SLAC NATIONAL ACCELERATOR LABORATORY

Optimized Fourier Filter for Improved Laser Amplification Simulation

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Introduction

Overview:
At the Matter in Extreme Conditions Lab (MEC), high power optical lasers, such as the long pulse laser (LPL), are used to create exotic states of matter. LCLS's x-ray laser is used in tandem with the in-house LPL to study this matter's structure.

Long Pulse Laser:
Using a multi-staged laser amplification process, the LPL emits temporally shaped waveforms with a power upwards of 5 Gigawatts. The output of the front-end (10Hz) of the LPL is adjusted in order to account for gain saturation in the back-end.

Motivation:
As part of an ongoing effort to better understand and simulate results from the LPL, a deep-dive into convolution issues was required.

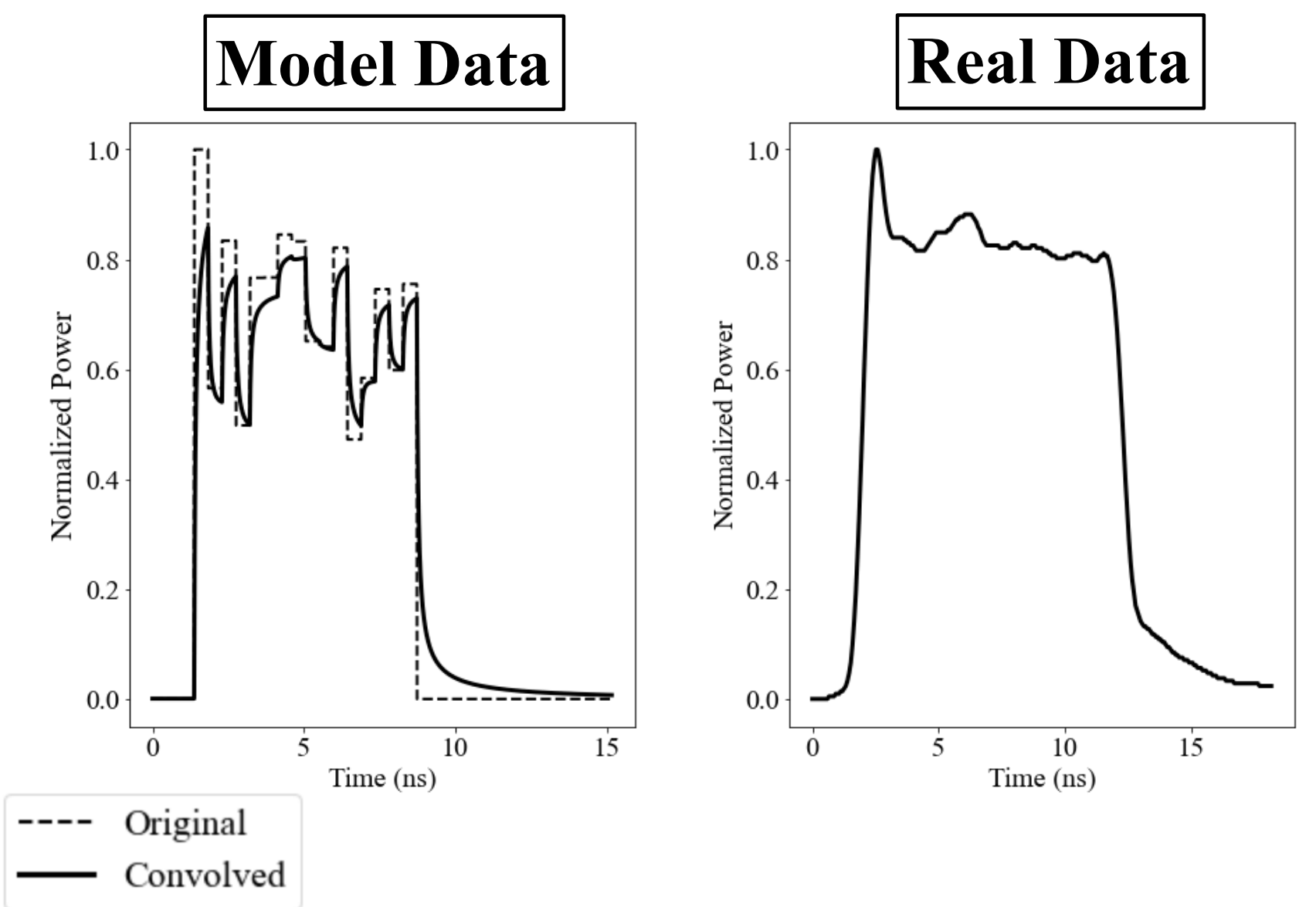
Linear Time-Invariant Systems

LTI Systems:
An LTI system can be entirely characterized by a function called the system's "impulse response." Its properties are described by this equation:

$$y(t) = (h*x)(t) \overset{\text{def}}{=} \int_{-\infty}^{\infty} h(t-\tau)x(\tau)\,\mathrm{d}\tau \overset{\text{def}}{=} \mathcal{L}^{-1}\{H(s)X(s)\}.$$

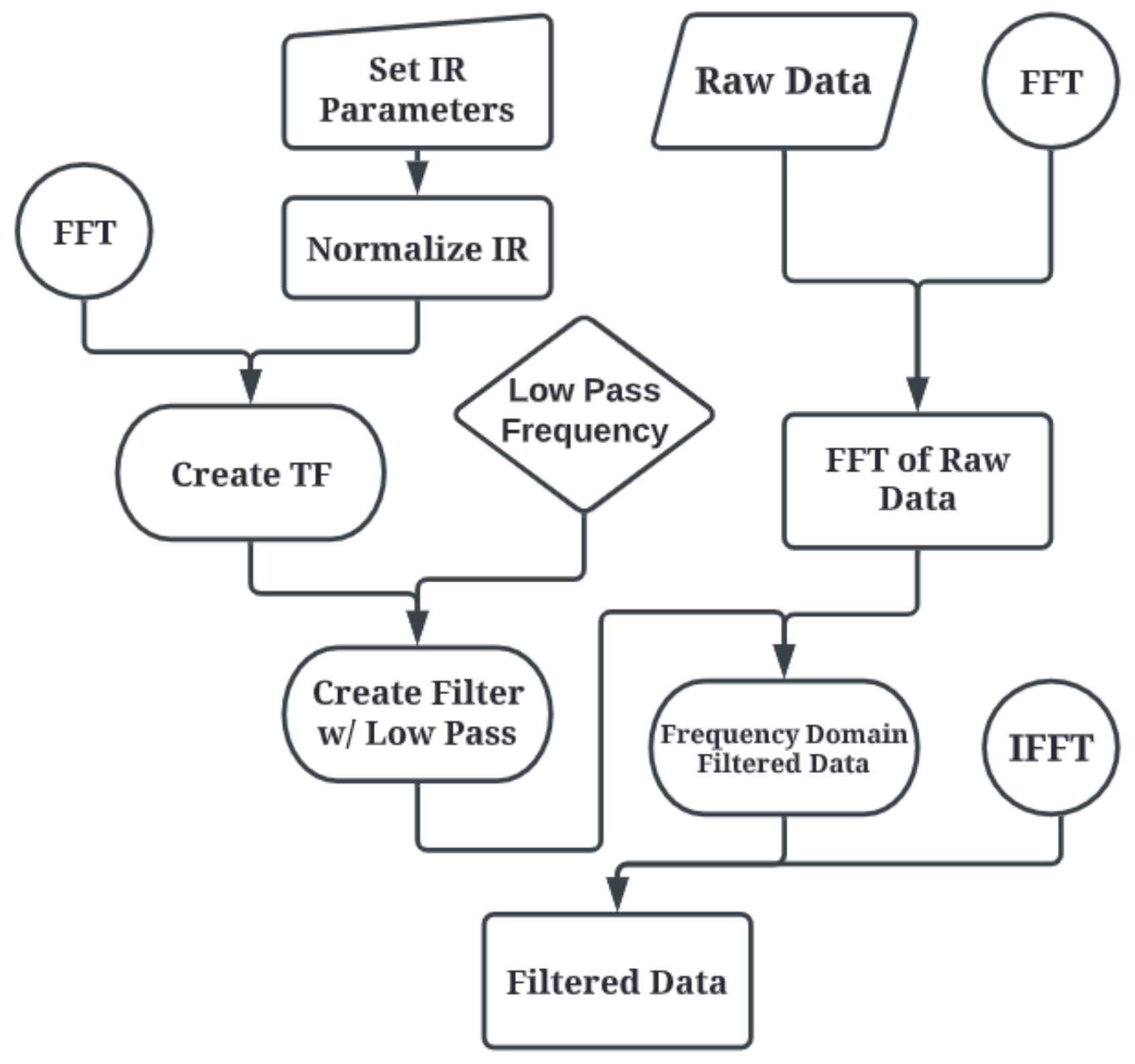
Where '*' is the convolution operator, y(t) is the measured signal, x(t), X(s) is the original signal, and h(t), H(s) is the impulse response in their respective domains.

Convolution of LPL Measurements:



The long tail at the end of the measured waveform is a trait of a convolved impulse response. As shown in the model data, this convolution leads to measurement that undershoots the front-edge of the original signal.

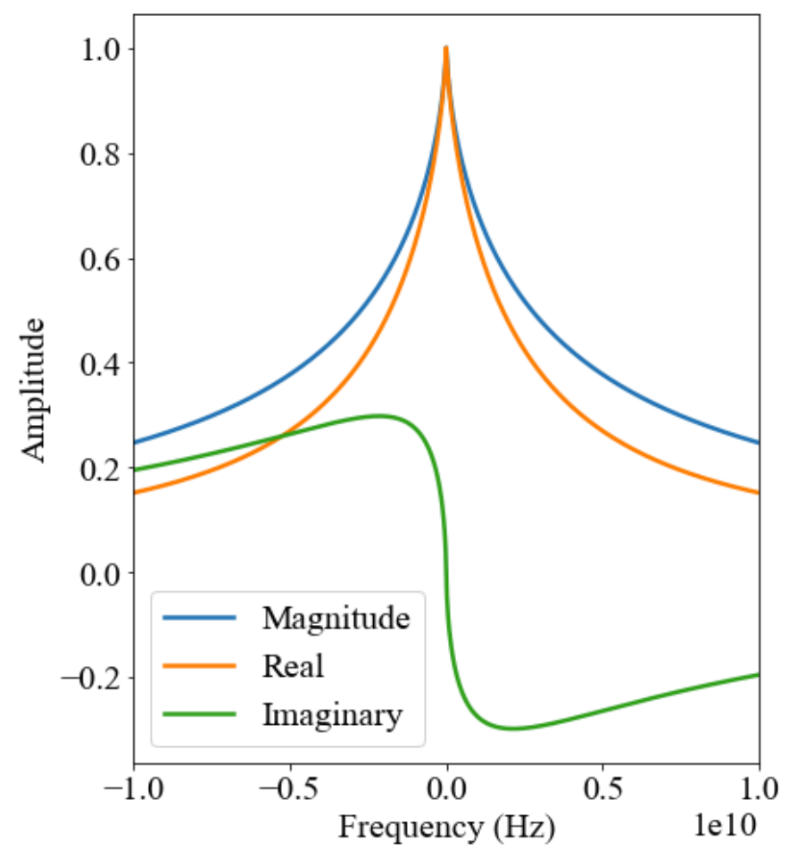
Filtering Algorithm

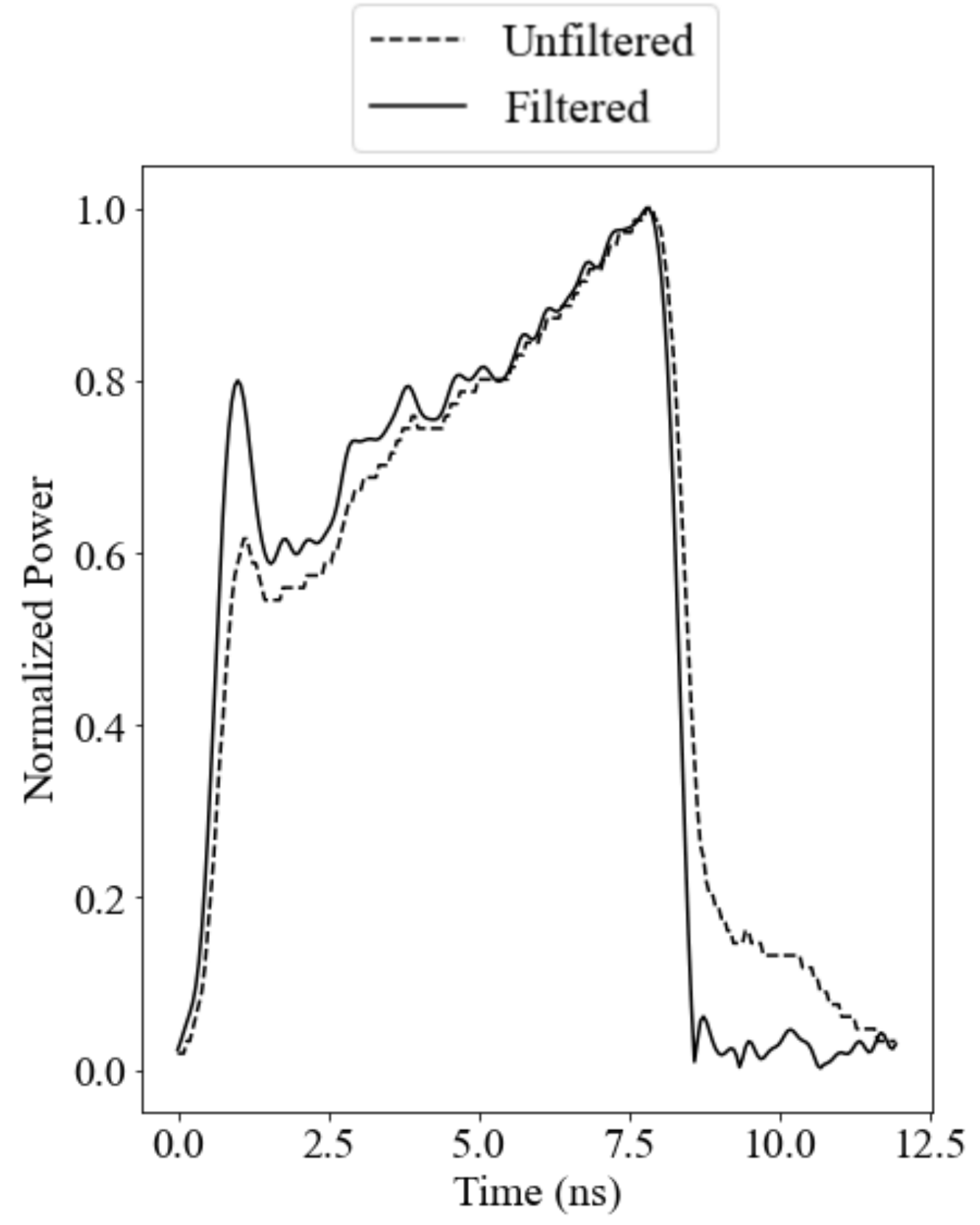


Optimized Function For Impulse Response Fit

$$\mathrm{h(t)} = \mathrm{N}((\alpha(\beta t+\delta)^{-\gamma})$$

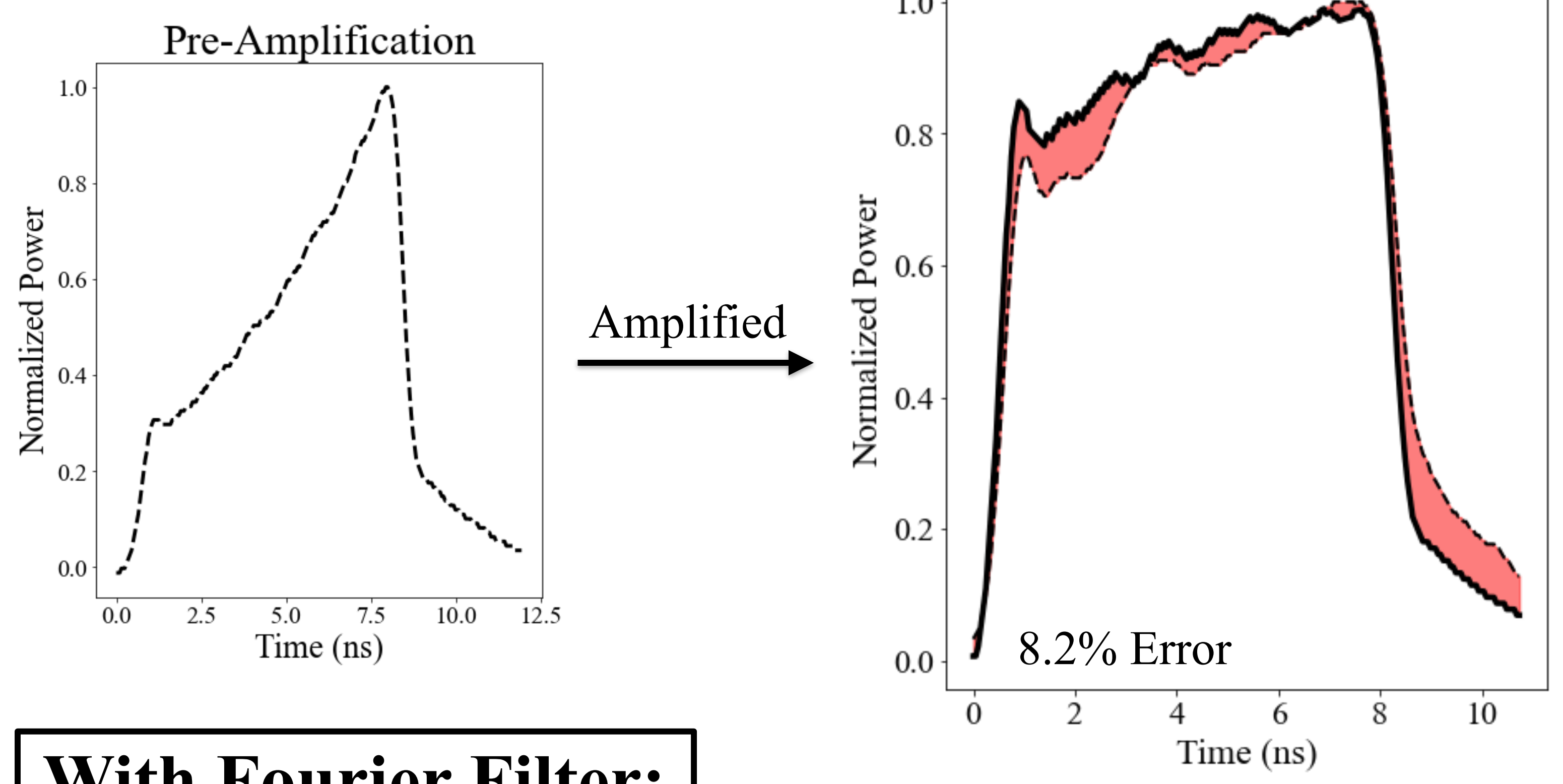
Transfer Function



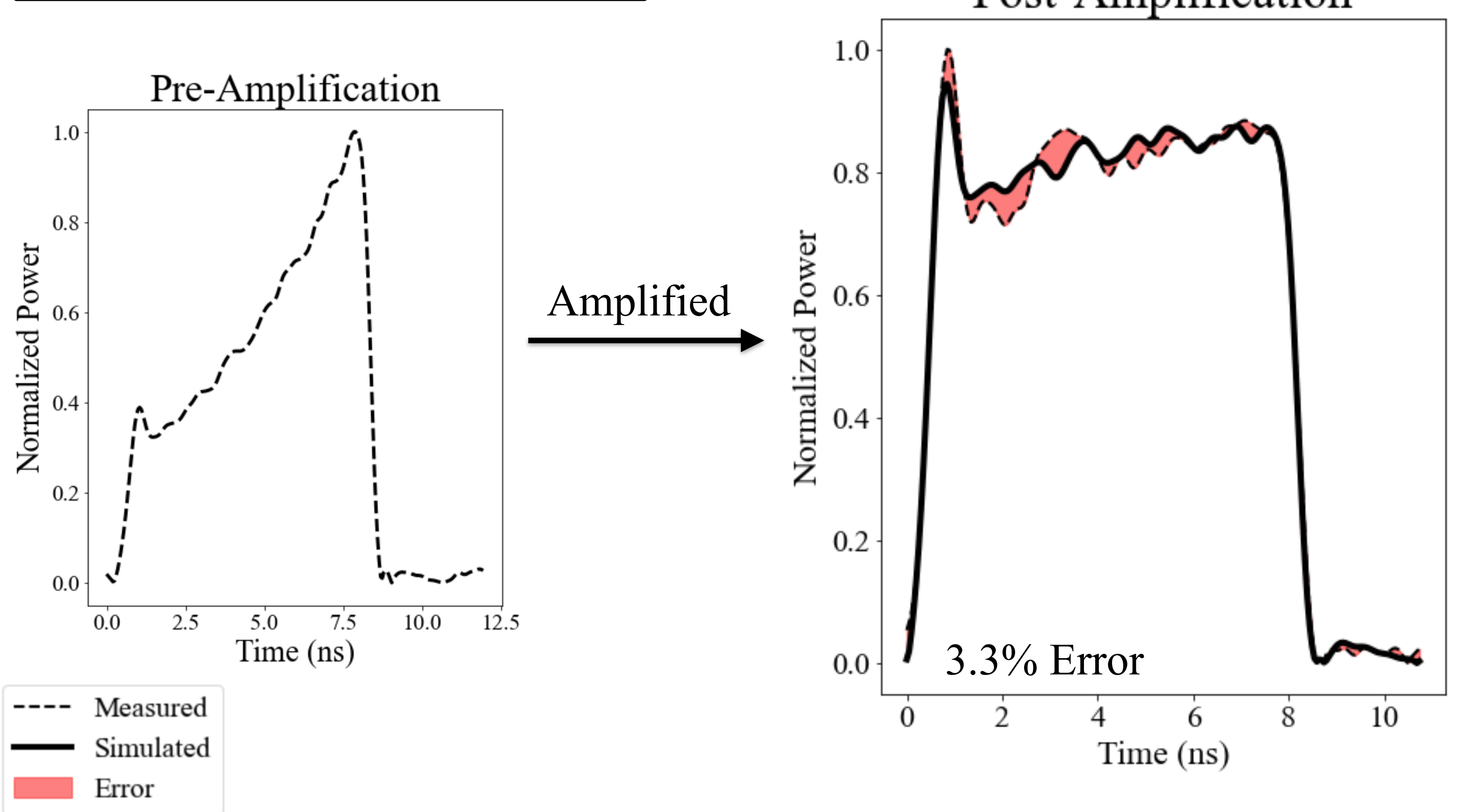


Comparing Simulations

Without Fourier Filter:



With Fourier Filter:



Purpose of Simulation:
To determine whether or not the filter is reconstructing waveforms that match the physics of laser amplification (based on the Frantz-Nodvik Equation) more accurately than the unfiltered data.

Details of Simulation:
Simulates the back-end of LPL with real data (filtered and unfiltered) as input. Back-end consists of 1 single-pass 25mm Nd:Glass amplifier, and 1 single-pass 50mm Nd:Glass amplifier. Simulation is then compared with measured results in "filtered space" and "unfiltered space."

Parameters:
- Initial Pulse Energy: 110 mJ
- 25mm Fluence Saturation: 50,000 J/m^2
- 25mm Pump Energy: 44 J
- 25mm Crystal Area: .2 mm^2
- 25mm Crystal Length: 40cm
- 50mm Fluence Saturation: 50,000 J/m^2
- 50mm Pump Energy: 130 J
- 50mm Crystal Area: .8 mm^2
- 50mm Crystal Length: 1.5cm

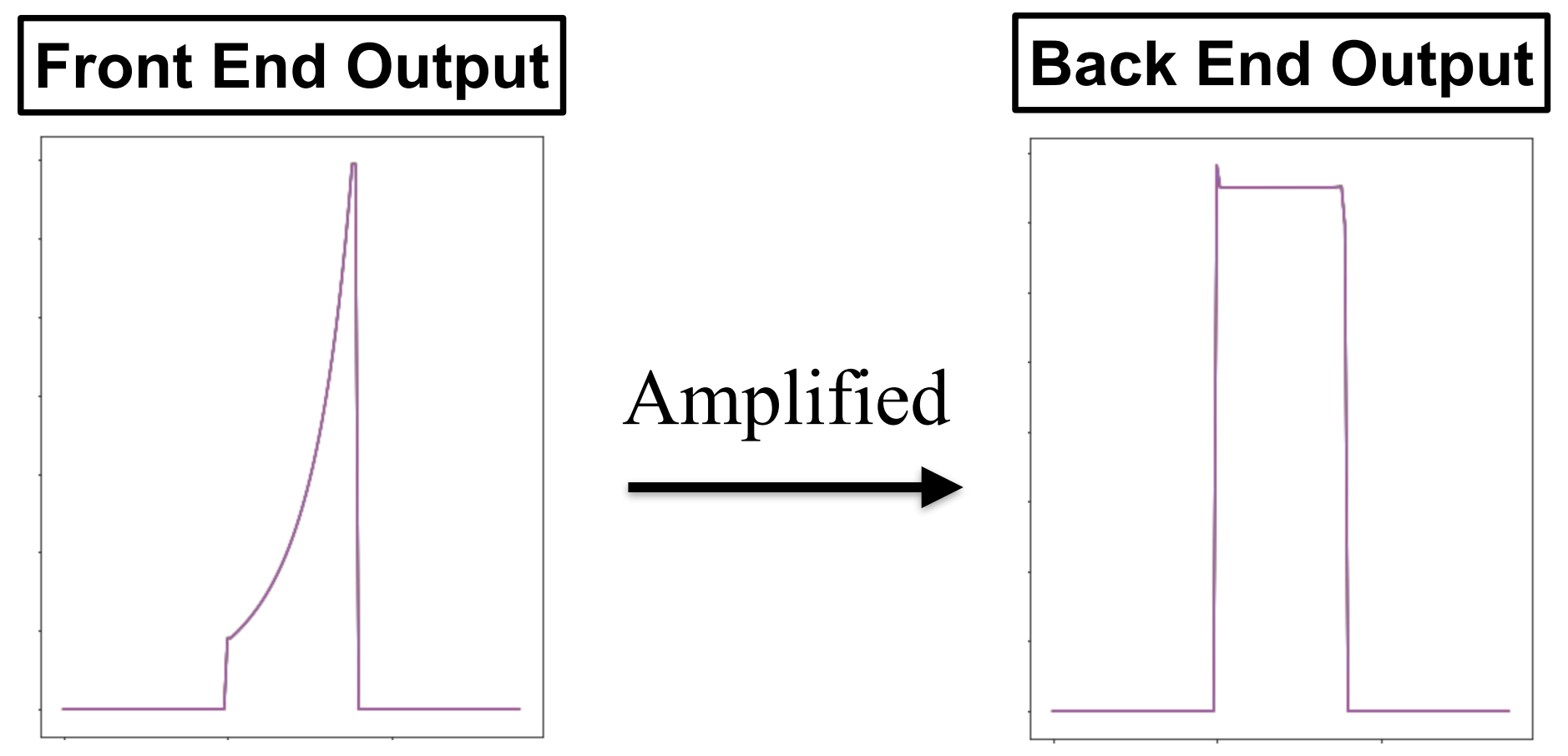
(While good estimates, further work must be done to verify these parameter values.)

Frantz-Nodvik Equation

Gain Saturation:
Because laser amplifiers cannot maintain a constant gain for arbitrarily high input power (conservation of energy!), the gain is reduced in time—dictated by the Frantz-Nodvik Equation:

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

Exponential Fit:
In order to compensate for gain saturation, the laser scientists in MEC aim for a temporally shaped exponential in the front-end, so a square wave is emitted from the back end (most common shot).



Conclusions

Outcome:
With a more than 2-fold reduction in error (8.2% to 3.3% error), the filter was mostly successful in reconstructing more physically plausible waveforms. Of course, many more runs are required to prove its efficacy. So far, it has been much more successful in accurately predicting the front and back edge of the amplified waveform than the unfiltered data. The filter may also be used for improved accuracy on data given to researchers.

Next Steps:
1. Determine exact parameter values of amplifiers for more accurate simulation.
2. Develop an algorithm to minimize error between simulated data and filtered data.

Acknowledgements

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