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Curved hydrodynamic optical-field-ionised waveguides

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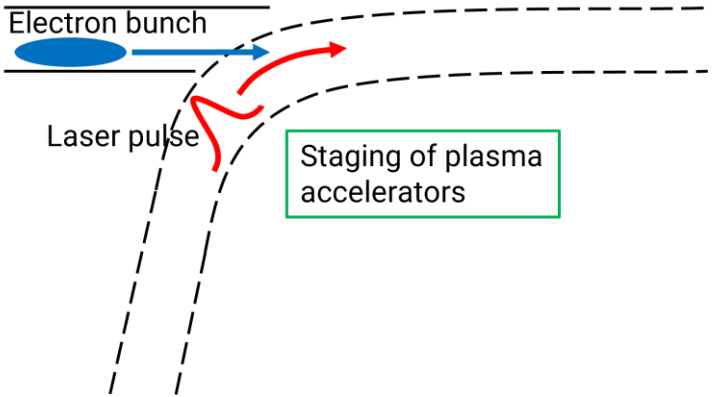
24 September 2025

Applications of curved plasma waveguides



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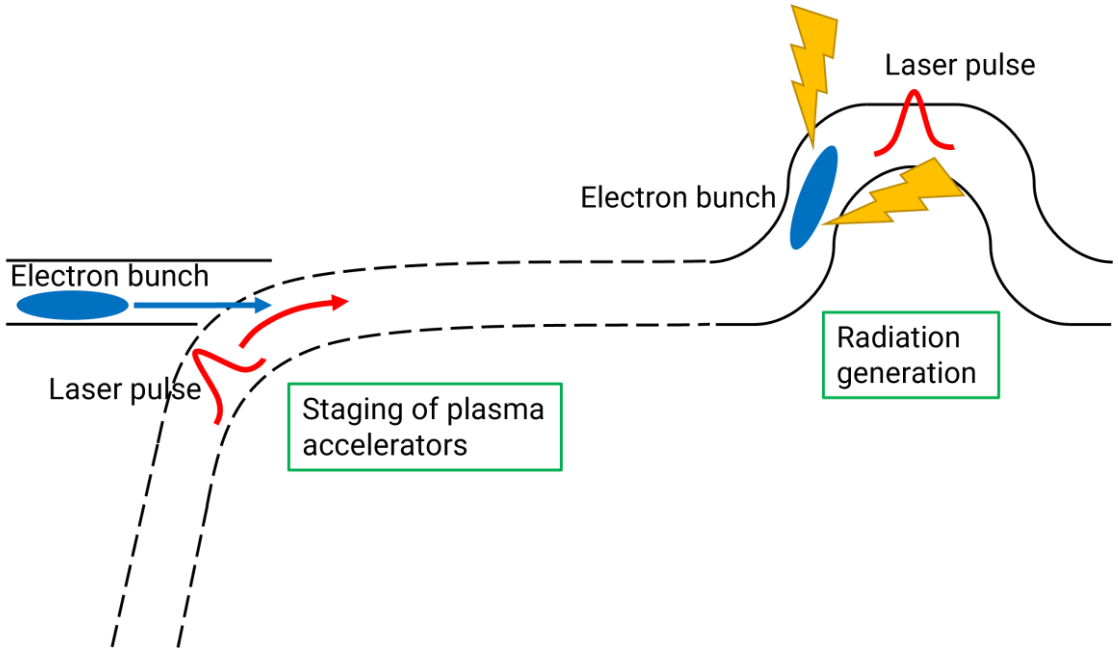

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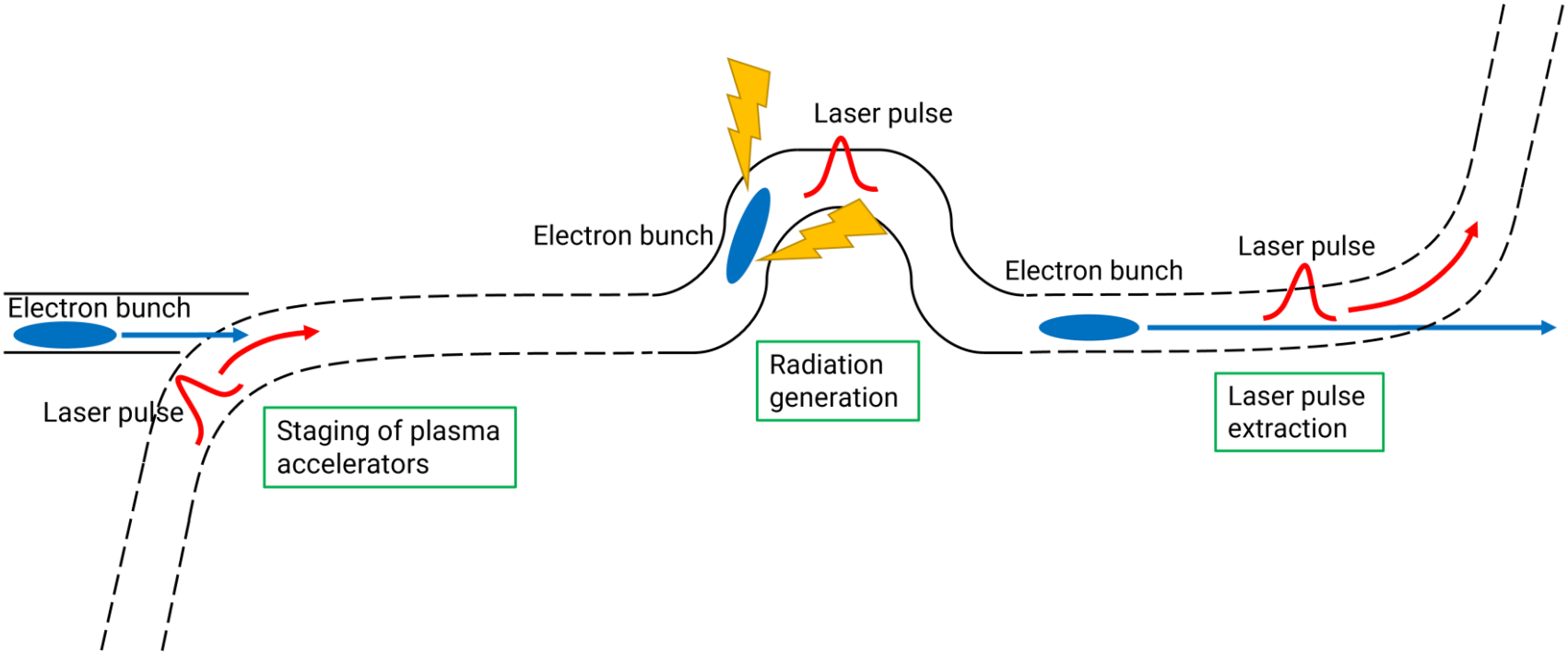
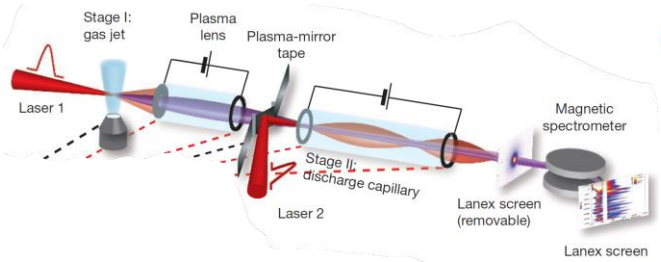


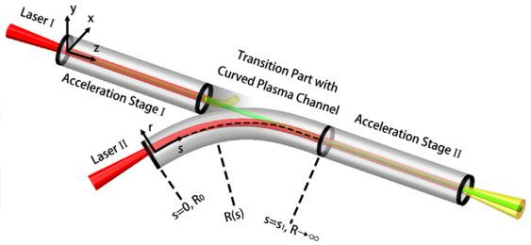
Simulations of staging with curved plasma waveguides

Multistage LWFA schemes

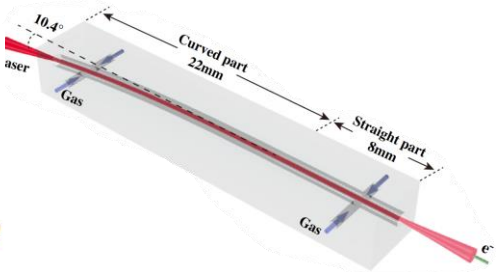
- No curved channels *staging* experiment has yet been performed
- All studies so far have used discharge capillaries, which are prone to laser damage especially at high pulse repetition rates



From: *Nature* **530**, 190–193 (2016)



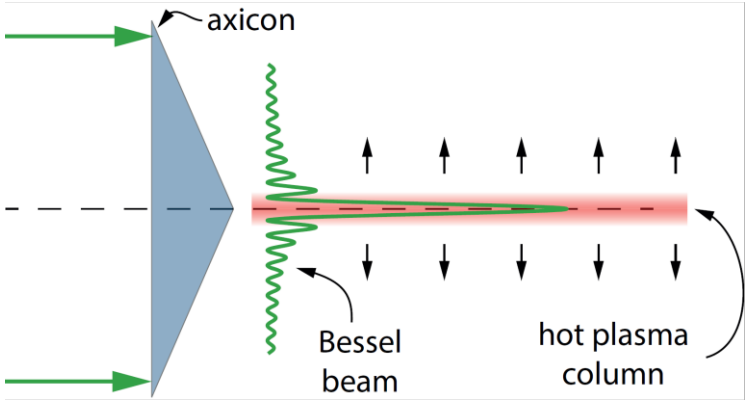
From: *Phys. Rev. Lett.* **120**, 154801 (2018)

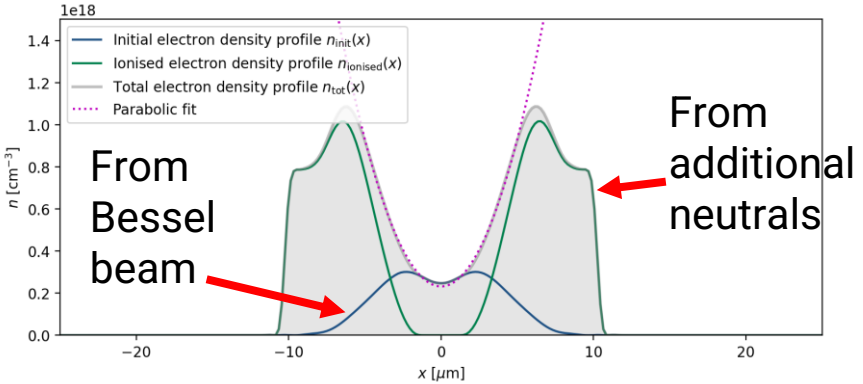


From: *Phys. Rev. Lett.* **130**, 215001 (2023)

Hydrodynamic optical-field-ionised plasma channels (HOFIs)

- Alternative plasma channel developed by the Oxford Group suitable for kHz rep rates
- **Immune to laser damage**
- Guiding of pulse in curved section is important due to ionisation of neutrals





Curved channel goals and setup

- Need capture efficiency ~100% and percent-level emittance growth for applications

- 2D simulations with full PIC code WarpX to model channel wall ionisation

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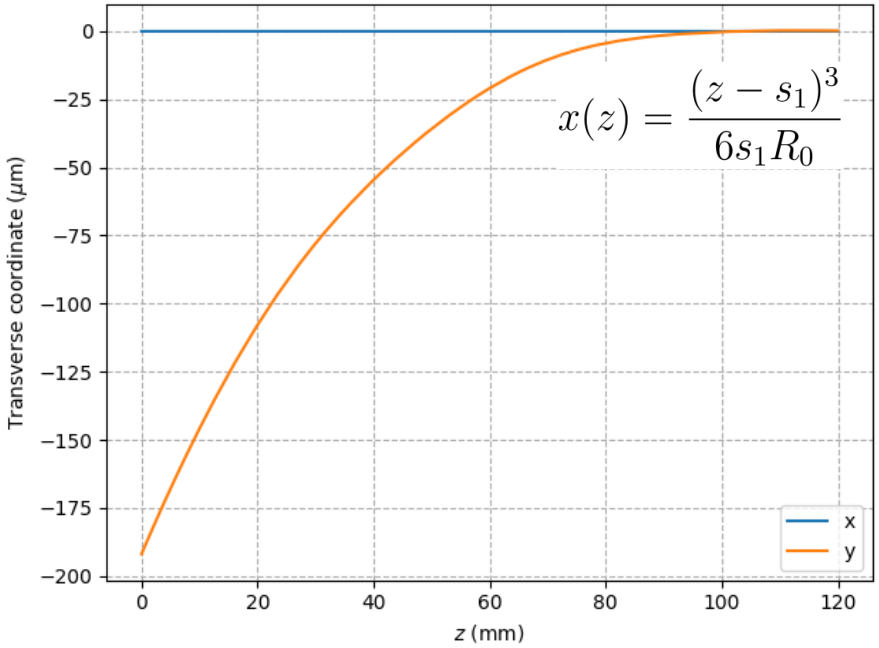
- Channel follows cubic curvature function with a displacement of 200 μm over 120 mm
- Minimises transverse laser pulse oscillations



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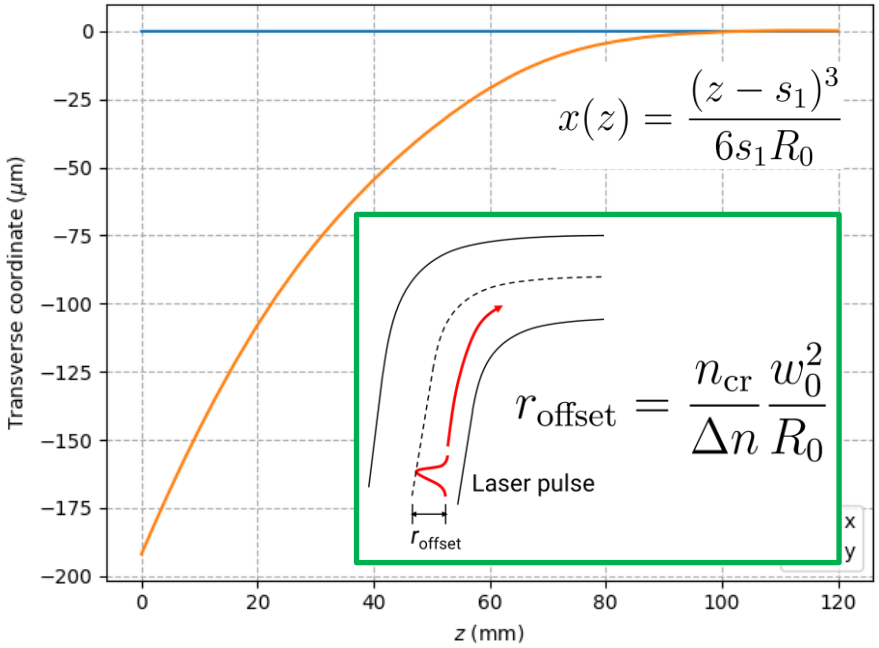

Pulse offset derived in:
Phys. Rev. Lett. **120**, 154801 (2018)

Optimisation of the staging scheme

- Laser pulse and channel parameters:
  - $a_0 = 2$, $w_0 = 50$ μm, $E_0 = 15$ J, $\tau_{FWHM} = 42$ fs, $n_0 = 2.5 \times 10^{17}$ cm^{-3}
- Bunch charge increased from 1pC to 45 pC
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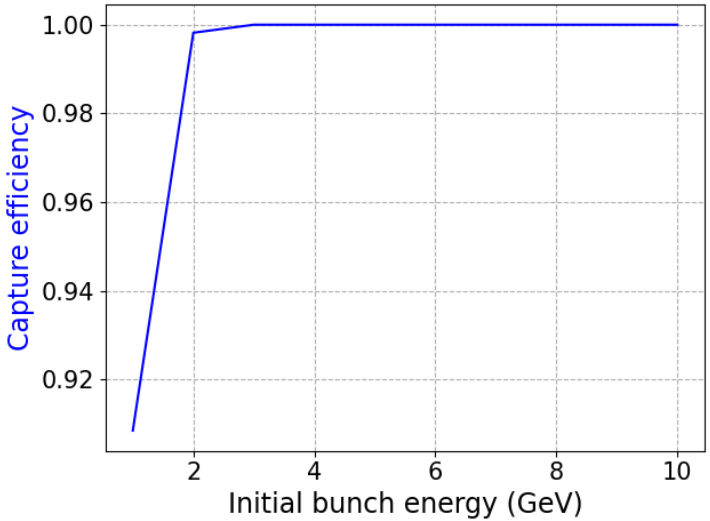
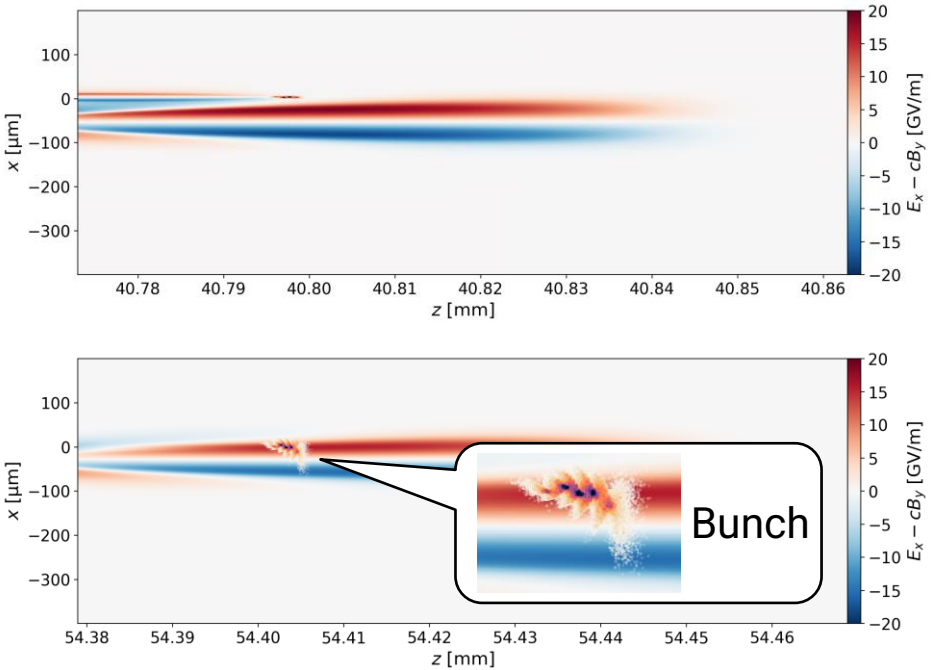
- Bunch charge increased from 1pC to 45 pC for beam-loading and blowout enhancement
- σ_x and σ_{px} chosen to give initial emittance of 1 mm mrad
- Bunch energy increased from 1 GeV to 10 GeV for rigidity and magnetic self-focusing
  - 100% capture efficiency achieved, but…



Challenges for the staging scheme

- Bunch passes through strong asymmetric transverse wakefields
- Emittance increases by >1000X

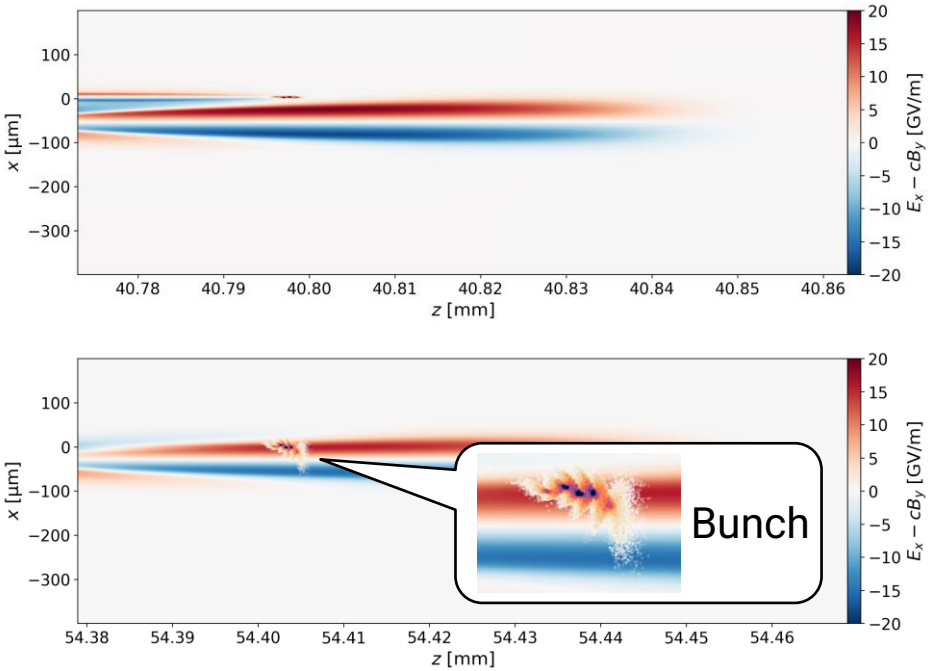


Challenges for the staging scheme

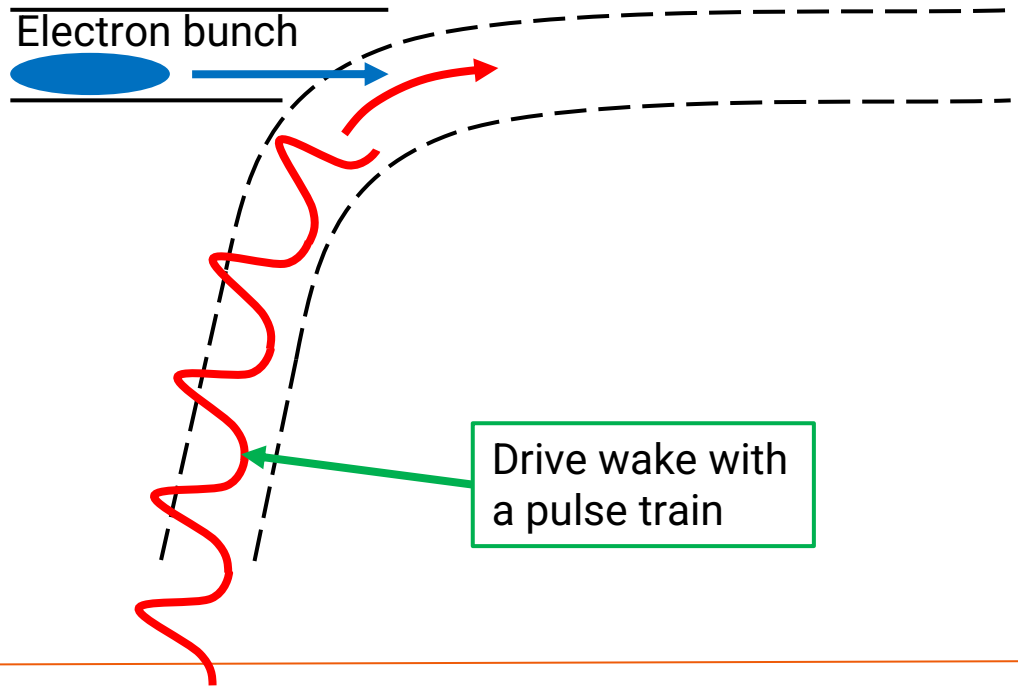
- Bunch passes through strong asymmetric transverse wakefields
- Emittance increases by >1000X

- Laser pulse guiding ✓
- Bunch capture ✓
- Emittance preservation ✗

- Need to identify methods to suppress the transverse fields in injection region



Suppressing wakefields in coupling region



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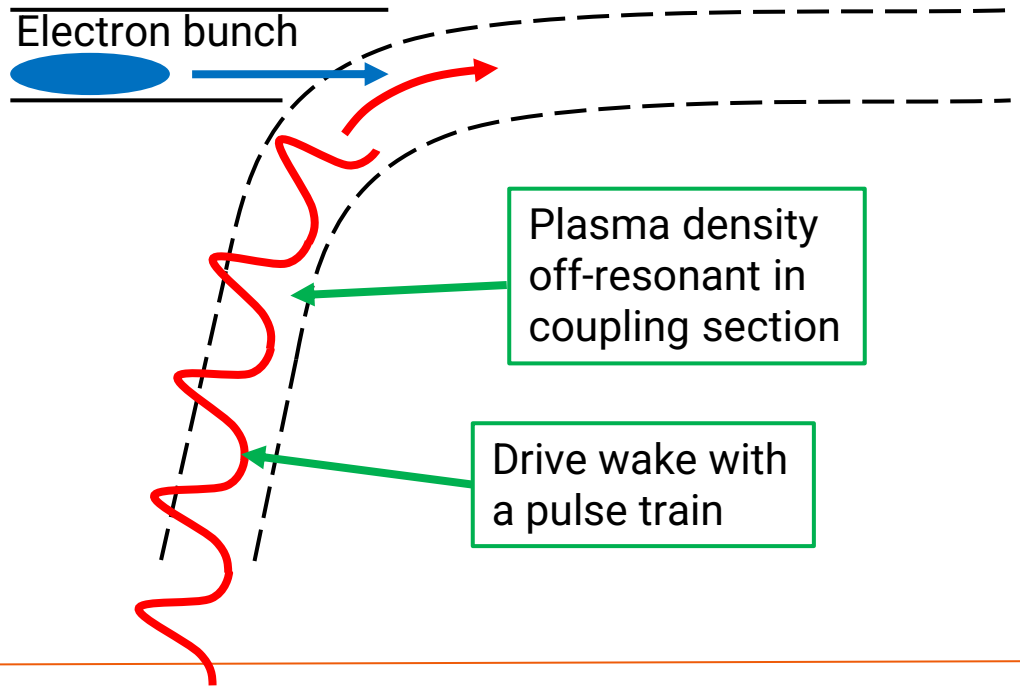

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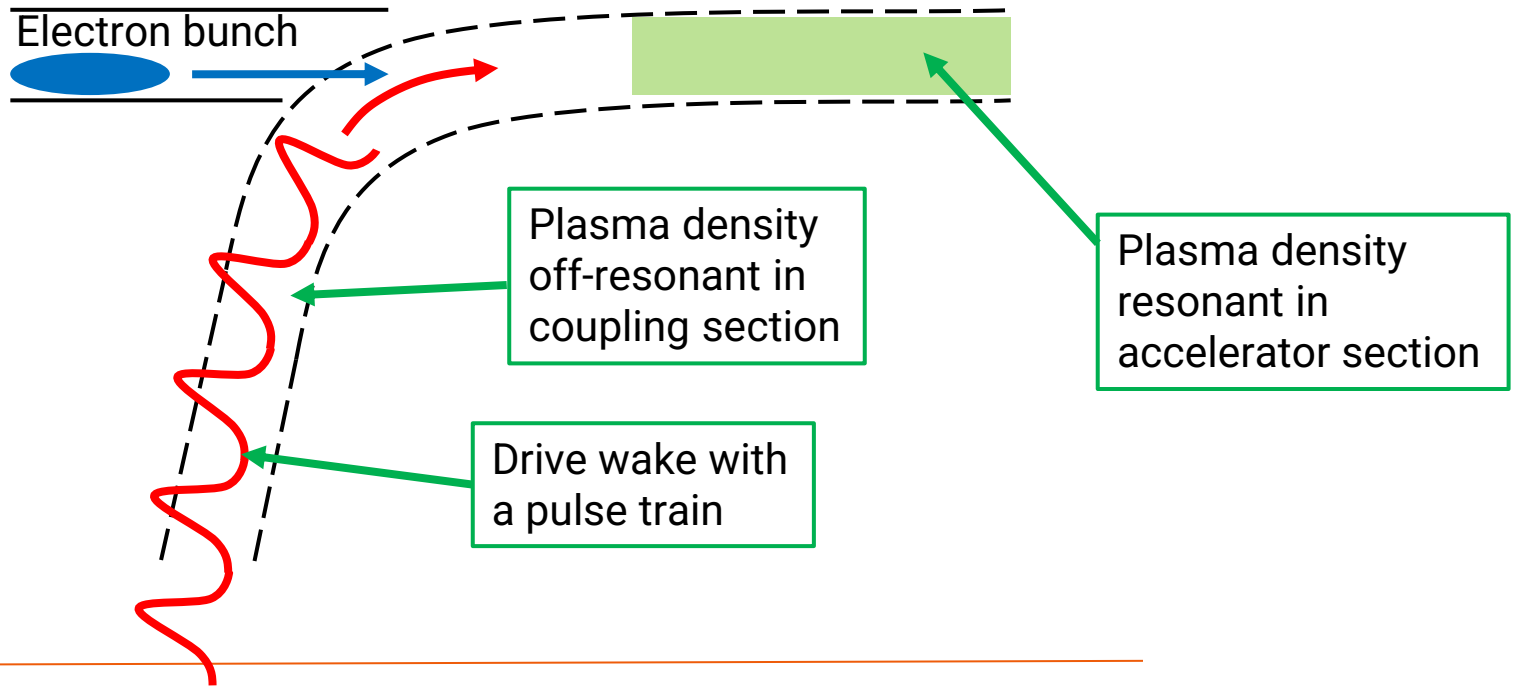
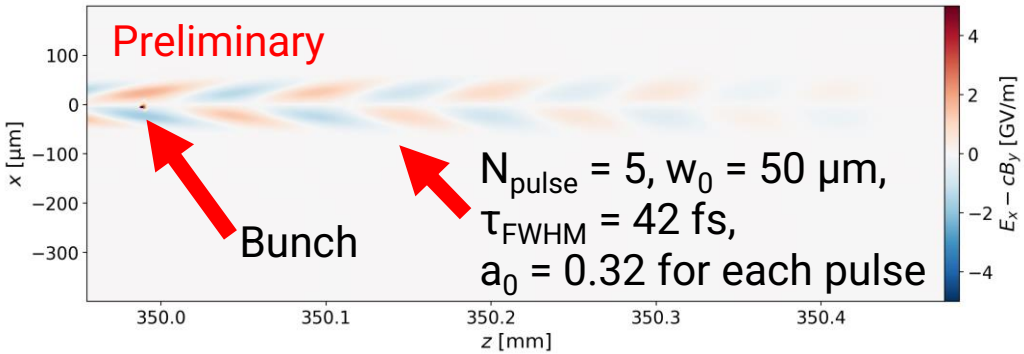


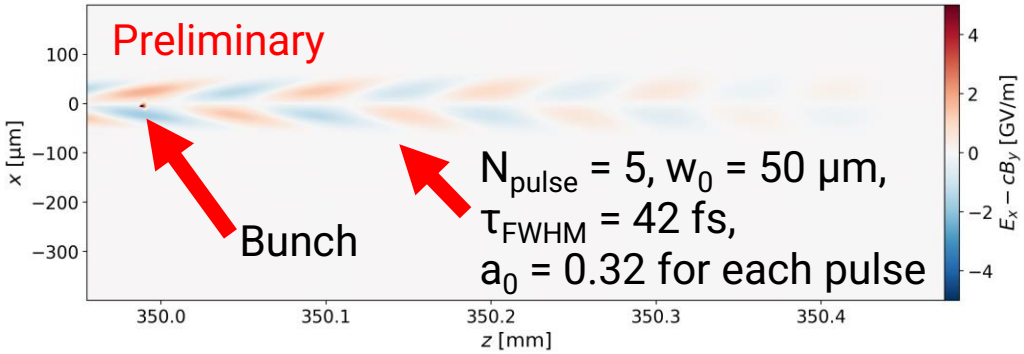
Staging in the linear regime

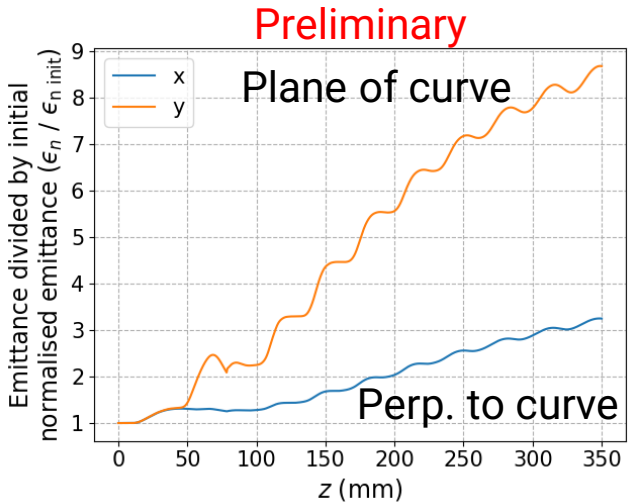
- Scanned by hand:
  - Off-resonant plasma density
  - Bunch position relative to pulse train



Staging in the linear regime

- Scanned by hand:
  - Off-resonant plasma density
  - Bunch position relative to pulse train
- Transverse fields strongly suppressed!
- Emittance growth <10X (vs >1000X)
- Preliminary result, further improvements possible

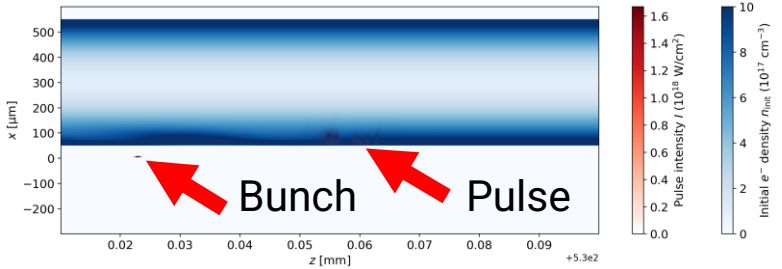


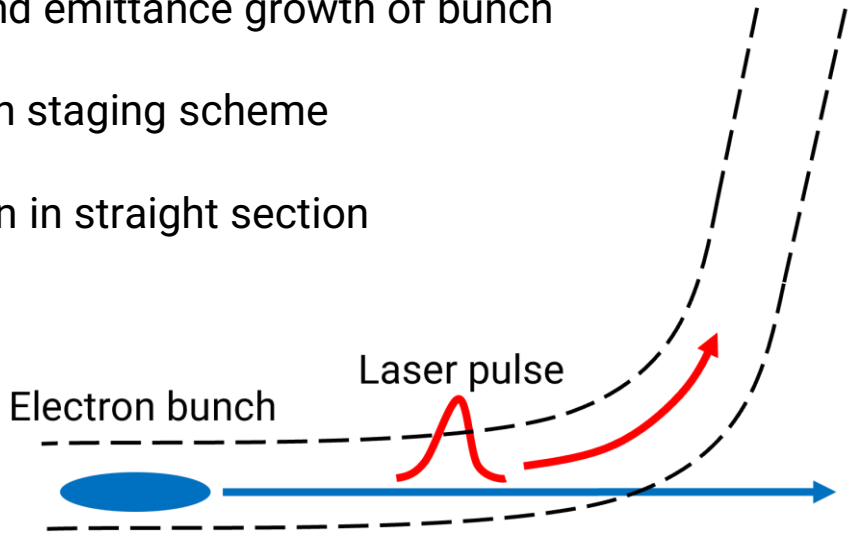


Simulations of pulse extraction with curved plasma waveguides

Pulse extraction setup

- Goal: Maximise transverse displacement of laser pulse while minimising transverse displacement and emittance growth of bunch
- Same pulse and bunch parameters as in staging scheme
- HiPACE++ for 500-mm long propagation in straight section

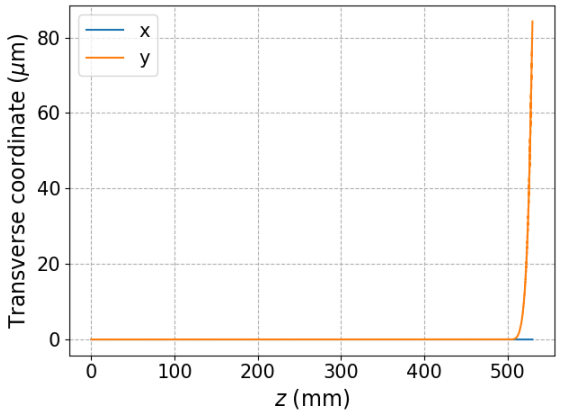




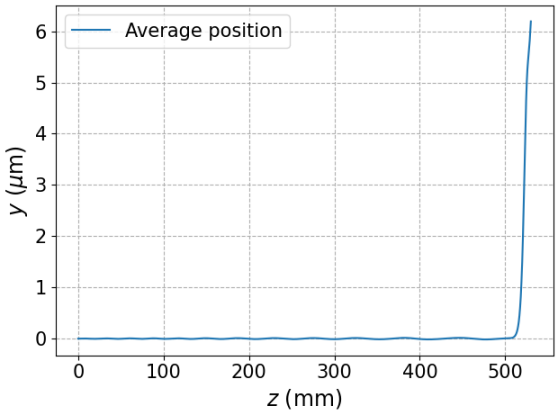
Pulse extraction results

- If laser pulse is properly depleted, emittance growth of bunch is controllable!
- Next step: compare emittance growth to plasma-mirror tape ejection schemes

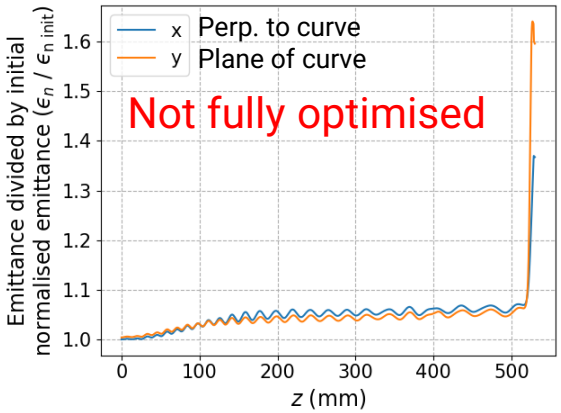
Transverse pulse position



Transverse bunch position



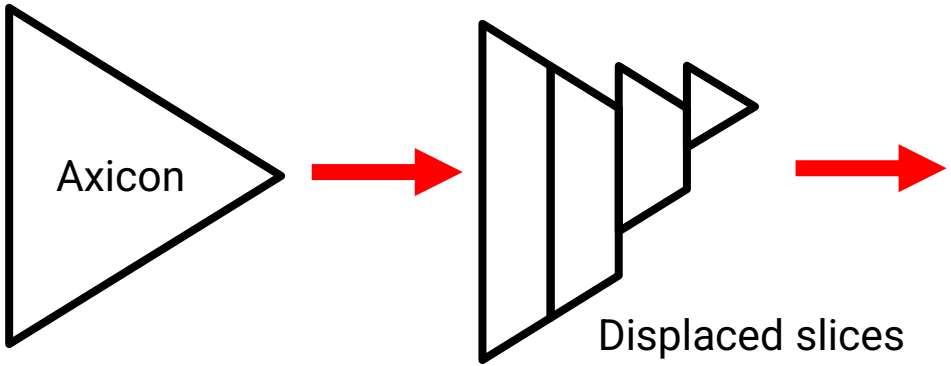
Relative emittance growth



Experimental demonstration of curved plasma waveguides

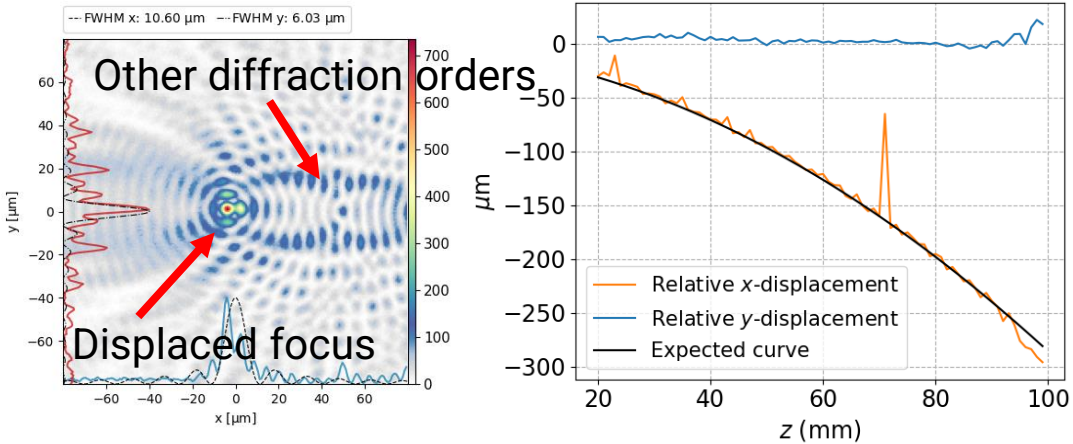
Trajectory control of Bessel foci

- To generate curved HOFI channels in the lab, channel-forming Bessel beam must follow a curved trajectory
- Exploits linear relation between *r*, the radial position at which light enters the axicon, and *z*, the longitudinal position along focus



Phase plate curve results

- Tested in our pulsed Ti:sapph beamline with kHz rep rate and 15 nm bandwidth
- Observed curved trajectory displacements >10 spot sizes over a distance of 120 mm with Bessel focus robust against laser pulse chromaticity



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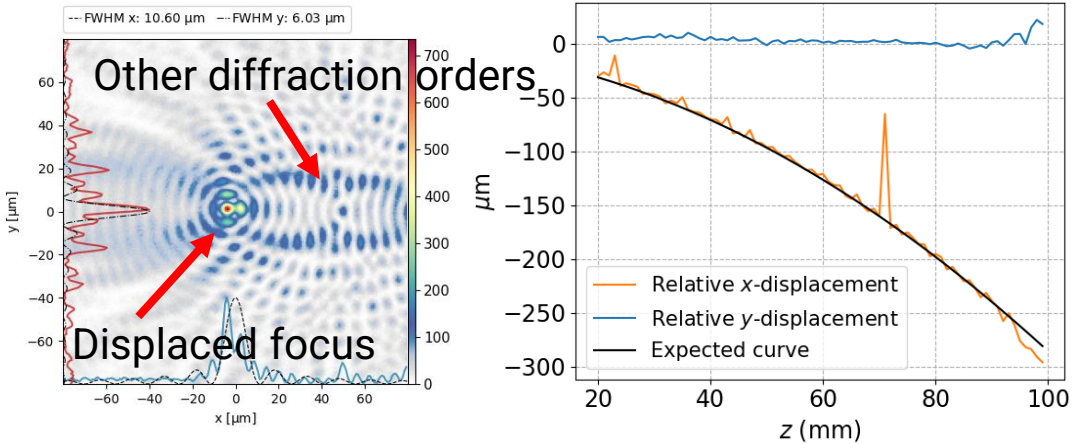
- Observed curved trajectory displacements >10 spot sizes over a distance of 120 mm with Bessel focus robust against laser pulse chromaticity
- Conducting a high-power HOFI generation experiment with displaced channel-forming beam



Conclusions and future work

- Curved HOFI waveguides are useful for a variety of applications

- Staging: Emittance growth is issue in quasilinear regime
- Can be mitigated by using pulse train to suppress wake excitation in coupling section

- Drive pulse extraction: Feasible without perturbing electron bunch

- Future work:
  - Generation & guiding in curved HOFI channels
  - Improve efficiency of phase plates (grayscale etching)

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