Analytical Calculations for Thomson Backscattering Based Light Sources

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ICAP'18
Key West
October 23 2018

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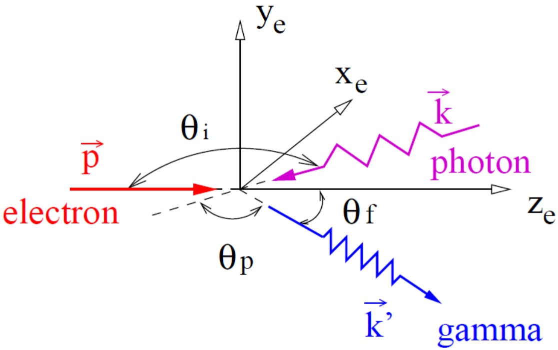
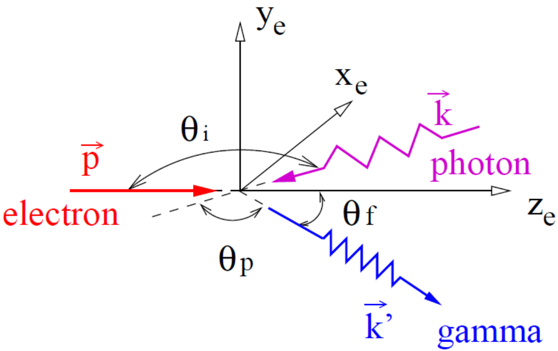


schematic taken from [1]

- scattering a high intensity laser off a relativistic electron beam
- Doppler shift allows for dramatic increase in photon energy



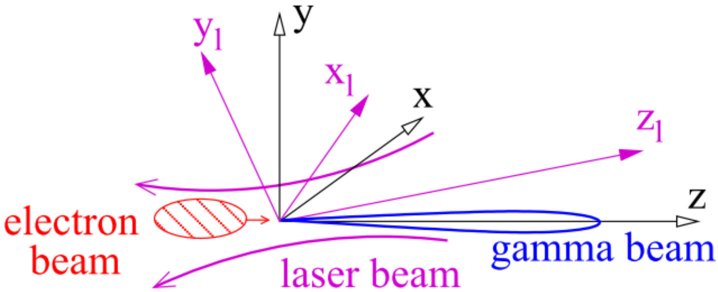
schematic taken from [1]

$$\nu' = \nu_0 \frac{1 - \beta \cos\theta_i}{1 - \beta\cos(\theta_f) + \frac{h\nu_0}{\gamma mc^2}(1 - \cos\theta_p)}$$

Motivation

- conventional X-ray sources require GeV electron beams
- Thomson sources can achieve high photon energies with relatively low energy electron beams (e.g. 40 keV photons from 50 MeV electrons)
- tunability

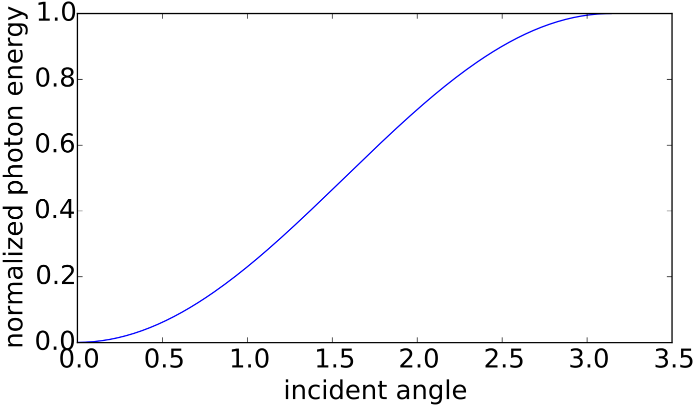
Properties: Tunability



schematic taken from [1]

- scattered photons travel in direction of electron beam
- cone of half angle $1/\gamma$

Properties: Tunability



- incident angle dictates Doppler shift and frequency of scattered photons

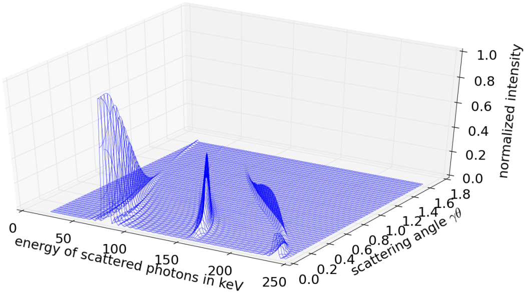
Analytical Calculations

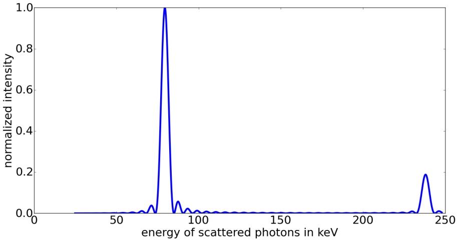
- Monte Carlo methods like CAIN [2] exist
  - high computation cost for large amounts of particles
- other analytical codes exist, but we couldn't find any with coherent treatment of radiation
- FEL codes include coherent treatment but the scenario doesn't match
- goal: quick code to prove concepts for new machines and prototyping

Analytical Calculations

- substantial work done by S. K. Ride, E. Esarey and others [3] [4]
- analytical integration of Liénard-Wiechert potentials using Bessel identities
- code does not integrate numerically
- evaluation of complex Bessel functions
- written in python

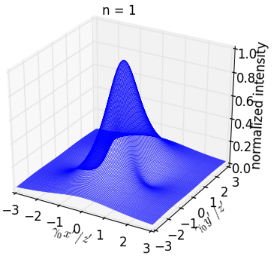
Code Validation: Linear Polarization





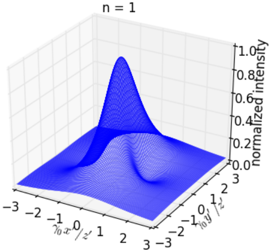
Normalized intensity for counterpropagating linearly polarized laser ($N = 7$, $\lambda = 500\,\mathrm{nm}$) and relativistic electron ($\gamma = 100$) as a function of photon energy and scattering angle.

Code Validation: Linear Polarization



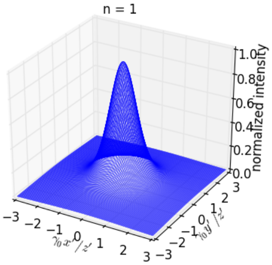
Normalized Intensity of radiation scattered by a relativistic electron ($\gamma = 10$) from a counterpropagating high intensity ($a_o = 2$) linearly polarized laser pulse, viewed in plane of the detector. The detector is located at z' and centered on the electron beam axis. Distances in x', y' are measured in units $\gamma_0(x'/z'), \gamma_0(y'/z') \propto \gamma_0\theta$. The first three harmonics are shown.

Code Validation: Linear Polarization



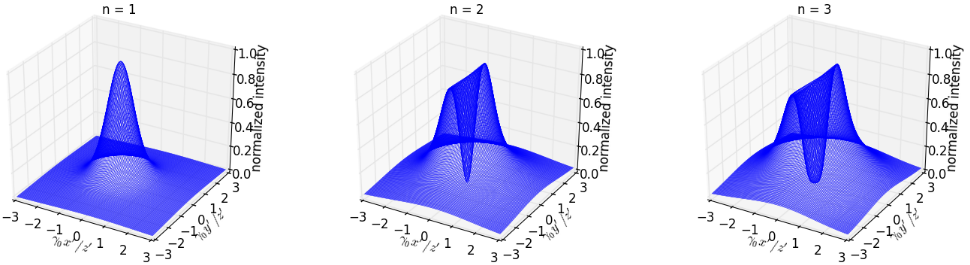
Normalized Intensity of transversely scattered radiation by a relativistic electron ($\gamma = 10$) traveling in plane of polarization of a high intensity ($a_o = 2$) linearly polarized laser pulse, viewed in plane of the detector. The detector is located at z' and centered on the electron beam axis. Distances in x', y' are measured in units $\gamma_0(x'/z'), \gamma_0(y'/z') \propto \gamma_0\theta$. The first three harmonics are shown.

Code Validation: Circular Polarization



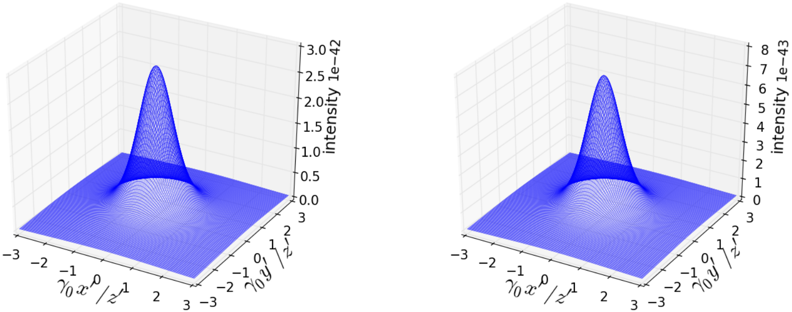
Normalized Intensity of radiation scattered by a relativistic electron ($\gamma = 10$) from a counterpropagating high intensity ($a_o = 2$) circularly polarized laser pulse, viewed in plane of the detector. The detector is located at z' and centered on the electron beam axis. Distances in x', y' are measured in units $\gamma_0(x'/z'), \gamma_0(y'/z') \propto \gamma_0\theta$. The first three harmonics are shown.

Code Validation: Circular Polarization



Normalized Intensity of transversely radiation scattered by a relativistic electron ($\gamma = 10$) from a high intensity ($a_o = 2$) circularly polarized laser pulse, viewed in plane of the detector. The detector is located at z' and centered on the electron beam axis. Distances in x', y' are measured in units $\gamma_0(x'/z'), \gamma_0(y'/z') \propto \gamma_0\theta$. The first three harmonics are shown.

Code Validation: Coherent Tests with Two Electrons



Intensity of radiation in arbitrary units produced by a single electron on the right and by two identical electrons treated coherently on the left. The coherent addition of radiation increases the intensity four-fold.

Code Validation: Coherent Tests with Two Electrons

- laser field can be compared to undulator field
- laser pulse introduces an additional phase factor

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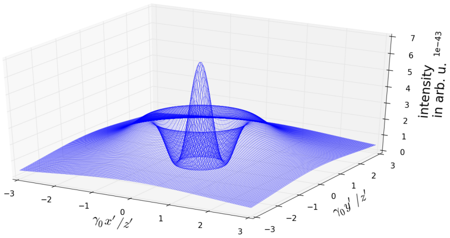
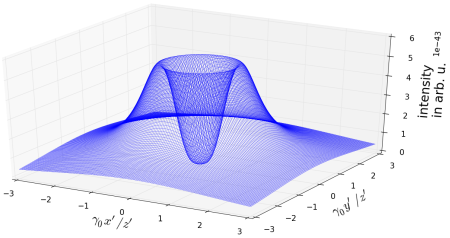
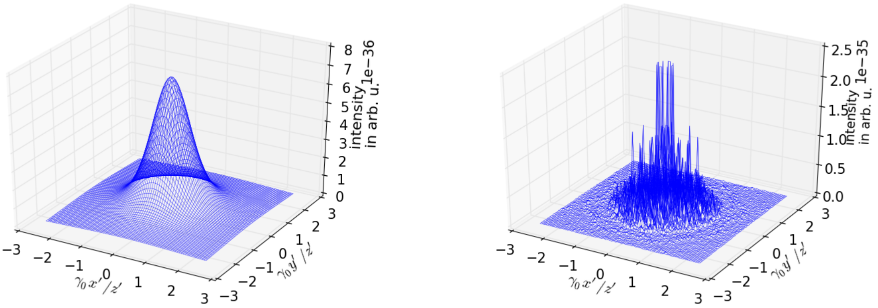




Coherent addition of radiation produced by two electrons half a wavelength apart. Laser phase factor has been omitted on the right.

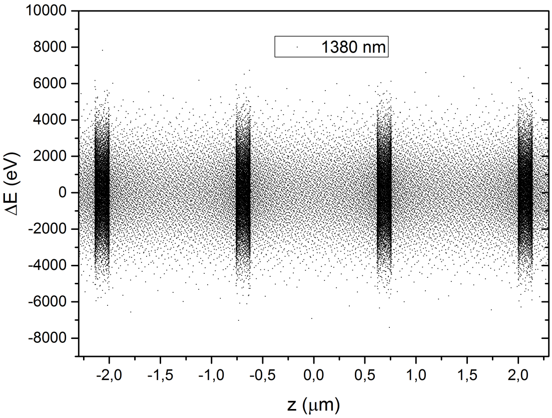


Intensity of radiation produced by a Gaussian bunch ($\gamma = 69.5$) interacting with a circularly polarized laser pulse ($\lambda = 2.665\,\mathrm{cm}$). Incoherent addition on the left, coherent addition on the right.

First Results: Gaussian Bunch

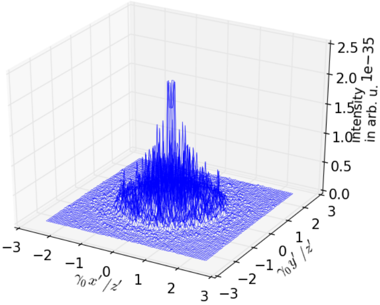
- 200 k particles simulated with 80 $\times$ 80 pixel detector resolution
- Gaussian energy spread and longitudinal distribution
- no transverse momenta or displacement
- incoherent increase in intensity matches expectations for number of particles
- coherent addition is very noisy
  - most radiation cancels out
  - spectrum is dominated by minority of particles
  - pseudo-random generation of bunch amplifies this effect

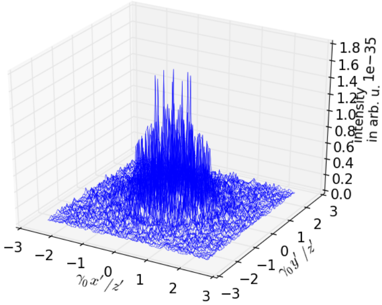
First Results: Microbunching



Energy spread and longitudinal electron distribution of the simulated bunch.

First Results: Microbunching





Intensity of radiation produced by a microbunched beam ($\gamma = 69.5$) interacting with a circularly polarized laser pulse ($\lambda = 2.665\,\mathrm{cm}$). Relatively low energy spread on the left, larger energy spread on the right

First Results: Microbunching

- 200 k particles simulated with 80×80 pixel detector resolution
- no transverse momenta or displacement
- strong microbunching of 60 % with non-zero bandwidth
- runtime: about 2000 s on a workstation CPU

Conclusion Outlook

- fast analytical code
- correctly handles coherent addition of radiation for two electrons
- emittance needs to be fully implemented
- noise levels of coherent addition need to be improved

Thank you for your attention!

[1] C. Sun and Y. K. Wu. Theoretical and simulation studies of characteristics of a compton light source. *Phys. Rev. ST Accel. Beams*, 14:044701, Apr 2011.

[2] K. Yokoya. *User manual of CAIN, version 2.42*, 2011.

[3] Eric Esarey, Sally K. Ride, and Phillip Sprangle. Nonlinear thomson scattering of intense laser pulses from beams and plasmas. *Phys. Rev. E*, 48:3003–3021, Oct 1993.

[4] Sally K. Ride, Eric Esarey, and Michael Baine. Thomson scattering of intense lasers from electron beams at arbitrary interaction angles. *Phys. Rev. E*, 52:5425–5442, Nov 1995.

Backup Slides

- substantial work done by S. K. Ride, E. Esarey and others [3] [4]
- integration of Liénard-Wiechert potentials

$$\frac{\mathrm{d}^2 I}{\mathrm{d}\omega \mathrm{d}\Omega} = \frac{e^2\omega^2}{4\pi^2 c}\left|\int_{-T/2}^{T/2}\left[\vec{n}\times\left(\vec{n}\times\vec{\beta}\right)\right] e^{i\omega\left(t-\frac{\vec{n}\cdot\vec{r}}{c}\right)}\mathrm{d}t\right|^2$$

- integral can be split by polarization

$$\frac{d^2 I_\theta}{d\omega d\Omega} = \frac{e^2\omega^2}{4\pi^2 c}\left|\int_{\eta_0}^{\eta_0}\left[\frac{d\vec{r}}{d\eta}\hat{e}_\theta\right] e^{i\Psi} dt\right|^2$$

$$\frac{d^2 I_\phi}{d\omega d\Omega} = \frac{e^2\omega^2}{4\pi^2 c}\left|\int_{\eta_0}^{\eta_0}\left[\frac{d\vec{r}}{d\eta}\hat{e}_\phi\right] e^{i\Psi} dt\right|^2$$

- integral can be split by polarization

$$\frac{\mathrm{d}^2 I_\theta}{\mathrm{d}\omega \mathrm{d}\Omega} = \frac{e^2\omega^2}{4\pi^2 c}\left|\int_{\eta_0}^{\eta_0}\left[\frac{\mathrm{d}\vec{r}}{\mathrm{d}\eta}\hat{e}_\theta\right] e^{i\Psi}\mathrm{d}t\right|^2$$

$$\frac{\mathrm{d}^2 I_\phi}{\mathrm{d}\omega \mathrm{d}\Omega} = \frac{e^2\omega^2}{4\pi^2 c}\left|\int_{\eta_0}^{\eta_0}\left[\frac{\mathrm{d}\vec{r}}{\mathrm{d}\eta}\hat{e}_\phi\right] e^{i\Psi}\mathrm{d}t\right|^2$$

- solution via Bessel identity

$$\exp\left(ib\sin\sigma\right) = \sum_{n=-\infty}^{\infty} J_n(b)\exp\left(in\sigma\right)$$