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# Fast focal zooming scheme for direct drive fusion implemented by inserting $KD_2PO_4$ crystal

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A B S T R A C T

The highly required uniformity of target in direct-drive fusion is difficult to achieve and maintain during the entire laser fusion implosion. To mitigate the increasing nonuniformity, the fast focal zooming scheme implemented by inserting an electro-optic (EO) crystal in the front end of beamline has been proposed. Functioning as a phase plate, the specifically designed EO crystal may add the induced spherical wavefront to the laser beam and alter its focusing characteristics. However, in order to zoom out the focal spot by half, the required voltage for $KD_2PO_4$ (DKDP) with single pair of electrodes is relatively high. In order to decrease the voltage while maintaining the zooming performance, the DKDP cylinder with multi pairs of electrodes has been presented. The continuous phase plate (CPP) is designed according to both the injected beam and the output field. However, the conventional CPP is designed based on the assumption of an injected beam without wavefront distortion, which would zoom in the focal spot variation in the focal zooming scheme. In order to zoom out the focal spot, a redesigned CPP has been proposed by adding a spherical wavefront to the phase variation of the conventional CPP and further optimizing. On the basis, the focusing characteristics of laser beam during the fast focal zooming process have been analyzed. Results indicate that the focal spot size decreases with the increasing voltage on DKDP crystal, meanwhile the uniformity maintains high during the focal zooming process.


## 1. Introduction

The direct-drive approach to inertial confinement fusion (ICF) employs laser beams for illuminating the capsule directly [1,2,3]. Compared with the indirect-drive approach, the direct-drive project requires relatively lower energy but higher illumination uniformity. The required high-uniformity is difficult to achieve and maintain during the entire laser fusion implosion due to the compressed target. One optional strategy is to obtain the highest initial uniformity by selecting a suitable ratio of focal spot to target. At later times the nonuniformity would grow but be slightly smoothed by the flowing plasmas [4]. In recent studies, the crossing beams are found to excite ion-acoustic waves which bring about obvious energy transfer [5,6], i.e. cross-beam energy transfer (CBET). It causes the incident energy to be transferred from the central portion of the laser beams to the edge, and significantly reduces the symmetry of the fusion capsule [7]. Based on a series of experiments on OMEGA, D.H. Froula et al. have demonstrated that reducing the radius ratio of focal spot to target would mitigate CBET and increase hydrodynamic efficiency [8]. These studies indicate that CBET may be alleviated by reducing the radius of the focal spots but at the cost of increasing nonuniformity. Furthermore, D.H. Froula et al. have presented the two-state focal zooming on OMEGA in order to mitigate CBET while holding low-mode uniformity [9]. In that two-sate focal zooming scheme, a zooming phase plate has been designed to zoom out the focal spot during the main pulse while maintaining the focal spot during the pickets.

To achieve high illumination uniformity and hydrodynamic efficiency during direct-drive fusion, the above schemes are mostly concentrated on static focal-spot control. The potential approaches involve modifications to the spatial coherence of the laser beam that causes far field zooming [10]. Time-dependent phase conversion and Smoothing by Spectral Dispersion (SSD) [11] are two representative ways. While the major purpose of SSD is to improve irradiation uniformity of focal spot in the sense of being averaged over a finite time interval, SSD broadens the focal spot to some extent. On the other hand, the conventional Continuous Phase Plate (CPP) is a static phase plate [12], which may even restrict focal zooming. In order to zoom out the focal spot dynamically, we have proposed a scheme for direct-drive facility implemented by inserting a specifically designed EO crystal in the front end of the beamline. The EO crystal with electrodes can generate the spherical phase modulation with applied voltage. The generated spherical wavefront is then used to transform the

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wavefront of the laser beam, and zoom out the focal spot on the capsule. Functioning as a dynamic phase plate, the DKDP crystal may transform the wavefront of the laser beam and alter the location and size of the focal spot. At the same time, the redesign of CPP is to meet the requirement of zooming out the focal spot. However, in order to zoom out the focal spot by half [16], the required voltage for DKDP crystal with single pair of electrodes is relatively high. Consequently, we have presented a new configuration of DKDP crystal with multi pairs of electrodes. In addition, a redesigned CPP has also been presented to achieving the dynamic focal zooming.

## 2. Fast focal zooming scheme for direct drive facility

### 2.1. Fast focal zooming scheme

The EO crystal has been used for a long time to fabricate zoom lens owe to the quick and effective refractive index modulation with appropriate configuration [13,14]. Taking the NIF beamline as a typical example, the fast focal zooming can be implemented by inserting the specific EO crystal in the front end of beamline to avoid obvious impact on the subsequent laser propagation and amplification (as shown in Fig. 1).

Fig. 1 illustrates the fast focal zooming scheme, in which a specific EO crystal is inserted in the front end of beamline. The EO crystal is assumed to be placed on one relay plane before the laser beam is injected into the main amplifier [15], causing no obvious impacts on the subsequent propagation of the laser beam. Fig. 2 shows the structure of specifically designed DKDP crystal which generates a lateral spherical optical path modulation. It is made up of one DKDP cylinder and two pairs of electrodes. The size of the DKDP cylinder is $\Phi 20\times 25$ mm. The two pairs of electrodes are parallel to each other and spaced 5 mm apart, with sizes of $\Phi 20\times 2$ mm. Two pairs of annular metal electrodes are coated on the side face, and the laser beam is incident on the head face.

As is shown in Fig. 1, the wavefront of the laser beam is spherically modulated after propagating through the EO crystal. Then, the laser beam propagates successively through a beam expander, a main amplifier, a frequency conversion system and a CPP. Finally, the laser beam is focused on the target by a lens. During the direct-drive laser fusion implosion lasting for several nanoseconds, the deuterium–tritium (DT) target is compressed rapidly. B.G. Logan et al. have briefly described how the laser beam and DT target ablator change with time during the entire implosion [16]. Both the target radius and the radius of focal spot decrease by half at the end of pulse duration (as shown in Fig. 3).

As is given in Fig. 3, the target radius reduces nearly by half at the end of the pulse duration (from 0.215 cm to 0.106 cm). This would result in great loss of energy and decrease of irradiation uniformity when the multiple laser beams slides away from the target. In order to match the focal spot of the laser beam with the compressed target, we may apply a fast-varying voltage to the DKDP crystal in the fast focal zooming scheme. The influences of fast focal zooming on the focusing characteristics of the laser beam are further analyzed.

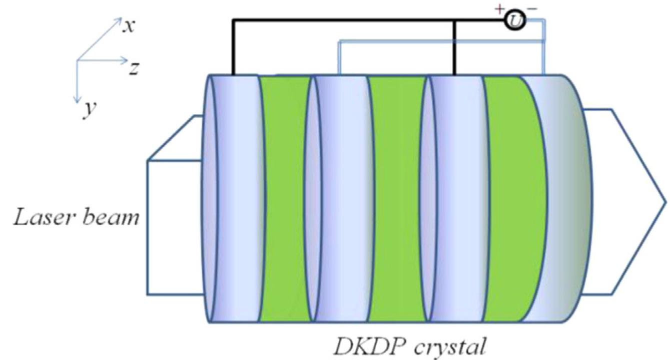


**Fig. 2.** Structure of DKDP crystal with two pairs of electrodes. The green part is the DKDP cylinder, and the silver parts are the metal electrodes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

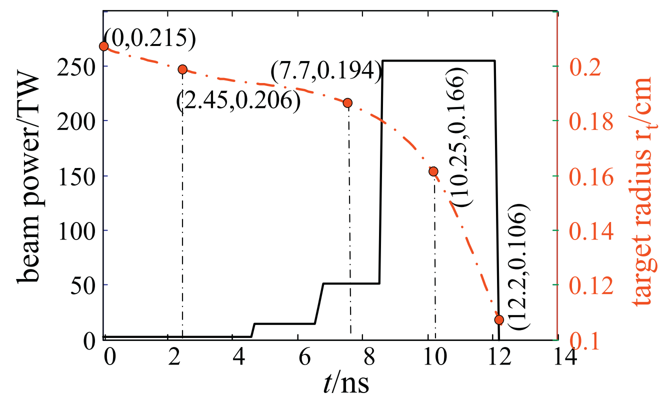


**Fig. 3.** Beam power shape (solid line) and target radius variation (dashed line) [17].

### 2.2. Model of fast focal zooming

For direct drive ICF facilities, beam smoothing technologies (involving smoothing by spectral dispersion, polarization scramblers and electric-optic wigglers, etc.) have been adopted to obtain highly uniform focal spots. For the sake of convenience and without loss of generality, considering the devices affecting the spatial coherence of laser beam, the light field after transmitting through the DKDP crystal is given as, *i.e.*,

$$E_0(x, y) = A_0 \exp\left(-\frac{x^{2N}+y^{2N}}{w^{2N}}\right)\exp\left\{i\omega_0 t + i\delta_m \sin\left[\omega_m\left(t - z/c + \xi_m x\right)\right]\right\} \times \exp\left(i\Phi_{ran} + i\Phi_{EO}\right) \quad (1)$$

where $A_0$ is the amplitude, $w$ is the beam waist, $N$ is the order of the super-Gaussian function, $\Phi_{EO}$ is the added wavefront by DKDP crystal. $\delta_m$ and $\omega_m$ are the modulation amplitude and angular frequency, respectively. $\xi_m = \mathrm{d}\theta/\mathrm{d}\lambda\cdot\lambda_0/c$, $\mathrm{d}\theta/\mathrm{d}\lambda$ represents grating dispersion, $\omega_0 = c/\lambda_0$ is the fundamental angular frequency of the laser. $\Phi_{ran} = \varphi_l + \varphi_h$ is Gaussian random phase, where $\varphi_l$ and $\varphi_h$ are low-frequency and high-frequency phase perturbation, respectively [18], i.e.,

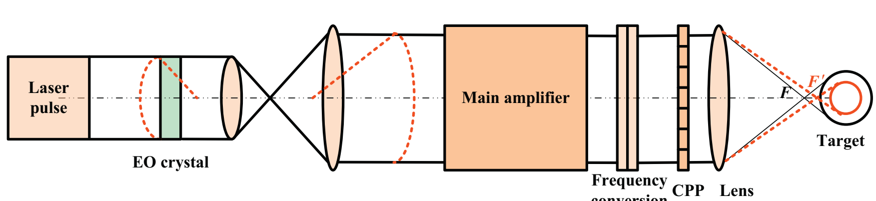


**Fig. 1.** Schematic illustration of fast focal zooming scheme in the beamline.