Numerical Modeling of Nonlinear Pulse Compression in Gas-Filled Multi-Pass Cells

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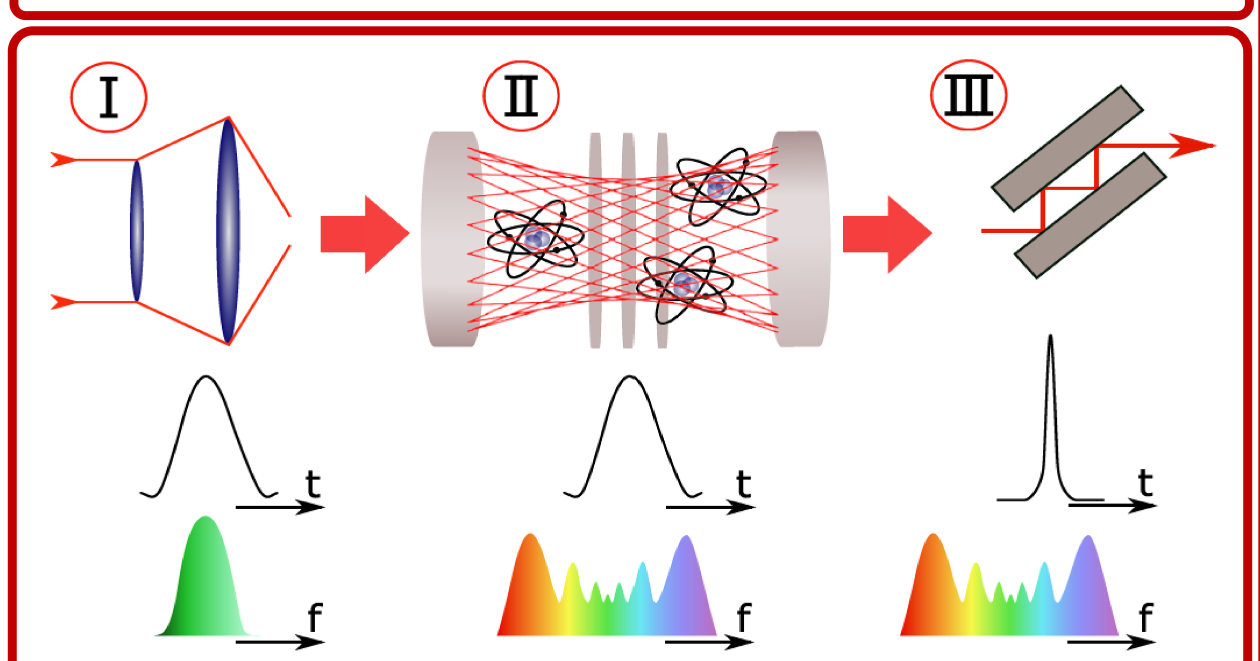
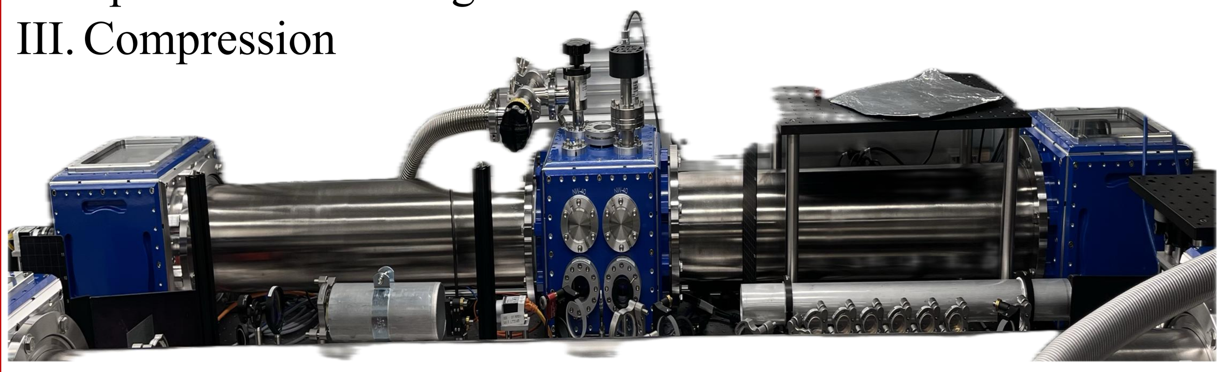
INTRODUCTION

- At LCLS, as well as the upgraded LCLS-II, high-powered lasers are at the forefront of enabling a plethora of cutting-edge science. This gives rise to the need for ultrashort pulses with high peak intensity, which is the actual currency for applications like particle acceleration.
- One way to reach the sub-50-fs regime is by using the approach OPCPA, but this technique requires strict spatiotemporal synchronization, costly crystals, and long interaction lengths of waveguides. A Herriott-type Multi-Pass Cell is increasingly being used to achieve spectral broadening as it fares much better in high average power. Using gas-filled MPCs allows us to achieve large compression factors in pulses in the gigawatt regime with minimum losses and good beam quality.
- The examination of one of the most important aspects of nonlinear compression in MPCs, the spectral broadening, requires the use of numerical simulations, which enables us to understand the compressibility and other nonlinear interaction.

THE HERRIOTT CELL



I. In coupling
II. Spectral Broadening
III. Compression

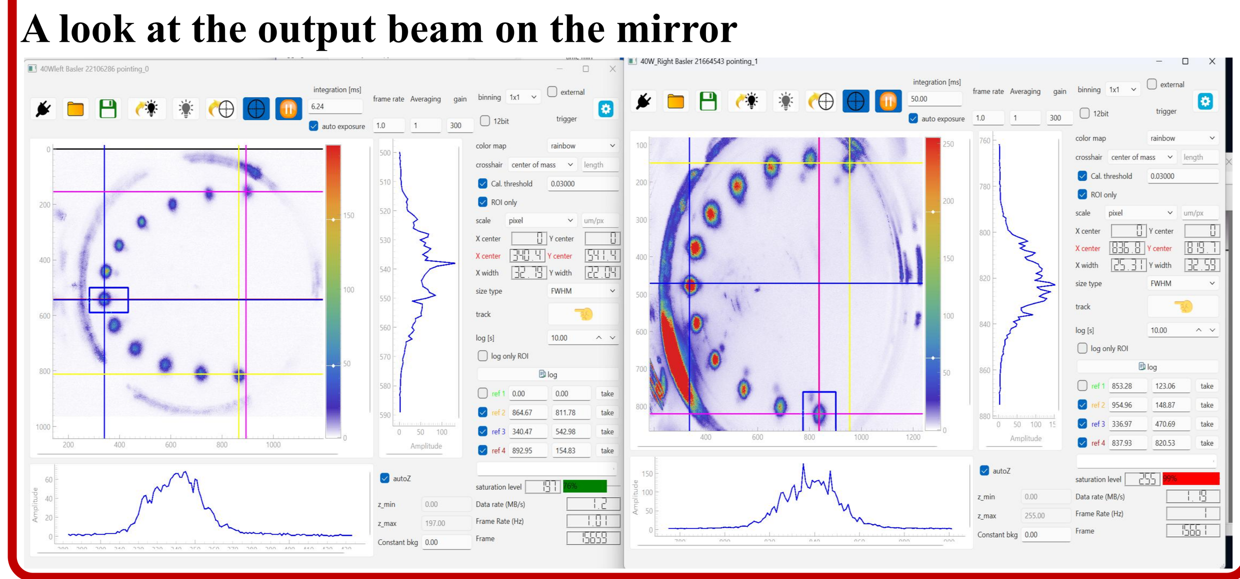


Ray Transfer Matrix

The ABCD Matrix lets us simulate the behavior of the pulse after several passes.
Roundtrip in a two-mirror cavity:

$$M_{\text{round trip}} = \begin{pmatrix}1 & L\\ 0 & 1\end{pmatrix}\begin{pmatrix}1 & 0\\ -\frac{2}{R} & 1\end{pmatrix}\begin{pmatrix}1 & L\\ 0 & 1\end{pmatrix}\begin{pmatrix}1 & 0\\ -\frac{2}{R} & 1\end{pmatrix}$$

A look at the output beam on the mirror



NUMERICAL SIMULATIONS

These are the effects I modeled in my simulation:

Self Phase Modulation

An intense laser pulse propagating through a nonlinear medium experiences a phase shift due to the optical Kerr effect. Consequently, the spectrum broadens and allows us to compress the pulse duration temporally.

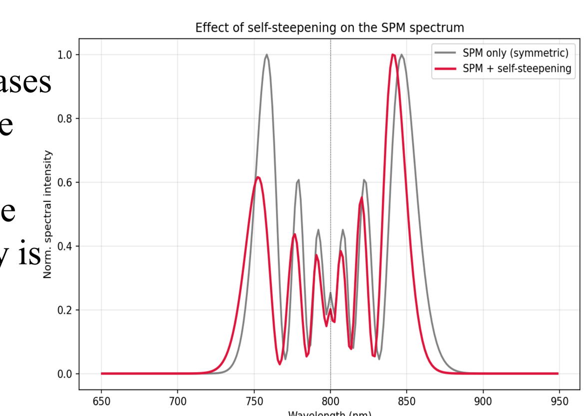
$$\phi_{NL}(t) = \gamma P(t) z$$

$$B_{\text{round trip}} = \pi\left(\frac{P_{\text{peak}}}{P_{\text{crit}}}\right)\arctan\left(\sqrt{\frac{L}{2R-L}}\right)$$

Self Steepening

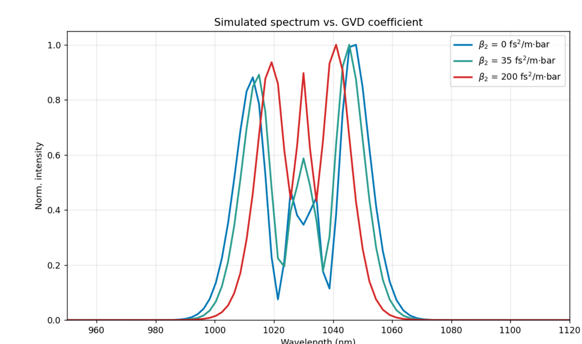
In noble gas, where the refractive index increases because of the nonlinearity, the intensity of the trailing edge of the pulse steepens until its intensity falls rapidly and the front of the pulse travels faster than the back where the intensity is higher.

$$A(z+dz) = A(z)\exp\left[i(\phi_{\text{SPM}} + \phi_{\text{ion}})\right] + \Gamma\,\tau_{\text{shock}}\frac{\partial}{\partial t}(|A|^2 A)dz$$



Dispersion

GVD can cause the pulse to spread out in time but its usually negligible in MPCs. Some levels of dispersion might change the shape of the pulse.



Ionization

During laser pulse propagation, extremely high peak energy causes the gas to ionize, emit free electrons and produce plasma which causes rapid beam degradation. It's very important for us to identify and operate below this threshold.

Ionization is being modeled using the ADK and the PPT theory.

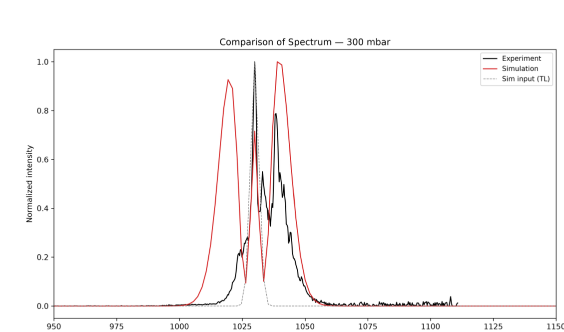
What if we changed the pressure?

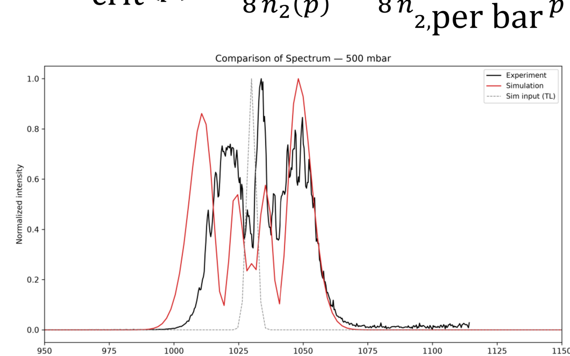
Pressure is correlated with nonlinearity as demonstrated by the equation,

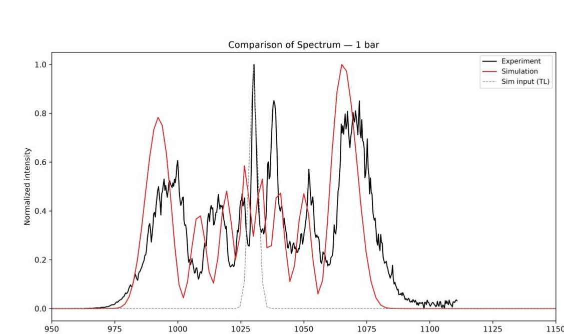
$$n_2(p) = n_{2,\text{per bar}} \times p$$

Which is then used to calculate the critical pressure:

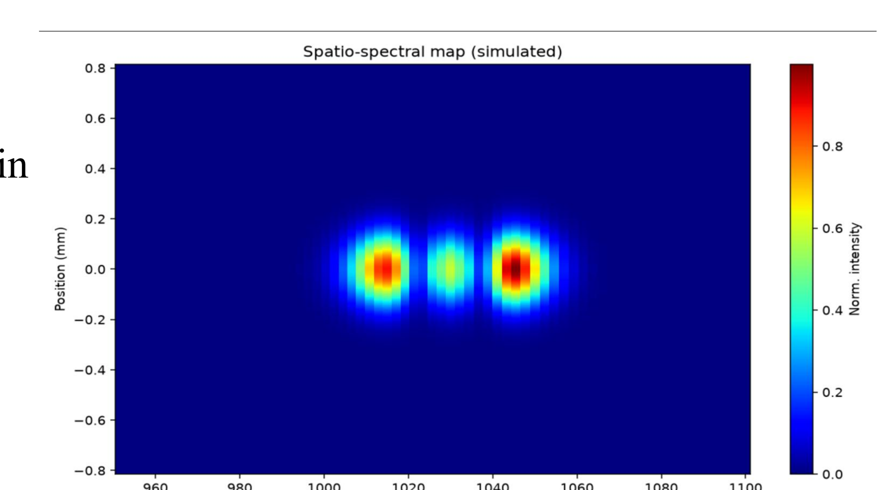
$$P_{\text{crit}}(p) = \frac{\lambda^2}{8\,n_2(p)} = \frac{\lambda^2}{8\,n_{2,\text{per bar}}\,p}$$







The modeled 2+1-dimensional graph shows us the change in intensity across the spatial domain.

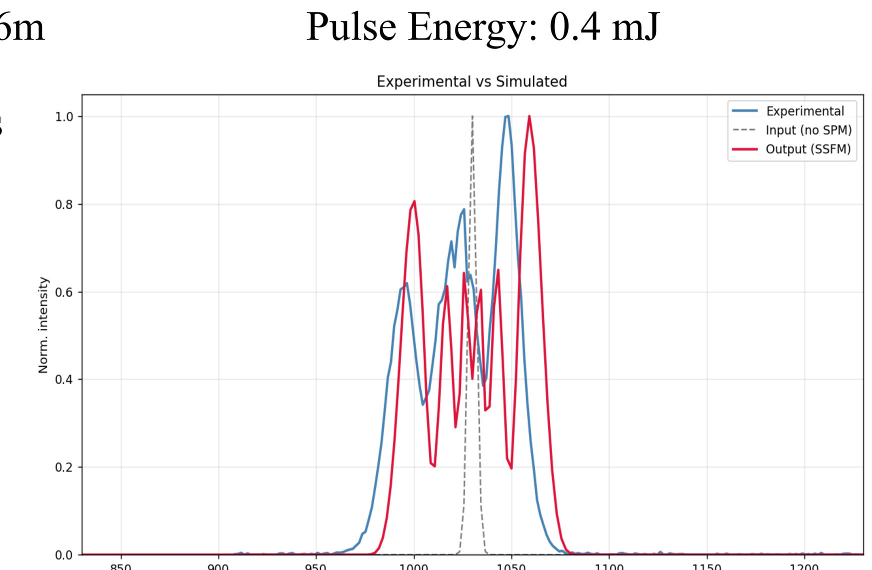


Let's Compare!

Gas: Krypton
Pressure: 1 bar
N_Passes: 25
Cavity Length: 0.996m

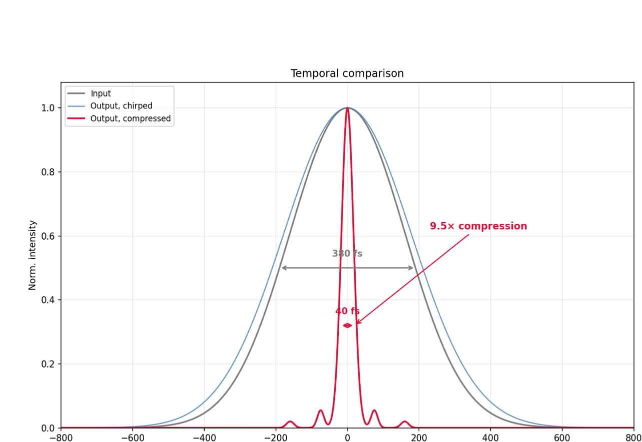
Pulse duration: 270 fs
Beam Waist Diameter: 203μm.
Wavelength: 1030nm
Pulse Energy: 0.4 mJ

The simulated results closely predict the nature of real-life spectra!



Now its time to compress!

The MPC broadens the spectrum but also stretches the pulse in time by adding chirp; an ideal compressor then collapses that broadened spectrum to shorter duration.



ALGORITHM

Split Step Fourier Method

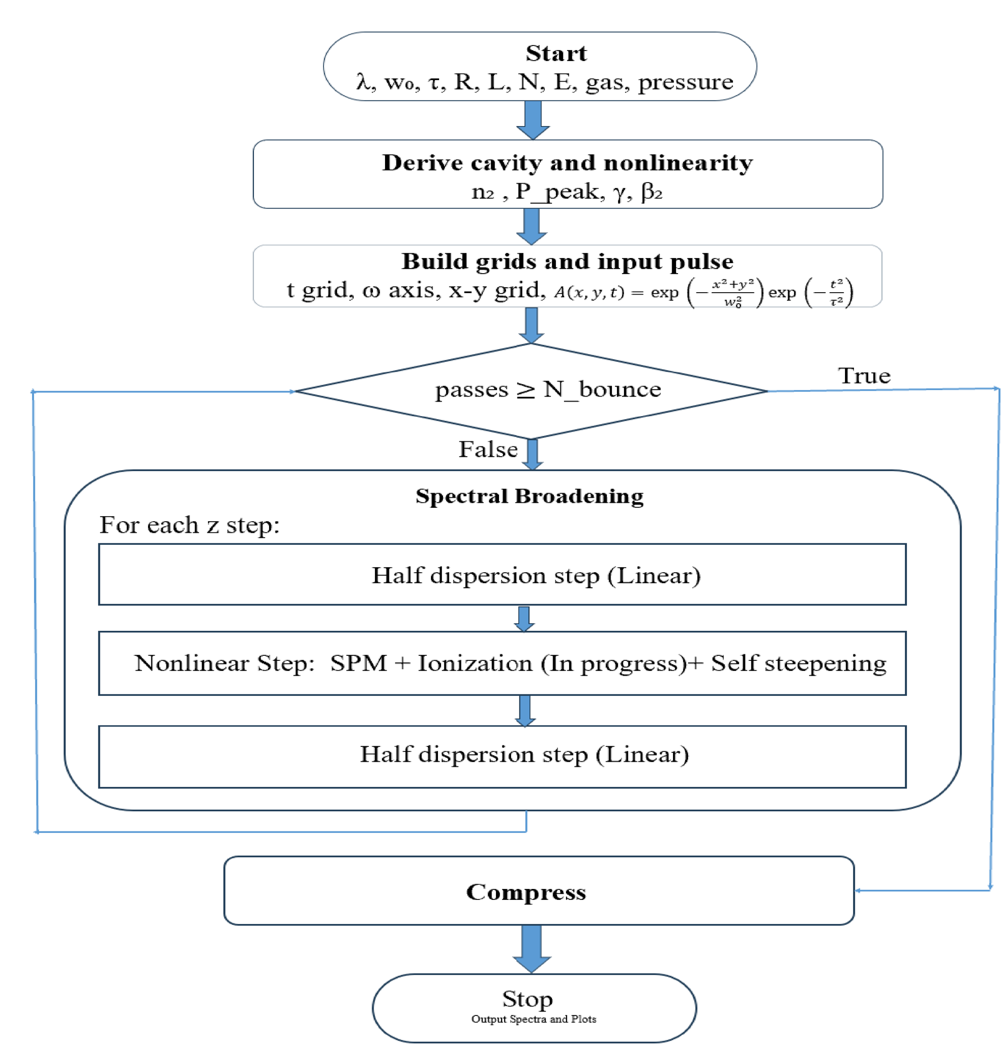
We use symmetric SSFM for the model as it allows for us to account for linear affects (dispersion, diffraction) in the frequency domain, while the Kerr effect is modeled in the space-time domain.

Linear complex envelope:

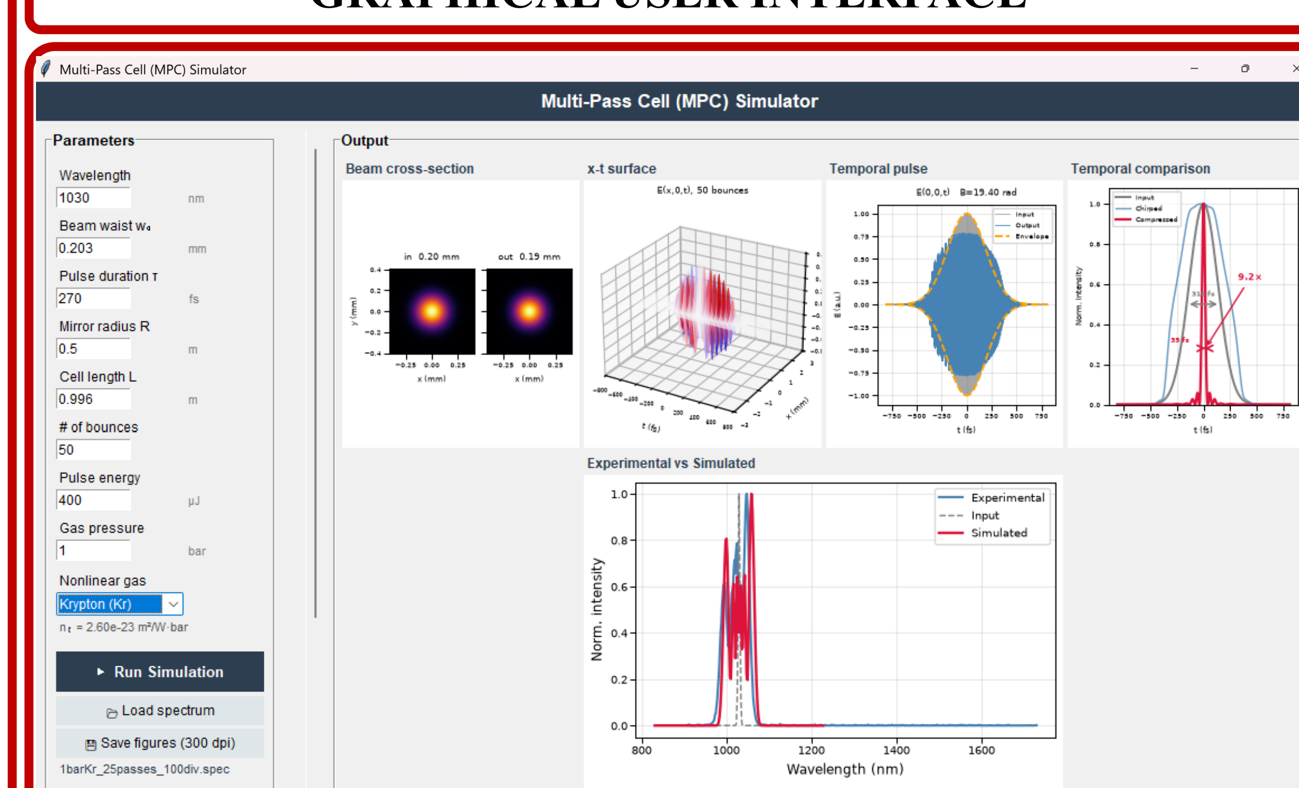
$$E(\omega, f_x, f_y, z+dz)$$
$$= E(\omega, f_x, f_y, z) \times \exp\left(ik(\omega)\sqrt{1-\frac{4\pi^2}{k(\omega)^2}(f_x^2+f_y^2)}\;dz\right)$$

Nonlinear Part:

$$E(t,x,y,z+dz) = E(t,x,y,z)\exp\left(ik_0 n_2 I(t,x,y,z)\,dz\right)$$



GRAPHICAL USER INTERFACE



CONCLUSION

As we wait for the coveted LCLS-II HE upgrade, it's essential for us to employ innovative physics and engineering for post-compression, aka "some of the shortest event mankind could ever generate." Multi-pass cells are a compact, cost-effective add-on to high-power industrial lasers. And for precise engineering of these cells, we need reliable simulations. The validated simulator provides a physically grounded design tool for gas-filled MPC compressors, correctly predicting achievable spectral broadening and enabling prediction of optimal parameters (gas pressure, number of passes, gas type) for target compression ratios.

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References

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