John Adams Institute for Accelerator Science
NSERC CRSNG

Curved hydrodynamic optical-field-ionised waveguides

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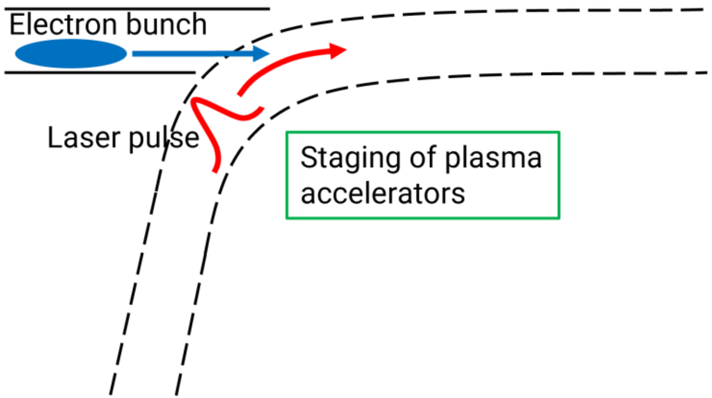
Overview

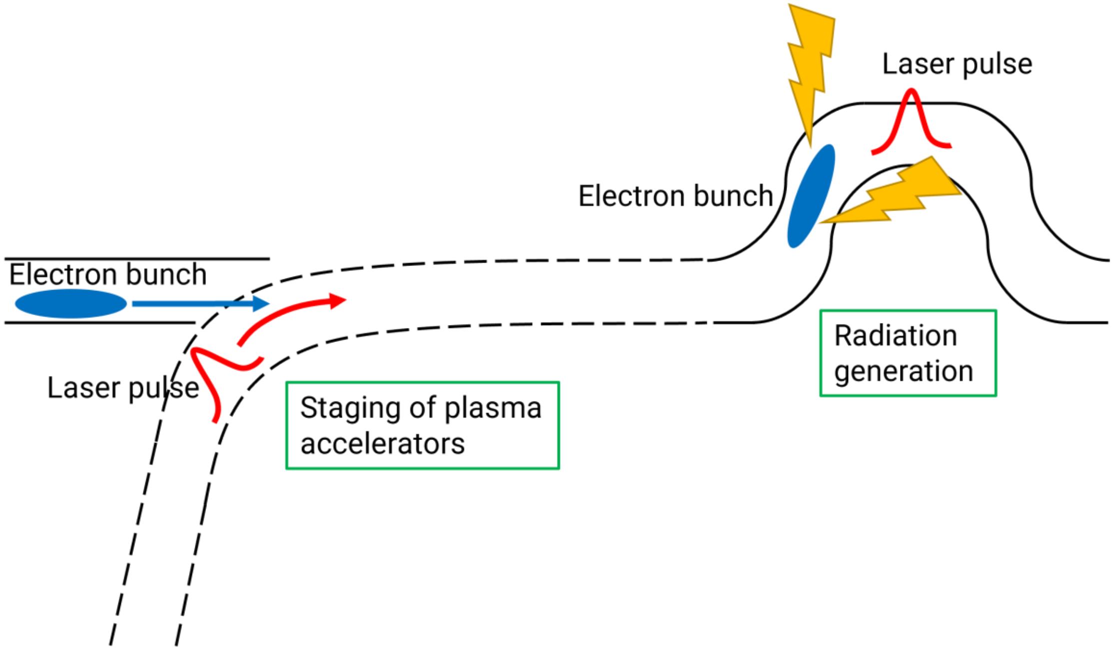
- Usefulness of curved plasma waveguides for LWFA
- Plasma accelerator staging simulations
- Pulse extraction simulations
- Experimental generation of curved plasma waveguides

Applications of curved plasma waveguides

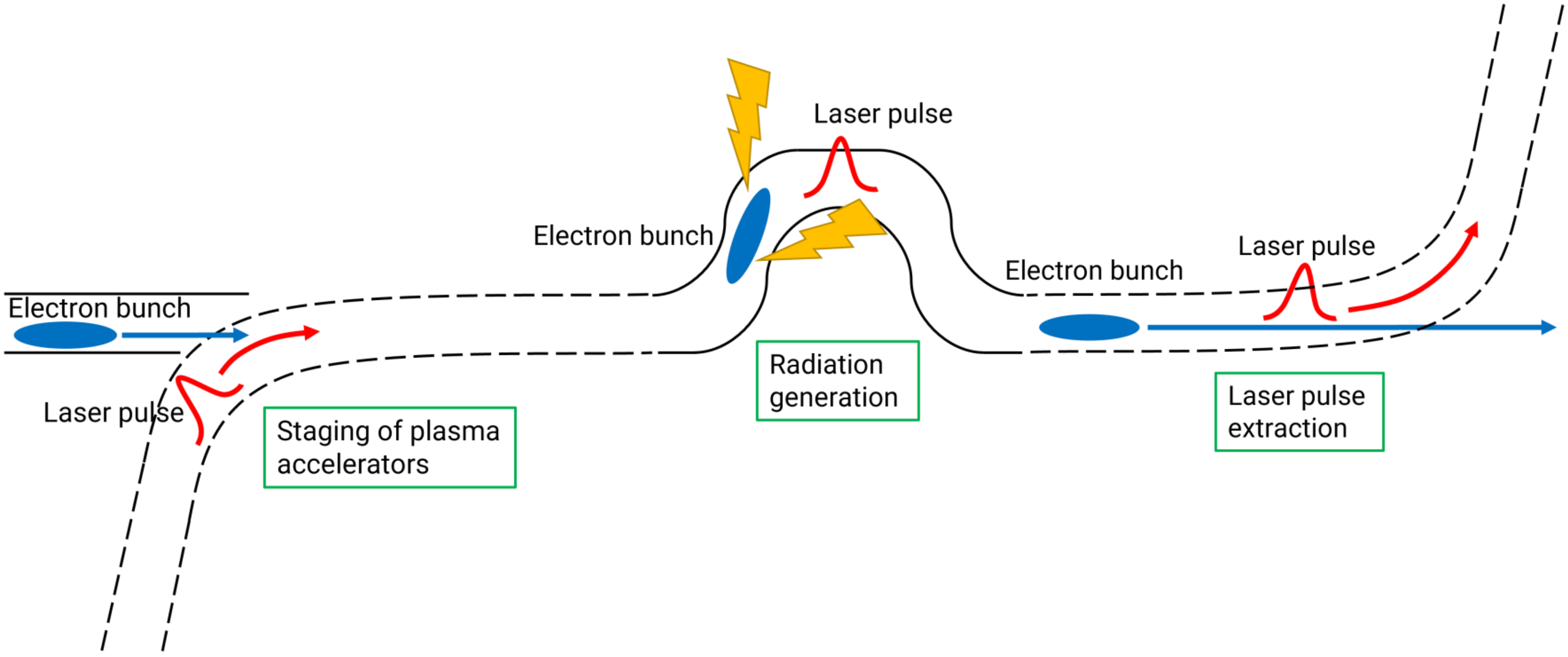


Staging of plasma accelerators

Applications of curved plasma waveguides



Applications of curved plasma waveguides



Staging of plasma accelerators

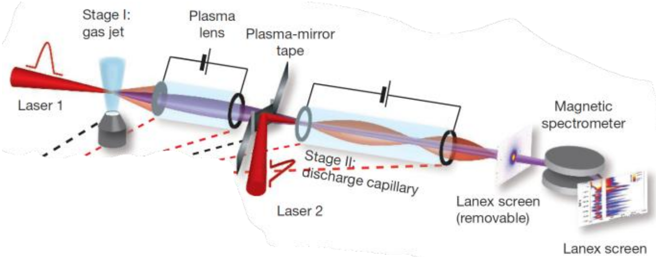
Radiation generation

Laser pulse extraction

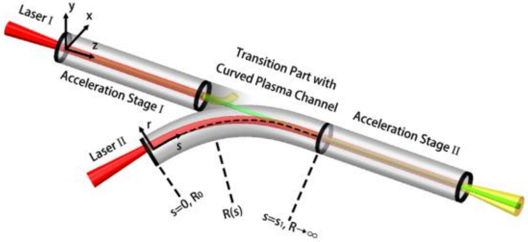
Simulations of staging with curved plasma waveguides

Multistage LWFA schemes

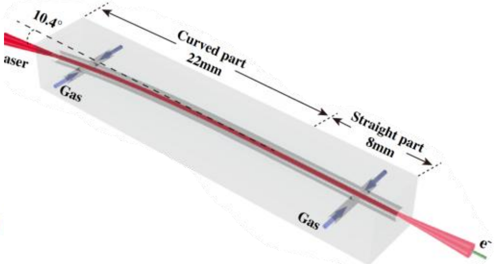
- No curved channels *staging* experiment has yet been performed (guiding ✓)
- All studies so far have used discharge capillaries, which are prone to laser damage especially at high pulse repetition rates



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



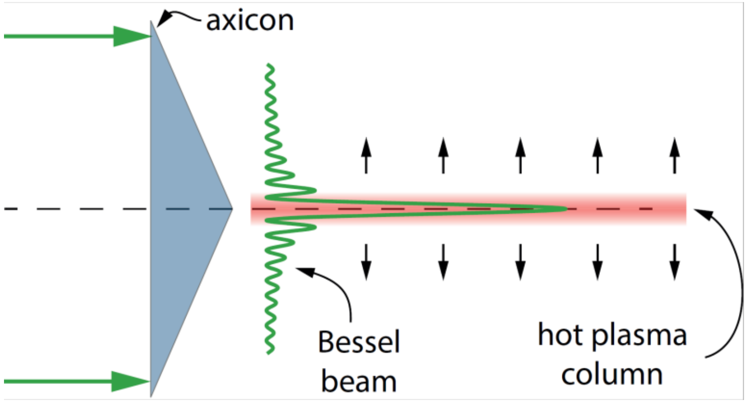
From: *Phys. Rev. Lett.* **120**, 154801 (2018)

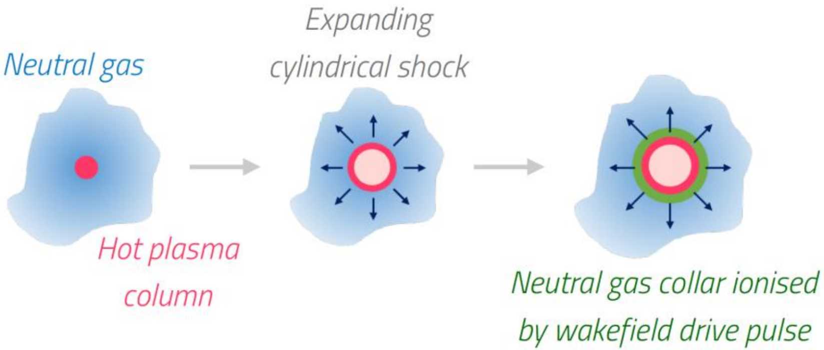


From: *Phys. Rev. Lett.* **130**, 215001 (2023)

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





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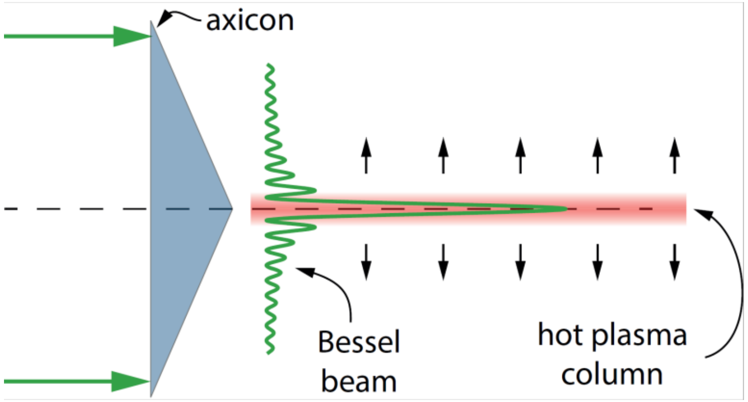

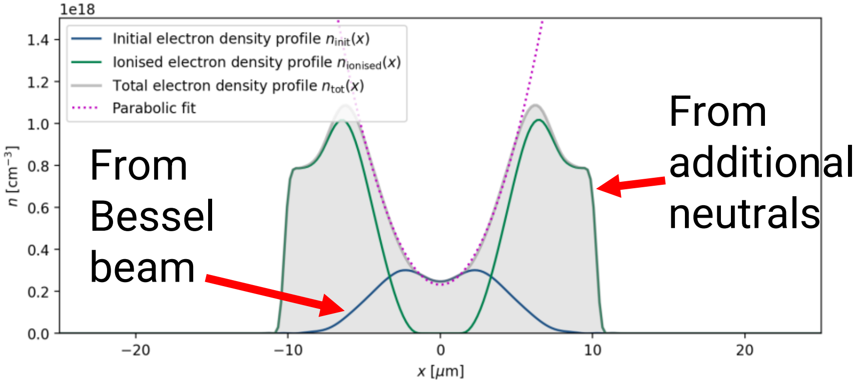

Curved channel goals and setup

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

- 2D sims with full PIC code WarpX to model channel wall ionisation and 3D sims with HiPACE++

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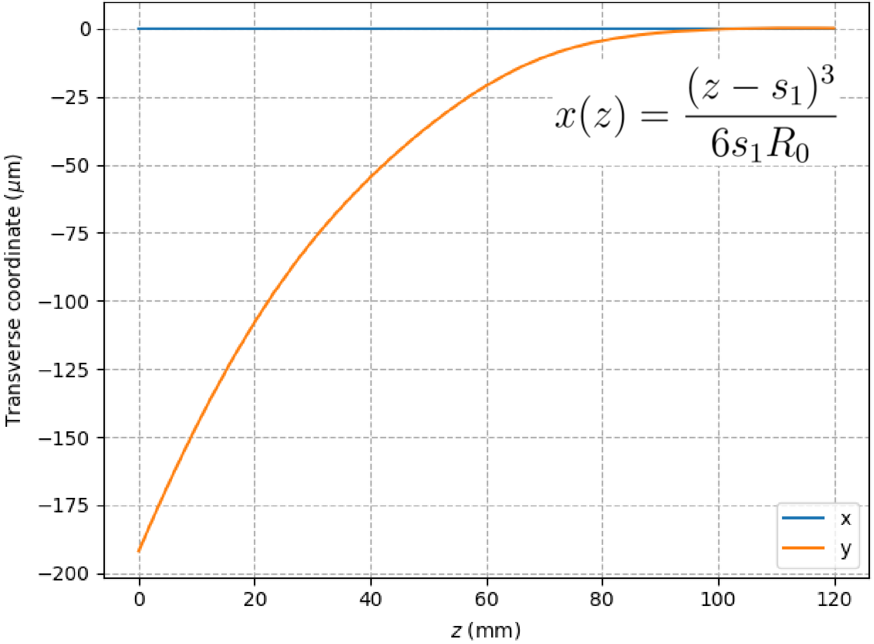
- Channel follows cubic curvature function with a displacement of 200 μm over 120 mm
- Minimises transverse laser pulse oscillations



$$x(z) = \frac{(z - s_1)^3}{6 s_1 R_0}$$

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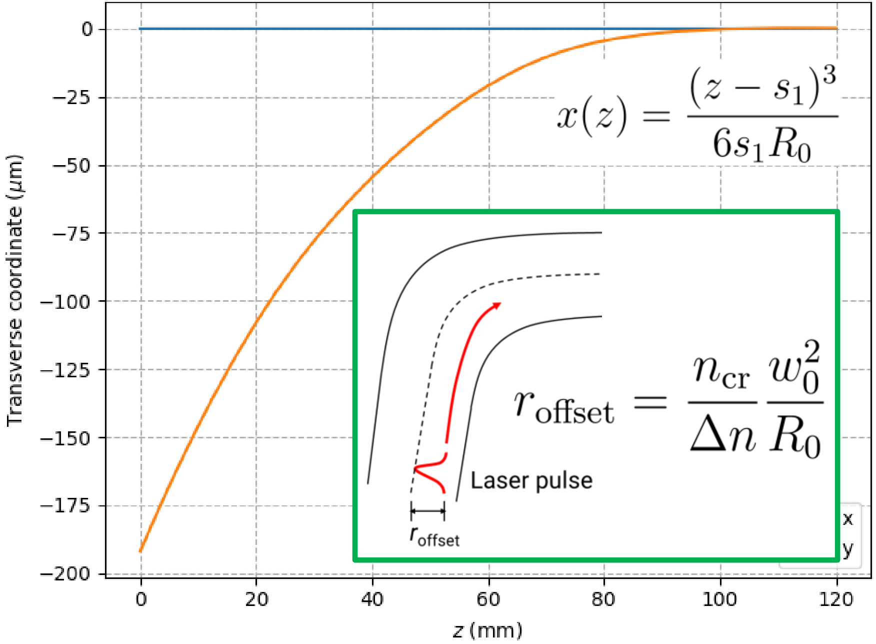

$$x(z) = \frac{(z-s_1)^3}{6 s_1 R_0}$$

$$r_{\text{offset}} = \frac{n_{\text{cr}}}{\Delta n}\frac{w_0^2}{R_0}$$

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

Optimisation of the staging scheme

- Laser pulse and channel parameters:
    - $a_0 = 1$, $w_0 = 30\ \mu m$, $E_0 = 4.2\ J$, $\tau_{FWHM} = 130\ fs$, $n_0 = 1.0 \times 10^{17}\ cm^{-3}$

- Bunch charge increased from 1pC to 45 pC
  for beam-loading and blowout enhancement

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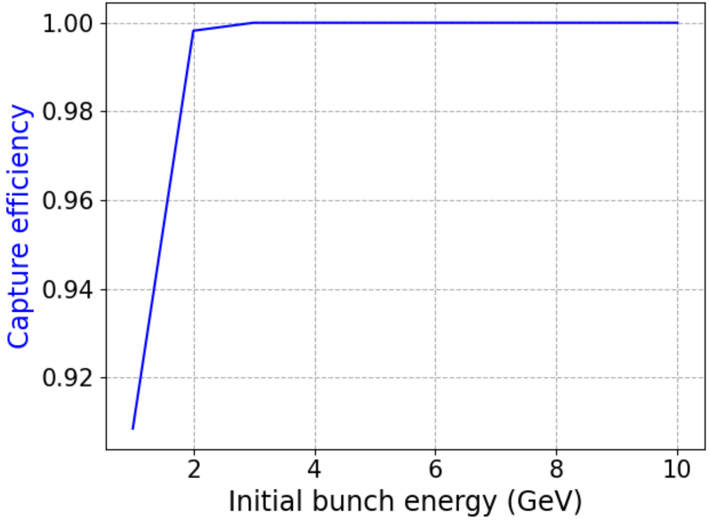
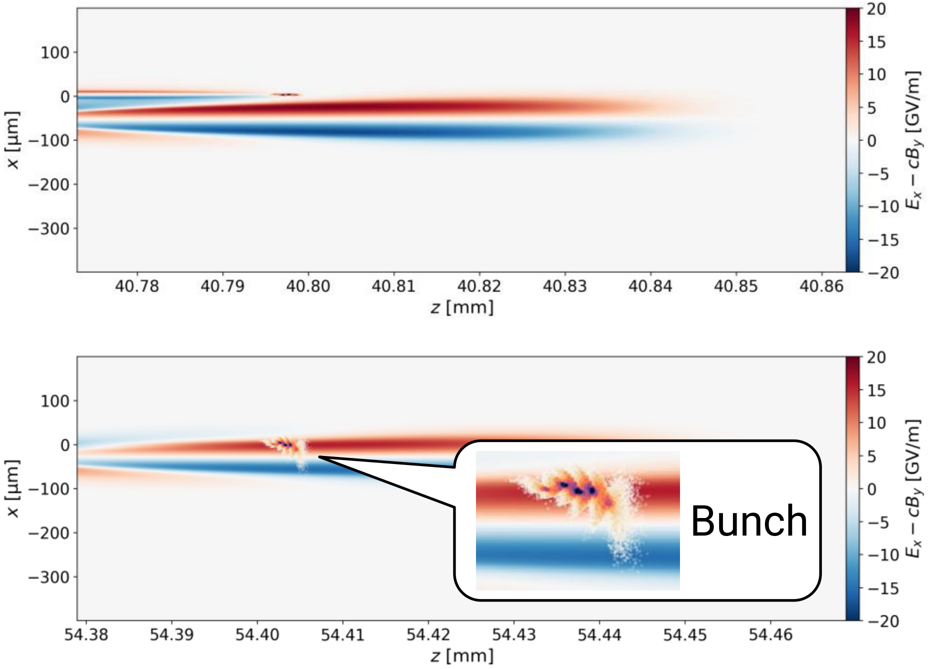
- Bunch charge increased from 1pC to 45 pC for beam-loading and blowout enhancement
- σ_x and σ_{px} chosen to give initial emittance of 1 mm mrad
- Bunch energy increased from 1 GeV to 10 GeV for rigidity and magnetic self-focusing
    - 100% capture efficiency achieved, but…



Challenges for the staging scheme

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

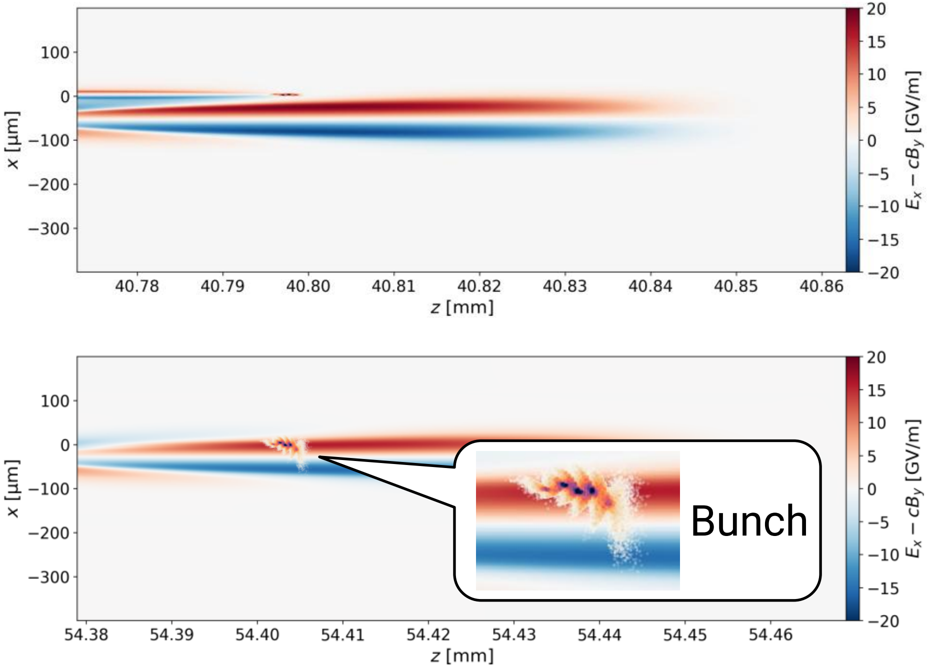


Challenges for the staging scheme

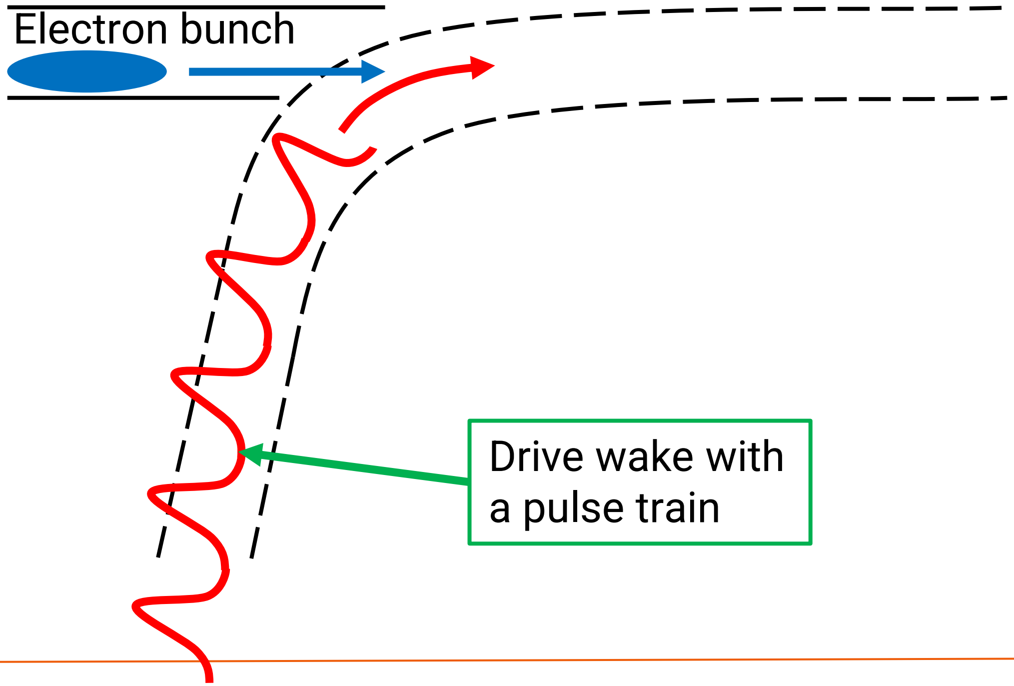
- Bunch passes through strong asymmetric transverse wakefields
- Emittance increases by >1000X

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

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



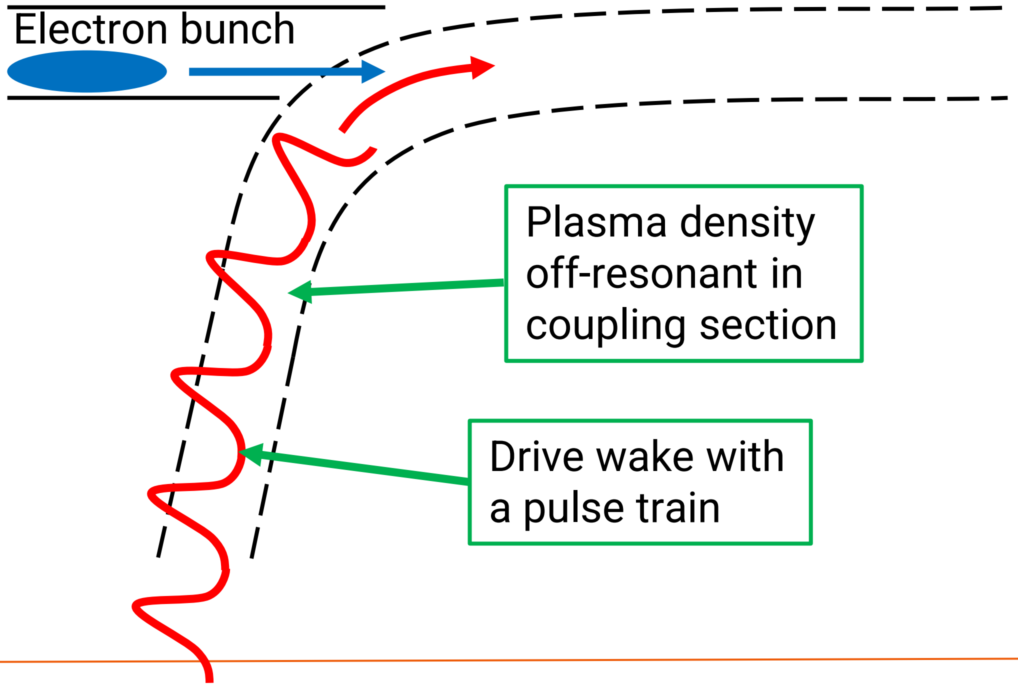
Suppressing wakefields in coupling region



Electron bunch

Drive wake with a pulse train

Suppressing wakefields in coupling region

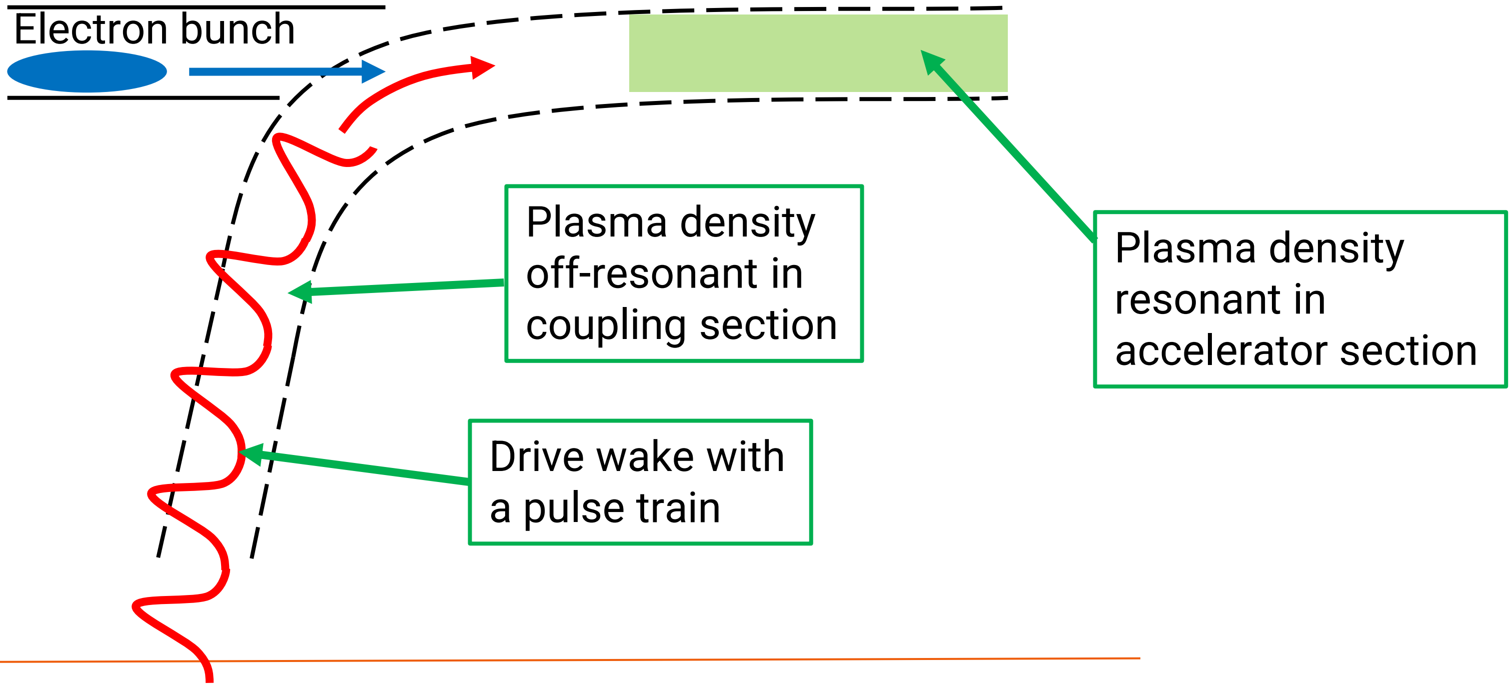


Electron bunch

Plasma density off-resonant in coupling section

Drive wake with a pulse train

Suppressing wakefields in coupling region



Electron bunch

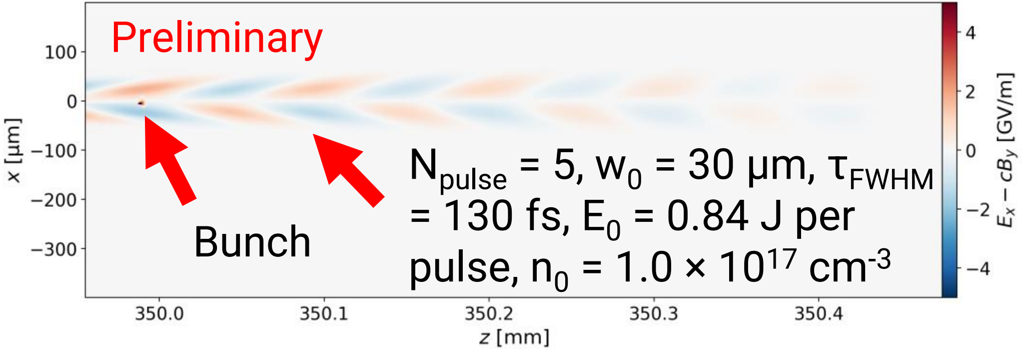
Plasma density off-resonant in coupling section

Drive wake with a pulse train

Plasma density resonant in accelerator section

Staging in the quasilinear regime

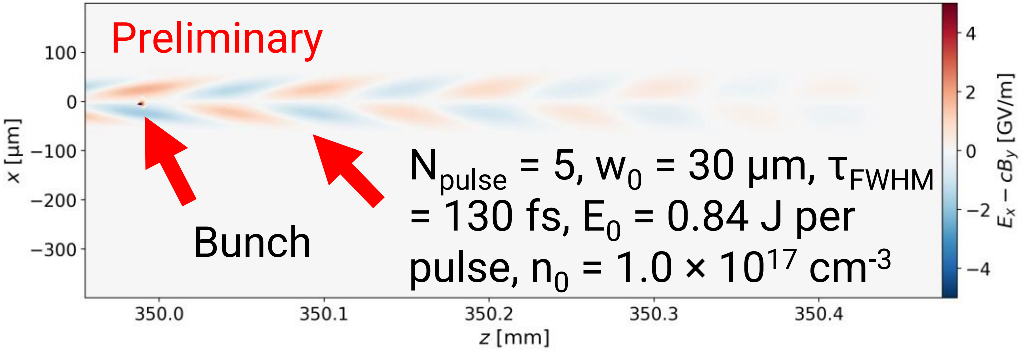
- Scanned by hand:
  - Off-resonant plasma density
  - Bunch position relative to pulse train
- Transverse fields strongly suppressed!



$N_{pulse} = 5$, $w_0 = 30$ µm, $\tau_{FWHM} = 130$ fs, $E_0 = 0.84$ J per pulse, $n_0 = 1.0 \times 10^{17}$ cm^{-3}

Staging in the quasilinear regime

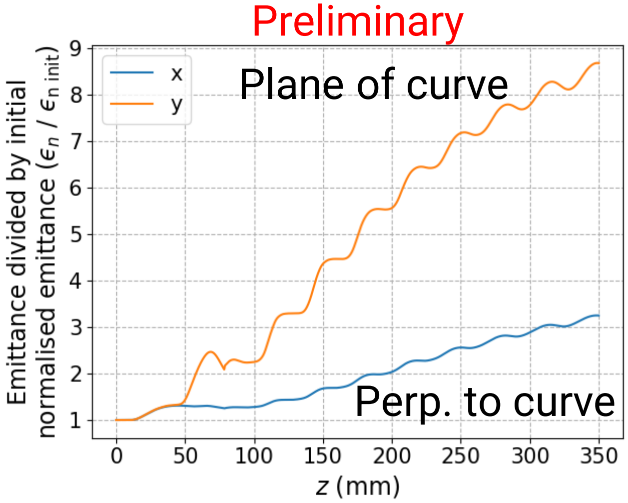
- Scanned by hand:
  - Off-resonant plasma density
  - Bunch position relative to pulse train
- Transverse fields strongly suppressed!
- Emittance growth <10X (vs >1000X)
- Preliminary result, improving with Bayesian opt.



Preliminary

Bunch

$N_{pulse} = 5$, $w_0 = 30\ \mu m$, $\tau_{FWHM} = 130$ fs, $E_0 = 0.84$ J per pulse, $n_0 = 1.0 \times 10^{17}\ cm^{-3}$



Preliminary

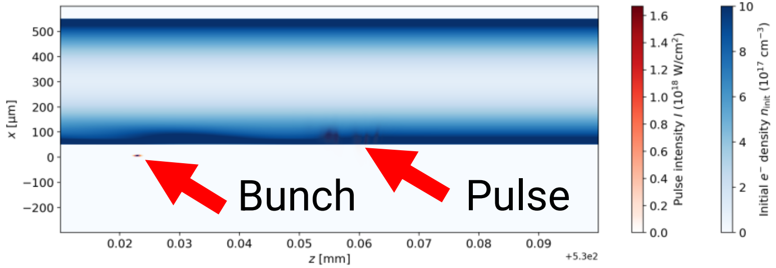
Plane of curve

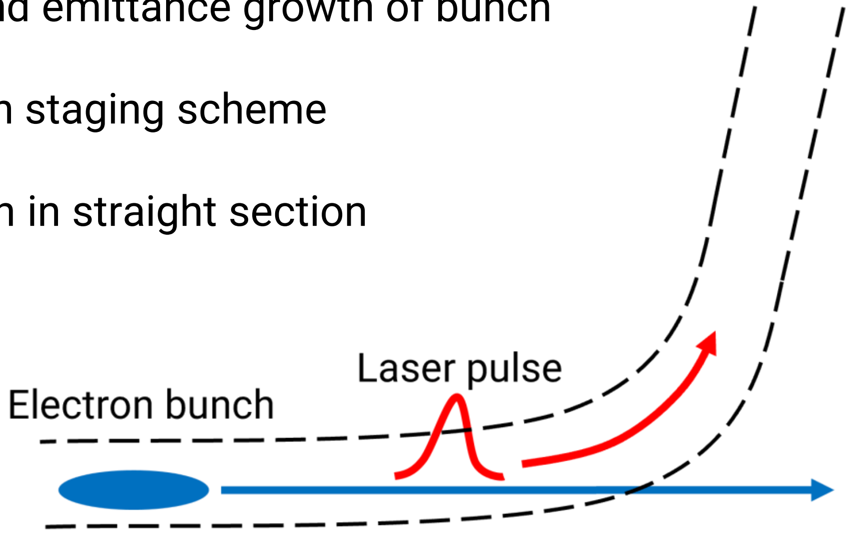
Perp. to curve

Simulations of pulse extraction with curved plasma waveguides

Pulse extraction setup

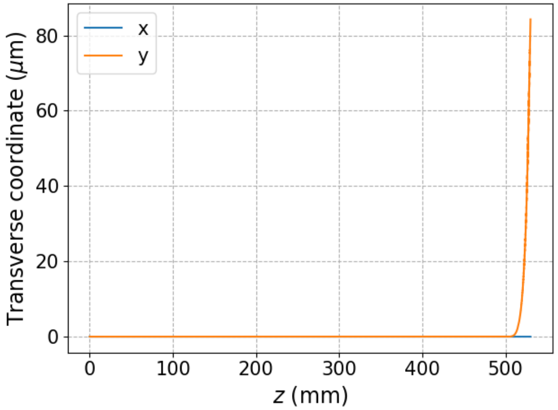
- Goal: Maximise transverse displacement of laser pulse while minimising transverse displacement and emittance growth of bunch
- Same pulse and bunch parameters as in staging scheme
- HiPACE++ for 500-mm long propagation in straight section

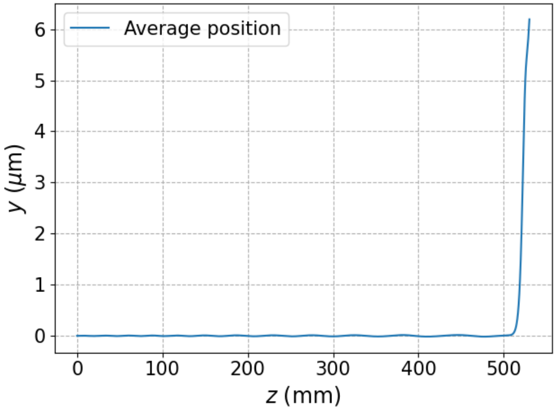


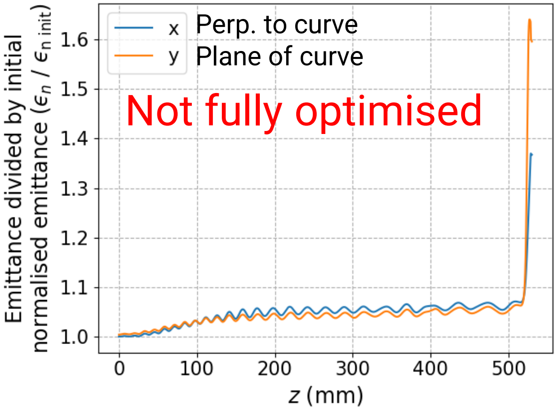


Pulse extraction results

- 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

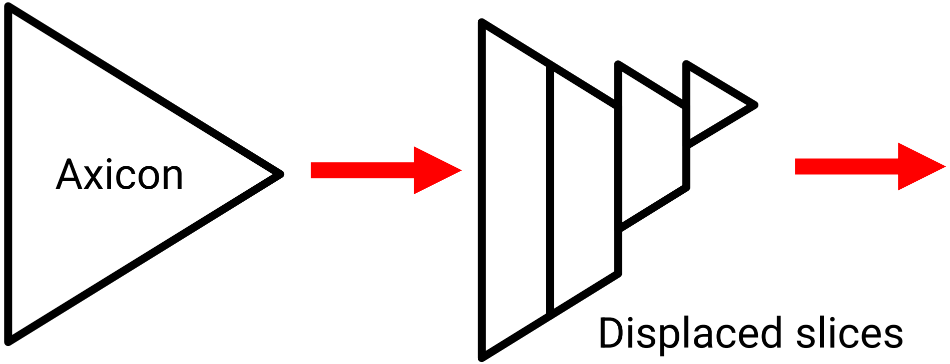

Relative emittance growth

Not fully optimised

Experimental demonstration of curved plasma waveguides

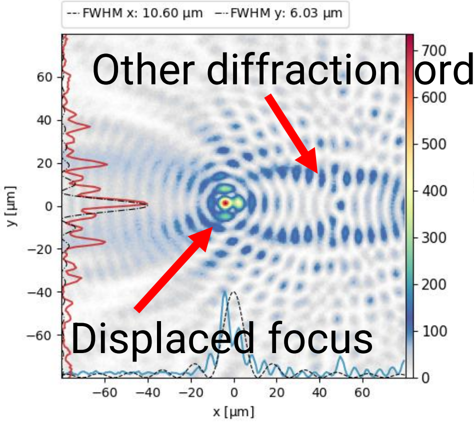
Trajectory control of Bessel foci

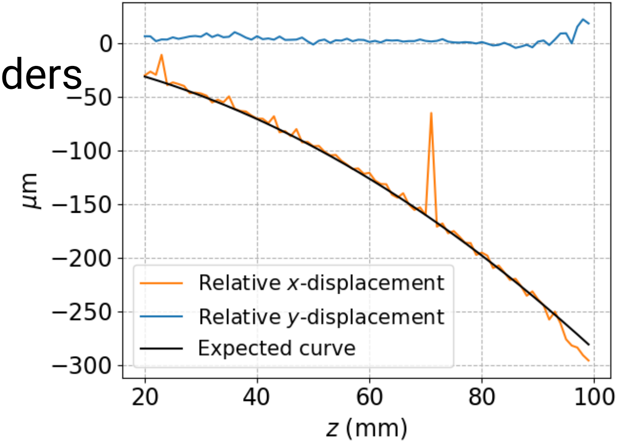
- To generate curved HOFI channels in the lab, channel-forming Bessel beam must follow a curved trajectory
- Exploits linear relation between *r*, the radial position at which light enters the axicon, and *z*, the longitudinal position along focus



Phase plate curve results

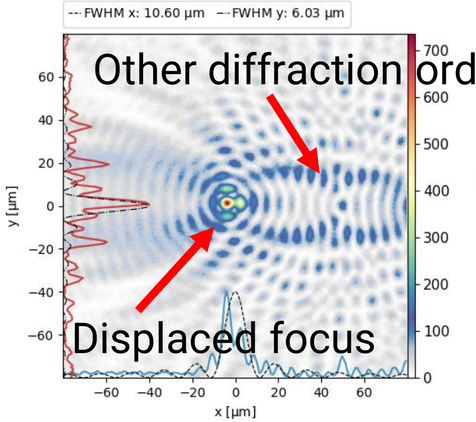
- Tested in our pulsed Ti:sapph beamline with kHz rep rate and 15 nm bandwidth
- Observed curved trajectory displacements >10 spot sizes over a distance of 120 mm with Bessel focus robust against laser pulse chromaticity



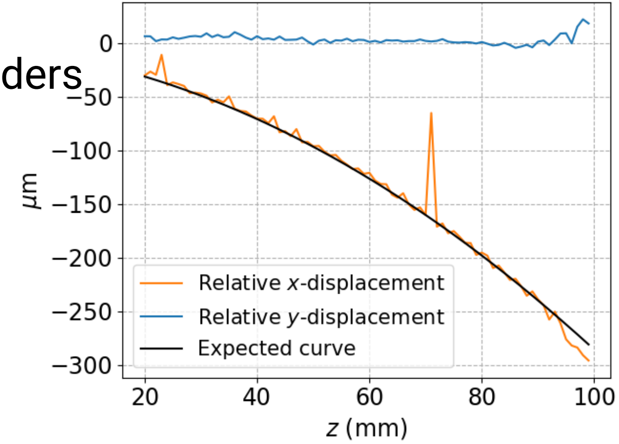


Phase plate curve results

- 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
- Conducting a high-power HOFI generation experiment with displaced channel-forming beam


Other diffraction orders

Displaced focus



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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Backup slides

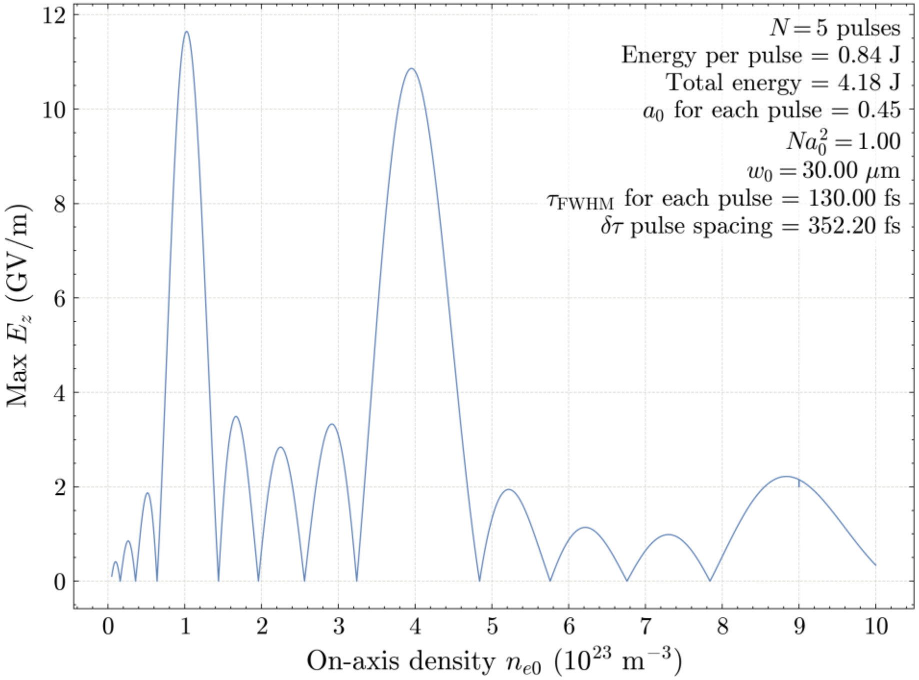
Pulse train resonance model

$$\frac{\delta n_\mathrm{e}}{n_\mathrm{e0}} = A\omega_\mathrm{p0}\tau_0 \left[1 + \left(\frac{2\sqrt{2}c}{\omega_\mathrm{p0}w_0}\right)^2\right] \exp\left[-\frac{(\omega_\mathrm{p0}\tau_0)^2}{16\ln 2}\right]$$

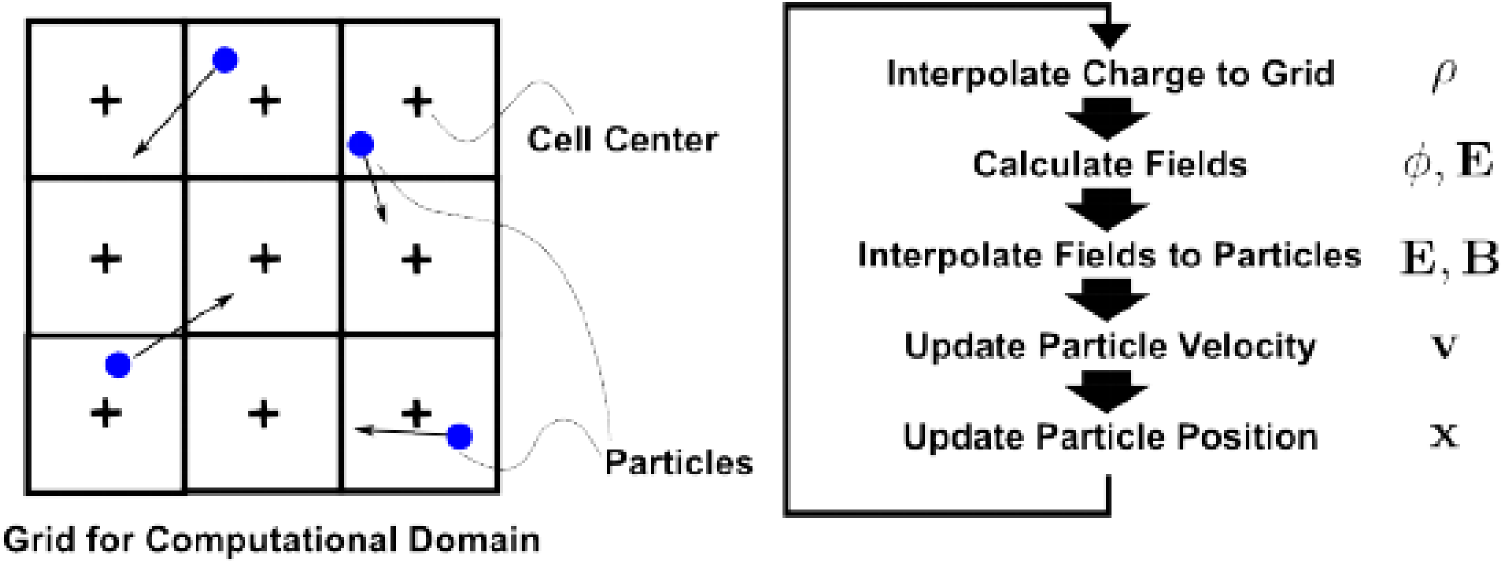
$$\left(\frac{\delta n_\mathrm{e}}{n_\mathrm{e0}}\right)_N = \left(\frac{\delta n_\mathrm{e}}{n_\mathrm{e0}}\right)_1 \left|\frac{\sin\left(\frac{1}{2}N\omega_\mathrm{p0}\delta\tau\right)}{\sin\left(\frac{1}{2}\omega_\mathrm{p0}\delta\tau\right)}\right|$$

From: *Phys. Rev. Lett.* **119**, 044802 (2017)

Pulse train resonance model



The Particle-in-Cell method



From: https://arc.aiaa.org/doi/10.2514/6.2014-4027/