ASYMMETRIC LASER RADIANT COOLING IN STORAGE RINGS*

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

Abstract

Laser pulses with small spatial and temporal dimensions can interact with a fraction of the electron bunches circulating in Compton storage rings. We studied synchrotron dynamics of such bunches when laser photons scatter off from the electrons with energy higher than the synchronous energy. In this case of 'asymmetric cooling', as shown theoretically, the stationary energy spread is much smaller than under conditions of regular scattering; the oscillations are damped faster. Coherent oscillations of large amplitude may be damped in one synchrotron period, which makes this method feasible for injection the bunches into a ring in the longitudinal phase space. The theoretical results are validated with simulations.

COMPTON SOURCES AND LIMITATIONS

Compton sources of intense gamma–ray photons have no competitor, see [1]. One of the most effective among them is the storage–ring based due to the maximal attainable average current of the relativistic electrons and the minimal power of an injector.

The main drawback of the ring–based source stems from requirement of large energy acceptance of the storage ring caused by quantum nature of radiation emitted – relatively high energy of gamma quanta emission causes significant recoils in momentum of circulating electrons. As was shown, for the Compton ring with the collision point (cp) set in the dispersion–free section and a 'wide' laser pulse (uniform distribution of photons within the bunch volume), partial energy spread induced by Compton interactions alone, reads (see e.g.[2, 3]):

$$\langle p^2 \rangle = \frac{7}{10}\gamma\gamma_{\mathrm{las}} \,, \qquad (1)$$

where $p \equiv (\gamma_i - \gamma)/\gamma$ denotes the electron energy deviation from the synchronous one; γ_i, γ are Lorentz–factors for individual electrons and for the synchronous particle, resp.; $\gamma_{\mathrm{las}} = E_{\mathrm{las}} \big/ m_0 c^2$ the ratio of the energy of the laser photon to electron's rest energy (the equivalent photon Lorentz factor). This spread is rather high and demands high rf voltage to keep the electrons steady circulating.

The damping (transition) time in this Compton source obeys well–known 'synchrotron damping ratio': it is equal to ratio of electrons energy to the radiation losses per unit time (per time of scattering off one average photon), $\nu^{-1} \approx 2\gamma\gamma_{\mathrm{las}}$.

We developed a method to reduce the steady–state spread by setting up cp in the dispersive section and irradiating the bunches by small–waist laser pulses. This method enable one to significantly reduce the damping time as well.

FAST ASYMMETRIC DAMPING

Theory

A simple model of fast radiative cooling allows theoretical study. Let us consider a model, in which electrons are scattering off laser photons if electron's energy deviation from the synchronous particle positive, $p > 0$. Then we suggest the head–on collision and a uniform laser pulse density for all $p > 0$. In addition, small perturbations of the electrons dynamics are suggested: For the period of synchrotron oscillations each electron has lost only a relatively small fraction of its energy, $\Delta p \ll 1$. Schematically collision setup is depicted in Fig.1.

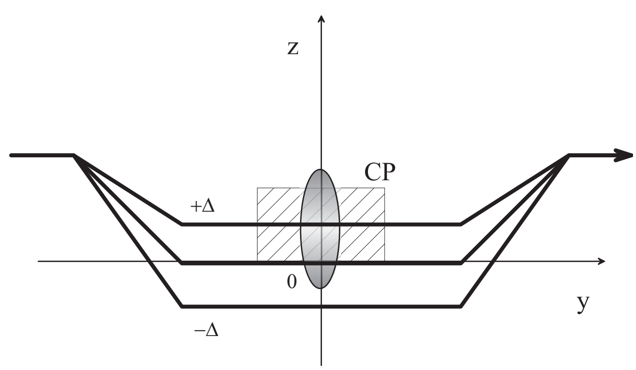

Figure 1: Trajectories at the collision point with positive $(+\Delta)$, negative $(-\Delta)$, and zero deviation of electron's energy. Laser–to–electron scattering area dashed (ideal) or in gray (realistic).

Principle of the asymmetric cooling is as follows. An average recoil caused by scattering off the photon modifies the deviation as:

$$\Delta \langle p^2 \rangle \approx -b \left[\frac{\langle p \rangle}{2} + \langle p^2 \rangle \right] + \frac{7}{40} b^2 \,, \qquad (2)$$

where $b \equiv 4\gamma\gamma_{\mathrm{las}}$.

The term in square brackets is responsible for cooling (damping), the second term for excitation; the steady state attained at compensation of the excitation by the damping, $\Delta \langle p^2 \rangle = 0$.

* Work supported by the Quantum Beam Technology Program and in parts of KAKENHI 17GS0210 project of MEXT.
† bulyak@kipt.kharkov.ua

At the symmetric interaction of electrons with the laser $\langle p \rangle = 0$, damping is producing by the quadratic term $\langle p^2 \rangle$. In the case of asymmetric cooling the linear term becomes dominant, $\langle p^2 \rangle / \langle p \rangle \sim \langle p \rangle \ll 1$, which leads to faster cooling and smaller steady–state spread:

$$\sqrt{\langle p^2 \rangle_{\rm as}} \approx \frac{7\sqrt{2}\pi}{40}\gamma\gamma_{\rm las} \approx 0.77\,\gamma\gamma_{\rm las}\,; \qquad (3)$$

$$\frac{{\rm d}\sqrt{\langle p^2 \rangle}}{{\rm d}\nu} \approx -\frac{2\sqrt{2}}{\pi}\gamma\gamma_{\rm las} \approx -0.9\,\gamma\gamma_{\rm las}\,, \qquad (4)$$

where ν is number of scatters undergone by each electron.

Eq. (2) allows analytic solution for temporal evolution of the rms spread. The spread as function of the average number of scatters for $E_e = 1\,$GeV, $E_{\rm las} = 1\,$eV are presented in Fig.2.

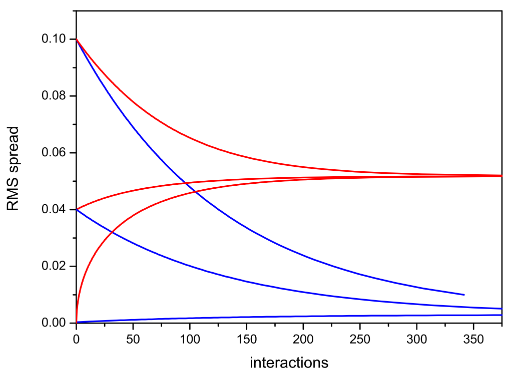

Figure 2: RMS spread vs interactions for asymmetric (blue) and symmetric (red) cooling ($E_e = 1\,$GeV, $E_{\rm las} = 1\,$eV).

As it can be seen from the figure, asymmetric cooling provides faster decrease in the spread and lower steady–state of the energy spread as compared with the symmetric one.

In real Compton rings it is almost impossible to provide such a scheme due to two main obstacles:

- Density of the laser photons across the waist is far from uniform with a sharp edge.
- Due to the transverse (betatron) oscillations, correlation between the transversal position of the electron at cp and its energy is diluted.

The last item is most severe since the transverse oscillations should be excited while cooling due to jump of the equilibrium position (see Fig.3).

Simulations

Simulations were done to validate the principle of asymmetric laser cooling in realistic conditions. A numeric model was created, which includes interactions of the circulating electron bunch with the 3D gaussian laser pulse at

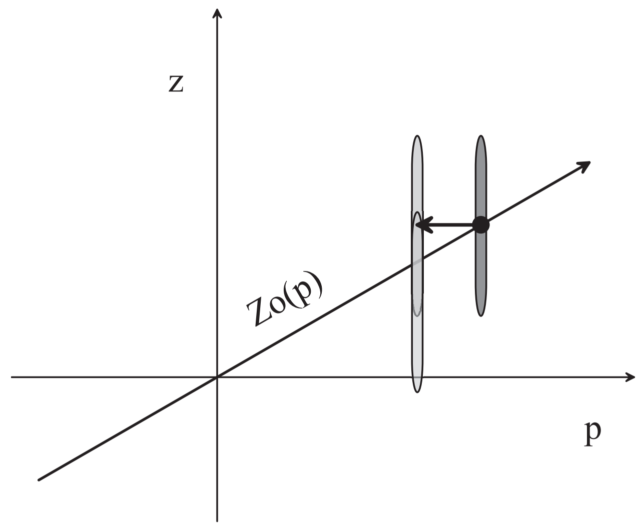

Figure 3: Effect of a recoil in (z, p) plane. In the dispersive section the center of z–oscillations oscillates along $Z_0(p)$ at the synchrotron frequency.

cp located in a dispersive section (see Fig.1). Crossing of the bunch and the pulse was at a certain angle in the horizontal, (x, y), plane.

Two parameters were controlled in the simulations:

- Dispersion at cp ψ_*: the reference orbit vertical position is $z_0(p) = \psi_* p$.
- Shift d of the laser pulse in z–direction from the reference orbit (shift of the laser ellipse center from the reference orbit $p = 0$ in Fig.1): laser's density $n(z) \propto \exp\left[-(z-d)^2/2\sigma_z^2\right]$.

A prototype of Compton ring dedicated for production of polarized gammas with maximal energy of 20 MeV was chosen for simulations. Main parameters are listed in Table 1.

Table 1: Main parameters of the electron bunch and the laser pulse at the collision point

Parameter	Value	Units
Electron energy	1.06	GeV
Betatron function, β_z	1.25	m
Photon energy	1.164	eV
Crossing angle	0.13963	(8 deg)
Pulse length	1.0	mm
Pulse width	20	μm
Pulse height	40	μm
Pulse energy	2	J

Simulated dependencies of the rms spread on the number of scattered off laser photons by the average electron (c.f. Fig.2) are presented in Fig.4.

Results of several runs of simulations are presented in Figs.5,6. Efficiency is defined as the number of photons scattered off per electron-pass through cp.

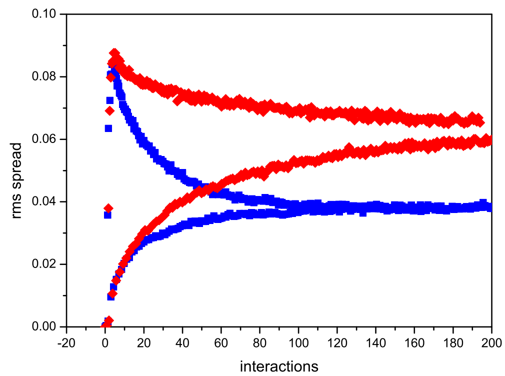

Figure 4: Spread vs interactions at $\psi_* = +0.2\,\mathrm{mm}$, $d = +30\,\mu\mathrm{m}$ (blue) and $d = 0$ (red).

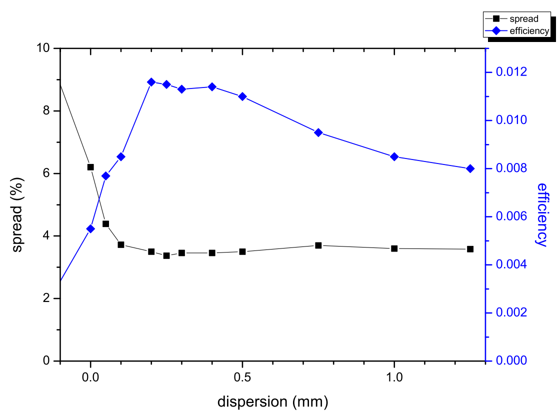

Figure 5: Spread and efficiency vs. dispersion at $d = +64\,\mu\mathrm{m}$.

Results of the simulations show significant reduction (almost two times) of the steady–state spread as compared with the symmetric case. Cooling time is also shortened. The transverse emittance in the direction of dispersion grows up. Growth of the vertical emittance exhibits Robinson's sum rule for the Compton cooling.

CONCLUSION

The asymmetric laser radiative cooling is capable to reduce the steady-state spread of electron energy in the bunches circulating in Compton rings. This makes less demanding parameters of the ring–based sources of gamma–ray beams such as the energy acceptance and required rf voltage, see [4].

Also construction of low–energy damping rings with the asymmetric laser cooling may be feasible.

Requirements on the laser system are relaxed compared with the regular symmetric cooling scheme as far as the size of the waist cross section is concerned (a ten times larger waist size may be optimum), but a higher pulse energy is required to produce the same number of gamma–ray photons.

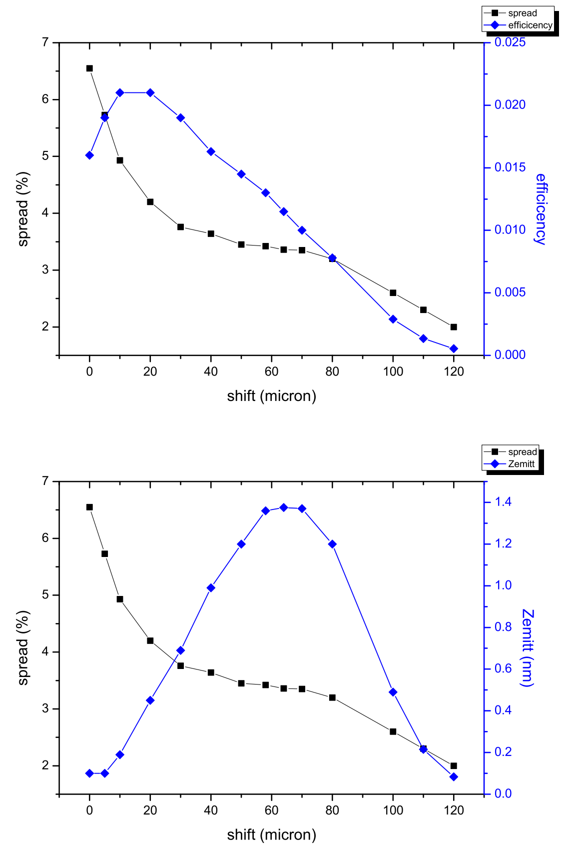

Figure 6: Efficiency (top) and z–emittance (bottom) vs. laser shift at $\psi_* = +0.2\,\mathrm{mm}$.

Acknowledgments

The authors are thankful to PosiPol collaboration people and Prof. Anatoly Dovbnya for helpful discussions.

REFERENCES

[1] F.V. Hartemann *et al*. *Phys. Rev. ST Accel. Beams*, 8:100702, 2005.

[2] J. Urakawa *et al*. *Nucl. Instrum. Methods*, A 532(1-2):388–393, 2004.

[3] Eugene Bulyak *et al*. "Beam dynamics in Compton rings with laser cooling." In *IPAC 2010, Kyoto, Japan*, 2010.

[4] E. Bulyak *et al*. "Compton gamma-sources: Beam dynamics and performance." In *PosiPol07, Orsay, France*. 2007.