1. Introduction

In laser driven inertial confinement fusion (ICF), the temporal shape control of the laser pulse is crucial to ensure an optimal interaction of laser-target [1–5]. The prototype of SG-III laser facility (the facility is called as ‘Technical integration line’ at the beginning, and so TIL is used as an abbreviation up to now) is designed and constructed for ICF research, which contains a frequency-tripled, ND: glass laser system capable of irradiating fusion target at energy of 10 kJ with 8 beams [6]. Different from previous TIL experiments, which uses square pulses at durations less than 3 ns, current experiments require arbitrary shaped pulses at durations as long as 20 ns with flexibility. This is a challenge for TIL. Generating the input pulse for a desired output pulse requires an accurate model of the laser system.

A TIL beam is composed of different specific stages [6], as presented in figure 1: the Frontend system that shapes the pulse temporally; the preamplifier system, which is the first stage of amplification (gain of $10^9$); the main amplifier system that provides the energy; and finally, the frequency conversion and focusing system that convert 1053 nm wavelength ($1\omega$) to 351 nm wavelength ($3\omega$) for a better interaction with the target. Gain saturation in the amplifiers and the presence of frequency convertors cause a significant distortion of the pulse shape; so we construct a calculated procedure modeling these effects to produce the desired pulse. Base on different shots cycle and physical theories, the traditional procedure contains three steps [7–10]. The first step is the calculation of $1\omega$ pulse shape required at the frequency convertors [11]. Then the resultant $1\omega$ pulse is used as input for a calculation that accounts for the distortion of the pulse caused by gain saturation in amplifiers [12]. The calculation yields the needed master oscillator pulse. At last the input pulse is generated by a close loop feedback control process, which uses an electro optic modulator driven by an electrical pulse from arbitrary waveform generation (AWG) to vary the intensity of light at the input of the system [13–15]. In general, the complete calculation needs complicated codes (For example, the SG99 in SG-III laser facility [16, 17], the RAINBOW in OMEGA [9, 18], the Miro in LMJ [19] and the LPOM in NIF [20, 21]) which contain the spatial and temporal distribution, and so a lot of parameters are required which are difficult to obtain. It’s inconvenient to some flexible laser facility such as TIL.
Therefore, it is necessary to develop a more flexible model for long term operation.

The requirements of pulse shape and energy on the target are frequently varied in TIL for various experiments. In this article, high efficiency controlling methods for long term operation are studied in TIL. Section 1 is the introduction. Section 2 presents the new techniques developed to produce shaped pulses on TIL, which could obtain the input pulse more precisely and quickly. In section 3, the close loop feedback control process is analyzed and a matrix was proposed to replace the dot-dot correspondence to relate the electrical signal and the impulse amplitudes, which improves the iterative efficiency. In section 4 we show some typical pulses operated in TIL for physical experiments, which verifies the capability to control the temporal shape of laser pulse exactly, and section 5 summarizes our results.

2. Pulse-shape modeling and controls in long term operation

In reality, the imperfections of beam and optics would affect the formula expression of physical process, it is impossible to model all the actual conditions conveniently [12, 17, 19]. Therefore we have proposed a semi-empirical model. In the model, the number of adjustable parameters is reduced with simplified procedure, and imperfections are treated as the uncertainty of the dominating parameters. Additionally, in order to improve accuracy, a statistical method is applied to analyze the variation.

For the frequency conversion process, a subsection function is used to replace the theoretical non-expressive equations, which contains power exponent at low intensity, simple polynomial at high intensity, as expressed by

$$I_3 = \begin{cases} \eta_1 I_1^t & I_1 < 0.8 \text{ GW cm}^{-2} \\ \eta_2 I_1 (a I_1^2 + b I_1) & I_1 \geq 0.8 \text{ GW cm}^{-2} \end{cases}$$

Where \(I_1, I_3\) are 1\(\omega\) and 3\(\omega\) intensity, respectively. The adjustable parameters contain two parts, one is related with the efficiency shape expressed as \(\eta_1 I_1^t\) and \(\eta_2 I_1 (a I_1^2 + b I_1)\), where \(t\), \(a\) and \(b\) are the shape parameters, the other is scaling factor expressed as \(\eta\). Efficiency shape is considered as steady and scaling factor is statistically analyzed to represent the imperfection and trend. The relationship of 1\(\omega\) intensity to 3\(\omega\) intensity comes from the operation data as shown in figure 2, the correlation coefficient is 0.982 and it indicates that the proposed semi-empirical model can express frequency conversion process for the TIL operation range properly.

For the amplification process, the F–N solution is expressed as [22]

$$E_{out} = E_s \ln \{1 + [\exp \left(\frac{E_{in}}{E_s}\right) - 1] g_0\}.$$  

Where \(g_0\) is small-signal gain, \(E_s\) is saturation fluence. To account for the pulse distortion arising from saturation in the amplifier chain, we use time dependence F–N solution to calculate the dependence of the amplifier gain on the amount of energy extracted from the laser media

$$\int_0^T F_{out}(t) dt = E_s \ln \{1 + [\exp \left(\frac{\int_0^T F_{in}(t) dt}{E_s}\right) - 1] g_0\}.$$  

Figure 1. Functional diagram of a TIL beam.

Figure 2. The semi-empirical model for frequency conversion process.

Figure 3. Relative deviation varied with shots sequence number.
1. The parameters are statistically averaged with multiple shots to reduce the high-frequency instability of the random deviation.

2. The weight coefficients are introduced in the calculation, which is heavier at the later shots in the model to express the tendency.

3. The model removes the data that exceeds the defined threshold autonomously, which are considered as mistakes in operation and would not appear again.

4. With the statistical analysis, some elements associated with other conditions are introduced in the model to further improve the prediction precision, such as the transmission or temperatures is varied with shots number in 1 d.

Considering the four factors, the parameter for next shot is obtained from previous data as

$$G_{n+1} = \frac{1}{p(m(n+1))} \sum_{i=1}^{\infty} (G_{ip}(m(1))q_1 + G_{ip}(m(2))q_2 + \ldots + G_{ip}(m(n))q_n)$$

$$\sum_{i=1}^{\infty} (q_1 + q_2 + \ldots + q_n)$$

(4)

Where $F(t)$ is power of the pulse, which calculates the integral $\int_{t_0}^{t} F_{in}(t) dt$ for each time interval in the pulse. The time derivative of $F_{in}(t)$ then yields the required input pulse. In the semi-empirical model, the saturation fluence is considered as steady and the small-signal gain is statistically analyzed to account for the imperfection from spatial variations in gain, transmission, changes in pinhole transmission and so on.

The parameters are associated with the state of the facility and therefore varied on the long time operation. To express the tendency and improve the control precision, we have created a statistical method to analyze the parameters variation from previous shots. Taking the scaling factor of frequency conversion function (equation (1)) for example, as shown in figure 3, the relative deviations of the parameter is varied with the shots sequence number. This shows that the operation data is disordering but the profile as the red line shows has an obvious tendency. The tendency could be obtained to improve the precision of prediction for the next shot. So we have proposed a calculated expression, which contains four functions.

3. Improvements of injection pulse shape control

Figure 4 shows a block diagram for the injection pulse shape control system. From the diagram structure of figure 4, we can see that the optical pulse is determined by the electrical pulse, and then the electrical pulse is generated from AWG, which is driven by an electrical pulse generated from AWG. The other is the pulse energy control; after the pulse goes through propagation and amplification, a half-wave plate and a polarizer are used to regulate the energy. Different from NIF which has two electro optic modulator to shape pulse, the TIL pulse shaping control has only one to cut costs and save space, the absence is square pulse modulator, which can achieve sharp edge [14].

The pulse edge characteristics are systematically analyzed. From the diagram structure of figure 4, we can see that the electrical pulse is generated from AWG, which is driven by an electrical pulse generated from AWG. The AWG sums many impulses as electrical pulse generators; each has a width of 150 ps pulse and a temporal separation of 100 ps. The impulse amplitudes are programmable parameters. Generally, the electrical impulse would impact their neighboring signal, as shown in figure 5, without the square pulse modulators, the boundary effect makes it more difficult to get the desired sharp-edge pulse waveform.

To produce the desired sharp-edge electrical pulse waveform, point to point algorithm is traditionally used to calculate the electrical pulse waveform. This method cannot represent the impacts of impulses, so we proposed a matrix algorithm to relate electrical signal and impulse amplitudes. The relation equation is $V = MA$, where $V$ is the electrical pulse waveform, $A$ is impulse amplitudes, $M$ is the relational matrix as expressed in equation (5) and its parameters $k_i$ is shown in figure 5(a).

$$G$$ is the parameter, subscript $n$ is the sequence number, $q_n$ is the function of $n$ and $m(n)$. The model could self-adapt to ensure the output of shaped pulses in long term operation without being interrupted for parameter calibration.
and then being transformed to electrical signal.

\[ V = \frac{k_0}{1 + e^{-\frac{t}{T_{\text{th}}}}} - c_0, \quad V \leq V_m. \]  \hspace{1cm} (6)

Here the parameters \( I_0, V_0 \) and \( c_0 \) are determined for specified system, \( V_m \) is the electrical signal threshold. We designed the electrical signal threshold for the convenience of control, when a signal is below electrical threshold; the optical signal has a more accurate theoretical expression with electrical signal.

Then the electrical signal is decomposed to impulse amplitudes. The impulse amplitudes are calculated as equation (7), which is the startup of the first loop

\[ A_i = M^{-1} \left[ V_0 - c_0 \ln \left( \frac{k_0}{T_{\text{th}}} - 1 \right) \right] \max(I_i) \leq I_m. \]  \hspace{1cm} (7)

The iterative shaping process continues until a defined convergence criterion has been satisfied. The default convergence strategy uses a standard deviation methodology for quantification. On each pulse shaping iteration the integral deviation on the entire pulse that included average and maximum relative deviation is calculated. Convergence is met when the integral deviation is less than a configurable threshold.

Based on these configurable parameters the iterative shaping process typically takes 3–6 iterations and about 5 min to shape any arbitrary waveform.

Last is the pulse energy close loop. The energy regulation module is placed in pre-amplifier optical path, which contains two optical components: a rotatable half-wave plate and a fixed polarizer whose polarization angle matches the optical system. The half-wave plate angle is scaled relative to zero reference with the module transmission being expressed as \( T = \cos^2 \theta \). This module can regulate output energy without distorting pulse shape.

4. The realization of the arbitrary shaped pulse in TIL

With the model applied in the pulse shaping process, a variety of pulse shapes were produced, the pulses have a dynamic range of more than 100 and the rising edge (it contains pickeets) of less than 100 ps, which are largely determined by the performance of AWG waveform generator and measuring equipment. Figure 6 shows some typical TIL pulse shapes in physical experiments, which contain the high-contrast shock ignition pulse shape, the three-steps pulse shape, the hohlraum constant temperature pulse shape, the exponential (\( t^2 \)) pulse shape and the picket pulse shape, the variety represents the broad range of TIL pulse shaping capability. It is obvious from figure 6 that the measured and specified pulse shapes are in exceedingly good agreement, indicating that the models are highly accurate. The only disagreements are located at the region of pulse tail, which are due to the measuring equipment lacking the ability to respond to rapid pulse drops. Nevertheless, the less than 10% RMS deviation for integral pulse is enough to meet the requirement in experiment. Additionally, the processing time is about half an hour, which is fast enough to meet the interval requirements of two sequential shots.
The output has demonstrated that we can accurately model the performance of the TIL system. Now TIL has operated hundreds of shots with different shaped pulses in the physics experiments for almost 3 years, the processing accuracy and speed keep at almost the original level although the state and parameters are changed gradually.

5. Conclusion

A semi-empirical model was developed to produce a variety of pulse shapes on TIL in long term operation. In the frequency conversion and amplification processes, the model reduced the number of the adjustable parameters in calculation and treated imperfections as the uncertainty of the dominating parameters. Statistical variation is included to account for the systematic variations and suppress the random variations from previous shots. In the injection pulse shape control process, matrix algorithm was proposed to relate the electrical signal and the impulse amplitudes, which can satisfy the requirements of sharp-edge pulses and iterative efficiency. A variety of different shaped pulses were produced with a half an hour period and a 10% precision for almost 3 years although the state and parameters are changed gradually, which demonstrated that the performances of TIL are modeled accurately.

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References

[1] Dittrich T R et al 1999 Capsule design for the national ignition facility Laser Part. Beams 2 217–24
[2] Campbell E M et al 2017 Laser-direct-drive program: promise, challenge, and path forward Mater. Radiat. Extremes 2 37–54
[3] Ogden S J, Speck D R and Steven W H 1998 The NIF power balance Proc. SPIE 3492 78–104
[4] Lindl J D, Amendt P, Berger R L, Glendinning S G, Glenzer S H, Haan S W, Kauffman R L, Landen O L and Suter L J 2004 The physics basis for ignition using indirect-drive targets on the national ignition facility Phys. Plasmas 11 339–491
[5] Goncharov V N, Knauer J P, Mckenty P W, Radha P B, Sangster T C, Skupsy S, Betti R, McCrory R L and Meyerhofer D D 2003 Improved performance of direct-drive 96 inertial confinement fusion target designs with adiabat shaping using an intensity picket Phys. Plasmas 10 1906–18
[6] Li P, Jing F, Wu D S, Zhao R C, Li H, Lin H H and Su J Q 2012 Power balance on the SG-III prototype facility Proc. SPIE 8433 843317
[7] Jones O S, Speck D R, Williams W H and Renard P A 1998 The NIF’s power and energy ratings for ICF-shaped temporal pulses Proc. SPIE 3492 49–54
[8] Liu R H, Cai X J, Yang L, Zhang Z X and Bi J J 2004 Numerical simulation of output pulse shape for ‘Shenguang II’ Acta Phys. Sin. 53 4189–93
[9] Skeldon M D, Okishev A V, Keck R L and Seka W 1999 An optical pulse-shaping system based on aperture-coupled slinines for OMEGA pulse-shaping applications Proc. SPIE 3492 131–5
[10] Haynam C A 2007 National Ignition Facility laser performance status Appl. Opt. 46 3276–303
[11] Zhao S L, Zhu B Q, Zhan T Y, Cai X J, Liu R H, Yang L, Zhang Z X and Bi J J 2006 Research on pulse shape properties of high power Nd: glass laser frequency tripling Acta Phys. Sin. 55 4170–5
[12] Sacks R A et al 2008 Laser energetics and propagation modelling for the NIF J. Phys. 112 035024
[13] Feigenbaum E, Sacks R A and Shaw M J 2013 Enhancing the pulse shaping precision of energetic high aspect ratio infrared pulse in the national ignition facility laser system CLEO 2013 62
[14] Gordon B, Gaylen E, Don B and Eddy T 2012 The shaping of a national ignition campaign pulsed waveform Fusion Eng. Des. 87 1940–4
[15] Jolly A and Estrailier P 2004 Generation of arbitrary waveforms with electro-optic pulse-shapers for high energy-multimode lasers Opt. Lasers Technol. 36 75–80
[16] Hu D X et al 2015 Generation and measurement of complex laser pulse shapes in the SG-III laser facility Chin. Opt. Lett. 13 58–61
[17] Su J Q et al 2005 The code SG99 for high-power laser propagation and its applications Proc. SPIE 5267 527–31
[18] Donaldson W R, Maywar D N, Roides R G, Marcianter J R, Kelly J H, Zuegel J D and Keck R L 2008 8.5 GHz pulse-shape control with a 700:1 dynamic range on a frequency-tripled multiterawatt solid-state laser CLEO 2008 1–2
[19] Morice O 2003 Miro: complete modeling and software for pulse amplification and propagation in high-power laser systems Opt. Eng. 42 1530–41
[20] Spaeth M L et al 2016 National ignition facility laser system performance Fusion Sci. Technol. 69 366–94
[21] Lagin L J et al 2008 Status of the national ignition facility integrated computer control system (ICCS) on the path to ignition Fusion Eng. Des. 83 530–4
[22] Frantz L M and Nodvik J S 1963 Theory of pulse propagation in a laser amplifier J. Appl. Phys. 34 2346–9