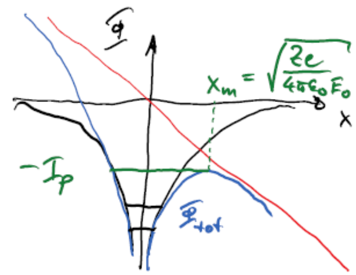
Physics – Laser-Plasma-Physics in half an hour

1. Generating a plasma – for example via field ionisation

$$\Phi_{tot} = -\frac{1}{4\pi\varepsilon_0}\frac{Ze}{x} - E_0 x \Rightarrow e\Phi_{tot}(x_m) = -I_P$$

$$E_0 = \frac{I_P^2}{4}\cdot\frac{4\pi\varepsilon_0}{Ze^3} = \cdots = \frac{1}{4}E_{Bohr}$$



2. Consider a plane wave propagating in x-direction

Electric field $\vec{E} = E_0 \cdot \begin{cases} \sin\phi\ \vec{e}_y & linear \\ \sin\phi\,\vec{e}_y \pm \cos\phi\,\vec{e}_z & circular \end{cases}$ $\qquad \phi = kx - \omega t$

Magnetic field $\vec{B} = \frac{E_0}{c}\cdot\begin{cases} \sin\phi\ \vec{e}_z & linear \\ \mp\cos\phi\,\vec{e}_y + \sin\phi\,\vec{e}_z & circular \end{cases}$

Poynting vector $\vec{S} = \varepsilon_0 c E_0^2 \cdot \begin{cases} \sin^2\phi\ \vec{e}_x & linear \\ 1\cdot\vec{e}_x & circular \end{cases}$ $\qquad I = |S| = \frac{E_{Laser}}{area\cdot duration}$

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3. Single electron – non-relativistic motion

$$\frac{d\vec{v}}{dt} = -\frac{e}{m}\left(\vec{E} + \vec{v} \times \vec{B}\right) \approx \frac{e}{m}\vec{E} = -\frac{e}{m}E_0 \cdot \begin{cases} \sin\phi \;\vec{e}_y & linear \\ \sin\phi\,\vec{e}_y \pm \cos\phi\,\vec{e}_z & circular \end{cases}$$

$$\xrightarrow{\text{yields}} \frac{\vec{v}}{c} = -\frac{eE_0}{m\omega c} \cdot \begin{Bmatrix} \cos\phi \;\vec{e}_y & linear \\ \cos\phi\,\vec{e}_y \mp \sin\phi\,\vec{e}_z & circular \end{Bmatrix} + \vec{v}_0$$

Normalized vector potential

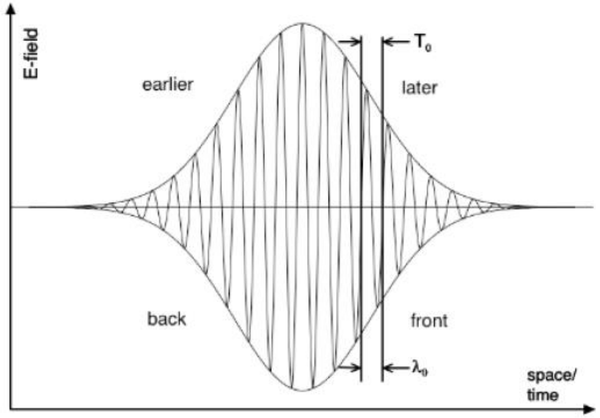
$$a_0 = \frac{eE_0}{m\omega c}$$

4. Single electron – relativistic motion $\frac{d\vec{p}}{dt} = -e\left(\vec{E} + \vec{v} \times \vec{B}\right)$

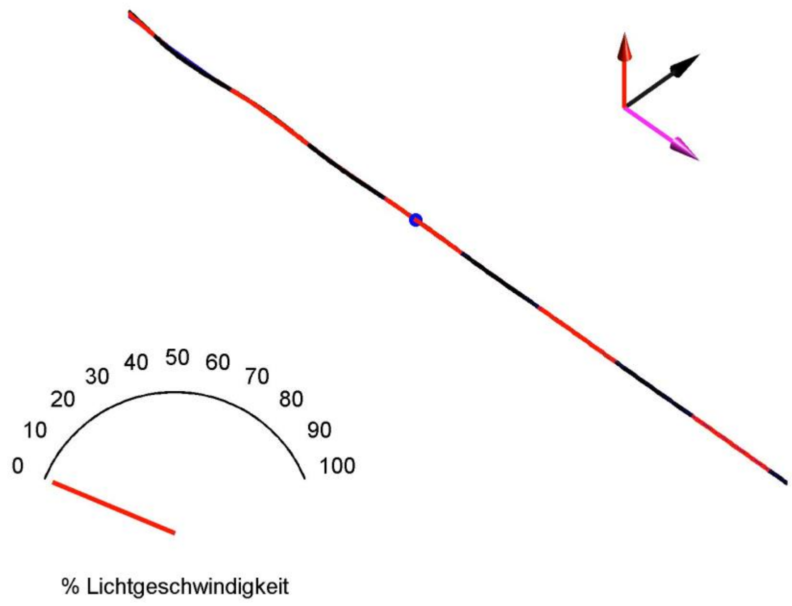
5. Einfachste Beschreibung eines Laserpulses

Für Gaußpulse: $t_{FWHM} \cdot \omega_{FWHM} = 8\ln 2 = 5.55$

$$E(t) = E_A(t)\cos(\omega t + \phi) = \frac{1}{2}\left(\tilde{E}(t)e^{i\omega t} + c.c.\right)$$



Numerical solution – linear polarisation



Relativistic effects in a collisionless plasma – the simplest picture

Assume free electrons and a neutralising background of immobile ions

$$\Delta\vec{E} - \frac{1}{c^2}\frac{\partial^2 \vec{E}}{\partial t^2} = -\mu_0 \frac{\partial j}{\partial t} \qquad \frac{\partial j}{\partial t} = e n_e \frac{\partial \vec{v}}{\partial t} \approx e n_e \frac{e\vec{E}}{m\gamma}$$

$$-\vec{k}^2 + \frac{\omega^2}{c^2} = \frac{1}{c^2}\cdot\frac{ne^2}{\varepsilon_0 m\gamma} = \frac{\omega_p^2}{c^2}$$

ω_p … Plasmafrequenz

$$\Rightarrow k^2 = \frac{\omega^2}{c^2}\left(1 - \frac{\omega_p^2}{\omega^2}\right) = \frac{\omega^2}{c^2}\eta^2(\omega)$$

$\eta(\omega) = \sqrt{1 - \frac{\omega_p^2}{\omega^2}}$ … Brechungsindex

Rein imaginär für $\omega < \omega_p$
Reflektiv (überdicht)

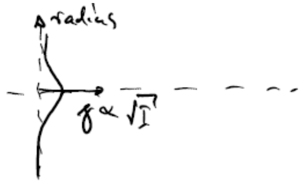
Rein reell für $\omega > \omega_p$
Transparent (unterdicht)

Joerg.Schreiber@lmu.de

Relativistic effects in a collisionless plasma – the simplest picture

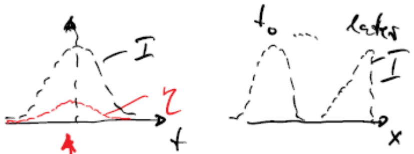
$$\eta = \sqrt{1 - \frac{n_e e^2}{\gamma m_e \varepsilon_0 \omega^2}}$$ … Brechungsindex

- rel. Self-focussing :



η im Zentrum größer als außen ⇒ Fokussierend

- rel. pulse-steepening (self-phase modulation) :



v_g größer als "Puls front"

- rel. induced transparency : Transparenz f. $\omega > \omega_p$ (η reell)

$$\omega > \frac{n_e e^2}{\gamma m_e \varepsilon_0}$$

Summary

- Relativistic Laser-Intensity means that the electron moves with velocity close to the speed of light. Then the longitudinal component of the Lorentz force becomes larger than the transversal. For linear polarisation, this transition happens for $I\lambda^2 > 1.37 \cdot 10^{18} \frac{W}{cm^2} \mu m^2$
- The relativistic intensity is much larger than any field ionisation threshold. Therefore, all media can be considered as at least partially ionised.
- In the plasma, the relativistic motion of the electrons results in nonlinear collective response, in particular given rise to relativistic
  - Self-focusing
  - Pulse front steepening
  - Induced transparency
- The strong laser fields and the resulting fields that it generates in a plasma, through collective effects, is the source of all plasma based particle acceleration mechanisms and hence the basis for application of laser particle acceleration