Multi-code numerical studies of optical plasma channel

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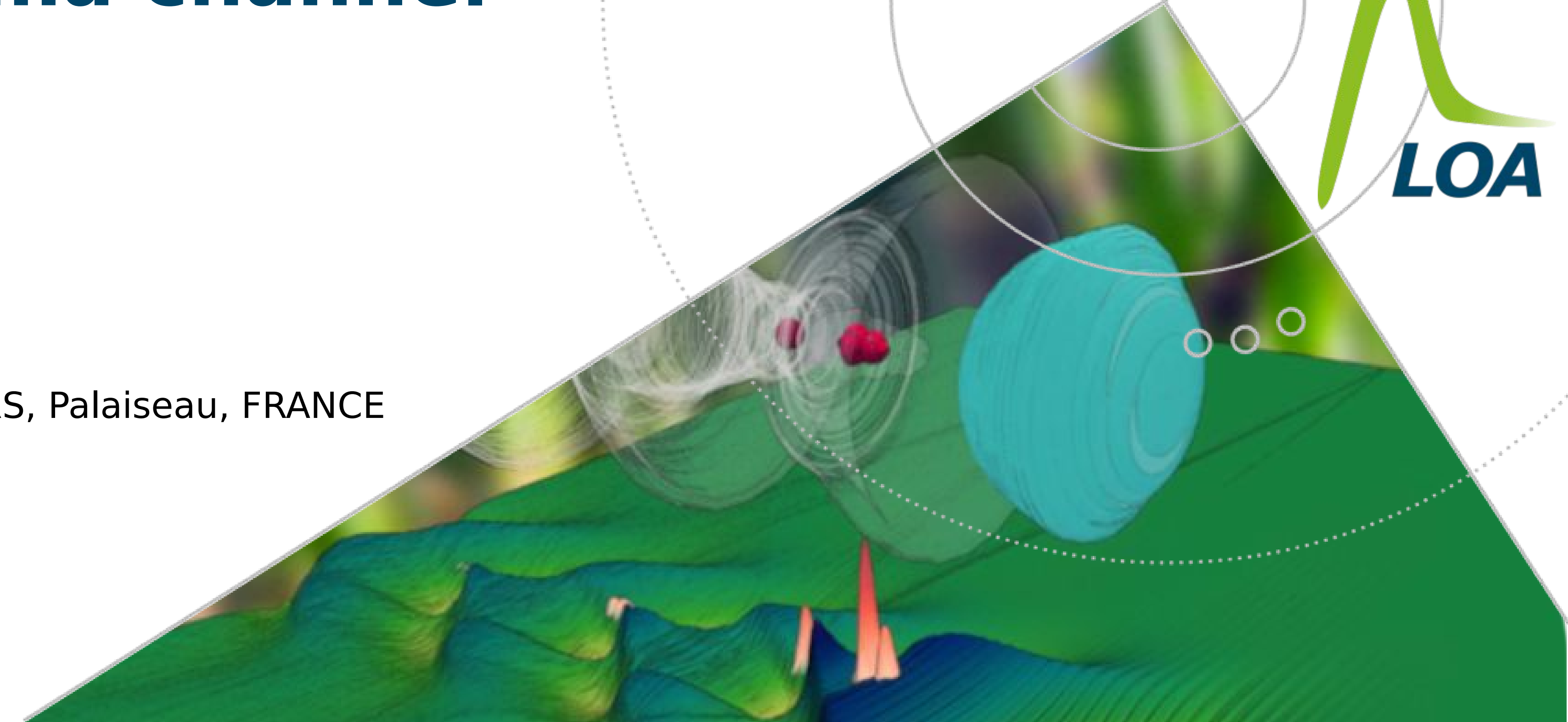
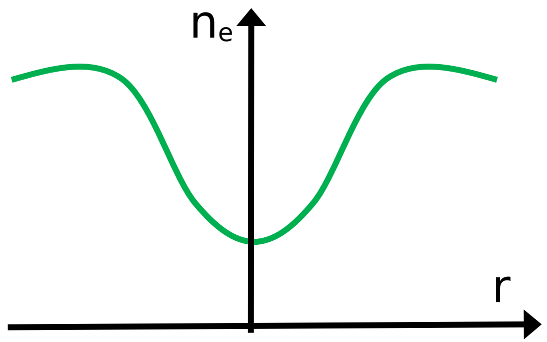


Plasma Wave-Guide



Refractive index $\eta = \sqrt{1 - n_e / n_c}$

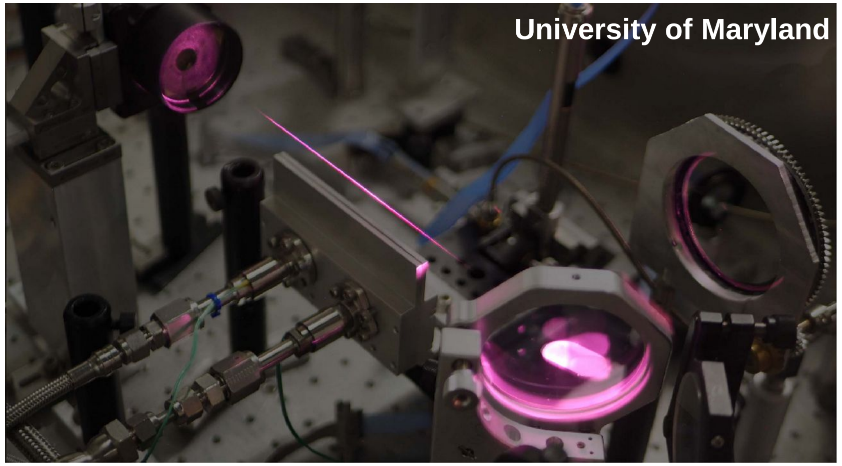
➨ acts as a lens

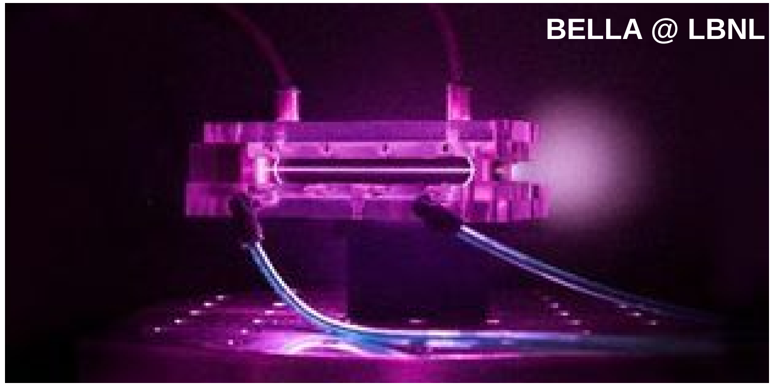
➢ The channel results from the expansion of a hot plasma column.

➢ It can be generated either by a discharge or by a laser.

Optical guide

Durfee *et al.*
PRL **71**,
2409-2412 (1993)





Capillary discharge

Buttler *et al.*
PRL **89**,
185003 (2002)

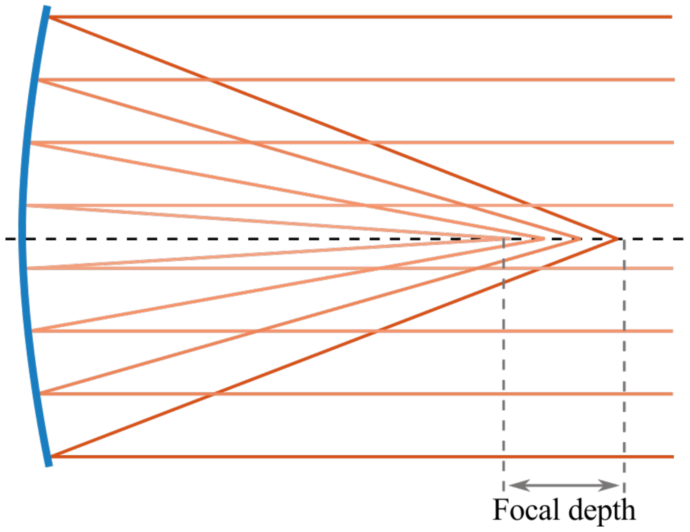
A New Optics for All-Optical Guiding: Axiparabola

An **axiparabola** is a reflective optic that generates a long and high-intensity focal line with a small waist.

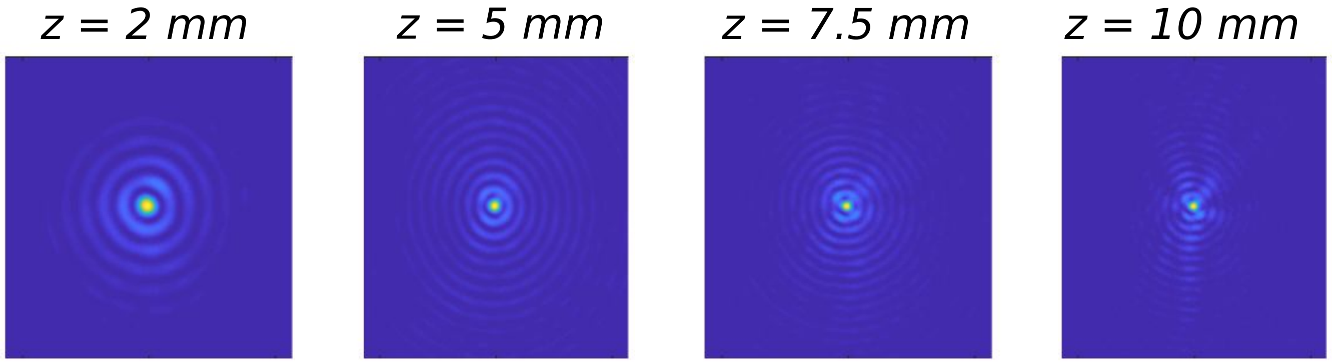
$$f(r) = f_0 + \delta(r)$$

Top hat beam and constant intensity line :

$$f(r) = f_0 + \delta_0 \frac{r^2}{R^2}$$



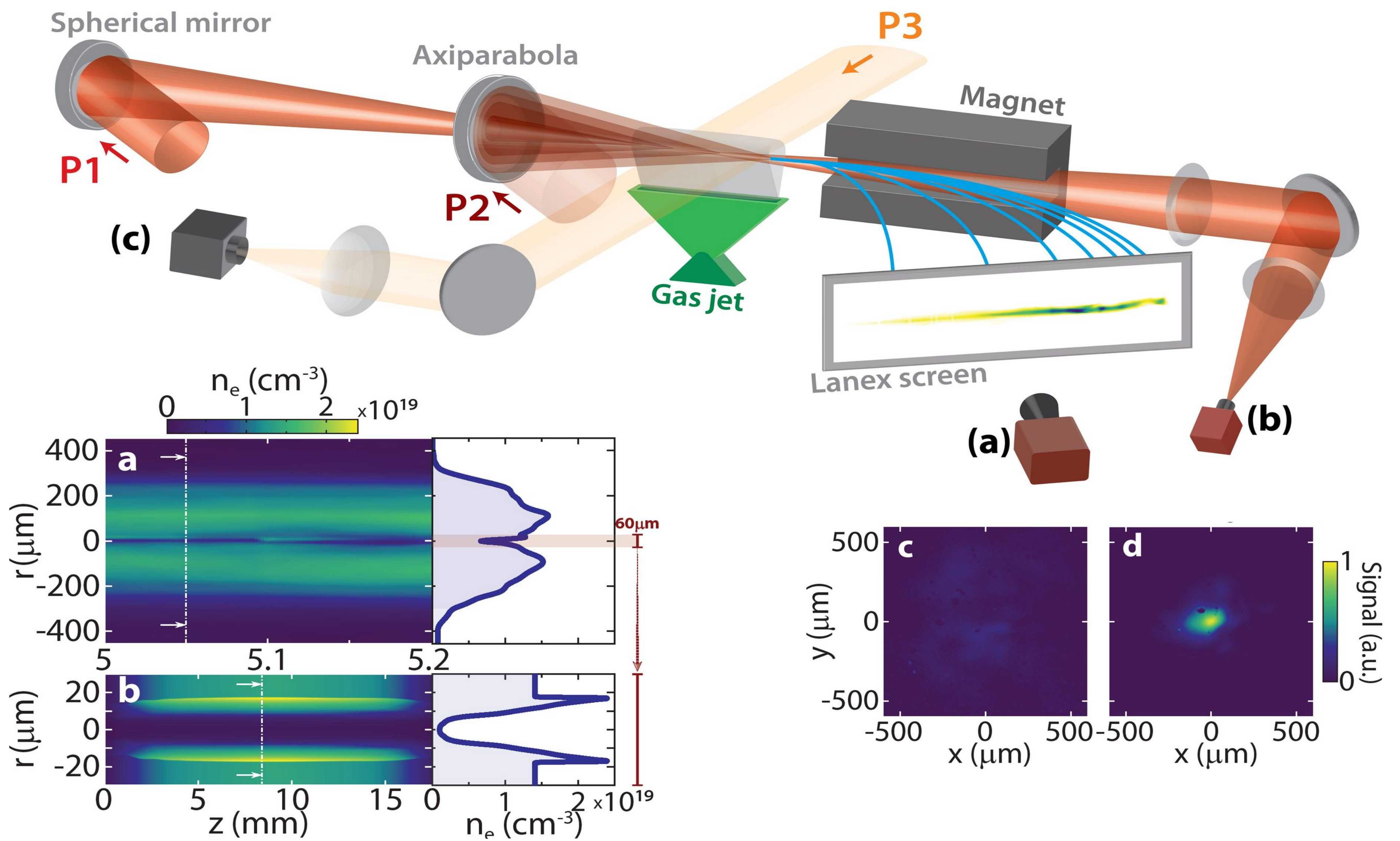
Laser focal spot along the line



The surface can be shaped to get non-monotonic intensity profiles, curved lines...

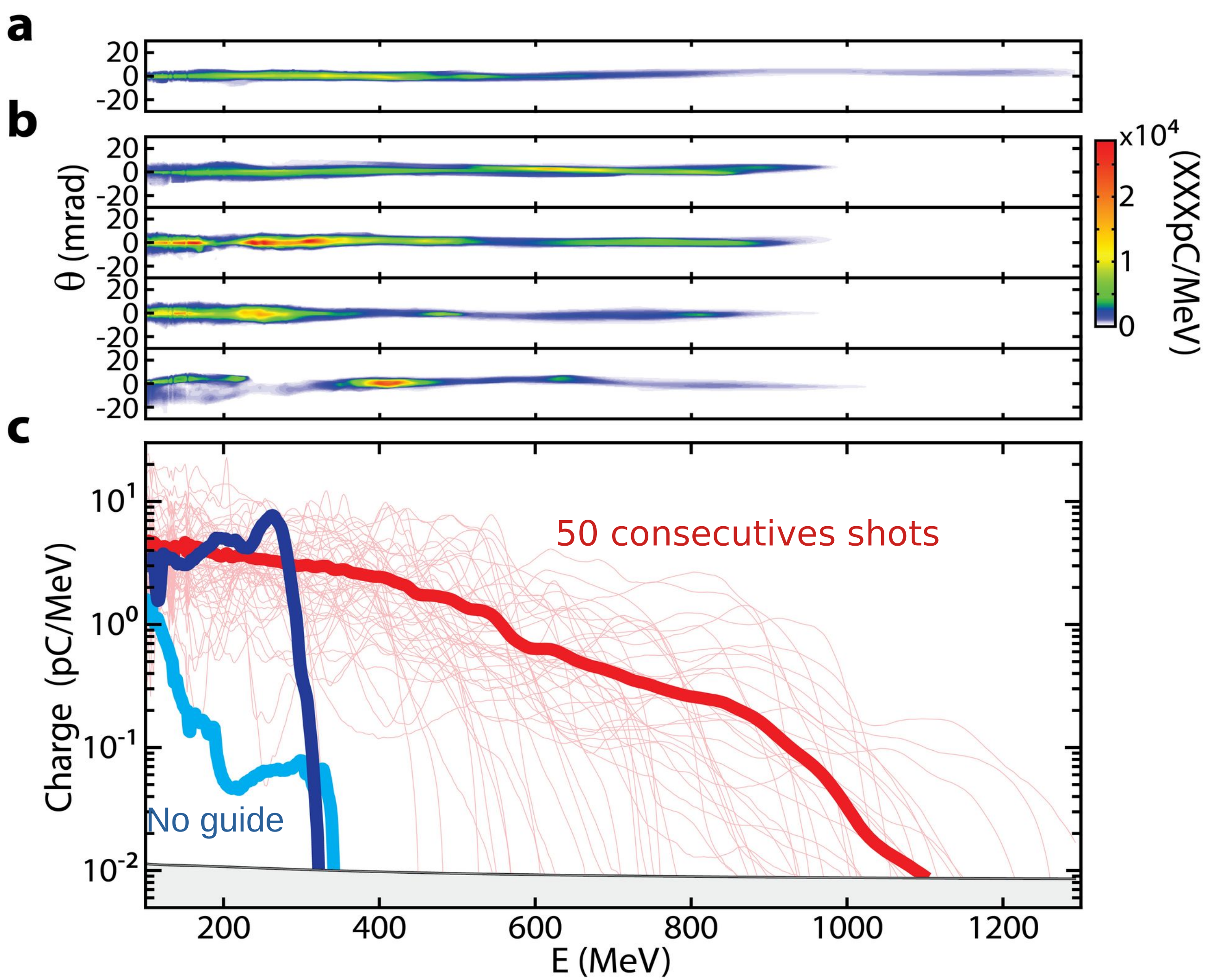
Smartsev et al Optics Letters **44**, 3414-3417 (2019)

Acceleration in a Laser-Generated Waveguide



Acceleration in a Laser-Generated Waveguide

Ionization injection (gas= Hydrogen + 1% Nitrogen)



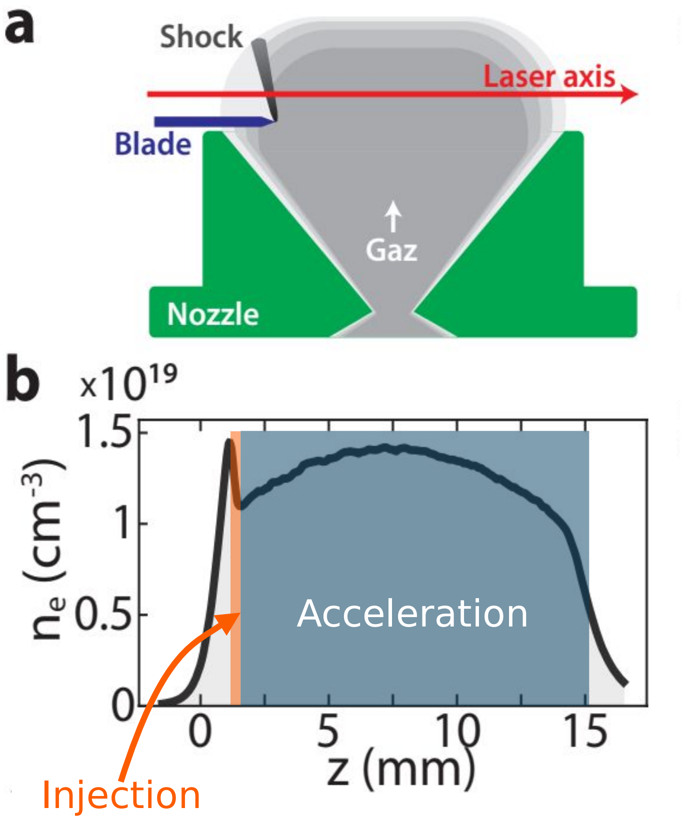
- ◆ 1.7 J – 30 fs laser for aceleration
- ◆ 15 mm gas jet
- ◆ 5 mJ for generating the waveguide
- ◆ Up to ~1.1 GeV electron energy

◆ 70% of shots with guiding and electron energy > 600 MeV

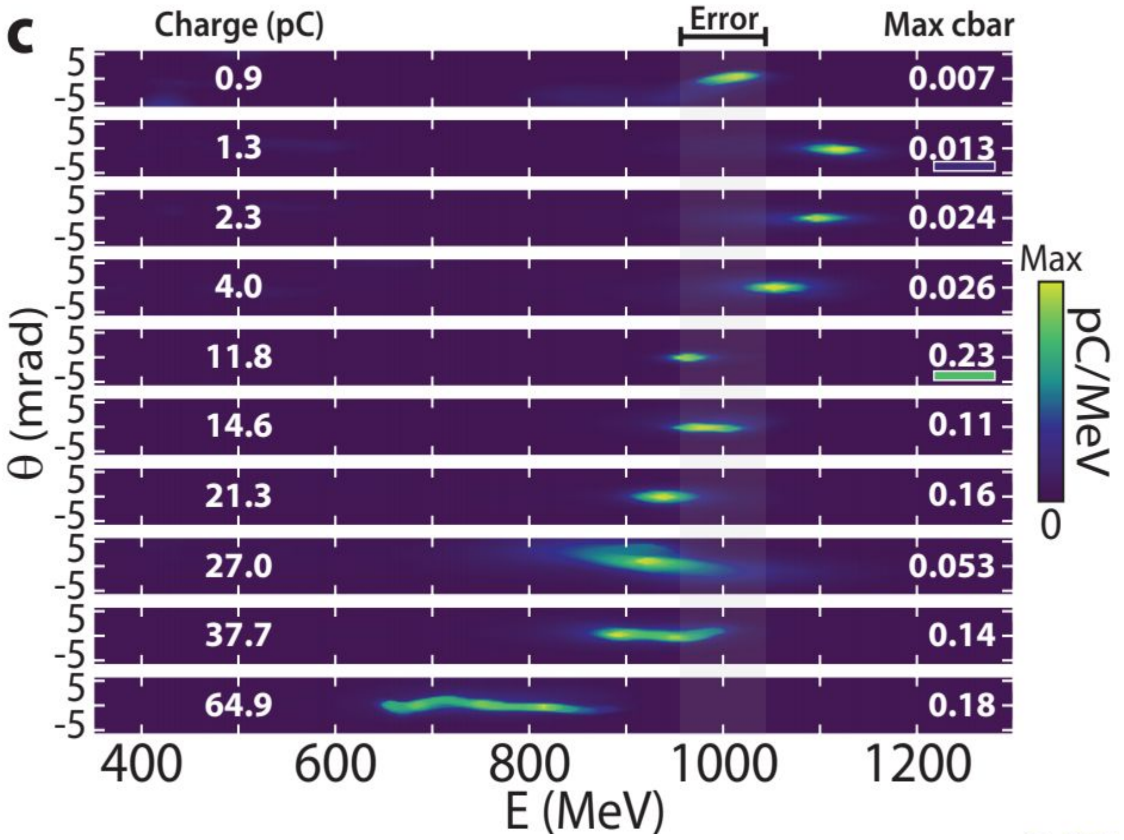
◆ 50 pC above 350 MeV (2% conversion efficiency)

Controlled Injection in a Laser-Generated Waveguide

Density transition injection



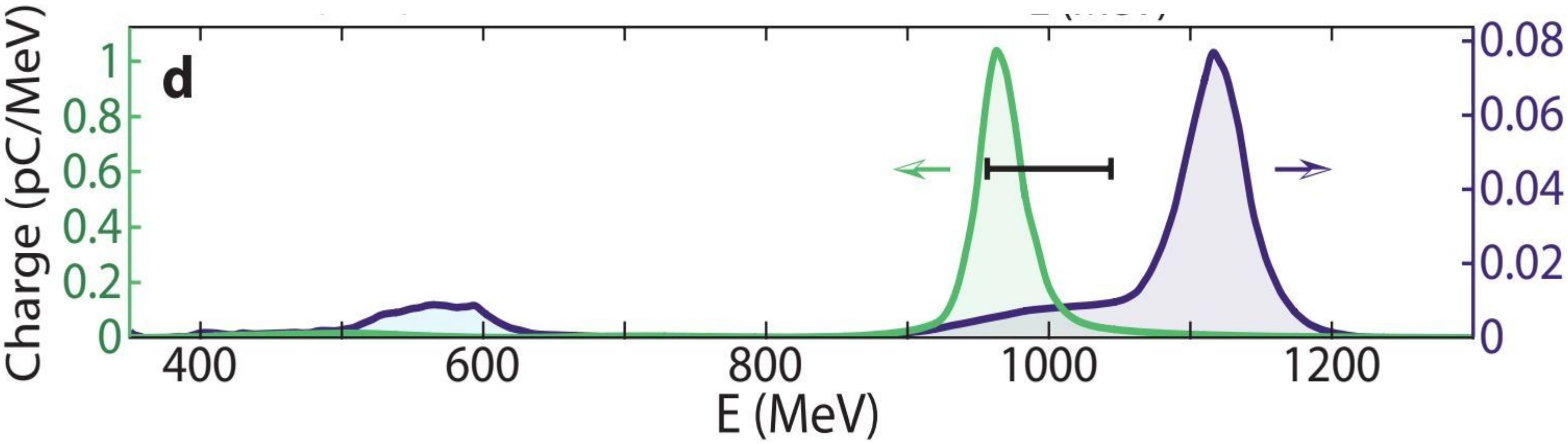
10 shots selected from a series of 14 sorted by charge



Guided laser ➡ peaked spectra > 600 MeV

Oubrerie et al. Light Sci Appl 11, 180 (2022)

Guiding and Beam-Loading



◆ Down to 2% energy spread (3.6% without divergence deconvolution)

◆ Conversion efficiency of 1% for GeV beams and up to 6% for the most loaded ones.

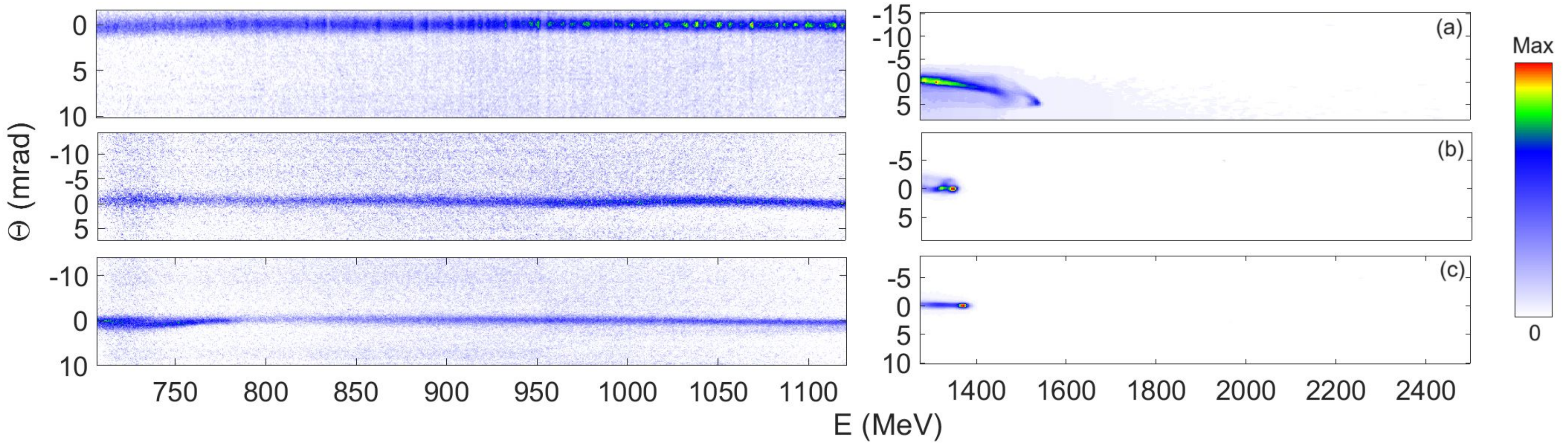
Oubrerie et al. Light Sci Appl 11, 180 (2022)

Increasing the Laser Energy with a PW-class Laser

View of the experiment

Target (6 cm long nozzle + blade)

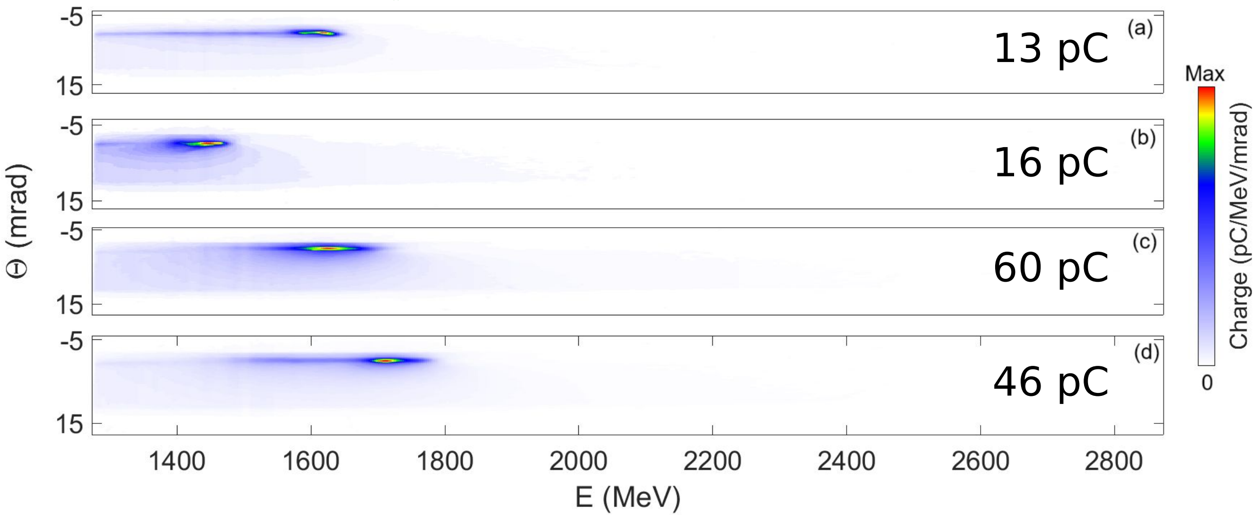
Apollon laser ~ 10 J on target, 25 fs
Helium gas



No blade, no guiding
→ Continuous spectra
→ Max energy ~ 1.4 GeV

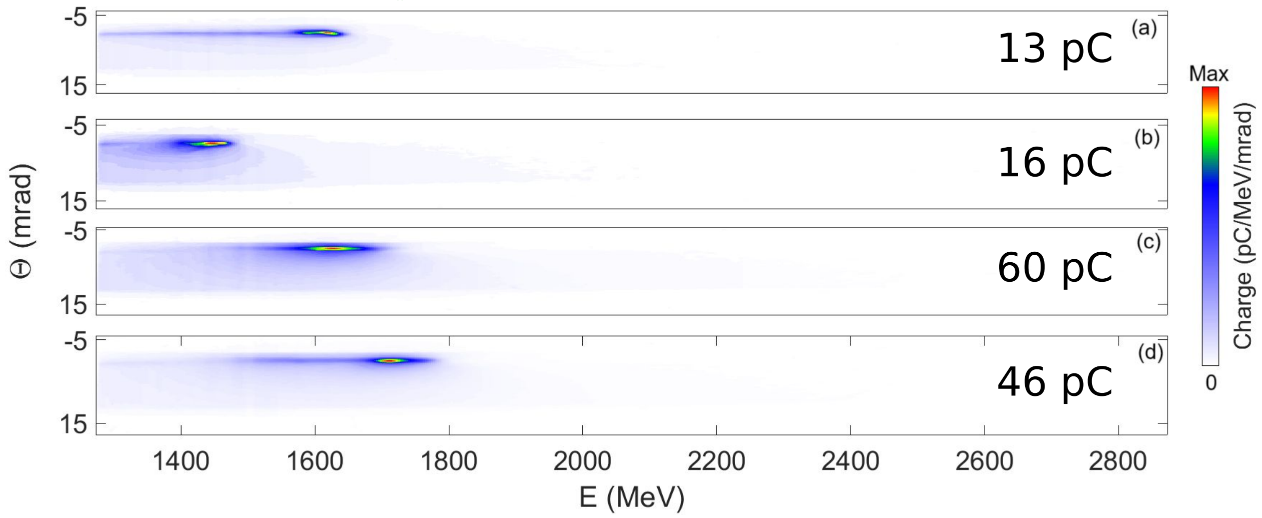
Increasing the Laser Energy with a PW-class Laser

Blade

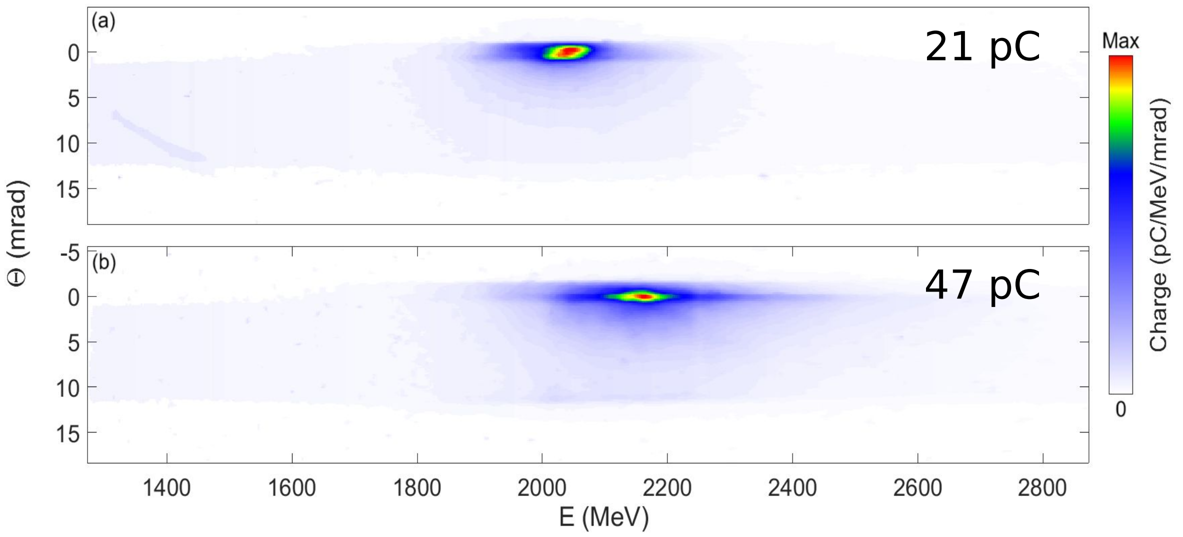


Increasing the Laser Energy with a PW-class Laser

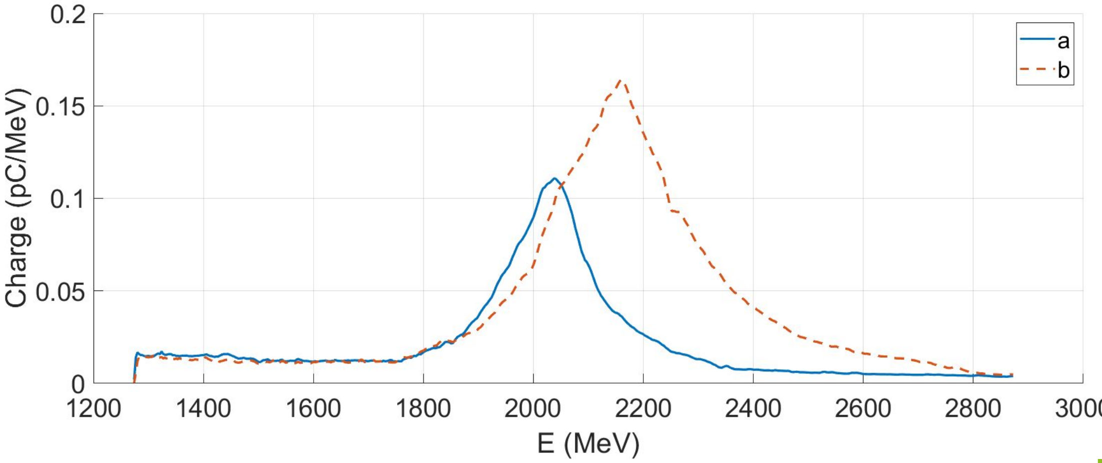
Blade



Blade + guiding

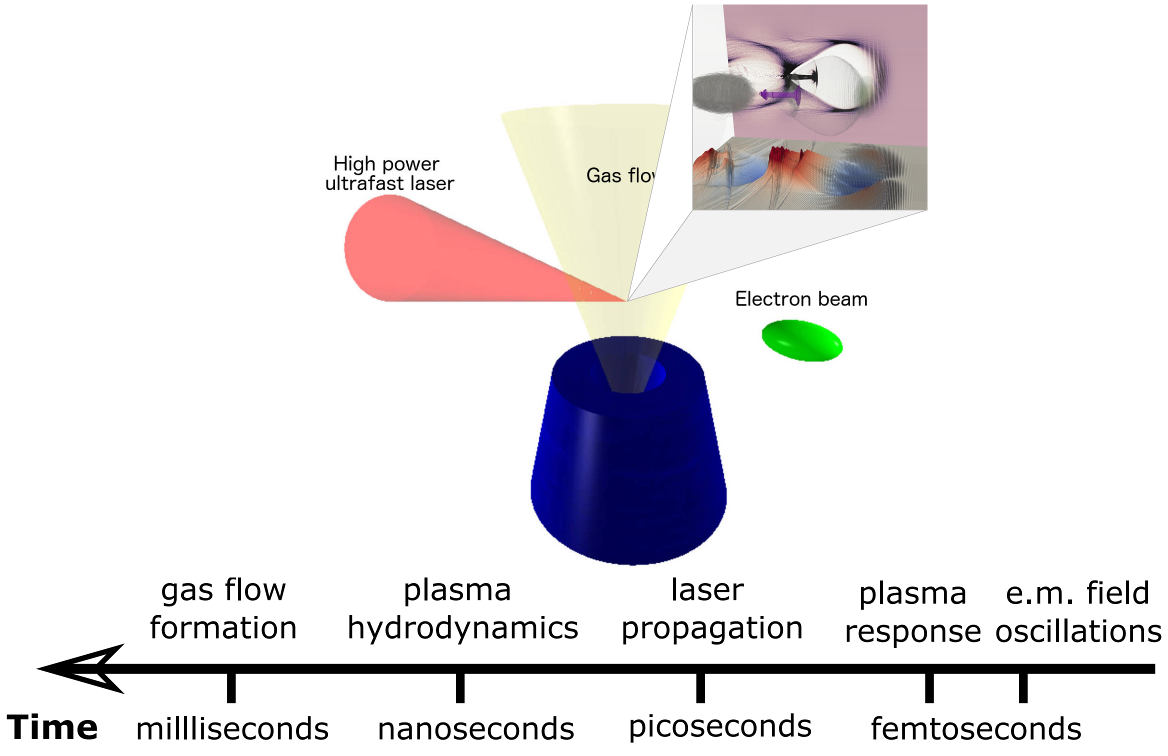


- 2.2 GeV
- 1% conversion efficiency
- 10% energy spread



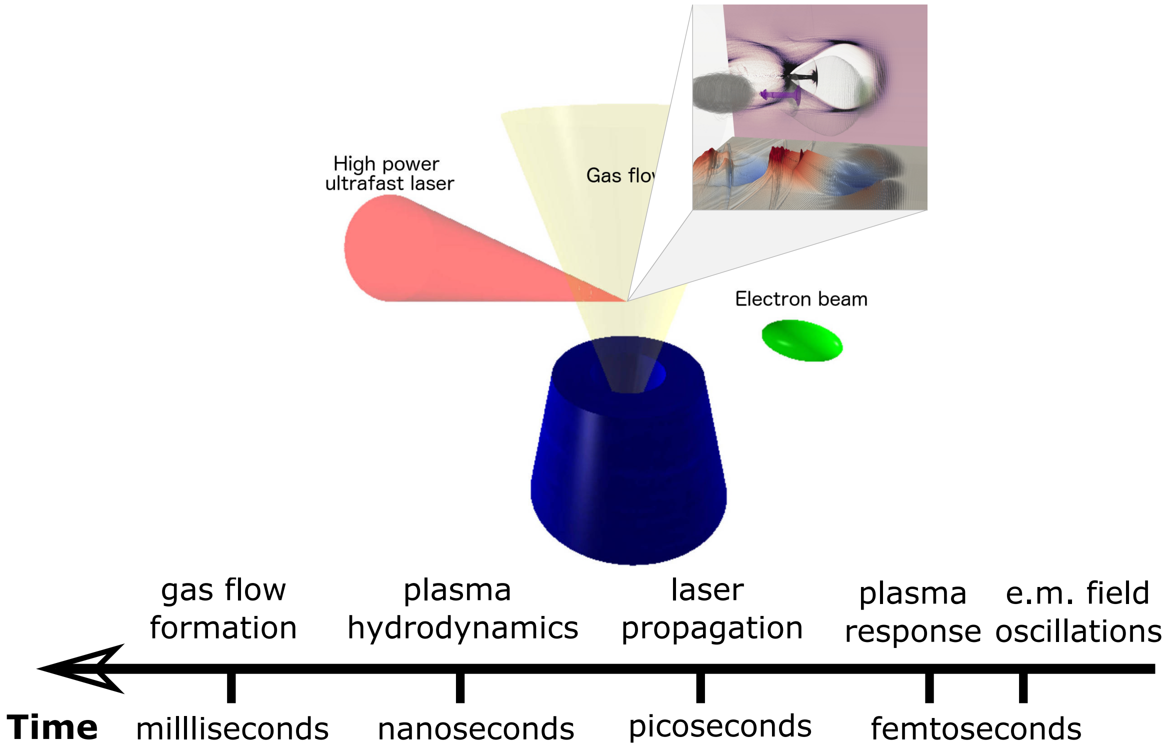
Up to 5 GeV, w/o controlled injection in
Miao et al. PRX 12, 031038 (2022)

Time scales



- 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

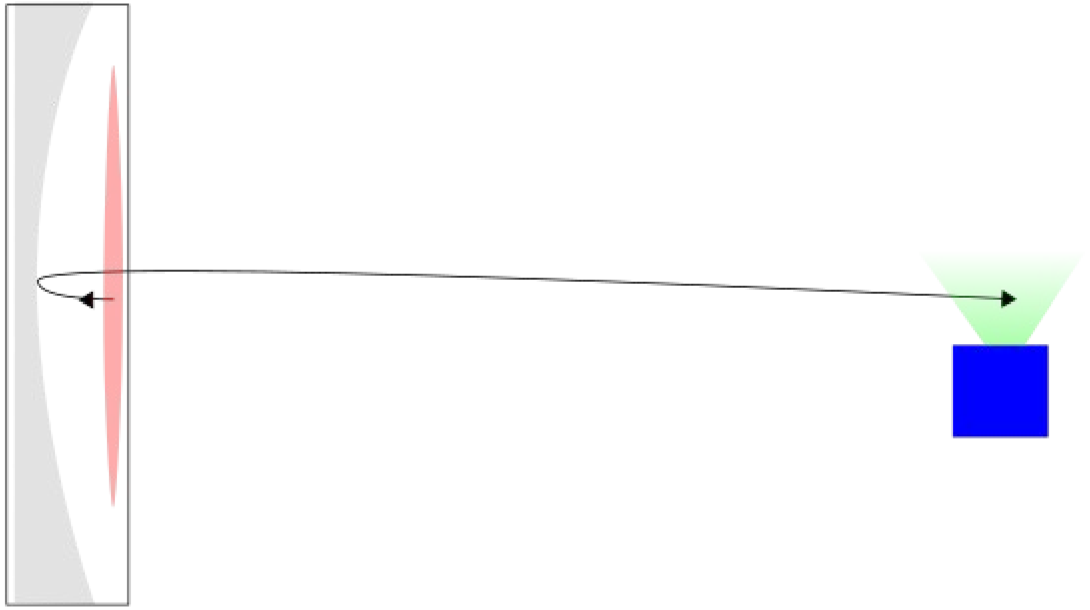
Time scales



- Femto second laser with complex structure and large angle
- Propagation – optical field ionization – electron fast heating (no PIC)
- Relaxation of strongly non-equlibrium anisotrop plasma (need PIC)
- Plasma expansion and channel formation (need MHD)

Need for the multi-code workflow

Optical propagation with Axiprop



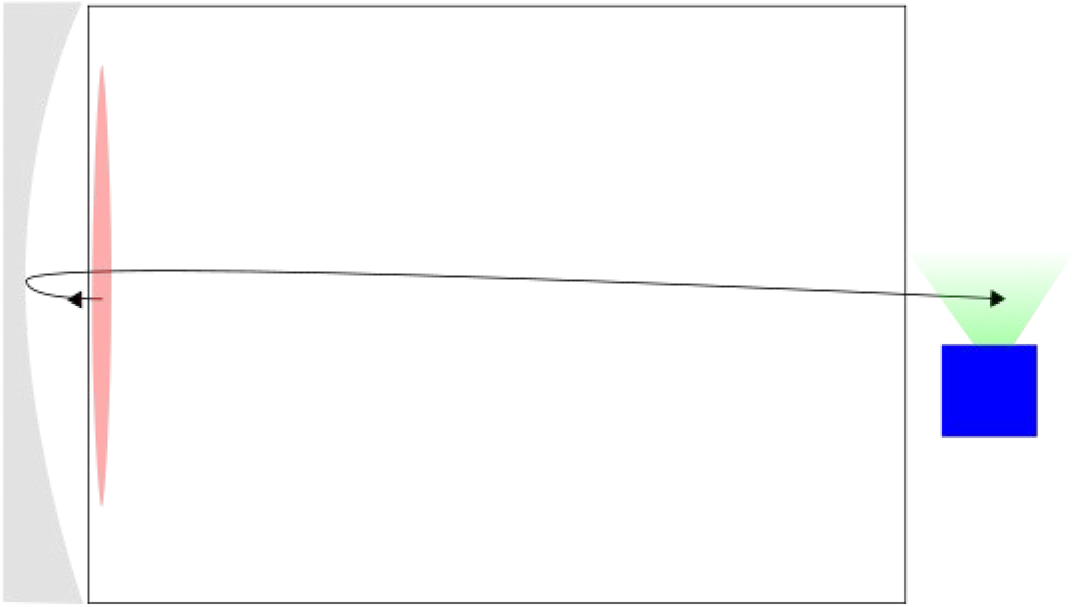
- Initial laser state: flat pulse + optics
- Vacuum propagation to the plasma position (large beam to small beam)
- Propagation through the plasma:
  - simple/relativistic/ionizable plasmas
  - ADK (carrier resolved/envelope)
  - explicit (RK4) and implicit (Adams-Moulton) solvers
  - adaptive step, iterative strategies
  - carrier resolving OFI probe
- API to explore output and export to *LASY*

```
prop0 = PropagatorResamplingFresnel(...)

LaserObject = ScalarFieldEnvelope( k0, t_axis ).make_gaussian_pulse(
    prop0.r, tau, R_las, Energy=LaserEnergy, n_ord=10 )

E0 = LaserObject.Field_ft.copy()
E0 *= mirror_axiparabola_coeffs(prop0.kz, prop0.r, Cn, R_mirr)
E0 *= hole_profile
```

Optical propagation with Axiprop



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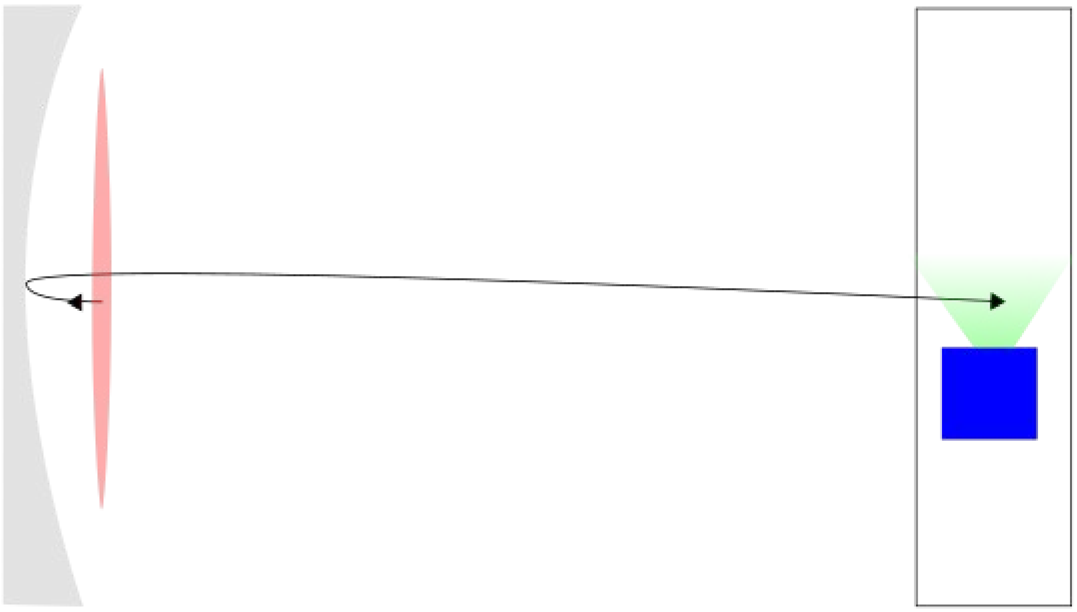

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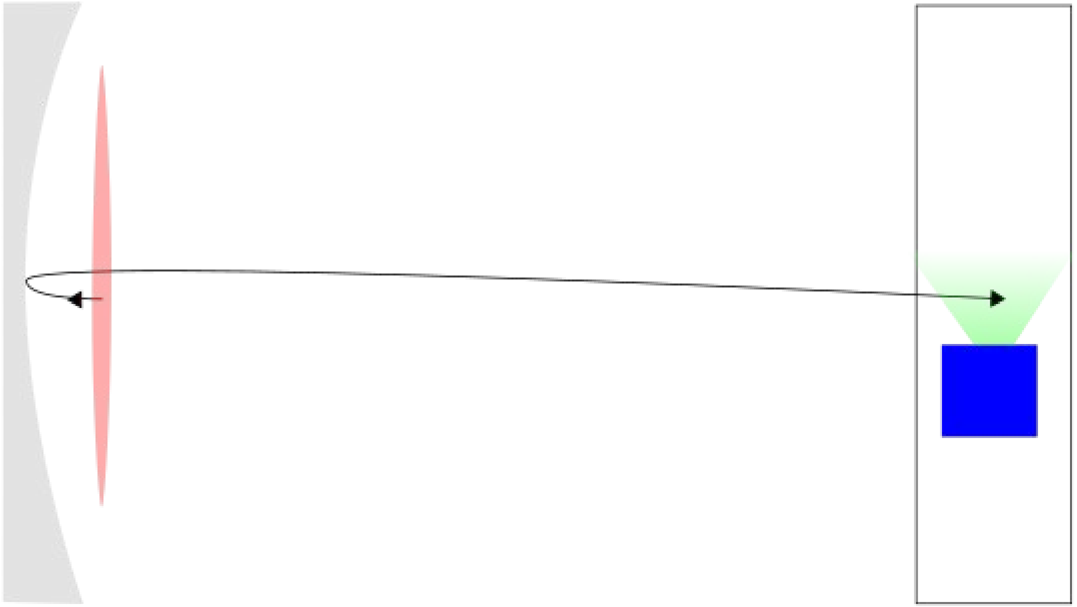
```
sim = SolverAM2(...)

sim.physprocs = [
    PlasmaIonization( n0_gas, dens_func, sim, my_element='He' ),
    OFI_heating( n0_gas, dens_func, sim, my_element='He' ),
]

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

Optical propagation with Axiprop



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```
ts = DiagsAPI( './case_He/diags/' )
diags_var = ts.get_various('./new_solver/case_He_04/')

laser_axiprop = ts.get_container( i_record )

laser_lasy = export_to_lasy( laser_axiprop )
laser.write_to_file()
```

LASY: LAser manipulations made eaSY

An open-source Python library to facilitate the use of realistic laser profiles in simulations

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[2]Laboratoire d'Optique Appliquée LOA, 181 Chemin de la Hunière 91762 Palaiseau, France
[3]Commissariat à l'Énergie Atomique CEA Paris-Saclay, 91191 Gif-sur-Yvette, France
[4]Lawrence Berkeley National Laboratory, 1 Cyclotron Rd, Berkeley, California 94720, USA
[5]Universität Hamburg, Mittelweg 177, 20148 Hamburg

Motivation

- **Realistic laser profiles** are key for realistic simulations of laser-plasma interaction [1].
- Start-to-end workflows require interfacing simulation tools with **different laser representations**.
- **Laser manipulations** (conversions, propagation, etc.) are required and error-prone.

➤ LASY simplifies these workflows with **modern programming methods** (Open-source, Python, CI/CD, data standards).

Experimental data
3D data (e.g. INSIGHT [2]) or
separate transverse + spectral

Simulation output
Electric field or vector potential
separate transverse + spectral

Analytic profiles from LASY
Gaussian, Hermite-Gauss,
Laguerre-Gauss

LASY

- Convert electric field ↔ vector potential
- Convert full field ↔ laser envelope
- Construct 2D cylindrical/3D Cartesian profile
- Filter/smooth data
- Propagate in vacuum to desired location
- Write to file

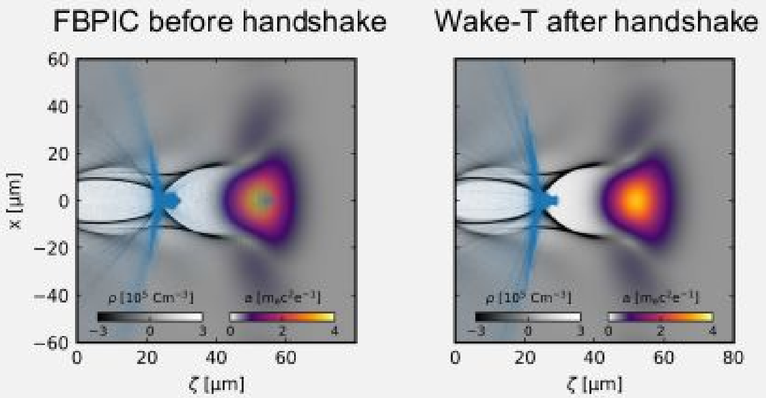
→ openPMD

Simulation/post-processing

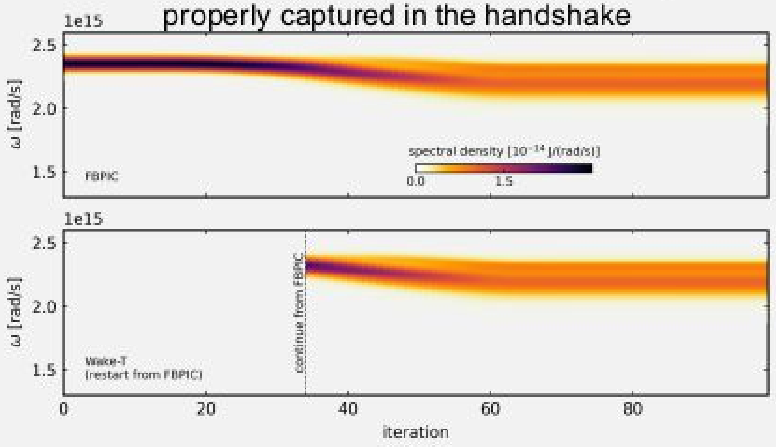
From simulation to simulation

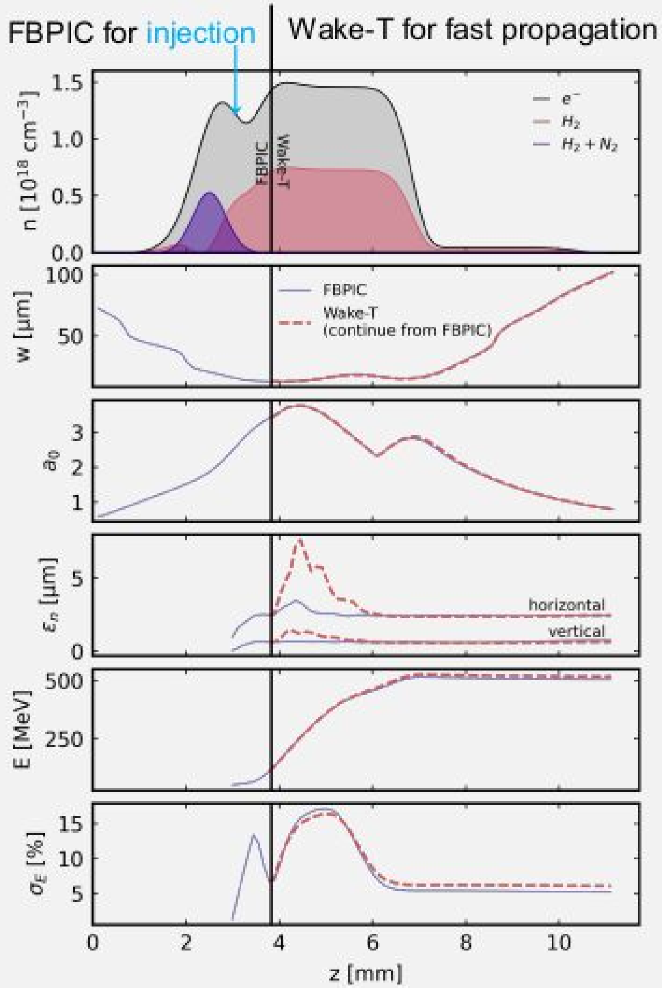
LASY makes it easier to combine codes with different laser representations

- **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



Like other properties, the laser spectrum is properly captured in the handshake





Plasma channel (Apollon exp) with axiprop

- Axiparabola: $f_0 \cong 0.5$m, $\delta f \cong 16$ cm
- Laser: 50fs, 31mm spot
- Slit-nozzle 6cm gas target with Helium

Simple OFI model:

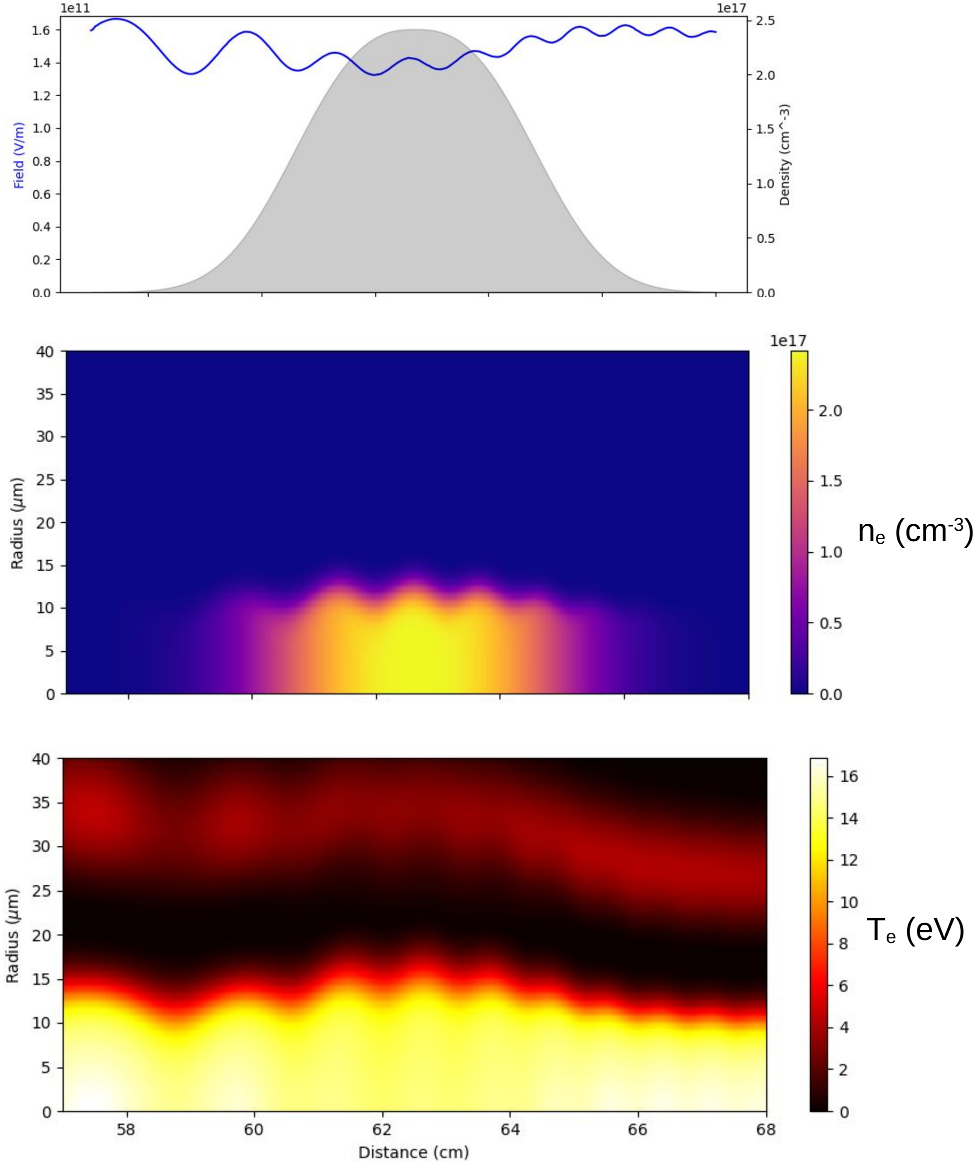
Axiprop OFI:

ADK (carrier resolved/envelope) + $E_e = \left(\frac{qA_{x_0}}{c}\right)^2 \frac{1}{2m_e}$

After isotropization/“maxwellization”: $T_e \sim 16$ eV.

Should we already use these data for MHD?

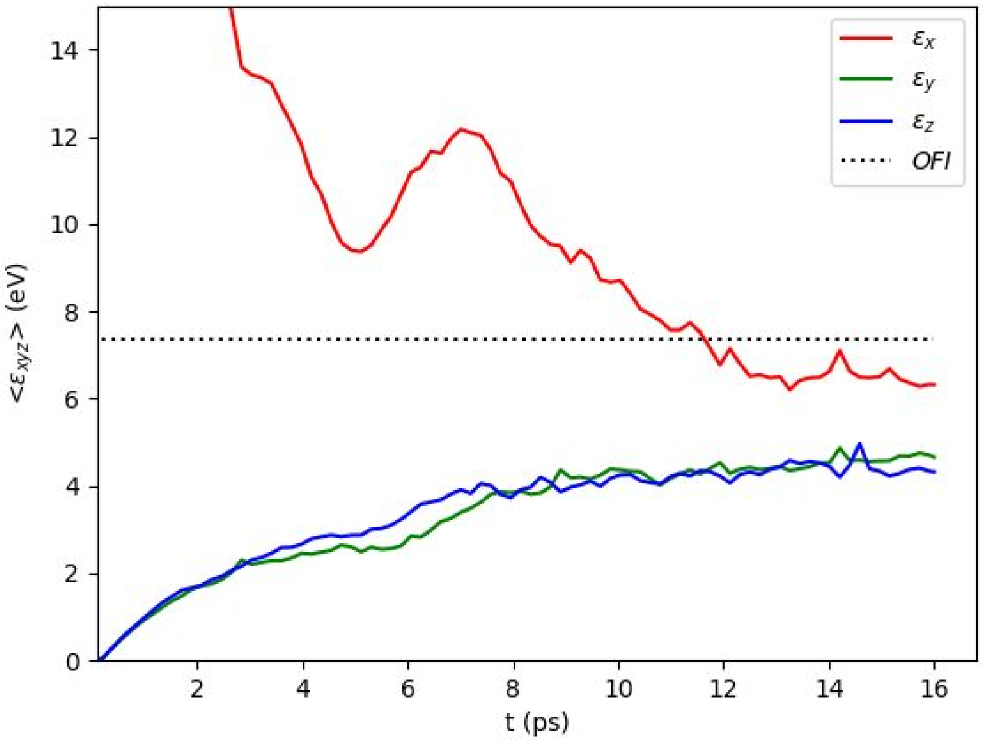
Let’s check with collisional PIC

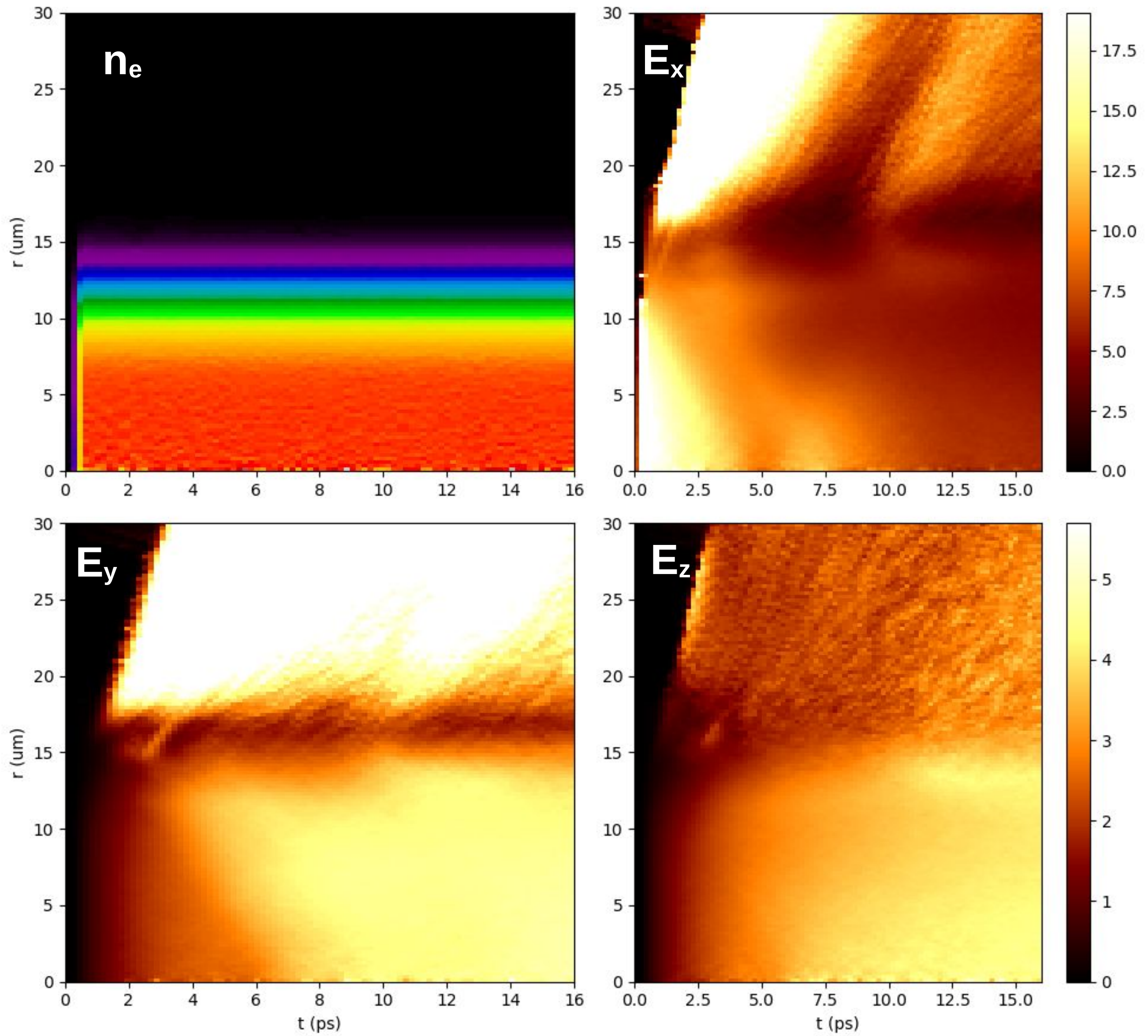


Apollon plasma channel: WarpX

Small 3D simulations (80 mJ)

- x,y [-35, 35] um
- L_z=3.5 um
- 192 x 192 x 128 cells
- 1 x 3 x 3 ppc
- e-e, e-i collisions





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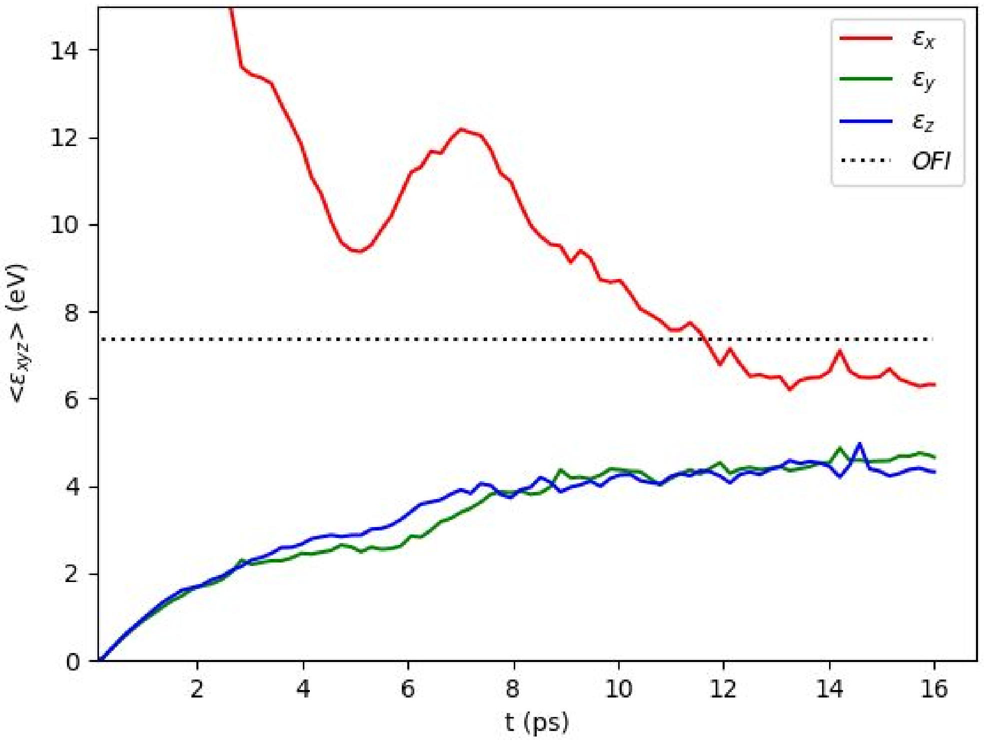
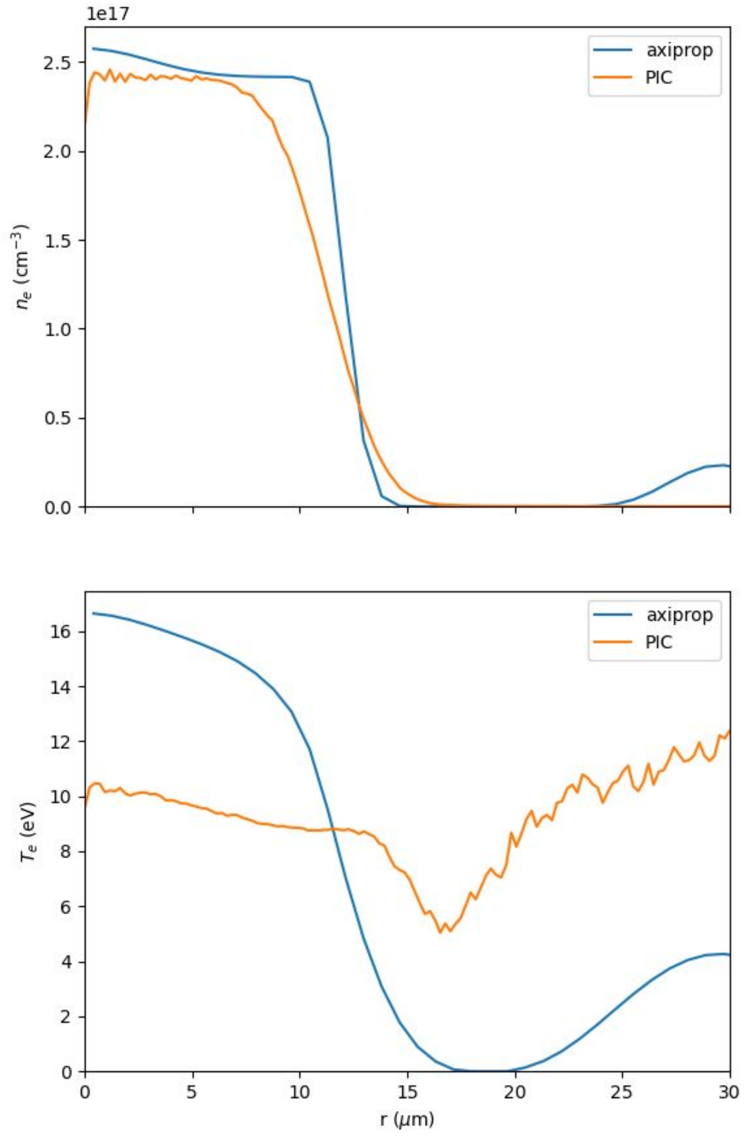
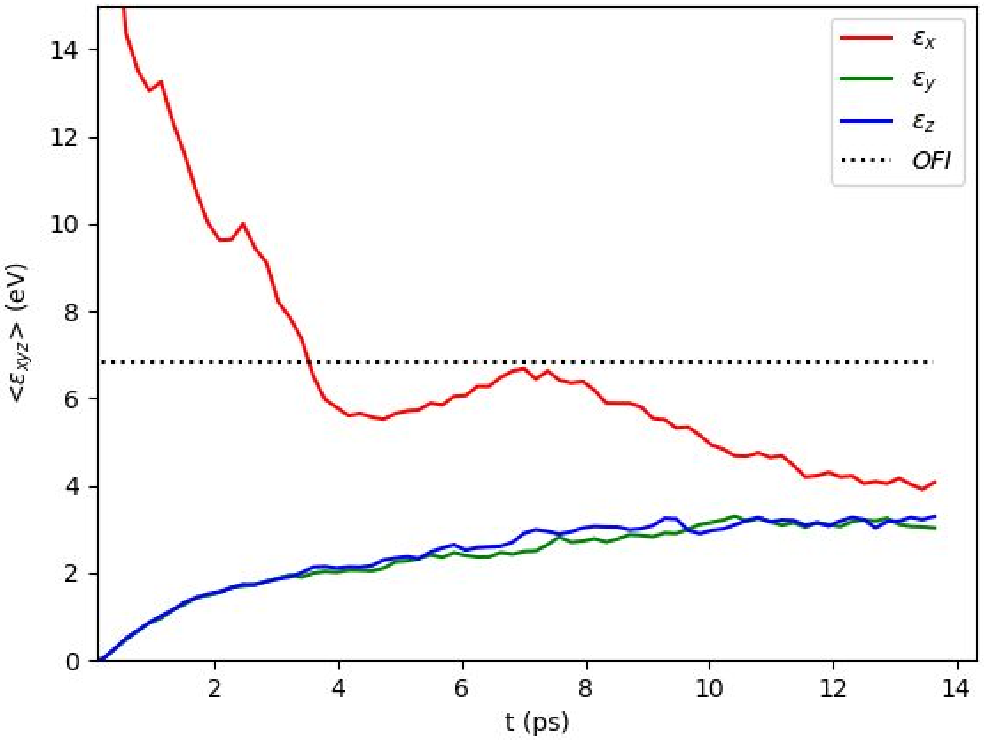


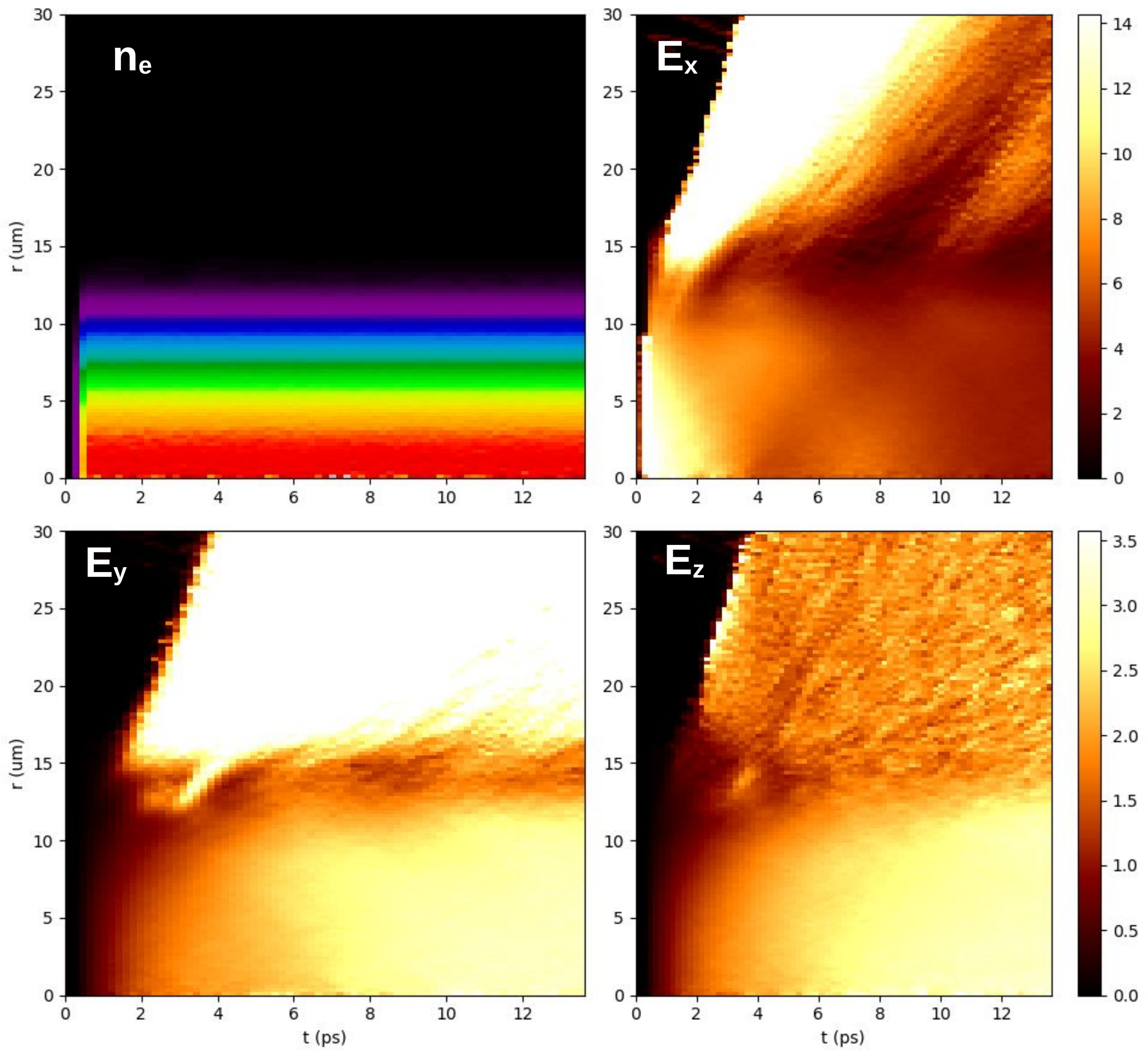


Apollon plasma channel: WarpX

Small 3D simulations (55 mJ)

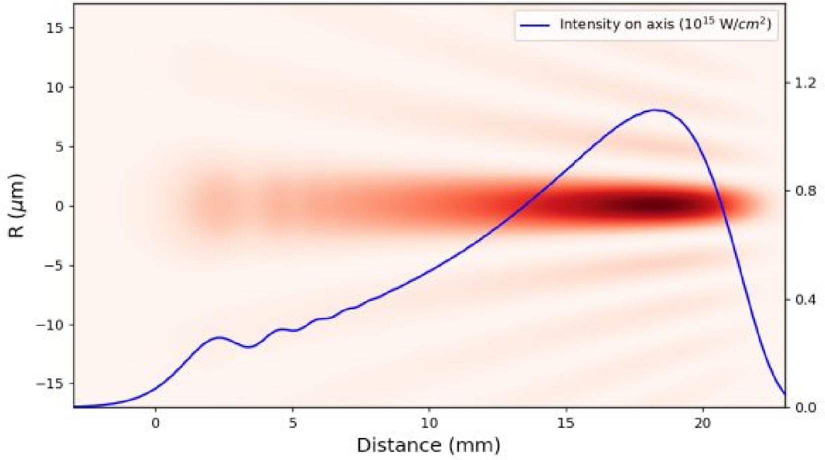
- x,y [-35, 35] um
- L_z=3.5 um
- 192 x 192 x 128 cells
- 1 x 3 x 3 ppc
- e-e, e-i collisions

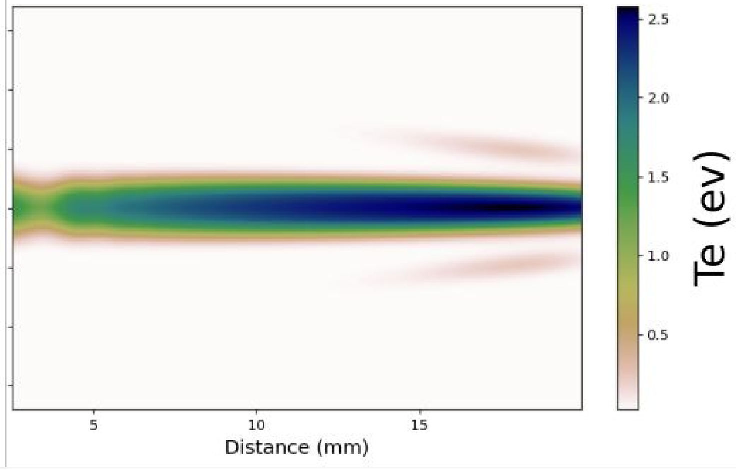




Channel formation with FRONT3D code (older results)

- Optical propagation (AxiProp) → OFI heating (home-made)





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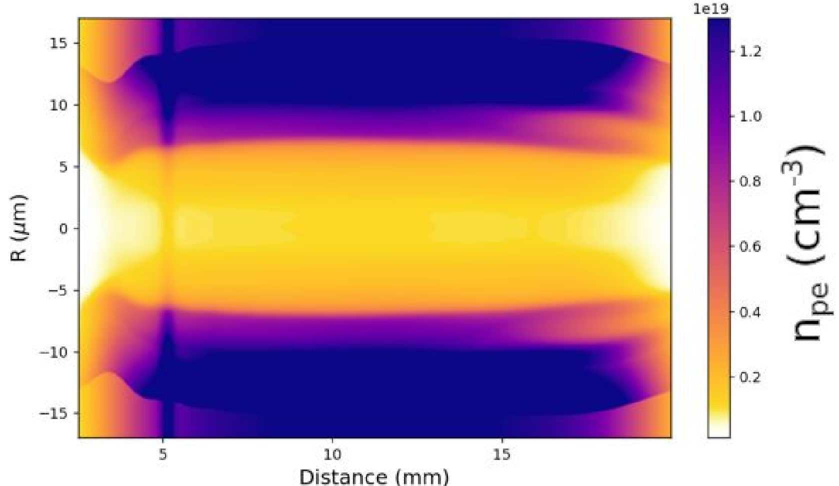

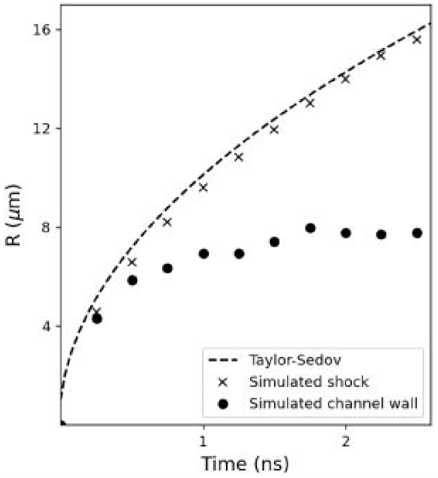

Conclusions

- Containers for laser data exports for multi-code laser plasma studies
- Combination of optical and PIC codes is important for laser plasma channeling
- Close to ionization threshold OFI is very sensitive and should be explored