Electron Beam Dynamics in the 50 MeV ThomX Compact Storage Ring

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Abstract

ThomX is a high flux compact X ray source based on Compton back scattering between a relativistic electron beam and an intense laser pulse. To increase the repetition rate, the electron beam is stored in a 50 MeV ring. The main drawback of such a scheme is the low energy of the electrons regarding collective effects and intrabeam scattering. These effects tend to spread or even disrupt the stored bunch and they limit its charge, especially in low energy rings machine where damping plays a negligible role. Thus such collective effects reduce the maximum X-ray flux and it is important to investigate them to predict the performance of this type of X-ray source. In addition, Compton back scattering acts on the electron beam by increasing its energy spread. This presentation will show firstly the impact of collective effects on the electron beam, essentially during the first few thousand turns when they are the most harmful. Then, the reduction of the X-ray flux due to Compton back scattering and intrabeam scattering will be investigated on a longer time scale.

INTRODUCTION

ThomX is based on a 50 MeV storage ring operating in a pulsed mode at a target current of 20 mA [1]. The electron bunch charge considered is then 1 nC. The synchrotron equilibrium is not reached. Because of the low beam energy, the degradation of the electron bunch is not slowed down by damping. Accordingly, we have to take care of all sources of electron bunch degradation. The Compton interaction rate is determined by the stored electron bunch characteristics which follow themselves from the linac performances. The bunch is ejected when the scattered radiation characteristics are no more suitable for users. This paper will present first the collective effects involved mainly during the first turns and the IntraBeam Scattering (IBS) and Compton Back Scattering (CBS) effects that take place on a longer time scale. In the last part of this paper, the flux reduction evaluation and the spectrum distribution evolution will be dealt with.

COLLECTIVE EFFECTS

The ThomX electron bunch is very sensitive to wakefield effects mainly due to its low energy, its short length and the fact that there is no damping during the storage time. There are various sources of wakefields: Beam pipe geometry (bellows, pump ports, RF taper, RF HOM etc ...), resistive wall effect, Coherent Synchrotron Radiation (CSR enhanced by the short bend radius). In addition the injected bunch from the linac suffers from a strong longitudinal phase space mismatch. 2D and 6D tracking simulation codes including these effects have been developed. The injected bunch is short, only 4 ps rms long, and exhibits the standard curved banana shape in the longitudinal phase space resulting from the 3 GHz linac acceleration. During the first turns in the ring, the bunch phase space profile will undergo a complex dynamics under the effect of the collective effects as shown in figure 1. This turbulent process will progressively lead to the matching of the ring longitudinal phase space over the first thousand turns. The bunch length will reach about 25 ps rms while the energy spread will remain unchanged. In this process, the CSR is the dominant collective effect.

The important point is the need for longitudinal and transverse feedbacks. Their design is under way to cope with any source of bunch oscillation and to provide a center of mass damping. To summarize, these sources are for each plane:

- Injection miss steering: Position and time/energy jitter from the linac and from the transfer line,
- Transition time: First ~1000 turns when strong collective effects occur, enhanced by injection mismatch between the linac and the ring,
- Storage time : Impedance, HOM and ions.

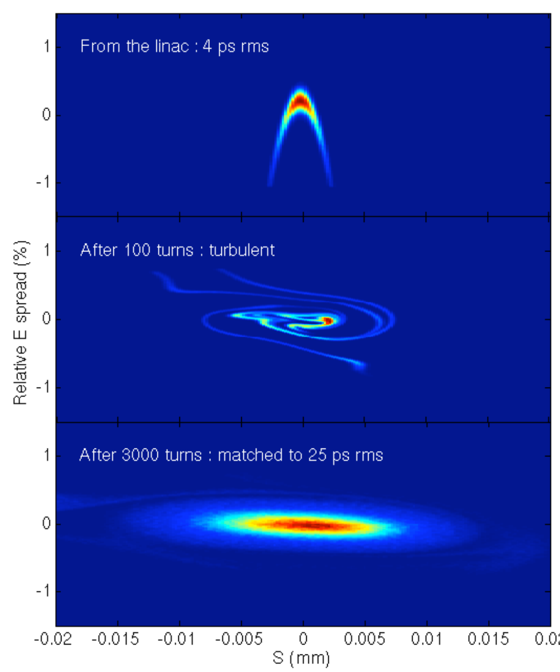

Figure 1: Longitudinal phase space evolution during the first few thousand turns after injection from the linac. Charge 1 nC. Simulation realised with a 2D tracking code including the effects of the longitudinal feedback, the CSR, the space charge and the resisting wall.

In the transverse plane, the most critical instabilities are supposed to be the head-tail and resistive-wall arising from the vacuum chamber impedance, as well as those due to ions. The resistive-wall instability threshold estimated in frequency domain with 28 mm aperture stainless steel chambers turns out to be as low as ~5 mA due to the long radiation damping time. The growth rate at 20 mA is nearly 1 ms with little dependence on the number of bunches. MOSES calculations were carried out with a broadband resonator impedance scaled from that modelled for SOLEIL. While the TMCI (transverse mode coupling instability) threshold turned out to be as high as 90 mA, that of the head-tail was low for the same reason as the resistive-wall, corresponding to ~0.16 ms growth time at 20 mA. Regarding the ion instabilities, the critical mass for the 2-bunch case is less than 1 implying the possibility of trapping all species. The asymptotic growth rate of the fast beam-ion instability for 40 mA consisting of 2 bunches is ~0.1 ms, as deduced from the linear model of T. Raubenheimer and F. Zimmermann [2]. Multibunch tracking is being performed to pursue these instabilities in more detail. As regards transverse feedback, a simple analogue system damping the few most dangerous coupled-bunch modes may be better suited for ThomX in view of the 1 or 2 bunch operation envisaged. The optimisation is underway.

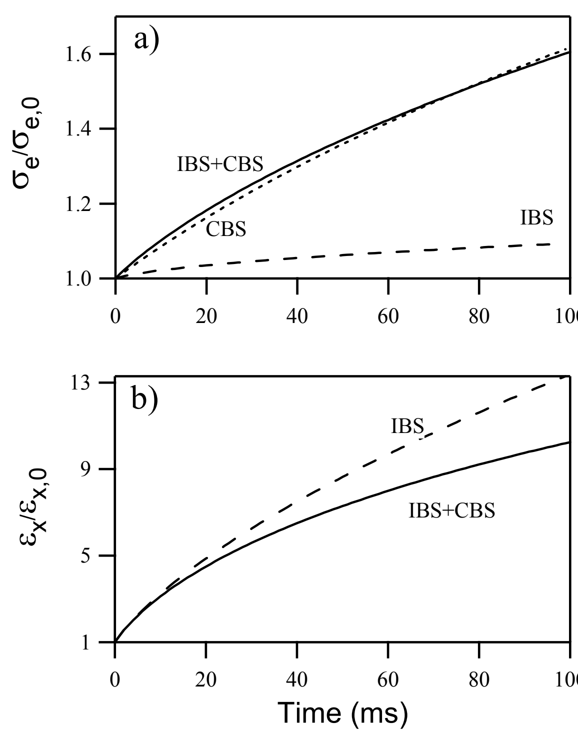

Figure 2: Evolution of the normalised a) energy spread and b) emittance versus time. Solid line: IBS and CBS are considered, dotted line: only CBS, dashed line: only IBS. Each quantity is normalised to its value at injection. Geometric emittance $\varepsilon_{x,0}$=5 10^{-8} m rad, energy spread : $\sigma_{e,0}$=0.3%, charge 1 nC, energy 50 MeV

INTRABEAM SCATTERING

Intrabeam scattering results from Coulomb scattering between particles within the electron bunch, inducing an energy change to both particle affected by the collision. Thus IBS increases the energy spread. In addition to the longitudinal effect, a horizontal emittance growth is induced proportionally to the H function of the ring optics. This decreases the electronic density at the interaction point directly linked to the X-ray flux. Derived from the diffusion equation which described the IBS, especially in the Bjorken-Mtingwa model [3], the growth rate T_i of each quantity can be expressed as:

$$\frac{1}{T_e}=\frac{1}{\sigma_e}\frac{d\sigma_e}{dt};\ \frac{1}{T_{x,y}}=\frac{1}{\sqrt{\varepsilon_{x,y}}}\frac{d\sqrt{\varepsilon_{x,y}}}{dt} \qquad (1)$$

σ_e being the energy spread and $\varepsilon_{x,y}$ either the horizontal or the vertical emittance.

Each growth time is calculated along the ring using the proper optical function. Calculations for the ThomX case have been done for the lattice illustrated in [4]. As expected, the energy spread is not much affected by IBS unlike the emittance (see fig. 2). The major contribution to the energy spread growth time comes from the interaction region where the beta function is low and the H function vanishes, while the horizontal emittance grows mainly in the dispersive regions. As the Compton back scattering acts also on the energy spread, it has to be taken into account to evaluate the emittance degradation.

COMPTON BACK SCATTERING

Compton back scattering affects the electron beam as the synchrotron radiation (SR), but with a different energy scale. Since the cross section is low, the average energy lost by electrons is low in rings coupled to an infrared laser. CBS damping is negligible during the storage time. In contrast, the excitation term is proportional to the average energy of emitted X ray $\langle E_x \rangle$ in the keV range. CBS contribution to the energy spread increase during a time interval Δt can be expressed as:

$$\sigma_{e,cbs}^2=\left(\frac{1}{2}\frac{\langle E_x\rangle}{E_0}\right)^2\frac{\dot{N}_x}{N_e}\Delta t \qquad (2)$$

E_0 is the electron beam energy, N_e the number of electrons in the bunch, $\dot{N}_x$ is the number of emitted photons per second i.e. the flux. Assuming a constant beam size across the interaction region - thus without taking into account the effect of the laser Rayleigh length nor the hourglass effect- the flux is given by:

$$\dot{N}_x=\frac{\sigma_{th}N_eN_\gamma\cos\phi f/2\pi}{\sqrt{\sigma_{y,e}^2+\sigma_{y,\gamma}^2}\sqrt{\left(\sigma_{x,e}^2+\sigma_{x,\gamma}^2\right)\cos^2\phi+\left(\sigma_{z,e}^2+\sigma_{z,\gamma}^2\right)\sin^2\phi}} \qquad (3)$$

where σ_{th} is the Thomson cross section, N_γ the number of photons per laser pulse, f the repetition frequency, ϕ the half of the angle of collision, $\sigma_{x,y,z,e,\gamma}$ stands for the three dimensional bunch r.m.s. sizes for the electrons (index e) and for the laser pulse (index γ). Calculation (see fig 3 caption for the input parameters) of the energy spread growth has bean done taking into account the proportionality between the energy spread and the bunch length. Time step is set to 1ms, and the flux is updated at each step. The energy spread rise is dominated by the CBS effect (see fig. 2). It reaches 60% after 100ms. On the other hand IBS has a strong impact on the horizontal emittance which is multiplied by a factor thirteen after 100ms. Combination of both effects limits this emittance degradation because of the faster energy spread rise induced by CBS. This produces a faster decrease (compare to the IBS case alone) of the electronic density in the dispersive regions. The resulting effect is a reduced IBS emittance growth rate during the first ms.

Nevertheless, at the interaction point, the increase in size due to the emittance growth has a relatively small impact on the scattered photon flux. Although the horizontal emittance degradation reaches a factor ten, the flux is only reduced by 30% after 100ms, half of it being due to the CBS effect.

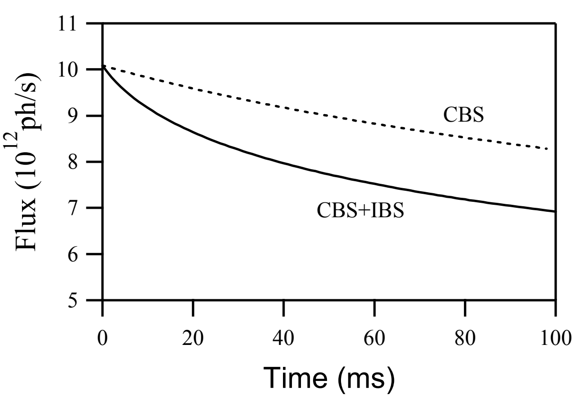

Figure 3: Total flux evaluated with eq. 3 versus time. Solid line: IBS and CBS are taken into account, dotted line: only CBS. Laser pulse energy : 30 mJ @ 1.06 µm, Electron bunch charge 1 nC@ 50 MeV, IP transverse beam rms dimension 70 µm (5 10^{-8} of emittance), IP transverse laser pulse rms dimension 40 µm, Laser pulse rms duration 20 ps, Electron beam rms duration 14 ps, Initial rms energy spread 0.3 %

The flux value integrates all the scattered photons while users are more interested in the brilliance or the quality of the energy spectrum. To evaluate the evolution of the latter parameters, Monte Carlo simulations of the Compton interaction have been performed with CAIN [5]. The total flux obtained is in agreement with the results of eq. 3. On the other hand, assuming an emittance of 40 10^{-8} m rad instead of 5 10^{-8} m rad, the brilliance is reduced by a factor 5. The emittance rise impacts on the number of scattered photon and the photon source area. If one maintains the same flux by reducing the horizontal betatron function, the brilliance (for an emittance of 40 10^{-8} m rad) is only half instead of being divided by five (compared to the case of an emittance of 5 10^{-8} m rad).

We are also interested in the energy spectrum evolution. One way of selecting a fraction of the energy spectrum of the scattered photons is to insert a diaphragm. The energy of the scattered photon is correlated to the scattering angle. The distribution of the photon energy whose scattering angle is less than 1 mrad is shown in fig. 4. When the emittance is larger (red, blue curves), the spectrum broadens. Then the number of photons N_λ (between 43 and 45 keV) is reduced at least by a factor 3. Even though the total flux value of the blue curve is the same as the one of the black curve, it corresponds to the worst case i.e. N_λ is reduced by a factor five. Nevertheless in this case, the bigger angular divergence at the IP reduces N_λ because of the Compton energy angle dependence. So the optimal beta function at IP has to be found to maximize N_λ.

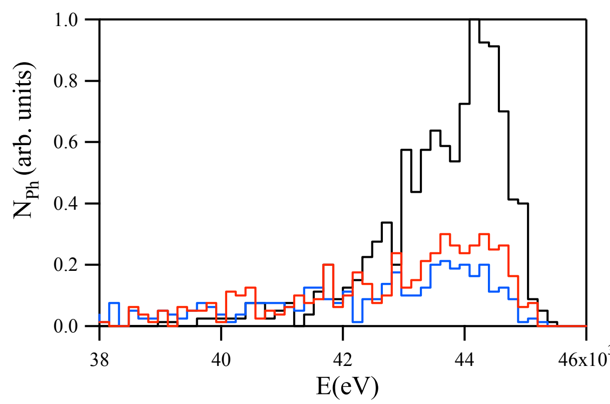

Figure 4: Energy distribution of the scattered photons whose scattering angle is less than 1 mrad. Black: ε_x= 5 10^{-8}m rad, ε_y=5 10^{-8}m rad, β_x=0.1m, β_y=0.1m; red: ε_x= 40 10^{-8}m rad, ε_y=5 10^{-8}m rad, β_x=0.1m, β_y=0.1m; blue: ε_x= 40 10^{-8}m rad, ε_y=5 10^{-8}m rad, β_x=0.0125m, β_y=0.1m.

CONCLUSION

Collective effects, IBS and the recoil effects that stem from the photon back-scattering process play major roles in the design of an X ray source based on a low energy electron ring coupled to a laser. The absence of significant damping makes the stored electron bunch very sensitive to these effects and the X ray production rate tends to decrease rapidly during the storage time. In ThomX, this rate should decrease by less than two during the 100 ms storage cycle.

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