Mutli-code simulation of optically guided LWFA experiment at LOA

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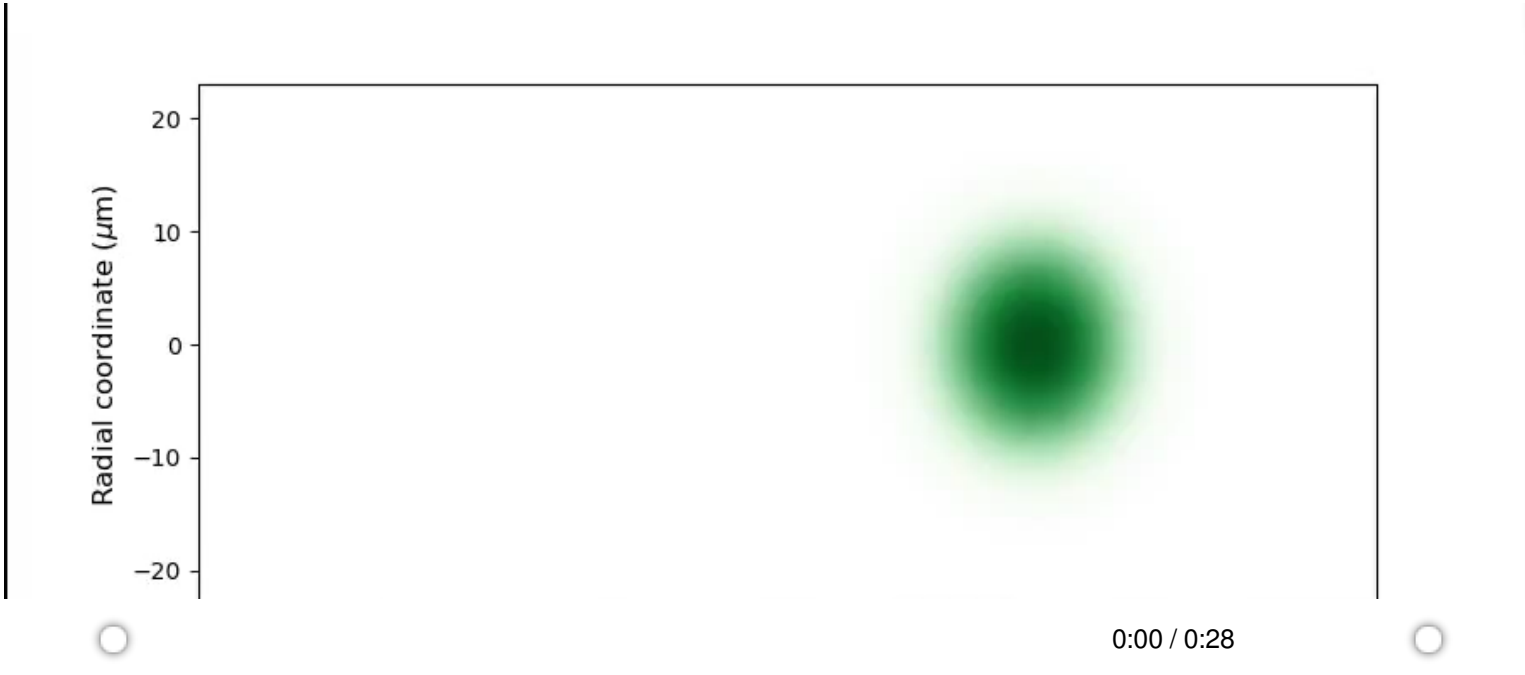
General Context

General Context

LWFA in a nutshell

- strong, $a_0 \gtrsim 1$, laser travels through a plasma
- laser size/duration are roughly resonant with plasma, $\lambda_p \sim R_0 \gtrsim c\tau \gg \lambda_0$
- nonlinear plasma wave with strong "radial" field for trapping and accelerating electrons



General Context

LWFA in a bigger picture

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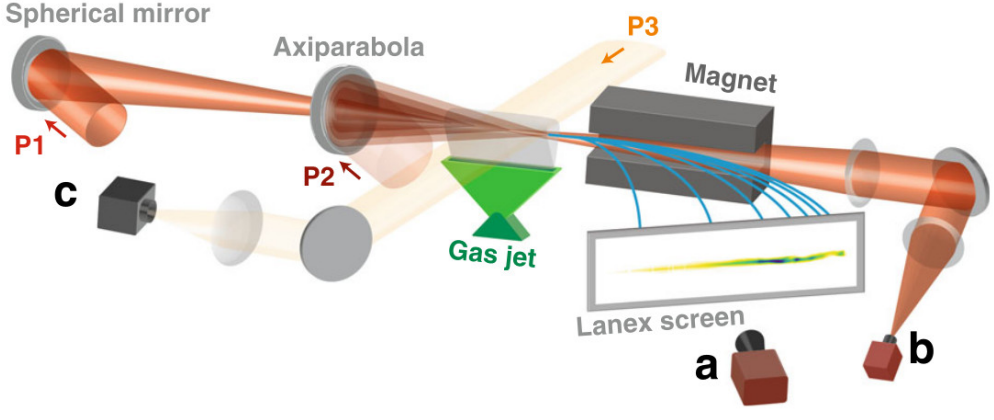
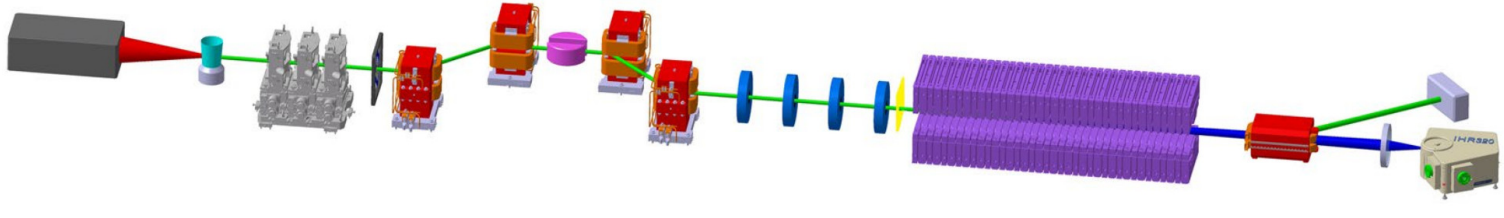
LWFA in a bigger picture

- design of guided LWFA with optical channel



- design of COXINEL LWFA-FEL

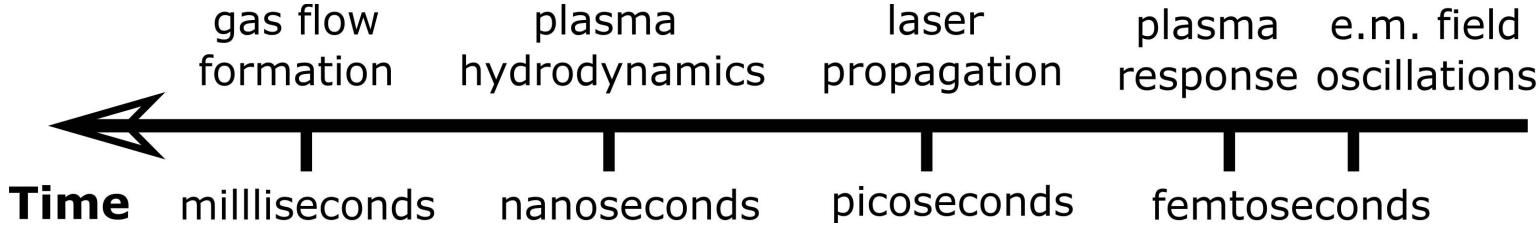


General Context

LWFA in the lab

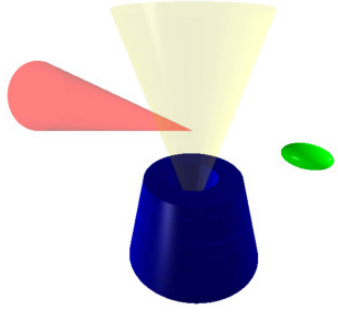
General Context

Multiple timescales, multiple physics



- gas flow: (super)sonic, transient/steady-state, turbulent, viscosity
- plasma hydro-dynamics and heat transport: channel/shock formation
- laser spot formation, measurements interpretation
- LWFA: e.m. field, plasma response, propagation

Required capabilities



Laser Plasmas

Optical codes

- fs pulses, ionized media

CFD codes

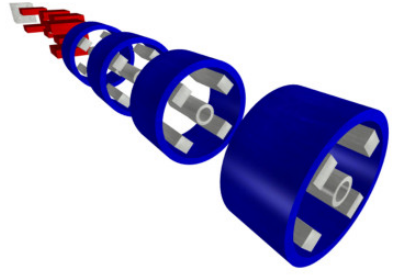
- compressible, viscosity, turbulence

MHD codes

- multi-species plasma

PIC codes

- 3D/quasi3D, relativistic, dispersionless, QSA
- Elementary processes



Beam Transport & Diags

Pusher trackers

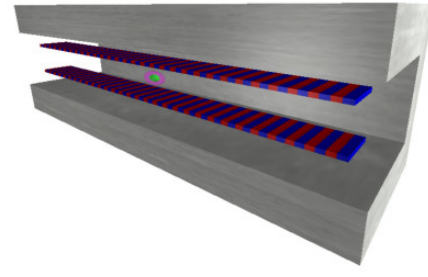
- Space-charge
- CSR

Matrix trackers

- Large e-spectra
- Beamline tuning

Magnetostatic codes

- Equipment modeling



Secondary Light Emission

SR light

- Orbit integration

FEL

- 3D/quasi3D, time-dependent, Non-averaged

Existing tools

PIC codes

- FBPIC[q3D, PSATD, GPU]
- WARPX[+q3D, PSATD, GPU]
- EPOCH (+ PSC)
- PIConGPU[+GPU]
- ChimeraCL[q3D, PSATD, GPU]
- HiPACE++[QSA]
- Architect[RZ, Fluid]
- QuickPIC[QSA]
- Piccante/ALaDyn[+XPL]
- VPIC
- Smilei
- iPic3D

Transport

- ELEGANT[ALL]
- ASTRA[RK,SC,SCR]
- OCELOT[MTRX,SC,SCR]
- AT[MTRX]
- Beta[MTRX]
- Synergia[PIC]

Hydrodynamics

- OpenFOAM
- COOLFluiD

Optical & SR radiation

- SynchRad[SR,GPU]
- AxiProp[Prop,GPU]
- SRW[SR,Prop]
- XRT[SR,Prop,GPU]
- CHIMERA[SR]
- Shadow3 (OASYS)[*]
- OPC[Prop]

FEL

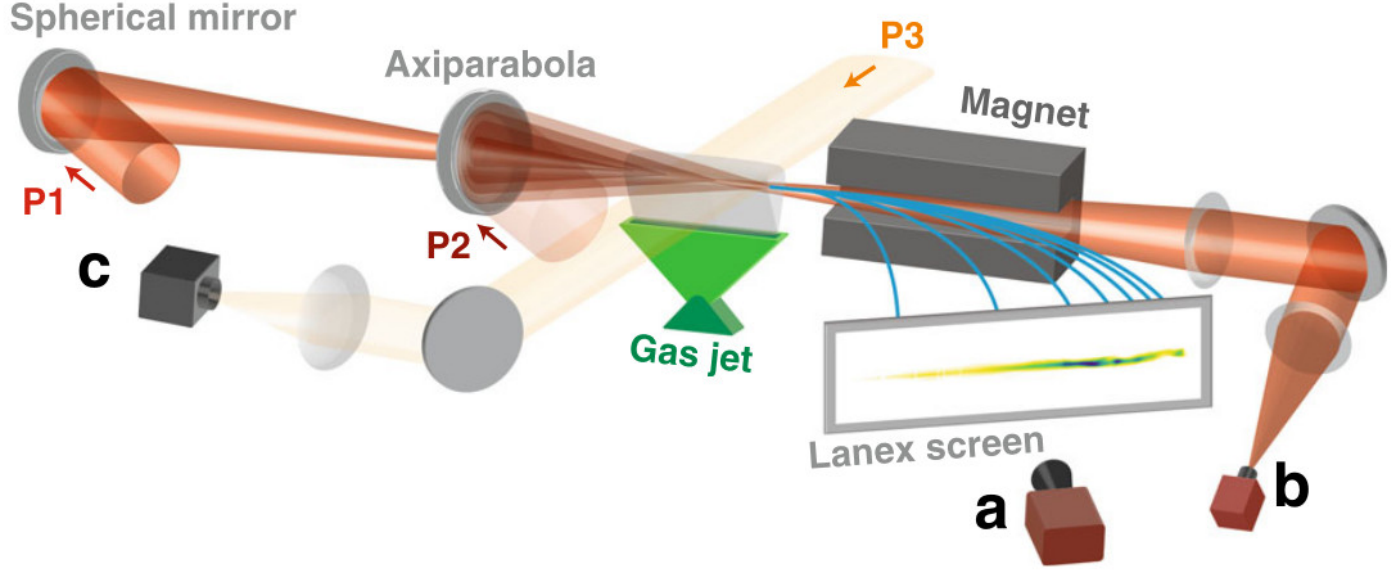
- GENESIS[3D,TD]
- PUFFIN[3D,TD, unav]
- CHIMERA[3D,PSATD,TD, unav]
- FEL Booklet (PARSIFEL)

LWFA in the optically produced channel

[Oubrerie et al. Light: Science & Applications (2022)11:180]

General setup at APOLLON

- Slit-nozzle of 6 cm with a shock, Hydrogen gas
- Axiparabola: flying focus line for high intensities
- two fs laser pulses: few mJ (channeling) and few J (driver)
- HOFI channel formation



LWFA in the optically produced channel

Simulation workflow components

Formation of axibeam and propagation in vacuum and in gas/plasma OFI heating profile

- Optical, PIC, MC codes

Gas expansion and channel formation

- MHD

LWFA

- PIC, QSA-PIC

LWFA in the optically produced channel

Optical propagation in ionizable media

Axiprop [https://github.com/hightower8083/axiprop]

- Paraxial and non-paraxial, *RT* and *XYT* optical vacuum propagators
- Explicit (RK4, adaptive) and implicit (AM2) solvers for the envelope wave equation in plasma
- ADK ionization for enveloped and frequency-resolved field
- used as propagator engine in LASY project

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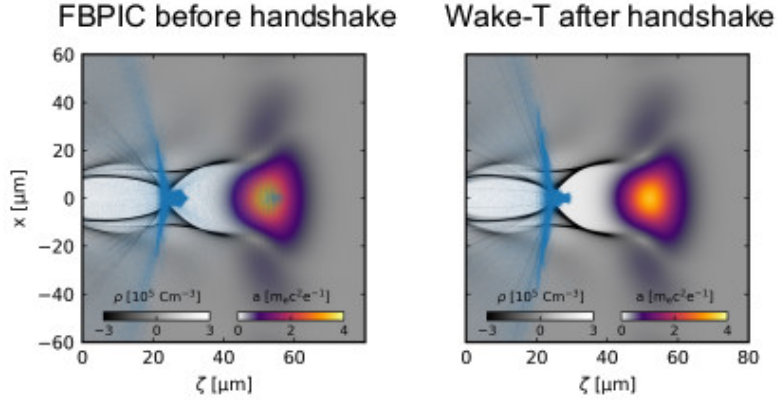
Example:

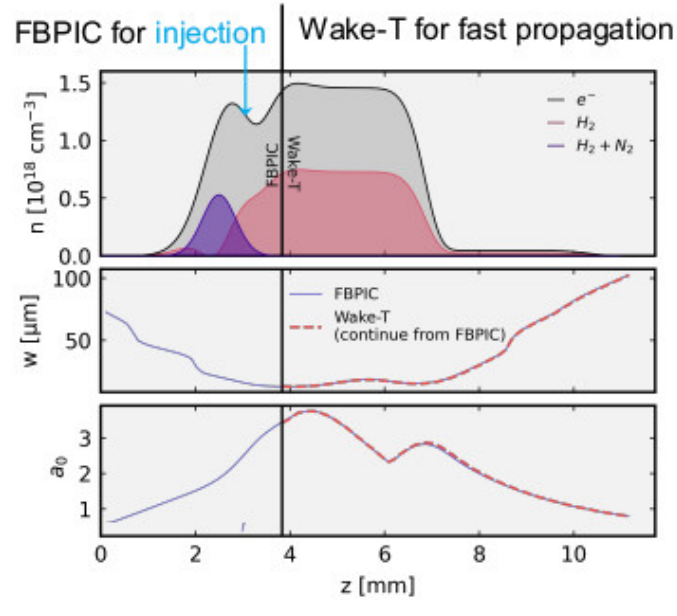
```
from axiprop.lib import PropagatorResampling,
PropagatorResamplingFresnel
from axiprop.simulation.lib import PropagatorResamplingStepping
from axiprop.simulation.plasma import PlasmaIonizationRefine
from axiprop.simulation.solvers import SolverAM2  # SolverRK4
```

From simulation to simulation

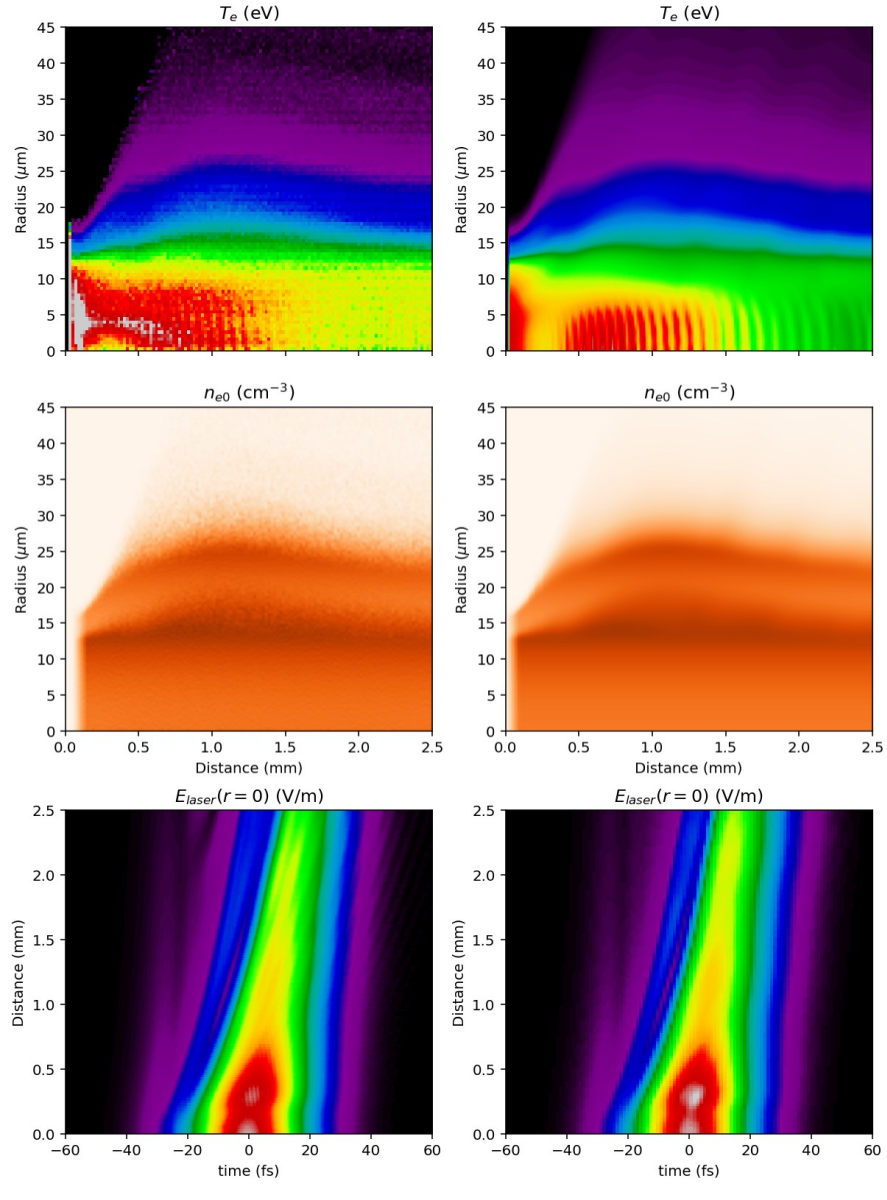
LASY makes it easier to combine codes with different laser representations

- **FBPIC** [5]: electromagnetic PIC code capturing injection
  Laser pulse: self-consistent electric and magnetic fields
- **Wake-T** [6]: quasi-static code for fast & accurate simulations on a laptop
  Laser pulse: envelope of the vector potential





benchmarking vs FBPIC (left)

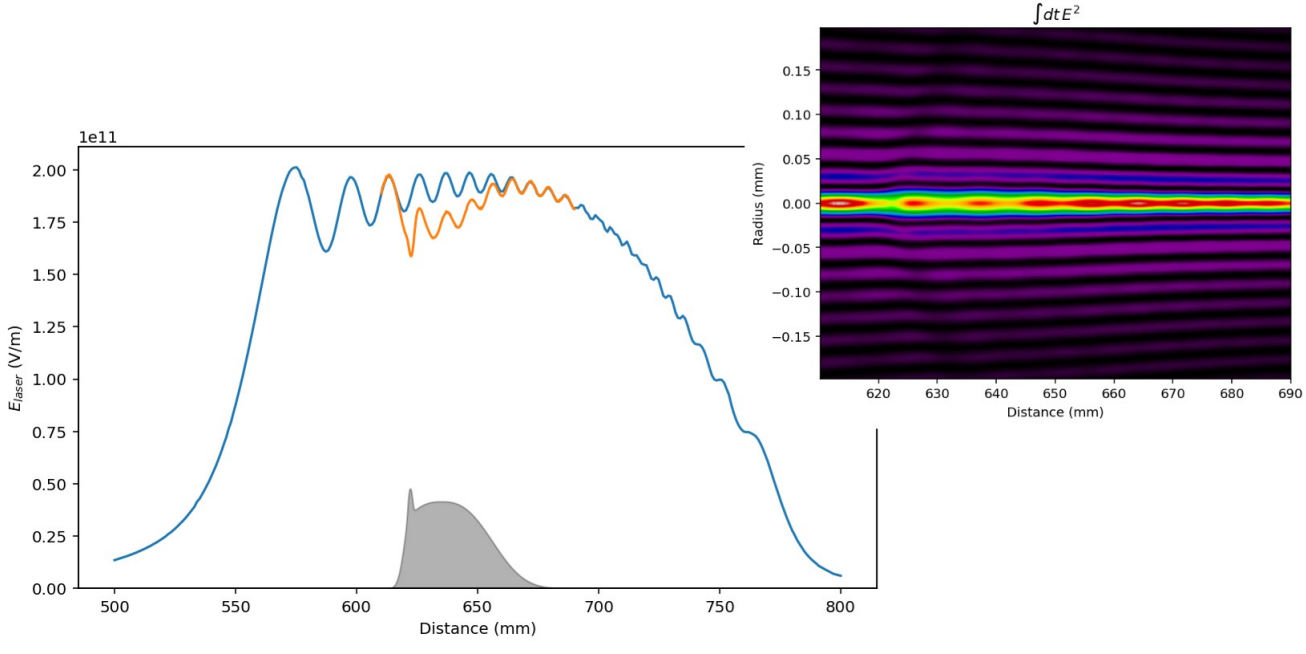

T_e (eV)
T_e (eV)
Radius (μm)
Radius (μm)
n_{e0} (cm^{-3})
n_{e0} (cm^{-3})
Radius (μm)
Radius (μm)
Distance (mm)
Distance (mm)
$E_{laser}(r=0)$ (V/m)
$E_{laser}(r=0)$ (V/m)
Distance (mm)
Distance (mm)
time (fs)
time (fs)

Guided LWFA example:

```
# Propagators: initial and in-plasma
prop0 = PropagatorResamplingFresnel(**init_fresnel_rt(
  dz=z_0, kz_axis=kz_axis, r_axis=(R_0, Nr_0),
  r_axis_new=(R_1, Nr_1) ))

prop_plasma = PropagatorResamplingStepping(r_axis=prop0.r_new,
kz_axis=kz_axis )

# create field, apply axiparabola and bring to plasma
E0 = ScalarFieldEnvelope(k0, t_axis).make_gaussian_pulse(
  prop0.r, tau, R_las, Energy=LaserEnergy, n_ord=10).Field_ft

E0 = E0 * mirror_axiparabola_num(prop0.kz, prop0.r, f0, d0, R_mirr )
E0 = prop0.step( E0, z_0 )

# create a solver, add plasma physics, run
sim = SolverAM2(prop_plasma, t_axis+z_0/c, k0, z_0)
sim.physprocs = [
  PlasmaIonizationRefine(n0_gas, dens_func, sim, my_element='H') ]

sim.run( E0, Lz=Lz, dz0=dz0, N_diags=N_diags )
```

LWFA in the optically produced channel

Propagation in the Helium jet



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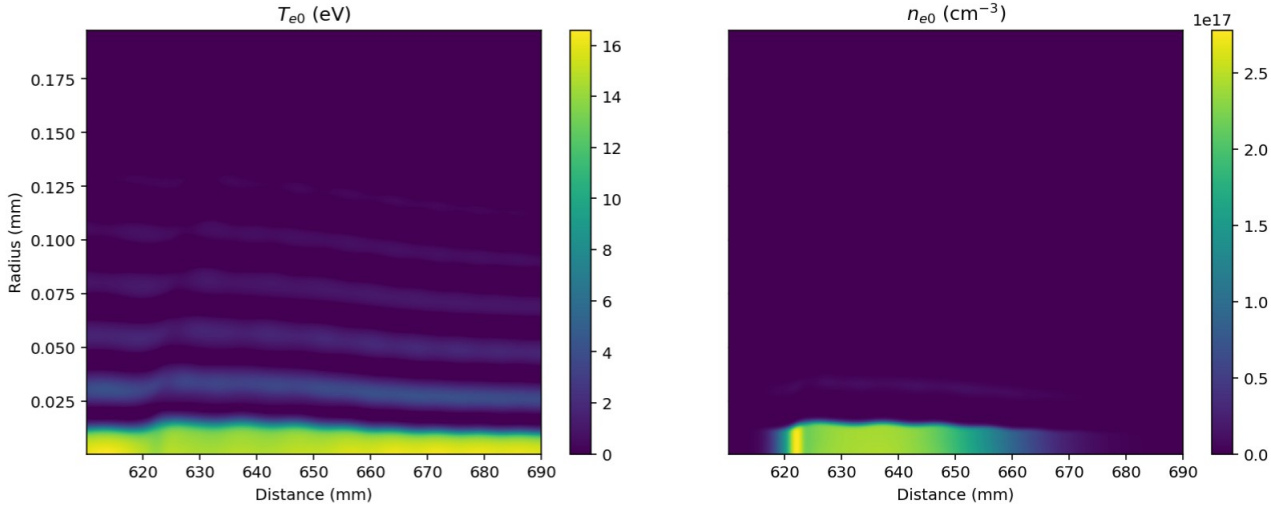

LWFA in the optically produced channel

Channel formation modeling

- FRONT multidimensional Eulerian MHD (Riemann solvers, ionization, conductivity)

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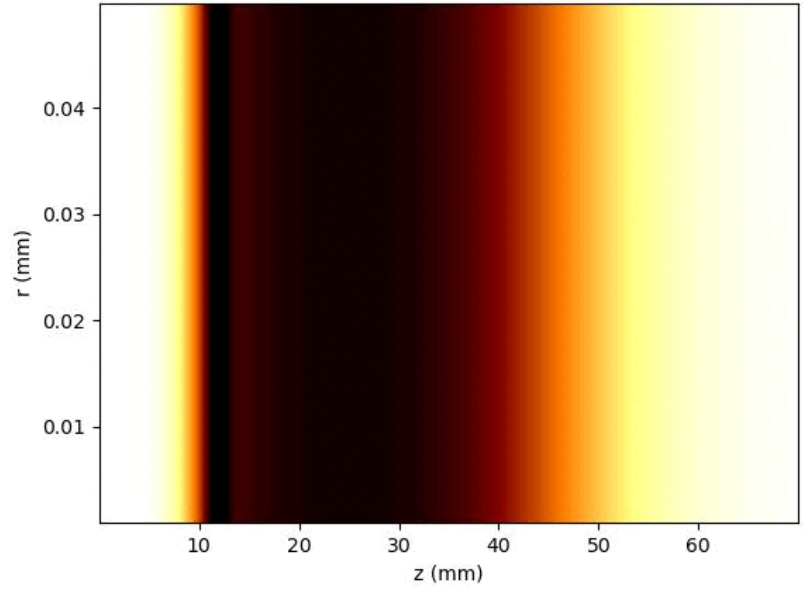

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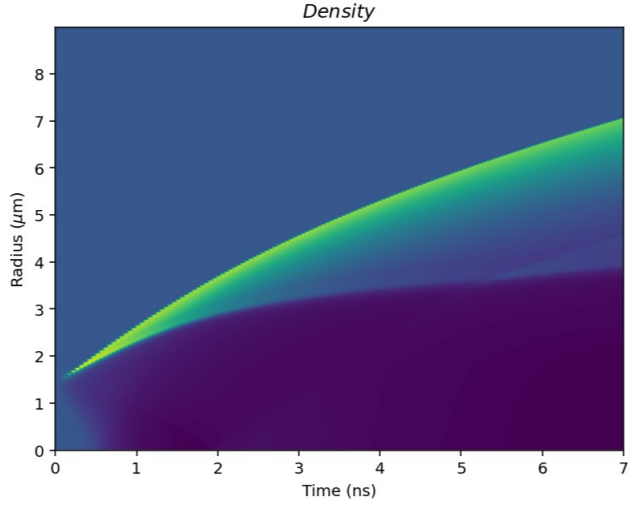

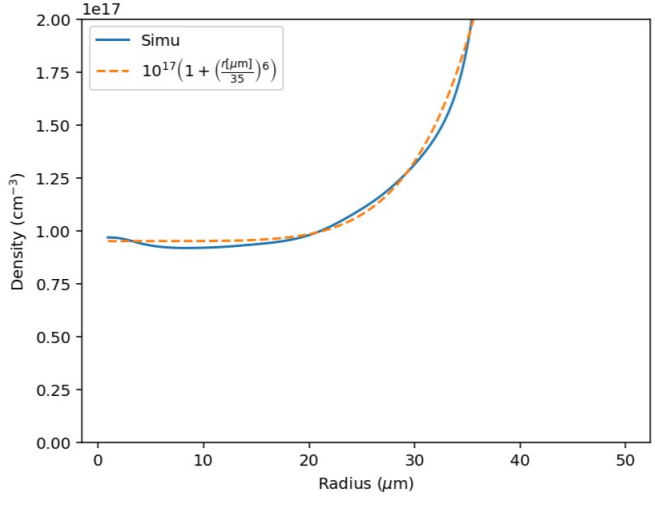

LWFA in the optically produced channel

Acceleration in the channel

- Lorentz-boosted frame simulations with FBPIC
- Laser 10J, 30fs, plasma from MHD