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

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

F.Avella[1,2*], L. A. Gizzi[1,3], P.Tomassini[4]

[1] Consiglio Nazionale delle Ricerche, Istituto Nazionale di Ottica (CNR-INO), Pisa, Italy.

[2] Università di Pisa, Dipartimento di Fisica 'Enrico Fermi', Pisa, Italy.

[3] Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Pisa, Italy.

[4] Extreme Light Infrastructure - Nuclear Physics, Magurele, Romania.

* e-mail: federico.avella@ino.cnr.it, paolo.tomassini@eli-np.ro

ABSTRACT

PIC simulations are a powerful instrument in modeling and predicting the outcomes of a Laser Plasma Acceleration experiment. However, the results of this kind of simulations can be profoundly different from the experimental reality because of the initialization of highly idealized laser fields not accounting for the effects of phase aberrations. We show a new Python package to retrieve the phase and to rebuild the transverse profile of laser fields from Near Field (NF) and Far Field (FF) fluence measurements, to be then automatically initialized in a PIC simulation. The phase retrieval is based on the *Gerchberg-Saxton algorithm*, where the reconstruction of fields is obtained with a propagator solving the Helmholtz equation in Fourier space. Main features of *Laser Pulse reconstructor For Particle In Cell simulations* (LP4PIC) will be shown with some examples and comparisons. Using LP4PIC it is also possible simulating and retrieving the propagation of any custom or experimental field passing through a phase or absorption mask, eventually applying aberrations.

PROPAGATION: SOLVING HELMHOLTZ EQUATION

Consider a complex, scalar, monochromatic field $U(x,y,z) = u(x,y,z,)e^{ikz}$, where k is the wavenumber associated to carrier wavelength, arising from an aperture $\mathscr{A}$ on which an input field distribution $U_0(x,y)$ impinges. Being $U(x,y,z)$ the solution to *Helmholtz equation:*

$$\nabla^2 U + k^2 U = 0 \tag{1}$$

and $\widehat{U}(k_x,k_y;z)$ its Fourier transform according the transverse directions, under *paraxial approximation* we can find the solution $U(x,y,z)$ of an input field U_0 focused in z by an optical element placed in $\mathscr{A}$ in terms of its Fourier transform as follows:

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

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

- Retrieves the input field distribution **(NearField)** from a fluence distribution $I(x,y)$, applying the transmission function $T(x,y)$ of a chosen (*On-axis Parabola* or *Spherical* mirrors) or custom user-defined Mirror and a phase $\phi(x,y)$:

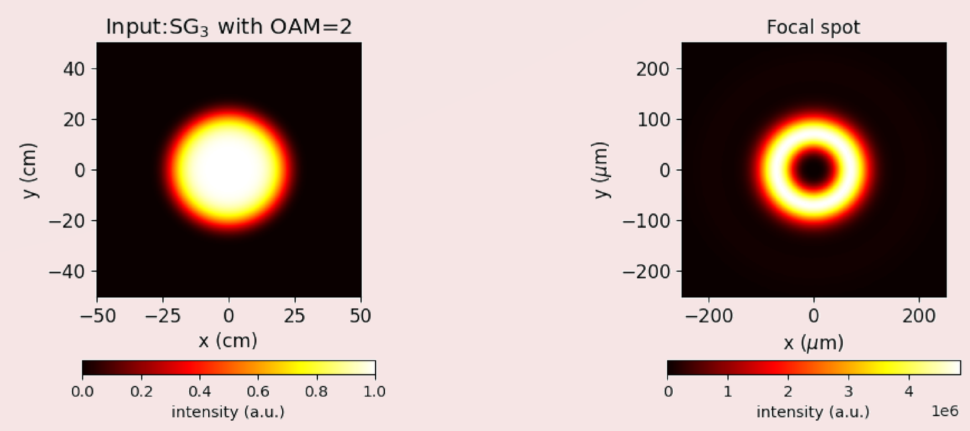
$$U_0(x,y) = \sqrt{I(x,y)}T(x,y)e^{i\phi(x,y)} \tag{3}$$

- Propagates in z, in terms of Fast Fourier Transform *FFT*, according to eq. (2)
- Retrieve $U(x,y;z)$ applying an inverse *FFT* **(FarField).**

FOCUSING A USER DEFINED NEARFIELD

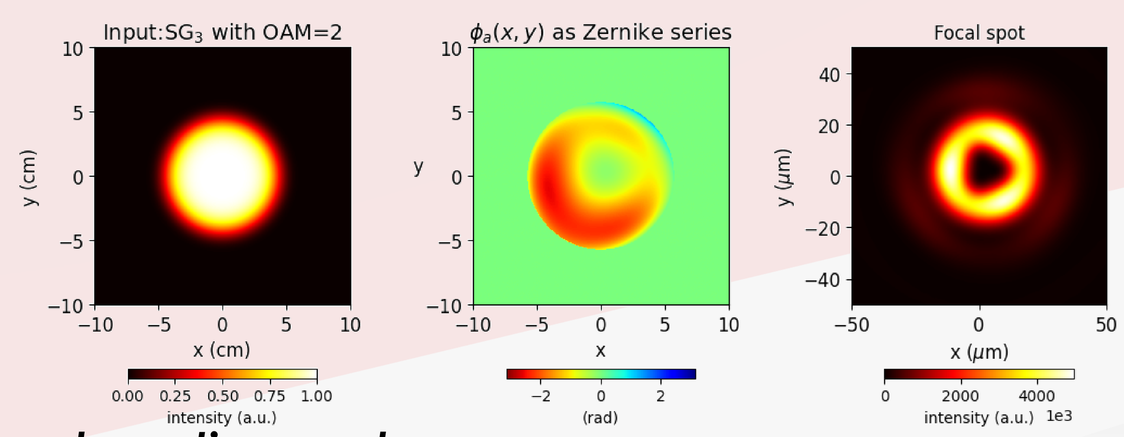
The phase map $\phi(x,y) = m\theta(x,y) + \phi_a(x,y) + \phi_{mask}(x,y)$ can include an Orbital Angular Momentum (**OAM**) m, an aberration phase ϕ_a given in terms of Zernike series (user provided aberration coefficients) and a user defined phase/absorption mask ϕ_{mask}.

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



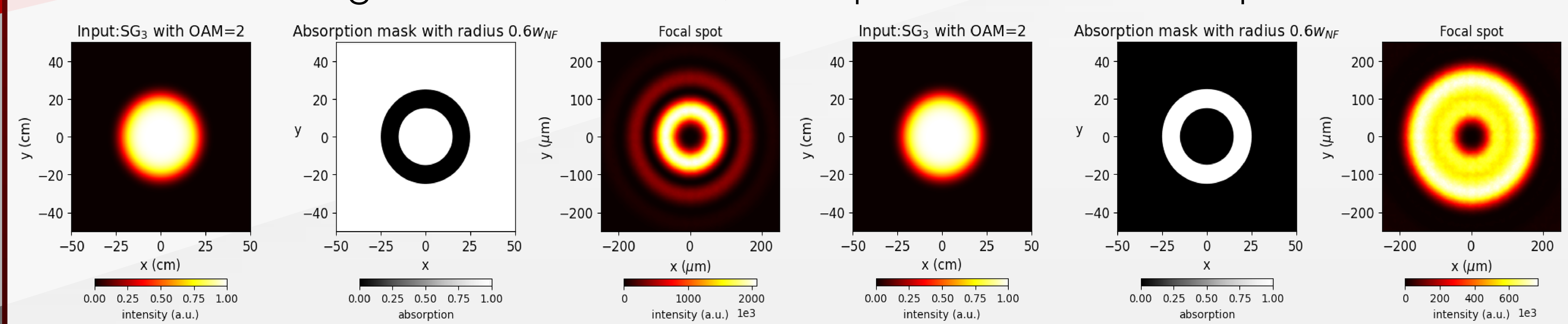
- ***Including aberrations***

Aberrations coefficients are given according *Noll index* convention.

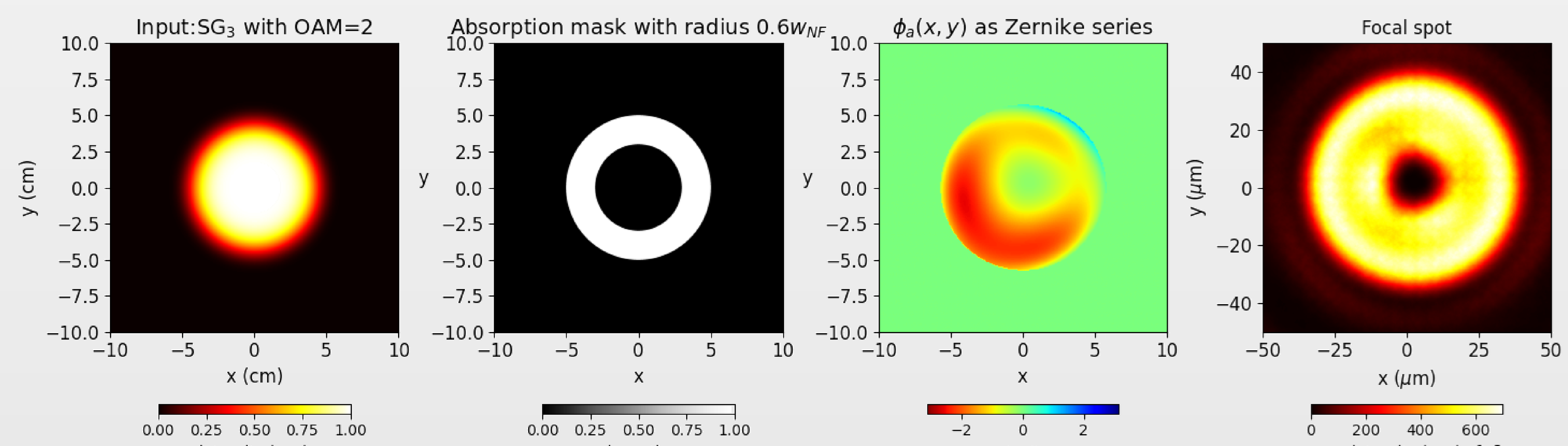


- ***Applying an absorption mask***

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

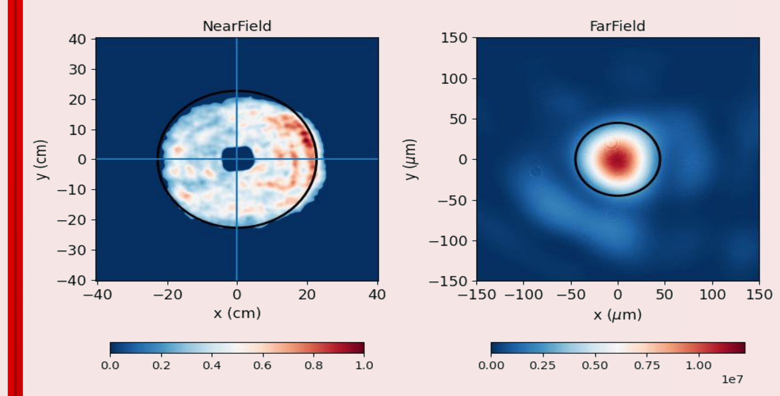


- ***All these operations to be called as 'methods' before the propagation***



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.

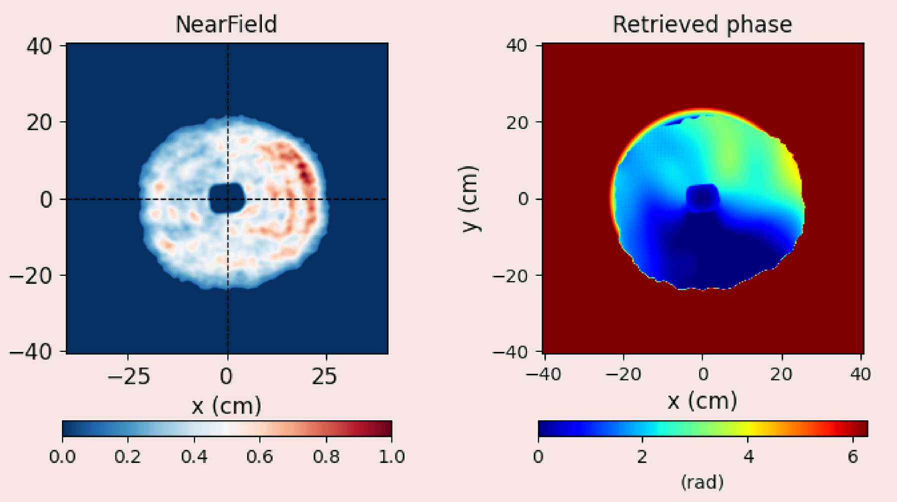
GS algorithm

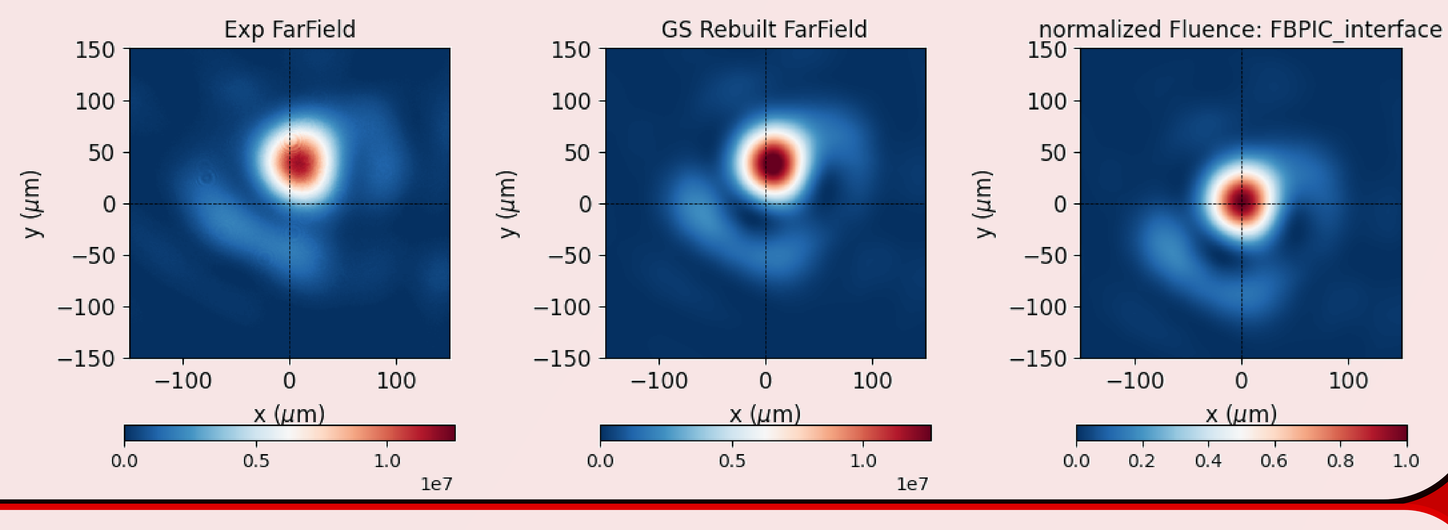
Seed $U^{(NF)\prime} = \sqrt{I^{NF}}e^{i\phi_0}$

$$U^{(FF)} = P[U^{(NF)\prime}] \rightarrow U^{(FF)\prime} = \sqrt{I^{FF}}\frac{U^{(FF)}}{|U^{(FF)}|} \rightarrow U^{(NF)} = P^{-1}[U^{(FF)\prime}] \rightarrow U^{(NF)\prime} = \sqrt{I^{NF}}\frac{U^{(NF)}}{|U^{(NF)}|}$$

In few rounds (< 50) the **GS loop** retrieves the phase from the two input images.

Then the propagator rebuilds the transverse fields in the FF, which will be used to initialize laser fields in a **PIC simulation.**

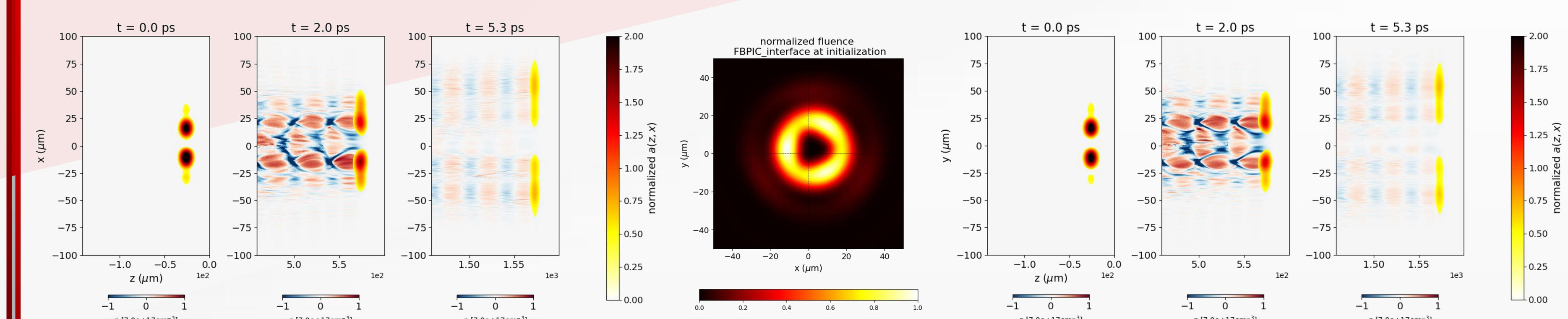




AN INTERFACE TO INITIALIZE IN FBPIC

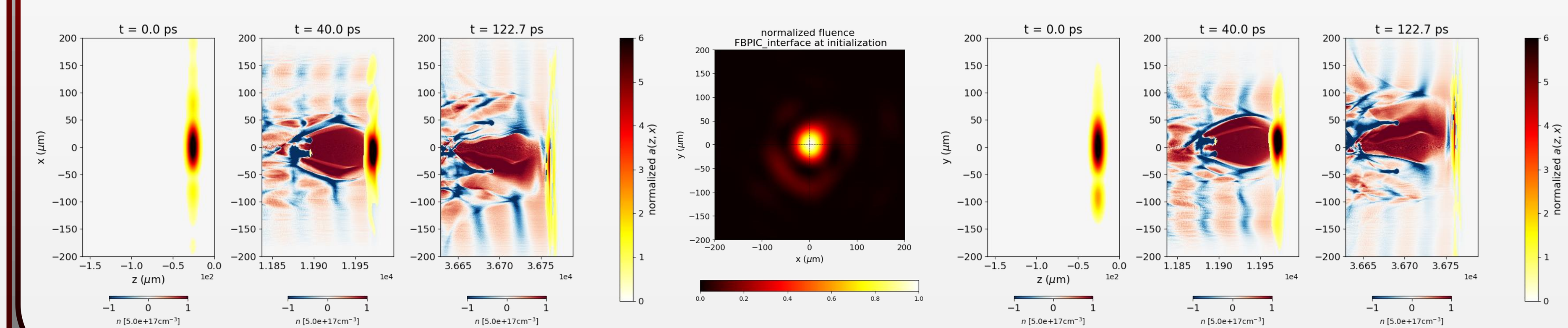
LP4PIC is provided with an interface to initialize a *laser* object, according the FBPIC prescription (same as WarpX), once transverse field distribution is retrieved and a longitudinal envelope is provided.

- ***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

- Reconstructor numerical tools required for more reliable simulations
- Including spectral informations to retrieve a complete 3D reconstruction
- Planning to implement other interfaces: WarpX (the same paradigma of FBPIC), Epoch,…
- Working on module implementing Zernike transform of retrieved phase to estimate aberrations coefficients

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