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Coherent radiation from modulated electron beams in a Compton laser

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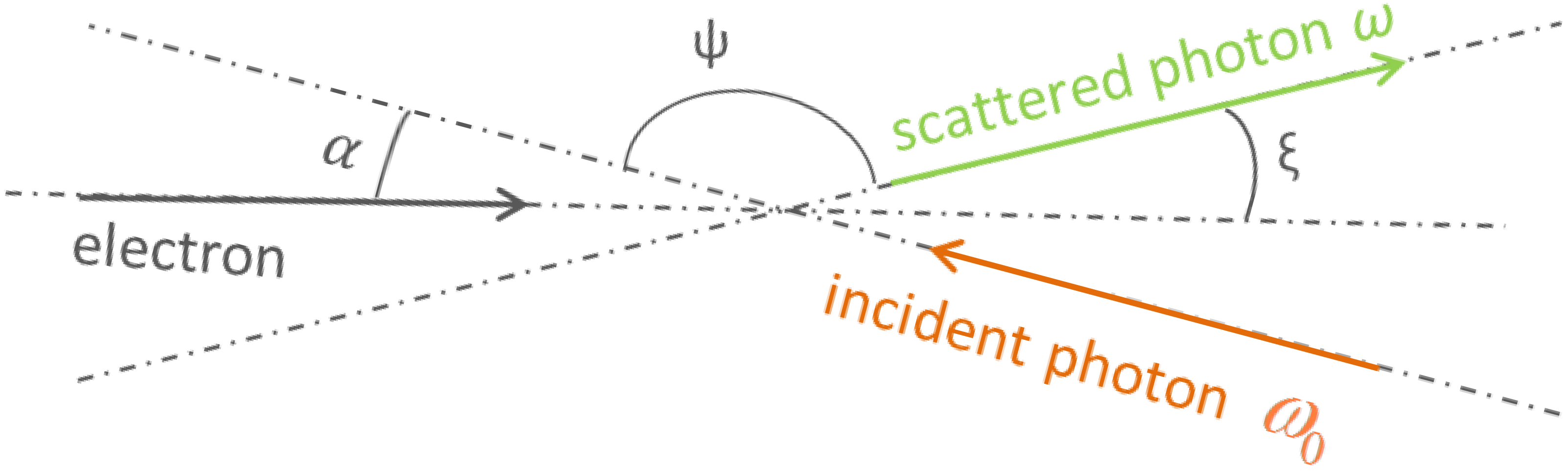
Compton backscattering



$$\omega = \omega_0 \frac{1+\beta\cos\alpha}{1-\beta\cos\xi+\dfrac{\hbar\omega_0}{\gamma m_e c^2}\left(1-\cos\psi\right)}$$

Compton backscattering

$$\omega = \omega_0 \frac{1+\beta\cos\alpha}{1-\beta\cos\xi + \frac{\hbar\omega_0}{\gamma m_e c^2}\left(1-\cos\psi\right)}$$

recoil

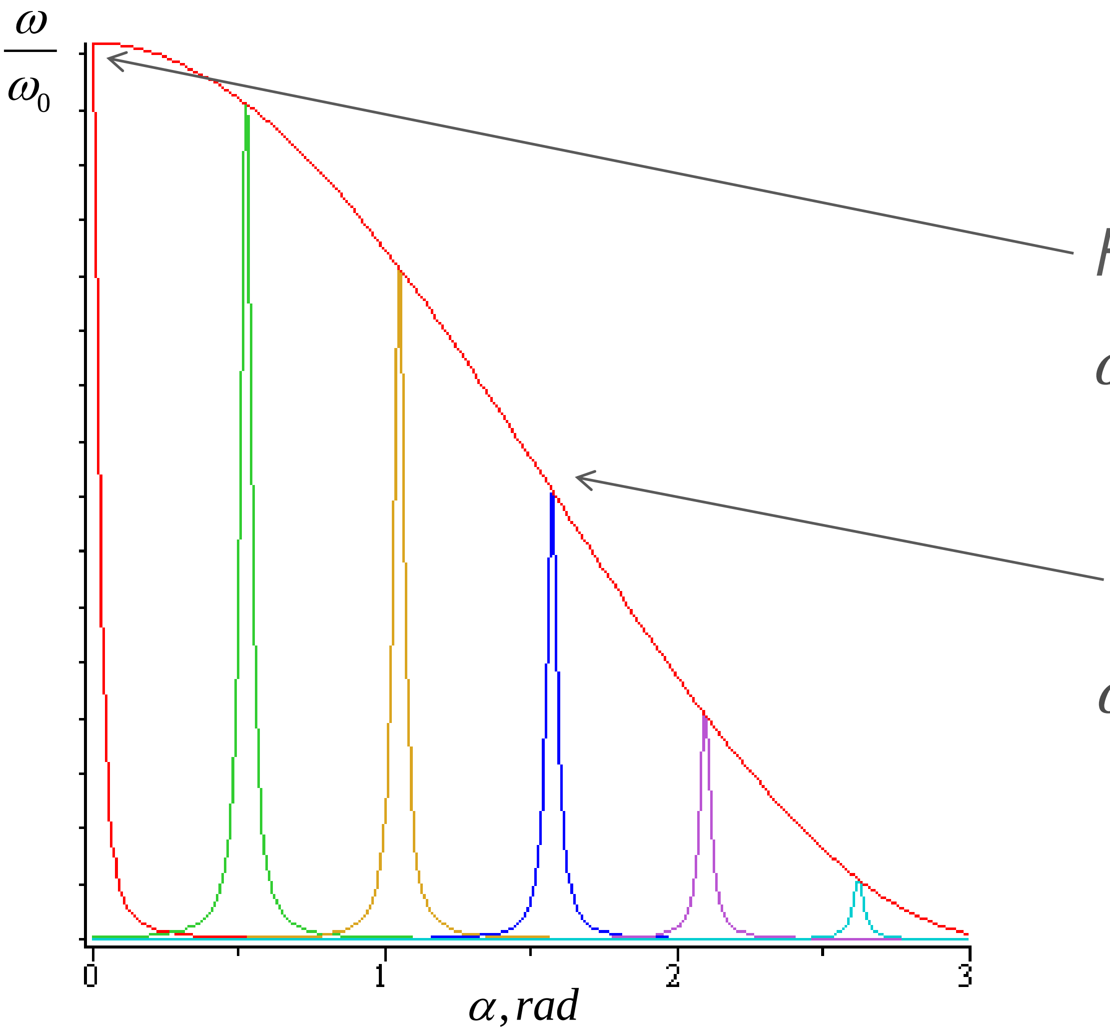
low energy photons & relativistic electrons

$$\frac{\hbar\omega_0}{\gamma m_e c^2} \ll 1$$

Thomson scattering with Doppler shift

$$\omega = \omega_0 \frac{1+\beta\cos\alpha}{1-\beta\cos\xi}$$

Compton backscattering



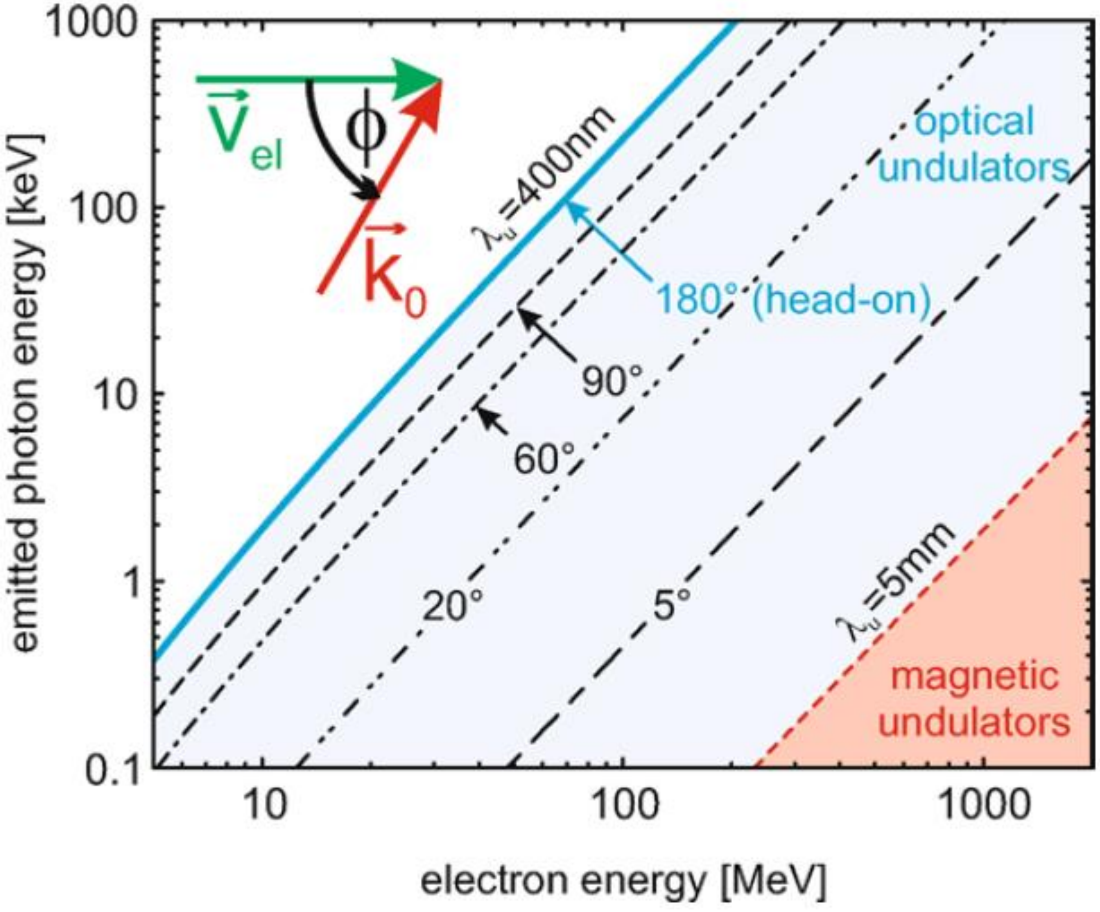
Head-on collision

$\alpha = 0^\circ \qquad \omega \approx 4\gamma^2\omega_0$

Lateral collision

$\alpha = 90^\circ \qquad \omega \approx 2\gamma^2\omega_0$

Optical undulator vs. magnetic undulator



A.D. Debus et al., Traveling-wave Thomson scattering and optical undulators for high-yield EUV and X-ray sources, Appl. Phys. B ***100****, 61 (2010)*

Coherent radiation

$$N_{photon} \sim \sigma_{Thomson} \frac{N_{laser} \boxed{N_{electron}}}{\sigma^2_{laser} + \sigma^2_{electron}}$$

incoherent

$$\sigma_{Thomson} = \frac{8}{3}\pi r_{el}^2 \simeq 6{,}652 \cdot 10^{-29}\ \mathrm{m}^2$$

*Trains of small electron bunches - **Coherent** regime*

$$N_{photon} \sim N^2_{electron}$$

At present

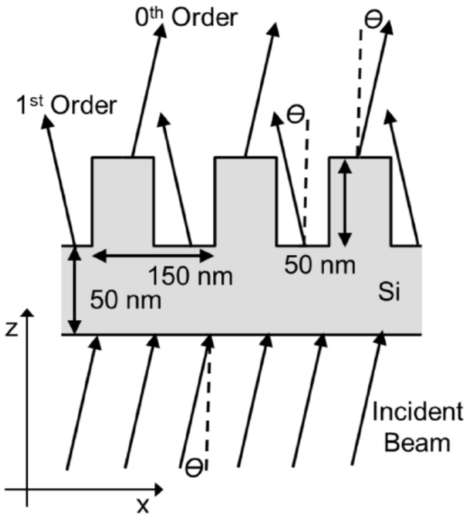
Micro-bunch duration ~ femtoseconds

Bunch spacing ~ picoseconds and sub-picoseconds

Future

Attosecond bunch duration

Nano and sub-nano modulated electron beams



Modulation period ≈1.24 nm

*E.A. Nanni, W.S. Graves, D.E. Moncton, Nanomodulated electron beams via electron diffraction and emittance exchange for coherent x-ray generation, Phys. Rev. Accel. Beams **21**, 014401 (2018)*

Modulated electron beams

Spectral and angular distribution of radiation energy from electron beam

$$\frac{dW^{bunch}(\mathbf{n},\omega)}{d\omega d\Omega} = \frac{dW^{el}(\mathbf{n},\omega)}{d\omega d\Omega} F^{bunch}$$

For one electron

Bunch form-factor

$$p_\mu = p_{0\mu} - \frac{e}{c}A_\mu + \frac{k_\mu}{kp_0}\left(\frac{e}{c}p_0 A - \frac{e^2}{2c^2}A^2\right)$$

A.I. Nikishov, V.I. Ritus, JETP ***19****, 529 (1964)*

$$\frac{d^2W^{el}(\mathbf{n},\omega)}{d\omega d\Omega} = \frac{\omega^2}{4\pi^2 c^3}\left|\int dt\, e(t)\left[\mathbf{nv}(t)\right]\times \exp\left\{i\omega t - i\mathbf{kR}(t)\right\}\right|^2$$

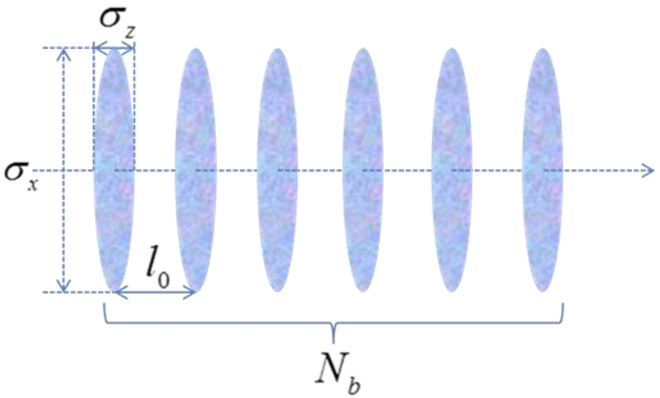
S.K. Ride, E. Esarey, M. Baine, Phys. Rev. E ***52****, 5425 (1995)*

$$F^{bunch} = NF^{inc} + N(N-1)F^{coh}$$

$$F^{inc} = \int_V d\mathbf{r}\left|e^{-i\mathbf{k}(\mathbf{r}-\mathbf{r}_0)}\right|^2 P(\mathbf{r})$$

$$F^{coh} = \left|\int_V d\mathbf{r}\, e^{-i\mathbf{k}(\mathbf{r}-\mathbf{r}_0)} P(\mathbf{r})\right|^2$$

$$P(\mathbf{r}') = \frac{1}{N_b \pi^{3/2}\sigma_x\sigma_y\sigma_z}\sum_{k=0}^{N_b-1} e^{-\frac{x'^2}{\sigma_x^2}-\frac{y'^2}{\sigma_y^2}-\frac{(z'-kl_0)^2}{\sigma_z^2}}$$



Electron beam form-factor

$$F^{coh} = F^{l} F^{tr}$$

$$F^{l} = \exp\left[-\frac{\sigma_z^2\left(k_z\cos\alpha - k_x\sin\alpha\right)^2}{2}\right]\frac{1}{N_b^2}\frac{\sin^2\left(N_b l_0\left(k_z\cos\alpha - k_x\sin\alpha\right)/2\right)}{\sin^2\left(l_0\left(k_z\cos\alpha - k_x\sin\alpha\right)/2\right)}$$

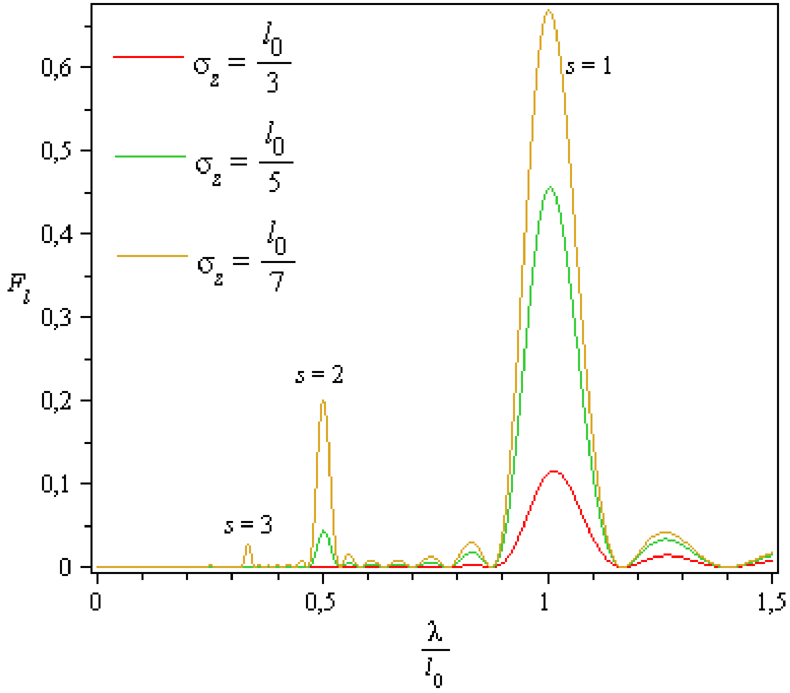
$$F^{tr} = \exp\left[-\frac{\sigma_y^2 k_y^2}{2} - \frac{\sigma_x^2}{2}\left(k_x\cos\alpha + k_z\sin\alpha\right)^2\right]$$

Resonance condition

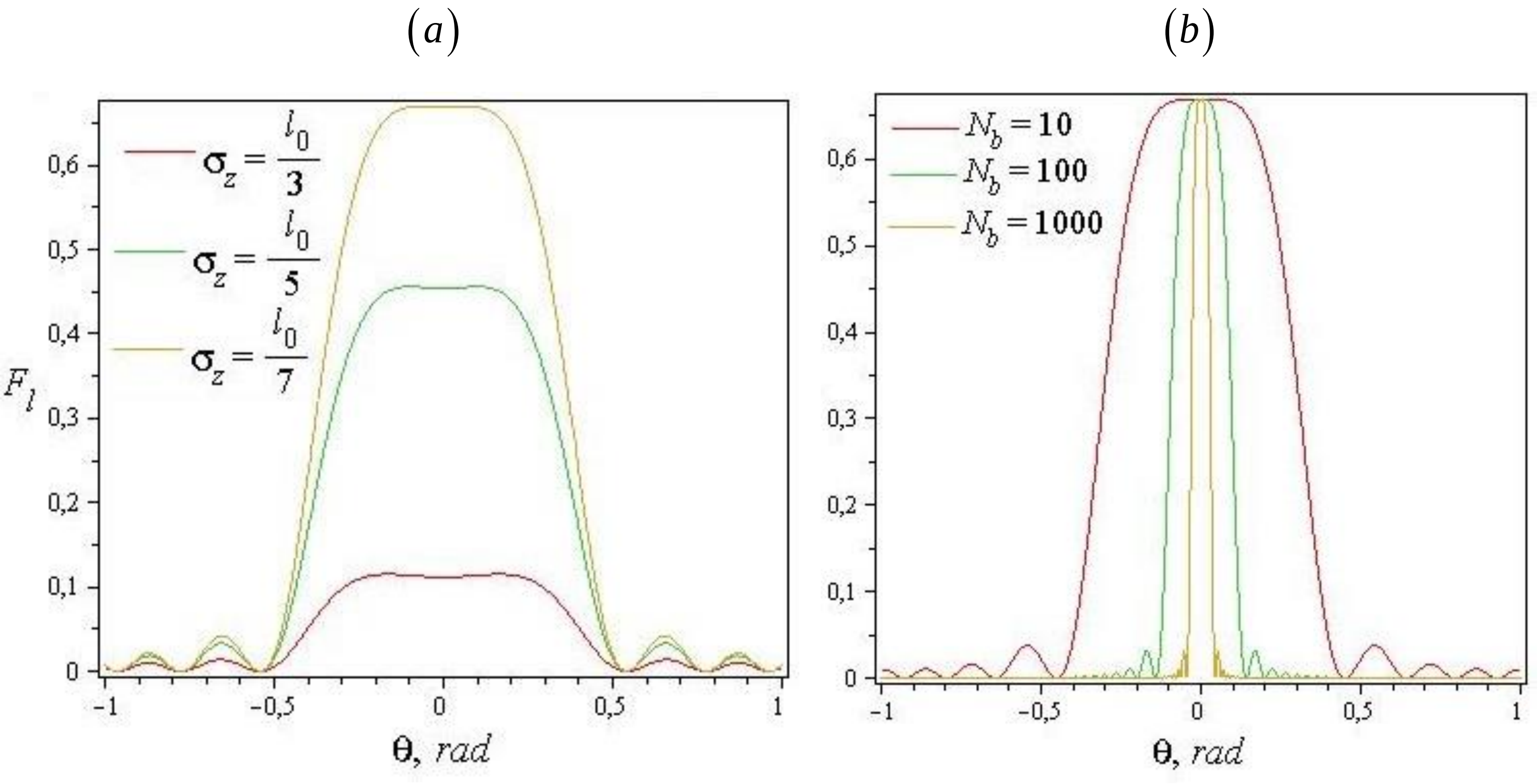
$$\lambda = \frac{l_0}{s}\left(n_z\cos\alpha - n_x\sin\alpha\right)$$

$$\mathbf{n} = \left(\sin\theta\cos\varphi,\ \sin\theta\sin\varphi,\ \cos\theta\right)$$

$$s = 1,\ 2,\ \ldots$$

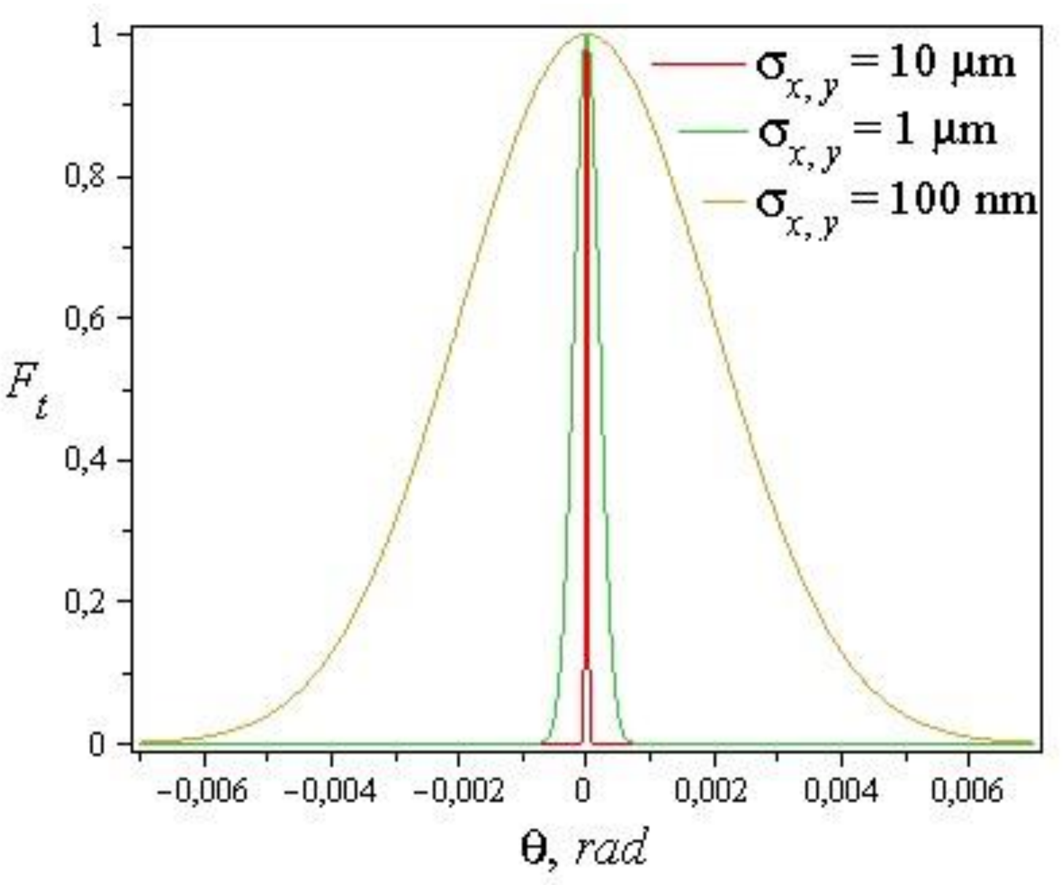


Longitudinal form-factor



$l_0 = 1,24\ \text{nm}$, $\hbar\omega \simeq 1\ \text{keV}$, $\varphi = 0^\circ$, $\alpha = 0^\circ$, $(a)\ N_b = 7$; $(b)\ \sigma_z = l_0/7$

Transverse form-factor



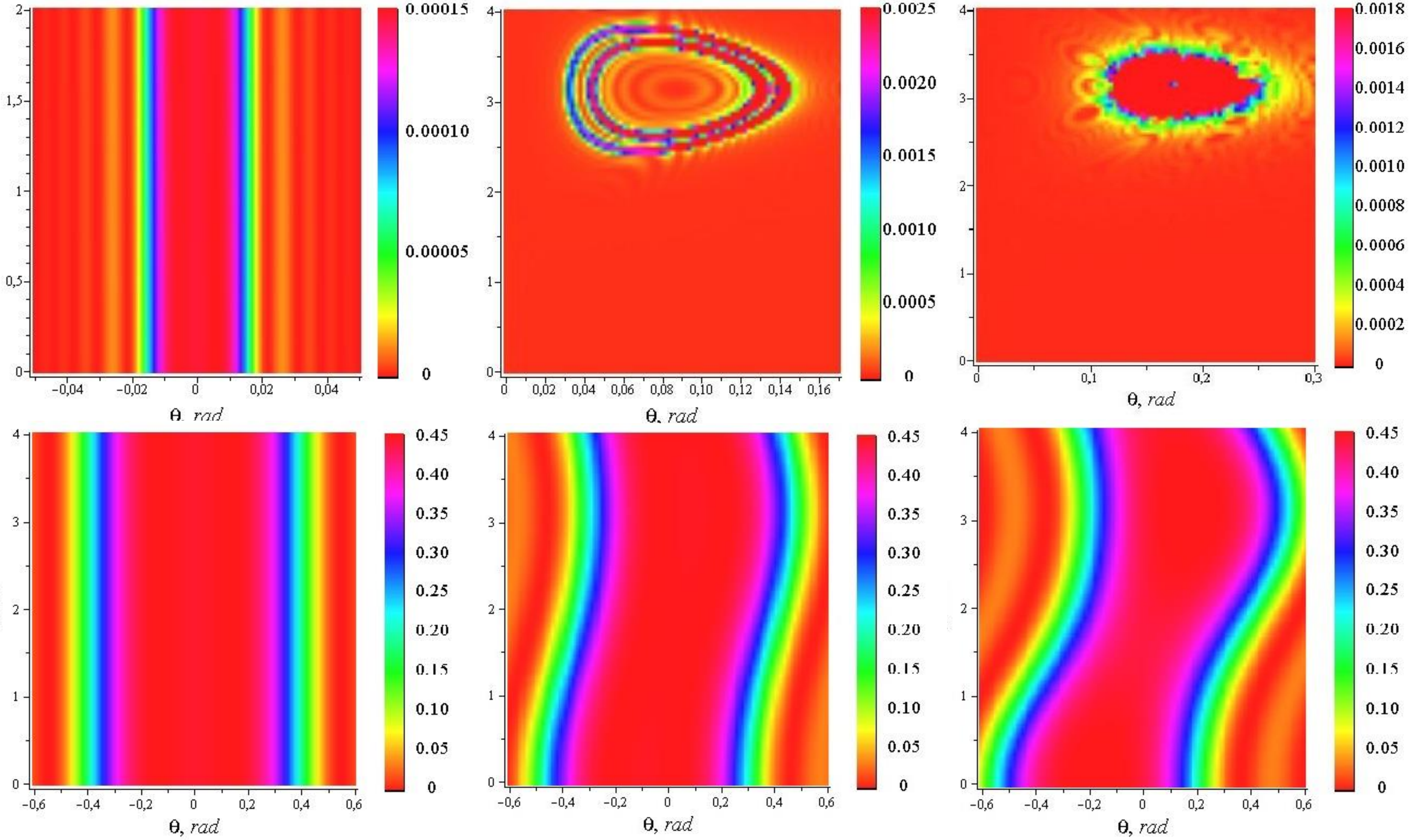
$l_0 = 1,24$ nm, $\hbar\omega \simeq 1$ keV, $\varphi = 0^\circ$, $\alpha = 0^\circ$

Lateral collision

$\alpha = 0^\circ$ $\alpha = 5^\circ$ $\alpha = 10^\circ$

Single eletctron angular distribution

Longitudinal form-factor



$l_0 = 1,24$ nm, $\hbar\omega \simeq 1$ keV, $\lambda_0 = 10\ \mu$m, $a_0 = 0,003$, $\gamma = 45$, $\sigma_{x,y} = 10^{-7}$ m, $\sigma_z = l_0/5$, $N_b = 7$

Thank you for attention!