LP4PIC: Laser Pulse reconstructor For Particle-In-Cell simulations

Custom laser beam profiles from experimental measurements with rebuilt aberration phase, initialized in PIC simulations

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ABSTRACT

The results of a *particle-in-cell* (PIC) simulation can be profoundly different from the outcomes of an experiment, because of the initialization of highly idealized laser fields. We present a new Python package to initialize, in a FB-PIC simulation, realistic laser profiles retrieved from fluence measurements. The code can perform a phase retrieval based on the *Gerchberg-Saxton algorithm*, where the reconstruction of fields is obtained thanks to a Fourier-based propagator solving Helmholtz equation. Main features of *Laser Pulse reconstructor For Particle In Cell simulations* (LP4PIC) will be shown with some examples and comparisons. Finally, the retrieved phase of a measured fluence profile can be projected on the space of Zernike polynomials to estimate aberration coefficients.

PROPAGATION: SOLVING HELMHOLTZ EQUATION

Being $U(x,y,z) = u(x,y,z,)e^{ikz}$ the solution to *Helmholtz equation* and $\widehat{U}(k_x,k_y;z)$ its Fourier transform according the transverse directions, under *paraxial approximation* we can relate it to an input field U_0 focused in z by an optical element in terms of their Fourier transform as follows:

$$\widehat{U}(k_x,k_y;z) = \widehat{U_0}(k_x,k_y)e^{-i\frac{(k_x^2+k_y^2)}{2k}z}e^{ikz} \quad (1)$$

The propagation module of **LP4PIC** implements three main operations:

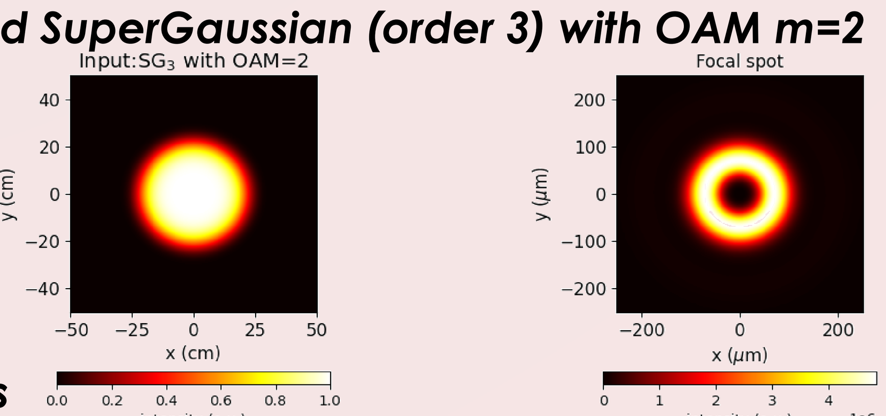
- Retrieving of the input field distribution **(NearField)** from:
  - *I.* $I(x,y)$ fluence distribution
  - *II.* $T(x,y)$ transmission function of a Mirror (*On-axis Parabola/Spherical* built-in or custom user-defined)
  - *III.* $\phi(x,y) = m\theta(x,y) + \phi_a(x,y) + \phi_{mask}(x,y)$ phase map, where m is Orbital Angular Momentum (**OAM**), ϕ_a is aberration phase given in term of Zernike series, ϕ_{mask} is user defined absorption/phase mask :

$$U_0(x,y) = \sqrt{I(x,y)}T(x,y)e^{i\phi(x,y)} \quad (2)$$

- Propagates in z, in terms of Fast Fourier Transform *FFT*, according to eq. (1)
- Retrieve $U(x,y;z)$ applying an inverse *FFT* **(FarField).**

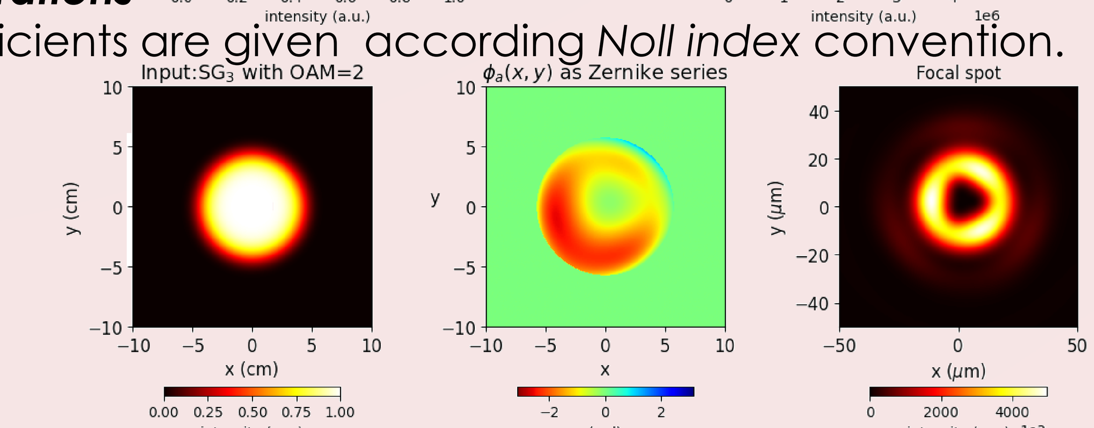
FOCUSING A USER DEFINED NEARFIELD

- ***Focusing a collimated SuperGaussian (order 3) with OAM m=2***



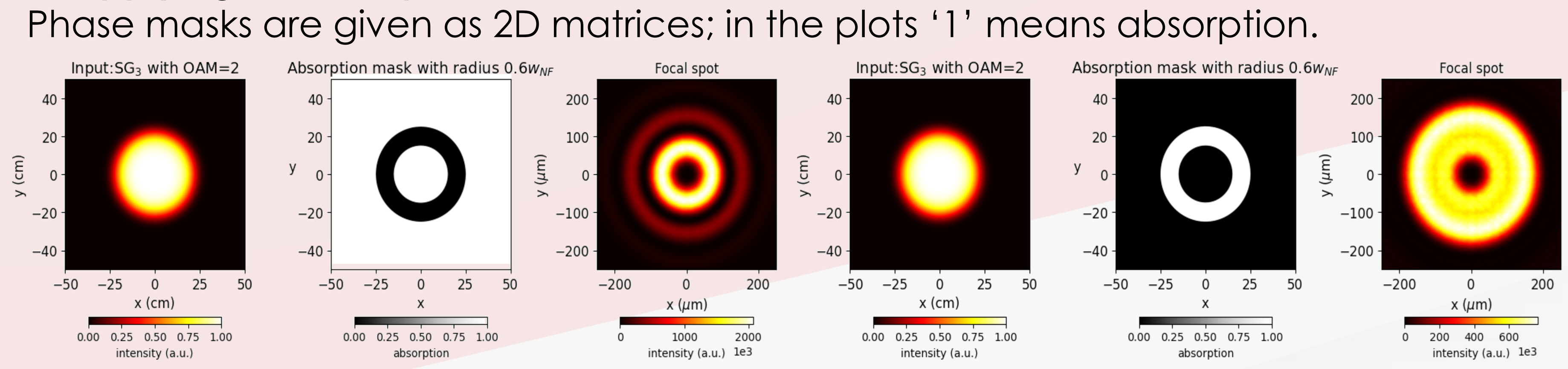
- ***Including aberrations***

Aberrations coefficients are given according *Noll index* convention.

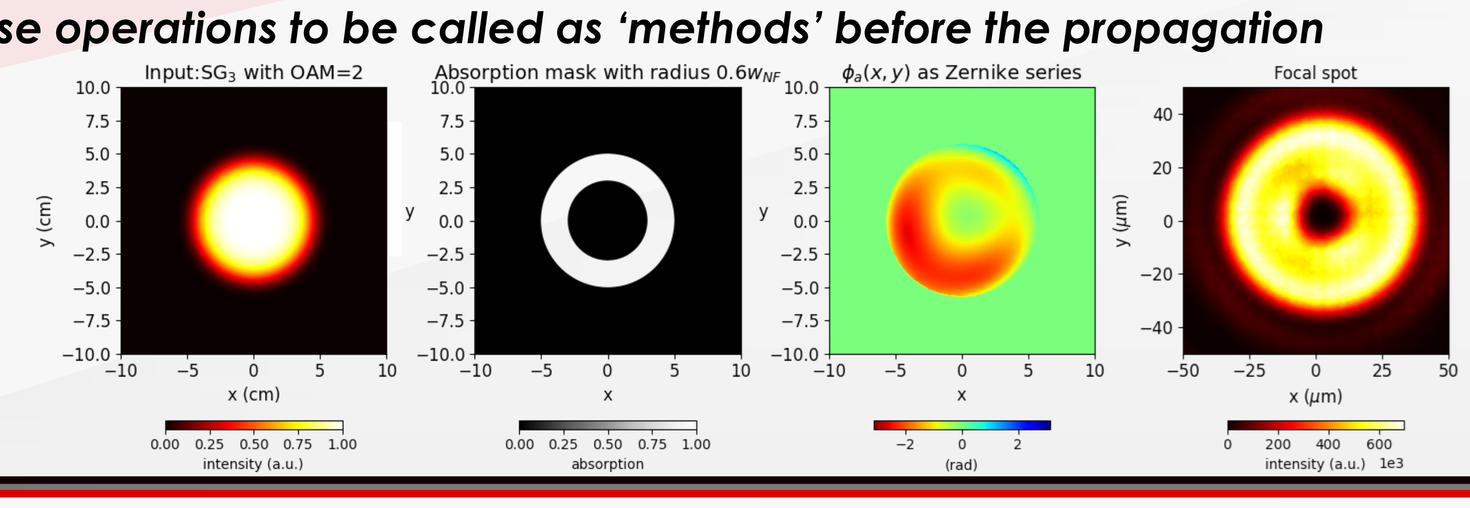


- ***Applying an absorption mask***

Phase masks are given as 2D matrices; in the plots '1' means absorption.

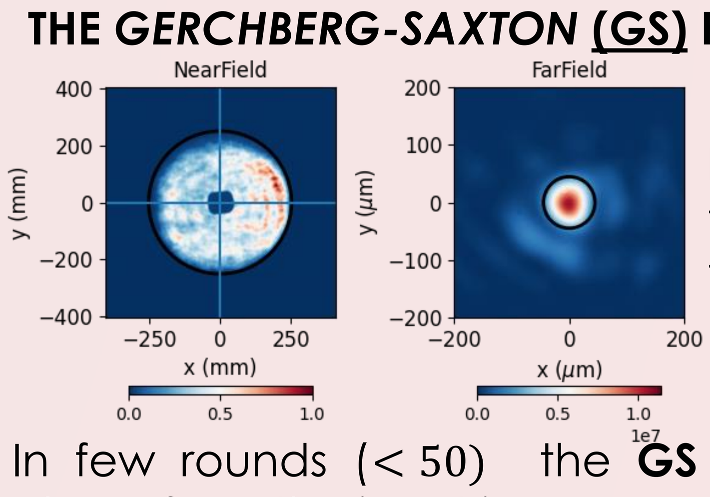


- ***All these operations to be called as 'methods' before the propagation***



RETRIEVING THE PHASE FROM EXPERIMENTAL MEASUREMENTS

THE *GERCHBERG-SAXTON* (GS) PHASE RETRIEVAL MODULE

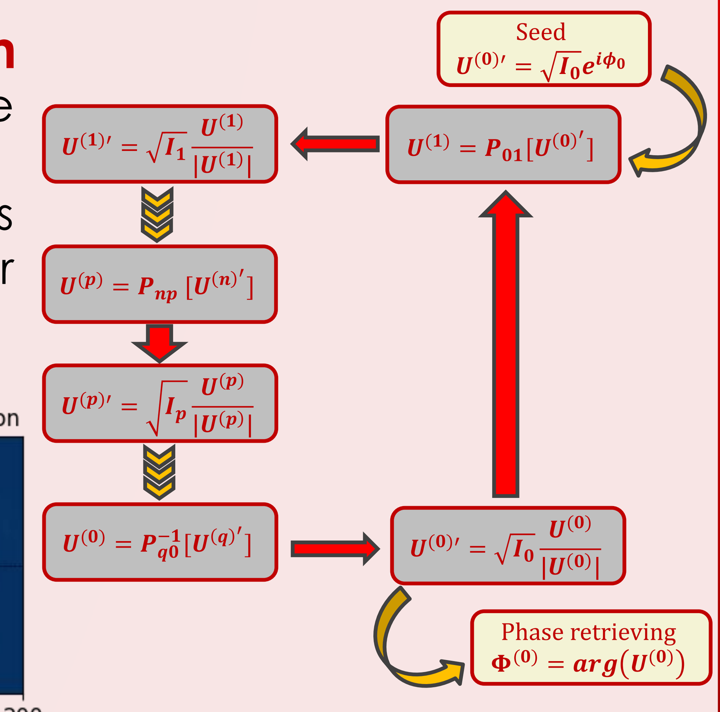


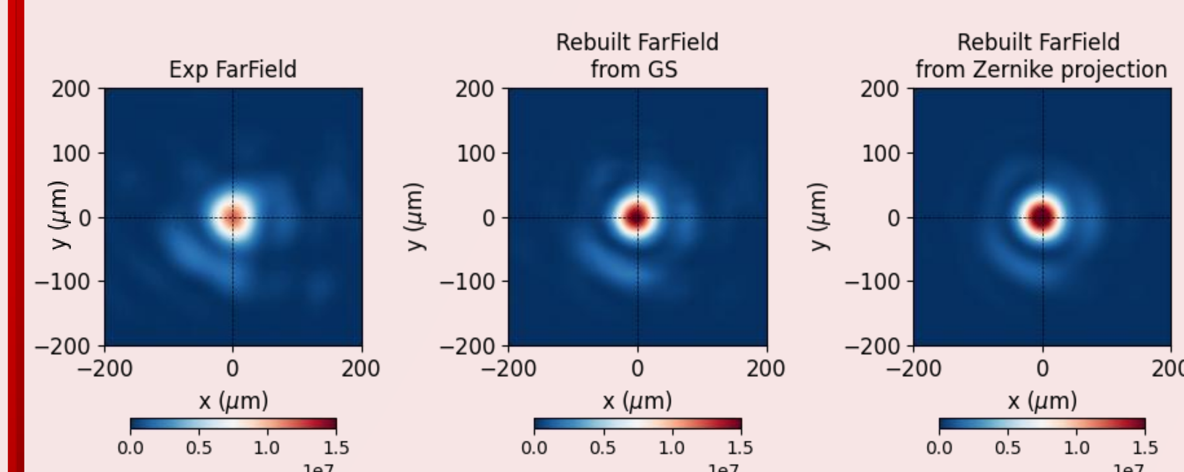
Input images

LP4PIC is provided with a ImageReader module for the pre-processing of the images before feeding the *Gerchberg-Saxton* phase retriever.

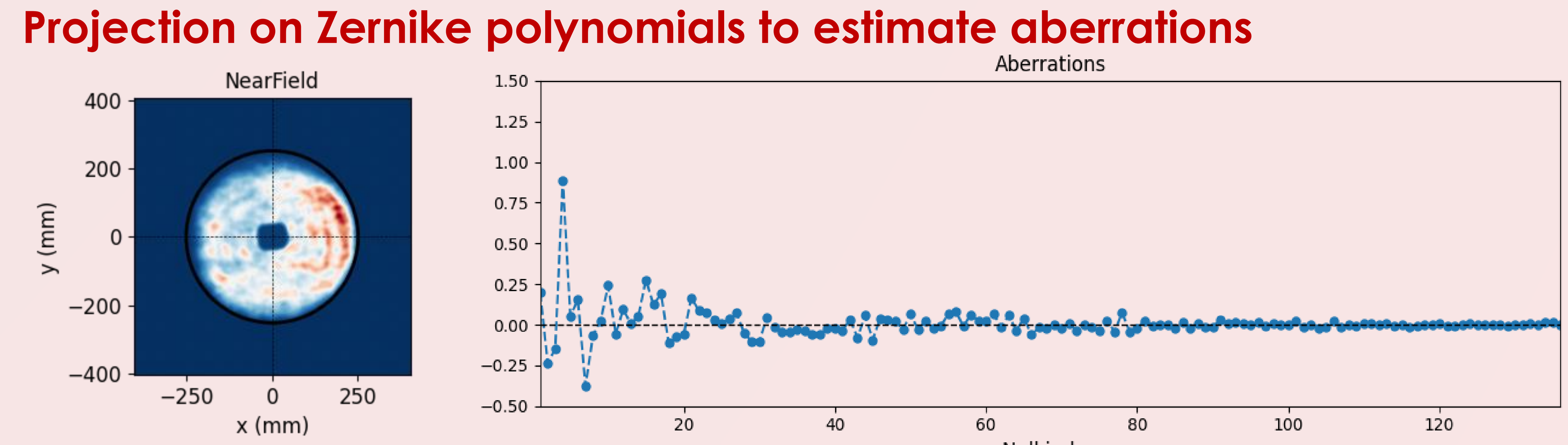
GS algorithm

In few rounds (< 50) the **GS loop** retrieves the phase from the input images. Then the propagator rebuilds the transverse fields in the focus, which will be used to initialize laser fields in a **PIC simulation**.

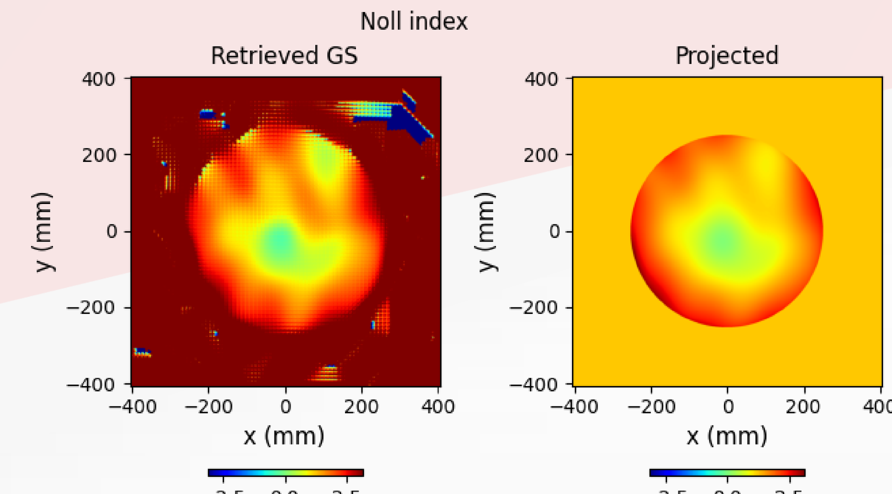




Projection on Zernike polynomials to estimate aberrations



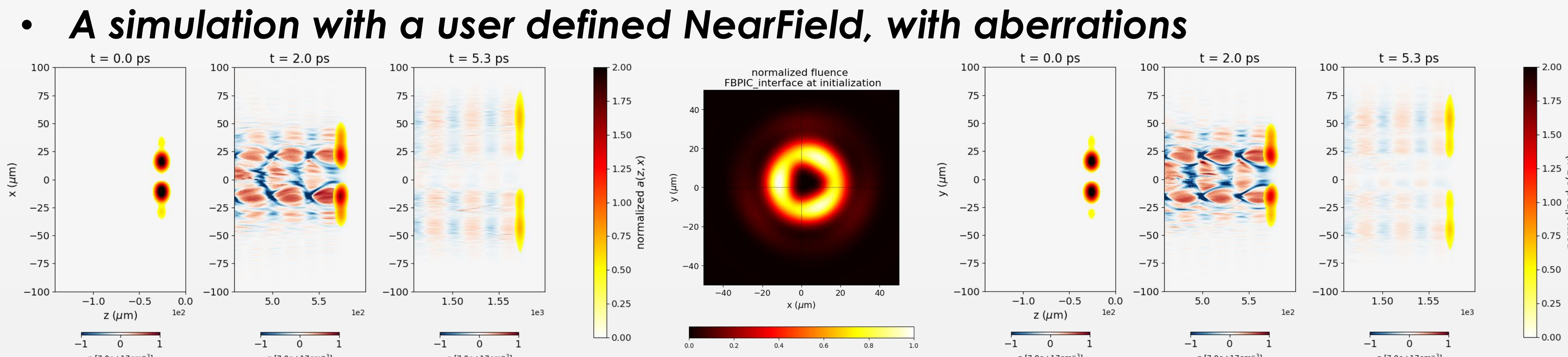
We can perform a *Zernike transform* on the unit circle, normalizing the box on an estimation of beam radius, to retrieve aberration coefficients and to reconstruct the phase ϕ_a as the series of polynomials.



AN INTERFACE TO INITIALIZE IN FBPIC

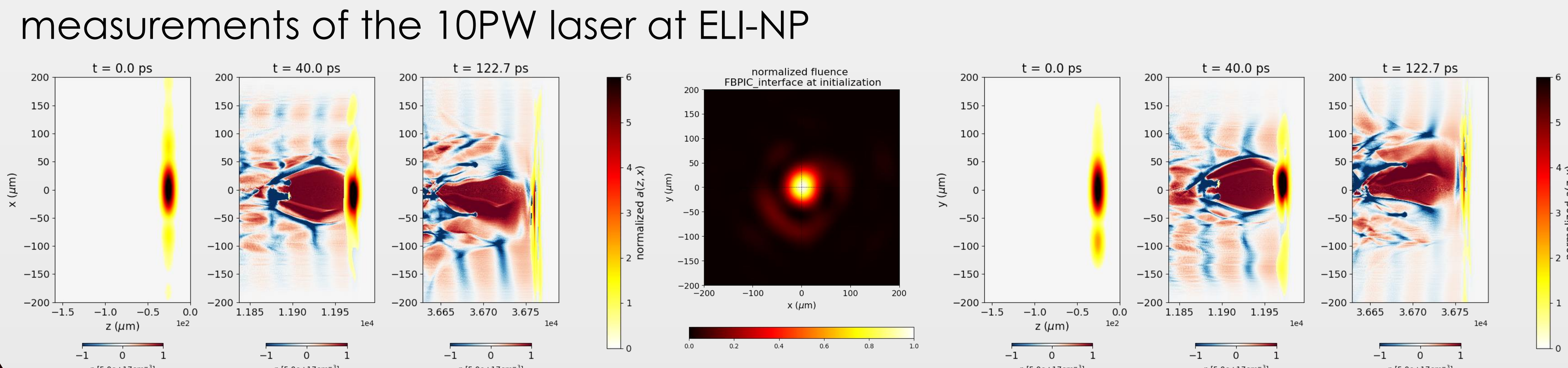
The laserprofiles module of **LP4PIC** allows to initialize a *laser* object, according the FBPIC prescription (same as WarpX), providing a transverse field and a longitudinal envelope. Profiles are renormalized according to given pulse energy.

- ***A simulation with a user defined NearField, with aberrations***



- ***A simulation based on experimental measurements***

A 10 PW LWFA line simulation with laser reconstruction from fluence measurements of the 10PW laser at ELI-NP



Conclusions and perspectives

- Numerical tools for laser reconstruction are required for more reliable simulations.
- LP4PIC can be used to estimate aberrations affecting a laser pulse after parbola.
- Including spectral informations to retrieve a complete 3D reconstruction
- Planning to implement other interfaces: WarpX (the same paradigma of FBPIC), Epoch,…

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