BEAM DYNAMICS IN THE LASER-ELECTRON STORAGE RING FOR A COMPTON X-RAY SOURCE*

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Abstract

We present the lattice analysis and simulation study of the beam dynamics in the pulse mode of the laser-electron storage ring. Compton Scattering (CS), Intra-beam Scattering (IBS) with non-Gaussian beam and Synchrotron Radiation (SR) are taken into consideration. Emittance growth, energy spread and phase space of the electron beam, as well as spatial and temporal distribution of the scattered photon are studied in this paper.

INTRODUCTION

The idea of utilizing a Laser-Electron Storage Ring (LESR) for the purpose of increasing frequency and luminosity of x-ray by means of Compton Scattering was proposed by Huang and Ruth in 1998 [1]. There are two main operation mode proposed for this scheme: the steady mode and the pulse mode. In this paper, we focus on the pulse mode of the LESR, in which electron beams are injected and dumped at the frequency of 50Hz.

We will present the lattice design, simulation method and simulation results in this paper.

LATTICE DESIGN

Requirements for LESR lattice

We propose a compact race-track design with the circumference of 12 meter. The scheme is based upon the traditional lattice design for compact storage ring [2, 3].

The main requirements of the lattice are:

- Beta function at the Interaction Point (IP) should be small to enhance scattered photon yield.
- Two long straight sections should be dispersion-free in order to place IP, RF cavity and injector.
- Because of the low beta insertion at the IP, strong sextupoles are placed in dispersive section to correct natural chromaticity; hence, harmonic sextupoles are necessary for enhancing dynamic aperture

The layout of the ring lattice is illustrated in Fig.1.

Dynamic aperture

The conventional definition of the dynamic aperture (DA) only takes non-linear lattice elements into consideration. However, in order to identify the effect of Compton Scattering (CS) to the electron, we calculated dynamic aperture taking both CS and SR into consideration. The parameters we use in the simulation are listed in Tab.1, and the result is presented in Fig.2. The DA without the effects of CS is illustrated by area in light grey.

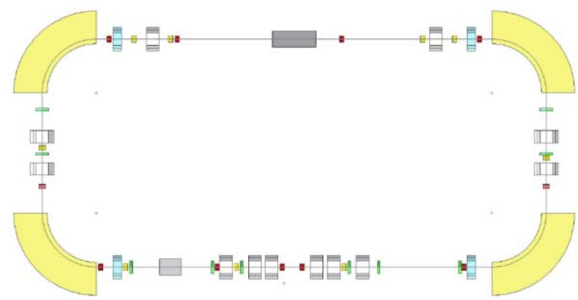

Figure 1: Layout of the ring lattice. For the beta function and dispersion function, see [8].

Table 1: Parameters of electron beam and laser pulse

Parameters	Value
Electron	
RMS bunch length, ps	10
RMS transverse size, μm	25
Energy, MeV	50
Transverse emittance, mm mrad	0.02
Relative energy spread	0.18%
Laser	
Transverse spot size, μm	20
Wavelength, nm	800
Rayleigh length, mm	6
Pulse length, fs	100

We can see from the figure that, the DA decreases as the laser energy increases. When laser energy comes to 1J, the DA becomes intolerant for stable operation. Nevertheless, when laser energy is below 100mJ, the DA changes little compared with that without the effect of CS.

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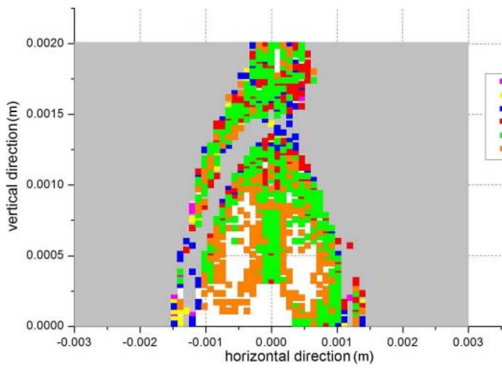

Figure 2: Dynamic aperture at the IP at different laser energy.

BEAM DYNAMICS

The most important effects in the beam dynamics of the laser-electron storage ring are synchrotron radiation (SR), Compton Scattering (CS), and Intra-beam Scattering (IBS). Due to the fact that the electron beam is dumped long before equilibrium parameters are achieved, and because of the quantum nature of CS and IBS, the central limit theorem may not be adequate to apply to the beam dynamics, i.e. the distribution of the electron beam may not be Gaussian distribution. Hence, in the simulation, we have to apply a full Monte-Carlo method to describe the beam dynamics.

Synchrotron radiation

The energy loss due to synchrotron radiation is 1.42eV, and photon emitted per electron per turn is N=6.48. The longitudinal damping time is 1.44 sec. Therefore, the effect of SR is not strong in the pulse mode, in which the injection time of the electron beam is about 20ms. Nevertheless, we apply a Monte-Carlo method in which photons are tracked particle by particle.

Compton Scattering

We apply a full 3D Monte-Carlo method to simulate the temporal and spatial distribution of the scattered photon. We basically follow the approaches by that of Yokoya [5].

Intra-beam Scattering

The prevailing method of evaluating IBS emittance growth rate is the approaches by those of Bjorken-Mtingwa (BM) [6]. However, the formulas are based upon the assumption that the electron beam is Gaussian. This assumption may not be adequate in the pulse mode, especially when the beams injected are not Gaussian or the laser energy is high.

In order to calculate IBS growth rate, we apply the Binary Collision Model (BCM) in the simulation code [7], which was first used in plasma physics. The main idea of the BCM algorithm is to place macro-particles into different cells in "IBS interaction area". The macro-particles in the same cell are arranged in pairs, and the paired macro-particles collide with each other. The scattering angles of the collision are chosen such that the changes of the invariants are the same as those caused by IBS.

SIMULATION RESULTS

Electron beam

The simulation results of electron beam emittance and energy spread are illustrated in Fig.3. With the parameters listed in Tab.1, IBS is the dominant factor that determines the transverse emittance. We can see in Fig.3 that, horizontal emittance growth rate decreases as laser energy increases. The reason is that, higher laser energy causes higher energy spread and longer RMS bunch length, which decreases the intensity of the electron in the bunch, and finally decreases the IBS growth rate in transverse direction.

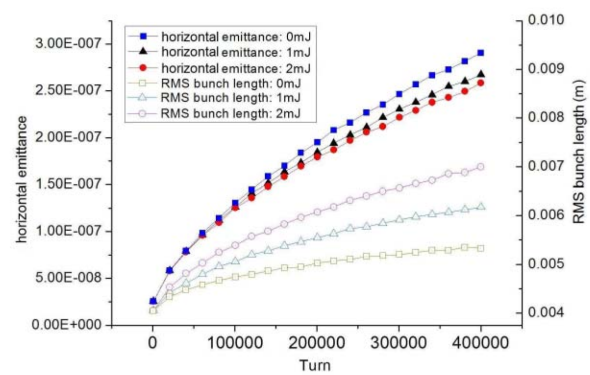

Figure 3: Horizontal emittance growth and bunch length growth. We take CS, SR and IBS into consideration.

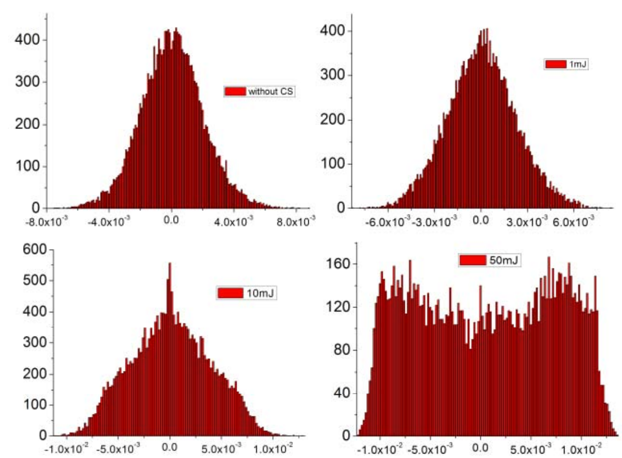

Figure 4: Longitudinal momentum deviation at different laser energy.

The longitudinal momentum deviation at the time 10 ms (the injection period is 20 ms) at the laser energy of 0, 1, 10, 50mJ is presented in Fig.4. We apply a RF phase manipulation scheme in which RF phase is changed as scattered photon yield decreases, in order that the energy spread can be minimized. As we can see in the figure, when laser energy comes to 50mJ, the longitudinal energy distribution can hardly be described as Gaussian. This result justifies the necessity of applying the BCM to calculate IBS growth rate. Large energy spread can be witnessed at higher laser energy, which essentially enhances the bunch length and decreases the scattered photon yield.

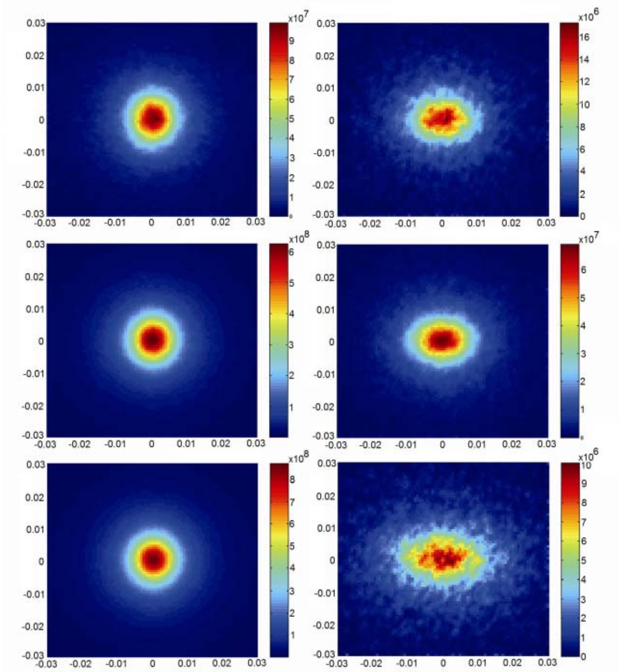

Figure 5: Spatial distribution of scattered photon yield at a CCD placed 1.5 meter away from the IP.

Scattered photon

The scattered photon yield is presented in Fig.5. The figure presents the spatial distribution of the number of scattered photon detected by a virtual CCD placed 1.5 meter away from the IP. The laser energy is 1, 10, 50mJ. The left column is the spatial distribution of the total yield, and the right column is that of the last 100,000 turns. We can see that the spatial distributions of the last 100,000 turns are slightly different from the total yield. The reason is that horizontal emittance of the electron beam size have been enhanced at the end of the injection period, either due to IBS or CS. Fig.6 presents the temporal distribution of scattered photon yield in an injection period at the laser energy 1mJ. The peak intensity is 4.74×10^{12} /sec. The photon yield decreases to 1/2 of its value at the end of the pulse.

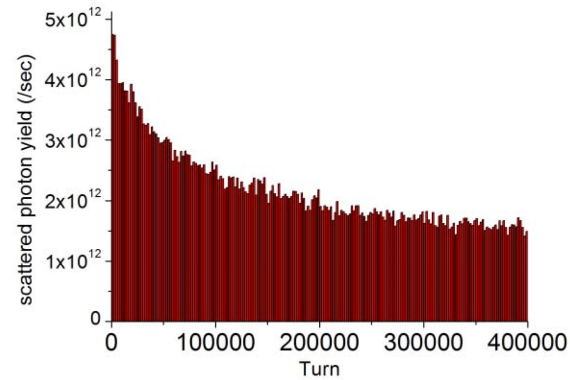

Figure 6: Scattered photon yield at the laser energy of 1mJ.

SUMMARY

The lattice analysis for the pulse mode of the LESR is presented. We likewise present the simulation results of the beam dynamics and scattered photon yield.

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