Machine learning assisted pulse shaping for double cone ignition implosions

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Hydrodynamic instability is the fundamental physical challenge for inertial confinement fusion. Implosions can compress fusion fuel to the extreme conditions required for thermonuclear reactions, but defects in the laser and the target can also be amplified during the implosion acceleration, breaking the spherical symmetry of the shell and leading to fuel mixing or shell breakup. There are two general ideas to suppress the instability: First, minimizing the seed from laser imprinting, which includes optical smoothing of the spot, optimization of beam overlap, and precision target fabrication. Second, improve the ablation of the interface to suppress the growth of the instabilities, which mainly relies on laser pulse shaping. The optimal pulse shape is related to the seed detail and the implosion geometry, it is difficult for manual pulse shape tuning to achieve the optimal implosion performance.

In the novel double cone ignition (DCI) [1] scheme, a pair of gold cones is used to guide the implosion of shells (Figure 1). DCI reduces the illumination solid angle and the ns-driver energy requirement. However, the instability risk of DCI is high due to its direct drive design and its distinctive overlap pattern. In our work [2], machine learning is used to randomly sample a large number of pulse shapes in fluid simulations, extract laser imprint features and RTI growth rate, and evaluate pulse shape performance based on compression areal density and instability amplitude. As the number of samples increases, machine learning gradually summarizes the potential relationship between pulse shape and implosion performance, and promotes pulse shape evolution based on this relationship. In the demo application in DCI, the machine learning performs a targeted pulse optimization based on the specific focal spot and beam overlap patterns extracted from the real laser device. The optimized pulse achieves good compression shock synchronization, preserves the spectral characteristics of the laser imprint, and accounts for the coupled evolution of the laser imprint and RTI. Compared to the manually tuned pulse shape, the machine-optimized pulse improves the unmixed fuel layer thickness by a factor of 4 while maintaining a similar compression areal density (Figure 2). This work is a successful application of machine learning methods to enable experiments to achieve fast iterative optimization with high confidence.

References

[1] Zhang, Jie, et al. "Double-cone ignition scheme for inertial confinement fusion." Philosophical Transactions of the Royal Society A 378.2184 (2020): 20200015.
[2] Tao, Tao, et al. "Laser pulse shape designer for direct-drive inertial confinement fusion implosions." High Power Laser Science and Engineering 11 (2023): e41.

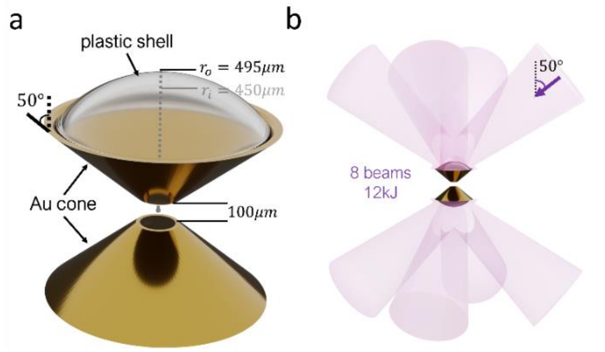

Figure 1: Geometry of the DCI scheme. (a) target consists of gold cones and the fuel-containing shell, shell has an initial radius of 450 μm and a thickness of 50 μm. (b) Driver laser setup, the total drive energy is 12 kJ, the laser spot power perturbation RMS~15%.

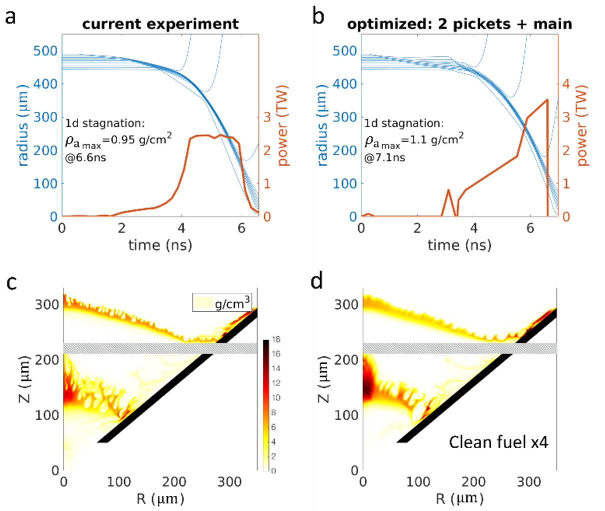

Figure 2: (a) manually tuned pulse shape and its implosion streamline, (b) pulse shape and its implosion streamline optimized by machine learning, (c)-(d) density perturbation of the shell layer at the imprint stage and at the end of acceleration.