Propagation of trains of laser pulses in pre-formed plasma channels

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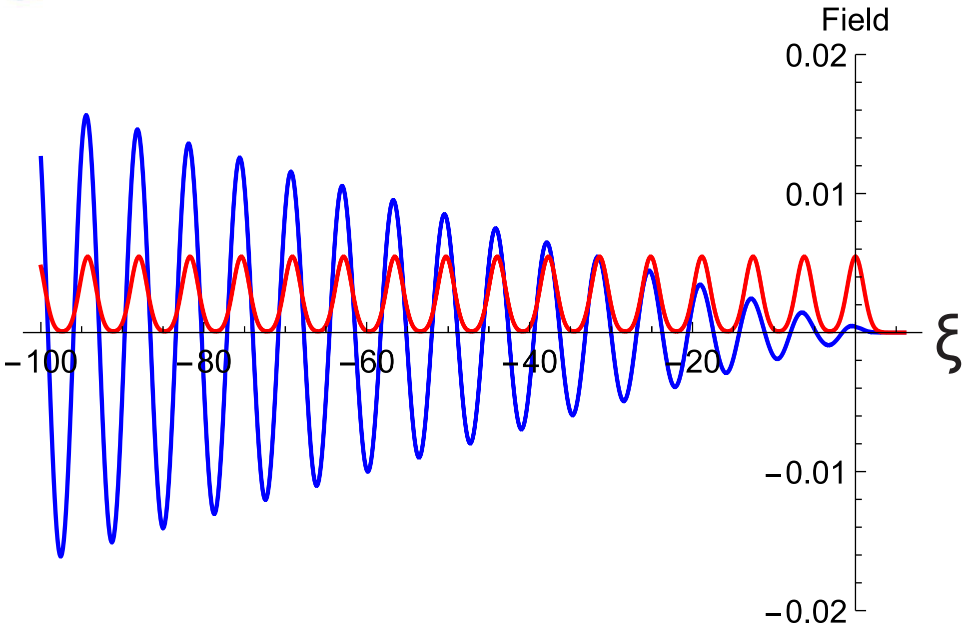
Introduction



Multi-Pulse Laser Wakefield Acceleration
MP-LWFA

▶ Fibre and thin-disk lasers for MP-LWFA

- kHz rate
- high efficiency
- excellent spatial quality and pointing
- lower peak power on optics
- lower intensty for ionization injection
- compact
- fast feed back diagnostics

▶ No self-guiding beacuse of lower peak power

▶ A plasma channel/dielectric capillary needed

- choosing suitable plasma channel
- propagation over dephasing distance to get ~ GeV level accelerator--> 25 cm; EPOCH 2D
- pump laser frequency shifts lead to the accelerator length shorter than the dephasing length for energies large enough

Related presentations

- realted presentations:

- S. Hooker; WG1 on Monday and Plenary on Tuesday.
- M. Streeter; WG7 on Monday.
- C. Arran; poster session on Wednesday.
- M. Shalloo; WG5 on Tuesday.
- P. Tomassini; Plenary on Thursday.
- J. Holloway; WG1 on Thursday.

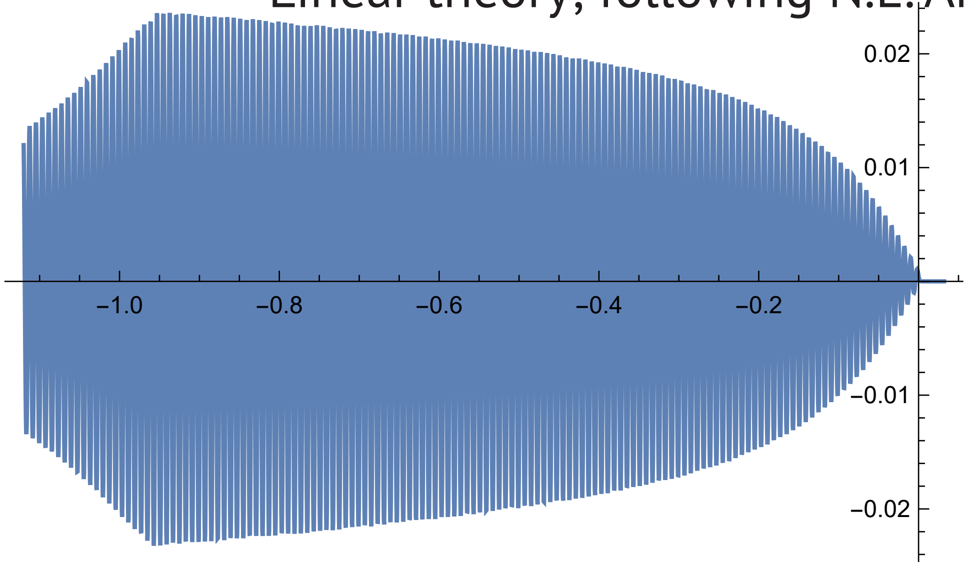
Plasma channel of power α

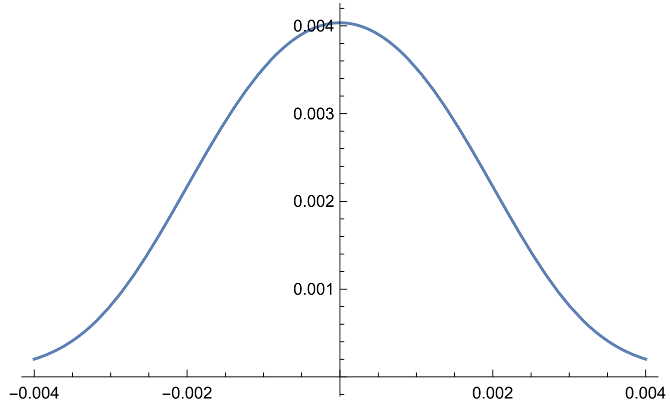
For α = 2
the potential of the wake doesn't grow linearly and transverse profiles of the wake become narrow. The wake behind the laser train decays quickly

$$n_e(\rho) = n_e(0) + \frac{1}{\pi r_e W_M^2}\left[\frac{\rho}{W_M}\right]^{\alpha}$$

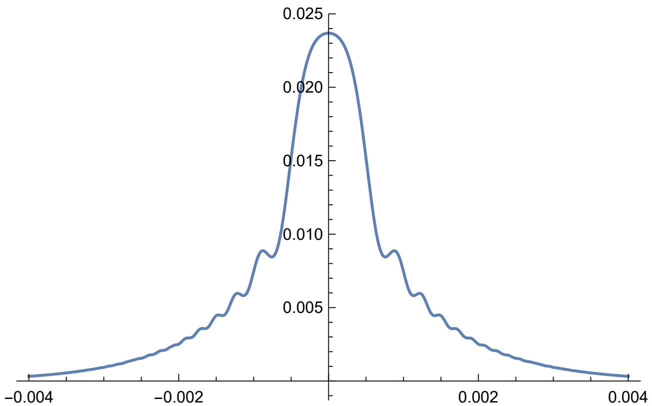
Linear theory; following N.E. Andreev et al. Phys. Plasmas **4**, 1145 (1997)

α = 2

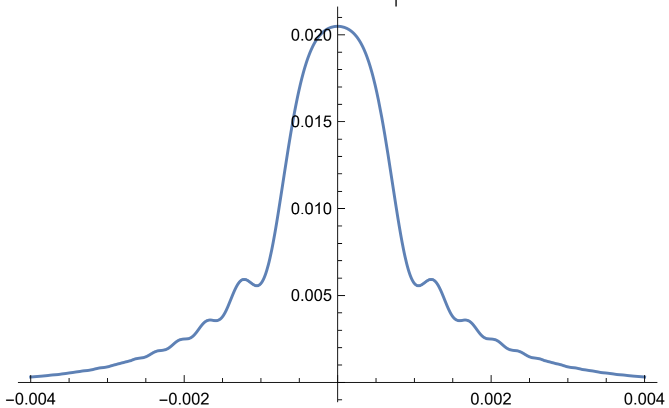




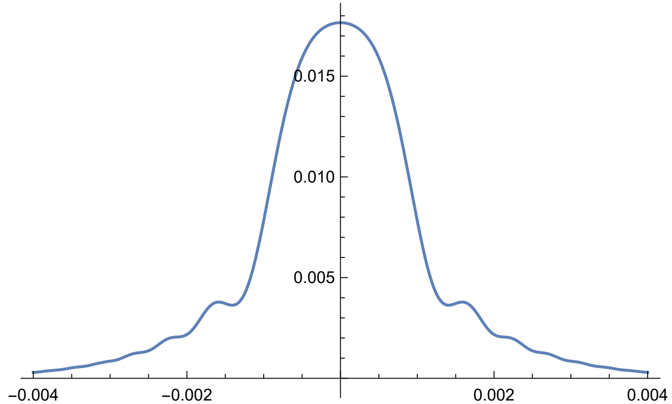
at the head of the train



at the back of the train



50% down the train



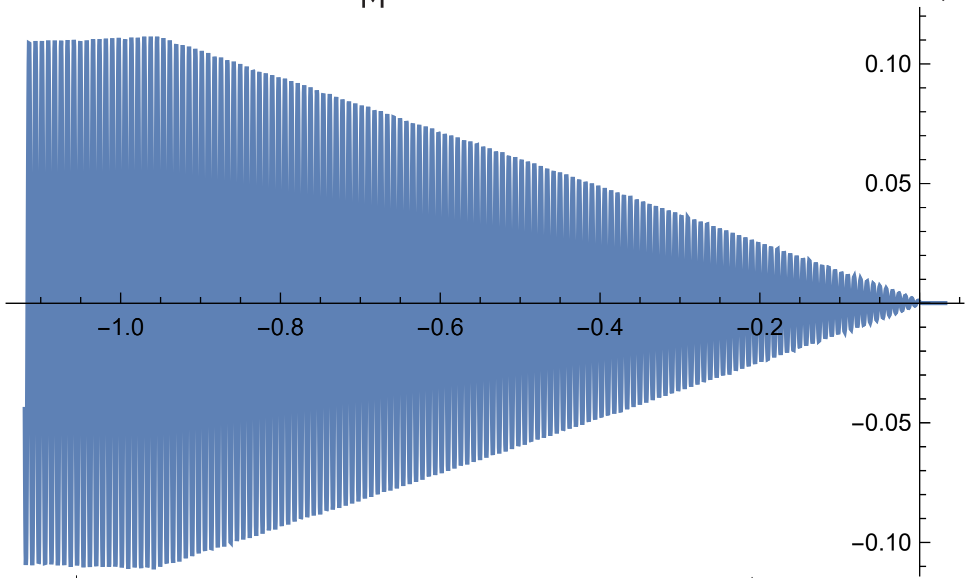
30% down the train

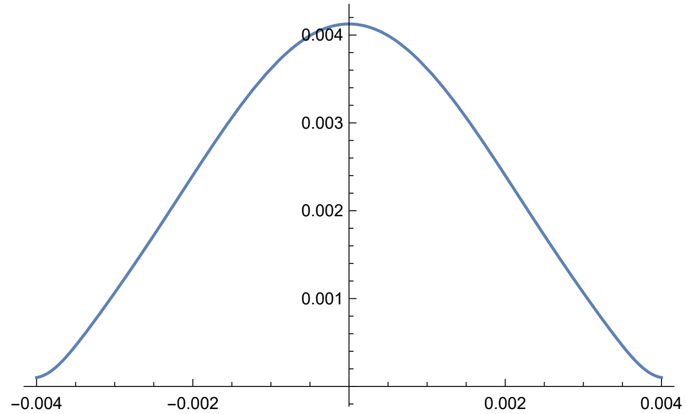
Plasma channel of power α

For α = 10 (plots below) the potential of the wake grows linearly. Transverse profiles of the wake become narrow but acceptable. The wake behind the laser train doesn't decay quickly.

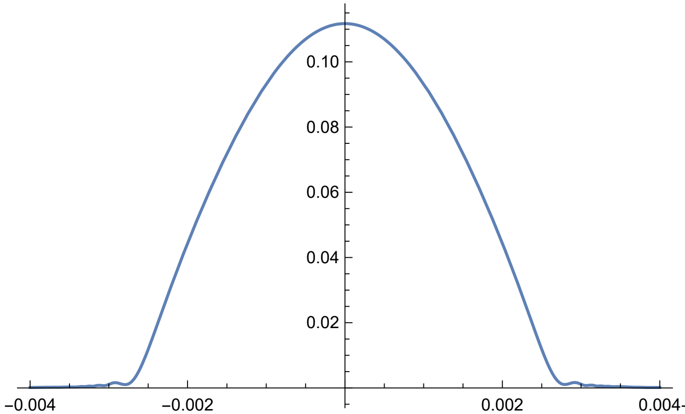
For α = 6 and larger, the channel works for long trains of laser pulses (here 120). The matched spot size W_M doesn't depend on α (excellent approximation).

α = 10

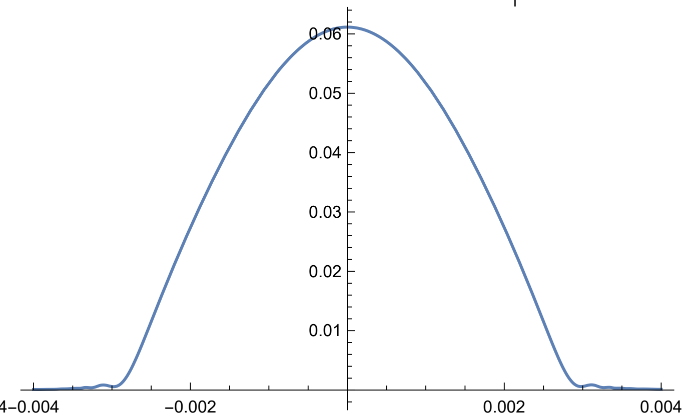




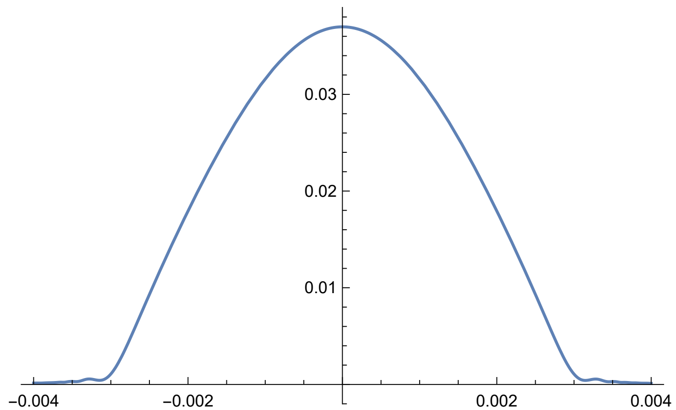
at the head of the train



at the back of the train



50% down the train



30% down the train

Parameters

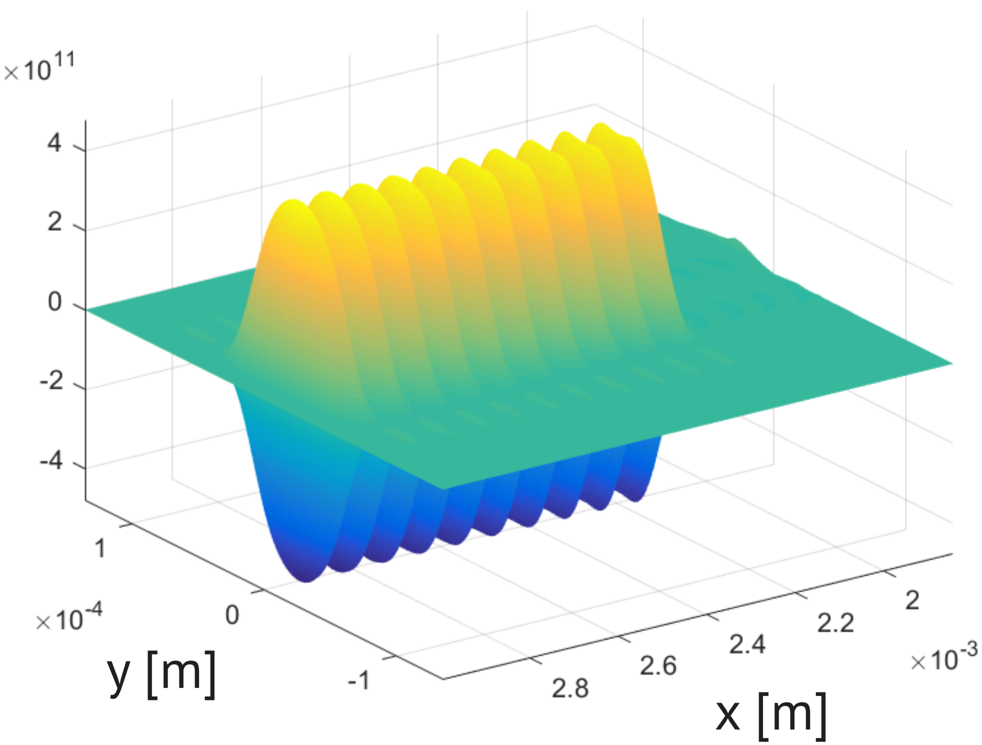
▶ A train of 10 identical laser pulses

Each pulse:

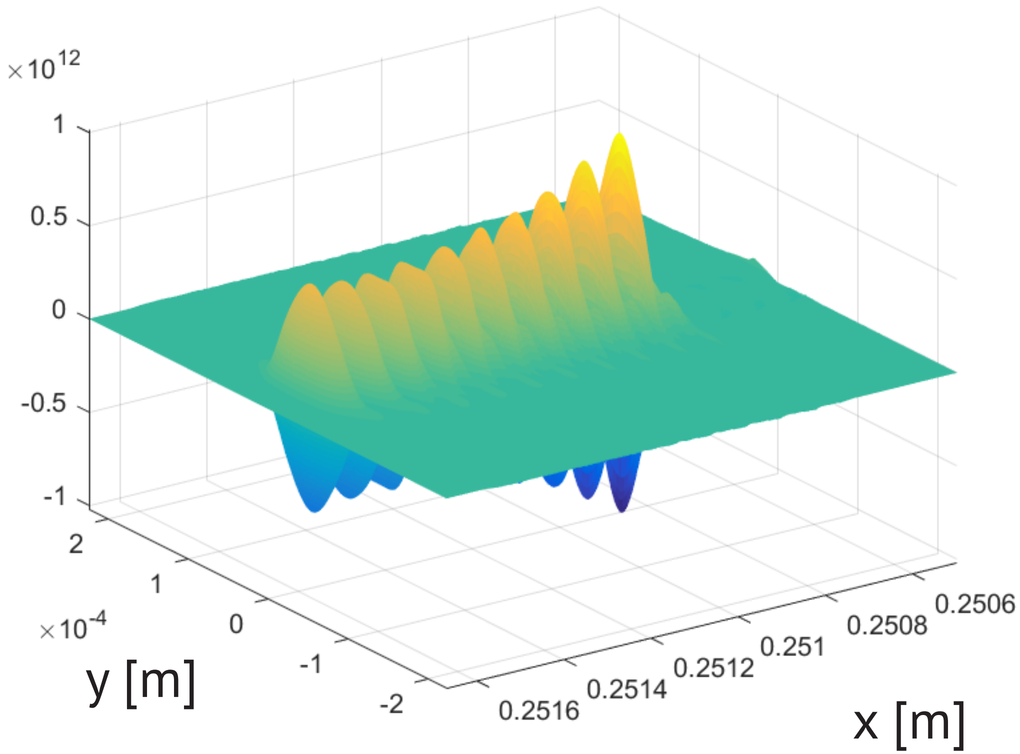
- $\lambda_0 = 1\ \mu$m, $\omega_0 = 1.9\text{x}10^{15}$ Hz, $k_0 = 6.3\text{x}10^6\ \text{m}^{-1}$
- 80 mJ, FWHM 100 fs, $w_0 = 40\ \mu$m, Gaussian envelope
- $a_0 = 0.148$
- plasma density on axis = $1.75\text{x}10^{17}\ \text{cm}^{-3}$,
  $\lambda_p = 80\ \mu$m, $\omega_p = 2.4\text{x}10^{13}$ Hz, $k_p = 7.8\text{x}10^4\ \text{m}^{-1}$
  $k_p\, w_0 = \pi$
- plasma channel $\alpha = 10$
- plasma channel length = 25 cm = dephasing length

▶ PIC code EPOCH 2D v4.8.0 on ARCHER

E_y transverse electric field in V/m

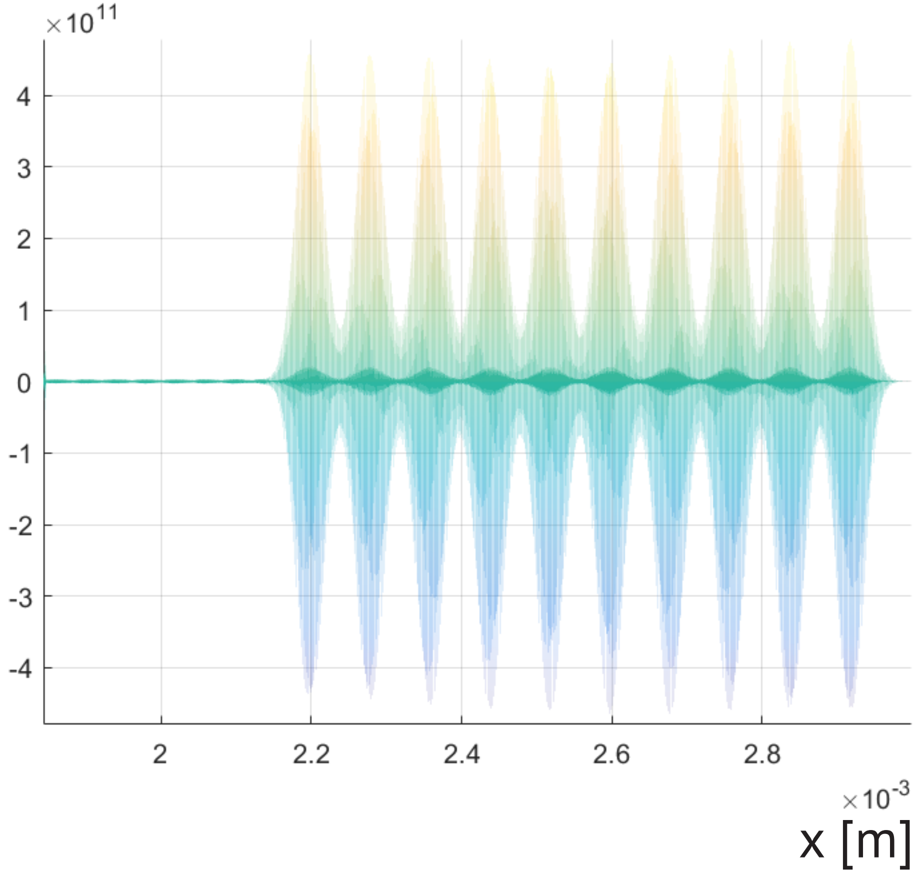


after 2 mm propagation

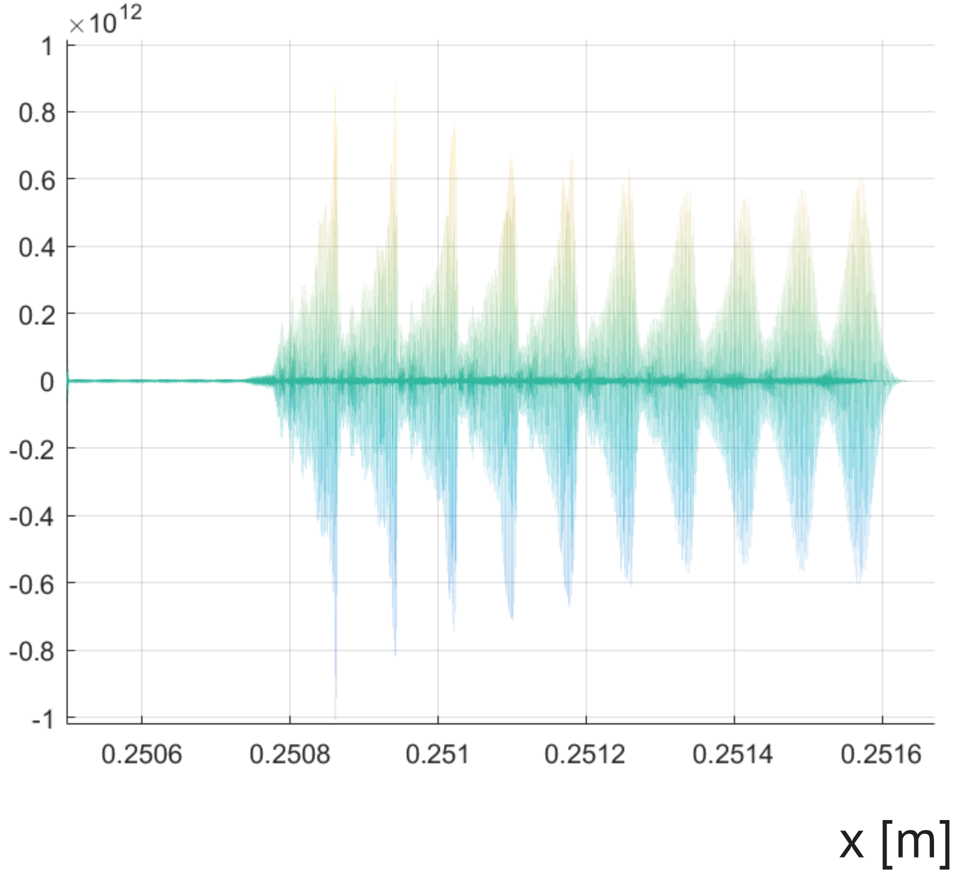


after 25 cm propagation

E_y transverse electric field in V/m

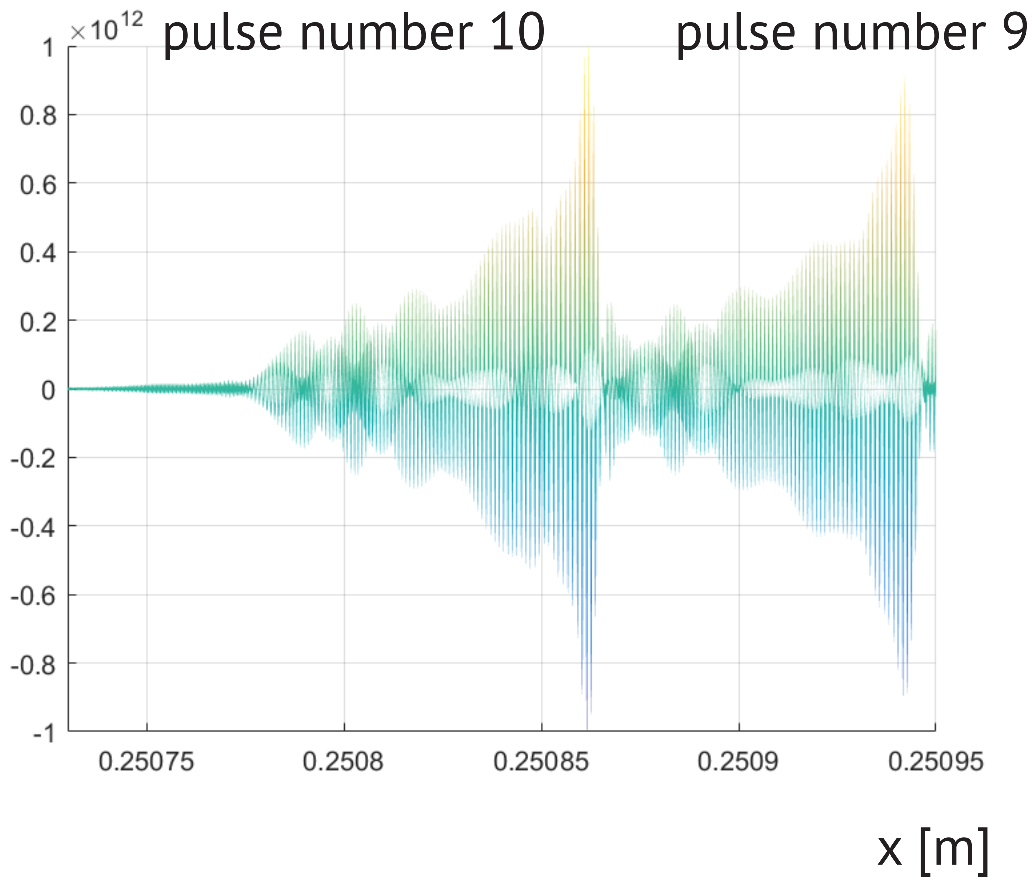


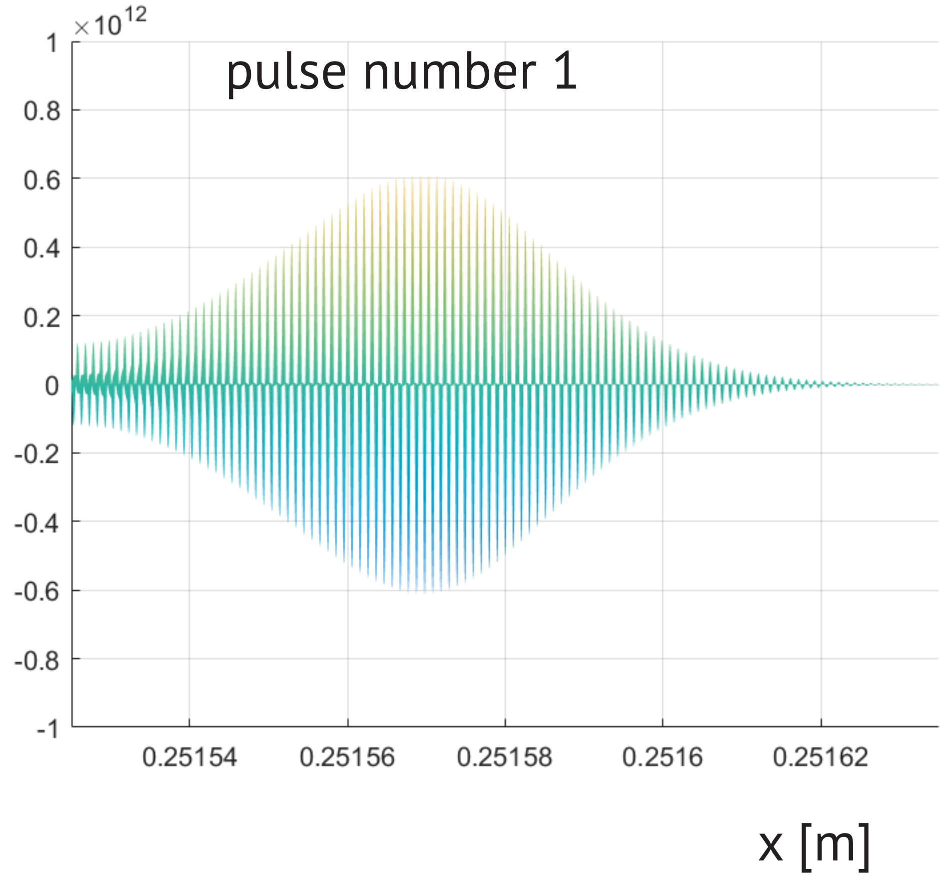
after 2 mm propagation



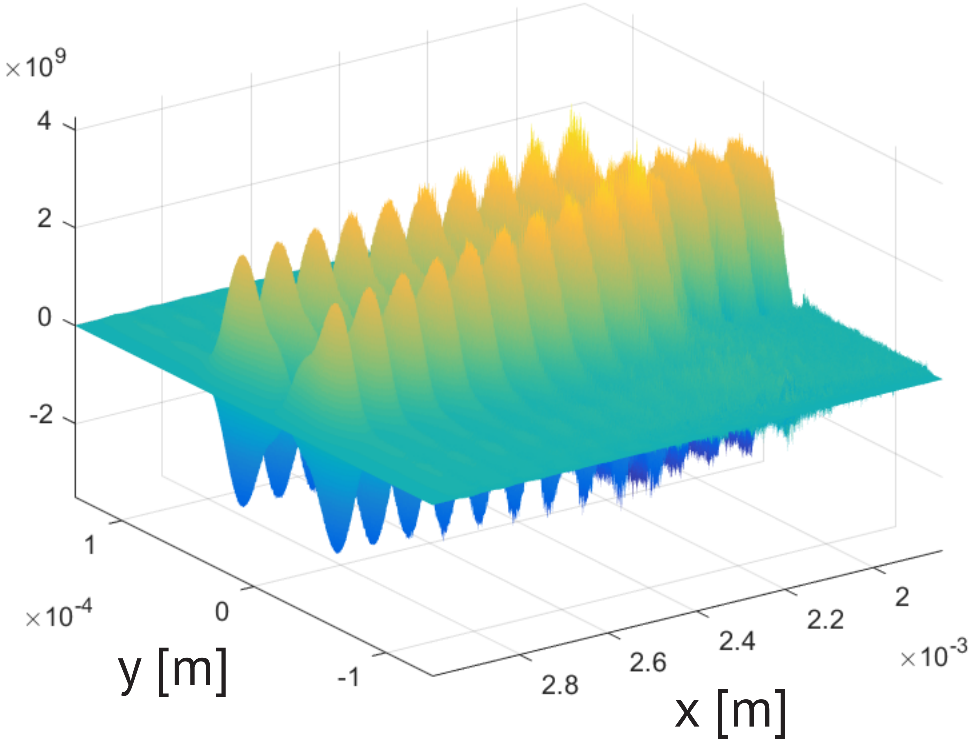
after 25 cm propagation

E_y transverse electric field in V/m after 25 cm propagation

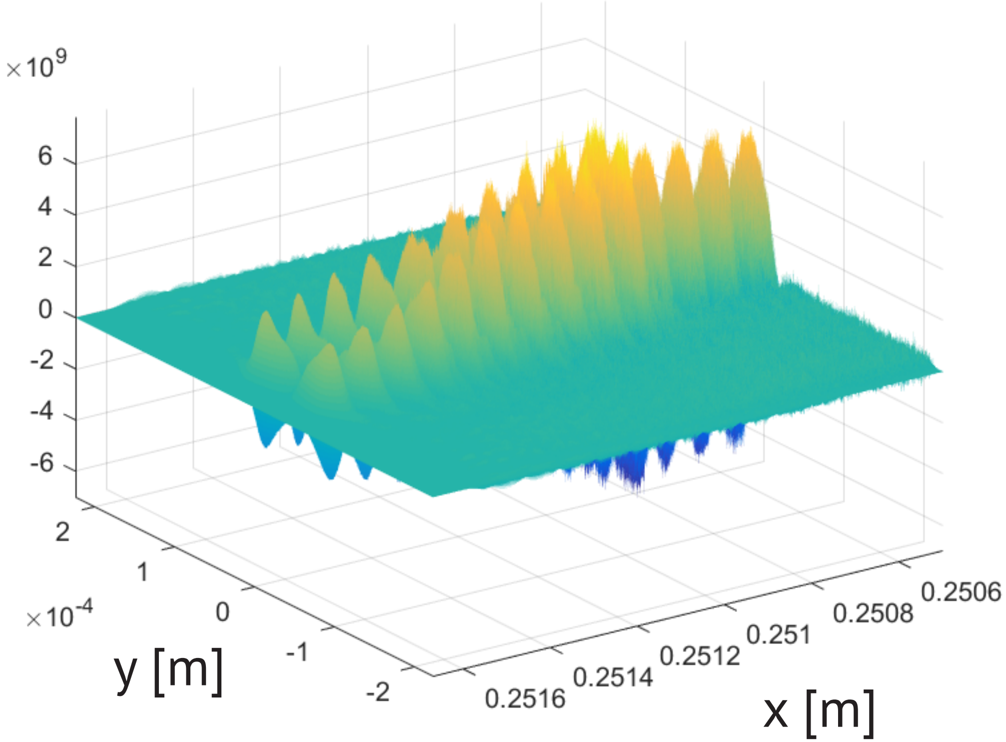




E_x longitudinal electric field in V/m



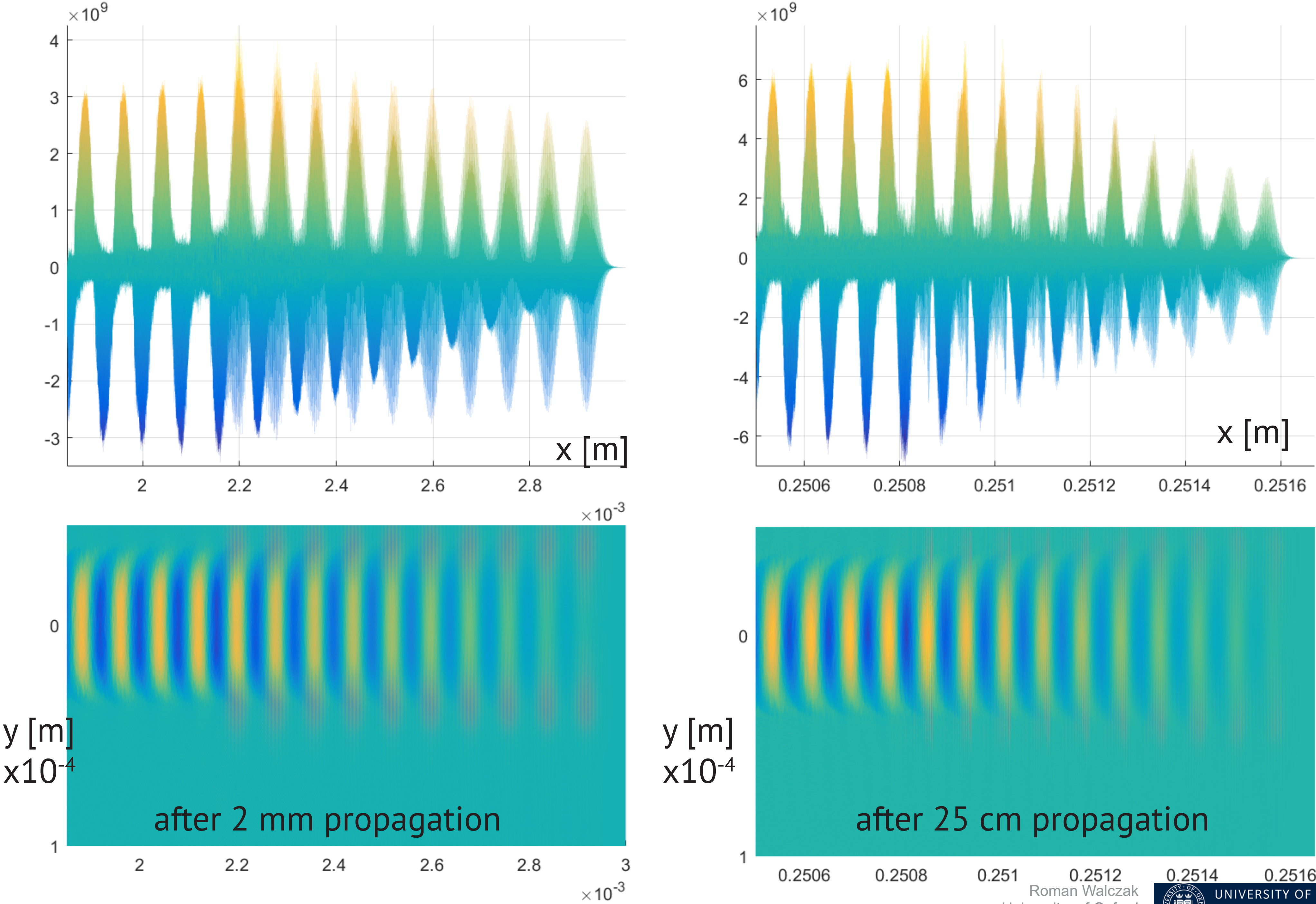
after 2 mm propagation



after 25 cm propagation

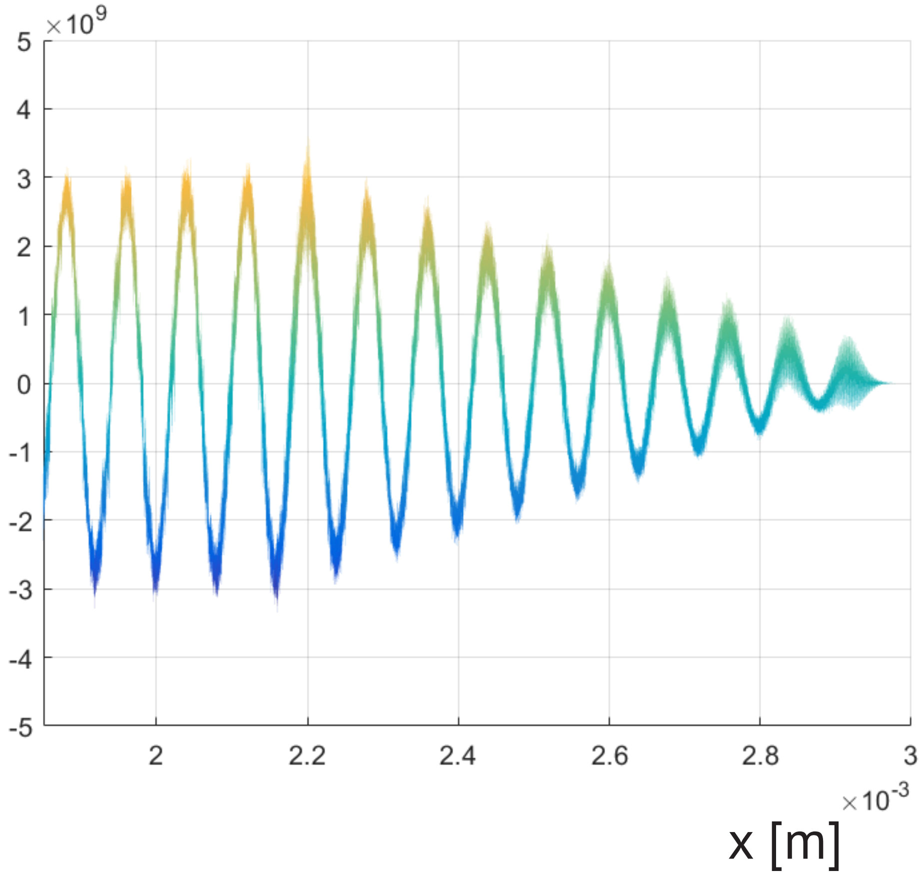
E_x longitudinal electric field in V/m

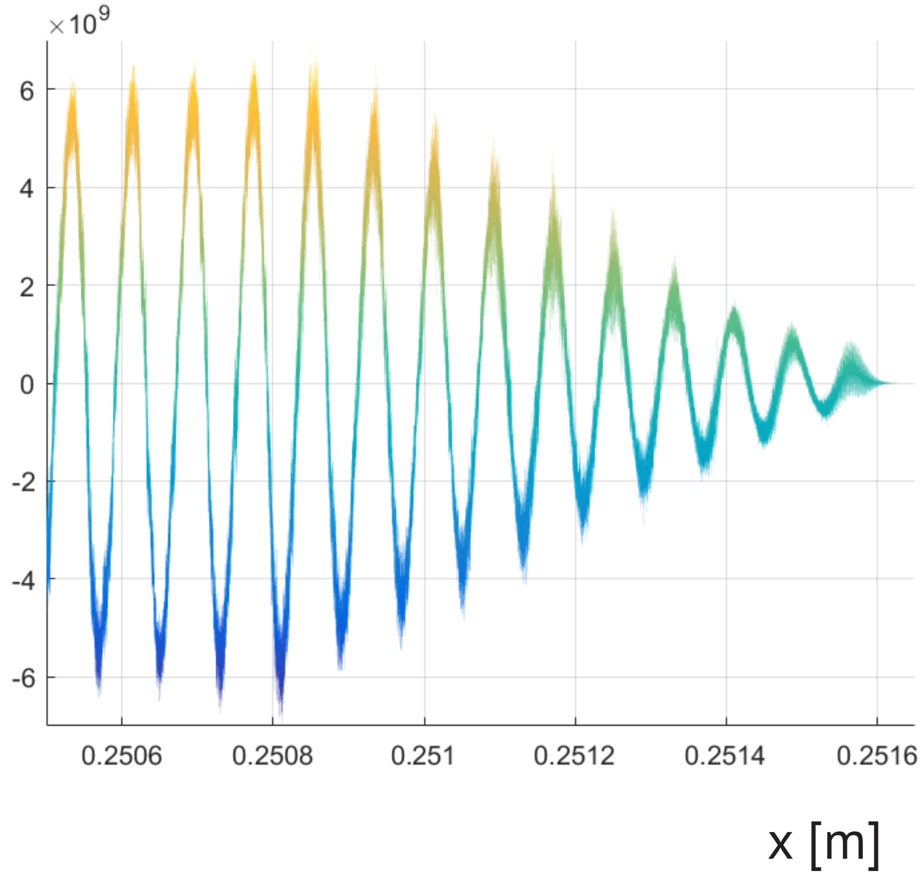
E_x



E_x on axis

E_x longitudinal electric field on axis in V/m

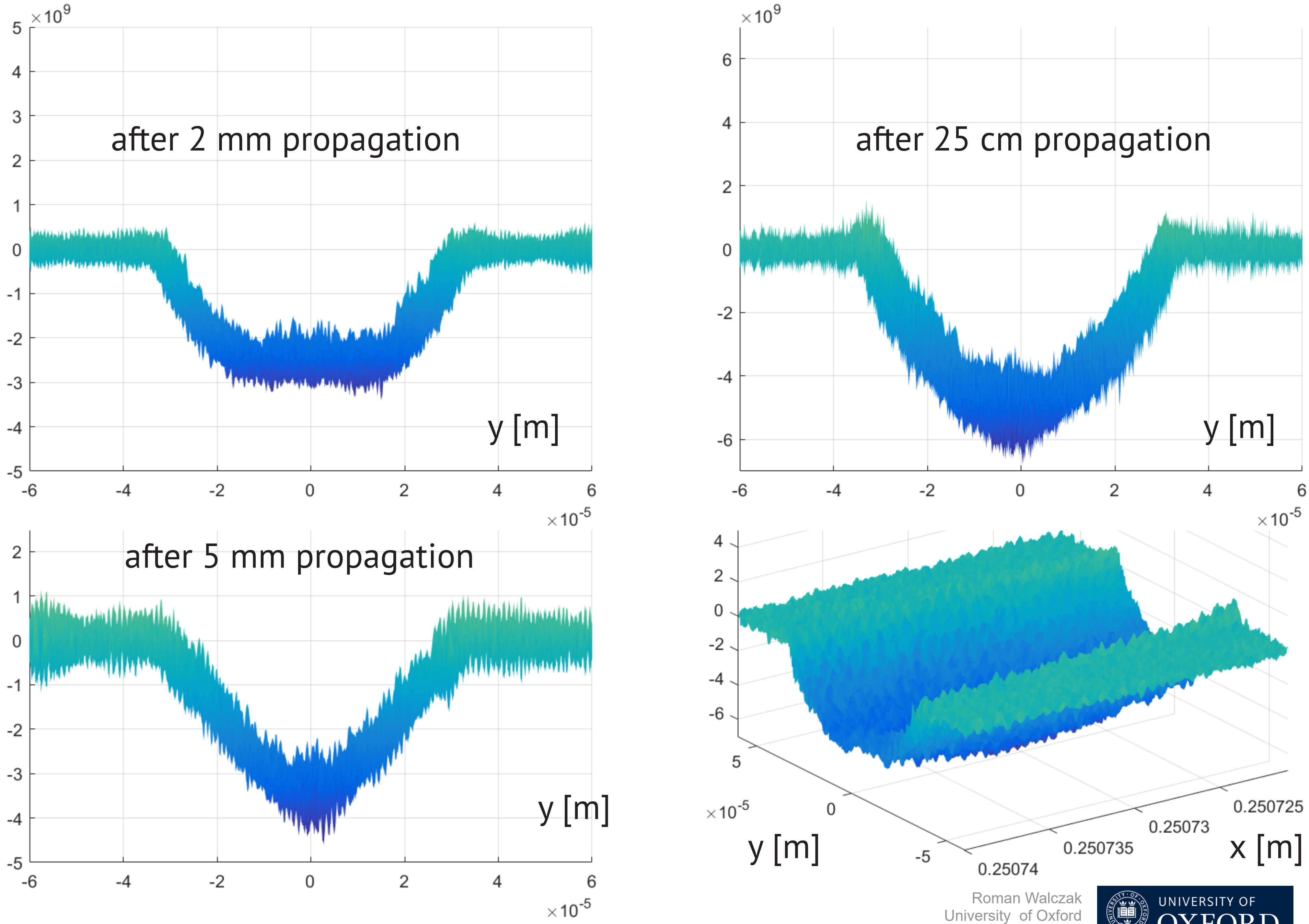




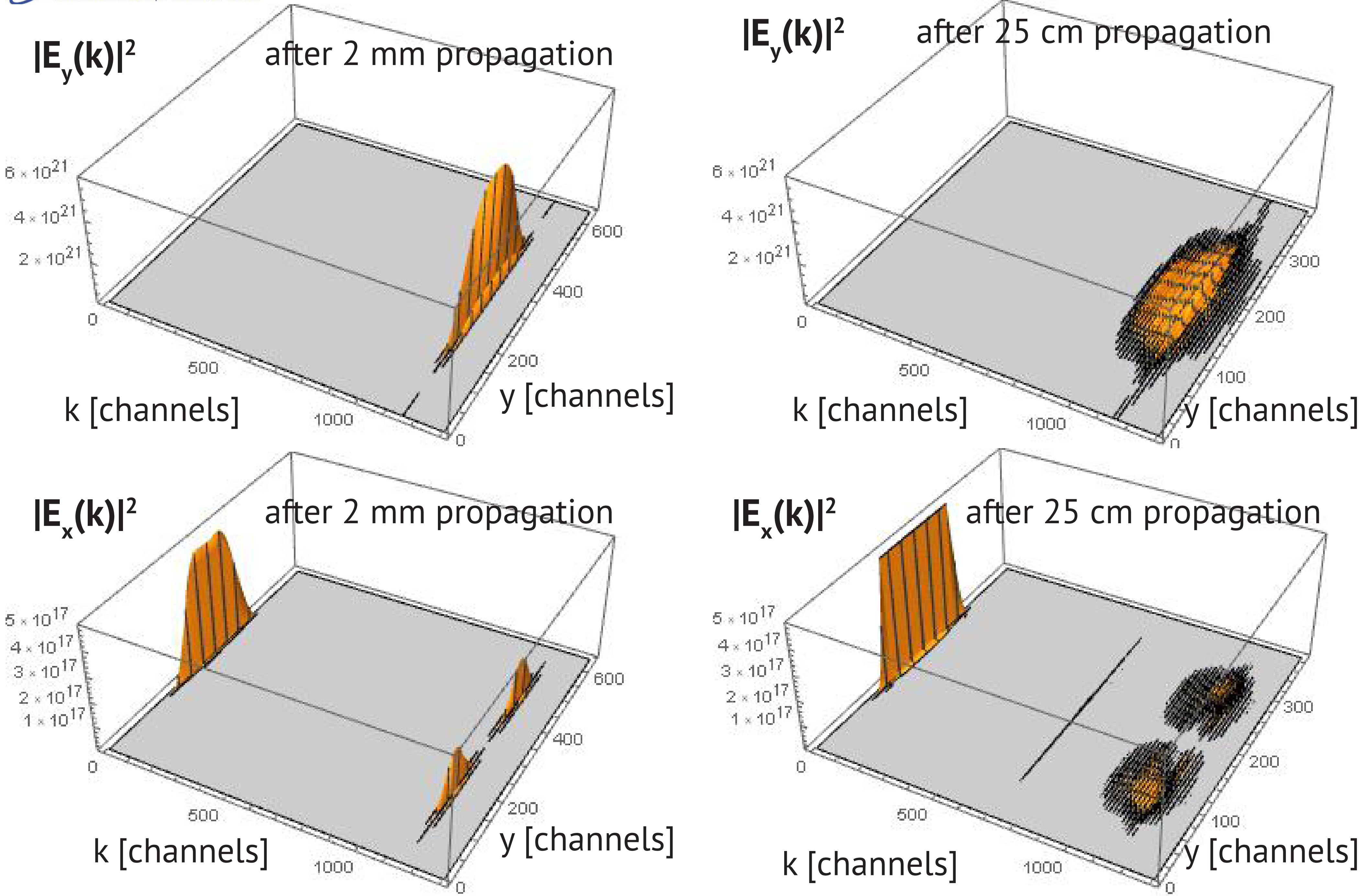
after 2 mm propagation

after 25 cm propagation

E_x longitudinal electric field of the second bucket in V/m



E(k) fast Fourier transform of the electric field



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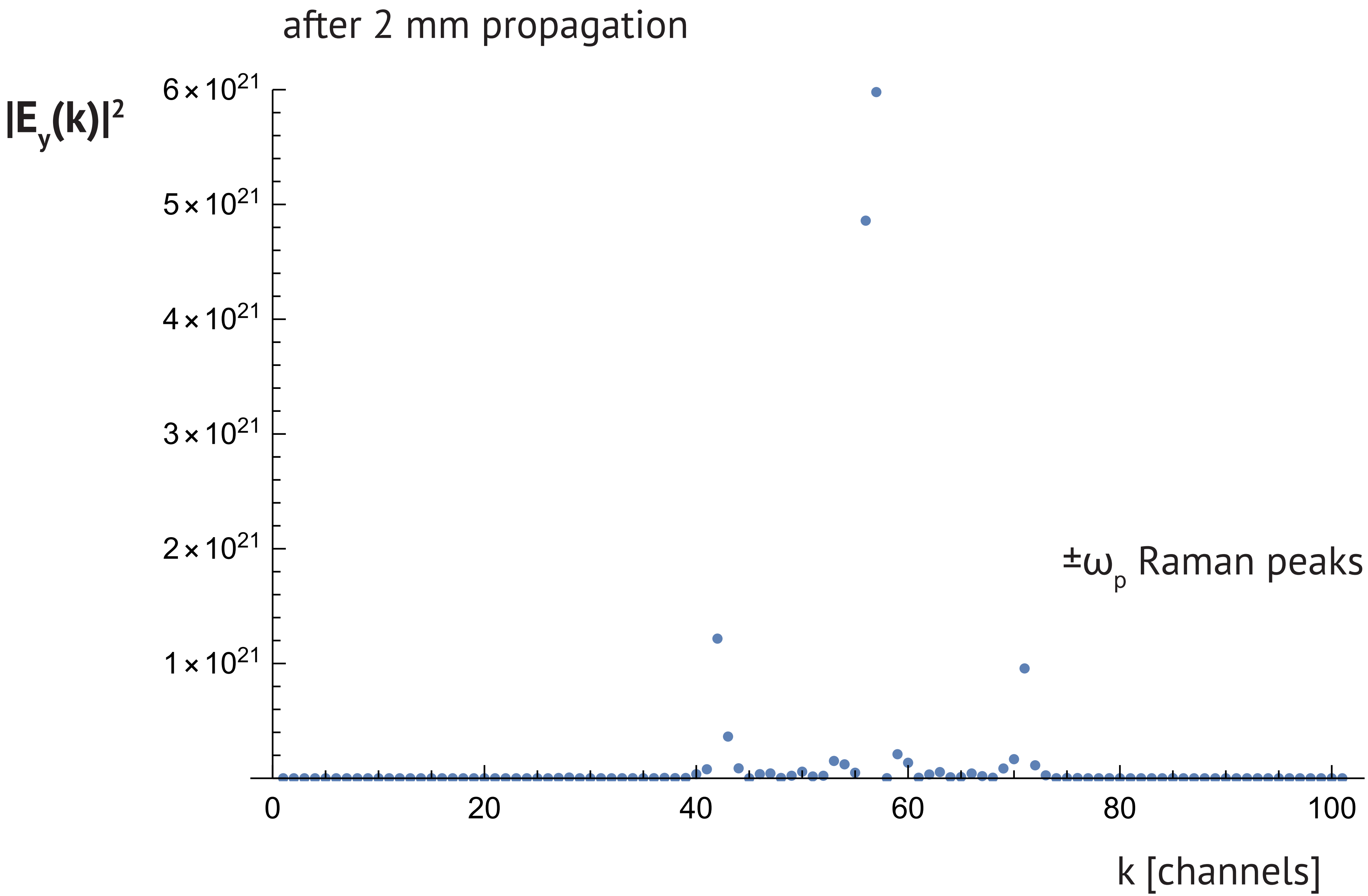
$E_y(k)$ fast Fourier transform of the electric field

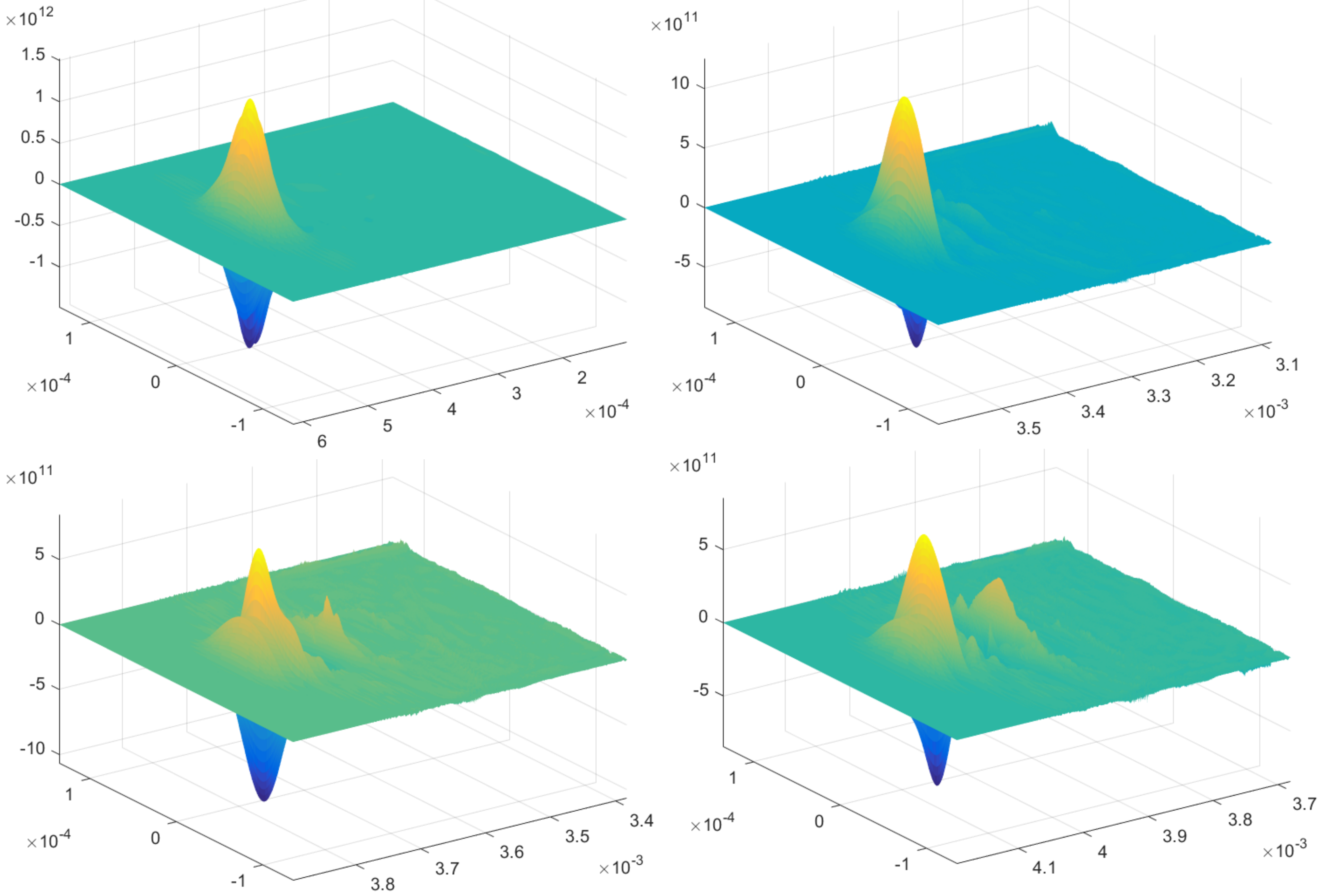


8 μ pump laser

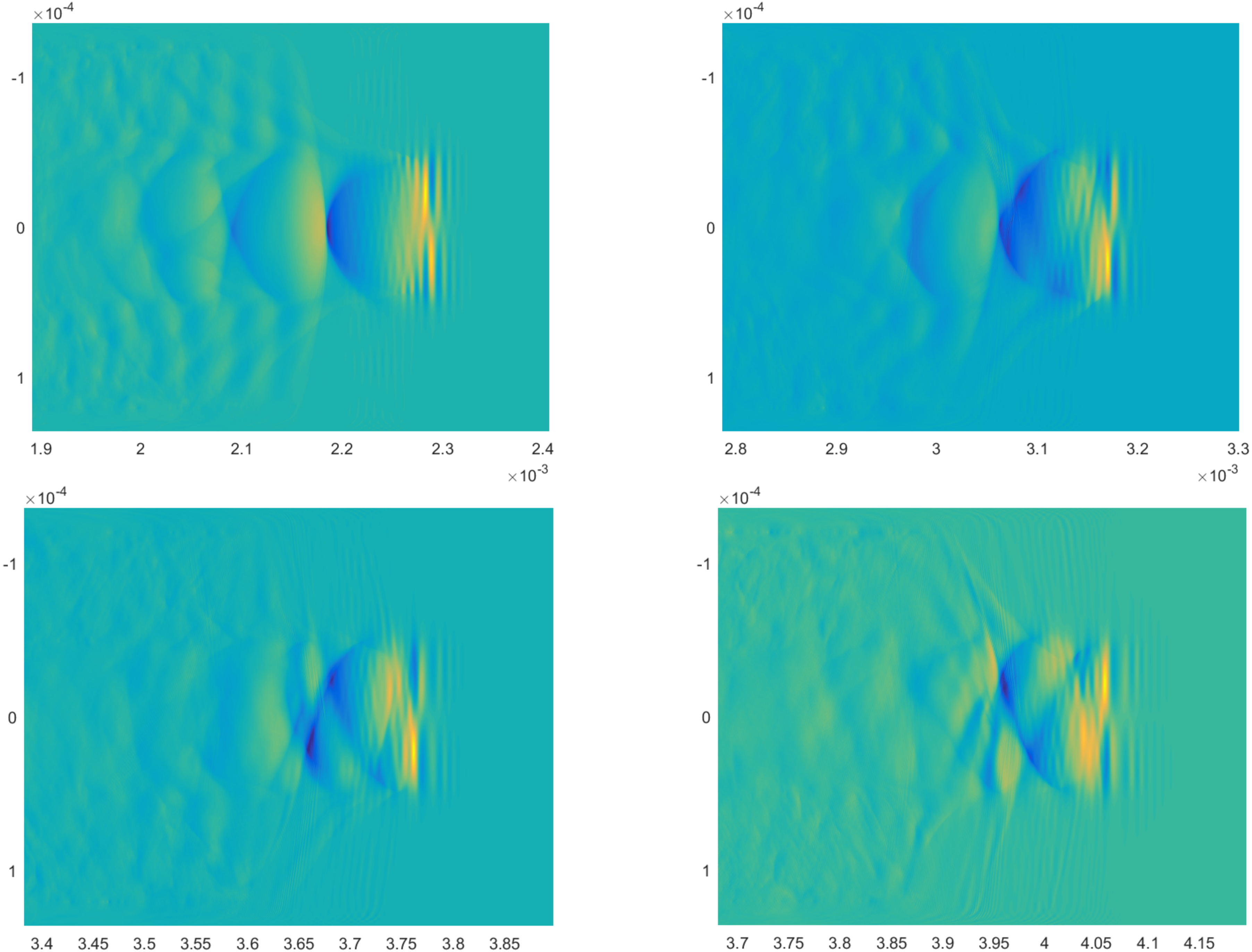
- A single laser puls with the energy of 500 mJ @ λ_0 = 8 μm, a_0 = 3.
- dephasing length = 5.3 mm
- Other parameters as before.

- To note:
- the same wake as before would be created by a single pulse with 12.5 mJ @ 8 μm; a_0 = 0.467. The dephasing length would be 3.9 mm.

E_y; 8 μ pump laser



E_x; 8 μ pump laser



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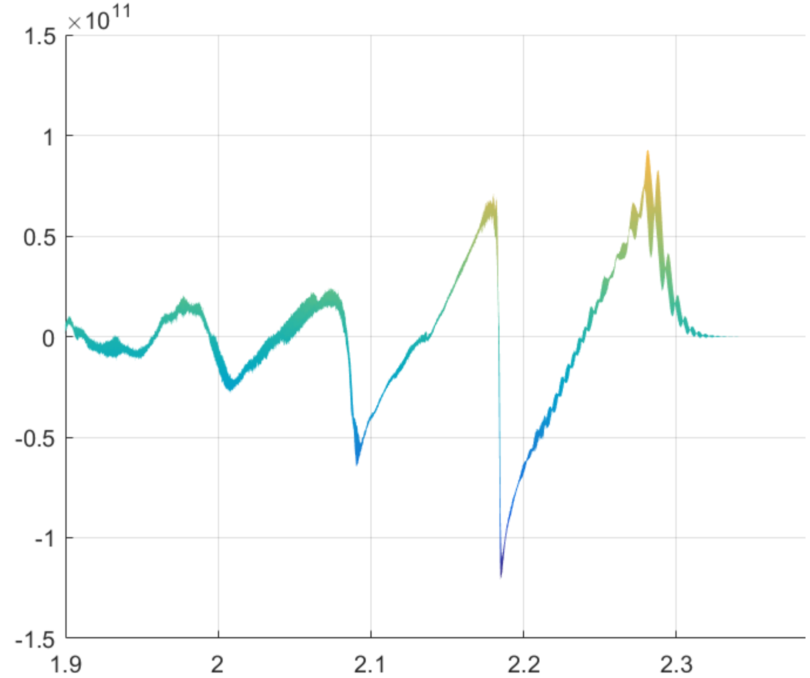
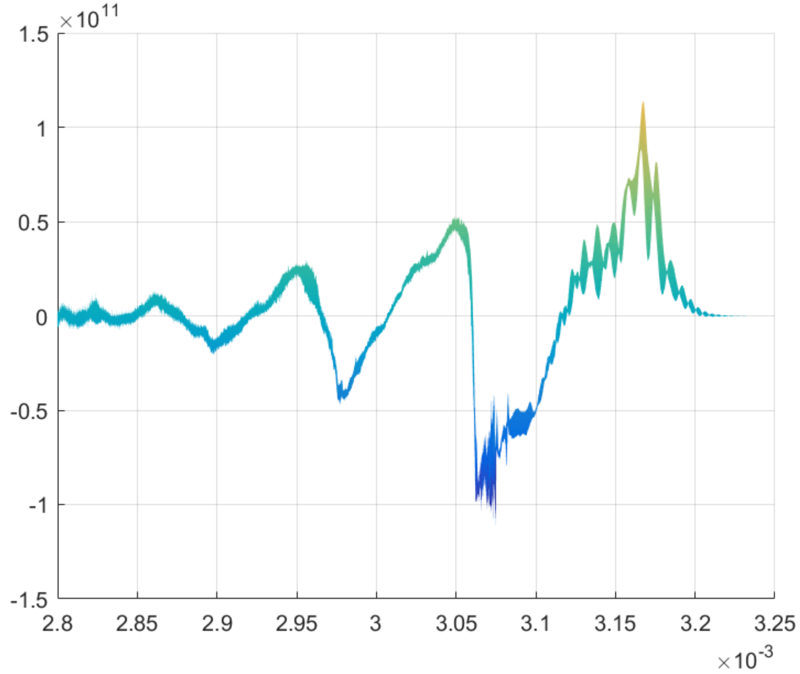
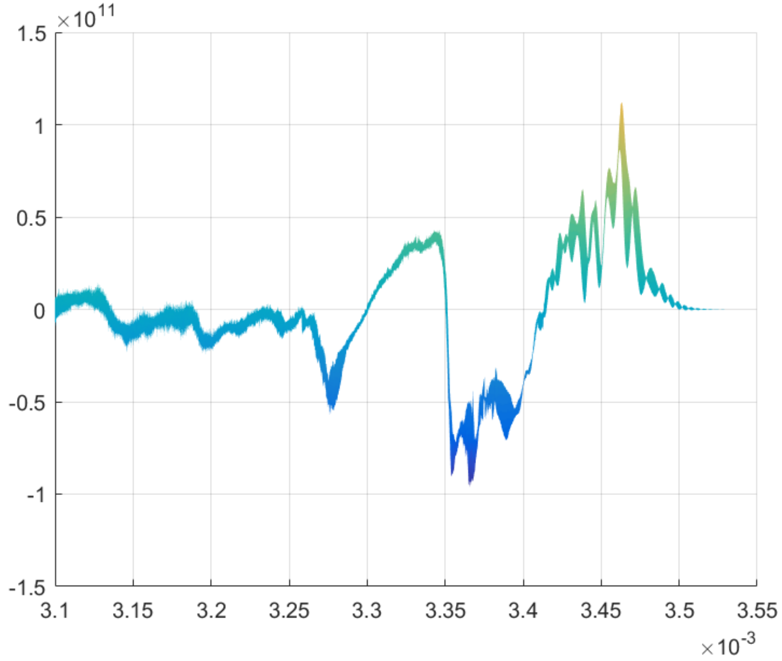
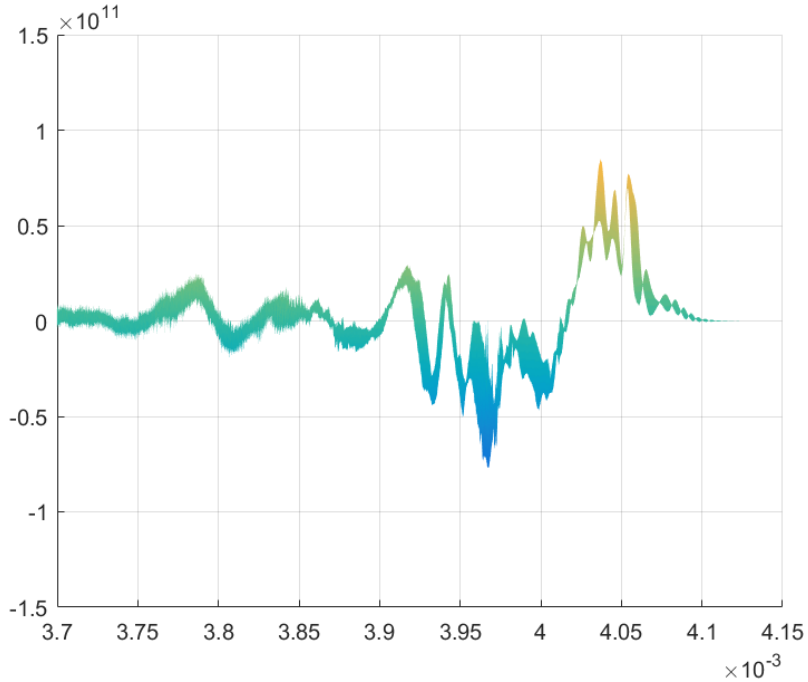
E_x on axis; 8 μ pump laser









Summary

► Plasma channels ~r^{α} for α = 6 or larger are suitable for propagation of long trains of laser pulses. Matching spot size doesn't depend on α.

● A train of 10 laser pulses with total energy of 800 mJ @ 1 μ was propagated over 25 cm in a plasma channel with α = 10 and the density on axis = 1.75×10^{17} cm^{-3} demonstrating that MP-LWFA accelerating electrons to GeV energies at low density is possible.
● At this density, emerging fibre and thin disk laser technologies can be considered for MP-LWFA.
● Pump depletion is small and agrees with linear theory expectation.
● Red and blue frequency shifts are significant and eventually limit accelerator energy and amount of usable pump laser energy. This has been demonstrated at the pump wavelength increased to 8 μ. At a_0 = 3, possible accelerator length is about factor 2 shorter than the dephasing length. The self-injection might also play a role (to be checked how big). The pump depletion might contribute as well at some level; the depletion length is about twice as long as the dephasing length

► Frequency shifts and GDD, particularly important for large wavelength pump laser, need to be carefully considered and taken into account designing accelerators.