Optical investigation to minimize the electron bunch arrival-time jitter between fs laser pulses and electron bunches for Laser-Driven Plasma Wakefield Accelerators

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Plasma Wakefield Acceleration (PWA)

- Plasma-based particle accelerators driven by lasers as compact and useful accelerators for the future
- Accelerating gradients in plasmas about 3–4 orders of magnitude higher than in conventional accelerators
- Based on the plasma response to a short laser pulse
- Generation of a longitudinal electric field with a phase velocity close to the speed of light
- Acceleration of the electron bunch with high electric field gradient

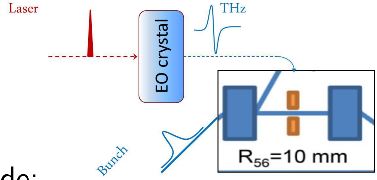
Features of Plasma Wakefield Acceleration

- Dependence of acceleration on plasma density n_{pl}
- Plasma wavelength λ_{pl} determined by n_{pl}
  $\lambda_{\mathrm{pl}} \approx 1[\mathrm{mm}]\sqrt{\frac{10^{15}\mathrm{cm}^{-3}}{n_{\mathrm{pl}}}}$
- Size of plasma accelerating structure determined by n_{pl}
- $n_{\mathrm{pl}} \approx 10^{17}\ \mathrm{cm}^{-3}$ wavelength is 0.1 mm
- Requirement on timing and synchronization is 3 μm.
- For electron with light velocity equivalent to 10 fs.

→ Synchronization between electron bunch and laser around **some** femtoseconds **needed**

Shot-to-shot feedback system

- Development of a new shot to shot feedback system with a time resolution ≤ 1 fs



- Operating mode:
  1. Generation of Terahertz (THz) pulses by optical rectification of high energy laser pulses in a nonlinear crystal (in work)
  2. Energy modulation of the electron bunch using the THz pulses (planned)

Requirements for THz generation

- Conversion efficiency

$$\eta == \frac{\pi\epsilon_0 c \int_0^\infty \mathrm{d}\Omega \ n(\Omega)|A(\Omega, z)|^2}{F_\mathrm{p}}$$

- Stability
- Choice of the crystal

→ Influence of the optical properties

→ Systematic calculation

Outline

- Modeling of THz generation
- Different modeling/approximations of the optical properties
- Results
- Influence of the intensity decreasing of the laser pump
- Summary and outlook

Description of the THz generation

- Wave equation in a nonlinear and dispersive medium

$$\left(\nabla^2 + \frac{\omega^2}{c^2}\varepsilon(\omega)\right)\vec{E}(\omega,\vec{r}) = -\mu_0\omega^2 P_{\mathrm{NL}}(\omega,\vec{r})$$

- Neglecting of the laser depletion in the crystal
- Solution Ansatz: $E(\omega, z) = A(\omega, z)\mathrm{e}^{-\imath k(\omega) z}$
- Two solution strategies:
  1. Solving the whole second order equation
  2. Slope Varying Approximation (SVA):
     Neglecting of $\propto \frac{\partial^2 A}{\partial z^2}$ $\rightarrow$ First order equation

THz generation in SVA

- First order THz wave equation (SVA)

$$\frac{\partial}{\partial z}A(\Omega,z) = -\frac{\alpha(\Omega)}{2}A(\Omega,z) - \imath\frac{\Omega}{2k(\Omega)c^2}\frac{P_{\mathrm{NL}}(z,\Omega)}{\varepsilon_0}\mathrm{e}^{\imath k(\Omega)z}$$

- Polarization

$$P_{\mathrm{NL}}(\Omega,z) = \varepsilon_0\chi^{(2)}\int_0^\infty \mathrm{d}\omega A_{\mathrm{p}}(\omega+\Omega,z)A_{\mathrm{p}}^*(\omega,z)\mathrm{e}^{\imath(k(\Omega+\omega)-k(\omega))z}$$

- Relations to the dielectric function $\varepsilon(\Omega)$

$$n(\Omega) = \frac{k(\Omega)c}{\Omega} = \Re\sqrt{\varepsilon(\Omega)} \quad \text{und} \quad \alpha(\Omega) = \frac{2\Omega}{c}\Im\sqrt{\varepsilon(\Omega)}$$

Optical properties

- Two frequency ranges
  1. around the laser frequency ω_0 in polarization integral
  2. in THz for α und n

- Around ω_0:
  - Linear approximation: $k(\Omega + \omega) - k(\omega) \approx \frac{n_{\mathrm{gr}}}{c}\Omega$

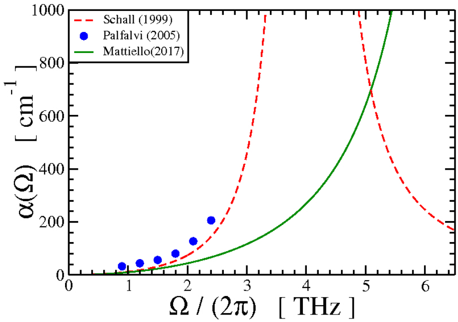
  $\rightarrow$ analytic solution for Gaussian laser pulses

  - Sellmeier equation for $k(\omega)$

Deng et al., *Optics Communications* **268**, 110-114 (2006)

Dielectric function in THz range

- Oscillator model: $\varepsilon(\Omega) = \varepsilon_\infty + \sum_j \frac{S_j \Omega_j^2}{\Omega_j^2 - \Omega^2 - i\Omega\Gamma_j}$



- congruent $\mathrm{LiNbO_3}$: models vs. data

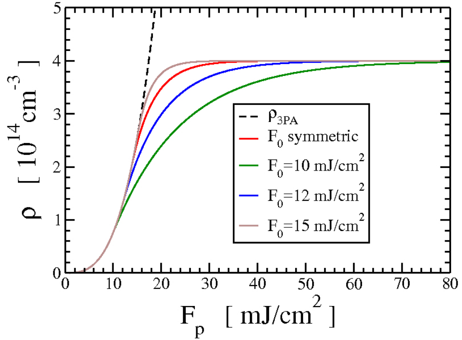
Contribution of the free carries (FC)

- Generation of free charge carriers by the laser pulse (FC)
- Different determination of the modified absorption
  - a. Approximation of the absorption coefficient: $\alpha \to \alpha + \alpha_{\mathrm{FC}}$
  - b. Systematic description in the dielectric function: $\varepsilon \to \varepsilon + \varepsilon_{\mathrm{FC}}$
- Drude model for the FC term $\varepsilon_{\mathrm{FC}}(\Omega) = -\frac{\omega_{\mathrm{pl}}^2}{\Omega^2 + i\Omega/\tau_{\mathrm{sc}}}$

with the plasma frequency $\omega_{\mathrm{pl}}^2 = \frac{e^2 \varrho(I_{\mathrm{p}})}{m^*}$

Modeling of the density of FC ϱ

3 photon absorption (3PA)

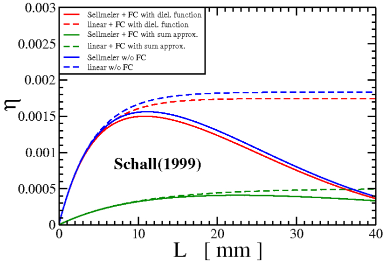


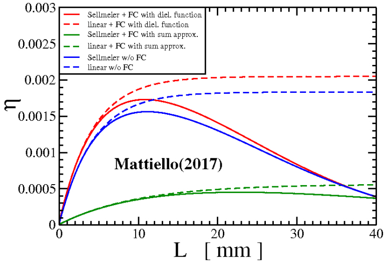
- Density of the free carries within 3PA: $\varrho_{3\mathrm{PA}}(I_\mathrm{p}) = \frac{\tau \lambda_0}{hc} \; \frac{1}{3} \gamma_3 I_\mathrm{p}^3$
- Saturation at the fluence $F_\mathrm{s} = 50 \; \mathrm{mJcm}^{-2}$, $\varrho_\mathrm{s} \approx 4 \times 10^{14} \mathrm{cm}^{-3}$
- Different parameterizations using: $\varrho(I_\mathrm{p}) = I_\infty - A \; \mathrm{e}^{-a(I_\mathrm{p} - I_0)}$
- Unique parameterization by I_0 or F_0 for a Gaussian pulse with duration $\tau = 25$ fs

- Investigation of the influence of the F_0 on η

Results for fixed fluence

SVA: Fixed fluence $F_{\mathrm{p}} = 5\ \mathrm{mJ/cm^2}$

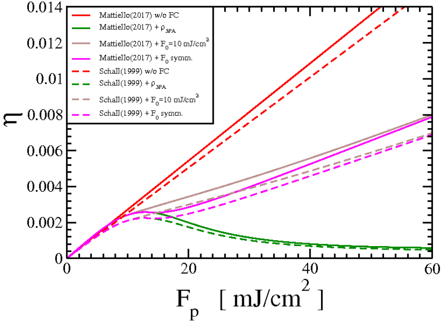




- Underestimation of η within FC approximation
- Strong influence of the FC contribution
- Dependence on the dielectric function parameters

Results as function of the fluence

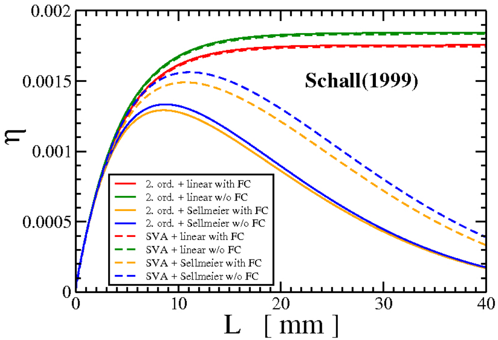
SVA: fixed crystal length $L = 5\ \mathrm{mm}$



- Strong influence of the FC parameterization: monotonic dependence vs. three regime behavior
- Non negligible dependence on the dielectric function

Comparison: Second order vs. SVA (I)

Fixed fluence $F_{\mathrm{p}} = 5\ \mathrm{mJ/cm^2}$



- Negligible deviation without FC
- Strong deviation by considering the FC contribution

Decreasing of the pump intensity

- Intensity decreasing induced by 3PA

$$I_{\mathrm{p}}(t,z) = I_0(t-t_0)\left(1+2\gamma_3 I_0^2(t-t_0)\right)^{-1/2}$$

- Influence on η in SVA:
  - Taylor Expansion
  - Fourier Transformation of the Taylor expansion

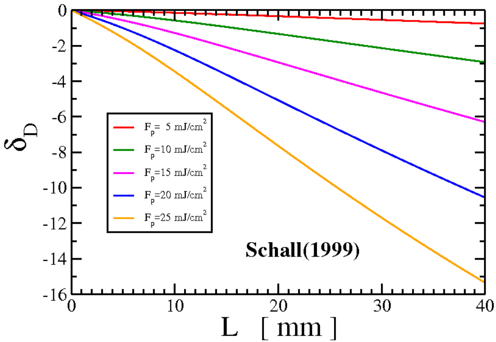
$$I_{\mathrm{p}}(\Omega,z) = \mathrm{e}^{-\imath qz}\sum_{n=0}^{\infty}\tilde{I}_n\, z^n \quad \text{with} \quad \tilde{I}_n = \frac{u_n}{2\sigma_n\sqrt{\pi}}\mathrm{e}^{-\frac{\Omega^2}{4\sigma_n^2}}$$

$\rightarrow$ $I_{\mathrm{p}}(\Omega,z)$ as the inhomogeneous term of the equation of motion

$\rightarrow$ For a Gaussian pulse $A(\Omega,z) = \sum_{n=0}^{\infty} a_n\, z^n$

Influence of the pump intensity decreasing

Deviation δ in SVA without FC



- Significant reduction of η
- Increasing of δ with the fluence $\rightarrow$ saturation expected

- **Summary**
  - Dependence of the conversion efficiency on the optical properties
  - Strong influence on the free carriers contribution
  - Important role of the second order terms and of pump intensity decreasing
  - Systematic treatment of the optical properties and the full wave equation

- **Outlook**
  - Further investigation of the pump intensity decreasing effects
  - Dynamic calculations of the free carriers density