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Nonlinear Compton – γ beam profiles

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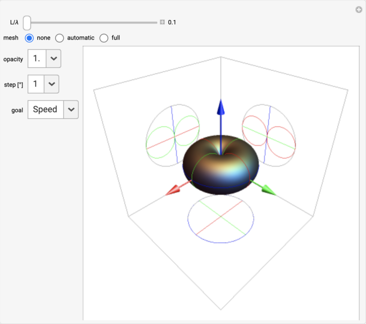
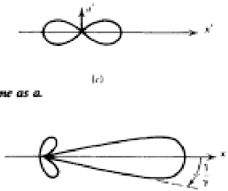
Weak Field $\xi \ll 1$: (Boosted) Dipole





(c)

Figure 4.11c Same as a.

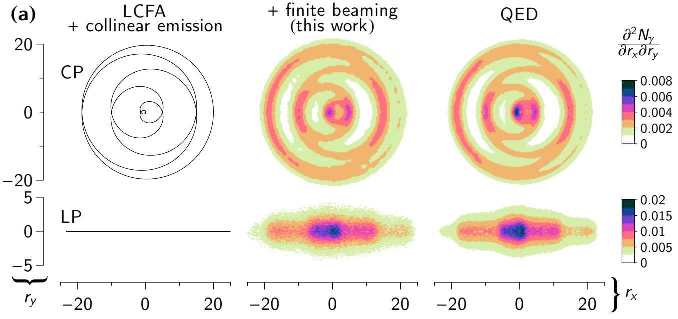
(d)

Figure 4.11d Angular distribution of radiation emitted by a particle with perpendicular acceleration and velocity.

- $\xi \ll 1$ pure harmonic electron oscillation $\boldsymbol{u} = \hat{\boldsymbol{x}}\,\xi \cos \omega t$ in rest frame
- relativistic beaming in LAB frame, typical emission angle $\theta \sim 1/\gamma$
- LUXE: 16.5 GeV $\Rightarrow \theta \sim 0.031$ mrad: **Size of gamma beam is 0.31 mm after 10 m propagation**

https://demonstrations.wolfram.com/DipoleAntennaRadiationPattern/

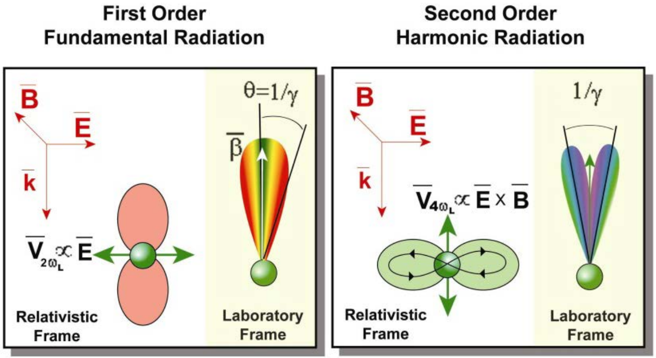
Extremely strong fields $\xi \gg 1$: LCFA

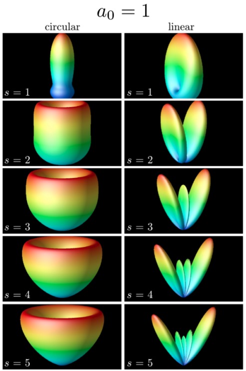


- Radiation is emitted in the direction of the instantaneous electron direction $\boldsymbol{\vartheta}$ with inherent angular spread $\theta \sim 1/\gamma$
- LP: $\tan\vartheta_x = \frac{u_x}{u_z} = \frac{\xi f(\phi)}{\gamma} \sin\phi$
- $\Rightarrow \theta \sim \xi/\gamma$ in polarization direction, $\theta \sim 1/\gamma$ perpendicular

T. Blackburn et. al. PRA **101**, 012505 (2020).

Intermediate Regime $\xi \sim 1$, LUXE





- LCFA not applicable
- An-harmonic oscillations ⇒ harmonics have higher multipoles
- Higher harmonics have larger emission angles, $\theta \sim \xi/\gamma$

left viewgraph courtesy of BNL

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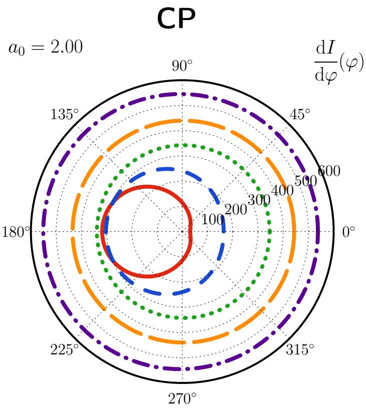
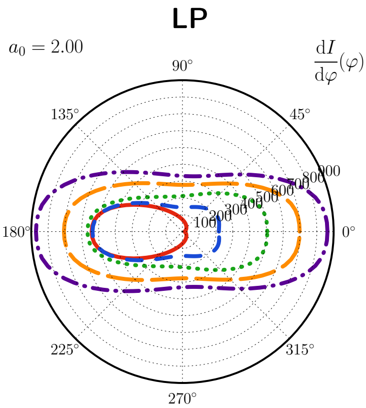
Pulse length/CEP dependence





Pulse duration: 1, 2, 3, 4, 5 cycle pulses

LUXE: > 5 cycles

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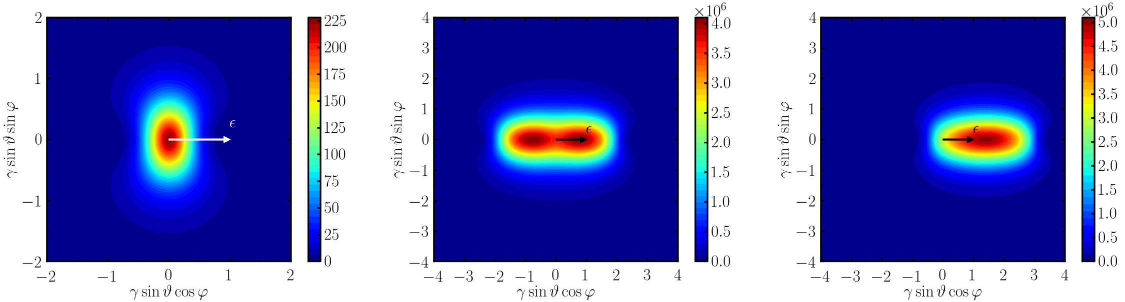
Gamma-beam profiles: Short pulse CEP effects

weak $\xi \ll 1$ || strong ($\xi \gtrsim 1$) & CEP1 || strong ($\xi \gtrsim 1$) & CEP2



DS and B. Kämpfer, PRA **88**, 012127 (2013)

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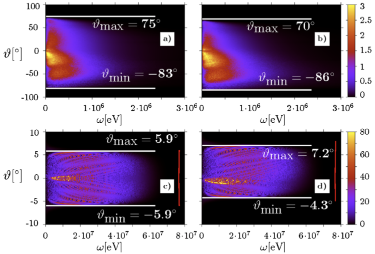
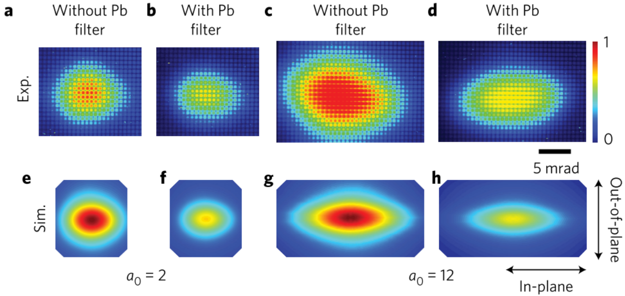
CEP[1]



ξ in nonlinear Thomson scattering[2,3]

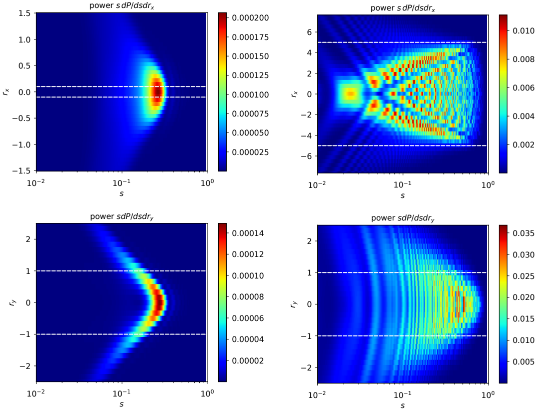


Model-independent ξ-inferrence[4]: $\xi^2 = 4\sqrt{2}\langle\gamma_i\rangle\langle\gamma_f\rangle(\sigma_\parallel^2 - \sigma_\perp^2)$

LCFA, $\xi \gg 1$, $\chi \lesssim 1$

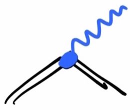
[1] F. Mackenroth et al PRL (2013), [2] Har-Shemesh et al Opt Lett (2012), [3] Yan et al Nature Phot (2017), [4] T. Blackburn et al PRAB (2020)

Numerically calculation using strong-field QED in Furry picture, 1 or 2-cycle flat-top plane-wave



weak ($\xi = 0.1$) || strong ($\xi = 5$)

MC simulations possible for LP at the moment



$$\left| \cdots \right|^2 \sim \frac{d^3N}{ds\,dr_x\,dr_y}$$

$$s = \frac{k^+}{p^+} \approx \frac{\omega}{E_i}$$

$$r_{x,y} = \frac{k_{x,y}}{ms} \approx \gamma\theta_{x,y}$$

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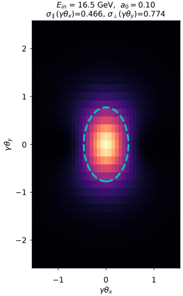
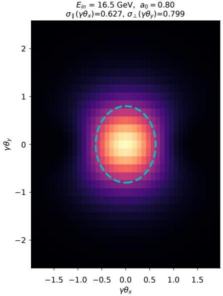
Extract angular moments of intensity distribution for fixed ξ

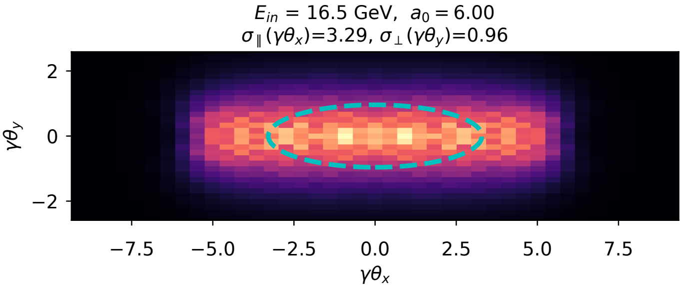
intensity distribution: $$\frac{d^2\mathcal{P}}{dr_x dr_y} = \int s \frac{d^3N}{dr_x dr_y ds} ds$$

total emitted power: $$\mathcal{P}(\xi) = \int \frac{d^2\mathcal{P}}{dr_x dr_y} dr_x dr_y$$

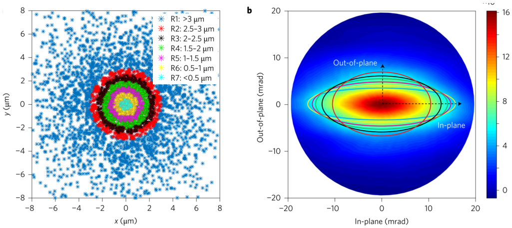
angular variance: $$\sigma_\parallel^2(\xi) = \mathcal{P}^{-1} \int (r_x - \bar{r}_x)^2 \frac{d^2\mathcal{P}}{dr_x dr_y} dr_x dr_y$$







Gaussian Focus Average



$$\text{1D:} \quad \xi = \xi(\phi) = \xi_0 \, e^{-\phi^2/2\Delta^2} \quad \Rightarrow \quad \langle \sigma^2_{\perp/\parallel} \rangle = \frac{\int \sigma^2_{\perp/\parallel}(\xi) \mathcal{P}(\xi) d\phi}{\int \mathcal{P}(\xi) d\phi}$$

$$\text{3D:} \quad \xi = \xi(\boldsymbol{x}_\perp, \phi) = \xi_0 e^{-\boldsymbol{x}_\perp^2/w_0^2} e^{-\phi^2/2\Delta^2} \quad \Rightarrow \quad \langle \sigma^2_{\perp/\parallel} \rangle = \frac{\int \sigma^2_{\perp/\parallel}(\xi) \mathcal{P}(\xi) d^2 x_\perp d\phi}{\int \mathcal{P}(\xi) d^2 x_\perp d\phi}$$

W. Yan et al, Nature Phot. **11**, 514 (2017).

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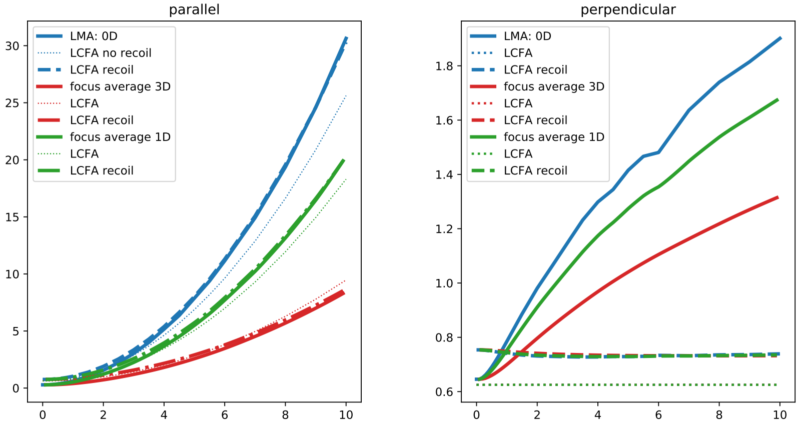
Gaussian Focus Average



LCFA: $\sigma_\perp^2 = \frac{5\gamma_i}{8\gamma_f}\,, \qquad \sigma_\parallel^2 = \frac{\xi^2}{4}\frac{\gamma_i}{\gamma_f} + \sigma_\perp^2\,,$

Blackburn et al PRAB 2020

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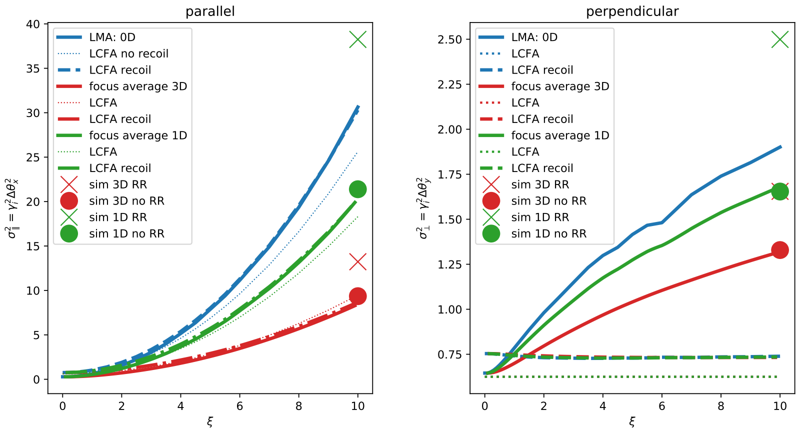
No, because:

- Simulations done here are restricted to *thin targets*: strictly only one emission per electron
- How to include multi-emission events (RR energy loss) in this averaging approach?
- **Conjecture:** Only first emission contributes to gamma profile since radiated power $\sim \gamma^2$ thus radiated power decreasing as electron loses energy (but smaller γ means larger emission angle)

$\Rightarrow$ Test this!

1. Tom Blackburn did simulation for $\xi = 10$ using LCFA MC method
2. Use results Compton event distributions $dN/d\xi$ from Tony's (CP) MP sims

Gaussian Focus Average compared with LCFA MC Simulations



Simulations with RR included do *not* agree well with numeric focus averaging approach

Simulations by Tom Blackburn (Dec 2020)

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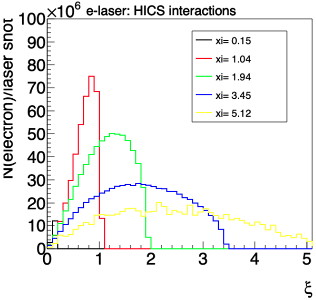
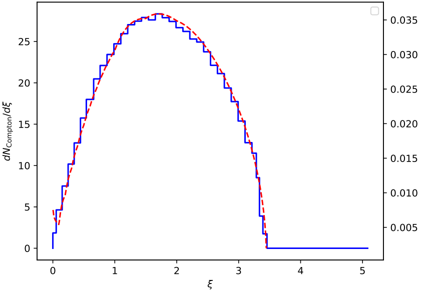
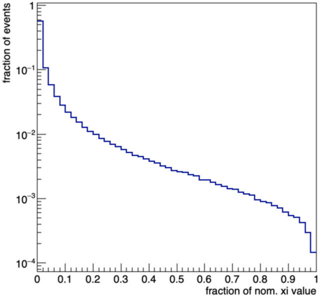
Convolution with ξ-Compton spectra from CP-MC simulation?

- They should represent the "true" distribution of Compton events, including multiple emission by a single electron
- However: no information on γ_i at the Compton event (i.e. no RR effects!)
- Tried to include in averaging, but "edge sampling effects" and middle plot







red curve in middle plot: $N_{LMA}(\xi) \times \frac{\sqrt{\log \xi_0/\xi}}{\xi}$

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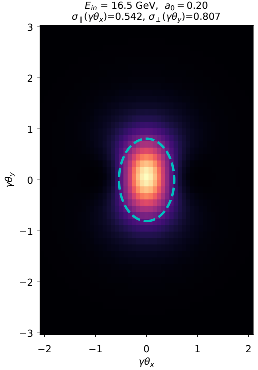
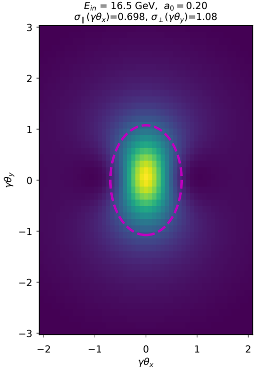
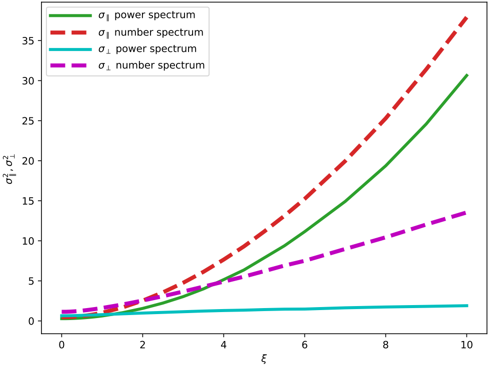
Power or Probability?

- What to use *depends on detector*
- Studies in the literature so far based on power spectrum ($\sim$ keV X-rays)
- Scintillation of multi-GeV γ-rays depends on number spectrum
- Differences are not too large







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Conclusions so far

- Typical γ-beam size is $(1\ldots\xi)\times0.3$ mm at position 10 m form strong-field IP
- The numeric focus averaging procedure is limited to "thin target" approximation
- Agrees with LCFA-MC simulations for $\xi = 10$ when RR is switched off in the latter
- Big deviation due to RR effects i.e. multiple scatterings per electron
- Probably we need to do LP-LMA-MC simulations for better results if precise predictions are needed

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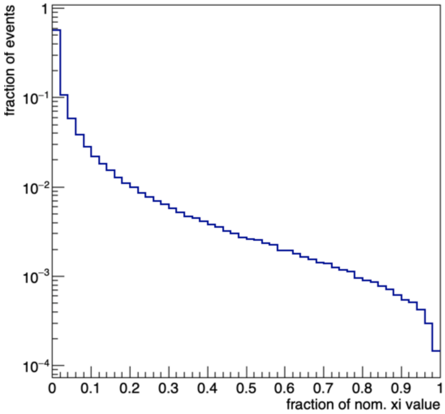

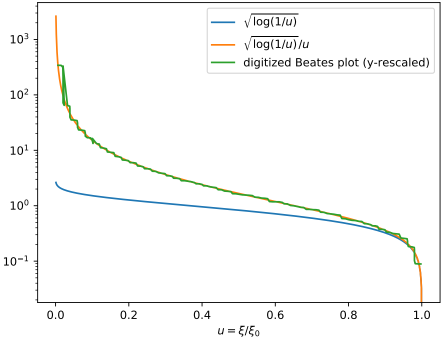

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$$\langle\sigma^2\rangle = \int \sigma^2(\xi)\mathcal{P}(\xi) d^2x_\perp d\phi \bigg/ \int \mathcal{P}(\xi) d^2x_\perp d\phi$$

turns into

$$\langle\sigma^2\rangle \sim \int \xi^4 d^2x_\perp d\phi \bigg/ \int \gamma^2\xi^2 d^2x_\perp d\phi$$

when assuming $\sigma^2(\xi) \sim \xi^2/\gamma^2$ and $\mathcal{P} \sim \gamma^2\xi^2$