Radiation supported plasma waves in non-equilibrium laser discharges

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Outline

Background and Motivation
- Background and Problem Definition
- Motivation and Objective

Physical Model
- Hydrodynamic Equations
- Radiation
- Numerical Method

Results
- Laser-Plasma Interaction
- Post-Discharge Evolution

Conclusion and Future Work

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Introduction

- First **Ruby Laser** built in 1960:
  - focused beam caused air breakdown
  - since then experiments to determine
    - breakdown mechanism
    - influence of λ, r_f, τ, p_b, power density

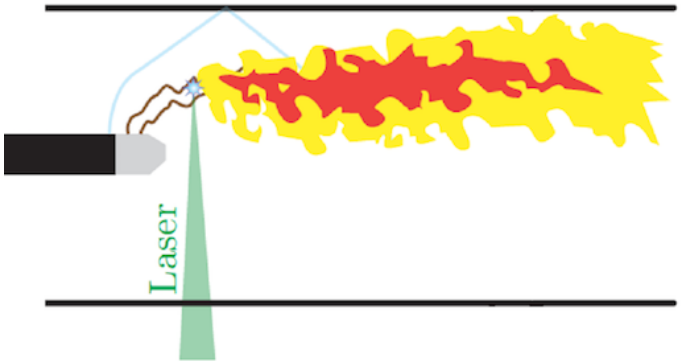


Figure: LIB ignition in XPACC scramjet

- **Laser Induced Breakdown (LIB)** is critical to modern technology:
  - **Plasma Assisted Ignition** for:
    - improving ignition reliability
    - enhancing flame stabilization
  - **Flow Control** for:
    - drag reduction
    - shock control

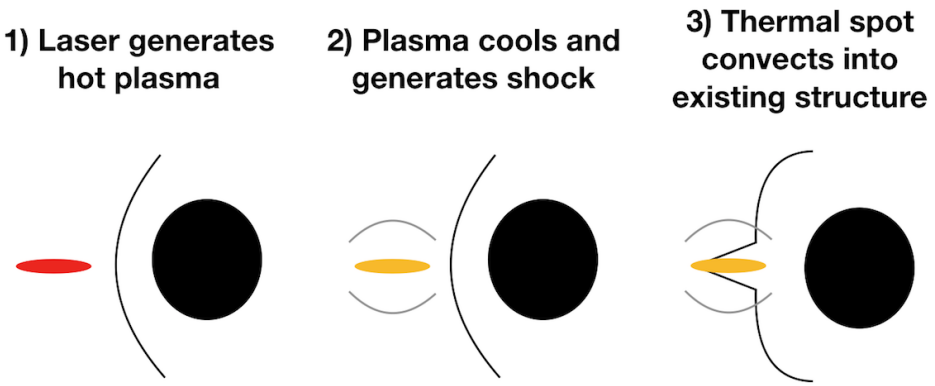
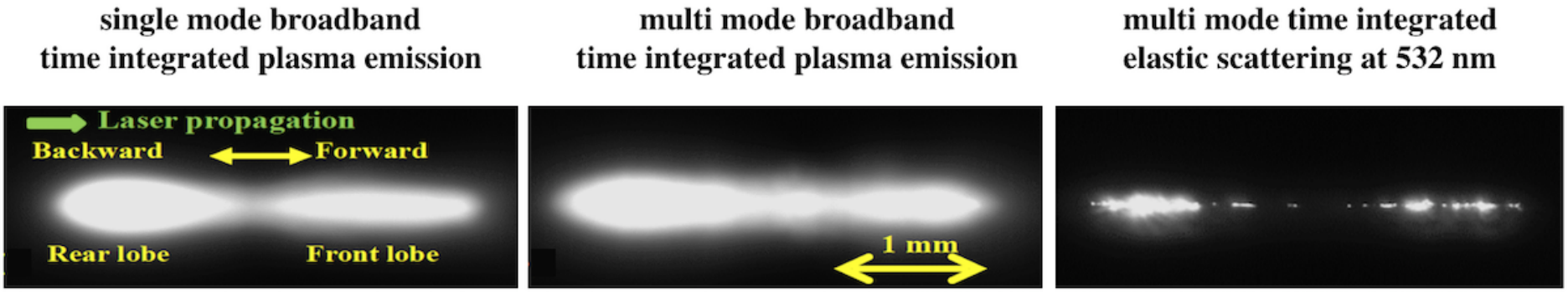


Figure: Laser generated drag reduction

Introduction: Motivation

- Onset and dynamics of **Plasma Kernels** is not very well understood
- Dynamics of **Rear** and **Front** lobes is not very well understood



Nishihara et al., "Influence of mode-beating pulse on laser-induced plasma", (J.Phys.D)

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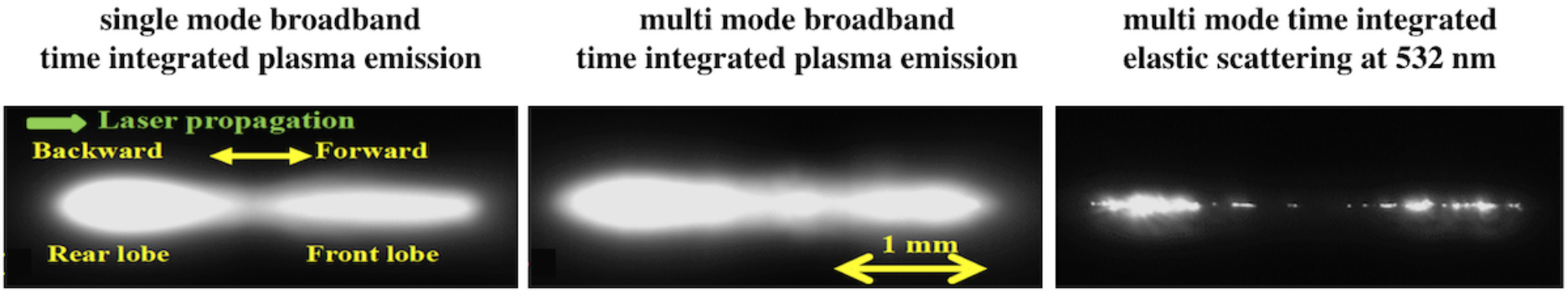

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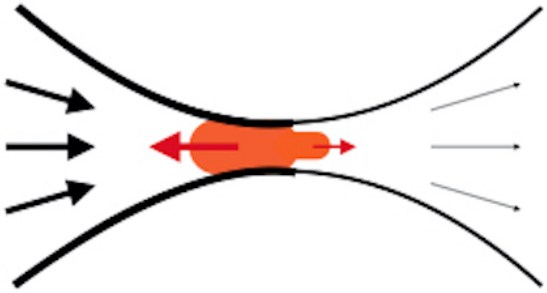
- Breakdown Wave Theory



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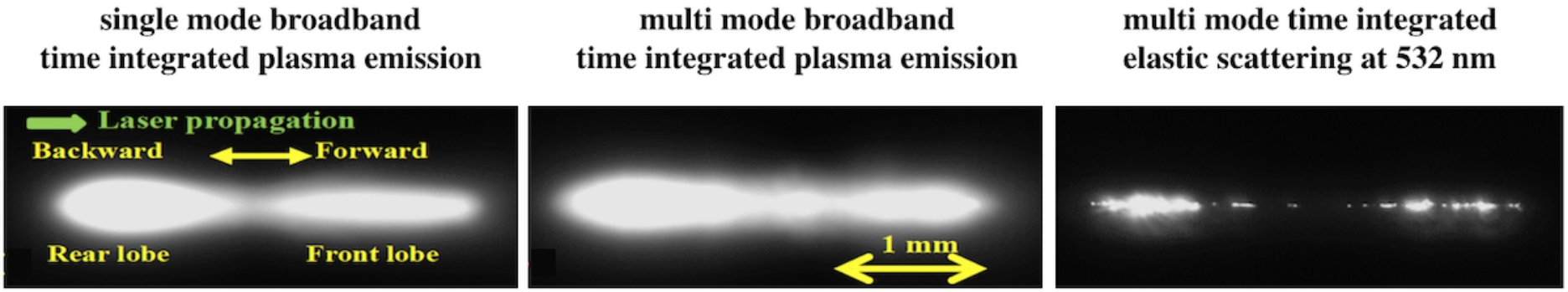

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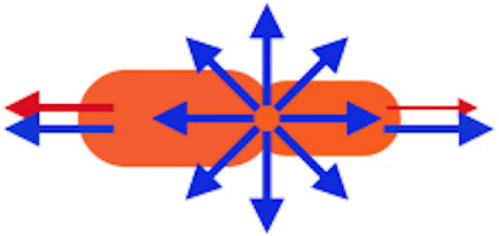
- Radiative Propagated Wave Theory



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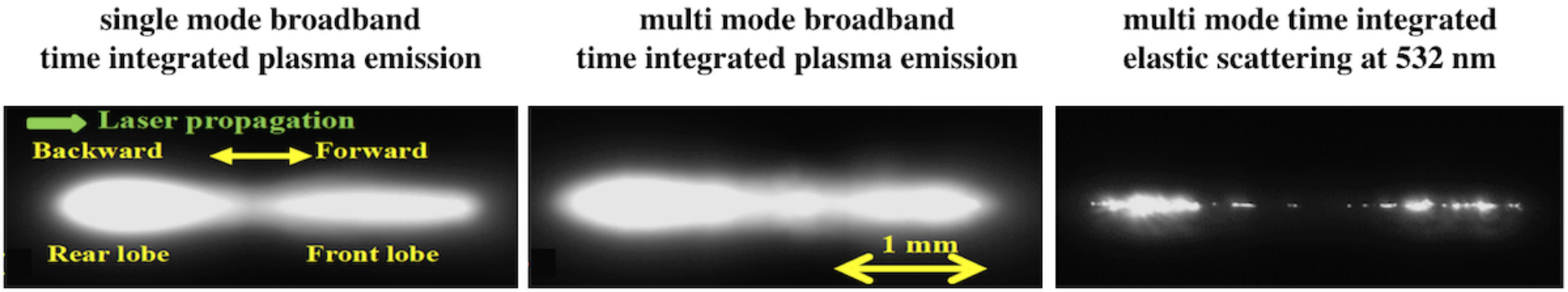

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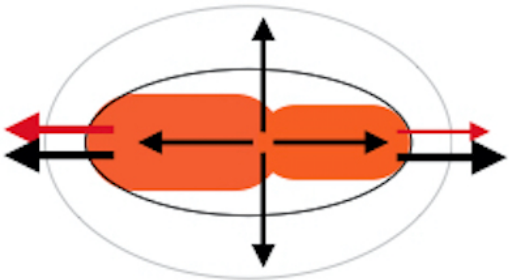
- Detonation Theory



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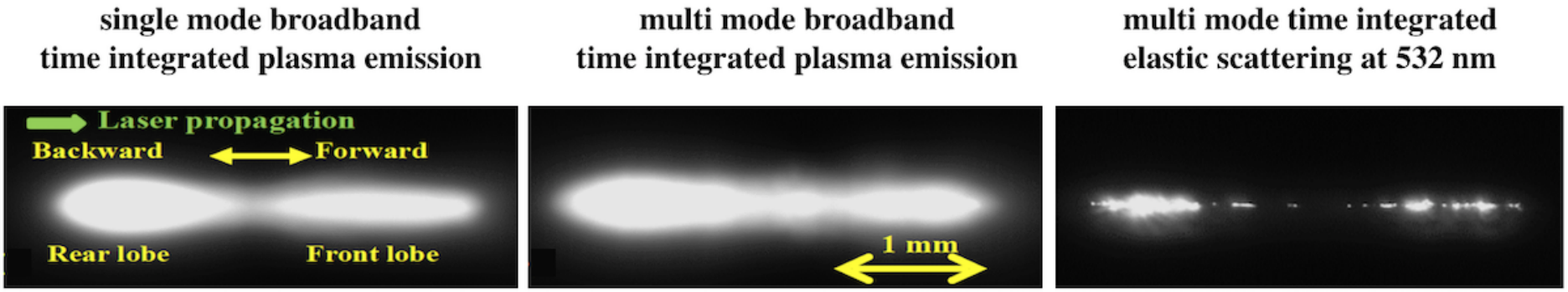

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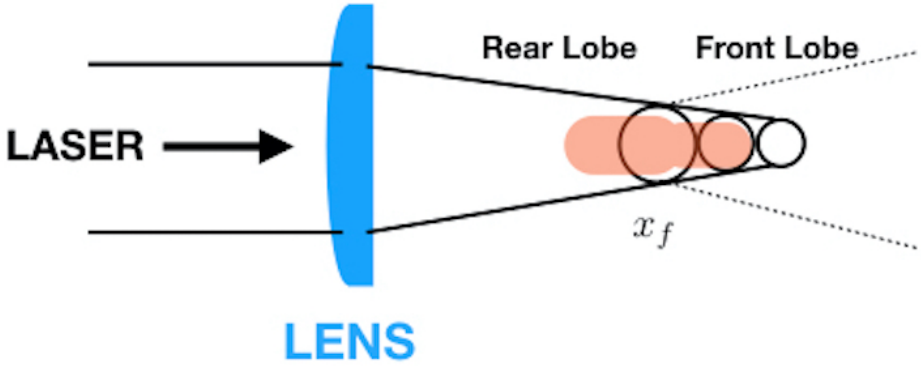
- Self Focusing Theory

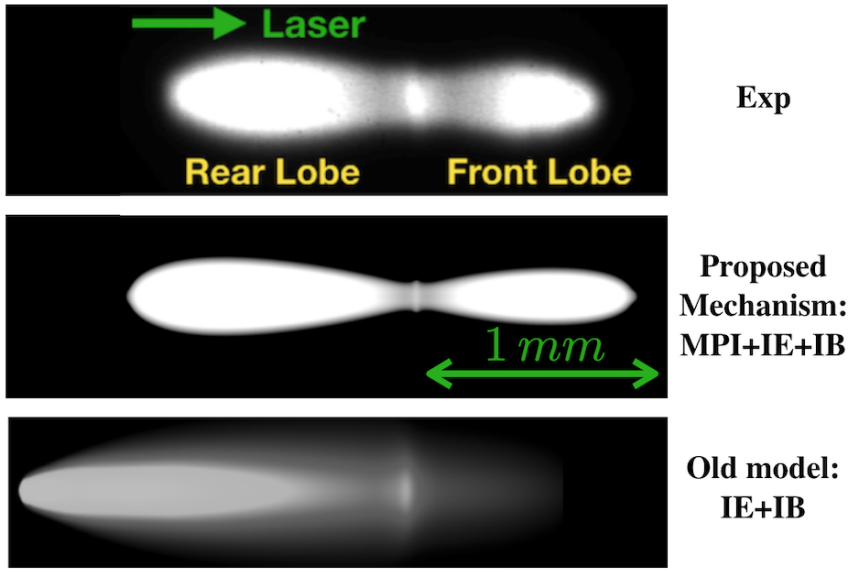


Introduction: Objective

Our objective is the construction of a **physics based model** for:

- developing predicitve capabilities on laser generated plasmas
- determining key mechanism of laser induced breakdown
- predicting hydrodynamic phenomena

- We propose a breakdown mechanism
  - triggered by:
    - *Multi-Photon Ionization* (MPI)
  - guided by:
    - *Multi-Photon Ionization* (MPI)
    - *Ionization by Electron Impact* (IE)
  - sustained by laser radiation
    - *Inverse Bremsstrahlung* (IB)



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Physical Model: Hydrodynamic Equations

- The mixture under investigation is 19 species Air

$$\frac{\partial \rho_s}{\partial t} + \nabla \cdot \left(\rho_s \boldsymbol{u}\right) + \nabla \cdot \boldsymbol{J}_s = \dot{\omega_s} + \dot{\omega_s}^{\mathrm{R}} \quad (s \in \ e^- \ \cup \ \mathcal{S}_h) \tag{1}$$

$$\frac{\partial \rho \boldsymbol{u}}{\partial t} + \nabla \cdot \left(\rho \boldsymbol{u} \otimes \boldsymbol{u} + p \underline{\underline{\mathbb{I}}}\right) - \nabla \cdot \underline{\underline{\tau}} = \boldsymbol{0} \tag{2}$$

$$\frac{\partial \rho E}{\partial t} + \nabla \cdot \left(\rho H \boldsymbol{u}\right) - \nabla \cdot \left(\underline{\underline{\tau}} \boldsymbol{u} - \boldsymbol{q}\right) = \Omega^{\mathrm{R}} \tag{3}$$

$$\frac{\partial \rho e^v}{\partial t} + \nabla \cdot \left(\rho e^v \boldsymbol{u}\right) + \nabla \cdot \boldsymbol{q}^v = \Omega_{\mathrm{VT}} + \Omega_{\mathrm{CV}} + \Omega_{\mathrm{VE}} \tag{4}$$

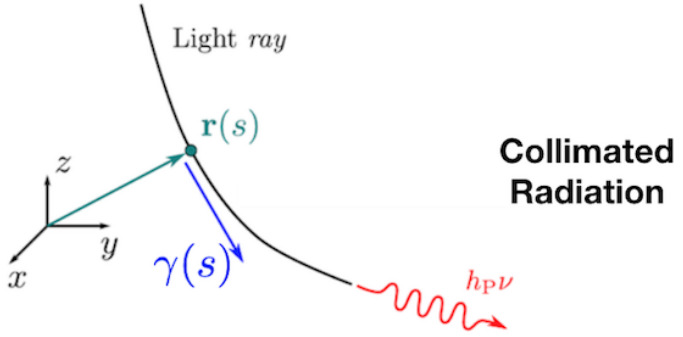
$$\frac{\partial \rho e^e}{\partial t} + \nabla \cdot \left(\rho e^e \boldsymbol{u}\right) + \nabla \cdot \boldsymbol{q}^e = -p_e \nabla \cdot \boldsymbol{u} + \Omega_{\mathrm{TE}} + + \Omega_{\mathrm{IE}} + \Omega_{\mathrm{DE}} - \Omega_{\mathrm{VE}} + \Omega_e^{\mathrm{R}} \tag{5}$$

Radiation: Radiative Transfer Equation

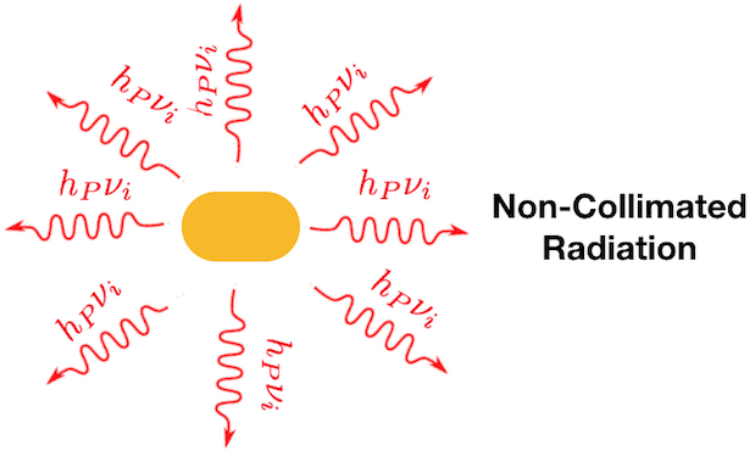
In the current model, the radiation field is split in
collimated (c) + **non-collimated (nc)** components

- **Collimated**: Laser at wavelength λ_0
  - monochromatic Laser
  - steady-state RTE
  - absence of emission, scattering and refraction

  A. Munafò, A. Alberti, C. Pantano, J. B. Freund, M. Panesi, "Modeling of Laser-Induced Breakdown Phenomena in Non-Equilibrium Plasmas", (AIAA Scitech 2018)

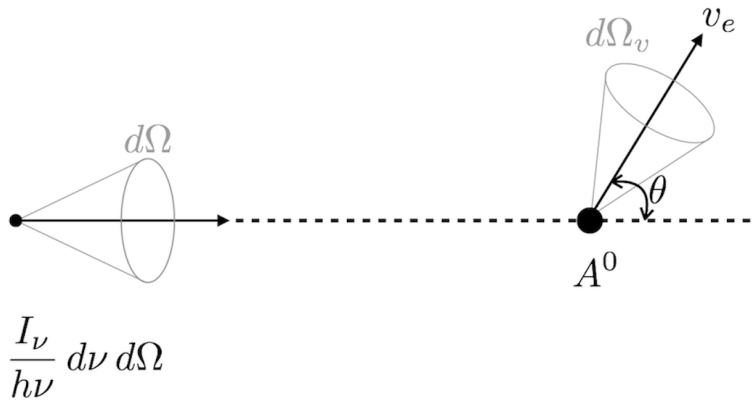


- **Non-Collimated**: Plasma response
  - entire spectrum
  - diffusion approximation



Radiation: Processes

- Multi-Photon Ionization (MPI): $A^0 \; + \; m\,h\,\nu \; \rightarrow \; A^+ \; + \; e^-$



$$\Omega^{mpi} = n_0 I^m_{\lambda_0}(m\,h\,\nu_0)\sigma$$

$$\Omega^{mpi}_e = n_0 I^m_{\lambda_0}(m\,h\,\nu_0 - \Delta E)\sigma$$

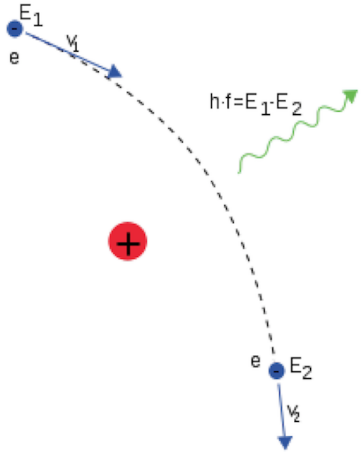
$$\omega^{mpi}_e = n_0 I^m_{\lambda_0}\sigma$$

- Inverse *Bremsstrahlung* (IB)

$$\kappa_{eh}(\lambda_0, T_{ve}) = \mathcal{Q}_{eh}(\lambda_0, T_{ve}) n_h n_e \left[1 - \exp\left(-\frac{h_P c}{\lambda_0 K_B T_{ve}}\right)\right]$$

$$\kappa^{ib}_{\lambda_0} = \sum_{h \in \mathcal{H}} \kappa_{eh}(\lambda_0, T_{ve})$$

$$\Omega^{ib} = \kappa^{ib}_{\lambda_0} I_{\lambda_0}$$



Numerical Method: HEGEL

- HEGEL (High-fidElity tool for maGnEtogasdynamics appLications)

A. Munafò, A. Alberti, C. Pantano, J. B. Freund, M. Panesi, "A computational model for nano-second pulse laser-plasma interaction", (in preparation).

- Equations are discretized in space with cell centered FV method
- The numerical inviscid flux is computed with:
  - ROE scheme with entropy fix (or Lax Friedrichs)
  - MUSCL reconstruction ($2nd$ order accuracy)
- The ODEs are integrated in time with dual time-stepping approach
  - pseudo time derivative: backward finite difference
  - physical time derivative: three-point backward ($2nd$ order accuracy)

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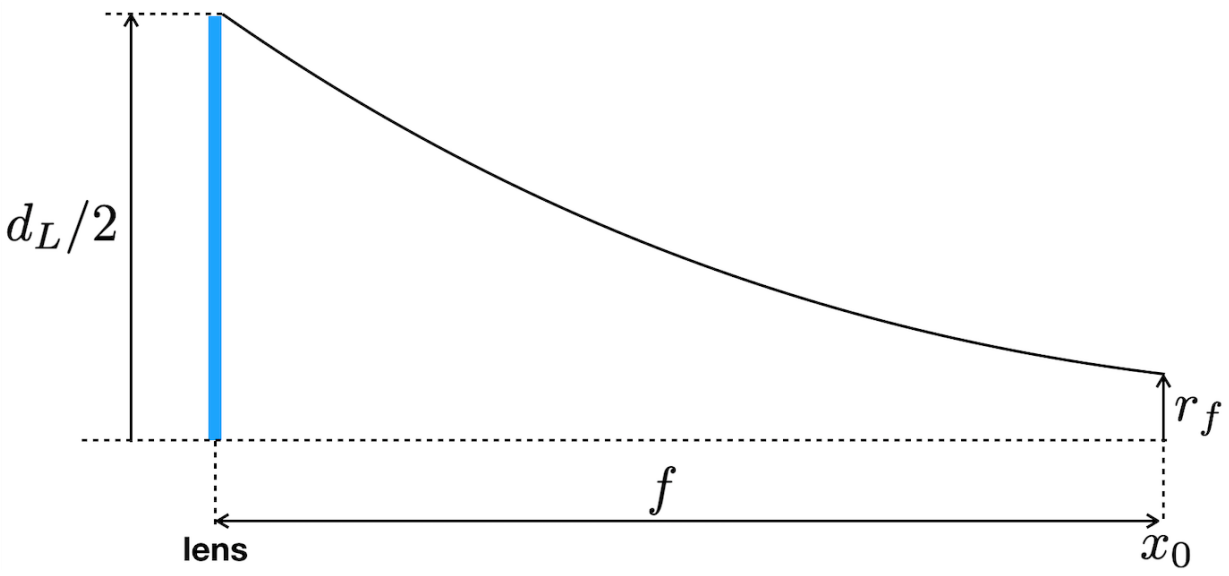
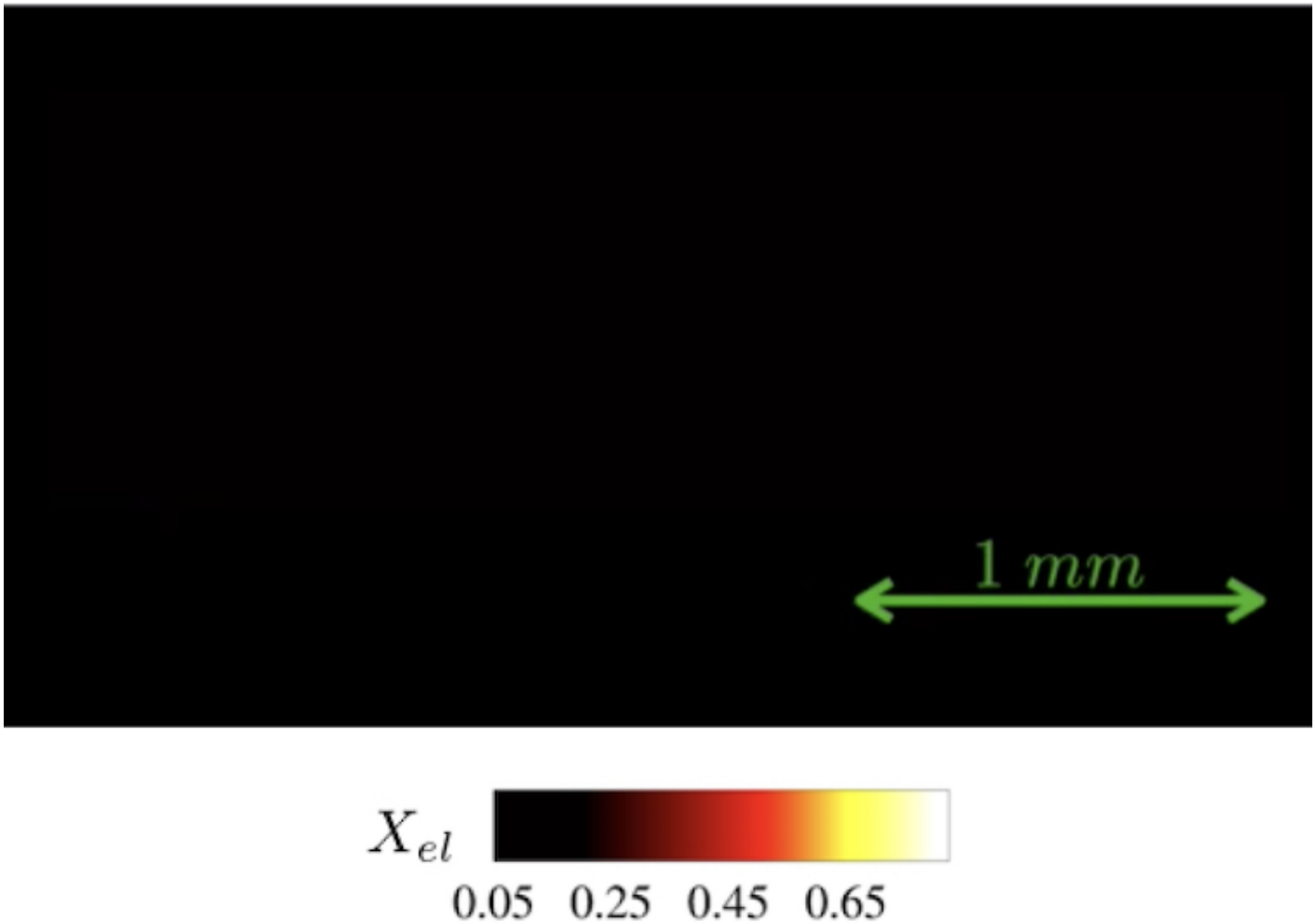
Results: Test Cases

- Laser geometry fitted from experiments



- Proposed Breakdown mechanism tested as a function of:
  - laser power density E_{in}, τ_{fwhm}
  - laser wavelength λ_0
  - background pressure p_b
  - laser operating mode

Breakdown Phase



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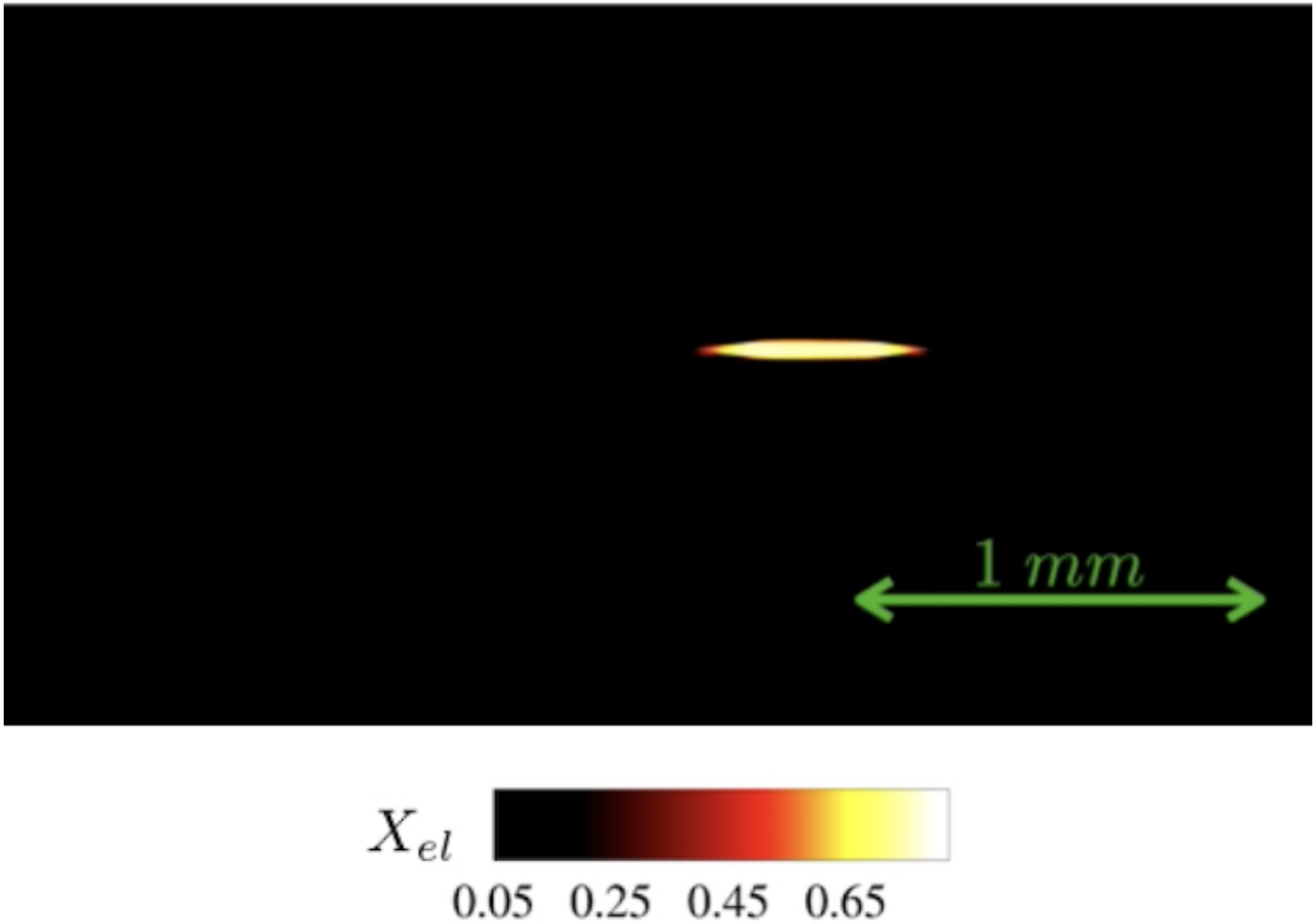

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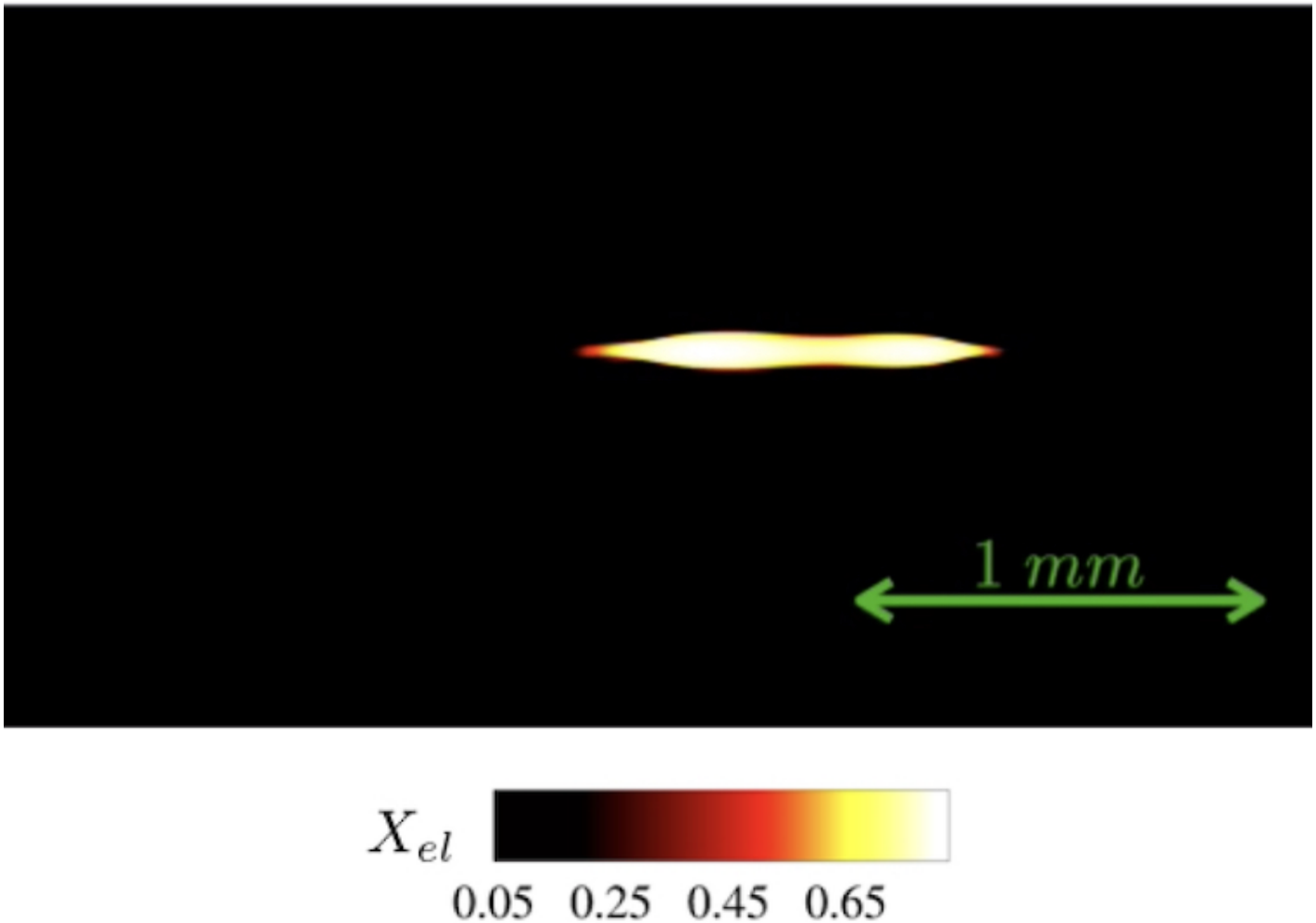

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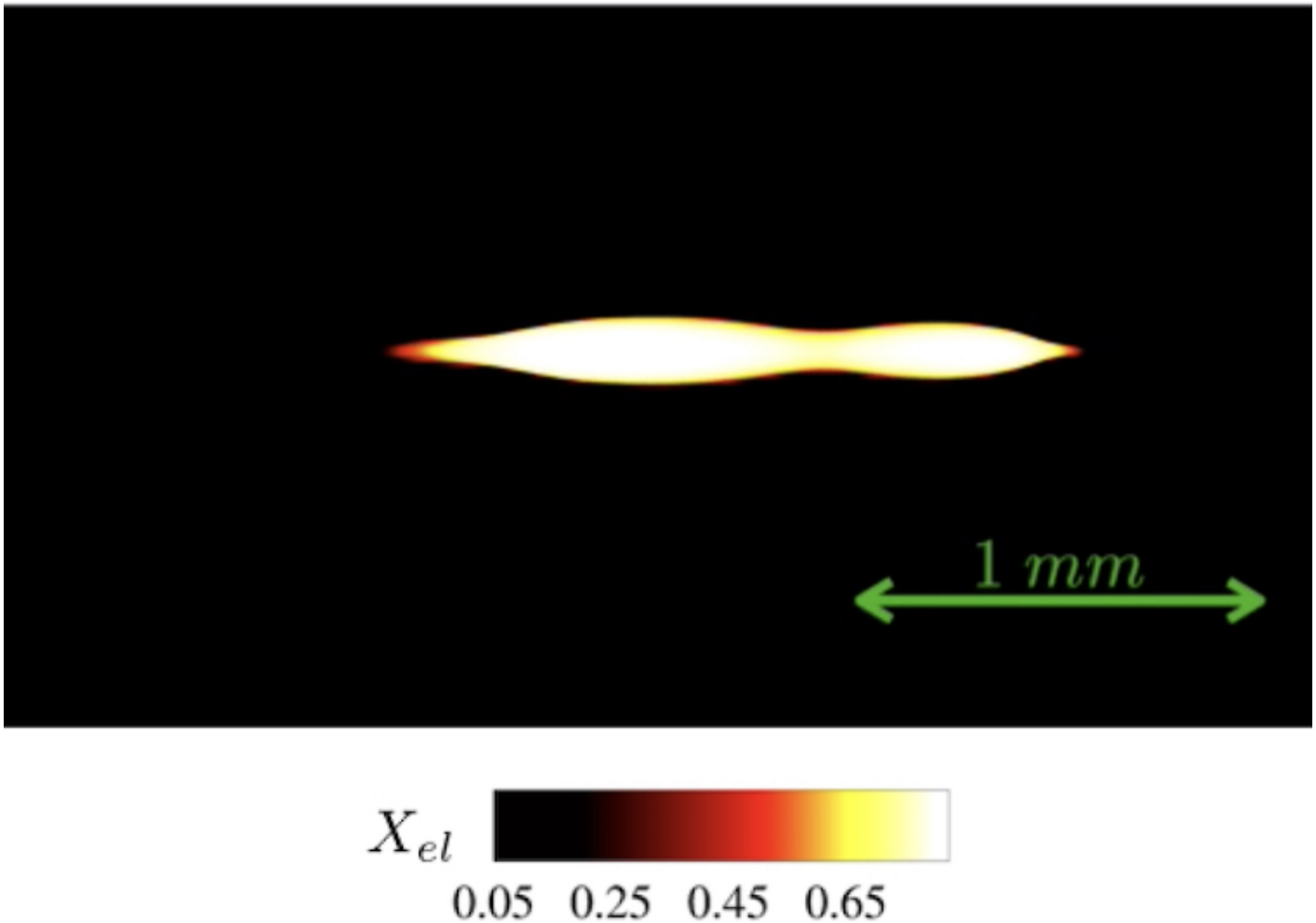

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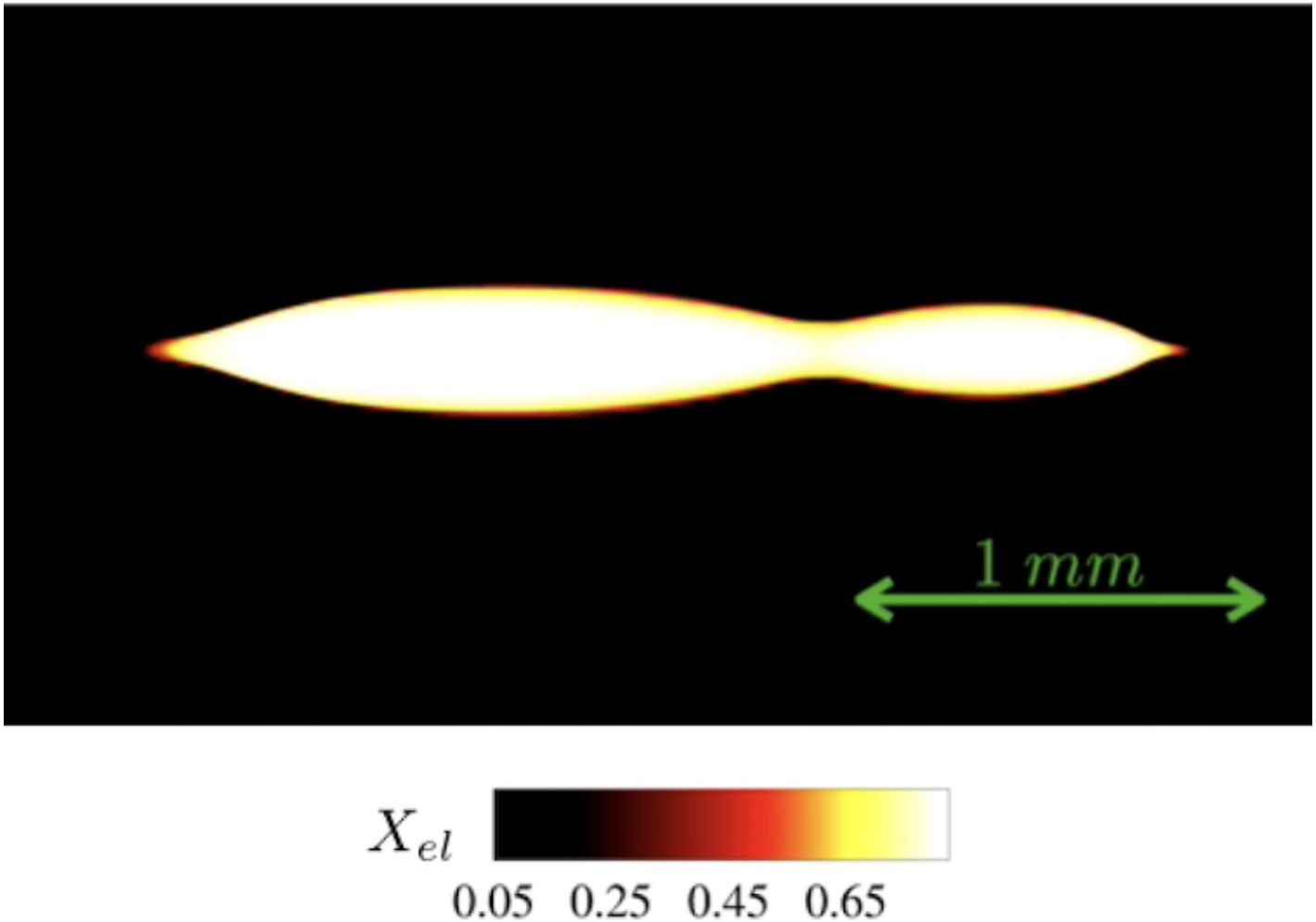

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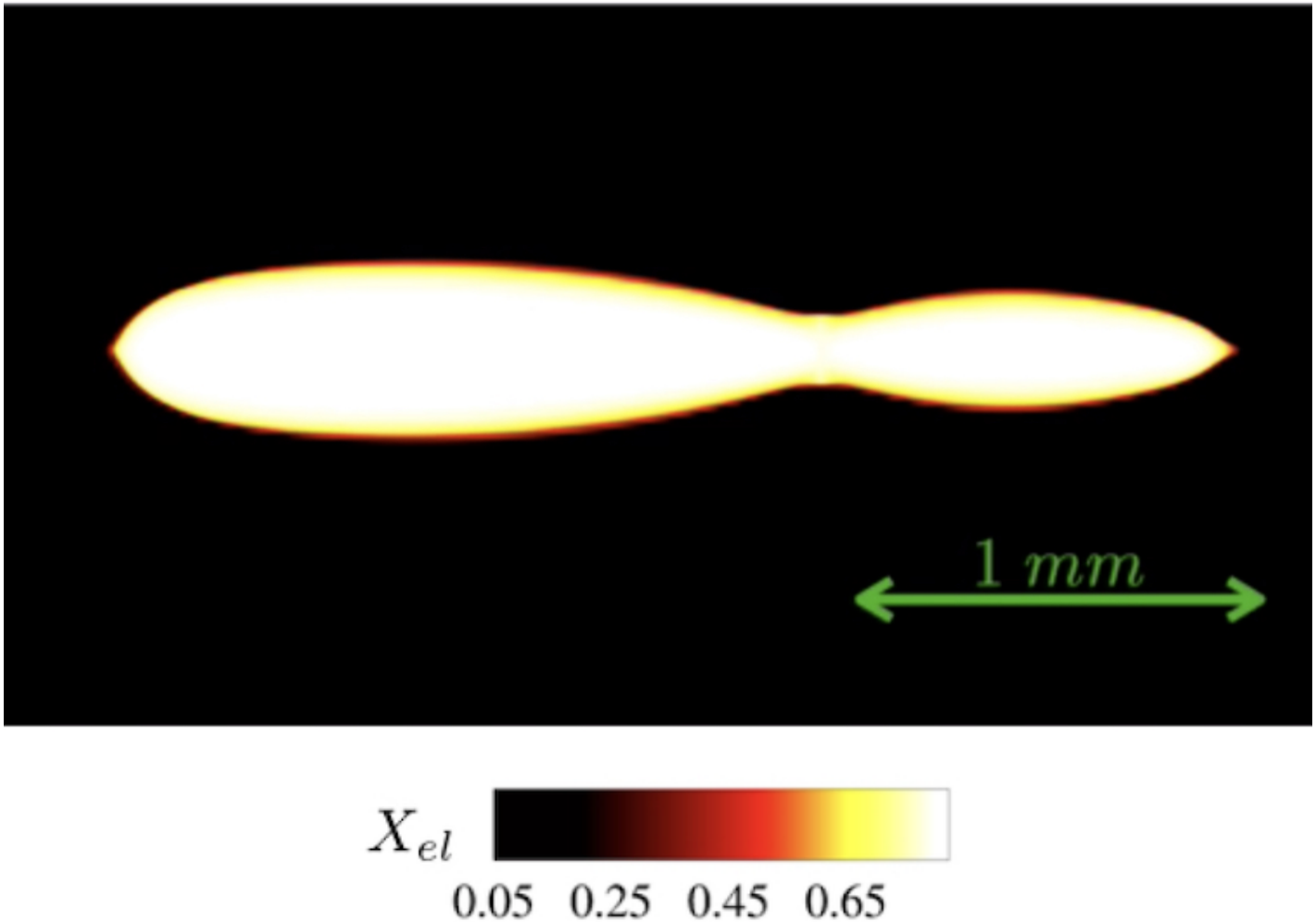

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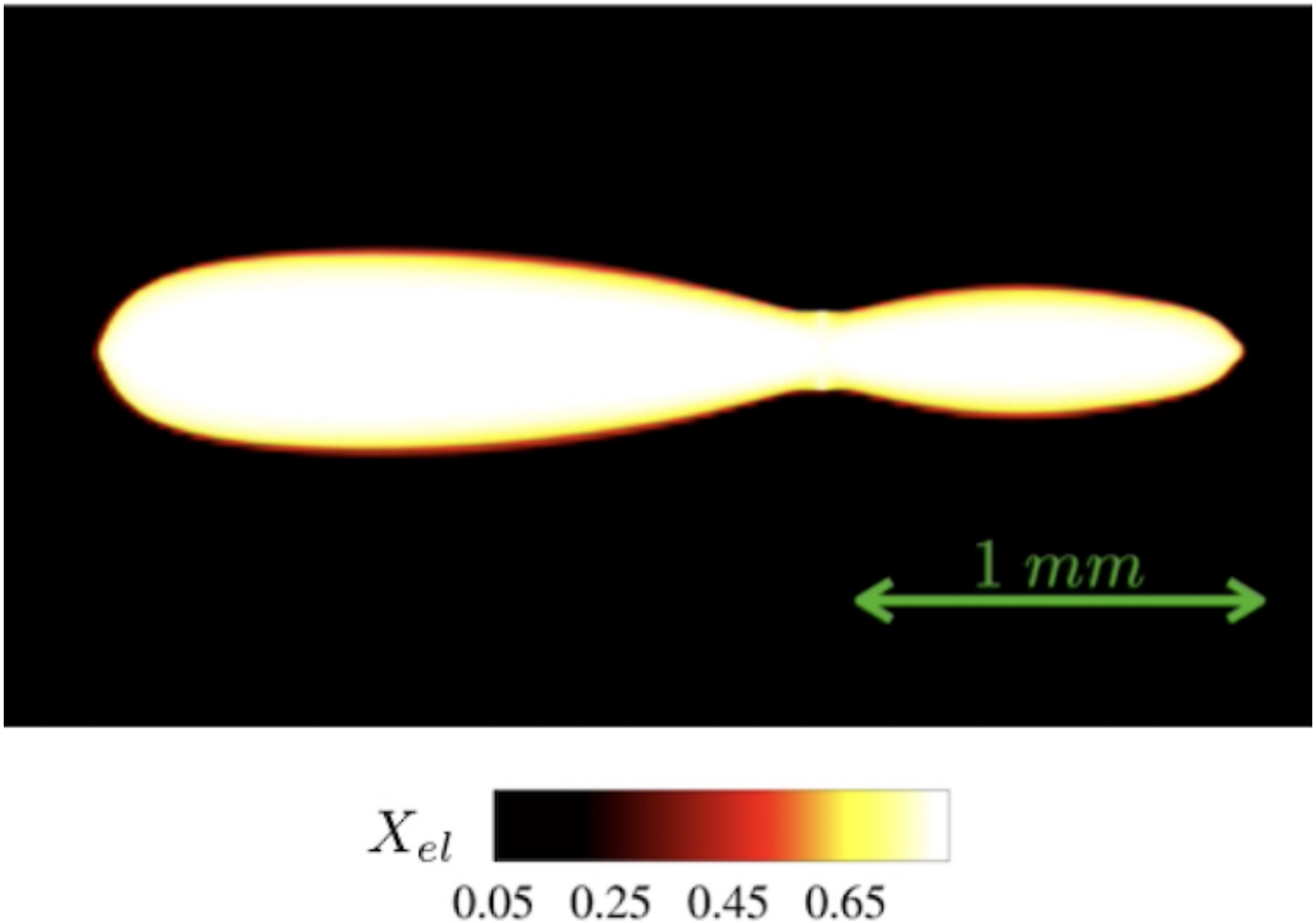

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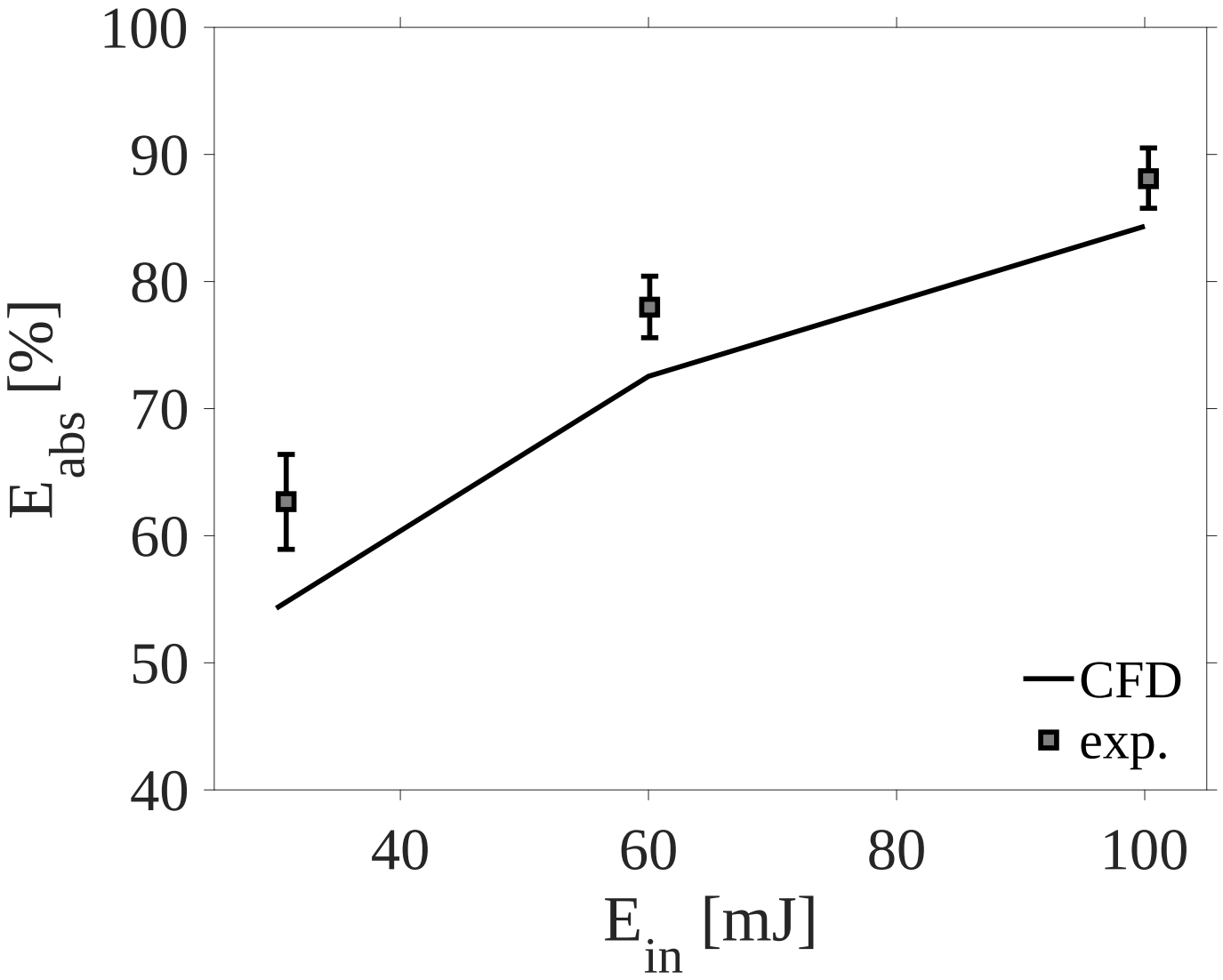
Breakdown Phase: model validation



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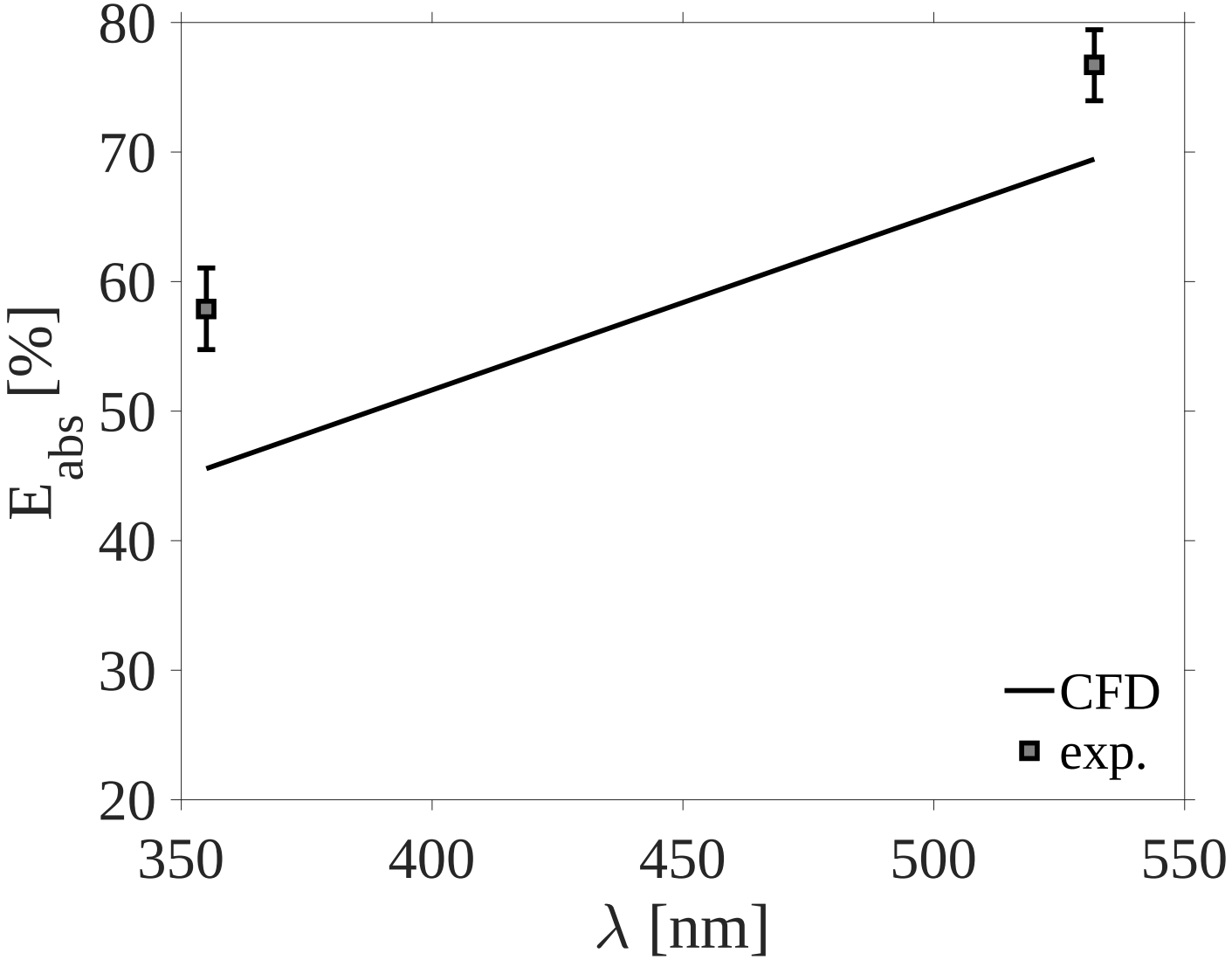

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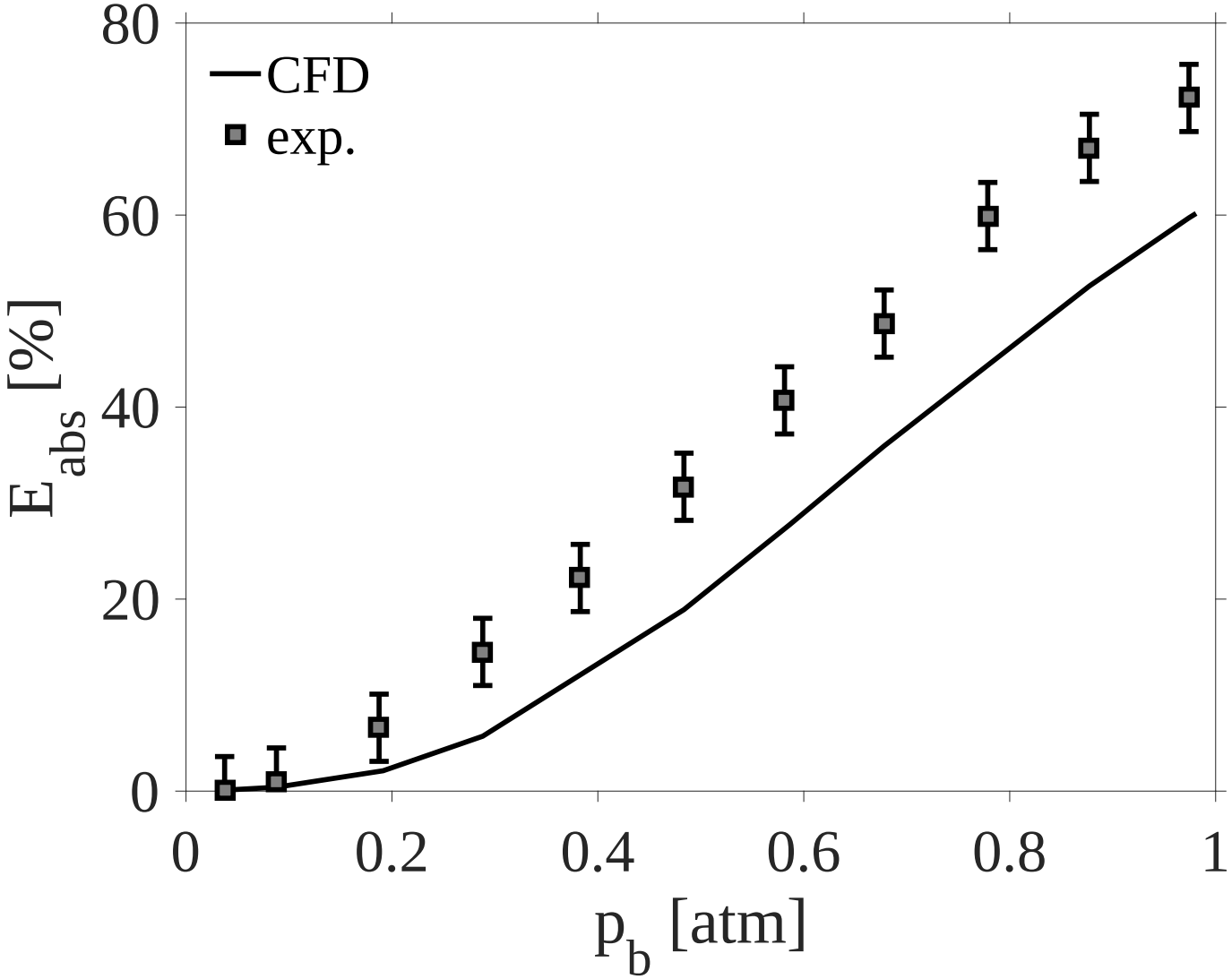

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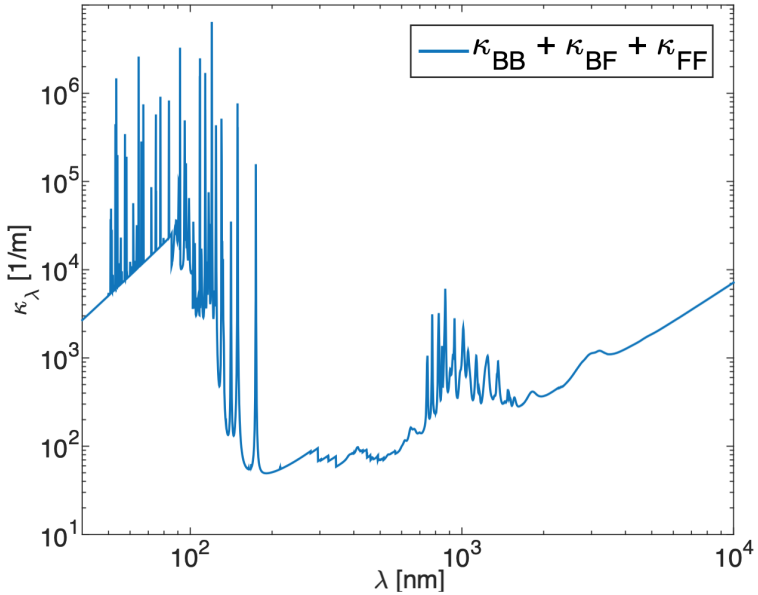
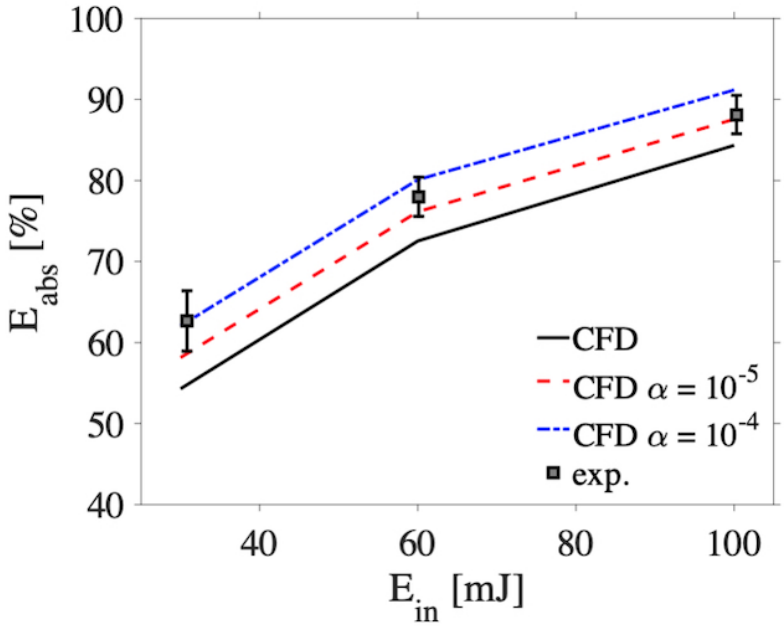
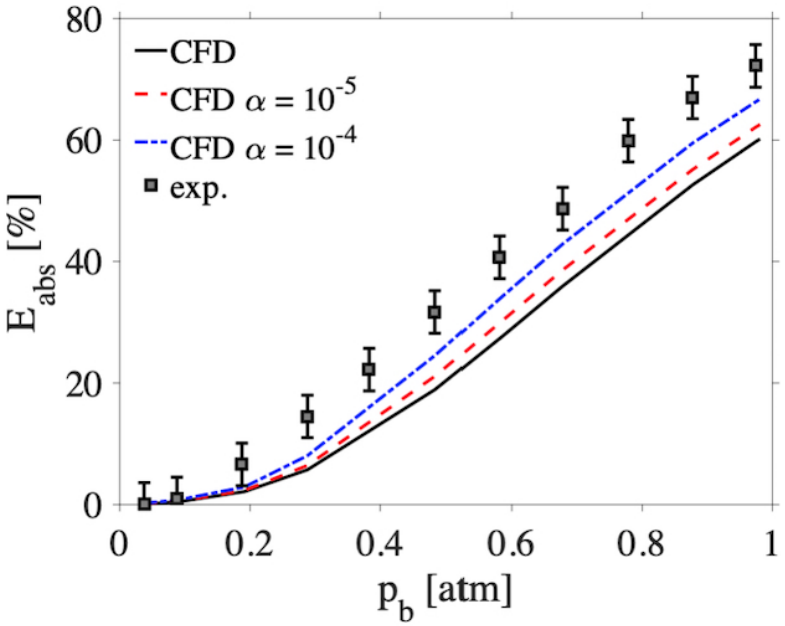
Breakdown Phase: Optically thick correction

$$\frac{1}{\kappa_r} = \frac{\int_0^\infty \frac{1}{\kappa_\lambda}\frac{\partial B_\lambda}{\partial T_e}\, d\,\lambda}{\int_0^\infty \frac{\partial B_\lambda}{\partial T_e}\, d\,\lambda}$$

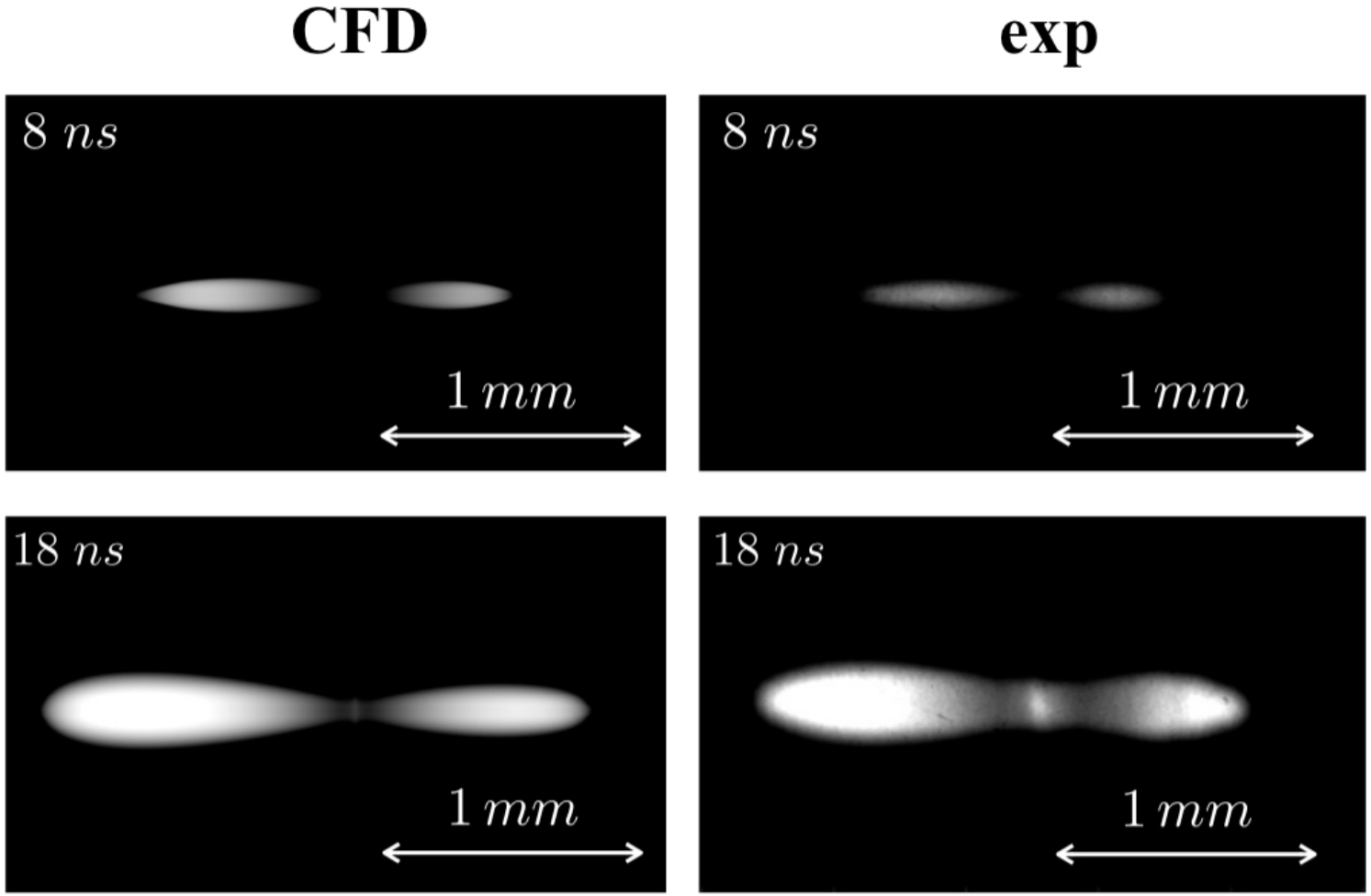
$$\lambda_{rad} = \frac{4}{3}\frac{a\,c}{\kappa_r}\alpha\, T_{ve}^3$$







Breakdown Phase: Plasma Emission



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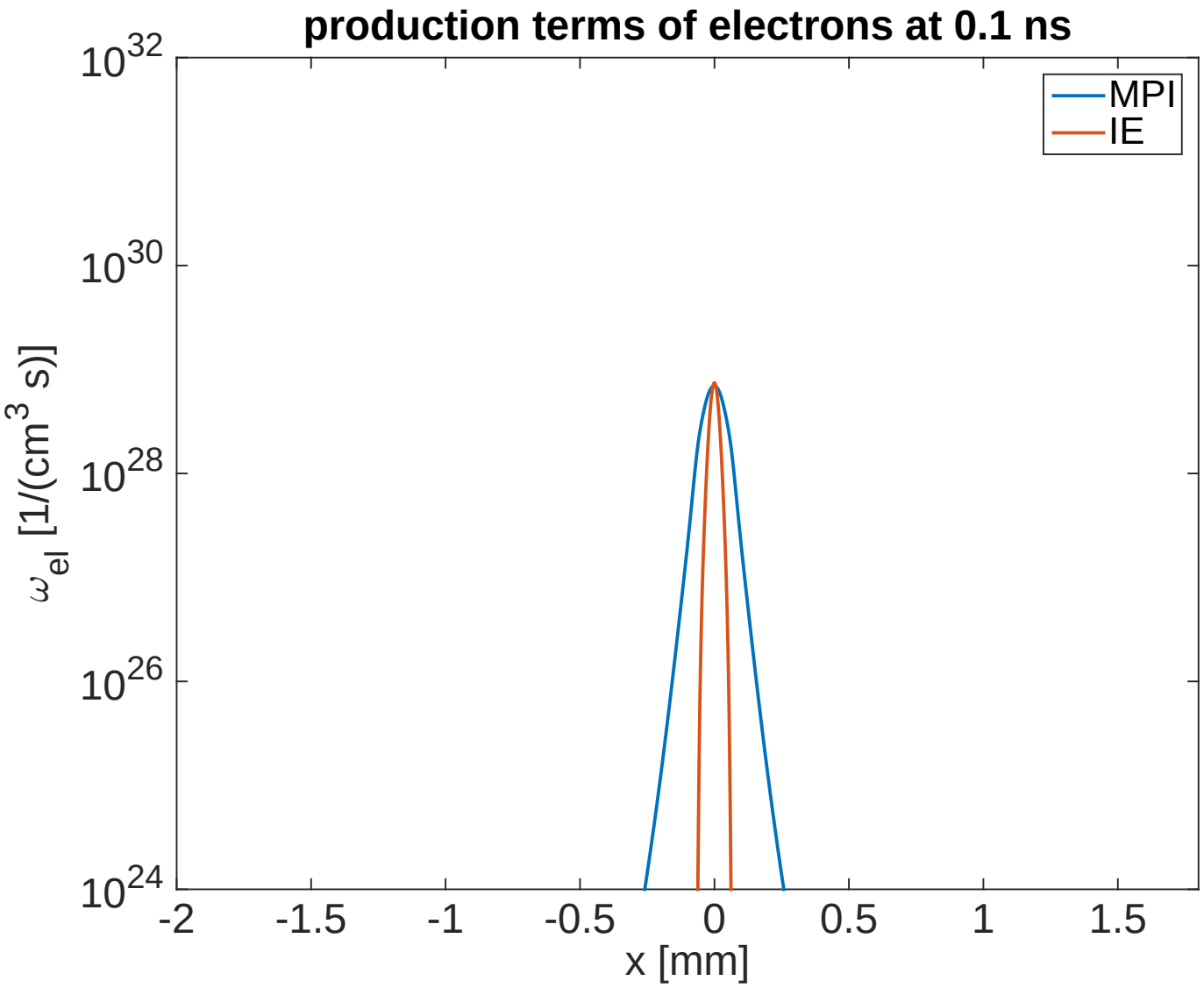
Breakdown Phase: Radiation Support



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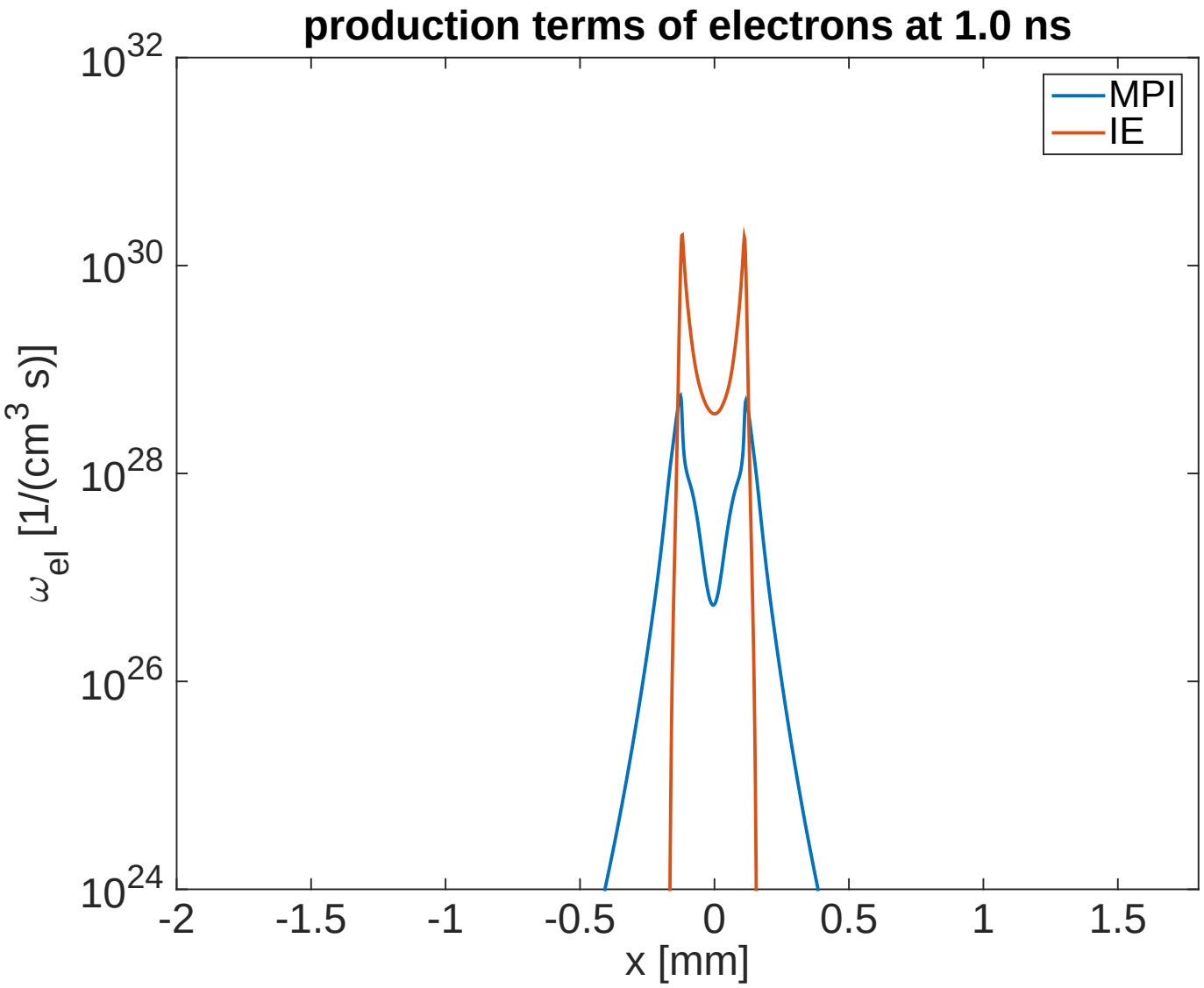

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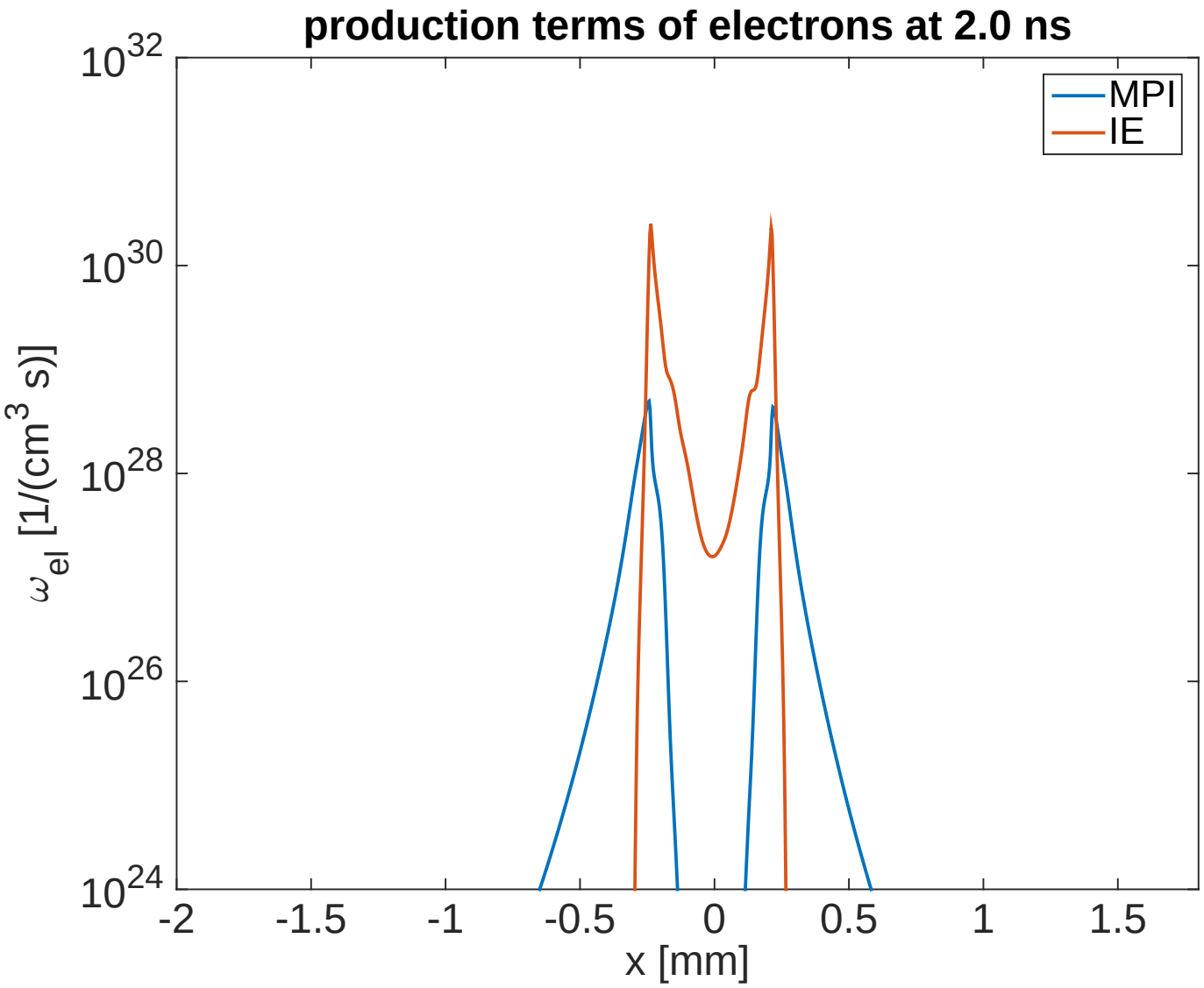

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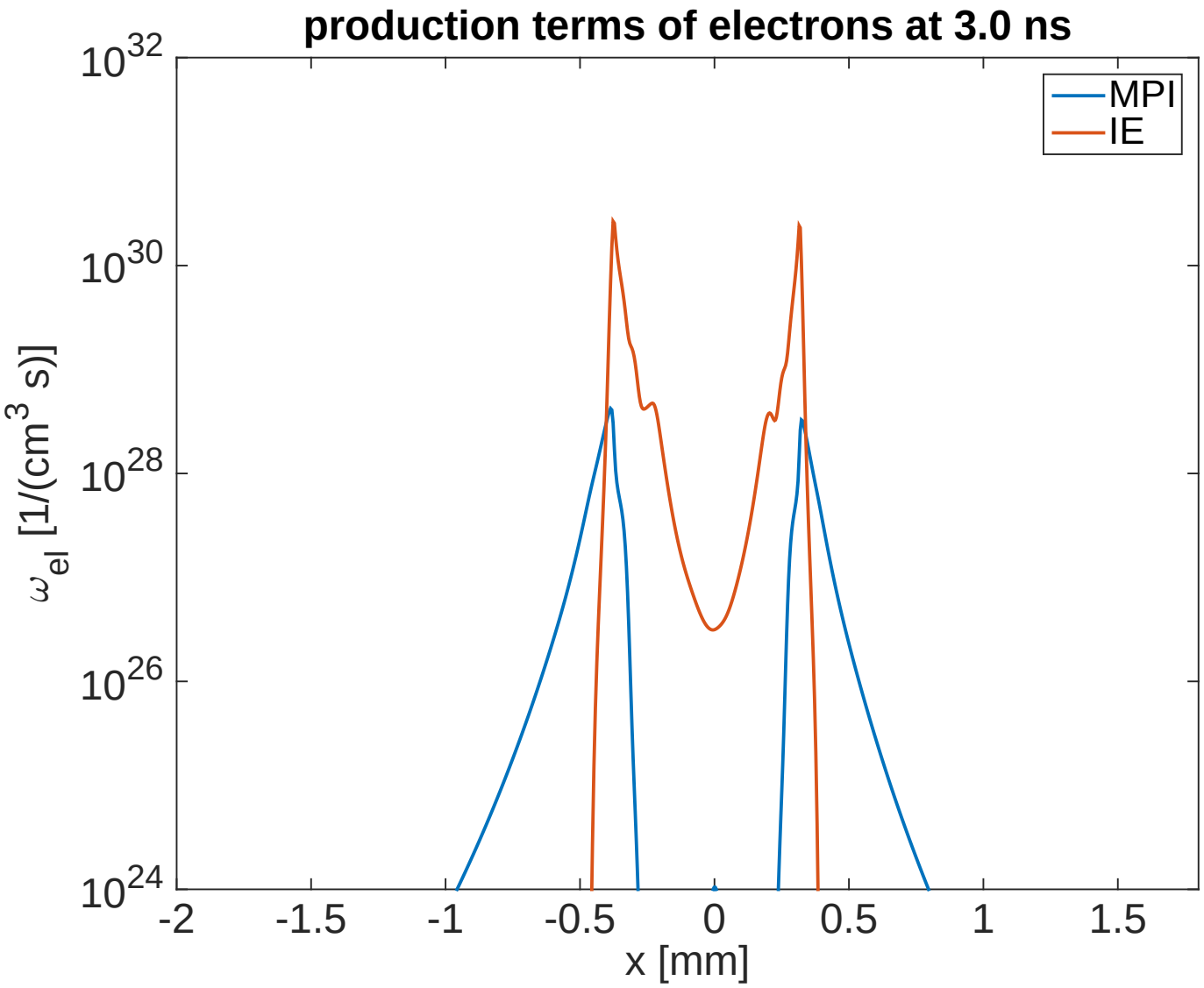

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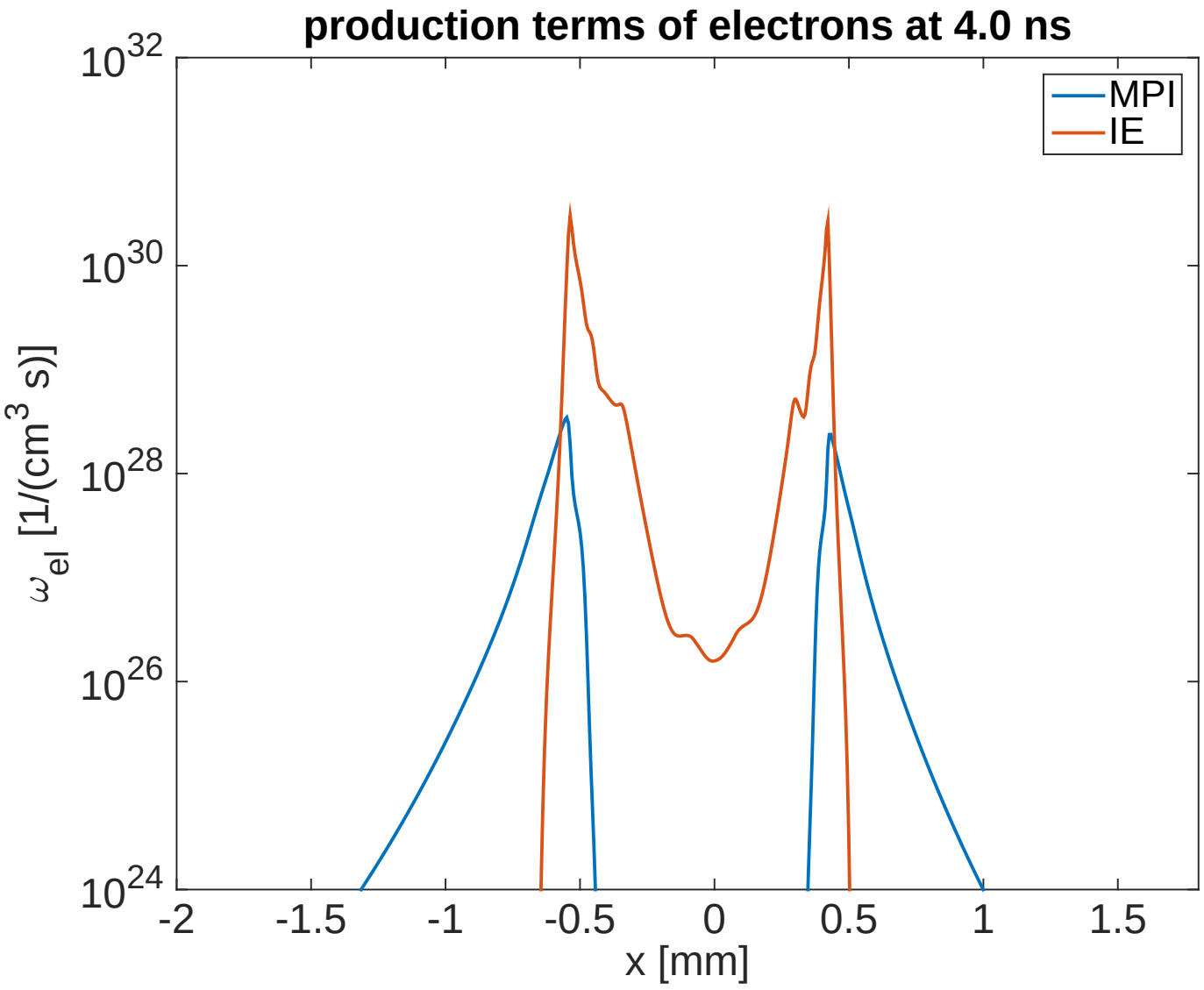
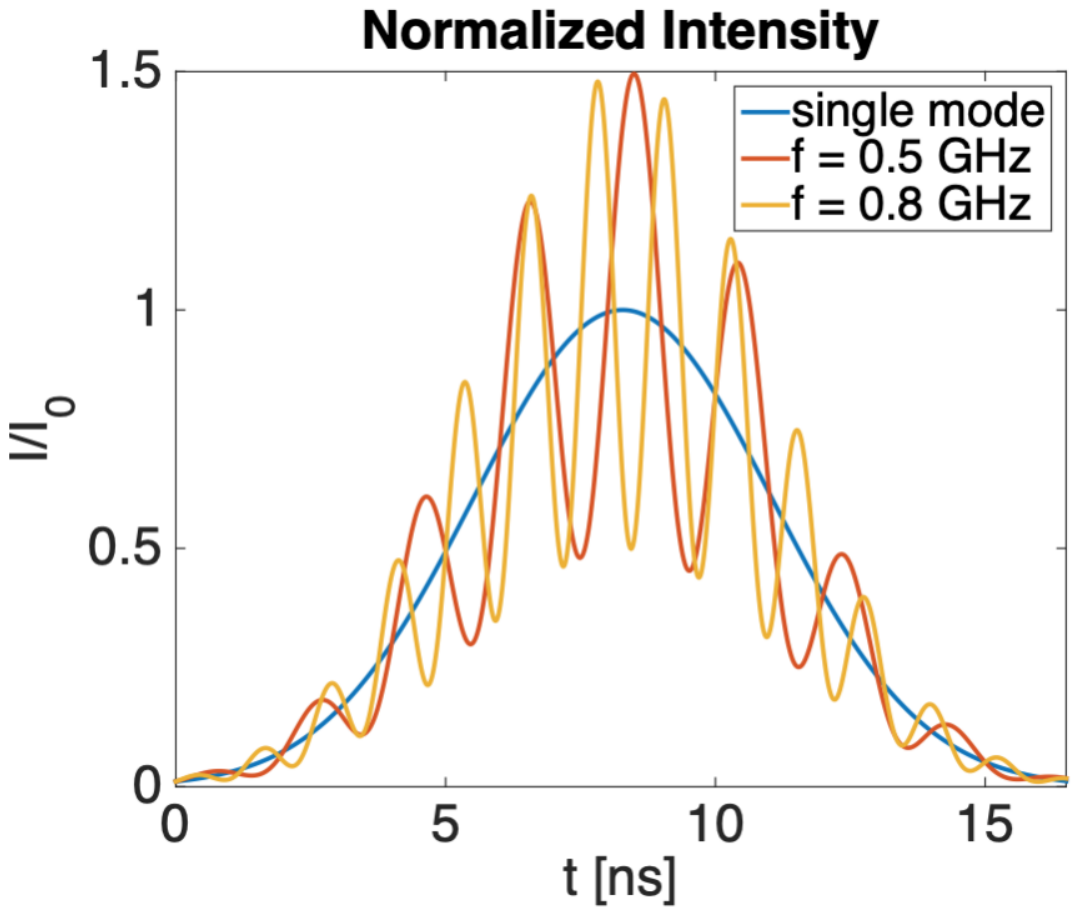
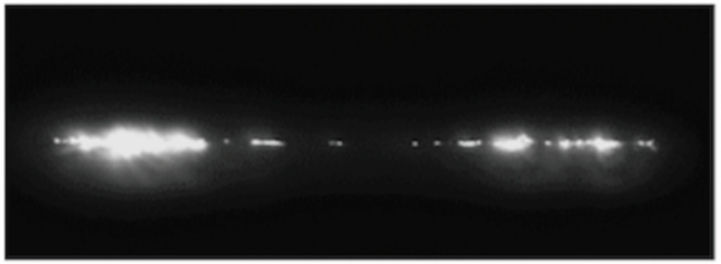


Breakdown Phase: beating mode dependence



multi mode time integrated elastic scattering at 532 nm



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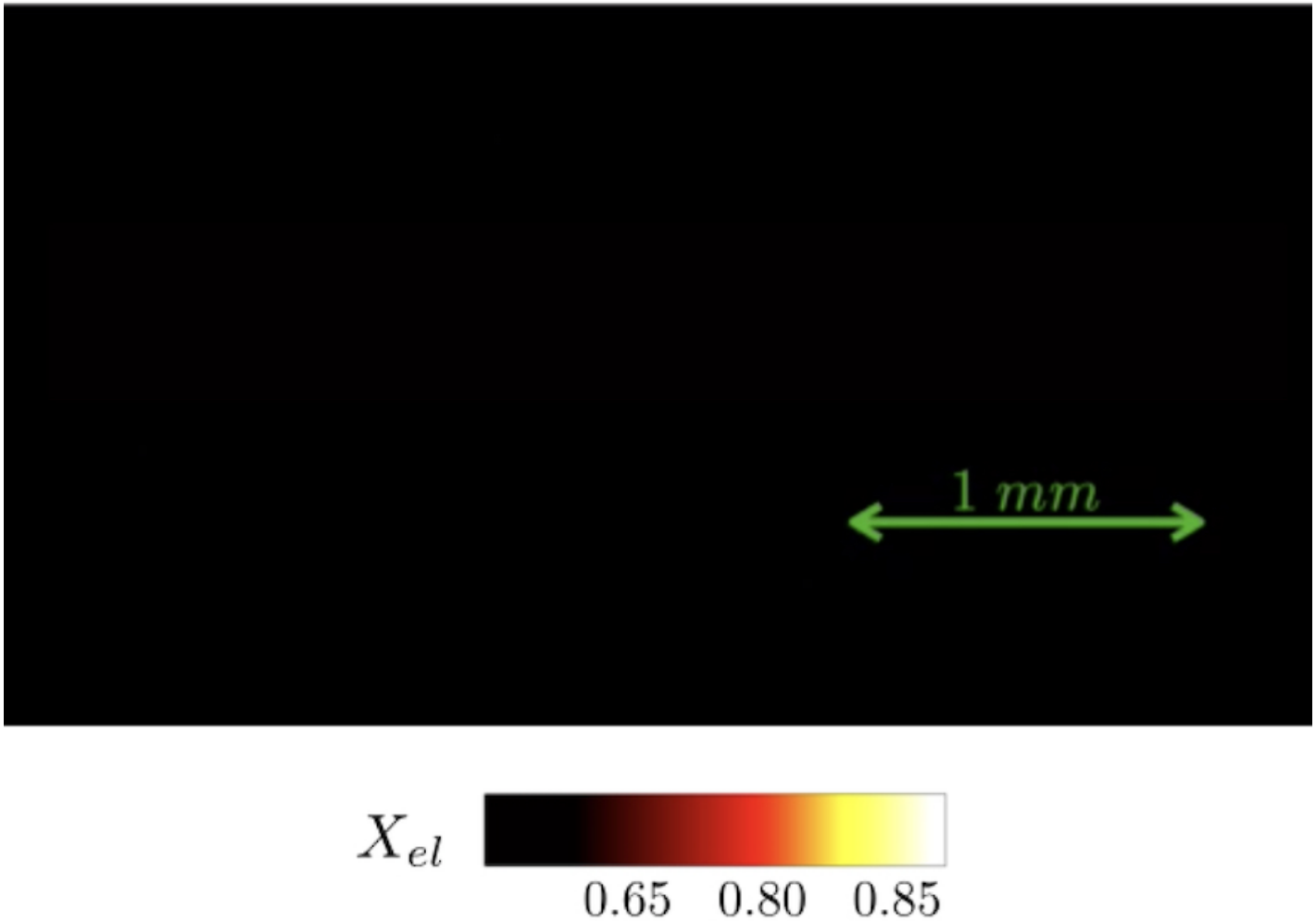

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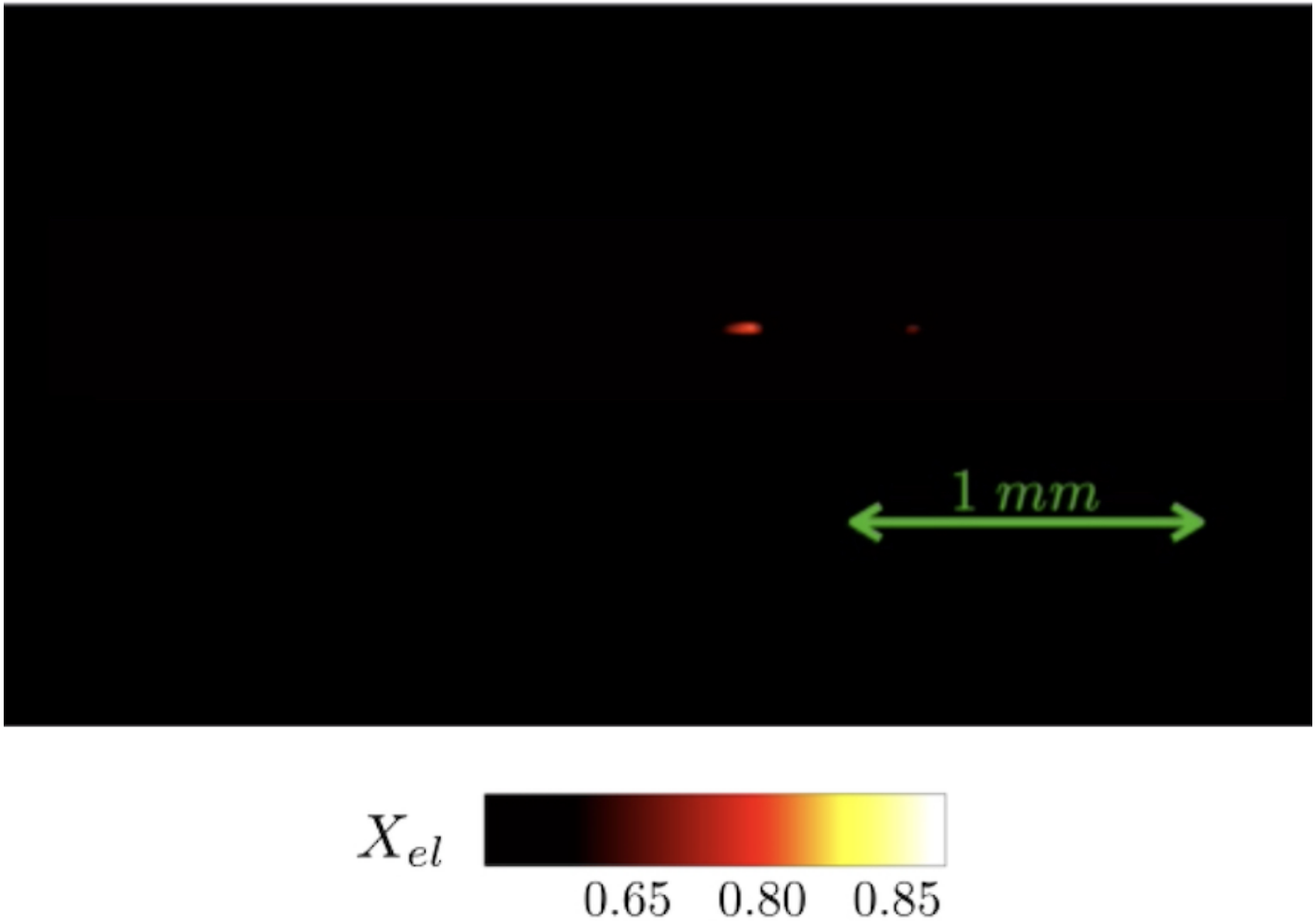
Breakdown Phase: beating mode dependence



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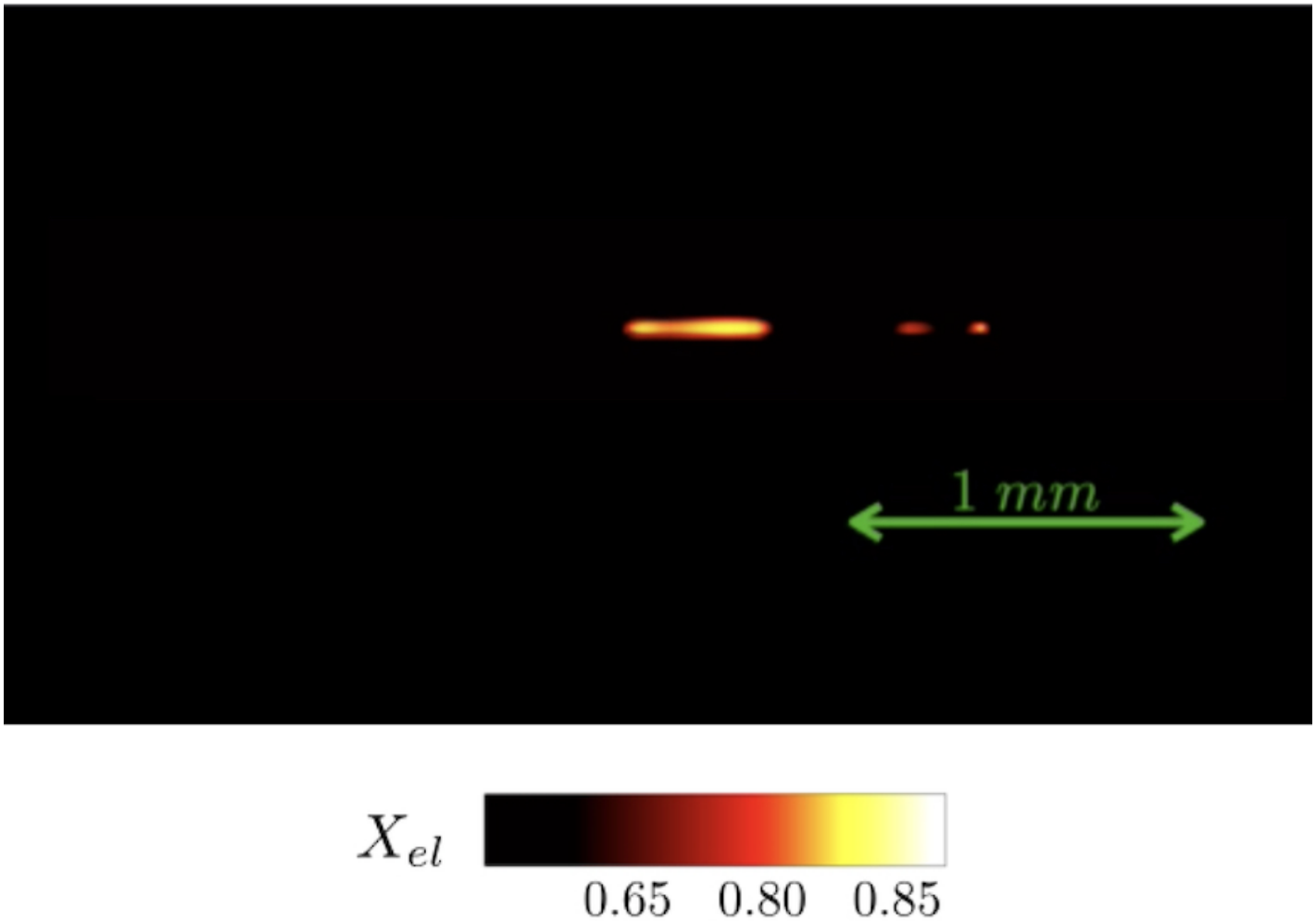

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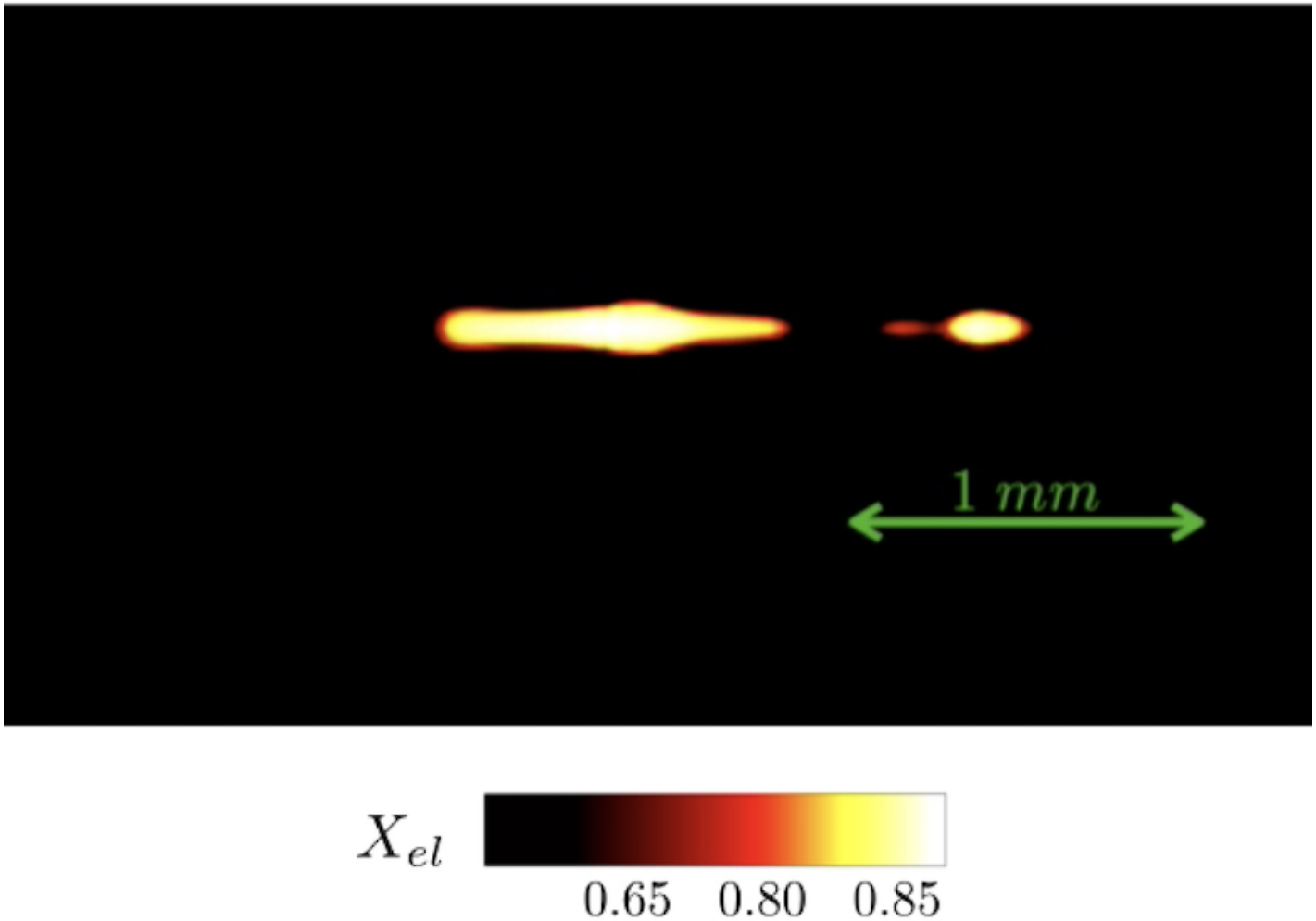

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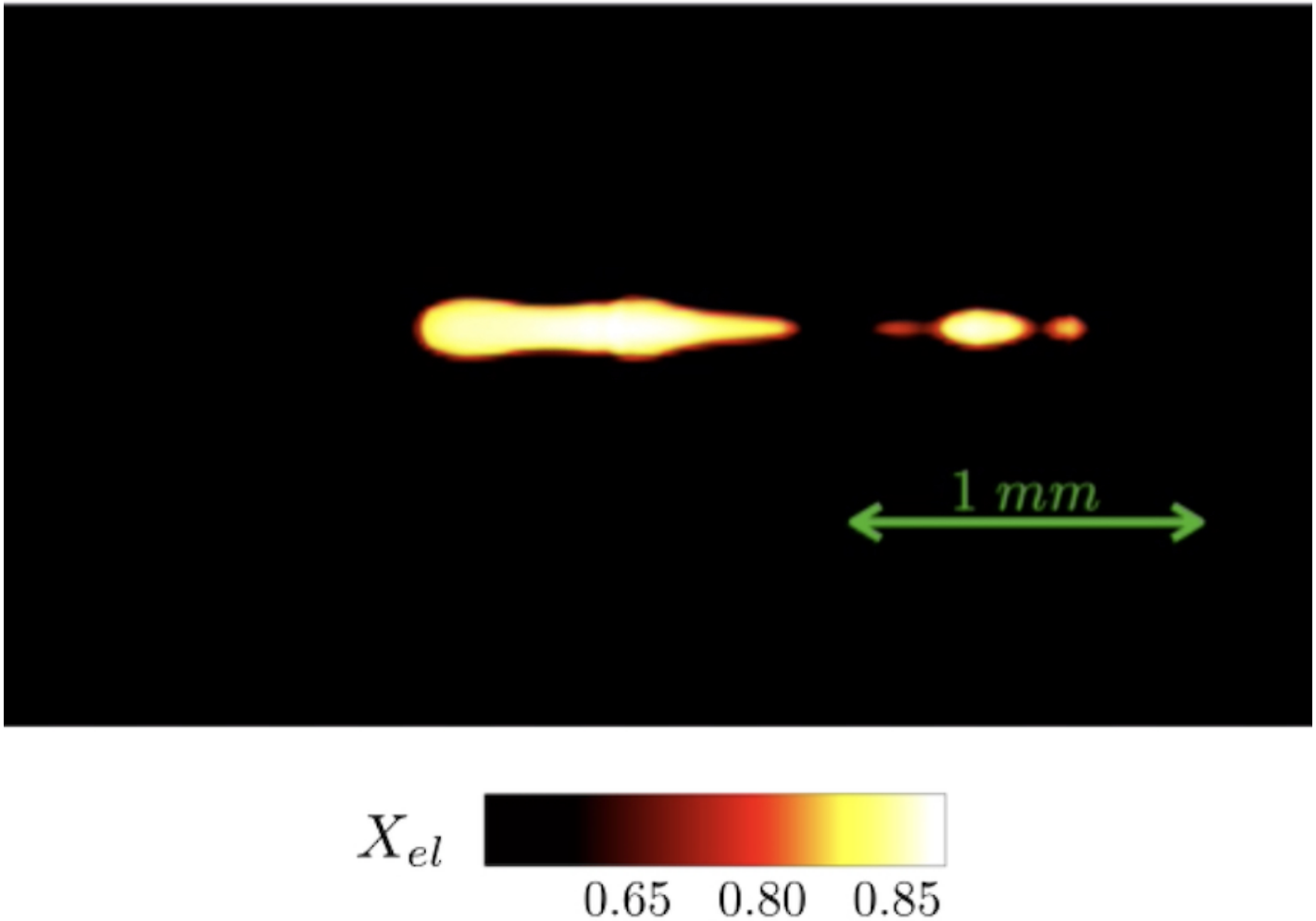

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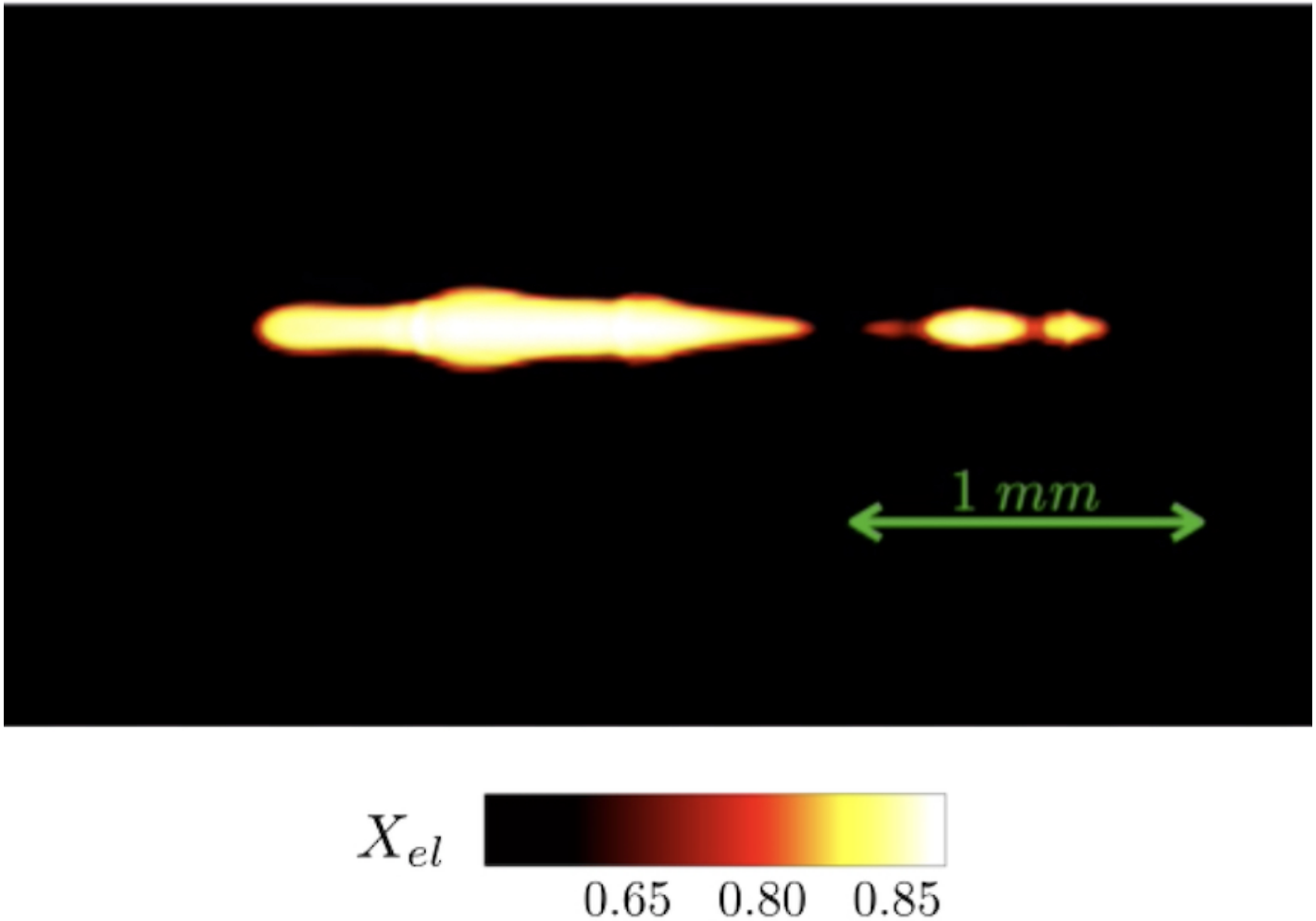

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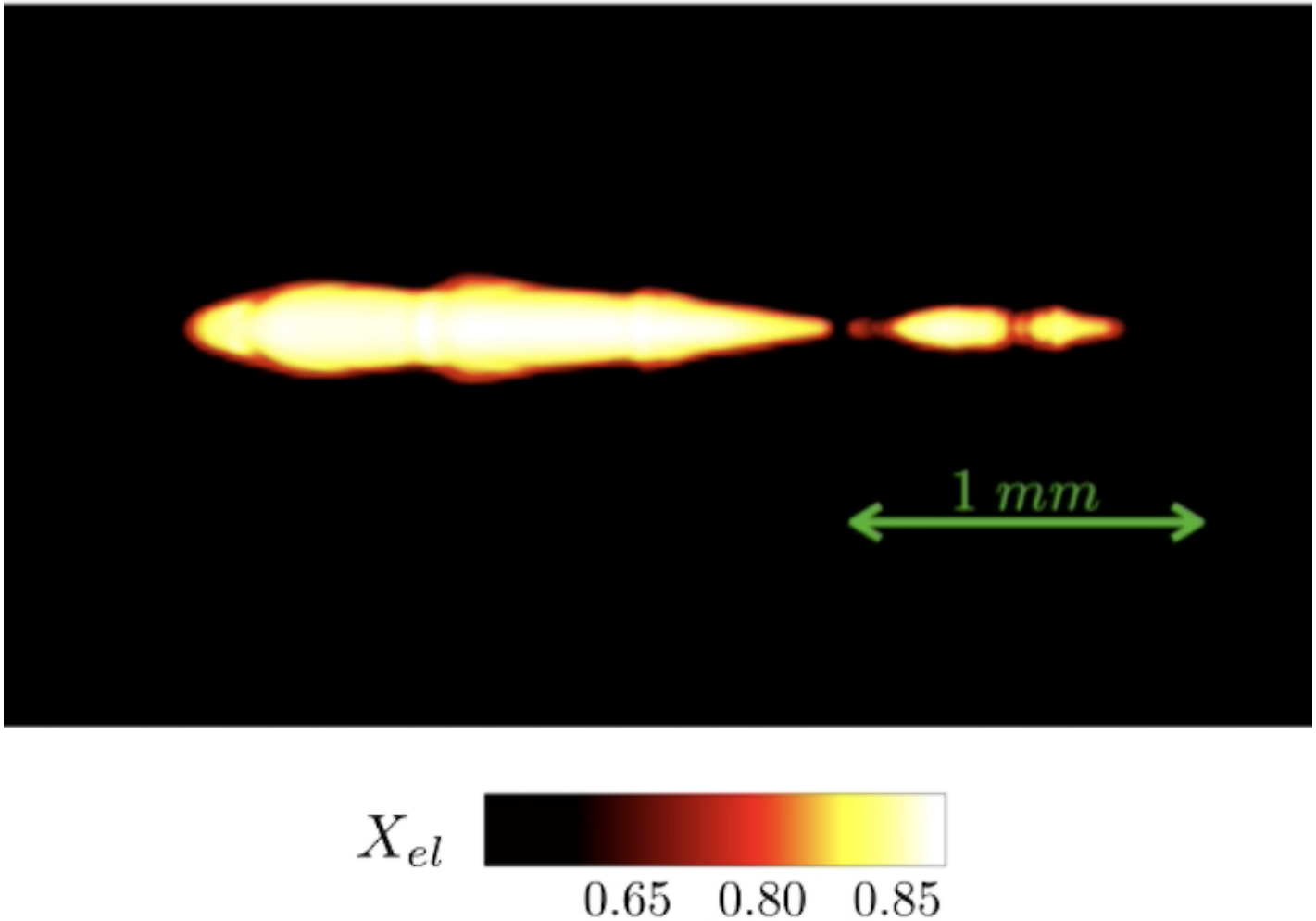

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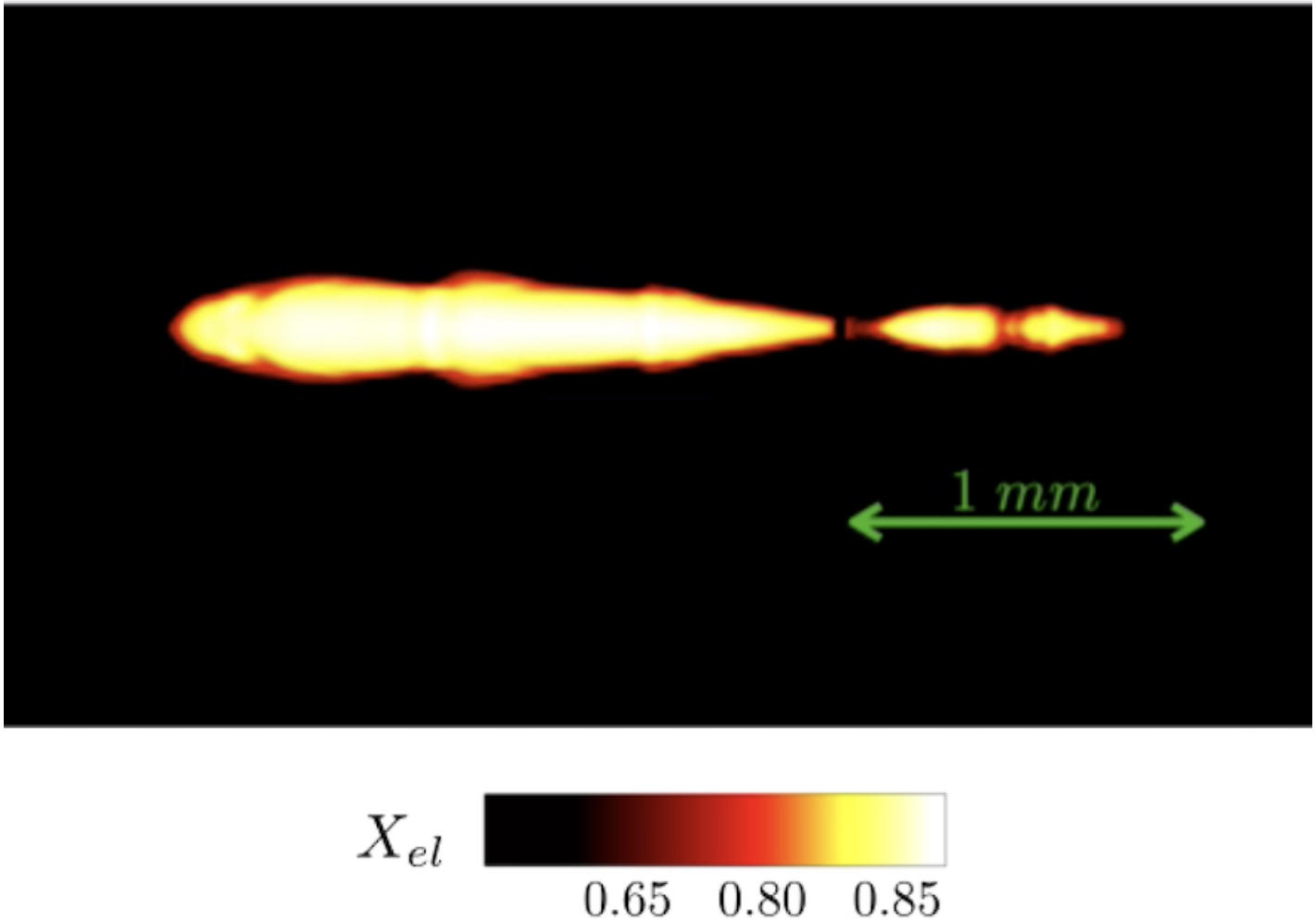

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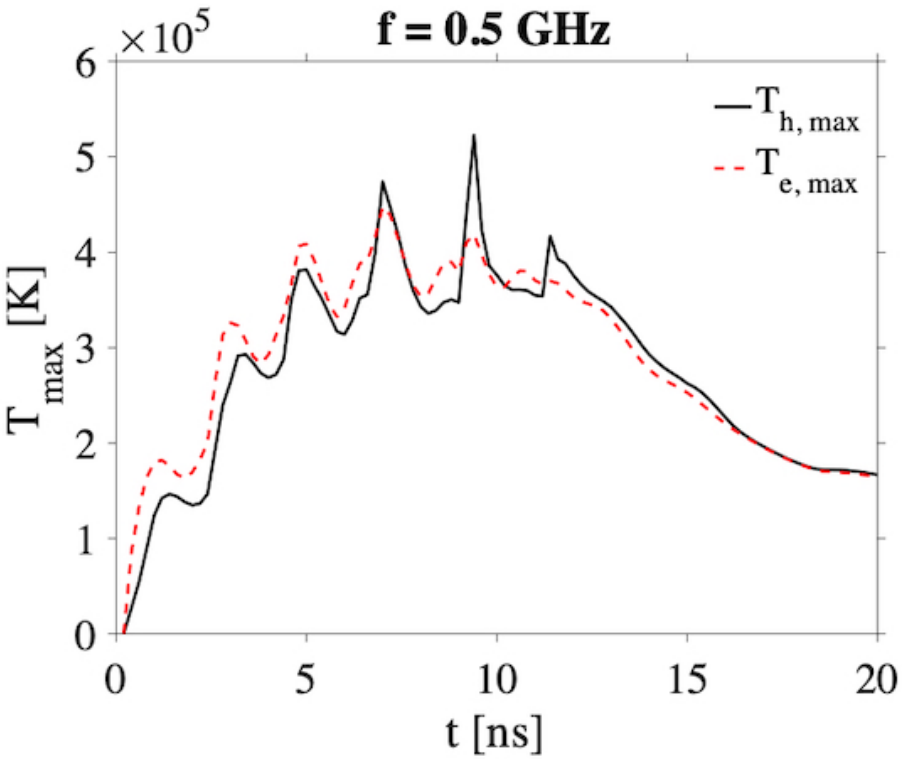

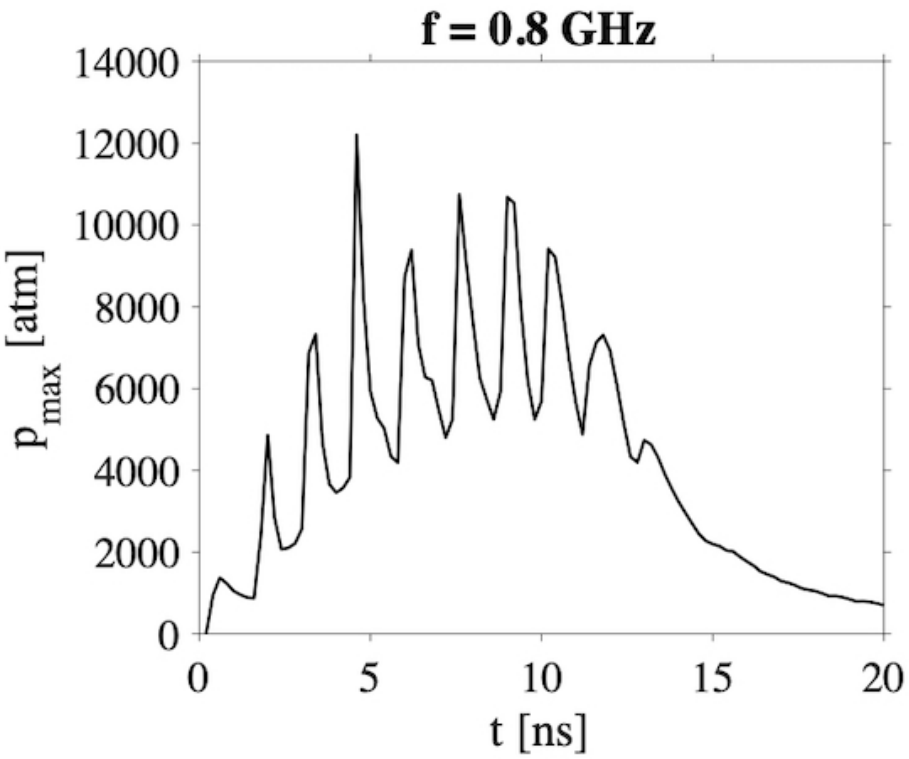

Post-Breakdown Phase

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Post-Breakdown Phase

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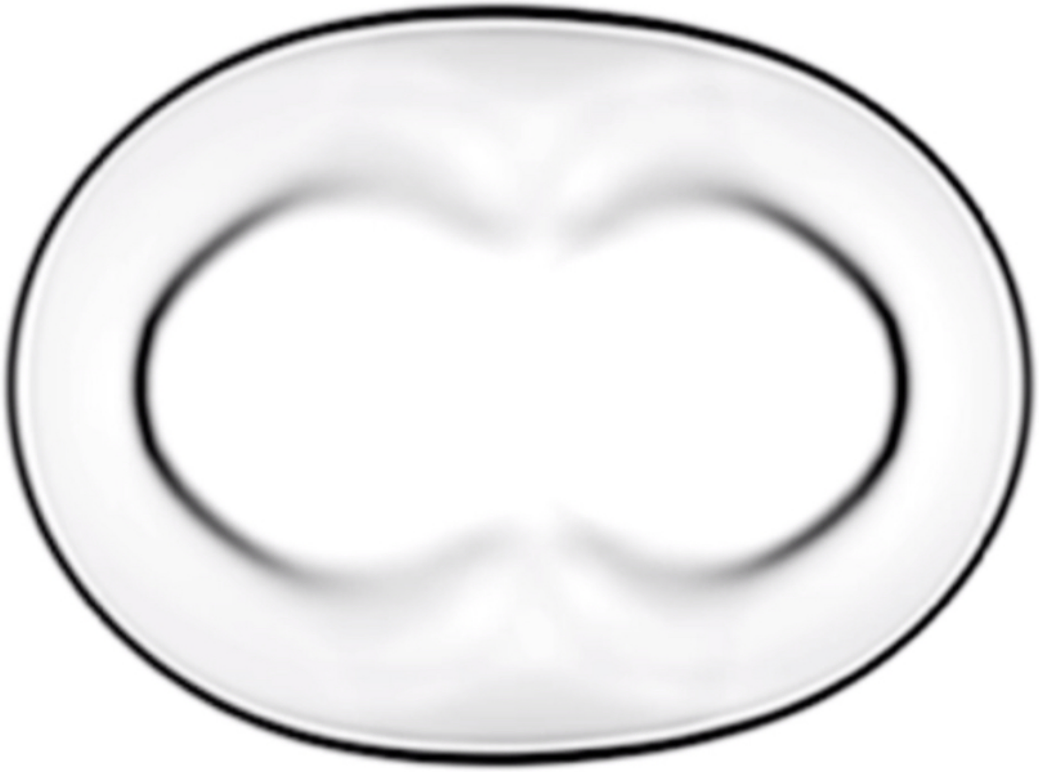
Post-Breakdown Phase



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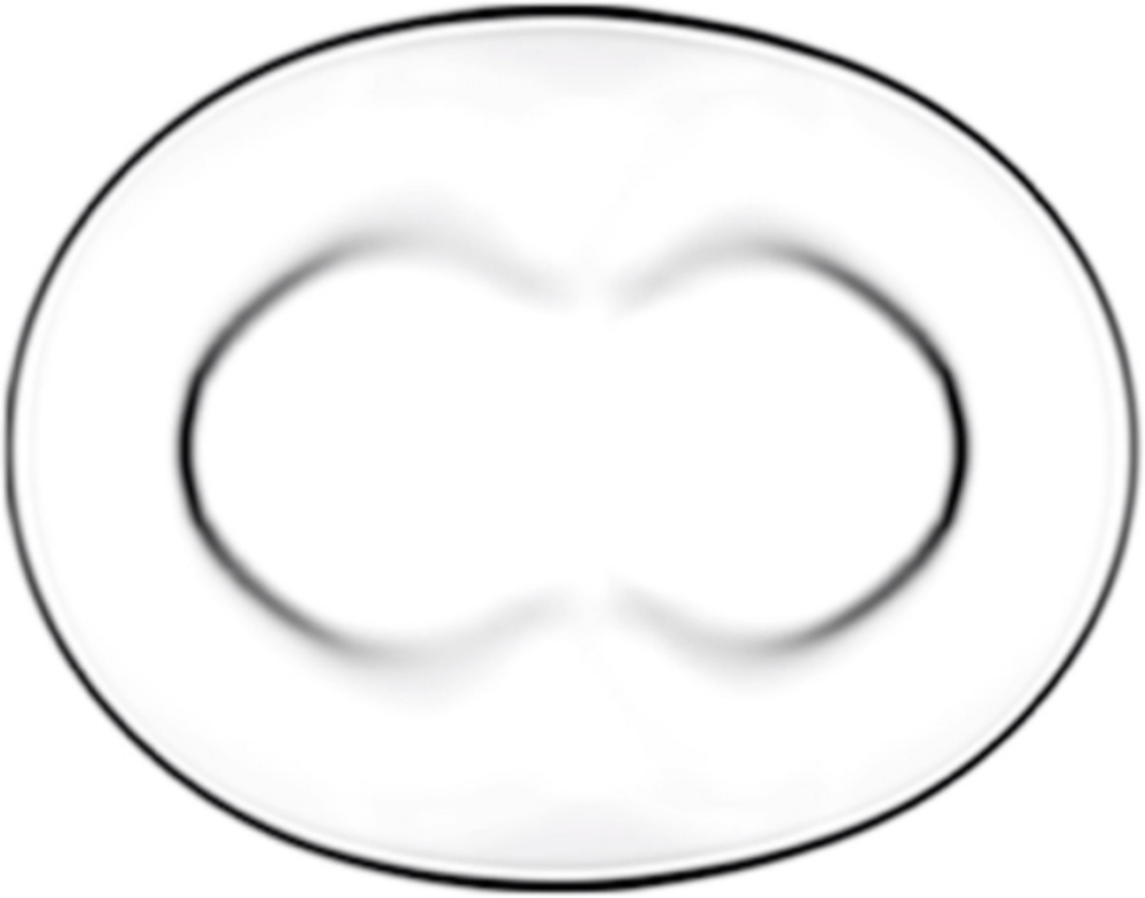
Post-Breakdown Phase



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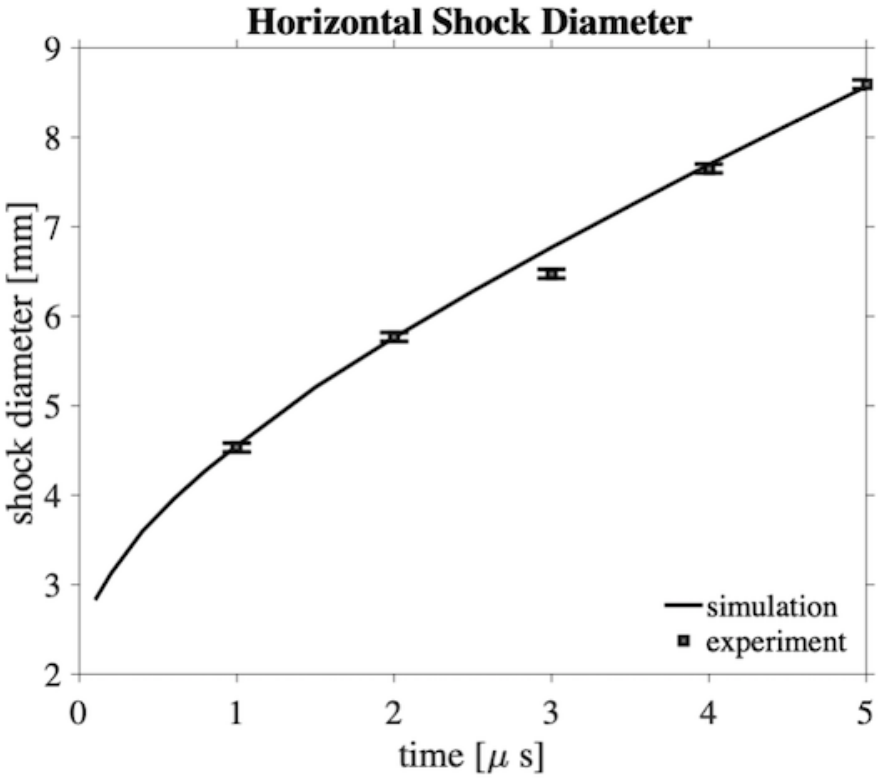
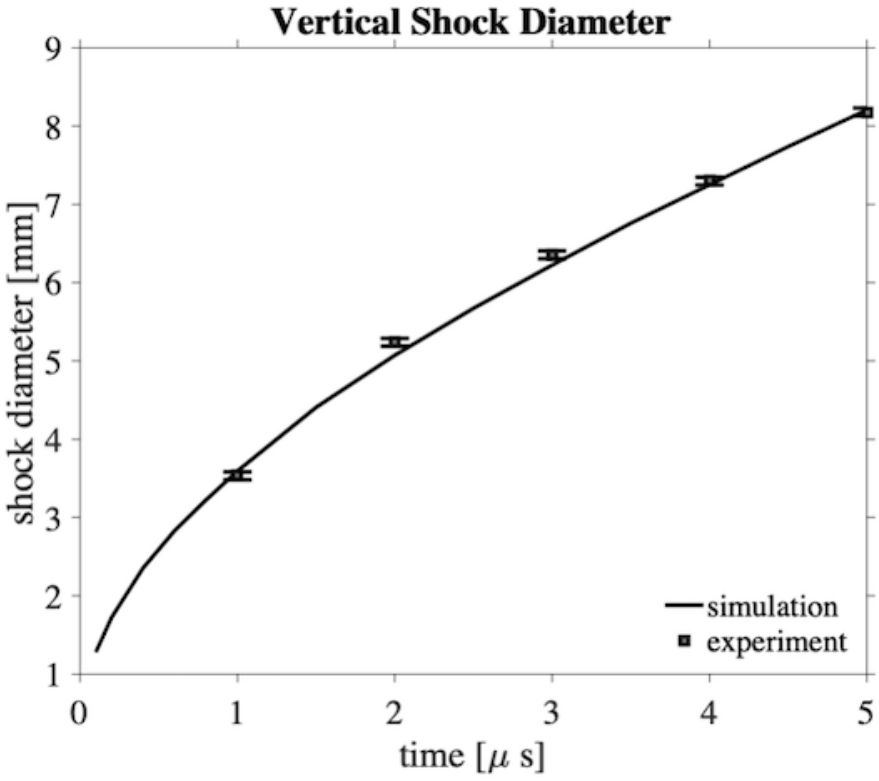
Post-Breakdown Phase: model validation





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Background and Motivation
Background and Problem Definition
Motivation and Objective

Physical Model
Hydrodynamic Equations
Radiation
Numerical Method

Results
Laser-Plasma Interaction
Post-Discharge Evolution

Conclusion and Future Work

Conclusion and Future Work

Summary:

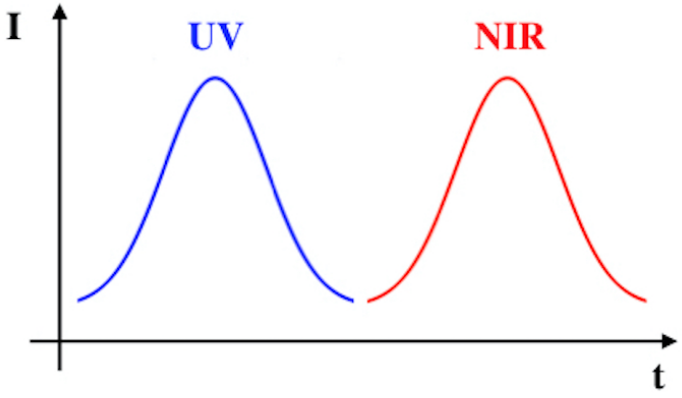
- **Validated** the suggested mechanism
  - triggered by *MPI*
  - guided by *MPI* (depletion of reactants) and *IE*
  - sustained by *IB*

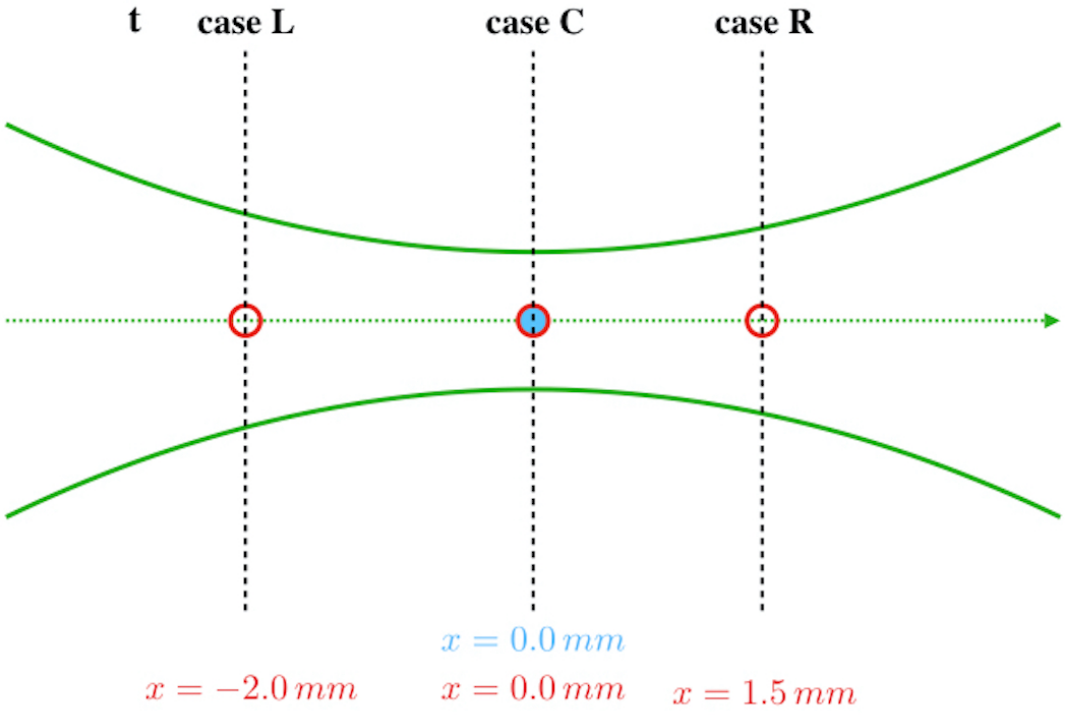
A. Alberti, A. Munafò, C. Pantano, J. B. Freund, M. Panesi, "Plasma kernel dynamics in non-equilibrium laser discharges", (in preparation).

Future Work:

- **Radiation Field**:
  - solve RTE in multi-dimension
- **Applications**:
  - model CFD cases of engineering interest
    - dual pulse
    - flow control (e.g., supersonic ignition, drag reduction)

Future Work: Dual Pulse





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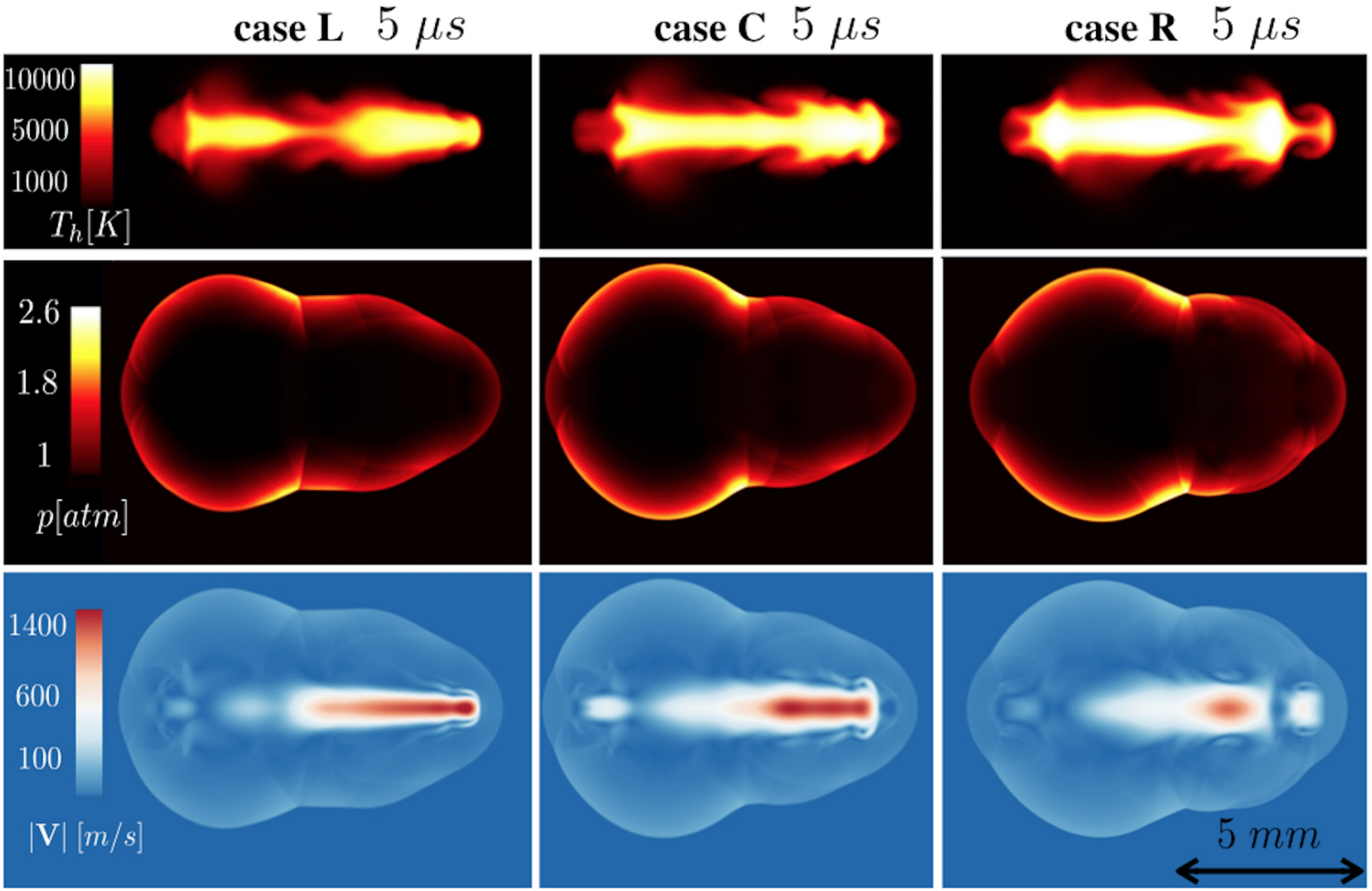
Future Work: Dual Pulse



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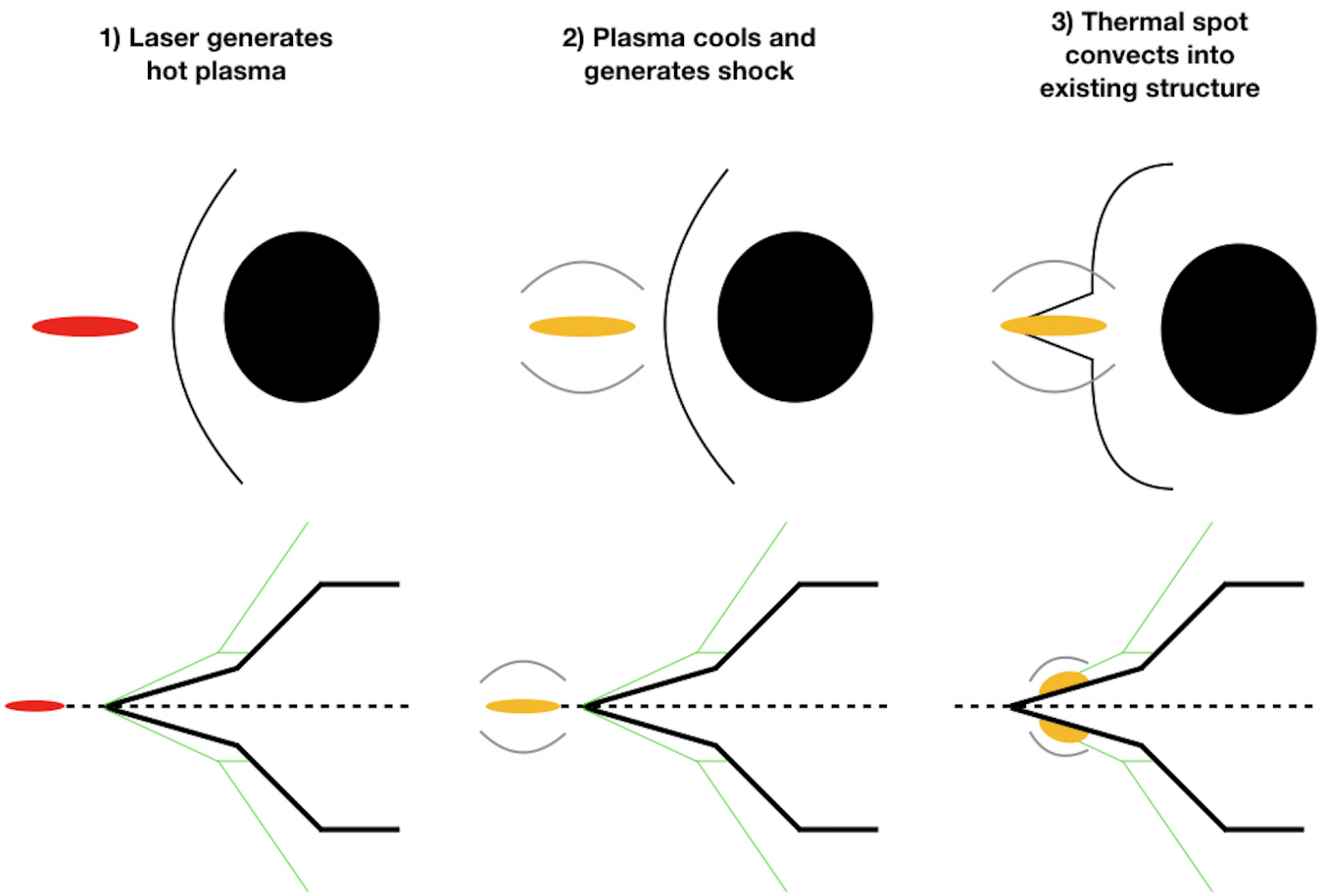
Future Work: Flow Control



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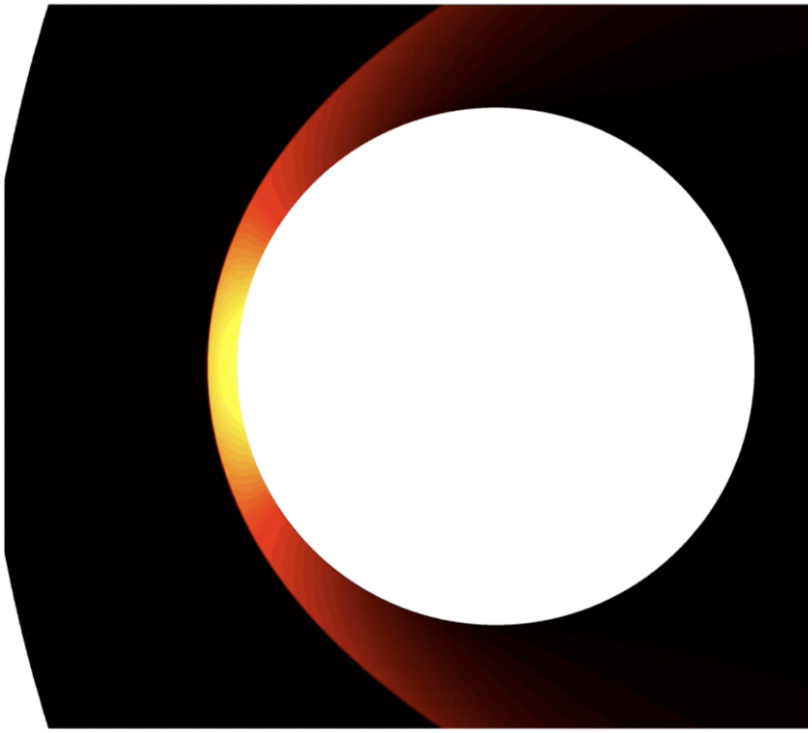

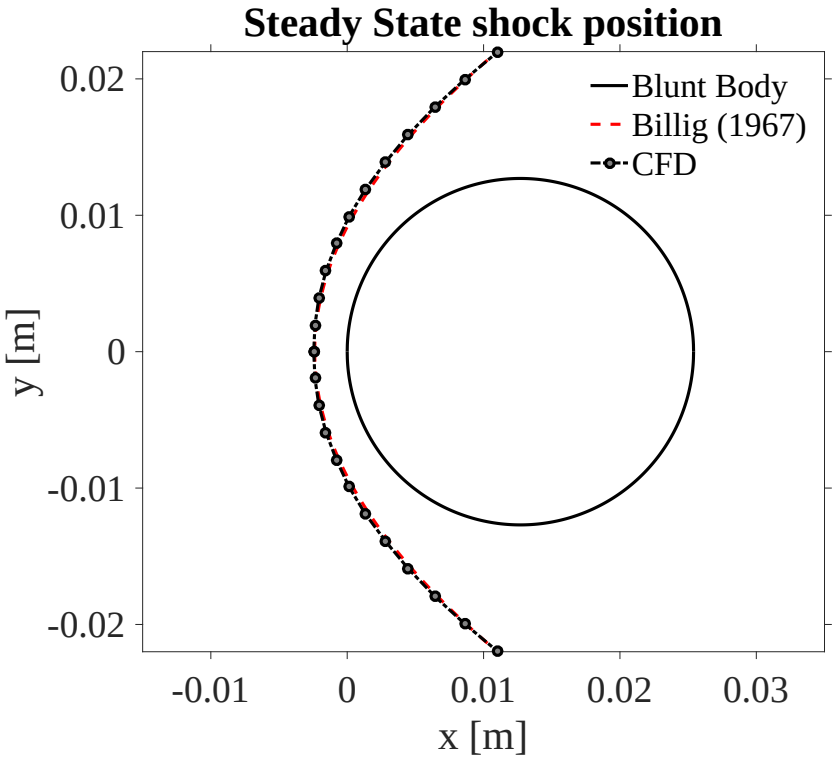

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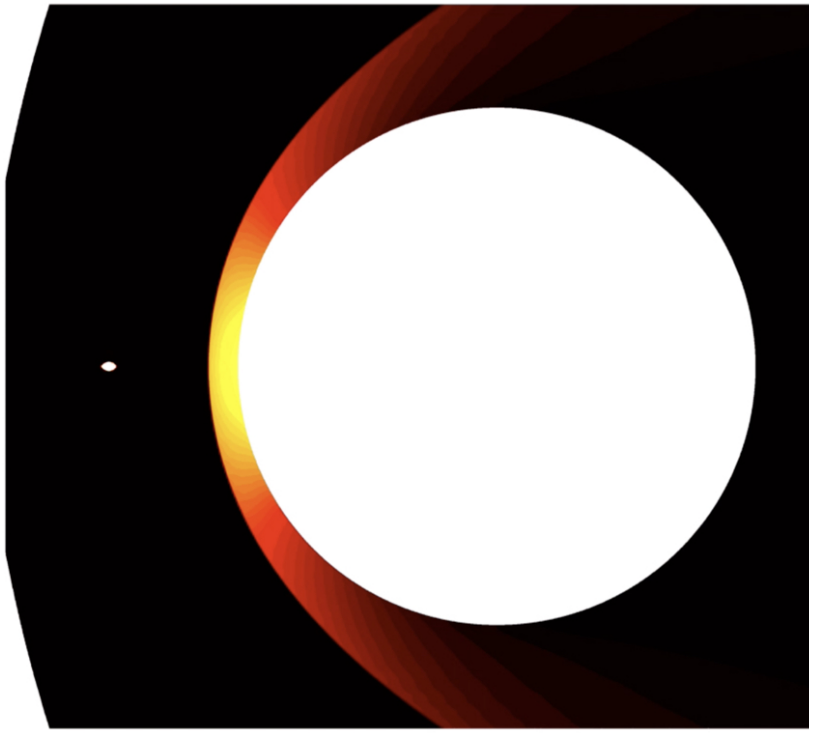

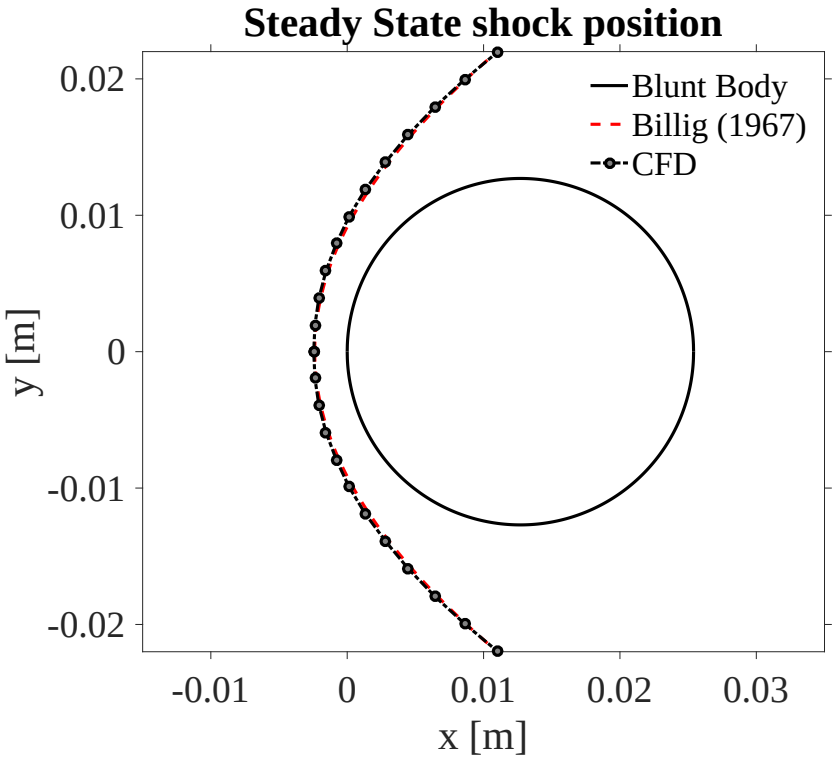

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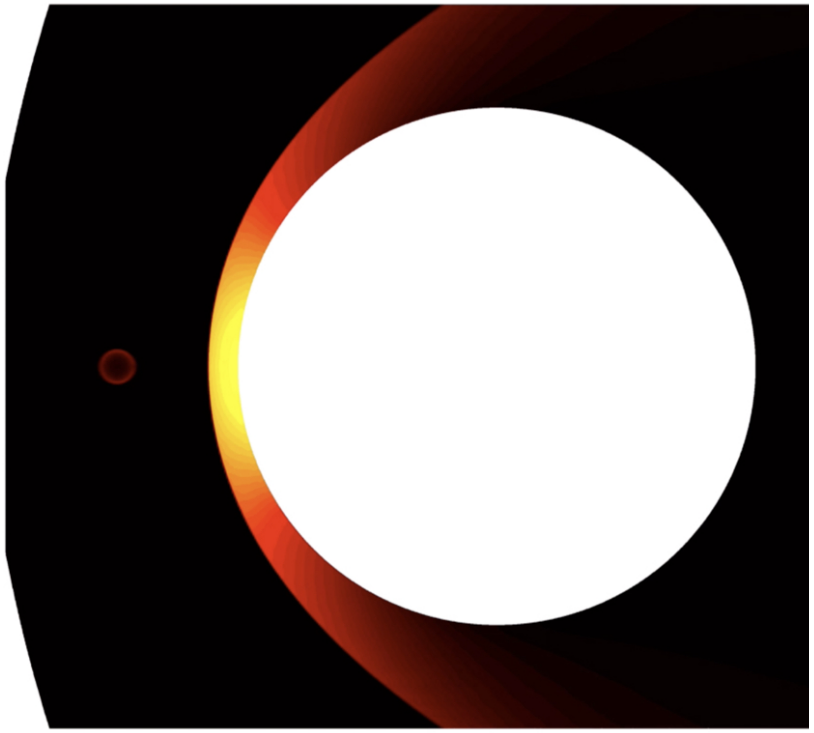

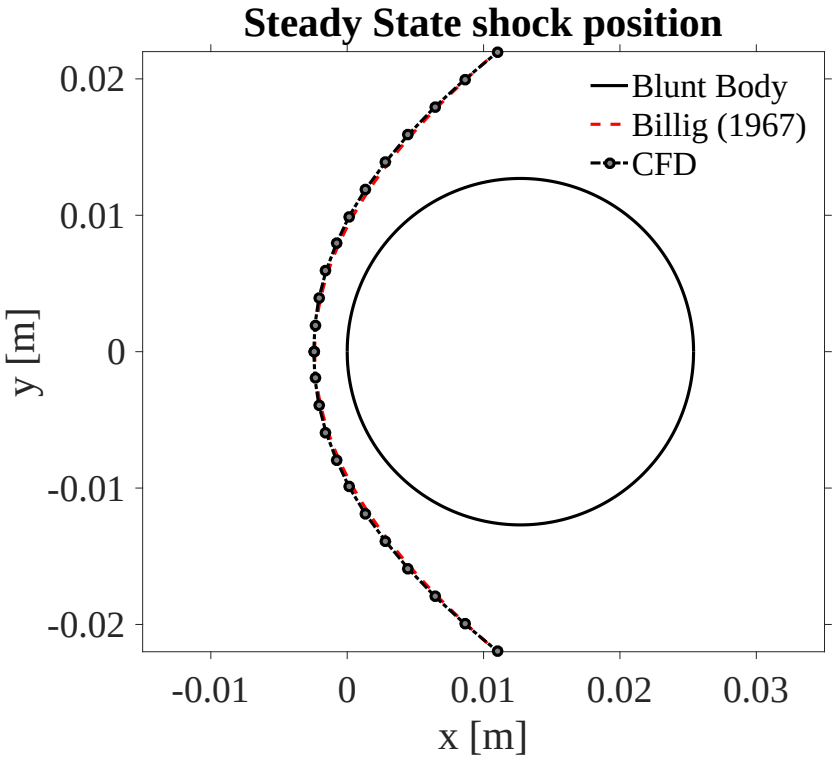

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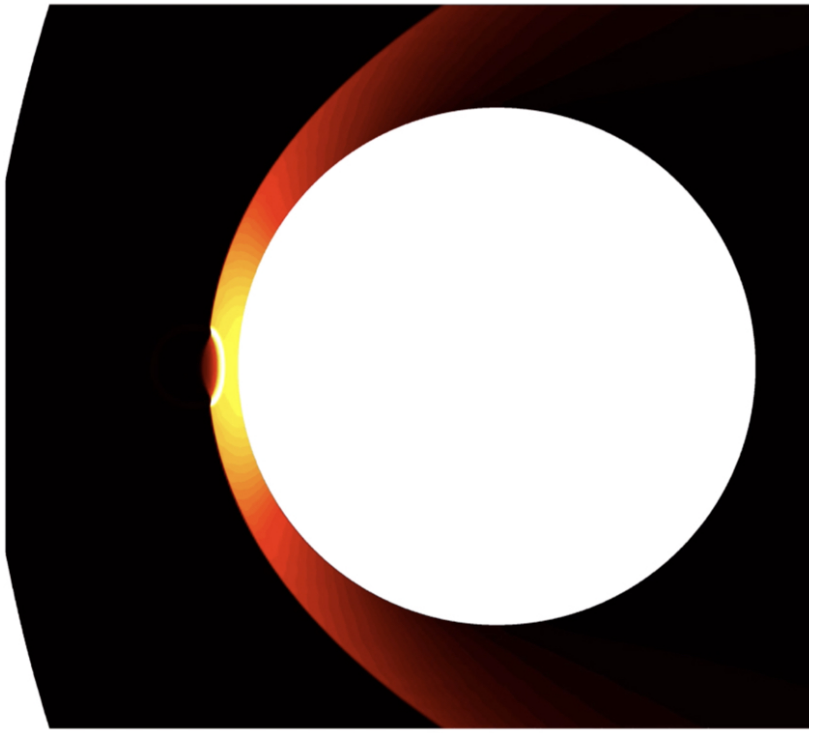

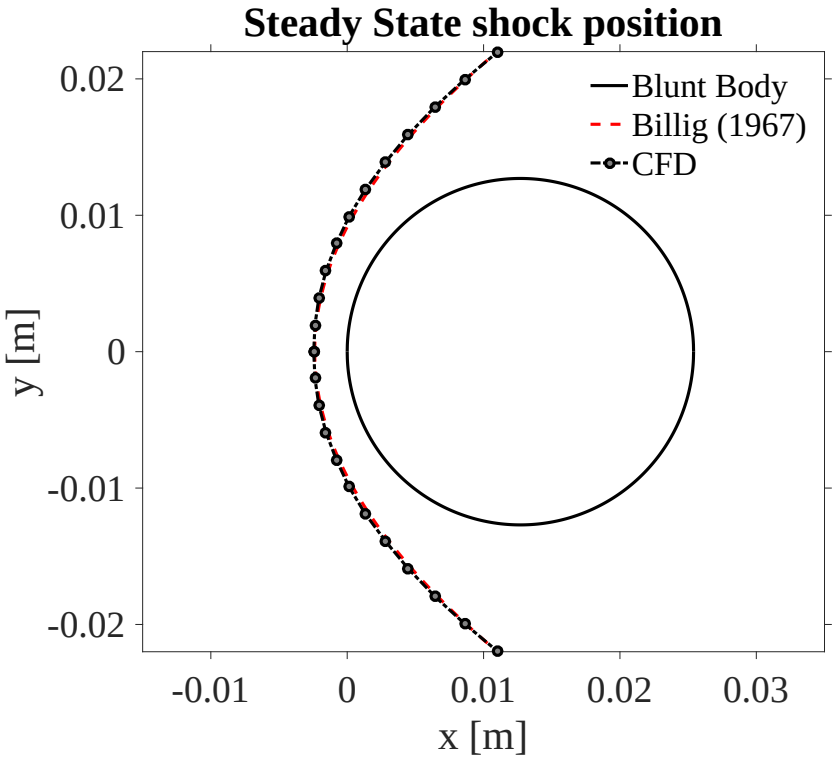

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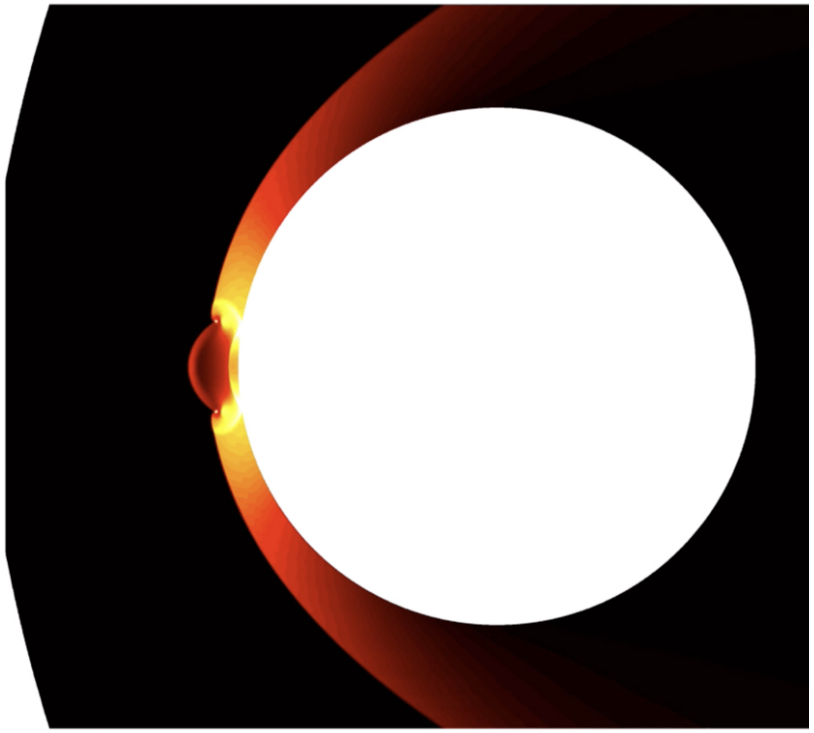

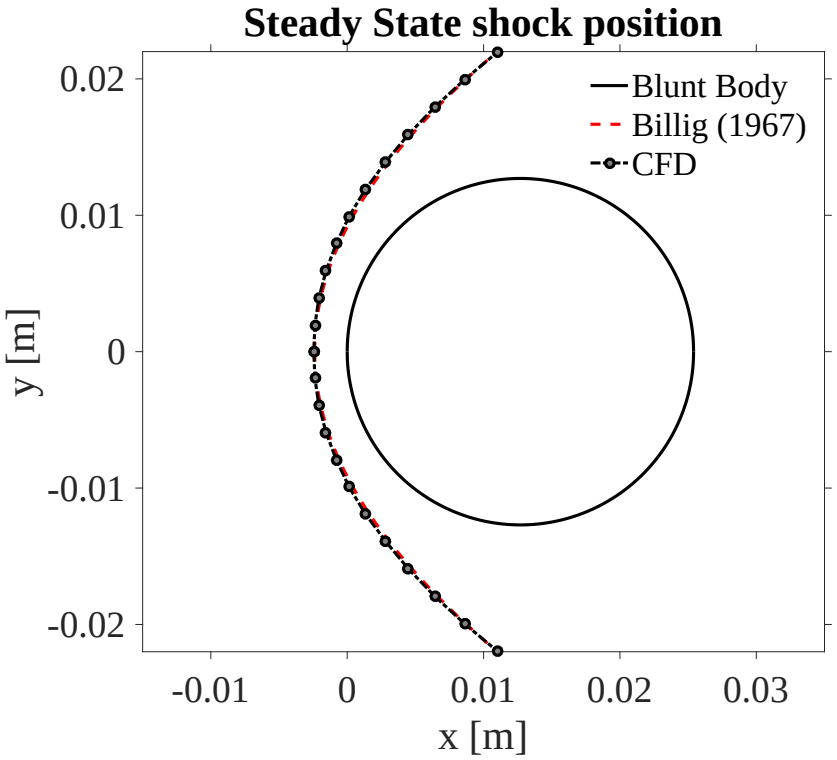

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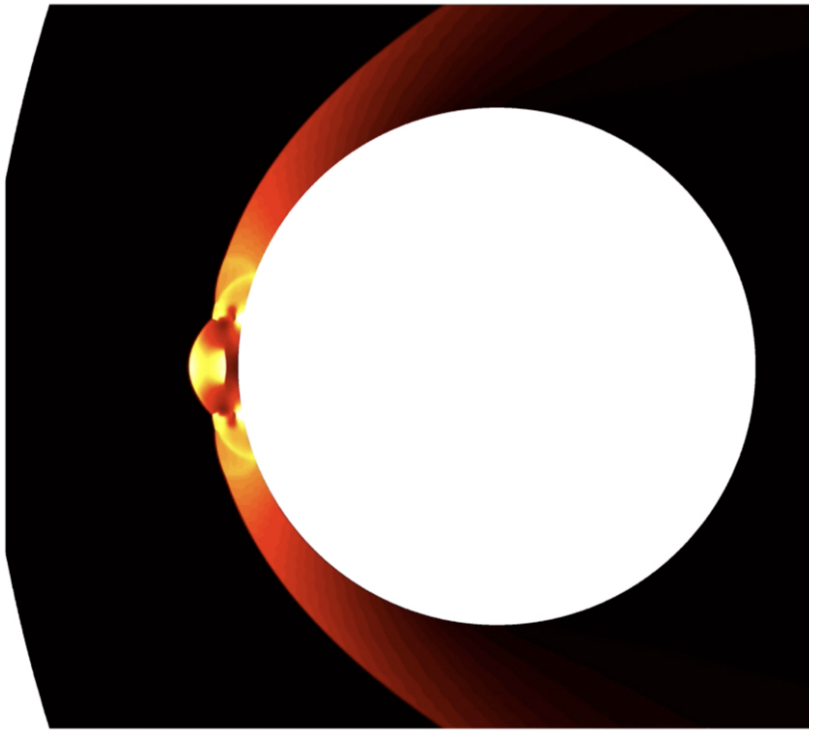

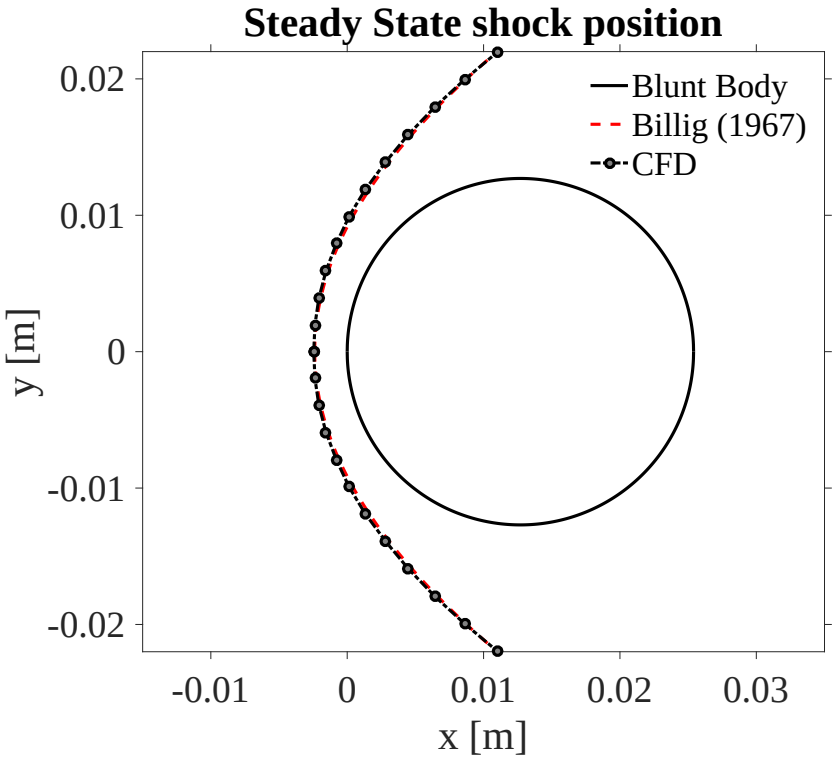

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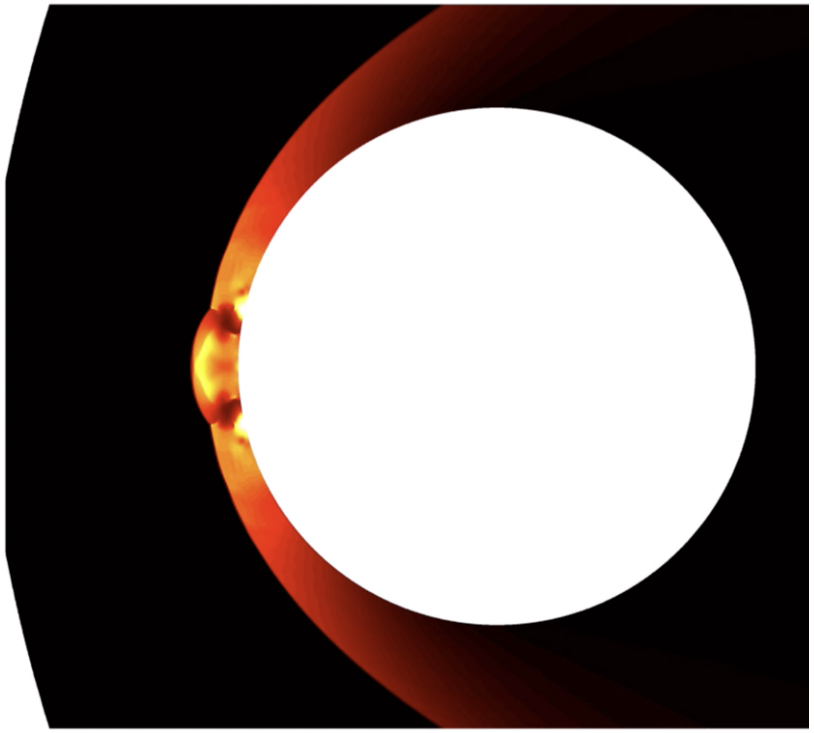

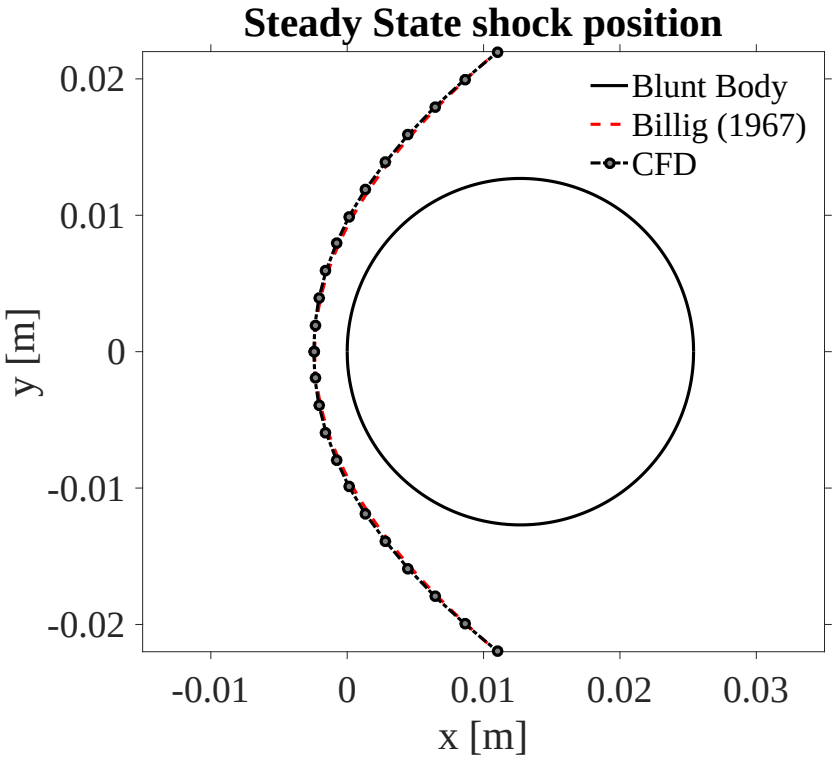

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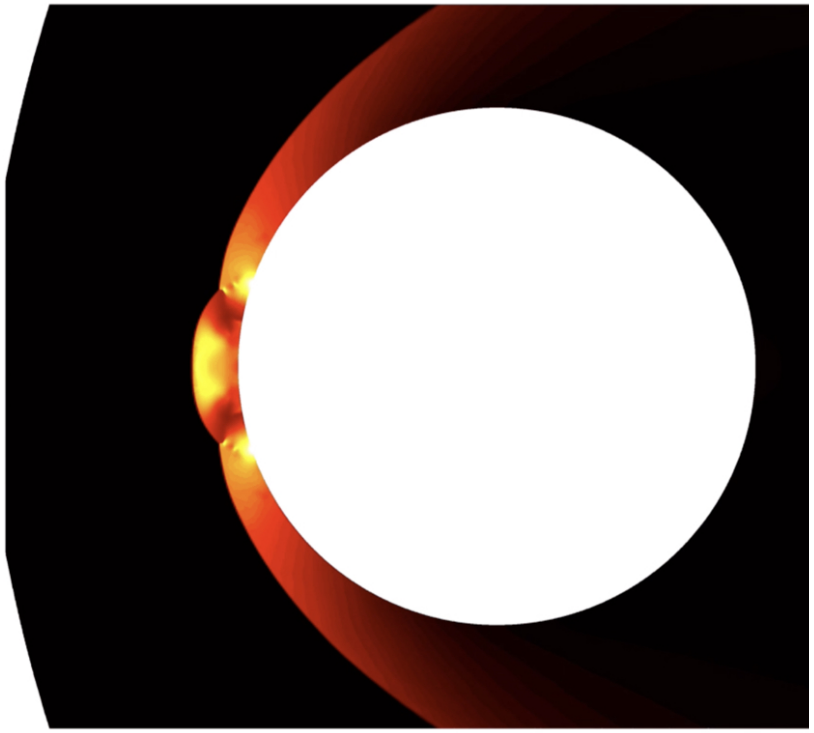

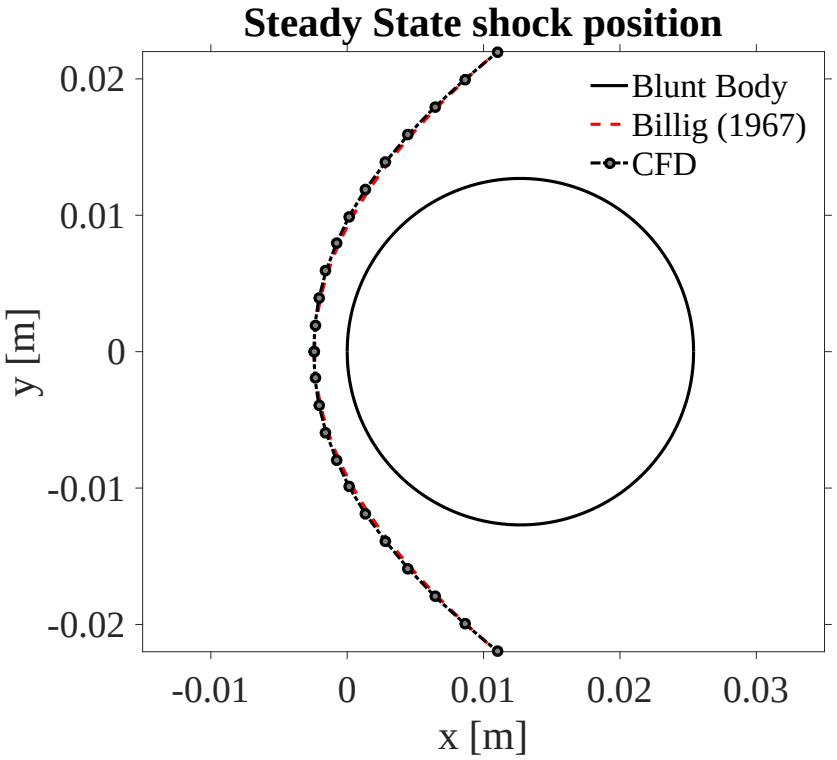

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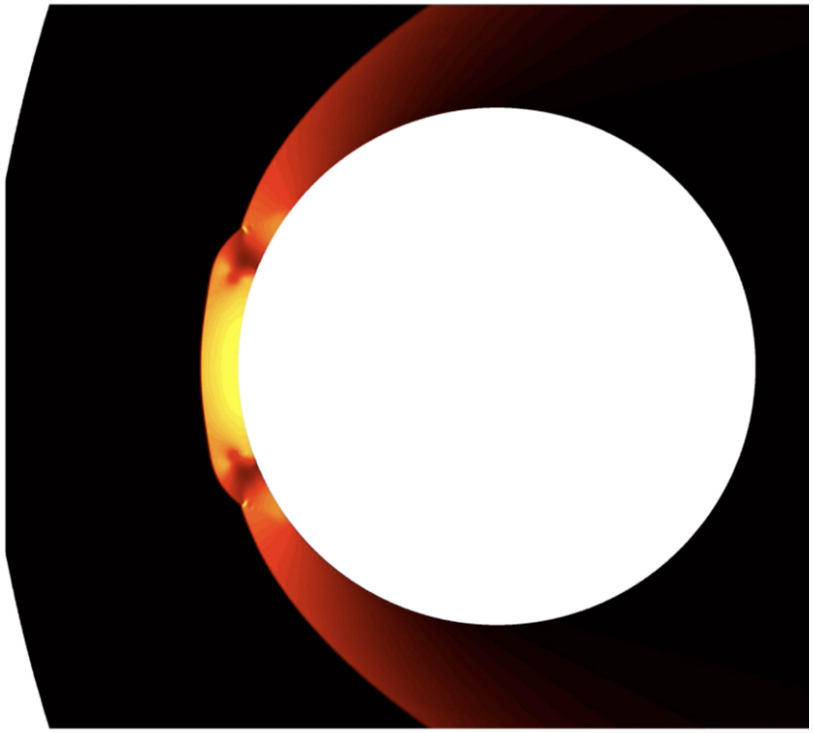

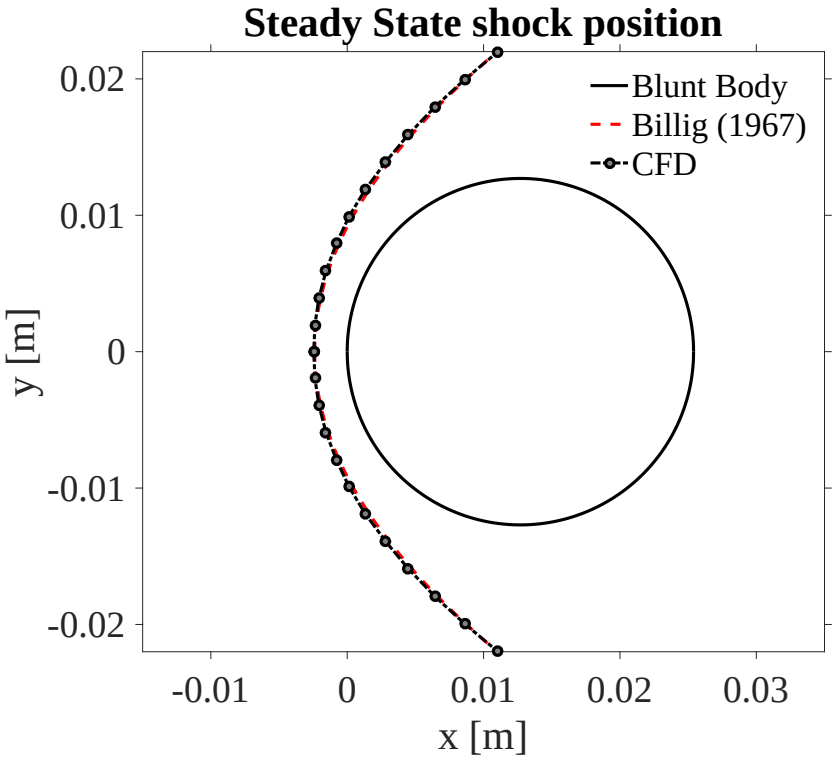

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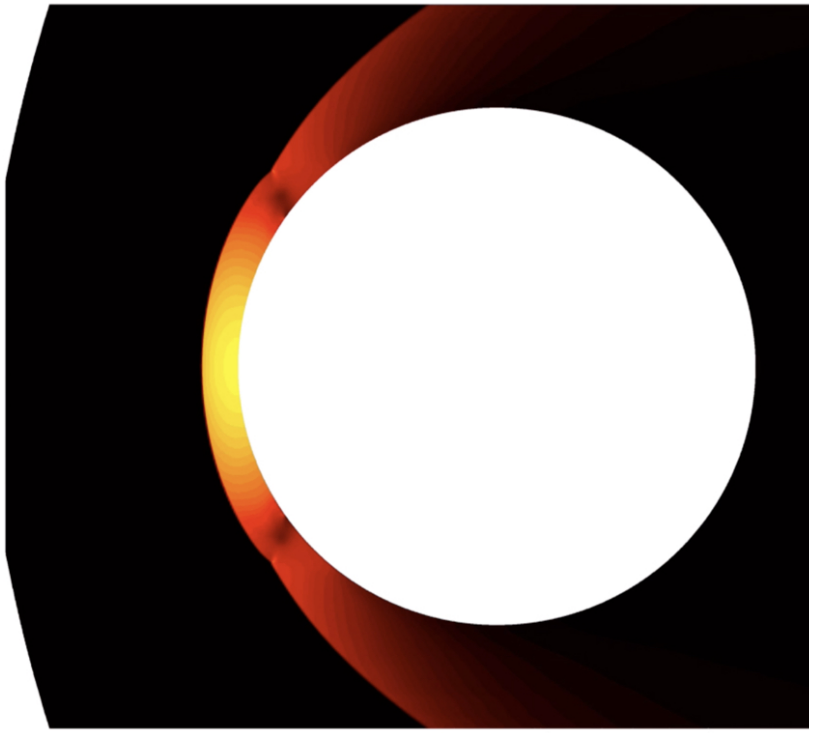

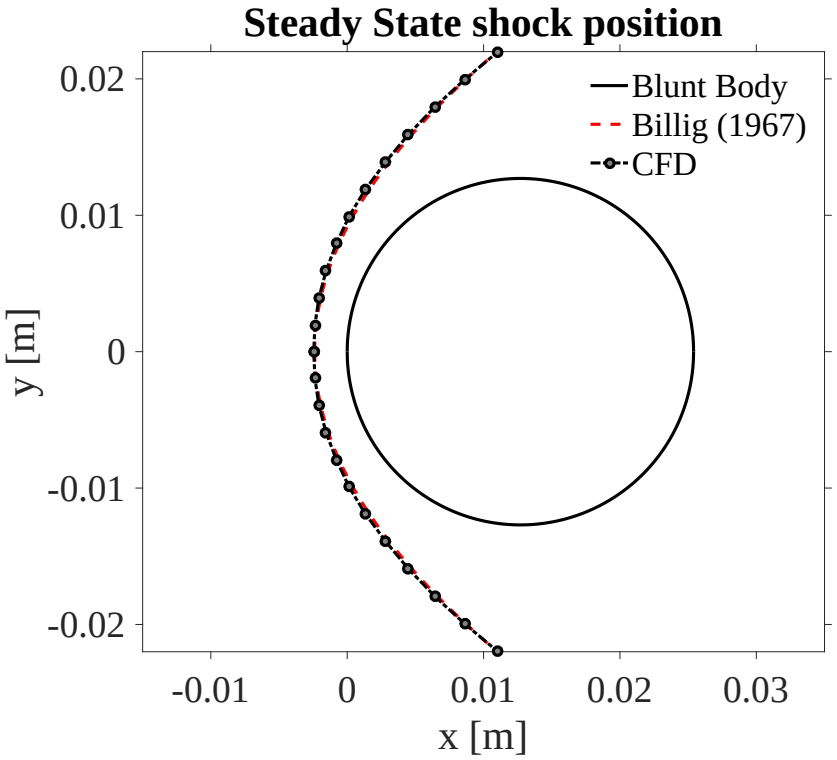

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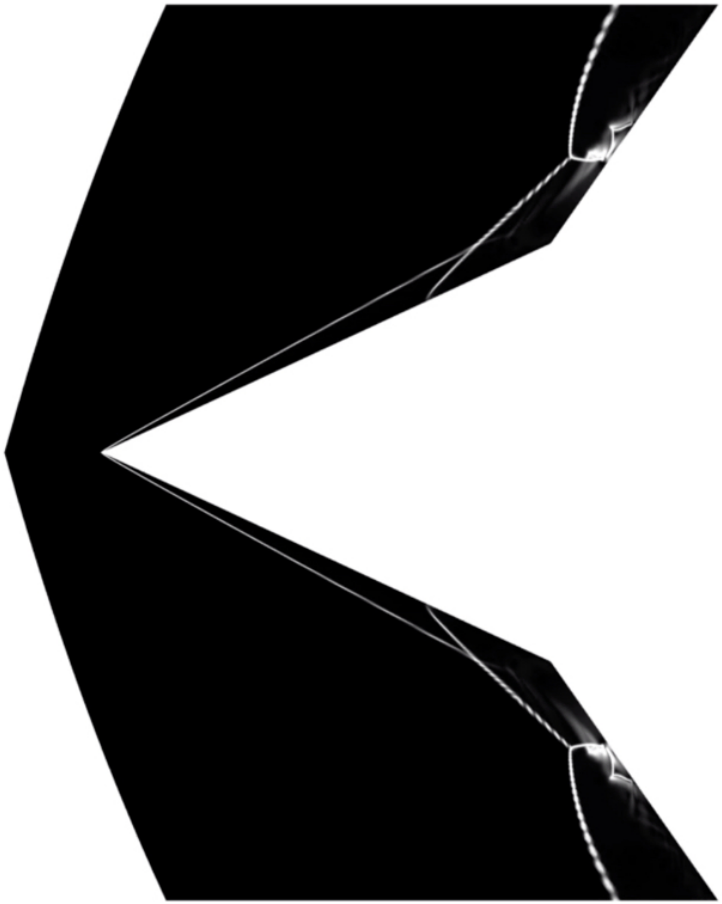

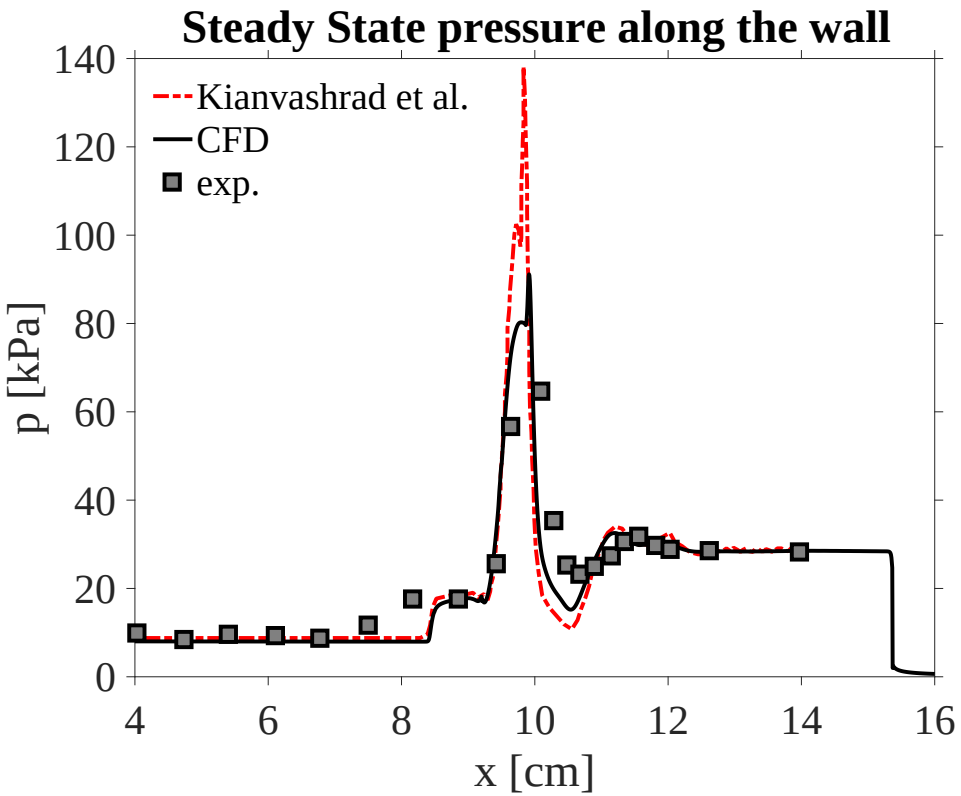

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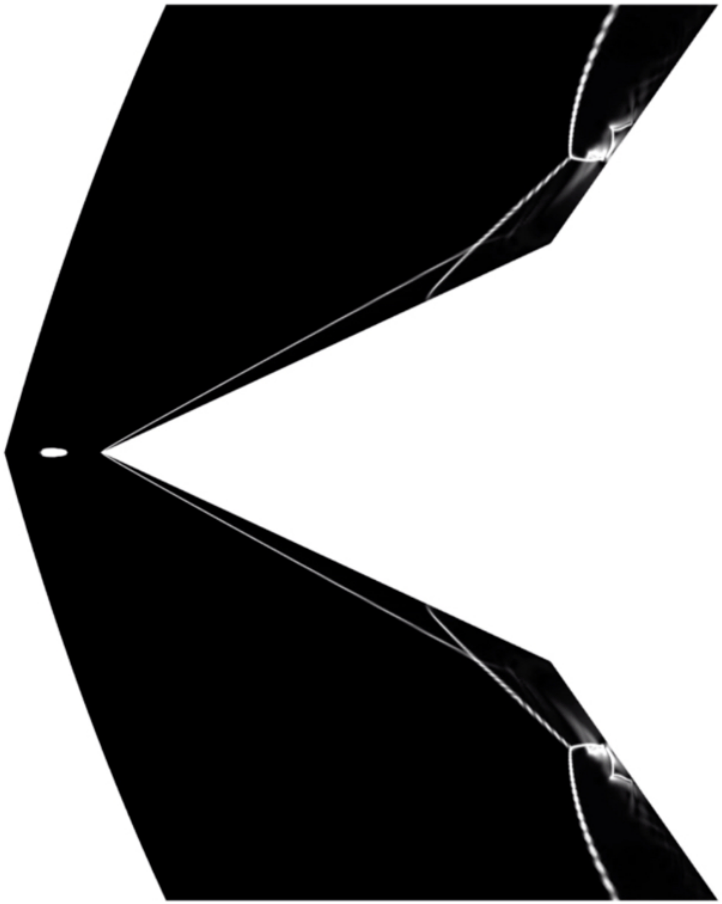

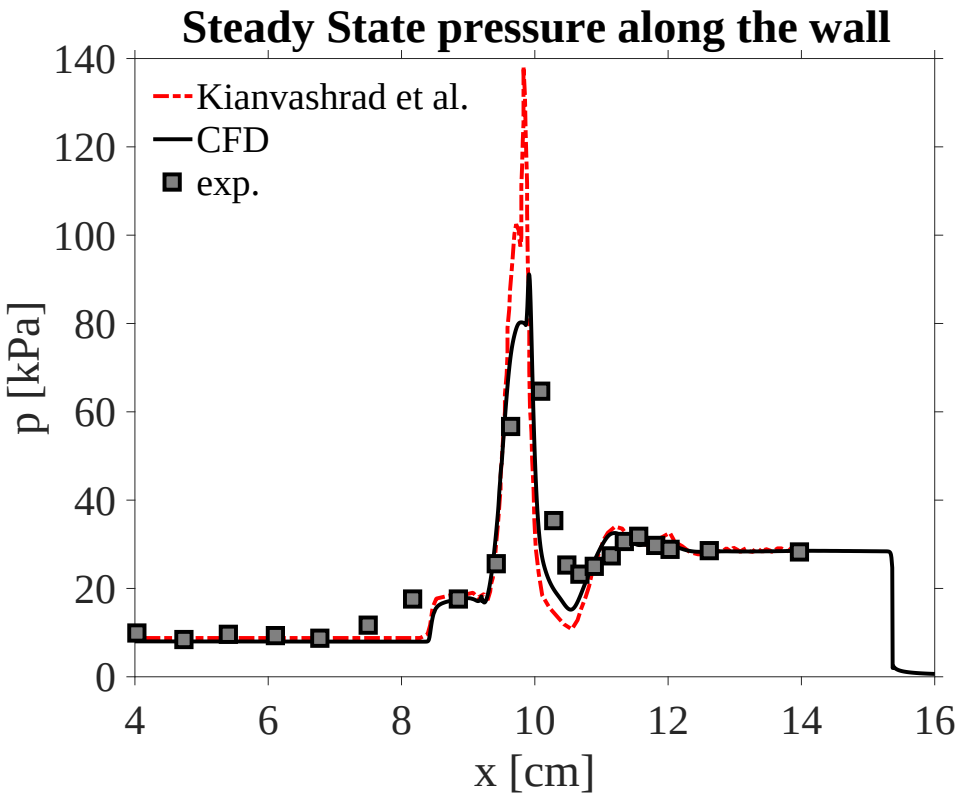

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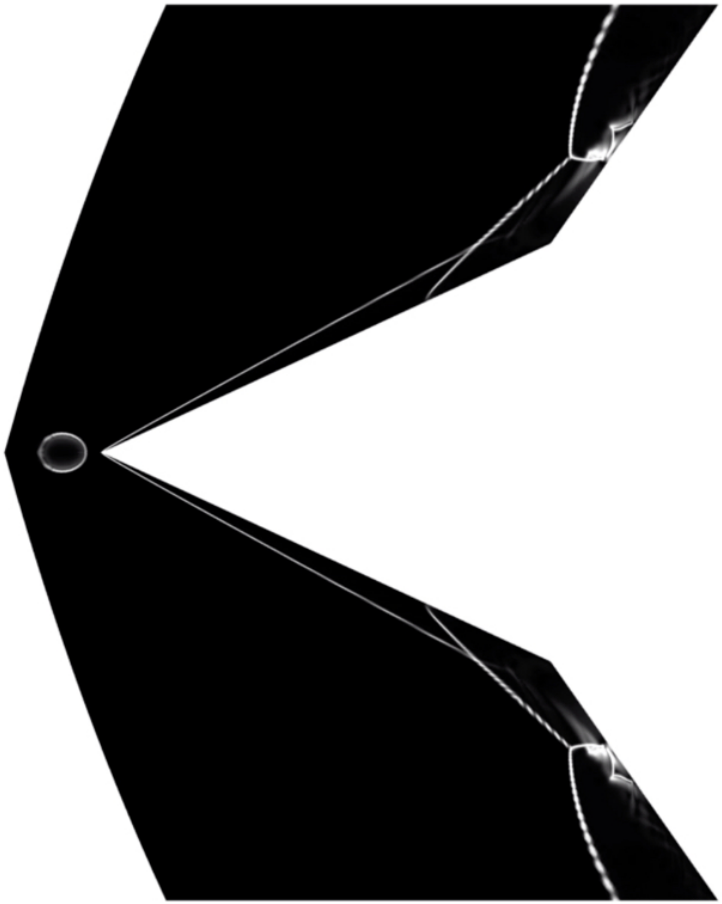

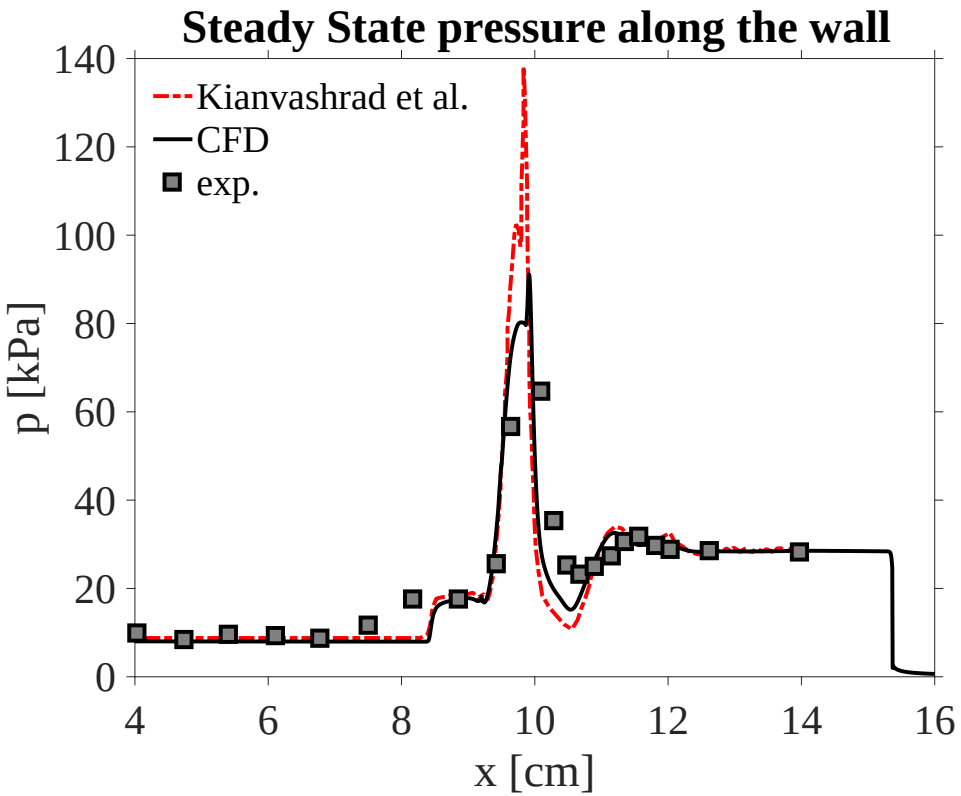

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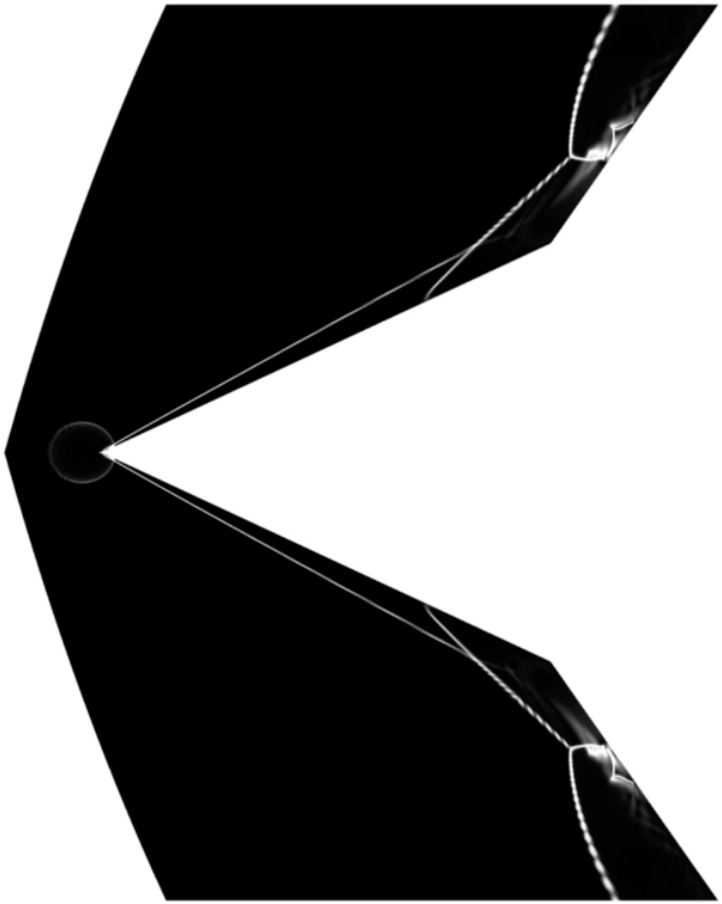

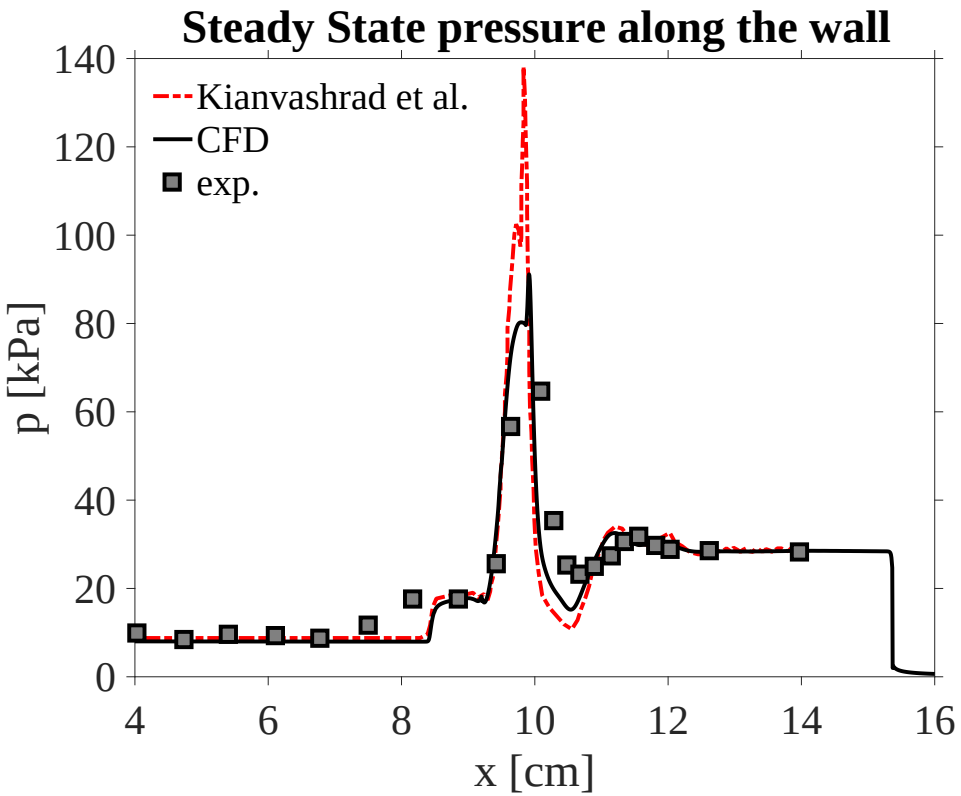

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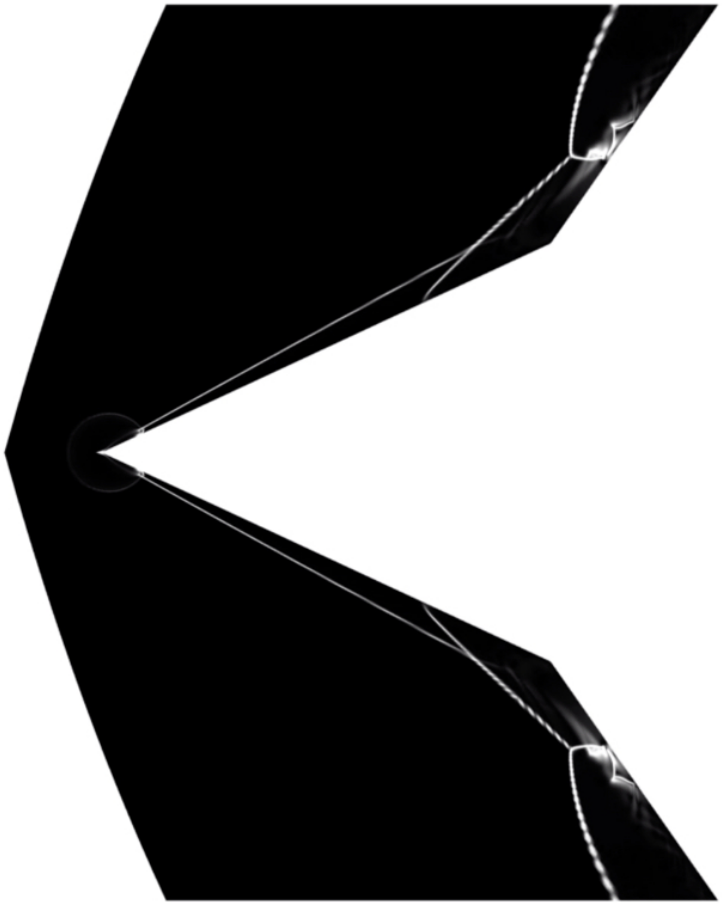

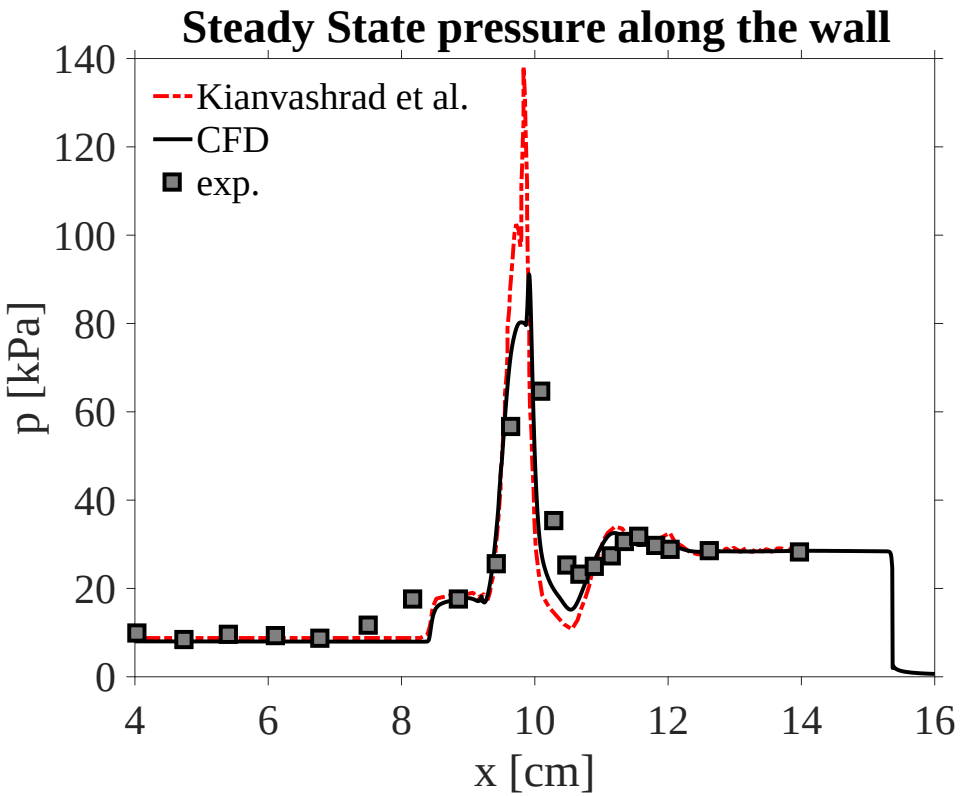

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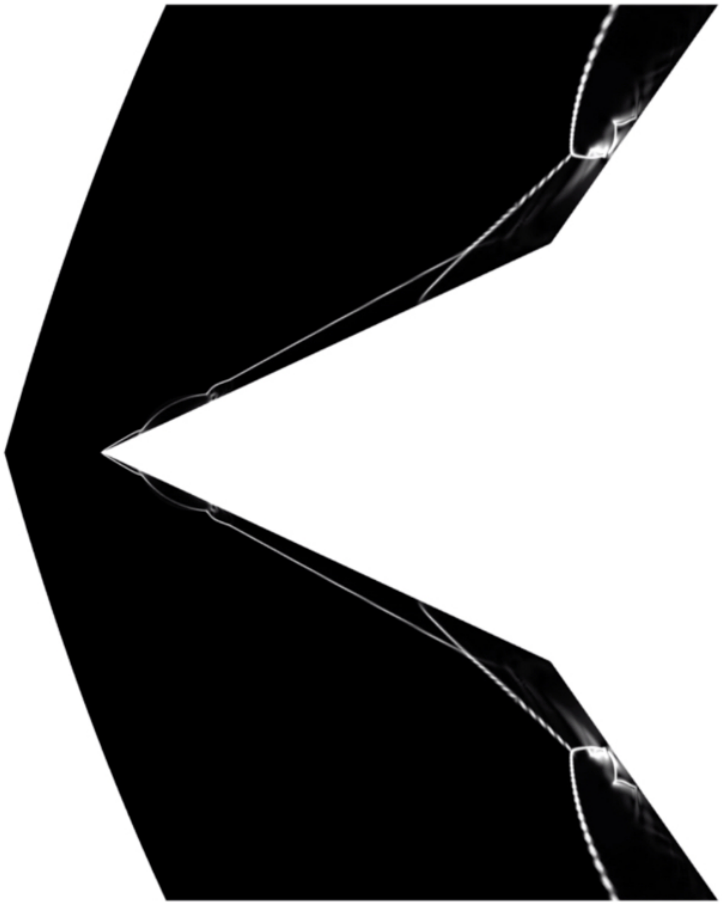
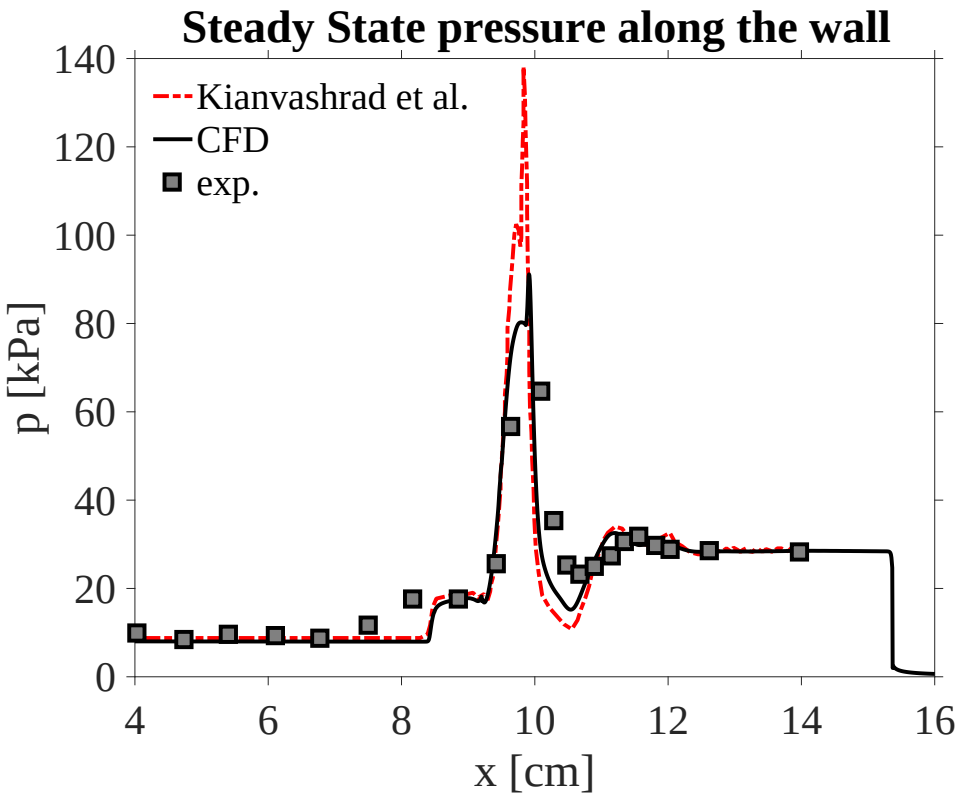
Future Work: Flow Control





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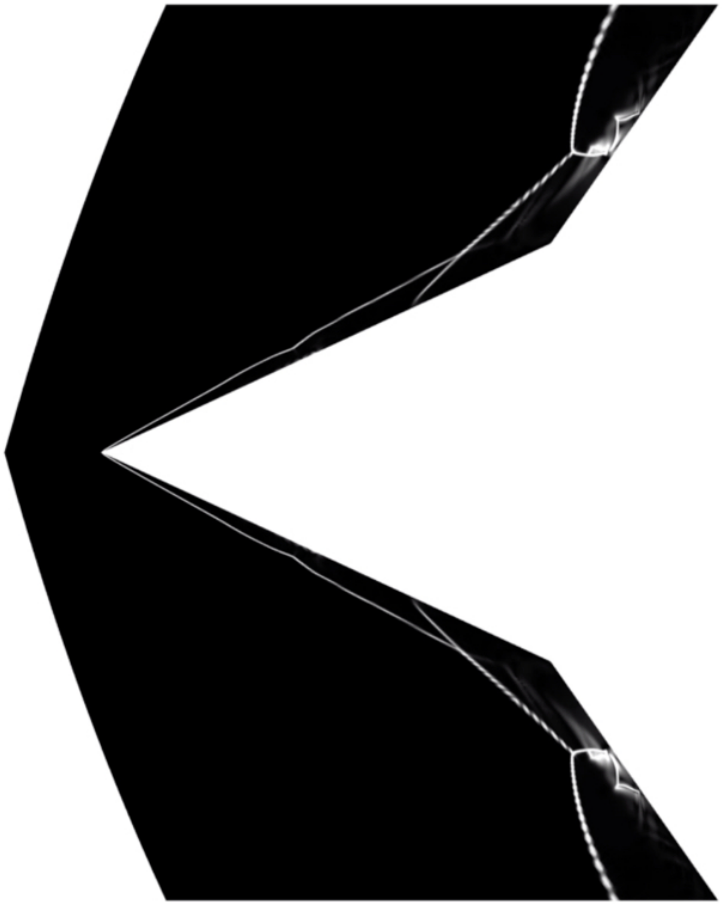

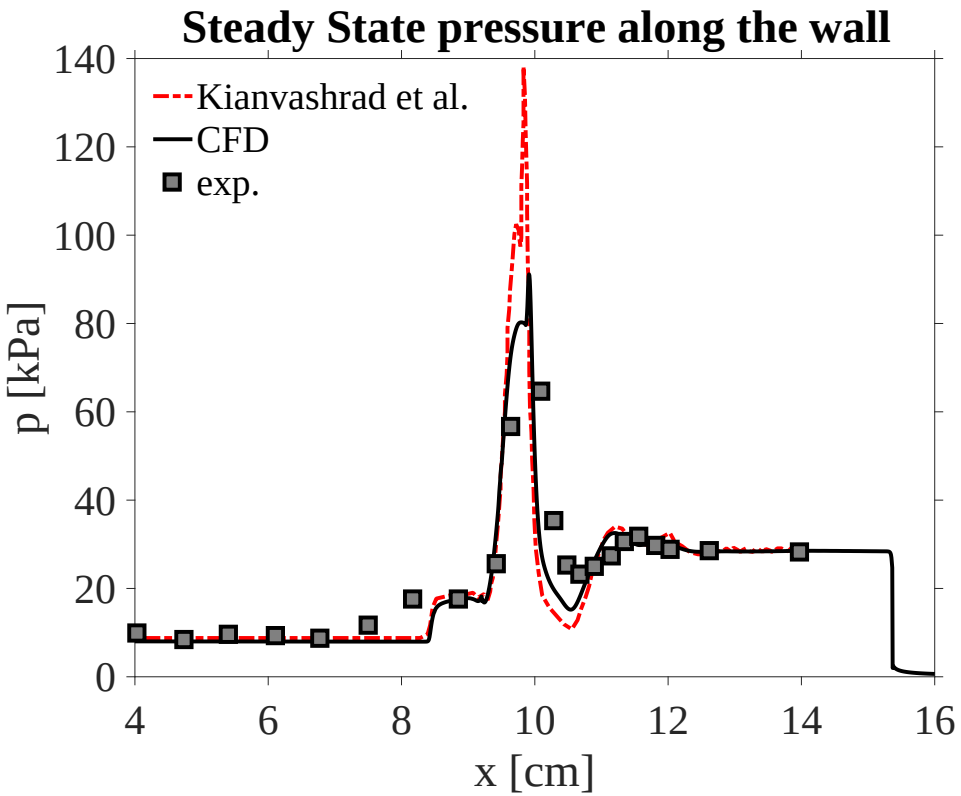

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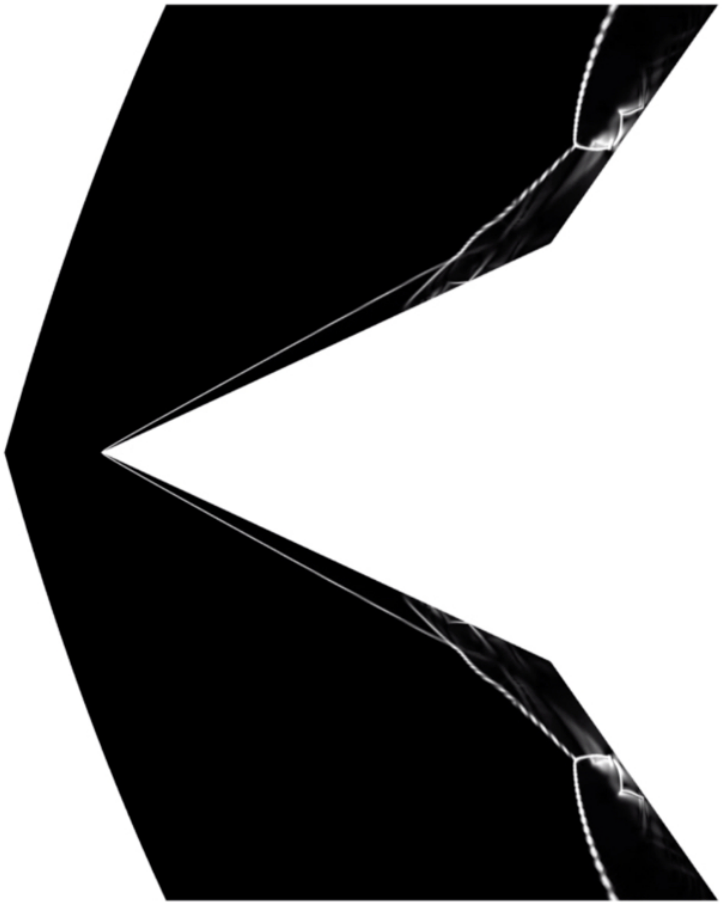

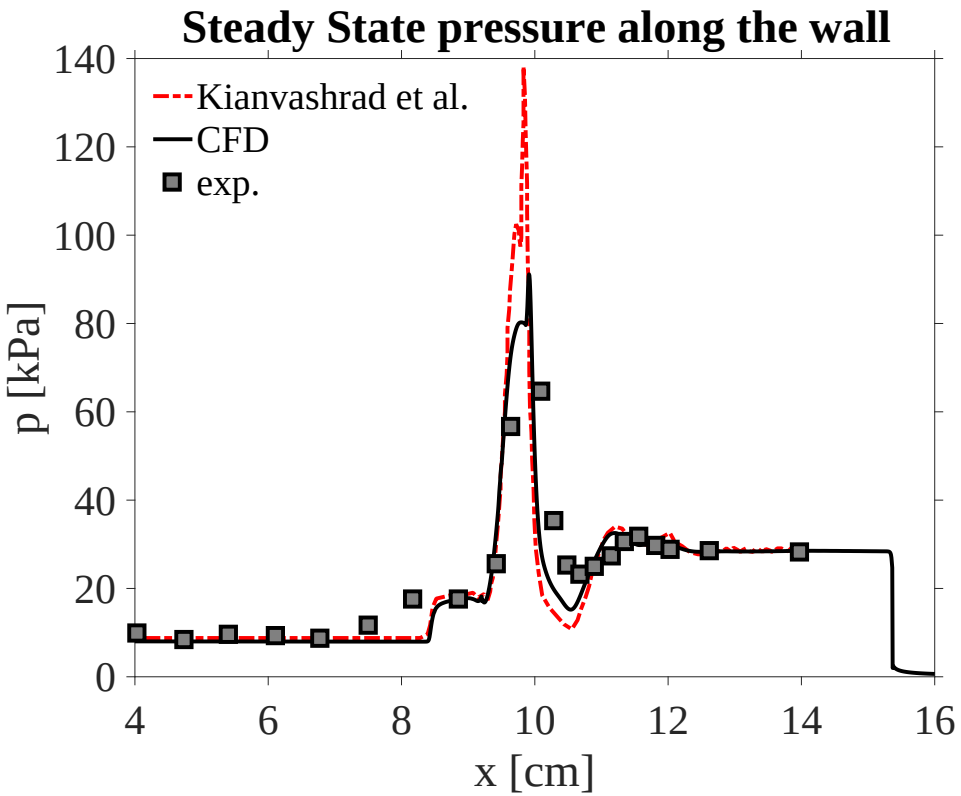

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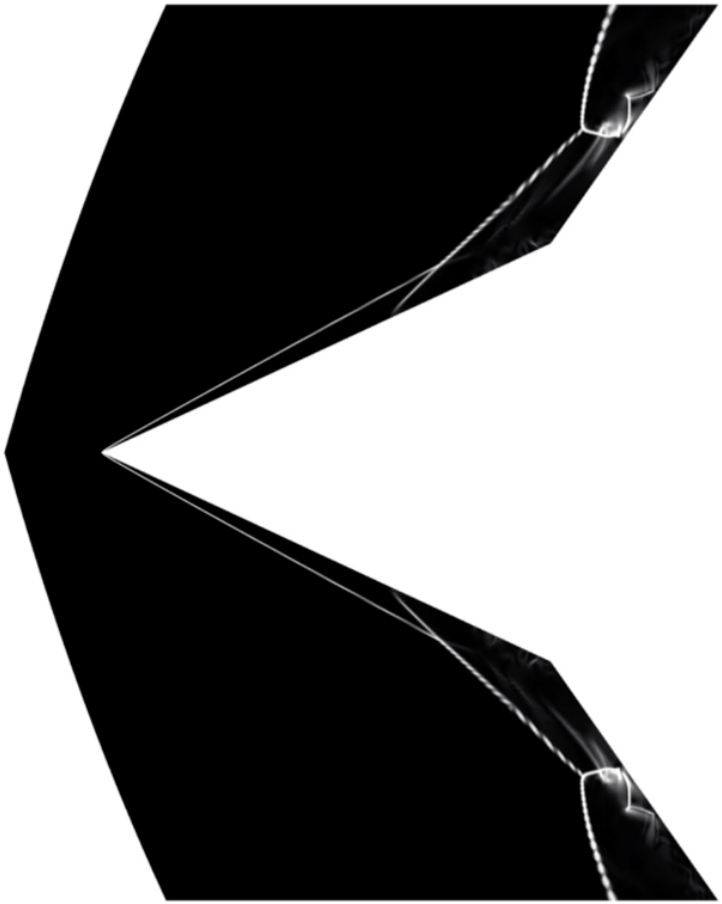

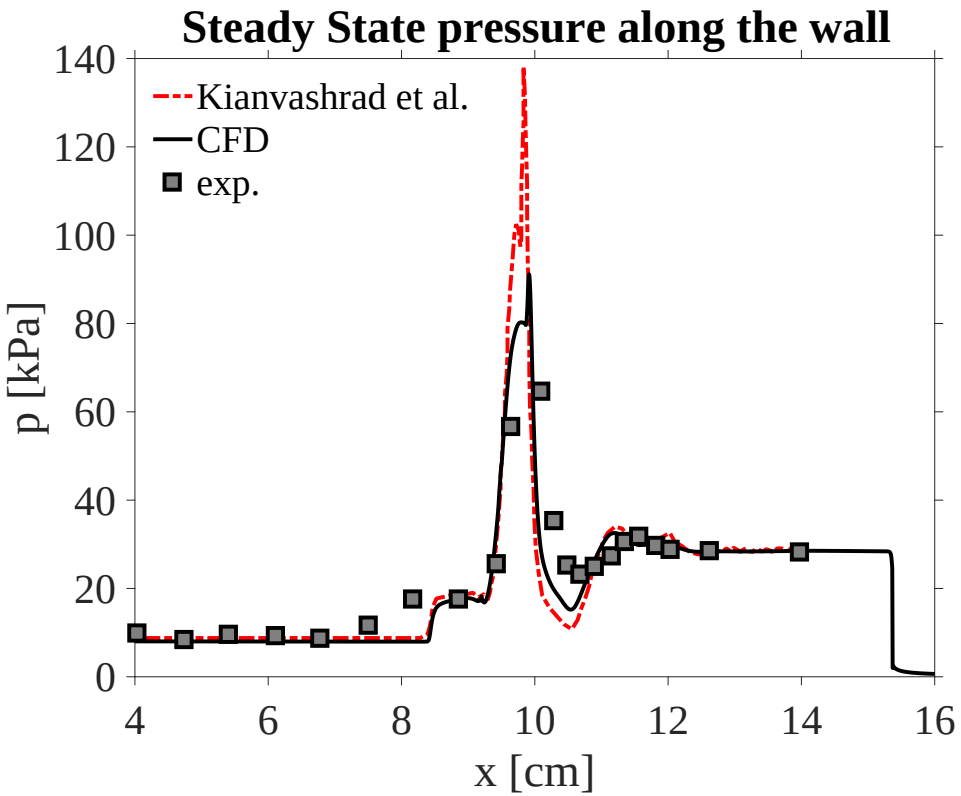

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Thanks!

Thank you for your attention

Questions?

Acknowledgments

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