Guiding Channels for Next-Generation LWFA:

Simulations of low-density and high rep. rate plasma channels

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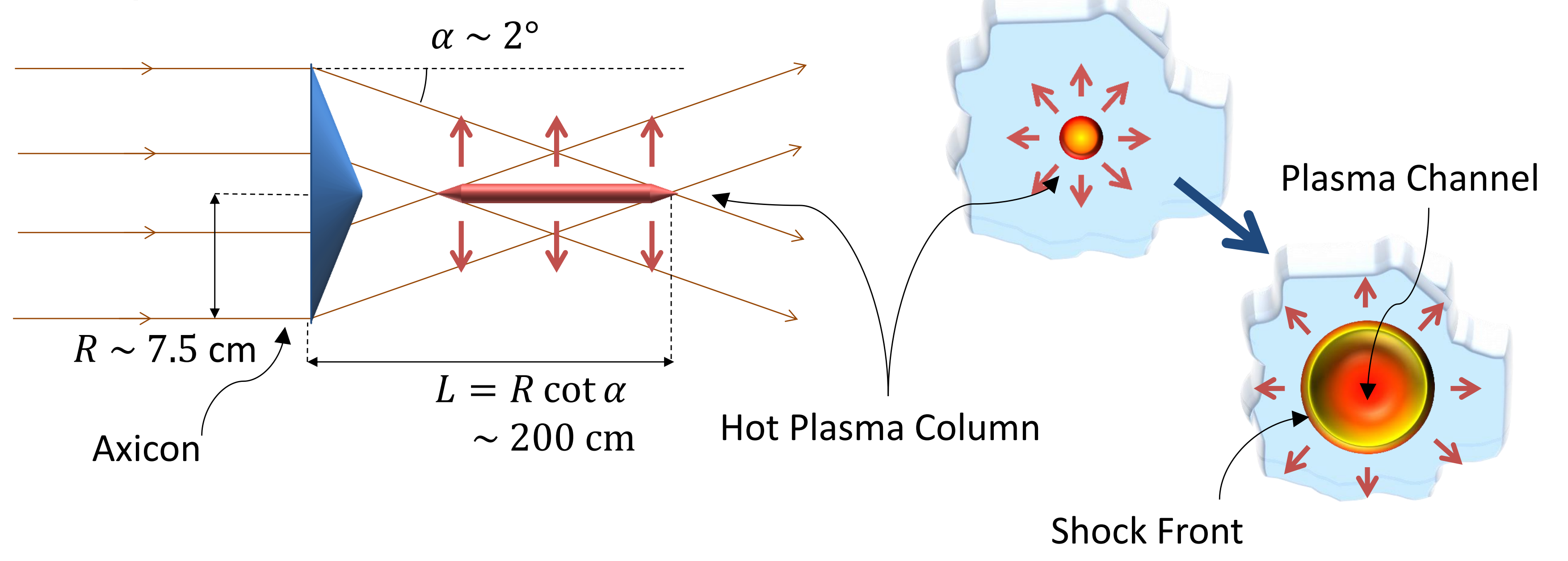
Outline:

- Axicons have been used for many years to form long plasma channels[1], but these were limited by the heating mechanism to high densities
- Optical Field Ionization **(OFI)** can heat electrons on the femtosecond timescale, independent of target density
- We simulate the creation of hot plasma columns using OFI and their subsequent evolution into plasma channels, which are all-optical and could operate at kHz repetition rates
- Our results demonstrate the creation of long (10s of centimetres) and low density (10^{17} cm^{-3} and below) plasma channels, which would be suitable for > 10 GeV LWFA stages

Scheme:

1. Create a long and hot plasma column along an axicon focus, using Optical Field Ionization from a femtosecond pulse
2. The column expands outwards into the cold neutral gas, forming a shock front and leaving a cavity on axis
3. After some time, a second co-propagating pulse can be guided by the plasma channel within this cavity



Key Physics:

- Operate at 10^{17} - 10^{18} cm^{-3} with $T_e \sim 10$ eV. 10s μm scale channel.
- Shock propagates near sound speed $c_s \sim 10$ km/s, expanding 10s of microns in nanoseconds
- Spitzer equilibriation and isotropization collision times are $\tau_{\text{coll}} \sim$ 1-10 ps
- Debye length $\lambda_D \sim$ 10-100 nm and only 10 ppm of electrons have $E_k > V \approx \alpha m_e {\omega_p}^2 {r_c}^2$ and can escape channel

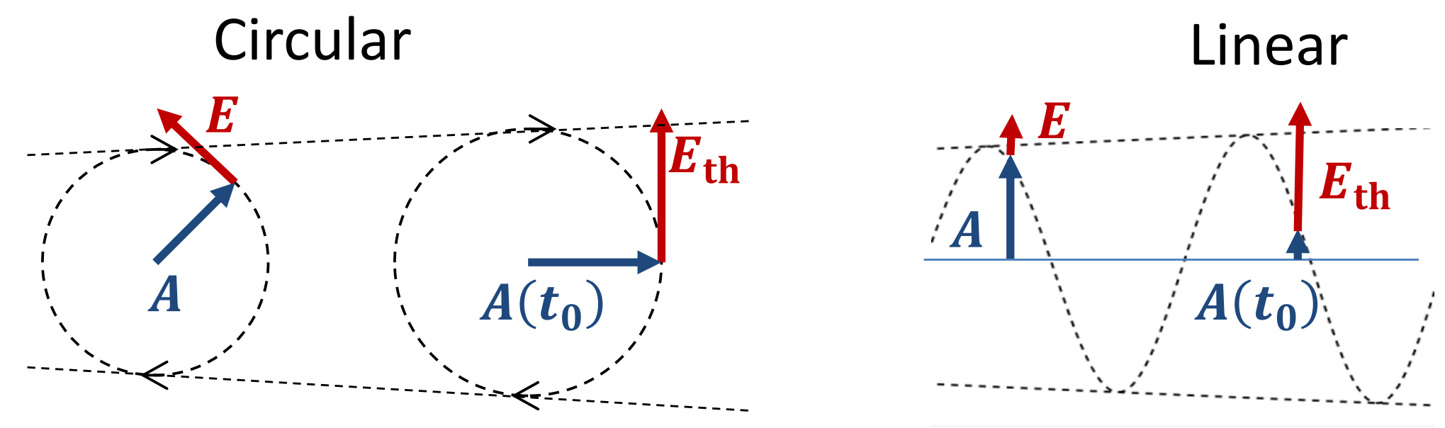
⇒ No charge separation and a thermal and isotropic velocity distribution means a fluid code can accurately describe channel expansion

- Repetition rate is limited by dissipation of the shock waves and plasma recombination, on much longer timescales

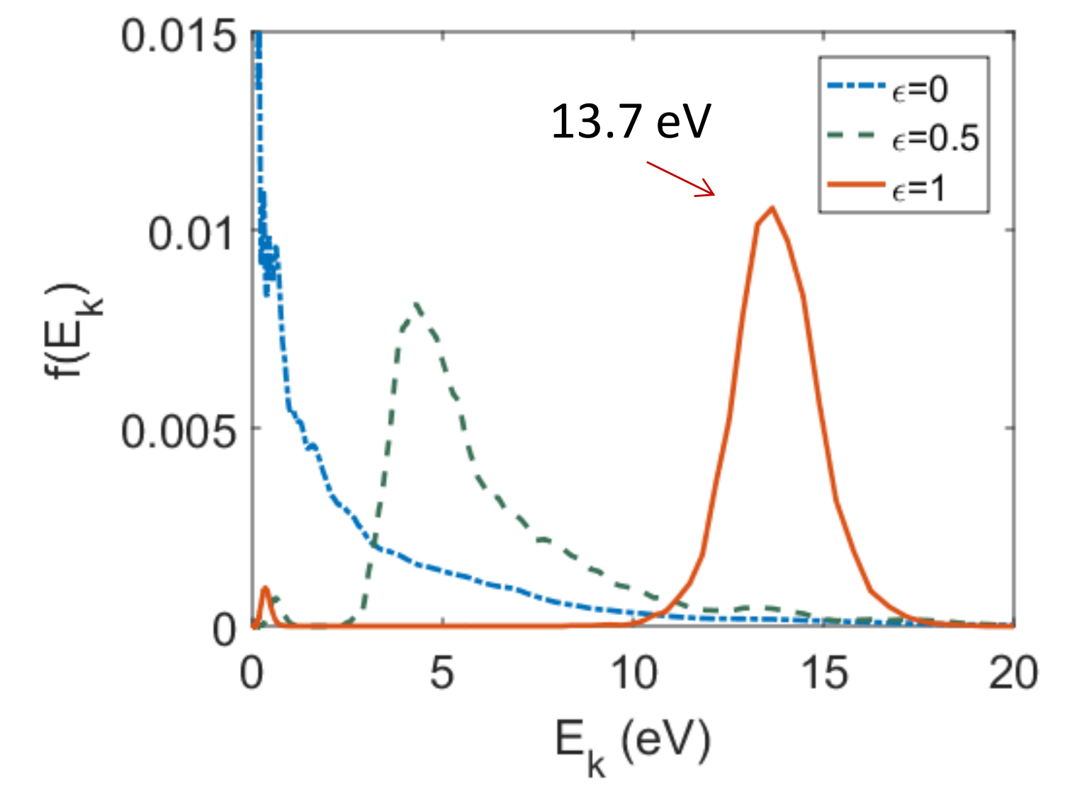
Process	Timescale	Model with:
Optical Field Ionization	fs	EPOCH PIC Code In-House Propagation Code
Thermalization & Isotropization	ps	Spitzer Collisions
Shock Propagation / Channel Expansion	ns	HELIOS Fluid Code
Laser Guiding	ns	In-House Propagation Code
Recombination / Quiescence	μs	-

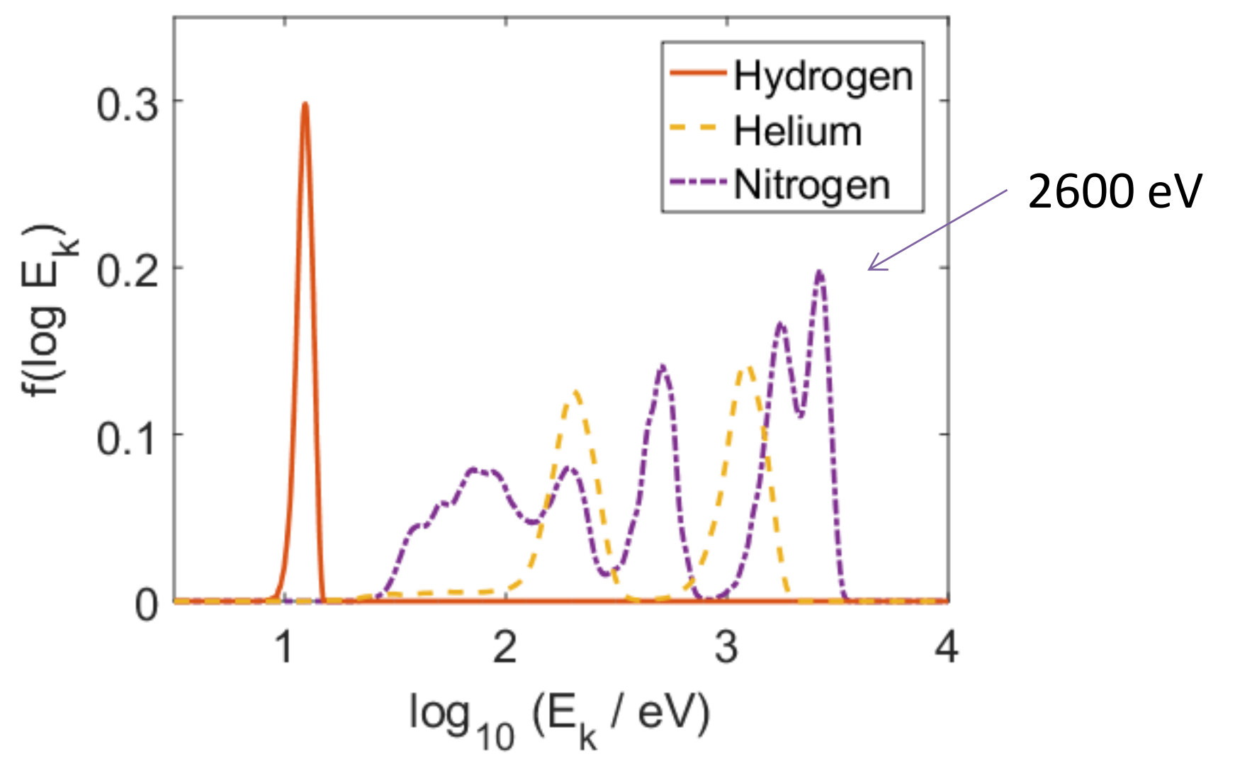
Heating with Optical Field Ionization:

- Canonical momentum $\mathbf{P}(\mathrm{t}) = \boldsymbol{p}(t) + e\boldsymbol{A}(t)$ is conserved, so electron momentum after a laser pulse has passed is $\boldsymbol{p_f} = \boldsymbol{p}(t_0) + \mathrm{e}\mathbf{A}(t_0)$.
- If an electron is born at rest after ionization at t_0, the final electron energy after only femtoseconds is therefore $E_k = \frac{|\boldsymbol{p_f}|^2}{2m_e} = \frac{e^2}{2m_e}|\mathbf{A}(t_0)|^2$
- Electrons are ionized mainly when $|\boldsymbol{E}(t_0)| \approx E_{\text{th}}$. $\boldsymbol{E} = -\frac{\partial \boldsymbol{A}}{\partial t}$ so $|\mathbf{A}(t_0)|$ can be very high, for a circularly polarized laser ($E_k \approx 2U_{\text{p}}$), or very low, for linear polarization ($E_k \approx 0$) [3]



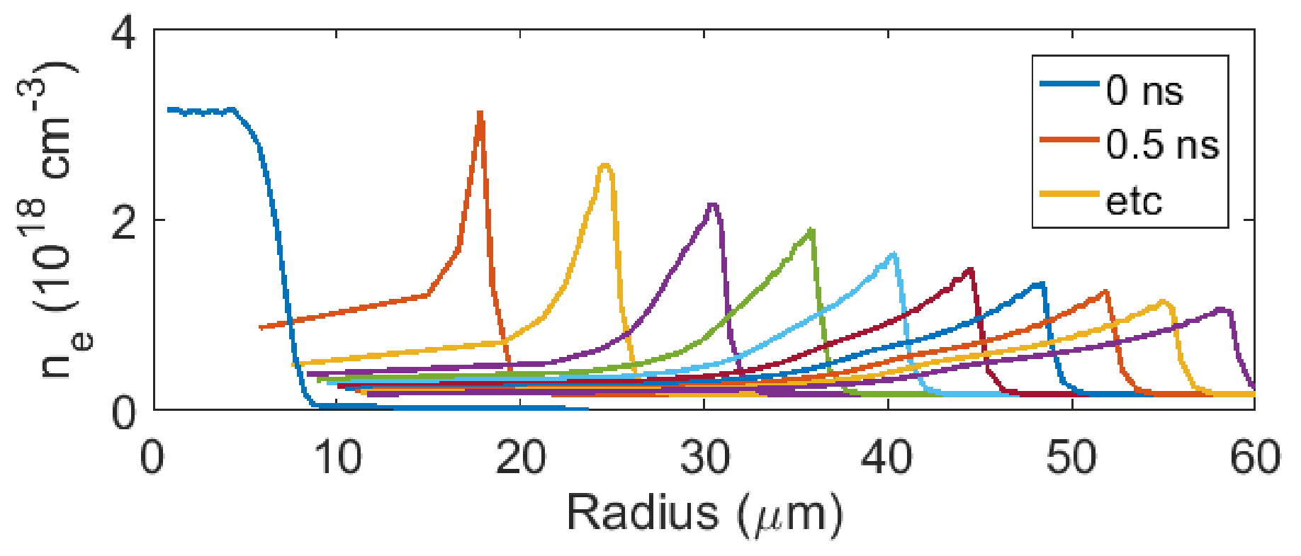
- Simulate this in EPOCH for Hydrogen at different laser ellipticities
- Changing the target species increases E_{th} and hence $|\mathbf{A}(t_0)|$and E_k

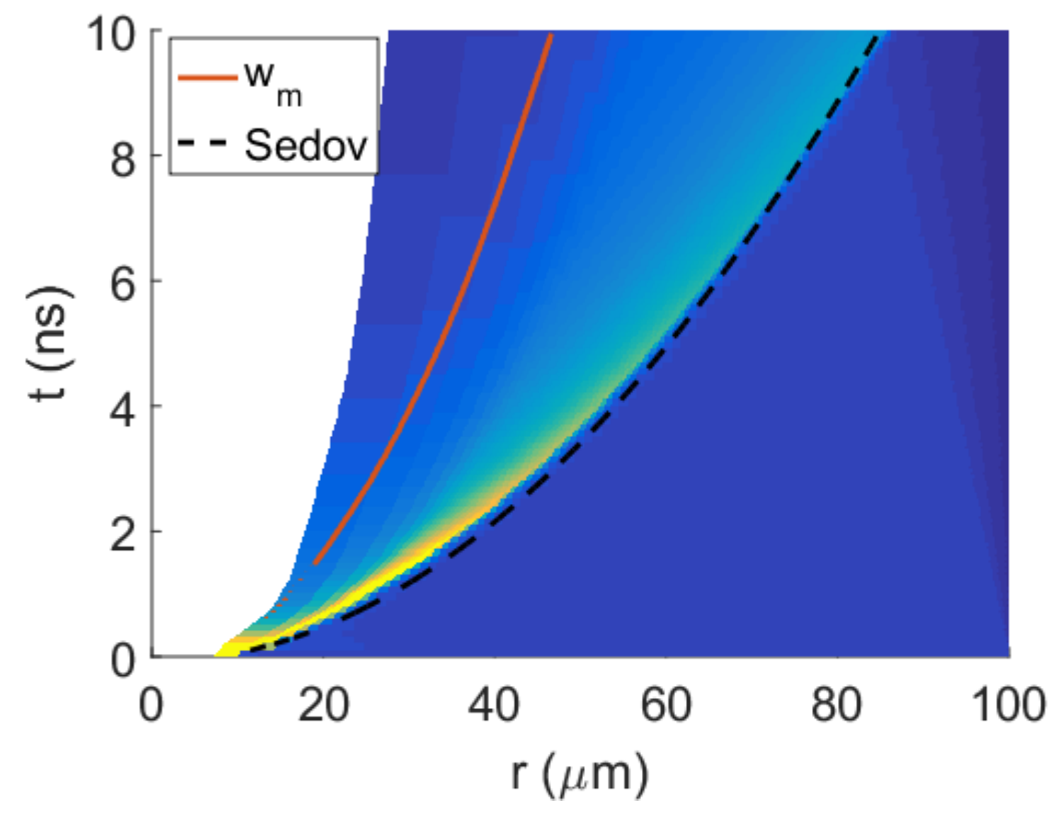




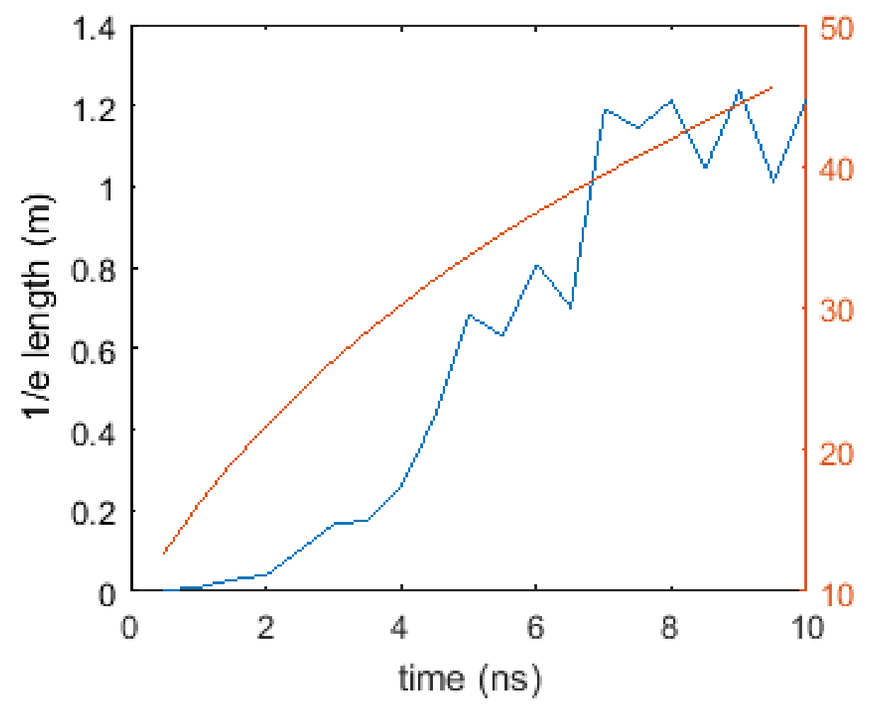
Channel Expansion:

- Simulate channel expansion with HELIOS fluid code, using initial conditions from simulating an axicon beam in Hydrogen
- Can compare to Sedov solution $r(t) = (\gamma + 1)^{\frac{1}{2}} \left(\frac{ZE_k}{M_{\text{ion}}}\right)^{\frac{1}{4}} (r_o\tau)^{\frac{1}{2}}$
- Fit matched spot with in-house beam propagation code [2] and find losses





- Calculated matched spot 20-40 μm, with 1/e attenuation length 40-100 cm
- Suitable to guide LWFA drivers over channels of lengths of up to a meter, well suited to the axicon
- On axis density falls to 10^{17} cm^{-3}



High Energy Gain LWFA stages:

- Dephasing between electrons and laser limits stage length, $L_{\text{dp}} \approx \frac{1}{2}\frac{{\lambda_{\text{p}}}^3}{{\lambda_L}^2}$
- OFI heating can produce channels this length using very little energy
- $\frac{E}{L} \sim \frac{2\,\lambda\, t_{\text{FWHM}}}{\pi} I_{\text{th}} < 100\ \text{mJ/m}$ for ionization at $I_{\text{th}} \approx 4\times10^{14}$ Wcm^{-2}
- At the dephasing length energy gain is $\Delta W \sim \frac{m_e\omega_{\text{p}}c}{e} L_{\text{dp}} \approx \pi \frac{n_{\text{crit}}}{n_e} m_e c^2$

On-Axis Density	Dephasing Length	Estimated Energy Gain	Axicon Parameters	Approx. OFI Energy Required
10^{17} cm^{-3}	90 cm	30 GeV	$\alpha = 2°, R = 3''$	< 90 mJ

[1] Axicon Channels - C. G. Durfee III et al, PRL 71, (1993)
[2] Waveguide Modes - H. Sheng et al, PRE 72, (2005)
[3] OFI Channels - Lemos et al, Phys. Plas. 20, (2013)

See also: J. Jonnerby, Experimental design, poster 144
R. J. Shalloo, Experimental results, WG5 Tuesday

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