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Developing an ultra-short laser pulse for probing relativistic laser-plasma interactions

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Abstract

Ultra-short laser pulses are essential to resolve femtosecond-timescale dynamics in plasma-based particle accelerators.

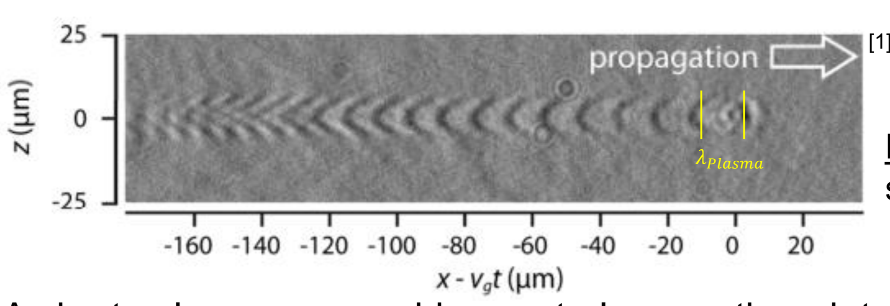
Here we present the process behind a high-intensity hollow-core beam line designed to spectrally broaden an input pulse spectrum by a factor 5.58, with an output pulse energy of ~2 mJ.
Our design enables Fourier limited compression of the pulse to ~6 fs and will be utilized to take crisp shadowgrams of plasma wave sub-structures in LWFAs and PWFAs and furthermore used as a photocathode injector laser in a PWFA.

The proposed experimental arrangement is based on the mechanism of self-phase modulation, which requires an intense, short laser pulse and a material with strong third-order nonlinearity.
We plan to use noble gases, which are well suited to act as nonlinear media with their comparatively high ionization levels and sufficiently large nonlinear refractive indices.
The required intensity for self-phase modulation is achieved by focusing a pre-compressed laser pulse down to a smaller beam diameter. A hollow-core fiber is used to maintain the intensity over a longer distance and clean the pulse profile for later use in shadowgraphy.

Challenges in designing such a hollow-core fiber beam line are spatial limitations, ionization de-focusing, laser induced damages on optics and self-focusing effects due to the high pulse intensity.

Motivation

Ultra-short laser pulses with pulse durations of a few femtoseconds are required to resolve processes on timescales of tens of femtoseconds, such as the structure and motion of plasma waves in relativistic laser-plasma interactions.
Resolving a plasma wave requires exposure times of $t_{max} \leq \frac{\lambda_{Plasma}}{2 * c_0}$.



Object size ~10µm → t_{max}~16fs

Figure 1: An exemplary shadowgram, indicating the size of the first plasma wave

A short pulse means a wide spectral range, though typical Ti:Sa lasers are limited in their spectral range.
Self phase modulation is exploited to widen the spectral range of laser pulses and furhter reduce the Fourier limited pulse duration.
In addition to the short pulse duration, a clean pulse profile is required to ensure a good contrast on the shadowgrams.
Since hollow-core fibers act as spatial filters, they are preferred over other methods, such as gas-filled Heriott cells or thin plates.

Self phase modulation

- Direct consequence of the intensity dependent refractive index $n = n_0 + n_2 I$
- Maximum phase shift given by $\Delta\phi_{max} = \frac{\omega_0 n_2}{c_0} I_0 L_{eff}$ [2]
- Spectral broadening factor is $F = \frac{\Delta\omega_{out}}{\Delta\omega_{in}} = \sqrt{1 + \frac{4}{3\sqrt{3}} \Delta\phi_{max}^{\ 2}} = \frac{\Delta\tau_{in}}{\Delta\tau_{out}}$ [2]
- Spectral broadening imprints positive chirp on the pulse

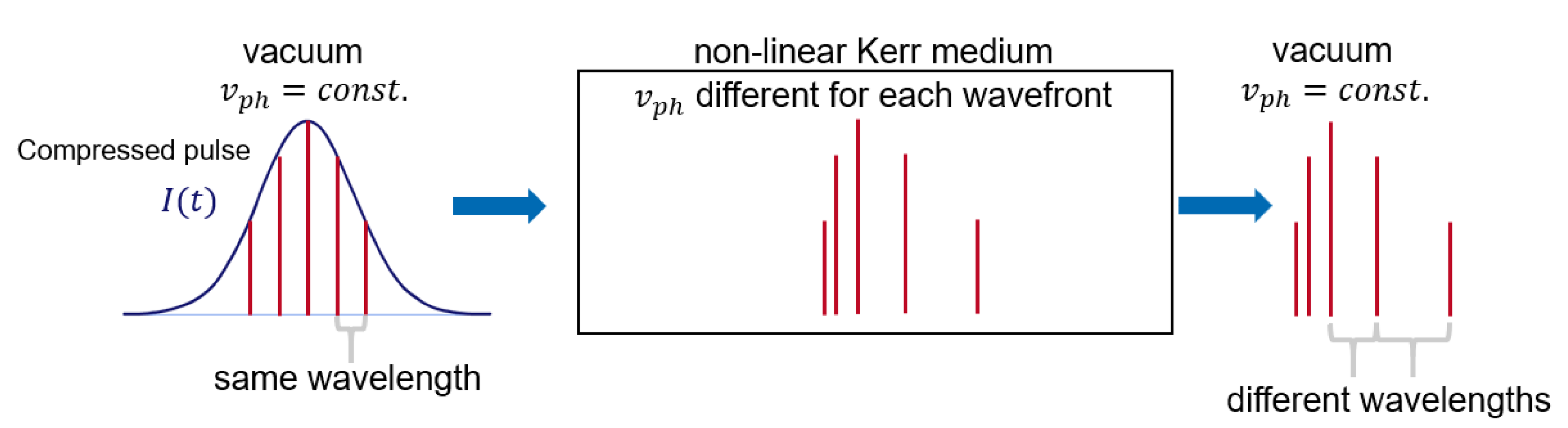


Figure 2: Simplified visualization of the physical process during self phase modulation.

Gaussian pulses and hollow-core fibers

- Pure Gaussian TEM modes can not exist inside the fiber, electronic hybrid modes are excited instead
- Coupling efficiency of excitation depends on focal spot size of laser and inner radius of fiber a
- Effective length of the nonlinear process depends on inner radius of fiber a, the fiber materials and the nonlinear mediums refractive index

$$\eta = \frac{4\left(\int_0^a r J_0(\frac{u_{1m} \cdot r}{a}) \exp\left(-\frac{r^2}{w^2}\right) dr\right)^2}{w^2 \int_0^a r J_0(\frac{u_{1m} \cdot r}{a}) dr} \quad [4]$$

$$L_{eff} = \frac{1 - \exp\left(-\frac{\alpha_m}{L}\right)}{\alpha_m} \quad [2]$$

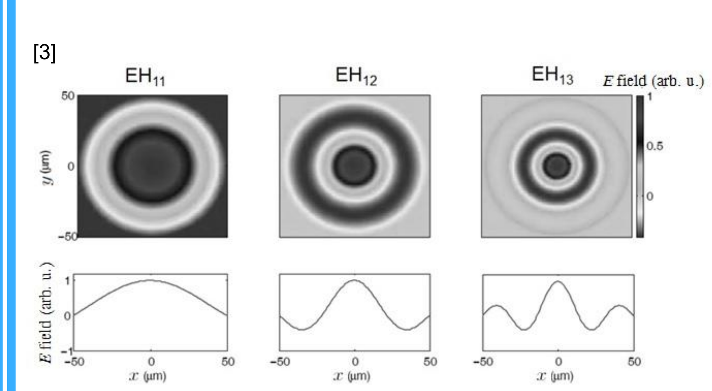


Figure 3: transverse profiles of the first three EH_{1m} modes.

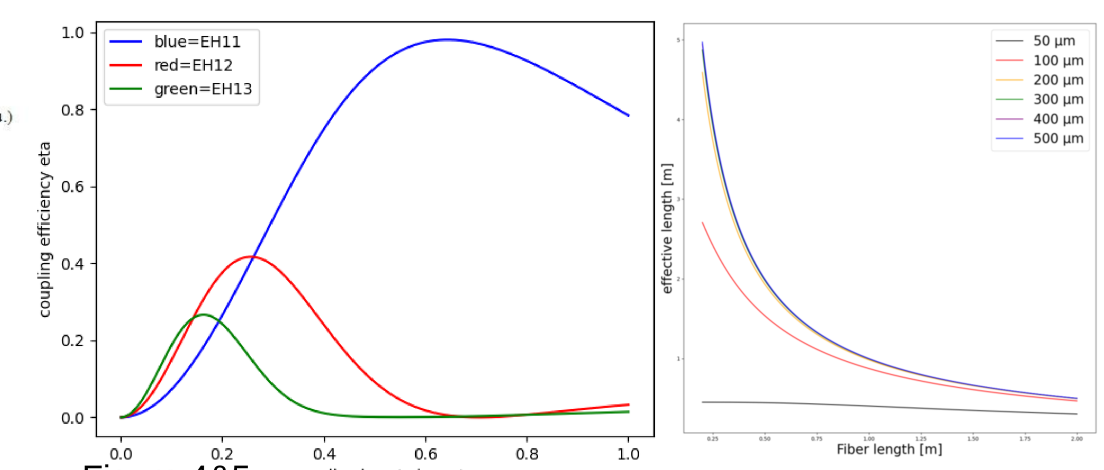
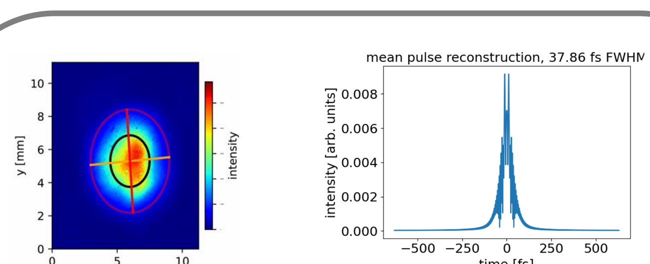


Figure 4&5: Coupling efficiency vs. Normalized spot size & Effective lengths for different radii

Designing the Beamline



Beam size

Pulse duration

Available space

$n_2 (10^{-20} cm^2/W)$	Eq. (11)	[8]	ESHG data
He	0.34	0.41	0.37
Ne	0.85	0.74	0.94
Ar	7.96	10.4	10.9
Kr	18.9	29.4	24.7
Xe	54.8	93.5	63.9

[5] Nonlinear refractive indices of noble gases

$$F = \frac{\Delta\tau_{in}}{\Delta\tau_{out}}$$

Define boundary conditions and desired beam parameters → Choose nonlinear medium → Calculate the broadening factor for the desired pulse duration → Calculate the intensity required to broaden the spectrum via SPM

$$I_0 = \frac{\lambda_0}{2\pi n_2 L_{eff}} \cdot \sqrt{(F^2 - 1) \cdot \frac{3\sqrt{3}}{4}}$$

the nonlinear medium is ionised

Calculate focal spot size assuming a beam energy → Calculate focal length → Choose commercially available focus mirror → Check ionization for selected focus mirror

$$I_0 = \frac{4 \ln 2}{\sqrt{\pi}} \cdot \frac{E}{\tau \cdot \pi w^2} \quad [7]$$

For a Gaussian pulse with a FWHM pulse duration τ and a full pulse energy E

$$\frac{n_e}{n_0} = 1 - \exp\left(-\int_{\infty}^{t} \hat{\omega}_{ADK}\, dt'\right) \quad [6]$$

Following the ADK model of ionisation rates via tunneling ionisation

Optics get damaged or B-Integral is too large

Check damage thresholds of sensitive optics → Check B-Integral in the window, find a suitable window position → Determine fiber radius for most efficient coupling into the EH_{11} mode

Calculate pulse fluence at the position of the sensitive optical component and compare with the scaled damage threshold of the optic

$$B = \frac{2\pi}{\lambda_0} \cdot \int_0^L \frac{n_2 I}{n_0} dl \leq 1$$

The design is an iterative process with three crucial check-points:
- The nonlinear medium is not ionised to prevent ionisation defocusing and energy loss by ionizing
- The pulse fluence is always lower than the optical damage threshold of the used optics such as mirrors, windows and the fiber itself
- The B-Integral is less or equal to 1 to ensure that nonlinear effects such as self focusing and beam breakdown are negligible

Sources

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[2] C. Vozzi et. al., Applied Physics B 80, 285–289 (2005).

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[4] M. Nisoli, et. al., IEEE Journal of selected topics in quantum electronics 4, 414–420 (1998)

[5] C. Bree et. al., IEEE Journal of Quantum Electronics 46, 433–437 (2010)

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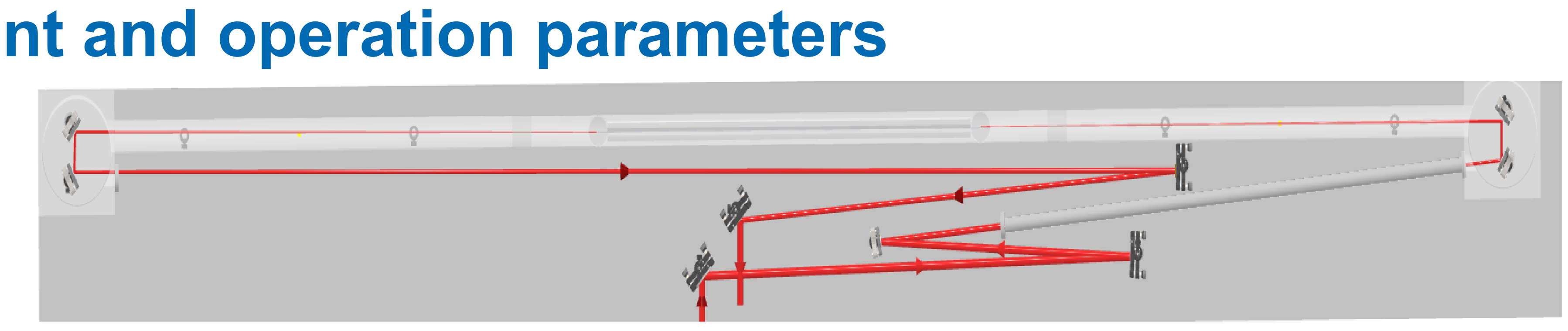
[7] R. Jung, “Laser-plasma interaction with ultra-shortlaser pulses”, PhD thesis (Heinrich-Heine-Universit ̈at D ̈usseldorf, 2007

Experimental arrangement and operation parameters

- 4mJ input pulse energy
- 2w = 8.6mm focused with f=4m to 239µm
- 975µm fiber diameter for 90% coupling efficiency
- Expected broadening factor F=5.58
- Expected Fourier limited pulse duration Δτ=6.3fs, aimed to achieve with a dedicated chirped mirror compressor



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