Study of transverse effects in a back-scattering coherent Thomson source of X-rays

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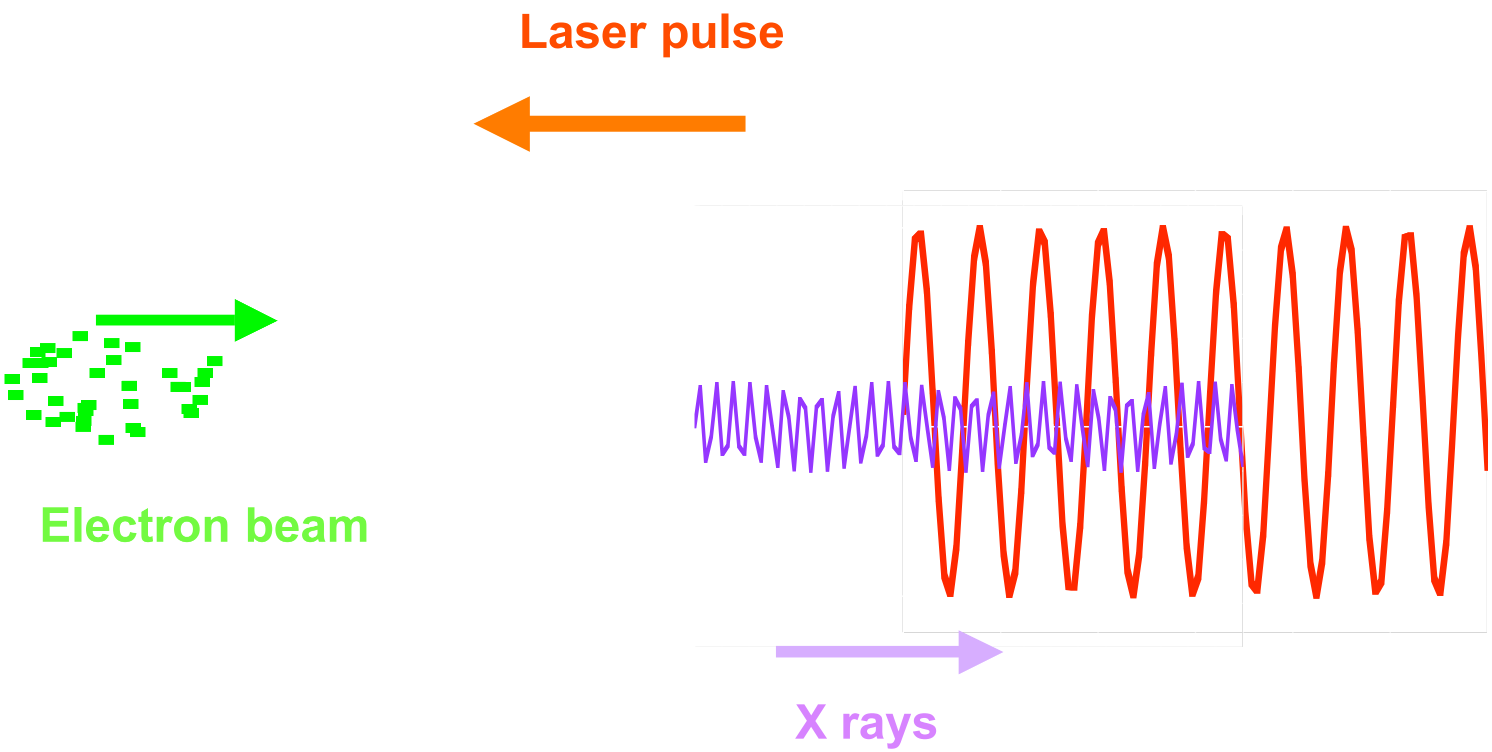
Thomson back-scattering



The incoherent linear and non linear radiation at $\omega=4\gamma^2\omega_L$ is usually evaluated by calculating the emitted intensity by each single electron and then summing all contributions at the collector.

If the laser pulse is long enough, collective effects can develop. The system electron beam + laser pulse behaves like a free-electron laser with an electromagnetic wiggler.

J. Gea-Banacloche, G. T. Moore, R.R. Schlicher, M. O. Scully, H. Walther, IEEE Journal of Quantum Electronics, QE-23, 1558 (1987).
B.G.Danly, G.Bekefi, R.C.Davidson, R.J.Temkin,T.M.Tran,J.S.Wurtele, IEEE Journ. of Quantum Electronics, QE-23,103(1987).
Gallardo, J.C., Fernow, R.C., Palmer, R., C. Pellegrini, IEEE Journal of Quantum Electronics 24, 1557-66 1988.

In particular, if the time duration of the laser pulse ΔT_L is larger than a few gain lengths, i.e. if

$$\Delta T_L > (10)\, L_g/c$$

the electron of the beam can bunch and the f.e.l. instability can develop.

The coherent radiation is expected to have a spectrum bandwidth very much narrower than the incoherent radiation, a less broad angular distribution and (if the saturation is reached) a larger intensity.

To evaluate the collective effects:

- The field or potential (instead of the intensities) must be calculated and summed at the collector, taking into account possible interferences

- In the trajectories of the electrons, the collective fields must be taken into account

3-d equations

single mode treatment

Slowly Varying Envelope Approximation

Averaged on radiation and laser wavelengths

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

Space charge effects neglected

Electrons modelled with macroparticles

Relativistic equations in the lab frame

Laser system:

Laser pulse characteristics:

wavelength λ=0,8 μm, power 1TW, time duration T=5 ps
Circular polarization, focal spot diameter w_0 >20 micron

$z_0 = \pi w_0^2/4\lambda_L$ > 2,5 mm Rayleigh length

$$\mathbf{A}_L(\mathbf{r},t) = \frac{a_{L0}}{\sqrt{2}}(g(\mathbf{r},t)e^{-i(k_L z+\omega_L t)}\hat{\mathbf{e}} + cc) + O(\frac{\lambda_L}{w_0})$$

Guided pulse: g(r,t) step function

Gaussian pulse:

$$g(\underline{r},t) = \Phi(z+ct)\frac{1+i\frac{z}{z_0}}{1+\frac{z^2}{z_0^2}}\exp\left[-4\frac{x^2+y^2}{w_0^2(1+\frac{z^2}{z_0^2})} - 4i\frac{x^2+y^2}{w_0^2(\frac{z}{z_0}+\frac{z_0}{z})}\right]$$

Electron equations

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

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

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

Collective ponderomotive effects

Radiation equation

$$\left(\frac{\partial}{\partial\bar{t}}+\frac{\partial}{\partial\bar{z}}\right)\bar{A}(\bar{\mathbf{x}},\bar{t}) - i\rho\frac{k_L}{k}\bar{\nabla}_\perp^2\bar{A} = b$$

Bunching factor

$$b = \frac{1}{N_s}\sum_s \frac{g(\mathbf{r}_s(t),t)}{\bar{\gamma}_s(t)} e^{-i\theta_s(t)}$$

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

Normalization

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

$$\bar{\mathbf{x}} = 2\rho k_L \mathbf{x}$$

$$\bar{t} = 2\rho\omega_L t$$

$$\frac{eA}{mc^2} = -i\left(\frac{\omega_b\sqrt{\gamma\rho}}{\sqrt{2}\omega_R}\right)\bar{A}$$

$$\bar{\gamma}_j = \gamma_j/\gamma_0 \qquad \mathbf{P}_j = \mathbf{p}_j/\gamma_0\rho \qquad \bar{a}_{L0} = \frac{e}{mc^2} a_{L0}$$

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

Resonance condition

$$\omega \approx \frac{4\gamma_0^2\omega_L}{1+a_{L0}^2}$$

Laser pulse: time duration up to 5 psec, power 1-3 TW, varying w0, λ=0,8-1 micron

Electron beam counterpropagating respect the laser pulse

Q=1nC, Lb=100-300micron, radius σ_0=10-20 micron, I=1-2,5 KA

Energy=15 MeV (γ=30) , transverse norm emittance up to 3 mm mrad,

$\delta\gamma/\gamma=10^{-4}$.

$\rho=5\ 10^{-4}$ gain length L_g= 100-150 micron

Radiation λ=3,5 Ang Z_R=1-4m

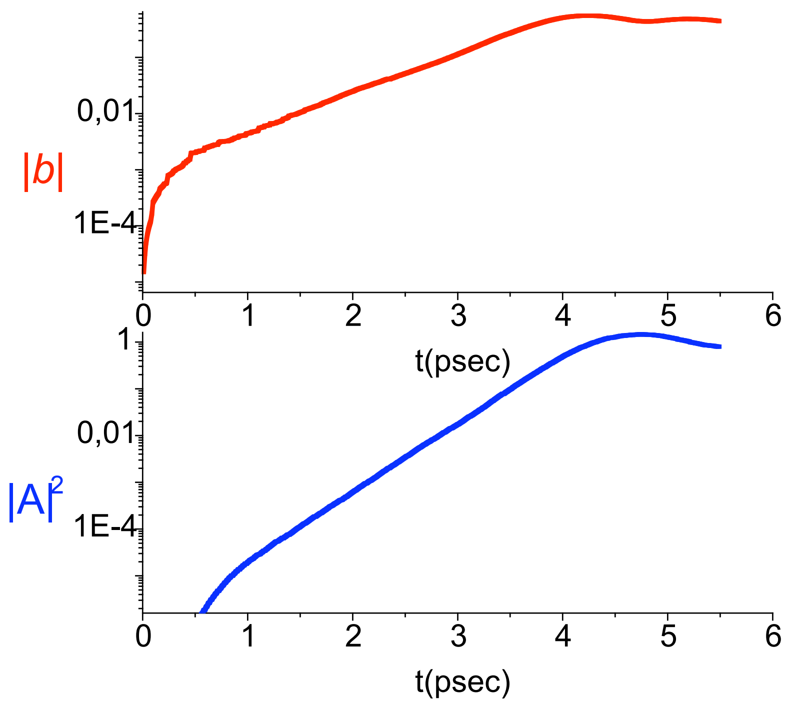
ρbar=2 ⟹ no quantum effects

3-d code

- Fourth order RKG for the particles
- Explicit finite differences scheme for the Schroedinger equation
- Start from noise

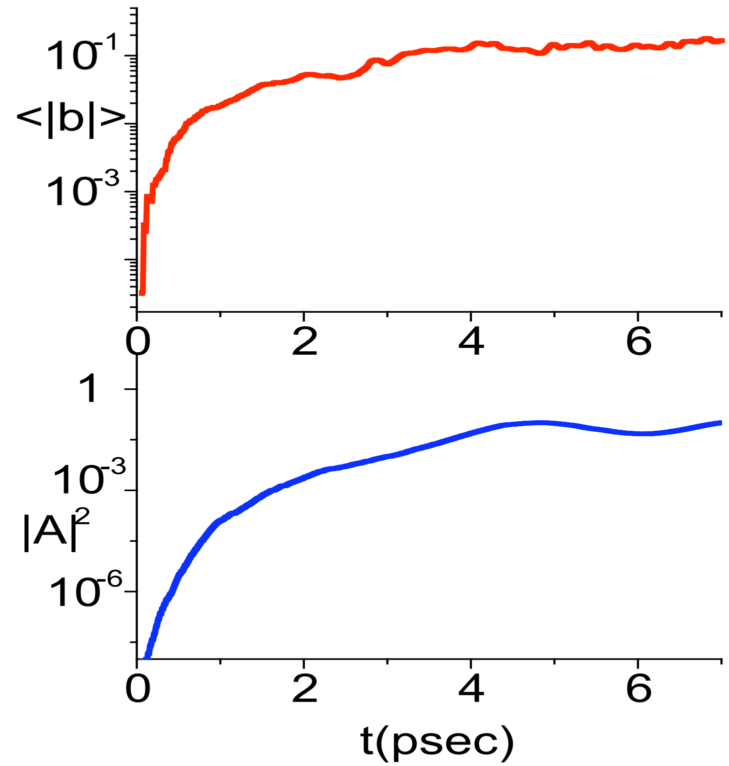
As usually for three-d codes, it is time-consuming

ε_n=0.45, guided pulse



$|A|^2_{sat}$=1.4 in 10 L_g (5psec)

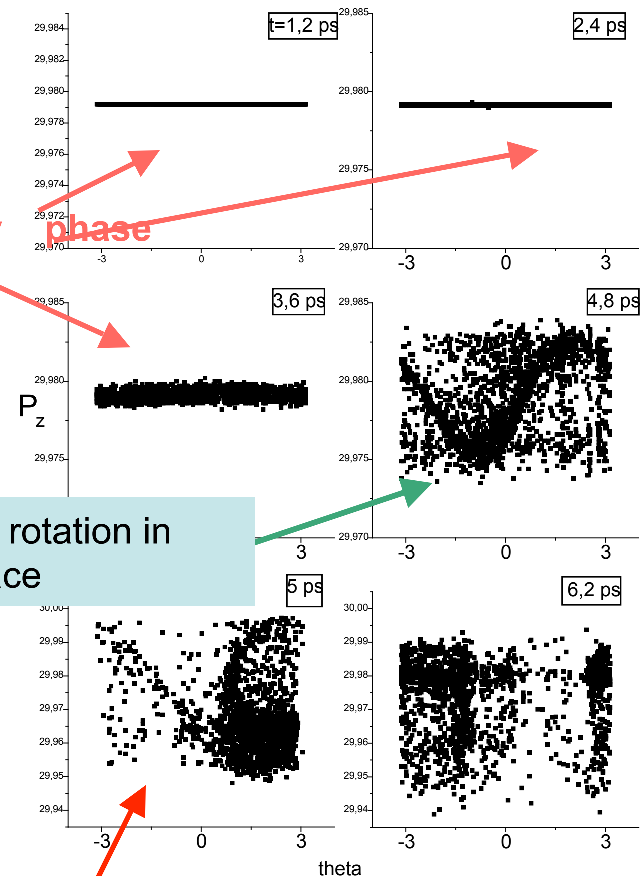
ε_n=1.13, w_0=500micr



$|A|^2_{sat}$=0,12 in 5psec

Phase space p_z versus the phase angle theta

Ideal case



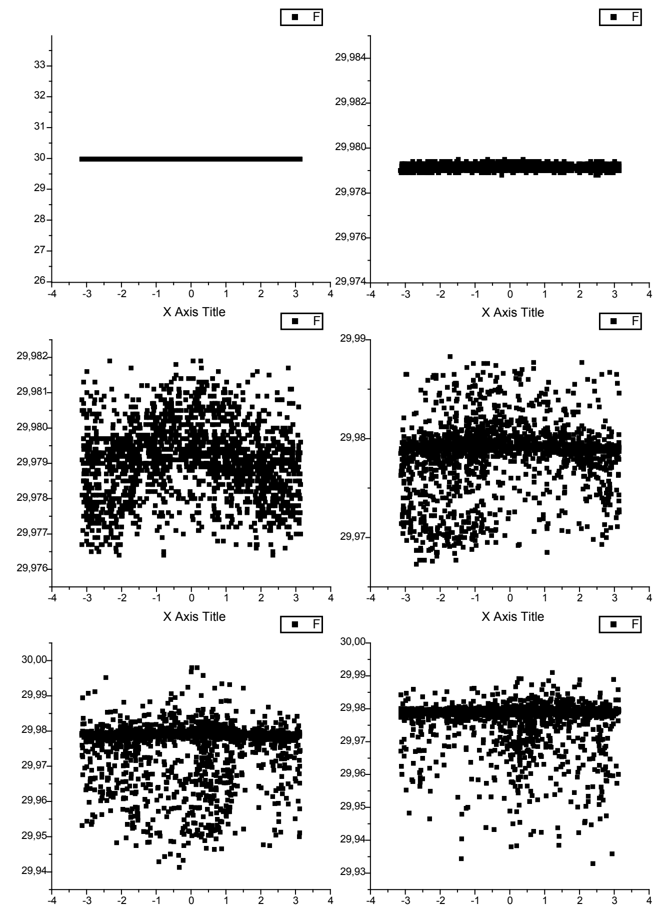
Lethargy phase

90 degree rotation in phase\space

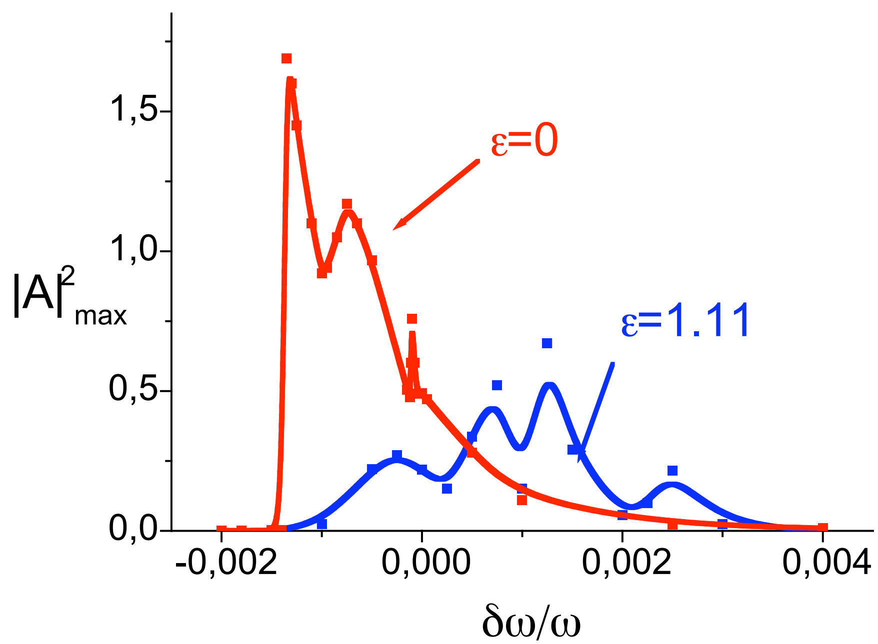
Saturation

Post saturation phase

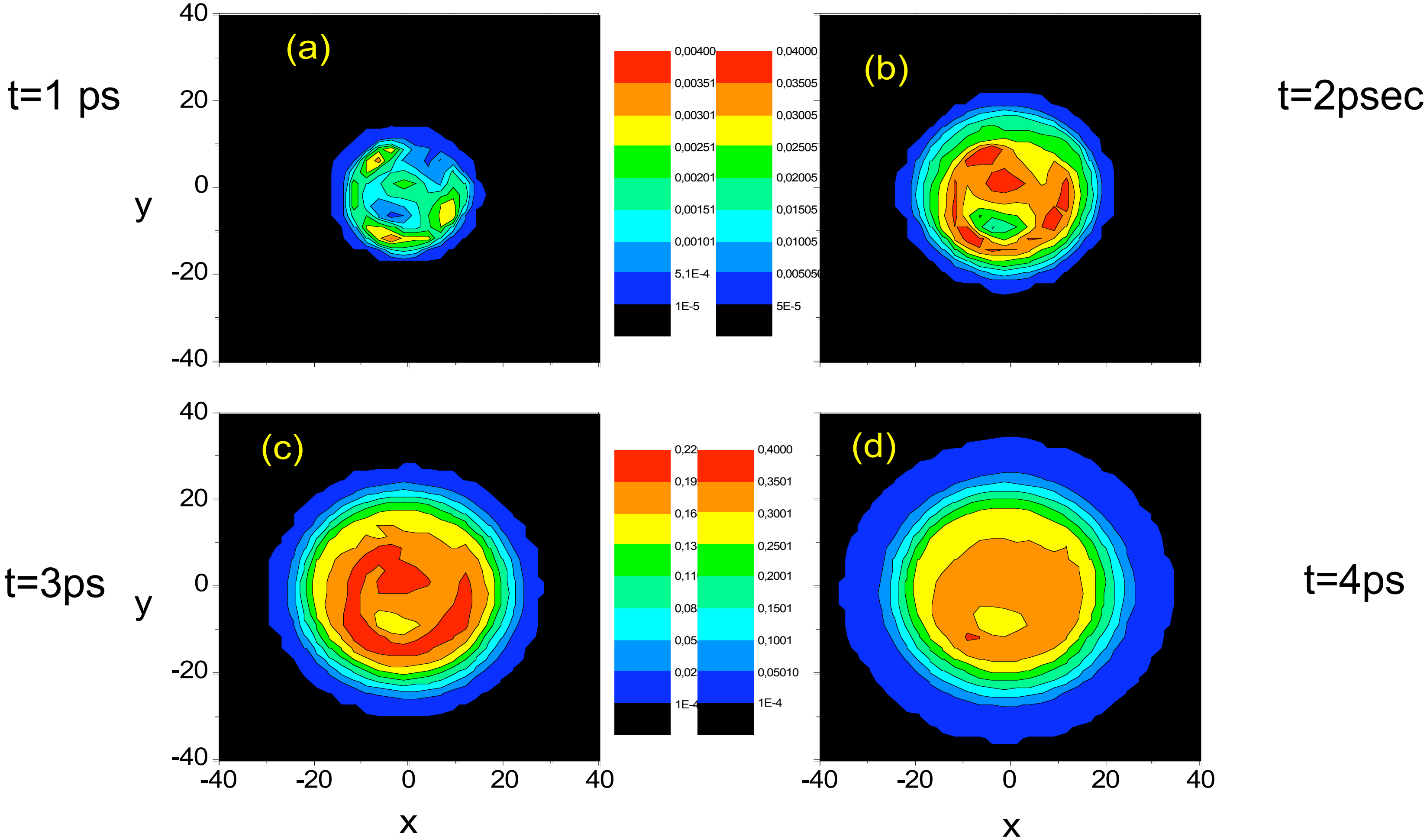
More realistic case



Radiation spectrum w0=1000

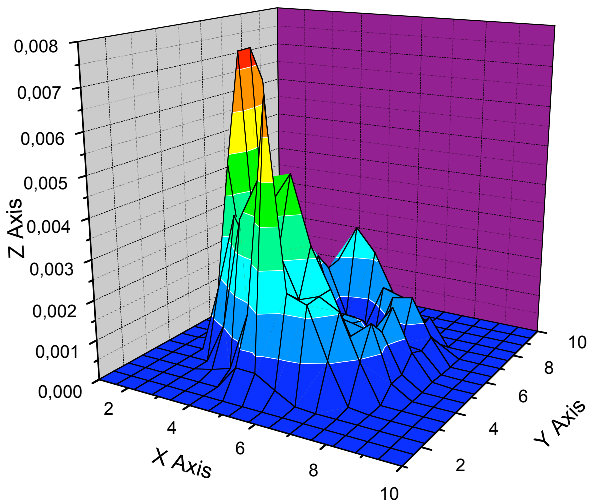


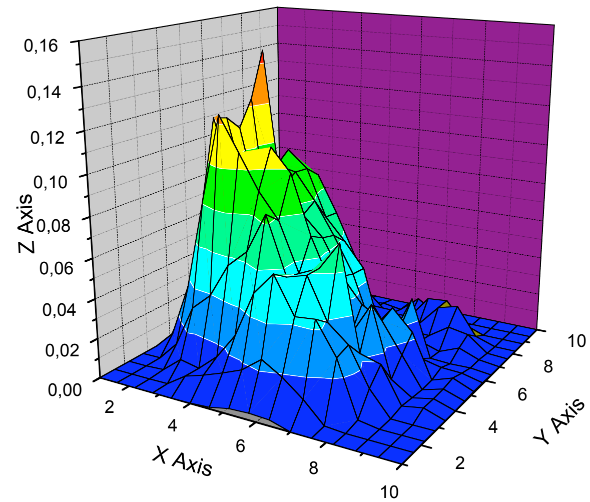
Transverse radiation intensity for emittance=1.8

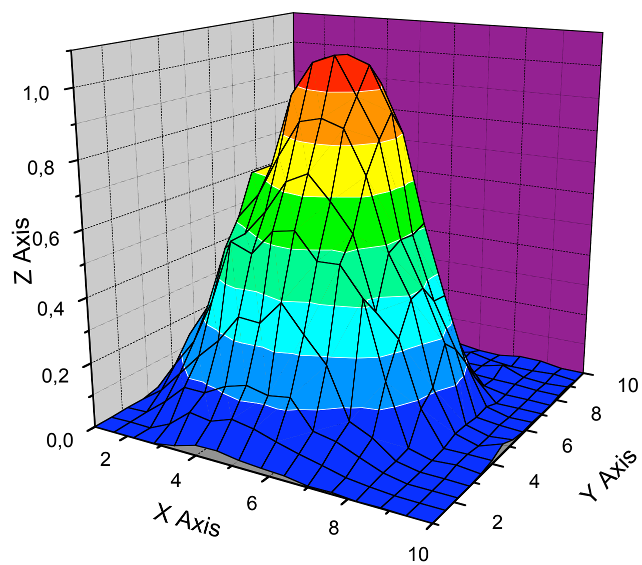


Initially more chaotic, then smoother

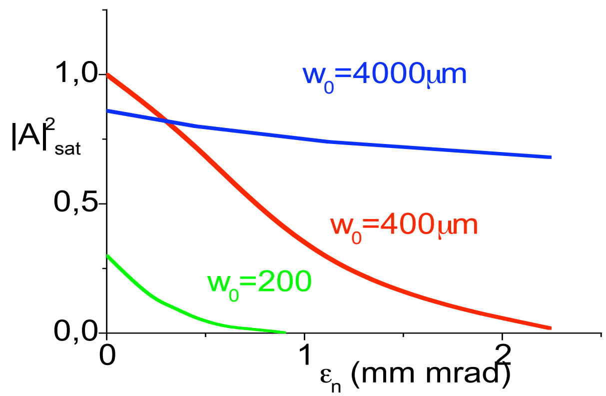
W0=1000, emitt=1,11 δγ/γ=10-4

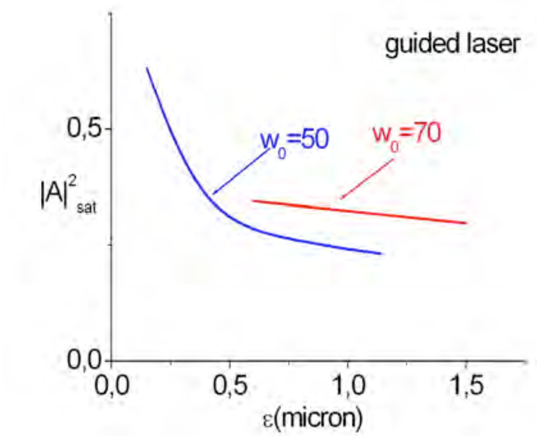






Saturation intensity value (averaged on the transverse section) versus the transverse normalized emittance for different w0





We have considerable emission also in violation of the Pellegrini criterion for a static wiggler. In fact, the emittances considered largely exceed the value $\gamma\lambda/4\pi$, that in this case is 8,5 10^{-4} micron. On the other hand, on the basis of the fact that Lg/Z_R=1.2 10^{-4}, the criterion of Pellegrini can be rewritten in a generalized form for both static and optical undulators as

$$\varepsilon_N \leq \alpha\sqrt{Z_R / L_g}\,\lambda_R \gamma / 4\pi$$

where $\alpha = \sqrt{d\omega / (\omega\rho)}$

and gives $\varepsilon_n < 0.25$

Conclusions

The growth of collective effects in the back scattering Thomson process is possible provided that:

A low-energy , high-brigthness electron beam is available with short gain length

The optical laser pulse is long enought to permit the bunching and the instauration of the instability.

In the interaction region the laser transverse and longitudinal profiles are flat.