XCIMER

MFEM Workshop 2024

Towards Predictive Modeling of the World's Most Powerful Fusion Laser at Xcimer

Milan Holec

10/23/2024

This is laser fusion on the grid

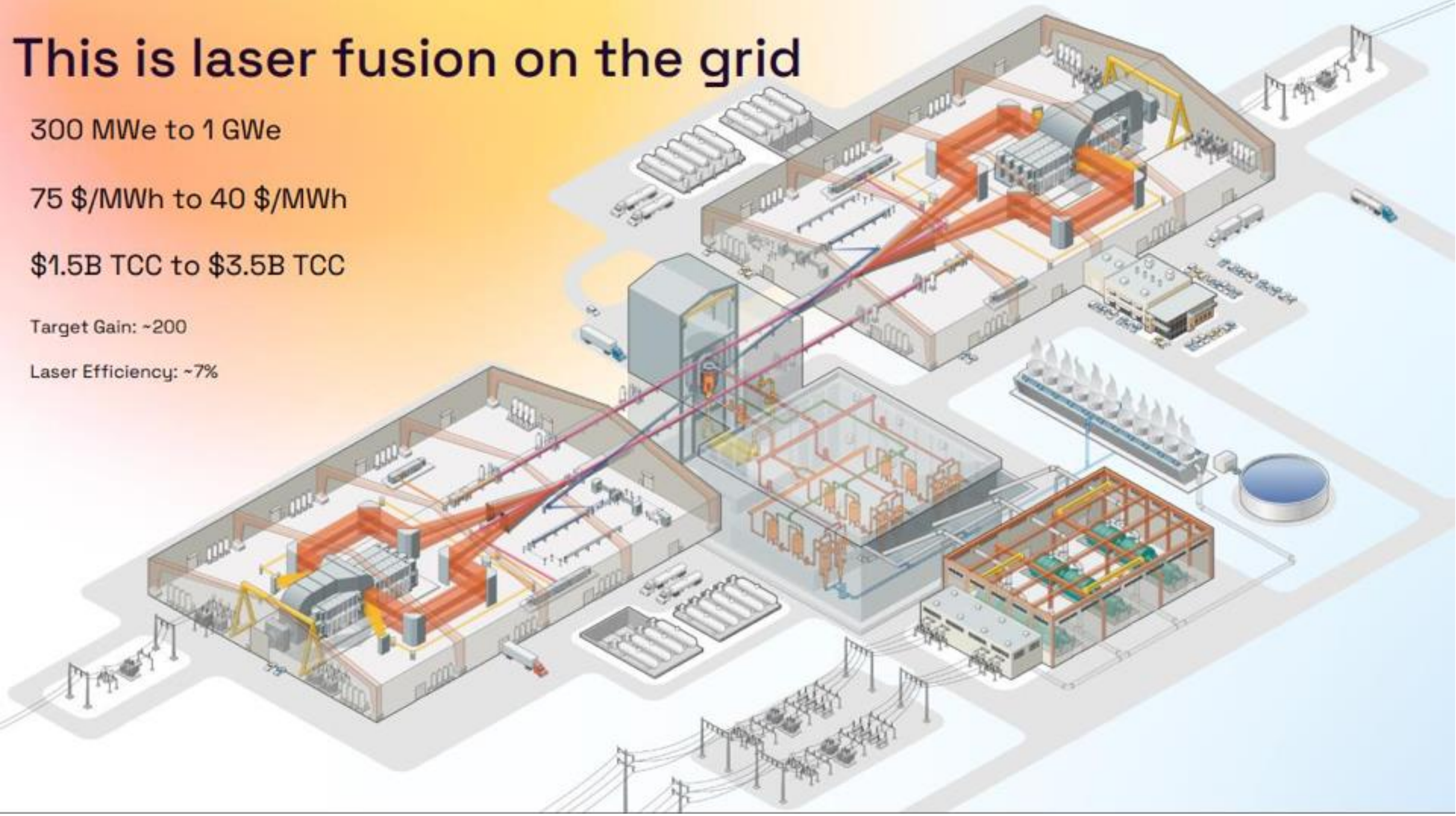
300 MWe to 1 GWe

75 $/MWh to 40 $/MWh

$1.5B TCC to $3.5B TCC

Target Gain: ~200

Laser Efficiency: ~7%



EYEBROW

Team

Computing & Theory

- nonlinear optics
- plasma kinetics
- radhydro/MHD
- applied math
- HPC
- data science

Milan Holec

Daniel Treiman

David Schmidt

Jacob Milberger

Rahul Kumar

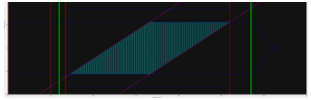
Warren Colomb

Ernesto Barraza-Valdez

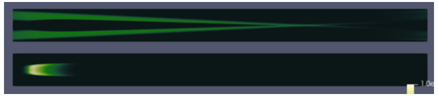
IRIS
digital twin / virtual beamline

Iris (greek goddess of the rainbow and the messenger of the Olympian gods) is Xcimer's simulation code to predict the seed profile throughout the Phoenix system.

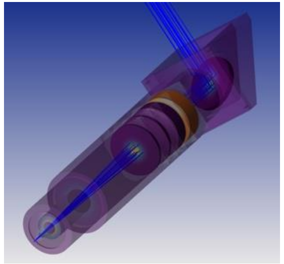
Fourier propagation (FFT)



Coupled-wave-system SBS (FEM)

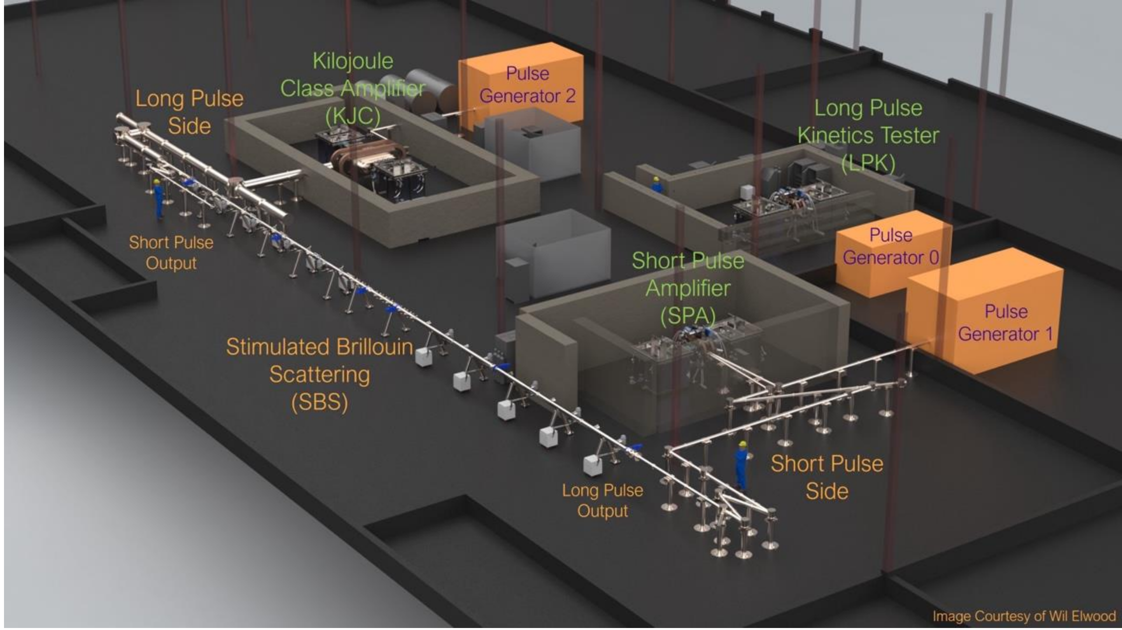


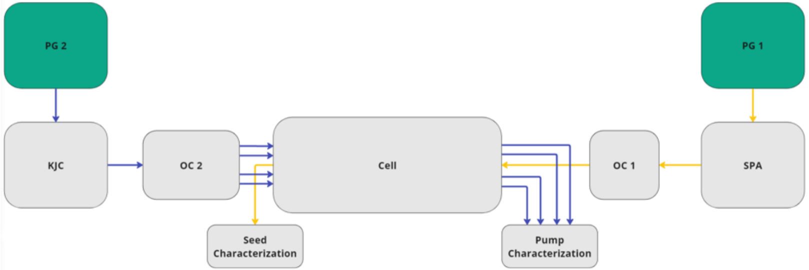
Zemax



XEC

Modular system (model plugins)
Python, C++, Matlab
Libraries: cws, ioglue, physutils, jeff, excalibur
High-performance computing (HPC)
MFEM-based high-order accuracy





Gas SBS model

$$\nabla^2\tilde{E} - \frac{n^2}{c^2}\left(\partial_{tt}^2\tilde{E} - \alpha_E\partial_t\nabla^2\tilde{E}\right) = \frac{\gamma_e}{4\pi\rho_0}\partial_{tt}^2(\tilde{\rho}\tilde{E}),$$

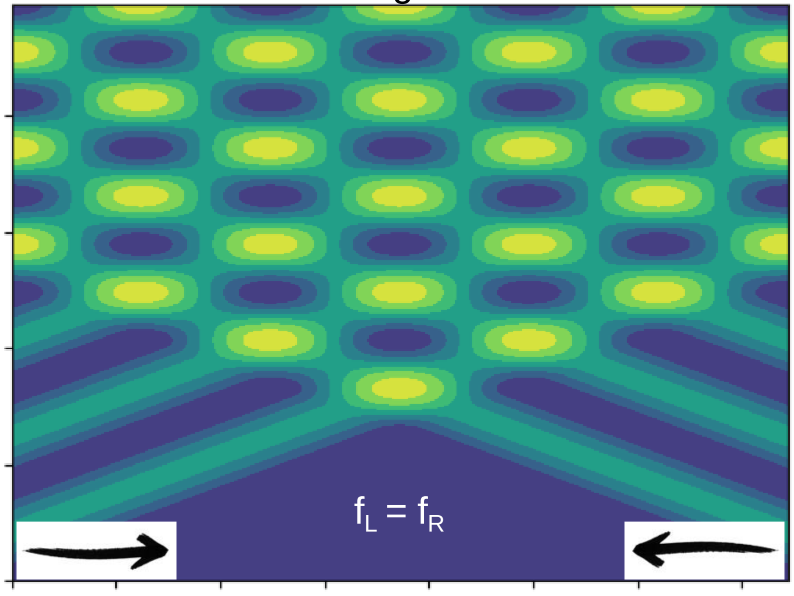
$$\nabla^2\tilde{\rho} - \frac{\gamma}{v_s^2}\left(\partial_{tt}^2\tilde{\rho} - \Gamma\partial_t\nabla^2\tilde{\rho}\right) = \frac{\gamma\,\gamma_e}{v_s^2 8\pi}\nabla^2\left\langle\tilde{E}^2\right\rangle,$$

IRIS

```
[6]: # SIMULATION
     # Load hpc-cws-3d library
     import cws
     # Assign desired boundary conditions
     config['pulseL_inflow'] = inflow_left_wave
     config['pulseR_inflow'] = inflow_right_wave
     config['cfl'] = 0.5
     # Run the simulation
     result = cws.beam1d(**config)

     dt = 1.55e-18, hx = 9.3e-08
     Number of pulseR unknowns: 800
     Number of pulseL unknowns: 800
     Simulation of 3200 timesteps until 4.96e-15
```

Standing wave



- Nonlinear Maxwell equations
- Wave optics: diffraction, self-focusing, speckles, …
- **Three-wave** nonlinear optics (electrostriction)
- 248 nm wavelength vs 100 m beamline (10^9 dofs in 1D)
- High-frequency separation

Base model

$$\partial_t A_0 + \frac{c}{n}\hat{\mathbf{k}}_0\cdot\nabla A_0 - \frac{ic}{2nk_0}\nabla^2 A_0 = -R|A_s|^2 A_0,$$

$$\partial_t A_s + \frac{c}{n}\hat{\mathbf{k}}_s\cdot\nabla A_s - \frac{ic}{2nk_s}\nabla^2 A_s = R^*\,|A_0|^2 A_s,$$

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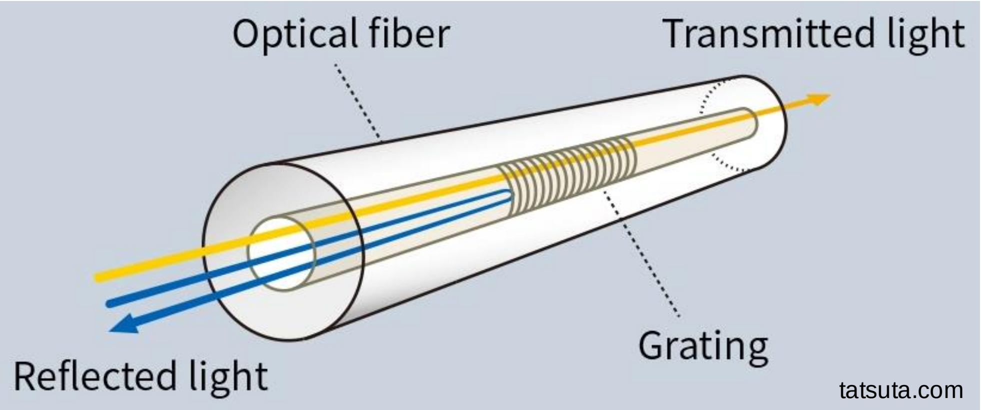

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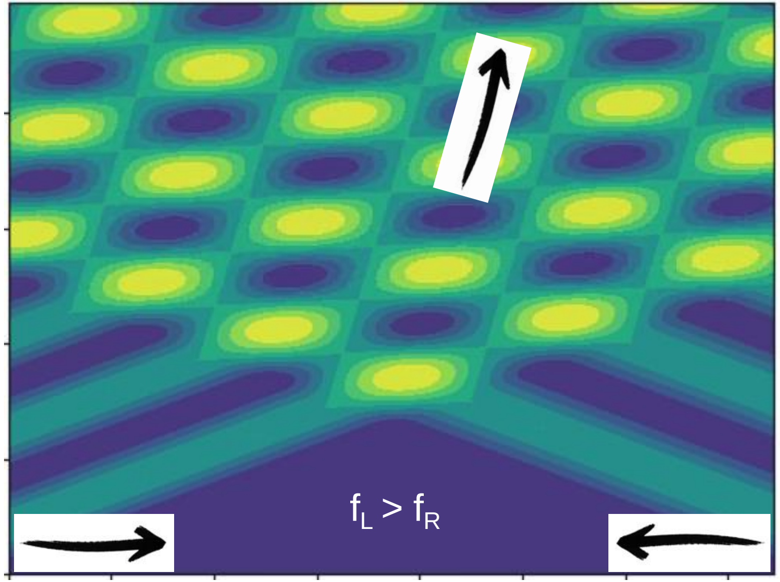
Moving acoustic wave



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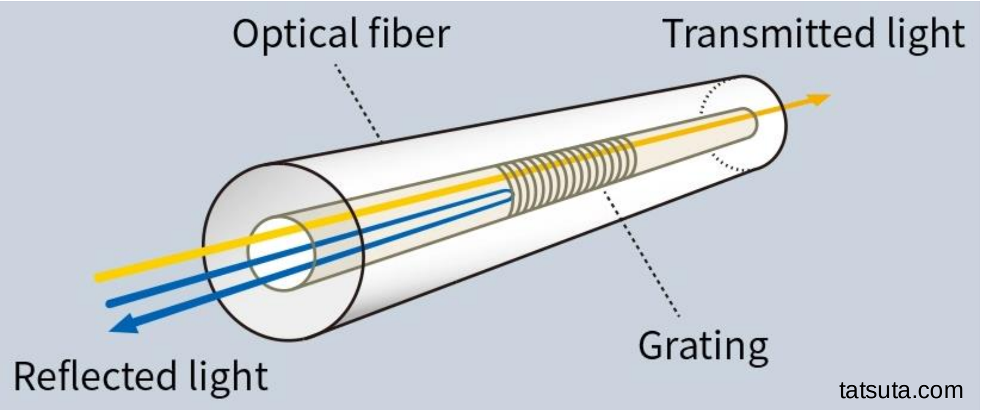
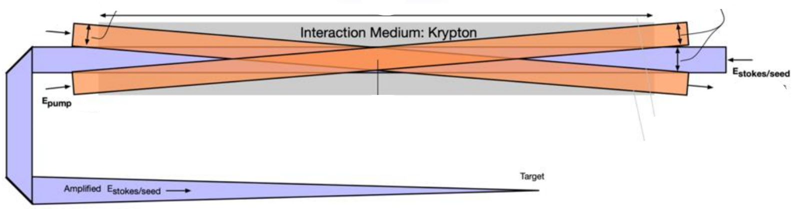
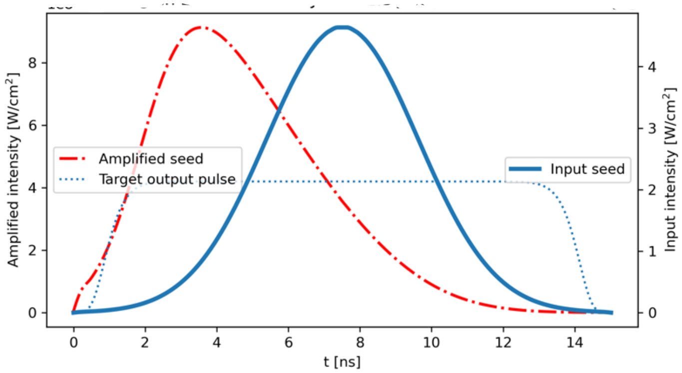
XEC

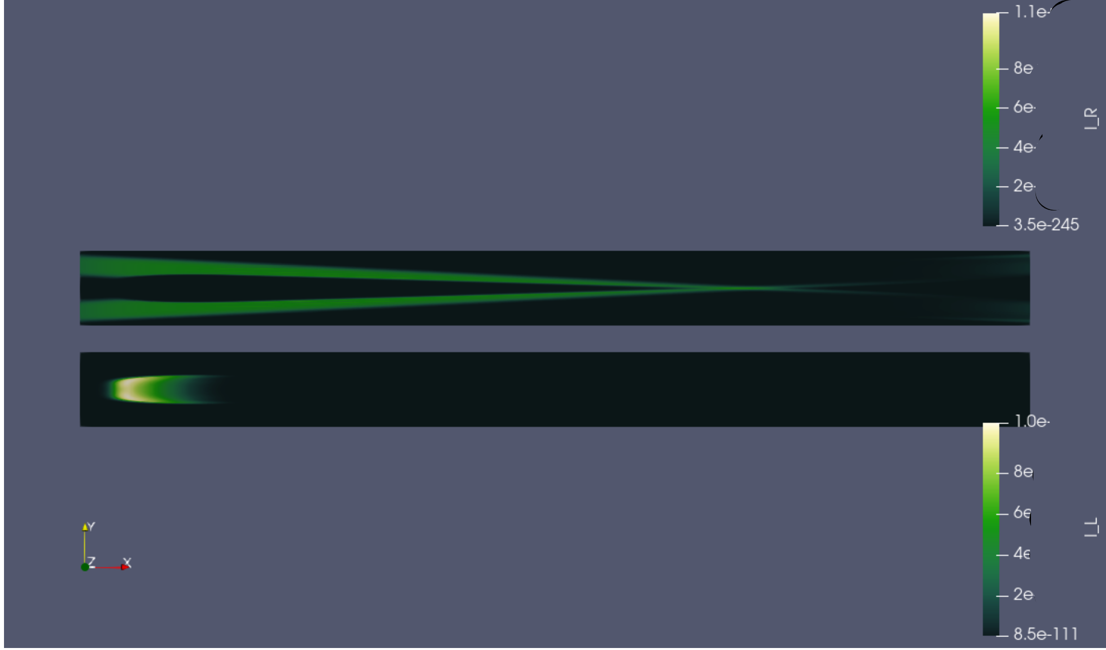


tatsuta.com

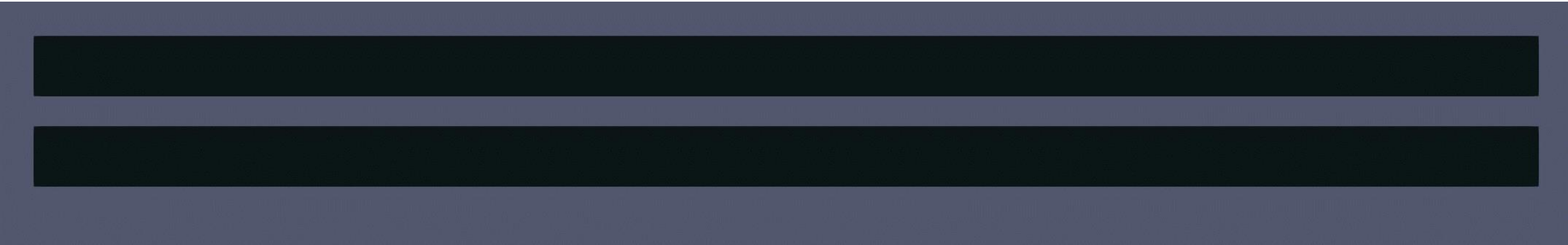
Phoenix – SBS cell







Proof-of-concept numerical experiment



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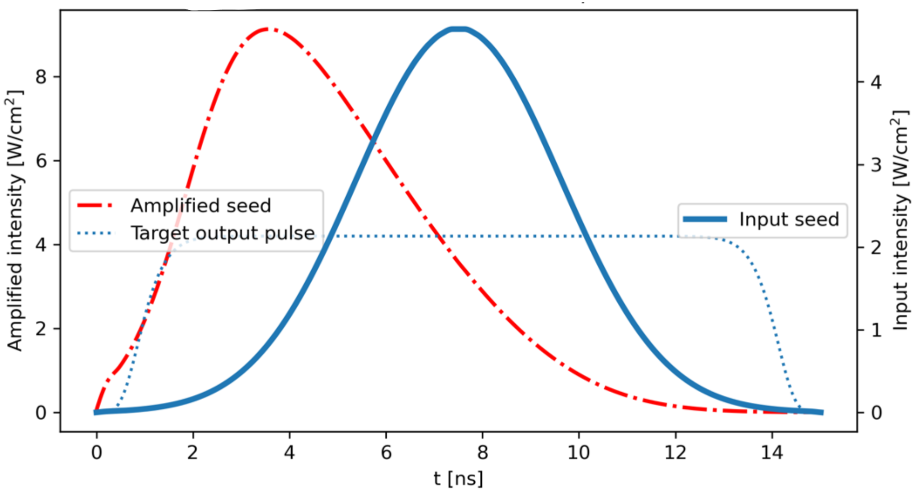
Simulation - SBS in 1D (~40% amplification)



$$\left(\frac{\partial}{\partial t} - c\frac{\partial}{\partial z}\right) I_s = c\gamma_B g(\omega_a) I_s I_o$$

$$\left(\frac{\partial}{\partial t} + c\frac{\partial}{\partial z}\right) I_o = -c\gamma_B g(\omega_a) I_s I_o$$

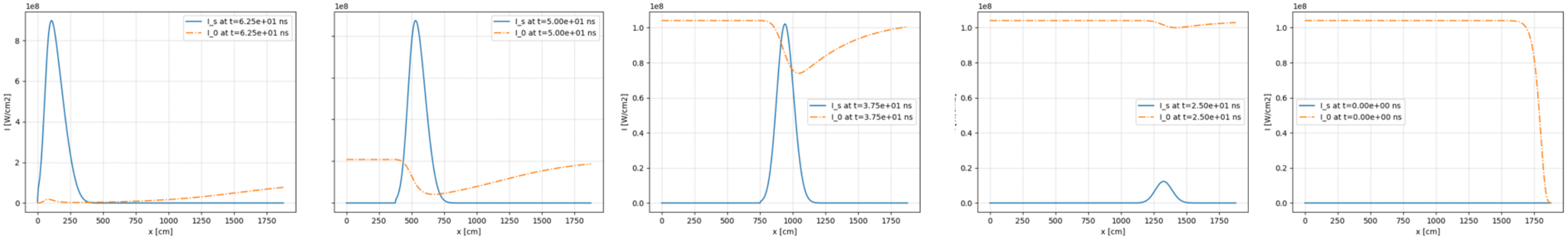
Integration after change of variables to coordinates co-moving with I_o and I_s

J. Murray et. al., "Raman pulse compression of excimer lasers for application to laser fusion," IEEE Journal of Quantum Electronics, 15(5) 342 (1979).

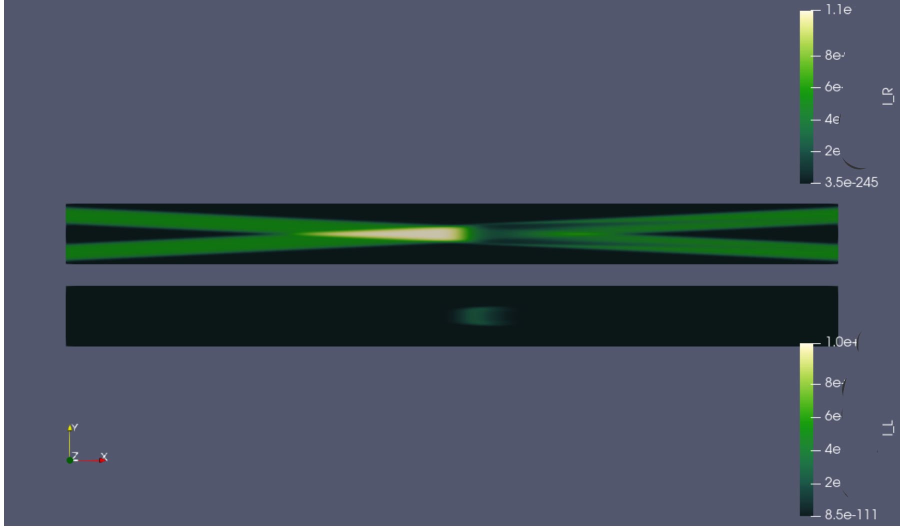
$$F_s^{out}/F_{sat} = \ln\left[1 + e^{F_o^{in}/F_{sat}}\left(e^{F_s^{in}/F_{sat}} - 1\right)\right]$$

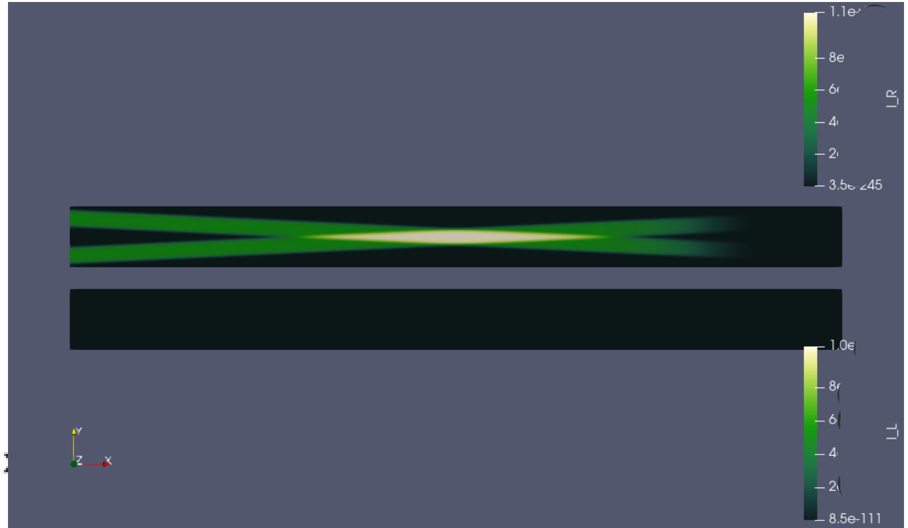
$$F_{sat} = \frac{2}{c\gamma_B} \qquad L_{int} = \frac{\tau_p c}{2} \qquad F_o^{in} = \int I_o(t_1, z)\,\frac{dz}{c}$$

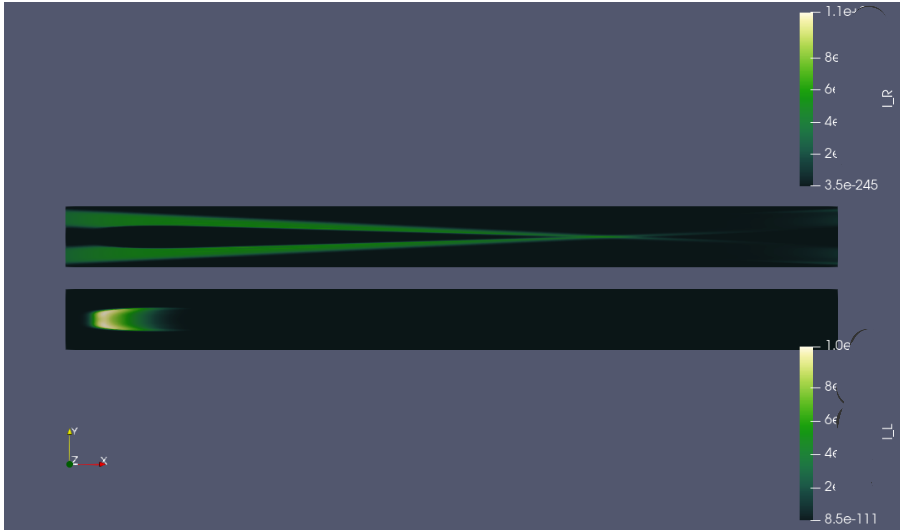
Fluence rerr ~10^{-6} vs. analytic solution



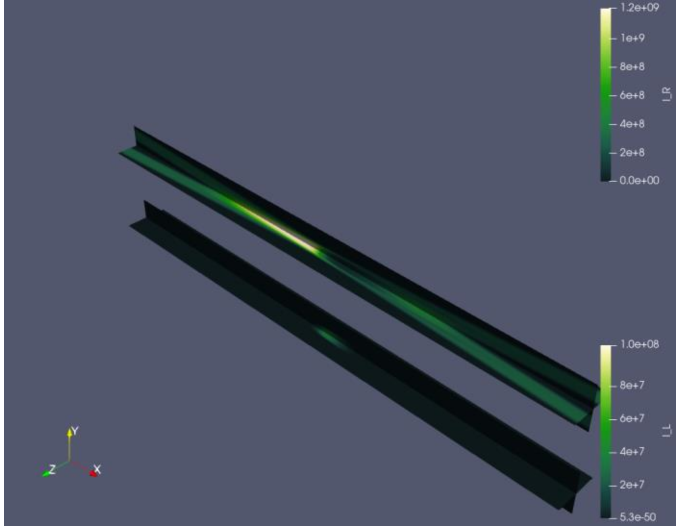
Simulation - SBS in 2D

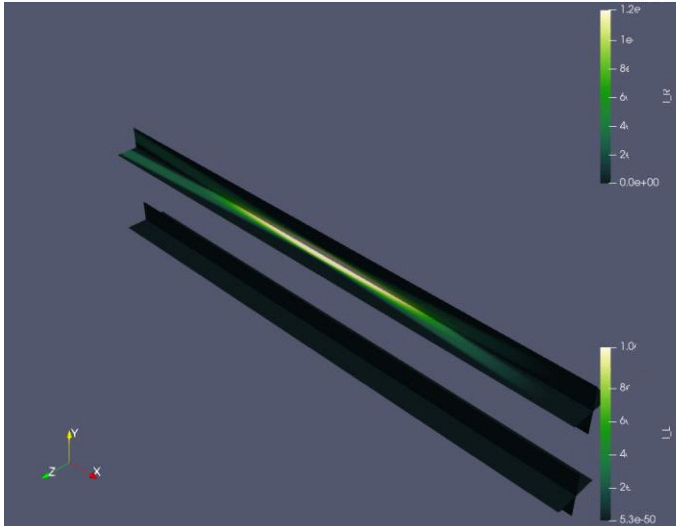


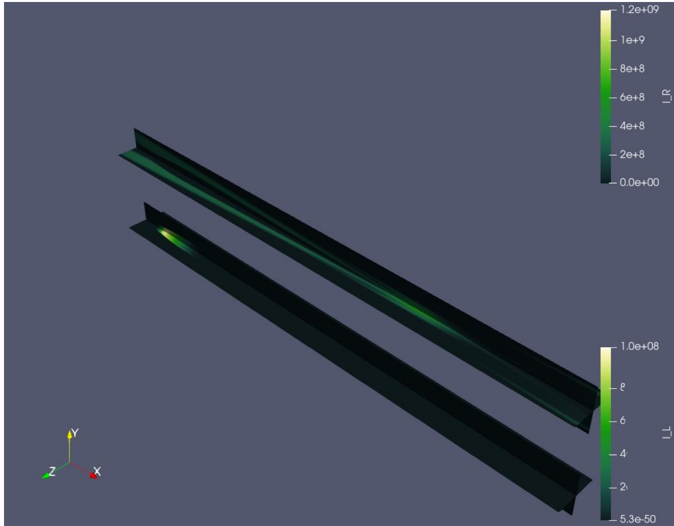




Simulation - SBS in 3D







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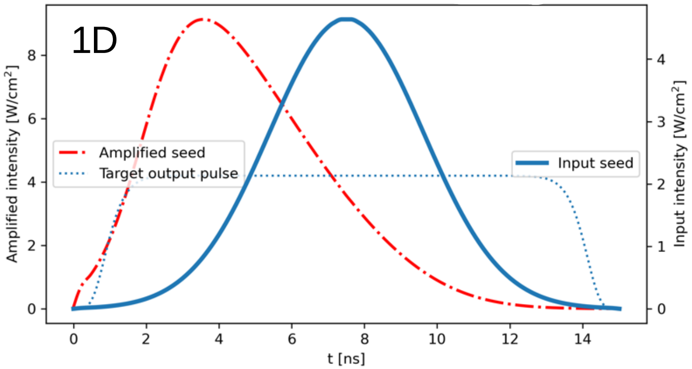
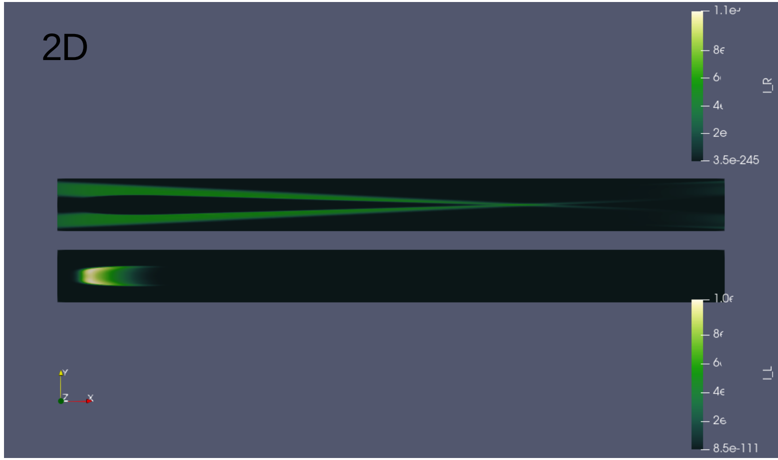
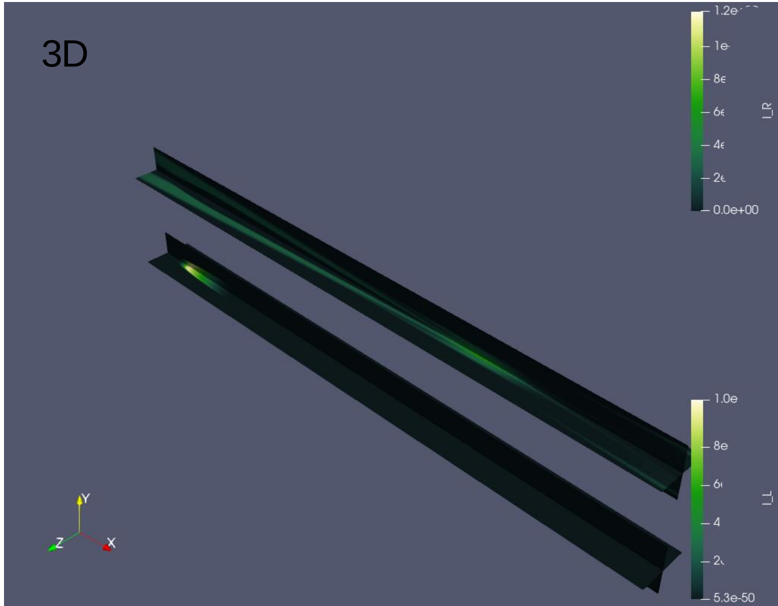
Simulation – 1D/2D/3D physics validation

- Realistic Phoenix dimensions and geometry
- High-order Finite Element Method
- Based on MFEM open-source library
- Consistent seed amplification in 1D, 2D, and 3D
- 3D requires massively parallel simulations

Efficient design of Phoenix system
leveraging super-fast 1D, geometrically consistent 2D, and complete 3D physics simulations!







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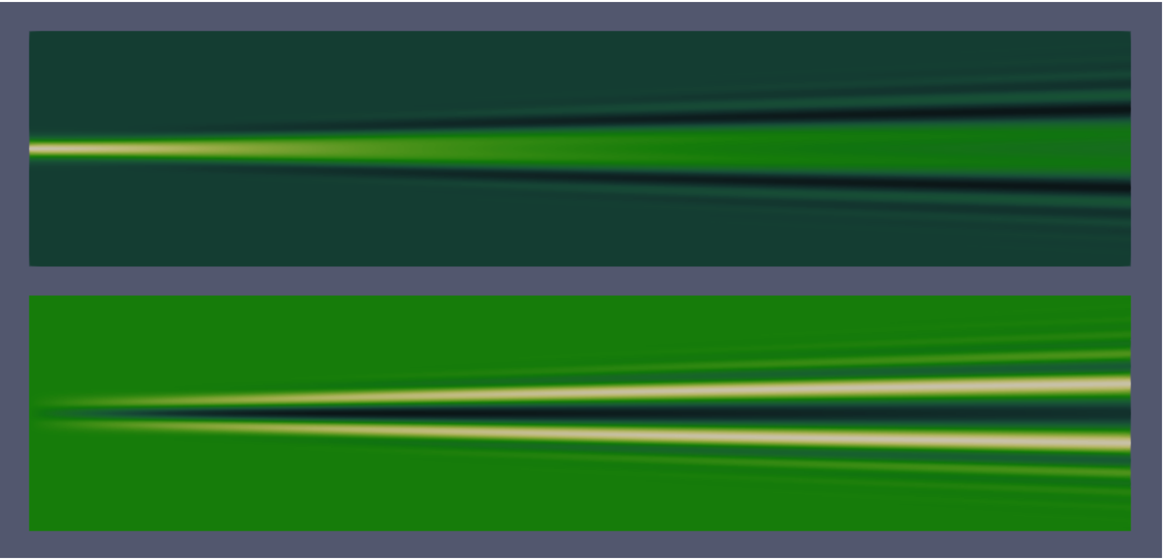
Diffraction benchmark

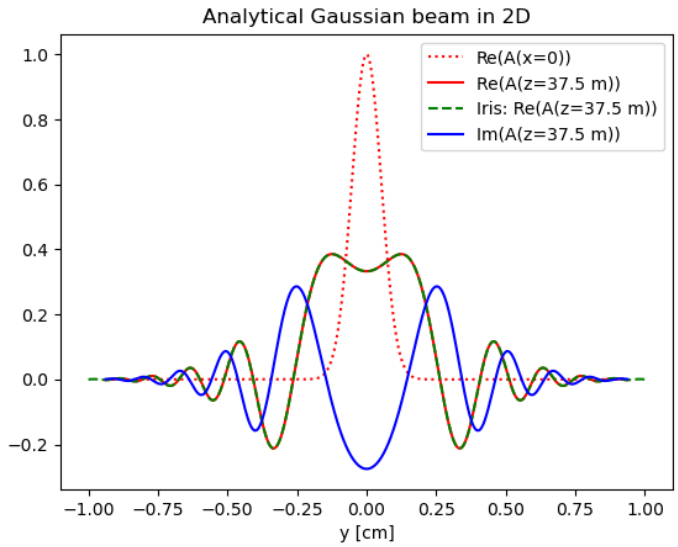
$$\partial_t A_0 + \frac{c}{n}\hat{\mathbf{k}}_0 \cdot \nabla A_0 - \frac{ic}{2nk_0}\nabla^2 A_0 = -R|A_s|^2 A_0, \quad (10)$$

$$\partial_t A_s + \frac{c}{n}\hat{\mathbf{k}}_s \cdot \nabla A_s - \frac{ic}{2nk_s}\nabla^2 A_s = R^* |A_0|^2 A_s, \quad (11)$$

Benchmark: Gaussian beam in 2D and 3D
rerr 10^{-3} vs analytical solution
4th order accurate scheme

Only 3 elements over the Gaussian feature
16x more accurate for dx/2

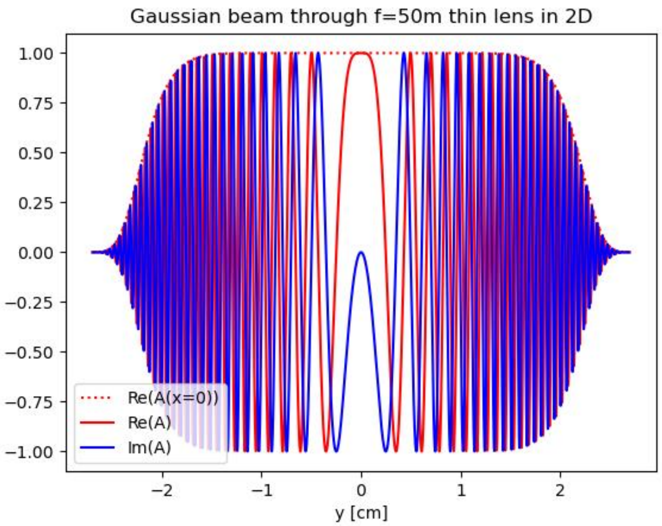


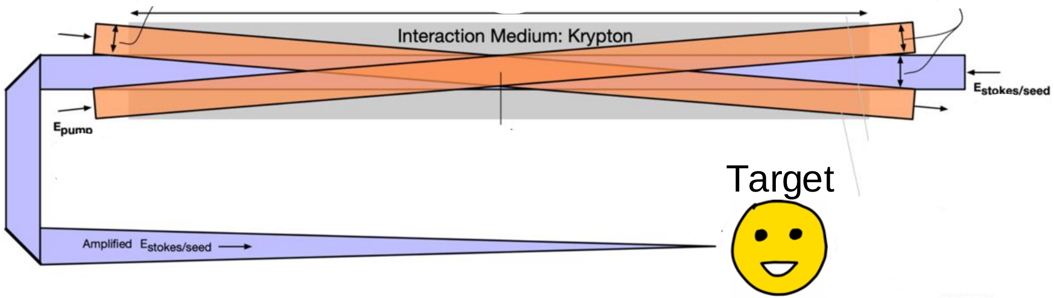


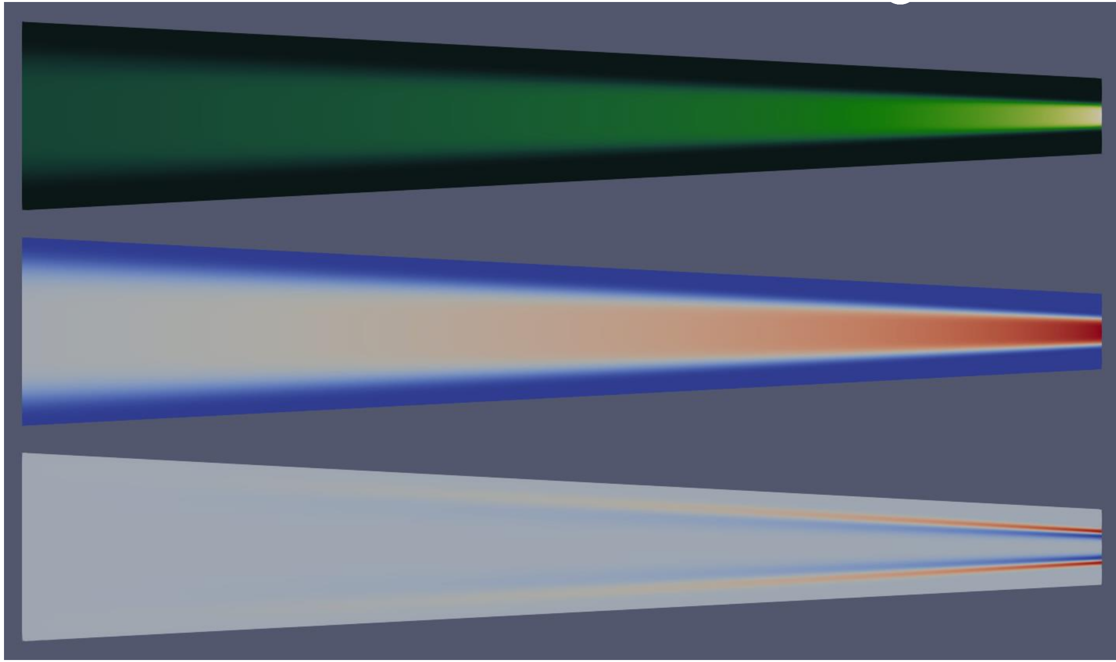
Phase transformations lens/phase-plate

Focusing element

- proof-of-concept of target irradiation
- improved accuracy by wedged mesh
- Serious high-frequency pollution!

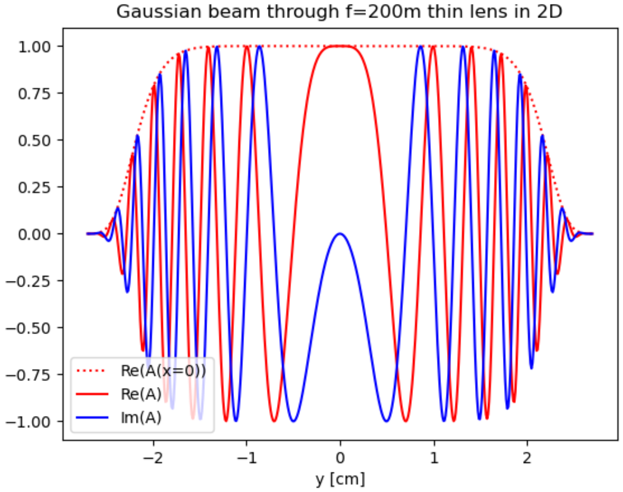






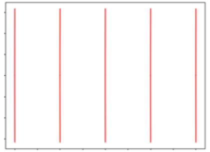
$$u_g(x,y,z,t) = a_0(x,y,z,t)\exp\left(i\left(|\vec{k}|(z+f(x,y,z)) - \omega t\right)\right)$$

Phase transformation
200m lens/phase-plate



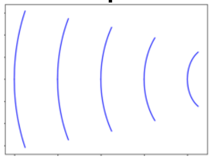
wavelength 2.1e-01 [cm] requires **6.2e+02** DOFs (p=3)

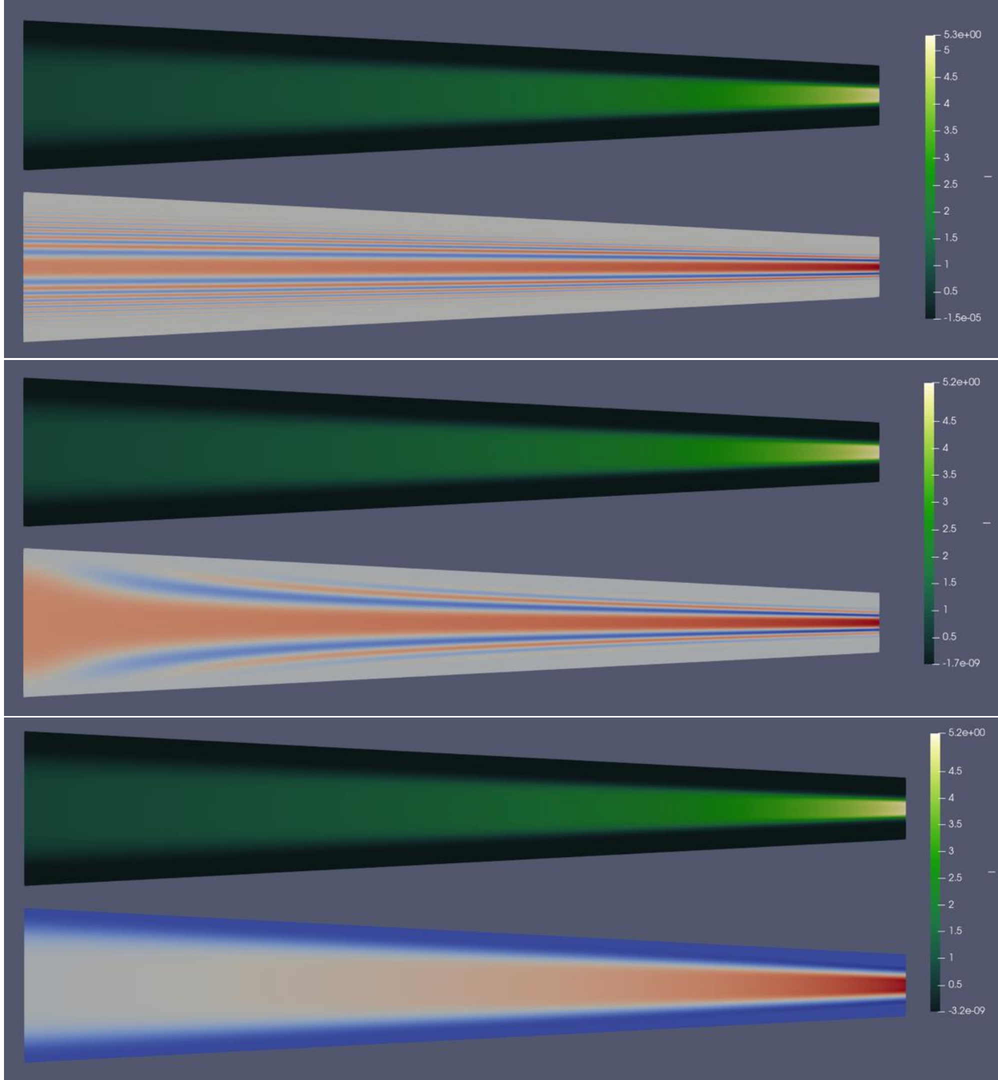
plane phase



incoming phase

exact phase





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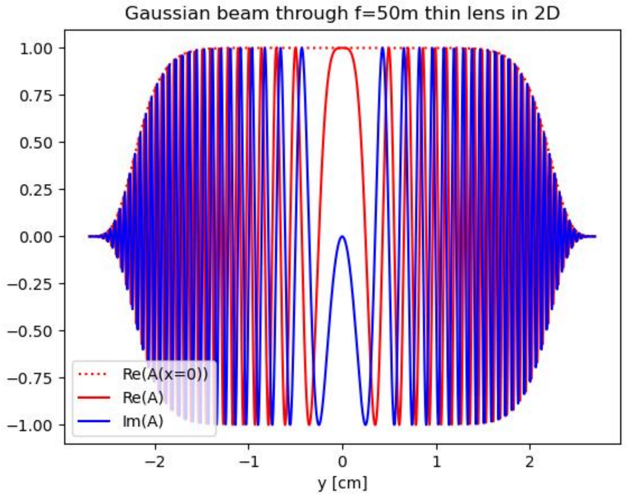
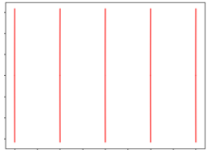
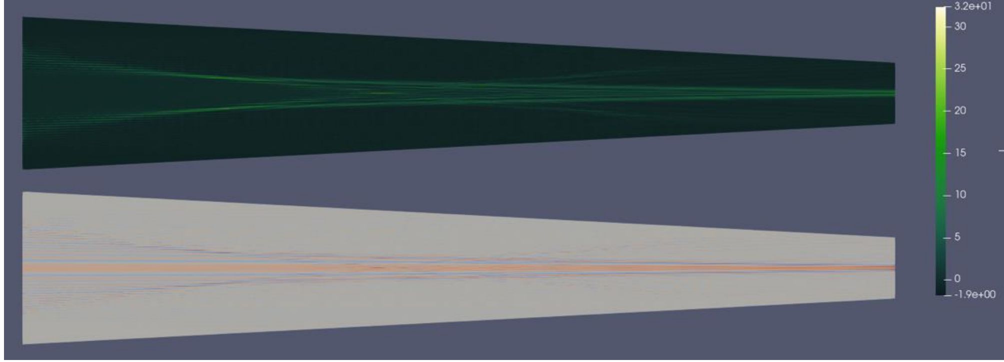
Phase transformation
50m lens/phase-plate



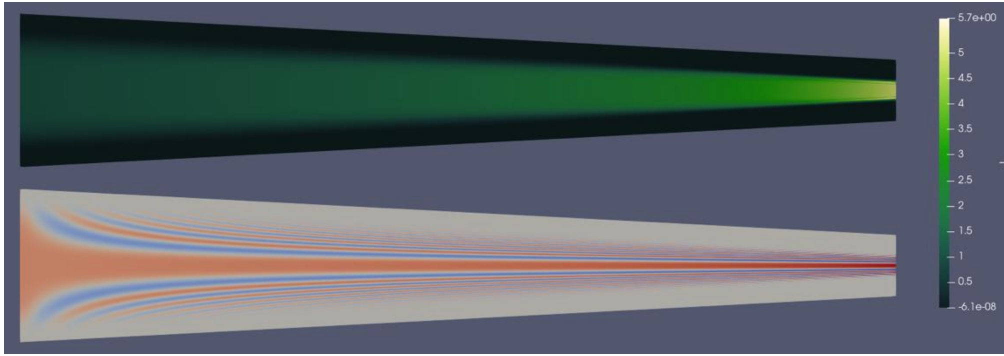
wavelength 5.4e-02 [cm] requires **2.4e+03** DOFs (p=3)

plane phase

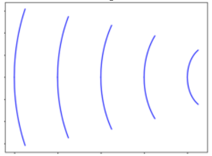


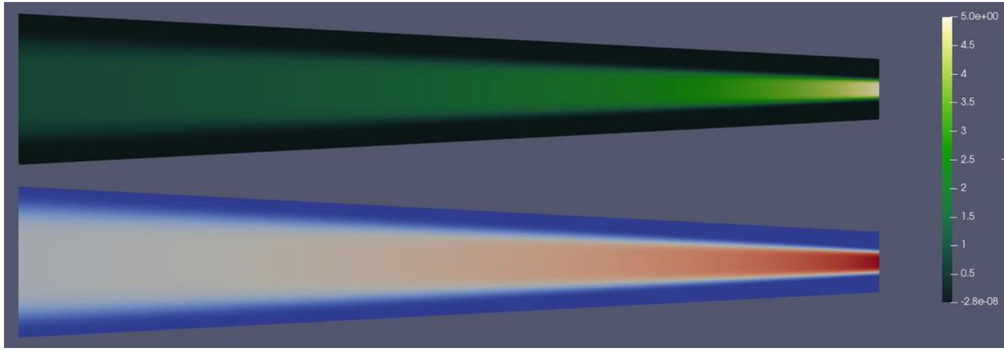


incoming phase



exact phase

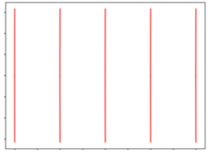


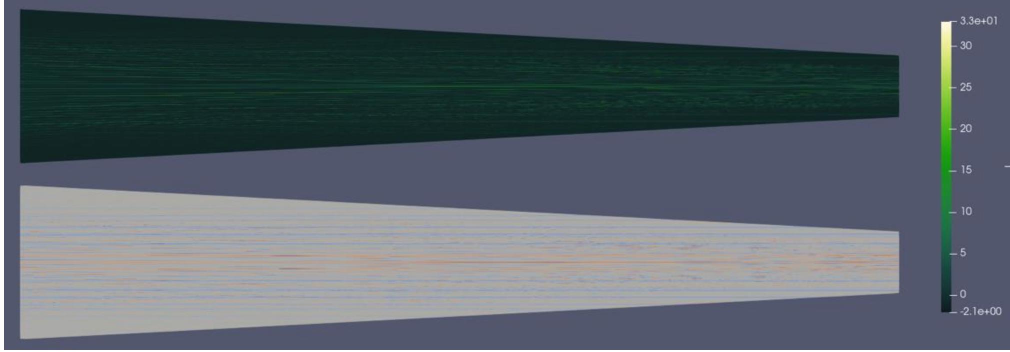


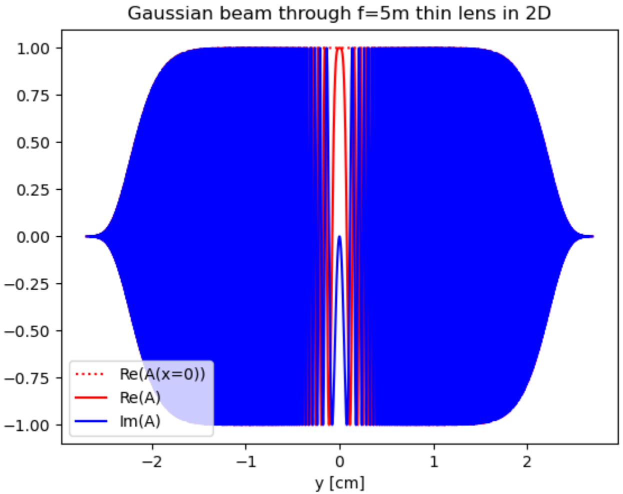
XEC

Phase transformation
5m lens/phase-plate

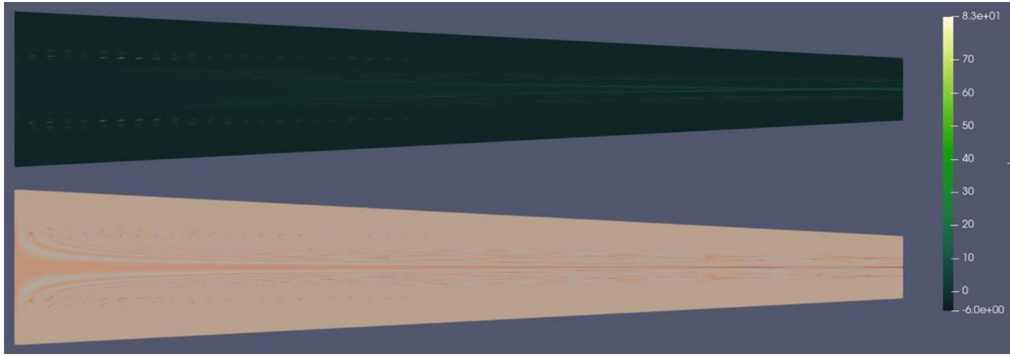
plane phase





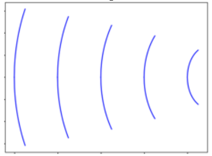


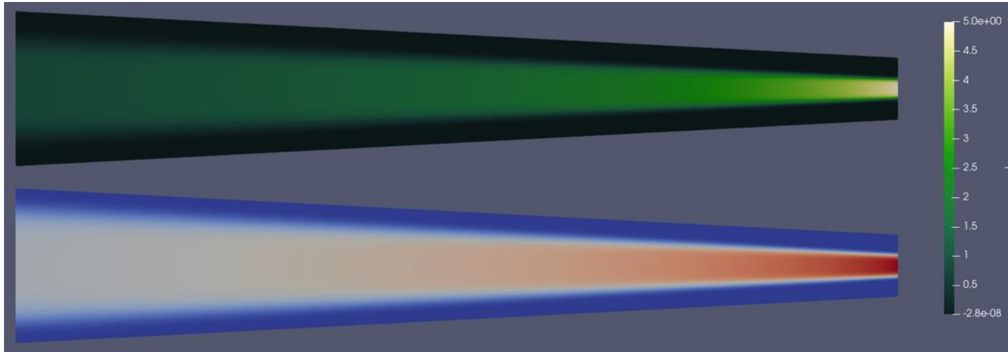
incoming phase



wavelength 5.5e-03 [cm] requires **2.4e+04** DOFs (p=3)

exact phase





Smart transform ~1e6 x less DOFs!

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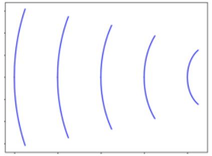
Takeaway:
MFEM + smart coordinate transforms rock!

- Complex high-order DG (p=3), no-upwind, symplectic time



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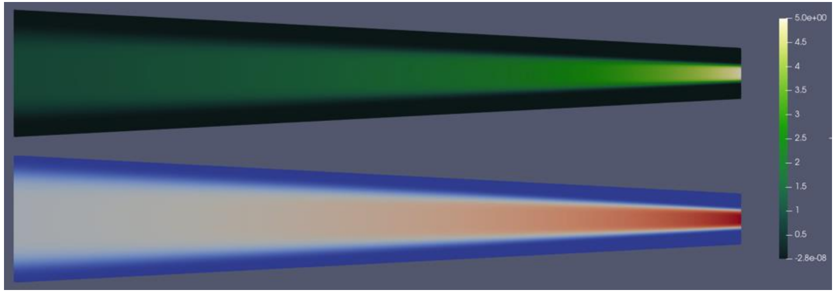
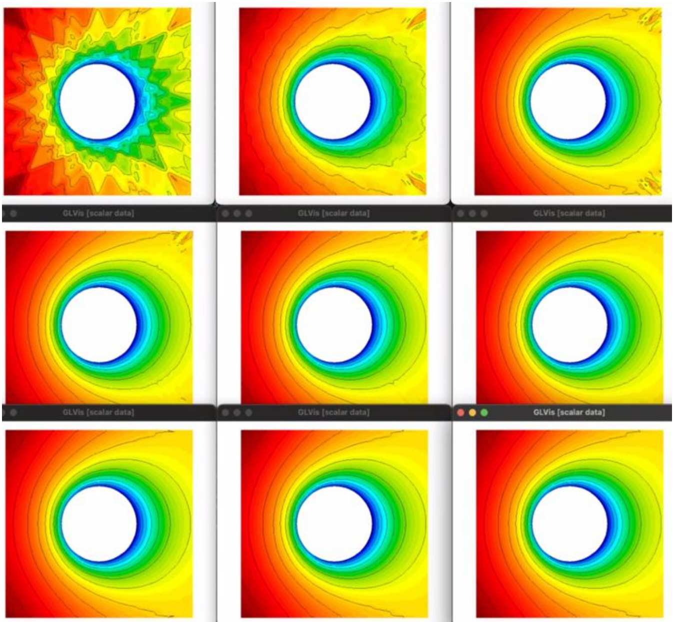


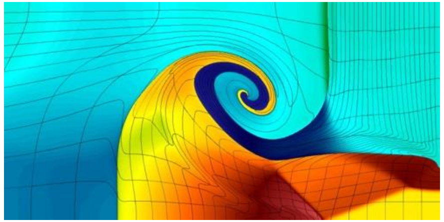
Accurate & robust Boltzmann physics

General-S_N the fastest HPC framework



Efficient IFE design (user friendly direct ALE)

Lagrangian hydro



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Eulerian hydro