
# Controlled Injection in a Channel-Guided LPA

## Via All-Optical Density Tailoring

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European Advanced Accelerator Concepts Workshop
Hotel Hermitage, Elba
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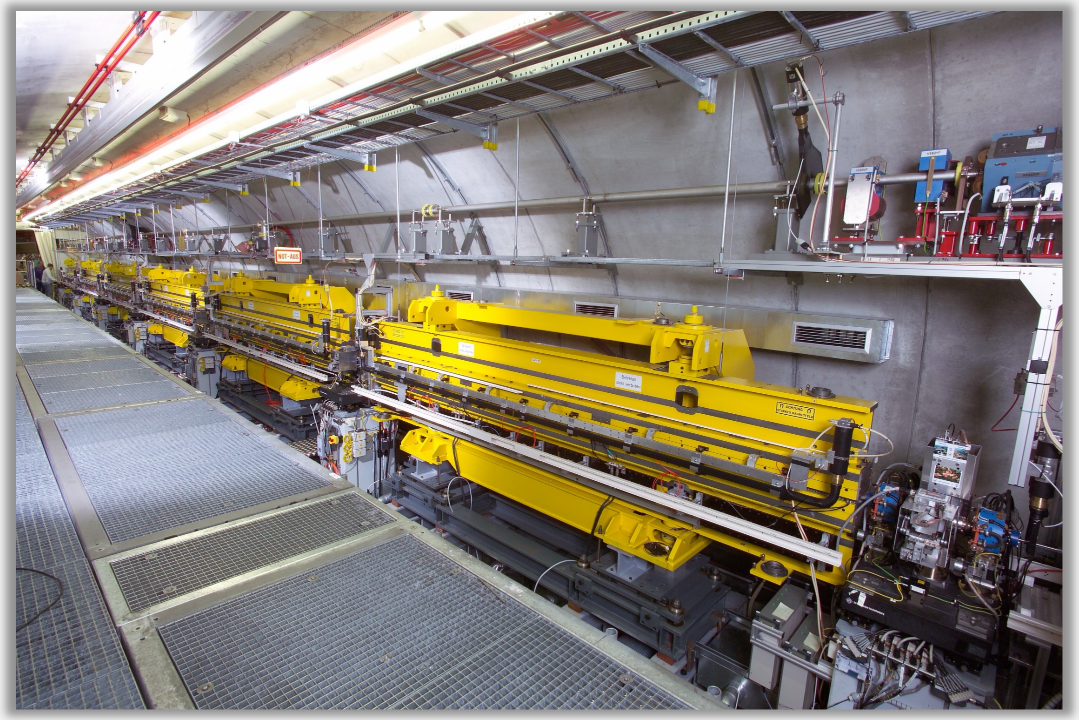
*Deutsche Forschungsgemeinschaft (DFG)*
*Projektnummer 531352484*

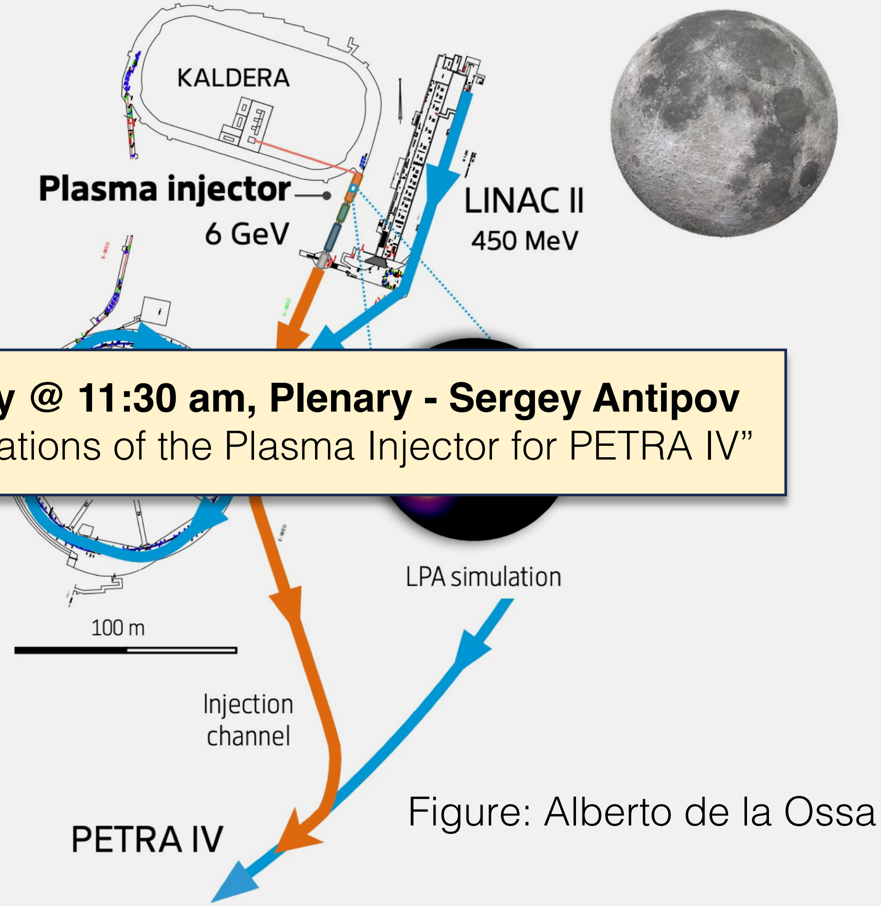
# High-Quality Multi-GeV Electron Beams Driven by LPAs

Critical for advanced light sources at DESY

## Compact X-Ray Free Electron Laser Driver



## Plasma Injector for PETRA IV Synchrotron




**Friday @ 11:30 am, Plenary - Sergey Antipov**
"Simulations of the Plasma Injector for PETRA IV"

Figure: Alberto de la Ossa

[1] I. Agapov et al., PETRA IV Plasma Injector CDR 10.3204/PUBDB-2024-06078 (2025)

# Plasma Sources

For high-quality multi-GeV electron beams

**Plasma Waveguide**
Extended interaction length

**Controlled Injection**
Within the plasma waveguide

**Tunability**
High-level of process control

**Material Robustness**

**Thermal Management**

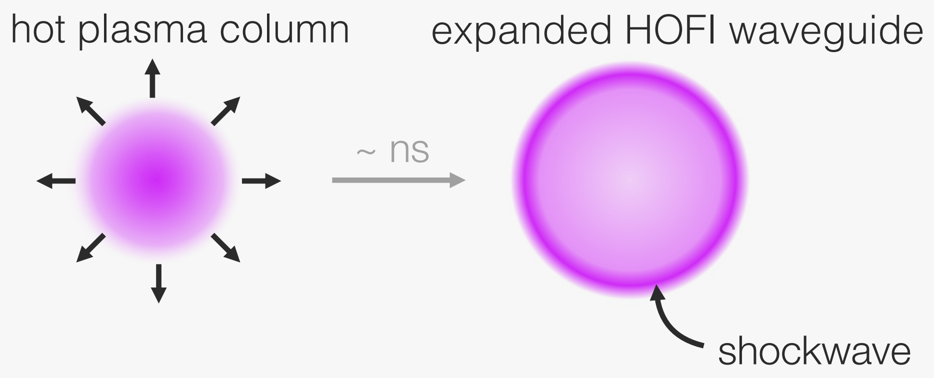
**Beamline integration**

**Vacuum Load**

# Optically Tailored Plasma Sources

Hydrodynamically generated structures suitable for waveguiding and for electron injection

## Transverse Tailoring

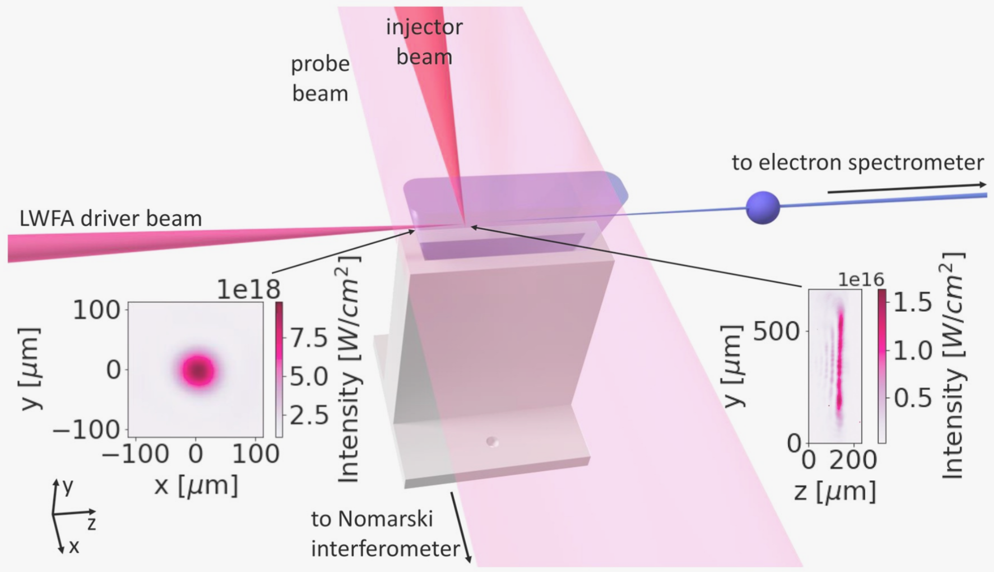



**Wednesday @ 18:20, Sala Bonarparte 1 – Anna Puchert**
"Laser Pulse Tailoring for HOFI Waveguide Generation"

**Plasma Waveguides [1,2]**

- Plasma column field ionised and heated by fs laser
- Expanding plasma drives shock into surrounding gas
- Generates radial density profile suitable for guiding

## Longitudinal Tailoring

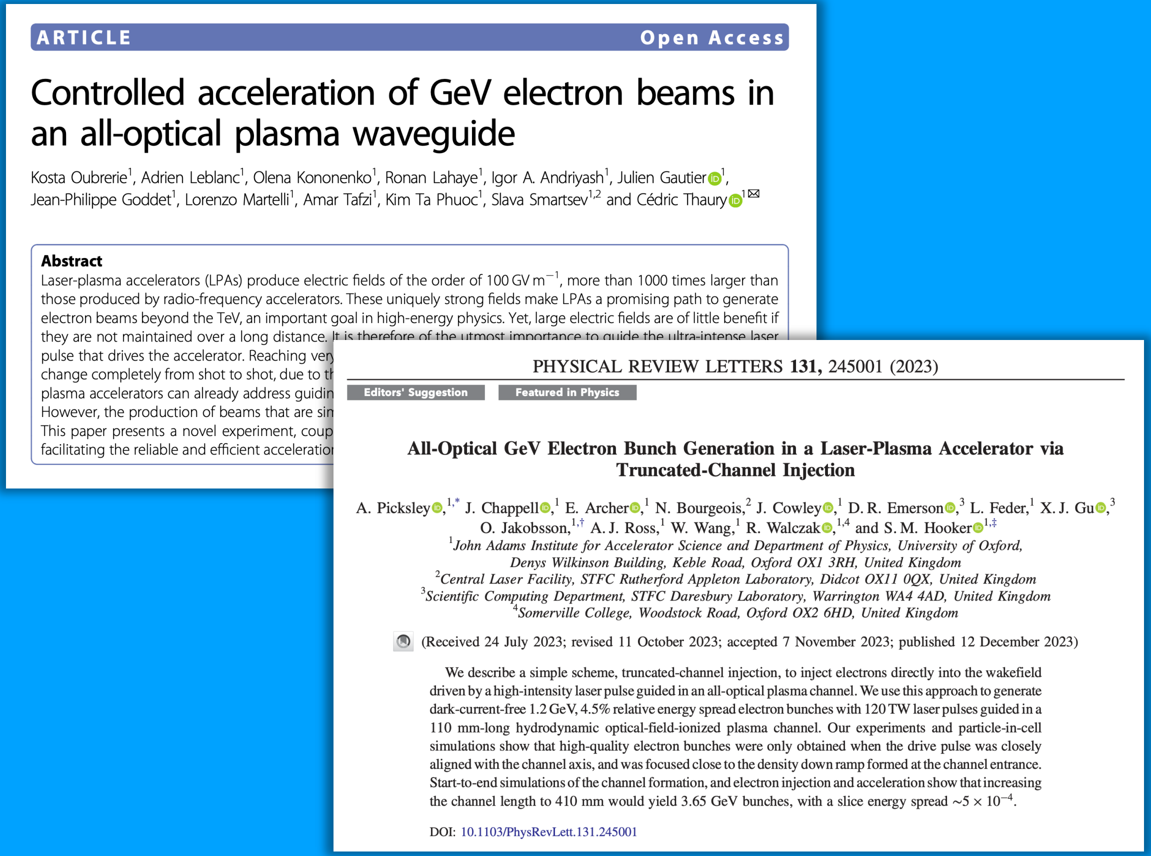



[12]


[1] C. G. Durfee & H. M. Milchberg, PRL 71, 2409 (1993)
[2] T. R. Clark & H. M. Milchberg, PRL 78, 2373 (1997)
[3] N. Lemos et al., Phys. Plasmas 20, 063102 (2013)
[4] A. Morozov et al., Phys. Plasmas 25, 053110 (2018)
[5] R. J. Shalloo et al., PRE 97, 053203 (2018)
[6] R. J. Shalloo et al., PRAB 22, 041302 (2019)
[7] A. Picklsey et al., PRE 102, 053201 (2020)
[8] B. Miao et al., PRX 12, 031038 (2022)
[9] J. Faure et al., Phys. Plasmas 17, 083107 (2010)
[10] P. Brijesh et al., Phys. Plasmas 19, 063104 (2012)
[11] S. Formaux et al., Appl. Phys. Lett. 101, 111106 (2012)
[12] K. v. Grafenstein et al., Sci. Rep. 13, 11680 (2023)

# Controlling Electron Injection

## Within Optically Formed Plasma Waveguides



ARTICLE — Open Access

Controlled acceleration of GeV electron beams in an all-optical plasma waveguide

Kosta Oubrerie[1], Adrien Leblanc[1], Olena Kononenko[1], Ronan Lahaye[1], Igor A. Andriyash[1], Julien Gautier[1], Jean-Philippe Goddet[1], Lorenzo Martelli[1], Amar Tafzi[1], Kim Ta Phuoc[1], Slava Smartsev[1,2] and Cédric Thaury[1]

**Abstract**
Laser-plasma accelerators (LPAs) produce electric fields of the order of 100 GV m$^{-1}$, more than 1000 times larger than those produced by radio-frequency accelerators. These uniquely strong fields make LPAs a promising path to generate electron beams beyond the TeV, an important goal in high-energy physics. Yet, large electric fields are of little benefit if they are not maintained over a long distance. It is therefore of the utmost importance to guide the ultra-intense laser pulse that drives the accelerator. Reaching ver… change completely from shot to shot, due to th… plasma accelerators can already address guidin… However, the production of beams that are sim… This paper presents a novel experiment, coup… facilitating the reliable and efficient acceleratio…

PHYSICAL REVIEW LETTERS **131**, 245001 (2023)

Editors' Suggestion — Featured in Physics

**All-Optical GeV Electron Bunch Generation in a Laser-Plasma Accelerator via Truncated-Channel Injection**

A. Picksley,[1,*] J. Chappell,[1] E. Archer,[1] N. Bourgeois,[2] J. Cowley,[1] D. R. Emerson,[3] L. Feder,[1] X. J. Gu,[3] O. Jakobsson,[1,†] A. J. Ross,[1] W. Wang,[1] R. Walczak,[1,4] and S. M. Hooker[1,‡]
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[3]*Scientific Computing Department, STFC Daresbury Laboratory, Warrington WA4 4AD, United Kingdom*
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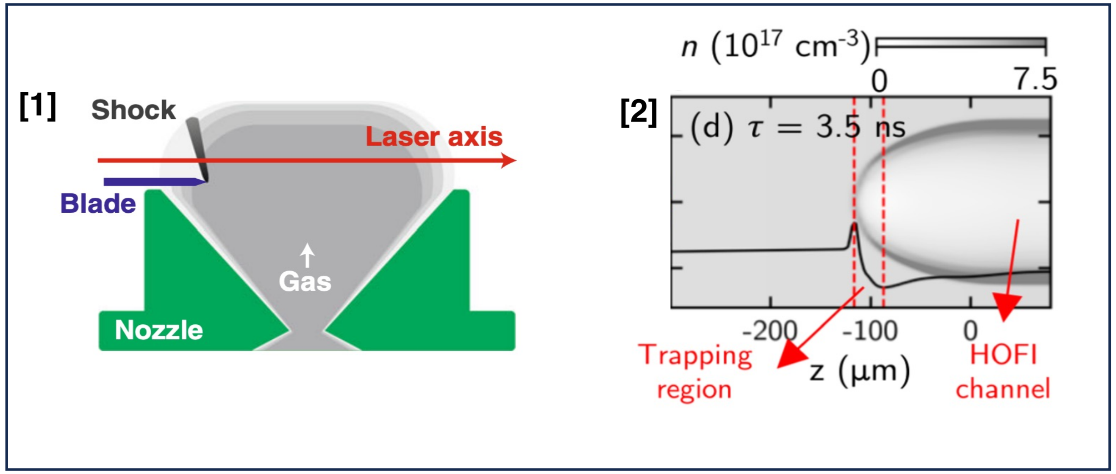
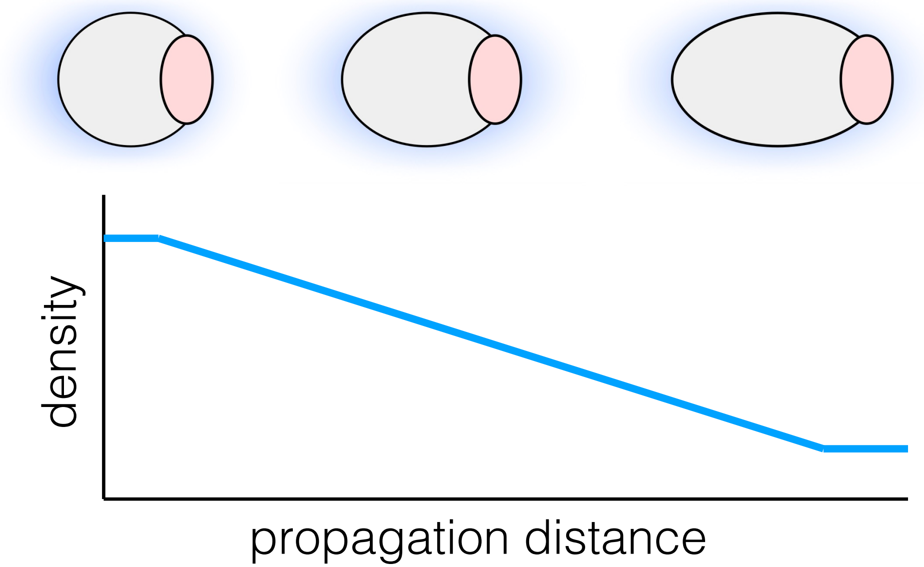
(Received 24 July 2023; revised 11 October 2023; accepted 7 November 2023; published 12 December 2023)

We describe a simple scheme, truncated-channel injection, to inject electrons directly into the wakefield driven by a high-intensity laser pulse guided in an all-optical plasma channel. We use this approach to generate dark-current-free 1.2 GeV, 4.5% relative energy spread electron bunches with 120 TW laser pulses guided in a 110 mm-long hydrodynamic optical-field-ionized plasma channel. Our experiments and particle-in-cell simulations show that high-quality electron bunches were only obtained when the drive pulse was closely aligned with the channel axis, and was focused close to the density down ramp formed at the channel entrance. Start-to-end simulations of the channel formation, and electron injection and acceleration show that increasing the channel length to 410 mm would yield 3.65 GeV bunches, with a slice energy spread ~5 × 10$^{-4}$.

DOI: 10.1103/PhysRevLett.131.245001




A density transition can facilitate generation of low-energy spread beams



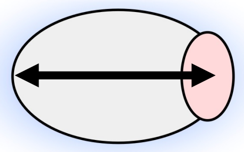


[1] K. Oubrerie et al., Light: Sci. App. 11, 180 (2022)
[2] A. Picksley et al., Phys. Rev. Lett., 131, 245001 (2023)
[3] J. E. Shrock, et al., Phys. Rev. Lett., 133, 045002 (2024)
[4] A. Picksley et al., Phys. Rev. Lett., 133, 255001 (2024)
[5] R. Lahaye et al., Phys. Rev. Acc. Beams 28, 091301 (2025)

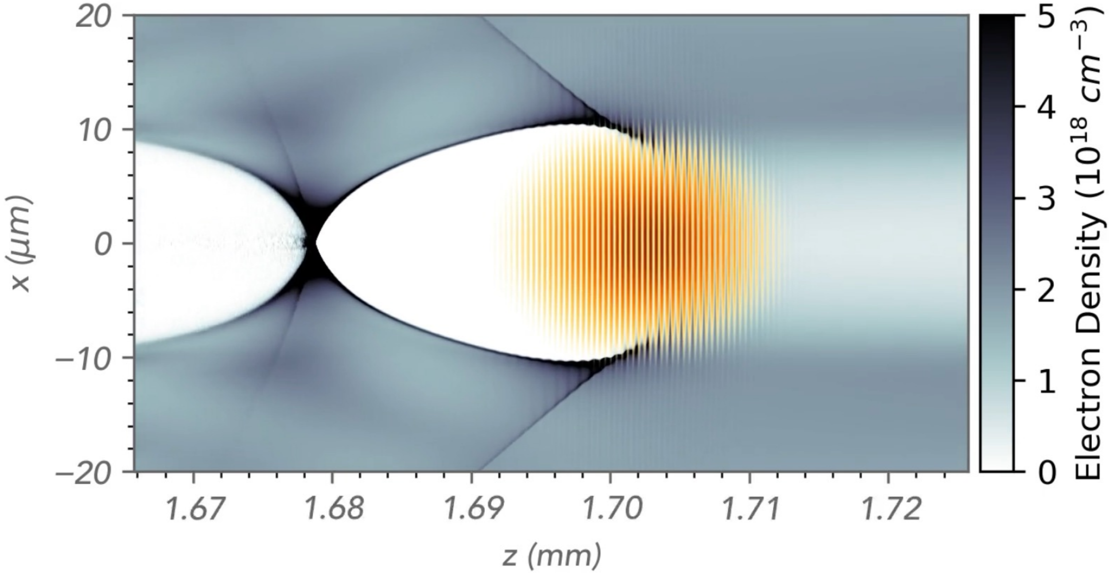
# Bubble Dynamics Within a Plasma Channel

## Radial Electron Density Profile Strongly Influences Bubble Length

**What Decreases Bubble Length**



| | |
|---|---|
| axial density | ↑ |
| laser intensity | ↓ |
| spot size | ↓ |
| channel curvature | ↑ |
| channel radius | ↓ |




$$n_e(r) = n_0 + \Delta n \left( \frac{r}{r_{ch}} \right)^{\alpha}$$

channel depth ($\Delta n$), curvature ($\alpha$), axial density ($n_0$), "channel radius" ($r_{ch}$)

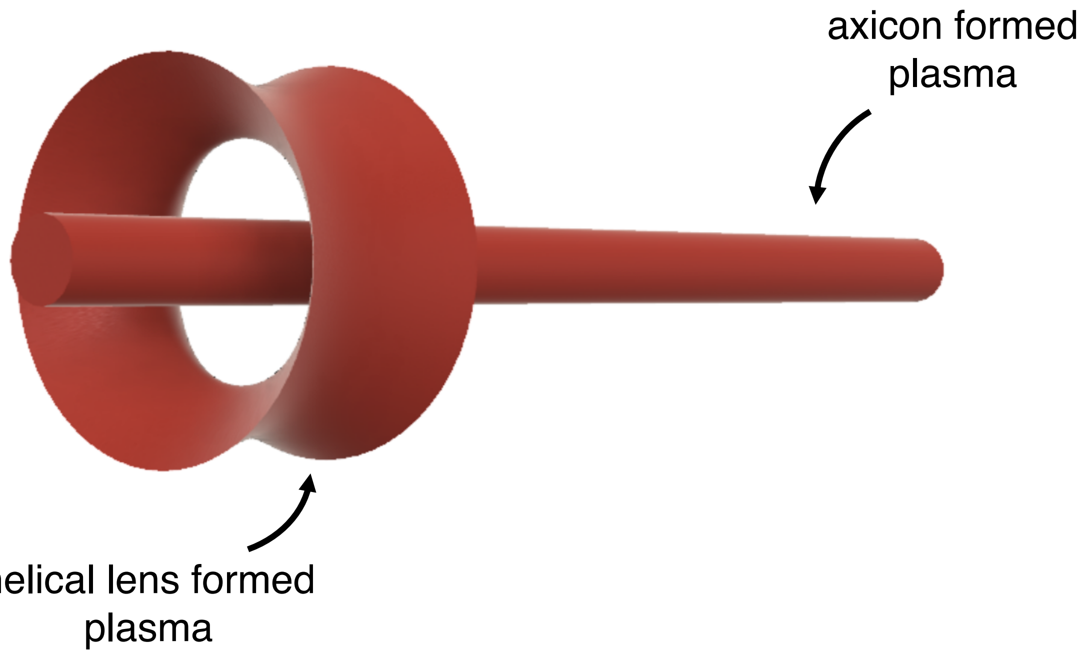
**Bubble Dynamics Can be Controlled By Radial Density Tailoring**


[1] W. Lu et al., PR-STAB 10, 061301 (2007)
[2] J. Thomas et al., POP 23, 053108 (2016)

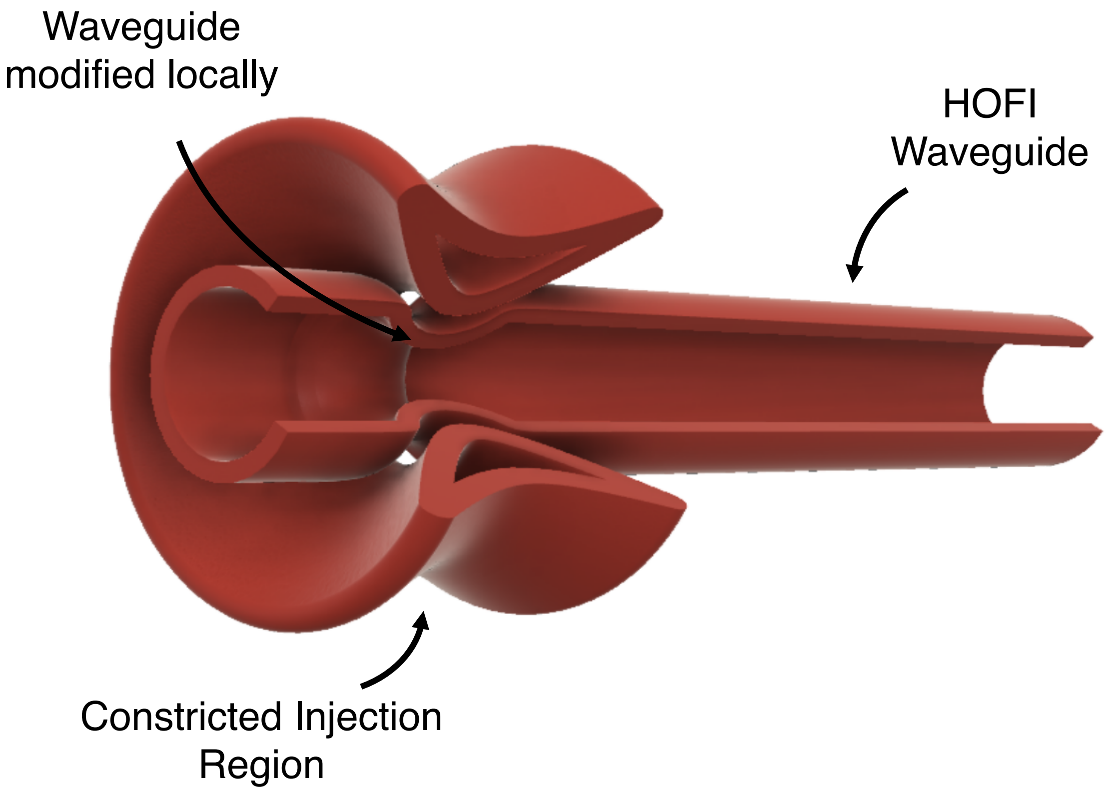
# Waveguide Constriction for Promoting Localized Injection

Generated through the collision of hydrodynamic shocks

## Plasma Formation




## Plasma Expansion / Interaction



# Start-to-End Simulation Framework

For Studying Multi-GeV Electron Acceleration from Optical Plasma Sources

**Tuesday @ Now, Sala Elena – Maxence Thévenet**
"Mainstreaming Start-to-End Realistic Simulations in Plasma Accelerator Research"

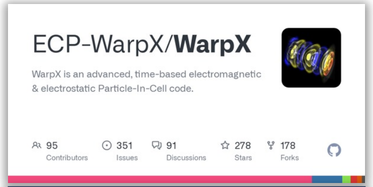
**Neutral Gas Profile**
Simulation of Gas Cell

Ansys
FLUENT

**Laser Pulse Shaping**
Plasma tailoring beams


& analytics

**Ionization**
Plasma density & temp.



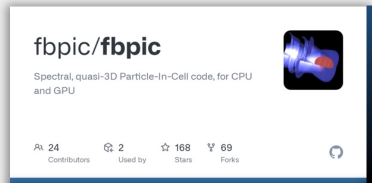

**Wednesday @ Poster Session – Rob Shalloo**
"LASY – Laser Manipulation Made Easy"

https://github.com/LASY-org/LASY
https://github.com/ECP-WarpX/WarpX
https://github.com/fbpic/fbpic
https://github.com/AngelFP/Wake-T
https://github.com/optimas-org/optimas

**Bayesian Optimization**
Plasma source formation + injection / acceleration

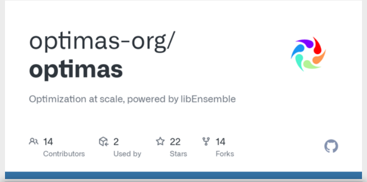
**Hydrodynamics**
Custom module


**Plasma Acceleration**
Injection and acceleration






Laser Handshake

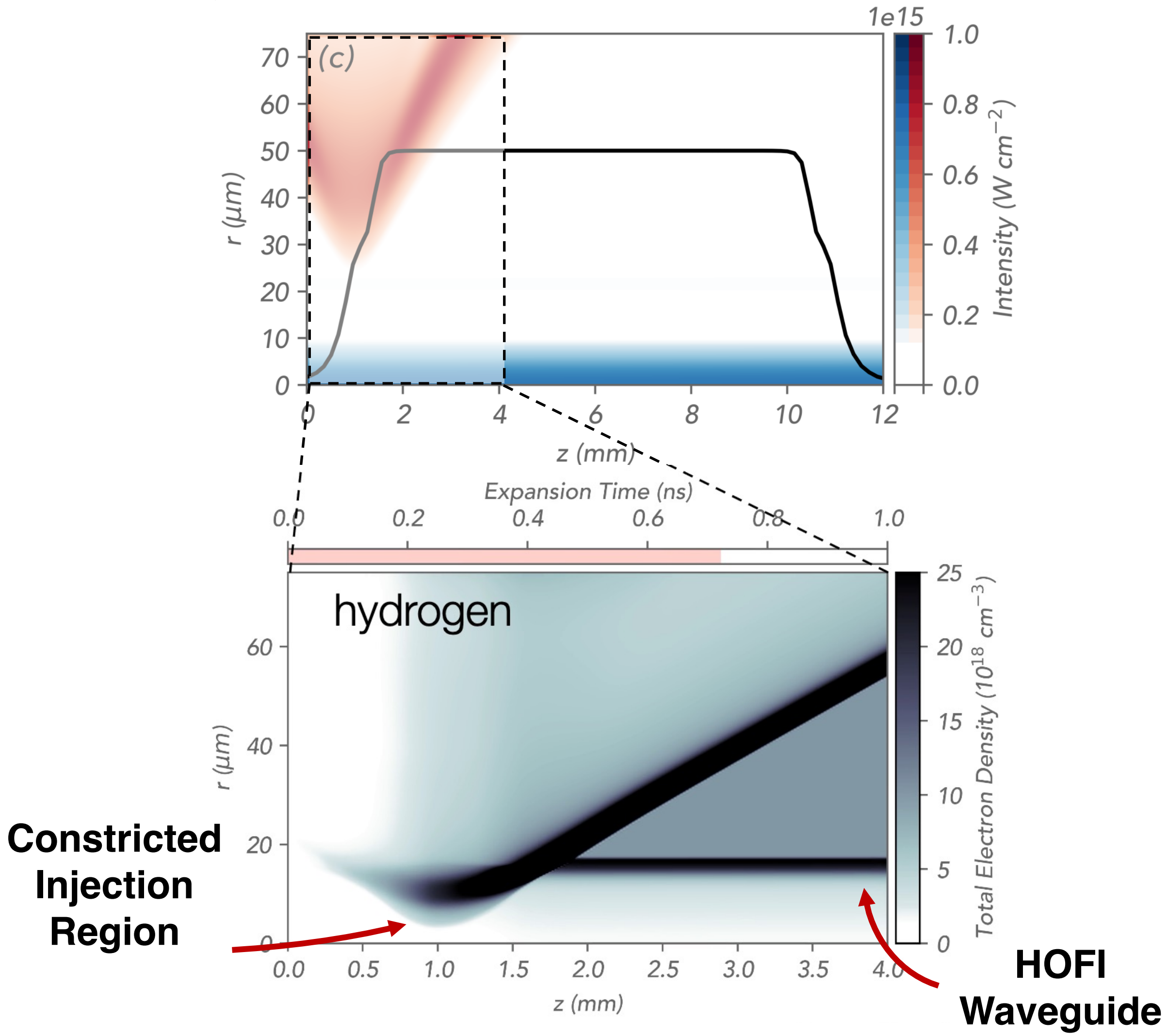



Open Source

[1] M. Mewes et al., Phys Rev Res. 5 033112 (2023)

# Creating a Constricted Waveguide

## Performed with an experimentally benchmarked hydro code [1]

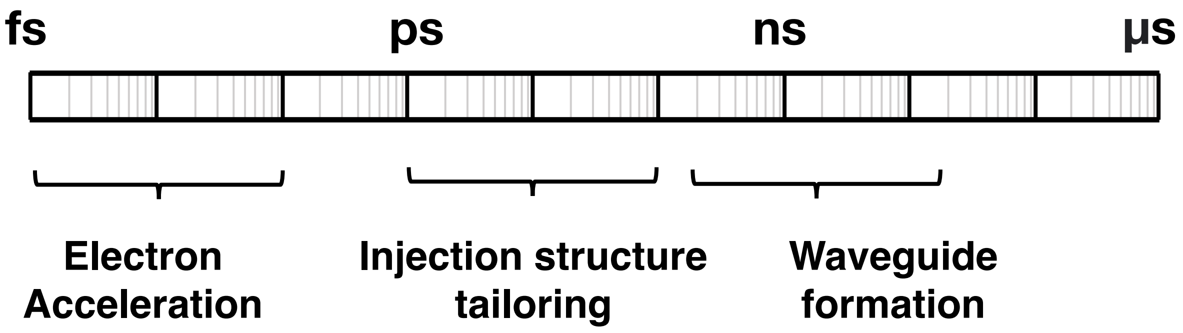



2D cylindrical geometry (r-z)

**Tunability**

High-level of process control

- Laser focusing geometry
- Laser wavelength
- Gas species
- Evolution timescales
- etc.

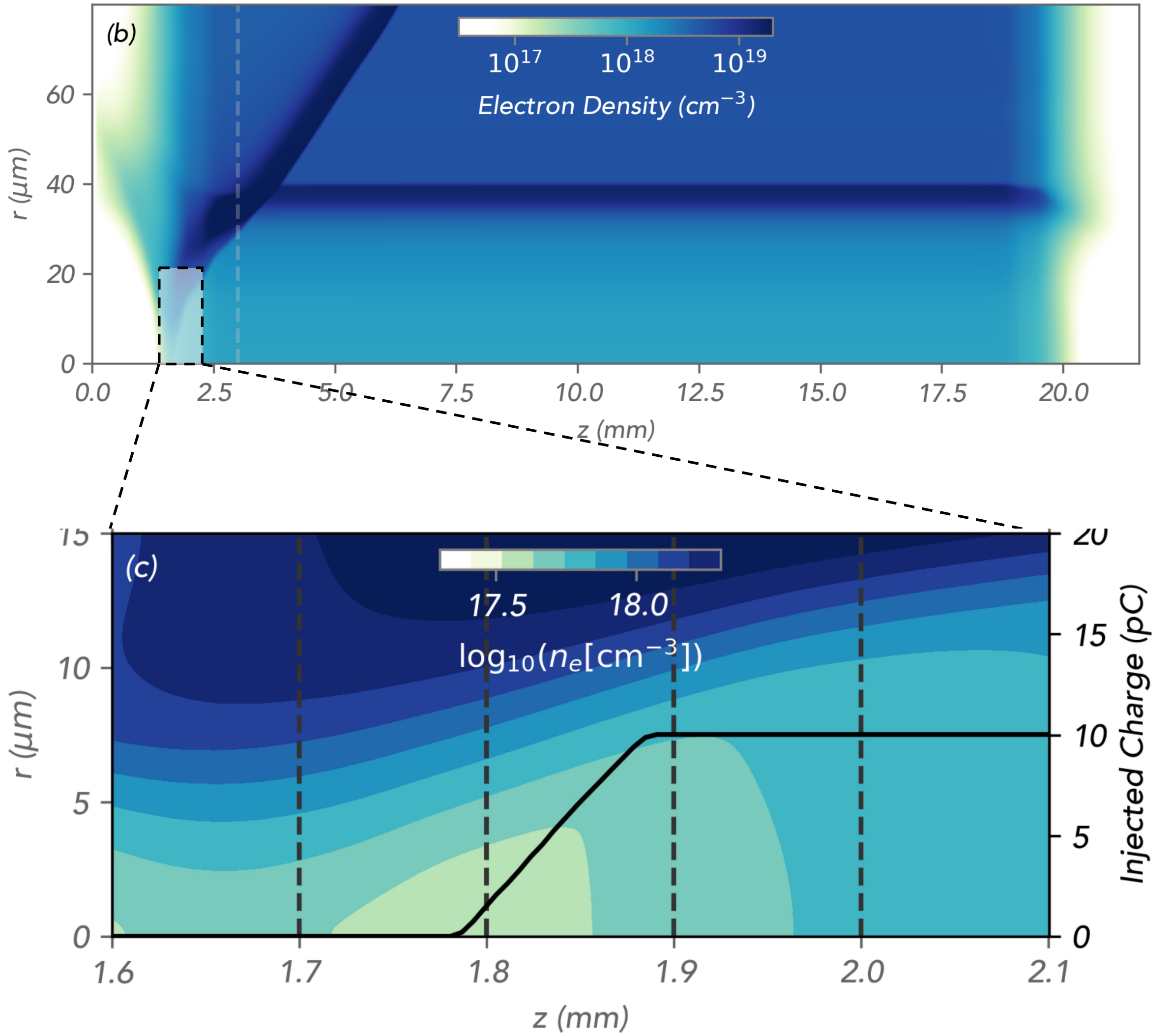




[1] M. Mewes et al., Phys Rev Res. **5** 033112 (2023)

# Injection in a Constricted Waveguide

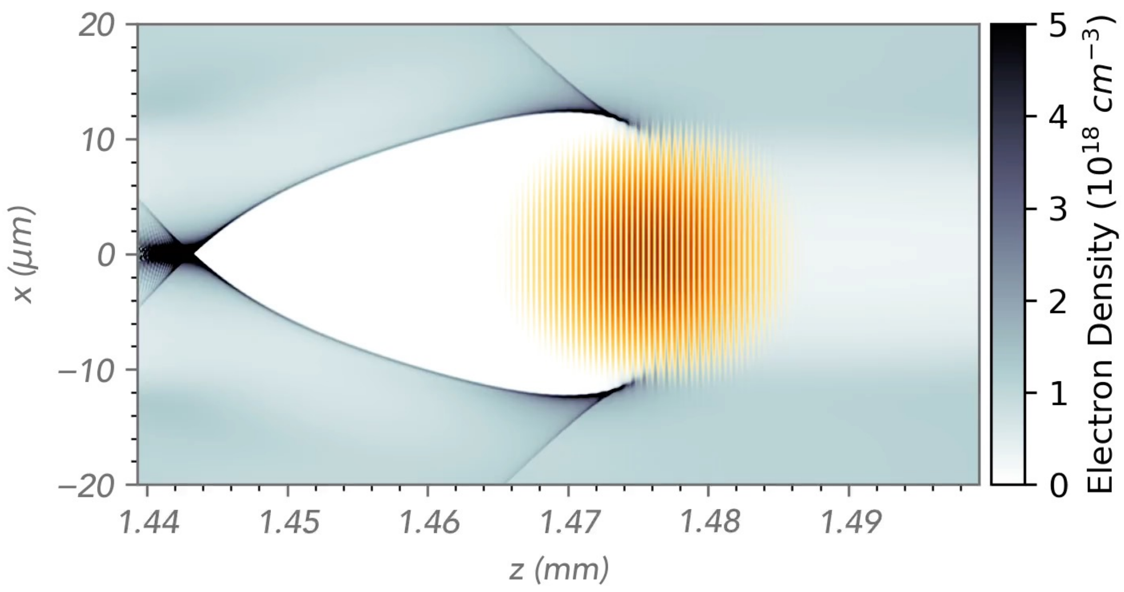
## Localized injection within the waveguide constriction




- Injection facilitated by elongation of bubble as laser leaves constricted plasma region

- Laser and plasma profile evolving during injection

- Dynamics complex and competing effects are difficult to isolate




**Distinct from pinched channel injection betatron source[1]**

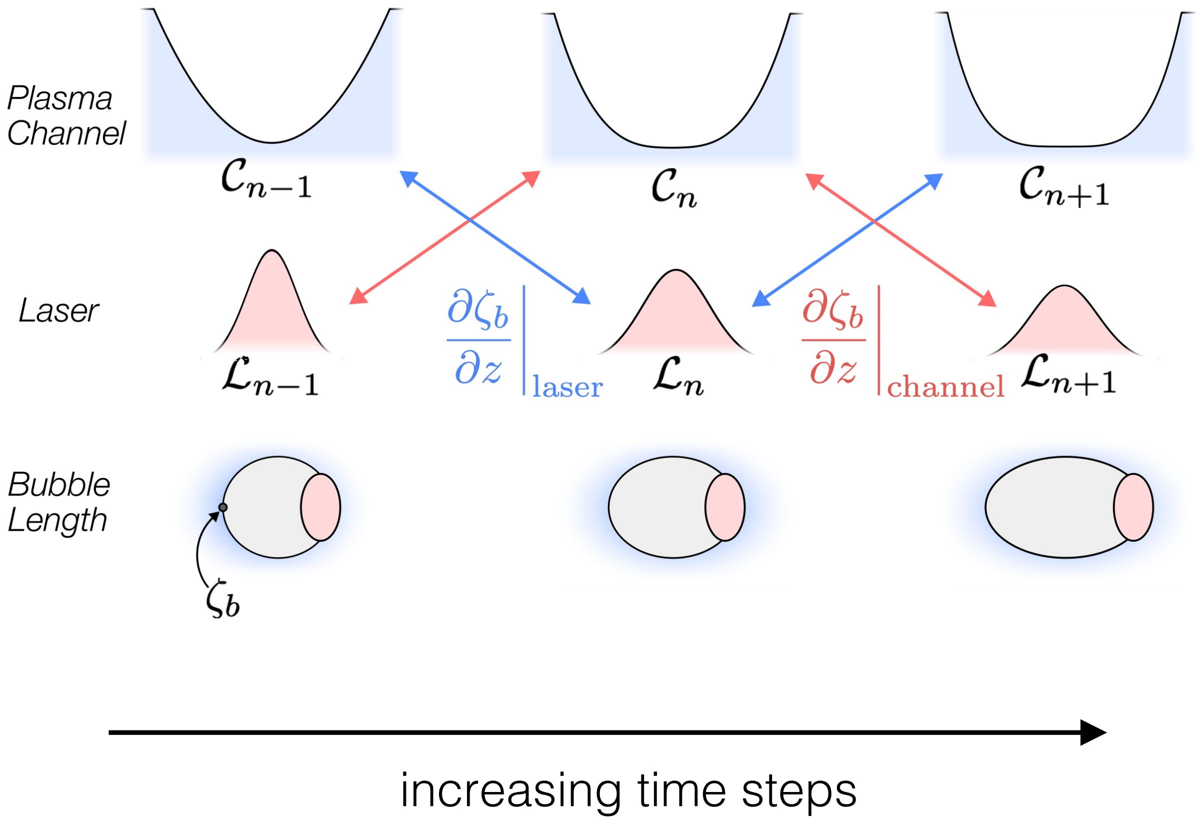
 [1] J. Liu et al., Plas. Phys. Contr. Fus.. **60** 065011 (2018) 

# Why Does the Bubble Elongate?

Isolating contributions of laser pulse and plasma profile to bubble elongation

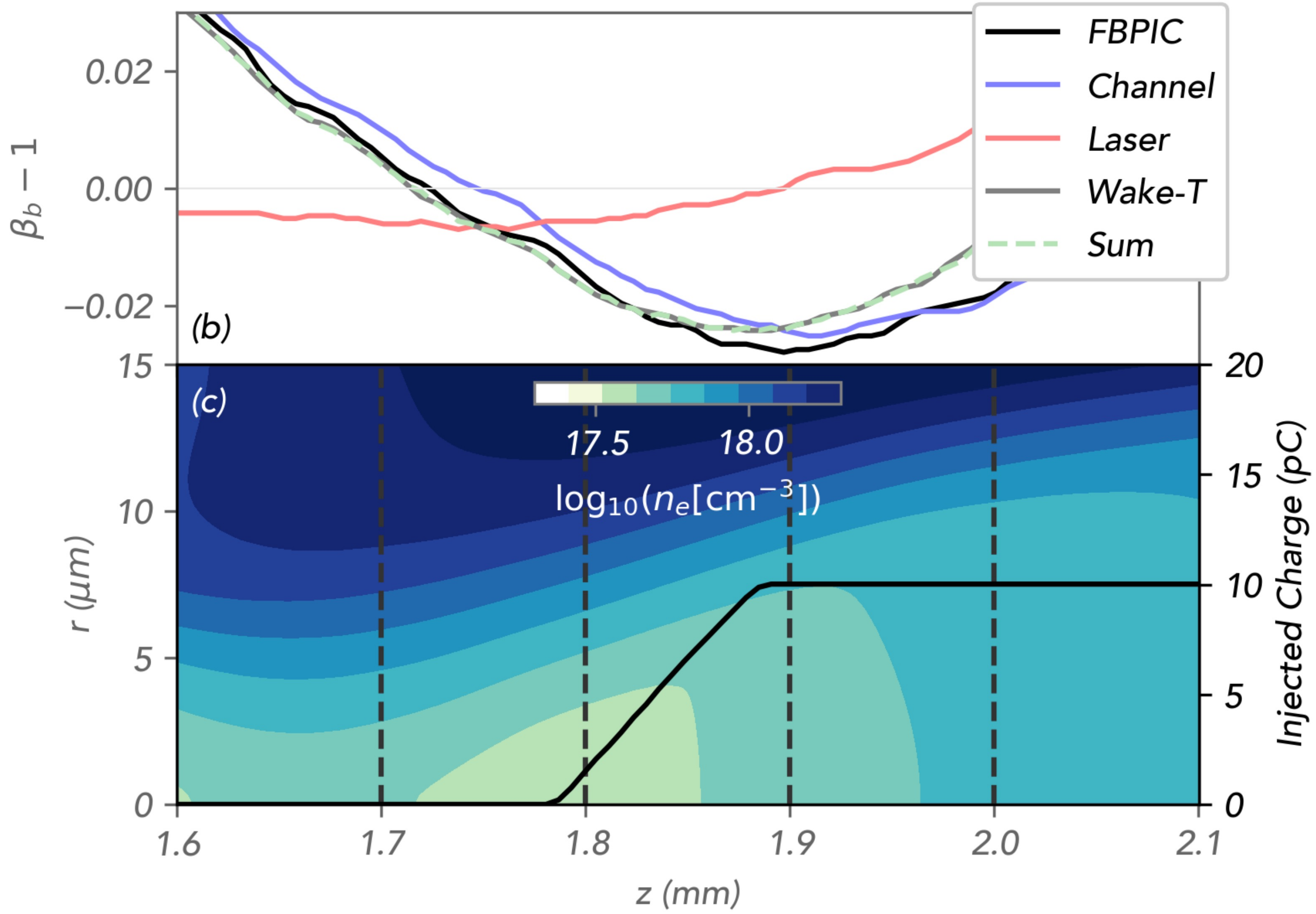
**Finite Difference Approach Based on Quasistatic PIC**

- LASY used to isolate laser pulse at each FBPIC time step
- Plasma response for consecutive plasma profiles calculated using Wake-T



# Why Does the Bubble Elongate?

## Investigating the Speed of the Back of the Plasma Bubble



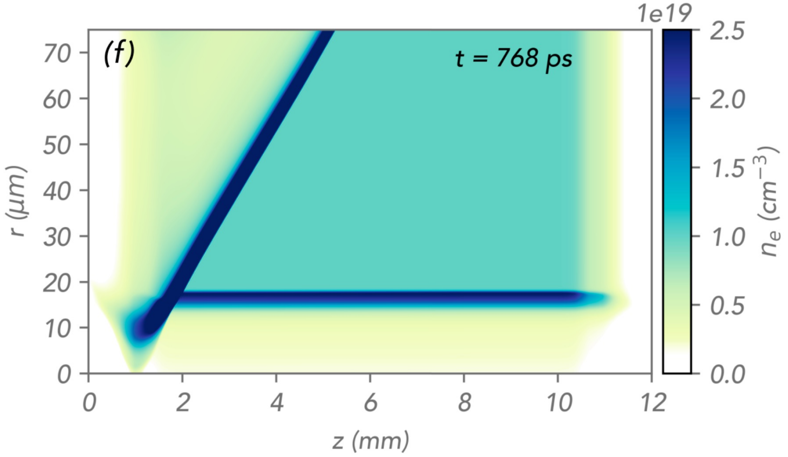

- Impact of laser and plasma evolution on bubble isolated
- Sum of changes from laser and plasma match total speed of back of bubble
- Bubble speed measured in wake-t matches FBPIC up until significant charge is injected

**Dominant contribution to bubble elongation comes from plasma structure evolution**

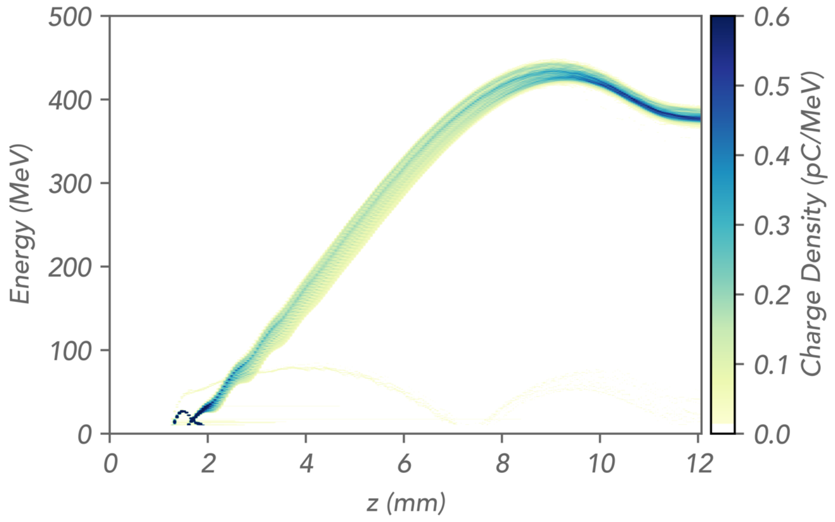
# Generation of High-Quality Electron Beams

With a ~0.4J Laser System

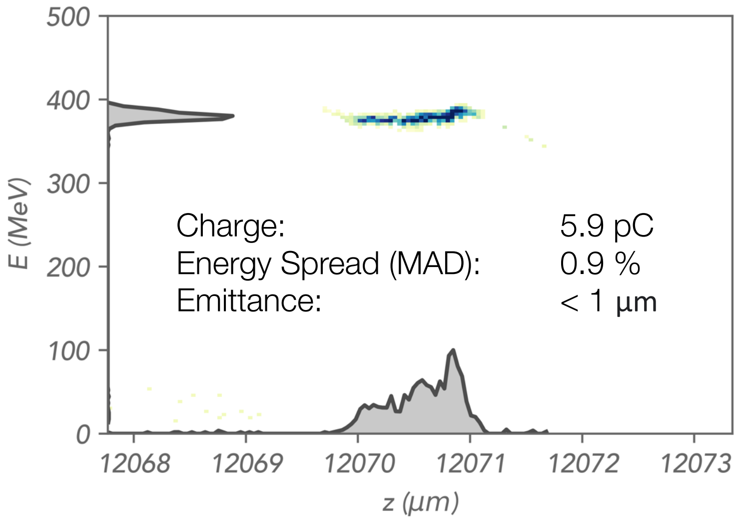
### Total Electron Density




### Electron Beam Evolution

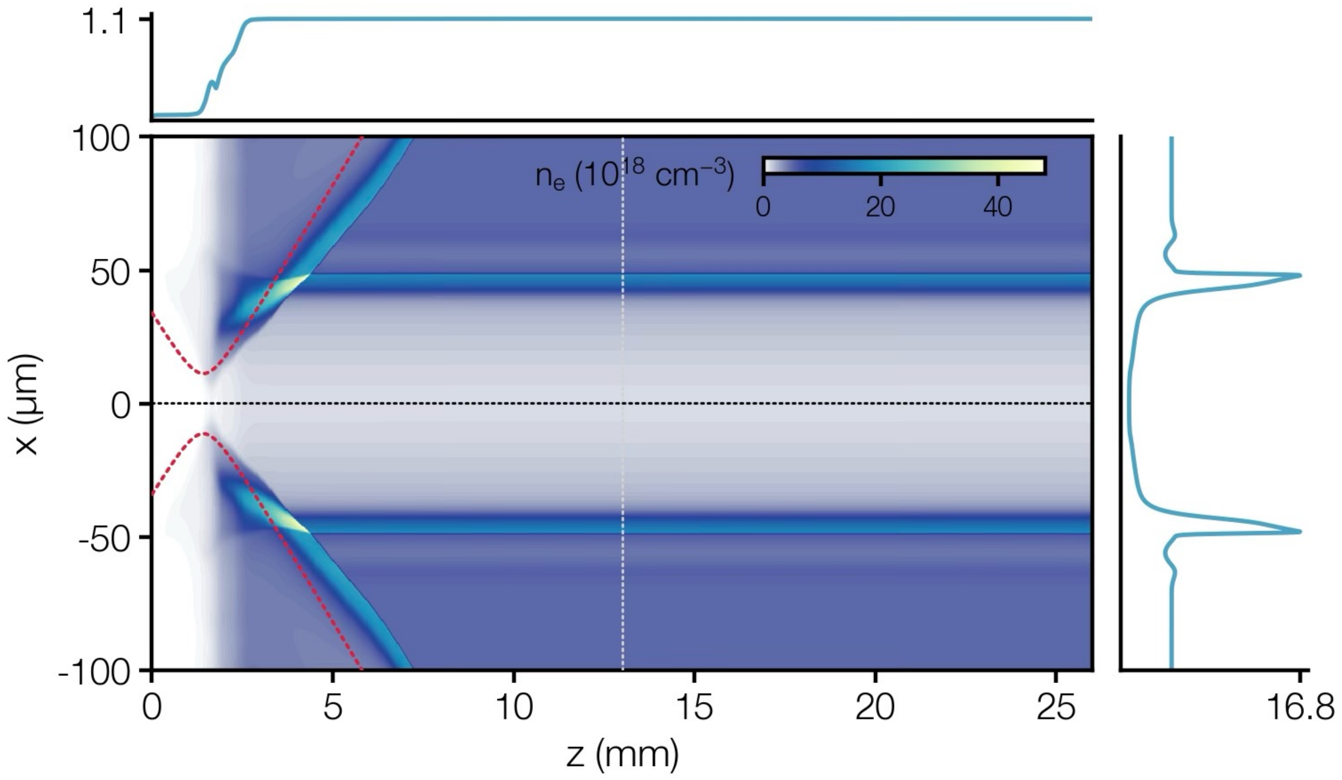


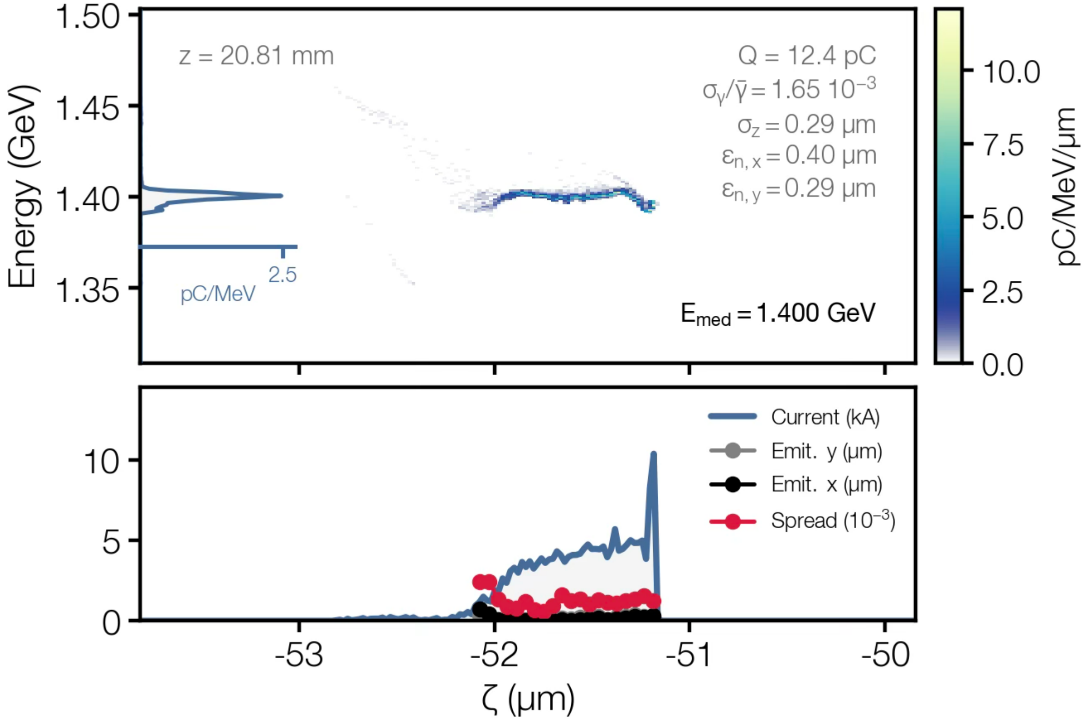

### Final Beam



# Generation of High-Quality Electron Beams

With a ~1.5J Laser System



# Summary
And Outlook

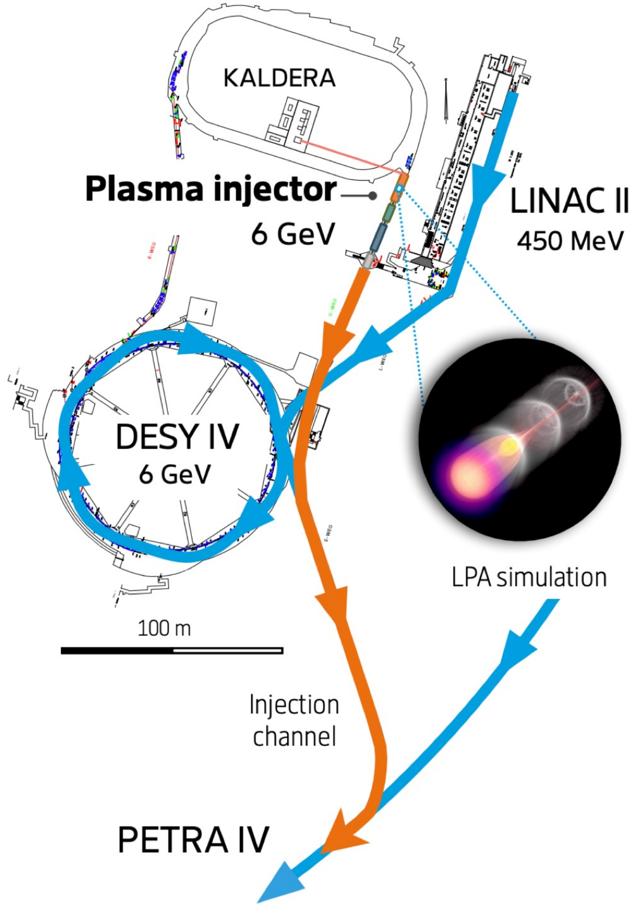
**New method of controlling injection into a plasma waveguide proposed**

- Based on waveguide constriction from colliding shocks
- Injection occurs due to rapidly evolving waveguide structure
- Tunability enabled through different timescales of key processes

**Start to End Simulations**

- Hydrodynamic structure formation
- Injection and acceleration of high-quality beams up to ~GeV level

**Check out our Paper on arXiv**
R. J. Shalloo et al., arXiv 2410.15937 (2024)




**Implications / Outlook**

- Charge is modest, but could be enhanced with addition of dopant
- Radial density profile should be considered as part of injection dynamics eg. design of future PETRA IV Plasma Injector

# Acknowledgements

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** Now at Lawrence Berkeley National Laboratory