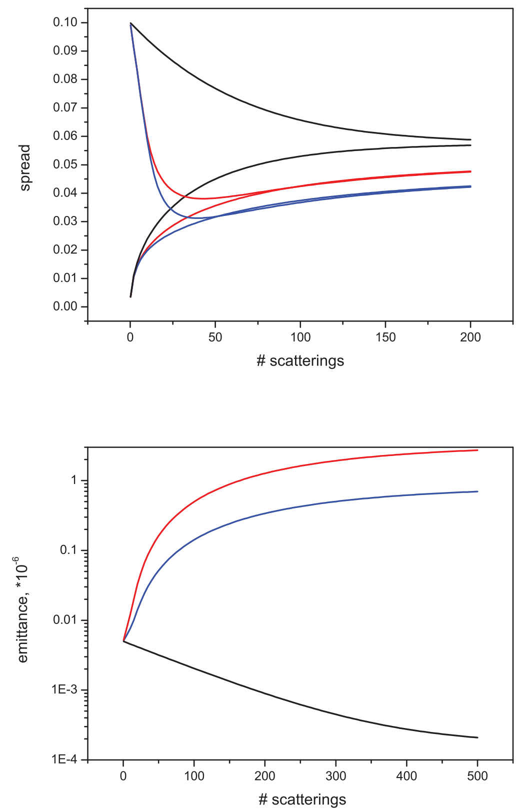

Figure 1: Spreads (top) and the emittance (bottom) vs number of scatterings for nondispersive (black), uncoupled (red) and coupled (blue) dispersive CP.

Therefore, the longitudinal spread is of prime importance. Regarding the transverse degrees of motion, the Compton partial emittances for a nondispersive CP can be smaller than the natural emittance of the synchrotron. For storage rings, the horizontal emittance usually is much larger than the vertical emittance if the betatron coupling is small. As a result, adding betatron coupling may not improve the performance of a Compton ring with vertical dispersion at the CP (causing additional excitation of vertical oscillations) if its integral vertical emittance is smaller than the horizontal one.

Extended simulations were performed for a realistic model of Compton gamma ray source that resembles the ATF Damping Ring of KEK [6]. The 2 MV RF voltage of the Damping Ring is taken to provide an energy acceptance of 3.2 %. The beta functions at the collision point are $\beta_{x,z} = 0.1, 2$ m. To realize asymmetric cooling a nonzero vertical dispersion is created at the CP. It should be noted that the Compton partial spread for this model is 5.6 %, and the partial emittances are $\epsilon_{x,z} = (3.5/70) \times 10^{-11}$ m.

Table 1 shows that transverse betatron coupling increases the performance only in cases when this coupling decreases the integral emittance along the dispersive degree of freedom (vertical in our simulations). Otherwise it decreases the bunch density and therefore the yield.

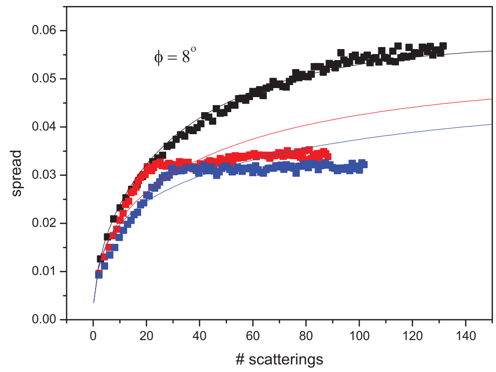

Figure 2: Simulated spread vs number of scatterings for nondispersive (black), uncoupled (red) and coupled (blue) dispersive CP – squares. Continuous curves represent theoretical behavior.

Table 1: Simulation results for a model of the ATF Damping Ring including laser CP; 2000 particles were tracked over 50 000 turns with the laser on, assuming natural synchrotron emittances of either $\epsilon_{x/z} = (2200/1.5) \times 10^{-11}$ m, or [asterisk] $\epsilon_{x,z} = 1.5 \times 10^{-11}$ m.

run	$D, \times 10^{-4}$ m	coup	$\sqrt{S}$, %	yield	lost
1	7.5	1	0.9	2.0	6
2	7.5	0	1.2	10.7	23
3	0	0	1.3	13.0	102
4*	7.5	1	1.2	13.0	5
5*	7.5	0	1.2	11.0	26
6*	0	0	1.3	13.9	83
7*	5	1	1.2	13.8	17
8*	5	0	1.2	12.3	23
9	5	1	0.9	1.6	3
10	5	0	1.2	12.7	21

From the formal point of view, in our analysis there is no difference between the vertical and the horizontal plane. In real storage rings the horizontal emittance is typically much larger than the vertical emittance. Under these conditions crossing laser and electron beam in the horizontal plane is preferred over vertical crossing, since it leads a larger photon yield. This is the reason why in the above examples for the ATF Damping Ring we consider only vertical dispersion at the CP.

SUMMARY AND CONCLUSIONS

Asymmetric cooling minimizes the energy spread of bunches circulating in a Compton storage ring significantly faster than under conditions of regular radiative cooling.

Transverse betatron coupling further increases the performance of the asymmetric cooling in laser-dominated ring gamma-ray sources.

For the case of synchrotron-radiation dominated rings, the effect of the coupling may be either positive or negative, depending on the (natural) synchrotron emittances: if the coupling results in a decrease of the 'dispersive' emittance the coupling will increase the yield and reduce the losses.

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