Radiation effects for the next generation of synchrotron radiation facilities

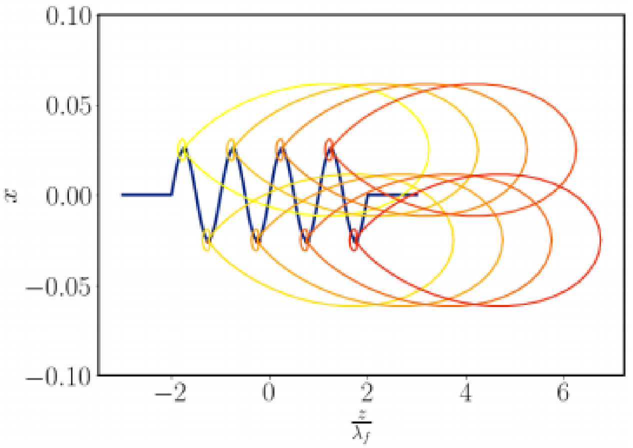
PhD Defence

Marcel Ruijter ,
Matricola 1842024
Cycle XXXIV

Supervisors: Luca Serafini
Vittoria Petrillo

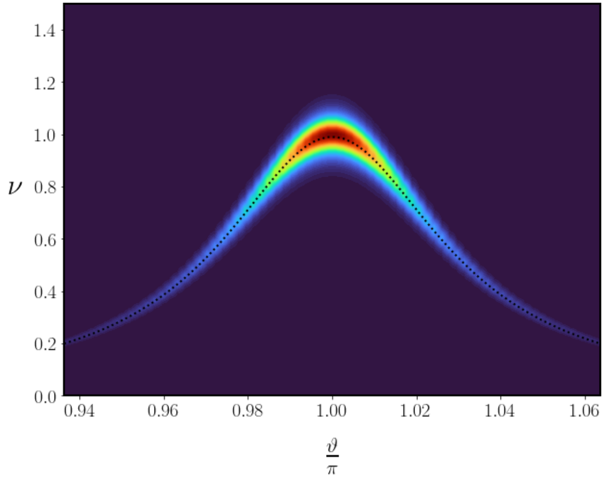
Generation of narrow bandwidth Synchrotron radiation

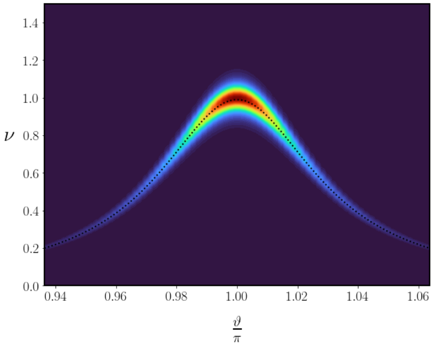
- Undulator / FEL
- Thomson Scattering



$$\langle P_{ower} \rangle \propto \gamma^2 U_{field}$$

$$\langle \lambda \rangle \propto \frac{\lambda_f}{\gamma^2}$$



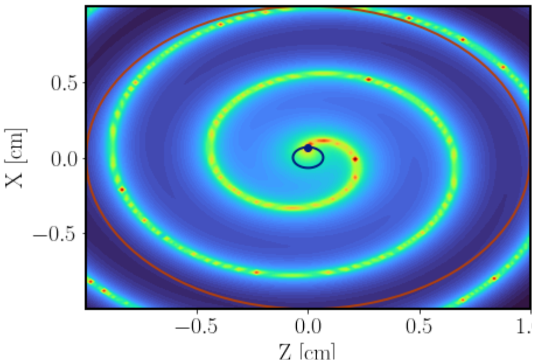


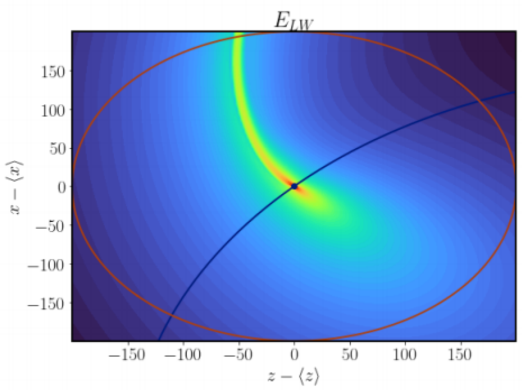
$$\langle P_{ower} \rangle \propto \gamma^2 U_{field}$$

$$\langle \lambda \rangle \propto \frac{\lambda_f}{\gamma^2}$$

	Electron Energy for FEL	Electron Energy for Thomson Scattering
eV – > 1 μm : Macroscale Material properties, Biological & Chemical processes	~50	-
keV – <nm : Medical treatment, invivo imaging, nuclear & atomic research	$\sim 10^3$	~ 50
MeV - <pm : Astro-, Quantum & Hadron physics	$\sim 10^5$	$\sim 10^3$

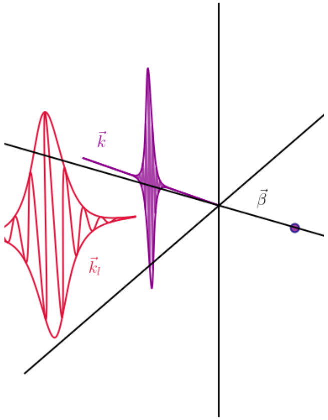
I. Self-fields

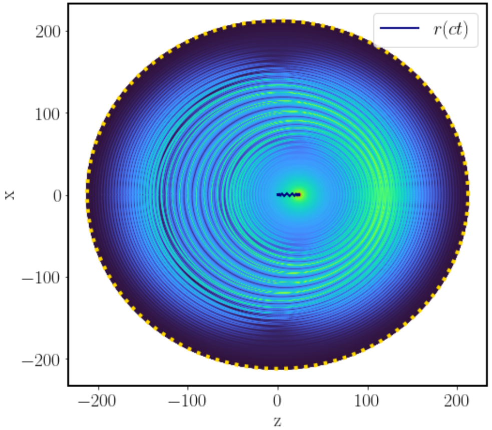




- Retarded time
- Models
  - 1D
  - 2D
  - 3D

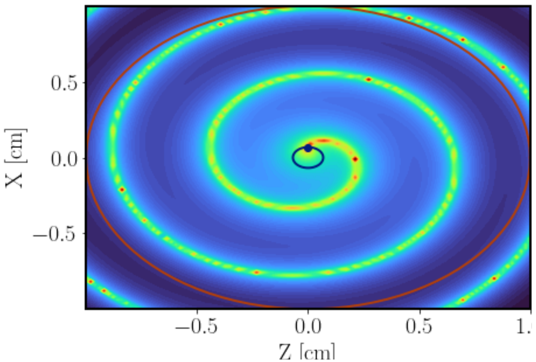
II. Thomson scattering

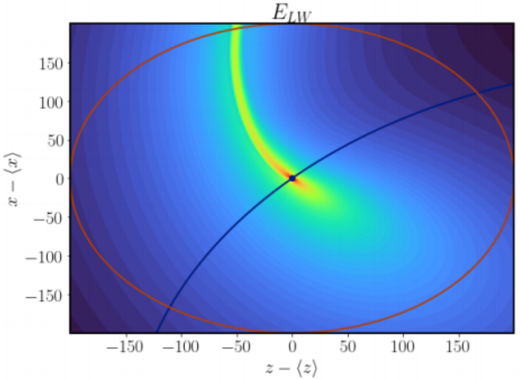




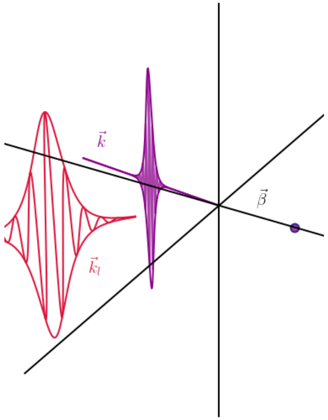
- Degenerate Cavity
- Energy Compensation
- Carrier Envelope Phase

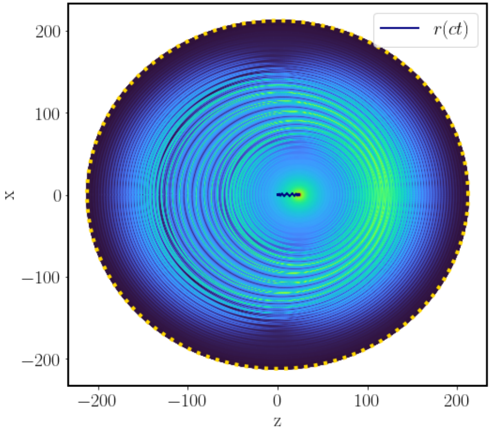
I. Self-fields





II. Thomson scattering





Lienard Wiechert Potentials

$$\vec{E}_{LW} = \vec{E}_{Coulomb} + \vec{E}_{Radiation}$$

$$c$$

I. Self fields

FEL

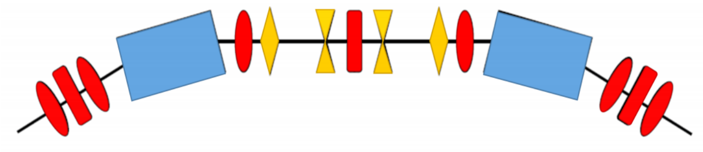
- Current km size – LINAC – to reach energy
- High brightness for radiation-bunch interaction
- High coherency ⇔ power $\propto N_e^{4/3}$

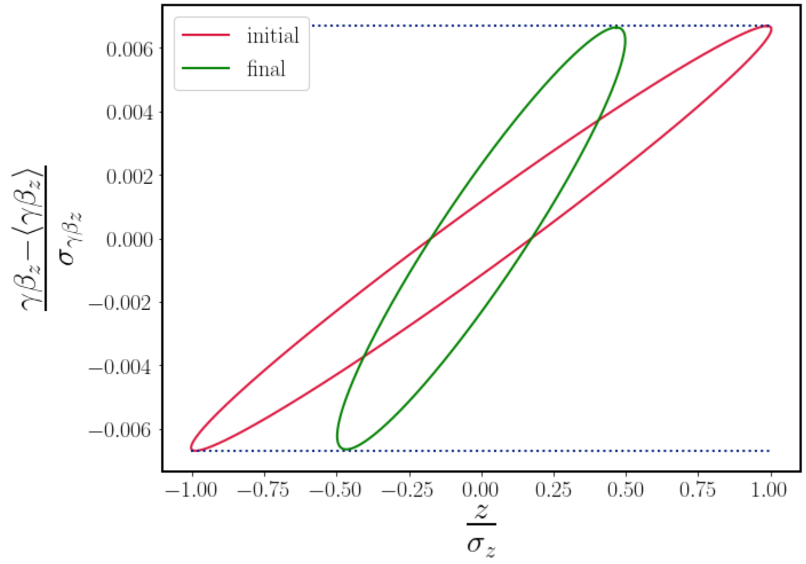
FEL

- Current km size – LINAC – to reach energy
- High brightness for radiation-bunch interaction
- High coherency ⇔ power $\propto N_e^{4/3}$

⇒ Compression

DBA



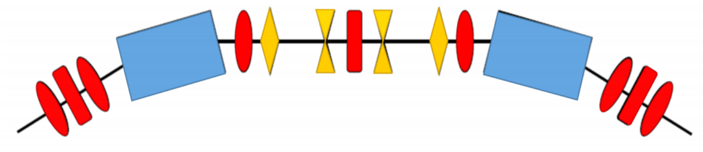


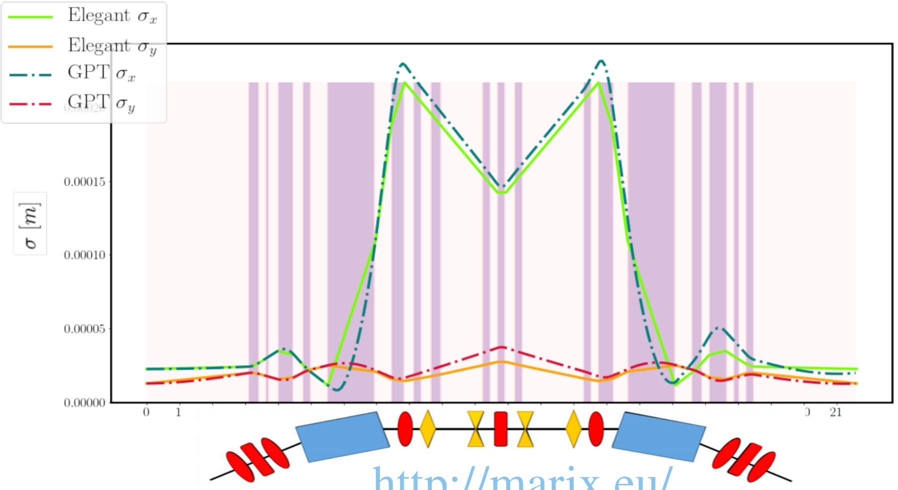
FEL

- Current km size – LINAC – to reach energy
- High brightness for radiation-bunch interaction
- High coherency ⇔ power $\propto N_e^{4/3}$

⇒ Compression

DBA





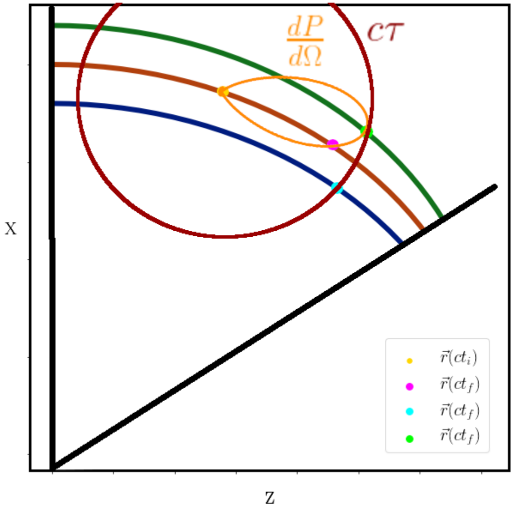
http://marix.eu/

Derbenev 1995,
Saldin 1997

Focus on wakefield (total electric field)

Criteria of applicability

$$\frac{R}{\gamma^3} \ll \sigma_z \qquad \frac{\sigma_r}{\sigma_z} \ll \left(\frac{R}{\sigma_z}\right)^{\frac{1}{3}}$$



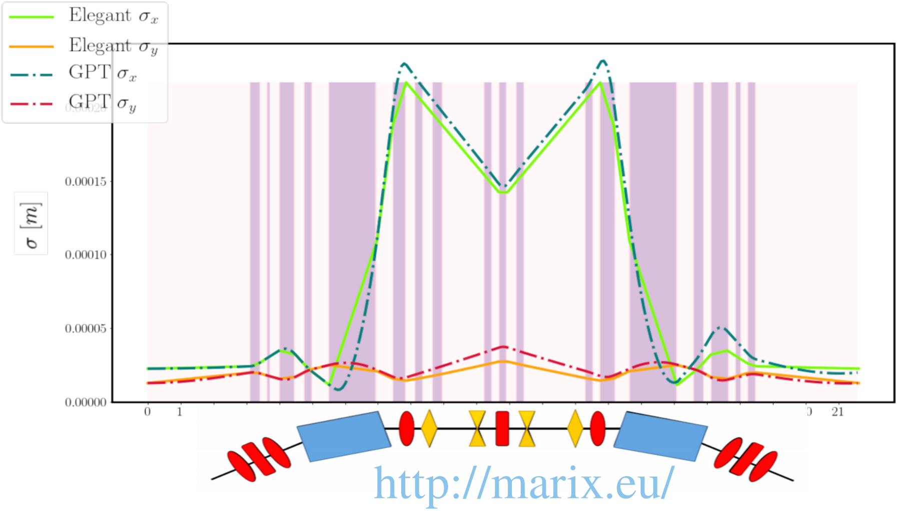
Derbenev 1995,
Saldin 1997

Focus on wakefield (total electric field)

Criteria of applicability

$$\frac{R}{\gamma^3} \ll \sigma_z \qquad \frac{\sigma_r}{\sigma_z} \ll \left(\frac{R}{\sigma_z}\right)^{\frac{1}{3}}$$

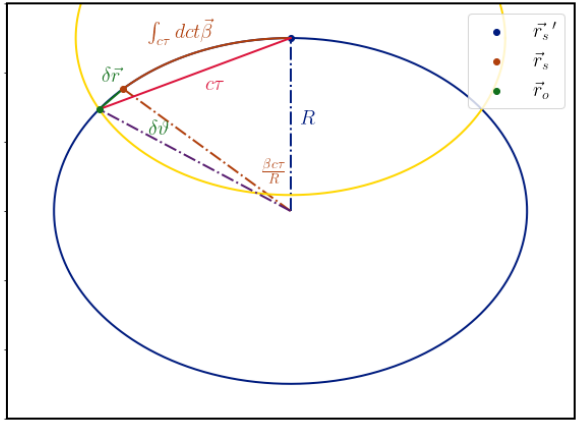
- Does it hold for large differences in transverse size bunch?
- What are the effects as the bunch focusses?



Revisited

$$R = \frac{\gamma \beta_{\perp} m c^2}{e B_0}$$

$$\frac{c\tau}{2R} - \sin\left(\frac{\beta c\tau}{2R} + \frac{\delta\vartheta}{2}\right) = 0$$

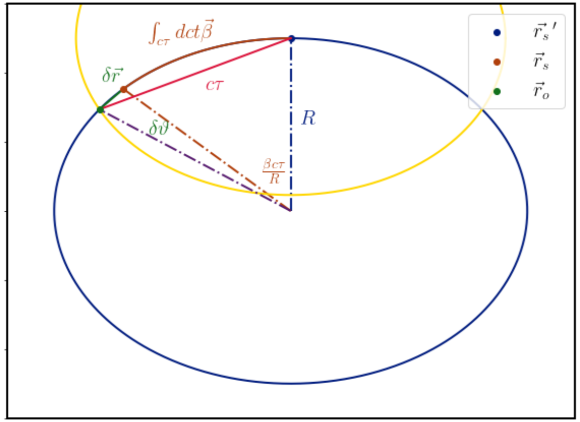


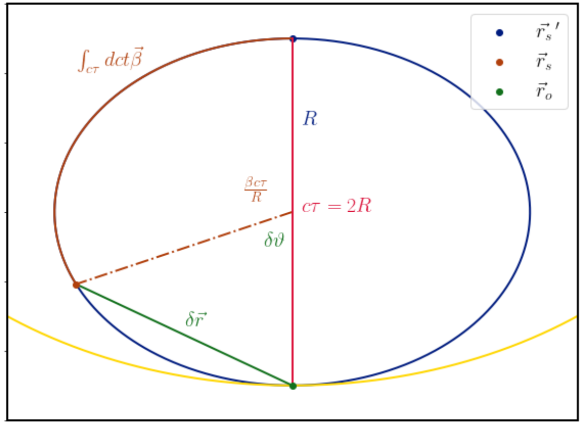
Revisited

$$R = \frac{\gamma \beta_{\perp} m c^2}{e B_0}$$

$$\frac{c\tau}{2R} - \sin\left(\frac{\beta c\tau}{2R} + \frac{\delta\vartheta}{2}\right) = 0$$

Argument sine $\leq \pi/2$
⇒ series up to 3rd order *always* suffice



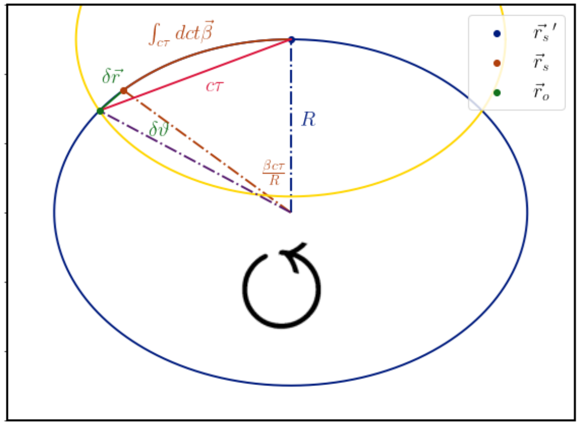


$\delta\vartheta = \pi - 2\beta$

Revisited

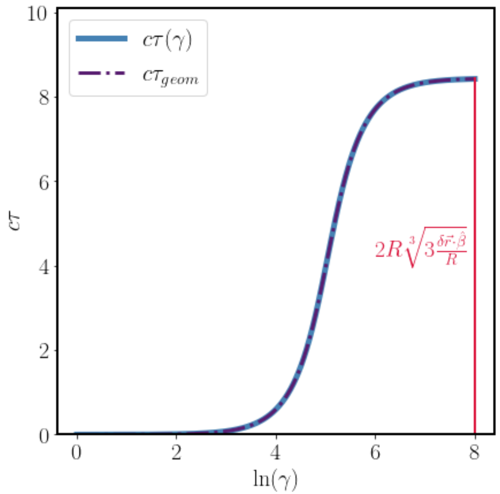
$$\frac{c\tau}{2R} - \sin\left(\frac{\beta c\tau}{2R} + \frac{\delta\vartheta}{2}\right) = 0$$

$$R = \frac{\gamma\beta_{\perp} mc^2}{eB_0}$$

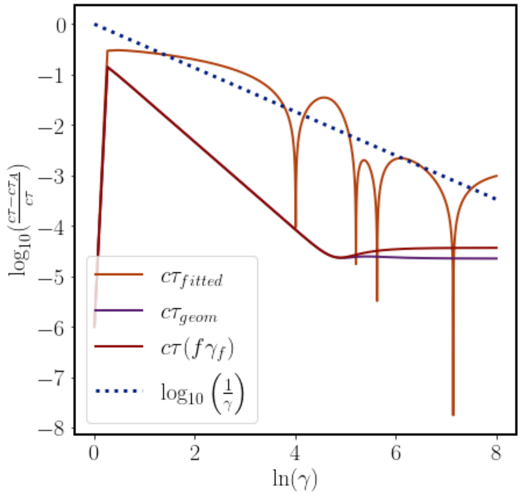


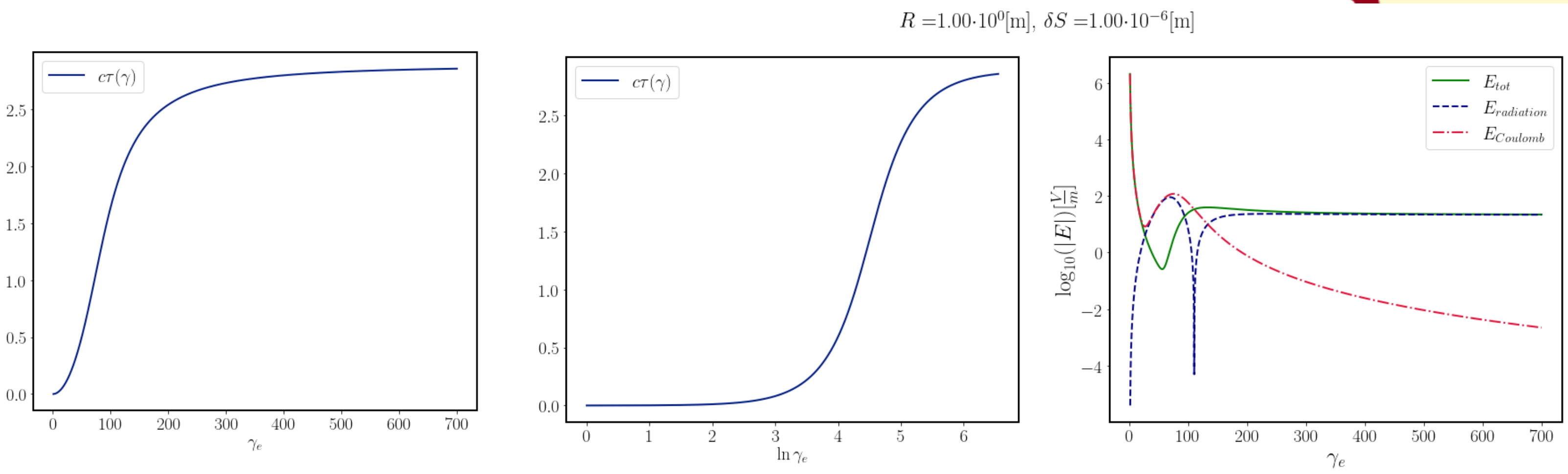
Behaviour of $c\tau$

Three approximated relations derived



Relative error





$$\vec{E}_{LW} = \vec{E}_{Coulomb} + \vec{E}_{Radiation}$$

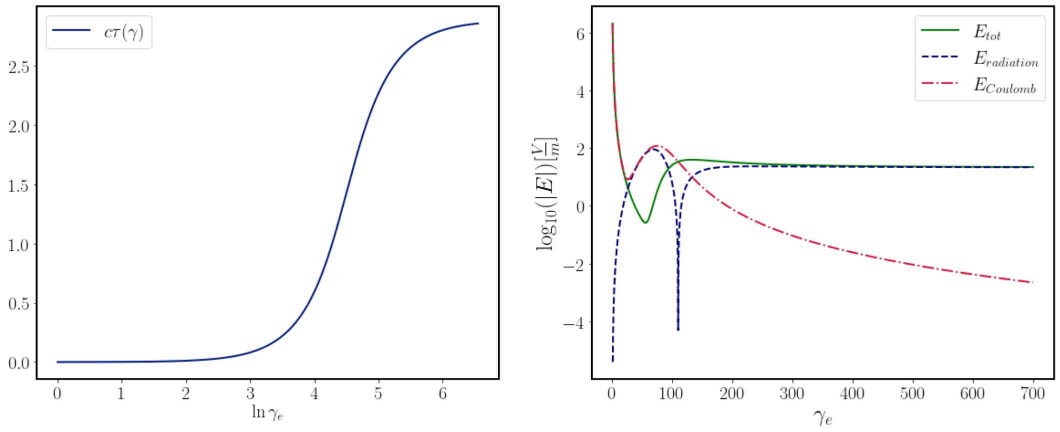
$$\vec{E}_{Coulomb} \propto \left(\frac{1}{\gamma c\tau}\right)^2$$

$$\vec{E}_{Radiation} \propto \left(\frac{1}{c\tau}\right)$$

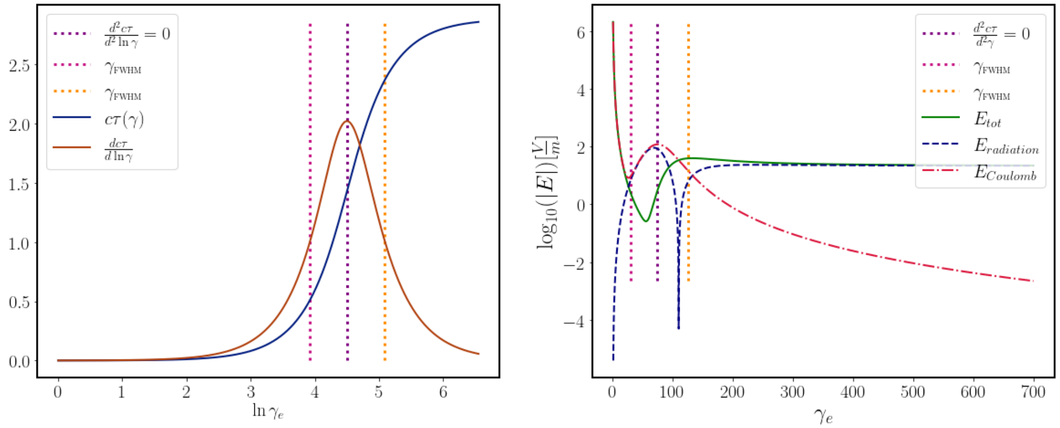
I. Self fields

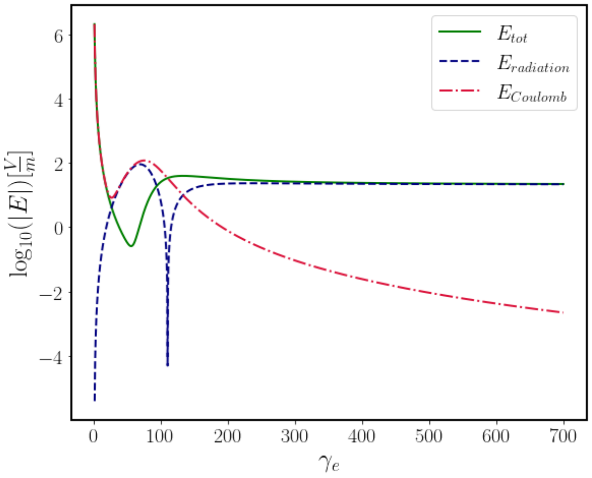
1D Model

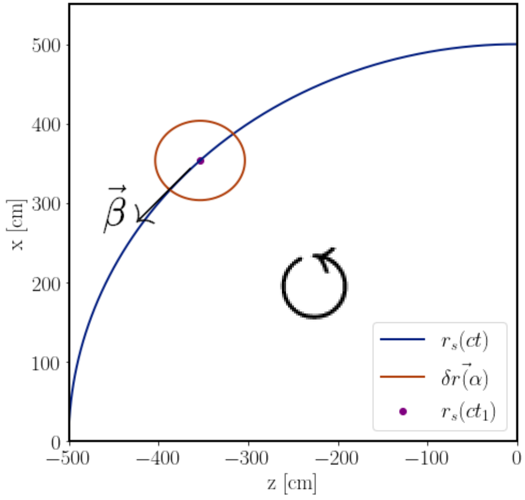
$R = 1.00 \cdot 10^{0}$[m], $\delta S = 1.00 \cdot 10^{-6}$[m]

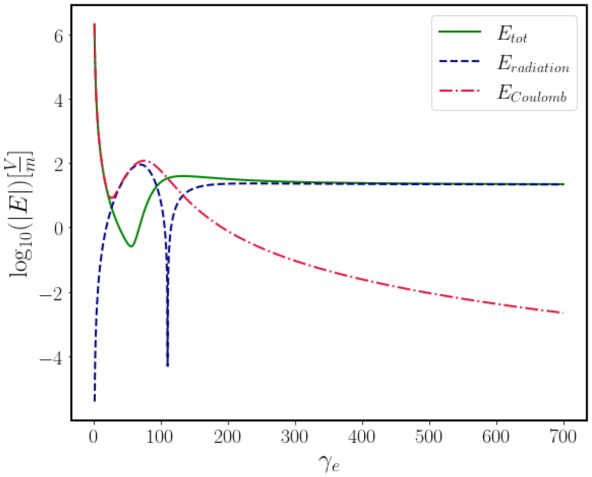


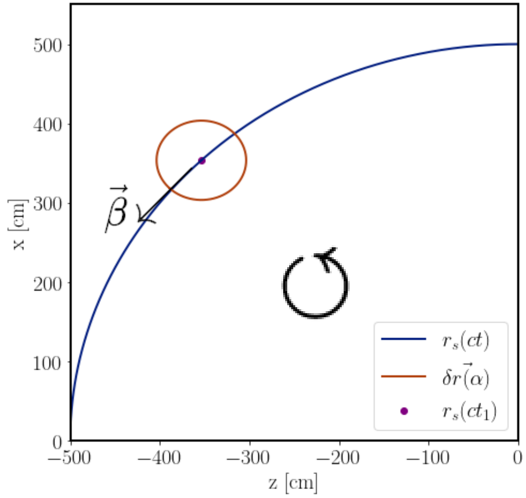
$R = 1.00 \cdot 10^{0}$[m], $\delta S = 1.00 \cdot 10^{-6}$[m]

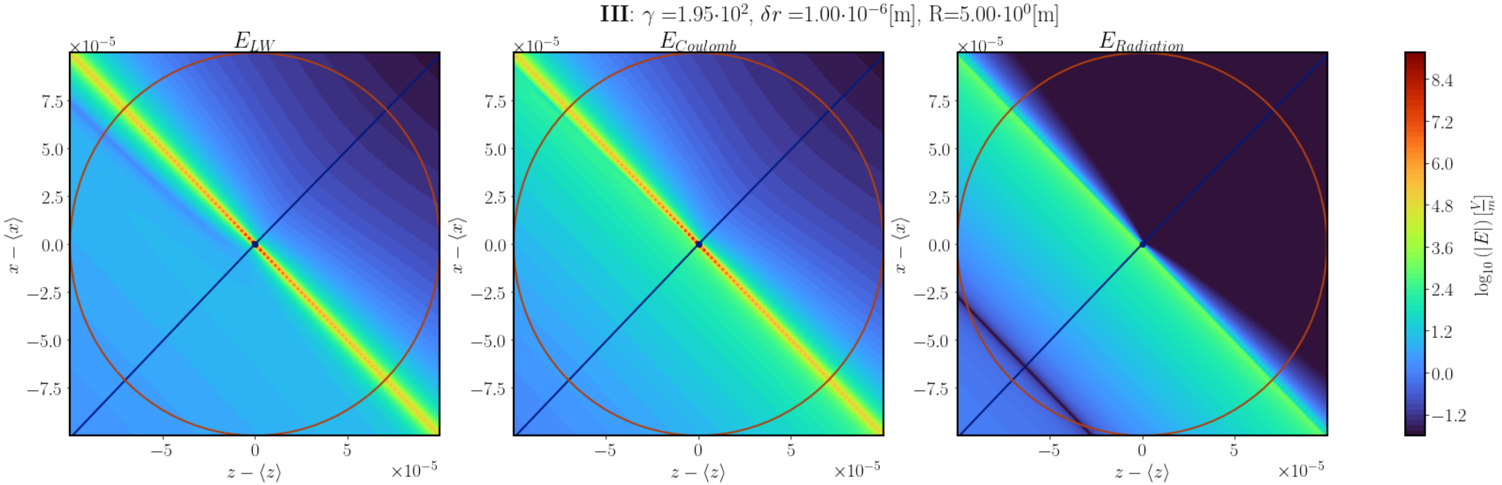



E_{tot}
$E_{radiation}$
$E_{Coulomb}$
$\log_{10}(|E|)[\frac{V}{m}]$
γ_e


$\vec{\beta}$
$r_s(ct)$
$\delta\vec{r}(\alpha)$
$r_s(ct_1)$
x [cm]
z [cm]

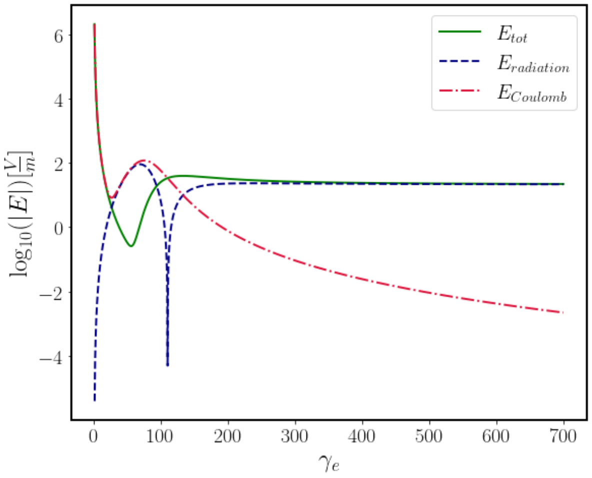


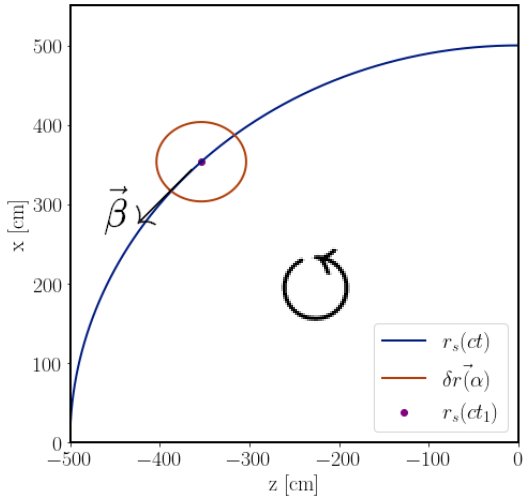




$$\vec{E}_{Coulomb} \propto \left(\frac{1}{\gamma c \tau}\right)^2$$

$$\vec{E}_{Radiation} \propto \left(\frac{1}{c \tau}\right)$$



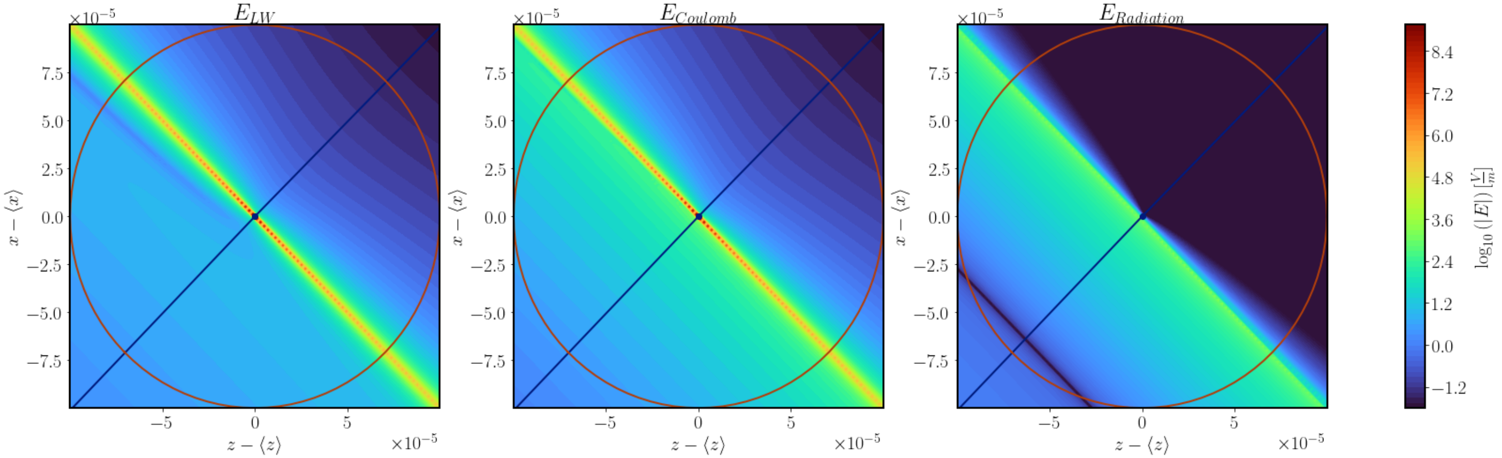


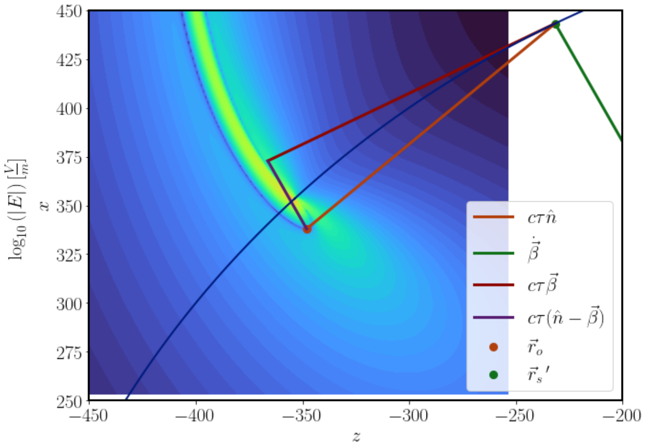
$$\vec{E}_{Coulomb} \propto \left(\frac{1}{\gamma c\tau}\right)^2$$

$$\vec{E}_{Radiation} \propto \left(\frac{1}{c\tau}\right)$$

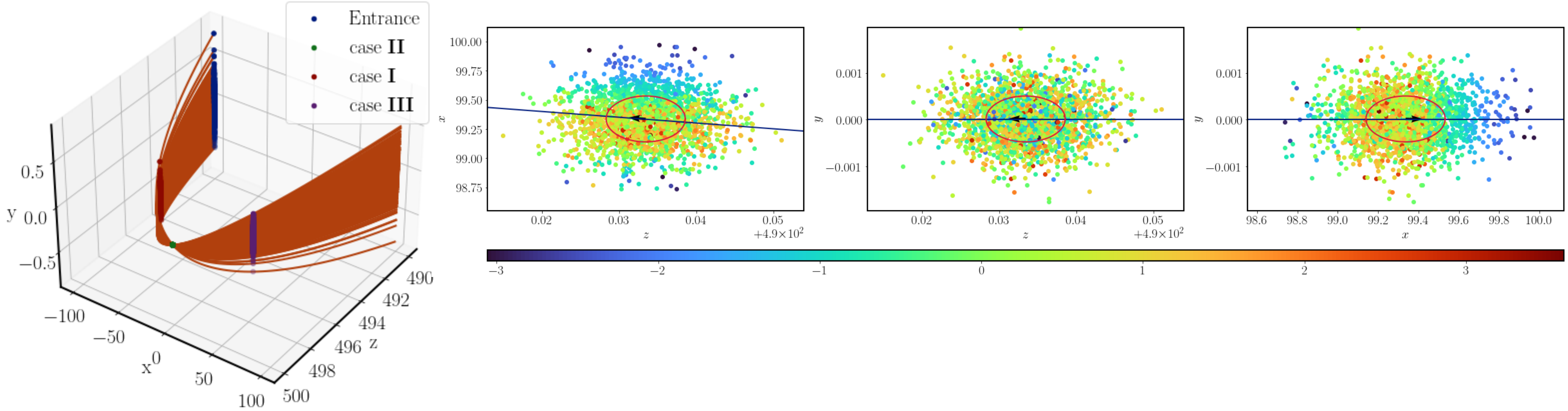
$$\vec{E}_{Radiation} \propto \hat{n} \times \left(\left(\hat{n} - \vec{\beta}\right) \times \frac{d\vec{\beta}}{dct}\right)$$

III: γ =1.95·10^2, δr =1.00·10^{-6}[m], R=5.00·10^0[m]





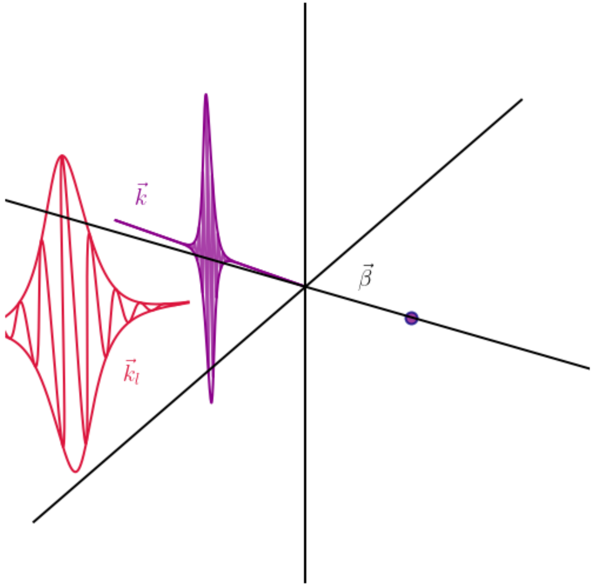
Model for a bunch traveling inside a dipole

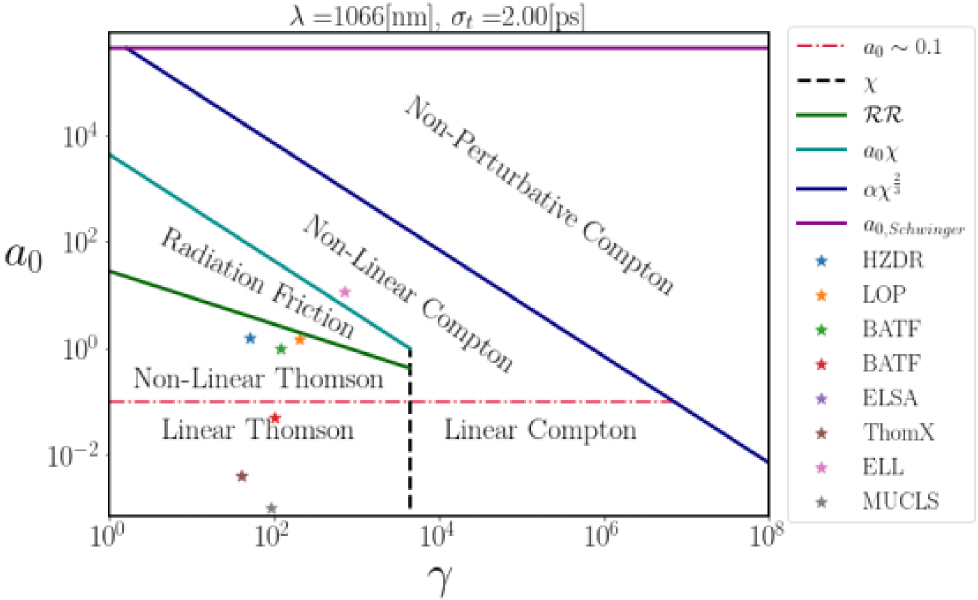


II. Thomson scattering

For research developed own Thomson & Particle tracking code:

- Classical: Linear & Non-Linear regime





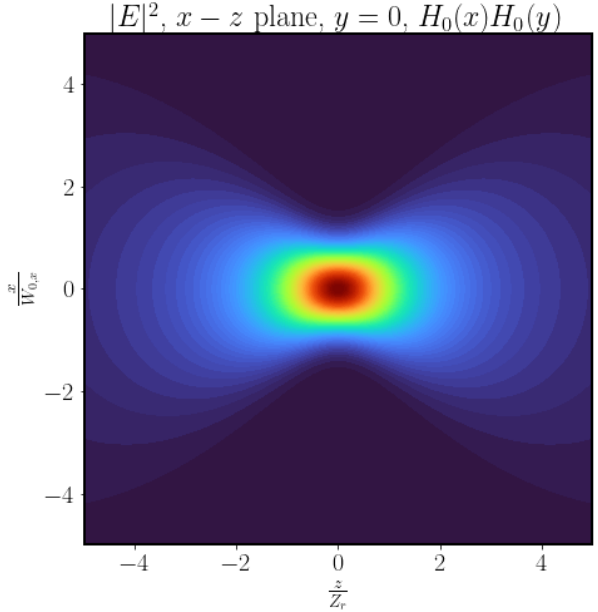
Scattering of High intensity lasers on Electrons

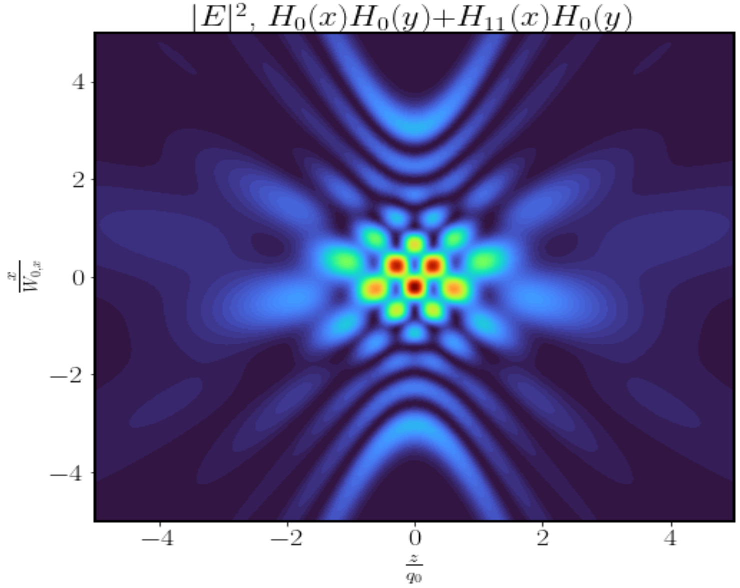
- Laser cavity: Fabry Perot — $I[\mathrm{W/cm^2}] \sim 10^{14}$ – $a_0 < 10^{-2}$
  - Degernerate Cavity
- Chirped Pulse Amplification — $I[\mathrm{W/cm^2}] \sim 10^{18}$ – $a_0 \sim 1$
  - Energy Compensation
  - Carrier Envelope Phase

Laser cavity: Fabry Perot

I[W/cm^2] ~ 10^{14} – $a_0 < 10^{-2}$ ⇒ Linear Thomson scattering

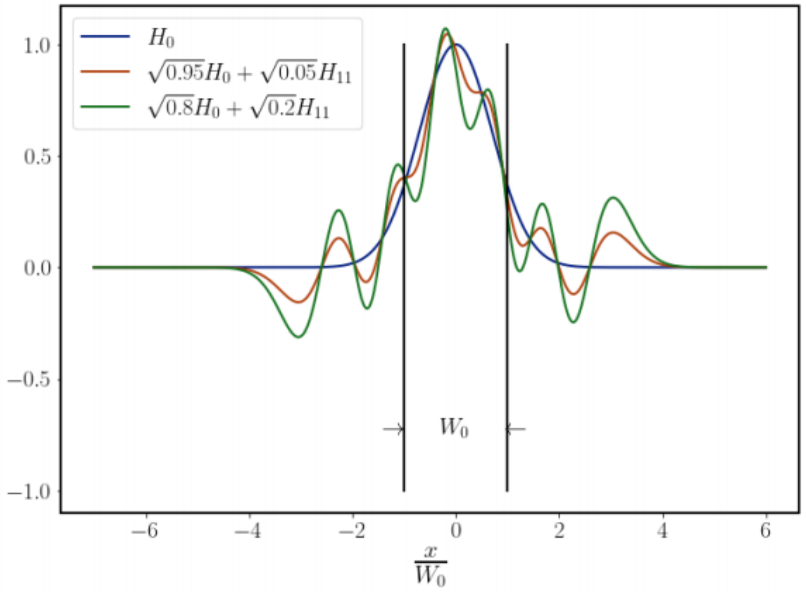
- Effect of Degenerate Cavity
- Higher modes $n>10$

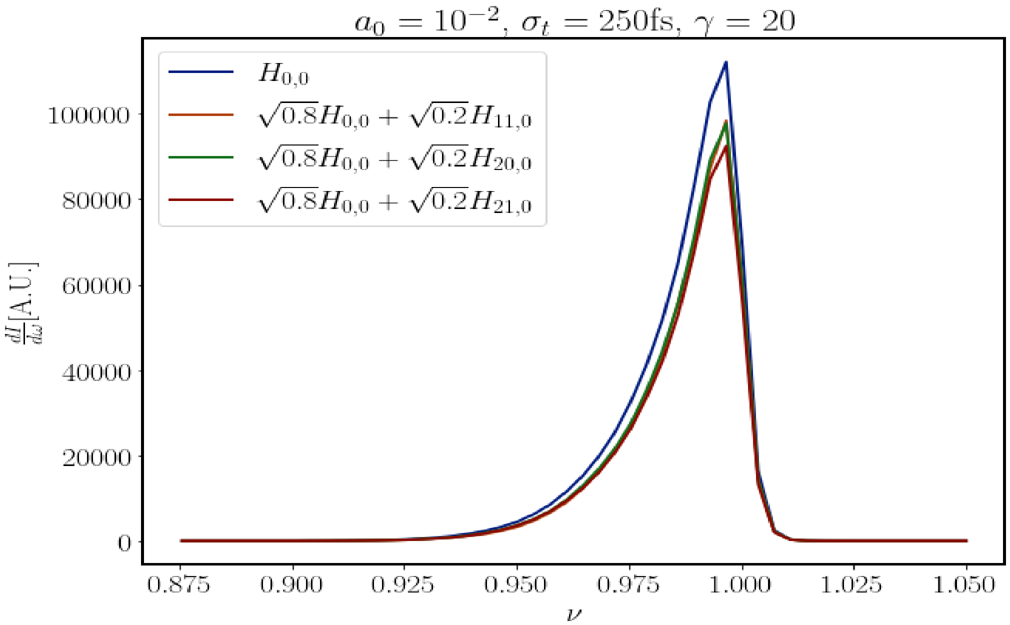




II. Thomson scattering

- Degenerate mode Power ~ 20%
- Degenerate modes incoherent summation suffices. $W_e \sim W_0$
- No distinction between different modes in Thomson spectrum

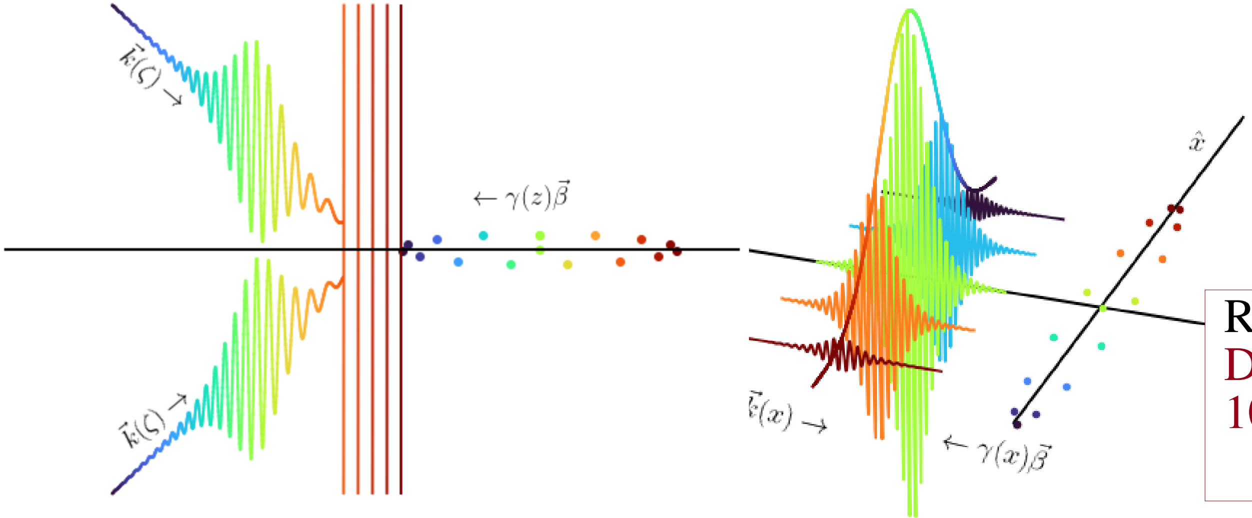




Linear Thomson scattering
Compensation of electron energy by chirped laser

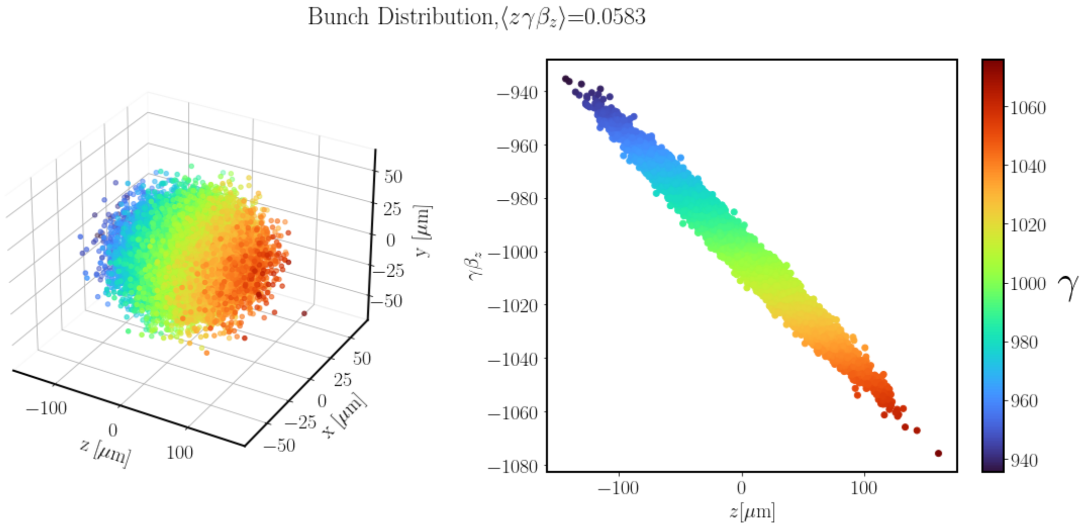
- Increase flux through larger bunch charge
- Two geometries

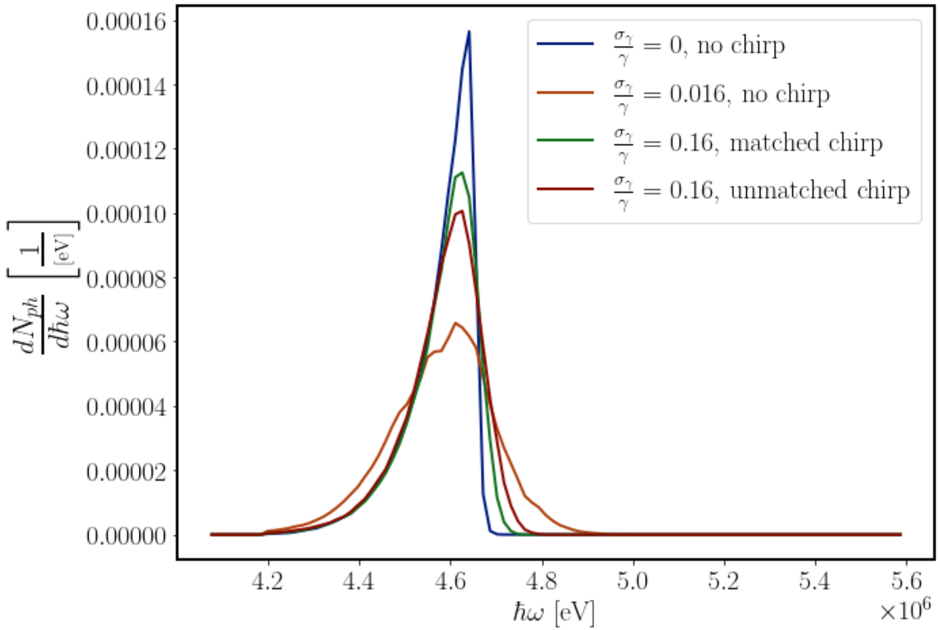
$$\langle \lambda \rangle \propto \frac{\lambda_f}{\gamma^2}$$



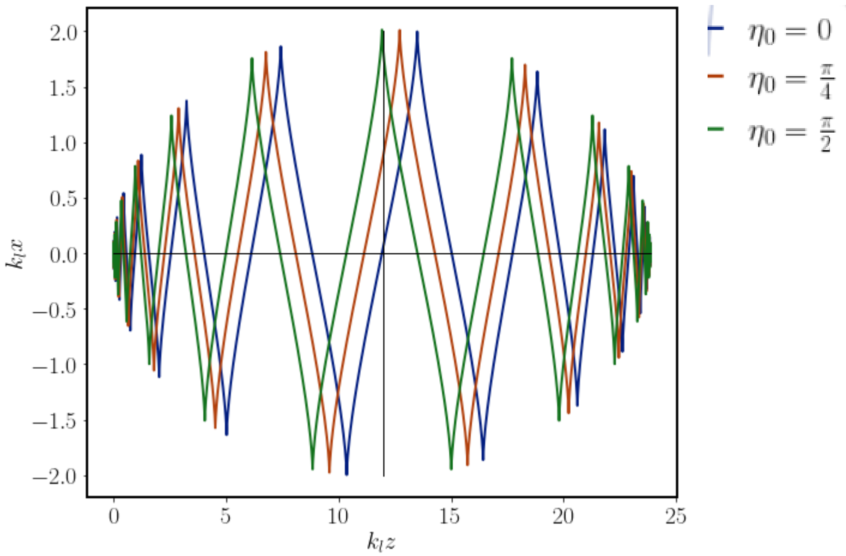
Ruijter et al, 2021
DOI: 10.1103/PhysRevAccelBeams.24.020702

- Retrieval of ideal Thomson spectrum
- Partial compensation if
  - Mismatch in chirp & electron energy
  - Uncorrelated energy spread





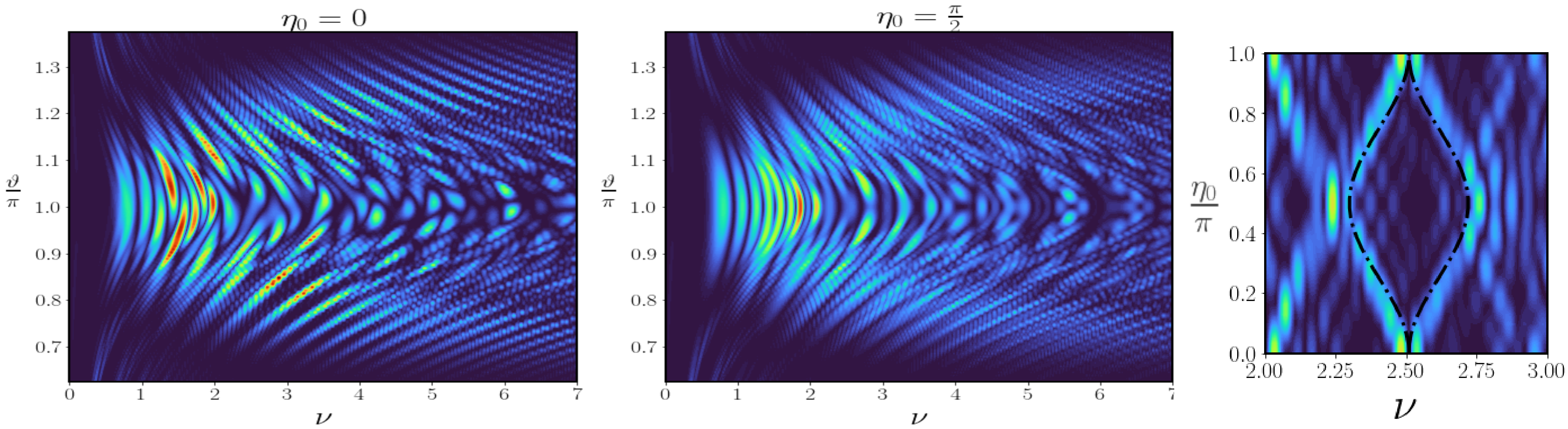
- $a_0 \geq 1$: Laser too intense to measure (matter turns into plasma)
- Carrier Envelope Phase : $L_{pulse} \sim \lambda_L$



Ruijter et al, 2021
DOI: 10.3390/cryst11050528

- Non-linear regime ⇒ emission of harmonics

- Possible to measure through Thomson scattering
  - Spectrum
  - Angular Emission



Diagnostic tool ⇒ low γ ⇒ λ~200 nm & remain classical

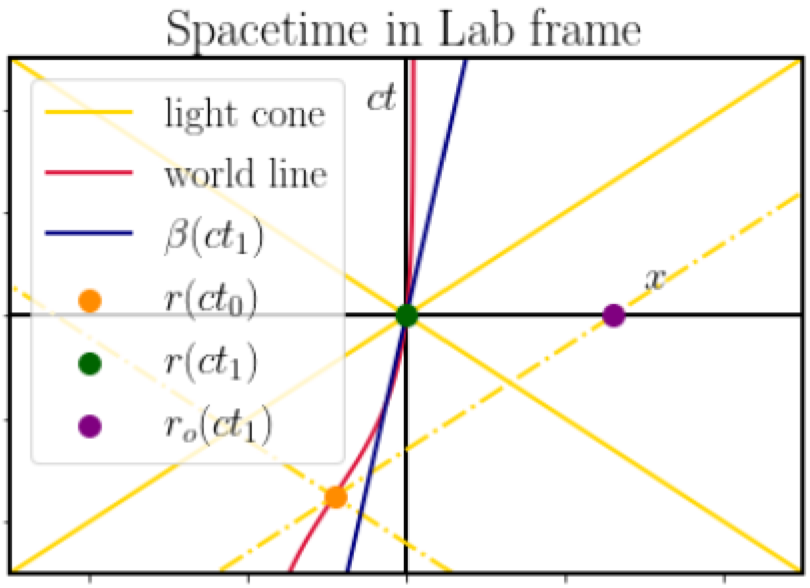
Conclusions

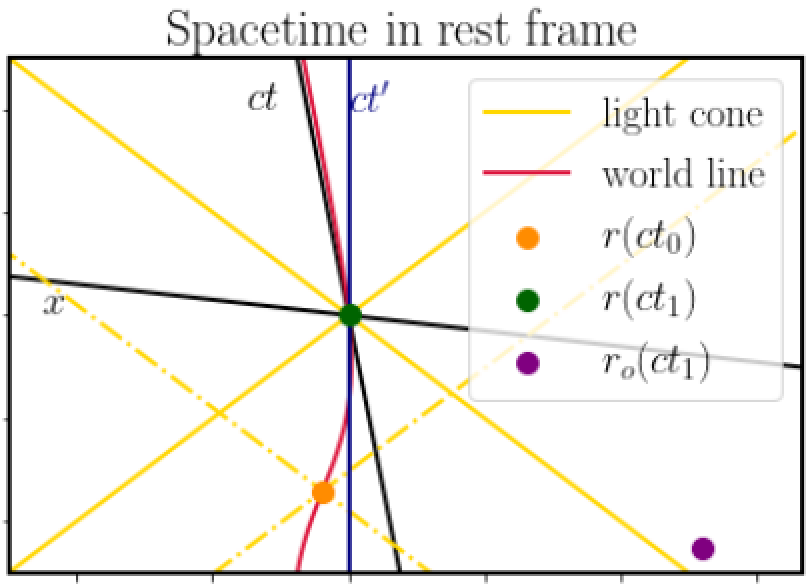
- 1D model
  - Extension
  - Relations Coulomb or Radiation field dominant
- 2D model
  - Asymmetry in behaviour of $c\tau$
  - Region where Radiation field is *zero*
- 3D model
  - Good agreement numerical and approximations
  - Optimize code & parallelisation

Conclusions

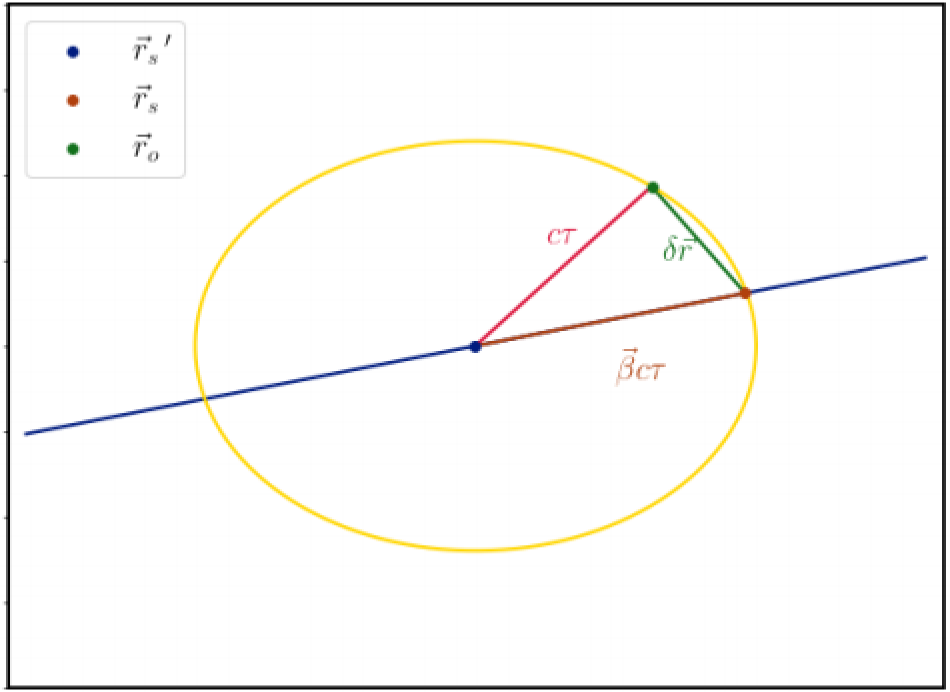
- Effect of Degenerate Cavity
  - Coherent summation might be required
  - For 20% power in higher modes incoherent summation sufficies within W_0
  - No distinction between different modes in Thomson spectrum
- Energy Compensation
  - Two geometries
  - Could increase flux through larger bunch charge
  - Quadratic chirp
- Carrier Envelope Phase: Thomson scattering as diagnostic Tool
  - Requires $a_0 > 1$ for harmonics to overlap
  - Shift in energy peaks of harmonics

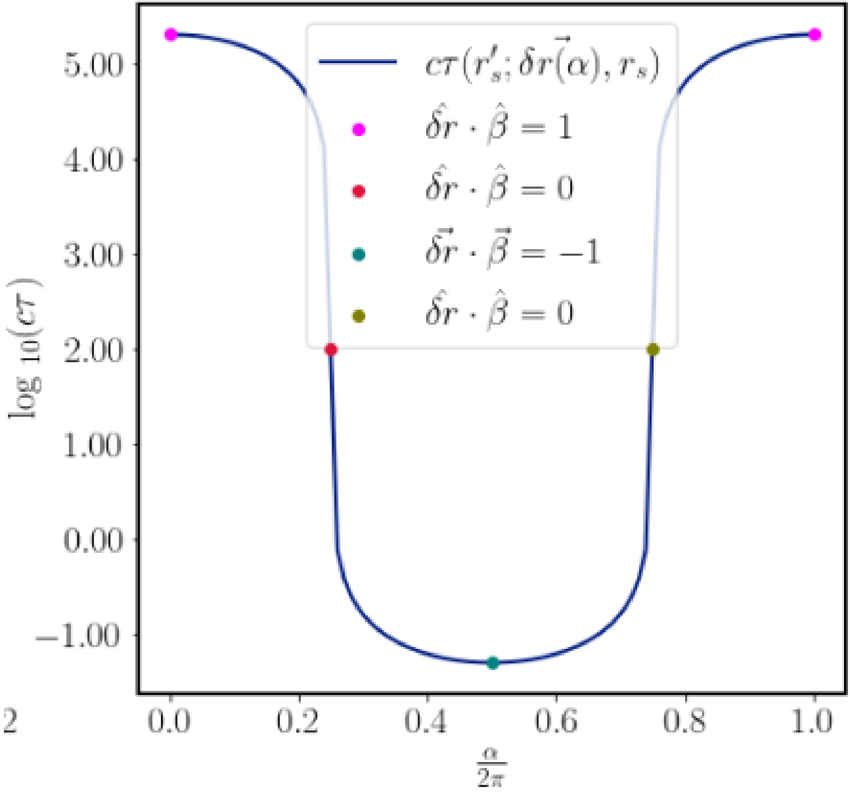
Lorentz Transformations with acceleration



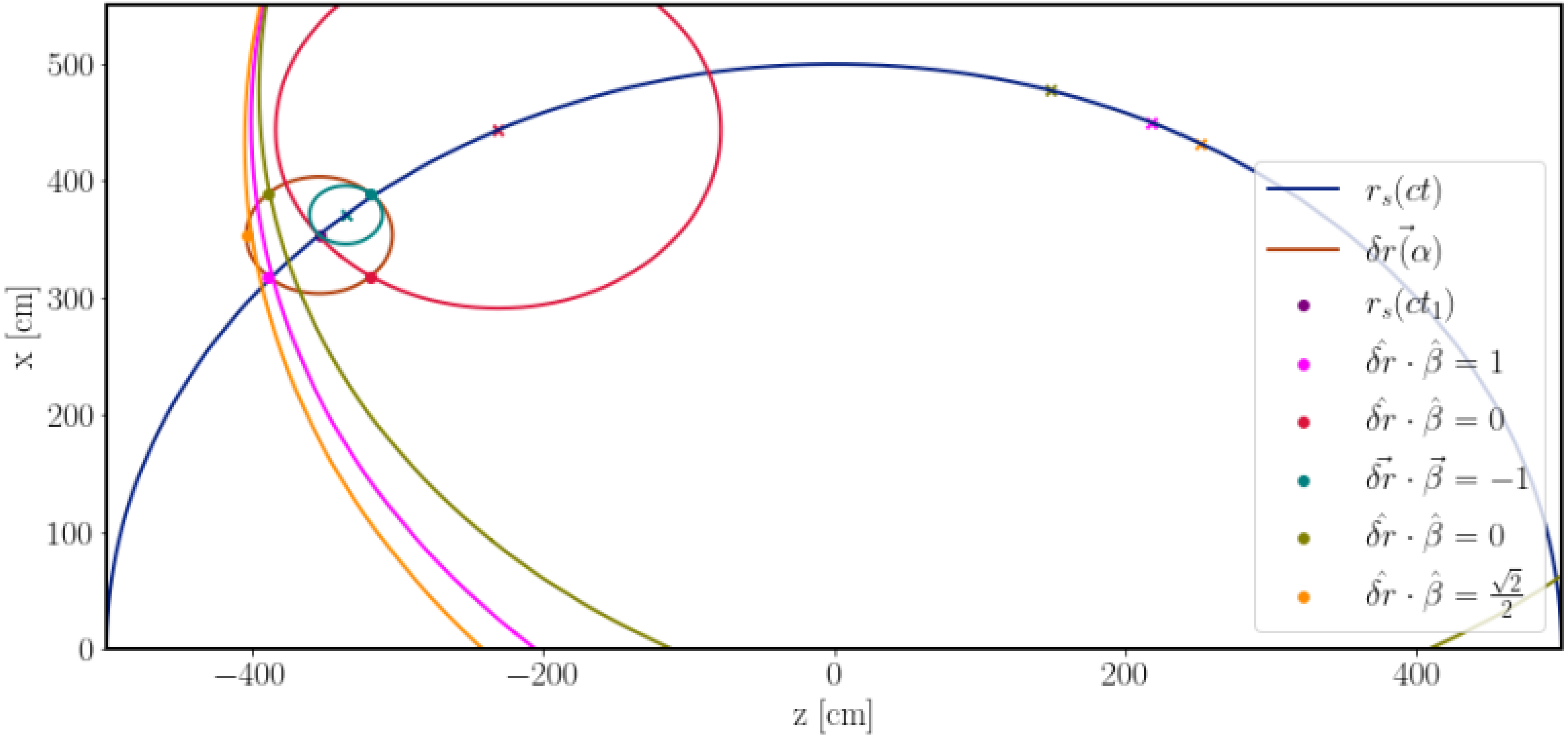


Uniform linear motion motion (2D)





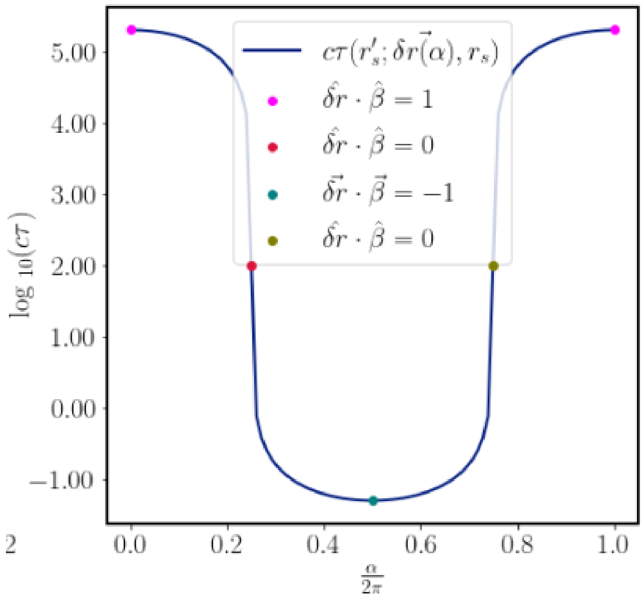
Retarded time 2D

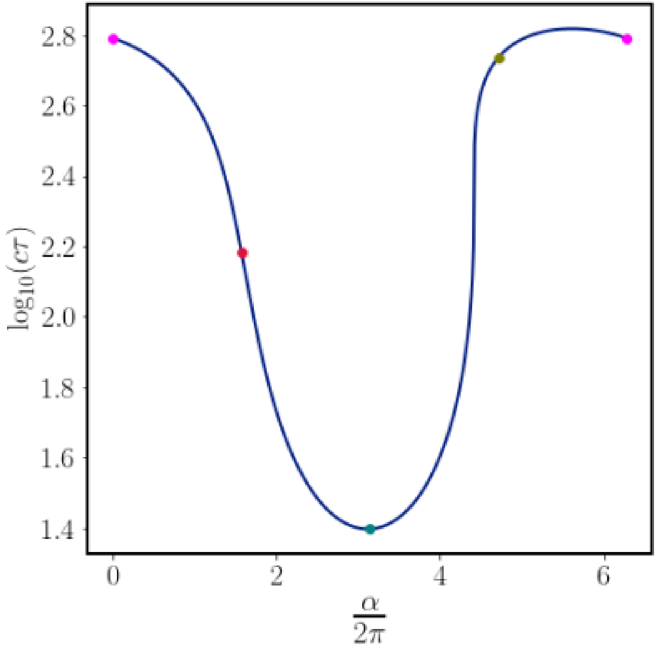


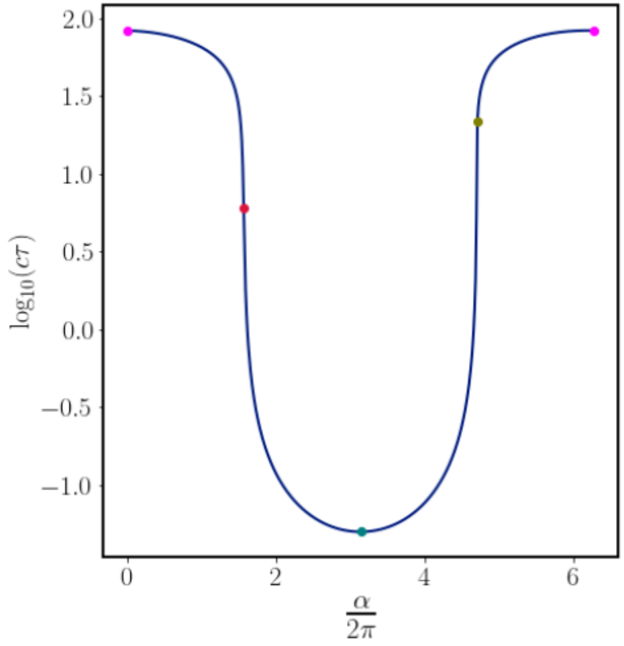
Back Up Slides

$\gamma = 10^3$, R= 5[m], δr

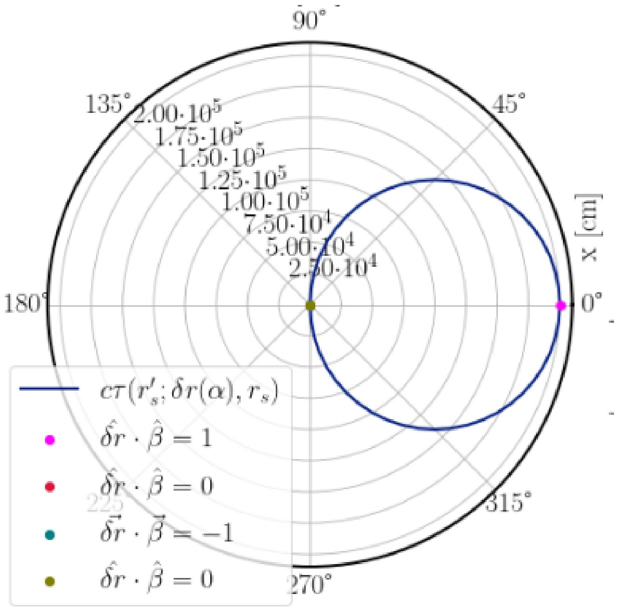
Uniform linear	Circular large δr	Circular small δr

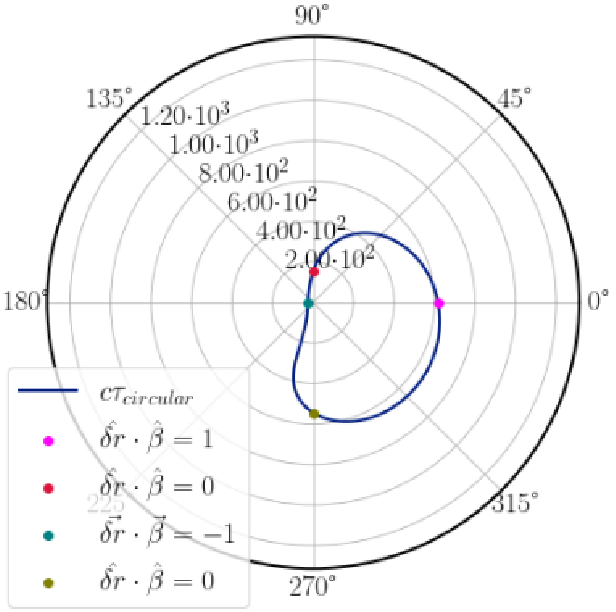


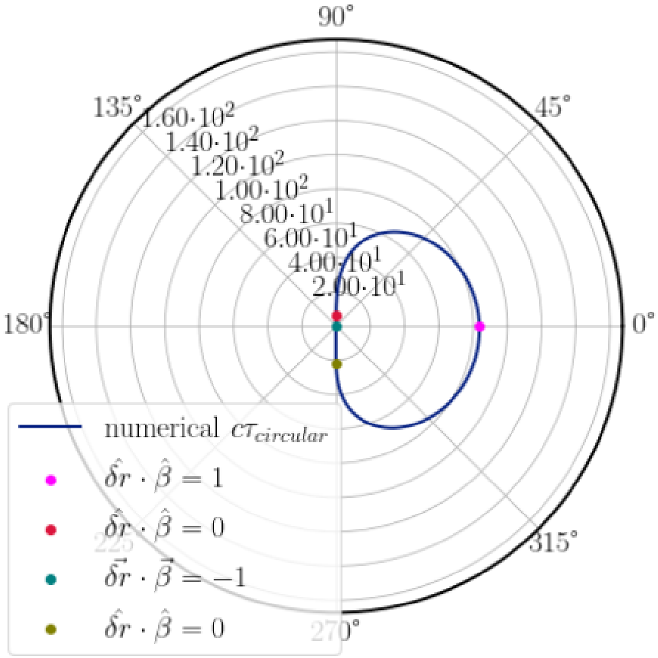




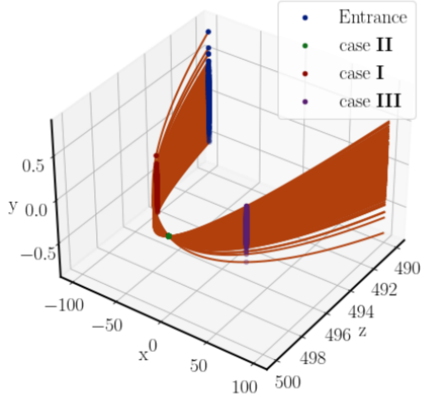
$\gamma = 10^3$, R= 5[m], δr

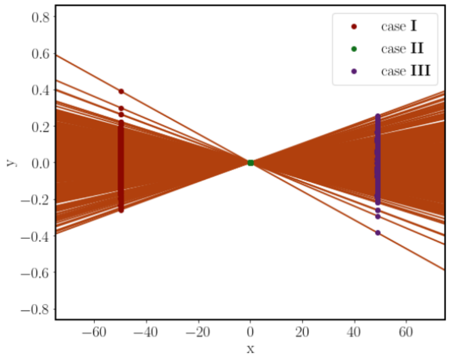


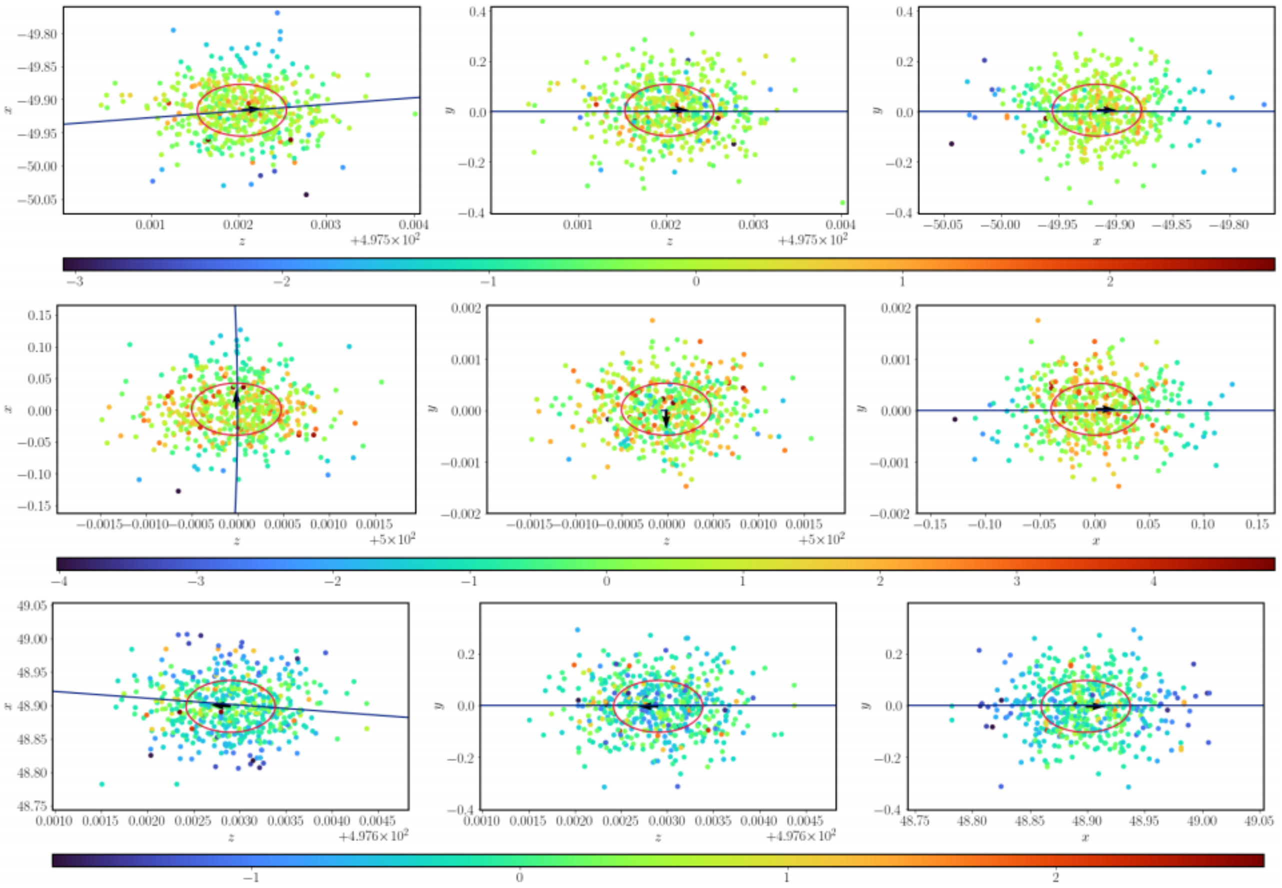




Back Up Slides







Meaning a_0

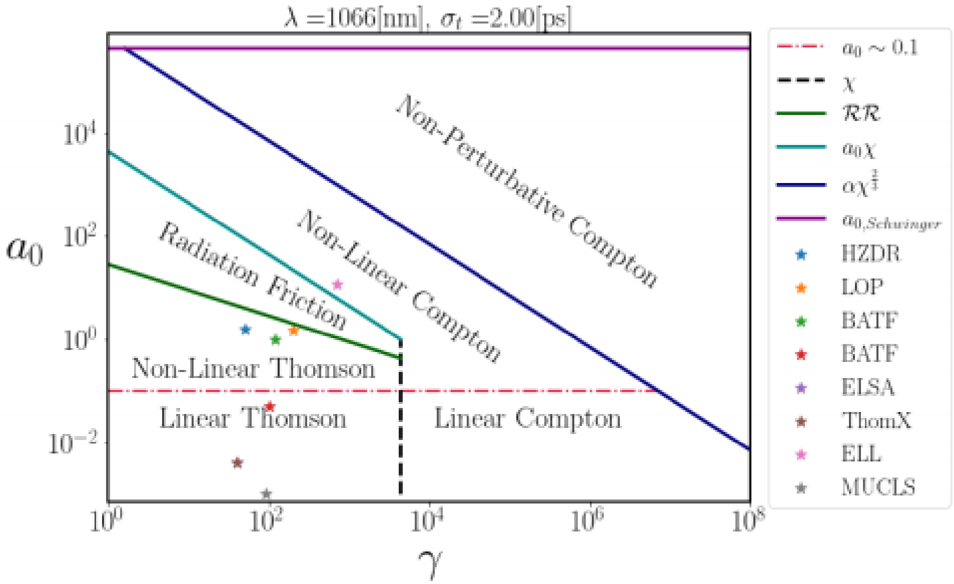
$$a_0 = \frac{eA_0}{mc^2} = \frac{eE_0}{mc\omega_{U_f}} = \frac{eB_0}{mc\omega_{U_f}} \tag{1.4}$$

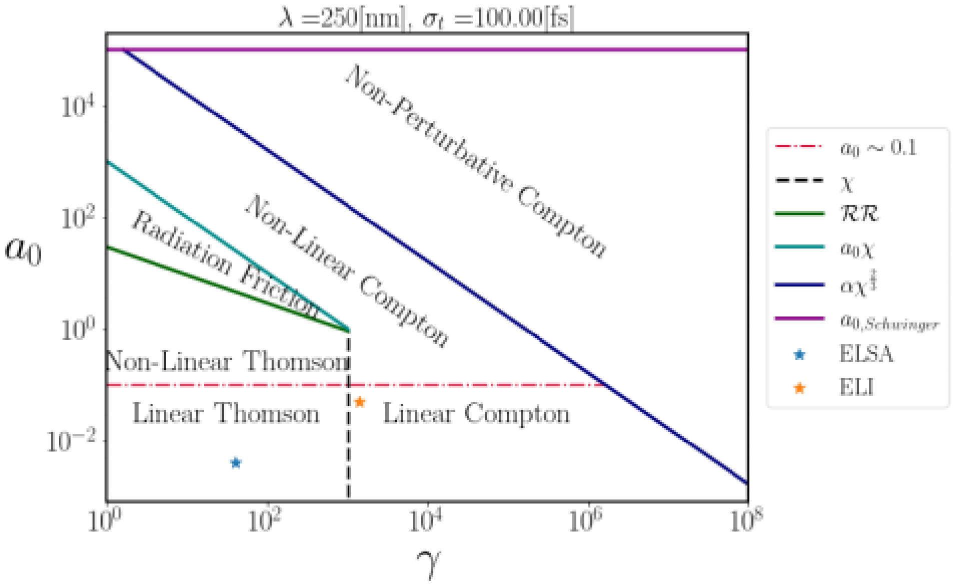
and is related to the energy density of the field ($U_f \propto (\omega_{U_f} a_0)^2$). It also describes when higher harmonics by an electron are emitted. For this we need the quantum picture of this parameter: a_0 represents the energy gain of an electron within one Compton wavelength per photon [27, 31, 32]. If $a_0 \geq 1$ then more than one photon is absorbed by the electron and emitted as one, thus giving the higher harmonics.

Scattering Classical vs Quantum

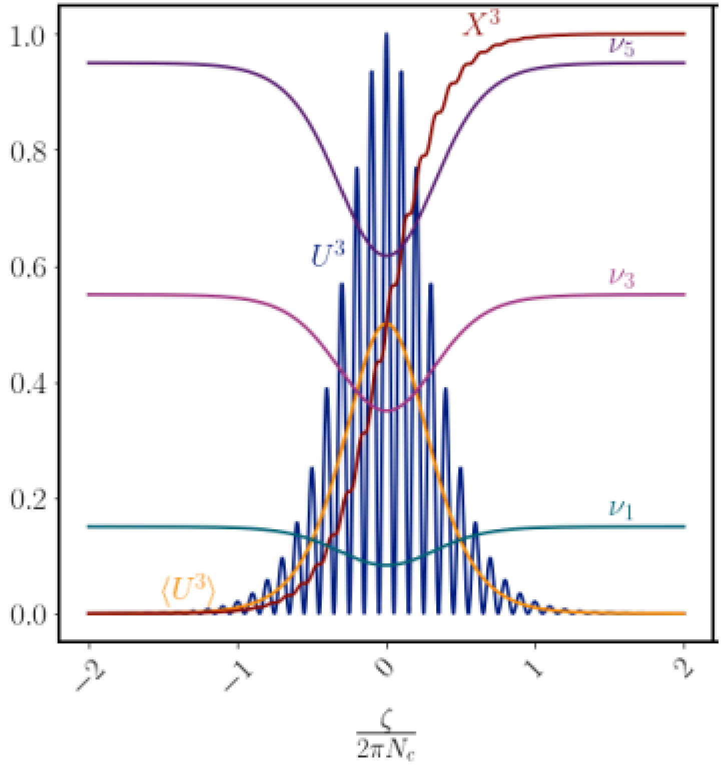
$$\omega \propto \frac{\omega_l}{f(\vartheta) + \chi}$$

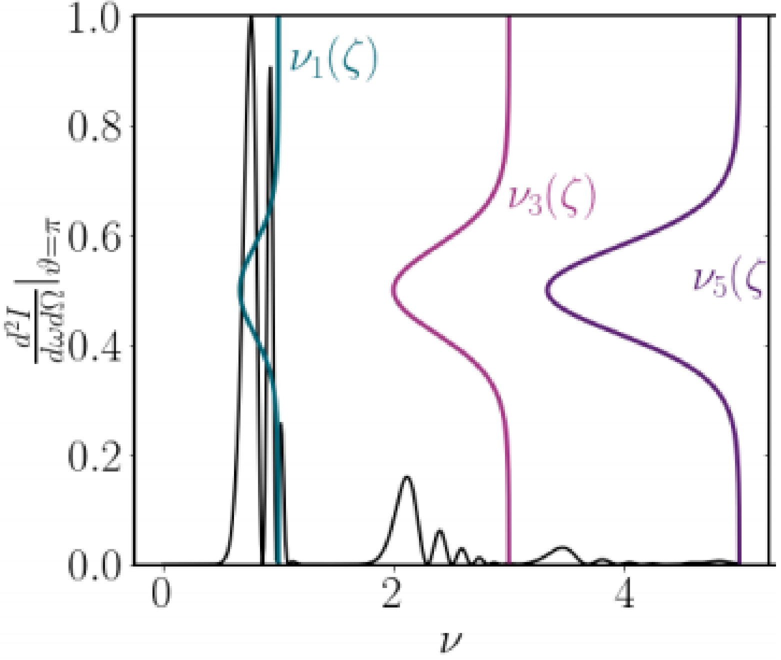
$$\chi = 2\frac{\hbar\gamma(1+\beta)\omega_l}{mc^2} \approx 4\frac{\hbar\gamma\omega_l}{mc^2}$$





Thomson Dynamics linearly polarized laser pulse





CEP – Harmonics & Interference