Chromatic Effects on Plasma Channels Formed with an Axicon Lens

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Introduction

- To reach 10s of GeV in a single laser-plasma accelerator stage, the driving laser will need to remain focused over 100s of mm.
- One way to achieve this is with a HOFI plasma channel [1] which can be formed using an axicon, as successfully demonstrated by the Oxford group using the RAL Astra-Gemini TA2 laser facility [2].
- During the experiment, it was found that ~ 10 higher intensity was required on the axicon to form the plasma channel than predicted.
- To investigate this, a numerical code has been written to model the effect of dispersion through an axicon.

Axicons

A refractive axicon is a conical lens which forms an extended line focus.

The transmitted beam has a characteristic Bessel shaped profile:

$$U_{\text{out}} \propto J_0[(n-1)k\rho'\alpha]$$

at output radius ρ' for wavelength $\lambda = 2\pi/k$.

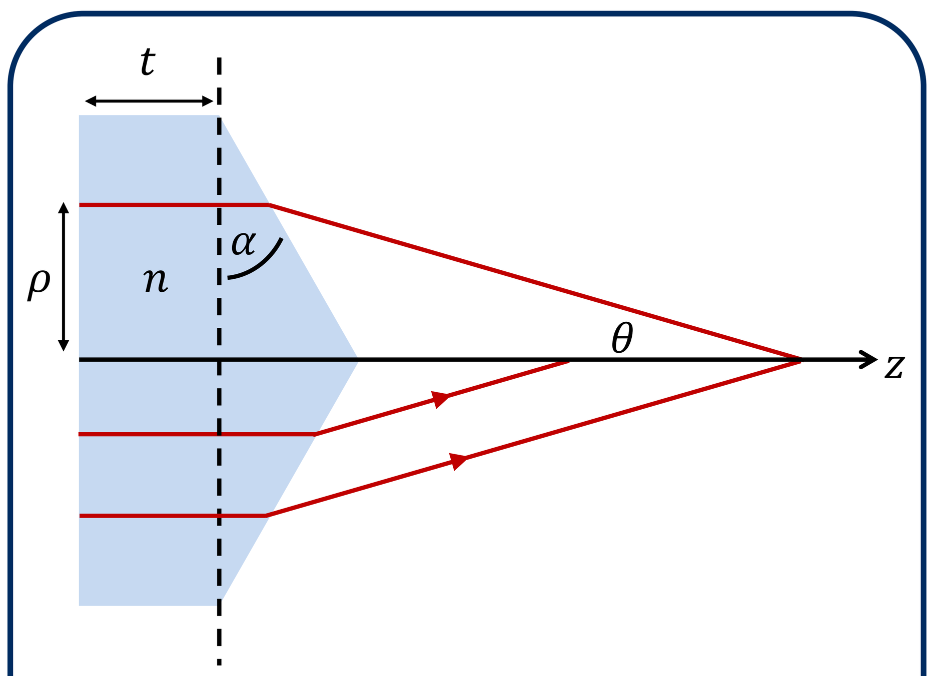


Diagram of a refractive axicon of refractive index n, with rays (red) entering from the left

Chromatic aberrations may arise in the axicon focus due to;

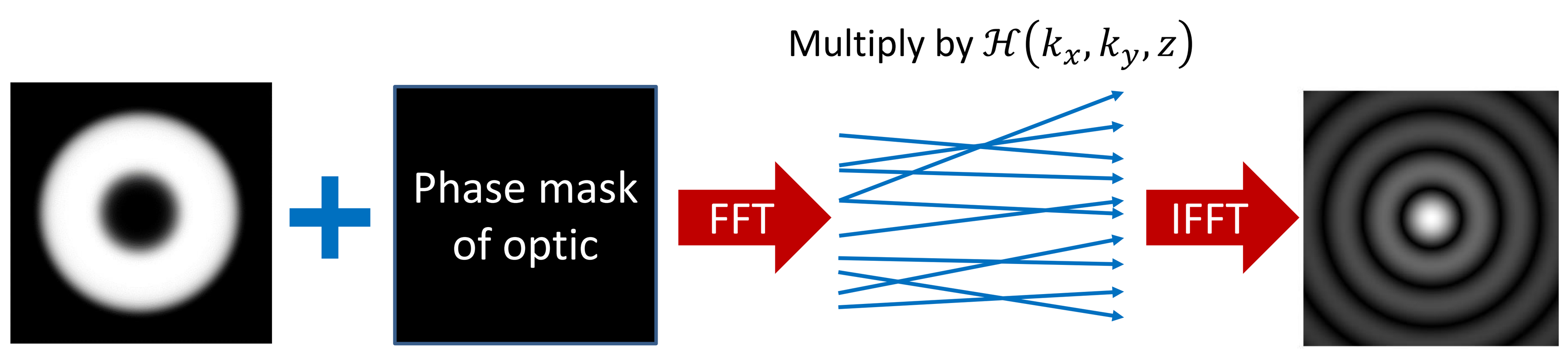
- Direct k dependence of the Bessel function.
- Dispersion in $n(k)$, causing a variation in approach angle θ and pulse stretching.

Numerical Code - ASM

The Angular Spectrum Method can be used to propagate an initial transverse field, $U(x,y,0)$, to output plane z via the following steps;

- Transform $U(x,y,0)$ into wavenumber (k_x,k_y) space.
- Multiply by the propagator function $\mathcal{H}(k_x,k_y,z) = \exp(-\mathrm{i}\, k_z\, z)$.
- Perform inverse Fourier transform to retrieve new field, $U(x,y,z)$.

This process is for a single wavelength. To model a laser pulse, the code first discretizes the spectrum of wavelengths, propagates each wavelength using ASM and sums the resulting complex fields (at a fixed (x,y) position).



Flow chart illustrating how the ASM numerical code works for each wavelength.

[1] R.J. Shalloo *et al.*, *Physical Review E*, **97**(5), 1–8 (2018)
[2] R.J. Shalloo *et al.*, *Physical Review Accel. Beams*, **22**(4), 1-6 (2019)
[3] Y. Wang *et al.*, *Journal of the Optical Society of America* A **34**(7), (2017)
[4] J. W. Goodman, Introduction to Fourier Optics, (2005)

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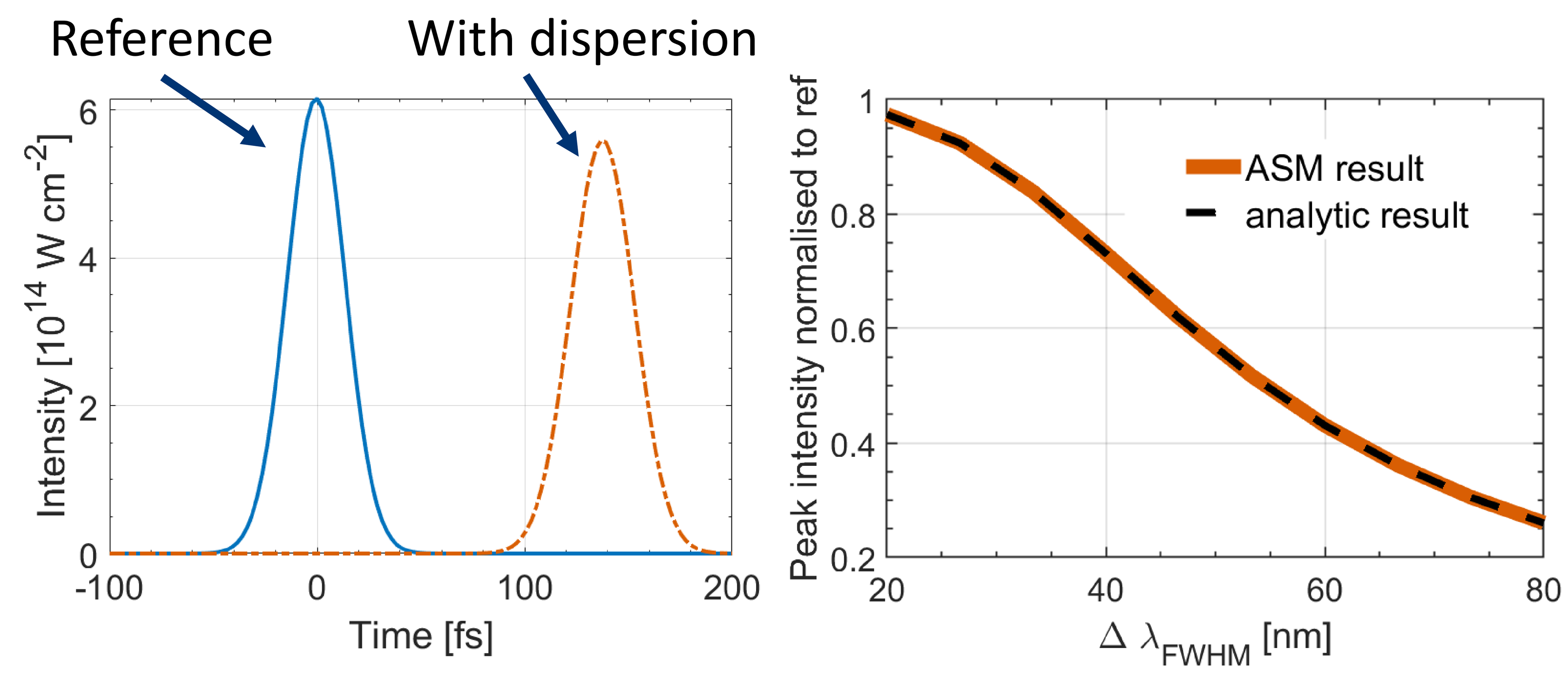
Results

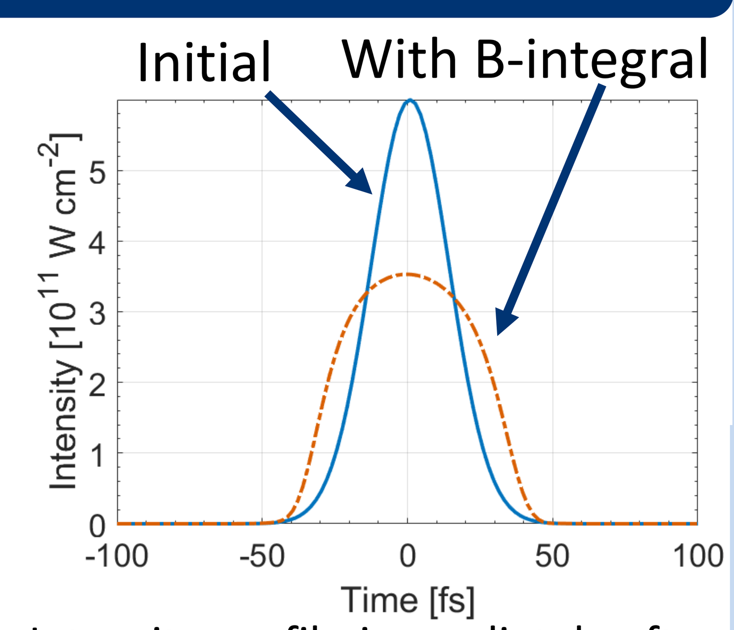


Temporal intensity profiles at focus for initial Gaussian beam with $I_0 = 10^{11}$ Wcm^{-2} , $\lambda = 805$ nm, $\Delta\lambda_{\text{FWHM}} = 30$ nm (left). Axicon parameters; $\alpha = 5.52°$, t = 3 mm, fused silica. Initial beam radius 25.4 × 0.1 mm. Reference has $n(\lambda)$ = const.

Other Factors

Factors which may have further reduced the on-axis intensity are;

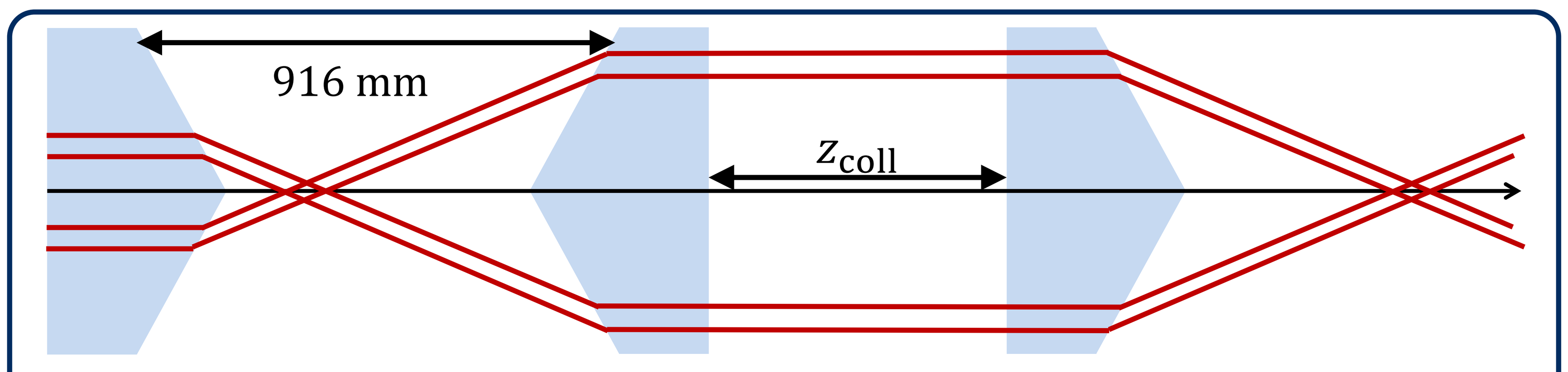
- B-integral through the axicon (Right).
- Imperfections in the experimental near field of the laser.
- The ionisation threshold of the H_2 gas not matching predictions.
- The plasma's own refractive index distorting the Bessel focus.



Intensity profile immediately after t = 3 mm substrate.

Axicon Beam-Expander

The ASM code can be applied to other optics studies, such as of the aberrations induced by a mis-aligned two axicon beam-expander.



Beam expander layout, with collimated distance to final focusing axicon, z_{coll}. Annulus radii in experiment: initial 6-15 mm, final 25-34 mm; all axicons $\theta = 2.5°$

In experiment, focal spot quality was very sensitive to misalignments of the axicons in the expander. The effect of a small offset of the first axicon, δx_1 is modelled below (all distances scaled down by 10).

a) Perfectly aligned　b) $\delta x_1 = 1$ mm, $z_{\text{coll}} = 5{,}252$ mm　c) $\delta x_1 = 1$ mm, $z_{\text{coll}} = 10{,}504$ mm

Conclusions and Future Work

- The study of chromatic effects through refractive axicons has revealed that dispersion reduces the peak intensity by $\sim 10\%$.
- This is **not** enough to fully account for the increased intensity that was required to form the plasma channel on experiment.
- The ASM code can also be applied to other more exotic phenomena, such as curved plasma channels and flying foci.