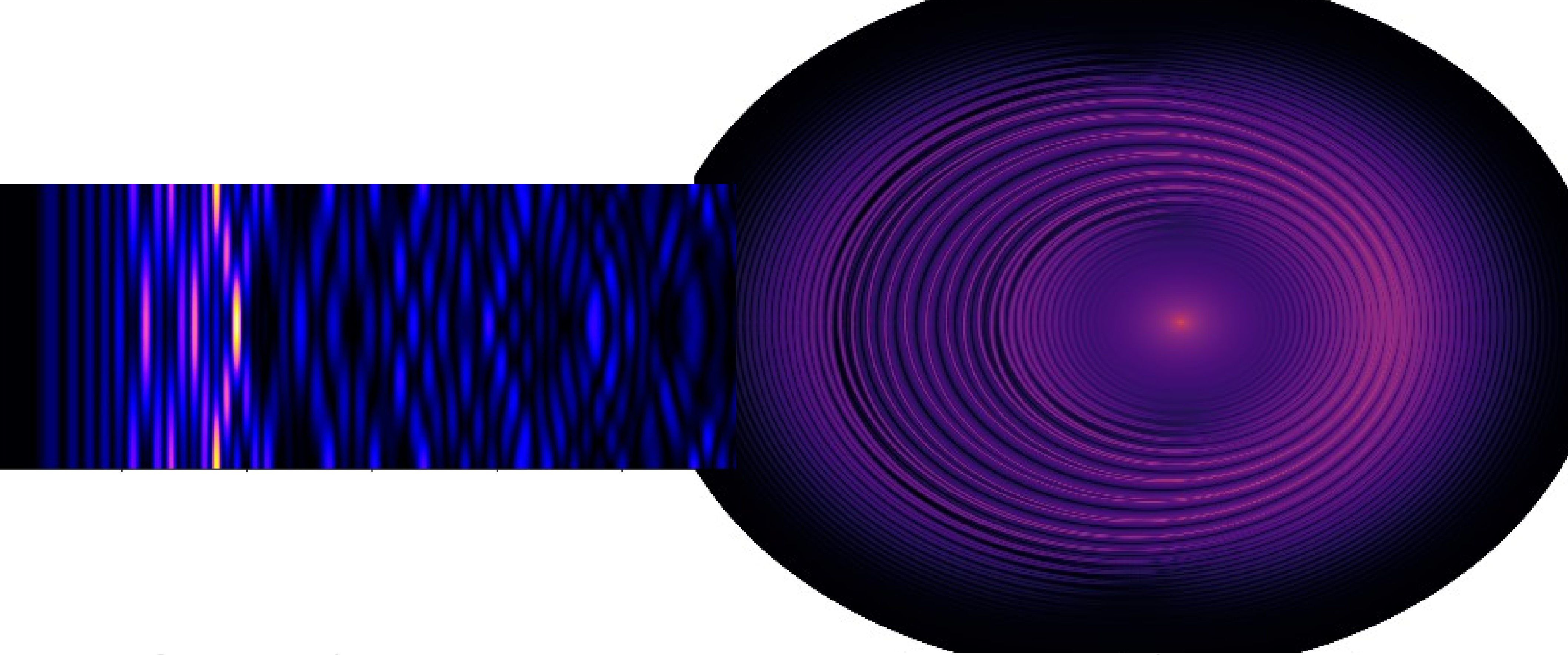

Carrier Envelope Phase signatures in Thomson scattering Spectrum

Marcel Ruijter
Università La Sapienza di Roma
Università degli Studi di Milano

Education

- B.Sc. Engineering Physics
  Fontys University of Applied Sciences,
  Eindhoven, The Netherlands

- Pre-master Applied Physics,
  Eindhoven University of Technology,
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- M.Sc. Photonics
  Friedrich Schiller Universität,
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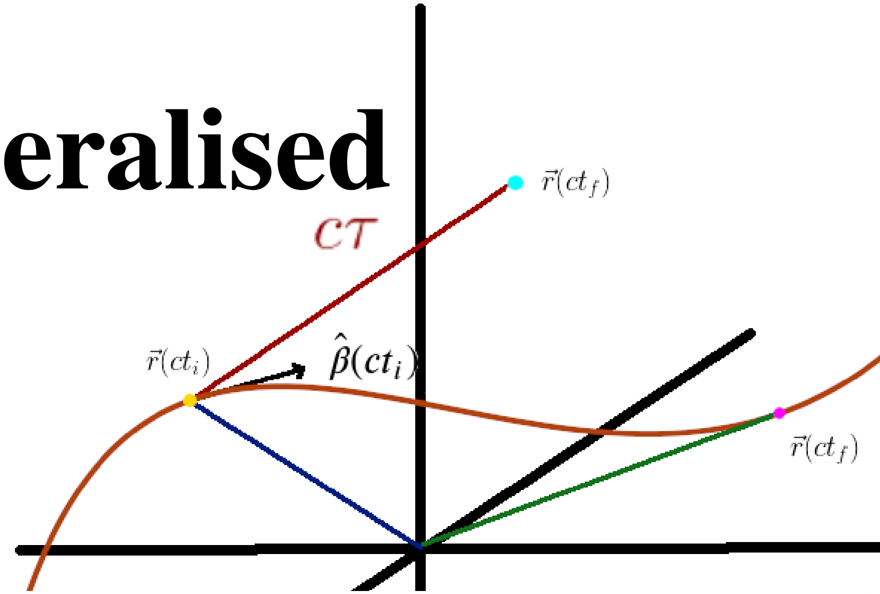
- (Current) PhD Accerlerator Physics,
  Università degli Studi di Roma La Sapienza,
  Roma, Italy

  Supervisors: Vittoria Petrillo, Luca Serafini

PhD Topics: most generalised

Lienard Wiechert potentials



$$\vec{E}(ct,\vec{r}(ct)) = q\left(\frac{\hat{n}-\vec{\beta}}{\gamma^2(1-\hat{n}\vec{\beta})^3 c\tau^2} + \frac{\hat{n}\times\left(\left(\hat{n}-\vec{\beta}\right)\times\dot{\vec{\beta}}\right)}{(1-\hat{n}\vec{\beta})^3 c\tau}\right)\Bigg|_{ct_{ret}}$$

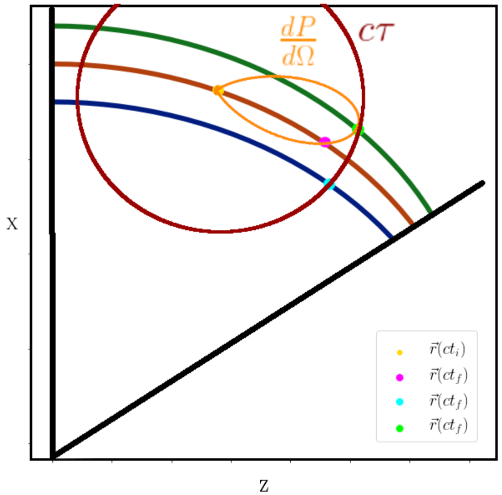
From Wikipedia, the free encyclopedia

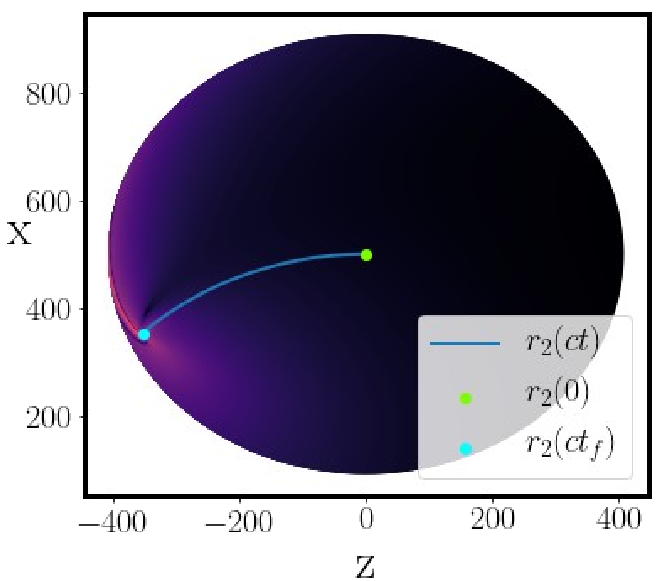
The **Liénard–Wiechert potentials** describe the classical electromagnetic effect of a moving electric point charge in terms of a vector potential and a scalar potential in the Lorenz gauge. Built directly from Maxwell's equations, these describe the complete, relativistically correct, time-varying electromagnetic field for a point charge in arbitrary motion, but are not corrected for quantum-mechanical effects. Electromagnetic radiation in the form of waves can be obtained from these potentials. These expressions were developed in part by Alfred-Marie Liénard in 1898[1] and independently by Emil Wiechert in 1900.[2][3]

In 1905, Poincaré was the first to recognize that the transformation has the properties of a mathematical group, and named it after Lorentz.[9] Later in the same year Albert Einstein published what is now called special relativity, by deriving the Lorentz transformation under the assumptions of the principle of relativity and the constancy of the speed of light in any inertial reference frame, and by abandoning the mechanistic aether as unnecessary.[10]

PhD Topics

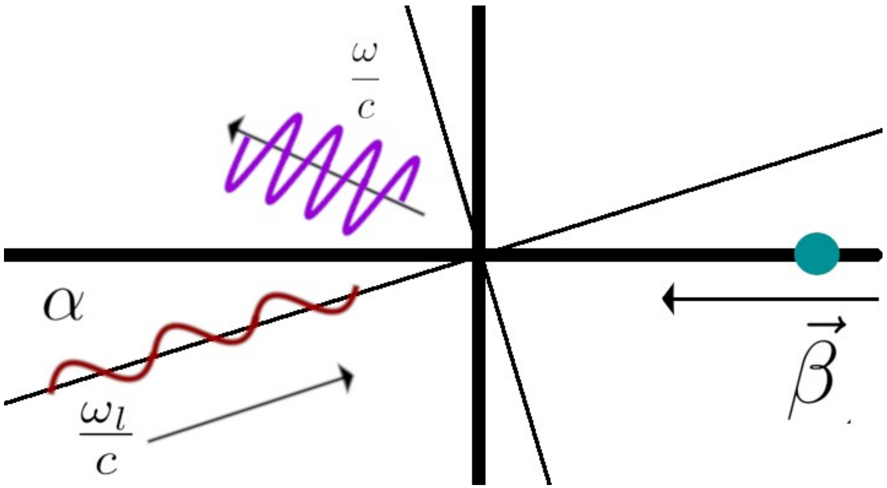
Retarded time
Particle interaction

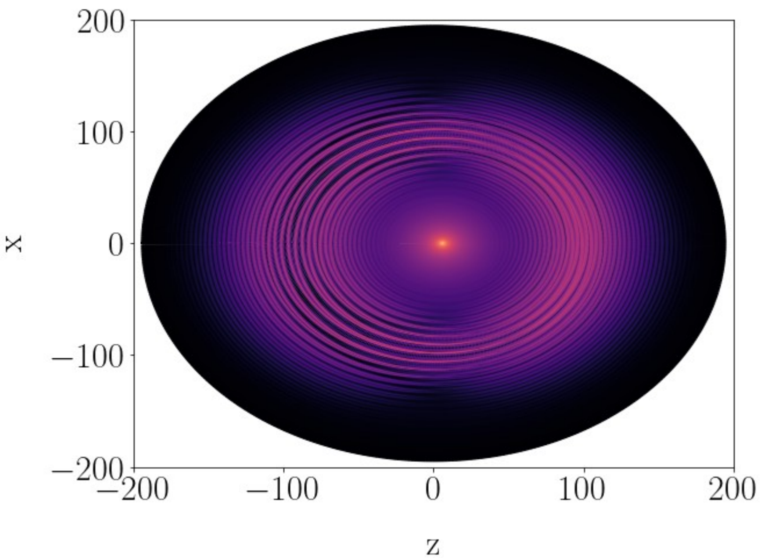




$\vec{E}\left(ct, \vec{r}\,(ct)\right)$

Scattering
Manipulation of laser pulse

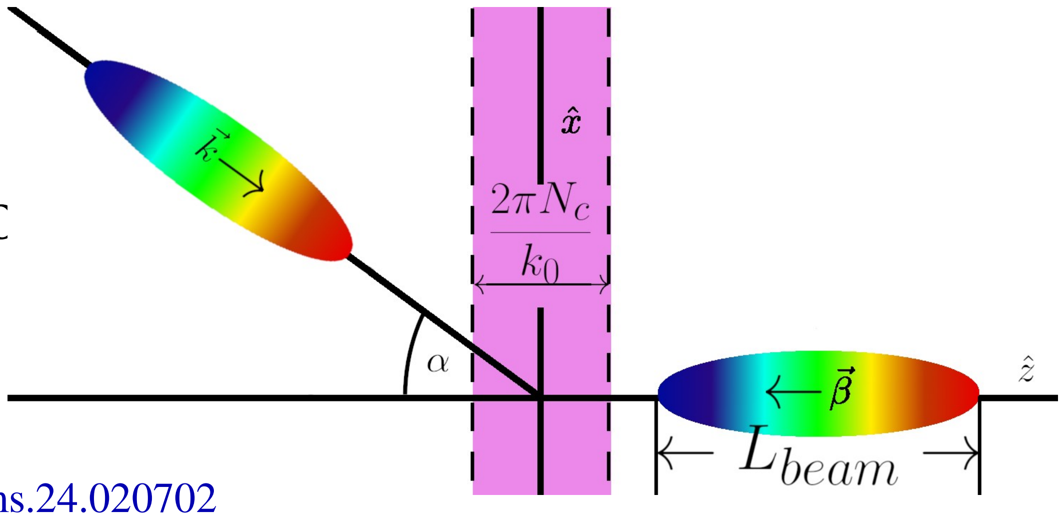




$\vec{E}\left(ct, \vec{r}\,(ct)\right)$

PhD Topics : Thomson scattering

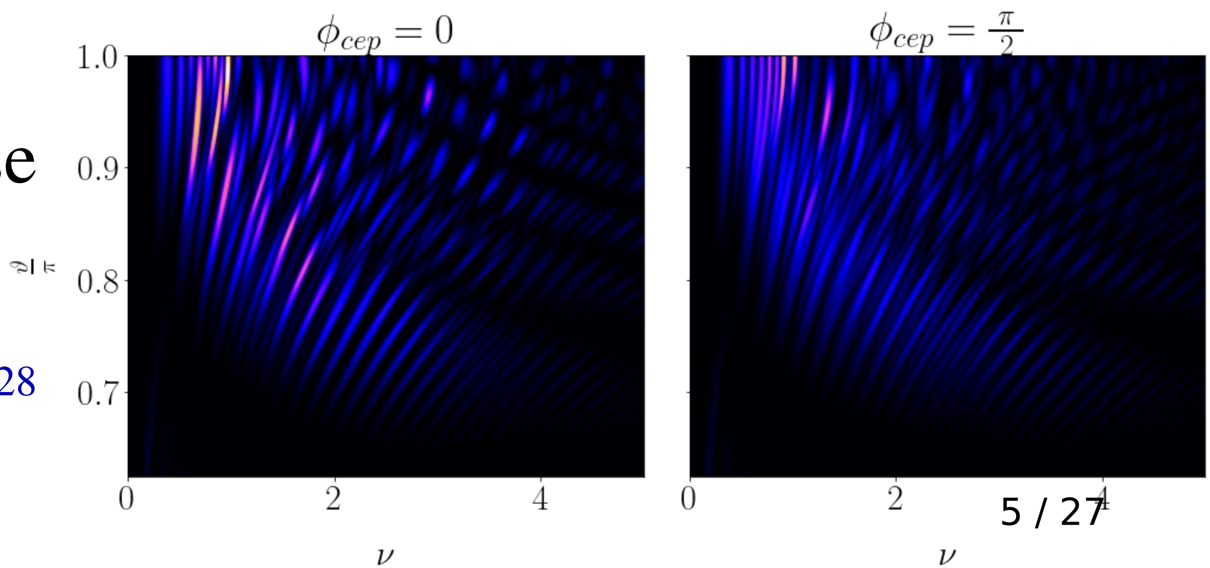
- Modulation of laser pulse frequency for compensatic energy spread electrons



Ruijter et al
https://doi.org/10.1103/PhysRevAccelBeams.24.020702

- Carrier Envelope Phase (CEP) dependency

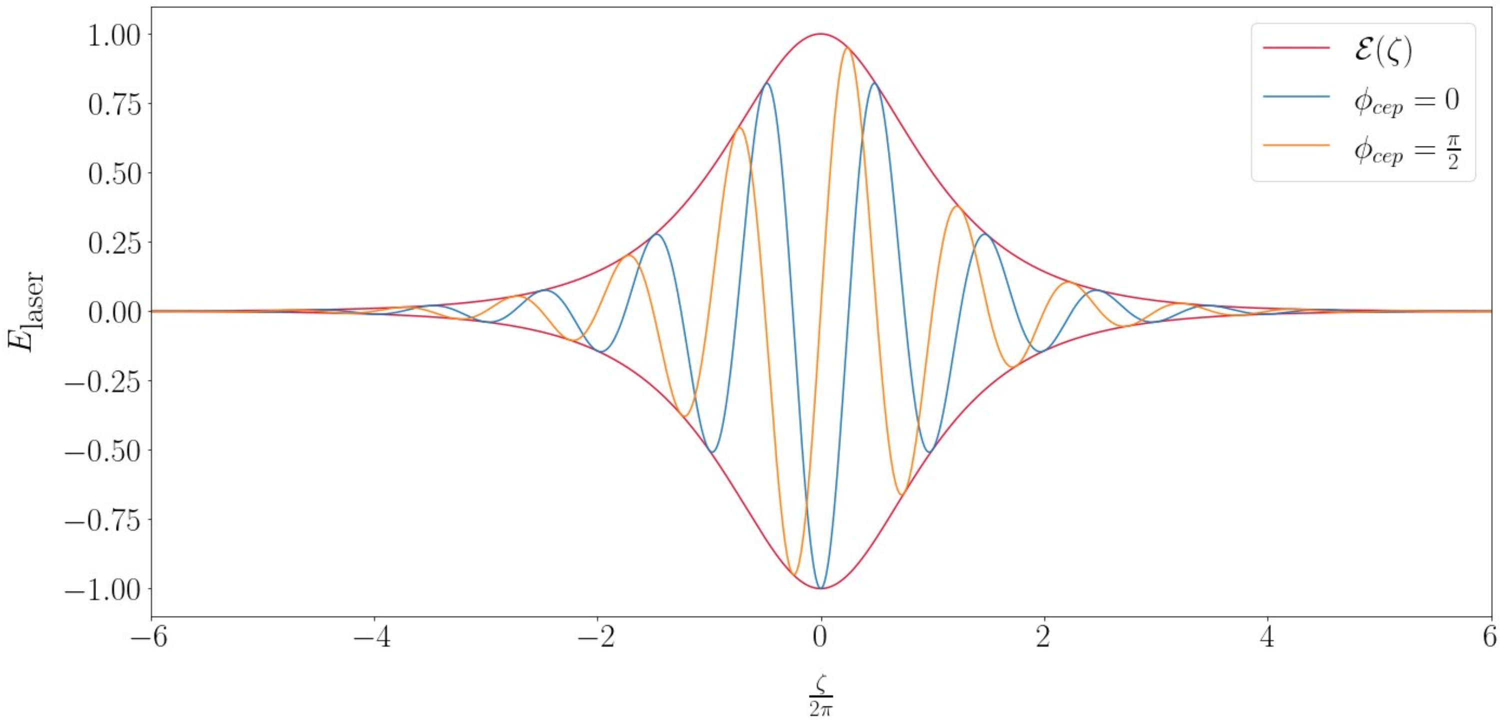
Ruijter et al
https://doi.org/10.3390/cryst11050528



CEP : what's the deal?

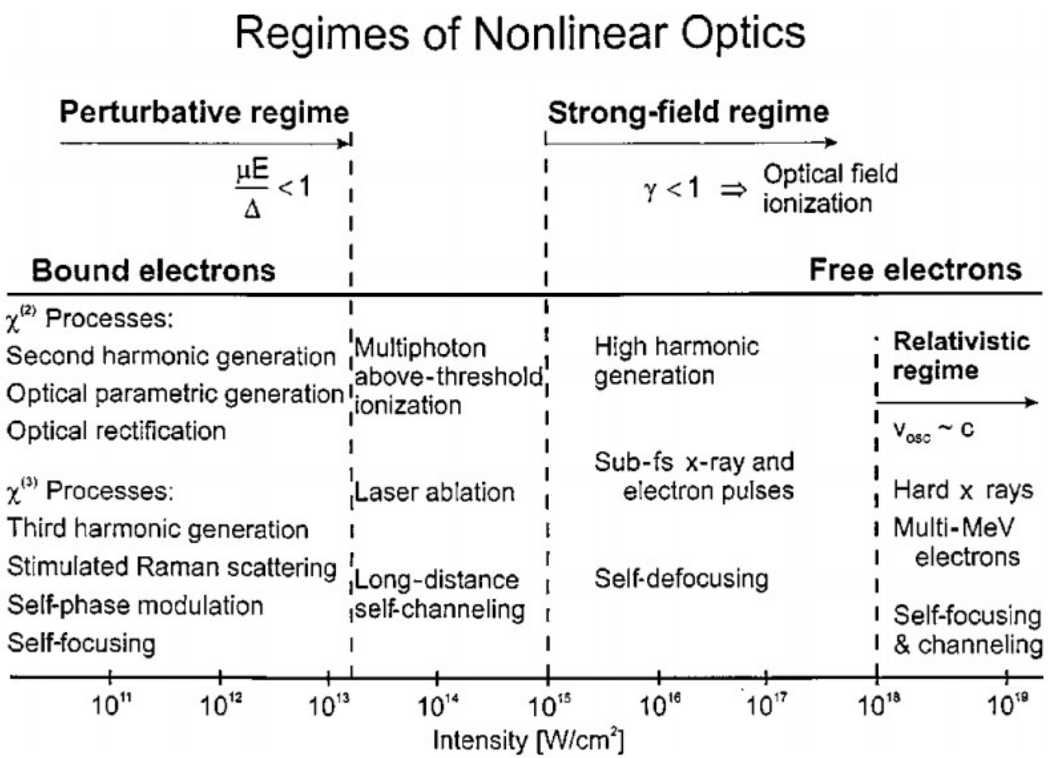
Short pulses ~ Length comparable to wavelength

Strong dependency CEP on the shape of the electric field near maximum Temporal profile

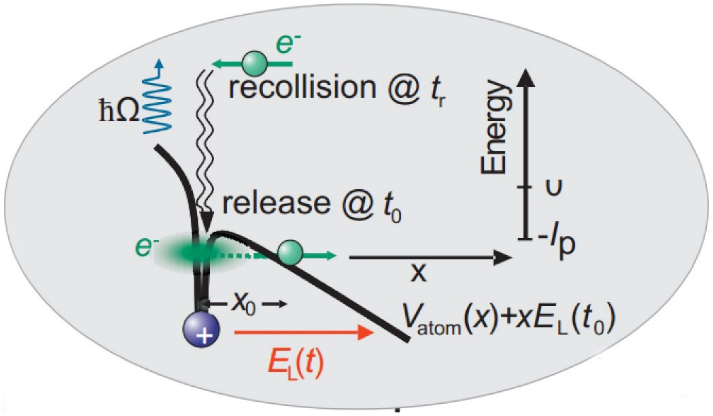


CEP : what's the deal?

- Interesing physics in the short pulse regime



T. Brabec & F. Krausz (2000)
https://doi.org/10.1103/RevModPhys.72.545



F. Krausz & M. Ivanov (2009)
https://doi.org/10.1103/RevModPhys.81.163

- CEP measurements for Intensities $<10^{15}$ W/cm^2

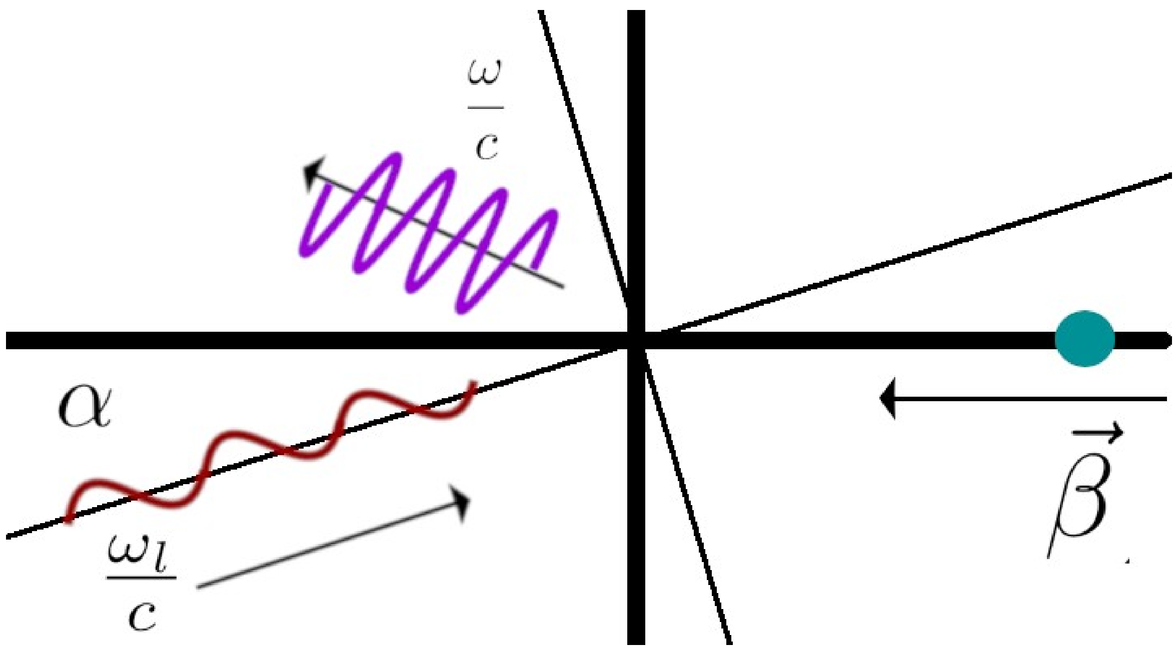
G.G. Paulus et al
https://doi.org/10.1103/PhysRevLett.91.253004

S. Fukahori
https://doi.org/10.1103/PhysRevA.95.053410

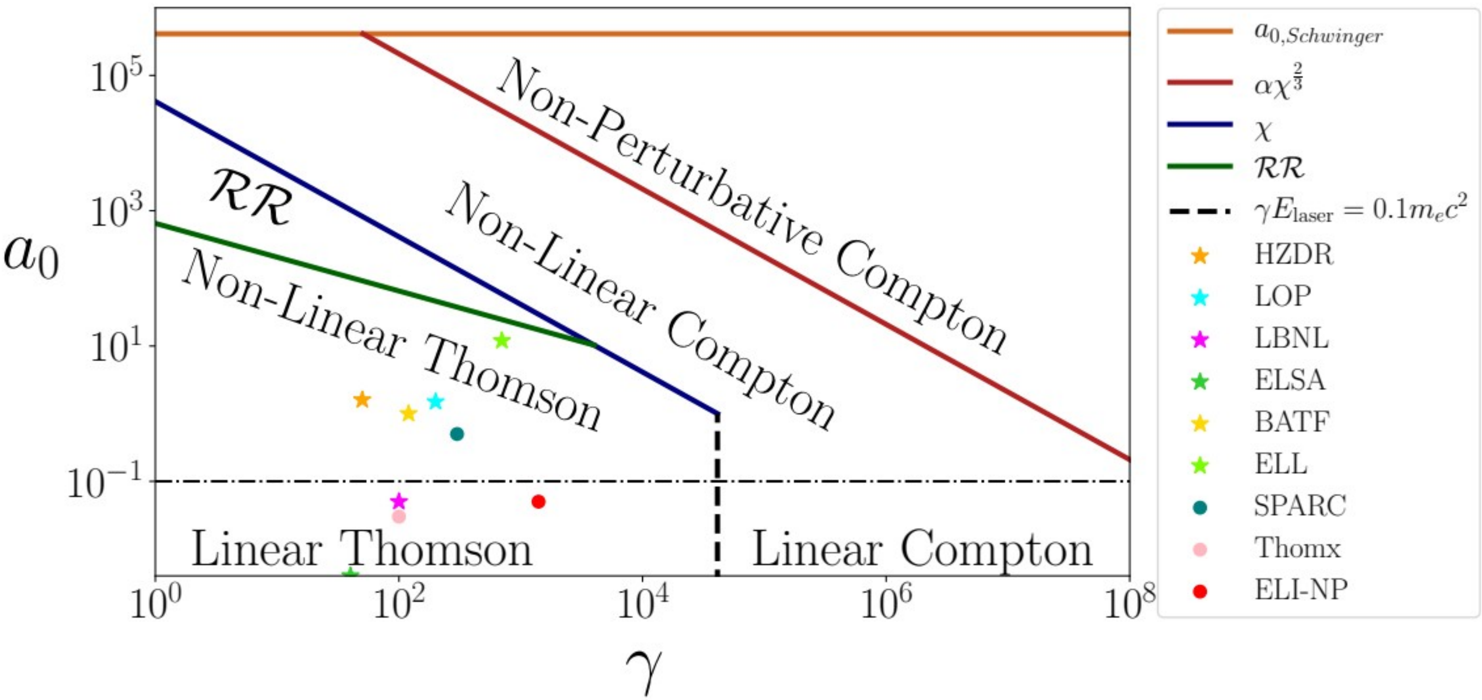
CEP : what's the deal?

Thomson scattering as diagnostic tool:

- Intensity profile of laser pulse
- CEP measurement



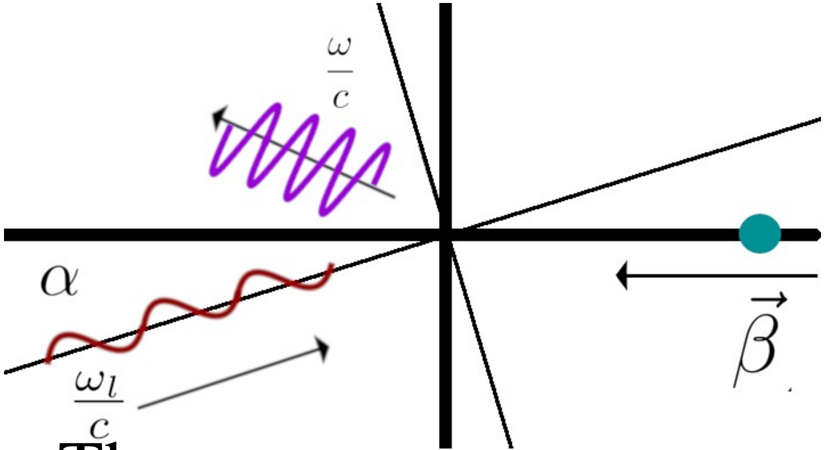
Energy regimes scattering processes



- J. Schwinger, Phys. Rev. 82, (5) 1951
- A. Fedotov, IOP: Conf. Ser. 826, 2017
- A.I. Nikishov and V.I. Ritus, Sov. Phys. JETP 19, 1964
- Y. Hadad et al, Phys. Rev. D 82, (9) 2010
- A. Di Piazza, Letters in Mathematical Physics 83, (3) 2008
- M. Ruijter et al, IOP 51, (22) 2018

B. Terzic et al
https://iopscience.iop.org/article/10.1209/0295-5075/126/12003/pdf

Thomson scattering



What does the linear & non-linear Thomson regime require?

- Energy loss particle due 1 photon collision

$$\frac{\hbar\omega_{\mathrm{lab}}\gamma}{mc^2} << 1$$

- Energy loss particle due field strength

$$\frac{\hbar\omega_{\mathrm{lab}}\gamma a_0}{mc^2} << 1$$

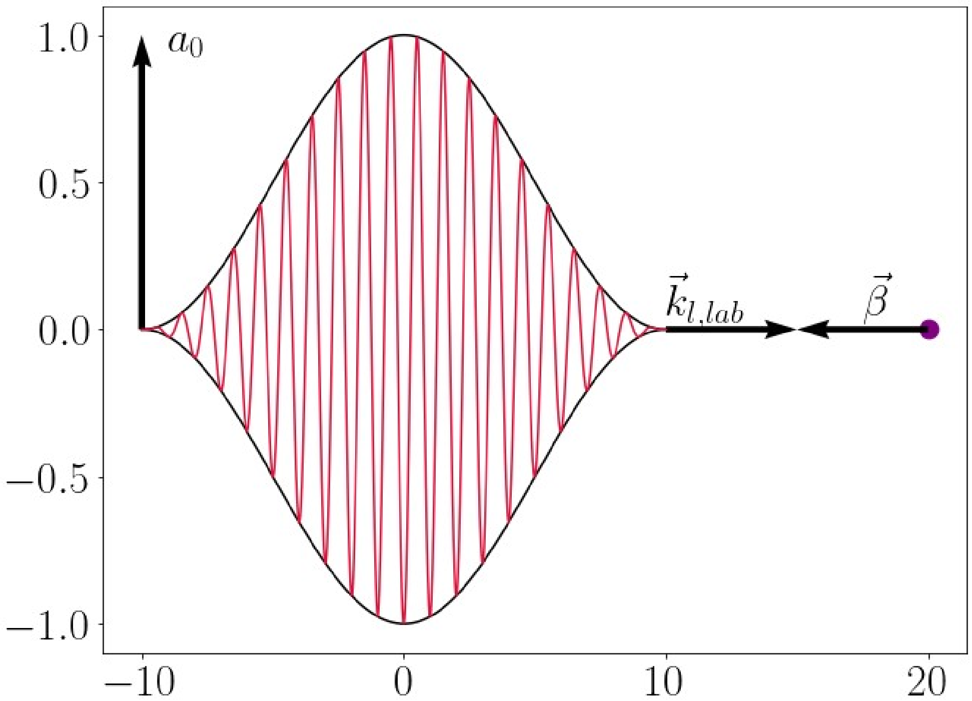
- Energy loss particle during all interaction

$$\tilde{\mathcal{E}}_{rad} a_0^2 N_c << 1$$

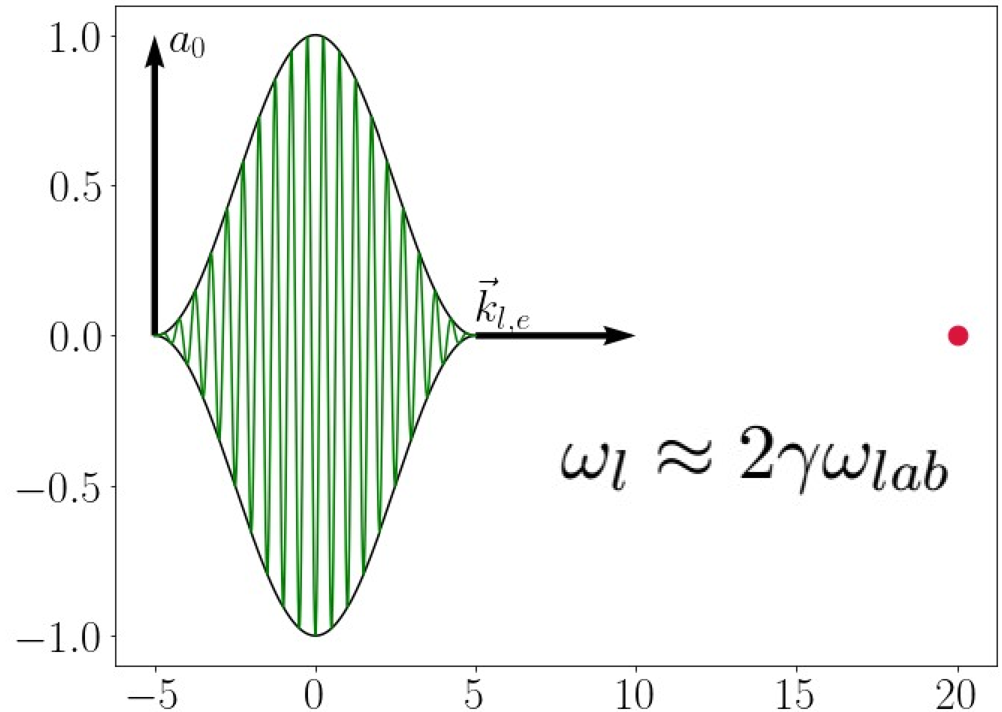
Solving the motion

Special relativity: No frame of reference is special

lab frame



frame e initialy at rest

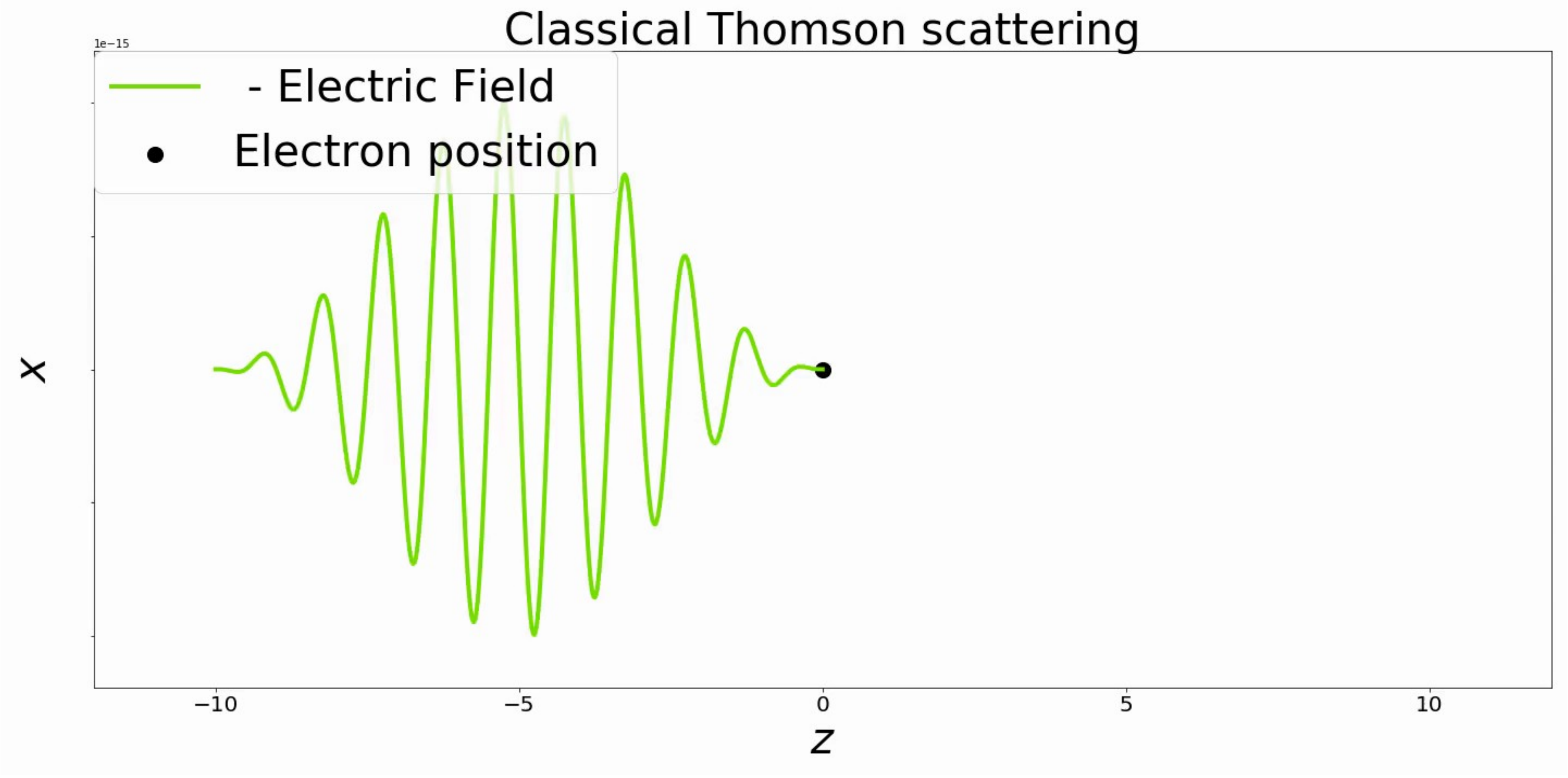


Lorentz invariants:

a_0 N_c

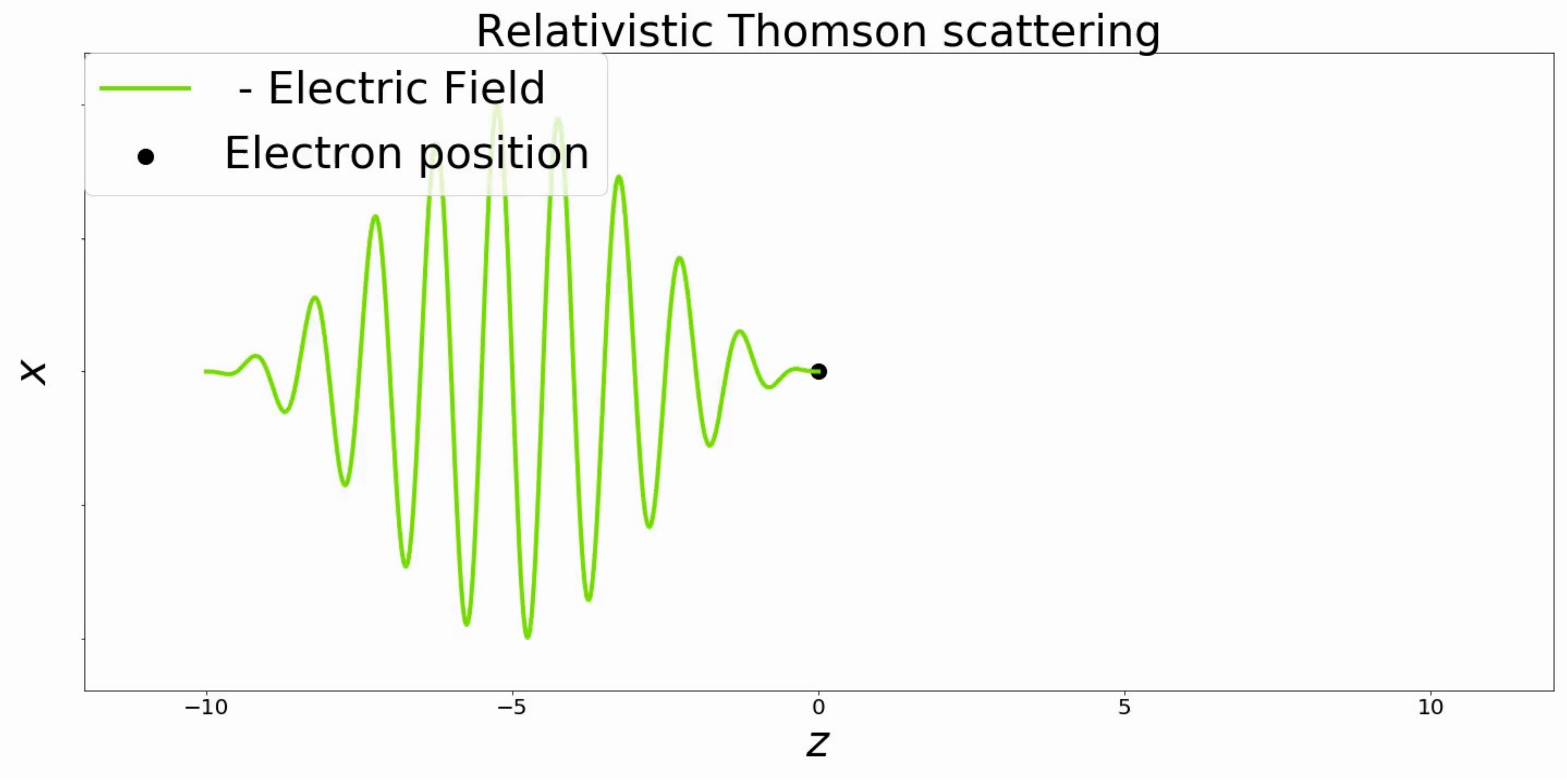
Solving the motion

Low intensity: a0 << 1



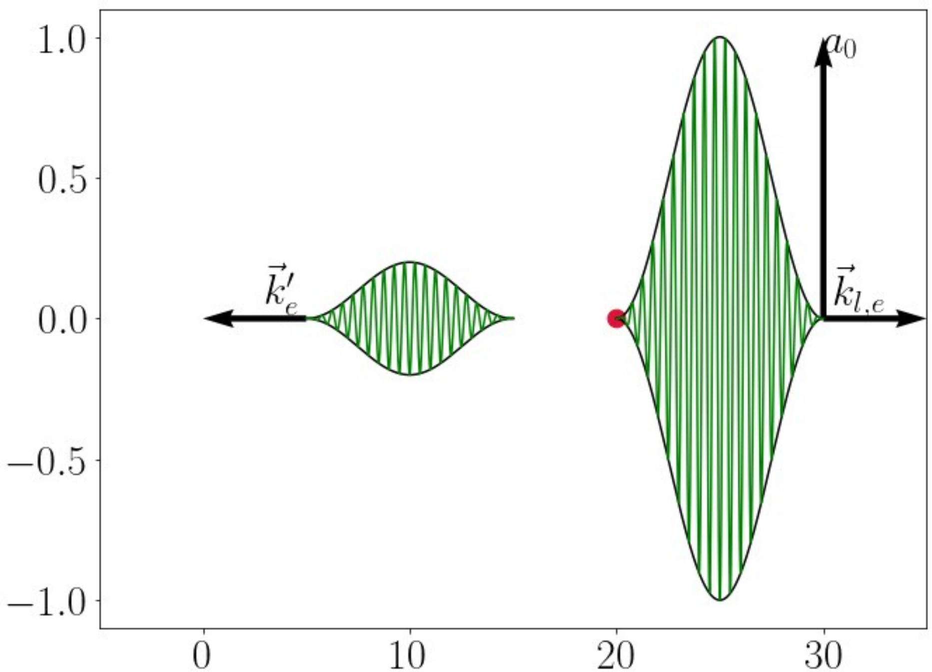
Solving the motion

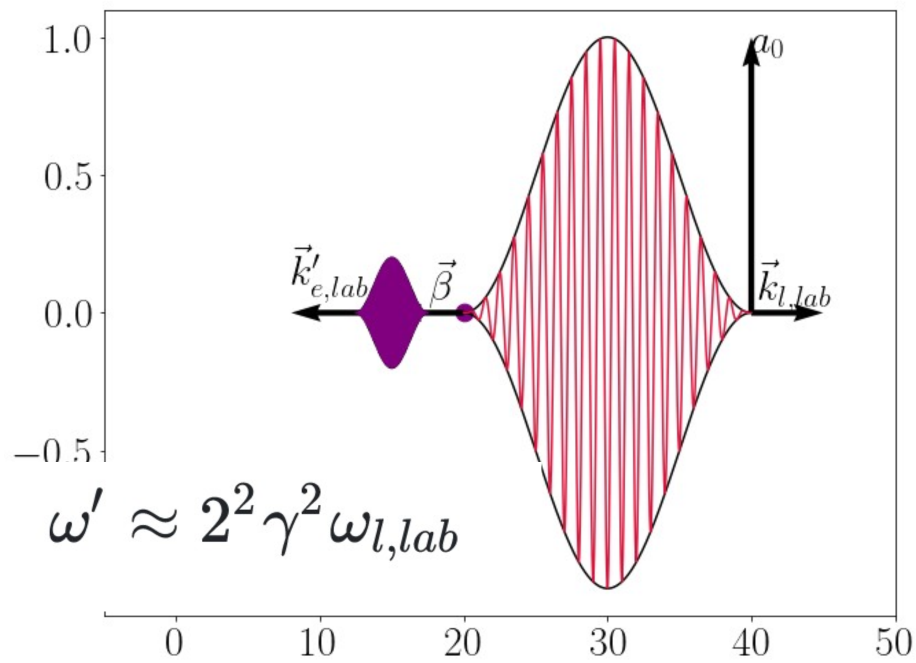
High intensity: a0>1



Solving the motion

Lorentz back transform gives second Doppler shift



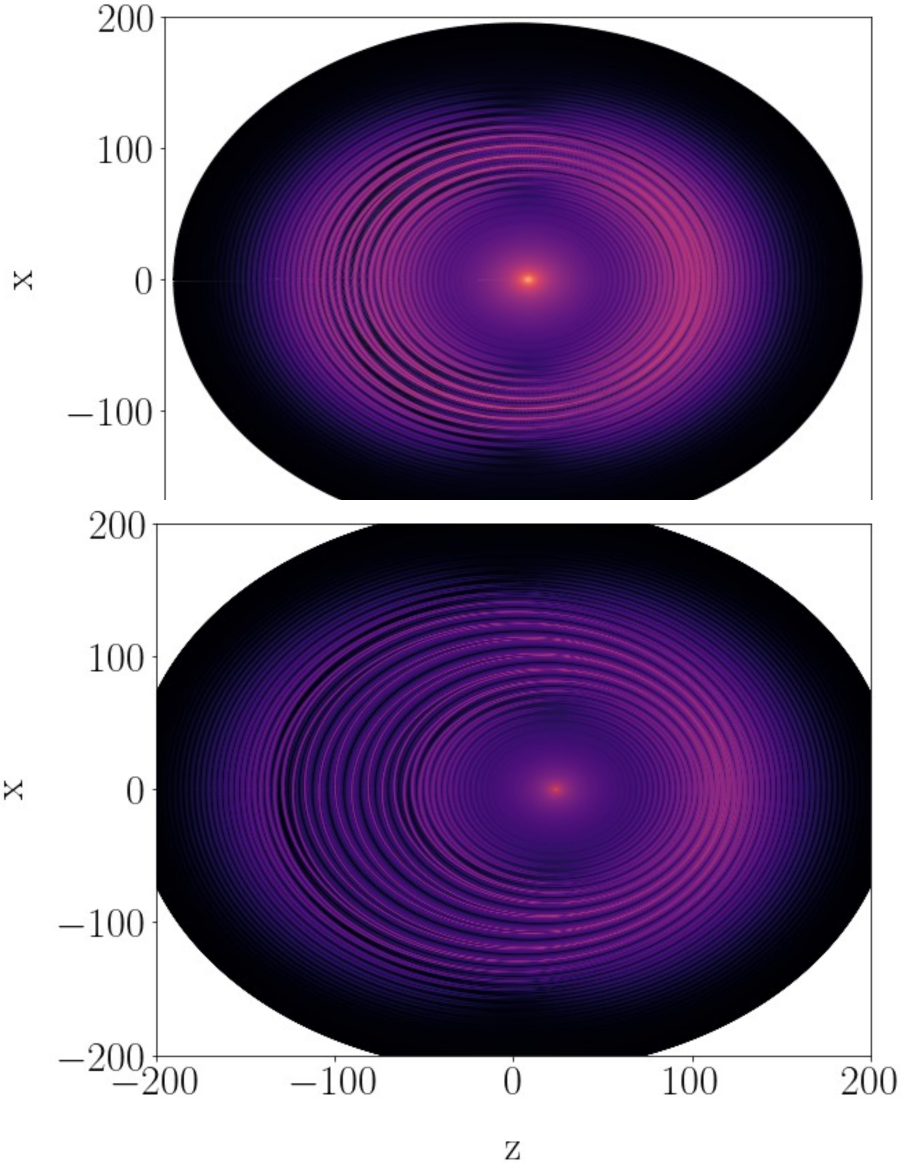


$$\omega' \approx 2^2\gamma^2\omega_{l,lab}$$

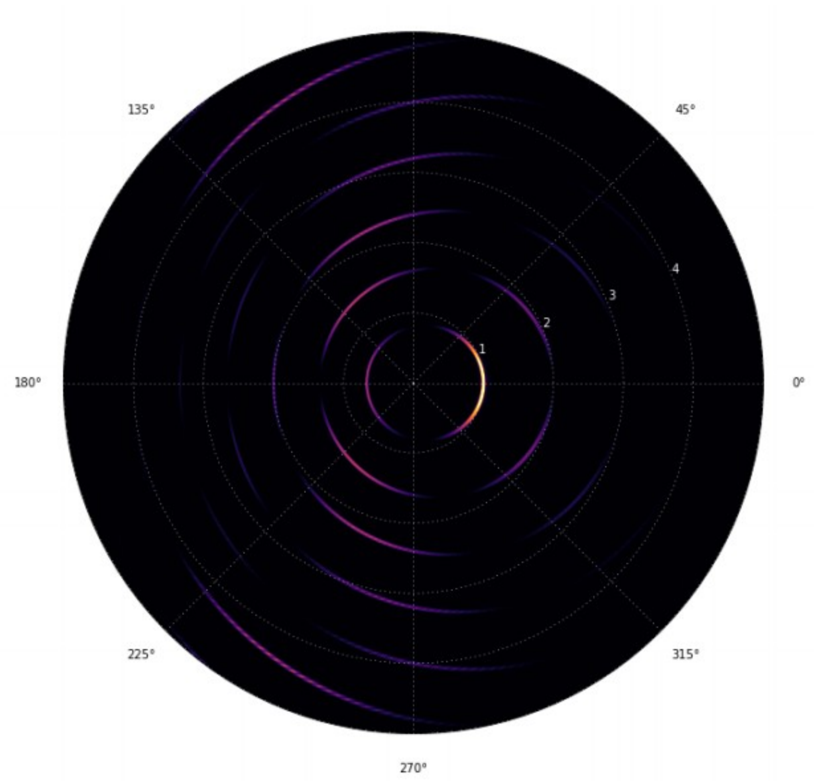
$$\nu = \frac{\omega}{2^2\gamma^2\omega_{l,lab}}$$

Emitted radiation

$\vec{E}\left(ct, \vec{r}\left(ct\right)\right)$



$$\frac{d^2 I}{d\omega d\Omega}$$



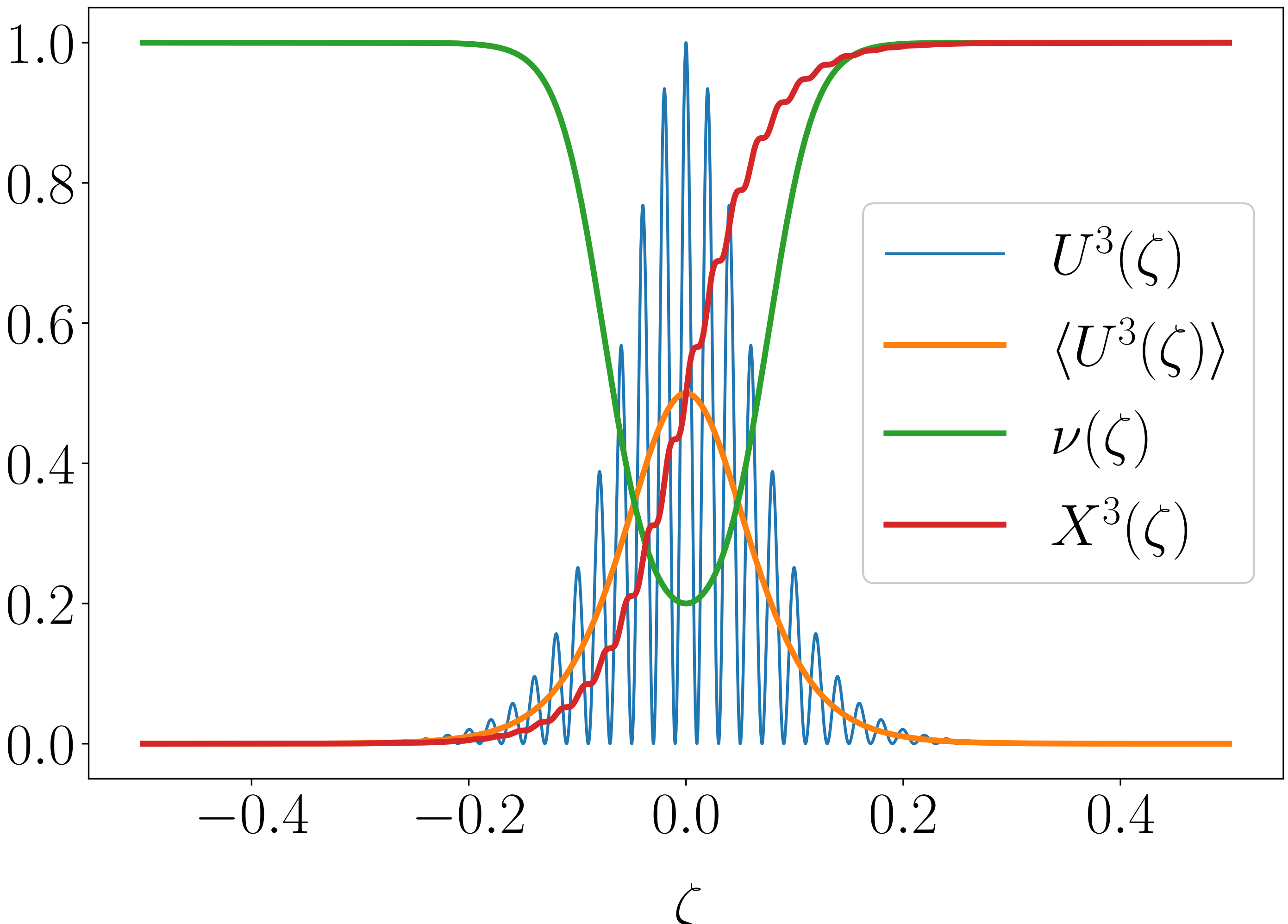
Emitted radiation from motion

$$\frac{d^2 I}{d\omega d\Omega} = \frac{e^2}{4\pi^2 c}\left|\omega \int_{-\infty}^{\infty} dt\ \hat{n} \times \hat{n} \times \vec{\beta}_i \exp\left[i\ \frac{\omega}{c}(ct - \hat{n} \cdot \vec{r}_i)\right]\right|^2$$

$$\frac{d^2 I}{d\omega d\Omega} = \frac{e^2}{4\pi c}\left|\sum_{\mathcal{H}} \int d\zeta\ G_{\mathcal{H}}\left(\zeta, \nu\right) \exp\left[iF_{\mathcal{H}}\left(\zeta, \nu\right)\right]\right|^2$$

Emitted radiation from motion

$$\frac{d^2 I}{d\omega d\Omega} = \frac{e^2}{4\pi c} \left| \sum_{\mathcal{H}} \int d\zeta \; G_{\mathcal{H}}\left(\zeta, \nu\right) \exp\left[i F_{\mathcal{H}}\left(\zeta, \nu\right)\right] \right|^2$$



$$\frac{d}{d\zeta} F_{\mathcal{H}} = \mathcal{H} + \nu \left(1 + \langle U^3 \rangle\right)$$

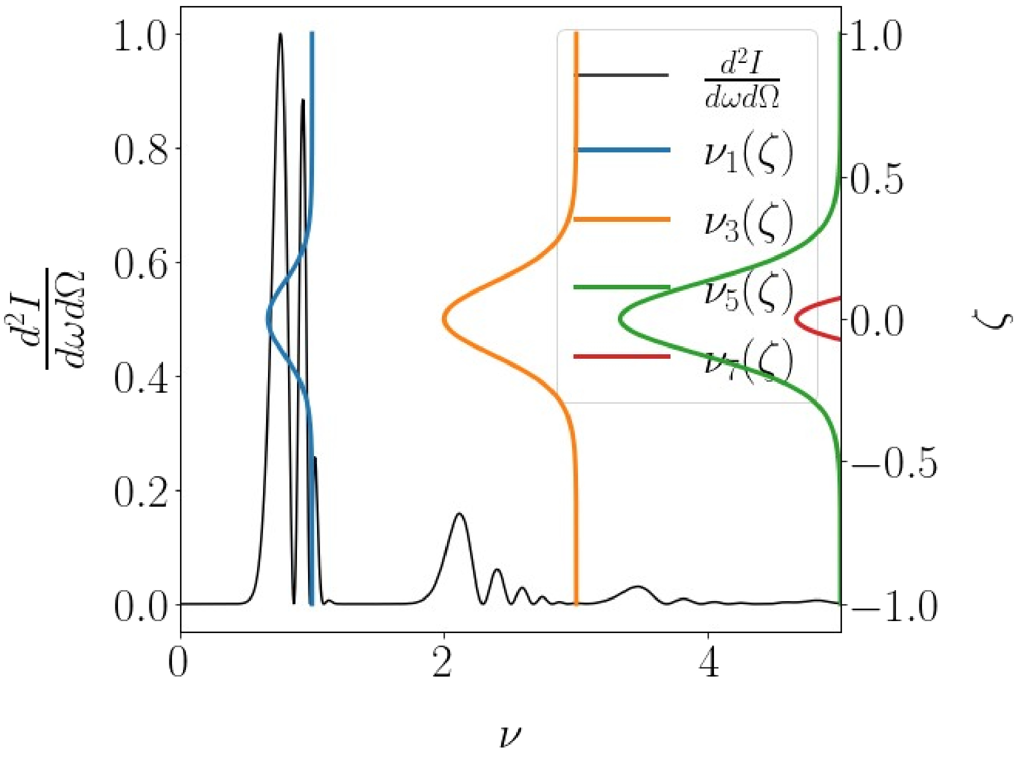
Analytical description of emitted radiation:
S. G. Rykovanov et a. - Phys. Rev. Accel. Beams 19, 030701 (2016)

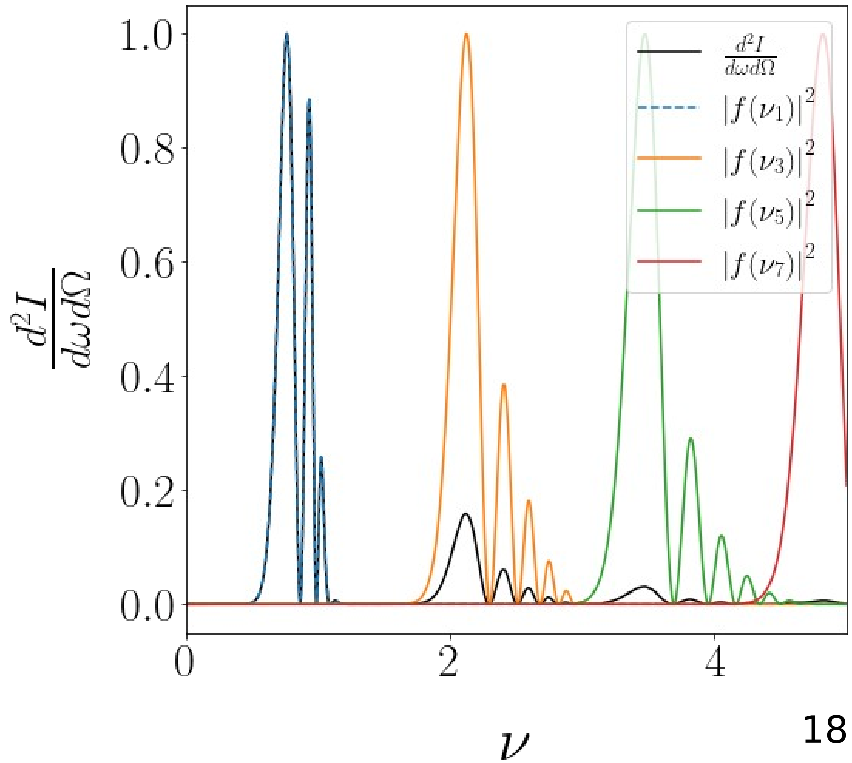
$$G_{\mathcal{H}} \propto \exp\left[i \mathcal{H} \phi_{cep}\right]$$

Sinlge electron – on-axis radiation

a0 << 1 $$|f_{\nu_1}|^2 + |f_{\nu_3}|^2 + \ldots.$$

CEP: global phase, not visible



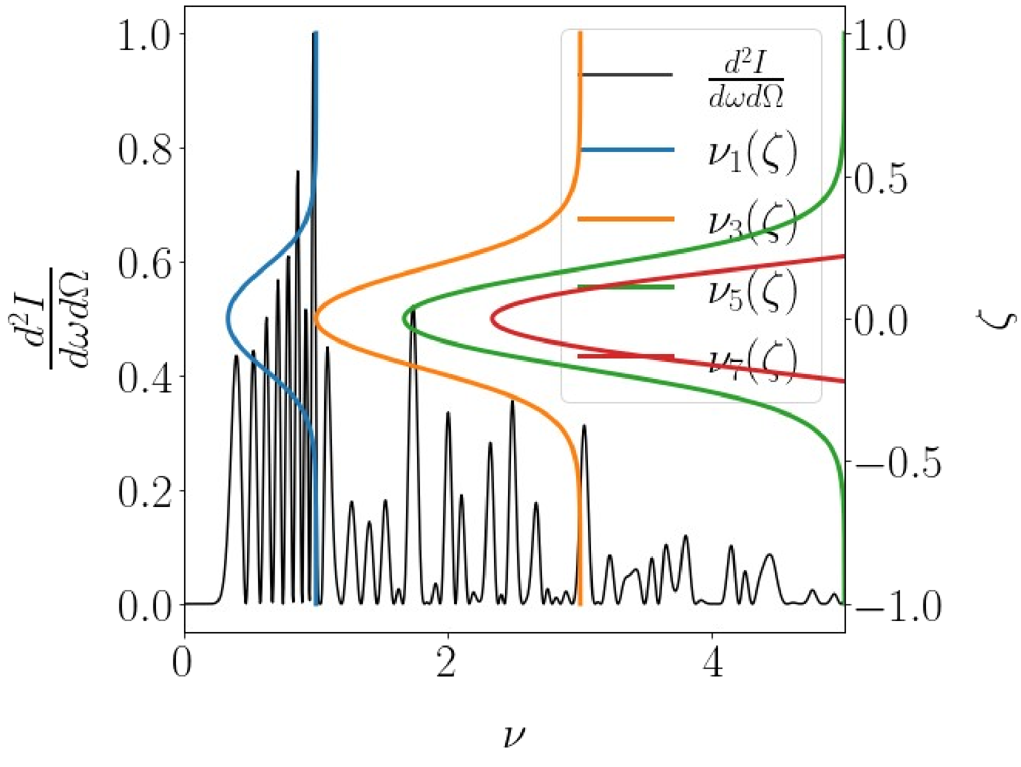


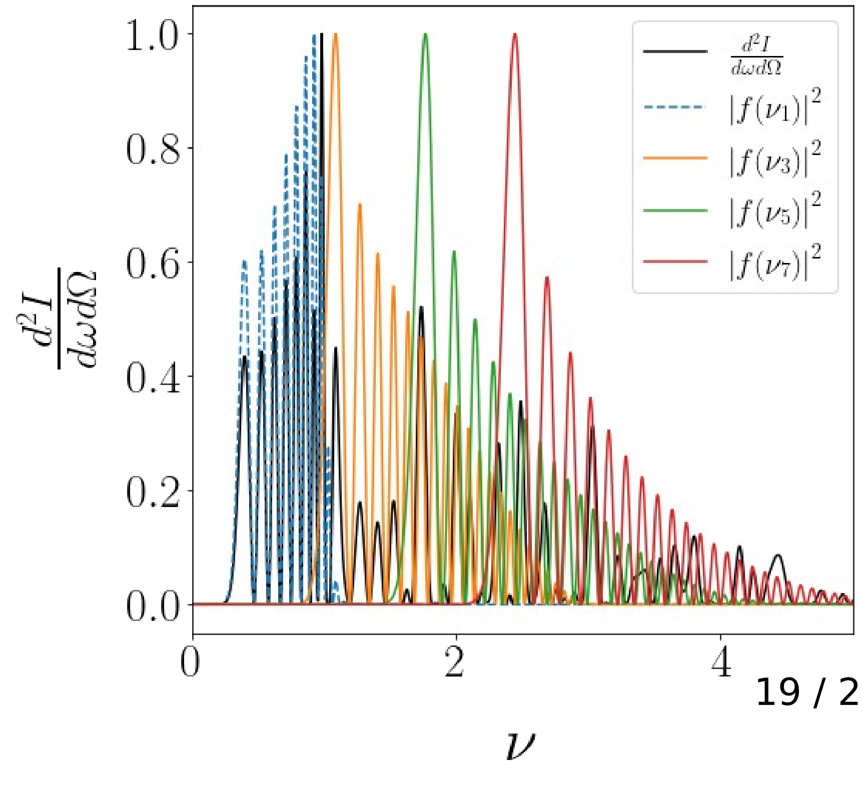
Sinlge electron – on-axis radiation

a0~1: Harmonics start to overlap

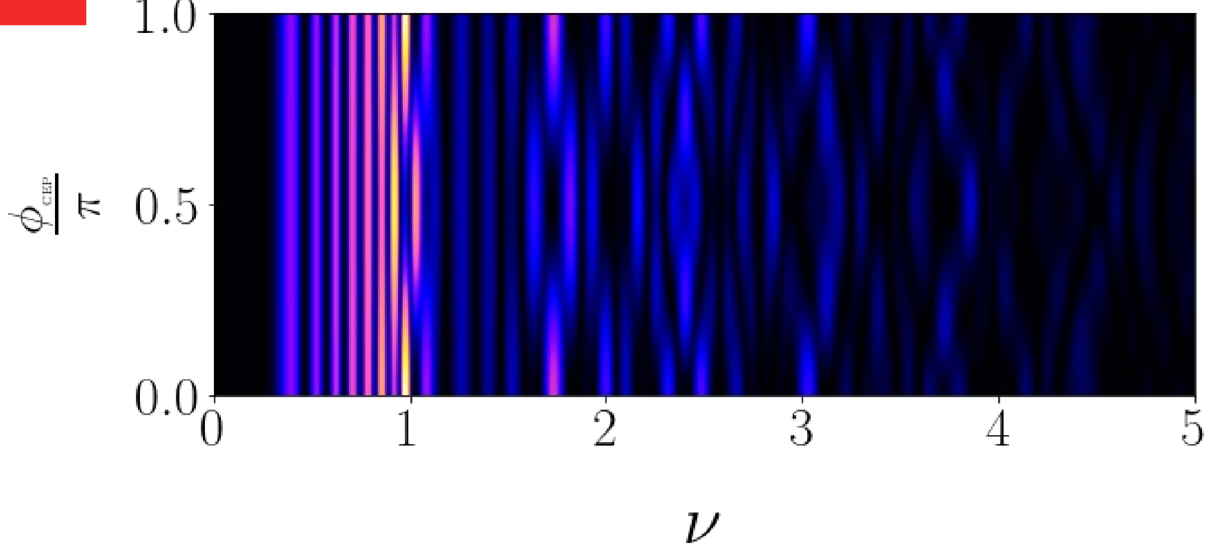
$$a_{0\Delta\mathcal{H}} = \sqrt{2\frac{\mathcal{H}_j - \mathcal{H}_i}{\mathcal{H}_i}}$$

$$|f_{\nu_1}|^2 + 2\mathcal{R}e\left(f_{\nu_1} f_{\nu_3}^*\right) + |f_{\nu_3}|^2 + \cdots$$

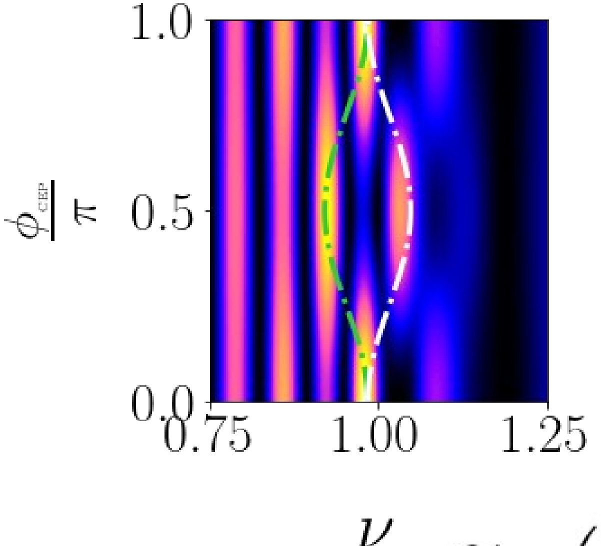


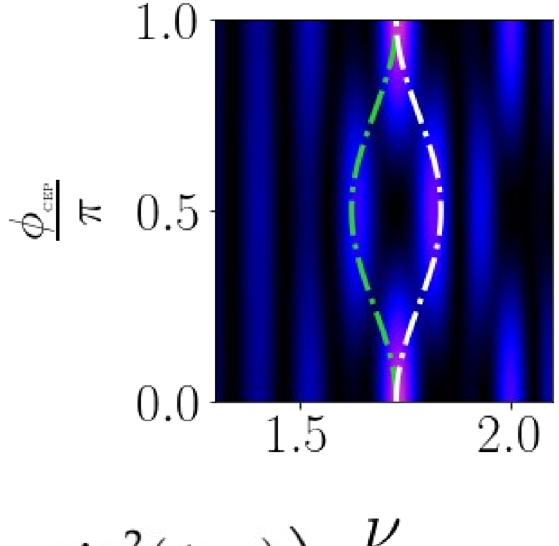


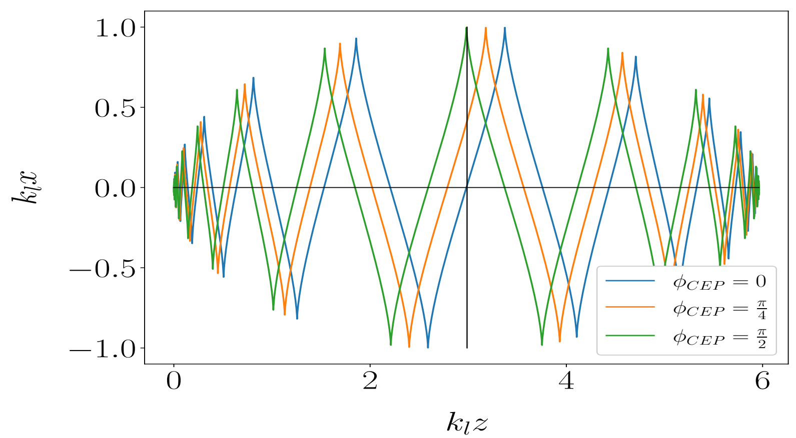
Sinlge electron – on-axis radiation



- Amplitude of a harmonic peak changes
  → position of the peak scales with



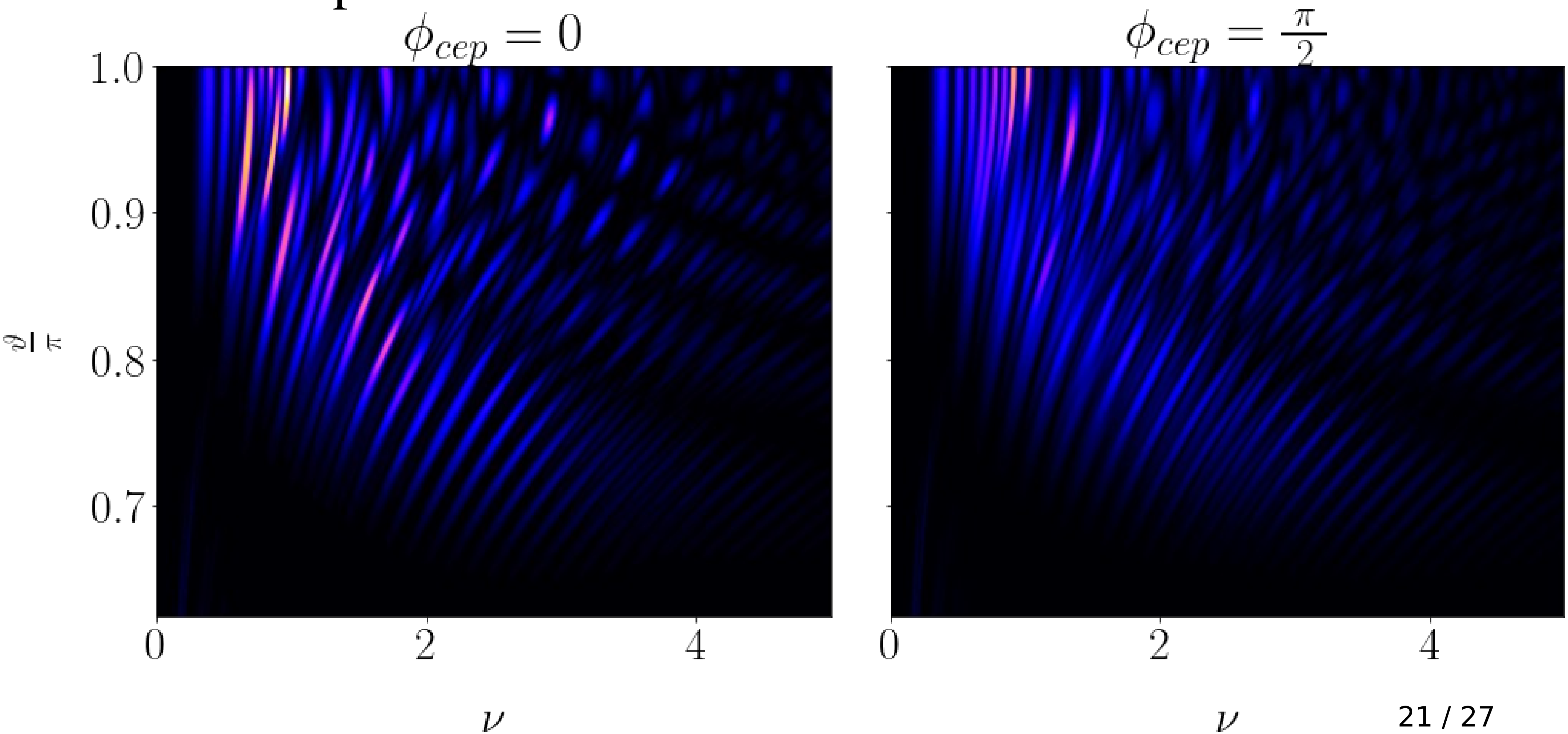




$$\nu_{\mathcal{H},cep} \propto \frac{\mathcal{H}}{1+\frac{a_0^2}{2}}\left(1 \pm \frac{\sin^2(\phi_{cep})}{\pi N_c}\right)$$

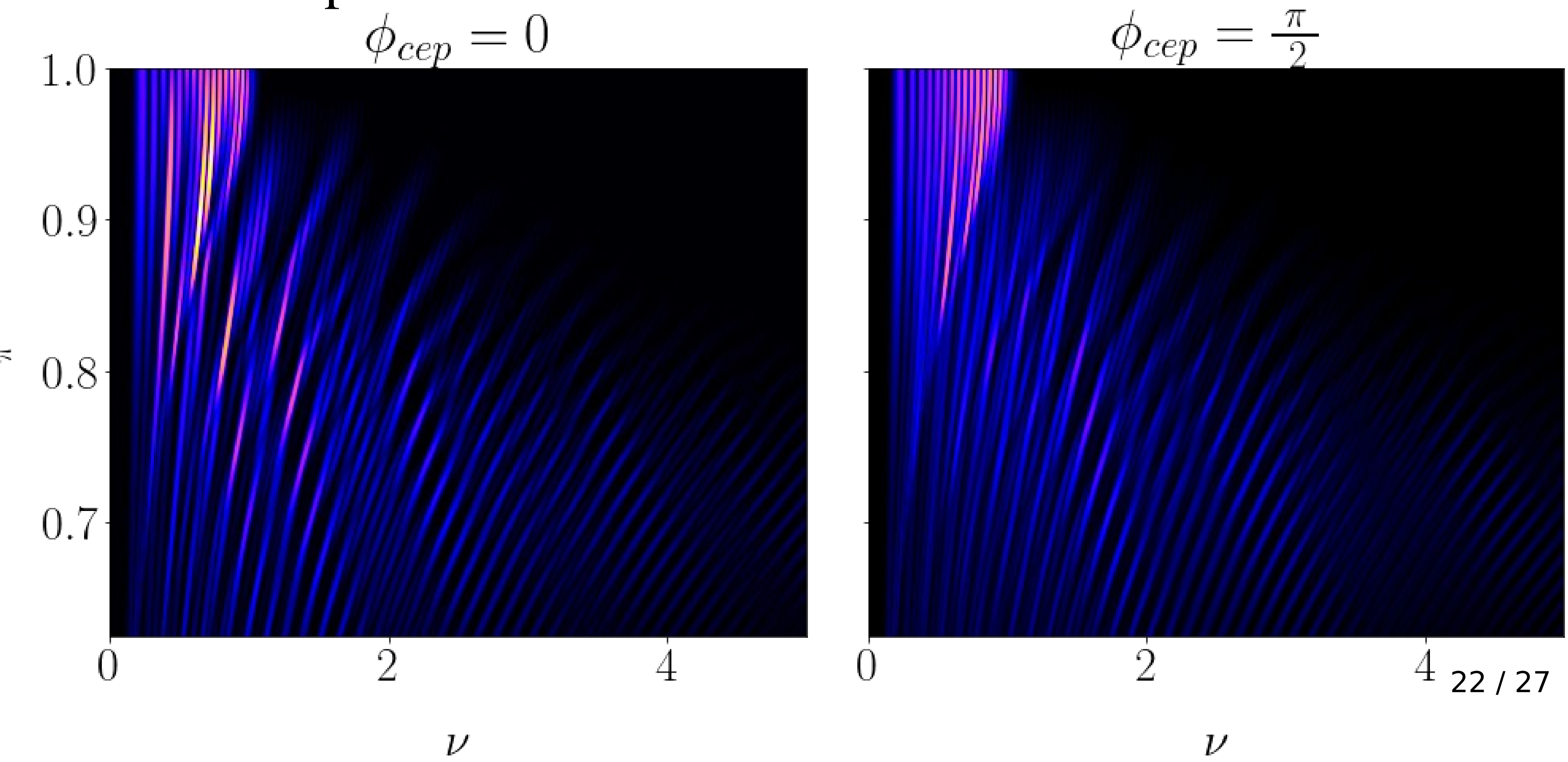
Single electron – off axis

- Linear polarization



Single electron – off axis

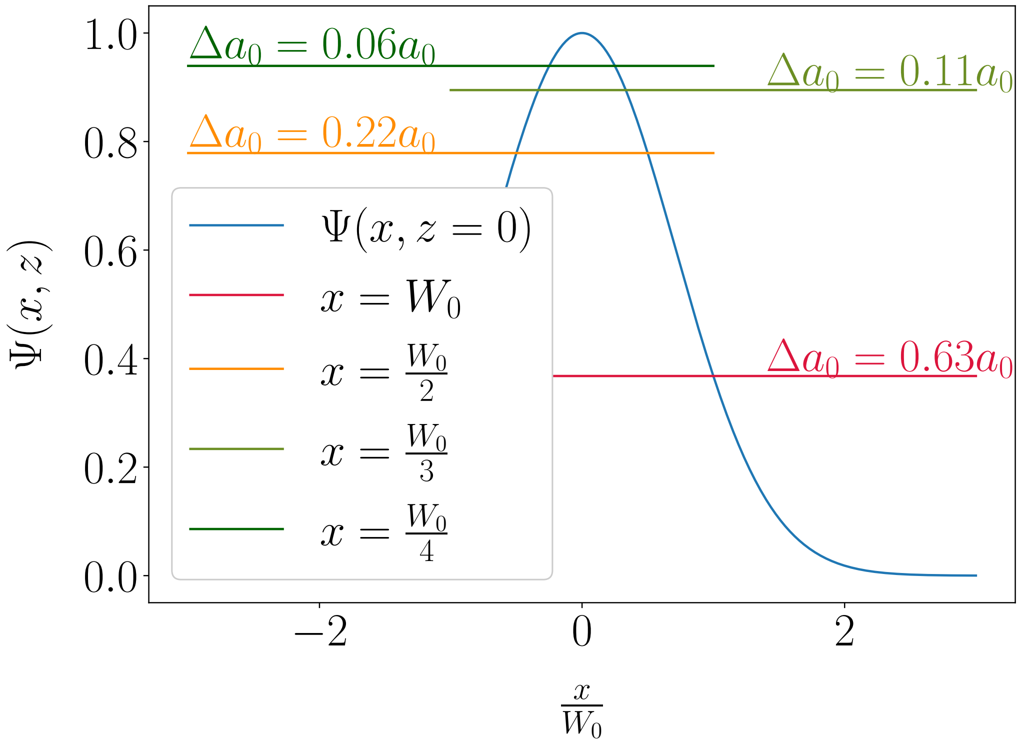
- Also for ciruclar polarization effect visible: harmonics overlap off axis!

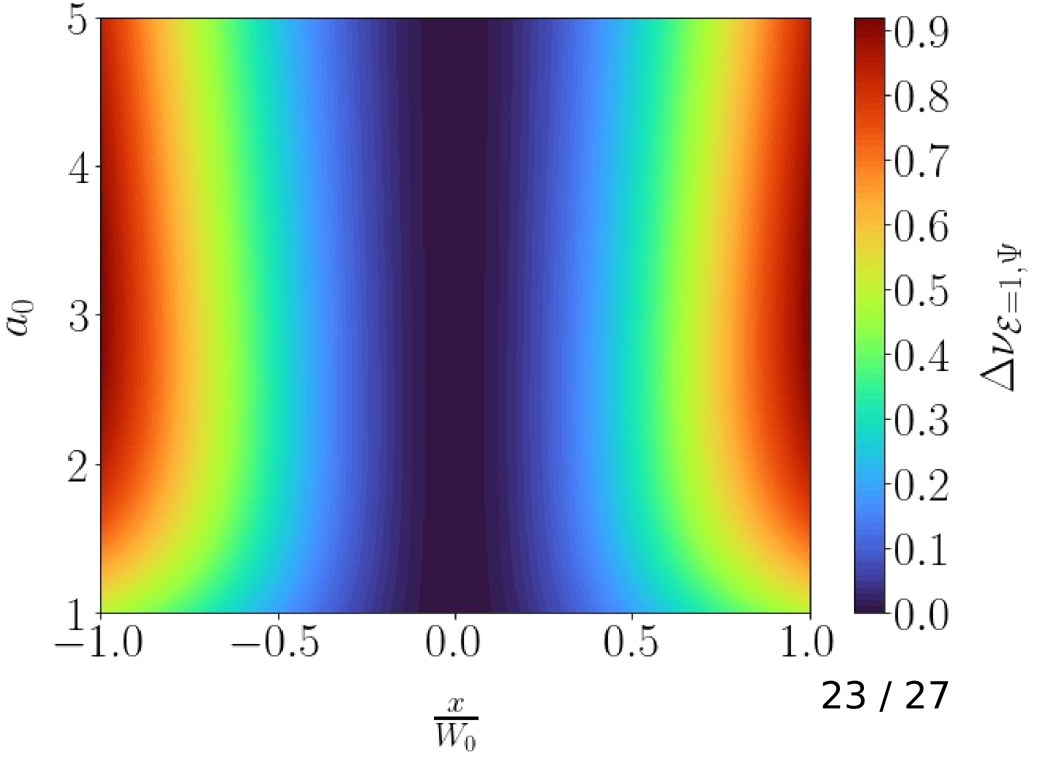


Bunch – 3D pulse

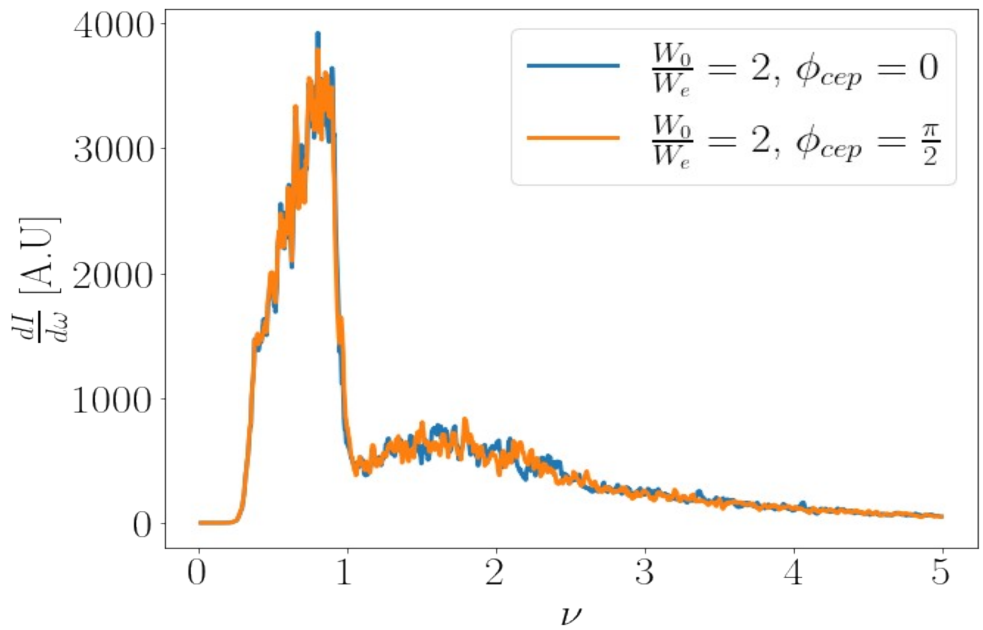
Electrons experience different intensities depending on their transverse position

$$\Delta\nu_{\mathcal{E}=1,\Psi} = \frac{\frac{a_0^2}{2}}{1+\frac{a_0^2}{2}}\frac{1-\Psi^2}{1+\frac{a_0^2\Psi^2}{2}}$$



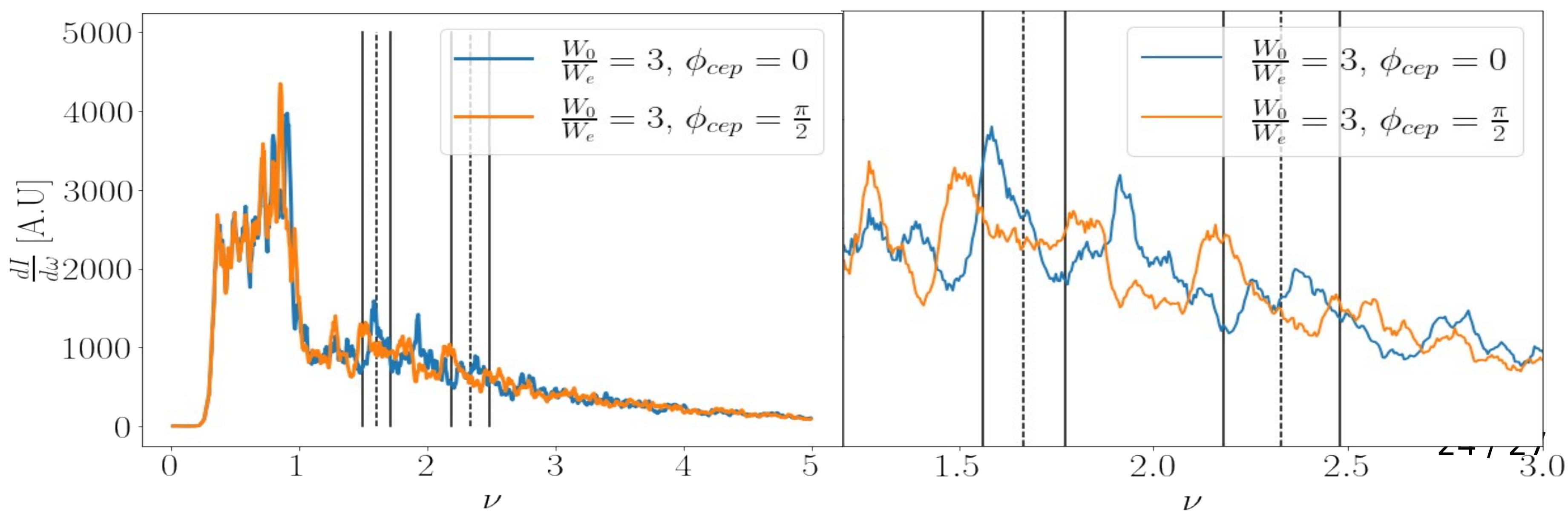


Bunch – 3D pulse



$$\nu_{\mathcal{H},cep} \propto \frac{\mathcal{H}}{1+\frac{a_0^2}{2}}\left(1 \pm \frac{\sin^2(\phi_{cep})}{\pi N_c}\right)$$

5[th] and 7[th] harmonics



Conclusion

- Analytical description how CEP influences Thomson spectrum:

$$\text{interval for } \phi_{cep} : \left[0, \frac{\pi}{2}\right] + k\pi$$

  - Single electron – Plane wave
    - Shift harmonic peaks $\nu_{\mathcal{H},cep} \propto \frac{\mathcal{H}}{1+\frac{a_0^2}{2}}\left(1 \pm \frac{\sin^2(\phi_{cep})}{\pi N_c}\right)$
  - Electron bunch – 3D pulse
    - Ratio laser – electron beam waist to ommit nonlinear broadening $\frac{W_0}{W_e} \geq 3$

Gaussian Laser Beams with Radial Polarization

Kirk T. McDonald
Joseph Henry Laboratories, Princeton University, Princeton, NJ 08544
(March 14, 2000; updated December 2, 2012)

$$\nabla^2 \mathbf{A} = \frac{1}{c^2} \frac{\partial^2 \mathbf{A}}{\partial t^2}.$$

$$A_j(\mathbf{r}, t) = \psi(r_\perp, z) g(\varphi) e^{i\varphi},$$

$$\nabla^2 \psi + 2ik \frac{\partial \psi}{\partial z} \left(1 - \frac{ig'}{g}\right) = 0,$$

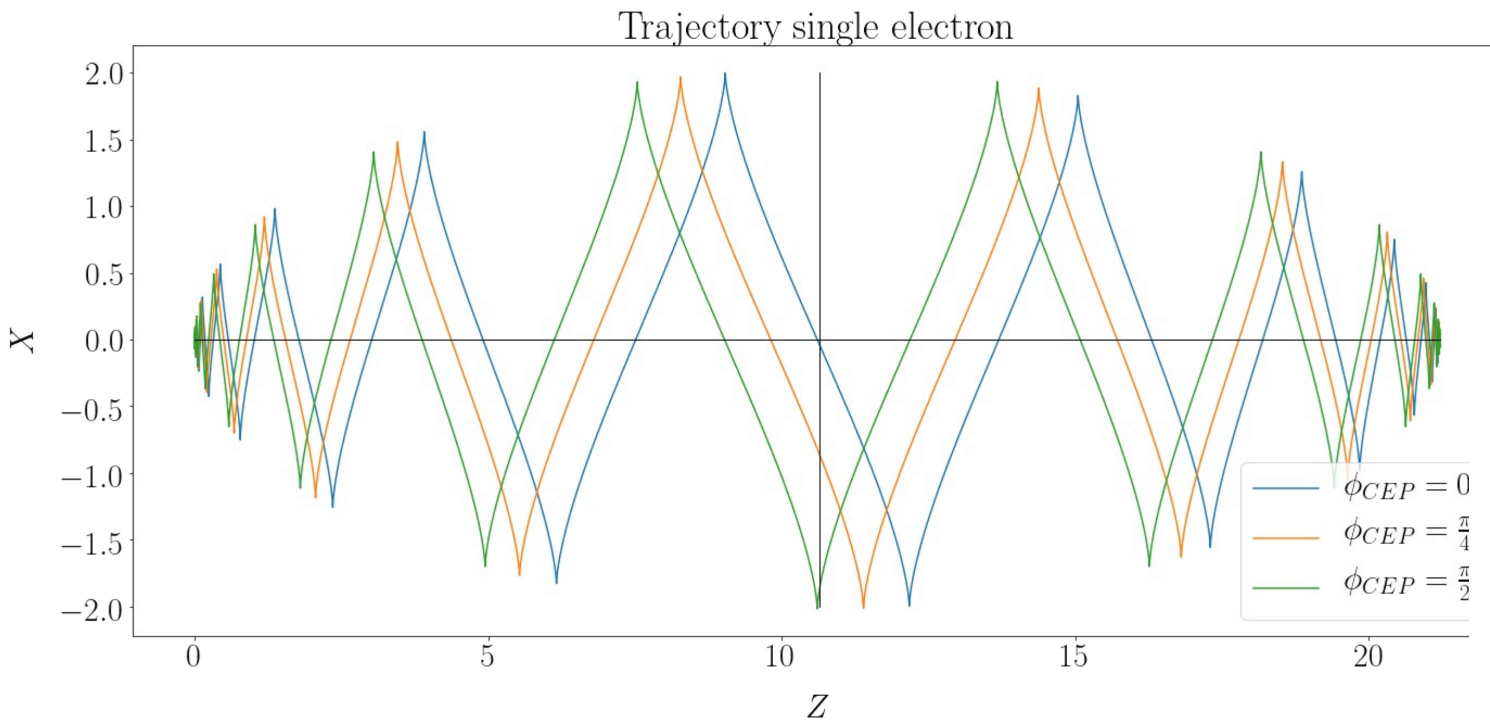
For a pulsed laser beam, g must obey

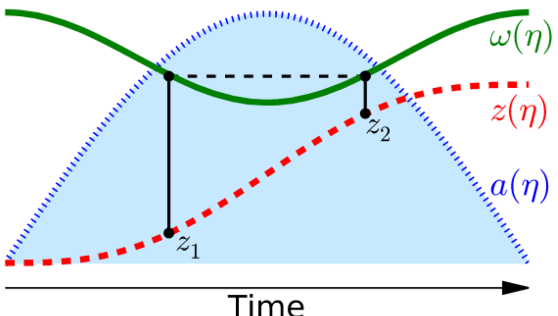
$$\left|\frac{g'}{g}\right| \ll 1$$

A more appropriate form for a pulsed beam is a hyperbolic secant
solitons):

$$g(\varphi) = \text{sech}\left(\frac{\varphi}{\varphi_0}\right).$$

CEP Dependence on Trajectory





Rykovanov et a. - Phys. Rev. Accel. Beams 19, 030701 (2016)

- Rectangular envelope function is not affected
- Short pulses: single/few maxima of cosine near peak intensity → large effect CEP on acceleration
- Long pulses: multiple maxima of cosine near peak intenity → minor effect of CEP