LOW ENERGY COMPACT STORAGE RING DESIGN FOR COMPTON GAMMA-RAY LIGHT SOURCE

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Abstract

Gamma-ray sources with high flux and spectral densities are highly demanded by many nuclear experiments. We design a low energy compact storage ring to produce gamma-ray with energy in the range of 4-20 MeV based on Compton backscattering technique. The storage ring energy is 500-800 MeV with the circumference of about 59 m and natural emittance of about 3 nm·rad at 500 MeV. In this paper, we present the storage ring lattice design and propose two collision configurations for Compton gamma-ray generation. Intrabeam scattering has been investigated which can increase emittance from 3 nm·rad to 6 nm·rad horizontally for 500 MeV ring. We also discuss how Compton scattering affects longitudinal and transverse beam dynamics by tracking macro particles using our parallel simulation code. Based on this study, we can further optimize our storage ring lattice design for the higher gamma-ray flux production.

INTRODUCTION

Z.Huang and R.D.Ruth [1] proposed a compact electron-laser storage ring for X-ray generation (Compton X-ray ring) with electron energy in tens MeV range based on Compton backscattering technique. So far there are no dedicated storage rings for Compton gamma-ray production. Motivated by high demands of gamma-ray sources in the fields of nuclear physics research and homeland security, we design a compact electron-laser storage ring for gamma-ray generation (Compton gamma ring). In principle, Compton gamma ring is similar to Compton X-ray ring; but the energy emitted by an electron during Compton scattering in Compton gamma ring is in the range of several to tens of MeV which will greatly affect beam dynamics of the storage ring. Therefore the RF cavity and ring acceptance need to be carefully optimized. Low emittance of the storage ring is preferred for the production of high flux and low energy spread gamma-ray source. To minimize the emittance, we choose a 5 Bend Achromat lattice for the ring design. However at low ring emittance, intrabeam scattering (IBS) effects can have significant impacts on the emittance. To mitigate this IBS effect, we can introduce harmonic cavity in the storage ring to lengthen the electron bunch. In this paper, we first present our storage ring lattice design, and discuss choices of the main RF cavity and harmonic cavity and the IBS effect on the electron beam emittance. We then introduce two collision schemes (head-on and cross angle) for gamma-ray production. At the end of the paper, we briefly discuss our tracking study on electron beam dynamics using our parallel simulation code by considering Compton scattering (CS) and synchrotron radiation (SR) simultaneously.

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STORAGE RING LATTICE

To achieve low emittance, a 5 Bend Achromat lattice is proposed for our Compton gamma ring design. We apply Multi-Objective Genetic Algorithm (MOGA)[2] to design and optimize this storage ring lattice. The optic functions of a candidate lattice are shown in Fig.1. It has natural emittance of 3.37 nm·rad. The lattice is composed of four symmetrical arcs. Each arc consists of 5 dipoles with 18° bending angle, 10 quadrupoles and 10 sextupoles. All dipoles have quadrupole field which can focus electron beam vertically and defocus that horizontally. Two families chromatic sextupoles inside the arcs are used to correct the chromaticity induced by the strong quadrupole field. Two families geometry sextupoles in the straight are used to minimize nonlinear effects introduced by chromatic sextupoles to increase the dynamic aperture of the ring. The dynamic aperture is about 15 mm in horizontal direction and 10 mm in vertical direction. Fig.2 shows dynamic aperture and frequency map of the ring. The design parameters of the ring are summarized in Table.1. The ring can accommodate 4 long straight sections with lengths of 4.04 m each for injection, extraction, RF cavity and electron-laser interaction. Fig.3 shows the layout of the ring.

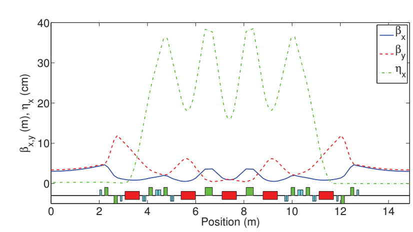

Figure 1: Ring optic functions: horizontal beta function (blue), vertical beta function (red dash), and horizontal dispersion (green dash).

RF SYSTEM AND INTRABEAM SCATTERING

For Compton gamma ring, the choice of the main RF system is affected not only by supplying the more energy losses induced by CS but also by optimizing the high flux gamma-

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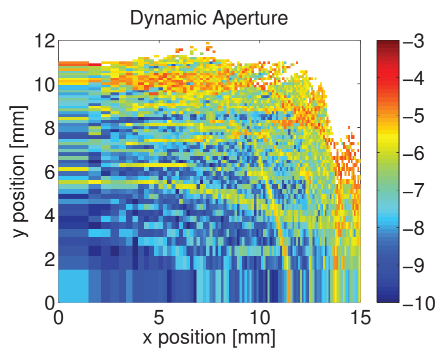

Figure 2: Dynamic aperture and diffusion rate of the ring.

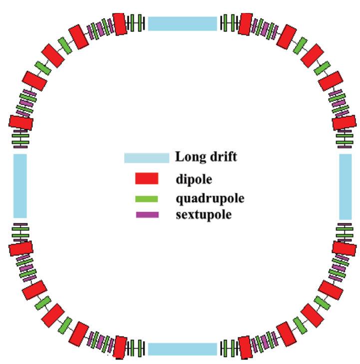

Figure 3: Layout of the ring.

Table 1: 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

Table 2: RF System Parameters

Parameter	Value	Units
Harmonic number	20	
Main RF frequency	101.45	MHz
Main RF voltage	800	keV
RF acceptance	0.061	
3rd cavity frequency	304.35	MHz
3rd cavity voltage	264.5	keV

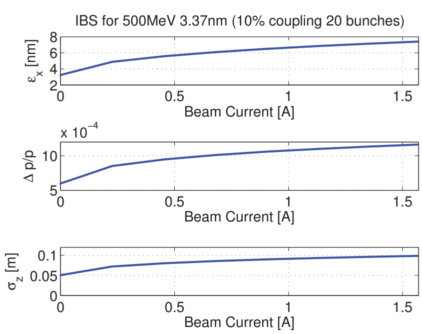

Figure 4: The ring emittance with IBS.

ray production. The main RF frequency should match laser frequency for steady interaction and high frequency is preferred to increase luminosity. However a higher frequency of the main RF cavity corresponds to a lower RF acceptance assuming the same RF voltage. But a large ring acceptance which is limited by the RF acceptance and ring dynamic aperture is essential to maintain particle losses at an acceptable level. We choose RF acceptance of 6% first to guarantee enough momentum acceptance, more precise value should base on more accurate and complex calculation for beam dynamics. At low ring energy and emittance, the IBS effect can significantly affect the electron beam emittance. To weaken the IBS effect, we introduce a 3rd harmonic cavity to lengthen electron beam. The parameters of the main RF and harmonic cavities are listed in Table.2. As shown in Fig.4, the IBS can blow-up the horizontal emittance from natural emittance 3.37 nm·rad to 6.5 nm·rad with a 10% coupling when stored current is 1 A. Fig.4 also indicates that it is not necessary to design the ring with lower natural emittance than 3 nm·rad at 500 MeV because IBS will eventually blow-up the emittance to a higher level. That's also one of the reasons why we choose 5BA lattice but not 7BA or 9BA. It should be pointed out that the equilibrium energy spread and emittance could reach a new balanced state after considering Compton scattering. Compton scattering can increase equilibrium energy spread to mitigate the IBS partly, because the growth rate of IBS is inversely proportional to energy spread.[3]

COLLISION SCHEMES AND RESULTS

We have studied two different collision schemes for the Compton gamma-ray production. One sets the interaction point (IP) in the center of straight section with an 8 deg crossing angle. Another one achieves zero crossing angle but the IP is located between dipoles. The two different schemes are illustrated in Fig.5. The parameters for the two cases are shown in Table.3. The laser frequency for head-on collision in case 2 is half of the frequency of the main RF cavity making sure that the length L_1 of laser cavity is long enough to avoid interference between mirror and electron beam. Table.3 shows that the head-on collision increases the luminosity by about 20 times compared to the collision with 8 deg crossing angle. It is preferred to achieve higher luminosity in terms of the gamma flux, however too high luminosity may induce unstable perturbation in transverse emittance and more electron losses. The dynamics will be discussed in the next section.

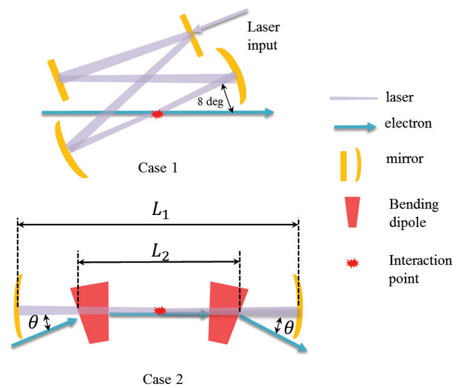

Figure 5: Collision schemes.

Table 3: Parameters and Results for Collision

Parameter	Case1	Case2
Beam current [A]	1	1
Number of bunches	20	20
e^- emittance [nm· rad]	6.5	6.5
Coupling [%]	10	10
e^-/laser length [mm]	80/6	80/6
e^- Hor./Ver.beta [m]	3/3.3	2/5
Laser energy per pulse [μ J]	200	200
Laser wavelength[μm]	1	1
Laser frequency[MHz]	101.45	50.73
Laser rms size [μm]	40	40
Crossing angle [deg]	8	0
Luminosity [$cm^{-2} \cdot s^{-1}$]	2.92×10^{35}	5.96×10^{36}
Total γ flux[ph/s]	1.89×10^{11}	3.87×10^{12}

DYNAMICS OF COMPTON GAMMA RING

CS and SR are two main effects that can disturb the beam dynamics by kicking electrons suddenly. Current theories consider the two processes as independent Poisson events; calculating the equilibrium parameters independently from Campbell's theorem and SR theory. Final equilibrium parameters are the sum of weighted parameters of the two processes with energy emitted by an electron per turn as weighted factor[4][5]. We can preliminarily evaluate ring design, rf and laser requirements by using the equilibrium parameters estimated from those theories. However the real dynamic process of the Compton gamma ring is more than these simple theories and it is essential to understand this dynamic process to optimize the Compton gamma ring design and gamma-ray production. The maximum energy loss of an electron per turn can be one or several percents in the Compton gamma ring. That energy loss may induce significant electron loss if the beam dynamic aperture and RF parameters aren't optimized properly. Furthermore the luminosity of CS will be influenced. So we are developing a parallel tracking code by integrating Compton scattering process into accelerator modeling code TRACY[6] to track the phase space coordinate of every macro electron by considering CS and SR simultaneously. In this simulation, the electrons are tracked for several damping times until reaching equilibrium state. For each turn, electrons interact with laser photons at IP. After the interaction, the momentum of electrons are modified according to Compton scattering theory and these electrons are further tracked through the ring to the end of each turn. Based on this tracking study, we can optimize the ring, RF, and laser parameters using electron loss rate and luminosity of CS as objectives. The preliminary tracking results has confirmed with theory. And we find that increasing the laser intensity will induce additional growth of the horizontal emittance because of the horizontal and longitudinal coupling in dipoles. The increases of horizontal beam size can reduce the luminosity of CS. That means higher intensity of laser may not produce more gamma-ray. Optimization on luminosity and lattice should be performed based on more precise and comprehensive simulation studies.

CONCLUSION

We have designed a compact Compton storage ring for producing high flux, low energy spread gamma-ray source in the range of 4-20 MeV. The parameters of the ring have been optimized for the gamma-ray production. IBS can't be negligible in the low emittance 500 MeV ring. The increase of horizontal emittance due to Compton scattering will affect the final luminosity and equilibrium parameters. We are performing the macro particles tracking to study electron beam dynamics by combining Compton scattering and synchrotron radiation simultaneously. Based on this tracking study, eventually we can optimize the Compton gamma ring for high gamma-ray flux productions.

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