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EuPRAXIA
Preparatory Phase

Arbitrary laser-pulse injection in PIC codes

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High power laser pulses in the laboratory

Lasers are non-ideal

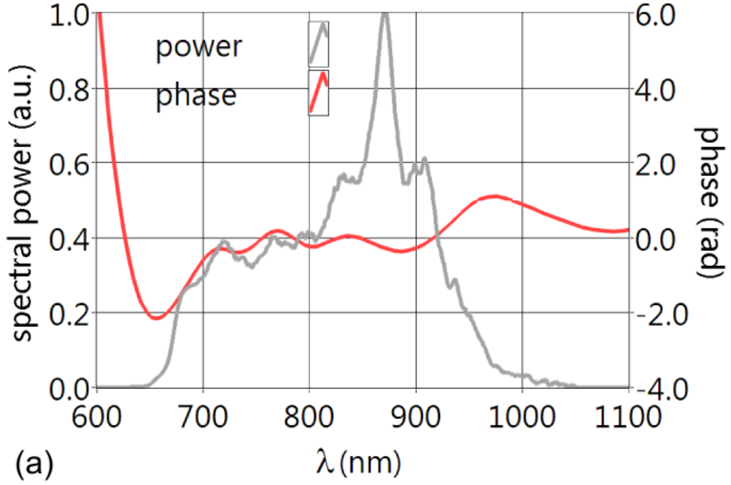
- Non-standard wave-fronts
- Spectral phase variations

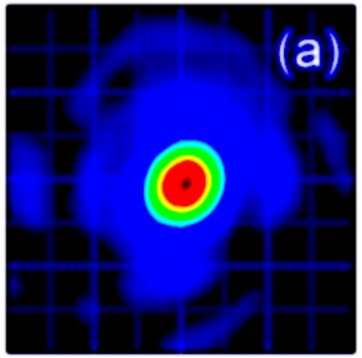
Experimental measurements can fully characterise e.m. fields

- Fluence
- Spectral-phase
- Full 3D reconstructions
- Spectrograms

We developed a new tool that allows to inject arbitrary laser pulses in PIC codes that strictly satisfy Maxwell's equations

Measurements





General laser injection method

Exact solution

Plane waves: exact solutions of Maxwell's equations

$$\mathbf{E}(\mathbf{r},t) = E_0 \exp(i\mathbf{k}\cdot\mathbf{r} - \omega t)\mathbf{e}_{pol}$$

$$\mathbf{B}(\mathbf{r},t) = \frac{1}{\omega}\mathbf{k}\times\mathbf{E}(\mathbf{r},t)$$

Linearity

Maxwell's equations in free space

$$\nabla\cdot\mathbf{E} = 0 \qquad \nabla\cdot\mathbf{B} = 0$$

$$\nabla\times\mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t} \qquad \nabla\times\mathbf{B} = \frac{1}{c^2}\frac{\partial\mathbf{E}}{\partial t}$$

Sum of solutions is still a solution!

New algorithm

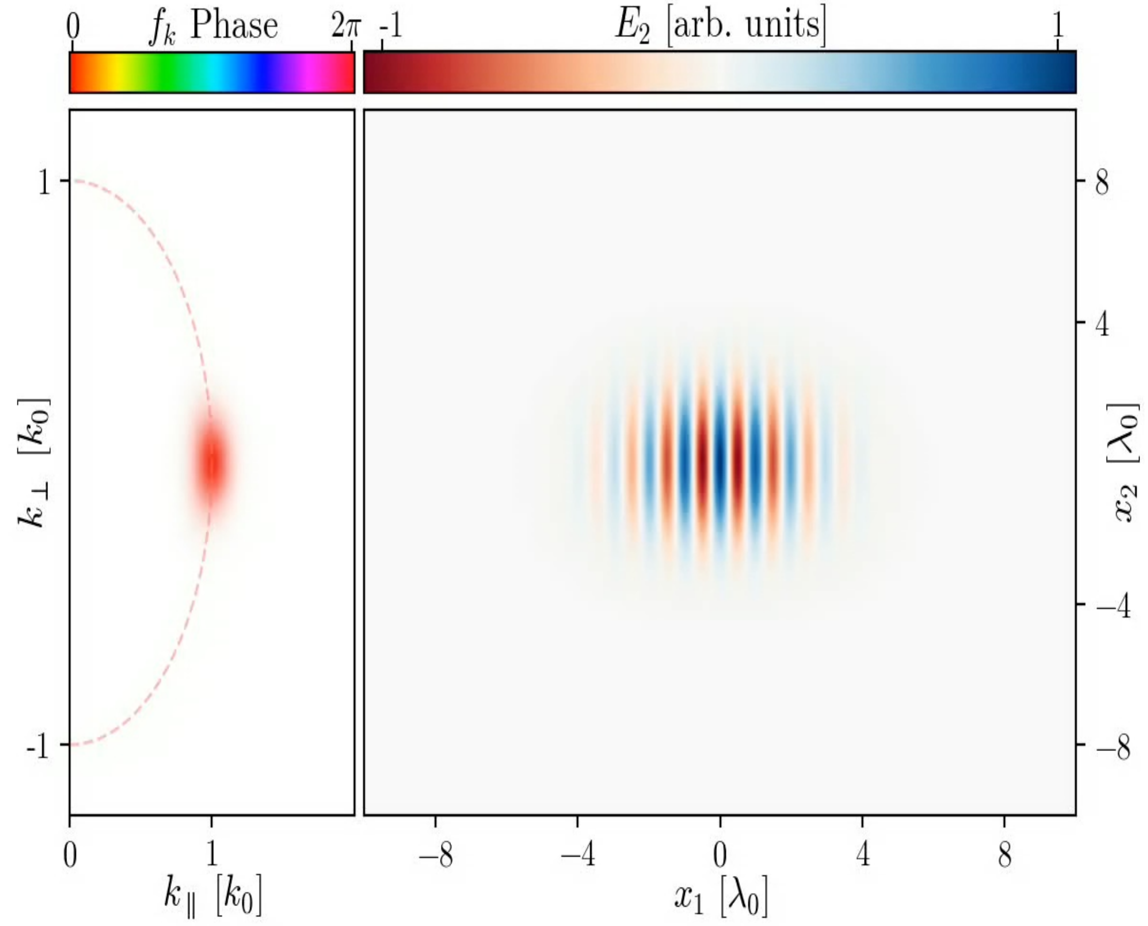
Using Fourier transforms, decompose any wave-packet as a sum of plane waves, with a defined k wave vector and thus a specific amplitude $f_k(\boldsymbol{k})$

$$\mathbf{E} = \int \mathbf{e}_{pol}(\mathbf{k})\, f_k(\mathbf{k})\, e^{i\mathbf{k}\cdot\mathbf{r} - i\omega(\mathbf{k})t}\, \mathrm{d}\mathbf{k}$$

$$\mathbf{B} = \int \frac{1}{c}\mathbf{e}_{\mathbf{k}}\times\mathbf{e}_{pol}(\mathbf{k})\, f_k(\mathbf{k})\, e^{i\mathbf{k}\cdot\mathbf{r} - i\omega(\mathbf{k})t}\, \mathrm{d}\mathbf{k}$$

Controlling pulse properties with $f_k(k)$ function

Funded by the European Union



We can control:

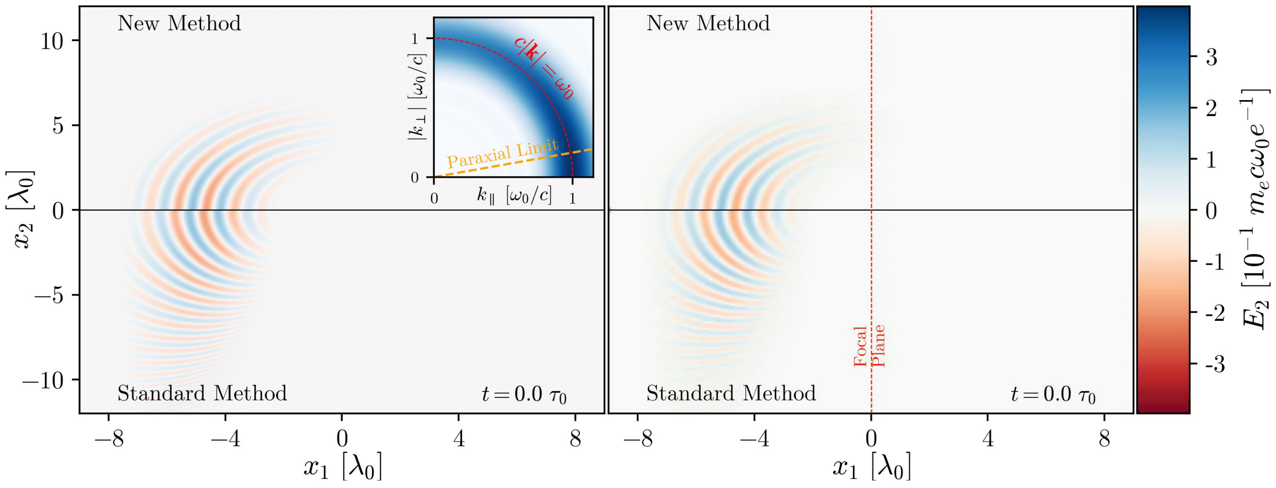
- Main Frequency
- Transverse Size
- Longitudinal Size
- Focus Position
- Relative Injection Position
- Transverse Profile

Basically Arbitrary Control over Pulse Shape

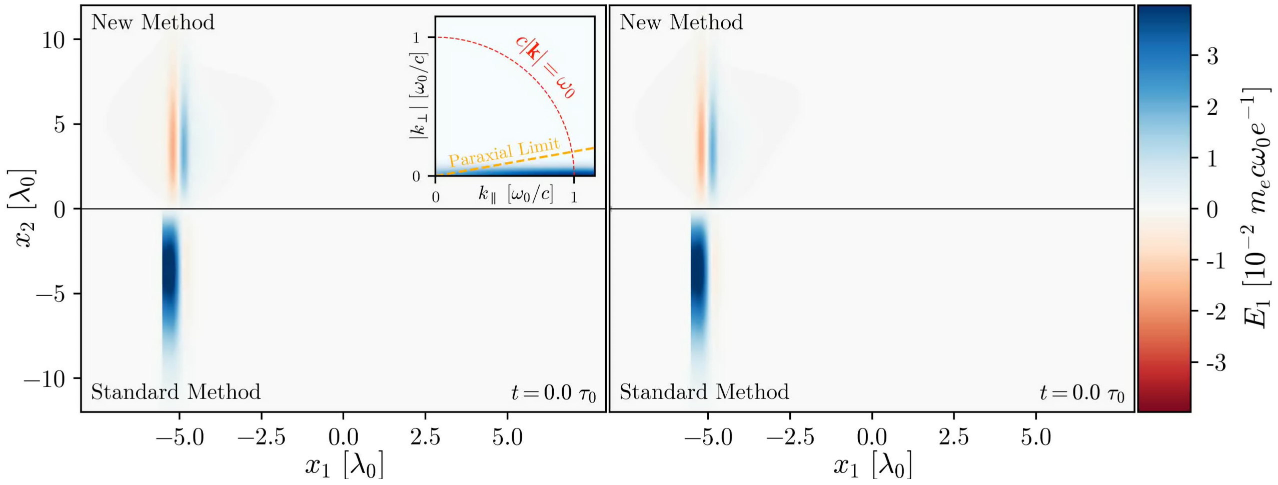
Arbitrary pulse injection in Osiris

✓ **Beyond paraxial and envelope approximation:**
Precise description of tight-focus and ultra-short e.m. fields

Transverse electric field of a non-paraxial laser pulse



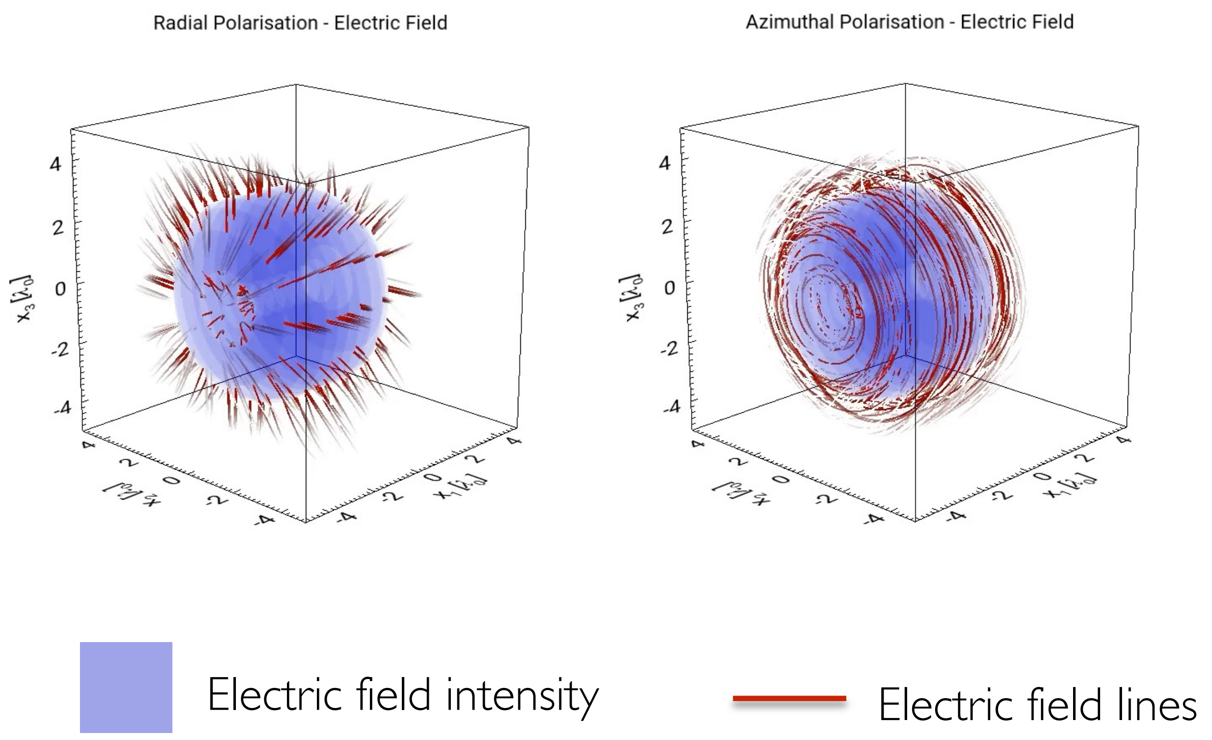
Transverse electric field of a single cycle laser pulse



Arbitrary pulse injection in Osiris

- **Beyond paraxial and envelope approximation:**
  Precise description of tight-focus and ultra-short e.m. fields

- **Elliptical, radial and azimutal polasation build in**
  Direct injection of new polarisation states



Arbitrary pulse injection in Osiris

Funded by the European Union

Beyond paraxial and envelope approximation:
Precise description of tight-focus and ultra-short e.m. fields

Elliptical, radial and azimutal polasation build in
Direct injection of new polarisation states

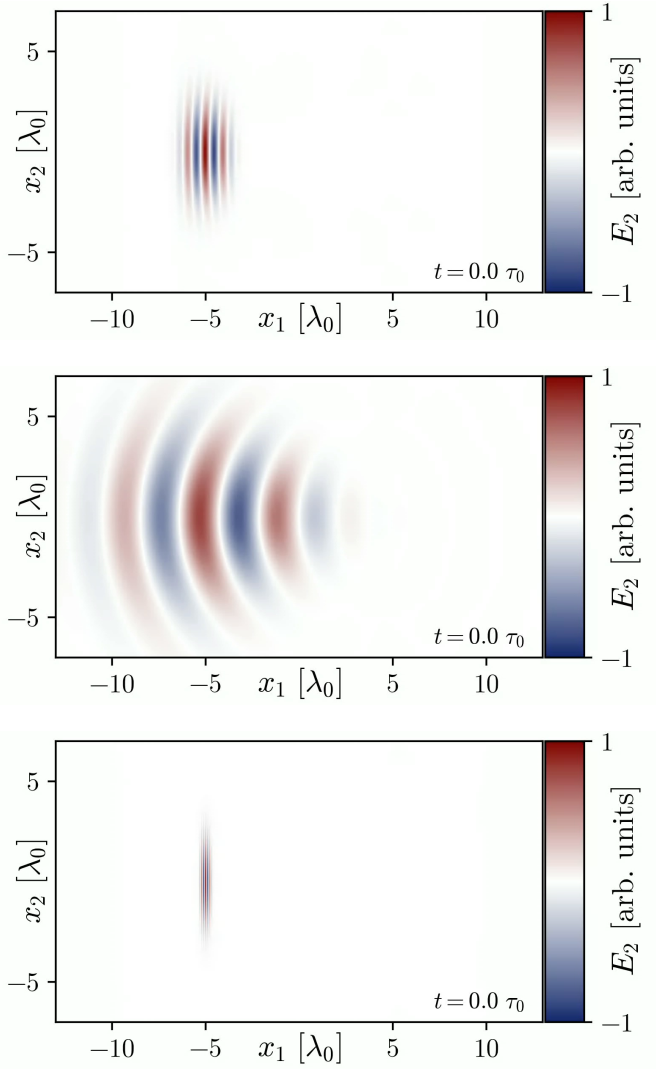
Arbitrary Lorentz boosts
Pulses can be injected in any inertial reference frame

Transverse electric field of a pulse in different frames

Laboratory

Co-propagating reference frame
$\beta_1 = 0.9$

Counter-propagating reference frame
$\beta_1 = -0.9$



Arbitrary pulse injection in Osiris

- **Beyond paraxial and envelope approximation:**
  Precise description of tight-focus and ultra-short e.m. fields

- **Elliptical, radial and azimutal polasation build in**
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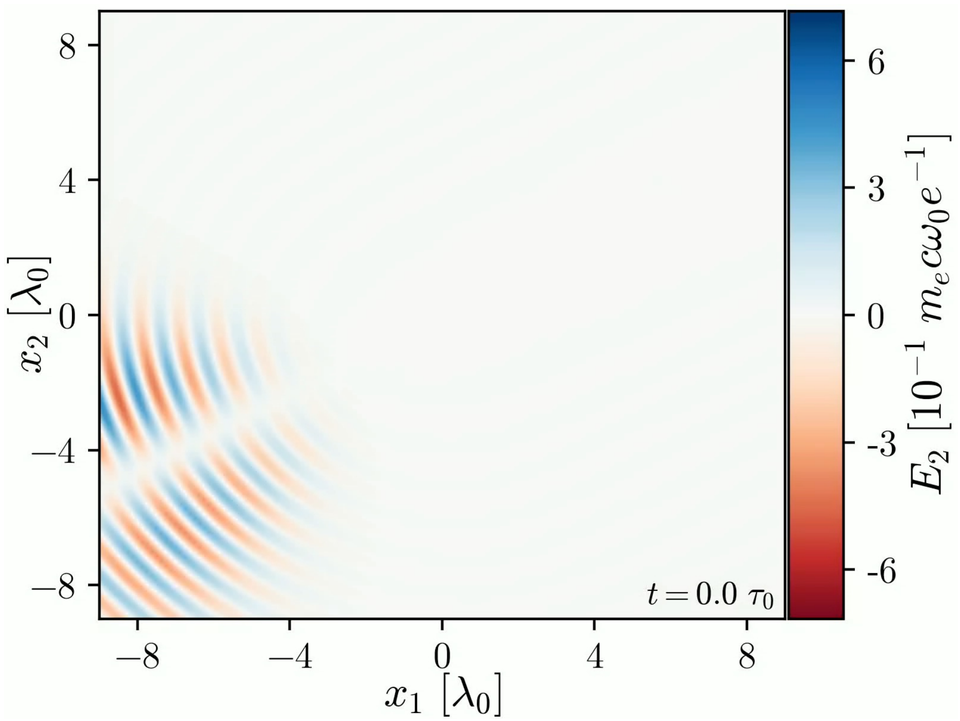
- **Arbitrary Lorentz boosts**
  Pulses can be injected in any inertial reference frame

- **Angled injection**
  Pulses can be injected travelling in any direction

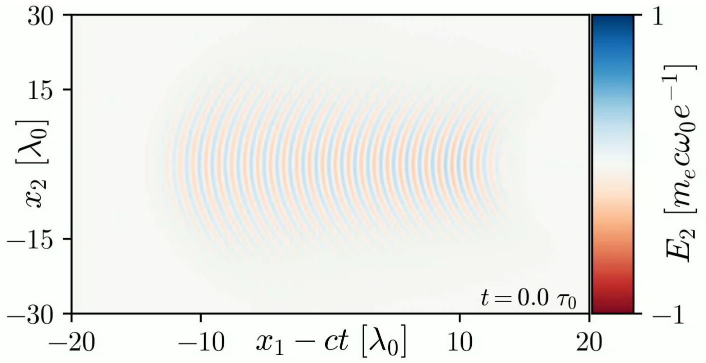
Transverse electric field of a 1st order Hermite Pulse injected at 30º



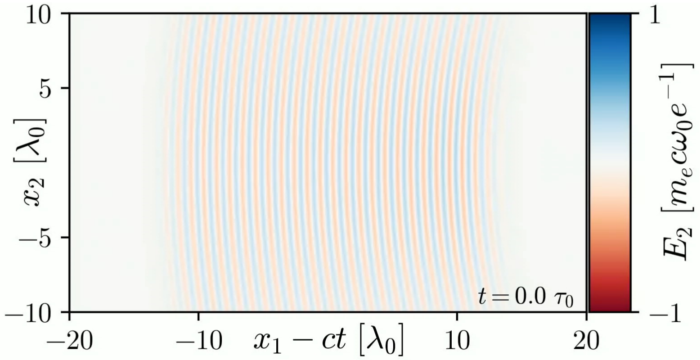
Arbitrary pulse injection in Osiris

- **Beyond paraxial and envelope approximation:**
  Precise description of tight-focus and ultra-short e.m. fields
- **Elliptical, radial and azimutal polasation build in**
  Direct injection of new polarisation states
- **Arbitrary Lorentz boosts**
  Pulses can be injected in any inertial reference frame
- **Angled injection**
  Pulses can be injected travelling in any direction
- **Wall injection from side walls**
  Allows for transversely smaller simulation domains

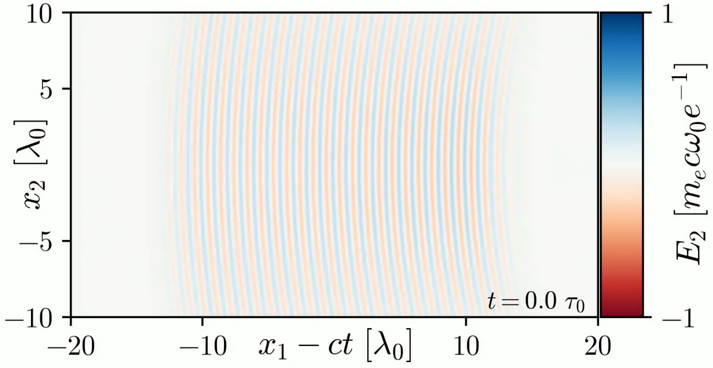
Wide box



Narrow box **without** additional Wall-injection



Narrow box **with** Wall-injection from top/bottom walls



Conclusions

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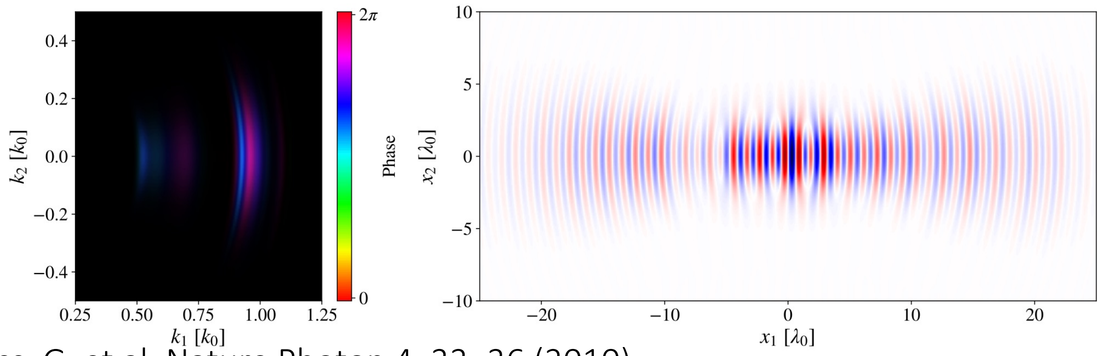
New numerical tool ready to inject any pulse:

- Pulse injection from spectrum and spectral phase
- Arbitrary injection (single cycle/ultra-tight focus, structured, any polarisation...)
- Div B = 0 (up to precision of numerical scheme)
- Injected pulse satisfies Faraday's and Ampere's law simultaneously
- Near absence of backward propagating ghost pulses

Future work: complementary Zernike polynomial description (new post-doc coming in November)

Pulse injection from spectrum and spectral phase



Krauss, G. et al. Nature Photon 4, 33–36 (2010)

Single cycle pulse injection