Quantum effects in production of gammas for positrons

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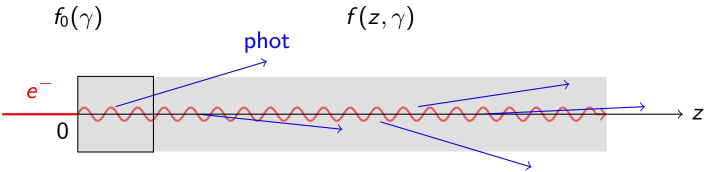
Problem general setup: ultra–relativistic electrons, quantum recoils



problem setup

- periodic force with given envelop – undulator, laser pulse
- radiation: statistically independent photons, given spectra
- recoils decrease electrons' energy
- goal:evolution of initially given electron spectrum along the field special attention – front end of the field

motivation

- ILC positron source: effect of the undulator on the beam parameters
- ILC alternative Compton positron source – performance
- lack of analytic description for small average number of photons emitted
- drawbacks of the diffusive approximation

Kinetic equation for electron spectrum $f(z,\gamma)$
Landau 1944; Akhiezer, Shul'ga 1996; Khokonov 2004

System of units: $m_e = c = \hbar = 1$, initial distribution $f_0(\gamma) \equiv f(z=0,\gamma)$

$$\boxed{\frac{\partial}{\partial z} f(z,\gamma) = \int \left[f(z,\gamma+\omega) W(z,\gamma+\omega,\omega) - f(z,\gamma) W(z,\gamma,\omega) \right] \mathrm{d}\omega}$$

where $W(z,\gamma,\omega)$ is the probability density
Approximation: $\gamma \gg 1,\ \omega_{\max} \ll \gamma,\ \ W(z,\gamma,\omega) = \psi(z) w(\gamma,\omega) \approx \psi(z) w(\omega)$
Kinetic equation casts into

$$\boxed{f_x' = f \star w - f}$$

with $f \star w \equiv \int f(\gamma+\omega) w(\omega) d\omega$ cross correlation; $x = \int_0^z \psi(z')\, \mathrm{d}z'$ number of emitted photons.

Fourier transform of electron spectrum evolution then the inverse

$$\hat{f} = \sum_{n=0}^{\infty} \frac{\mathrm{e}^{-x} x^n}{n!} \left(\hat{f}_0 \check{w}^n\right) \qquad f(x,\gamma) = \sum_{n=0}^{\infty} \frac{\mathrm{e}^{-x} x^n}{n!} F_n(\gamma) ,$$

with $F_0(\gamma) = f_0(\gamma) = f(x=0,\gamma)$ the initial distribution (spectrum),

$$F_n(\gamma) = \int F_{n-1}(\gamma+\omega) w(\omega)\, \mathrm{d}\omega$$

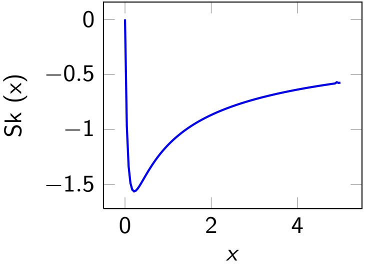
mean energy $\overline{\gamma}$ variance $\overline{(\gamma-\overline{\gamma})^2}$ skewness $\overline{(\gamma-\overline{\gamma})^3}$ $\Rightarrow$ linear of x

$\overline{\gamma}(x) = \overline{\gamma_0} - x\,\overline{\omega}$; $\mathrm{Var}[\gamma](x) = \mathrm{Var}[\gamma_0] + x\,\overline{\omega^2}$; $\mathrm{Sk}[\gamma](x) = \mathrm{Sk}[\gamma_0] - x\,\overline{\omega^3}$

Relation with distance along the axis: $z \rightarrow x(z) = \int_0^z \psi(z')\, \mathrm{d}z'$.

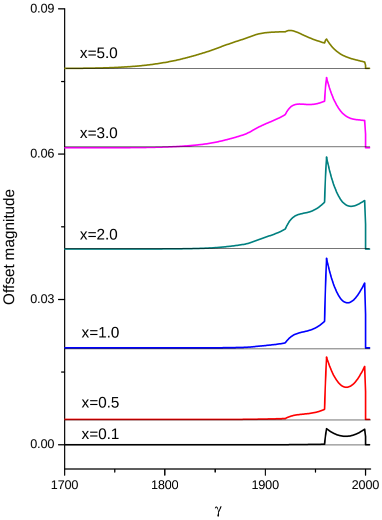
Evolution in general

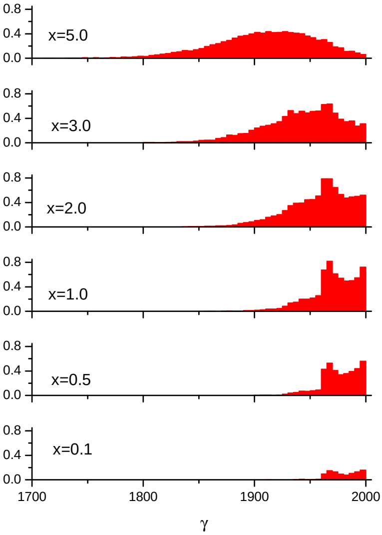
Pearson's skewness $\frac{\overline{(\gamma-\overline{\gamma})^3}}{\overline{(\gamma-\overline{\gamma})^2}^{3/2}}$



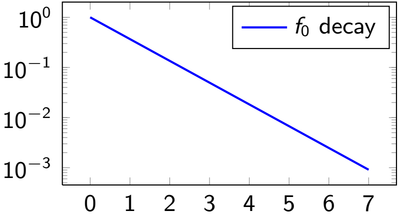
- Contribution of the initial distribution, f_0, decays as e^{-x}
- Mean energy decreases linearly with x
- Variance (spread) increases linearly
- Tail on the left (negative skewness)
- Asymmetry $\sim 1/\sqrt{x}$

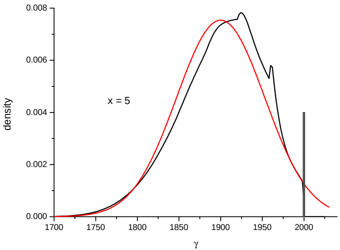
Gamma Sources: Analytic vs. Simulation
$f_0 = \delta(\gamma - \gamma_0)$ not included

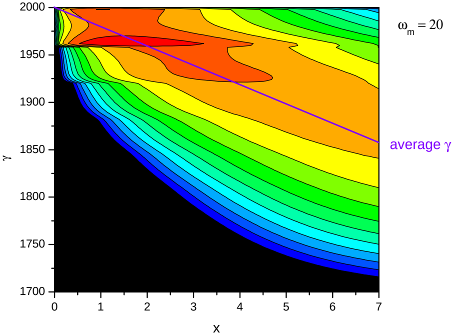


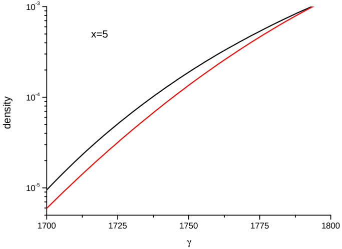


Compton source, 1 GeV + 1 eV





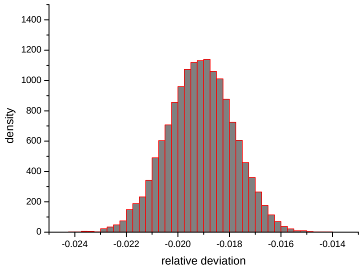




Simulations – ILC undulator: $K = 0.92$ vs $K = 0.46$ at 150 GeV
$f_0 = \delta(\gamma - \gamma_0)$, 15 000 particles

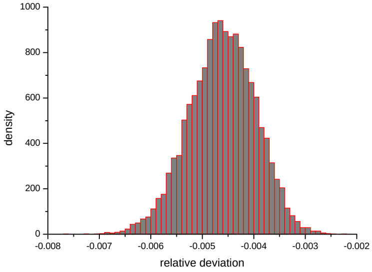
relative deviation $\equiv \frac{\gamma - \gamma_0}{\gamma_0}$

K=0.92 (300 gammas)



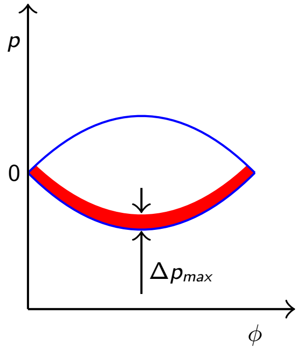
mean = - 0.019; st.dev = 1.29E-3;
min = -0.024; max = -0.014
min=mean-0.005; max=mean+0.005

K=0.46 (70 gammas)



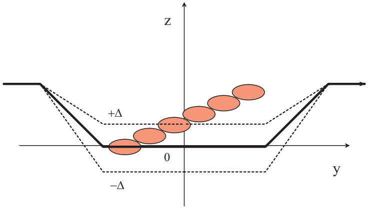
mean = - 0.0046; st.dev = 6.48E-4;
min = -0.0077; max = -0.0023
min=mean-0.0031; max=mean+0.0023

longitudinal phase space



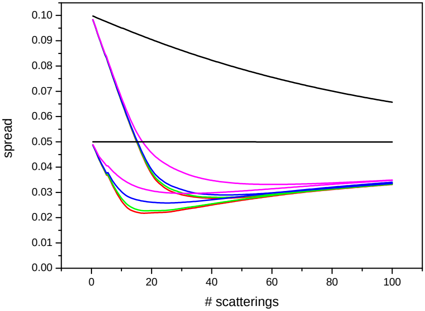
- electrons escape the separatrix downward, in the 'tail direction'
  separatrix cuts out the tail
- rate of losses $\propto$ bunch density$\times$laser density
- red band width $\propto$ tail length$\times$synchrotron period

We proposed to mitigate quantum losses via *the asymmetric cooling*



Model setup

Laser radiation field exists at $z \geq 0$



Spread vs. # scatterings

Table: Results of simulation dependence on crossing angle ϕ (3.0 mm dispersion at CP, 2 m beta function).

run	ϕ, rad	shift, μm	yield $\times 10^{-5}$	lifetime, turn	yield$\times$l.t.
14j20p	0.0	+30	31.90	19 857	6.33
14j20	0.0	0	41.30	12 872	5.31
14j20m	0.0	-30	58.00	7 689	4.46
13j20pp	0.03	+30	1.88	2 422 370	45.54
13j20p	0.03	0	1.58	1 649 434	26.06
13j20m	0.03	-30	1.75	1 447 969	25.30
12j20p	0.13963	+30	1.35	20 582 321	277.86
12j20	0.13963	0	1.26	13 081 740	164.83
12j20m	0.13963	-30	1.28	12 248 299	156.78

Summary and Discussion

summary

- Kinetic equation for electron spectra in gamma–sources solved
- Spectrum substantially differs from the diffusion model at small number of photons, converging to that when many photons emitted
- For Compton sources account for asymmetry of the electron spectrum is important
- Diffusion model sufficient for the undulator-based gamma sources

discussion

- Diffusion model sufficient for the undulator-based gamma sources
- For Compton sources (both ring– and ERL–based) account for asymmetry of the electron spectrum is important
- Quantum effects may reduce or limit performance of gamma– and hard x–ray sources
- Quantum recoils affect beam dynamics