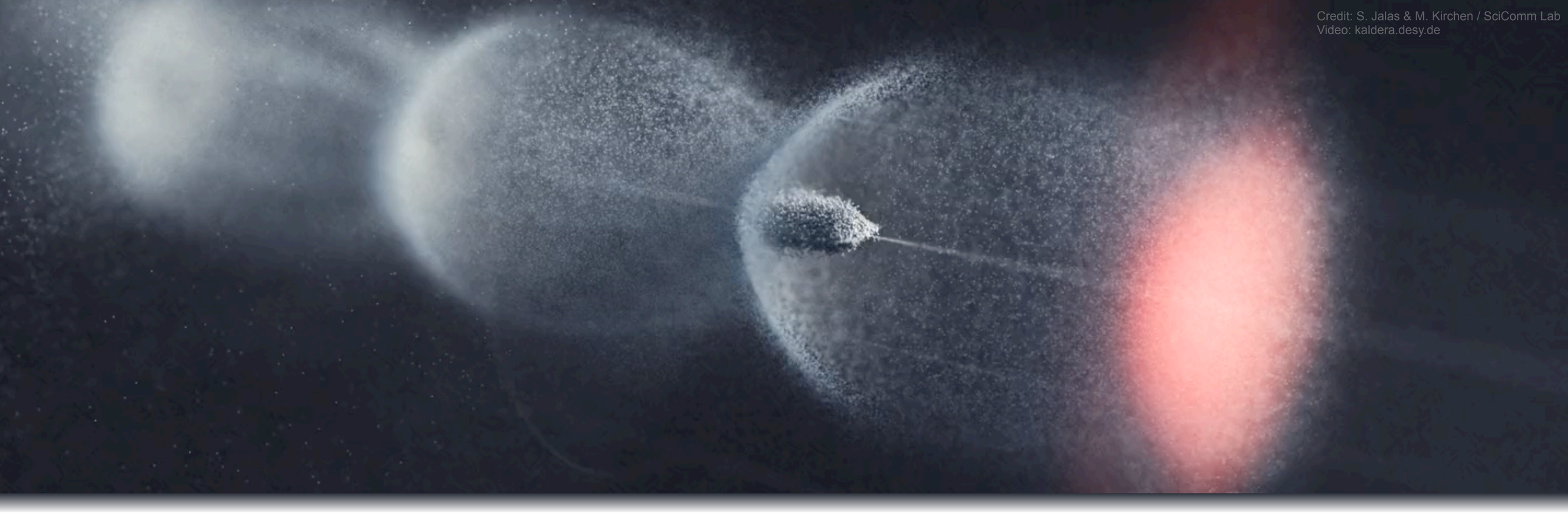


HELMHOLTZ

LASY (**LA**ser manipulation**S** made eas**Y**)

Enabling realistic laser pulses in start-to-end simulations

K. Põder [1], R. J. Shalloo [1], I. Andriyash [2], L. Fedeli [3], A. Ferran Pousa [1], A. Huebl [4], S. Jalas [1], M. Kirchen [1], R. Lehe [4], A. Sinn [1], J.-L. Vay [4] & M. Thévenet [1]

[1] Deutsches Elektronen Synchrotron (DESY)
[2] Laboratoire d'Optique Appliquée (LOA)
[3] Commissariat à l'énergie atomique et aux énergies alternatives (CEA),
[4] Lawrence Berkeley National Laboratory (LBNL)

A modern simulation study combines multiple codes

Simulation studies gain from being:

We contribute to this ecosystem

Multi-physics
- Hydrodynamics (HOFI, discharge, etc.) — **COMSOL-plasma**
- Beam dynamics, application

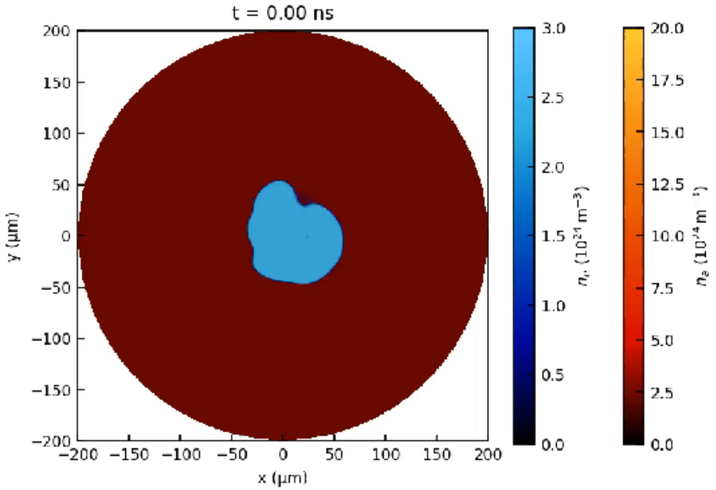
Energy efficient
- Efficient codes for reduced model — **HiPACE++, Wake-T**
- Combine the most appropriate tools — **(see next slide)**

Realistic
- Experimental laser profiles
- Experimental plasma/beam profiles

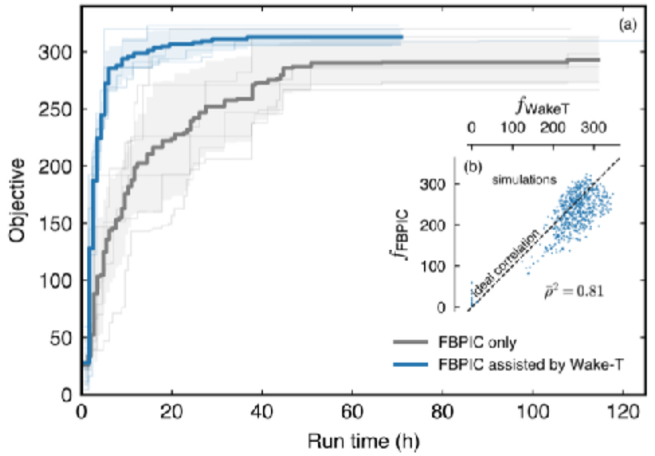
Comprehensive
- Ensembles of simulations
- (Bayesian) Optimization

optimas

Scalable optimization on experiments and simulations



Collaboration with UNIVERSITY OF OXFORD

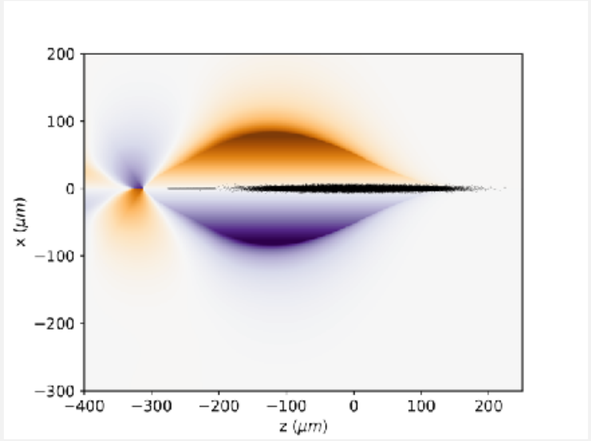


Collaboration with BERKELEY LAB Argonne NATIONAL LABORATORY

Fully converged simulations with reduced models at modest cost

HiPACE++

- Open-source, GPU-capable multi-physics 3D quasistatic particle-in-cell code (laser-driven or beam-driven), C++
- Collaboration DESY. BERKELEY LAB



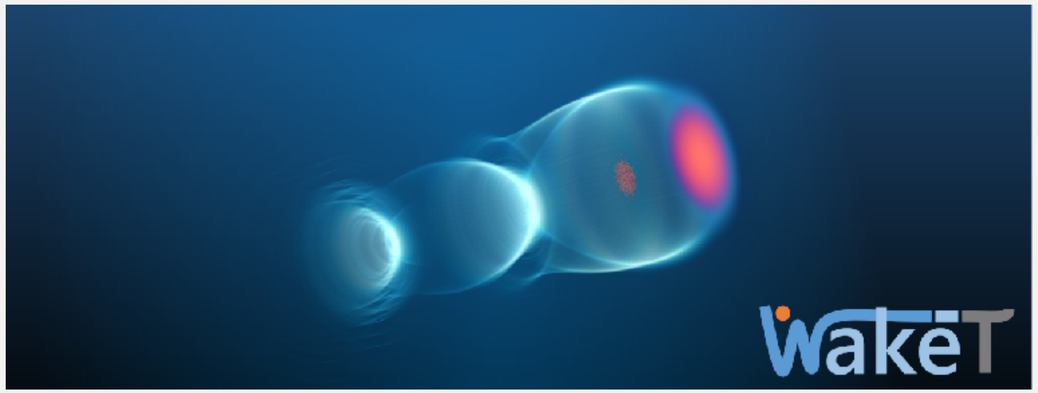
Fully converged (nm-scale resolution with mesh refinement) 3D simulations of a 20 GeV stage starting at 175 GeV for a 135 nm emittance beam w/ ion motion takes 30 min on 16 GPU-equipped nodes (Frontier has 9400) → small allocation allows thousands

S. Diederichs et al., Comput. Phys. Comm. 278: 108421 (2022)
https://agenda.infn.it/event/35577/contributions/208606
https://github.com/Hi-PACE/hipace

BLAST BEAM PLASMA & ACCELERATOR SIMULATION TOOLKIT

WakeT

- Open-source, 2D (axisymmetric) quasistatic code for (laser/beam-driven), incl. ion motion, Python



1 plasma stage takes seconds-to-minutes on a laptop, suitable for design studies. 20 stages + optimization to 150 GeV in < 1 hour

A. Ferran Pousa et al., J. Phys.: Conf. Ser. (2019)
A Ferran Pousa, et al. Proc. IPAC23, 1533
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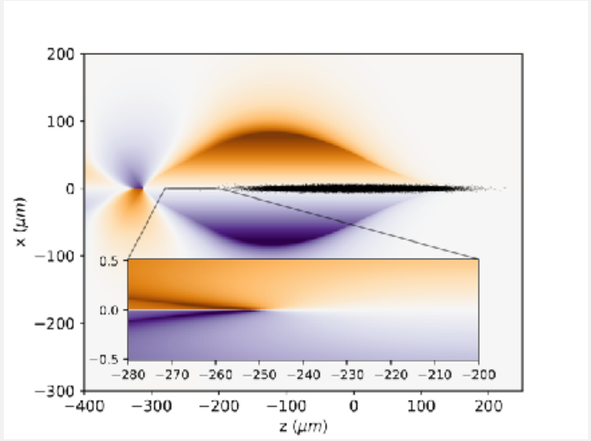

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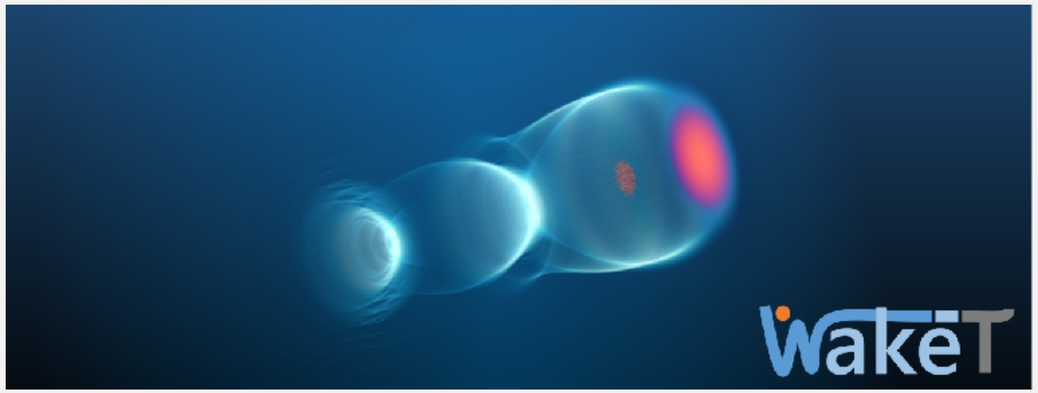

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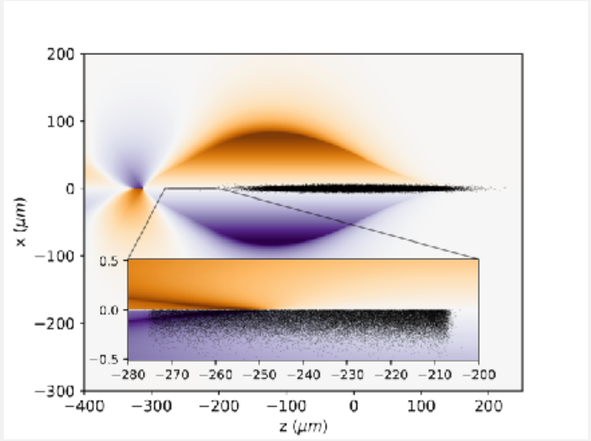

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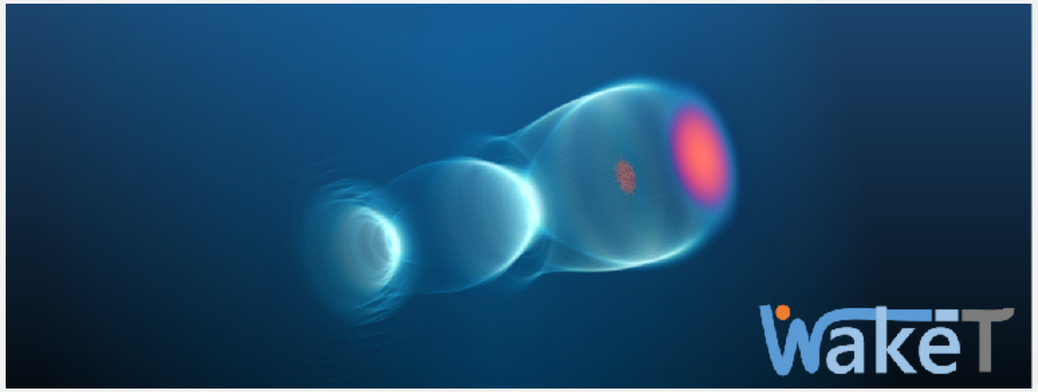

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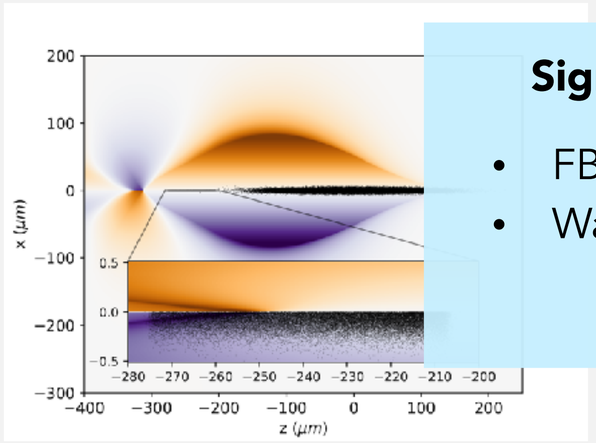

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BLAST BEAM PLASMA & ACCELERATOR SIMULATION TOOLKIT

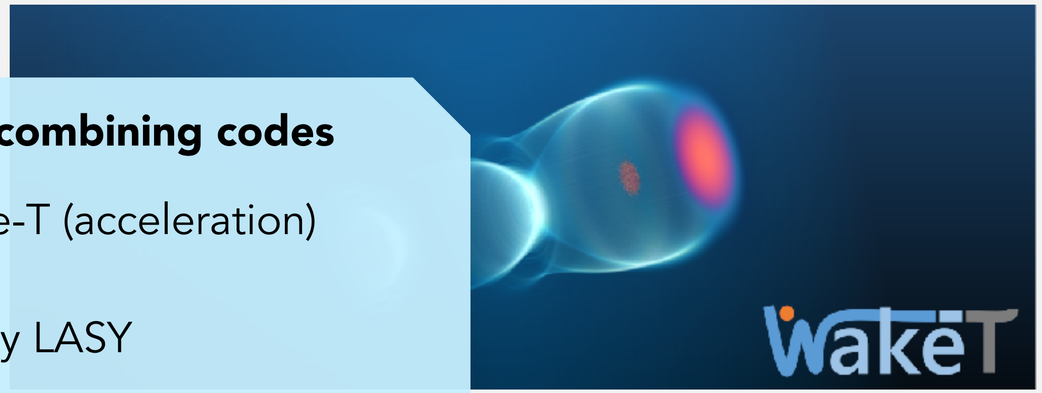
Significant speedup by combining codes

- FBPIC (injection) + Wake-T (acceleration)
- WarpX + HiPACE++

→ enabled by LASY

Wake-T

- Open-source, 2D (axisymmetric) quasistatic code for (laser/beam-driven), incl. ion motion, Python



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BLAST BEAM PLASMA & ACCELERATOR SIMULATION TOOLKIT

LASY is a cornerstone of our S2E simulation ecosystem

Simulation studies gain from being:

Multi-physics
- Hydrodynamics (HOFI, discharge, etc.)
- Beam dynamics, application

Energy efficient
- Efficient codes for reduced model
- Combine the most appropriate tools

Realistic
- Experimental laser profiles
- Experimental plasma/beam profiles

Comprehensive
- Ensembles of simulations
- (Bayesian) Optimization

LASY

A Python library to simplify laser profile manipulations

➢ Use measured laser profiles in simulations

➢ Combine codes together (e.g. electromagnetic & quasistatic PIC)

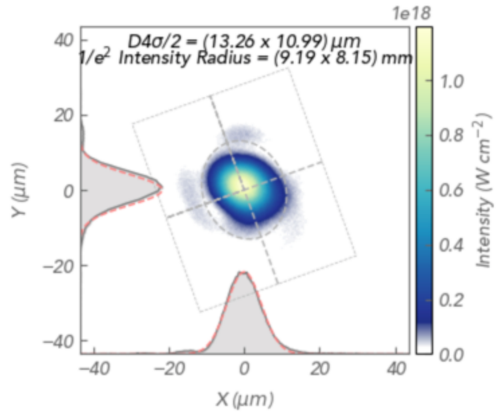
LASY is a community effort

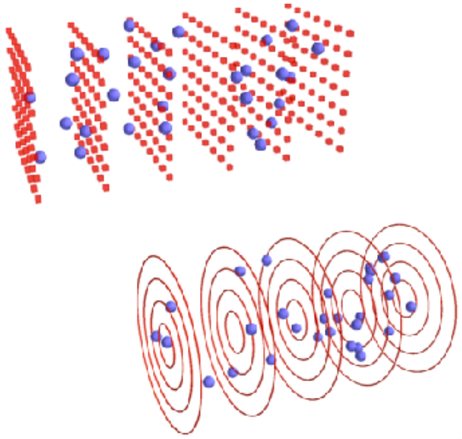
Introducing LASY

Laser initialisation in Simulations is becoming more complex

This brings exciting new possibilities but can be challenging

Realistic laser profiles are key for realistic simulations of laser-plasma interactions [1]

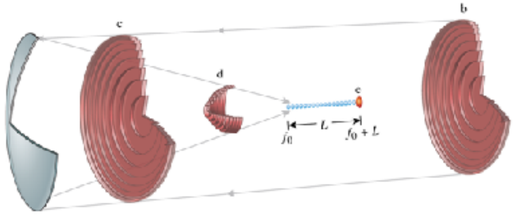




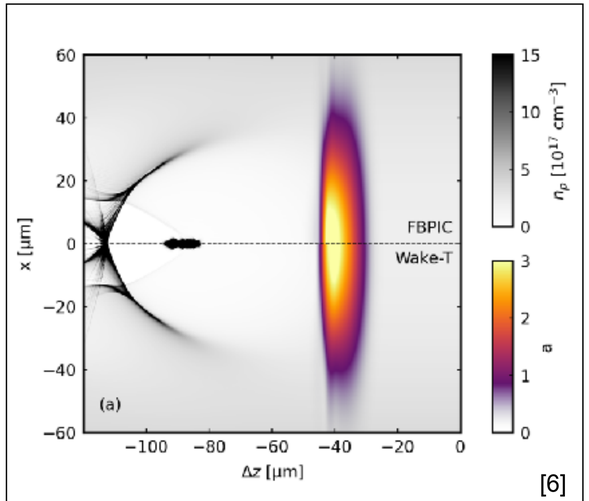
[2]

Start-to-end workflows require interfacing simulation tools with **very different conventions and representations**

Implementing **laser profiles with sophisticated structure** (e.g. flying-focus, OAM, STC etc.) is challenging) [3-5]



[3]



[6]

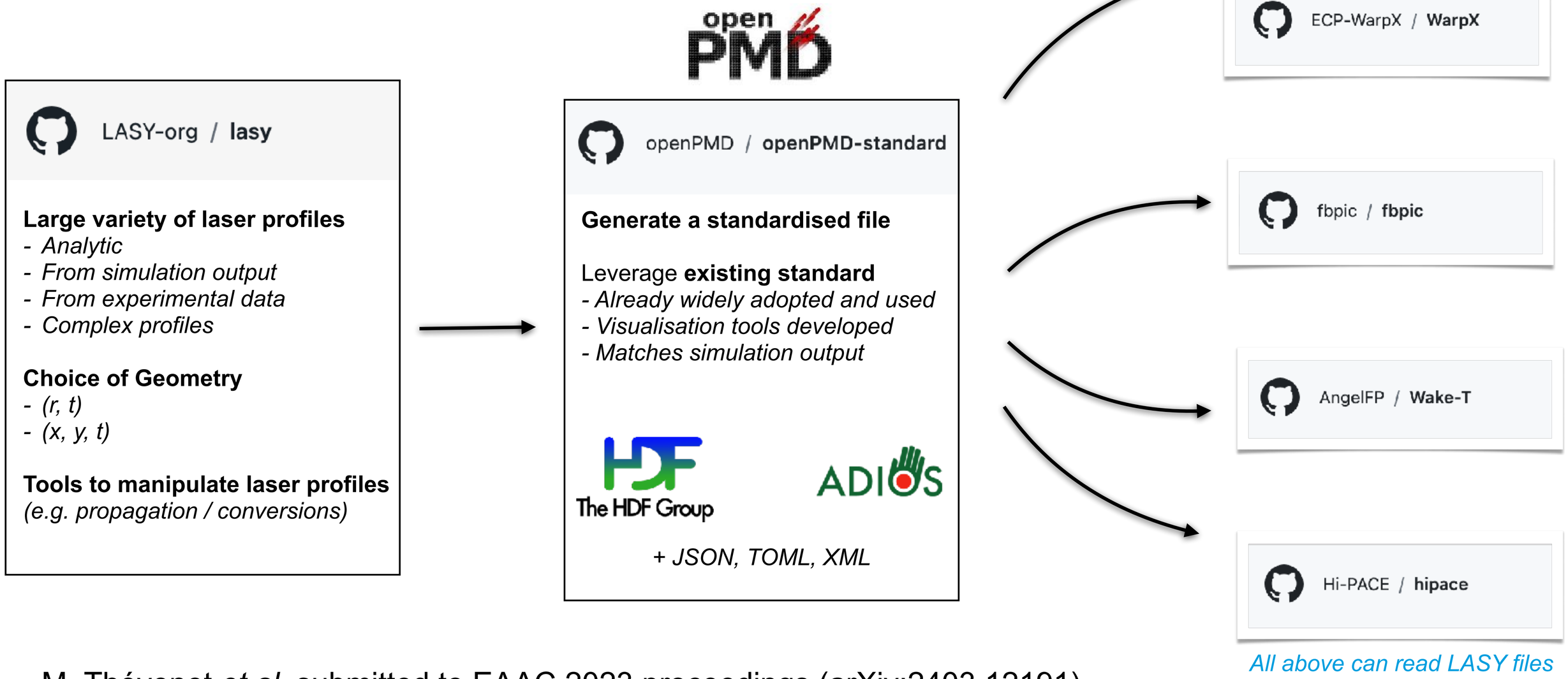
No standard initialisation conventions can make comparing results complex

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

[1] B. Beaurepaire et al., *Phys. Rev. X* **5**, 03102 (2015)
[2] https://fbpic.github.io/
[3] J. P. Palastro et al., *Phys. Rev. Lett.* **124**, 134802 (2020)
[4] C. Caizergues et al., *Nat. Photon.* **14**, 475 (2020)
[5] A. Debus et al., *Phys. Rev. X* **9**, 031044 (2019)
[6] A. Ferran Pousa et al., *Phys. Rev. Accel. Beams* **26**, 084601 (2023)

Introducing LASY

An Open-Source Community Solution

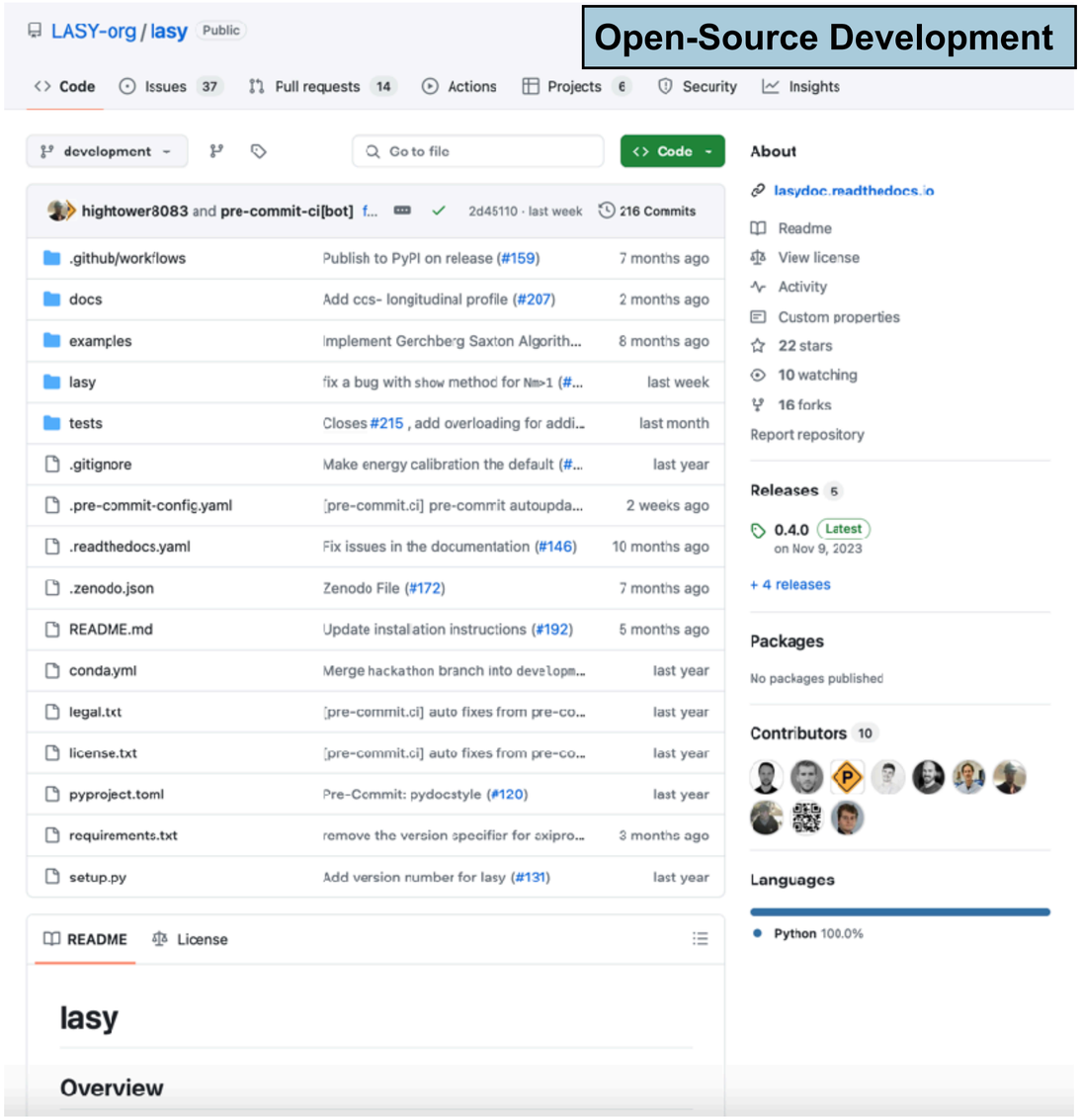


M. Thévenet *et al*, submitted to EAAC 2023 proceedings (arXiv:2403.12191)

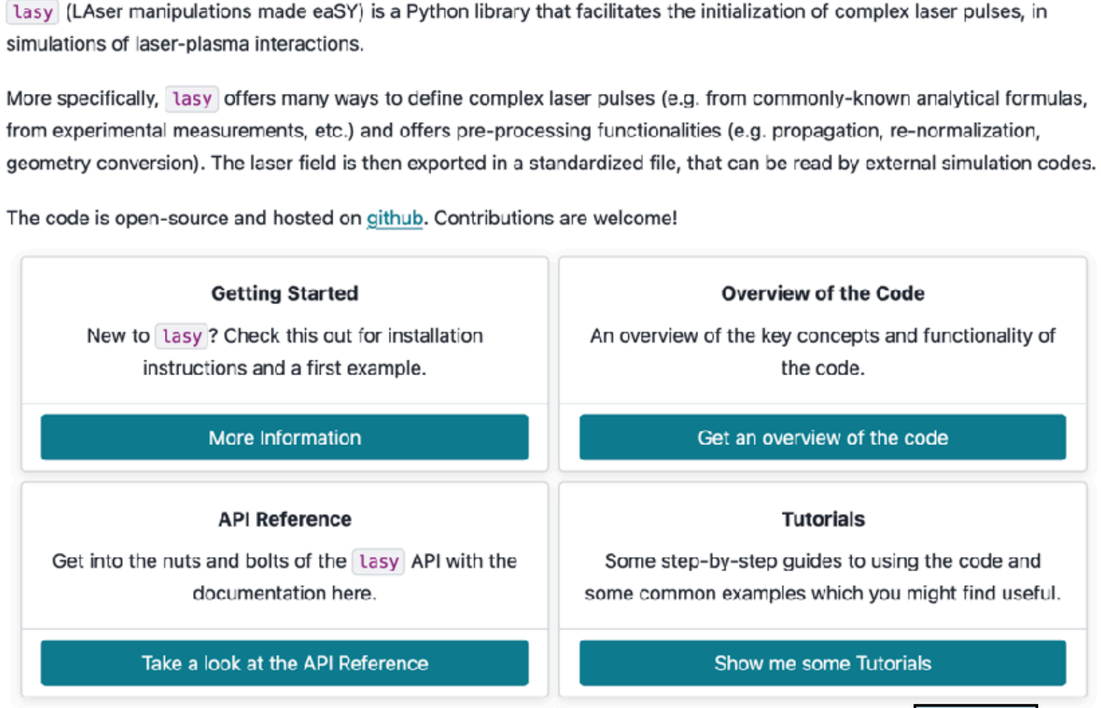
Introducing LASY

An Open-Source Community Solution

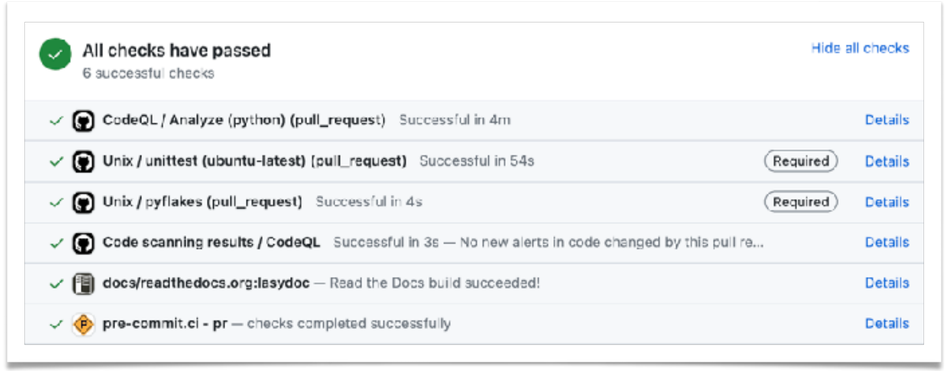
Open-Source Development



Online Documentation



CI/CD



Introducing LASY

An Open-Source Community Solution

Ángel Ferran Pousa
Sören Jalas
Manuel Kirchen
Rob Shalloo
Alexander Sinn
Maxence Thévenet

Axel Huebl
Remi Lehe
Jean-Luc Vay

Igor Andriyash

Luca Fedeli
Thomas Clark

Spencer Jolly

New Contributors Highly Encouraged!

Defining A Laser Pulse

Laser Profile Initialisation

Analytic Profiles

Large variety of transverse analytic profiles already included

- *Gaussian*
- *Supergaussian*
- *Jinc*
- *Laguerre Gaussian*
- *Hermite Gaussian*

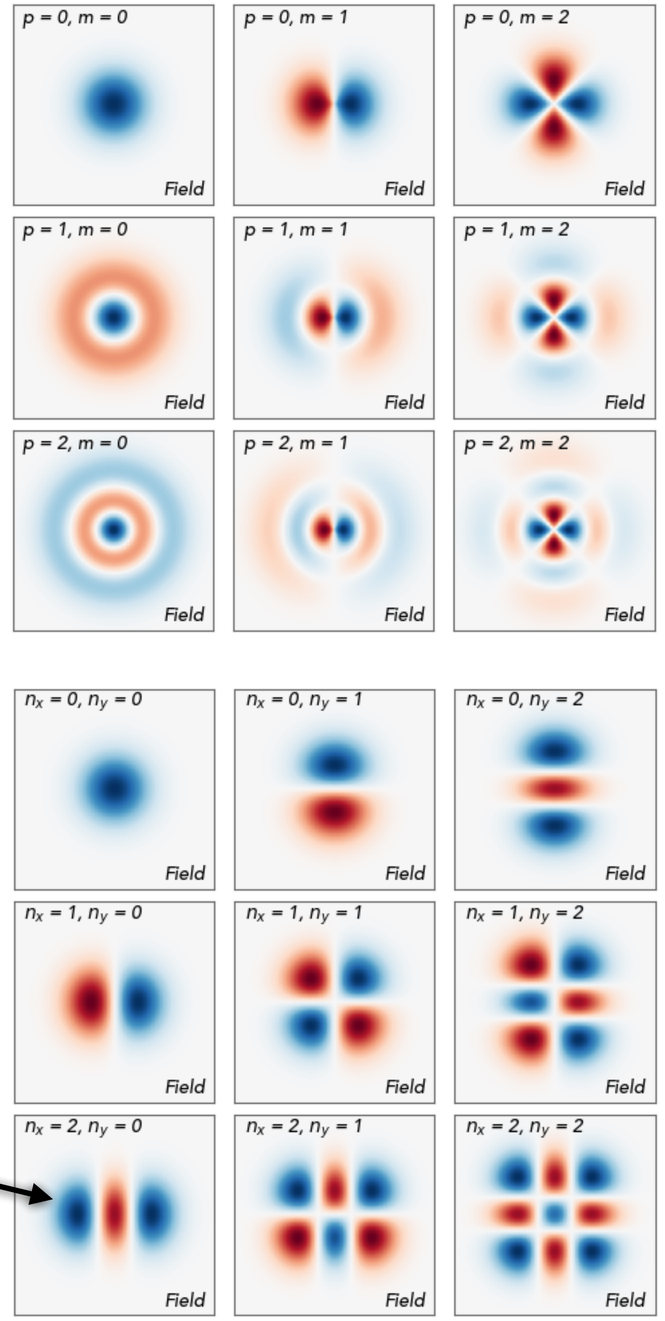
Longitudinal Profiles can be defined separately

Profiles can then be Combined

```python
from lasy.profiles.transverse.hermite_gaussian_profile import HermiteGaussianTransverseProfile

w0      = 10e-6
n_x     = 2
n_y     = 0

transverse_profile = HermiteGaussianTransverseProfile(w0,n_x,n_y)
```



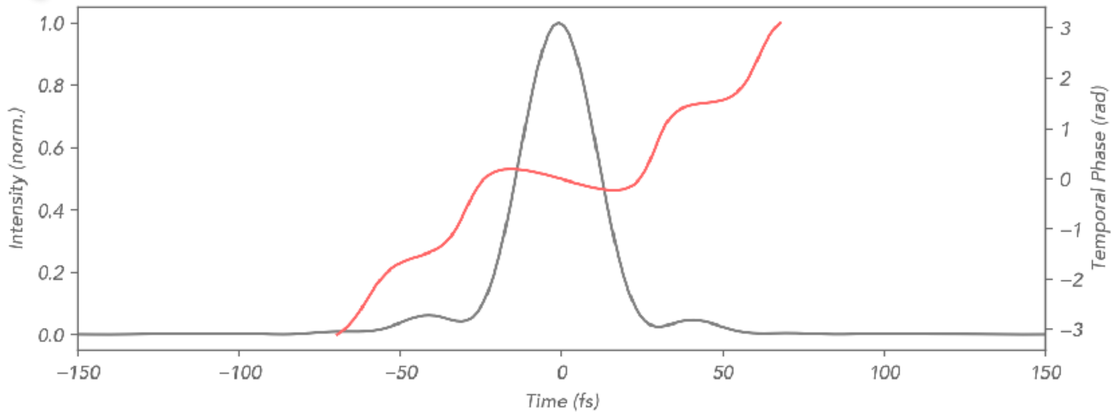
Laser Profile Initialisation

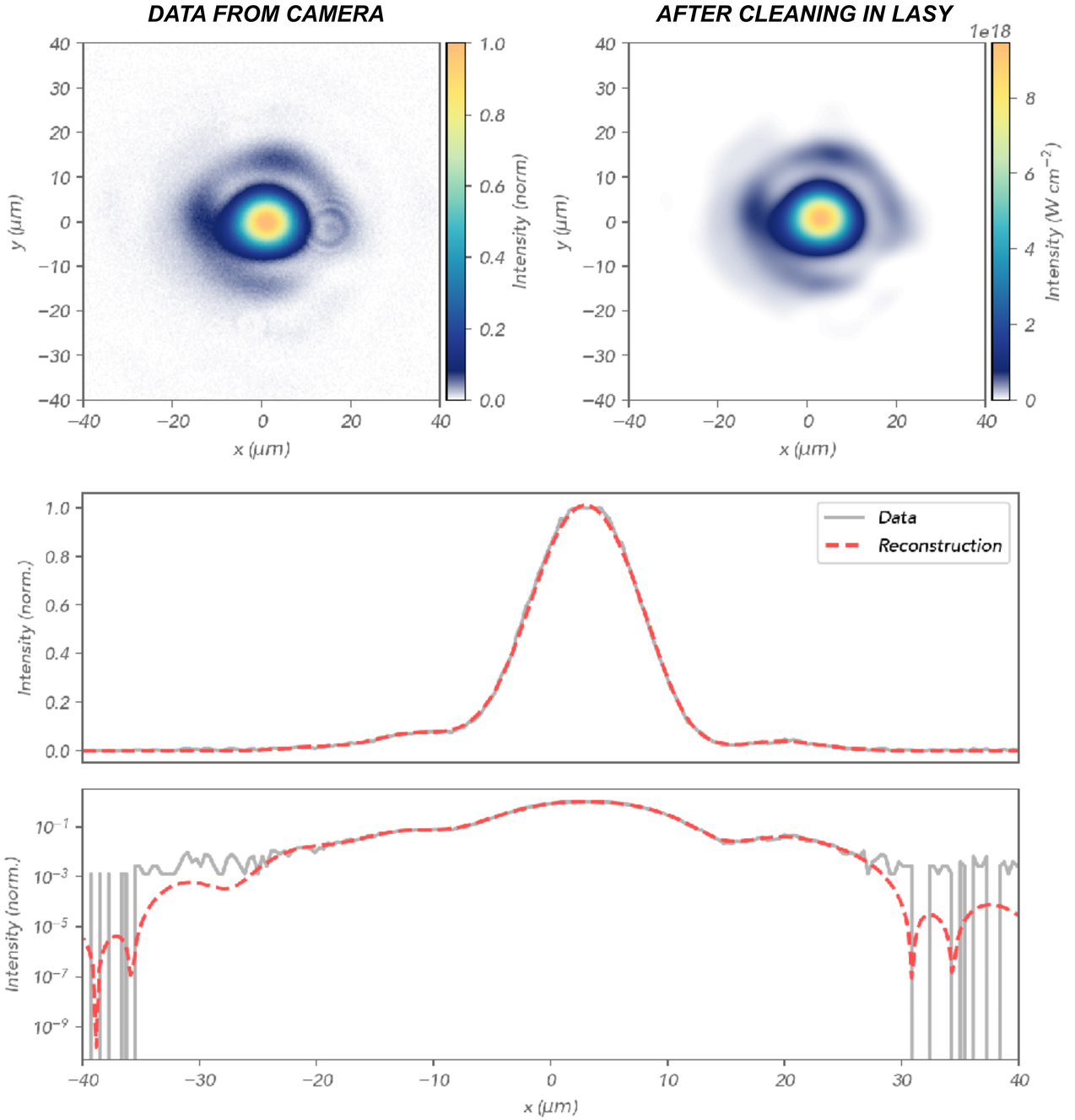
From Experimental Measurements

Incorporate Laser Fluence Measurements (e.g. Camera)
Some post-processing available in LASY

Incorporate Pulse Duration Measurements (e.g. Wizzler)

Incorporate advanced diagnostics (e.g. INSIGHT)





Laser Profile Initialisation

From Simulation to Simulation

FBPIC [1]: Electromagnetic PIC code capturing injection

Laser pulse: self-consistent electric and magnetic fields

Wake-T [2]: Quasi-static code for fast & accurate simulations on a laptop

Laser pulse: envelope of the vector potential

FBPIC
- Run simulation
- Output data

LASY
- Directly read openPMD data from FBPIC
  - Convert full-field to envelope representation
  - Convert electric field to vector potential
- Save to standard format

Wake-T
- Initialise LASY data
- Continue Simulation

[1] R. Lehe et al., *Comput. Phys. Commun.* **203**, 66 (2016)
[2] A. Ferran Pousa et al., *Journ. Phys. 1350.1 IOP Publishing* (2019)

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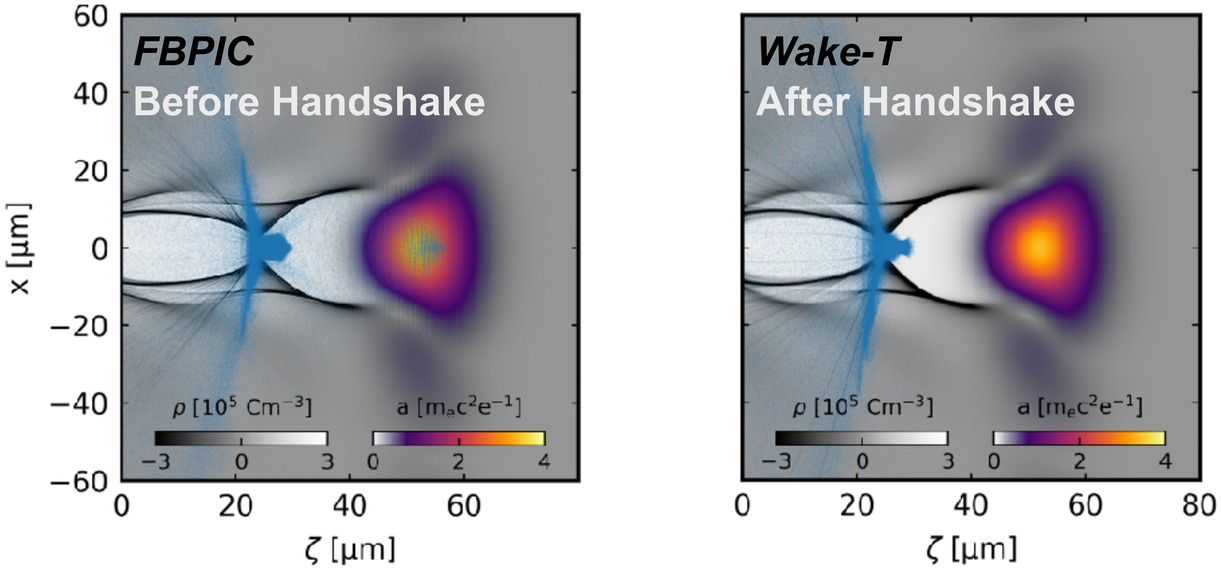

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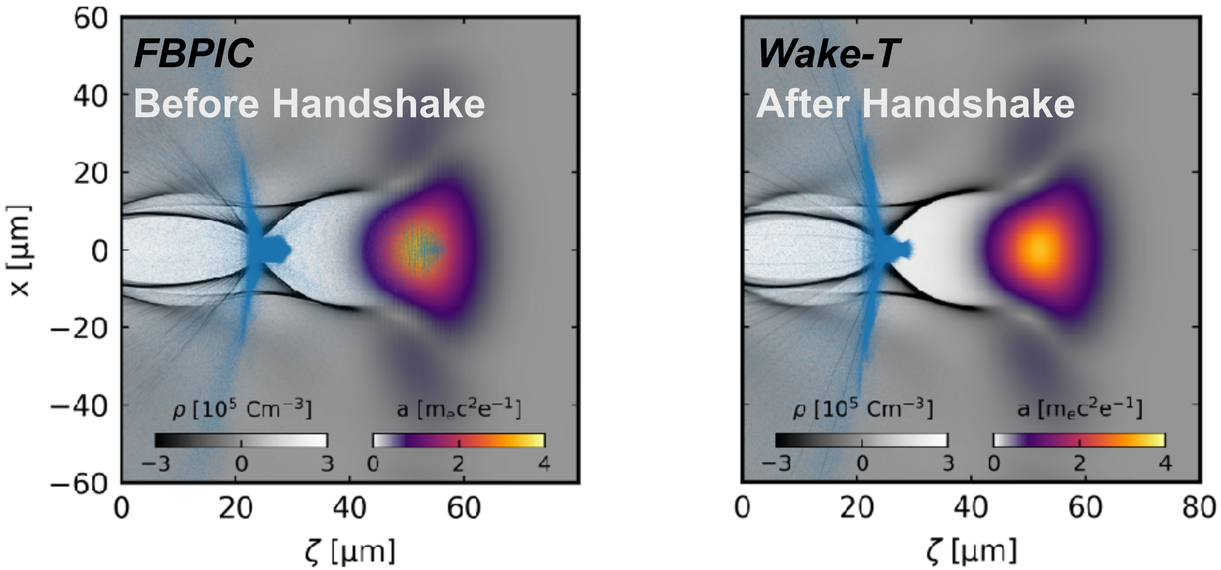

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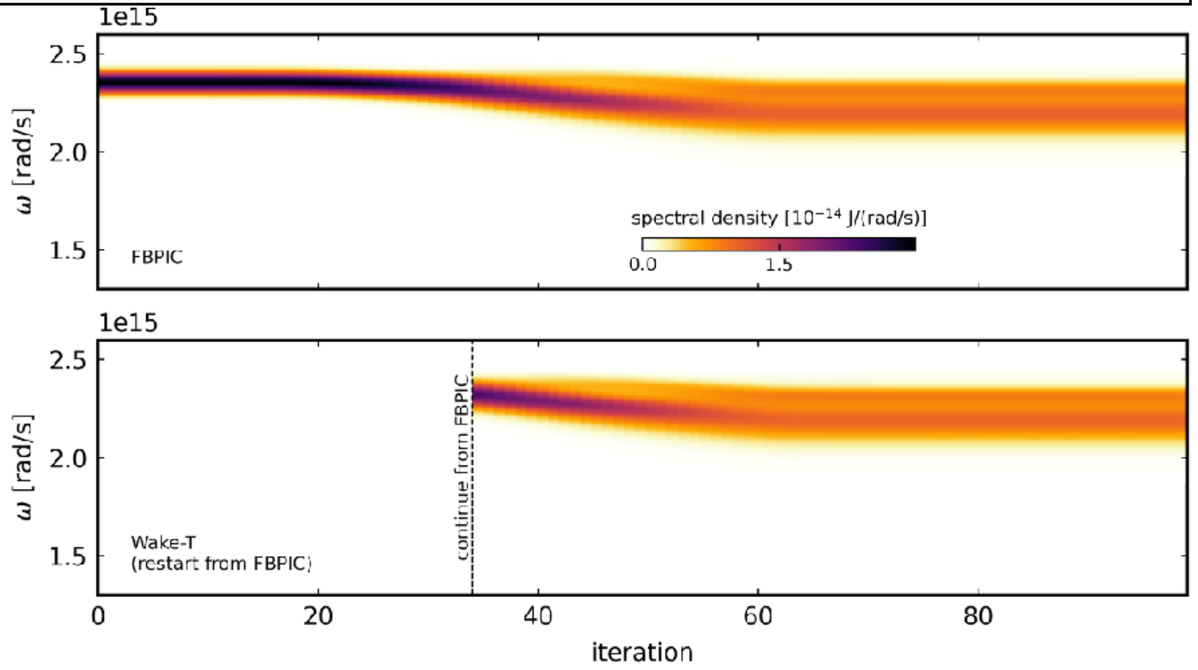

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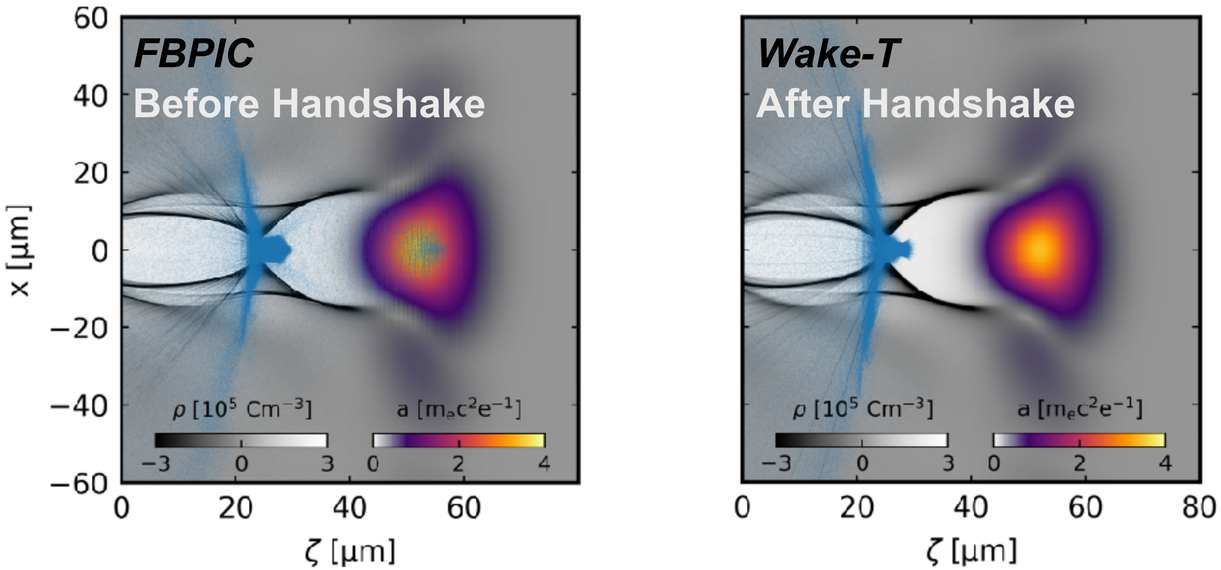

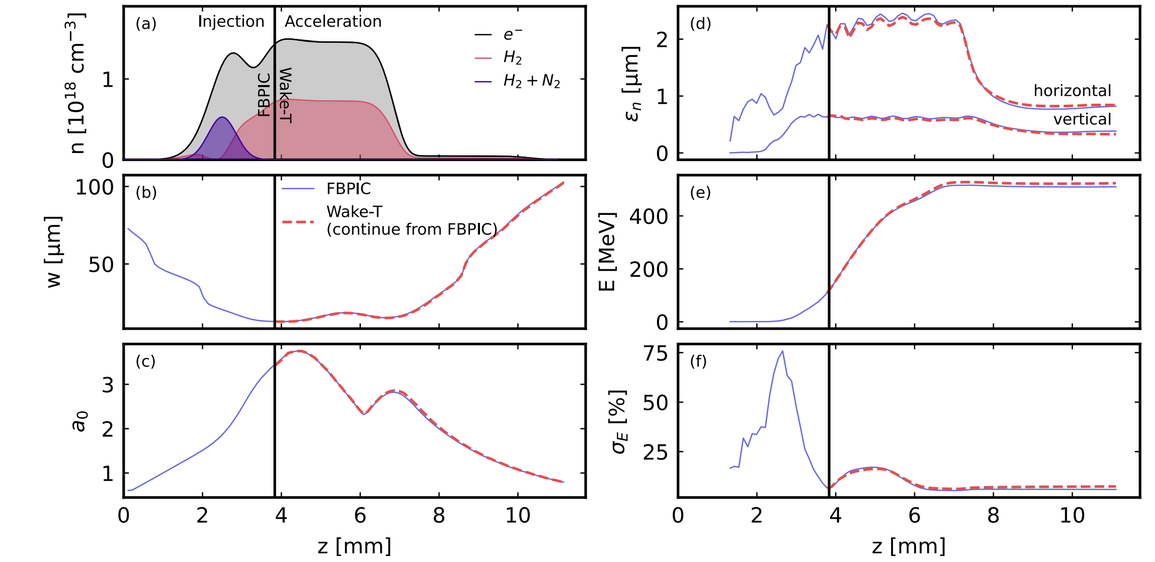

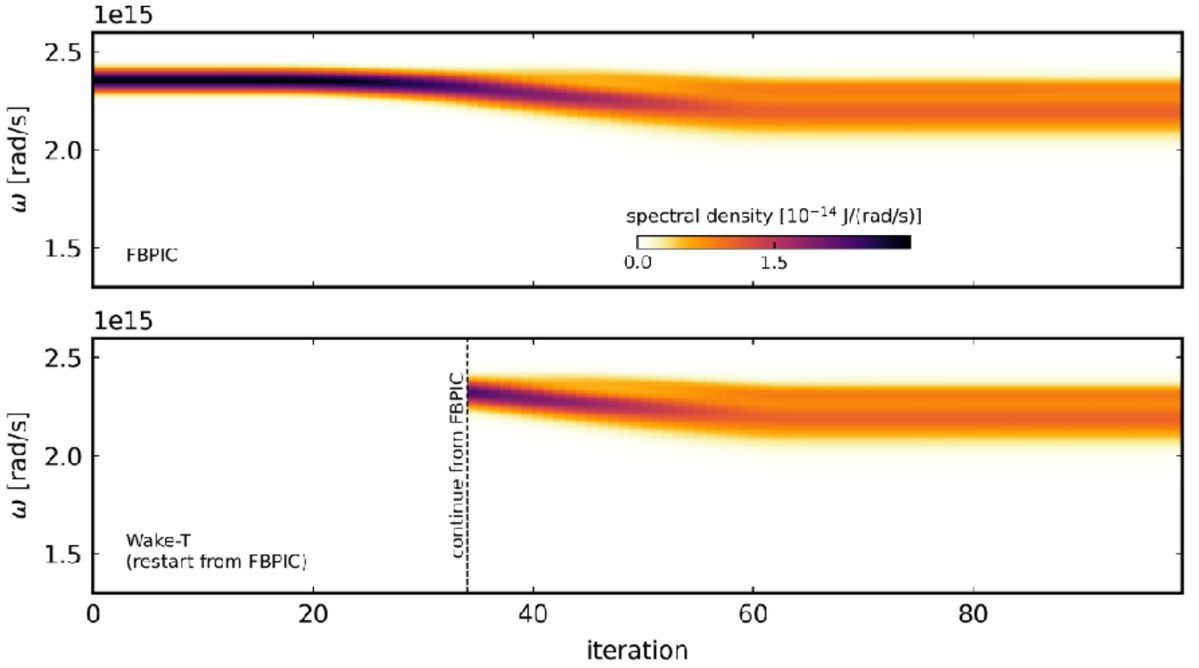

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Laser Profile Initialisation

Spatio-Temporal Couplings (STCs)

Lasers with STCs are possible in LASY

Currently under development

First implementation of spatial chirp ready for review

Possibility to incorporate flying focus and other pulses of interest

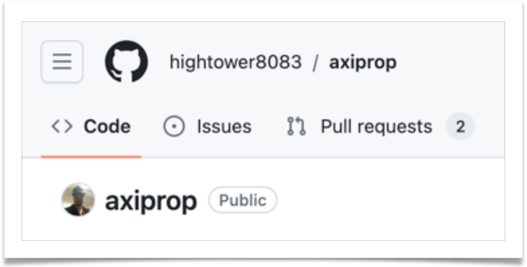
Watch this space!

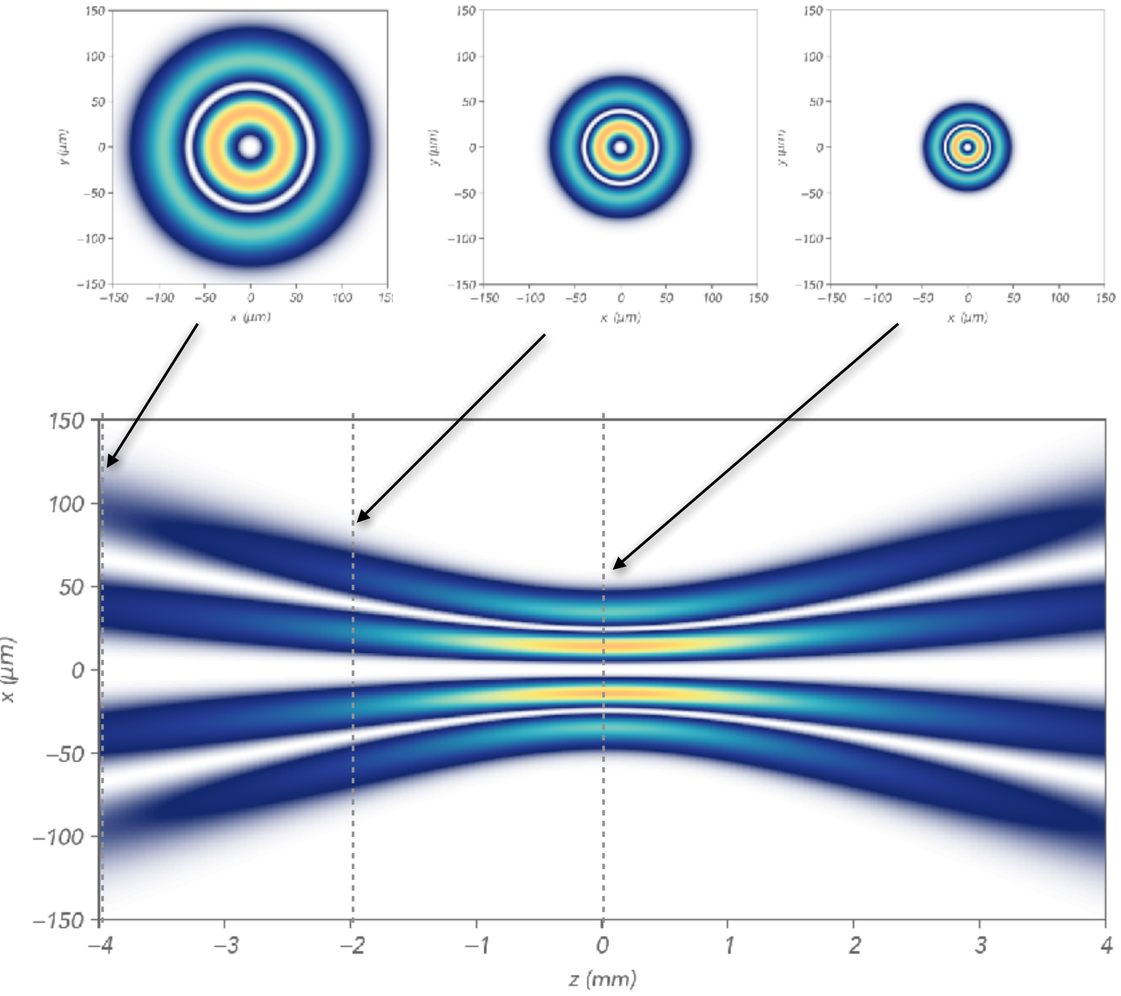
Laser Pulse Manipulation

Laser Pulse Manipulation

Propagation in Vacuum

Powered by Axiprop
I. Andriyash





Laser can be defined in one plane and then numerically propagated to where it is needed

Propagation algorithms
- Cartesian or cylindrical geometry
- On CPU or GPU

```
laser.propagate(-0.5*mm)
```

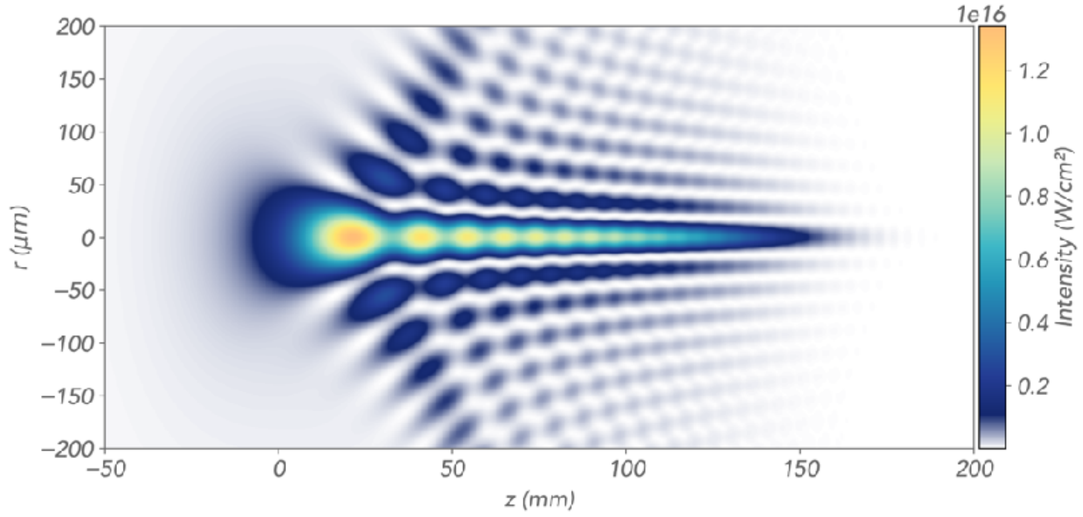
Laser Pulse Manipulation

Adding Optical Elements

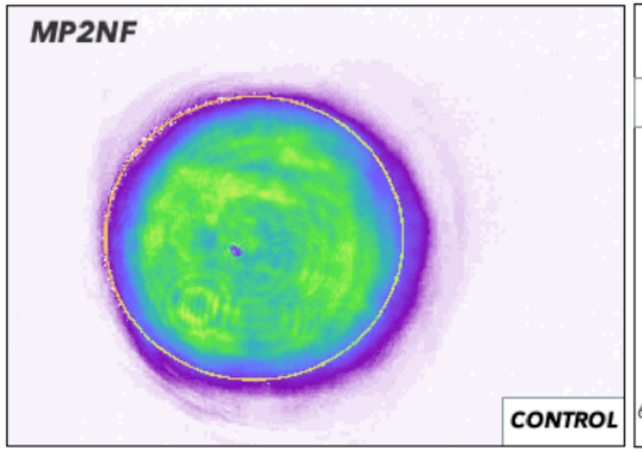
Plans to add optical elements to LASY (PR #199)

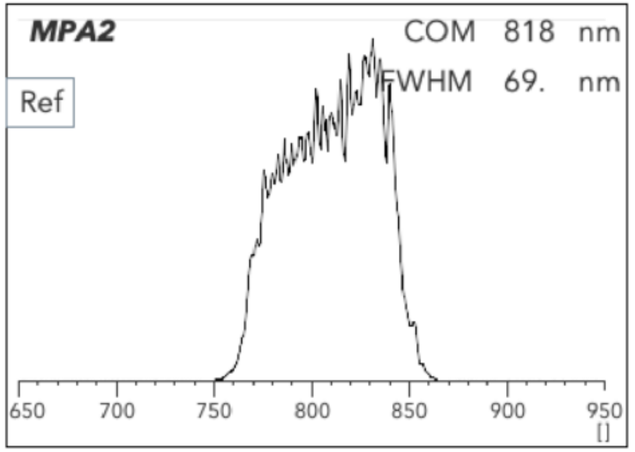
Example: **Axiparabola**

```
laser.propagate( f0, AxiParabola(f0, delta, R) )
```

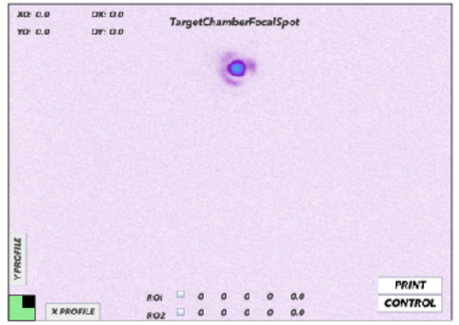


Example:
Defining laser based on NF measurements from Online Diagnostics





Calculate focal profile and use for simulations



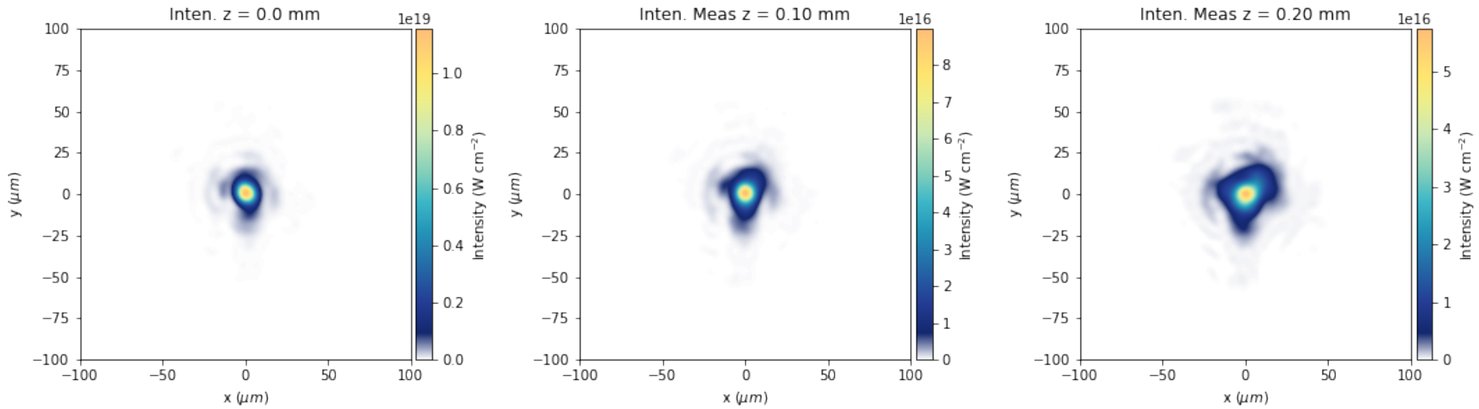
Laser Pulse Manipulation

Gerchberg Saxton Algorithm

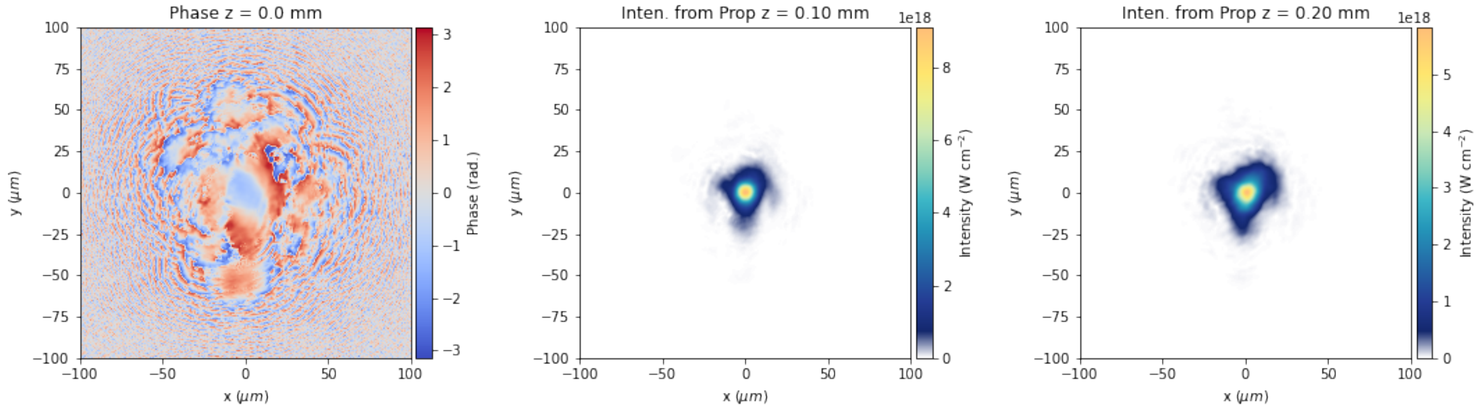
```
phaseBackward, phaseForward, amp_error = gerchberg_saxton_algo( laser1, laser2, propDist )
```

Iterative algorithm to calculate laser phase

Measured laser profiles



Retrieved phase
+
Calculated intensity downstream

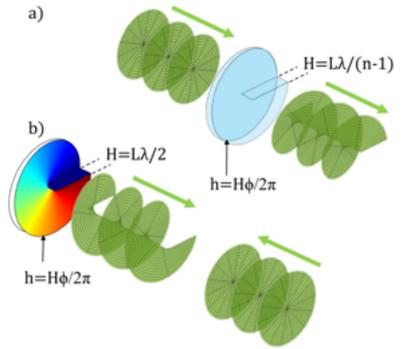


[1] L. T. Dickson et al. *Phys. Rev. Accel. Beams* **25**, 101301 (2022)

Modelling complex experimental pulses

LASY allows leveraging existing openPMD infrastructure to visualise and simulate complex pulses

Generate

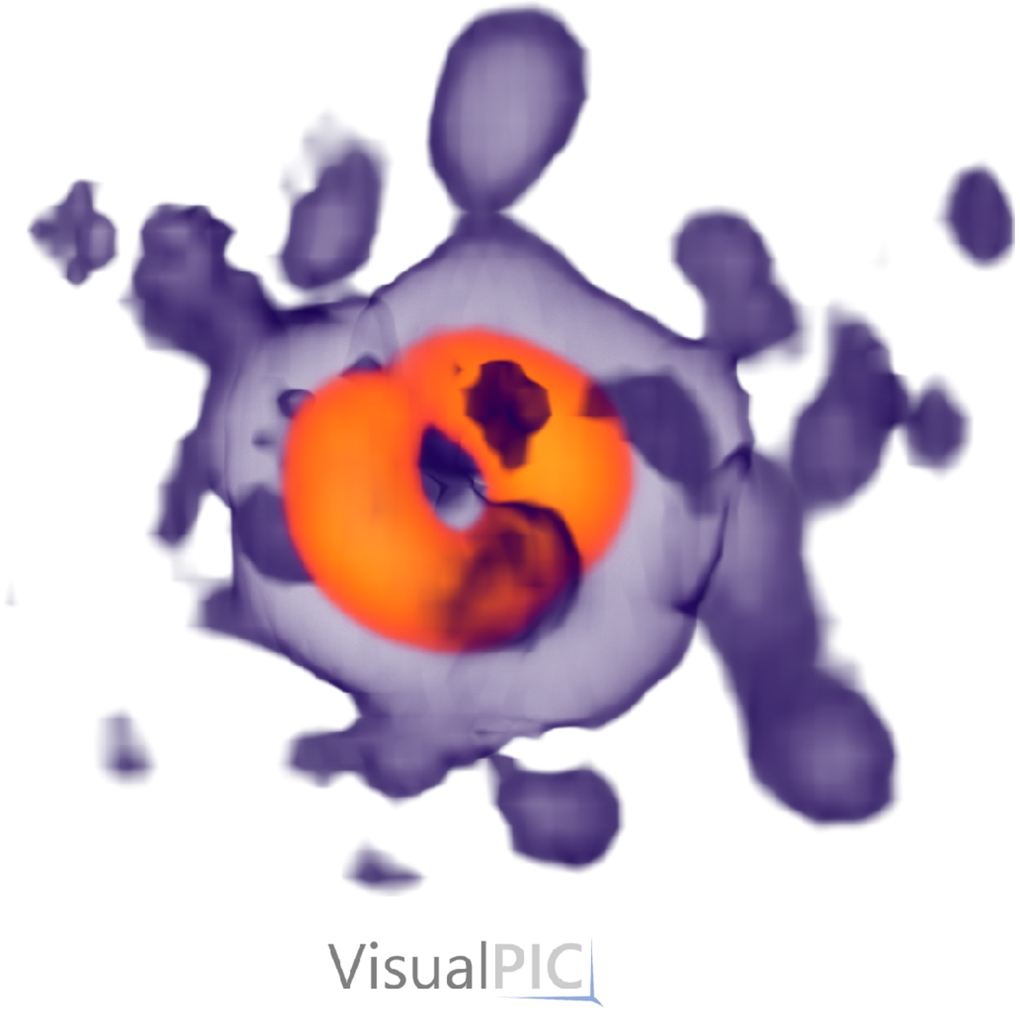


Longman et al, Phys Plaamas **29**, (2022)

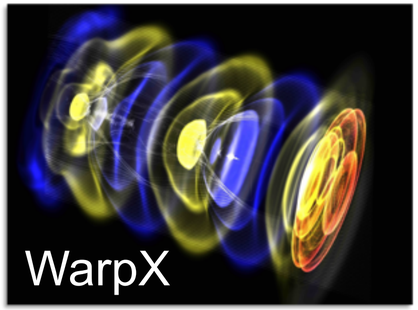
Measure

INSIGHT, Sourcelab

Visualise



Simulate



Examples

Getting Started with LASY

Installation and First Simulation

Installation Instructions

```
pip install lasy
```

```
from lasy.profiles.gaussian_profile import GaussianProfile
from lasy.laser import Laser
```

Import functions and classes

```
wavelength     = 800e-9  # Laser wavelength in meters
polarization   = (1,0)   # Linearly polarized in the x direction
energy         = 1.5     # Energy of the laser pulse in joules
spot_size      = 25e-6   # Waist of the laser pulse in meters
pulse_duration = 30e-15  # Pulse duration of the laser in seconds
t_peak         = 0.0     # Location of the peak of the laser pulse in time

laser_profile = GaussianProfile(wavelength,polarization,energy,spot_size,pulse_duration,t_peak)
```

Define the laser based on physical characteristics

```
dimensions     = 'rt'                              # Use cylindrical geometry
lo             = (0,-2.5*pulse_duration)           # Lower bounds of the simulation box
hi             = (5*spot_size,2.5*pulse_duration)  # Upper bounds of the simulation box
num_points     = (300,500)                         # Number of points in each dimension

laser = Laser(dimensions,lo,hi,num_points,laser_profile)
```

Define the grid initialise the laser object

```
z_R            = 3.14159*spot_size**2/wavelength    # The Rayleigh length
laser.propagate(-z_R)                               # Propagate the pulse upstream of the focal plane
```

```
100% ████████████████████████████████████████ 00:00<00:00 [2429.64it/s]
```

Propagate or manipulate as you want

```
file_prefix    = 'test_output' # The file name will start with this prefix
file_format    = 'h5'          # Format to be used for the output file

laser.write_to_file(file_prefix, file_format)
```

Dump to file

Initialisation of Laser Pulse with Experimental Data

Example

Imports

Define Laser Parameters
Import Experimental Data

Create: Longitudinal Profile
Transverse Profile
Combine them

Initialise Laser Object

Propagate and dump to file

```python
from lasy.profiles.transverse.transverse_profile_from_data import TransverseProfileFromData
from lasy.profiles.longitudinal.longitudinal_profile_from_data import LongitudinalProfileFromData
from lasy.profiles.CombinedLongitudinalTransverseProfile import CombinedLongitudinalTransverseProfile
from lasy.laser import Laser
import numpy as np


fluence      = np.load('laser_fluence.npy')     # Import the fluence data
calib        = 0.3e-6                           # Camera calibration in um/pixel
temporalData = np.load('temporal_profile.npy')  # Import temporal data
wavelength   = 800e-9                           # Central Wavelength
pol          = (1,0)                            # Polarisation
laser_energy = 0.5                              # Laser Energy


transProf    = TransverseProfileFromData(fluence, (0 , 0), (cols*calib, rows*calib)
longProf     = LongitudinalProfileFromData(temporalData, (-150e-15,150e-15))
profile      = CombinedLongitudinalTransverseProfile(wavelength, pol, laser_energy, longProf, transProf)


lo = (-75e-6,-75e-6,-150e-15)    ;      hi = (75e-6,75e-6,150e-15)  ;   npts = (100,100,100)
laser = Laser('xyt',lo,hi,npts,profile)


laser.propagate(-500e-6)
laser.write_to_file('reconstructed')
```

LASY enables contemporary high quality simulations

Flexible open-source toolkit to simulate realistic laser pulses in most efficient manner

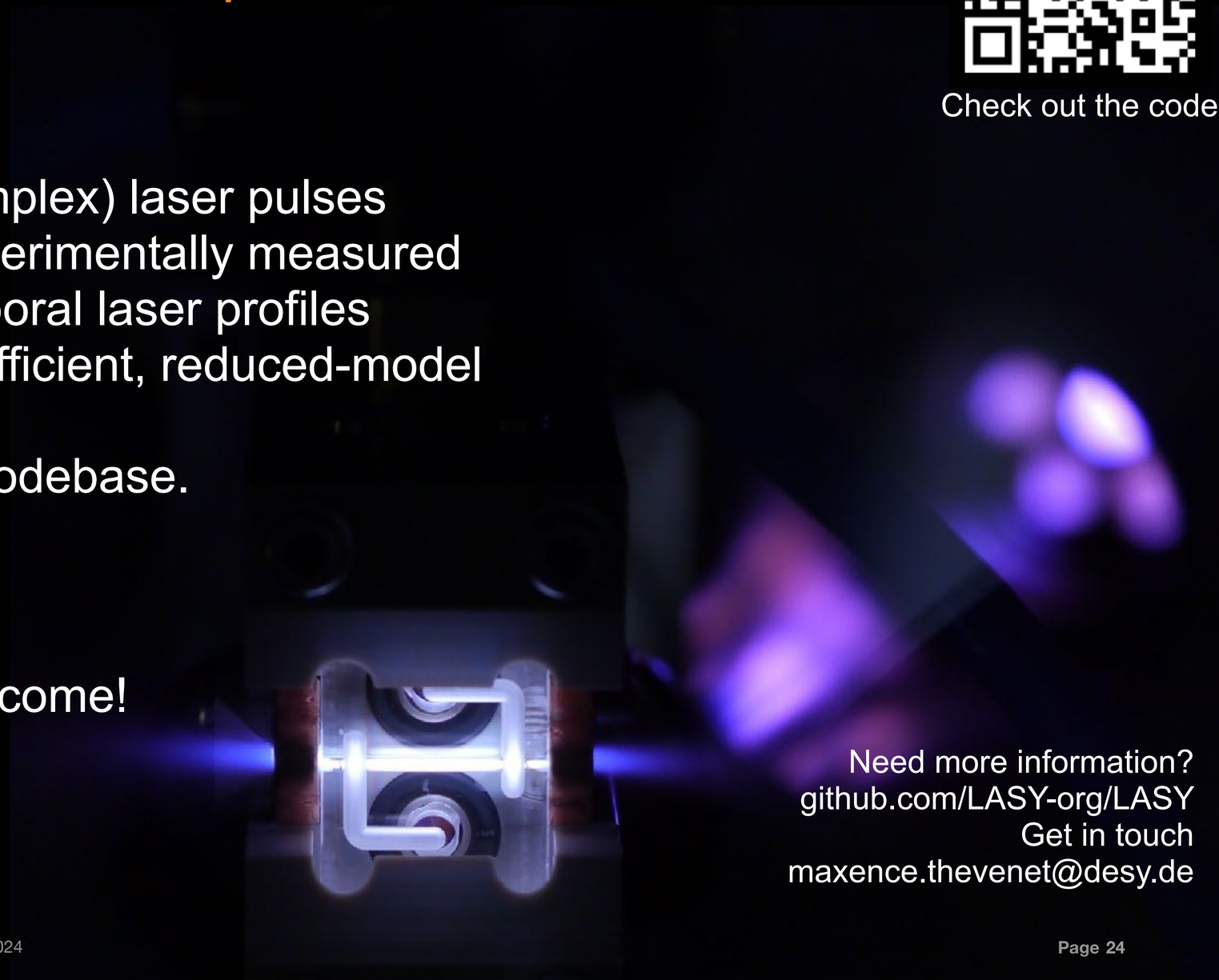
Check out the code

LASY allows

- Creating and manipulating (complex) laser pulses
- Importing and manipulating experimentally measured spatial, temporal or spatio-temporal laser profiles
- Interfacing full EM codes with efficient, reduced-model codes

in a modern, standard-embracing codebase.

Contributions to the code (*very*) welcome!



Need more information?
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