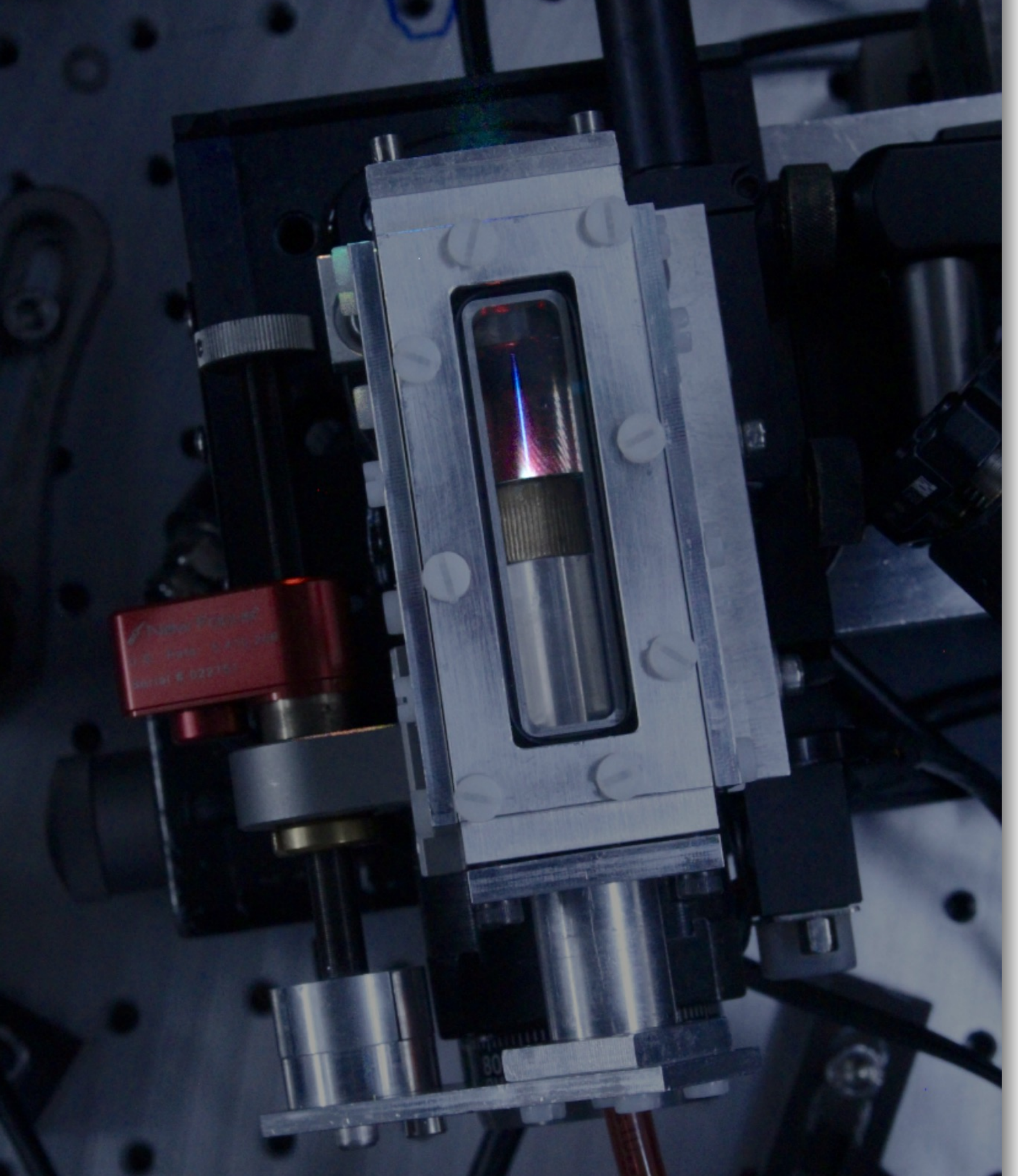

ADVANCED ACCELERATOR CONCEPTS WORKSHOP
7th November 2022, NY, USA

SIMULATIONS OF HYDRODYNAMIC OPTICAL-FIELD-IONISED PLASMA CHANNELS

TEAM

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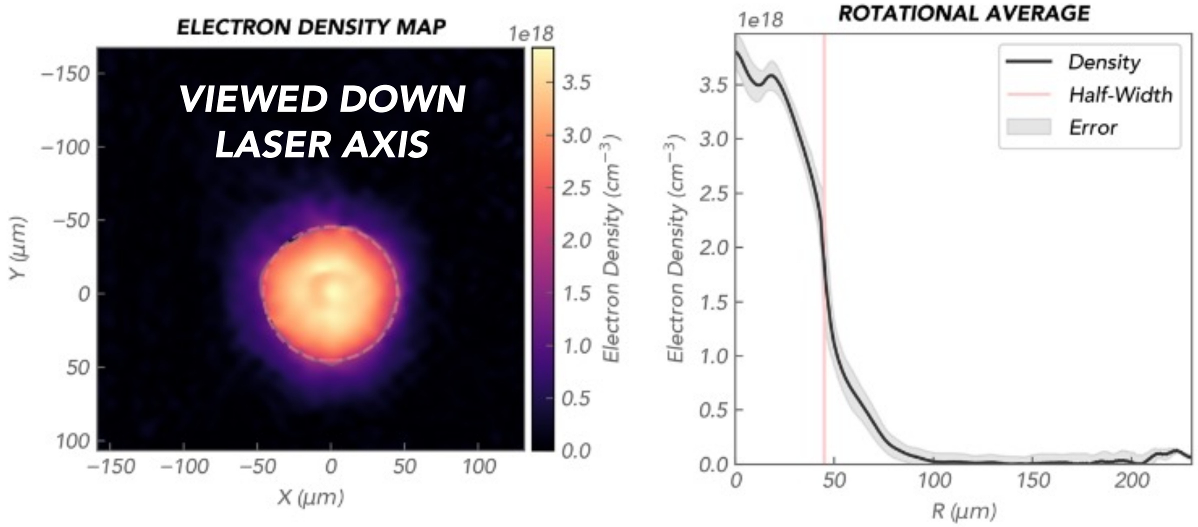
OPTICAL-FIELD-IONISATION CAN BE USED TO FORM PLASMA CHANNELS

A PROMISING PLASMA WAVEGUIDE FOR HIGH ENERGY LPAS

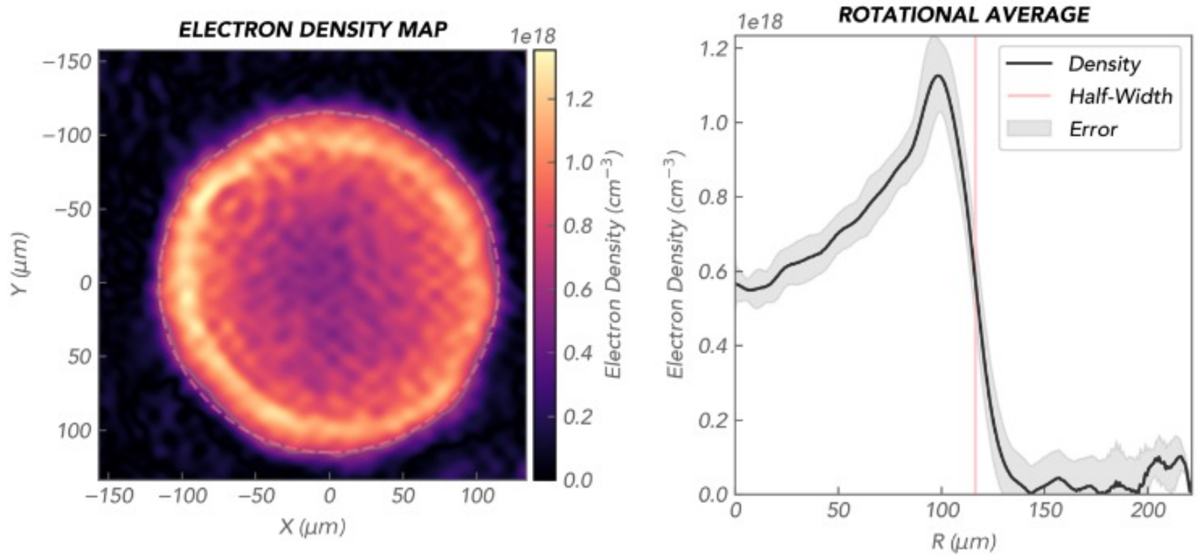
WAVEGUIDE FORMATION

1. Plamsa column ionised and heated by fs laser
2. Hot plasma expands outwards driving shockwave
3. Creates radial density profile suitable for guiding



ADVANTAGES

1. New waveguide formed on each shot
2. Heating mechanism independent of electron density
3. Waveguides formed in free space



[1] N. Lemos, Phys. Plas. **20**, 063102 (2013)
[2] R. J. Shalloo et al., Phys. Rev. E **97**, 053203 (2018)

EXPERIMENTAL PROGRESS HAS BEEN QUICK

BUT SIMULATIONS PROVE TRICKY

PHYSICAL REVIEW ACCELERATORS AND BEAMS **22,** 041302 (2019)

3414 Vol. 44, No. 14 / 15 July 2019 / *Optics Letters* **Letter**

PHYSICAL REVIEW ACCELERATORS AND BEAMS **23,** 081303 (2020)

PHYSICAL REVIEW LETTERS **125,** 074801 (2020)

PHYSICAL REVIEW E **102**, 053201 (2020)

PHYSICAL REVIEW RESEARCH **2**, 043173 (2020)

PHYSICAL REVIEW ACCELERATORS AND BEAMS **25,** 011301 (2022)

PHYSICAL REVIEW X **12,** 031038 (2022)

Oubrerie et al. *Light: Science & Applications* (2022)11:180
https://doi.org/10.1038/s41377-022-00862-0

Official journal of the CIOMP 2047-7538
www.nature.com/lsa

ARTICLE **Open Access**

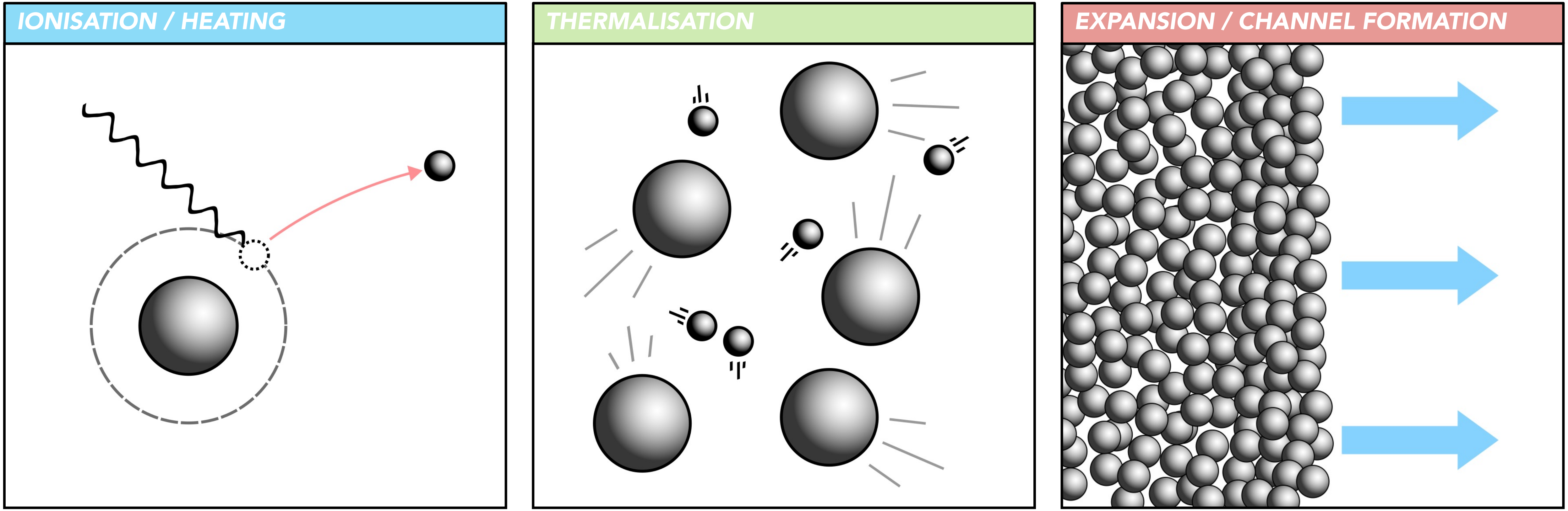
Controlled acceleration of GeV electron beams in an all-optical plasma waveguide

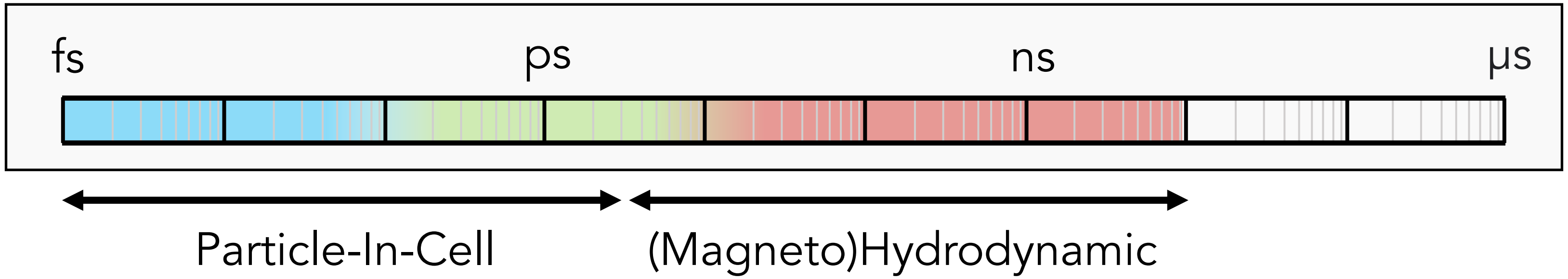
Kosta Oubrerie[1], Adrien Leblanc[1], Olena Kononenko[1], Ronan Lahaye[1], Igor A. Andriyash[1], Julien Gautier[1], Jean-Philippe Goddet[1], Lorenzo Martelli[1], Amar Tafzi[1], Kim Ta Phuoc[1], Slava Smartsev[1,2] and Cédric Thaury[1]✉

- ✓ High-intensity guiding
- ✓ New plasma channel optics
- ✓ Meter-scale plasma channels
- ✓ Improved guiding confinement
- ✓ kHz Formation of plasma waveguides
- ✓ >GeV electron acceleration

MECHANICS OF PLASMA CHANNEL FORMATION

IMPORTANT PHYSICAL PROCESSES SPAN SMALL TO LARGE TIMESCALES





THE HYDRODYNAMIC PLASMA MODEL

AN OVERVIEW OF KEY PHYSICS

- Single, quasi-neutral fluid
- Two temperatures (2T), separate for electrons from heavy particles (ions, atoms, molecules)
- Ionization state tracked via collisional reaction rates and diffusion
- No explicit EM fields required

Flow

$$\frac{\partial \rho}{\partial t} + \vec{\nabla}\cdot(\rho\vec{v}) = 0$$

$$\frac{\partial \rho\vec{v}}{\partial t} + \vec{\nabla}\cdot(\rho\vec{v}\vec{v}) = -\vec{\nabla}p - \vec{\nabla}\cdot(\eta\vec{\nabla}\vec{v})$$

Electron energy

$$\frac{\partial C_e T_e}{\partial t} + \vec{\nabla}\cdot[(C_e T_e + p_e)\vec{v}] - \vec{v}\cdot\vec{\nabla}p_e - \vec{\nabla}\cdot(\lambda_e\vec{\nabla}T_e)$$
$$= -k_{e-h}(T_e - T_a) - \sum_{j,\alpha}\Delta E_j r_j$$

Similar for Atoms

Species α

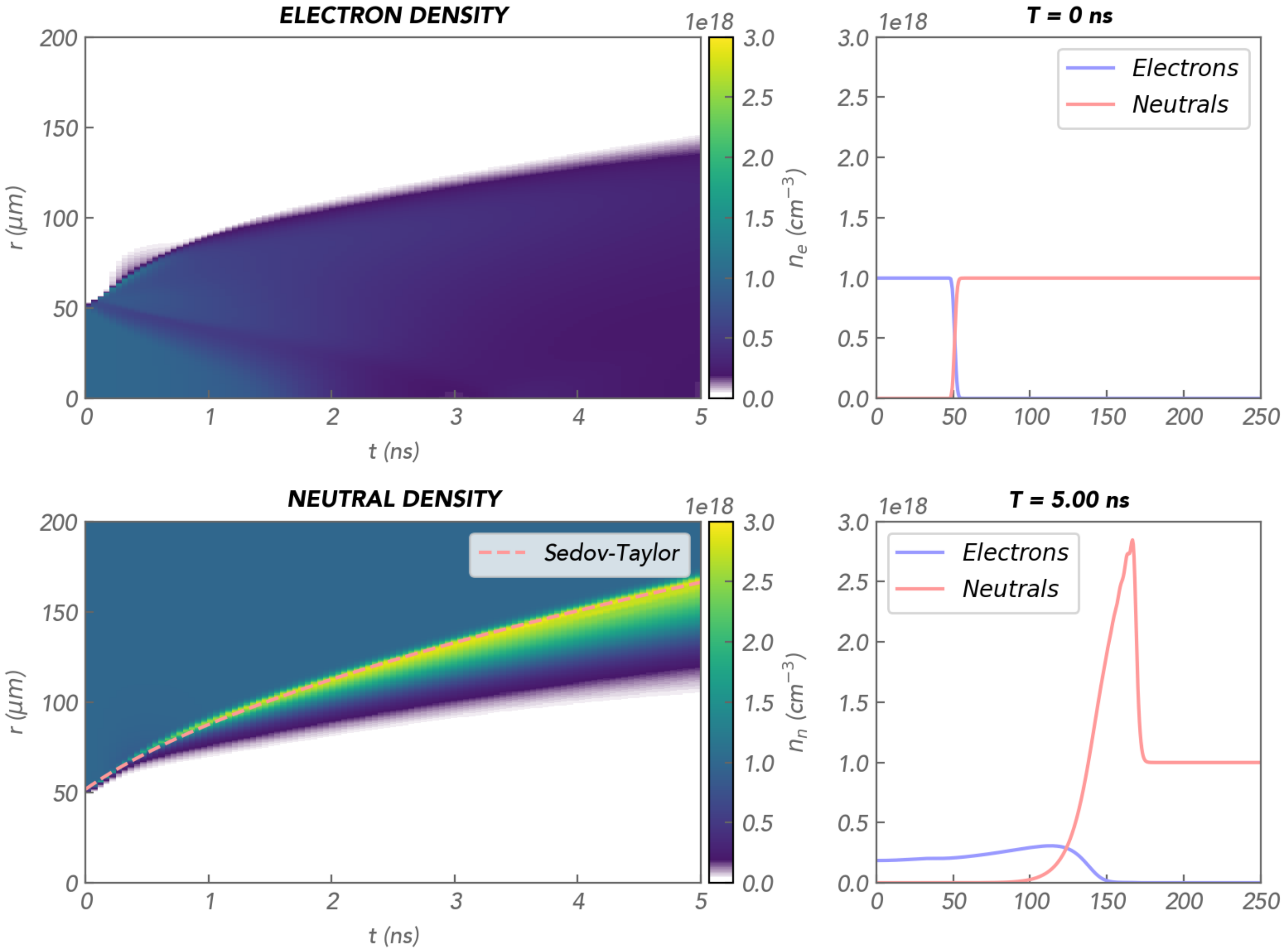
$$\frac{\partial n_\alpha}{\partial t} + \vec{\nabla}\cdot(n_\alpha\vec{v}) + \vec{\nabla}\cdot\vec{d}_\alpha = \sum_j c_{j\alpha} r_j$$

Key

ρ: mass density
v: flow velocity
p: pressure
B: magnetic field
τ: viscous stress tensor
n: number density
c: stoichiometric const.
r: reaction rate
C: heat capacity
T: temperature
λ: thermal conductivity
k_{e-h}: collisional energy transfer
ΔE: reaction energy
d: diffusion flow
Transport Coefficients

COMSOL MULTIPHYSICS®

SIMULATING HOFI PLASMA CHANNEL EXPANSION



SIMULATION PARAMETERS

Dimension: 1D Radial

Species: atomic hydrogen

Run Time: ~10 mins on PC
~500 grid points
~100 timesteps

RESULTS

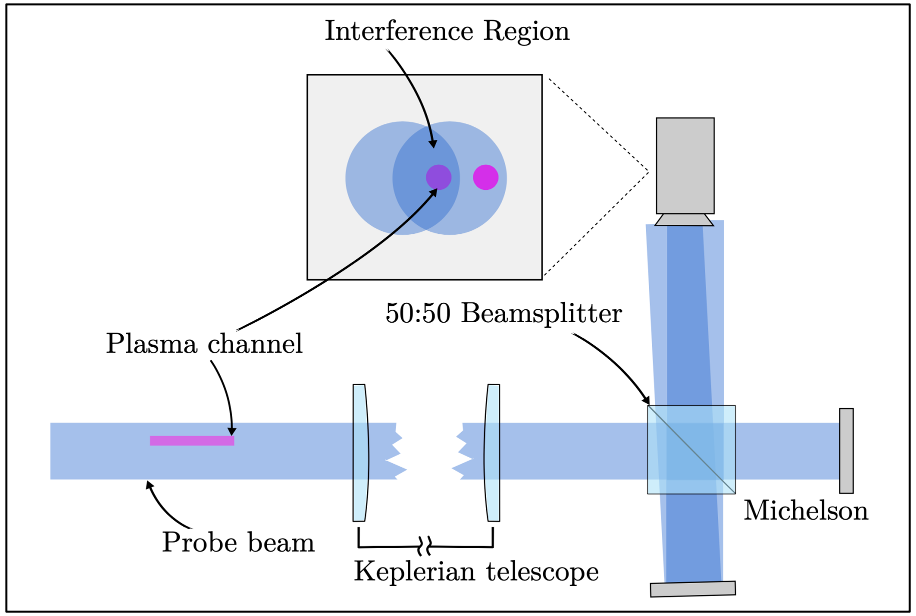
Channel formation on ns timescales

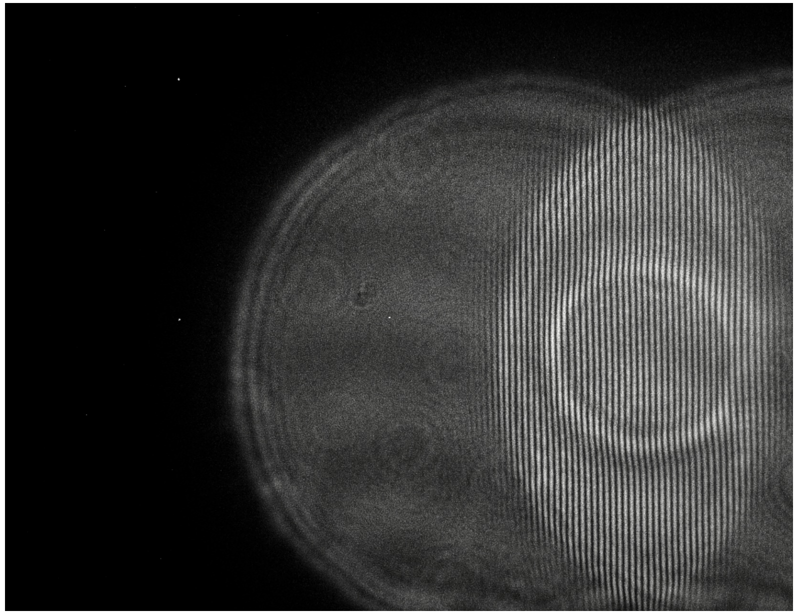
Good agreement with Sedov-Taylor

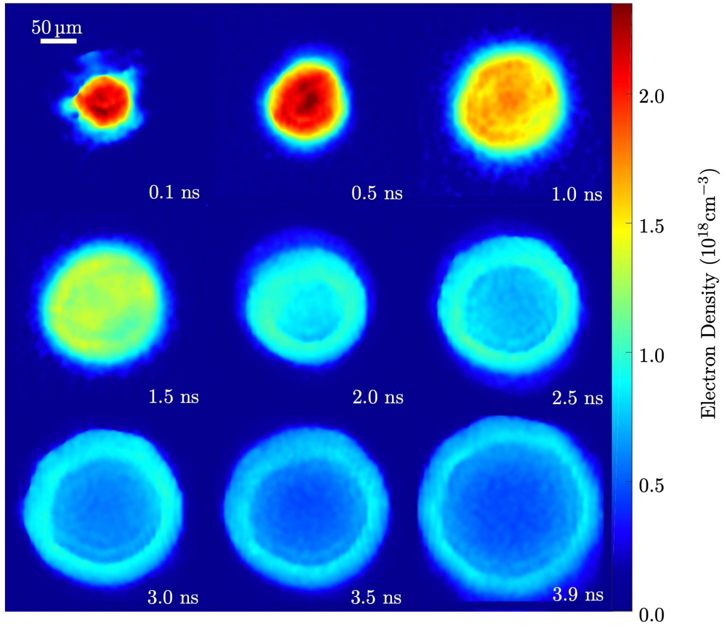
Neutrals play a key role in expansion

BENCHMARKING AGAINST EXPERIMENTAL DATA

2017 OXFORD EXPERIMENT







HOFI plasma channels generated in hydrogen gas cell using a spherical lens

Longitudinal interferometry used to measure electron density

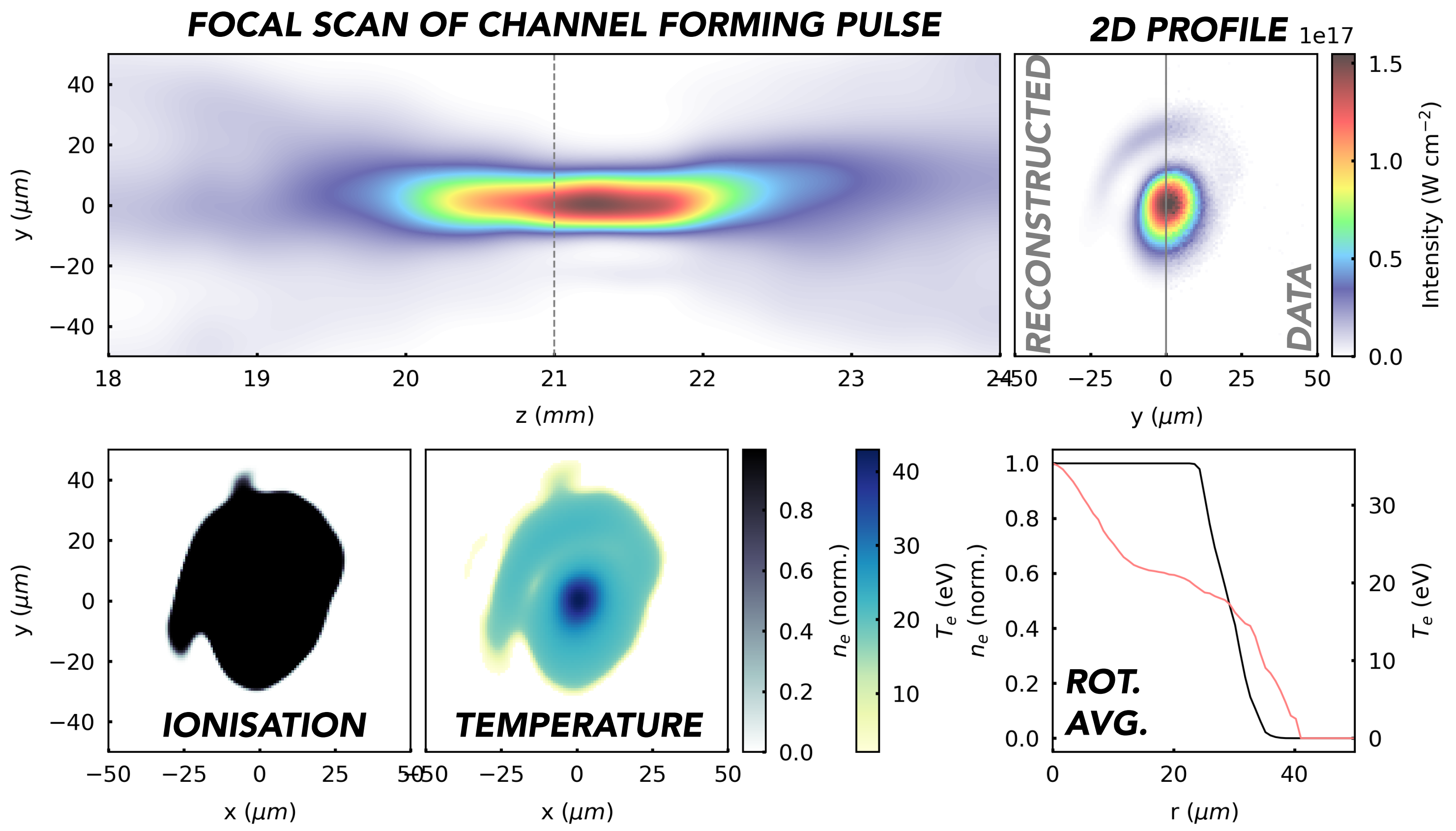
On-axis densities: $1.5 \times 10^{17}\ \mathrm{cm}^{-3} < n_e(0) < 1.0 \times 10^{18}\ \mathrm{cm}^{-3}$

Matched spot sizes: $61\ \mu\mathrm{m} < w_m < 33\ \mu\mathrm{m}$

[1] R. J. Shalloo et al., Phys. Rev. E **97**, 053203 (2018)

SIMULATION PROCESS

SIMULATING PLASMA EXPANSION FROM EXPERIMENTAL INITIAL CONDITIONS

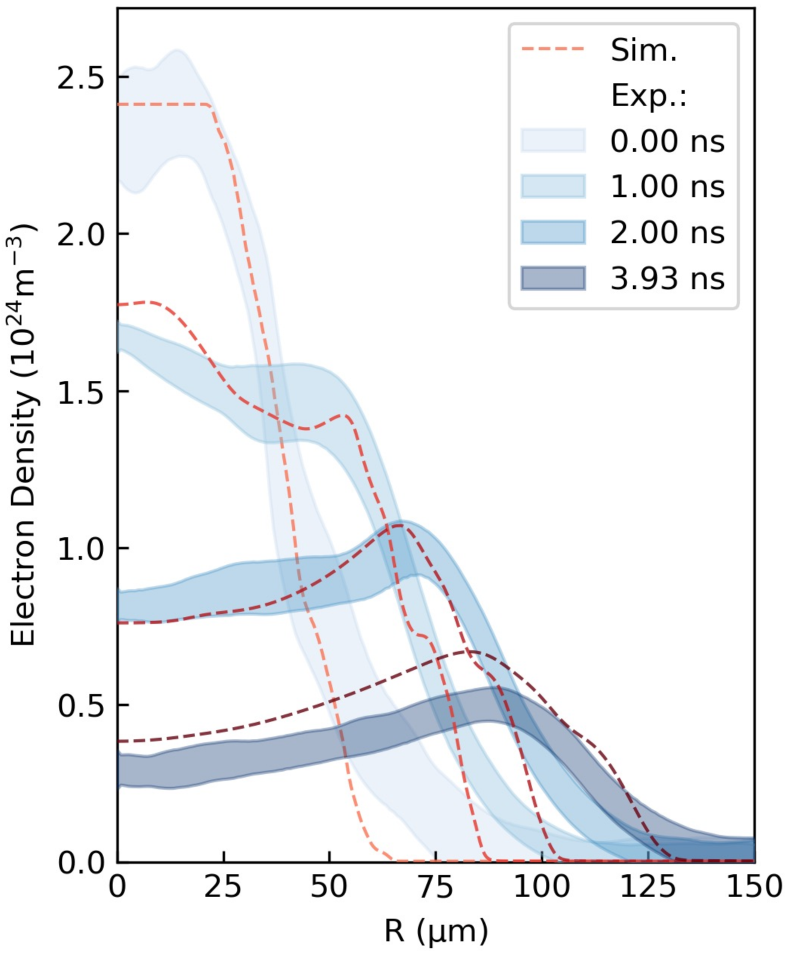


SIMULATION RECIPE

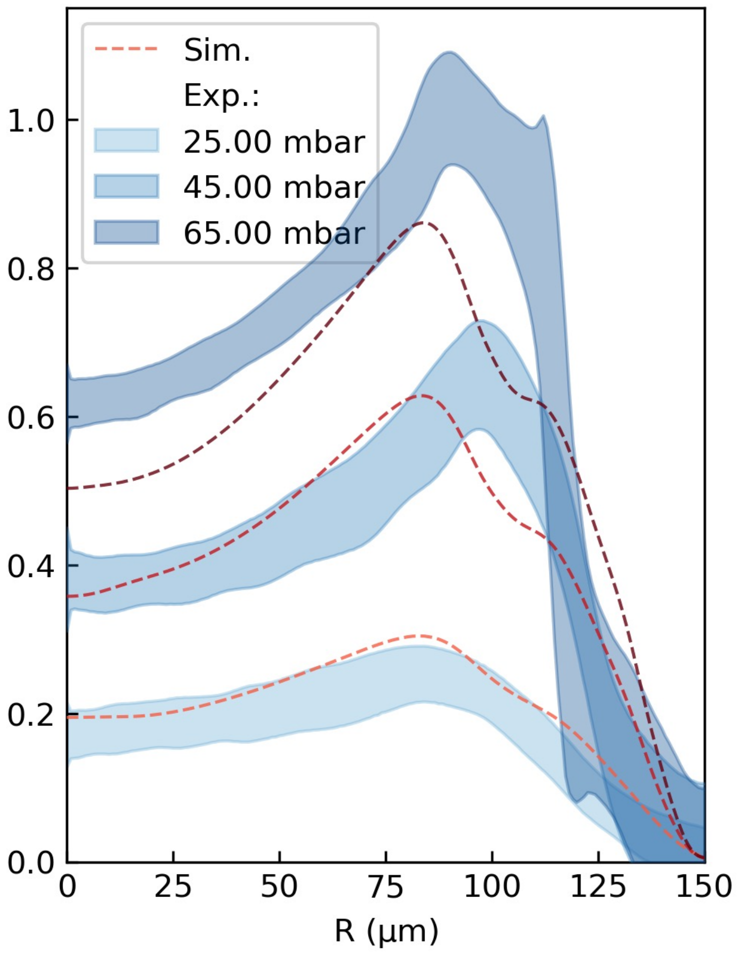
1. Simulate expansion of each transverse slice
   1. Hermite-Gauss Reconstruction of measured laser intensity profile
   2. Calculation of electron density and temperature
   3. Rotationally average
   4. Simulate hydrodynamic expansion
2. Longitudinally average plasma profiles at each timestep to mimic probe beam

BENCHMARK RESULTS
GOOD AGREEMENT BETWEEN SIMULATION AND EXPERIMENT

TIMING SCAN
Buffer pressure: 50 mbar



PRESSURE SCAN
Time: 3.93 ns

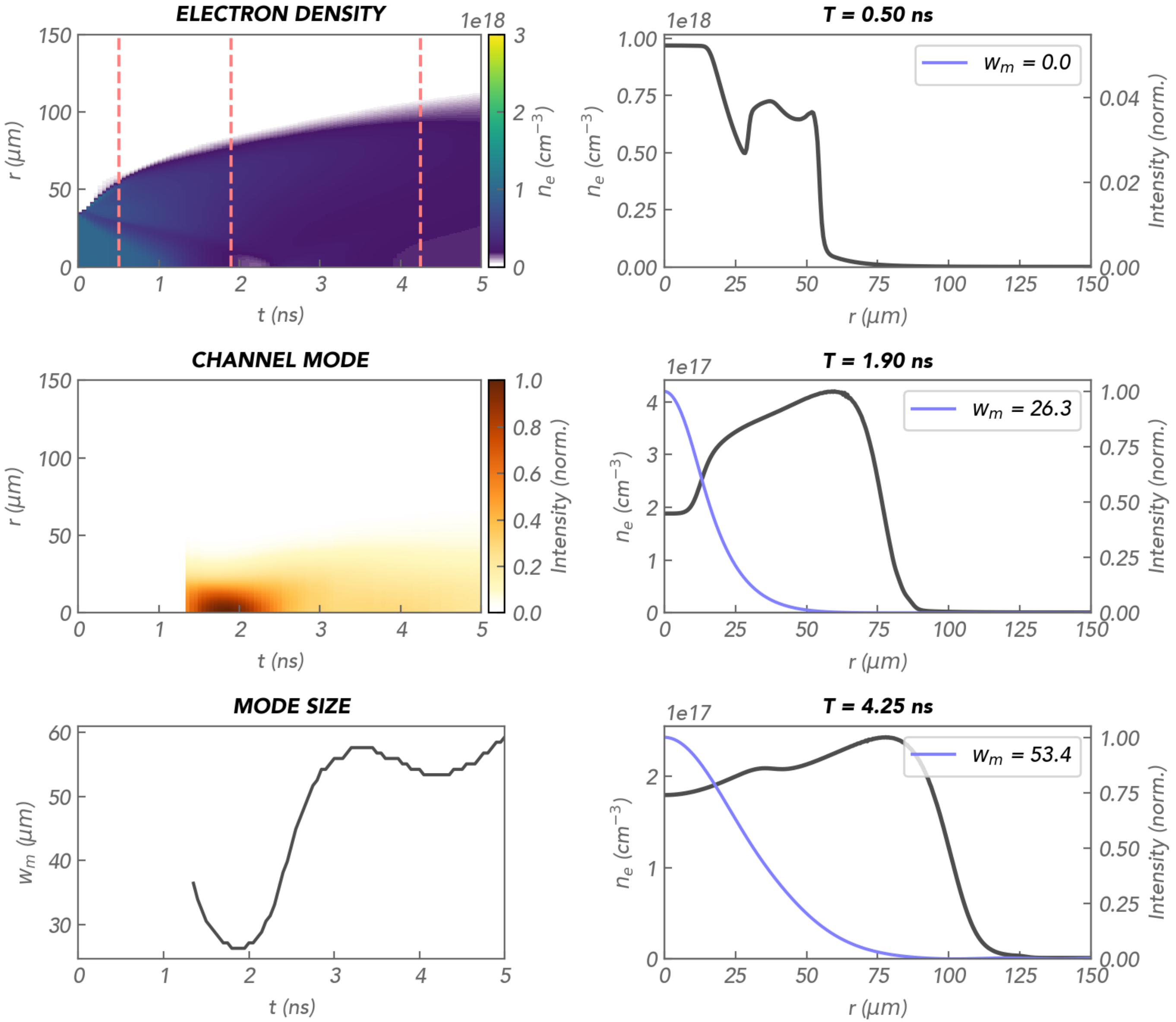


Some structures may be obscured by reduction to 1D

Good agreement at low initial pressures – ionization induced refraction expected to be problematic at higher pressures

INVESTIGATING MODAL STRUCTURE

LOW-INTENSITY LIMIT



MODAL SOLVER

Electric Field

Vacuum Wavevector

$$\nabla^2 E(r) + k_0^2 \eta^2(r) E(r) = 0$$

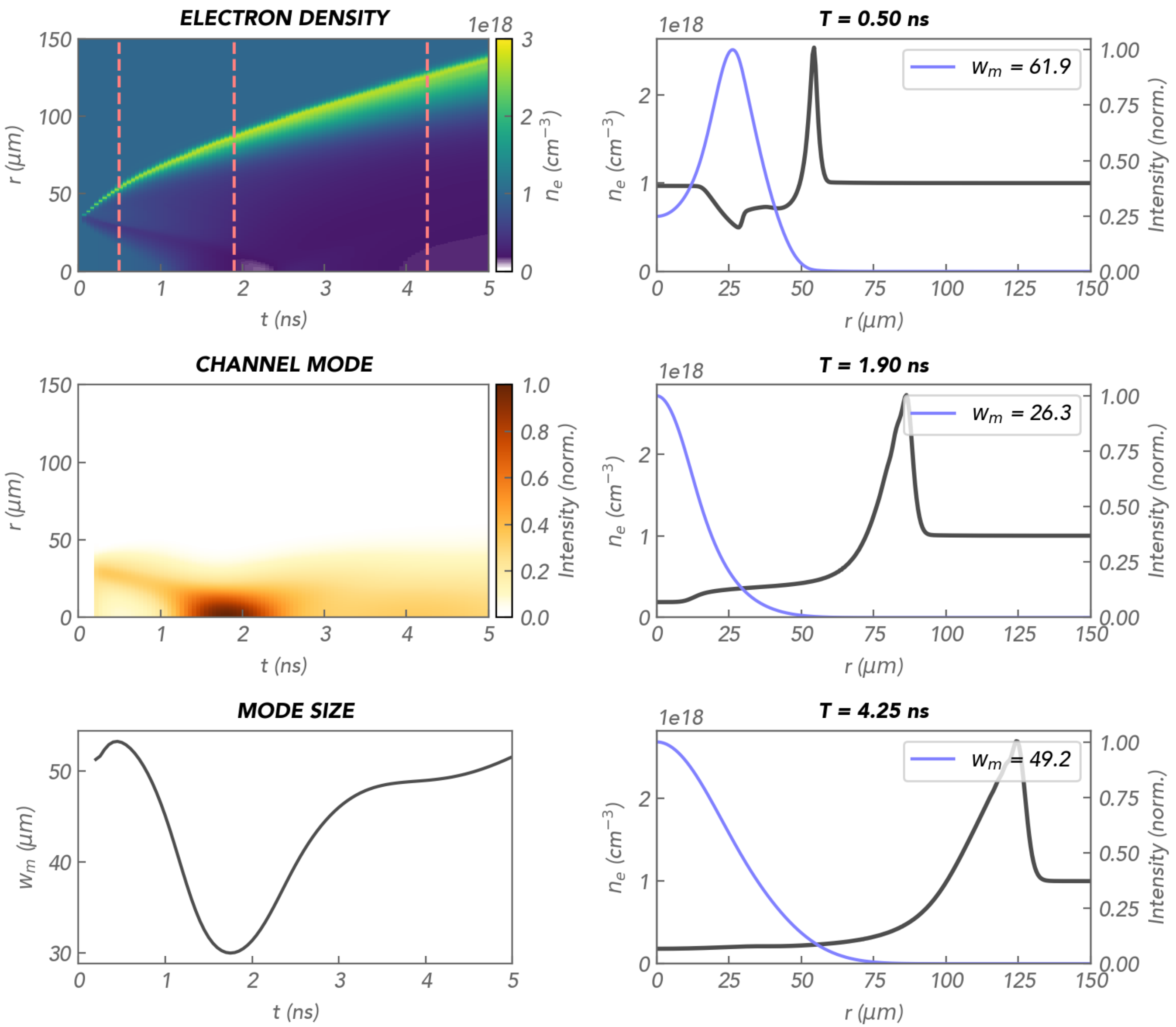
Radius

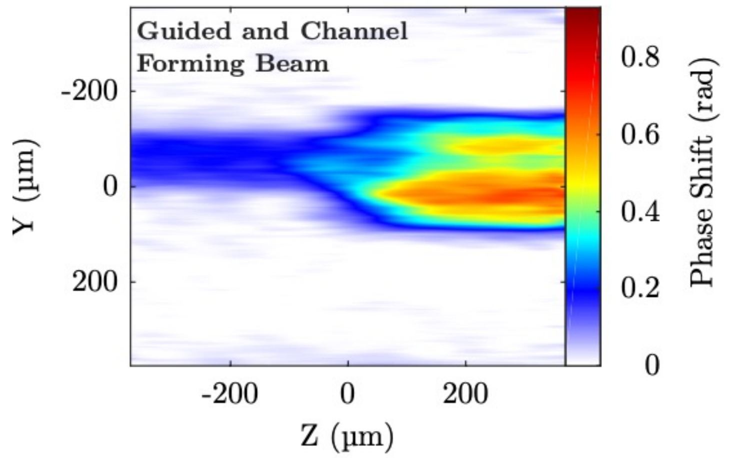
Plasma Refractive Index

- Refractive Index calculated from density
- Recast as eigenvalue problem
- Solve for modal structure

INVESTIGATING MODAL STRUCTURE

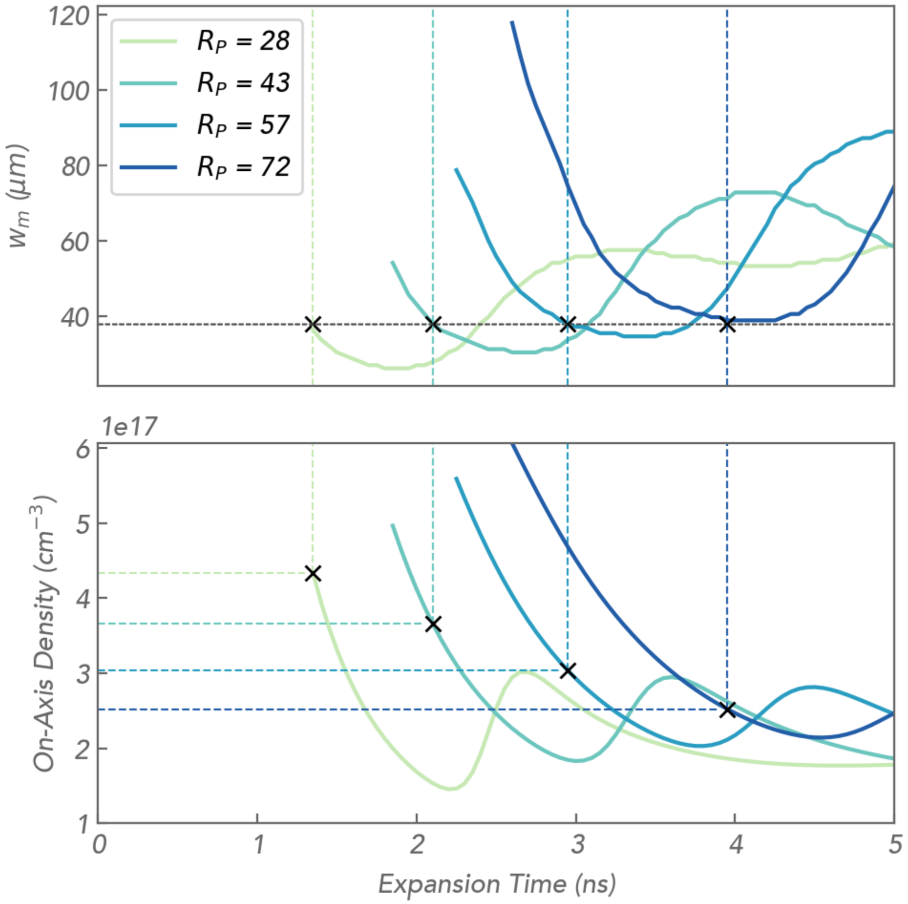
HIGH-INTENSITY LIMIT

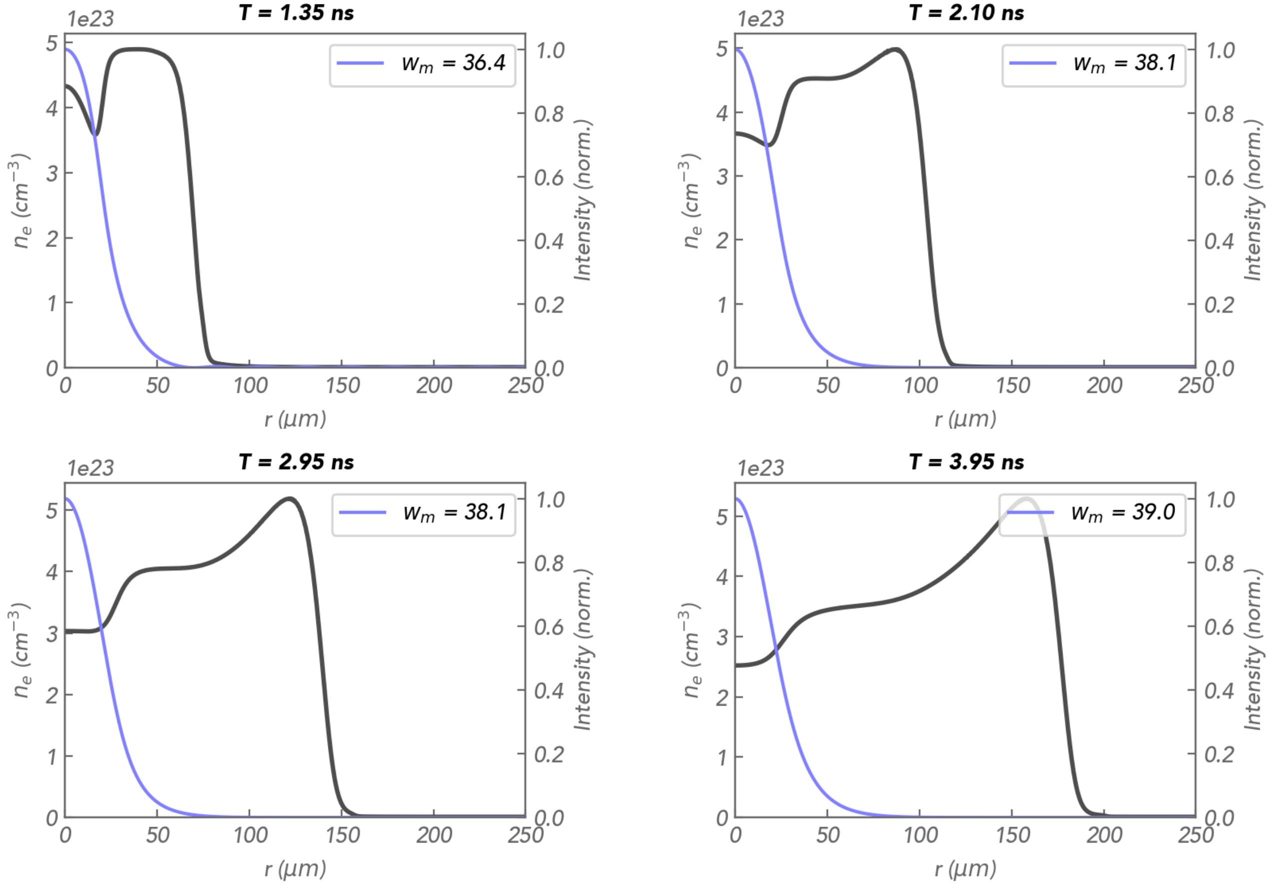




[1] A. Picksley et al., Phys. Rev. E **102**, 053201 (2020)
[2] R. J. Shalloo, PhD Thesis, University of Oxford (2018)

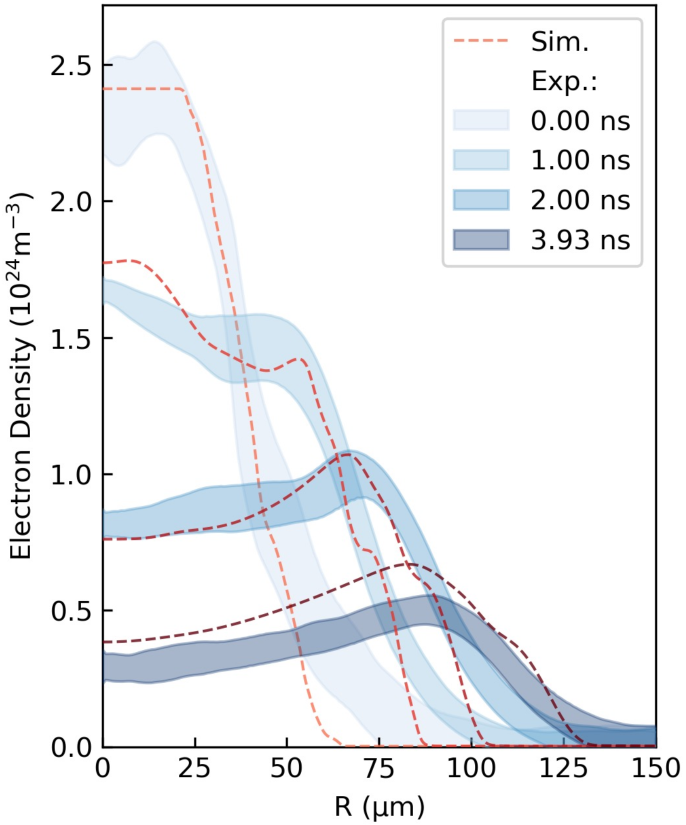
TOWARDS EXPERIMENTAL DESIGN
EXPLORING HOFI TUNABILITY

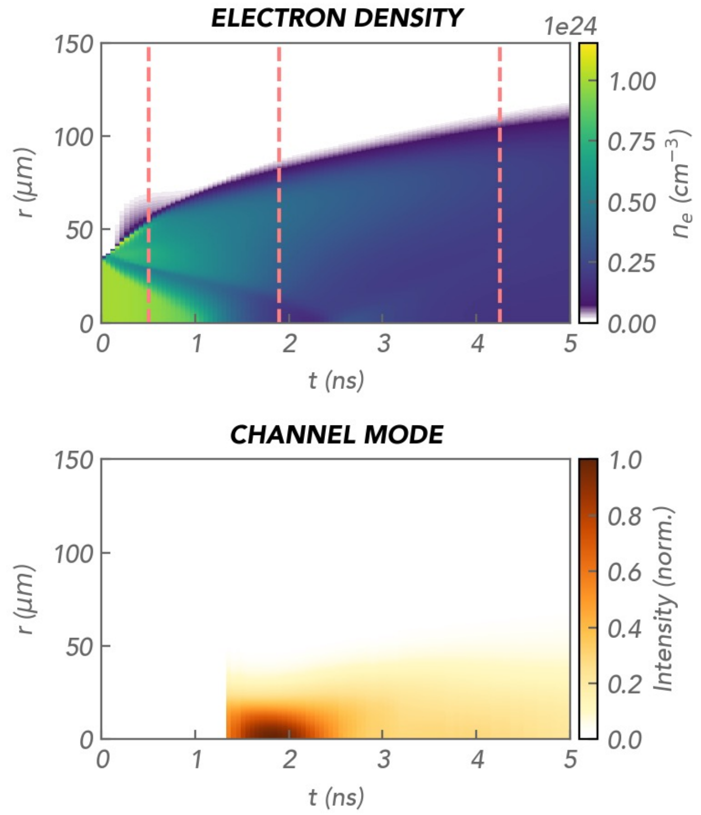




CONCLUSIONS

- Method for accurate HOFI simulations
- Verified with experimental benchmark
- Exploration of tuneability of plasma channels





NEXT STEPS

- Paper in preparation
- Further investigation of modal properties: loss, coupling
- Further model development (3D, other species etc.)

THANK YOU

OPEN FOR DISCUSSION & QUESTIONS