Toward spatially uniform pulse compression of top-hat beams at the subpetawatt level of peak powers

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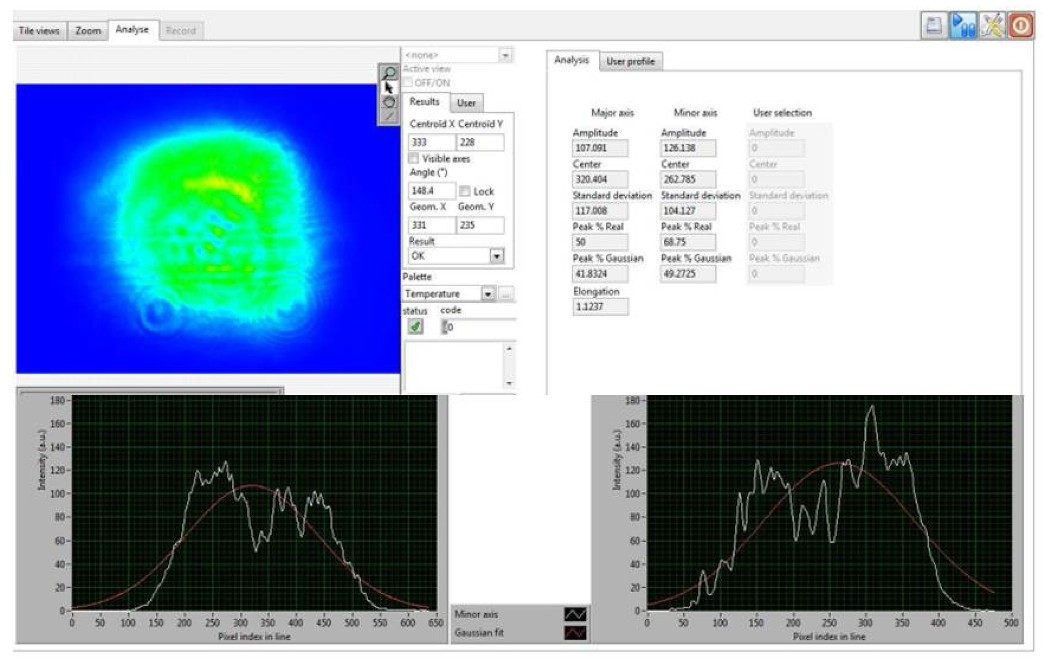
Kurchatov terawatt femtosecond laser system

High-peak-power laser beams with a top-hat transverse intensity profile are shown to offer unique options for the spectral and temporal nonlinear-optical transformations of high-intensity laser fields, promising a new technology of spatially uniform pulse compression at the subpetawatt level of peak powers.

Kurchatov terawatt femtosecond laser system: output beam profile



Identifying the physical scenarios that would enable efficient spectral transformation of extreme-power laser pulses in nonlinear media is a challenging problem, which involves several fundamental issues of extreme-light–matter interactions. In particular, along with self-focusing of a beam as a whole, high-power laser light can exhibit small-scale self-focusing due to the spatial modulation instability of the beam [1] relative to small intensity variations across the laser beam and small spatial inhomogeneities in the optical properties of nonlinear media. The spatiotemporal dynamics of ultrahigh-power laser beams gives rise to multifilamentary structure of the field, which has been verified by numerous laser experiments in gases, liquids, and solids [2, 3].
In this work, we address these issues through experimental studies and supercomputer simulations, analyzing the spatiotemporal dynamics of high-power laser pulses in a nonlinear, fast-ionizing solid-state medium. High-peak-power laser beams with a top-hat transverse intensity profile are shown to offer unique options for the spectral and temporal nonlinear-optical transformations of high-intensity laser fields. A flattened transverse intensity distribution is shown to translate into a spatially uniform spectral broadening, enabling an extraordinarily uniform pulse compression within the entire laser beam. With a super-Gaussian laser beam used as a model, we examine, by means of (3 + 1)-dimensional supercomputer simulations [4], the key tendencies of this unusual scenario of nonlinear-optical field transformation in the regime of high laser intensities (Figs. 1 – 3). Spatial modulation instabilities, which tend to build up across a high-power laser beam, giving rise to beam breakup into multiple filaments, are identified as a universal physical factor limiting the beam quality, as well as the spatial uniformity of pulse compression [5, 6]. A new technology of spatially uniform pulse compression at the subpetawatt level of peak powers is envisaged. Experiments with a top-hat beam delivered as an output of an extreme-intensity short-pulse laser source put in operation at Kurchatov Institute are presented.

(3 + 1)-dimensional GNSE model

$$\frac{\partial}{\partial z}A(\omega,x,y,z)=\left[\frac{ic}{2\omega n_0}\Delta_\perp+i\tilde{D}(\omega)\right]A(\omega,x,y,z)+\tilde{F}\left[i\frac{\omega_0\tilde{T}}{c}n_2IA(t,x,y,z)\right.$$
$$\left.-\frac{U_iW(I)}{2I}A(t,x,y,z)\right]-\left(\frac{i\omega_0^2\omega}{2cn_0\rho_c\left(\omega^2+\tau_c^{-2}\right)}+\frac{\sigma(\omega)}{2}\right)\tilde{F}\left[\rho(t)A(t,x,y,z)\right]$$

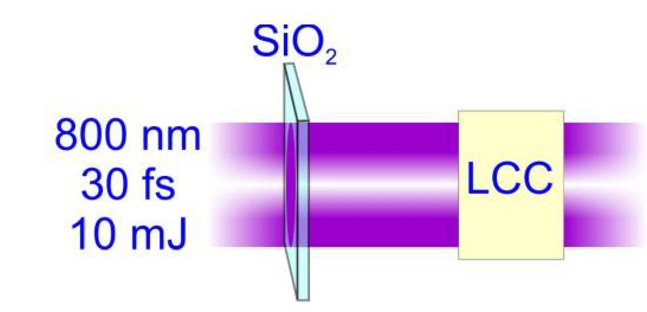
Field evolution equation includes

- ✓ dispersion of the medium
- ✓ beam diffraction
- ✓ optical nonlinearities due to the cubic and quintic susceptibilities of neutral gas
- ✓ ionization-induced nonlinearities
- ✓ pulse self-steepening
- ✓ plasma loss, refraction, and dispersion

Equation for the electron density

photoionization rate W calculated using the Popov--Perelomov--Terentyev version of the Keldysh formalism

Numerical Experiment



P>>Pcr

$P_{cr}(SiO_2)$= 2MW $P=1.7*10^5\ P_{cr}$

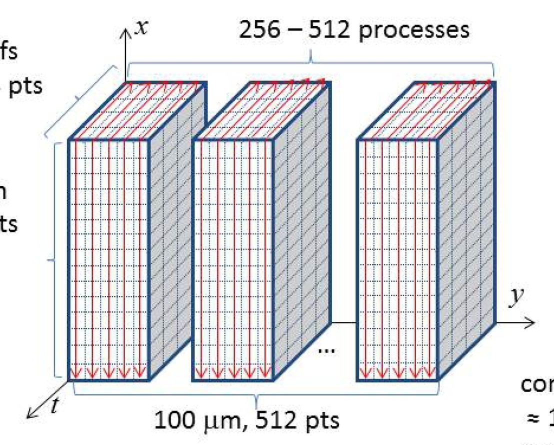
Lomonosov supercomputer   1 – 10 * 10^{15} flop

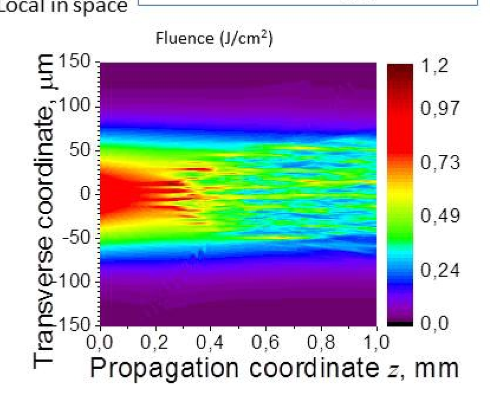
Numerical calculations

Split-step Fourier method: $\frac{\partial A(x,y,z,t)}{\partial z}=LA+NL[A]+PL[A]$

Local in Fourier domain   Local in space

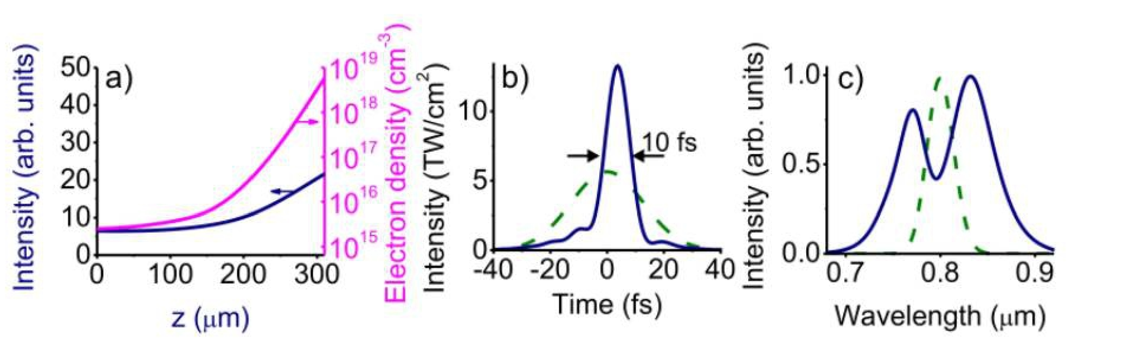
Efficient parallelization of each half-step
Operations: $N_{op}\sim N\log N$
Data transfer: $N_{data}\sim N$





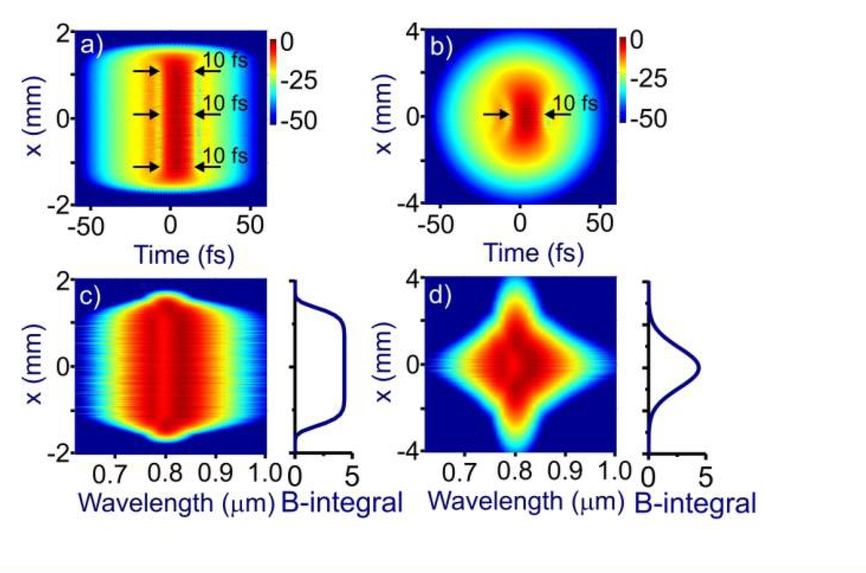
complex double-precision, (52 GB of RAM), ≈ 13000 steps in z (adaptive, nonlinear phase shift 0.003 rad/step).

Pulse compression of super-Gaussian beam



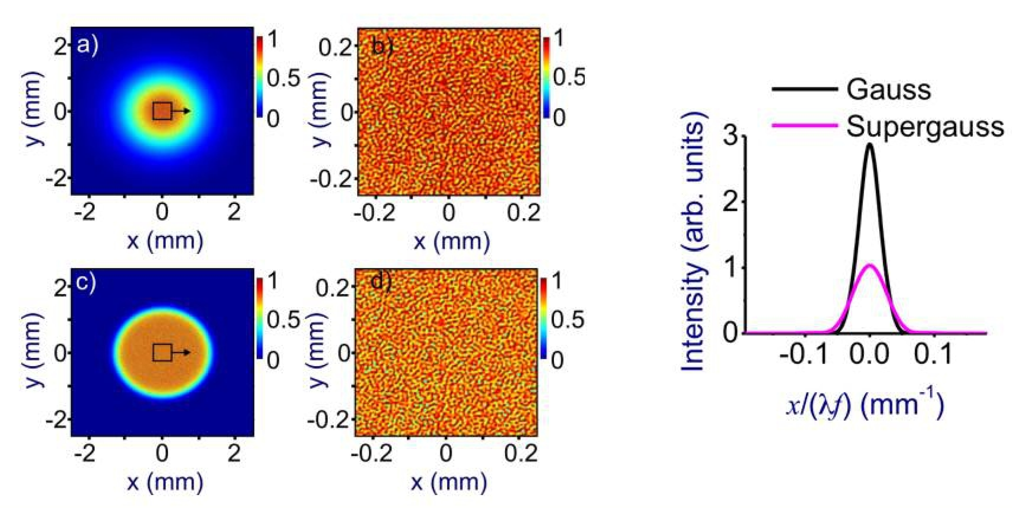
Results of (3 + 1)-dimensional supercomputer simulations of nonlinear-optical evolution of a high-intensity fifth-order super-Gaussian beam:
(a) the maximum field intensity (blue line) and electron density (red line) across the laser beam,
(b) the temporal envelope,
(c) the spectrum of the compressed (solid blue line) and input (dashed green line) laser pulse.

Supercomputer simulations of temporal and spectral evolution in super-Gaussian and a Gaussian beam



Temporal (a, b) and spectral (c, d) evolution in a fifth-order super-Gaussian (a, c) and a Gaussian (b, d) beam. The B integral across the beam is shown as a marginal

Hot-spot generation and beam breakup into multiple filaments for a Gaussian and super-Gaussian beam



Results of (3 + 1)-dimensional supercomputer simulations showing hot-spot generation and beam breakup into multiple filaments for a Gaussian (a, b) and a fifth-order super-Gaussian (c, d) beam. The blowup of the central part of the beam is shown in panels (b) and (d).

References

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