EFFECT OF COMPTON SCATTERING ON THE ELECTRON BEAM DYNAMICS AT THE ATF DAMPING RING*

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Abstract

Compton scattering provides one of the most promising scheme to obtain polarized positrons for the next generation of $e^- - e^+$ colliders [1]. Moreover it is an attractive method to produce monochromatic high energy polarized gammas for nuclear applications [2] and X-rays for compact light sources [3]. In this framework a four-mirror Fabry-Pérot cavity has been installed at the Accelerator Test Facility (ATF - KEK, Tsukuba, Japan [4]) and is used to produce an intense flux of polarized gamma rays by Compton scattering [5]. For electrons at the ATF energy (1.28 GeV) Compton scattering may result in a shorter lifetime due to the limited bucket acceptance. We have implemented the effect of Compton scattering on a 2D tracking code with a Monte-Carlo method. This code has been used to study the longitudinal dynamics of the electron beam at the ATF damping ring, in particular the evolution of the energy spread and the bunch length under Compton scattering. The results obtained are presented and discussed. Possible methods to observe the effect of Compton scattering on the ATF beam are proposed.

INTRODUCTION

For the future linear collider projects (ILC, CLIC), positron sources are considered as a critical and challenging component. This is essentially due to the very high beam intensity required, orders of magnitude higher than existing ones. The main solution to generate polarized positrons is by using high-energy polarized photons (gamma rays). These gamma rays can be produced by Compton scattering and be converted into $e^- - e^+$ pairs. To meet the requirements imposed by these future projects, one needs to increase significantly the flux of the gamma rays produced. This can be done by using a high average power laser system based on a Fabry-Pérot cavity and a high current electron beam.

In this framework, a four-mirror Fabry-Pérot cavity has been built and successfully installed at the Accelerator Test Facility (ATF) at KEK (Japan) to test the production of gamma rays [5].

During the collision between electrons and laser photons, energy is transferred. This results in an increased energy spread for the electron bunch. In a storage ring this increases the energy spread turn by turn and may have significant effect on the electron beam dynamics, reducing the

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gamma ray flux despite the synchrotron damping. Therefore, it is important to investigate this effect in the context of both the future positron sources and the accelerator–based compact light sources using Compton scattering [3].

LONGITUDINAL BEAM DYNAMICS WITH COMPTON SCATTERING

Longitudinal Dynamics in a Ring

During a revolution an electron looses a fraction of its energy by synchrotron radiation. To keep the electron beam in the ring, this energy loss has to be compensated by the energy given by the radio frequency (RF) cavities. The acceleration process by itself results in damping of the longitudinal oscillations in such a way that the trajectory of each electron tends toward center of the RF bucket. The damping is limited due to continuous excitation, so-called quantum excitation. The balance between the radiation damping and quantum excitation is reached at equilibrium defining an area occupied by the electrons in the RF bucket where the particle oscillations are stable.

All processes mentioned above, characterize the longitudinal dynamics of a beam in a storage ring like the ATF damping ring (DR). However, the presence of Compton collisions affects this dynamics.

Longitudinal beam dynamics can be described by two coupled variables related to the RF acceleration process and defined with respect to the synchronous particle:

- energy gained by the electron j, $\delta E_j = E_j - E_s$, where E_j and E_s are the energies of any given electron in the bunch and that of the synchronous particle respectively.
- longitudinal displacement from the synchronous particle that can be expressed also by the time difference $\tau_j = \tau_j - \tau_s$ between the arrival time of the electron at any particular position and the arrival time of the synchronous particle.

Since the synchronous particle has zero time difference and has the nominal energy, it is possible to use it as a reference system.

Simulation

The motion of electrons in the longitudinal phase space is described by a second order non linear differential equation. As a result, electrons oscillate in longitudinal position and in energy with respect to the synchronous particle.

In our simulation code we divide the electron beam in a large number of macro-particles (10^5 MP). To find the
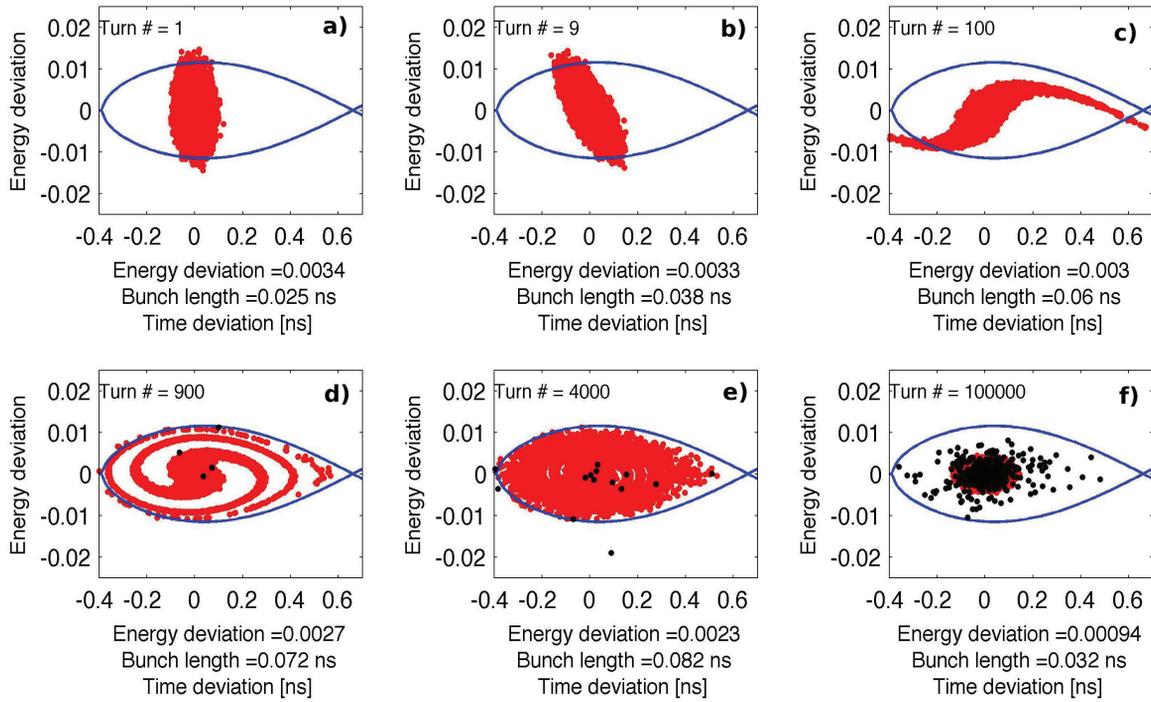
Figure 1: Evolution of the longitudinal phase space of one electron bunch at the ATF DR with Compton scattering. The bunch is modeled by 10^5 macro-particles and the laser power is 100 kW. The blue curve defines the separatrix. Macro-particles denoted in black underwent Compton scattering at least once.

oscillation amplitudes, we use a numerical solution of the equations of motion in which the energy change and time displacement per revolution are given by

$$\delta E_{i,n+1} = \delta E_{i,n} - U_{synchRad} + V_0 sin(\omega_{RF}t + \phi_s) - \\ - \delta E_{damp} - \delta E_{compt} + \delta E_{qe}$$

$$\tau_{i,n+1} = \tau_{i,n} - \alpha \frac{\delta E_{i,n}}{E}, \quad (1)$$

where $\delta E_{i,n}$ and $\tau_{i,n}$ are respectively the energy deviation and time displacement of the i-th macro-particle on the n-th turn, $U_{synchRad}$ is the energy loss per turn due to synchrotron radiation, V_0 is the peak voltage of RF cavity, ϕ_s is the synchronous phase, δE_{damp} is the fraction of energy deviation due to damping, δE_{compt} is the fraction of energy deviation due to Compton scattering, δE_{qe} is the fraction of energy deviation given by the quantum excitations, α is the first order momentum compaction factor and E is the electron energy. Reference [6] contains a full description of each term in Eq. 1.

The δE_{compt} term is calculated for each macro-particle on a turn by turn basis using a Monte-Carlo technique to decide if a given macro-particle has interacted and how much energy was lost due to Compton scattering. A spectrum of scattered gamma rays is obtained by using the simulation code CAIN [7].

Table 1 summarises the parameters used for the simulations. We do not expect other effects to significantly affect the longitudinal beam dynamics in the ATF DR.

Table 1: ATF Parameters

Description	Value
Electron energy, E	1.28 GeV
Electron charge, C_e	1.6 nC
Electron bunch length at injection, τ_{e0}	25 ps
Momentum compaction factor, α	0.002085
Harmonic number, h	330
Peak RF Voltage, V_0	250 kV
Longitudinal damping time, t_{damp}	19.5 ms
Energy spread at injection, ϵ_0	0.8 % FWHM
Revolution period, T_0	463 ns
Synchronous phase, ϕ_s	10.2 deg.
Energy loss per turn, $U_{synchRad}$	44 keV
Synchrotron frequency, Ω_s	10 kHz
RF bucket height, $(\frac{\Delta E}{E})_{max}$	0.012
Laser photon energy, E_{ph}	1.2 eV
Crossing angle, θ	8 deg.
Laser pulse length, τ_L	20 ps

RESULTS AND DISCUSSION

Using our simulation code, we studied the motion of the electrons after injection in the DR. On Fig. 1 the turn by turn evolution of the electron bunch injected into such bucket is shown as well as the boundary of the bucket (separatrix). When the energy change for an electron δE brings it beyond the separatrix, the electron is ejected from the

bunch and eventually lost.

One can see on Fig. 1 the effect of bunch mismatching inside the bucket. The injected bunch is shorter than the RF bucket but has a large energy spread, therefore, under the influence of the RF field it rotates in the longitudinal phase space (see Fig. 1: a, b, c). As the electron bunch is mismatched, it filamentates: the electrons spread out in the phase space and evolve into a spiral bounded by the sepa-ratrix. After $\sim 1 \times 10^3$ of turns the bunch fills the RF bucket and the damping process starts. After $\sim 2 \times 10^5$ turns (90 ms) the equilibrium between quantum excitation and damping is reached. However, this equilibrium is modified by Compton scattering (see Fig. 1: d, e, f).

In the absence of Compton scattering, at equilibrium all electrons remain within the separatrix. Bucket height is ~ 15 MeV, so low energy Compton scattering will displace the electrons within the separatrix (see Fig. 1 d, the scat-tered electrons are tagged in black). Whereas a larger per-turbations such as high energy Compton Scattering ($\Delta E > 15$ MeV) will kick some electrons out and those outside the bucket will get lost (see Fig. 1 e).

The evolution of the bunch length, the energy spread and the evolution of the number of macro-particles are pre-sented on Fig. 2, Fig. 3 and Fig. 4 respectively. If the laser power is below 100 kW, the effect of Compton scattering is quite small over $\sim 2 \times 10^6$ turns (1 s) .
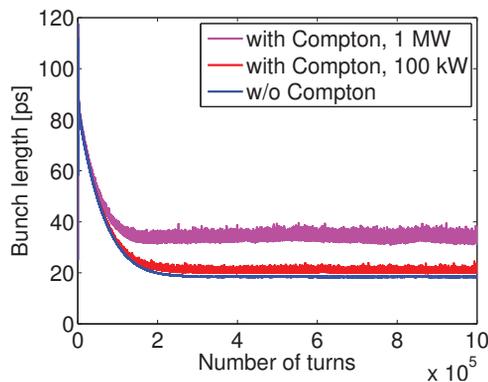
Figure 2: Evolution of the bunch length for different laser power over approximately 0.5 s. The damping period cor-responds to the $\sim 2 \times 10^5$ turns and after the equilibrium is reached.

For a laser power of 100 kW and 1MW the equilibrium bunch length and the energy spread are respectively $\tau_e = 22$ ps, $\epsilon = 0.06$ % and $\tau_e = 34$ ps, $\epsilon = 0.1$ %. Figure 4 shows that for 1 MW of laser power, the electrons loss rate is significantly increased.

The main effect of Compton Scattering on the ATF beam is a reduction of its lifetime. This could be observed by monitoring the evolution of the current in the DR over a second or more. For the laser power below 100 kW, the Compton effect on the electron beam dynamics at the ATF DR are rather small which makes them difficult to observe. For high enough laser power bunch lengthening could be
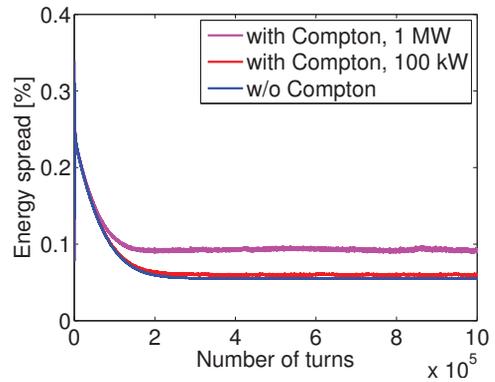
Figure 3: Evolution of the energy spread for different laser power over approximately 0.5 s.
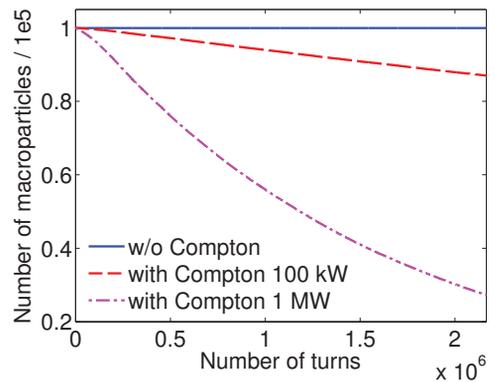
Figure 4: Evolution of the number of macro-particles for different laser power over 1 s.

observed using a streak camera.

CONCLUSIONS

In the context of the Mightylaser project, we simu-lated the electron beam dynamics under Compton scatter-ing at the ATF DR. Compton scattering reduces the elec-tron beam lifetime in the present set-up but the electrons remaining within the bucket are quickly damped. At higher laser power (~ 1 MW) changes in energy spread and bunch length will become observable as well.

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