BEAM DYNAMICS IN COMPTON-RING GAMMA SOURCES

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Abstract

Electron storage rings of GeV energy with with laser pulse stacking cavities are promising intense sources of polarized hard photons to generate polarized positron beams. Dynamics of electron bunches circulating in a storage ring and interacting with high–power laser pulses is studied both analytically and by simulation. Common features and difference in the bunch behavior interacting with an extremely high power laser pulse and a moderate pulse are shown. Also considerations on particular lattice designs for the Compton gamma rings are presented.

INTRODUCTION. WHAT ARE COMPTON GAMMA SOURCES?

We refer to the notion ‘Compton gamma source’ as an electron ring with a powerful laser system which is able to generate polarized photons with the energy of a few tens of MeV by scattering off polarized laser photons from ultrarelativistic electrons, see [1, 2].

The gamma sources in principle are similar to the Compton medical x–ray sources [3] except that

- Energy of emitted gammas of some tens of MeV is comparable with available RF voltage;
- Number of interactions experienced by each electron in average per pass of interaction point (IP) is about unity;
- The magnetic lattice of the gamma sources must provide large energy acceptance;
- These rings can not generate gammas continuously.

TREATMENT OF BUNCH DYNAMICS IN COMPTON RINGS

Electron–Laser Photon Interactions

Schematically the process of scattering off a laser photon by the circulating electron is depicted in Fig. 1.

The recoil momentum vector has the random length $P_{\rm recoil}$ and random directing angles ϕ and ψ from the electron momentum. At the Compton scattering of photons by an ultrarelativistic electron, $P_{\rm recoil}$ scales as γ^2:

$$P_{\rm recoil} = E_{\rm x}^{\rm max} \zeta \gamma^2 / \gamma_s^2 \ , \tag{1}$$

where γ, γ_s are the Lorentz factors of the interacting particle and of the synchronous one, respectively, $E_{\rm x}^{\rm max}$ is the

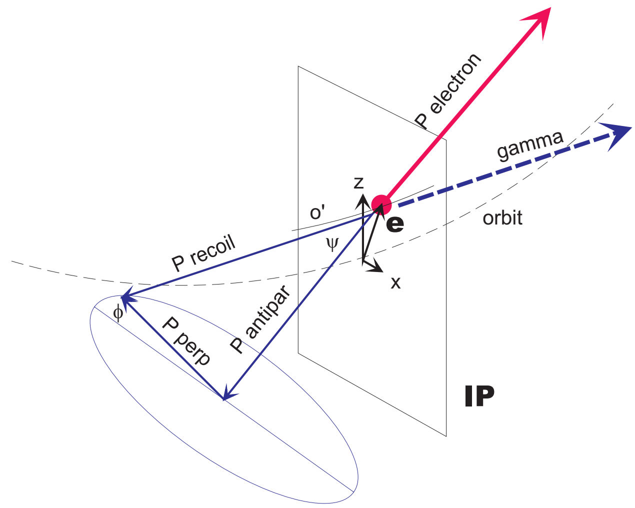

Figure 1: Electron recoil from the laser photon scattering.

maximal energy in Compton spectrum (for a close to head–on collision $E_{\rm x}^{\rm max} = 4\gamma^2 E_{\rm las}$, with $E_{\rm las}$ the energy of laser photons), ζ the reduced gamma energy (the ratio of the energy of scattered gamma to the maximal energy in spectrum) $\zeta = E_{\rm x} / E_{\rm x}^{\rm max}$.

The reduced energy of a gamma ζ is a random number distributed over interval $[0, 1]$ with density (see [4])

$$F(\zeta) = \frac{3}{2} \left[1 - 2\zeta \left(1 - \zeta\right)\right] \ . \tag{2}$$

Since Compton scattering at both the electron and laser photon energies and the laser pulse densities obeys two–particle kinematics, the angle ψ between electron trajectory direction and that of the recoil momentum is dependent upon the absolute value of the recoil, i.e., the lateral kick $P_{\rm perp}$ is a function of the recoil:

$$P_{\rm perp} = \frac{b}{\gamma} \sqrt{\zeta \left(1 - \zeta\right)} \ ,$$

with $b = 4E_{\rm las}\gamma_s / m_e c^2$.

Longitudinal dynamics of a circulating electron are described with finite difference equations

$$\begin{aligned} \frac{\Delta\varphi}{\Delta\tau} &= \kappa_1 p + \kappa_2 p^2 + \kappa_3 p^3 \ ; \\ \frac{\Delta p}{\Delta\tau} &= -U_{\rm rf} \sin\varphi + F(p, \tau) \ , \end{aligned} \tag{3}$$

where τ is the reduced time variable (in turns), κ_i the phase slip factor of i–th order, φ the phase ($\varphi = 0$ for the synchronous electron), $p = (\gamma - \gamma_s)/\gamma_s$ the relative energy

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deviation, $U_{\rm rf} = eV_{\rm rf}/E_s$, $F(p,\tau)$ a (stochastic) function representing non-conservative interactions. Set of equations (3) represents the change of 'coordinate' φ and 'momentum' p over a turn, thus $\Delta\tau = 1$.

Analytical treatment of the synchrotron and betatron oscillations in storage rings perturbed by the Compton interactions as well as the synchrotron radiation emission consists in its reduction to the Kramers equation – this equation describes a nonlinear oscillator with viscous friction and random Gaussian excitation. For the Kramers equation $F(p,t) = \alpha p + \sqrt{S}\xi(t)$ with $\xi(t)$ being unity white noise, α the friction factor, $\kappa_2 = \kappa_3 = 0$.

What is Known So Far

For a sufficiently high RF voltage and linear lattice the Kramers equation yields asymptotes for the partial Compton transverse emittances at $t \to \infty$ (see [5])

$$\epsilon_c = \frac{3\beta_{\rm ip}}{10}\frac{E_{\rm las}}{\gamma m_e c^2}\,, \qquad (4)$$

with $\beta_{\rm ip}$ being the betatron function magnitude at the interaction point (IP), $E_{\rm las}$ the energy of the laser photon.

The partial steady state r.m.s. relative energy spread $s_{\rm c}$ reads

$$s_{\rm c}^2 \equiv \left(\frac{\sigma_E}{\gamma m_e c^2}\right)^2 = \frac{7}{10}\frac{\gamma E_{\rm las}}{m_e c^2}\,. \qquad (5)$$

If the bunch undergoes synchrotron excitation and damping, the resultant squared energy spread equals the weighted sum of the partial synchrotron and Compton spreads

$$s^2 = \frac{s_{\rm sr}^2(\Delta E)_{\rm sr} + s_c^2(\Delta E)_{\rm c}}{(\Delta E)_{\rm sr} + (\Delta E)_{\rm c}}\,, \qquad (6)$$

where $(\Delta E)_{\rm sr,c}$ are the partial energy losses per turn due to synchrotron– and Compton–radiation emission, respectively.

The transverse emittances behave in a similar way.

Usually, the energy spread due to Compton scattering exceeds the synchrotron one, while the transverse emittances may be larger or smaller than the natural (synchrotron) ones depending on the beta–function magnitude at IP.

Pulse Mode of Operation

Since the Compton gamma ring can not generate gammas steadily, the pulsed mode of operation is accepted. In the pulsed mode the laser is switched on during a relatively short period of the operating cycle. The remaining time of the cycle is used for cooling down the bunches via synchrotron (and wiggler) radiation emission.

Yield in the pulsed mode will be significantly enhanced if the RF–phase manipulation scheme is employed. The idea of phase manipulation consists in providing interactions with the laser pulse at a shifted RF phase, different from the synchronous one. In this mode, the RF phase is manipulated as following

1. Fast ('shock') advance in RF phase;
2. 'Plateau' to provide interaction with laser;
3. Slow adiabatic return into the initial position.

A simulated trajectory of the bunch centroid in the longitudinal phase space is presented in Fig. 2.

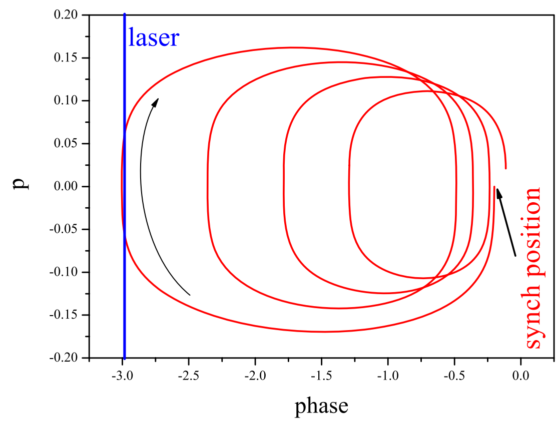


Figure 2: Trajectory of the bunch centroid in RFPM mode.

SIMULATIONS

The simulating code having been used to evaluate the longitudinal beam dynamics in gamma rings (see [1]) has been upgraded to incorporate RF–phase manipulation mode and the transverse degrees of freedom as well.

For simulation of the transverse motion, the synchrotron damping and random transverse excitations of the betatron oscillations were added providing a given emittance at a given damping rate depending on the synchrotron losses.

The Compton scattering is simulated by random kicks distributed in accordance with the ultrarelativistic or small-angle approximation (2), including a γ^2 dependence on the electron energy. The magnitude of the transverse deflections is determined from the total kick; the angle ϕ in Fig. 1 is random, uniformly distributed over $[0, 2\pi]$, while the angle ψ follows from the two-particle kinematics.

Two simulations were done, the first intended to validate the theoretical predictions for steady states, and the second to simulate the ILC Compton gamma source in the pulsed mode.

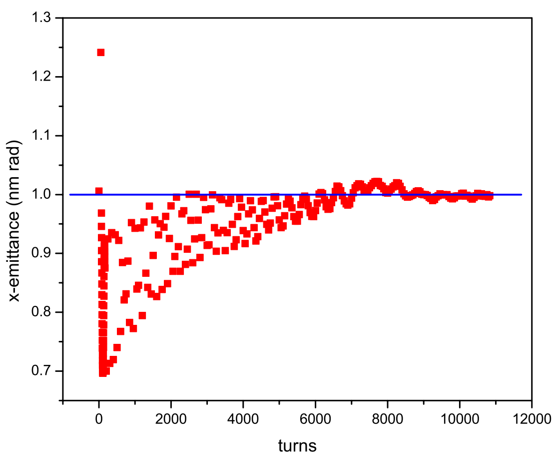
Simulations of the steady–state parameters of the bunch circulating in a Compton ring (with moderate energy) have validated our theoretical predictions:

- The partial Compton emittances are independent of the frequency of electron-to-photon interaction;
- The simulated energy spread is in agreement with estimates in which the recoil momenta are assumed to be random without systematic component, even though in the simulation the random perturbations are not centered;

- Total emittances (Compton + synchrotron damping and excitation) agree with the theoretical predictions;
- Transition periods to the steady state obey the Kolomenskij–Lebedev–Robinson theorem with the vertical and betatron damping times equal to each other, and two times shorter than the synchrotron one.

For simulations of the gamma source, the *YAG nl* lattice [1] was choosen. The emittances together with the betatron amplitudes at IP, β_{ip}, were set such that the partial Compton radial emittance was smaller than the synchrotron one, while the vertical one larger: at $\beta_x^{(\mathrm{ip})} = \beta_z^{(\mathrm{ip})} = 0.5\,\mathrm{m}$ the partial Compton emittances were $\epsilon_x^{(\mathrm{C})} = \epsilon_z^{(\mathrm{C})} = 1.35 \times 10^{-10}\,\mathrm{m\,rad}$, and the natural (synchrotron) emittances $\epsilon_x = 1 \times 10^{-9}\,\mathrm{m\,rad}$, $\epsilon_z = 5 \times 10^{-11}\,\mathrm{m\,rad}$. The laser was switched on from 68–th through 168–th turns.

Results of simulations are presented in Fig. 3.



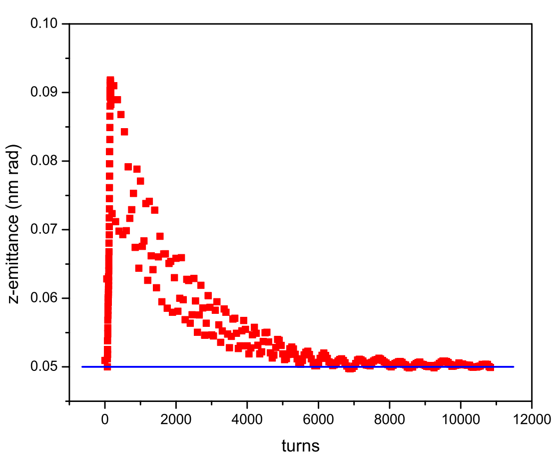


Figure 3: Horizontal (top) and vertical (bottom) emittance variations with turns. The blue lines indicate the synchrotron emittances.

As it can be seen from Fig. 3, the horizontal emittance is cooling down due to laser interactions, while the vertical one increasing. Oscillations in emittances are caused by the coherent synchrotron oscillations inherent in the RF–phase manipulation mode, possibly related to the temporary adiabatic damping or anti-damping of betatron oscillations.

Results of a 3D simulation of repeated working cycles in the ILC YAG Compton ring for the pulsed mode with RF phase manipulation on/off are consistent with those presented in [1], which were obtained for an idealized 1D model.

The laser–induced transverse kinetics of the electron bunches circulating in the Compton gamma sources does not deteriorate the performance of these sources estimated without account of the transverse degrees of freedom: With the proper small betatron amplitudes at the interaction point, the transverse natural emittances may even be reduced due to the bunch–to–laser interactions.

SUMMARY AND OUTLOOK

Single–particle dynamics of electron bunches in Compton gamma sources has been studied analytically and with simulations. Analytical estimations for the steady state bunch parameters are in good agreement with those from the simulations.

The study shows that interactions of the electrons with the laser photons do not affect significantly the transverse degrees of freedom. The ‘bottleneck’ is the longitudinal dynamics: the ring’s energy acceptance should be unusually high.

Further study should comprise multi–particle dynamics (collective effects) due to the required large bunch population. Also, methods for attaining short bunches will be developed.

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