Curved hydrodynamic optical-field-ionised waveguides

Darren Zeming Chan,[1] J. Chappell,[1] L. Feder,[1] B. Greenwood,[1] A. Harrison,[1] S. Kaloš,[1]
R. Lahaye,[1] D. McMahon,[1] J. Thistlewood,[1] S. Thorpe,[2, 3] R. Walczak,[1] and S. Hooker[1]

[1]*Department of Physics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, United Kingdom*
[2]*Physical and Theoretical Chemistry, Department of Chemistry, University of Oxford, Oxford OX1 3QZ, United Kingdom*
[3]*The Kavli Institute for Nanoscience Discovery, Dorothy Crowfoot Hodgkin Building, University of Oxford, Oxford OX1 3QU, United Kingdom*

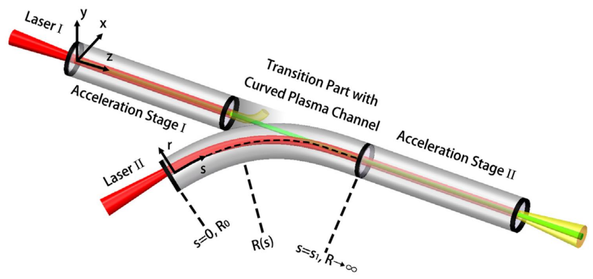
Abstract

Curved plasma waveguides have been proposed as a means to: guide fresh laser pulses into multistage plasma accelerators [1, 2], replace plasma mirror tapes used to eject depleted laser pulses [3], and to bend electron bunches for radiation generation [4-6]. However, all curved channel experiments so far have employed discharge capillaries, which are prone to laser damage especially at high pulse repetition rates.

In contrast, hydrodynamic optical-field ionised (HOFI) channels are free-standing and hence immune to laser damage. Furthermore, they have been demonstrated to operate at kHz repetition rates [7-10]. Particle-in-cell simulations show, for a parameter regime relevant to PW-scale facilities, that curved HOFI channels can be used to introduce a fresh laser drive pulse in a staged laser-wakefield accelerator. A 100% electron capture efficiency can be achieved between stages although the asymmetric sheath fields led to emittance blow-up. We have demonstrated experimentally that introduction of the appropriate phase modulation can curve the trajectory of the channel-forming Bessel beam by more than 10 laser spot sizes in a distance of 120 mm. Data collection for a curved HOFI experiment is ongoing.

Applications of curved plasma waveguides

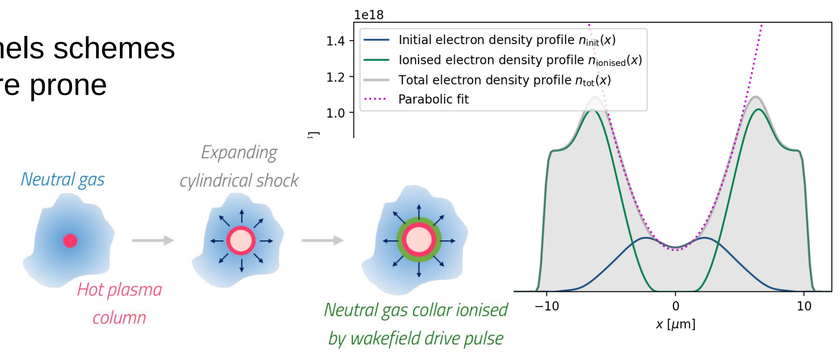
- Staging of laser wakefield accelerators: Fresh pulses need to be introduced into each stage from the side
- Off-ramp for extracting depleted pulses at the end of an accelerator stage
- Radiation generation: Channels with kinks induce transverse pulse and hence bunch oscillations



From: Luo et al., Phys. Rev. Lett. **120**, 154801

Hydrodynamic optical-field-ionised waveguides

- Current curved channels schemes use capillaries that are prone to laser damage
- HOFI channels are free-standing, thus **immune to damage**
- They have been demonstrated at kHz

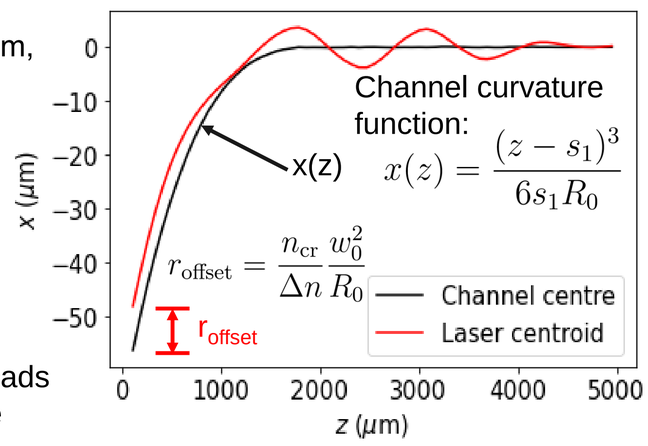


Simulations of curved plasma waveguides

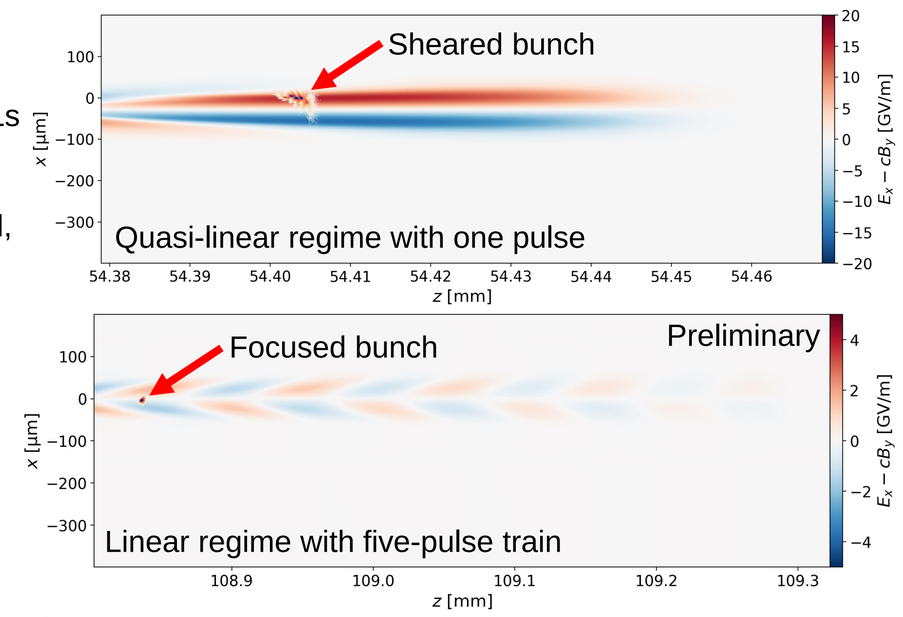
Staging:

- Assess the feasibility of **free-standing** HOFI waveguides to introduce laser pulses
- 2D simulations with full PIC code WarpX to model HOFI neutral collar ionisation
- Need capture efficiency >95 % and percent-level emittance growth

- Pulse parameters: $a_0 = 2$, $w_0 = 50$ μm, $E_0 = 15$ J, $\tau_{FWHM} = 42$ fs
- HOFI channel parameters: $n_0 = 2.5 \times 10^{17}$ cm^{-3}, variable radius of curvature starting from 12 m



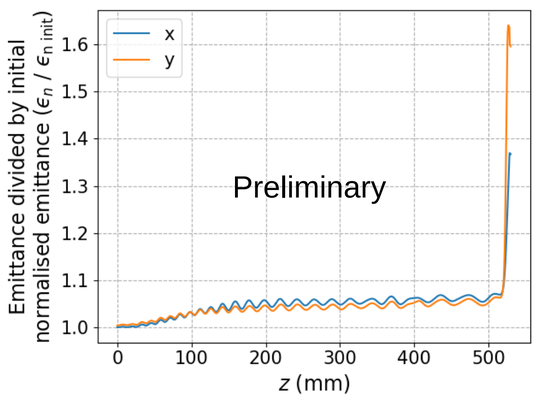
- Bunch charge increased to 45 pC for beam-loading and blowout enhancement
- Bunch position and momentum spreads chosen according to beam envelope evolution equation
- Initial emittance chosen as 1 mm*mrad -> FELs



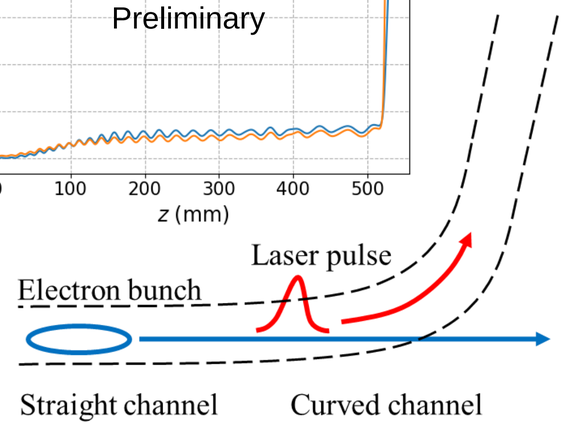
- 100% capture efficiency achieved, but strong transverse wakes lead to bunch shearing and >1000X emittance growth
- Staging with a pulse train off-resonant with ω_p: ~10X emittance growth

Pulse extraction:

- Goal: Maximise transverse displacement of pulse while minimising transverse displacement and emittance growth of bunch
- 3D quasi-static PIC code HiPACE++ required for 500-mm long propagation

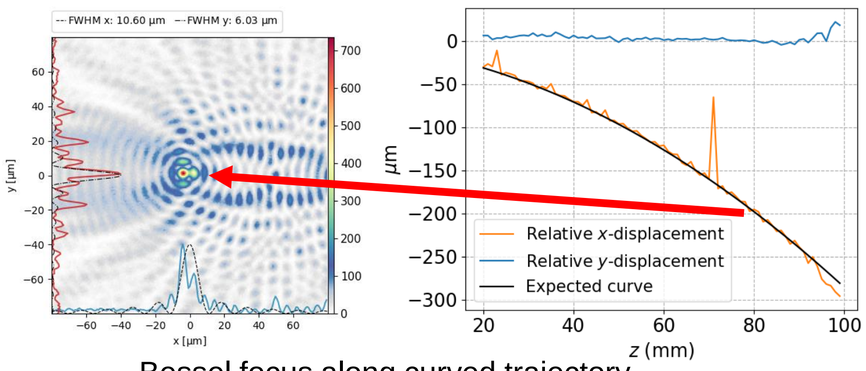


- If pulse is properly depleted, emittance growth of bunch is controllable!
- Next steps: optimise and then compare emittance growth to that of plasma-mirror tape ejection schemes



Demonstration of curved plasma waveguides

- Series of experiments to demonstrate that channel-forming beam can follow curve
- Exploit linear relation between *r*, the radial position at which light enters the axicon, and *z*, the longitudinal position along focus
- Input phase to axicon is modulated with a phase plate that we manufacture ourselves with laser lithography and reactive ion etching
- Exploring grayscale etching procedures to achieve multiple depths simultaneously and thus increase diffraction efficiency
- Using our beamline with a kHz rep rate and 15 nm bandwidth, observed trajectory displacements >10 spot sizes over longitudinal distance of 120 mm
- Conducting a high-power HOFI experiment with channel-forming and guided beams and interferometry



Bessel focus along curved trajectory

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