Simultaneous space-time focusing with radially-chirped laser pulses for ionization injection in LWFAs

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Ionization Injection

Controlled injection methods seek to **reduce shot-to-shot variations and energy spread** of electron bunches injected into laser-driven wakefield accelerators (LWFAs). **Optical ionization injection** utilises additional laser pulses to release electrons within the wakefield.

Simultaneous space-time focusing (SSTF) occurs when a transversely-chirped ultrashort laser pulse is focused using a conventional lens. SSTF ensures that the **shortest pulse duration emerges only at the focal point**, where all frequencies overlap spatially. Here we investigate the use of simultaneous space-time focusing (SSTF) to **localize ionization injection**.

Laguerre-Gaussian

Laguerre-Gaussian beam at any longitudinal position [1]

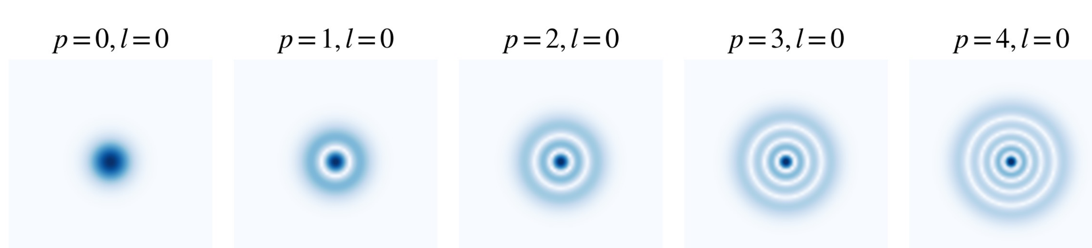
$$LG_p^{\ell}(\mathbf{r}) = \sqrt{\frac{p!}{\pi(|\ell|+p)!}}\left(-\frac{q^*(z)}{q(z)}\right)^n \frac{e^{-ikr^2/2q(z)}}{r}\left(\frac{i\sqrt{kz_R}\,r}{q(z)}\right)^{|\ell|+1} L_p^{|\ell|}\left(\frac{kz_R r^2}{|q(z)|^2}\right)e^{-i\ell\phi}$$

where q is the complex radius of curvature: $q(z) = z - z_0 + iz_R$

and k is the wavenumber, in free-space: $k = \omega/c$

Reconstruction of Arbitrary Beams

Arbitrary beam as a sum of Laguerre-Gaussian modes

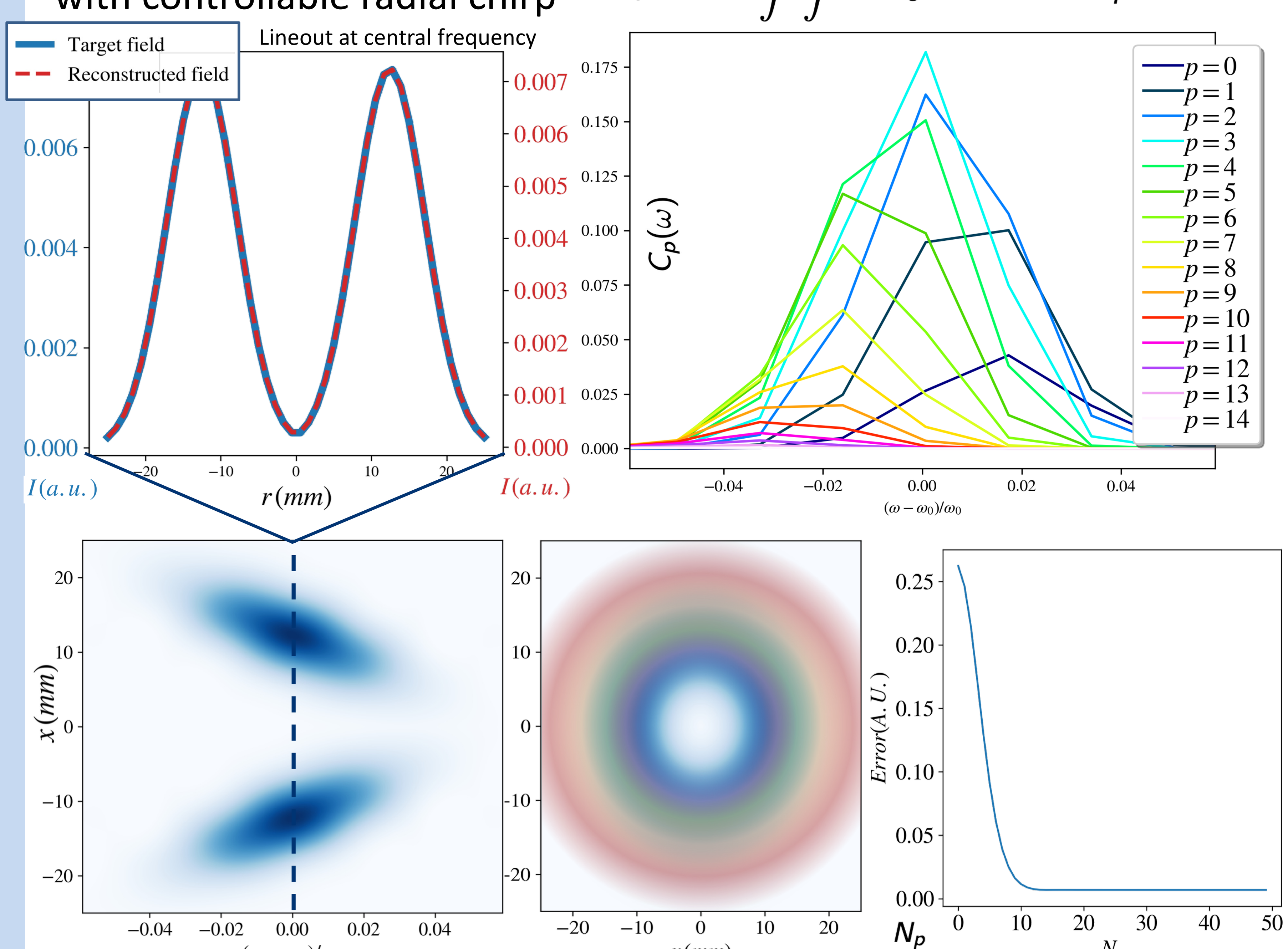


$\ell = 0$ (No OAM)

Overlap integral defines mode contributions:

Target field: Gaussian annulus with controllable radial chirp

$$C_p(\omega) = \int\int \tilde{U}_{\text{target}}(\mathbf{r},\omega) * LG_p^{\ell}(\mathbf{r})\, dx\, dy$$



Reconstructed field: $\tilde{U}_{\text{reconstructed}}(\mathbf{r},\omega) = \sum_{0}^{N_p} C_p(\omega) * LG_p^{\ell}(\mathbf{r})$

Parameters: $\lambda_0 = 800\,\text{nm}$, $\tau_{p,0} = 40\,\text{fs}$ laser pulse with $f/40$ imaging

[1] Giuseppe Vallone, "Role of beam waist in Laguerre–Gauss expansion of vortex beams," Opt. Lett. 42, 1097-1100 (2017)
[2] J. P. Taché, "Derivation of ABCD law for Laguerre-Gaussian beams," Appl. Opt. 26, 2698-2700 (1987)
[3] Stuart A. Collins, "Lens-System Diffraction Integral Written in Terms of Matrix Optics," J. Opt. Soc. Am. 60, 1168-1177 (1970)
[4] J. W. Goodman, Introduction to Fourier Optics, (2005) [5] P. Gibbon, Short Pulse Laser Interactions with Matter (2005)
[6] Bareza, N., Hermosa, N. Subluminal group velocity and dispersion of Laguerre Gauss beams in free space. Sci Rep 6, (2016)

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Method 1: Analytic Propagation

$$q' = \frac{(A*q+B)}{(C*q+D)}$$

Propagate **each** mode downstream [2], sum over weighted modes

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -1/f(\omega) & 1 \end{pmatrix}$$

Lens

Additional mode-dependent Guoy phase shift at lens:

$$\ldots \times e^{-i(2p+\ell+1)\left[\psi(0,z_0,z_R) - \psi(0,z_0',z_R')\right]}$$

$$\psi(z,z_0,z_R) = \tan^{-1}\left(\frac{z-z_0}{z_R}\right)$$

Method 2: Collins' Diffraction Integral

Propagate the superposition of **all** modes downstream directly

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1 & z-z_0 \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 \\ -1/f(\omega) & 1 \end{pmatrix}$$

Free-space **Lens**

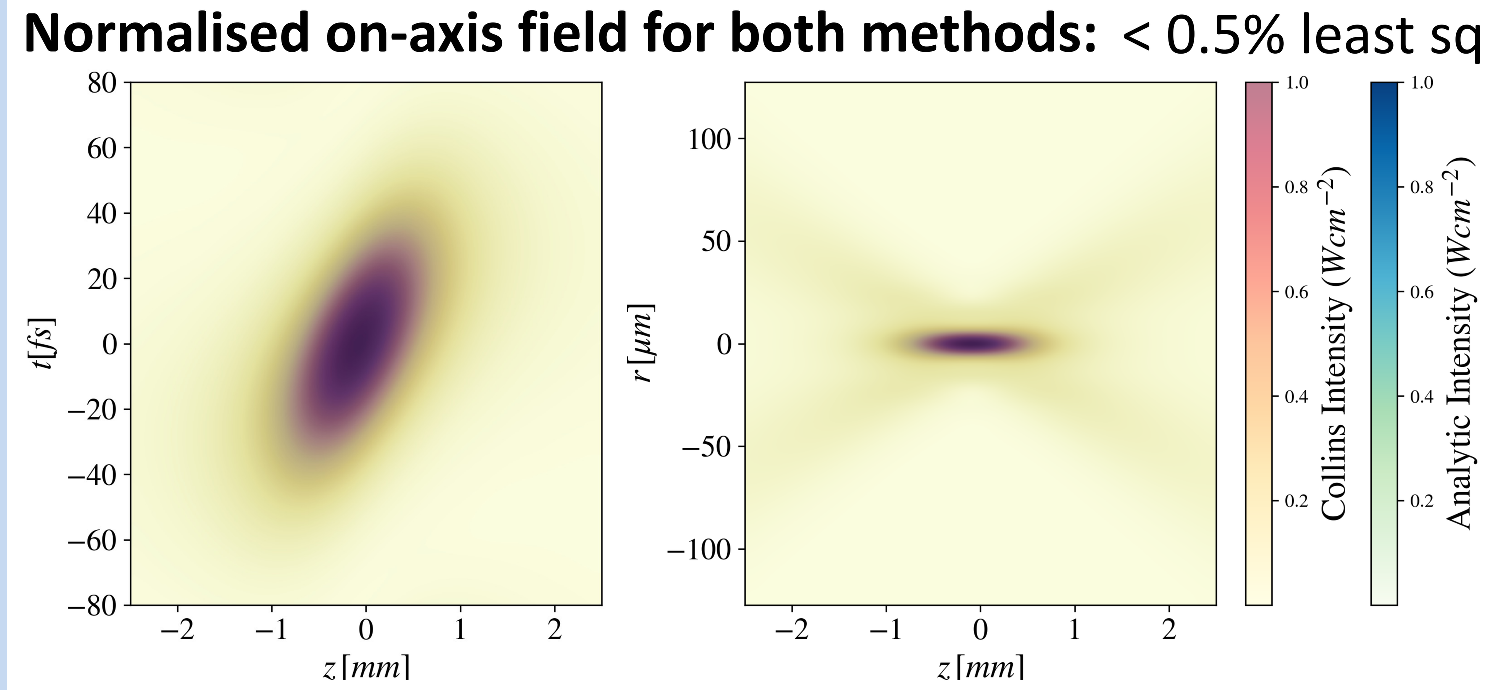
$$\tilde{U}_{\text{out}}(\mathbf{r},\omega) = \frac{1}{i\lambda B}e^{ik(z-z_0)}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\tilde{U}_{\text{in}}(\mathbf{r}_0,\omega)e^{ikS}\,dx_0\,dy_0$$

$$S = \left[\frac{1}{2B}\left(A(x_0^2+y_0^2) + D(x^2+y^2) - 2(xx_0+yy_0)\right)\right]$$

Also based on the ray-matrix [3], diffraction integral calculated numerically via FFT [4]

Results

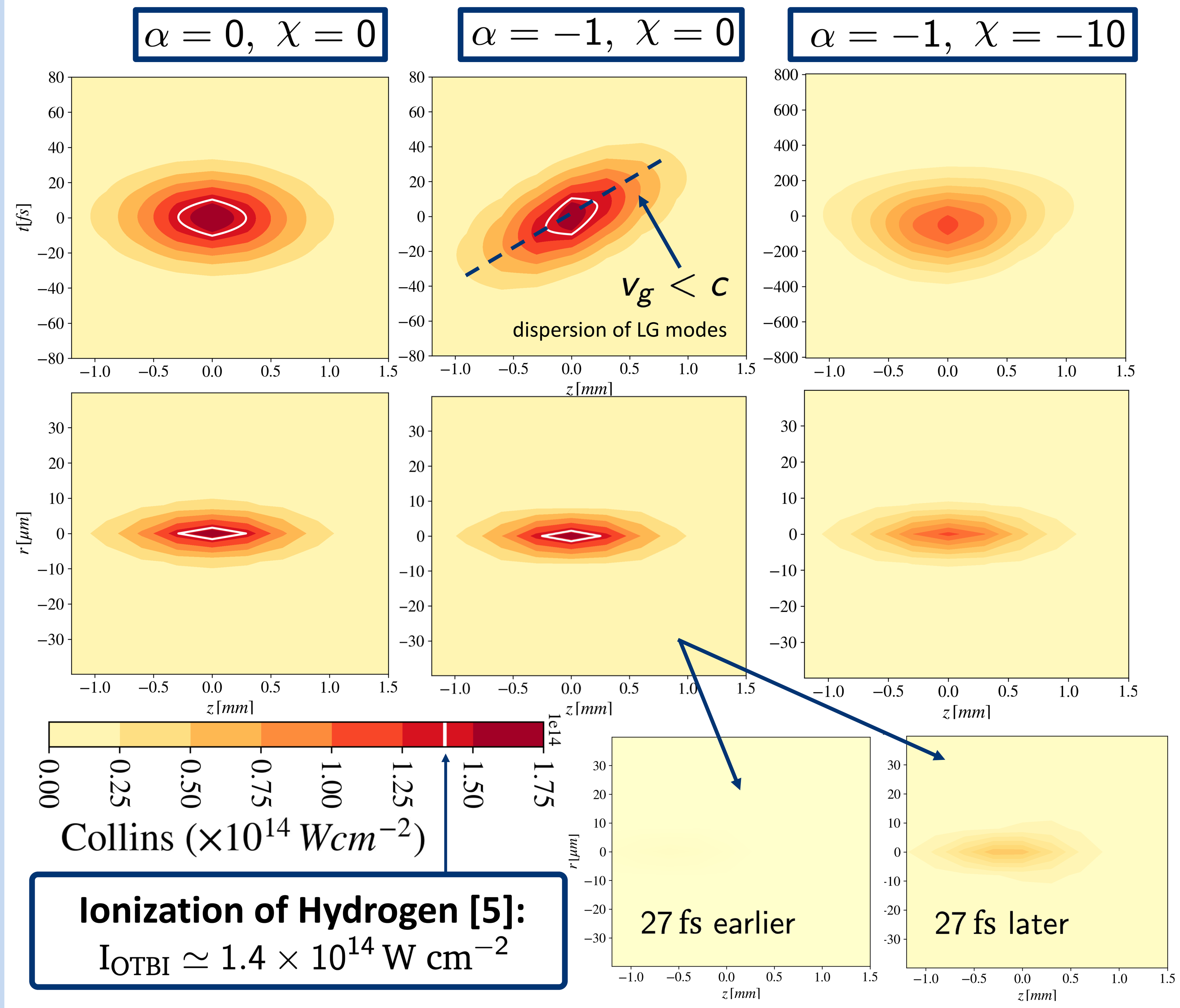
Normalised on-axis field for both methods: < 0.5% least squares error



Radial α Temporal chirps χ

Collins' results: pulse shaping with radial and temporal chirps of input

$\alpha = 0,\ \chi = 0$ $\alpha = -1,\ \chi = 0$ $\alpha = -1,\ \chi = -10$



Ionization of Hydrogen [5]: $I_{\text{OTBI}} \simeq 1.4 \times 10^{14}\ \text{W cm}^{-2}$

Conclusions and Future Work

Found good agreement between two different methods used to propagate radially-chirped beams. Potentially observed dispersion of structured beams in free-space [6]

Work planned to analyse focal volumes on finer grids and to model ionisation injection by implementing these beams in PIC codes