FURTHER STUDY ON FAST COOLING IN COMPTON STORAGE RINGS*

Eugene Bulyak†, KIPT, Kharkov, Ukraine
Junji Urakawa, KEK, Tsukuba, Japan
Frank Zimmermann, CERN, Geneva, Switzerland

Abstract

Compton sources of gamma-ray photons can produce ultimate intensity, but suffer from large recoils experienced by the circulating electrons scattering off the laser photons. We had proposed the asymmetric fast cooling which enables to mitigate the spread of energy in Compton rings. This report presents results of further study on the fast cooling: (1) A proper asymmetric setup of the scattering point results in significant reduction of the quantum losses of electrons in Compton rings with moderate energy acceptance. (2) Proposed pulsed mode of operation in synchrotron–dominated rings enhances overall performance of such gamma-ray sources. Theoretical results are in good accordance with the simulations. Performance of an existing storage ring equipped with a laser system is also evaluated.

INTRODUCTION

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

In previous work we demonstrated that small sizes of the laser pulse lead to a reduction of the steady-state emittances by up to a factor of 1/2. In our recent paper [2], we studied – both theoretically and with simulations – a model which considered the interaction of electrons circulating in a Compton ring with the laser pulses to occur in a dispersive section of the ring. In this model it was supposed that only electrons with positive energy deviation were exposed to the laser photons. It was shown that under these conditions the energy spread in the bunch as well as the cooling time may be sufficiently reduced.

In the present paper we report further studies on the asymmetric cooling including an account of the transverse oscillations. The study covers both theory and extended simulations.

ASYMMETRIC COOLING

Earlier we presented a method of asymmetric laser cooling of bunches circulating in Compton rings [2, 3]. This method is based on setting up the collision point (CP) at a location of nonzero (horizontal or vertical) dispersion and with a definite asymmetry of the laser pulse along the direction of dispersion.

For a semi infinite laser field, i.e. a transverse pulse overlap range $z \geq 0$ where z denotes the transverse coordinate along the dispersion, the following set of equations describes the evolution of the second moments of the electron-bunch density distribution:

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

where $S \equiv \langle p^2 \rangle$ is the squared momentum spread, $\varepsilon = \epsilon/\beta$ the normalized transverse emittance, $g = D/\beta$ the normalized dispersion at CP, and $b \approx 4\gamma\gamma_{\mathrm{las}}$ the maximal recoil undergone by the electron scattered off the laser photon, $G \equiv g\sqrt{S/\varepsilon}$. The nonlinear functions $E_c(G)$ and $F_s(G)$ coupling the longitudinal and the transversal motions are

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

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

Numerical solutions of the equations (1) show the following features (see Fig.1):

- The steady-state (asymptotic) energy spread is fairly independent of the dispersion value.
- The steady-state value of the parameter $g\sqrt{S/\varepsilon}$ is also rather insensitive to the dispersion, and therefore $\varepsilon(\tau \to \infty) \sim g^2$.
- The cooling time – the number of scatterings necessary to reach a minimal spread – is approximately inversely proportional to g and strongly depends on the initial emittance value.
- The time interval in which the transverse emittance approaches its asymptotic value is much longer than the cooling time for the energy spread.

Detailed simulations of the asymmetric cooling produce a bunch behavior in agreement with these theoretical predictions; Fig.2. In the simulations, the semi-infinite transverse laser pulse density was modeled by two parallel Gaussian pulses with $\sigma_z = 50\,\mu$m; the center of the first pulse was shifted by $\Delta = 25\,\mu$m, that of the second pulse by $75\,\mu$m.

---

[*] Work supported by the Quantum Beam Technology Program of MEXT and Grant-In-Aid for Scientific Research (S) (KAKENHI No. 23226020) of JSPS.

[†] bulyak@kipt.kharkov.ua

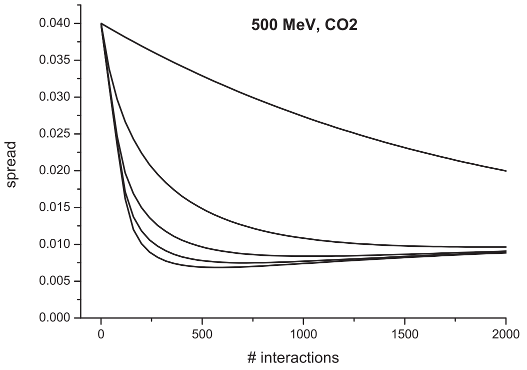

Figure 1: Cooling process for $g = (0, 1, 2, 3, 4) \times 10^{-3}$ from top to bottom, resp.

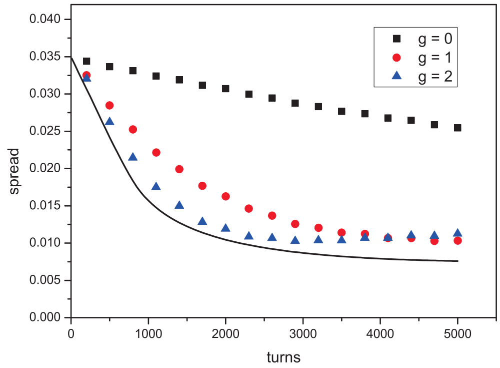

Figure 2: Simulations, solid curve – theoretical for $g = 2 \times 10^{-3}$. Electron energy 500 MeV, two CO2 laser pulses with 1 Joule in each.

Results

As can be seen from this study, the asymmetric laser cooling in a Compton ring enables the construction of a damping ring with relatively low energy and short cooling time. For example, in the aforementioned model the energy spread cooled down from 3.6% to 1% in less than 400 μs.

QUANTUM LIFETIME

Fluctuations of radiation emitted by the electrons circulating in storage rings cause losses of the electrons – so called quantum losses (the inverse of the quantum lifetime) [4]. In Compton sources the quantum losses are much higher due to the higher energy of the emitted quanta [1]. These losses are of prime importance in Compton gamma sources, where in a single collision electrons can lose a fraction of energy comparable to the ring energy acceptance. A plot of the longitudinal phase space together with the region from which beam particles may be lost from the RF bucket in a single scattering event is presented in Fig. 3: Only particles within the band extending from the bottom separatrix up to the yellow curve may be lost.

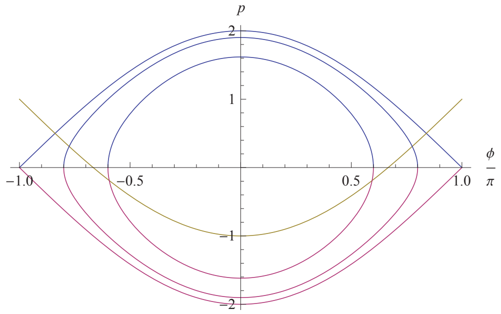

Figure 3: Scheme of Compton quantum losses.

Proper asymmetric setup of CP helps to reduce the quantum losses in gamma sources and thus improves efficiency.

Theory

Consider the ensemble of electrons experiencing recoils. The density of this ensemble in the longitudinal phase plane (ϕ, p) is proportional to the product of the bunch density and the laser pulse density convoluted with the probability of suffering a definite reduction of the momentum, $\xi = p' - p$, due to recoil. The fraction of this density shifted outside the separatrix determines *the quantum losses.*

A laser pulse with density profile $L(\phi, p)$ scattered off a bunch with density $G(\phi, p)$ yields the density probability $S(\phi, p; b)$:

$$\begin{aligned} S(\phi, p; b) \quad &= \quad \int \mathrm{d}p' \int \mathrm{d}\xi \, \delta(\xi + p - p') \times \\ & \qquad w(p', \xi; b) L(\phi, p') G(\phi, p') \, , \qquad (2) \end{aligned}$$

where $w(p', \xi; b)$ is the spectrum of the recoils, i.e. the probability for an electron with energy ξ to be transformed into an electron with energy p'.

The lost fraction, $Q = Q(b; \text{ring parameters})$, is then

$$Q = \int_{-\pi}^{\pi} \mathrm{d}\phi \int_{-\infty}^{-p_{\mathrm{s}}(\phi)} \mathrm{d}p \, S(\phi, p; b) \, , \qquad (3)$$

where $-p_{\mathrm{s}}$ is the bottom branch of the longitudinal separatrix. Thus, the quantum loss rate per scattering is

$$\tau_{\mathrm{qlt}}^{-1} = Q \, ,$$

provided that $S(\phi, p; b)$ is normalized to unity.

The evolution of the distribution of recoiled electrons at a certain phase ϕ over the longitudinal phase space is sketched in Fig.4. An initial bunch density (yellow) scatters off symmetric (red) or asymmetric (blue) laser pulse – top panel. (The laser pulse is supposed to be semi-infinite transversely.) The densities of scatterings are presented in the middle panel. The corresponding densities of recoiled electrons are presented in the bottom panel.

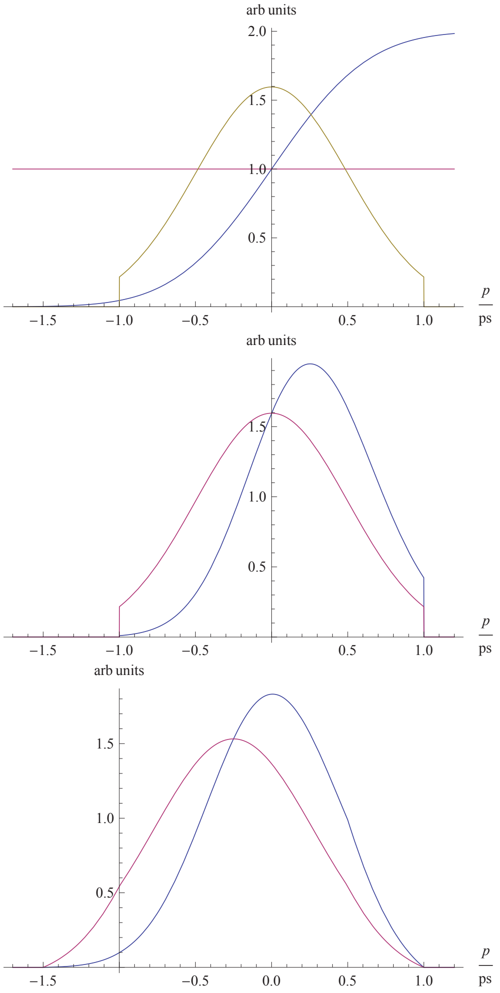

Figure 4: Density mapping.

As it can be seen from the picture, asymmetric CP substantially reduces quantum losses (density tail below the separatrix, $p/p_\mathrm{s} < -1$, bottom panel).

Mapping of semi-infinite laser field onto the phase plane,

$$L(\phi, p) = 1 + \mathrm{erf}\left(\frac{g\,p}{\sqrt{2\varepsilon_z}}\right)\,, \tag{4}$$

is determined by the dispersion at the CP and by the transverse emittance. The scaling factor is $g/\sqrt{\varepsilon} \sim \sqrt{\beta_\mathrm{cp}}$.

'Proof-of-Principle' Experiment.

Quantum losses are exponentially proportional to the ratio of the maximal recoil, b, to the separatrix height, p_s. For Compton gamma sources based on conventional storage rings, e.g. ATF DR [5], the maximal recoil is about equal to the longitudinal energy acceptance, $b \approx p_\mathrm{s}$.

Even if the maximal recoil b is about the acceptance half-width, the asymmetric scheme produces significant reduction of the quantum losses.

Table 1 summarizes simulation results for the ATF DR at 1 GeV beam energy, equipped with a laser resonator stored 10 mJ laser pulse of 1.16 eV photons, for 0.14 rad crossing angle, 3.0 mm dispersion, 2 m beta function at CP (max $p_\mathrm{s} = 0.016 \approx b = 0.018$).

Table 1: Yield/turn/electron, **y**, and lifetime, τ, for different laser pulse displacement Δ.

Δ , μm	**y,10^{-5}**	**τ, Mturn**	**y×τ**
+30	1.35	20.6	277.86
0	1.26	13.1	164.83
−30	1.28	12.2	156.78

The simulations show that even in the case of a ring energy acceptance comparable with the maximal recoil, the asymmetric CP will provide detectable enhancement in the beam lifetime. Also the efficiency of gamma-ray generation will increase: each electron will scatter off a large number of gammas during its lifetime in the storage ring.

SUMMARY AND CONCLUSION

The study of asymmetric cooling shows that the minimum energy spread of the circulating bunches is attained in a significantly shorter time than under conditions of regular radiative cooling.

Asymmetric fast cooling will make it possible to construct relatively low-energy damping rings with rather short cooling period when intense lasers generating low-energy photons become available.

Since the associated transverse emittance is increasing much more slowly, a pulsed mode of operation of the gamma sources will be feasible, with synchrotron radiative cooling in between consecutive gamma-ray bursts.

A proper asymmetric setup of the collision point in Compton rings gamma sources results in significant reduction of the quantum losses of electrons in rings with moderate energy acceptance. This allows constructing Compton sources of intensive gamma-ray beams based on storage rings with moderate rf voltage.

A 'proof-of-principle' experiment may be carried out at existing storage rings with state-of-the-art laser systems.

REFERENCES

[1] E. Bulyak, P. Gladkikh, L. Rinolfi, T. Omori, and J. Urakawa, "Beam dynamics in Compton rings with laser cooling," IPAC'10, Kyoto, May 2010, TUPD093, `http://www.JACoW.org`

[2] E. Bulyak, J. Urakawa, and F. Zimmermann. "Asymmetric laser radiant cooling in storage rings," PAC'11, New York, March, 2011, MOP064, `http://www.bnl.gov/pac11/`

[3] E. Bulyak, J. Urakawa, and F. Zimmermann. "Fast cooling of bunches in Compton storage rings," IPAC'11, San Sebastian, Sept, 2011, WEPZ011, `http://www.jacow.org/`

[4] A. Wrulich. "Single-beam lifetime," *CAS 5th general accelerator physics course (1992),* CERN 94-01, vol.1, p.409, 1994.

[5] F. Hinode et al. (eds.), *ATF Accelerator Test Facility Design and Study Report,* KEK Internal 95-4, 1995.