SCALLOPS :
Simulation of Crystal Amplification of Laser Light and Optical Pulse Shaping

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Introduction

At the Matter in Extreme Conditions (MEC) instrument, scientists use high-power optical lasers to create exotic states of matter and use LCLS's x-ray to study their structure. For this reason, optical lasers lie at the center of the experiments at MEC.

In this project, we develop software to simulate the evolution of laser pulses in the amplifiers of MEC's current facilities – the short-pulse and long-pulse laser – as well as its future projects, including the petawatt upgrade and laser CARP. SCALLOPS helps scientists to predict spectral and temporal profiles of the amplified laser pulse as well as to select input to have proper output.

Keywords: simulation, laser amplifier, gain reshaping

Theory

Our software accounts for the following ideas related to the amplification of laser pulses:

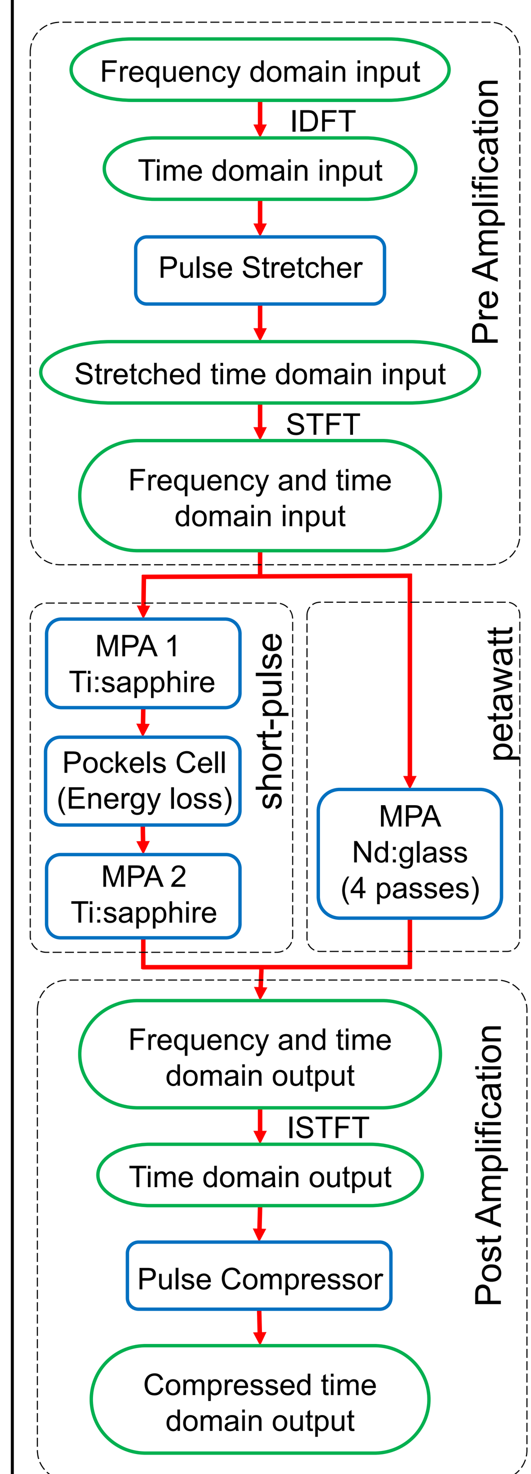
1. **Pump energy distribution in amplifying crystal:** Simulate with uniform distribution for transverse pumping and Beer-Lambert law for longitudinal pumping.
2. **Gain saturation:** Calculate amplified output energy given by Frantz-Nodvik equation to account for gain saturation:

$$J_{out} = J_{sat} \ln\left[1 + g_0\left(e^{J_{in}/J_{sat}} - 1\right)\right]$$

3. **Gain reshaping:** Later parts of the laser pulse experience less gain since earlier parts already remove some energy stored in the crystal. As a result, the pulse shape in time and frequency may change.
4. **Gain narrowing:** Different wavelengths experience different gain in the crystal. The output could have a narrower spectrum and result in a longer pulse duration compared to the input pulse.

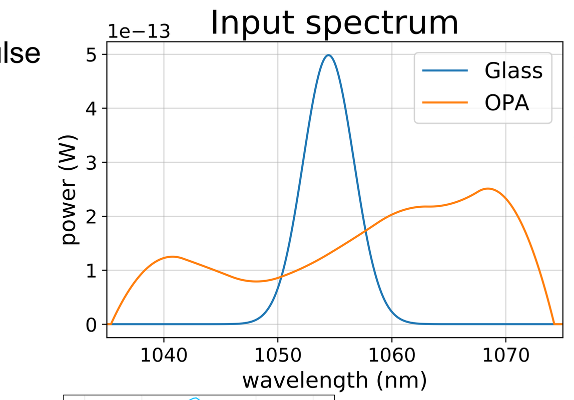
Short Pulse Laser and Petawatt Laser

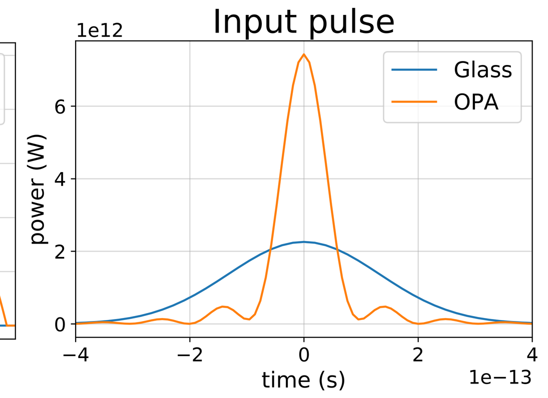
To achieve a very short pulse duration, a short-pulse laser needs a broad spectral bandwidth. To precisely simulate a multi-wavelength laser, SCALLOPS utilizes a Short Time Fourier Transform (STFT) to find changes in the pulse spectrum through time. This allows us to simulate changes in the pulse shape and pulse duration as a result of gain reshaping and narrowing. We benchmarked our code by simulating performance of MEC's Ti:sapphire short-pulse laser and comparing to measurements.



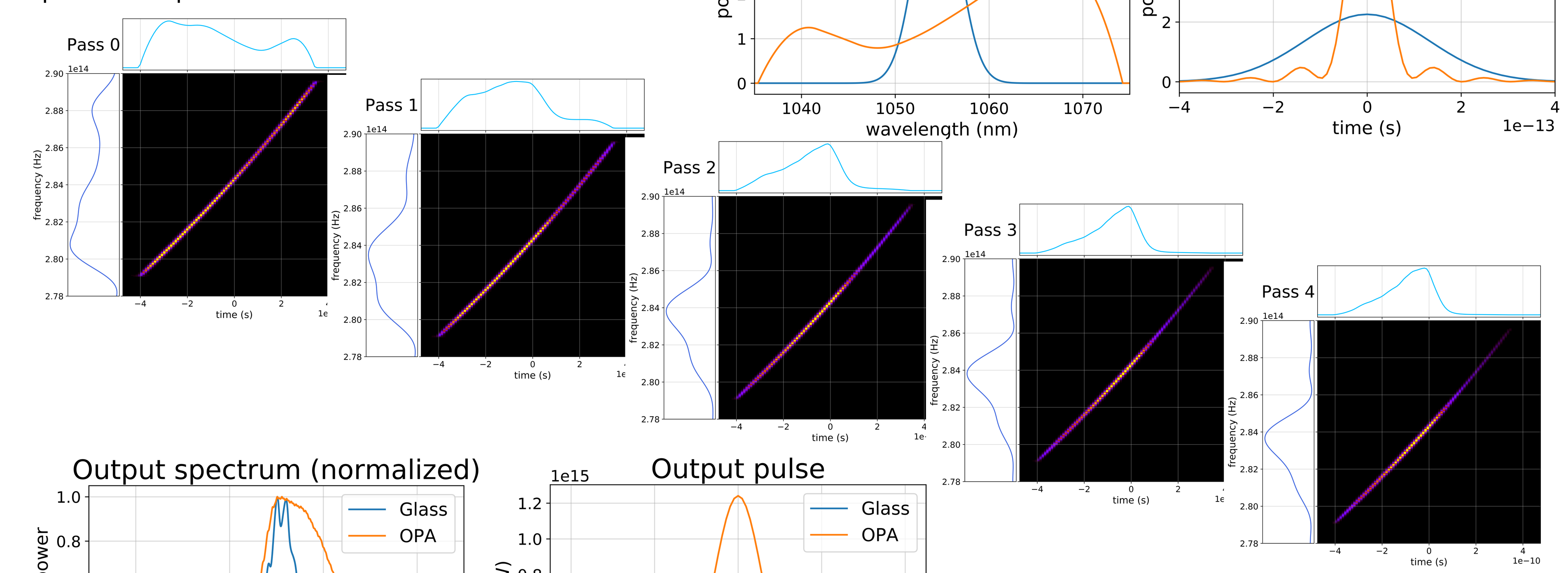
Furthermore, we run simulations for the proposed petawatt laser upgrade for MEC. Unlike the current short-pulse laser, the petawatt laser uses Nd:glass as a lasing medium, which has a narrower gain bandwidth; thus, gain narrowing will have a greater effect on laser amplification. Here, we run a simplified simulation of the petawatt amplifier to compare the effects of seeding with a glass- and OPA-based front end. Because of gain narrowing, seed pulses from a glass front end will have a narrower spectrum compared to a carefully-adjusted OPA. This will be crucial to achieve >1 PW peak power.

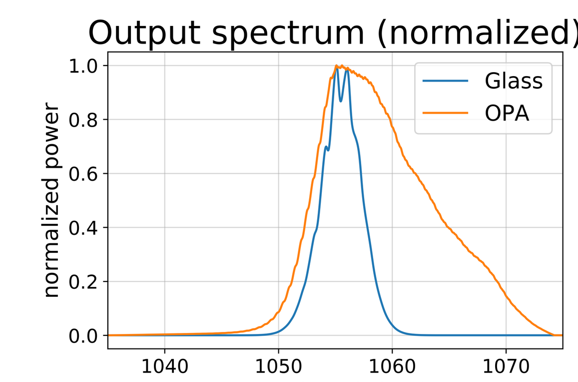
► Input spectrum and transform-limited pulse duration for both input pulses.

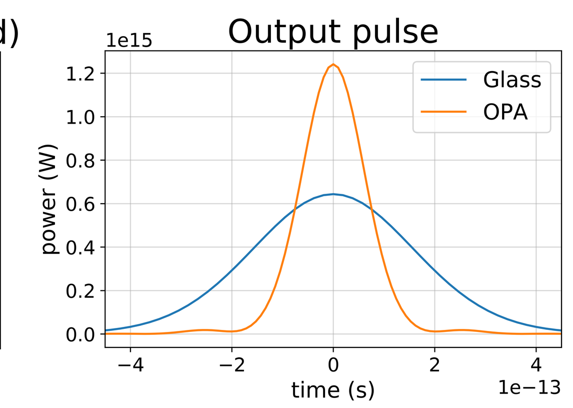




▼ STFT spectrograms show spectro-temporal evolution of the OPA laser pulse as it pass through the petawatt amplifier four times.







◄ Output spectrum (normalized) and output pulse when seeding with either front end. Transform-limited pulse durations are ~380 fs and ~150 fs for seeding with the glass- and OPA-based front end systems, respectively.

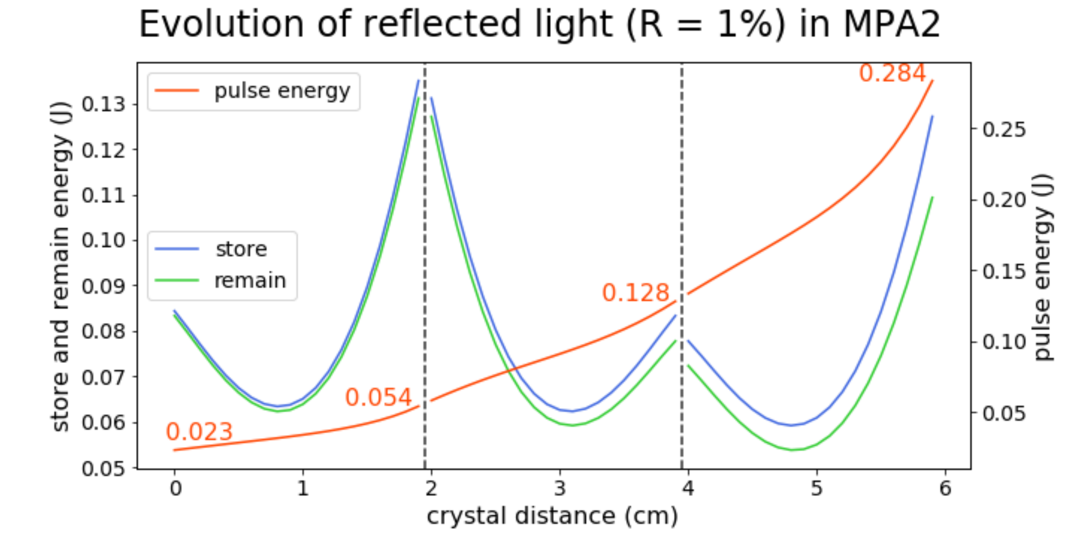
The output seeded by the glass front end will have higher energy since the input spectrum is centered around the peak of the gain spectrum of the lasing medium. However, because the glass front end has a much narrower spectrum, the output pulse duration seeding with the glass front end is longer because of gain narrowing. As a result, only the output seeded with the carefully-adjusted OPA front end can reach a peak power of > 1 PW.

Laser CARP

Laser CARP (Collector of At-Risk Photons) is a novel project to further prevent damage in the short-pulse laser system due to reflected light from the target. By using another laser "CARP" to remove the energy left inside the crystal after the amplification process, the back-reflected light will experience much less gain and be less likely to damage optical instruments.

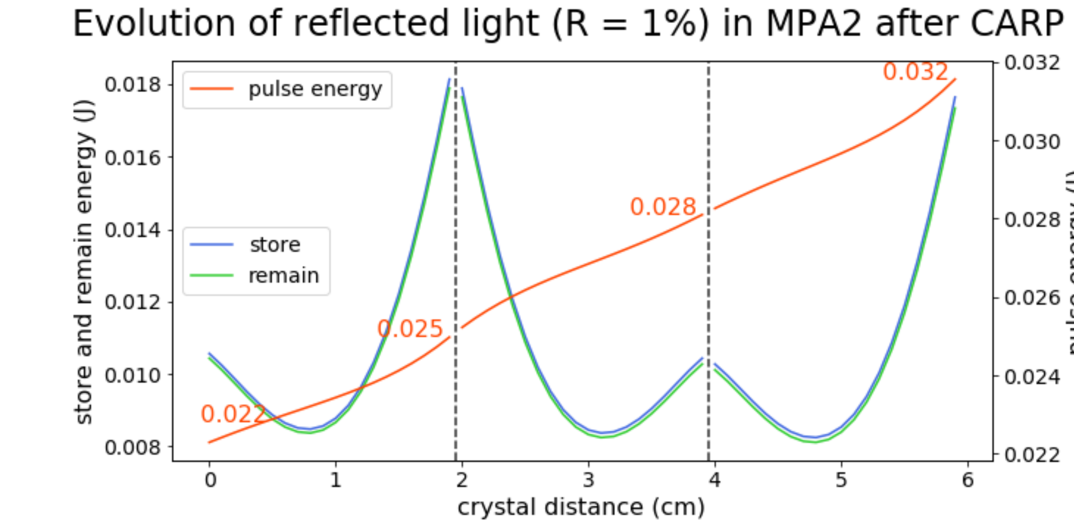
First, we suppose that 1% of the amplified light is reflected back to the amplifier. Without CARP, this reflected light gets amplified with a gain of ~ 13. With this much energy, the re-amplified reflected light could potentially damage the internal optical components.

Evolution of reflected light (R = 1%) in MPA2

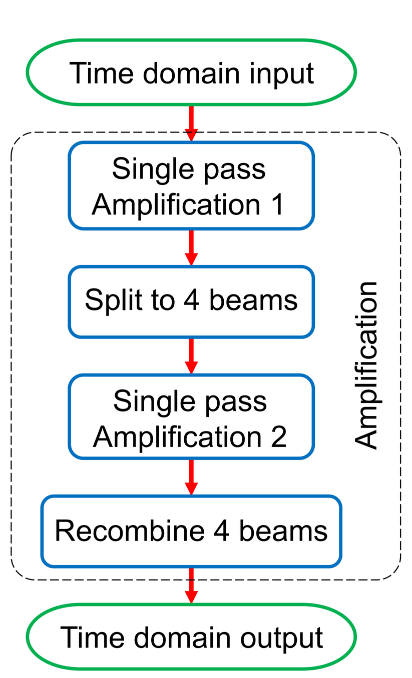


Now, we plan to use an OPO laser with energy ~ 100 mJ and pulse duration ~ 6 ns as a laser CARP. SCALLOPS shows that after 5 passes of CARP, gain in the amplifier could be lowered to < 1.5. This process takes ~ 50 ns – fast enough to finish before the reflected light returns.

Evolution of reflected light (R = 1%) in MPA2 after CARP

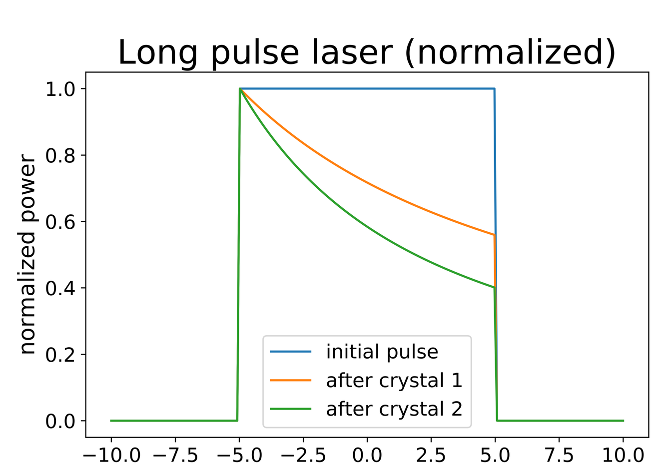


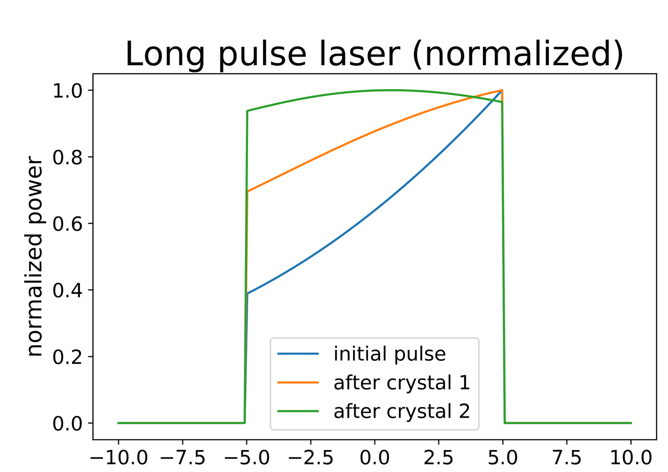
Long Pulse Laser



In the long-pulse laser system, MEC uses a temporal pulse shaper to create different pulse shapes required by different users' experimental setups. SCALLOPS helps choose the seed waveform needed to achieve a desired pulse for launching a shockwave.

Here, we run simulations to demonstrate the effect of gain shifting. If we seed with a square pulse, the output pulse will not remain a square pulse. Thus, we need to properly adjust the seed waveform to get a square output pulse.





Conclusion

We have demonstrated that SCALLOPS can simulate laser amplification for monochromatic lasers – like a long-pulse laser – as well as for broad-bandwidth lasers – like a short-pulse laser. Moreover, SCALLOPS helps verify the possibility for laser CARP as well as simulate preliminary calculations for the petawatt laser system.

SCALLOPS could be further improved in several ways. One interesting improvement is to simulate nonlinear crystals used for harmonics generation which could further change the pulse's waveform. These crystals are used in various laser amplification facilities, including at MEC.

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