Physics and applications of Thomson/Compton back scattering

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Cosenza 6 Novembre 2013

Introduction to Thomson and Compton back scattering.

Properties of the photon distribution

Electron distribution, deformation and information.

Examples of X and Gamma sources.

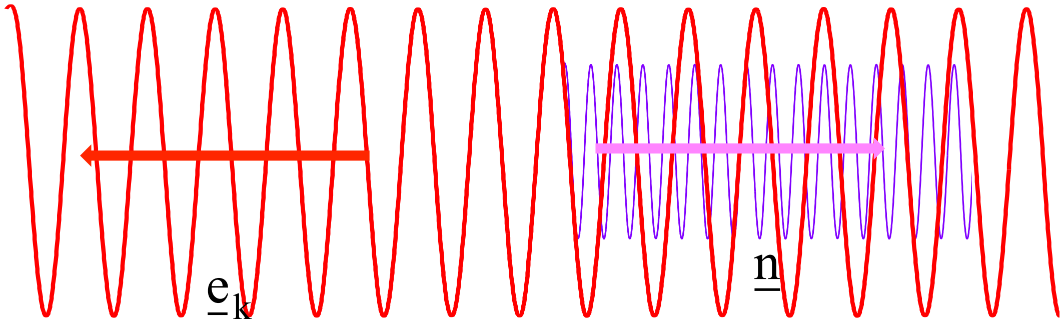
Comments and conclusions.

Classical model

Laser pulse

Relativistic electron

$\underline{\beta}_0$



X/gamma radiation

From the double Doppler effect :

$$\nu = \nu_L \frac{1 - \underline{e}_k \cdot \underline{\beta}_0}{1 - \underline{n} \cdot \underline{\beta}_0} \approx 4\gamma_0^{\,2} \nu_L$$

$$\lambda = \lambda_L \frac{1 - \underline{n} \cdot \underline{\beta}_0}{1 - \underline{e}_k \cdot \underline{\beta}_0}$$

Head to head scattering
Radiation on axis

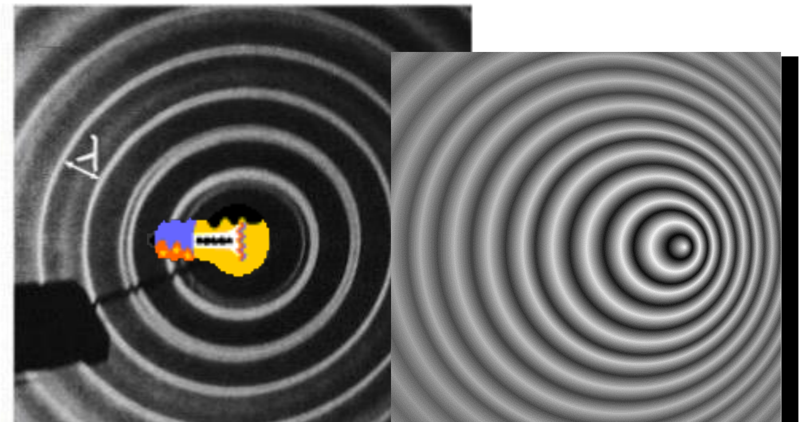
$$\lambda = \lambda_L \frac{1}{4\gamma_0^{\,2}}$$

effetto Doppler relativistico

$$\begin{cases} x' = \gamma(x - vt) \\ y' = y \\ z' = z \\ t' = \gamma\left(t - \dfrac{vx}{c^2}\right) \end{cases}$$

$$\gamma = \frac{1}{\sqrt{\left(1 - \frac{v^2}{c^2}\right)}}$$

Sorgente ferma:
frequenza $\nu_0 = 1/T_0$
lunghezza d'onda $\lambda_0 = c/\nu_0$
N creste
per un tempo Δt_S
$\lambda_0 = c\Delta t_s/N$



$\Delta t_R = \gamma \Delta t_S$

Sorgente in moto di avvicinamento con velocità V vista dal ricevitore:
lunghezza d'onda $\lambda = (c\Delta t_R - V\Delta t_R)/N$
N creste per un tempo Δt_R

Il numero N di creste si conserva

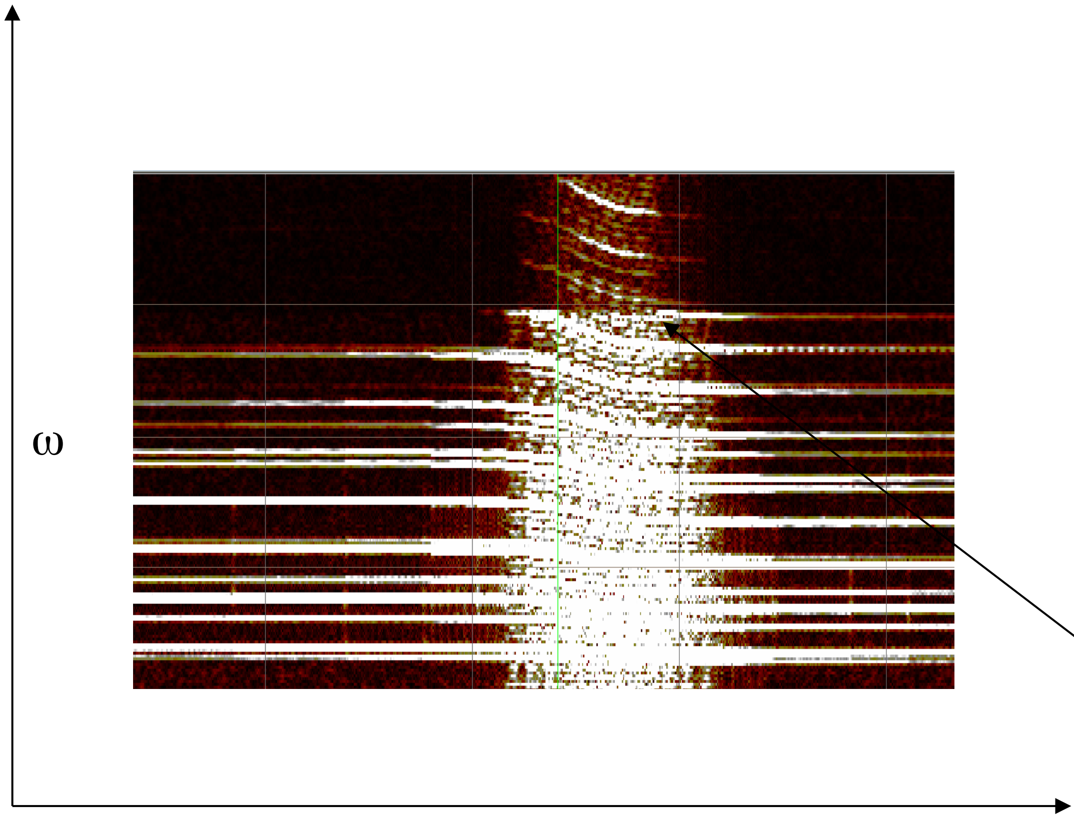
$$\frac{c\Delta t_S}{\lambda_0} = \frac{(c-V)\Delta t_R}{\lambda} = \frac{\gamma(c-V)\Delta t_S}{\lambda} = \gamma\nu\frac{(c-V)}{c}\Delta t_S$$

$$\nu_0 = \sqrt{\frac{\left(1 - \frac{V}{c}\right)}{\left(1 + \frac{V}{c}\right)}}\,\nu$$

Effetto Doppler non relativistico: esempio delle onde acustiche

$$\nu_0 = \sqrt{\frac{(1+\frac{V}{c})}{(1-\frac{V}{c})}}\,\nu$$

$$\nu = \sqrt{\frac{(1-\frac{V}{c})}{(1+\frac{V}{c})}}\,\nu_0$$



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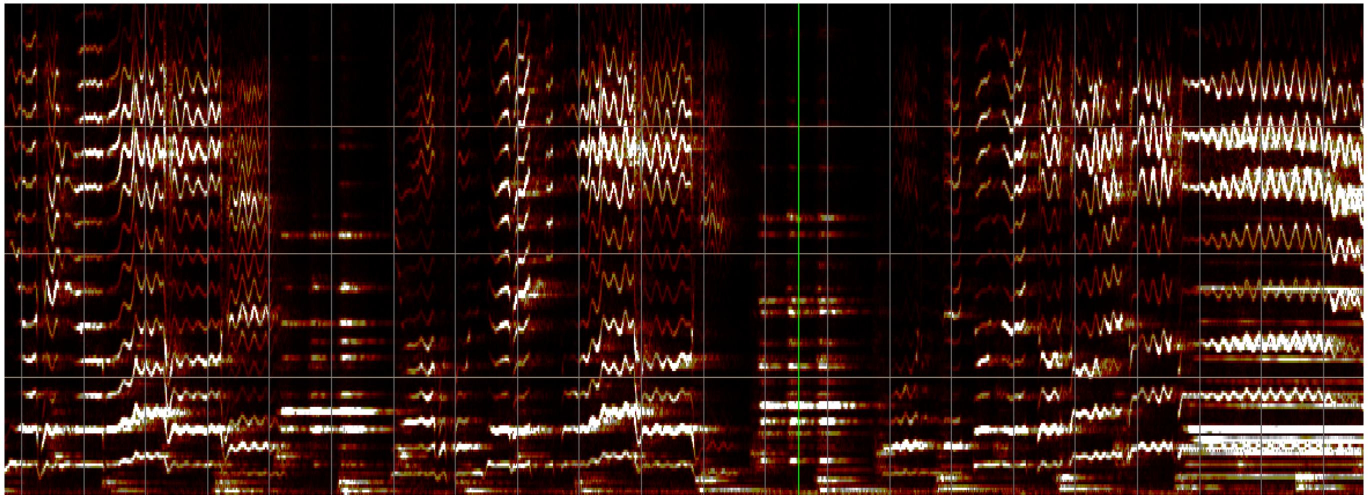
Spettrogramma

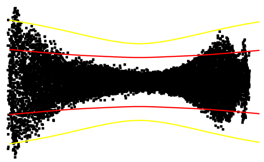
(è l'analogo di uno spartito)

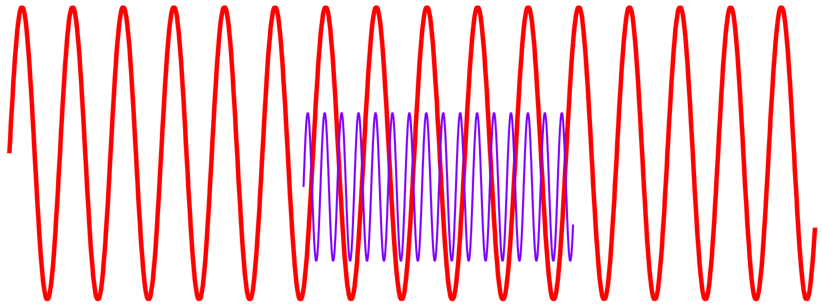
red shift della frequenza
quando la sorgente si allontana

Spartito e Spettrogramma:Di Stefano, Callas, Gobbi,Lazzarini
Bella figlia dell’amore
Verdi: Rigoletto



Scattering Thomson come applicazione dell'effetto Doppler





$$\nu_{L\_SRE} = \sqrt{\frac{(1+\frac{V_e}{c})}{(1-\frac{V_e}{c})}}\nu_{L\_Lab}$$

scattering o emissione
nel sistema di riferimento
dell'elettrone

$$\nu_{ST\_SRE} = \nu_{L\_SRE}$$

$$\nu_{ST\_lab} = \sqrt{\frac{(1+\frac{V_e}{c})}{(1-\frac{V_e}{c})}}\nu_{ST\_sre}$$

$$\nu_{ST\_lab} = \sqrt{\frac{(1+\frac{V_e}{c})}{(1-\frac{V_e}{c})}}\nu_{L\_SRE} = \sqrt{\frac{(1+\frac{V_e}{c})^2}{(1-\frac{V_e}{c})^2}}\nu_{L\_Lab} = \frac{(1+\frac{V_e}{c})}{(1-\frac{V_e}{c})}\nu_{L\_Lab} = \frac{(1+(\frac{V_e}{c}))^2}{(1-(\frac{V_e}{c})^2)}\nu_{L\_Lab}$$

$$\approx 4\gamma^2\nu_{L\_Lab}$$

A Frascati: SL_Thomson

Laser Ti::Sa
λ_0=800 nm, P=1 TW

Elettroni

E=30 MeV
γ=60

Radiazione emessa:
$\lambda=\lambda_0/4\gamma^2$

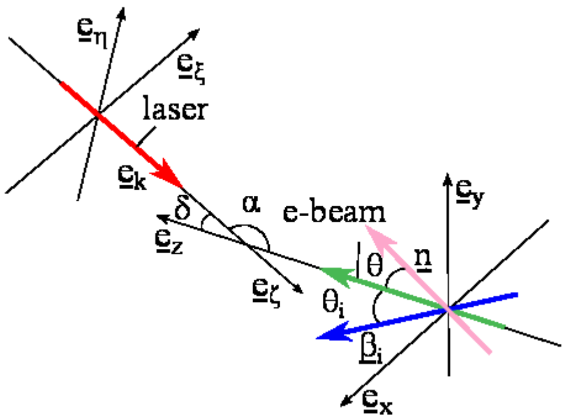
$=8\ 10^{-7}/(4\ 60^2)$m

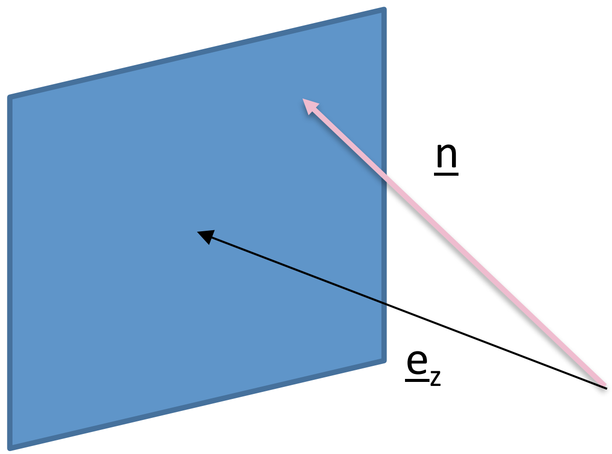
$=5.55\ 10^{-10}$m

Raggi X!!

From the electron orbits and the Liénard-Wiechert potentials **in the far zone** one can write the expression of the electric field [Jackson..]:

$$\mathbf{E} = \frac{e}{c}\left[\frac{\mathbf{n}\times\left[(\mathbf{n}-\boldsymbol{\beta}(t'))\times\dot{\boldsymbol{\beta}}(t')\right]}{R(1-\mathbf{n}\cdot\boldsymbol{\beta}(t'))^{3}}\right]_{ret}$$





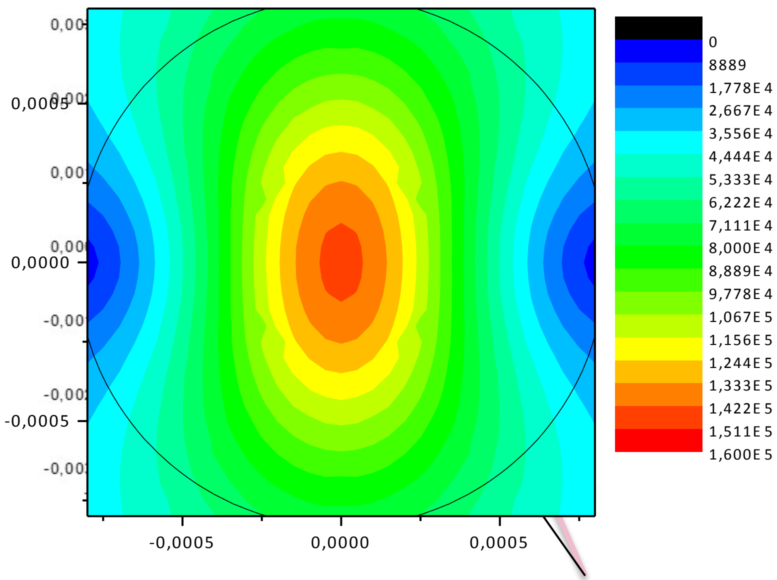
From the motion equation of the electrons

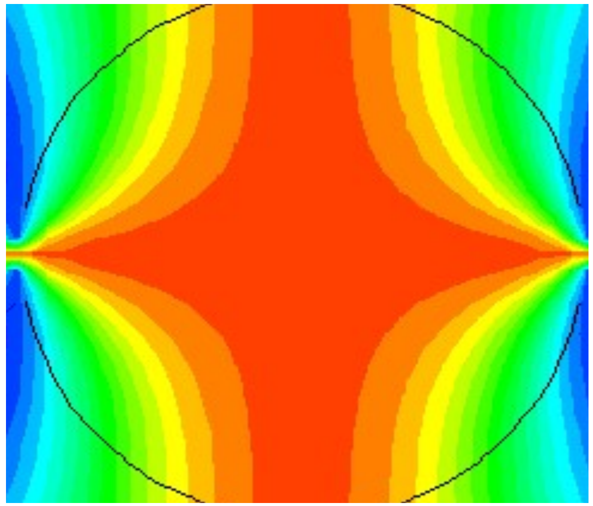
$$\frac{d\mathbf{p}}{dt} = -e(\mathbf{E}_L + \boldsymbol{\beta} \times \mathbf{B}_L)$$

If **E** and **B**=**k**x**E** are electric and magnetic field of the incoming laser,

$$\dot{\boldsymbol{\beta}} = \frac{d\boldsymbol{\beta}}{dt} = -\frac{e}{mc\gamma}(\mathbf{E}_L(1 - \boldsymbol{\beta} \cdot \mathbf{e}_k) + \boldsymbol{\beta} \cdot \mathbf{E}_L(\mathbf{k} - \boldsymbol{\beta}))$$

Total intensity and Stokes parameter $|E_x|^2-|E_y|^2$ on the screen at 1 m, $\gamma=1200$





Classical double differential spectrum

The double differential spectrum for **one electron** is:

$$\frac{d^2W_i}{d\omega d\Omega} = \frac{e^2}{4\pi^2 c}\left|\int_{-\infty}^{+\infty} dt e^{i\omega t}\,\frac{\mathbf{n}\times\left[(\mathbf{n}-\beta(t'))\times\dot{\beta}(t')\right]}{(1-\mathbf{n}\cdot\beta(t'))^3}\right|^2 = \hbar\omega\frac{\mathrm{d}^2\mathrm{N_i}}{\mathrm{d}\omega\mathrm{d}\Omega}$$

And for all the beam:

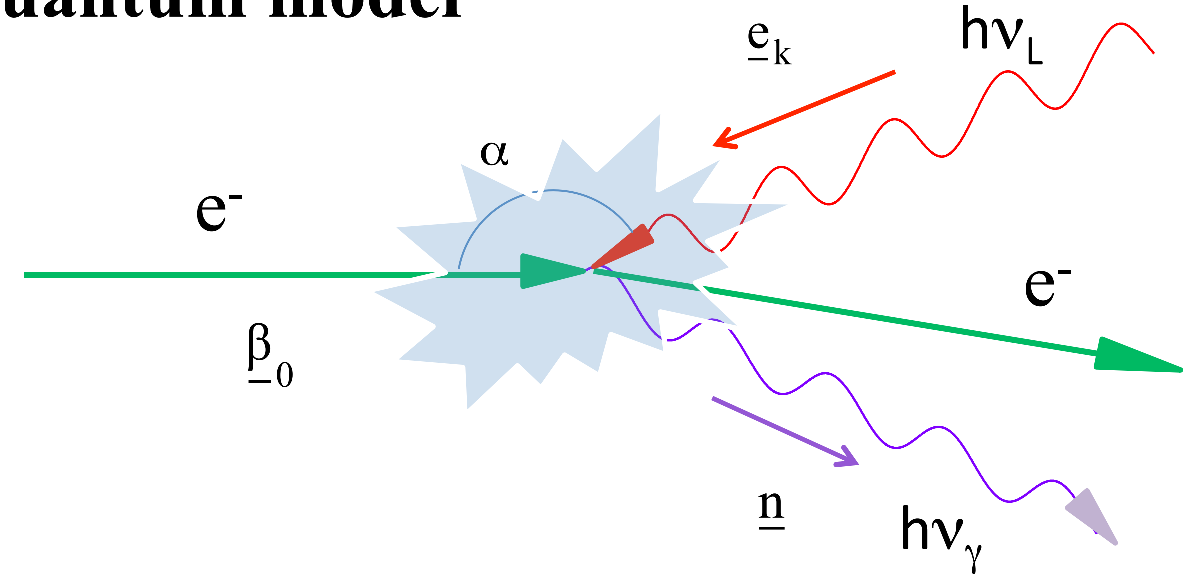
$$\hbar\omega\frac{\mathrm{d}^2\mathrm{N}}{\mathrm{d}\omega\mathrm{d}\Omega} = \hbar\omega\sum_i\frac{\mathrm{d}^2\mathrm{N_i}}{\mathrm{d}\omega\mathrm{d}\Omega}$$

$$\Psi \equiv \gamma\vartheta_M$$

$$N(\Psi) \cong \pi\alpha\Im N_e\left(\frac{cT}{\lambda}\right)a_0^2\Psi^2\,\frac{(1+\Psi^2+\frac{2}{3}\Psi^4)}{\left(1+\Psi^2\right)^3}$$

Full treatement of linear and nonlinear TS for a plane-wave laser pulse with analytical expression of the distributions as well as several approximate expressions in ***P. Tomassini et al.***, Appl. Phys. B **80**, 419 (2005).

Quantum model



Before the scattering

Electron energy $mc^2\gamma_0$
momentum $mc\boldsymbol{\beta}\gamma_0$

Photon energy $h\nu_L$
momentum $h\underline{\mathbf{k}}_L/2\pi$

After the scattering

Electron energy $mc^2\gamma$
momentum $mc\boldsymbol{\beta}\gamma$

Photon energy $h\nu$
momentum $h\underline{\mathbf{k}}/2\pi$

Energy and momentum conservation laws

γ_0:initial Lorentz factor

$$mc^2\gamma_0 + h\nu_L = h\nu + mc^2\gamma$$

$$mc\,\underline{\beta}_0\gamma_0 + h\underline{k}_L/2\pi = mc\underline{\beta}\gamma + h\underline{k}/2\pi$$

$$\begin{cases} mc^2(\gamma-\gamma_0) = -h(\nu-\nu_L) \\ mc(\underline{\beta}\gamma-\underline{\beta}_0\gamma_0) = -h(\underline{k}-\underline{k}_L)/2\pi \end{cases}$$

$$\begin{cases} mc^2(\gamma-\gamma_0) = -h(\nu-\nu_L) \\ mc(\underline{\beta}\gamma-\underline{\beta}_0\gamma_0) = -h(\underline{k}-\underline{k}_L)/2\pi \end{cases}$$

Energy and momentum conservation laws

γ_0:initial Lorentz factor

$$\begin{cases} (\gamma-\gamma_0) = -h(\nu-\nu_L)/mc^2 \\ (\underline{\beta}\gamma-\underline{\beta}_0\gamma_0) = -h(\underline{k}-\underline{k}_L)/(2\pi\ mc) \end{cases}$$

$$\gamma = \frac{1}{\sqrt{(1-\frac{v^2}{c^2})}} = \frac{1}{\sqrt{(1-\beta^2)}}$$

$$\underline{\beta}\gamma = \underline{\beta}_0\gamma_0 - h(\underline{k}-\underline{k}_L)/(2\pi\ mc)$$

$$\beta^2 = 1 - \frac{1}{\gamma^2}$$

$$\beta^2\gamma^2 = \beta_0^2\gamma_0^2 + h^2(k^2+k_L^2-2\underline{k}\cdot\underline{k}_L)/(2\pi\ mc)^2 - 2h\gamma_0(\underline{\beta}_0\cdot\underline{k}-\underline{\beta}_0\cdot\underline{k}_L)/(2\pi\ mc)$$

$\gamma^2 - \cancel{1}$ $\quad$ $\gamma_0^2 - \cancel{1}$

$\beta^2 = 1-1/\gamma^2 \Rightarrow \gamma^2\beta^2 = \gamma^2-1$ $\qquad$ $\beta_0^2 = 1-1/\gamma_0^2 \Rightarrow \gamma_0^2\beta_0^2 = \gamma_0^2-1$

$$\gamma^2 = \gamma_0^2 + h^2(k^2+k_L^2-2\underline{k}\cdot\underline{k}_L)/(2\pi\ mc)^2 - 2h\gamma_0(\underline{\beta}_0\cdot\underline{k}-\underline{\beta}_0\cdot\underline{k}_L)/(2\pi\ mc)$$

$$\gamma^2 = \gamma_0^2 + h^2(k^2+k_L^2-2\underline{k}\cdot\underline{k}_L)/(2\pi\, mc)^2 - 2h\gamma_0\,(\underline{\beta}_0\cdot\underline{k} - \underline{\beta}_0\cdot\underline{k}_L)/(2\pi\, mc)$$

$$(\gamma-\gamma_0) = -h(\nu-\nu_L)/mc^2$$

$$\gamma=\gamma_0-h(\nu-\nu_L)/mc^2$$

$$\gamma^2=\gamma_0^2-2\gamma_0 h(\nu-\nu_L)/mc^2+h^2(\nu-\nu_L)^2/(mc^2)^2$$

$$\gamma_0^2-2\gamma_0 h(\nu-\nu_L)/mc^2+h^2(\nu-\nu_L)^2/(mc^2)^2$$
$$-\gamma_0^2 = h^2(k^2+k_L^2-2\underline{k}\cdot\underline{k}_L)/(2\pi\, mc)^2 - 2h\gamma_0\,(\underline{\beta}_0\cdot\underline{k} - \underline{\beta}_0\cdot\underline{k}_L)/(2\pi\, mc)$$

$$-2\gamma_0 h(\nu-\nu_L)/mc^2+h^2(\nu-\nu_L)^2/(mc^2)^2$$
$$= h^2(k^2+k_L^2-2\underline{k}\cdot\underline{k}_L)/(2\pi\, mc)^2 - 2h\gamma_0\,(\underline{\beta}_0\cdot\underline{k} - \underline{\beta}_0\cdot\underline{k}_L)/(2\pi\, mc)$$

$$-2\gamma_0\ (\nu-\nu_L)/mc^2+h\,(\nu-\nu_L)^2/(mc^2)^2$$
$$=h\,(k^2+k_L{}^2-2\underline{k}\cdot\underline{k}_L)/(2\pi\, mc)^2-2\ \gamma_0\,(\underline{\beta}_0\cdot\underline{k}-\underline{\beta}_0\cdot\underline{k}_L)/(2\pi\, mc)$$

$$-2\gamma_0\ (\nu-\nu_L)/c^2+h\,(\nu-\nu_L)^2/(mc^4)$$
$$=h\,(k^2+k_L{}^2-2\underline{k}\cdot\underline{k}_L)/m(2\pi c)^2-2\ \gamma_0\,(\underline{\beta}_0\cdot\underline{k}-\underline{\beta}_0\cdot\underline{k}_L)/(2\pi\ c)$$

$\nu=c/\lambda=ck/2\pi$ $\qquad$ $\nu_L=c/\lambda_L=ck_L/2\pi$

$$-2\gamma_0\ (\nu-\nu_L)/c^2+h\,(\nu^2+\nu_L{}^2-2\nu\nu_L)/(mc^4)$$
$$=h\,(k^2+k_L{}^2-2\underline{k}\cdot\underline{k}_L)/m(2\pi c)^2-2\ \gamma_0\,(\underline{\beta}_0\cdot\underline{k}-\underline{\beta}_0\cdot\underline{k}_L)/(2\pi\ c)$$

$$-2\gamma_0\ (\nu-\nu_L)/c^2-h\ 2\nu\nu_L/(mc^4)$$
$$=-h\ 2\underline{k}\cdot\underline{k}_L/m(2\pi c)^2-2\ \gamma_0\,(\underline{\beta}_0\cdot\underline{k}-\underline{\beta}_0\cdot\underline{k}_L)/(2\pi\ c)$$

$$-\cancel{2}\gamma_0\ (\nu-\nu_L)/c^2 - h\,\cancel{2}\nu\nu_L/(mc^4)$$

$$= -h\,\cancel{2}\underline{k}\cdot\underline{k}_L/m(2\pi c)^2 - \cancel{2}\ \gamma_0\,(\underline{\beta}_0\cdot\underline{k} - \underline{\beta}_0\cdot\underline{k}_L)/(2\pi\ c)$$

$$\gamma_0(\nu-\nu_L)/c^2 + h\,\nu\nu_L/(mc^4) = h\,\underline{k}\cdot\underline{k}_L/m(2\pi c)^2 + \gamma_0\,(\underline{\beta}_0\cdot\underline{k} - \underline{\beta}_0\cdot\underline{k}_L)/(2\pi\ c)$$

$$\nu = c/\lambda = ck/2\pi \qquad \nu_L = c/\lambda_L = ck_L/2\pi \qquad \underline{n} = \underline{k}/k \qquad \underline{e}_{kL} = \underline{k}_L/k_L$$

$$\underline{k} = 2\pi\nu\underline{n}/c \qquad \underline{k}_L = 2\pi\nu_L\underline{e}_{kL}/c$$

$$\gamma_0\ (\nu-\nu_L)/c^2 + h\,\nu\nu_L/(mc^4) = h\,\nu\nu_L\,\underline{n}\cdot\underline{e}_{kL}/(mc^4) + \gamma_0\,(\nu\underline{\beta}_0\cdot\underline{n} - \nu_L\underline{\beta}_0\cdot\underline{e}_{kL})/c^2$$

$$\gamma_0\ (\nu-\nu_L) + h\,\nu\nu_L/(mc^2) = h\,\nu\nu_L\,\underline{n}\cdot\underline{e}_{kL}/(mc^2) + \gamma_0\,(\nu\underline{\beta}_0\cdot\underline{n} - \nu_L\underline{\beta}_0\cdot\underline{e}_{kL})$$

$$\gamma_0\ (\nu-\nu_L) - \gamma_0\,(\nu\underline{\beta}_0\cdot\underline{n} - \nu_L\underline{\beta}_0\cdot\underline{e}_{kL}) = -h\,\nu\nu_L/(mc^2) + h\,\nu\nu_L\,\underline{n}\cdot\underline{e}_{kL}/(mc^2)$$

$$\gamma_0\ (\nu-\nu_L) - \gamma_0\,(\nu\underline{\beta}_0\cdot\underline{n} - \nu_L\underline{\beta}_0\cdot\underline{e}_{kL}) = -h\,\nu\nu_L(1-\underline{n}\cdot\underline{e}_{kL})/(mc^2)$$

$$\gamma_0\ c(1/\lambda - 1/\lambda_L) - c\gamma_0\,(\underline{\beta}_0\cdot\underline{n}/\lambda - \underline{\beta}_0\cdot\underline{e}_{kL}/\lambda_L) = -h\,(1-\underline{n}\cdot\underline{e}_{kL})/(\lambda\lambda_L m)$$

$$\gamma_0\, c(1/\lambda - 1/\lambda_L) - c\gamma_0\,(\underline{\beta}_0 \cdot \underline{n}/\lambda - \underline{\beta}_0 \cdot \underline{e}_{kL}/\lambda_L) = -h\,(1-\underline{n}\cdot\underline{e}_{kL})/(\lambda\lambda_L m)$$

$$\gamma_0 c \frac{\lambda_L - \lambda}{\lambda_L \lambda} - \gamma_0 c \frac{\boldsymbol{\beta}_0 \cdot \mathbf{n}\lambda_L - \boldsymbol{\beta}_0 \cdot \mathbf{e}_{kL}\lambda}{\lambda_L \lambda} = \frac{-h(1-\mathbf{n}\cdot\mathbf{e}_{kL})}{m\lambda_L\lambda}$$

$$(\lambda_L - \lambda) - (\boldsymbol{\beta}_0 \cdot \mathbf{n}\lambda_L - \boldsymbol{\beta}_0 \cdot \mathbf{e}_{kL}\lambda) = \frac{-h\,(1-\mathbf{n}.\mathbf{e}_{kL})}{mc\gamma_0}$$

$$(1-\boldsymbol{\beta}_0 \cdot \mathbf{n})\lambda_L - (1-\boldsymbol{\beta}_0 \cdot \mathbf{e}_{kL})\lambda = \frac{-h\,(1-\mathbf{n}.\mathbf{e}_{kL})}{mc\gamma_0}$$

$$\boldsymbol{\lambda} = \boldsymbol{\lambda}_L \frac{1-\underline{\mathbf{n}}\cdot\underline{\boldsymbol{\beta}}_0}{1-\underline{\mathbf{e}}_{kL}\cdot\underline{\boldsymbol{\beta}}_0} + \frac{h}{mc\gamma_0}\,\frac{1-\underline{\mathbf{e}}_{kL}\cdot\underline{\mathbf{n}}}{1-\underline{\mathbf{e}}_{kL}\cdot\underline{\boldsymbol{\beta}}_0}$$

$$\gamma_0 (\nu-\nu_L) - \gamma_0 (\nu \underline{\beta}_0 \cdot \underline{n} - \nu_L \underline{\beta}_0 \cdot \underline{e}_{kL}) = -h\,\nu\nu_L (1-\underline{n}\cdot\underline{e}_{kL})/(mc^2)$$

$$\gamma_0 \nu - \gamma_0 \nu \underline{\beta}_0 \cdot \underline{n} + h\,\nu\nu_L (1-\underline{n}\cdot\underline{e}_{kL})/(mc^2) = -\gamma_0 \nu_L \underline{\beta}_0 \cdot \underline{e}_{kL} + \gamma_0 \nu_L$$

$$\nu\,(\gamma_0 - \gamma_0 \underline{\beta}_0 \cdot \underline{n} + h\,\nu_L (1-\underline{n}\cdot\underline{e}_{kL})/(mc^2)) = -\gamma_0 \nu_L (\underline{\beta}_0 \cdot \underline{e}_{kL} - 1)$$

$$\nu = \nu_L \frac{1-\underline{e}_k \cdot \underline{\beta}_0}{1-\underline{n}\cdot\underline{\beta}_0 + \frac{h\nu_L}{mc^2\gamma_0}(1-\underline{e}_k\cdot\underline{n})}$$

$$\lambda = \lambda_L \frac{1-\underline{n}\cdot\underline{\beta}_0}{1-\underline{e}_k\cdot\underline{\beta}_0} + \frac{h}{mc\gamma_0}\frac{1-\underline{e}_k\cdot\underline{n}}{1-\underline{e}_k\cdot\underline{\beta}_0}$$

If $\underline{e}_k=-\underline{e}_z$ and $\underline{\beta}_0=\beta_{0ez}$

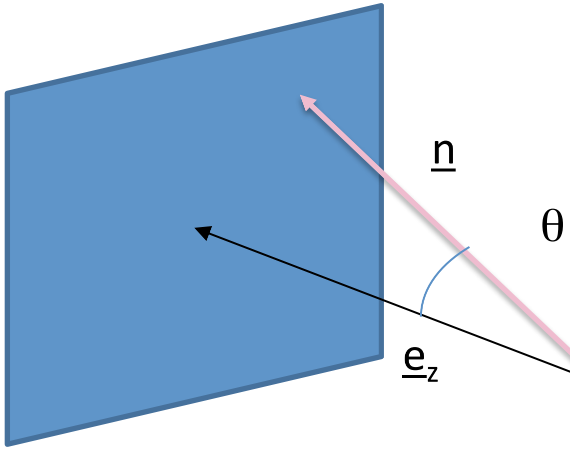
$$\boldsymbol{\lambda} = \boldsymbol{\lambda}_L \frac{1-\beta_0\cos\theta}{1+\beta_0} + \frac{h}{mc\gamma_0}\frac{1+\cos\theta}{1+\beta_0}$$

For $\beta=0,\gamma=1$

$$\boldsymbol{\lambda} = \boldsymbol{\lambda}_L + \frac{h}{mc}(1+\cos\theta)$$

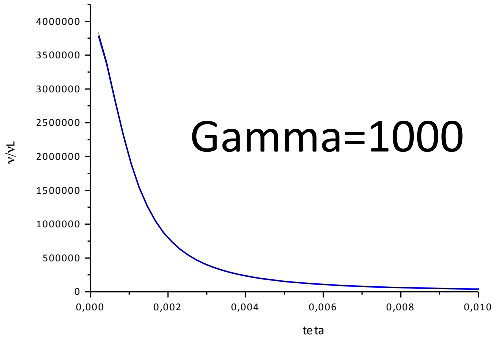
$$\nu = \nu_L \frac{1-\underline{e}_k\cdot\underline{\beta}_0}{1-\underline{n}\cdot\underline{\beta}_0+\frac{h\nu_L}{mc^2\gamma_0}(1-\underline{e}_k\cdot\underline{n})}$$

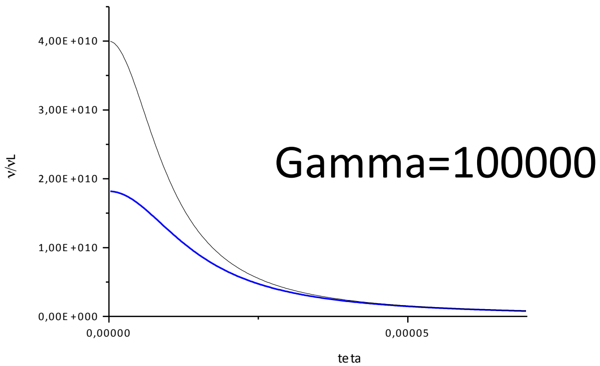
$$\boldsymbol{\nu} = \boldsymbol{\nu}_L \frac{1+\beta_0}{1-\beta_0\cos\theta+\frac{h\nu_L}{mc^2\gamma_0}(1+\cos\theta)}$$



For example
$\lambda_L=0.8\ 10^{-6}$

$$\frac{h\nu_L}{mc^2} = \frac{1.5}{0.511\ 10^6} = 3\,10^{-6}$$





On the axis: θ=0

$$\boldsymbol{\lambda} = \boldsymbol{\lambda}_{\mathbf{L}} \frac{1-\beta_{\mathbf{0}}\cos\theta}{1+\beta_{\mathbf{0}}} + \frac{h}{mc\gamma_0}\frac{1+\cos\theta}{1+\beta_0}$$

$$\boldsymbol{\lambda} = \boldsymbol{\lambda}_{\mathbf{L}} \frac{1-\beta_{\mathbf{0}}}{1+\beta_{\mathbf{0}}} + \frac{h}{mc\gamma_0}\frac{2}{1+\beta_0}$$

And with γ>>1

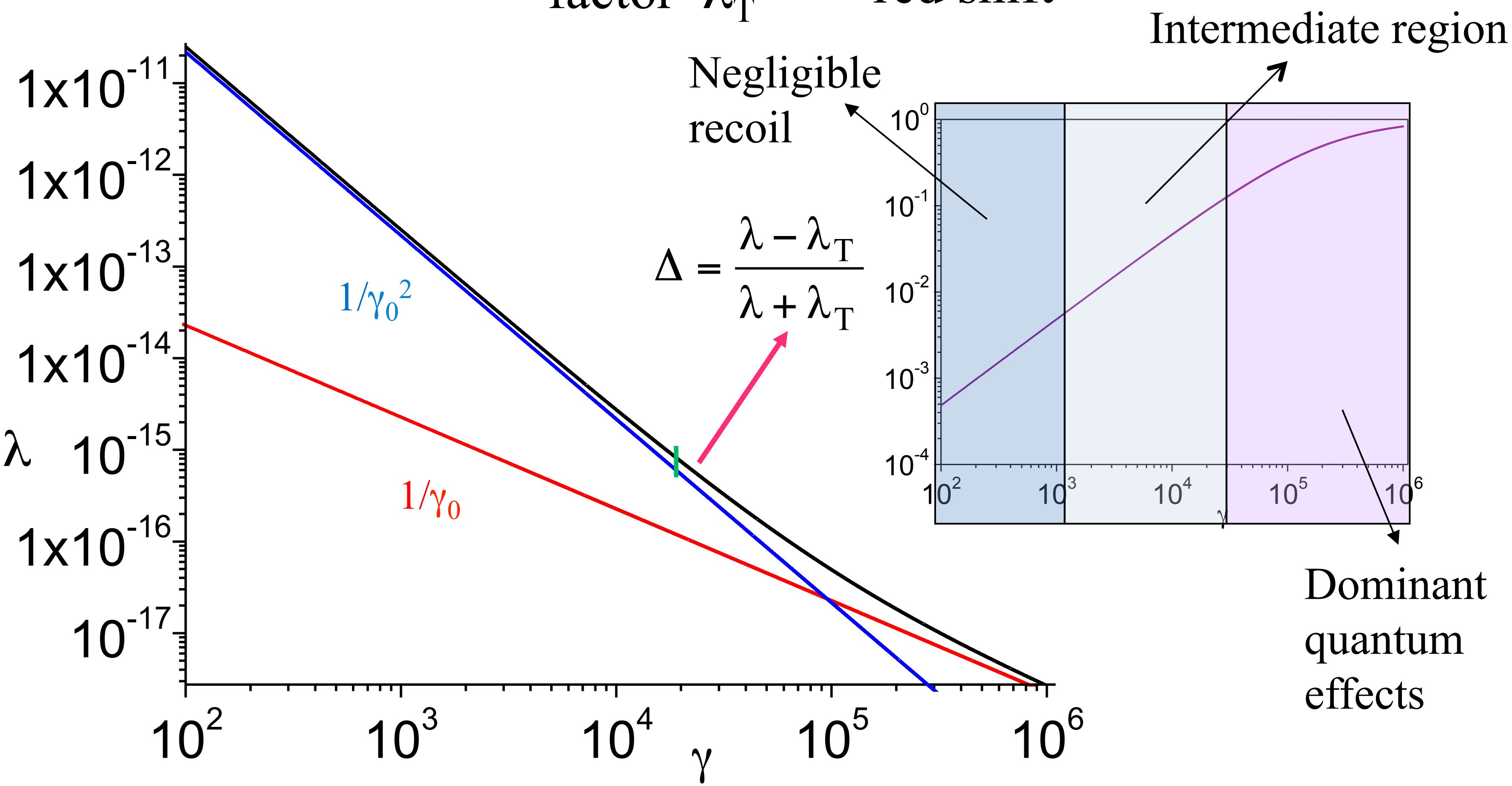
$$\boldsymbol{\lambda} = \frac{\boldsymbol{\lambda}_{\mathbf{L}}}{4\gamma_0^2} + \frac{h}{mc\gamma_0}$$

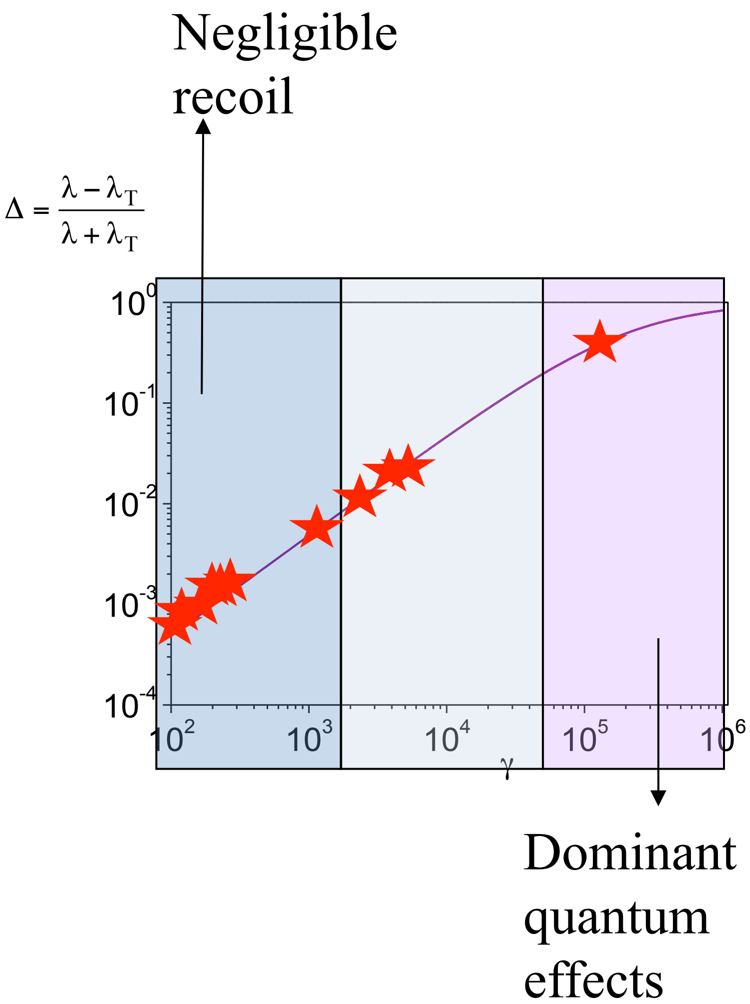
Back-scattering
Radiation on-axis

$$\lambda = \lambda_L \frac{1}{4\gamma_0^2} + \frac{h}{mc\gamma_0}$$

Thomson factor λ_T

Compton red shift





CLS	25 MeV	12 keV
PhoeniX	25-30 MeV	12-20 keV
Pleiades	20-100 MeV	20-500 keV
PlasmonX	30-150 MeV	20-500 keV
LSS (ATF)	60 MeV	80 keV
STAR		

Quantum cross-section for electron-photon interaction (Klein and Nishina)

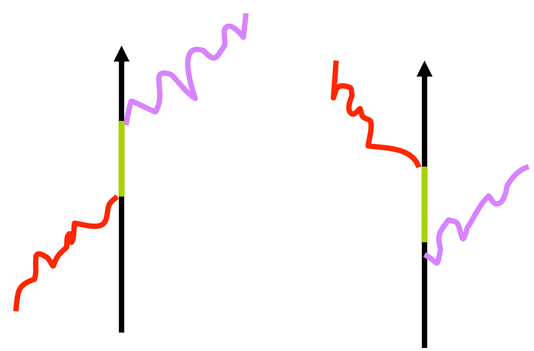
Dirac Equation: $$i\frac{\partial\psi}{\partial t} = (\hat{H}_0 + \hat{H}_{int})\psi$$

Radiation potential:

$$\hat{A} = hc(\underline{e}_L\sqrt{\frac{1}{\omega_L}}(e^{i(\underline{k}_L\cdot\underline{r}-\omega_L t)}\hat{a}_L + e^{-i(\underline{k}_L\cdot\underline{r}-\omega_L t)}\hat{a}_L{}^+) + \underline{e}\sqrt{\frac{1}{\omega}}(e^{i(\underline{k}\cdot\underline{r}-\omega t)}\hat{a} + e^{-i(\underline{k}\cdot\underline{r}-\omega t)}\hat{a}^+))$$

Transition probability (perturbation theory or Feyman-Dyson graphs):

$$w_{n,m} = \frac{2\pi}{\hbar}\rho\left|\sum_{n'}\frac{H_{m,n'}H_{n',n}}{E_m - E_{n'}} + \sum_{n'}\frac{H_{m,n''}H_{n'',n}}{E_m - E_{n''}}\right|^2$$



Cross section **in the electron frame**:

$$\left(\frac{d\sigma}{d\Omega}\right)' = \frac{r_0^2}{4}\left(\frac{\nu'}{\nu'_L}\right)^2\left[4(\underline{e}'\cdot\underline{e}_L')^2 - 2 + \frac{\nu'}{\nu'_L} + \frac{\nu'_L}{\nu'}\right]$$

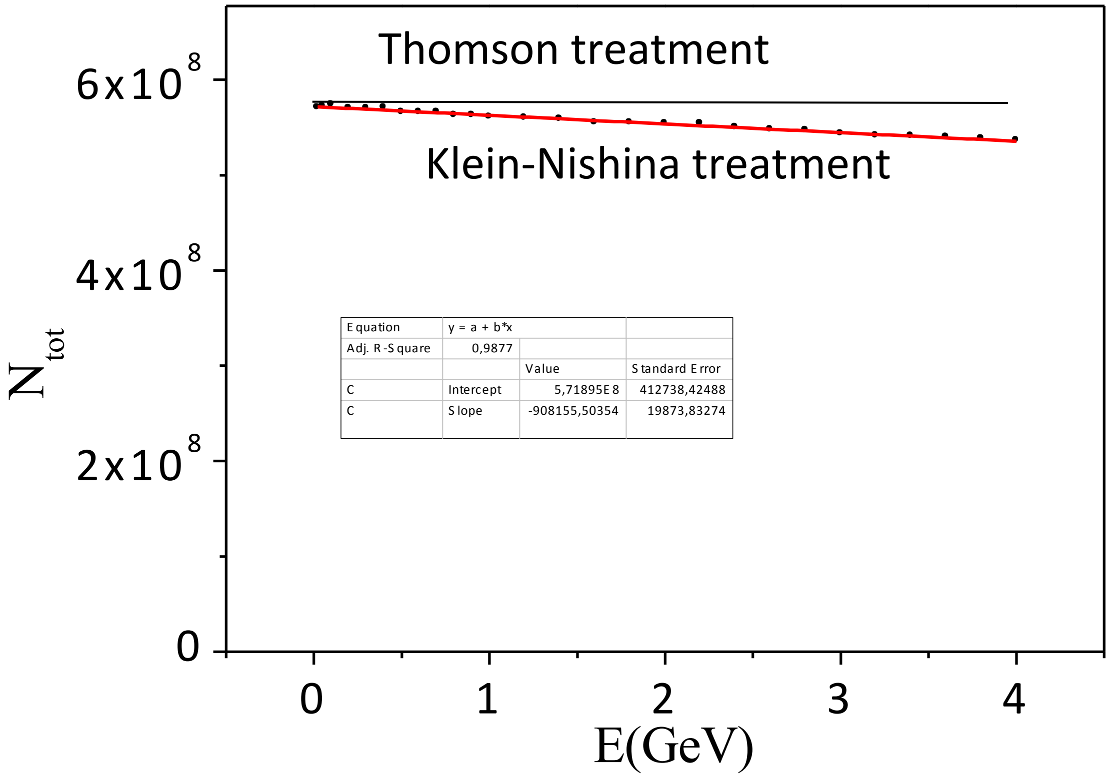
By Lorentz transforming frequencies, polarizations and differentials:

$$\frac{d\sigma}{d\Omega} = \frac{r_0^2 X}{4\gamma_0^2(1-\underline{\beta}_0\cdot\hat{\underline{k}}_L)^2}\left(\frac{\nu}{\nu_L}\right)^2$$

$$X = \frac{\nu_L}{\nu}\frac{(1-\underline{\beta}_0\cdot\hat{\underline{k}}_L)}{1-\underline{n}\cdot\underline{\beta}_0} + \frac{\nu}{\nu_L}\frac{1-\underline{n}\cdot\underline{\beta}_0}{(1-\underline{\beta}_0\cdot\hat{\underline{k}}_L)} - 1 + \left(1 + \frac{mc^2}{h\nu\gamma_0}\frac{1}{1-\underline{n}\cdot\underline{\beta}_0} - \frac{mc^2}{h\nu_L\gamma_0}\frac{1}{1-\underline{\beta}_0\cdot\hat{\underline{k}}_L}\right)^2$$

Double differential cross section **in the laboratory frame**:

$$\frac{d^2\sigma}{d\nu d\Omega} = \frac{r_0^2 X}{2\pi 2\gamma_0^2(1-\underline{\beta}_0\cdot\hat{\underline{k}}_L)^2}\left(\frac{\nu}{\nu_L}\right)^2\delta\left(\nu - \nu_L\frac{1-\underline{\beta}_0\cdot\hat{\underline{k}}_L}{1-\underline{n}\cdot\underline{\beta}_0 + \frac{h\nu_L}{mc^2\gamma_0}(1-\underline{n}\cdot\hat{\underline{k}}_L)}\right)$$



$$\sigma_{K-N} \approx \sigma_T \left(1 - \frac{2\hbar\omega_L}{mc^2}\gamma_e\right)$$

Extension to electron-laser beams

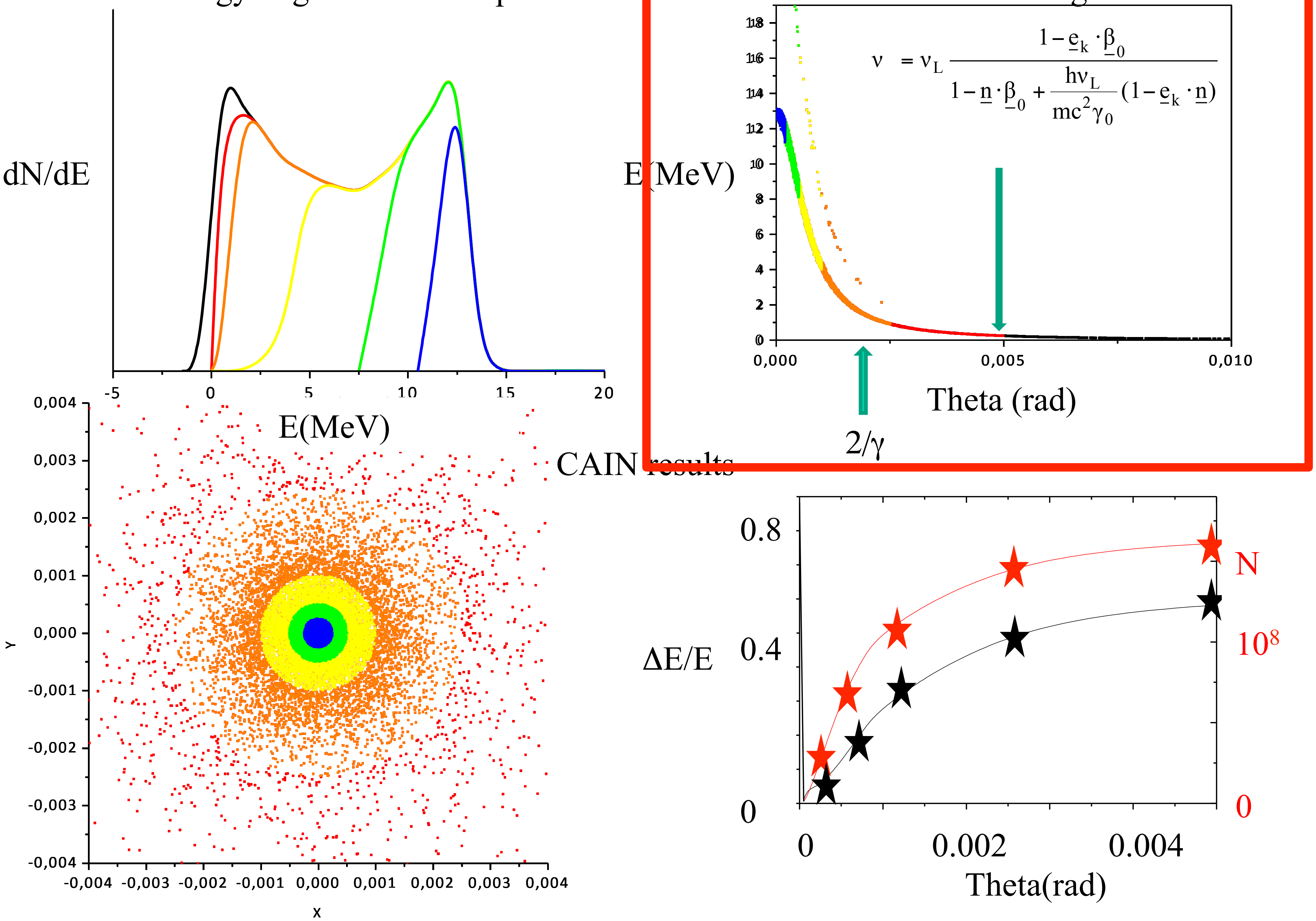
$$\frac{d^2N}{d\nu d\Omega} = \hbar c \int \frac{d^2\sigma}{d\nu d\Omega} \frac{d^2N_e}{d\underline{x}d\underline{p}} \frac{d^2N_L}{d\underline{x}_L d\underline{k}_L} (1 - \underline{\beta}_0 \cdot \hat{\underline{k}}_L) dt d\underline{x} d\underline{p} d\underline{k}_L$$

$$\frac{d^2N_e}{d\underline{x}d\underline{p}} = \delta(\underline{x} - \underline{x}_j(t))\delta(\underline{p} - \underline{p}_j(t))$$

$$\frac{d^2N_L}{d\underline{x}_L d\underline{k}_L}$$

Longitudinal and transverse Gaussian profiles

The energy-angle correlation permits the control of bandwidth and divergence

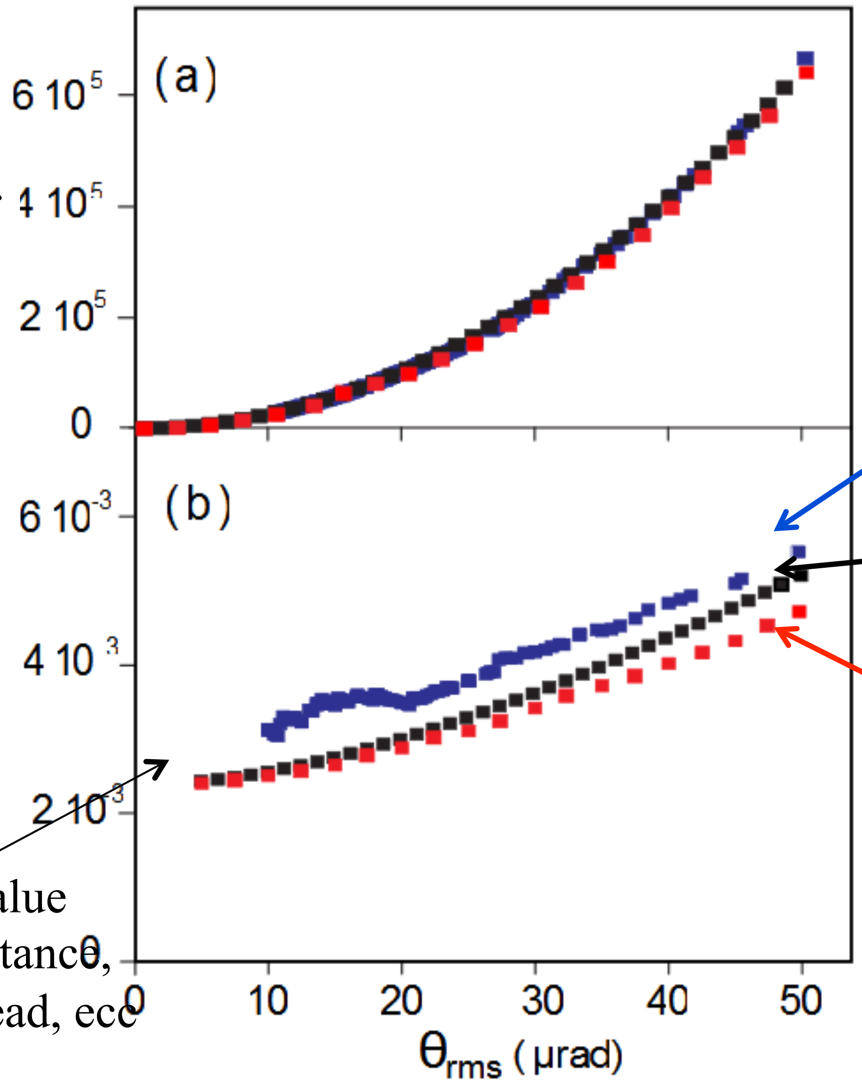


COMPARISON between classical (TSST), quantum semianalytical (Comp_cross) and quantum MonteCarlo (CAIN)

ELI-np data

Number of photons

bandwidth

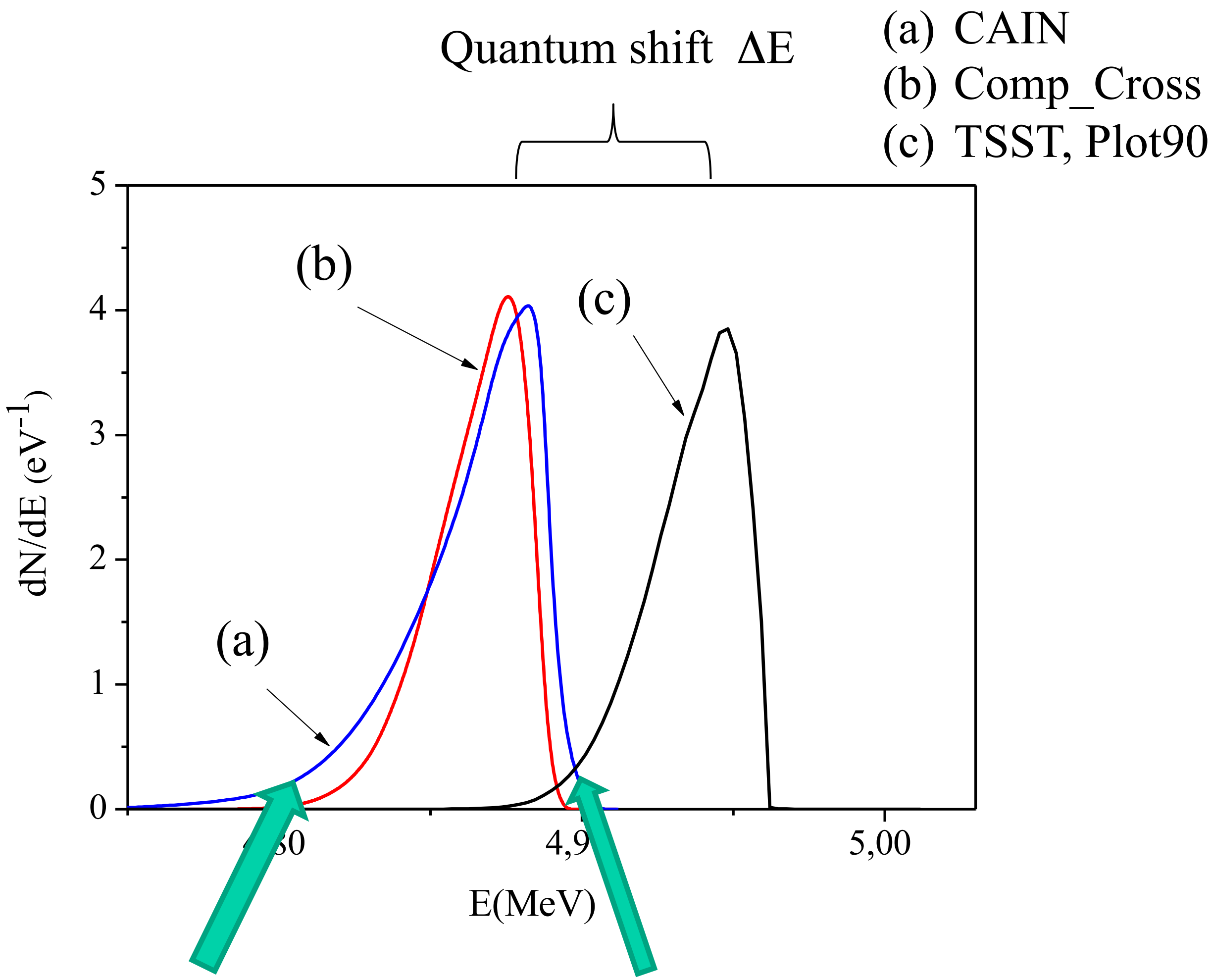


Limiting value due to emittance, energy spread, ecc

CAIN (quantum MonteCarlo)

TSST (classical)
Plot90(classical linear)
Developed by
P. Tomassini
V. Petrillo

Comp_Cross (quantum semianalytical)
Developed by V.Petrillo



A part from the quantum shift, the spectra are very similar

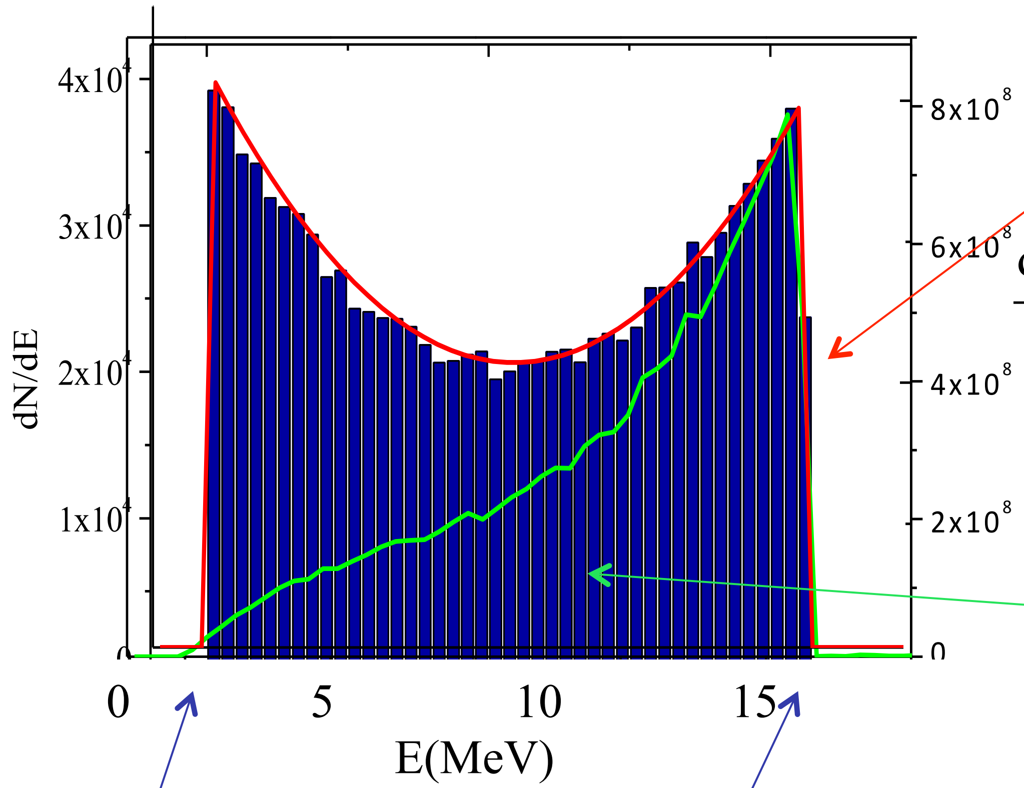
Electron distribution during and after the scattering

Encodes important informations about the scattering

Deterioration in the longitudianal phase space

Eventual transverse cooling

Photon distribution , linear case, Eli-np data



Total photon distribution

Photon energy distribution

$$\frac{dN_{ph}}{dE} \propto \frac{3}{\Delta E}\left[\left(\frac{E-E_{min}}{\Delta E}\right)^2 - \frac{E-E_{min}}{\Delta E} + \frac{1}{2}\right]$$
$$x H(E_{max}-E)H(E-E_{min})$$

$$E_{min} = \hbar\omega_L$$

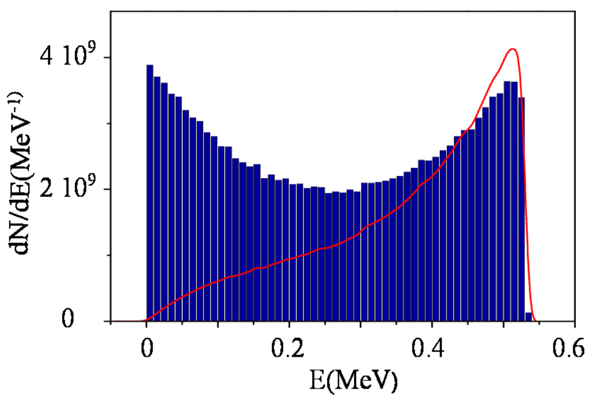
$$\frac{dE_{ph}}{dE} \propto \frac{E}{\Delta E}\left[\left(\frac{E-E_{min}}{\Delta E}\right)^2 - \frac{E-E_{min}}{\Delta E} + \frac{1}{2}\right]$$
$$x H(E_{max}-E)H(E-E_{min})$$

$$E_{max} = \frac{(1+\beta_e)\hbar\omega_L}{1-\beta_e + 2\hbar\omega_L/\gamma_e m_0 c^2}$$

$\Delta N_{ph}/\langle N_{ph}\rangle \approx 61\%$

$\Delta E_{ph}/\langle E_{ph}\rangle \approx 25\%$

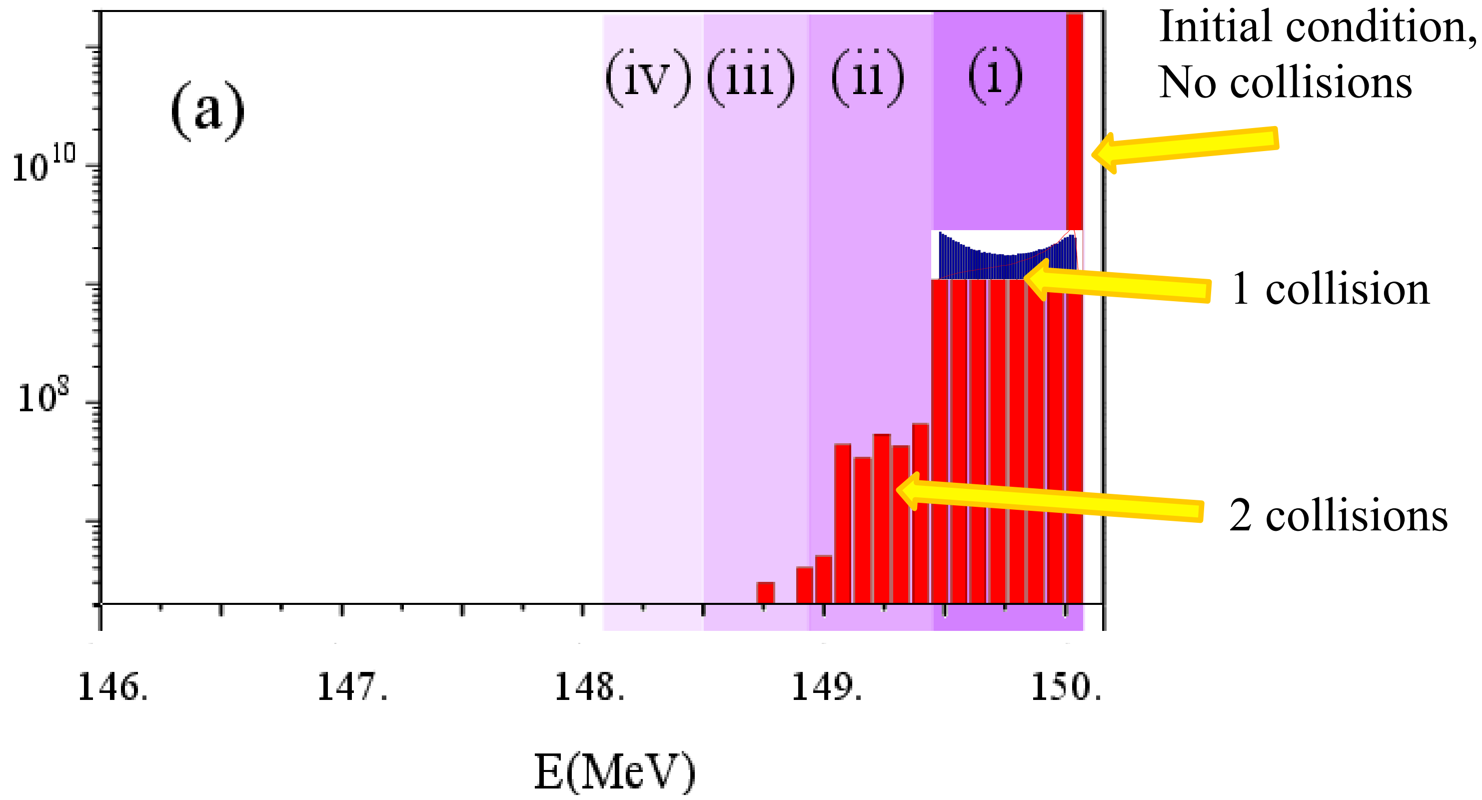
Electron energy distribution at varying laser time duration. Simulation made with CAIN.



Thomson SPARC-LAB at 150 MeV

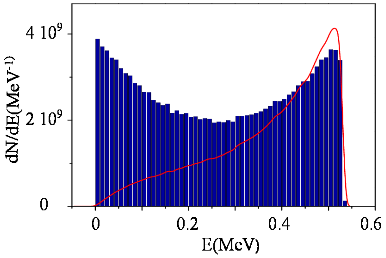
Photon distribution vs electron energy for a0 = 0.083 and

Δt=0.083ps

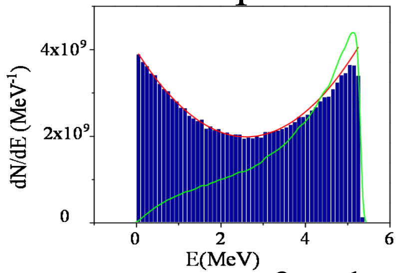


Electron energy distribution at varying laser time duration. Simulation with CAIN

PlasmonX case

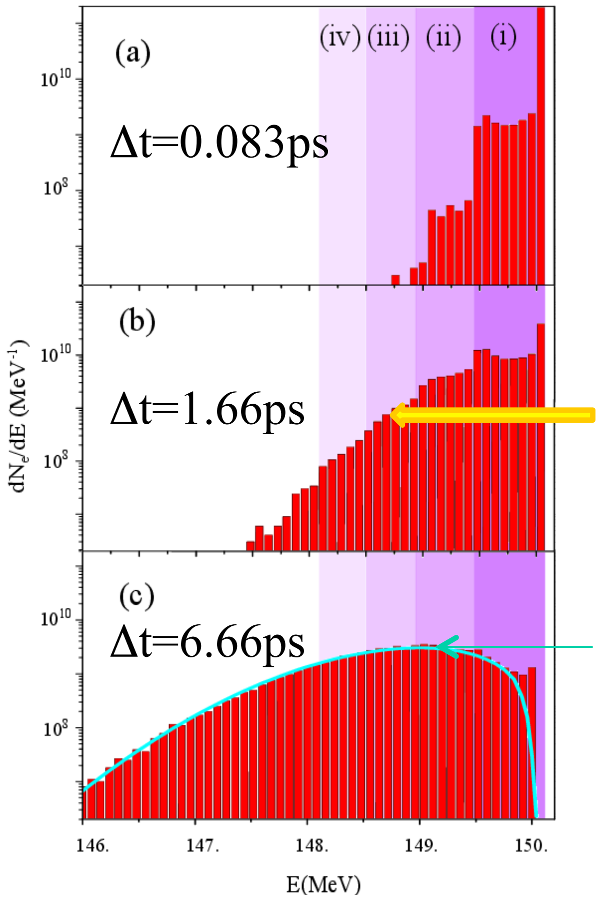


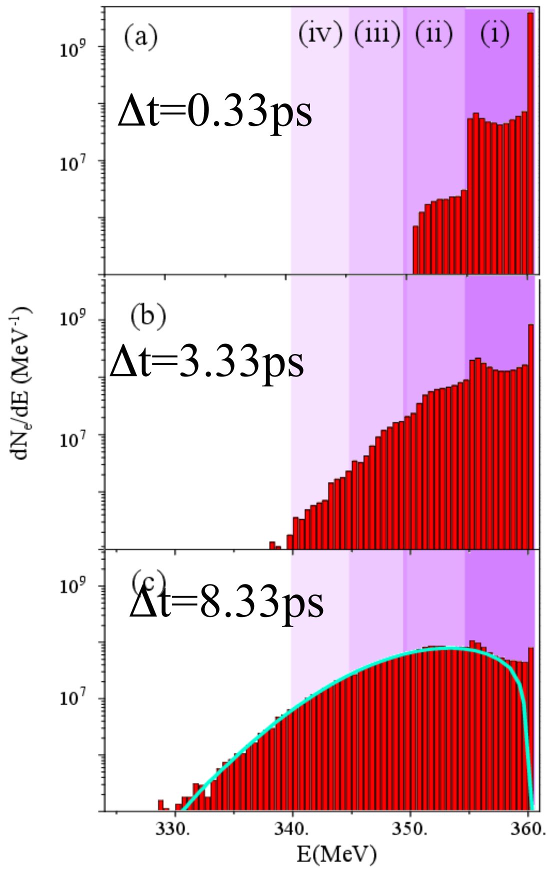
ELI-np case

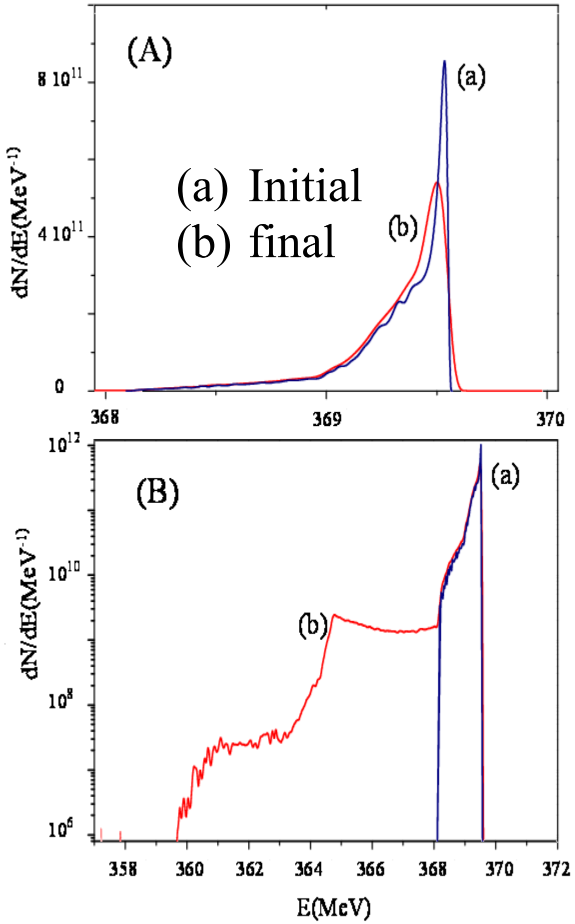


ELI simulated beam

Electron distribution vs electron energy for the a0 = 0.083







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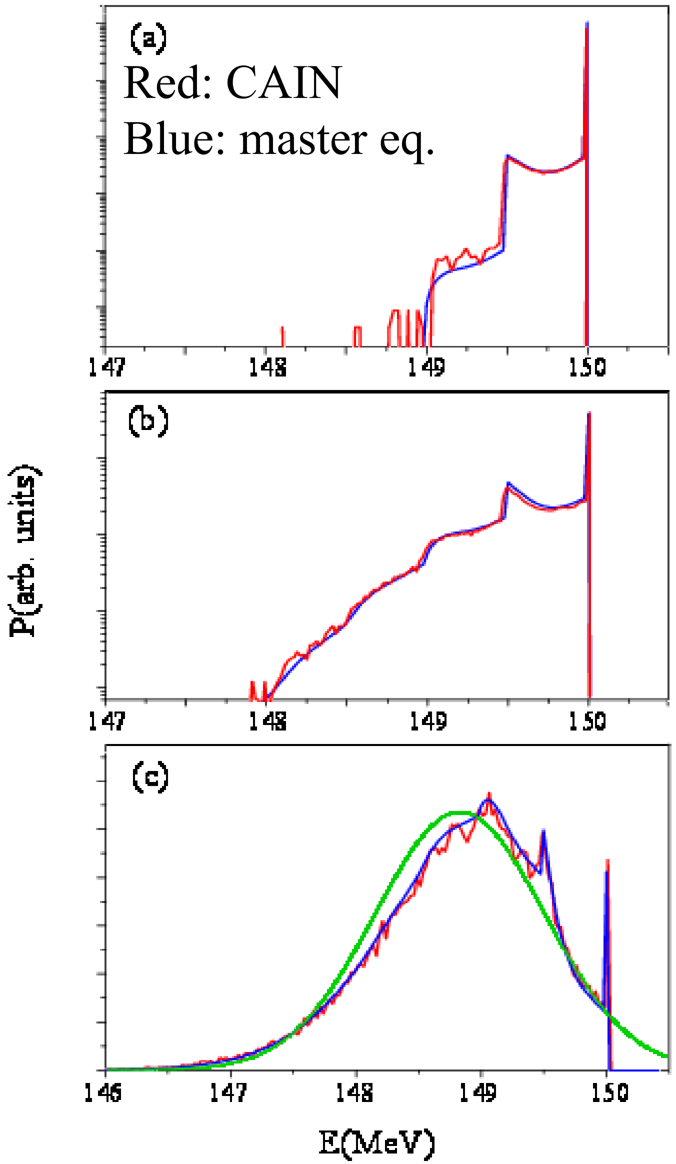


Thomson SPARC-LAB data, 150 MeV

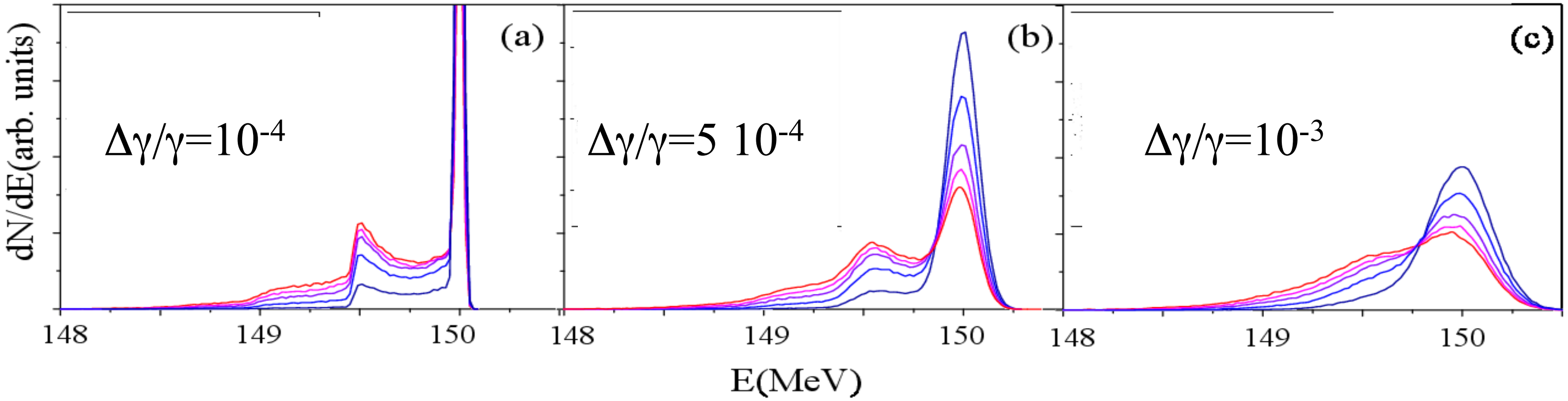
$$\frac{\partial P(E,t)}{\partial t} = \alpha \int dE^* W(E,E^*) P(E^*,t) - \alpha P(E,t)$$

$$W = \frac{dN_{ph}}{dE}$$

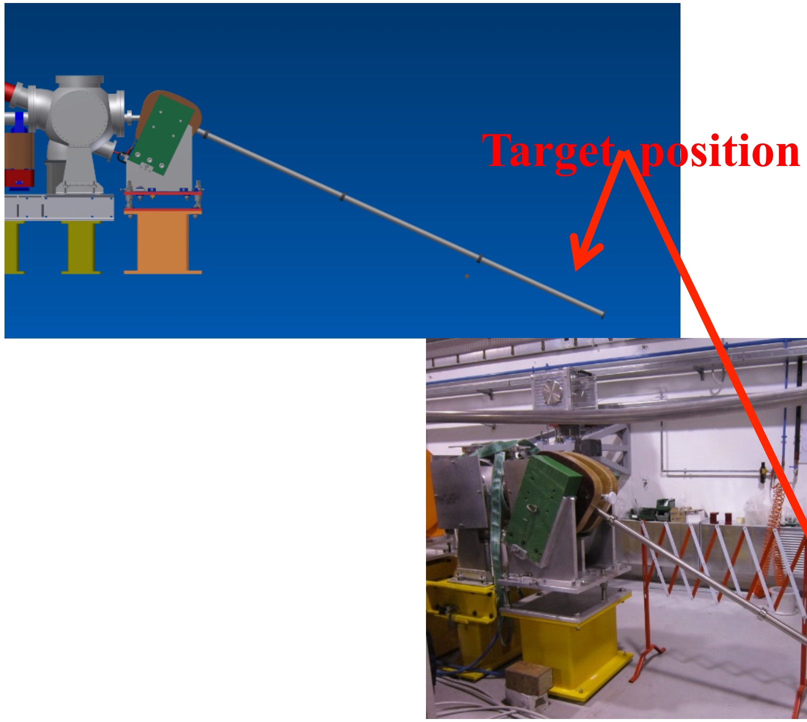
P is the electron distribution
Chapman-Kolmogorov master-equation for Markov process

$$\frac{dN_{ph}}{dE} \propto \frac{3}{\Delta E}\left[\left(\frac{E-E_{min}}{\Delta E}\right)^2 - \frac{E-E_{min}}{\Delta E} + \frac{1}{2}\right]$$
$$x H(E_{max} - E) H(E - E_{min})$$

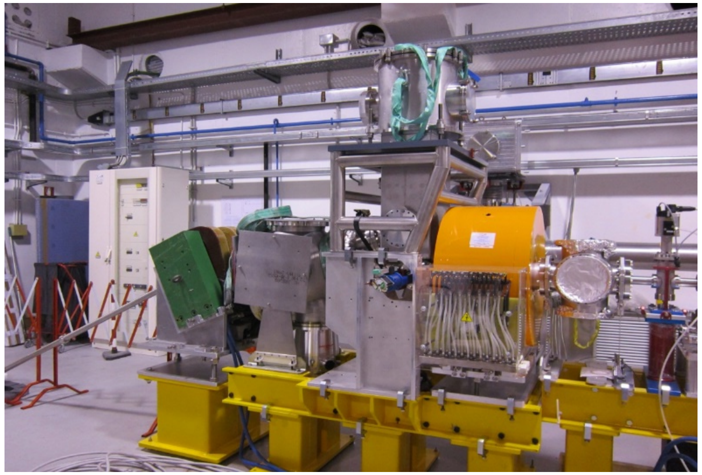
Submitted to NJP



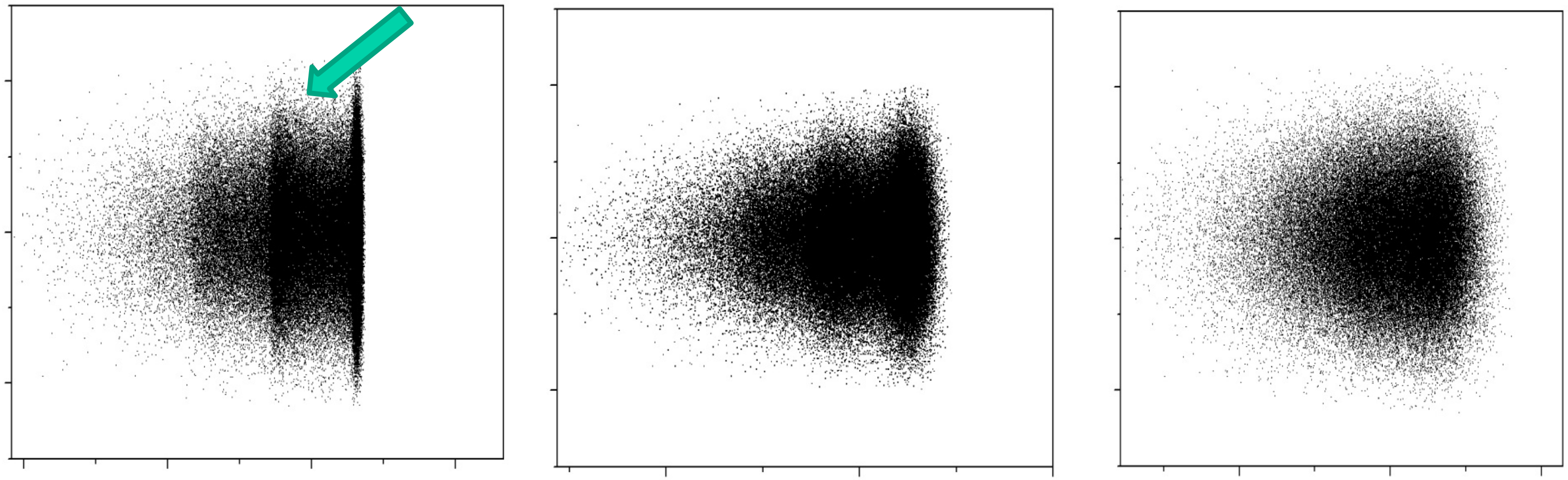
dN/dE(arb. units)
(a)
Δγ/γ=10-4
(b)
Δγ/γ=5 10-4
(c)
Δγ/γ=10-3
148
149
150
148
149
150
148
149
150
E(MeV)



Target position



Quantum structures exist only at low energy spread



CONCLUSIONS

Regarding the photon distribution

The quantum model is important to determine the radiation frequency for gamma factors larger than 1000.

The other characteristics of the radiation, i.e., for instance, the shape of the spectrum, the total number of photons, the bandwidth are not substantially affected by quantum effects.

If the laser is intense non linear effects play a significant role, but in the range analysed the linear model is convenient

Ambiguous mathematical procedures in the Klein-Nishina cross section derivation (such as, i.e., the use of improper eigenfunctions and squared Dirac delta functions), should be eliminated by a rigorous revision.

Regarding the electron distribution

The electron distribution evolves in time during the collision, presenting a sequence of stripes , connected to the quantum nature of the scattering

At longer times the process becomes diffusive, following the Fokker-Planck equation

A master equation derived by the Kolmogorov equation for Markov phenomena is able to describe the process

By deflecting the electron on a screen, one can detect the details of the energy distribution, confirming the quantum nature of the collisions

Scaling laws and their validation

Total number of photons
In the bandwidth

$$N = \frac{4.1 \, x 1.5 \, 10^{8} E_L(J) Q(pC) \psi^2}{h\nu_L(eV)(\frac{w_0^2}{4} + \sigma_x^2)\sqrt{1 + \frac{\delta^2(\sigma_x^2 + \sigma_{x,e}^2)}{(w_0^2 + 2\sigma_x^2)}}}$$

Bandwidth

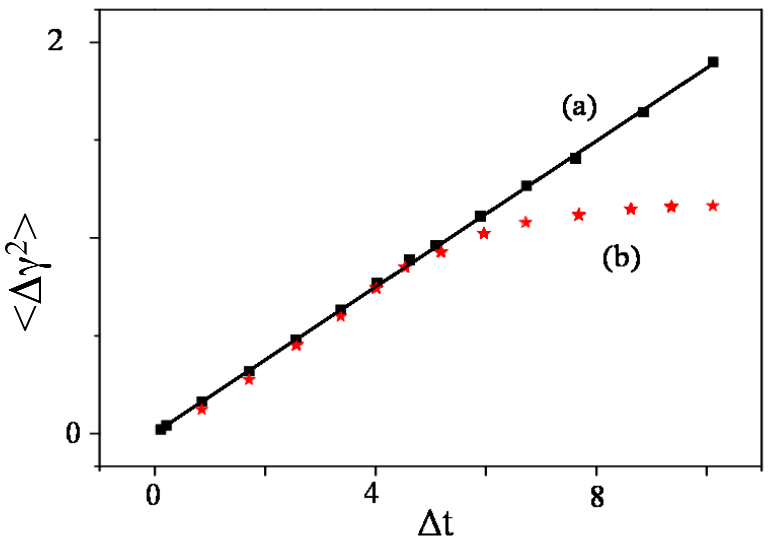
$$\frac{\Delta\nu_p}{\nu_p} = \sqrt{\psi^4 + \left(\frac{\varepsilon_n}{\sigma_x}\right)^4 + 4\left(\frac{\Delta\gamma}{\gamma}\right)^2 + \left(\frac{\Delta\nu_p}{\nu_p}\right)_L^2}$$

acceptance — emittance — energy spread — broadending due to laser

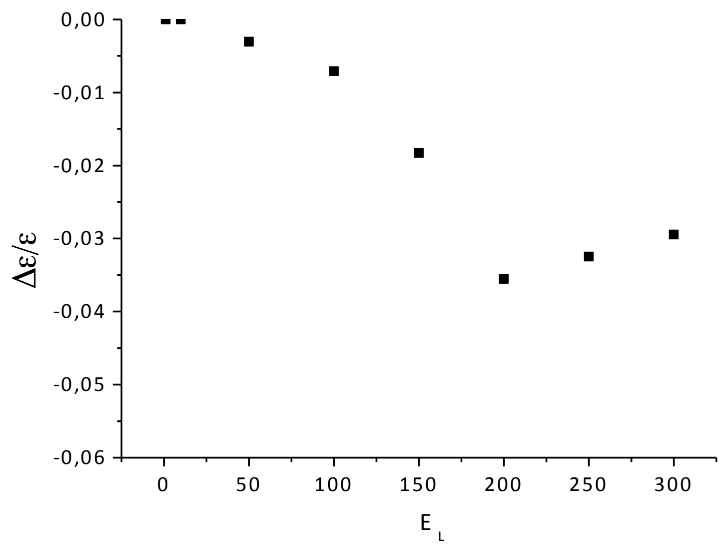
Spectral density

$$S = \left[\frac{dN}{d\nu}\right]_{peak}$$

Increase in the energy spread



decrease in emittance



Contributors to the work:

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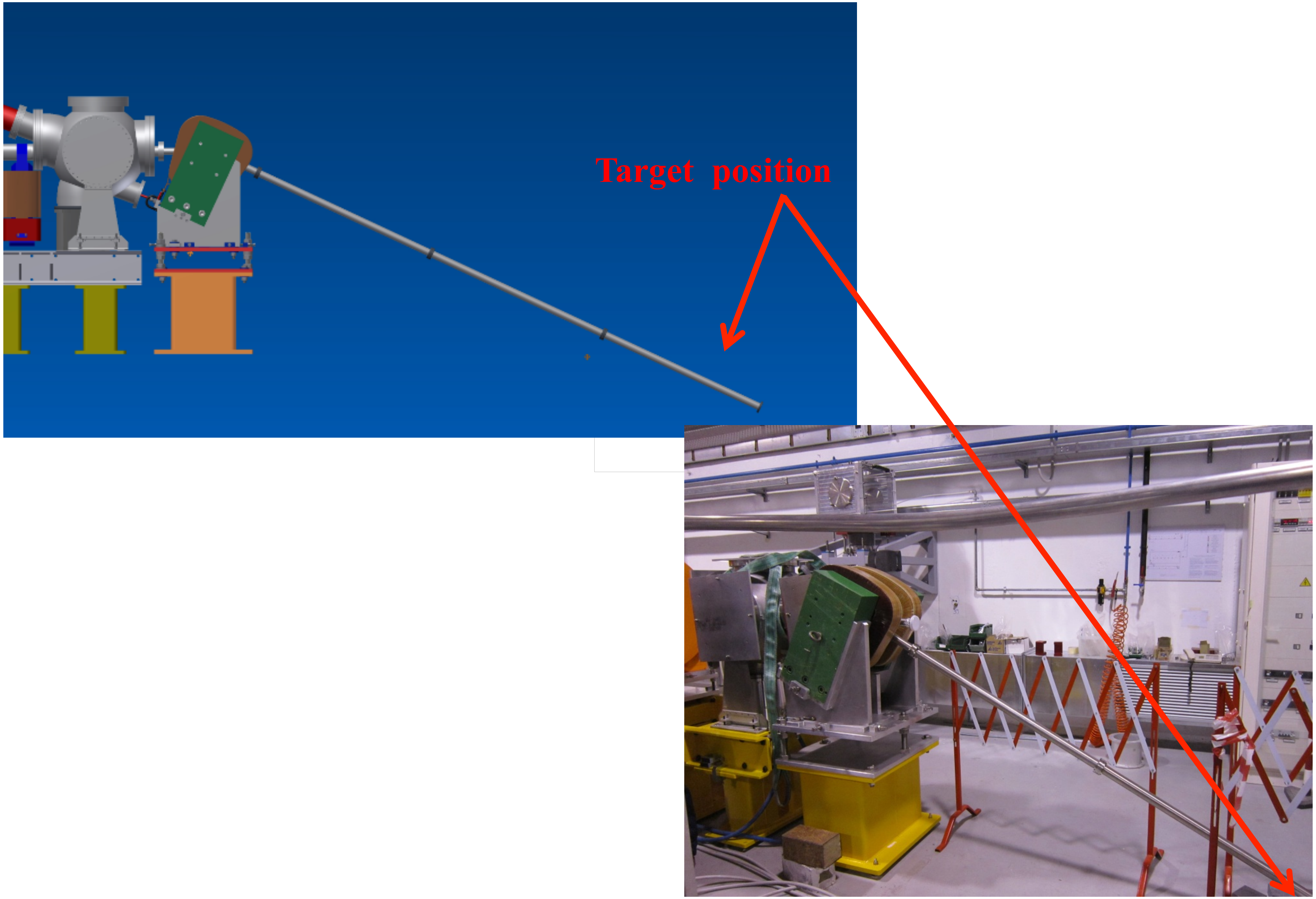
Thanks to L. Giannessi, J. Rau, M. Ferrario, G. Dattoli,
G. Geloni, R. Bonifacio, G. Robb for stimulating discussions.

Thank You for the attention


Target position

Application to a gamma source: ELI-np

With an optimization procedure we obtain: **Working point at 460 MeV**

Charge Q (C)	$0.25 10^{-9}$
Energy E (MeV)	460
$\Delta\gamma/\gamma$	$5. 10^{-4}$
Emittance(mm-mrad)	0. 4/0.39
σ_x=18 μm	
σ_y=15 μm	

Laser photon energy (eV)	3.1
Laser energy E_L(J)	0.2
Laser rms time duration (ps)	1.5
Laser waist (μm)	25

Interaction angle 7.5°

Photon energy(MeV) 10.

Bandwidth rms=5 10^{-3}

N_{band}=1.6 10^5

S=1.56 photons/eV

Acceptance angle=52 microrad

Laser recirculation

S_{tot}=1.56*32*100=0.5 10^4 photons/eV

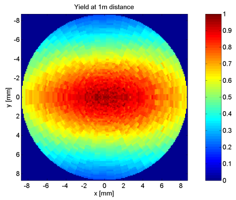
Multibunch techniques

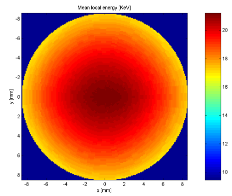
$\langle B_{tot}\rangle$=3.8 10^{14}

B_{peak}=1.3 10^{23}

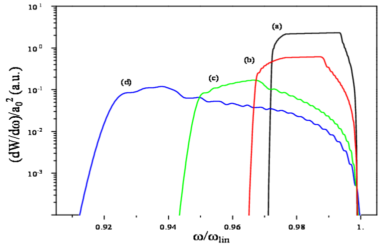
Experiments on Thomson@SPARC-LAB

Characterization of the source

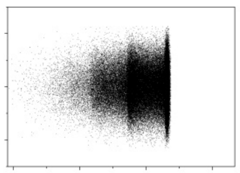




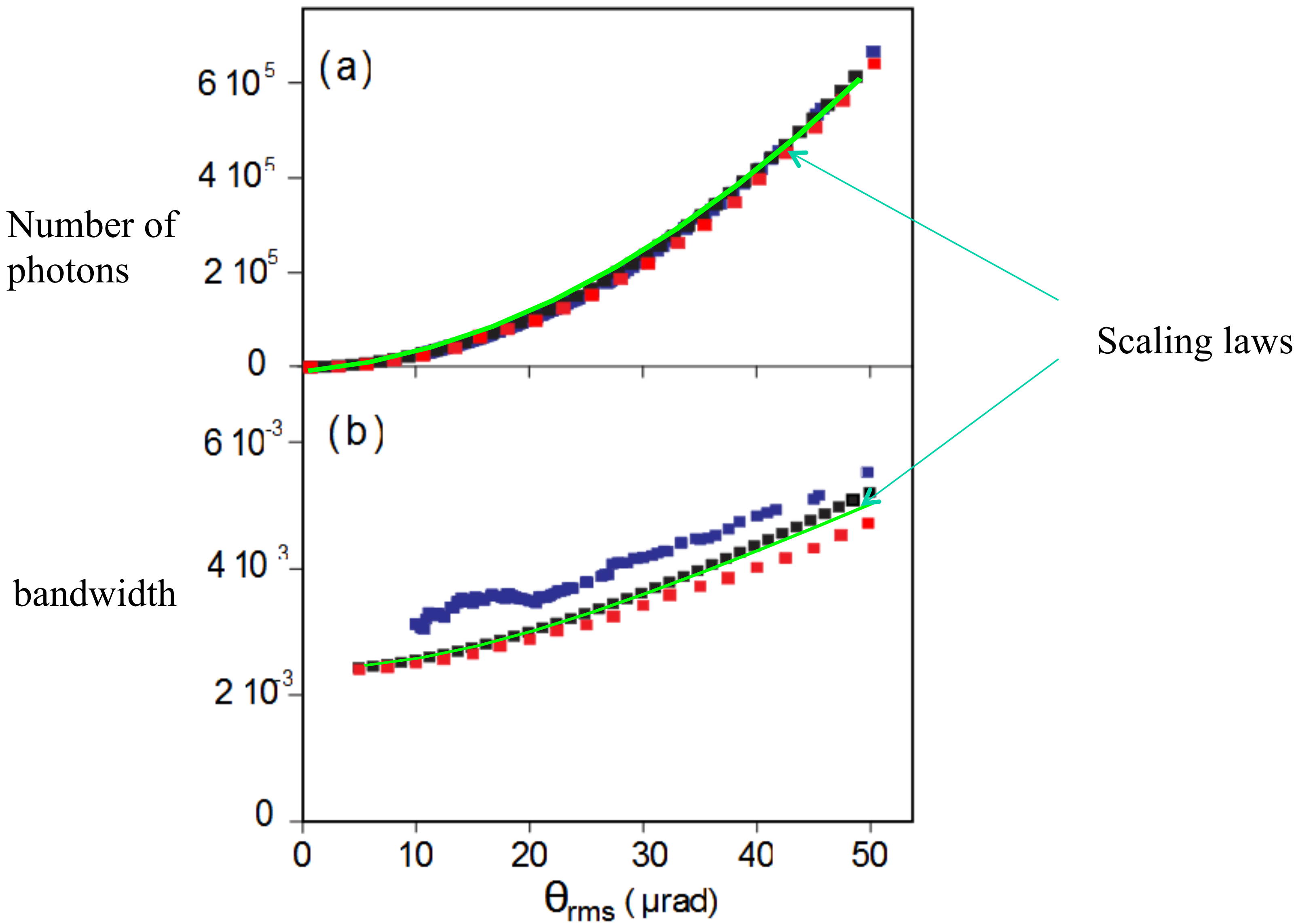
Insurgence of non linear effects



Quantum electron grouping



X two colors radiation



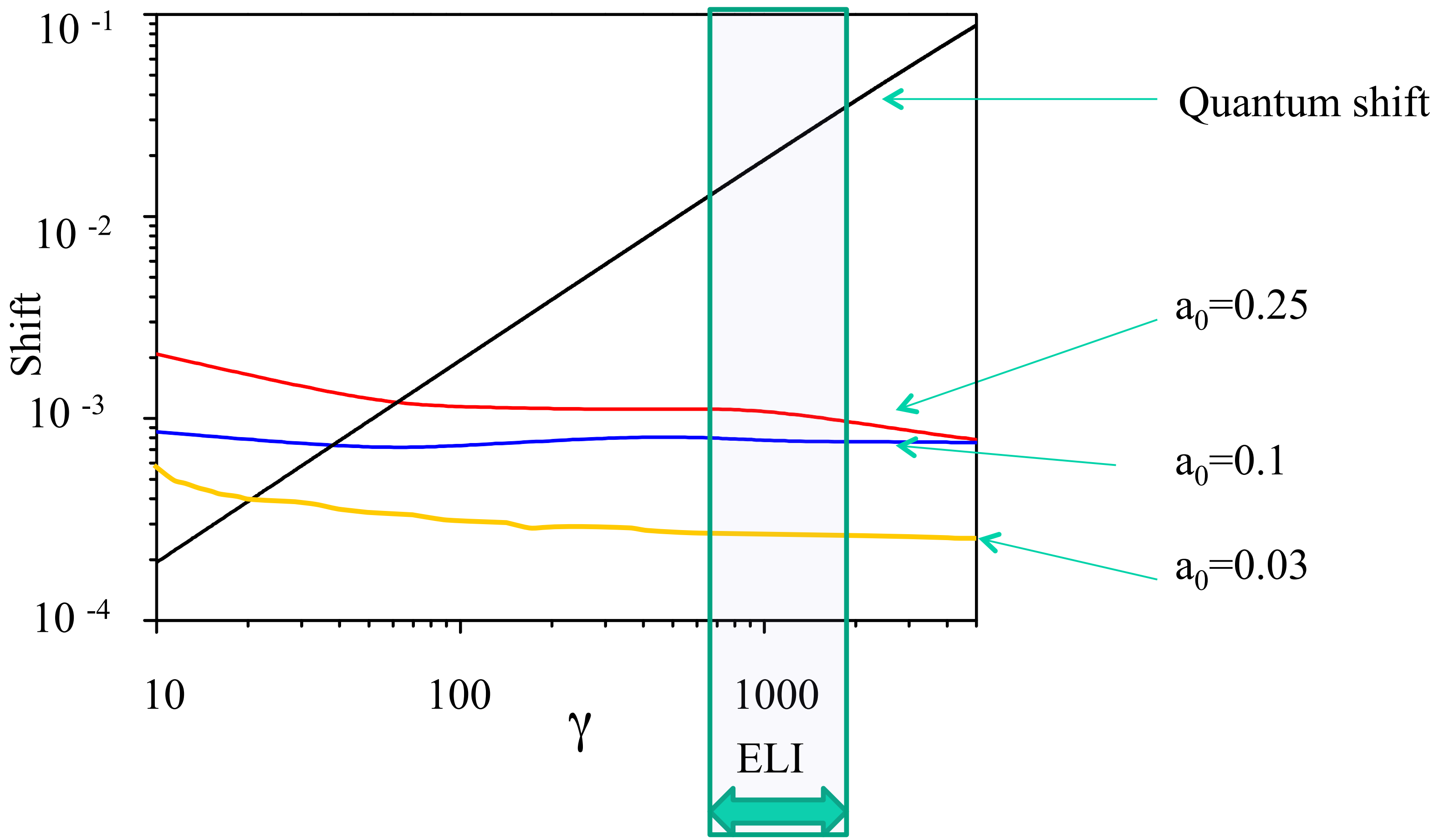
(a)
(b)
Number of photons
bandwidth
Scaling laws
6 10^5
4 10^5
2 10^5
0
6 10^-3
4 10^-3
2 10^-3
0
0
10
20
30
40
50
θrms (μrad)

Non linear effects

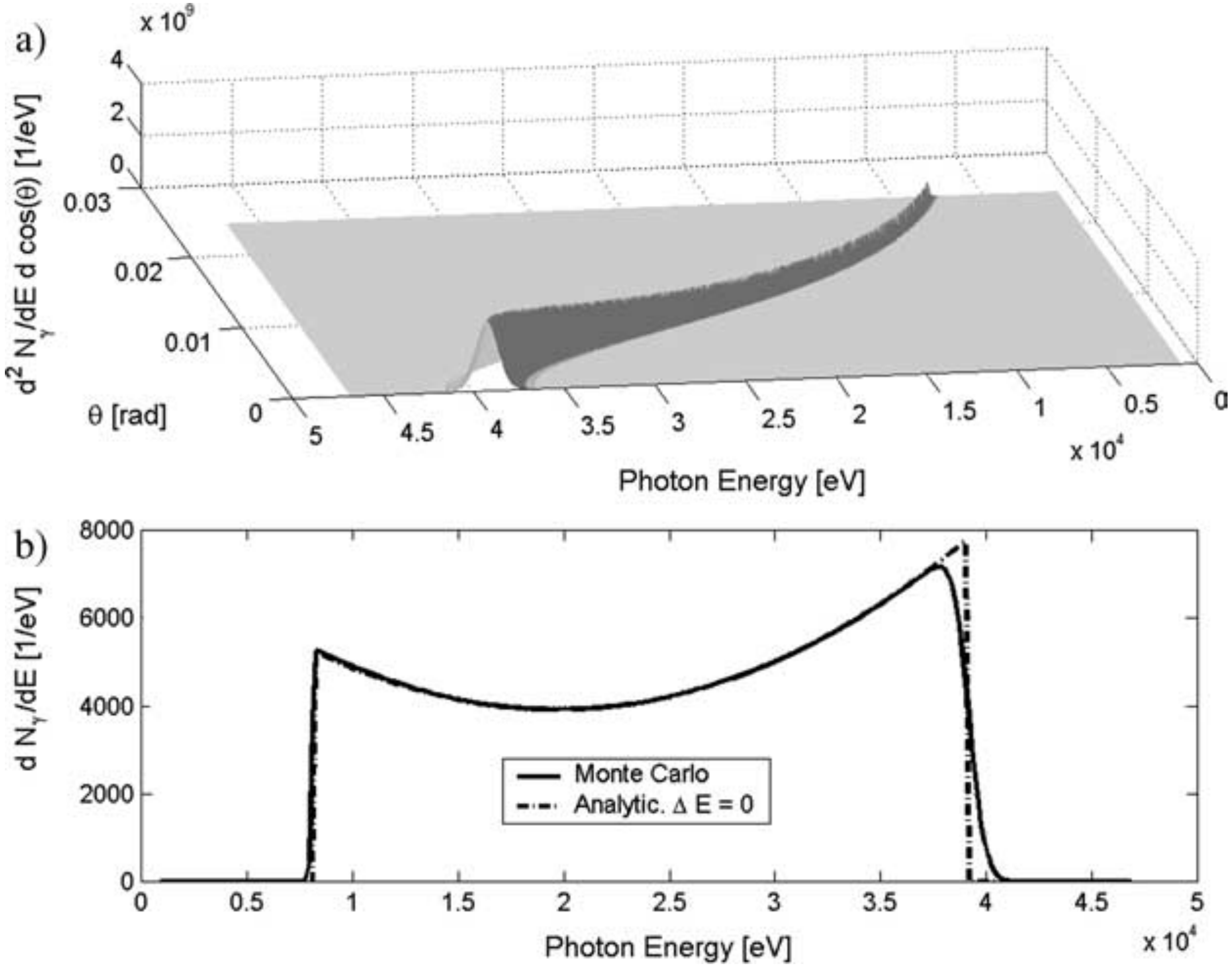
The derivation of the Klein-Nishina cross section is based on hypotesis of weak non linearity (development in series), quantum theory is not able to treat realistics laser fields.

For the evaluation of the non linearities due to high laser energy we use the classical model inserting the numerical trajectories obtained under a realistic laser pulse (taking into account gaussian profiles , curvature of the wave front, diffraction) into the radiation integral.

shift of the spectrum towards lower energies
broadening of the bandwidth
rising of side bands,
the growth of harmonics
enhancement of the background
superposition, shift and merging of the harmonics



The non-linear shift is subdominant with respect to the quantum one.



a)
x 10^9
4
2
0
0.03
0.02
0.01
0
d^2 N_γ/dE d cos(θ) [1/eV]
θ [rad]
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
x 10^4
Photon Energy [eV]
b)
8000
6000
4000
2000
0
d N_γ/dE [1/eV]
Monte Carlo
Analytic. Δ E = 0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
x 10^4
Photon Energy [eV]

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