

PLASMA
ACCELERATOR SYSTEMS FOR
COMPACT
RESEARCH
INFRASTRUCTURES



WP3 – Theory and simulations

Jorge Vieira (IST) and Andrea Rossi (INFN-Milan) for WP3



**Funded by
the European Union**

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Goal: Support the current design of high repetition rate plasma components for the EuPRAXIA project with beam/plasma/laser interaction simulations tools and theoretical models to guarantee acceleration, radiation and transport of high-quality electron beams.

Site 1 - beam driven



Site 2 - laser driven



TDR was recently released
<https://doi.org/10.15161/oar.it/k57qz-5qk09>

Stage 0: 400-500 MeV
 Stage 1: 1 GeV

Laser Phase 0: 3 J
 Laser Phase 1: 5 J

Key objective: produce high quality electrons for FEL in plasma

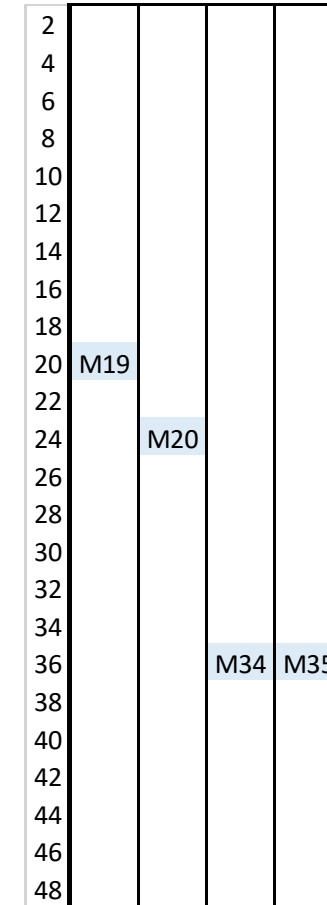
Task 3.1 Development of a toolkit for hydrodynamic simulations
DESY (Maxence Thevenet, Task Leader), INFN, ELI-ERIC, CLPU, CNRS

Task 3.2 Design in the High-Repetition Rate Regime.
ELI-ERIC (Alexander Molodzhentsev, Task Leader), INFN, DESY, CNRS

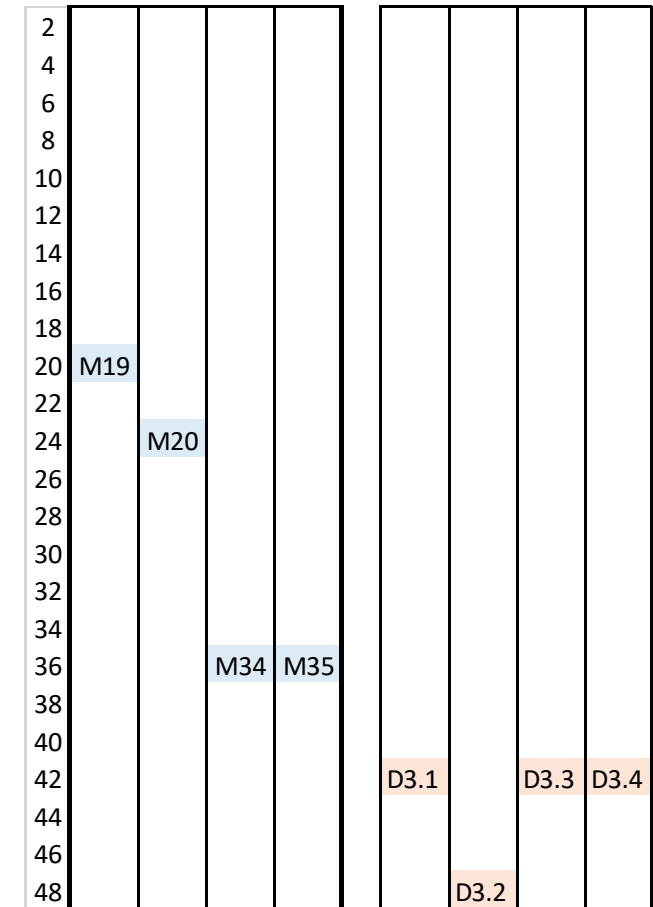
Task 3.3 Development of codes for radiation emission in a plasma module.
IST (Jorge Vieira, Task Leader), INFN, GSI, UROM, ELI-ERIC

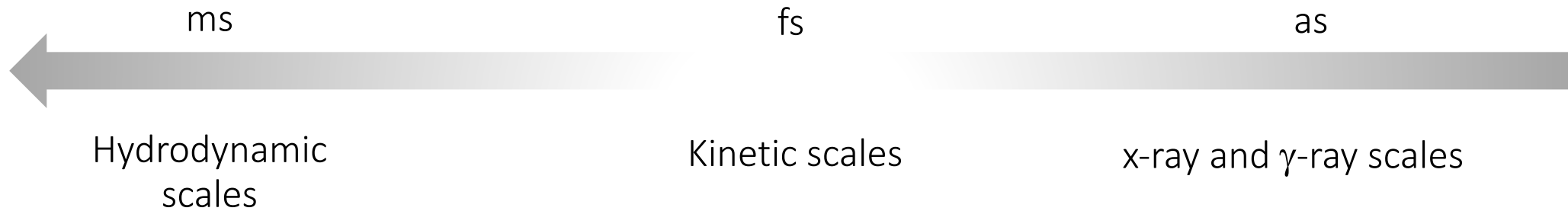
Task 3.4 Development of a toolkit for simulating acceleration in finite temperature plasma.
INFN_Mi (Andrea Rossi, Task Leader), UTOV, CNRS, DESYC

- **M19** Benchmark hydrodynamic simulations of capillary discharges in realistic conditions (2D or 3D).
- **M20** Analysis of different approaches, including the stability analysis of the accelerated beam caused by the jitter, to design the EuPRAXIA high repetition rate plasma module.
- **M34** Benchmark of the code against existing PIC codes implementing different physical models.
- **M35** Benchmark of a GPU based spatiotemporal radiation post-processing tool.



- **D3.1** An MHD open-source software toolkit for HOFI simulations.
- **D3.2** Exa-scale ready post-processing radiation diagnostics for PIC codes.
- **D3.3** A hybrid fluid-kinetic simulation tool able to take into account plasma finite temperature effects on acceleration.
- **D3.4** Design of the EuPRAXIA plasma module in the high-repetition-rate regime.

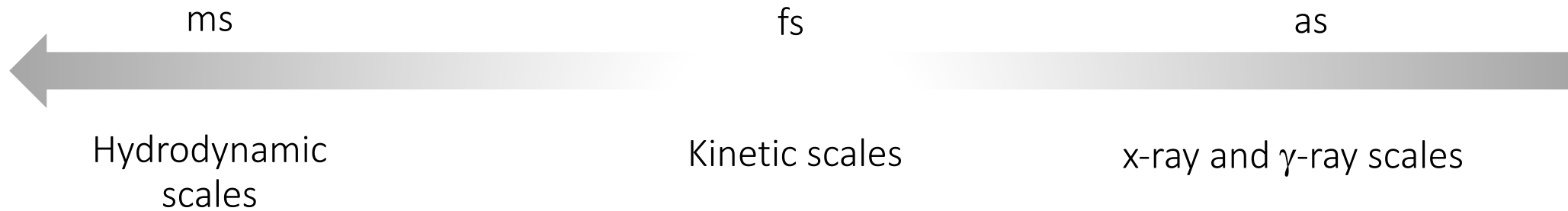




Plasma profile
<p>HOPI (high rep rate compatible)</p> <p>Discharge plasma</p> <p>Gas-jet (high rep rate compatible)</p>
Task 3.1

Plasma accelerator
<p>Ideal laser & plasma</p> <p>Non-ideal laser & ideal plasma</p> <p>Non-ideal laser & plasma</p>
Task 3.2 and 3.4

Radiation
<p>Betatron radiation</p> <p>Post-processing diagnostics</p> <p>FEL radiation</p> <p>Genesis, etc</p>
Task 3.3



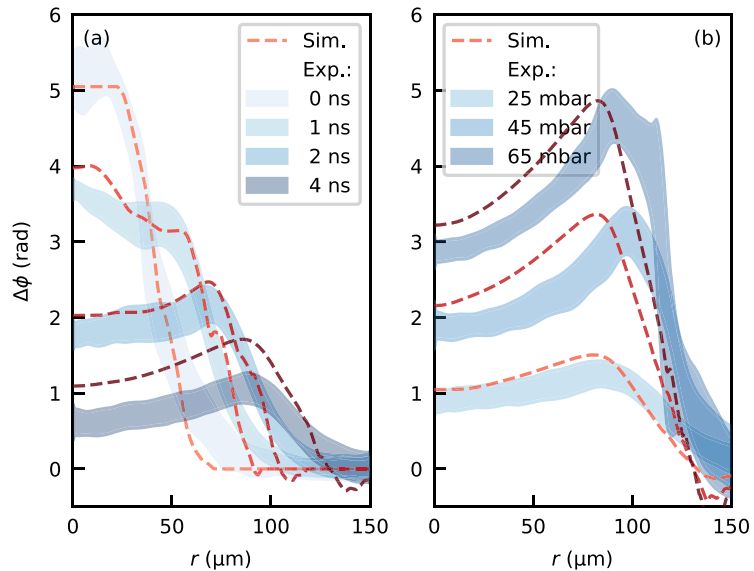
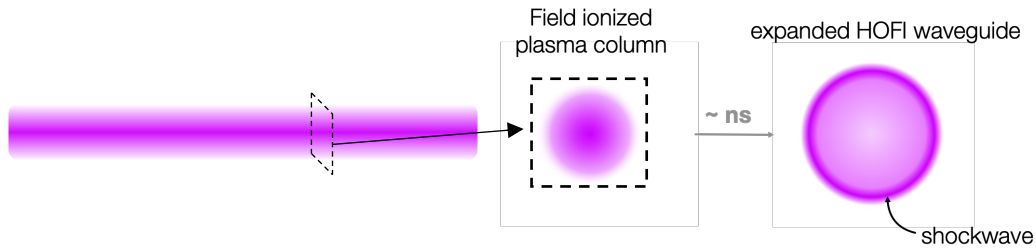
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Task 3.3

Where we started

Simulation of HOFI waveguide formation



M. Thévenet *et al.*

PHYSICAL REVIEW RESEARCH **5**, 033112 (2023)

Demonstration of tunability of HOFI waveguides via start-to-end simulations

S. M. Mewes^{1,2,*} G. J. Boyle³ A. Ferran Pousa¹ R. J. Shalloo¹ J. Osterhoff¹ C. Arran⁴ L. Comer⁵
R. Walczak⁶ S. M. Hooker⁶ and M. Thévenet¹

¹Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany

²Institut für Experimentalphysik, Universität Hamburg, Luruper Chaussee, 22761 Hamburg, Germany

³James Cook University, 1 James Cook Dr, Townsville City QLD 4814, Australia

⁴York Plasma Institute, Department of Physics, University of York, Heslington, York YO10 5DD, United Kingdom

⁵Cockcroft Institute for Accelerator Science and Technology, School of Engineering, The Quadrangle, University of Liverpool, Brownlow Hill, Liverpool L69 3GH, United Kingdom

⁶John Adams Institute for Accelerator Science and Department of Physics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, United Kingdom

Simulation toolkits available



HOFI waveguide

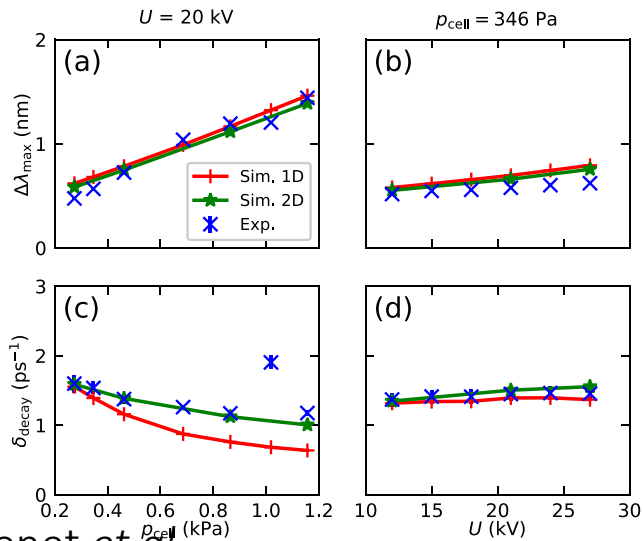
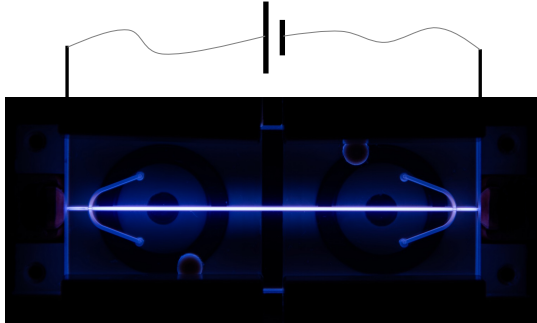


Simulation toolkit benchmarked with experiments



What we did

Simulation of discharge plasma formation



M. Thévenet *et al.*

PHYSICAL REVIEW RESEARCH 7, 043193 (2025)

Characterization of discharge capillaries via benchmarked hydrodynamic plasma simulations

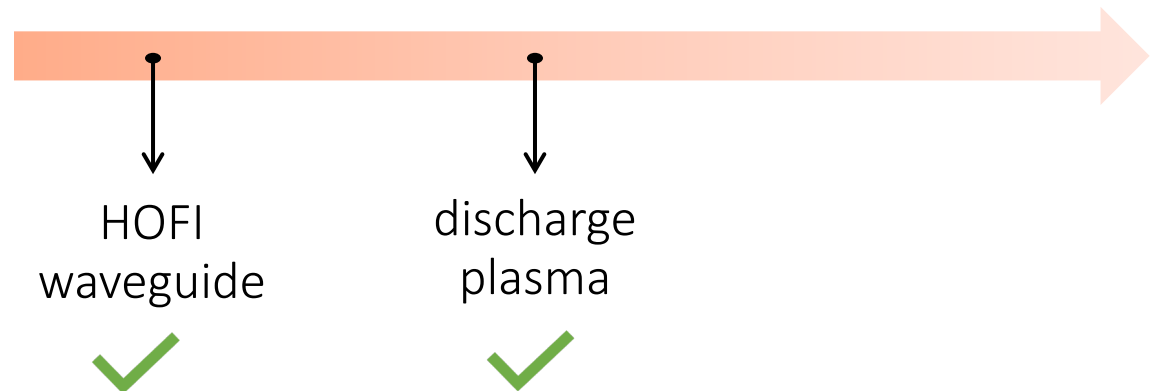
S. M. Mewes^{1,2,*}, G. J. Boyle³, R. D'Arcy^{1,†}, J. M. Garland¹, M. Huck¹, H. Jones¹, G. Loisch¹, A. R. Maier¹, J. Osterhoff^{1,‡}, T. Parikh¹, S. Wesch¹, J. C. Wood¹, and M. Thévenet¹

¹Deutsches Elektronen-Synchrotron DESY, Notkestraße 85, 22607 Hamburg, Germany

²Institut für Experimentalphysik, Universität Hamburg, Luruper Chaussee, 22761 Hamburg, Germany

³James Cook University, 1 James Cook Drive, Townsville City QLD 4814, Australia

Simulation toolkits available



Simulation toolkit benchmarked with experiments



Capillary (theoretical model)

1D Hydrogen-Filled Capillary Discharge (Bobrova et al.)

Model

- ▶ 1D radial simulation of a hydrogen-filled capillary discharge.
- ▶ Electron and ion dynamics governed by energy and continuity equations.
- ▶ Electron thermal conductivity uses Γ -functions from private communication with Bulanov.
- ▶ Radial profiles of electron temperature $T_e(r)$ and density $n_e(r)$ obtained from 1D IMEX solver.
- ▶ Capillary radius 1 mm, $t = 100$ ns

Governing equations

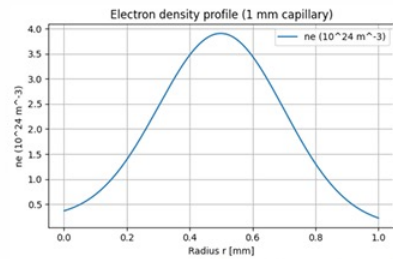
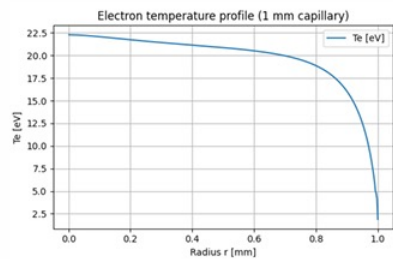
$$\frac{\partial \rho}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} (r \rho v) = 0$$

$$\rho (\partial_t v + v \partial_r v) = -\partial_r \Pi_{rr} - \frac{1}{r} (\Pi_{rr} - \Pi_{\phi\phi}) - \frac{1}{c} j B - \partial_r p$$

$$\partial_t \left(\frac{B}{\rho r} \right) + v \partial_r \left(\frac{B}{\rho r} \right) = \frac{c}{\rho r} \partial_r E$$

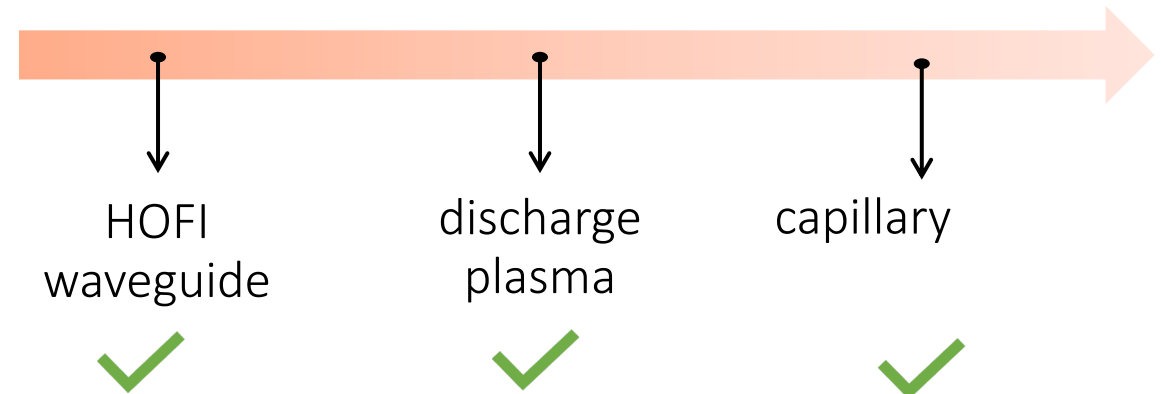
$$\rho \left(\frac{\partial \epsilon_e}{\partial t} + v \frac{\partial \epsilon_e}{\partial r} \right) + \frac{p_e}{r} \frac{\partial (rv)}{\partial r} = -\frac{1}{r} \frac{\partial (r q_e)}{\partial r} + C_{ei} (T_i - T_e) - Q_r + j E$$

$$\rho \left(\frac{\partial \epsilon_i}{\partial t} + v \frac{\partial \epsilon_i}{\partial r} \right) + \frac{p_i}{r} \frac{\partial (rv)}{\partial r} = -\frac{1}{r} \frac{\partial (r q_i)}{\partial r} + C_{ei} (T_e - T_i) - \Pi_{rr} \frac{1}{r} \frac{\partial (rv)}{\partial r} - \frac{v}{r} (\Pi_{\phi\phi} - \Pi_{rr})$$

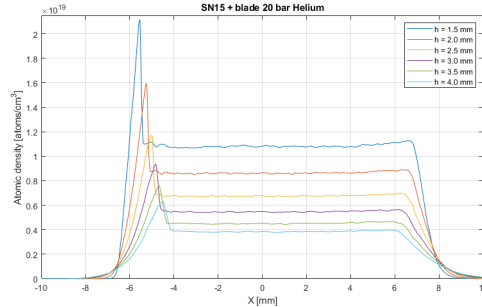
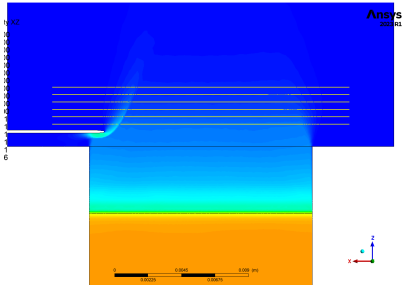


Mostafa Behtouei *et al.*

Simulation toolkits available



Gas jet (shock injection)



ANSYS

S.Lorenz / ELI Beamlines

*

Laser Wakefield Acceleration in a Capillary Gas Cell Producing GeV-Scale High-Quality Electron Beams

Srimanta Maity,^{1,*} Francesco Massimo,² Alex Whitehead,^{3,4} Pavel Sasorov,³ and Alexander Molodozhentsev³

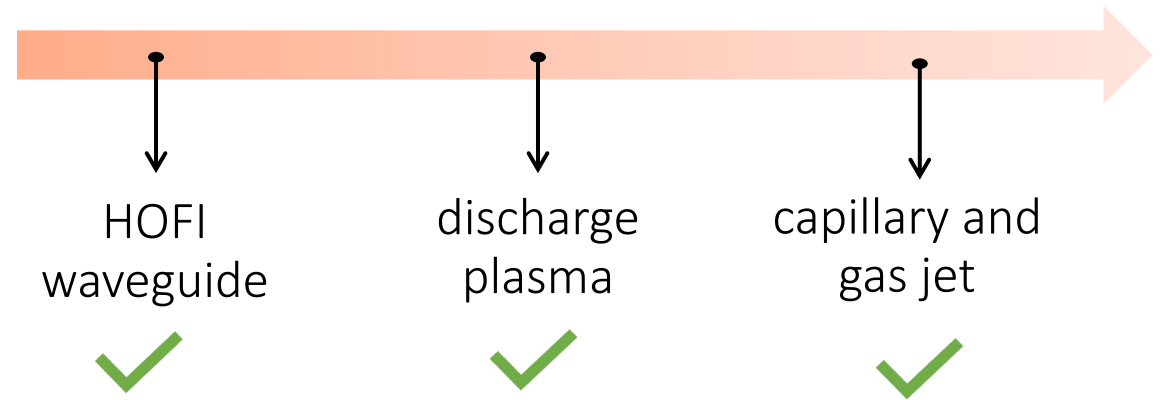
¹Atomic, Molecular and Optical Physics Division,
Physical Research Laboratory, Navrangpura, Ahmedabad 380009, India

²Laboratoire de Physique des Gaz et des Plasmas,
CNRS, Université Paris-Saclay, 91405 Orsay, France

³ELI Beamlines Facility, The Extreme Light Infrastructure ERIC,
Za Radnicí 835, 25241 Dolní Břežany, Czech Republic

⁴Czech Technical University in Prague, FNSPE, Břehová 78/7, 11519 Prague, Czech Republic

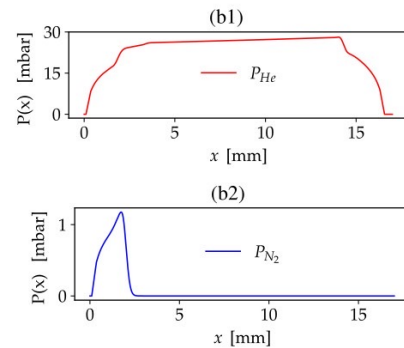
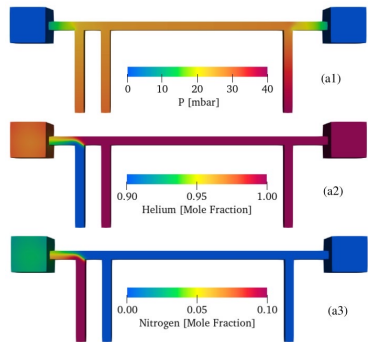
Simulation toolkits available



Simulation toolkit benchmarked with experiments

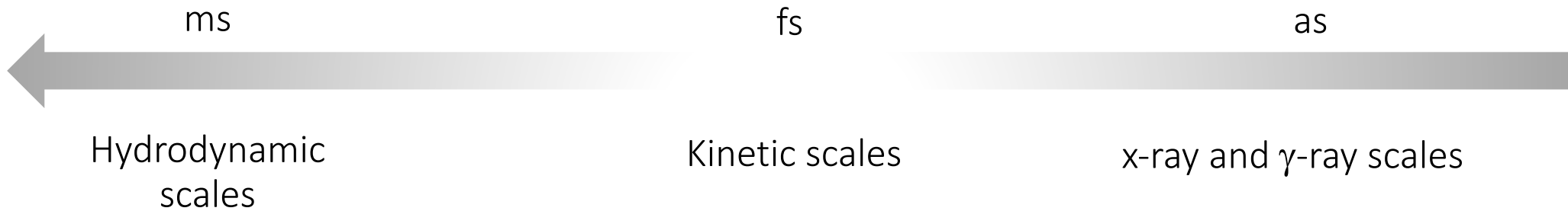


Capillary*



ANSYS

S. Maity / ELI Beamlines



Plasma profile

HOPI (high rep rate compatible)
Discharge plasma
Gas-jet (high rep rate compatible)

Task 3.1

Plasma accelerator

Ideal laser & plasma
Non-ideal laser & ideal plasma
Non-ideal laser & plasma

Task 3.2 and 3.4

Radiation

Betatron radiation
Post-processing diagnostics

FEL radiation
Genesis, etc

Task 3.3

Assumptions

- $\lambda_u=15$ mm
- $K_w=1$
- $\sigma_r=20$ μm

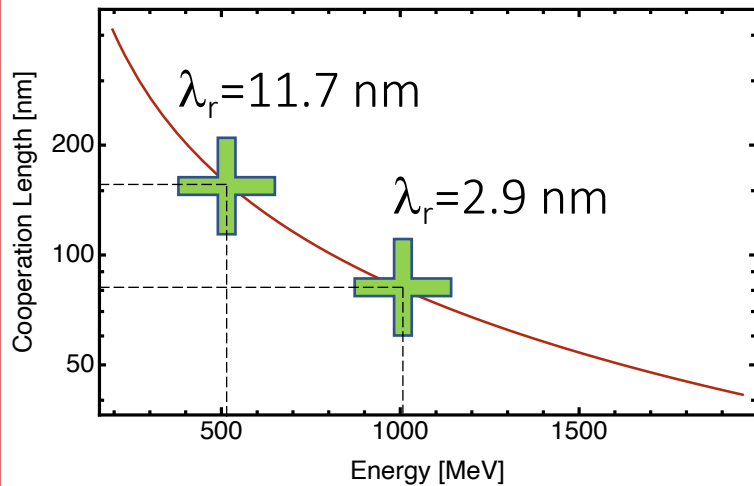
Emittance

- 500 MeV \rightarrow 2 mm-mrad
- 1 GeV \rightarrow 1 mm-mrad

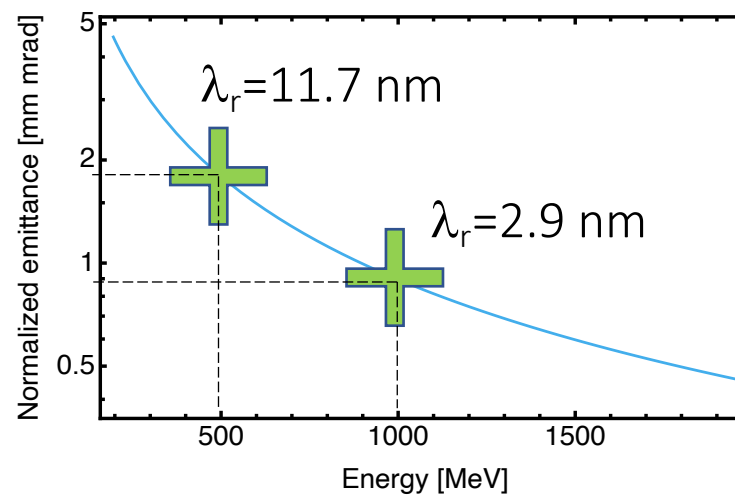
Energy spread

- 500 MeV \rightarrow 1%
- 1 GeV \rightarrow 0.5%

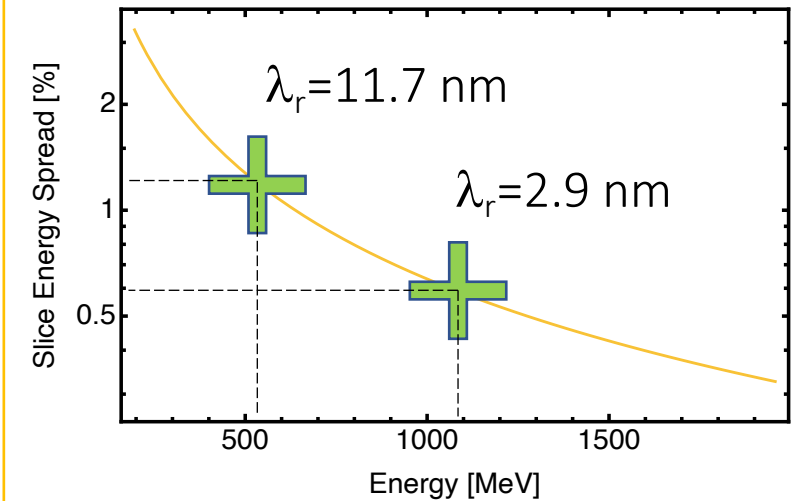
Cooperation length



Normalized emittance

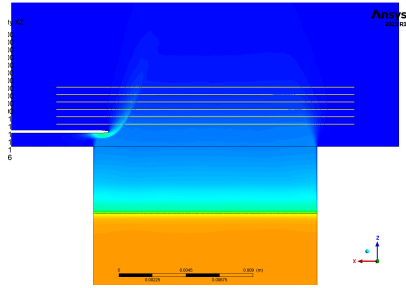


Energy spread

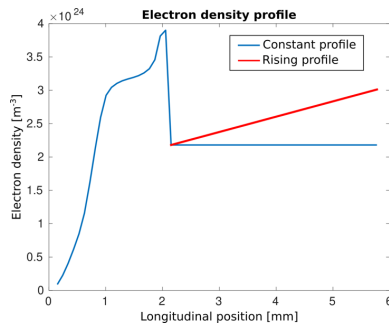


Plasma profile for shock injection

15 mm slit nozzle with blade



Simulated profile

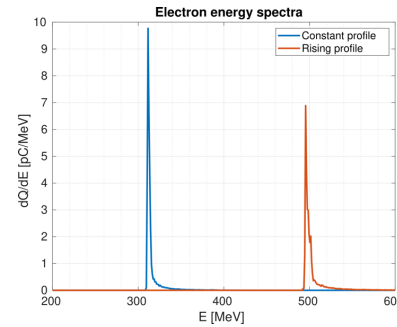


ANSYS

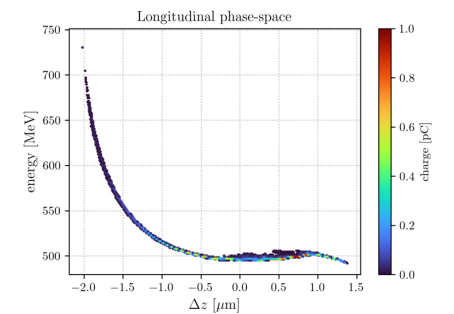
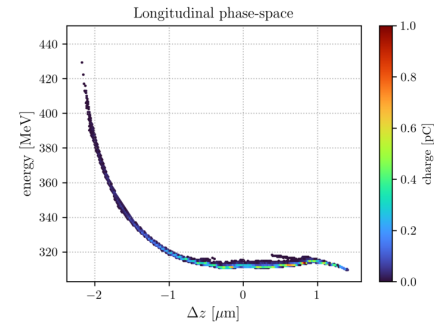
S.Lorenz / ELI Beamlines

PIC simulation results

A) Constant profile



B) Rising profile



OSIRIS simulation:

- 1.5 J laser (relevant to ELI beamlines)
- Plasma density profile similar to *K. Feng et al., arXiv:2501.09916 (2025)*

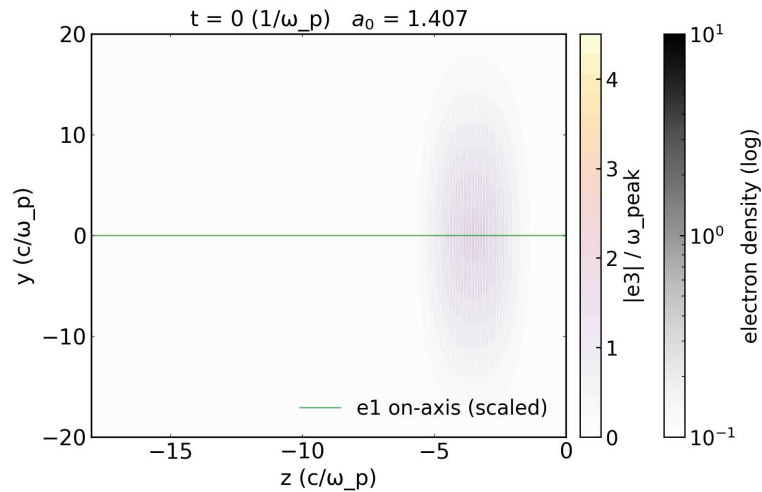
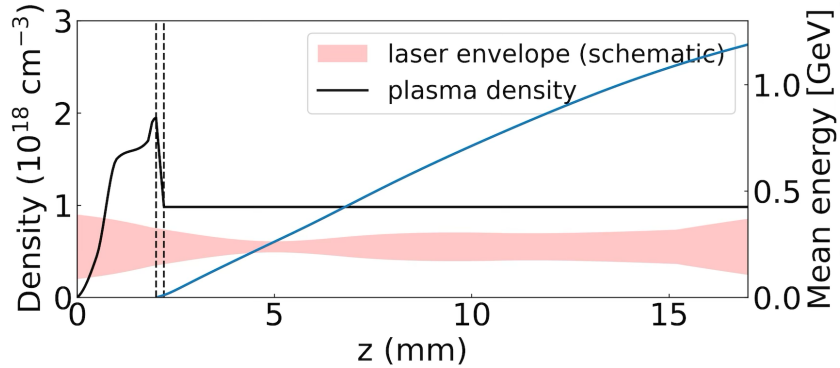
Beam parameters:

- 0.3 GeV case: Charge **34 pC** (22 pC at FWHM), $\delta E/E = 1.0\%$ (slice 0.57%)
- 0.5 GeV case: Charge **33 pC** (14 pC at FWHM), $\delta E/E = 0.6\%$ (slice 0.43%)

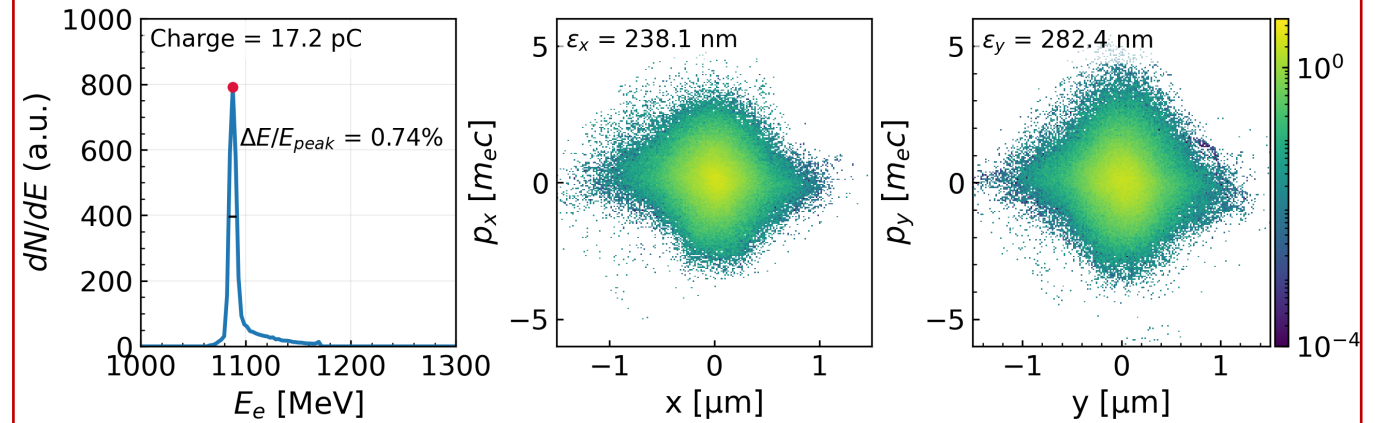


Shock-injection for GeV e- acceleration

Simulation profile and energy gain



PIC simulation - key results



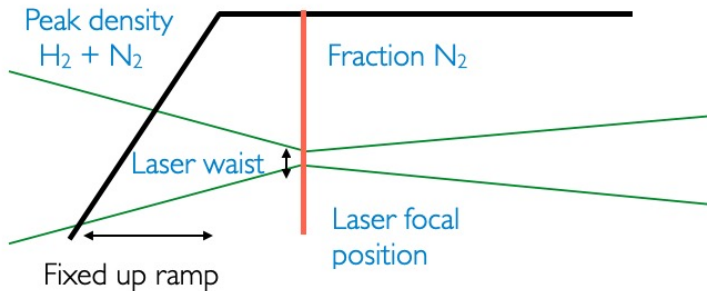
Laser: $a_0 = 1.9$ (5J)
 $w_0 = 37.4 \mu\text{m}$, $\tau = 38.3 \text{ fs}$
 Focus at $z = 5 \text{ mm}$
 Down-ramp length: $35 \mu\text{m}$

X. Wu *et al*

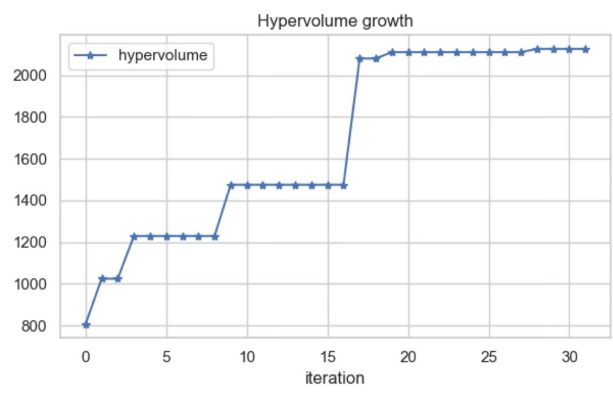


Shock-injection for GeV e- acceleration

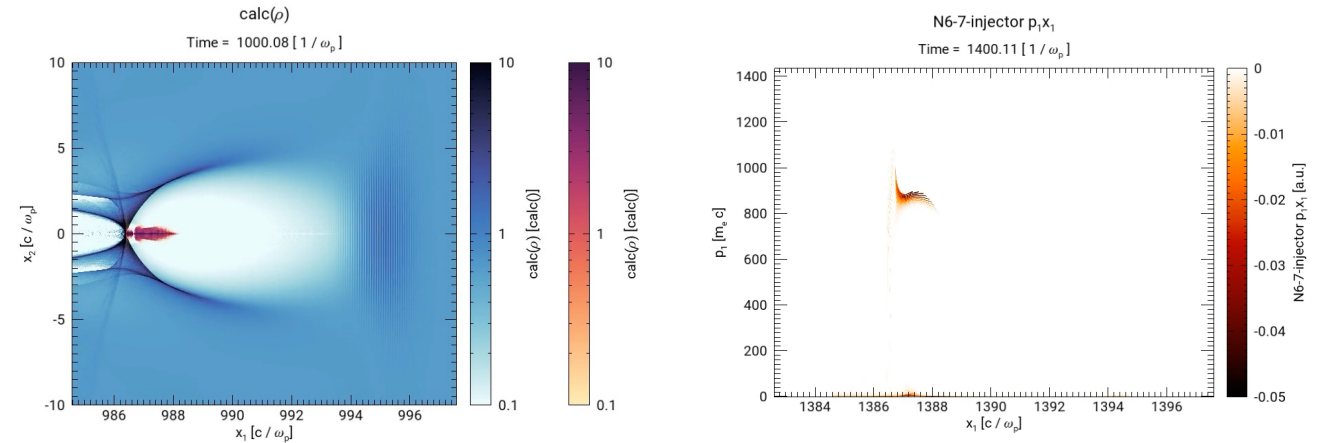
Density profile



Bayesian optimisation (BO), can help us find a regime where self truncation injection of electrons can occur



Self-truncated ionisation injection without self-trapping



Laser properties

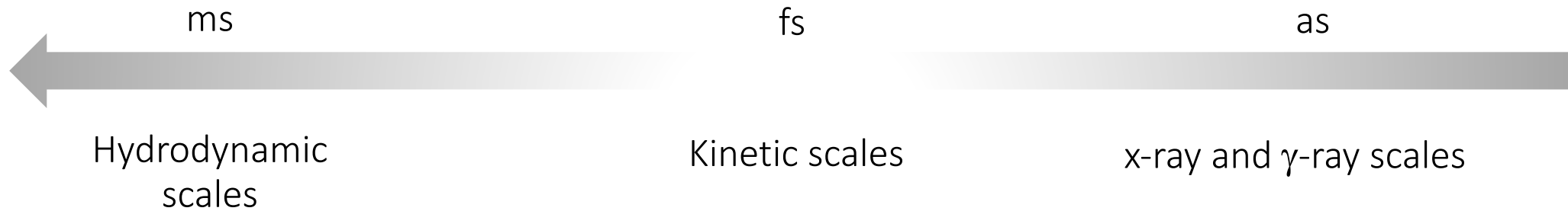
$a_0 : 2.346$
 $w_0 : 30 \text{ } [\mu\text{m}]$
 Focus. : $3.66 \text{ } [\text{mm}]$
 Duration: $30 \text{ } [\text{fs}]$
 Energy : $4.9 \text{ } [\text{J}]$
 Power : $168.7 \text{ } [\text{TW}]$

e-beam properties

Resolution [nm] * [nm]	26 * 50
Energy [MeV]	446.2
Energy spread RMS [%]	3.08
Projected emittance [mm mrad]	3.39/1.31
Divergence [mrad]	2.95/2.18
Charge [pC]	24.66

B. Thakur *et al*





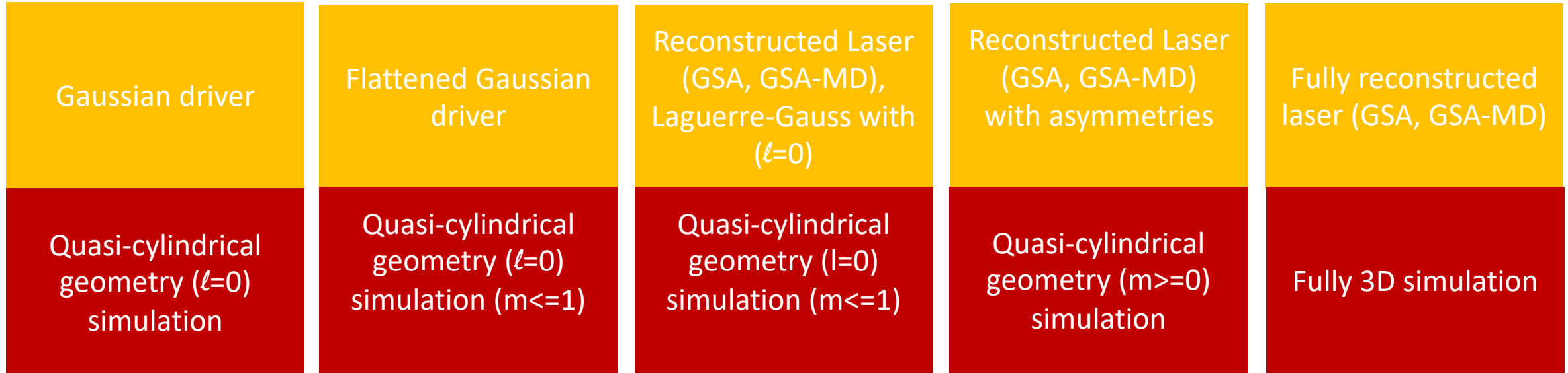
Plasma profile
HOPI (high rep rate compatible) Discharge plasma Gas-jet (high rep rate compatible)
Task 3.1

Plasma accelerator
Ideal laser & plasma Non-ideal laser & ideal plasma Non-ideal laser & plasma
Task 3.2 and 3.4

Radiation
Betatron radiation Post-processing diagnostics FEL radiation Genesis, etc
Task 3.3

Idealized

Realistic



Fast computations

Computationally demanding



Most articles in LWFA literature

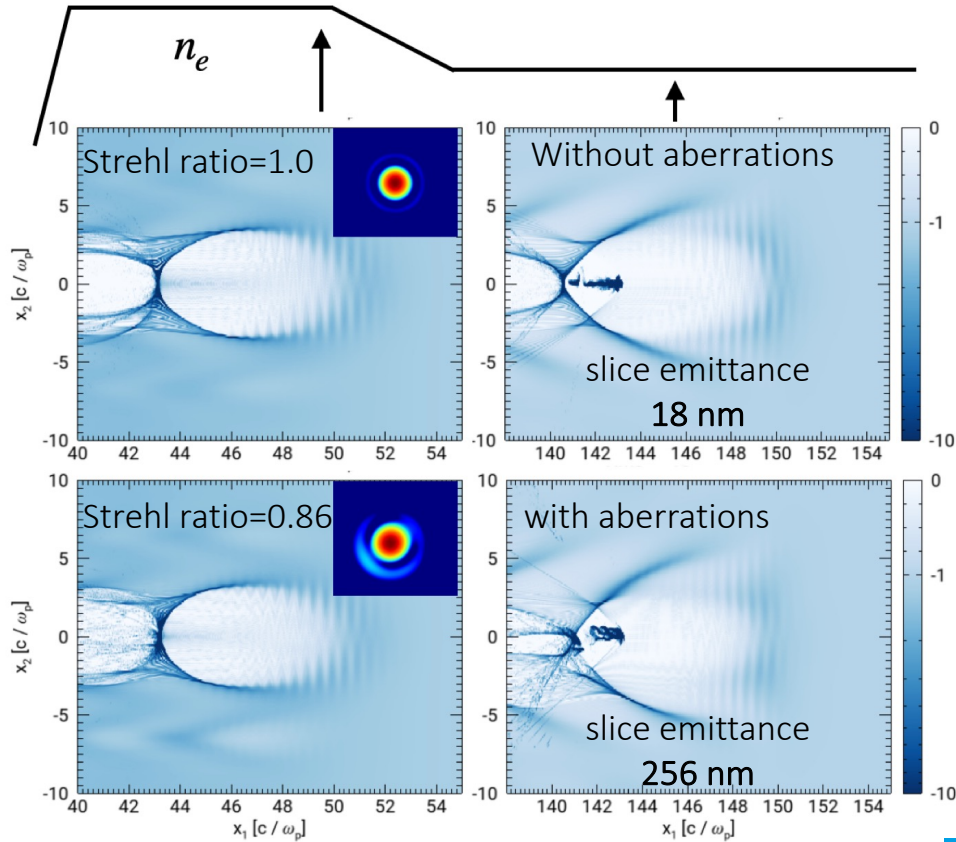
T. L. Steyn et al 2025, <https://arxiv.org/abs/2506.18047>

L.T. Dickson et al., PRAB 2022; I. Moulanier et al, PoP 2023

J. Ferri et al, Scientific Reports 2016

I. Moulanier, F. Massimo, B. Cros

Abserrations

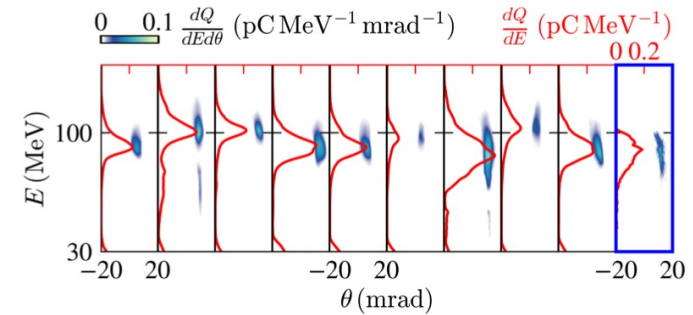


X. Wu *et al.*

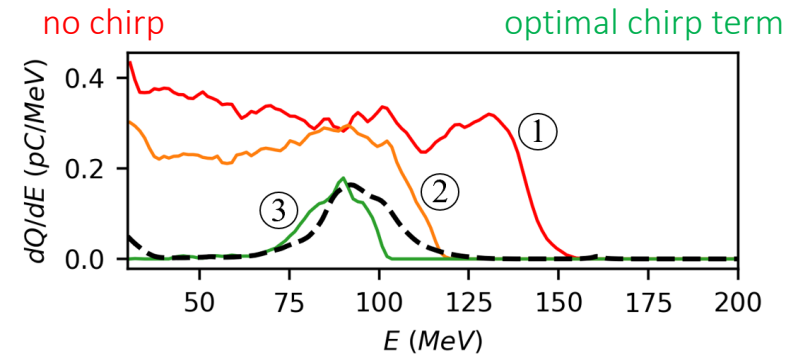


Frequency chirp

Electron spectra experiment @ Lund Laser Centre



Fully reconstructed laser

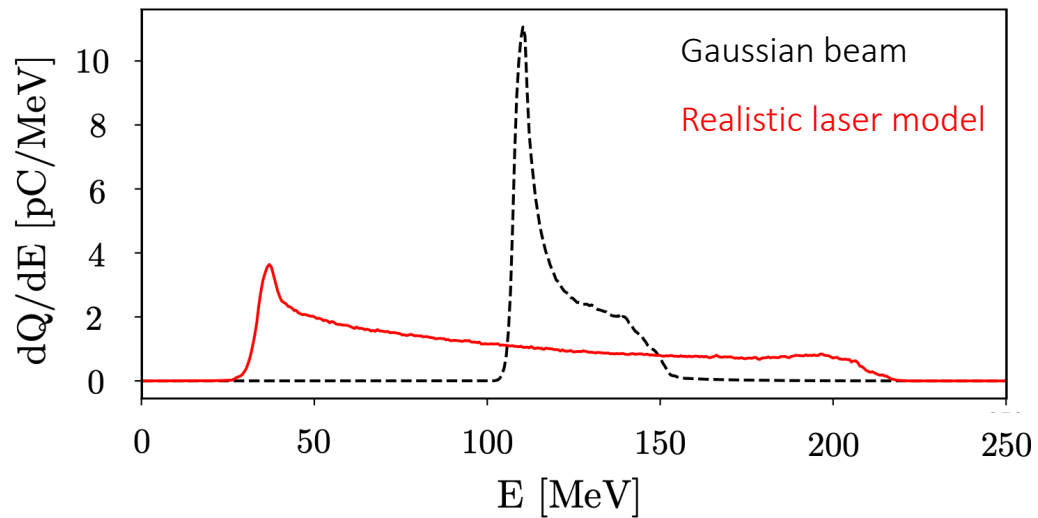


I. Moulanier, PhD thesis 2025 (<https://theses.fr/282680284>)
submitted to PoP (2026)



Optimal parameters depend on laser profile

Example: using a realistic laser model in a working point found for a Gaussian beam



F. Massimo et al., submitted
<https://hal.science/hal-05404087v1/document>

Laser field reconstruction for the modeling of laser–plasma interaction in cylindrical geometry

F. Massimo^{1*}, I. Moulanier^{1†}, A. Guerente¹, O. Khomyshyn¹, M. Masckala¹, T. L. Steyn¹,
 U. Schramm², A. Irman², B. Cros¹

- Ideal vs. Real: Optimal working point for highest quality electron acceleration may differ
- Simulations with realistic drivers are crucial

Fluid model: the closure problem

Relativistic Vlasov equation \rightarrow Moment equations \rightarrow Conservation laws: unclosed equations chain \rightarrow Need for a proper **closure**

Two choices

Two choices

Assume local equilibrium (LEC)

Probability distribution: $f = f_{eq}$

Consequence: pressure P isotropic

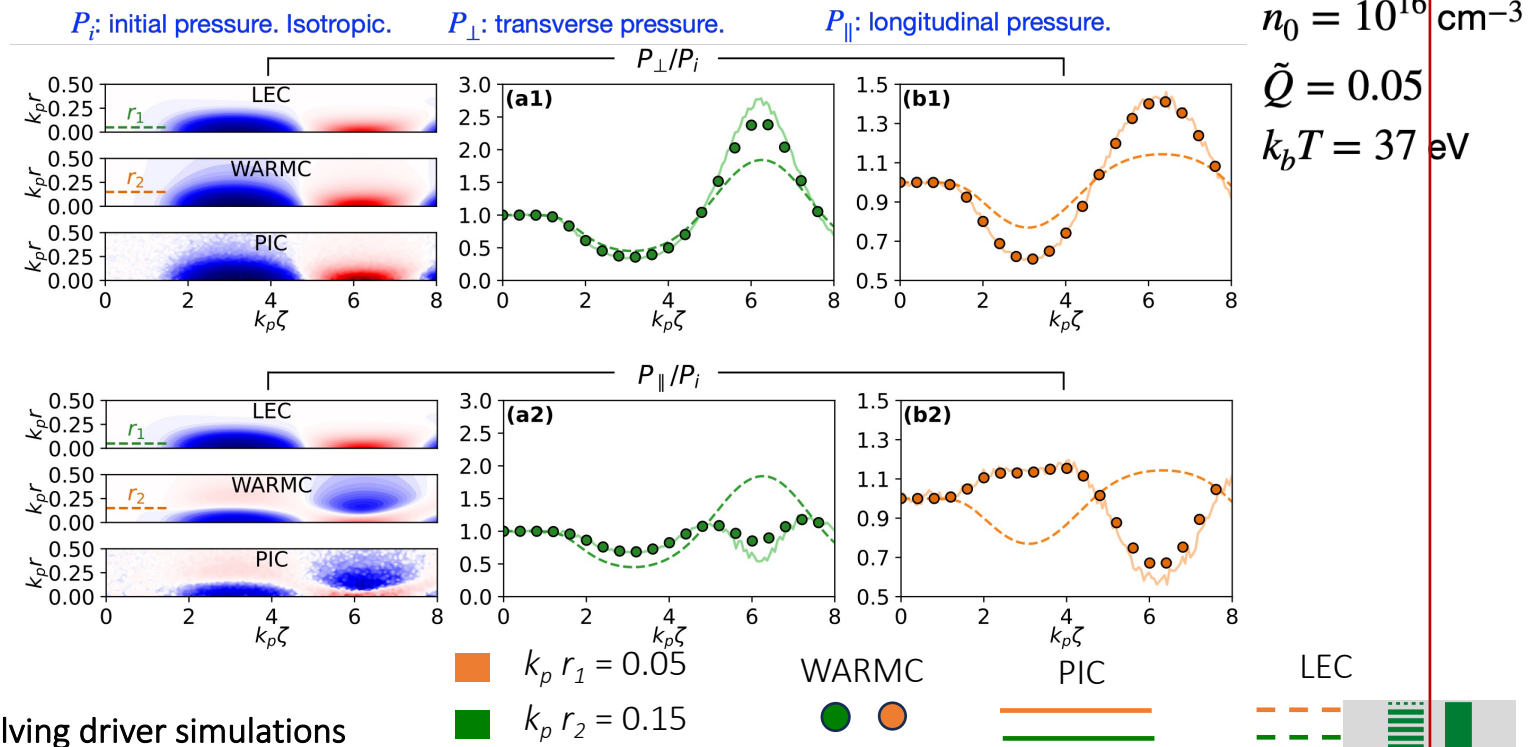
Truncate equations chain (WARMC)

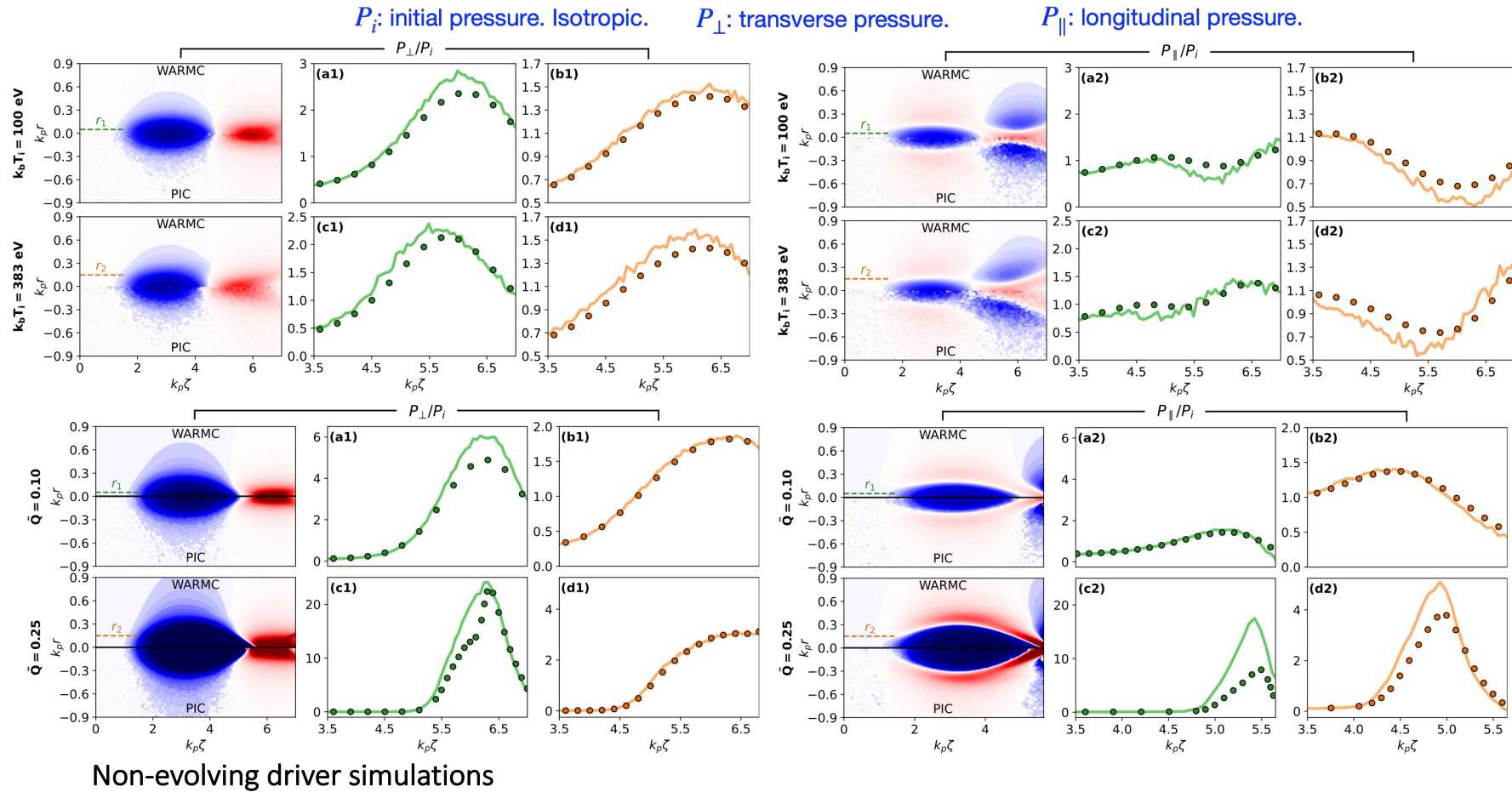
Implies small temperature: $k_b T \ll m_e c^2$

Probability distribution: $f \neq f_{eq}$

Consequence: pressure P anisotropic

WARMC works better

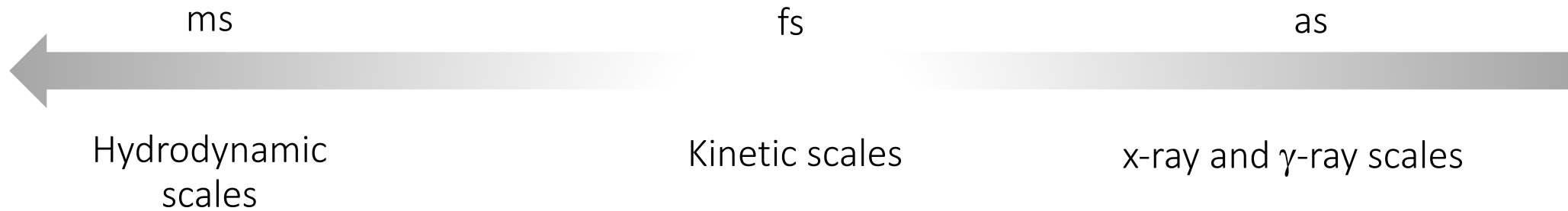




■ $k_p r_1 = 0.05$
■ $k_p r_2 = 0.15$

WARMC
 ● (green) ● (orange)
 PIC
 — (orange) — (green)
 LEC
 - - - (orange) - - - (green)

$n_0 = 10^{16} \text{ cm}^{-3}$
 $\tilde{Q} = 0.05$
 $k_b T = 37 \text{ eV}$



Plasma profile
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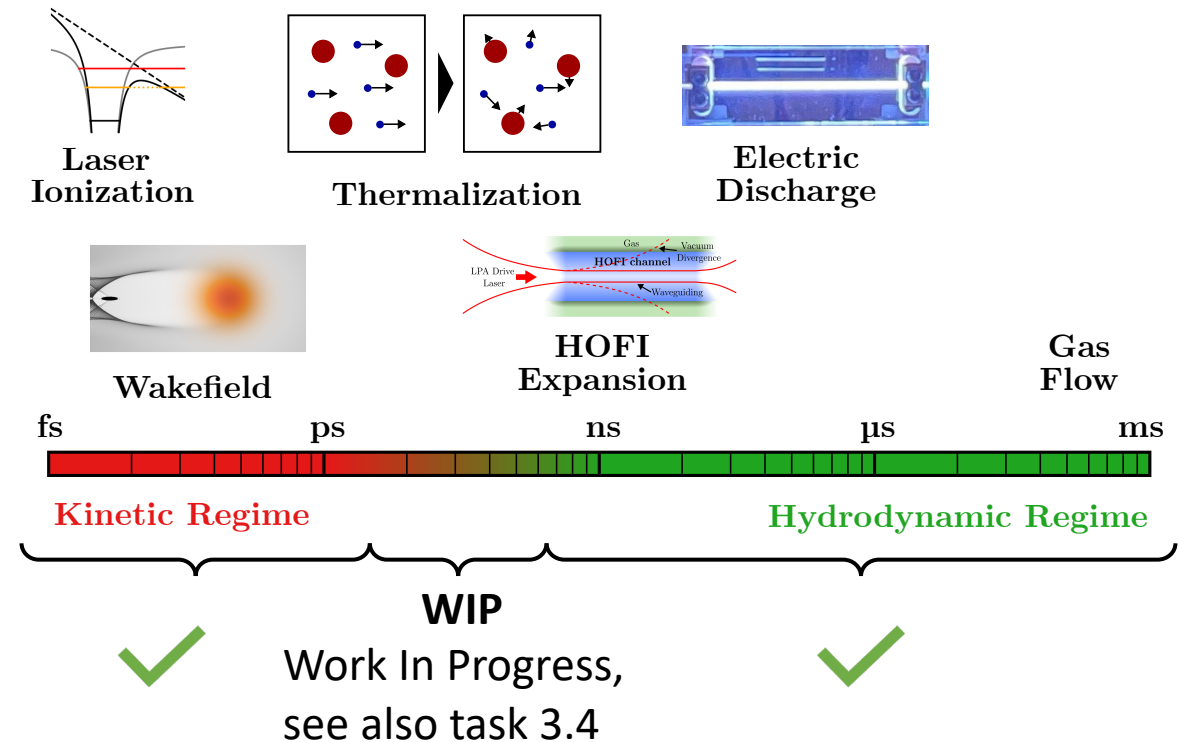
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Development of computational toolkits

Bridge the gap between hydrodynamic and kinetic scales

- **Fully kinetic:** OK with PIC codes (HiPACE++, Osiris, Smiley, etc)
- **Hydrodynamic:** OK (HYQUP toolkit, ANSYS, etc)
- **In-between:** several approaches (e.g., Lattice-Boltzmann, quasistatic kinetic)



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Down-ramp + ionization injection

Mixture of He + N₂ gases

Low conc. of N₂ gas (5% as dopant)

Height of the ramp - $\frac{1}{1 + hramp}$

Length of the ramp - L_{ramp}

Varying parameters -

```
var_1 = VaryingParameter("L_ramp", 0e-6, 30e-6)
var_2 = VaryingParameter("h_ramp", 0.5, 2.0)
var_3 = VaryingParameter("ramp_start", 400e-6, 700e-6)
```

Goal -

Energy range ~ 400 MeV

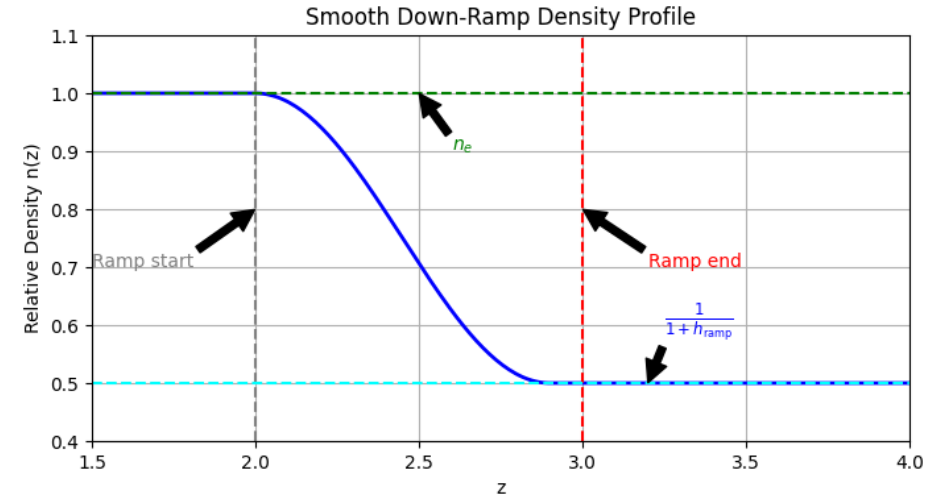
Good charge (pC)

Lower emittance

Low energy spread

Objective function –

$$f = \frac{q E_{med}}{100 E_{mad} \sqrt{\epsilon}}$$



Cosine-function down-ramp

Analyzed parameters -

```
# Define additional parameters to analyze.
energy_med = Parameter("energy_med")
energy_mad = Parameter("energy_mad")
charge = Parameter("charge")
emittance = Parameter("emittance")
divergence = Parameter("divergence")
```

- **Multi-scale simulations**
 - Bridge gap between hydrodynamics and kinetic scales (on-going)
- **LWFA**
 - Shock-injection is the most promising injection technique so far. Works for stage 0.
 - Reduce energy spread for 1 GeV case is required (e.g., by using tailored density profiles, on-going)
 - Self-truncated ionisation injection: injection volume may be too large
- **Non-ideal effects**
 - Laser pulse: optimal parameters depend on details of laser spectrum/profile
 - Finite plasma temperature effects: reduced codes reproduce PIC
- **Radiation**
 - Simulate radiation from FEL (on-going)
 - Radiation from post-processing tools in plasma (on-going)