Coherent optical transition radiation from short electron bunches with non-gaussian charge distribution

A.POTYLITSYN (IAPP), G.KUBE (DESY)

First measurements of COTR spectra

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Observation of Fine Structures in Laser-Driven Electron Beams Using Coherent Transition Radiation

Y. Glinec,[1] J. Faure,[1] A. Norlin,[1] A. Pukhov,[2] and V. Malka[1,*]

[1] *Laboratoire d'Optique Appliquée - ENSTA, UMR 7639, CNRS, École Polytechnique, 91761 Palaiseau, France*

[2] *Institut fuer Theoretische Physik I, University of Duesseldorf, 40225 Duesseldorf, Germany*

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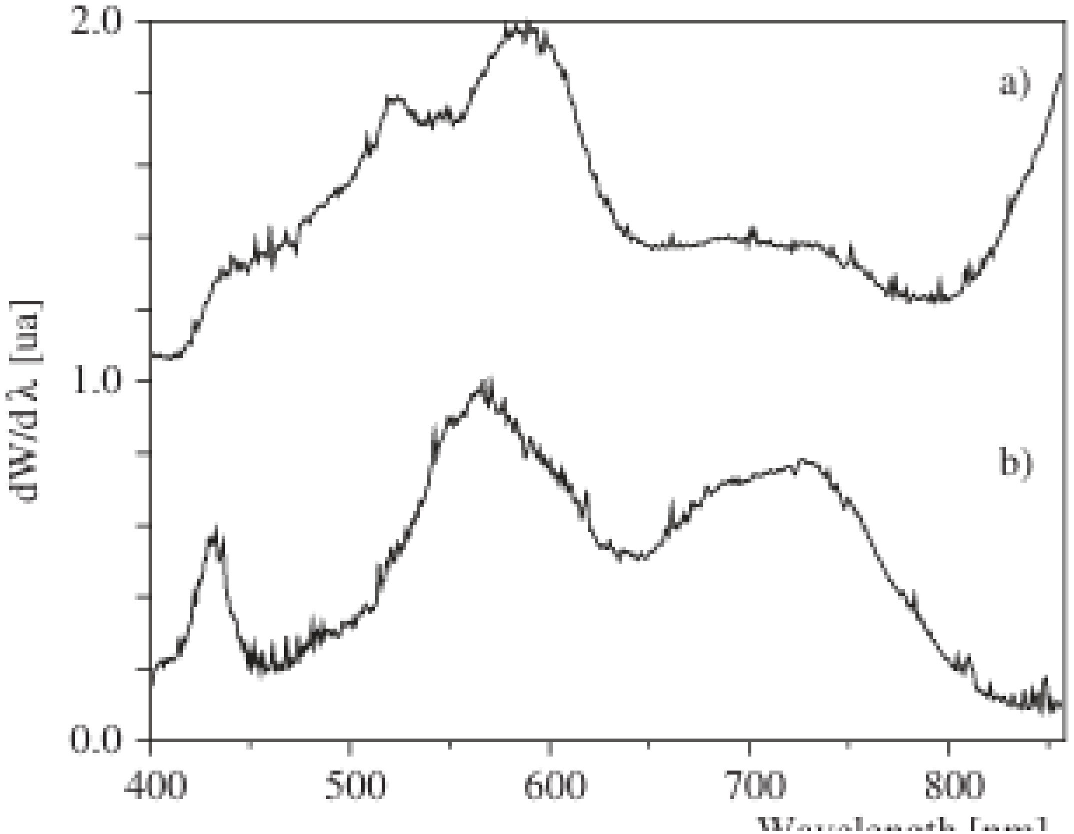
Experimental conditions

The experiment is performed on the Ti:sapphire laser in "salle jaune" at Laboratoire d'Optique Appliquée (LOA), which operates in chirped-pulse amplification mode at 820 nm [13]. The laser delivers 30 fs at full width at half maximum (FWHM) linearly polarized pulses with on-target energies of 1.1 J. The laser beam is focused with an $f/18$ off-axis parabolic mirror onto a sharp-edged, constant density profile, 3 mm-diameter supersonic helium gas jet, which provides an initial plasma electron density n_e of 5.0×10^{18} cm^{-3}. The waist of the focal spot is 18 μm, resulting in vacuum focused intensities of the order of 3.6×10^{18} W/cm^2, which corresponds to a normalized laser vector potential, $a_0 = eA/m_e c^2$, of 1.3.

Measured COTR spectra ,Ee > 100 MeV



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OTR spectrum from the single electron
(ϑ_m is the angular aperture)

$$dN/d\lambda = 1/\lambda * \frac{\alpha}{\pi}\left[\ln\left(1+\gamma^2\theta_m^2\right)-\frac{\gamma^2\theta_m^2}{1+\gamma^2\theta_m^2}\right].$$

Longitudinal formfactor

$$F(\omega) = \left| \int dz\, f(z) \exp\left[-i\omega \frac{z}{\beta c} \right] \right|^2,$$

$$f(z) = f(\beta ct)$$

Gauss charge distribution

$$f(z) = Exp[-z/\sigma)^2/2]/\sqrt{2\pi}$$

$\sigma = \dfrac{s_b}{2.355}$, S_b - FWHM of charge distribution

Formfactor for Gauss distribution

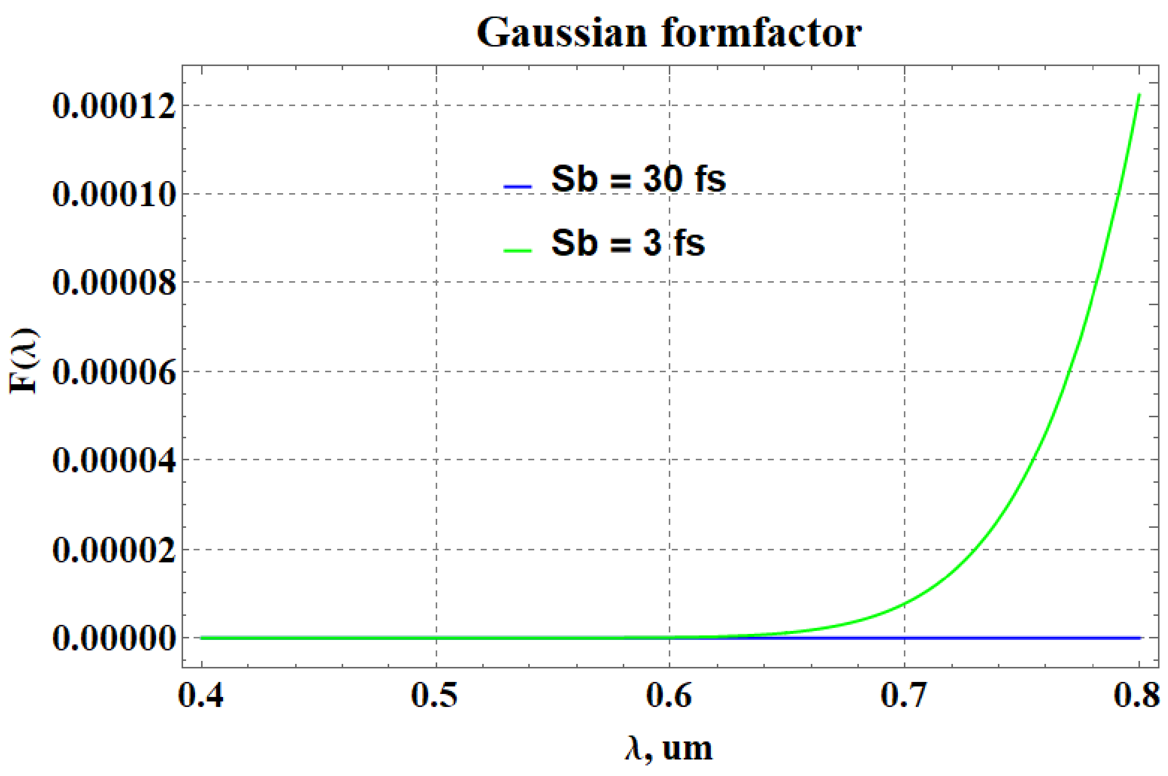
$$F_g = \exp\left(-\omega^2\sigma^2 / c^2\right) = \exp\left(-\omega^2 s_b^2 / 6.55 c^2\right).$$

COTR spectrum from each electron in the bunch with population Ne

- $dNcotr/d\lambda = [1-(Ne - 1)*F(2\pi c/\lambda)]* dN/d\lambda$
- Equation is obtained neglecting by the transverse formfactor

- Gaussian formfactor : $F(\omega) = Exp[-(2*Pi*\sigma /\lambda)^2]$
- For $\lambda = 2\sigma$ -> $F(\omega) = 2*10^{-5}$
- For $\lambda = \sigma$ -> $F(\omega) = 2.8*10^{-18}$
- Exponential decrease without any peaks

Gaussian formfactors with FWHM > 3 fs



For gaussian bunches with

$\sigma >$ 0.9/2.355= 0.38 um

there is no coherent contribution in the light range

Non-gaussian bunch charge distribution

- The gaussian charge distribution may be considered as an idealized model due to the fact that the charge density is determined over infinite interval.
- Charge distribution of the subpicosecond bunches is determined by the laser pulse shape interacting with a photocathode during finite time. This fact leads to a violation of the monotonic formfactor decay typical for gaussian bunches. At high frequencies ($\omega \gg c/\sigma$) there can appear oscillations in the spectrum and resulting photon yield will be much intense in comparison with radiation from gaussian bunch at that range.

Triangle charge distribution

$$f_{tr}(t,\tau_B) = \begin{cases} \frac{1}{\tau_B} + \frac{1}{\tau_B^2}t, & 0 > t \geq -\tau_B \\ \frac{1}{\tau_B} - \frac{1}{\tau_B^2}t, & 0 < t \leq -\tau_B \\ 0, & \text{out} \end{cases}$$

Rectangular charge distribution

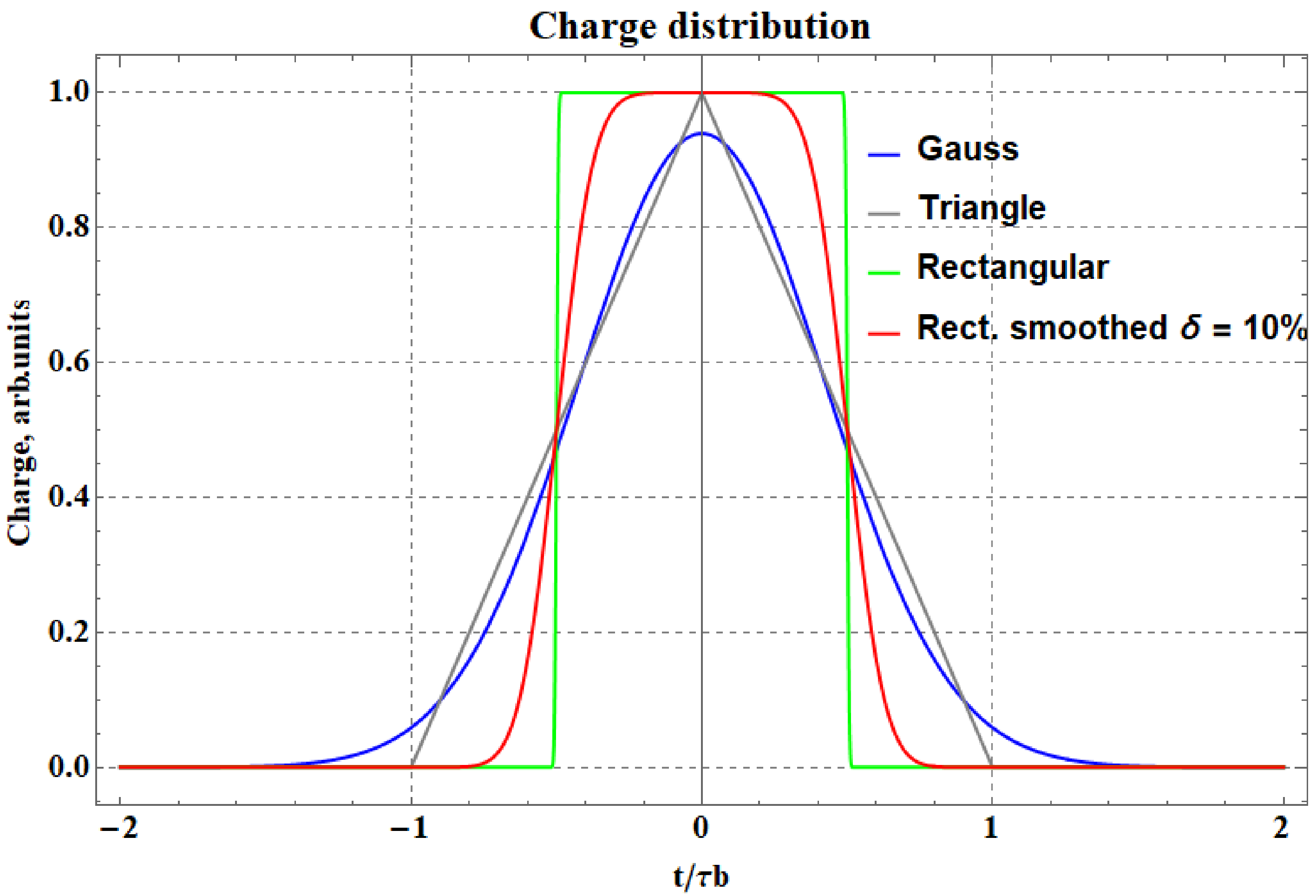
$$f_{re}(t,\tau_B) = \begin{cases} \frac{1}{\tau_B}t, & |t| \leq 0.5\,\tau_B \\ 0, & \text{out} \end{cases}$$

Smoothed rectangular charge distribution (convolution of the rectangular and gaussian ones)

$$f_{sm}(t,\tau_B,\delta) = \frac{1}{\sqrt{2\pi}\tau_B}\int_{-\tau_{B/2}}^{\tau_{B/2}} \exp\left[-\frac{(t-z)^2}{2\delta^2}dz\right]:$$

A smoothing parameter δ << τb = FWHM

Different charge distributions with the same FWHM



Non-gaussian formfactors

Triangle distribution

$$F_{tr} = \left[\sin(s_b\omega/2c)/(s_b\omega/2c)\right]^4;$$

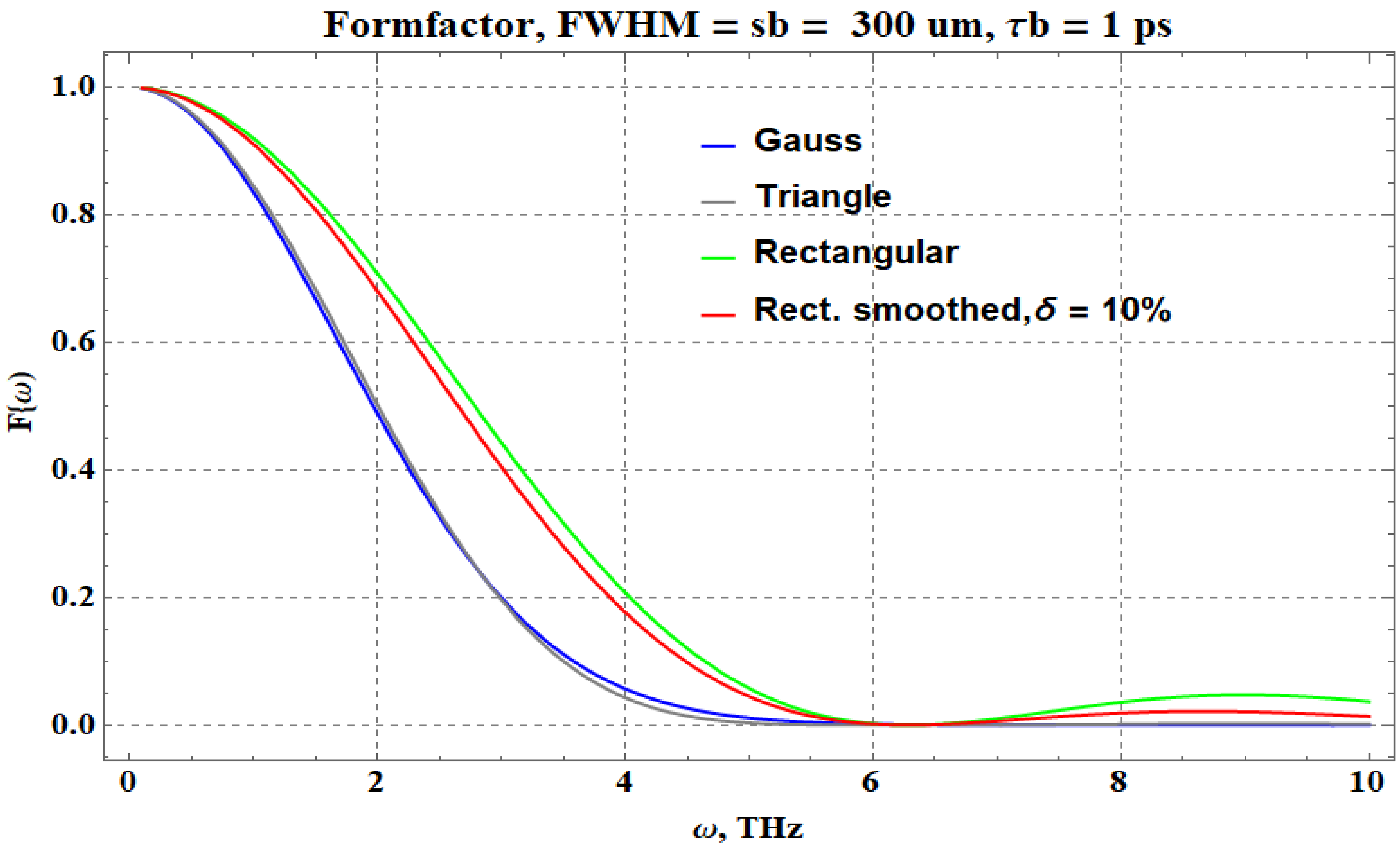
Rectangular distribution

$$F_{re} = \left[\sin(s_b\omega/2c)/(s_b\omega/2c)\right]^2$$

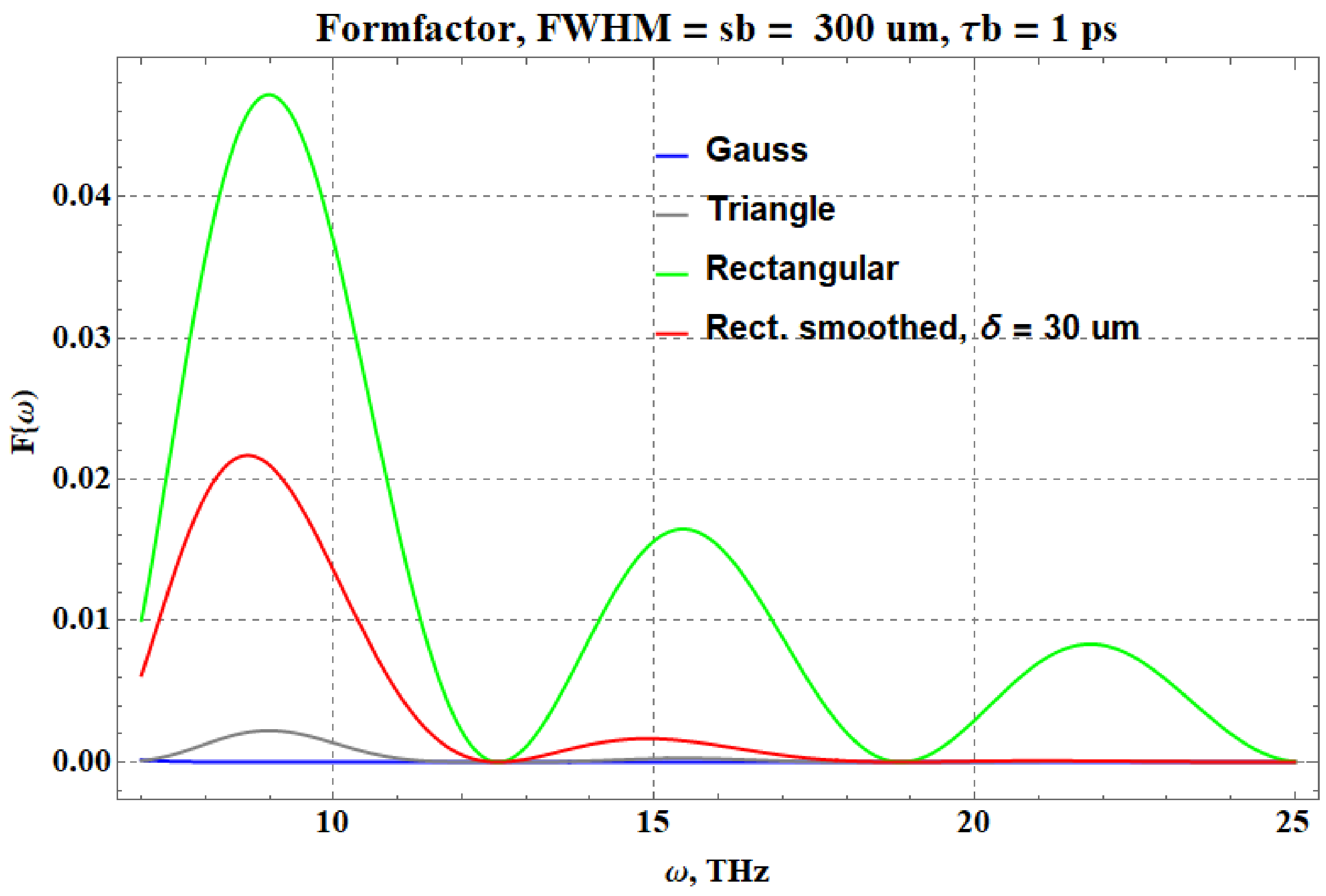
Smoothed rectangular distribution

$$|F_{SM} = \exp\left(-\delta^2\omega^2/c^2\right)\left[\sin(s_b\omega/2c)/(s_b\omega/2c)\right]^2$$

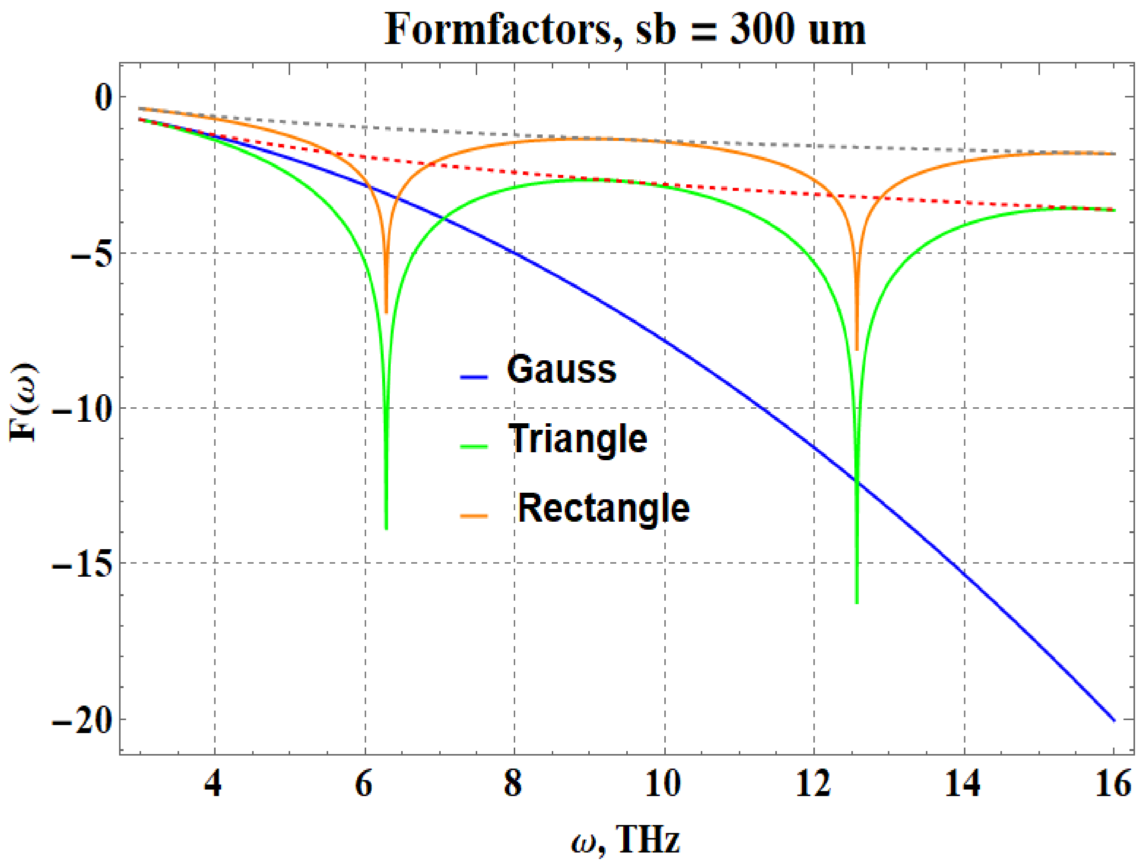
Comparison of formfactors for different charge distributions



Comparison of formfactors at high frequencies



Formfactor decay



For frequencies $\omega > 2\pi s_b / c$

there is an exponential suppression of COTR from

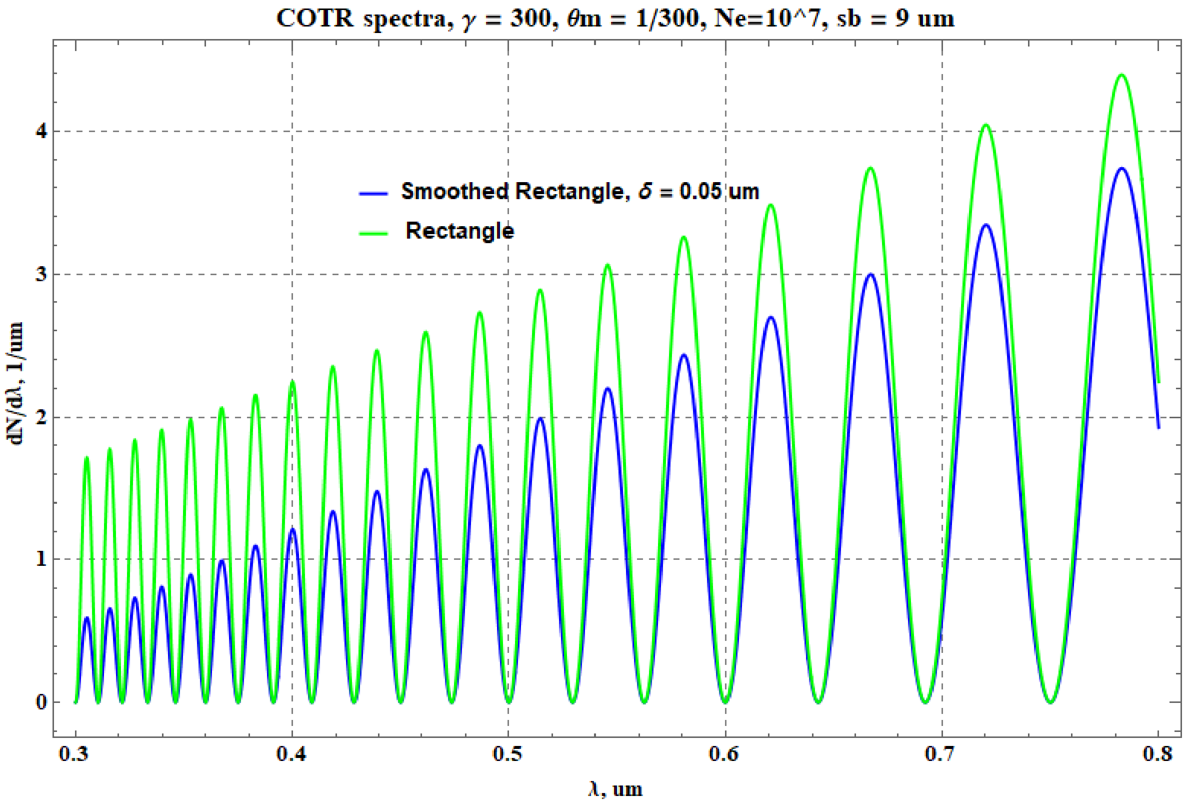
gaussian bunches.

For non-gaussian bunches such a suppression is power one

(rectangular distribution - $1/\omega^2$, triangle distribution – $1/\omega^4$

-dashed curves)

COTR spectrum from a bunch with rectangle charge distribution



sb = 9 um

γ = 300

Θmax = 1/300

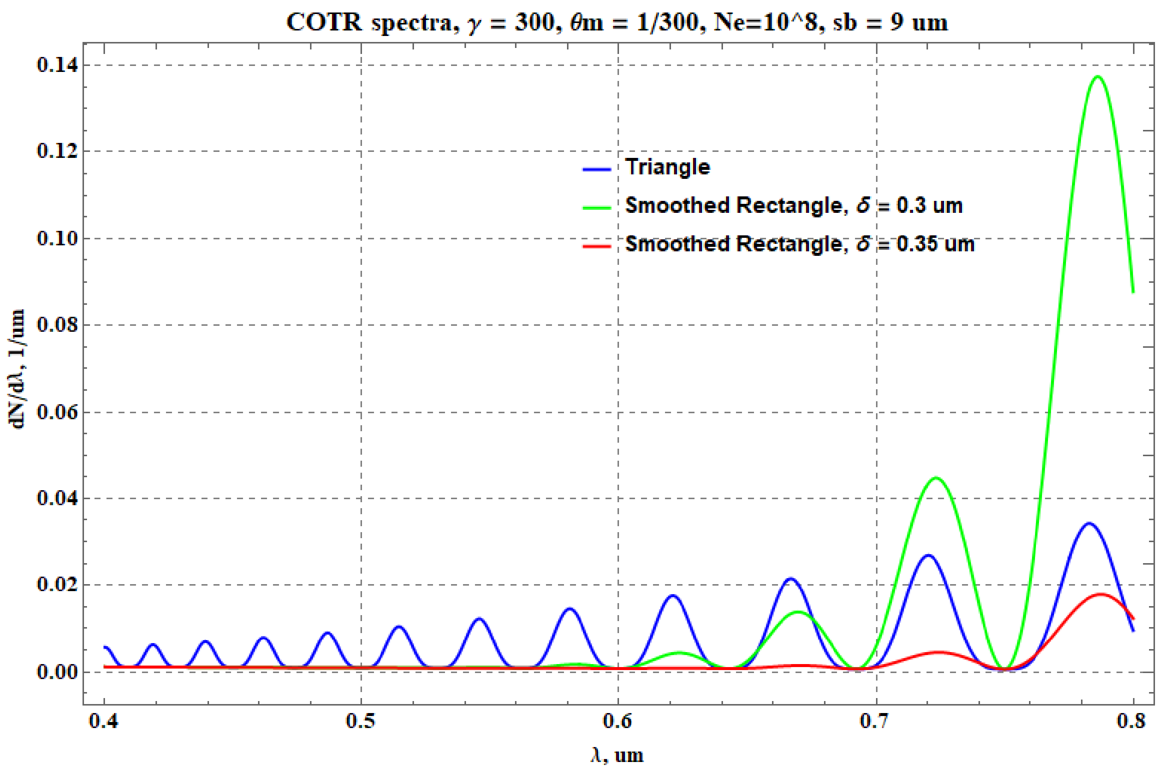
Ne = 10^7

Green - rectangle

Blue - smoothed rectangle,

δ = 0.05 um

COTR spectrum from a bunch with triangle and smoothed rectangle charge distribution



sb = 9 um

$\gamma = 300$

Θmax = 1/300

Ne = 10^7

Blue - triangle

Green - smoothed rectangle,

$\delta = 0.3$ um

Red - smoothed rectangle,

$\delta = 0.35$ um

Simulation of the longitudinal bunch profile
Y.Glinec et al. PRL,98, 194801, (2007)

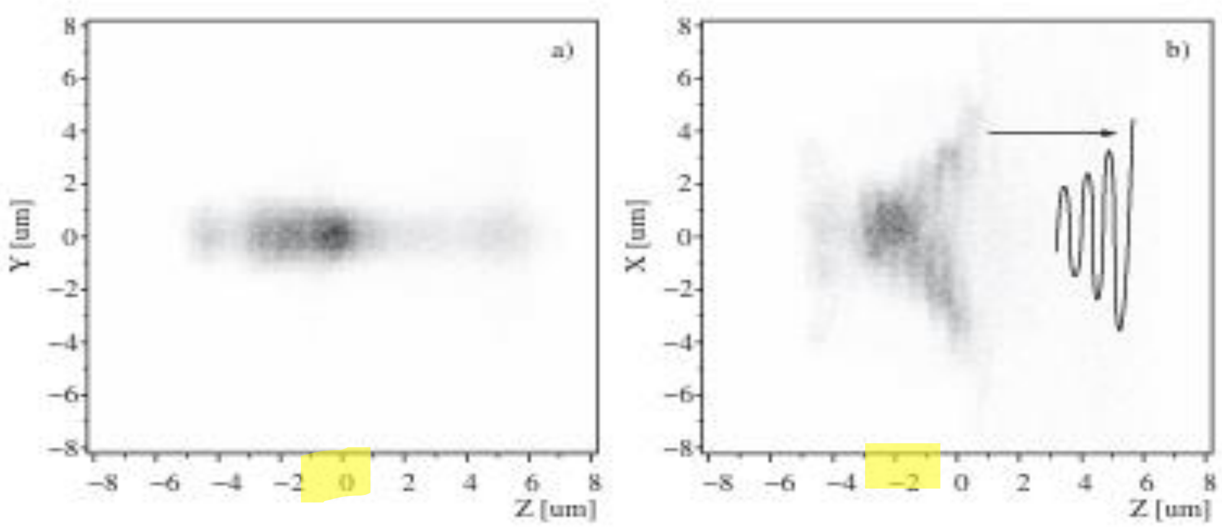


FIG. 3. Electron distribution from 3D PIC simulation, containing electrons above 100 MeV: (a) perpendicular to the plane of polarization of the laser, (b) in the plane of polarization of the laser. The electrons move from left to right. A structure in the electron distribution can be seen as the electrons overlap with the transverse laser field. This structure is reproduced with a solid line shifted to the right.

Simulated COTR spectrum
Y.Glinec et al. PRL,98, 194801, (2007)

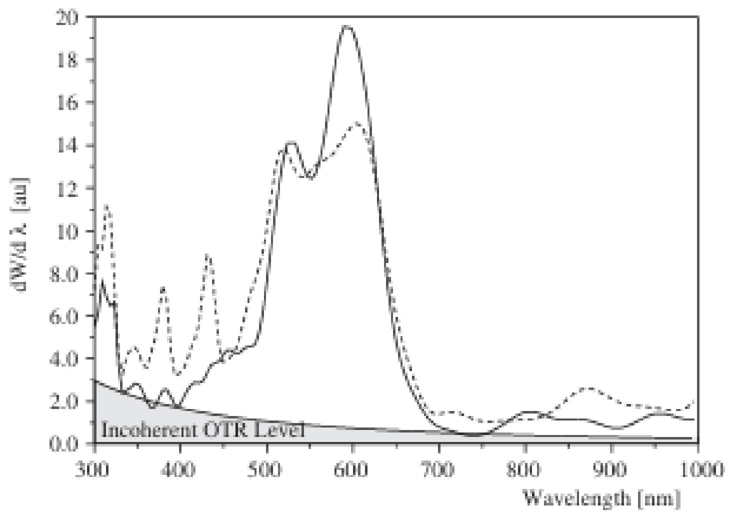
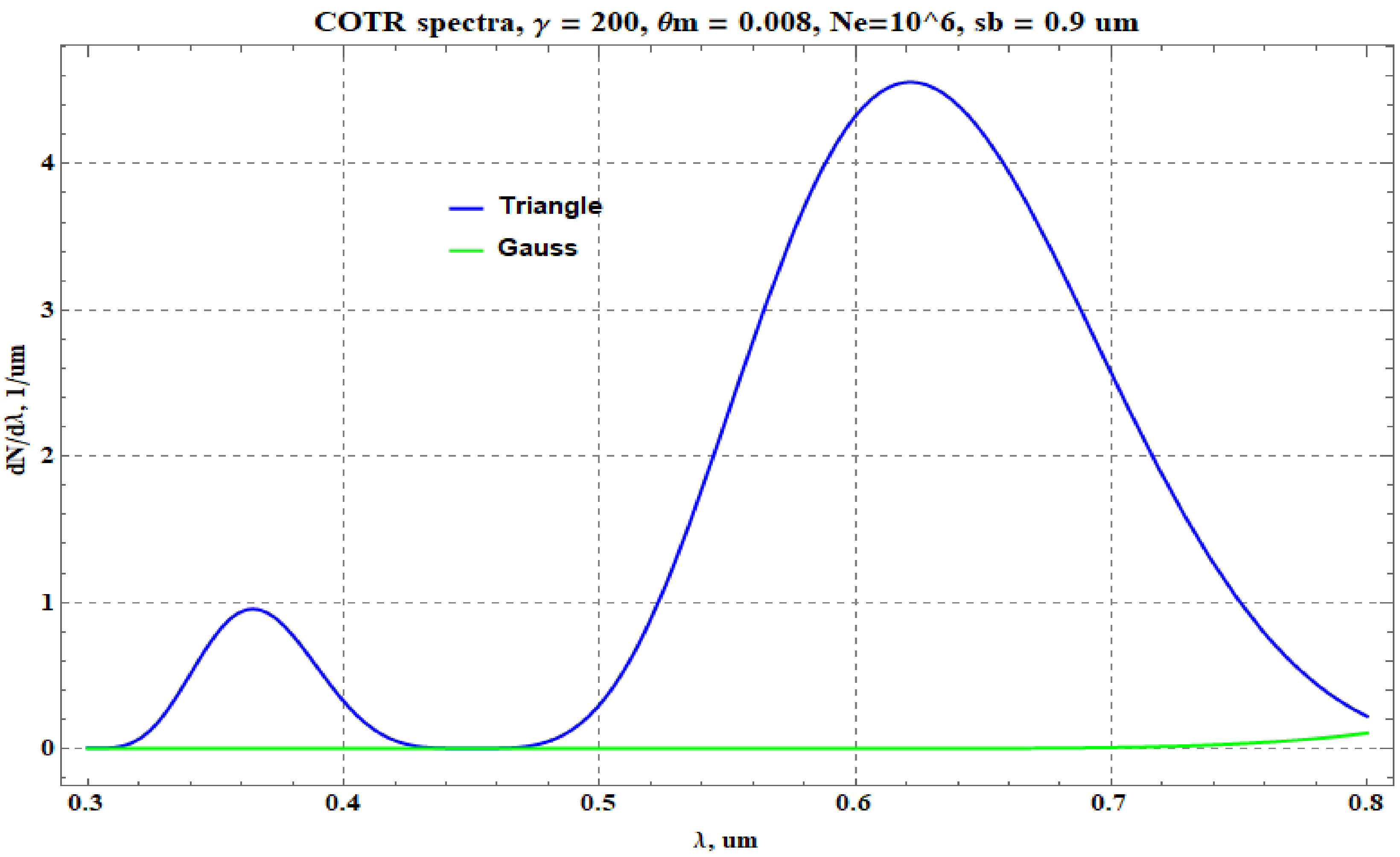
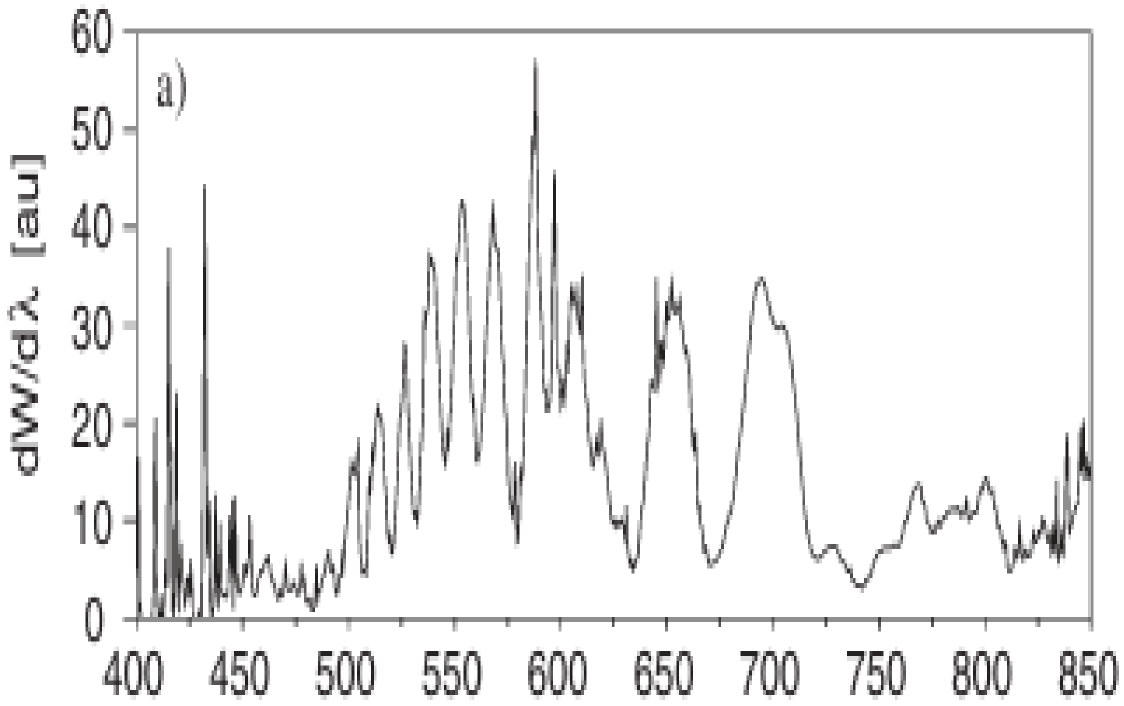


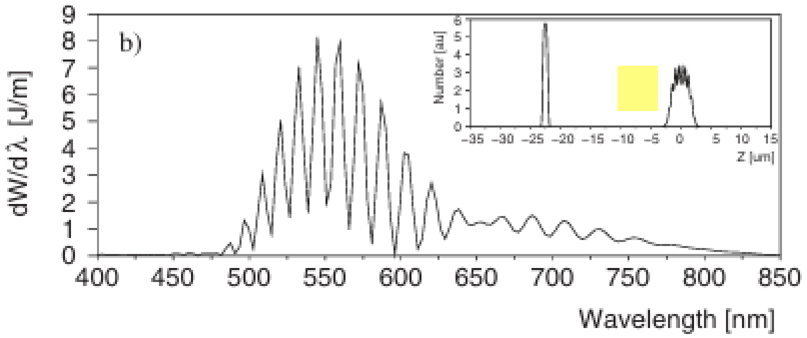
FIG. 4. OTR spectrum generated at a metal-vacuum boundary placed at 100 μm from the electron distribution in Fig. 3, using the angular distribution (solid line) and the spatial distribution (dashed line). The ratio between the coherent peak and the incoherent level scales linearly with the number of particles (150 000 electrons are used in the simulations).

Comparison of COTR spectra for gaussian bunch (green) and triangular one (blue), sb =0.9 um



COTR spectra measured (left) and simulated(right) Y.Glinec et al. PRL,98, 194801, (2007)





Formfactor F_{tr} for triangle distribution with maximum at Δz :

$$F_{\mathrm{tr}}(\omega, s_b, \Delta z) = \left| f_{\mathrm{tr}}(\omega, s_b, \Delta z) \right|^2,$$

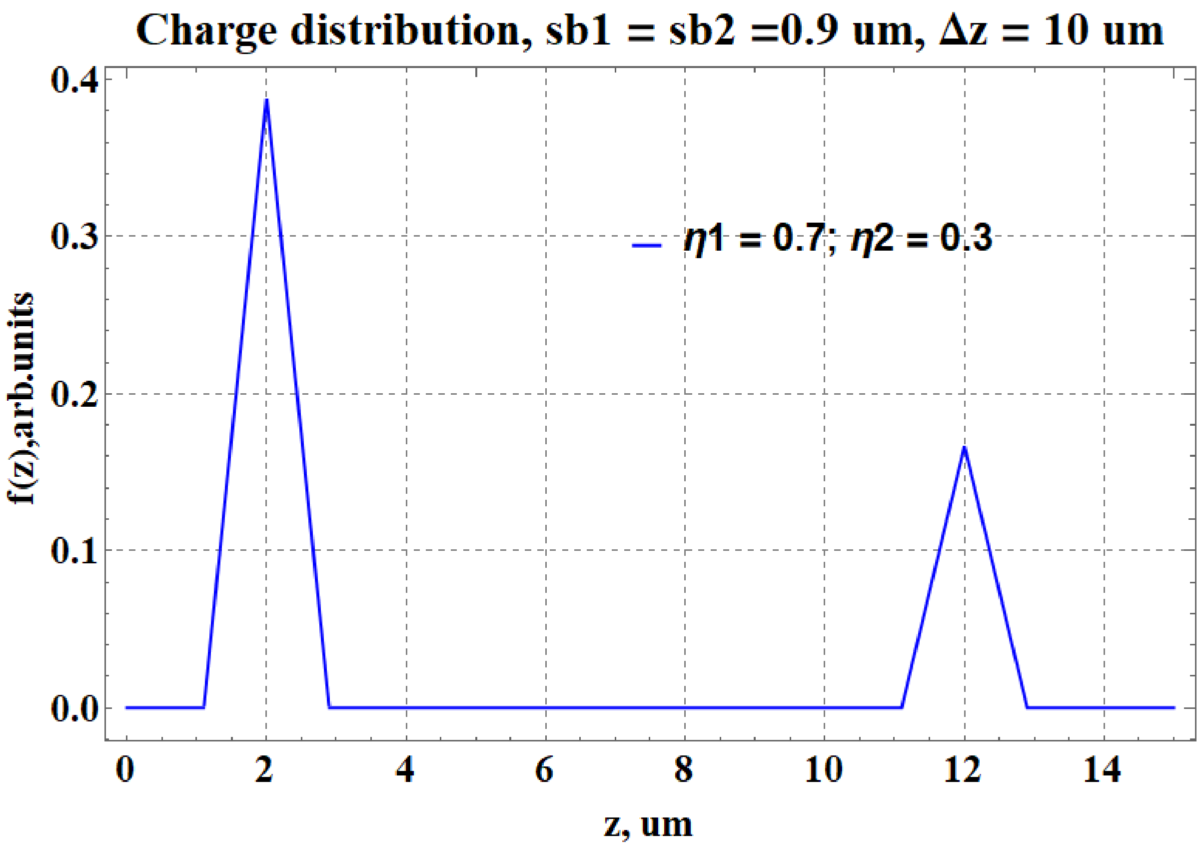
$$f_{\mathrm{tr}}(\omega, s_b, \Delta z) = \frac{1}{(\omega, s_b / c)^2} \left\{ \exp\left[-i \frac{(s_b - \Delta z)}{c} w \right] (-1 + \exp[i\omega s_b / c])^2 \right\}.$$

Formfactor F_{tr2} for two triangle spikes

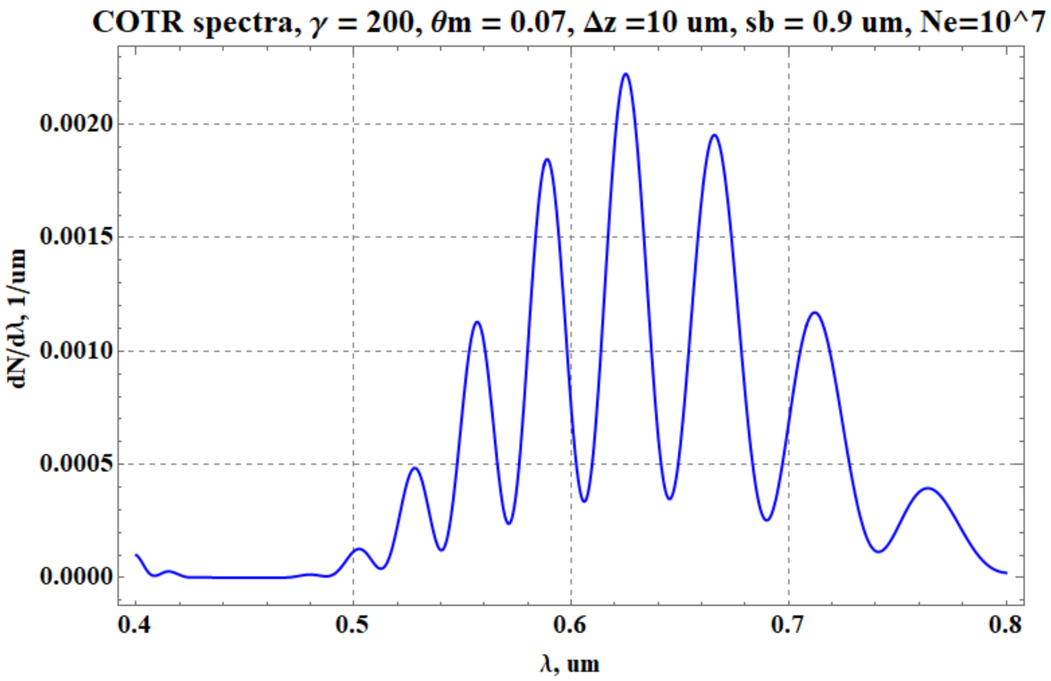
$$F_{\mathrm{tr}\,2} = \left| \eta_1 \ f_{\mathrm{tr}}(\omega, s_{b1}, \Delta z_1) + \eta_2 \ f_{\mathrm{tr}}(\omega, s_{b2}, \Delta z_2) \right|^2, \ \Delta z_2 - \Delta z_1 = L.$$

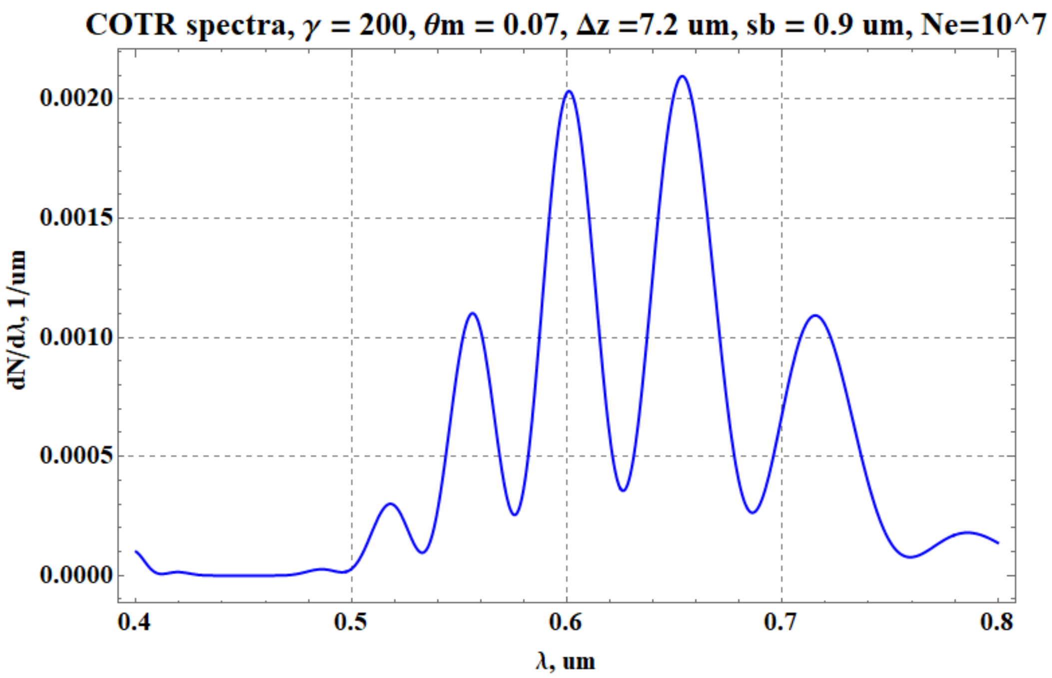
For two identical bunches the formfactor obtained coincides with the train formfactor with Nb=2

Bunch profile with two triangle spikes
sb1=sb2=0.9 um, Δz =10 um, η1=0.7, η1=0.3



Comparison of COTR spectra from asymmetric two bunches (left-Δz =10 um,right- Δz =7.4 um





COTR spectra measured at FLASH beam
S.Wesch et al. arXiv:1109.0458v1

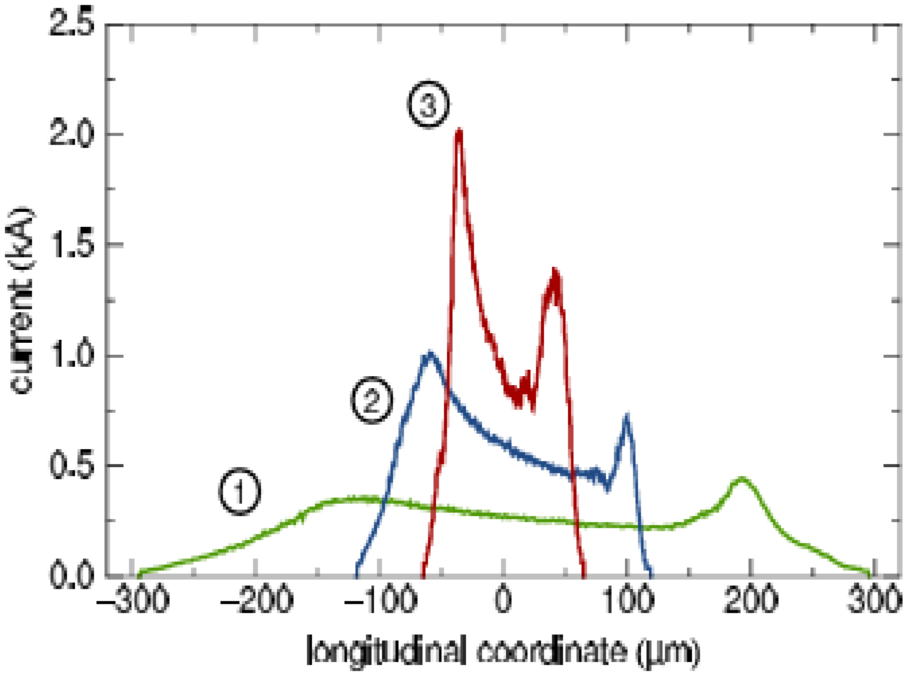
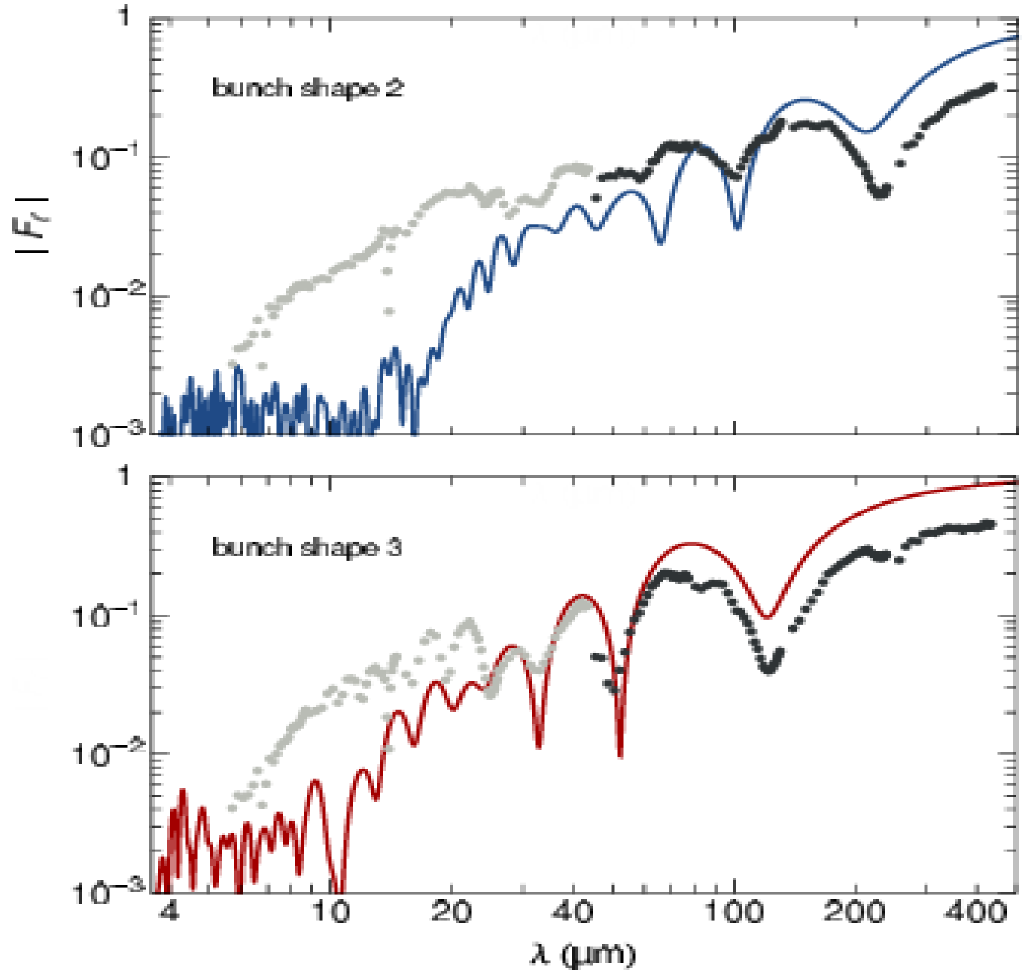
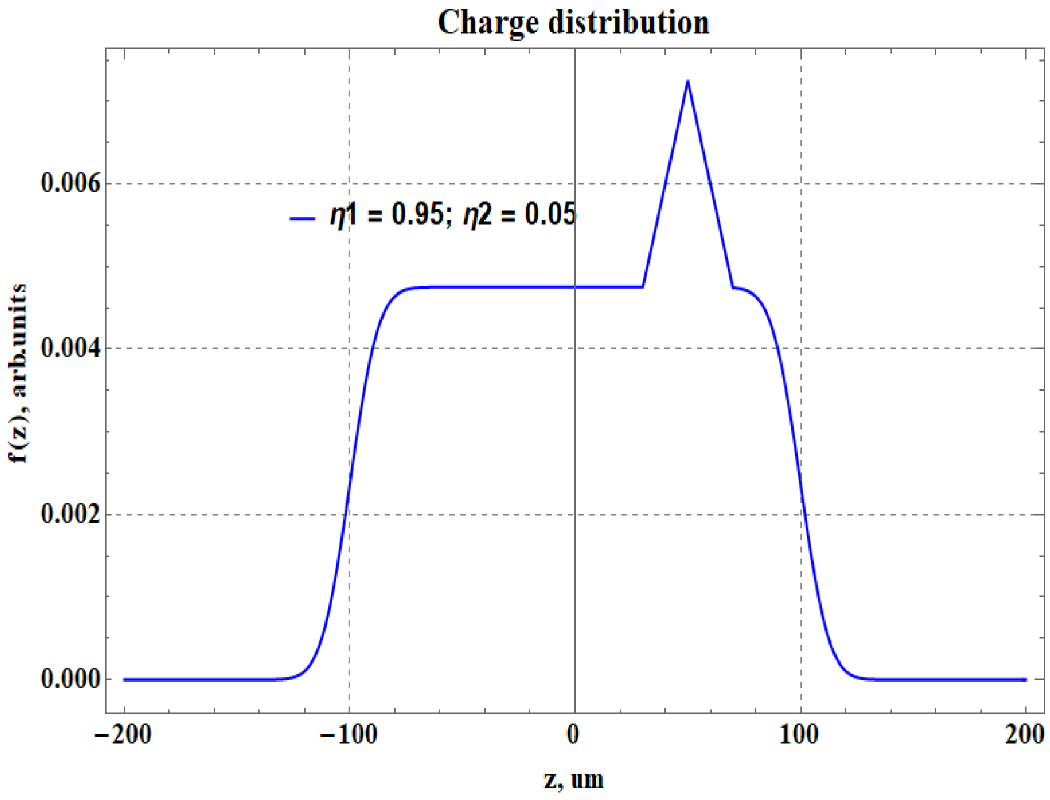


Figure 16: Longitudinal profiles of three different electron bunch shapes in the FLASH linac as measured with the transverse deflecting microwave structure.



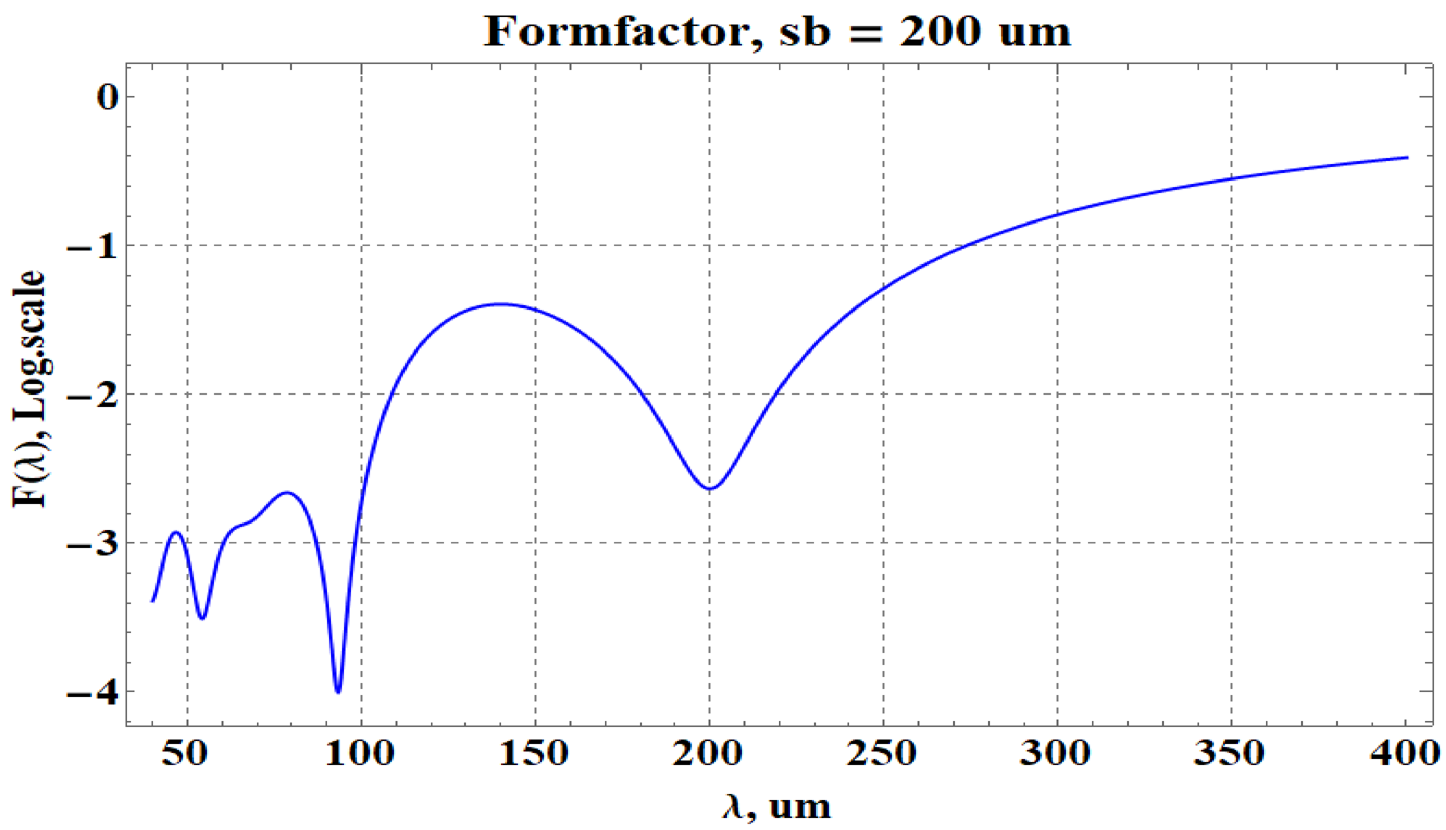
Approximation of the FLASH bunch profile



Superimposed on the uniform charge distribution in a bunch of the length sb1 = 200 um and intensity $\eta 1 = 0.7$ is a short triangle spike with a length of sb2 = 20 um and

intensity $\eta 2 = 0.3$

Formfactor (Log.scale)



Conclusion

a) Measured COTR spectra demonstrate reasonable yield for frequencies much higher than c/sb with sharp spectral peaks

b)Formfactor F(ω) for the gaussian bunch charge distribution is exponential suppressed for frequencies ω > c/sb

c) Non-gaussian formfactor is enhanced significantly the gaussian one in the range of spectral peaks due to power law decay at high frequencies

d) Observation of the coherent radiation in the wavelength range λ << sb confirmed the non-gaussian bunch charge distribution

e) Results of the COTR spectra measurements may be used for subpicosecond bunch length diagnostics

Thanks for your attention!