THREE DIMENSIONAL ANALYSIS OF THE X-RADIATION PRODUCED BY A COLLECTIVE THOMSON SOURCE

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Abstract

The interaction between a very high brightness electron beam and a relativistically intense optical laser pulse produces X rays via coherent Thomson back scattering with FEL collective amplification. The phenomenon is, however, very selective, so that the characteristics of both electron and laser beam must satisfy tight requirements in terms of beam current, emittance, energy spread and laser amplitude stability within the pulse. The three-dimensional equations governing the radiation phenomena have been studied and solved numerically for the particularly interesting values of wavelengths of 1 Ang, 1 nm and 12 nm.

INTRODUCTION

The collective effects that develop in the classical Thomson back scattering between a high brightness electron beam and a high power laser pulse produce X-rays at a level a few orders of magnitude larger than the incoherent radiation. The physical system consisting in the electron bunch and the laser pulse has the same characters as a free-electron–laser and it has been studied in previous papers [1-2]. The lasing process, however, is rather difficult to start up and requires therefore a very careful definition of both beam and laser parameters. The most critical quantities are the emittance of the electron beam, its average radius, current and energy spread. On the other hand, both level and spatial distribution of the laser energy together with the control of the power fluctuations are the most important issues regarding the laser pulse.

MODEL EQUATIONS

The three-dimensional equations governing the growth of the free-electron-laser instability in a Thomson source are very similar to those written in the case of a static undulator [3-4].

The substantial difference is in the structure of the external field, that is electromagnetic, with magnetic and electric components depending on time and with transverse and longitudinal power distributions characteristic of the laser pulse. The expression assumed for the potential of the laser, which is counter-propagating respect to the electron beam and has a circular polarization, is:

$$\mathbf{A}_L(xyzt) = \frac{a_{L0}}{\sqrt{2}}\left(g(xyzt)e^{-i(k_L z+\omega_L t)}\hat{\mathbf{e}} + cc\right) + O\left(\frac{\lambda_L}{\sigma_L}\right) \quad (1)$$

where: a_{L0} is the laser parameter, g is a complex shape factor with $|g|<1$, k_L and ω_L are respectively the laser wave number and frequency and terms of the order of the wavelength λ_L divided by the transverse non-homogeneities characteristic length σ_L are neglected.

The evolution equations written under the Slowly Varying Amplitude Approximation in the non-dimensional 'universal' scaling are:

$$\frac{d}{d\bar{t}}\bar{\mathbf{r}}_j(\bar{t}) = \rho\frac{\mathbf{P}_j(\bar{t})}{\bar{\gamma}_j(\bar{t})} \quad (2)$$

$$\frac{d}{d\bar{t}}P_{jz}(\bar{t}) = -\frac{\bar{a}_{L0}^2}{2\rho\gamma_0^2}\frac{1}{\bar{\gamma}_j}\left[\frac{\partial}{\partial\bar{z}}|g|^2\right]_{\bar{x}=\bar{r}_j} - \frac{2}{\bar{\gamma}_j}\mathrm{Real}\left[(g^*\bar{A})_{\bar{x}=\bar{r}_j}e^{i\theta_j(\bar{t})}\right] + ... \quad (3)$$

$$\frac{d}{d\bar{t}}\mathbf{P}_{j\perp}(\bar{t}) = -\frac{\bar{a}_{L0}^2}{2\rho\gamma_0^2}\frac{1}{\bar{\gamma}_j}\left[\bar{\nabla}_\perp |g|^2\right]_{\bar{x}=\bar{r}_j} - \frac{4\eta}{1+\frac{k_L}{k}}\frac{1}{\bar{\gamma}_j}\mathrm{Im}\left[(\nabla_\perp(g^*\bar{A}))_{\bar{x}=\bar{r}_j}e^{i\theta_j(\bar{t})}\right] + ... \quad (4)$$

$$\left(\frac{\partial}{\partial\bar{t}} + \frac{\partial}{\partial\bar{z}}\right)\bar{A} - i\eta\bar{\nabla}_\perp^2\bar{A} = \frac{V_b}{N_S V_b(t)}\sum_S \frac{g(\bar{\mathbf{r}}_S(\bar{t}),\bar{t})}{\bar{\gamma}_S(\bar{t})}e^{-i\theta_S(\bar{t})} \quad (5).$$

with the phase angles written in the same non-dimensional form as

$$\theta_j(\bar{t}) = \frac{k}{2\rho k_L}\left((1+\frac{k_L}{k})\bar{z}_j(\bar{t}) + (\frac{k_L}{k}-1)\bar{t}\right) \quad (6)$$

and

$$\gamma_j^2 = 1 + \gamma_0^2\rho^2 P_{jz}^2 + \bar{a}_{L0}^2(|g|^2)_{\bar{x}=\bar{r}_j(\bar{t})} + ... \quad (7)$$

In the preceding equations γ_0 is the average value of γ over all electrons of the beam at t=0, $\bar{\gamma}_j = \gamma_j/\gamma_0$,

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$\mathbf{P}_j = \mathbf{p}_j/\gamma_0\rho$, and $\bar{a}_{L0} = \frac{e}{mc^2} a_{L0}$ is the laser parameter.

Furthermore:

$$\eta = \frac{k_L}{k}\rho\,, \qquad (8)$$

the radiation potential is:

$$A = -i\left(\frac{\omega_b^2 \bar{a}_{L0}}{4\sqrt{2}\omega\omega_L \gamma_0 \rho}\right)\frac{e\bar{A}}{mc^2} \qquad (9)$$

with:

$$\mathbf{A}(xyzt) = A(xyzt)e^{i(kz-\omega t)}\hat{\mathbf{e}} + cc + O(\lambda / L_T) \qquad (10)$$

and the FEL parameter

$$\rho = \frac{1}{\gamma_0}\left(\frac{\omega_b^2 \bar{a}_{L0}^2}{16\omega_L^2}(1+\frac{\omega_L}{\omega})\right)^{\frac{1}{3}} \qquad (11)$$

is defined according to the usual FEL theory.

The resonant frequency turns out to have the expression $k \approx \frac{4\gamma_0^2 k_L}{1+a_{L0}^2}$, adopted in most 1D treatments of incoherent and coherent Thomson scattering.

NUMERICAL RESULTS

A case particularly important for its applications is the production of radiation characterized by wavelength λ_R of about 1 Angstrom. This value can be reached with a Ti:Sa laser with λ_L=0.8 µm, a_{L0}=0.8, $<\gamma>$=55, L_b=300 µm, r_b=7 µm, a total charge of 3 nC, for a current of 3 KA.

Cases with emittance ε_x=0.26 mm mrad (curve (a)) ε_x =0.54 mm mrad (curve (b)) and ε_x =0.8 mm mrad (curve (c)) are presented in Fig 1, where the power obtained in Watt is plotted versus z (in meter).

The factor ρ is 4.17 10^{-4}, and the radiation wavelength is λ_R =1.13 A. In this case we are at the limit of validity of the classical model, because the quantum factor q is 0.9, and quantum effects, arising when q>1, can play an important role [5,6]. However, the previous condition on q relies on one-dimensional models. Three-dimensional considerations [7] seem to point out a relaxation of the above condition due to the enlargement of the bandwidth associated to non-ideal and geometrical effects so that the requirement q>1 should be rather replaced by $q\rho > \max(\rho, \Delta\gamma/\gamma, \varepsilon_{n,x}^2/\sigma_x^2)$, where qρ is the relative energy separation between the quantum lines, ρ is the one-dimensional natural bandwidth and $\Delta\gamma/\gamma$ and $\varepsilon_{n,x}^2/\sigma_x^2$ are respectively the inhomogeneous line broadening due to energy spread and emittance effects. In our case we have qρ=4 10^{-4}, but for the case (a) $\varepsilon_{n,x}^2/\sigma_x^2$ does never go under 7 10^{-4}. The cases with larger emittance are, in this sense, even less critical respect to the presence of quantum effects. The cases presented require an amount of laser power outside the present status of the art, but achievable in the near future. In fact, for instance, in the case (b) with emittance ε_x =0.54 mm mrad, at saturation the beam has a maximum radius of about 15 µm; assuming for the laser in the waist a spot size of 20 µm, we obtain the needed laser power of more than 17 TW for at least 1.5 mm, corresponding to a total laser energy of about 85 J.

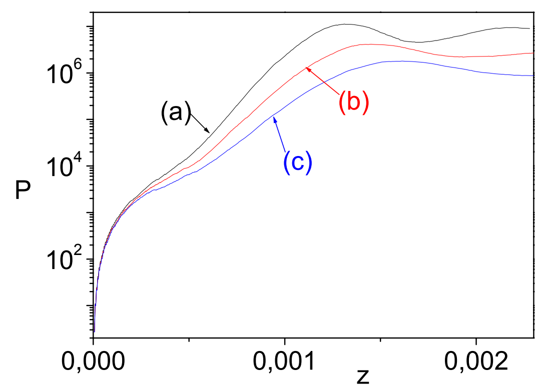

Fig 1: Radiated power P (in W) vs z (in m). a_{L0}=0.8, λ_L=0.8 µm, σ_x=3.5 µm, (corresponding to a maximum radius of 7 µm), $\Delta\gamma/\gamma=10^{-4}$, λ_R=1.13 A. (a) ε_x=0.26 mm mrad .(b) ε_x=0.54 mm mrad (c) ε_x=0.8 mm mrad.

Also the properties of the electron beam are extreme, due to the required condition of large current, low emittance, minimum energy spread, high focusing and relatively small γ. The transport and the focusing of the beam appear very difficult. Simulations made with Astra have shown that only few slices of the beam can attain these characteristics [8].

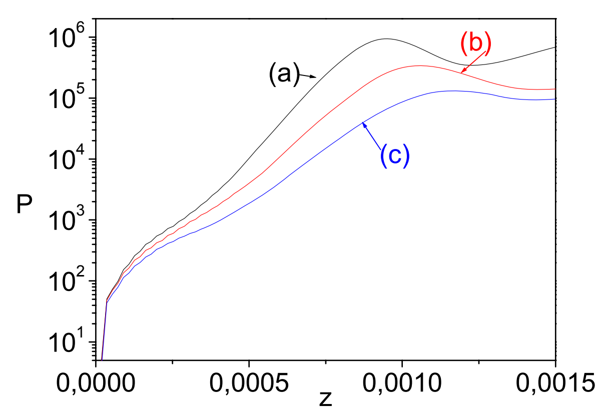

Fig 2: Radiated power P (in Watt) vs z (in meter) for an electromagnetic undulator. a_{L0}=0.8, λ_L=0.8 µm, σ_x=5 µm, (corresponding to a maximum radius of 10 µm), I=600 A, $\Delta\gamma/\gamma=10^{-4}$, λ_R=1.06 nm. (a) ε_x=0.26 mm mrad .(b) ε_x=0.54 mm mrad (c) ε_x=0.8 mm mrad.

A case equally interesting, but less difficult to realise is a radiation wavelength of about 1 nm.

In this case, in fact, the factor γ has been assumed γ=18.11 and a_{L0}=0.8, so that the resonant wavelength is about 1 nm. The total charge is Q=2 10^{-9} C, L_b=1 mm, so that the current I is I=600 A. Cases with different emittance are presented in Fig 2. The radiation power reaches 1 MW for the case with ε_x=0.26. The requirement of laser power can be evaluated by assuming a channel of 17 µm of maximum radius with a length of 1.1 mm for a power of 12 TW and a total energy of 48 J. Radiation with wavelength in the range of 10^{-9} m can be generated also by means of a CO_2 laser.

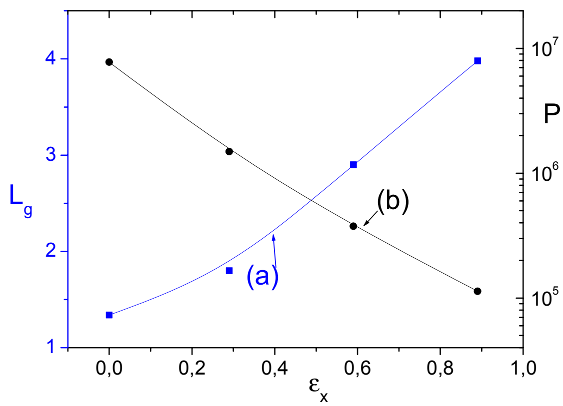

Fig 3: Gain length L_g in mm (curve (a), left scale) versus ε_x in mmmrad. Radiation power P in W (curve (b), right scale) versus ε_x in mmmrad for a_w=0.3, λ_w=10 µm, σ_x=12.5 µm (corresponding to a maximum radius of 25 µm).

The parameters assumed are: a_{L0}=0.3, λ_w=λ_L=10 µm, ε_x=0.3 mm mrad, σ_x=12.5 µm (corresponding to a maximum radius of 25 µm), $<\gamma>$=60, λ_R=0.7578 nm. The simulations show a power saturation value of 1.93 MW in less than 2.5 cm, with an average gain length of about 1.8 mm for an emittance of 0.3 mmmrad. In Fig 3, the gain length in mm and the saturation power in W are shown as function of the emittance.

Finally, we present the possibility of producing 12 nm radiation by means of the CO_2 laser. For this case, the properties of the electron beam have been relaxed. In fact, we have assumed a gamma of 16.5, a current of 150 A, an emittance of $\varepsilon_{n,x}$=1.06 mm mrad , a maximum radius of 30 µm (σ_x=15. µm), an energy spread of 1.3 10^{-4}, conditions inside the present status of the art of the production of high brightness electron beams. The saturation value of the radiation power is very low, namely ten Kilowatt, but larger by a factor 20 than the incoherent radiation produced in the same bandwidth. The power saturation value can be considerably incremented up to 10 MW by shifting the focus of the beam. In Fig 4 the radiation power and the rms radius are presented for a_{L0}=0.5 and for the focus of the beam shifted at z=0.68 cm in correspondence of the middle of the exponentiation phase.

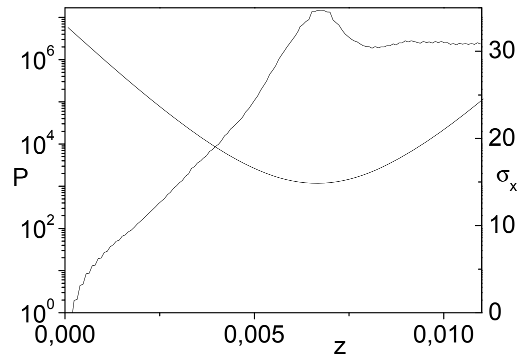

Fig 4: Left axis: radiated power P in Watt vs zin meter. Right axis: rms radius (in micron) vs z.

The laser power required is in this last case 100 GW with total energy 2.3 J, but considerable value of power radiation (namely P= 100 KW at 1 cm) can be reached also by limiting the laser parameter to a_{L0}=0.2, corresponding to 16 GW of laser power and 0.6 J of total energy.

In this paper we have demonstrated the possibility of using the collective Thomson back scattering for producing X rays of various wavelengths. In particular, the interesting values of 1 Ang, 1 nm, and 12 nm could be obtained by mean of the Ti:Sa or the CO_2 lasers. This last value of wavelength requires non prohibitive beam and laser pulse characteristics and can be proposed as an immediate test experiment for the study and the validation of the method.

REFERENCES

[1] A.Bacci, C. Maroli, V. Petrillo , L. Serafin: 'European Physical Journal Applied Physics', (2006), 2006080

[2] A.Bacci, M Ferrario, C. Maroli, V. Petrillo, L.Serafini: 'PRST AB',Vol.: 9 , (2006) 060704

[3] E.T. Sharlemann: 'J. Appl. Phys.',Vol.: 58, (1985), pg: 2154

[4] Ming Xie, "Design Optimization for an X-Ray Free Electron Laser Driven by SLAC Linac," Proc. 1995 PAC, Dallas, May 1-5, 183.

[5] J.B. Murphy and C. Pellegrini: 'J Opt.Soc. Am. B', Vol.: 2, (1985), pg.:259 .

[6] R. Bonifacio et al.: 'Nucl. Instrum. And Meth. A', Vol.: 543 ,(2005), pg.:645.

[7] Smetanin, I.V.; Nakajima, K.: 'The quantum operation regime of the X-ray Compton free-electron laser', Proceedings of the Second Symposium on Advanced Photon Research (JAERI-Con 2001-011) : 236-40, 2001

[8] A. Bacci, C. Maroli, V. Petrillo, A.R. Rossi, L.Serafini, 'Maximizing the brightness of an electron beam by means of a genetic algorithm', submitted to NIM B

