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DYNAMIC SIMULATION FOR LOW ENERGY COMPTON SCATTERING GAMMA-RAY STORAGE RING

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Abstract

We have designed a dedicated low-energy electron storage ring to generate gamma-rays based on Compton scattering technique. The natural emittance of the ring is 3.4 nm at 500 MeV beam energy and the ring circumference is about 59 m. The resulting maximum gamma-ray photon energy is about 4 MeV by interacting with $\sim$1 μm laser. Due to the large energy loss associated with the gamma-ray photon emission, the electron beam dynamics are greatly affected. We have simulated the whole physical process including Compton scattering, radiation damping and quantum excitation and find that the equilibrium energy spread may be increased by one order of magnitude depending on the laser parameters. We have studied the dependence of the equilibrium state on the laser intensity and wavelength, and the electron parameters based on our candidate ring lattice.

INTRODUCTION

Z.Huang and R.D.Ruth [1] proposed a compact electron-laser storage ring for X-ray generation with electron energy in the order of tens MeV based on Compton backscattering technique. The x-ray generated from laser-electron storage ring has excellent properties in terms of high brightness, monochromatic, high repetition and high flux comparable with traditional synchrotron radiation x-ray, and it only requires two order of magnitude smaller electron energy. Many compact laser-electron storage ring for x-ray generation was designed and built around the world[2,3]. Meanwhile monochromatic and high-flux gamma-ray is highly demanded by many nuclear experiments and atomic sciences, and laser-electron storage ring is the best choices for this gamma-ray generation.So far there are no dedicated storage rings for gamma-ray production. Motivated by high demands of gamma-ray sources in the fields of nuclear physics research, we design a compact electron-laser storage ring for gamma-ray generation (Compton Gamma-ray Ring).

We adopt Multi-Bend-Achromat technique with Multi-Objective Genetic Algorithm (MOGA)[4] to design and optimize a Compton Gamma-ray Ring aimed to higher flux for gamma-ray light source. A candidate ring lattice has been designed with an extremely small emittance of 3.37 nm for storage energy of 500 MeV using 5-bend-achromat technique in a circumference of 59.14 m[5]. The base luminosity we can achieve for gamma-ray based on the candidate lattice with realistical parameters is $\sim 2 * 10^{36}\ cm^{-2} \cdot s^{-1}$. An inevitable result for higher luminosity is higher loss possibility of electron. More electrons will be scattered by laser and lose their energy and they are more likely to escape from the longitudinal acceptance range. The maximum percentage of energy loss for an electron scattered by laser could be 1% (We call this type of loss as Compton Loss in this paper) in the storage ring for our designed gamma-ray generation, which is far greater than the Compton Loss in storage ring for x-ray generation, whereas the momentum acceptance is 2~3% along the ring. So it's important to investigate beam dynamics with macroparticle tracking studies by considering the operating parameters of the Compton Gamma-ray Ring.

We conduct our study about the dynamic effects assoicated with Compton scattering in storage ring primarily with parallel macroparticle tracking simulation by accelerator modelling library TRACY [6] and compare the results with analytical estimation by the formula from I. Chaikovska [7]. We vary the laser energy and wavelength which correspondingly change the luminosity for the collision to investigate how the Compton scattering influence the beam dynamics in storage ring, and also the stability associated with particle loss.

I. Chaikovska et al have shown that the Compton scattering in the storage ring could be considered as a shot noise process. Therefore by applying Campbell's theorem we can evaluate the average effects of the two independent Poisson excitation processes (Compton scattering excitation and synchrotron radiation excitation). The analytical formula to evaluate equilibrium energy spread and emittance for electron beam with this method is [7]:

$$\begin{aligned} \sigma_E^2 &= \frac{\sigma_{SR}^2 \Delta E_{SR} + \sigma_{comp}^2 \Delta E_{comp}}{\Delta E_{SR} + \Delta E_{comp}} \\ \epsilon &= \frac{\epsilon_{SR} \Delta E_{SR} + \epsilon_{comp} \Delta E_{comp}}{\Delta E_{SR} + \Delta E_{comp}} \end{aligned} \tag{1}$$

where the ΔE_{SR} and ΔE_{comp} are the average energy loss per particle per turn for synchrotron radiation and Compton scattering respectively. σ_{SR} and σ_{comp} are the equilibrium energy spread in presence of the synchrotron radiation and Compton scattering respectively, ϵ_{SR} and ϵ_{comp} represent the transverse emittance for the synchrotron radiation and Compton scattering respectively. As we can see, $\Delta E_{comp} \ll \Delta E_{SR}$ ($\Delta E_{SR} = 2.89\ keV$, ΔE_{comp} is $\sim eV$ to tens eV varing with luminosity) while $\sigma_{comp} \gg \sigma_{SR}$ (i.e. for our 500 MeV lattice, $\sigma_{SR} = 5.9 * 10^{-4}$, $\sigma_{comp} = 4.56 * 10^{-2}$ when laser wavelength is 800 nm), a rough estimation for equilibrium energy spread of the electron beam

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will be $\sigma_E \sim \sqrt{C + A * E_{laser}/\lambda_L}$, where C is related to storage ring parameters, A is related to electron parameters, E_{laser} is the energy of one laser pulse, λ_L is laser wavelength.

SIMULATION RESULTS

We developed a parallel simulation program based on TRACY with flexible setting for laser or electron parameters and location of interaction point. We can perform 6-D turn-by-turn tracking for macroparticles starting from any distributing bunch, which means any effects associated with dynamics in terms of damping effects, synchrotron radiation excitation and also the transverse-longitudinal coupling in storage ring has been taken into account. The Compton scattering in the interaction point is simulated with Monte Carlo method. Without loss of generality, we set one interaction point at the center of first straight drift and assuming a 0 deg collision angle between the electron and non-polarized laser photon. We create one bunch for the tracking so there are no multi-bunch effects, wake fields and impedance effects. We will track the macroparticles for about 700k turns to reach equilibrium. Also we have set the physical rectangular aperture of 15 mm and 10 mm for horizontal and vertical direction respectively at the exit of every element to estimate the particle loss during the tracking by removing the particles outside the aperture. Intra-beam scattering is not included yet in this simulation. The base parameter settings are listed in Table1. The laser parameters are given by using the Fabry Perot resonator [8]. The power stored in the resonator for our base setting should be 20 kW while higher power can be achieved. 10k macroparticles per bunch are enough to show the statistics results according to our scanning for the number of macroparticles. The simulation was performed with our candidate lattice whose parameters are listed in Table.2.

Table 1: Parameter Setting for Laser and Electron

Init. Electron Parameters		Laser Parameters	
Energy	500 MeV	Pulse Duration	10 ps
Hor.Emittance	6.5 nm	Rms Size(x/y)	40/40 μm
Ver.Emittance	0.65 nm	Wavelength	1030 nm
Bunch Length	15 mm	Pulse Energy	0.2 mJ
Energy Spread	0.06 %	Cavity Freq.	101.38 MHz

Including the base setting, we consider another three settings, labeled S1 through S4: *i)* the base setting (S1); *ii)* the pulse energy is replaced by 2mJ (S2); *iii)* The wavelength is replaced by 800 nm (S3); *iv)* the pulse energy is replaced by 2mJ and the wavelength is replaced by 800 nm (S4).

Fig.1 shows the results of horizontal emittance evolution for above four settings. For reference, the result by turning off the Compton scattering also plots together. If we refer to the formula of I. Chaikovska [7] for S1, the ϵ_{comp} should be 2.42 nm, so the equilibrium horizontal emittance will be 3.368 nm, very close to 3.37 nm, the lattice natural

Table 2: Compton Ring Design Parameters

Parameter	Value	Units
Beam energy	500	MeV
Circumference	59.14	m
Natural emittance	3.37	nm·rad
Bending radius	1.91	m
Hor./Ver.tune	6.21/4.21	
Mom.comp factor	1.35×10^{-2}	
Rad.loss per turn	2.89	keV
Energy spread	5.9×10^{-4}	
Hor./Ver.damping time	27/68	ms
Long.damping time	129	ms

emittance. And for other settings the estimated equilibrium horizontal emittance can be 3.356 nm for S2, 3.369 nm for S3, 3.366 nm for S4, which are all very close to the natural emittance. The simulation results show that the equilibrium horizontal emittance is between 3.4 nm and 3.5 nm for the four cases with Compton scattering on. The small shift compared to the estimation from formula is induced by second dispersion with a value about 2 m at the interaction point (also some noise). Subtracting the second dispersion effects, the emittance is more close to the estimation.

Fig.2 shows the results for vertical emittance. Combining Fig.1~2 we can conclude that there is no large impact on transverse emittance of electron beam by adding Compton scattering in the storage ring for our base parameter setting. But the influence on transverse direction will vary with different lattice and input laser parameters(eg. there is cooling effects while natural emittance is large enough).

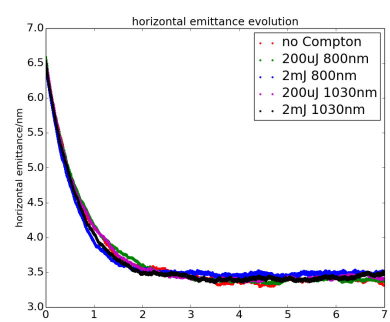

Figure 1: Horizontal emittance evolution for different setting. There are five cases. No Compton scattering, S1~S4.

Fig.3 shows the energy spread evolution for the same setting. The equilibrium energy spread is $2.8 * 10^{-3}$ compared to $1.8 * 10^{-3}$ from theory estimation for S1, $6.0 * 10^{-3}$ compared to $5.5 * 10^{-3}$ for S2, $3.2 * 10^{-3}$ compared to $2.1 * 10^{-3}$ for S3, $7.0 * 10^{-3}$ compared to $6.2 * 10^{-3}$ for S4. There are some deviation between simulation and analytical estimation because the luminosity estimated from formula is smaller than the Monte Carlo simultion. A conclusion is that higher laser energy which will increase luminosity and smaller laser

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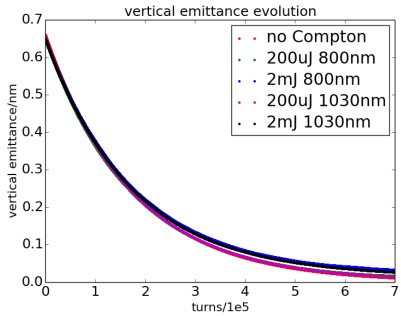

Figure 2: Vertical emittance evolution for different setting. There are five cases. No Compton scattering, S1~S4.

wavelength which can increase the energy of gamma-ray can make the equilibrium energy spread larger. This will also make stability worse as shown in following section. Too large energy spread can't be accepted because the bandwidth of emitted photons is scaled as $\sim \sqrt{(\gamma\theta) + 4\delta_e^2}$, where $\gamma\theta$ is normalized collecting angle and $\gamma\theta \ll 1$. For example, if we choose $\gamma\theta \sim 0.1$, it would be the best not exceed the value of 7e-3 for the equilibrium energy spread of the electron beam. This limitation will make some constrains for luminosity.

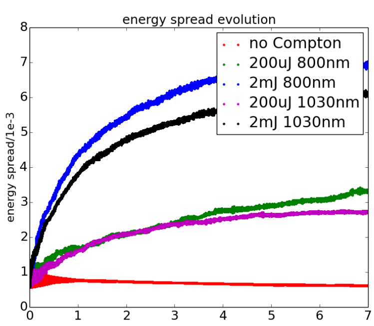

Figure 3: Energy spread evolution for different setting. There are five cases. No Compton scattering, S1~S4.

Fig.4 shows the results of the particle loss vs. time. The loss rate becomes linear at the equilibrium state and particle loss is more sensitive with the laser parameters. There is almost no loss in 700k turns for S1 and S3 in which cases the laser energy is 0.2 mJ. The total number lost in S4 is almost 6 times higher than in S2 although the different between their wavelength is only 20%. The simulation for particle loss is not very accurate due to lack of more realistic physical aperture information along the ring but the sensitivity to the laser parameters can draw more attention to optimize the input parameters to operate a more stable, economic ring with higher luminosity and narrower bandwidth.

CONCLUSION

The dynamics of electron beam associated with Compton scattering in storage ring have been investigated for our candidate Compton Gamma-ray Ring. The simulation results have good agreement with analytical estimation. For

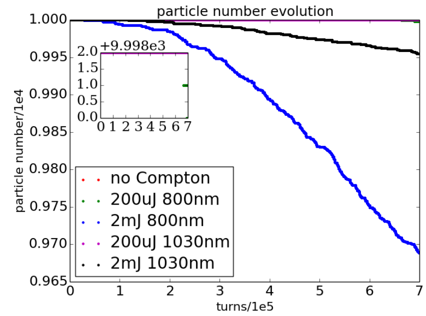

Figure 4: Particle number evolution for different setting. There are five cases. No Compton scattering, S1~S4. The small subfigure is reploted for three cases in terms of No Compton and S1,S2

our lattice, the transverse dynamics are insensitive to the laser parameters at our base setting. The equilibrium energy spread of electron beam which is highly related to the bandwidth of emitted gamma photons is very sensitive to the laser pulse energy, in other words, the luminosity. Higher luminosity increased by laser energy also means worse bandwidth, and more optimazation should be done for that based on the simulation results. Also particle loss is very sensitive to laser parameters particularly for wavelength. More accurate simulation about the loss should be developed to give more support on the optimazation for the ring lattice and parameter setting to achieve the more stable, economic gamma-ray light source operation with smaller bandwidth and higher flux.

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