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COMPTON BACKSCATTERING OF INTRACAVITY STORAGE RING FREE-ELECTRON LASER RADIATION

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We discuss the γ- ray production by Compton backscattering of intracavity S.R. FEL radiation. We use a semi-analytical model which provides the build up of the signal combined with the storage ring damping mechanism and derive simple relations yielding the connection between backscattered photons brightness and the intercavity laser equilibrium intensity.

1 Introduction

In a previous paper[1] hard x-ray production by Compton backscattering process (C.B.P) of intracavity visible free-electron laser (FEL) radiation has been discussed. A crucial element has been a phenomenological semi-analytical theory of FEL dynamics, which was capable of providing gain saturation effect, e-beam interaction induced energy spread and equilibrium intracavity intensity.[2] The backscattered photon brightness was then evaluated using a formalism adapted from that used in the derivation of the undulator brightness.[3] The laser dynamics was that of a single pass FEL, where the gain saturation mechanism is essentially due to the increase of the intracavity laser intensity. In this case the equilibrium intensity is proportional to the e-beam power density.

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In this work we consider a C.B.P. of an storage ring (S.R.) FEL. The e-beam is circulated many times in the optical cavity and therefore saturation is due to both the intracavity intensity and the induced energy spread. At the same time, the damping mechanism *cools* the e-beam and therefore, before reaching equilibrium, the laser power exhibits a number of oscillations on a time scale on the order of the damping time.[4] The equilibrium S.R. FEL power is, therefore, a compromise between the FEL interaction causing an intensity dependent energy spread and the subsequent radiation damping relaxing the e-beam to the original stationary configuration. As a consequence, the equilibrium intracavity power is a quantity proportional to the power $\mathcal{P}_s$ lost by the e-beam in the ring via synchrotron radiation.[5] We show that the S.R. FEL C.B.P. brightness is proportional to $\mathcal{P}_s$.

2 Storage Ring FEL Dynamics

On an S.R. FEL, the same high energy e-beam traverses many times the interaction region, allowing the growth of the optical signal and undergoing a cumulative induced energy spread. Such an effect translates into an e-beam lengthening and thus to a reduction of the peak current, this is the primary reason for the S.R. FEL saturation.[5] The intrinsic gain saturation, i.e. the gain reduction due to the increasing intracavity intensity plays a secondary roll. We can parameterize the S.R. FEL gain as: $G(x) = 0.85 g_0 E(x) B(x) T(x)$, where g_0 is the small signal gain and $x = \frac{I}{I_s}$ with I and I_s being the intracavity and saturation intensities. The function $E(x) = 1/\{1 + 1.7\mu_e^2(0)[1 + \frac{\sigma_i^2(x)}{\sigma_e^2(x)}]\}$ accounts for the gain reduction due to the natural ($\sigma_e(0)$) and induced energy spread ($\sigma_i(x)$) where $\mu_e(0) = 4N\sigma_e(0)$ and N is the number of wiggler periods. The factor $B(x) = 1/\{\sqrt{1 + (\frac{\sigma_i(x)}{\sigma_e(0)})^2}\}$ takes into account the peak current reduction due to bunch lengthening. Finally, $T(x) = \frac{1-e^{-\beta x}}{\beta x}$ is the term which in a single pass FEL yields the gain versus intensity saturation with $\beta \approx \frac{1.0145}{\pi}$. The induced energy spread $\sigma_i(x) = \frac{0.433}{N} e^{-\frac{\beta}{4}x} [\frac{\beta x}{1-e^{-\beta x}} - 1]^{\frac{1}{2}}$ is an x dependent function[6].

The rate equations providing the S.R. FEL dynamics assuming x_n small are,

$$
\begin{aligned}
\frac{d\tilde{x}}{dt} &= \frac{\tilde{x}}{T_0}\{\frac{1}{\sqrt{1+\tilde{\sigma}^2}} \frac{1}{[1 + 1.7\mu^2(0)(1+\tilde{\sigma}^2)]} - r\} \\
\frac{d\tilde{\sigma}^2}{dt} &= -\frac{2}{\tau_s}(\tilde{\sigma}^2 - \tilde{x})
\end{aligned} \qquad (1)
$$

T is the machine revolution period and τ_s is the longitudinal damping time;

we have also defined $\tilde{x} = \mu x$, $\mu = (\frac{0.433}{N})^2 \frac{\beta}{4} \frac{\tau_s}{T\sigma_e^2(0)}$, $T_0 = \frac{T}{0.85 g_0}$, $\tilde{\sigma}^2 = \frac{\sigma_i^2(x)}{\sigma_e^2(0)}$ and $r = \frac{\eta}{0.85 g_0}$ where η is the cavity loss. As was shown in ref.[4] the system executes a number of oscillations before approaching the equilibrium which is obtained by setting $\frac{d\tilde{x}}{dt} = 0$, $\frac{d\tilde{\sigma}^2}{dt} = 0$, yielding $(1+\tilde{x}_e)[1+1.7\mu_e^2(1+\tilde{x}_e)]^2 = \frac{1}{r^2}$ The equilibrium intracavity power can be written in terms of $\tilde{x}_e$ as $I_e = \frac{1}{\mu}\tilde{x}_e I_s$. Using Eq.1 and recalling $g_0 I_s = \frac{1}{2N} P_E$ where P_E is the e-beam power density and that $\frac{P_E T}{\tau_s} = \mathcal{P}_s$ where $\mathcal{P}_s$ is the synchrotron power emitted in one machine turn, we find $I_e = \frac{\chi}{2N}\mathcal{P}_s$ with[6] $\chi = 0.837\frac{\mu_e^2(0)}{g_0}\tilde{x}_e$. This last equation establishes the link between the equilibrium intracavity power density and $\mathcal{P}_s$; it should be viewed as a statement of the Renieri limit[5] with an explicit definition of the efficiency factor $\frac{\chi}{2N}$.

3 C.P.B. Brightness

The C.B.P. brightness can be calculated using the same methods used to evaluate the undulator brightness.[3] We define the wiggler parameter $K_R^2 \approx 2.3 \times 10^{-5}\lambda^2[cm] I[\frac{MW}{cm^2}]$ where λ is the laser wavelength and I is the power density in the optical cavity. The wiggler parameter at the equilibrium intensity is $K_R^2 \approx 2.3 \times 10^{-5}\lambda^2[cm]\frac{\chi}{2N}\mathcal{P}_s[\frac{MW}{cm^2}]$; the C.B.P. spectral flux[7] is given by $F_n = 1.73 \times 10^{14} N^* Q_n(K_R)\mathcal{I}[A][\frac{\#\,of\,photons}{s\,0.1\%\,bandwidth}]$ where N^* is the number of wave undulator periods, $\mathcal{I}$ is the peak current and the function Q_n defined in ref.[7] is proportional to K_R^2. In the limit of $K_R \ll 1$ and recalling that in the S.R. FEL the optical pulse has an r.m.s. length given by $\sigma_e[cm] = 0.5\sqrt{N\lambda\sigma_z}$ then the number of wiggler periods is $N^* \approx \frac{\sigma_e}{\lambda} = 0.5\sqrt{\frac{N\sigma_z}{\lambda}}$, we get $F_1 = 1.0 \times 10^9 \sqrt{\frac{\sigma_z \lambda}{N}}\lambda[cm]\mathcal{I}[A]\chi\mathcal{P}_s[\frac{MW}{cm^2}][\frac{\#\,of\,photons}{s\,0.1\%\,bandwidth}]$. Finally, the brightness is given by $B_1 = \frac{\gamma^2}{(2\pi)^2\epsilon_x^N\epsilon_y^N} \times F_1[\frac{\#\,of\,photons}{s\,mm^2\,mrad^2\,0.1\%\,bandwidth}]$ We have chosen as an example to illustrate the C.B.P. brightness, the case of the Super ACO storage ring FEL at Saclay[8]. Using the parameters in Tb. 1 we can estimate the brightness of the γ-rays obtaining $B_1 \approx 10^8[\frac{\#\,of\,photons}{s\,mm^2\,mrad^2\,0.1\%\,bandwidth}]$ at an energy $h\nu = 0.12\,GeV$. The present analysis does not include the quantum corrections due to the photon momentum recoil, which should be considered since $\frac{h\nu}{\gamma mc^2} \approx 0.2$. In conclusion, we have presented a semi-analytical treatment of Compton backscattering (γ-rays) radiation in an S.R. based FEL and its dynamical coupling to the intracavity intensity at equilibrium and the induced electron beam energy spread. We have shown that the brightness of the radiation Eq. 2 is proportional to the power lost $\mathcal{P}_s$ by the e-beam in the ring due to synchrotron emission, the peak current, the wavelength and the square root of the length of the FEL pulse. For the storage ring FEL with parameters analogous to that of Super ACO, the brightness of the γ-ray radiation due to Compton backscattering is $10^8[\frac{\#\,of\,photons}{s\,mm^2\,mrad^2\,0.1\%\,bandwidth}]$. Finally, we notice that the effect of the C.B.P. interaction on the beam lifetime is negligible.

Table 1
Electron and laser beam parameters

Electron beam		Wiggler	
ϵ_x^N [mm-mrad]	37	Period [cm]	4.0
ϵ_y^N [mm-mrad]	0.9	Length [cm]	400
Energy γ	1000.	Wiggler parameter K	1.0
Peak current $\mathcal{I}$ [A]	50		
Initial Energy spread $\sigma_e^2(0)$	8×10^{-4}		
Pulse length σ_z[cm]	1		
Laser beam		**γ - ray beam**	
Nominal wavelength λ[nm]	40	Energy [GeV]	0.12
Small signal gain g_o	0.025	Pulse length [ps]	33
Long. damping time [ms]	1.5	B_1 $[\frac{\#\, of\, photons}{s\, mm^2\, mrad^2\, 0.1\%\, bandwidth}]$	10^8
Rev. period T [ns]	240		
Efficiency χ	0.2		
Saturation intensity $I_s\,[\frac{MW}{cm^2}]$	4.3×10^5		
Synchrotron power $\mathcal{P}_s[\frac{MW}{cm^2}]$	345		

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