Application progress and prospect of 100-joule high power XeCl excimer laser

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ABSTRACT

High power excimer laser has the characteristics of good irradiation uniformity on target surface, repeatable operation and high electro-optical efficiency. It has played an important role in the research fields of inertial confinement fusion, high energy density physics, plasma physics, and so on. In this paper, the high power XeCl excimer laser device in Northwest Institute of Nuclear Technology is briefly introduced. Secondly, the application progress of the device is introduced, which mainly includes the research work in laser-plasma interaction, high temperature explosion simulation, high pressure flying plate drive, solid material sound velocity measurement, X-ray framing camera performance assessment, multi-angle shock diagnosis target structure verification. Finally, the future application of the device is prospected.

Keywords: High power excimer laser, Beam smoothing, Inertial confinement fusion, High energy density physics

1. INTRODUCTION

Excimer laser using gas medium, has the characteristics of short wavelength, high gain, wide frequency band and repeatable operation, can be scaled up to high energy, is an important driver of high energy density physics and fusion energy research, by the United States, Japan and other countries[1-7]. Since the 1980s, high power excimer laser has developed rapidly. The high energy KrF laser AURORA(5kJ,5ns) was developed at Alamos National Laboratory (LANL), Los Angeles, USA, and the SPRITE (KrF, 100J,10ns) was developed at Appleton Real Laboratories (RAL), Rutherford, UK[1][2]. The Electric Research Institute of Japan (ETL) developed the ASHURA facility(KrF, 660J,15ns) [3]. In the 1990s, RAL and ETL further upgraded their respective devices to TITANIA(1kJ,10ns) [4] and SUPER ASHURA(2.7kJ,20ns) [5], and the United States Naval Laboratory (NRL) successfully developed the NIKE device (KrF, 5kJ, 4ns) [6], The Lebedev Institute in Russia developed GARPUN(100J,100ns) [7]. The Chinese Institute of Atomic Energy and the Northwest Institute of Nuclear Technology (NINT) have successively developed electron-beam-pumped 100 joule class excimer lasers (CIAE: KrF/106J/100ns[8], NINT: KrF/157J/80ns and XeCl/136J/80ns[9]). The excimer laser has short wavelength, wide frequency band, high coupling efficiency with the target, and high threshold of laser-plasma instability and fluid hydrodynamic instability in the study of laser-driven inertial fusion. In recent years, NRL in the United States has carried out a lot of pioneering work in inertial confinement fusion with NIKE device, fully demonstrating the advantages of

Seventh International Symposium on Laser Interaction with Matter (LIMIS 2024), edited by Jin Guo, Cangtao Zhou, Pengling Yang, Yihua Hu, Proc. of SPIE Vol. 13543, 135430P · · 0277-786X · doi: 10.1117/12.3058747

excimer laser.

In recent years, the Northwest Institute of Nuclear Technology based on a 250J/200ns long pulse XeCl excimer laser MOPA system[10,11] built a nanosecond 100 joule high power excimer laser device, its output energy reaches 100J, pulse width can be adjustable between 2~8ns, the target laser power density is greater than 10^{13}W/cm^2, and a target area system has been developed [12-16]. Compared with large solid laser device, for the adoption of optical angular multiplexing pulse compression technology and the technology of Echelon Free Induced Spatial Inco herence (EFISI), the most prominent characteristics of the device are ajustable focal spot size, good uniformity, and adjustable pulse width, which is suitable for one-dimensional high pressure loading, high temperature plasma, X-ray radiation transport, astrophysics and other basic research [17-22]. This paper mainly introduces the typical experimental applications of this device in recent years and the prospect of future applications.

2. DEVICE INTRODUCTION

The high power XeCl excimer laser device is composed of laser ampilifier system, beam transmission and control system, target area system and so on. Among them, the laser ampilifier system includes a front end, a pre-amplifier for ultraviolet preionization discharge pump, two X-ray preionization discharge pump preamplifiers, a vacuum-insulated compact Marx electron beam pump preamplifier, and a linear transformer modular(LTD) electron beam pump main amplifier. In recent years, the research has broken through the high quality partially coherent seed source, smooth optical angular multiplexing beam transmission amplification, angular multiplexing beam coding and decoding, ASE control, automatic beam alignment and long-distance transmission stability, multi-beam target overlap, synchronous trigger control, online parameter diagnostic and other technologies. On the basis of the long pulse XeCl excimer laser MOPA system, the ns scale 100-joule high power excimer laser device has been successfully developed. The output laser wavelength is 308nm, the energy is larger than 100J, the pulse width is continuously adjustable between 2~8ns, and the power density of the target surface is greater than 10^{13}W/cm^2[15,16]. The layout of the device is shown in fig.1.

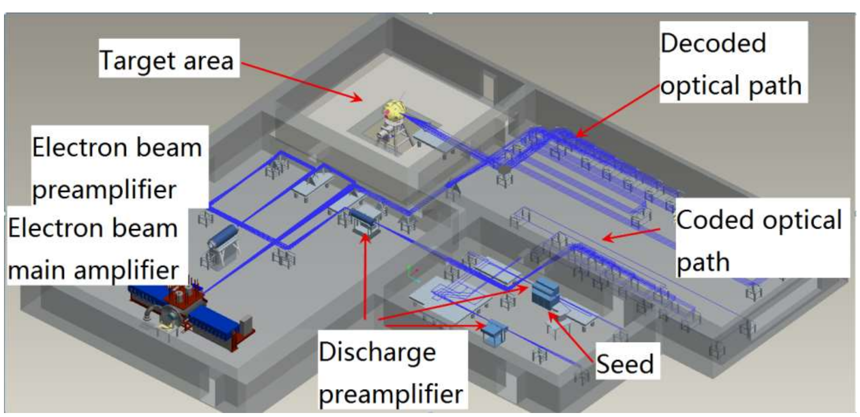

Figure 1. Overall layout of high power XeCl excimer laser device

The device is also equipped with a target area system[16], including vacuum target chamber, laser focusing optical system, target positioning and beam guidance system, laser parameter diagnosis system, and multiple sets of diagnositic equipments, testing parameters contain X-ray spectrum, X-ray image, visible light image, visible light spectrum, shock image and X-ray radiation flow. With the ability to carry out laser-plasma interaction, high temperature explosion simulation, extreme physical properties of material and other physical experiments.

3. APPLICATION PROGRESS

Based on the characteristics of the device, such as adjustable spot size, good irradiation uniformity and adjustable pulse width, many kinds of experiments were carried out, such as laser-plasma interaction[23-25], high temperature explosion simulation, extreme physical properties of material [26,27], and ICF diagnostic technology research[28], which supported the research work in the fields of frontier foundation and engineering application.

3.1 Laser-plasma interaction experiment

The study of laser-plasma interaction is the basis of astrophysics, high temperature explosion simulation, and performance assessment of X-ray test and diagnostic equipment, which mainly includes the research contents of laser-X-ray conversion efficiency, radiation spectral characteristics of high temperature plasma, radiation energy, and radiation power angle distribution. The radiation characteristics of high temperature plasma, such as solid targets with different atomic numbers and multi-layer targets, have been studied by using this device, and high temperature plasma radiation source with cosine distribution using thick target and high temperature radiation source with spherical distribution using thin film target have been obtained, and the laser-X-ray conversion efficiency has reached 15%[23-25]. Fig.2 shows the calculation results of the radiation temperature distribution of CH thin film target with different target thicknesses, and fig.3 shows the radiation spectra of 31eV CHO plasma obtained by using double-layer thin film target.

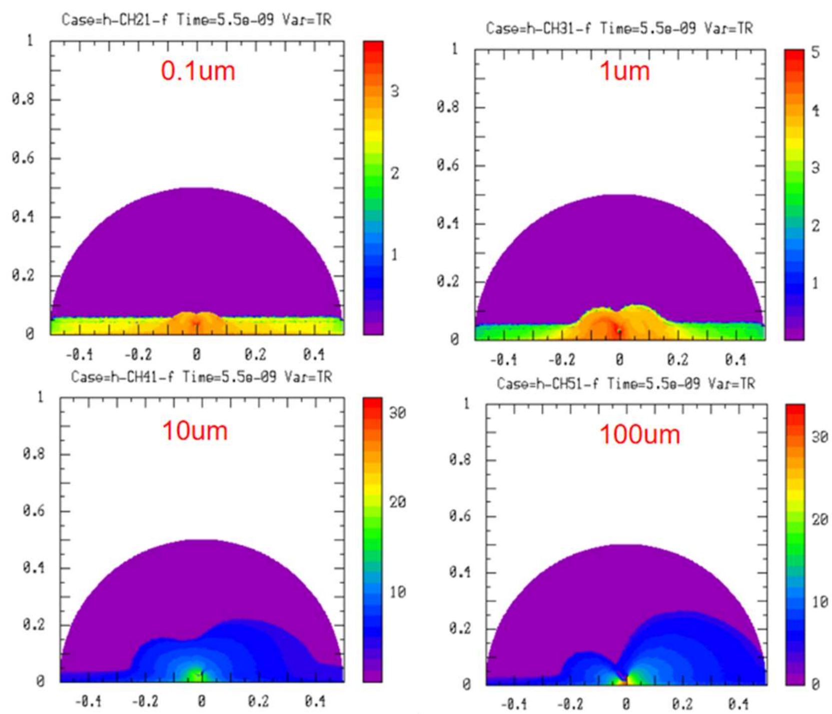

Figure 2. Calculation results of radiation temperature of CH targets with different target thicknesses

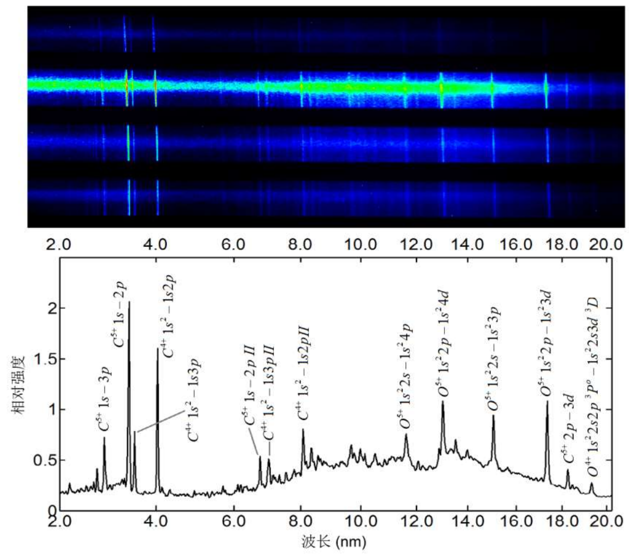

Figure 3. Radiation spectrum of 31eV CHO plasma (up) measured results, and (down) identification of spectral lines

3.2 High temperature explosion simulation experiment

High temperature explosion is characterized by high temperature, high proportion of radiation energy, complex physical process, evolution is very fast, and the study of its process has important technical support for astrophysics research. High power laser can easily achieve tens to hundreds of eV high temperature explosion environment, and without the help of any energy transmission medium, small electromagnetic interference, good repeatability, can be used for material high temperature radiation opacity and other physical parameters quantitative research, as well as radiation heat wave, shock wave propagation mechanism, spontaneous radiation evolution characteristics and high temperature explosion test and diagnosis technology research. Fig.4 shows the development image data of radiation shock wave in N_2 obtained on the device.

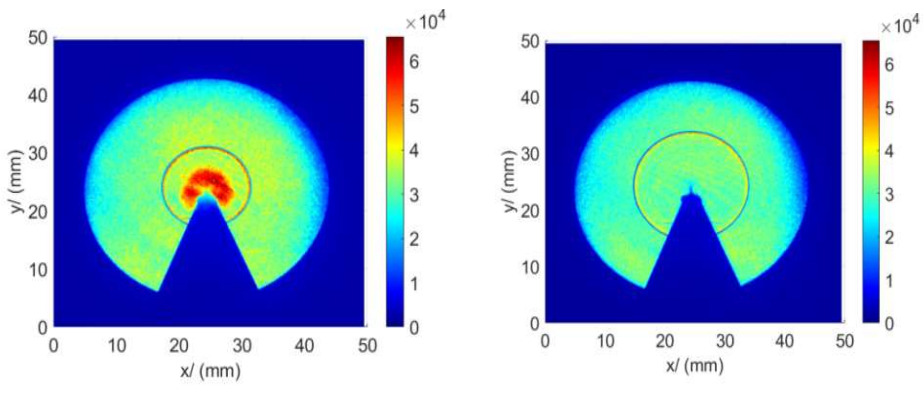

Figure 4. Evolution image of strong radiation shock wave in gas

3.3 Laser driven flying plate experiment

Laser driven flying plate technology has important applications in many research fields such as inertial confinement fusion physics, space physics, laser detonators and so on. In the field of fusion physics, using a long pulse width laser device to carry out laser-driven flying plate research can greatly improve the parameter range, improve the research efficiency, expand the research scope of the pressure parameter in the equation of state to the order of TPa, and broaden the parameter range that cannot be realized by traditional loading methods.

Direct-driven experiments and indirect-driven experiments were carried out on the high power excimer laser device, and the experimental data of the complete acceleration process and the X-ray focal spot on the target surface were obtained. The experimental results are basically in agreement with the theoretical simulation results. In the laser-driven flying plate experiment, the acceleration processes of multi-layer composite flyplate and single-layer flyplate were obtained, and the results are shown in fig.5. The experimental results show that a flying plate speed[15,16] of more than 9km/s has been obtained based on the high-power excimer laser device. This data exceeds the first cosmic speed, indicating that the device has the conditions to carry out research work such as space debris removal and protection.

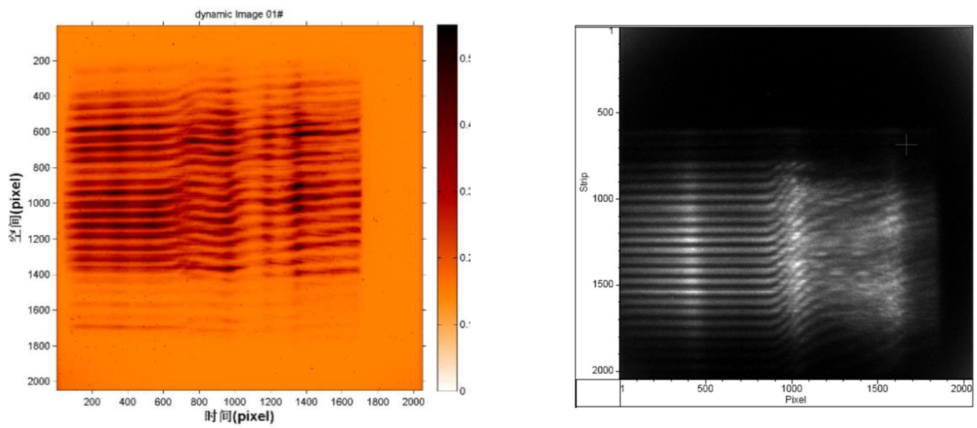

Figure 5. Experimental results of flying plate velocity (a) multilayer composite flying plate (b) single-layer aluminum flying plate

3.4 High pressure sound speed test for solid materials

The characteristics of adjustable laser pulse width and uniform irradiation make the excimer laser device has advantages in the study of material equation of state[26,27]. In this study, the thickness of the target material is closely related to the drive laser pulse width, for a wider laser pulse width can obtain the loading data of a thicker material, which can reduce the influence of scale effect. The adjustable pulse width of the device makes it possible to obtain a series of equation of state data of materials with different thickness. In addition, one-dimensional plane loading is a general method to obtain the state equation data, which requires the loading source to have large area and good uniformity, and usually requires the transverse dimension of the loading source to be far beyond the thickness of the target. The device's target spot can reach up to 800μm, and the homogeneity of the beam spot on the target surface is less than 2%. It is an ideal high pressure driving source for the study of the equation of state. The device has been used to carry out high pressure driving experiments, such as sound velocity measurement of material under high pressure using gas reservoir target. Fig.6 are Gas reservoir driven targets used for sound velocity measurement, and fig 7 shows the sound velocity results of alumium under high pressure. Before impact, the velocity of the flying plate is 4.44km/s, and after impact, the particle velocity at the interface is 2.9km/s.

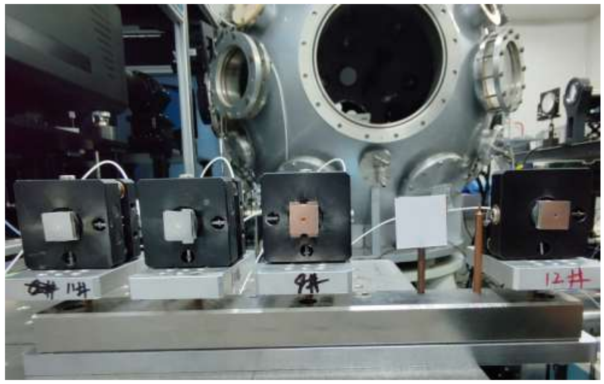

Figure 6. Gas reservoir driven targets used for sound velocity measurement

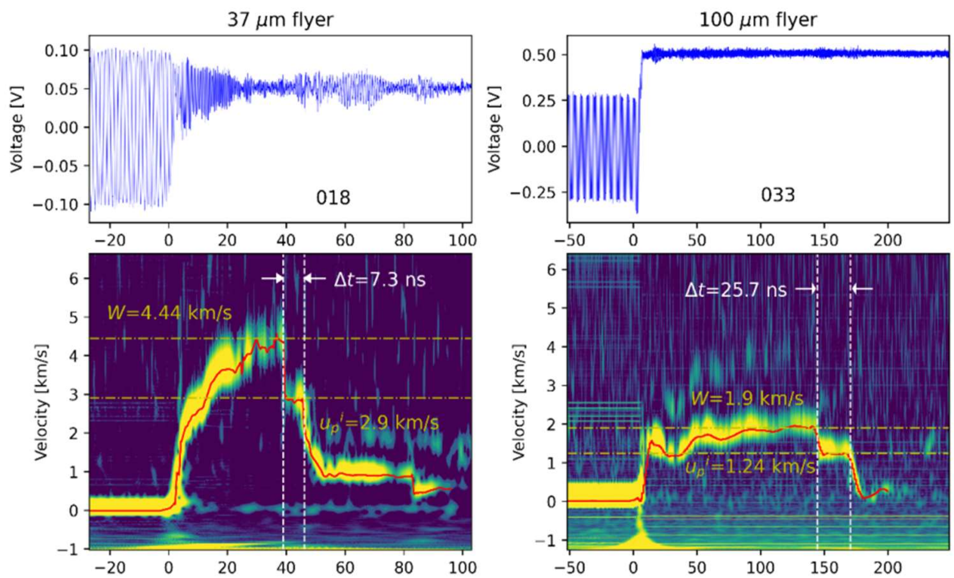

Figure 7. Sound velocity results of alumium under high pressure

3.5 X ray framing camera calibration experiment

The X-ray framing camera plays an important supporting role in the research of quantum physics, ultra-short laser physics, inertial confinement fusion and other research fields. The gold-plated microstrip is used as the cathode, and the gated high-voltage electrical pulse is applied to the cathode during operation, then high performance time gating is realized by controlling the waveform of the electrical pulse. Because the electric pulse will decay during transmission, and because of the edge effect may lead to uneven distribution in the cathode, and then affect the overall gain performance of the camera, so that the gain is a function of spatial position. Therefore, it is necessary to use the pulse X-ray with high intensity and uniform spatial distribution to evaluate and calibrate the gain function of the framing camera. According to the evaluation requirements of Φ106 X-ray framing camera newly developed in China, the camera performance calibration experiment was carried out. Fig.8 shows the performance calibration experiment photo of the camera.

Figure 8. Performance calibration experiment photo of Φ106 X-ray framing camera

3.6 Multi-angle shock diagnostic experiment

The number of beams in the device is up to 18 beams, and the spherical target can be directly driven by the accumulation of airspace, which is used for the research of inertial confinement fusion diagnosis technology. In the laser driven inertial confinement fusion experiment, there are many factors that will affect the compression symmetry of the target pellet, such as the cavity target size, laser waveform, inner and outer ring power ratio, and the mass of the target pellet, etc. In order to obtain the maximum compression of the target pellet, it is necessary to regulate its drive and compression symmetry, so that the target pellet can achieve a symmetric compression state, and then realize the quasi-one-dimensional implosion compression with high compression ratio. The biaxial VISAR diagnostic technology based on the arbitrary reflector velocity interferometer can carry out time-dependent characterization of the loading symmetry of the whole process of shock wave transmission, and is a new technical means to characterize the symmetry of the shock wave loading stage. Due to the very complex structure of the target, experimental verification is required before application.

Two axis VISAR target structure verification experiments were carried out on the device, and the compression velocity curves of the target pellet in the equatorial region and the polar region were obtained, which verified the diagnosis method of target pellet implosion based on optical diagnosis technology. Fig.9 shows the online sight image of dual-axis VISAR target. Bright spots of probe light can be observed in equatorial region and polar region; Fig.10 shows the compression velocity curves of the target pellet in equatorial region and polar region, which verifies the feasibility of the structure.

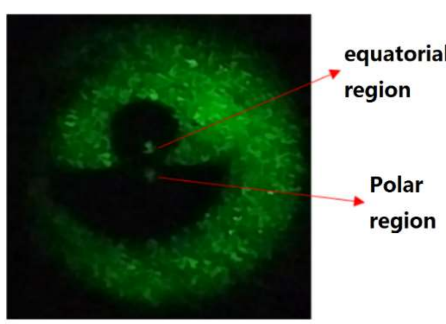

Figure 9. Online sight image of dual-axis VISAR target

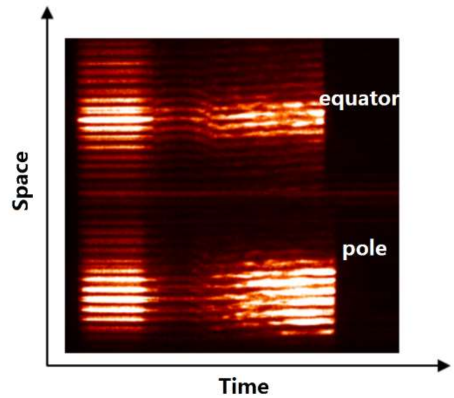

Figure 10. Compression velocity curves in equatorial region and polar region

4. PROSPECT

The characteristics of the device, such as multi-beam, uniform irradiation, adjustable pulse width and variable spot size, make it a multi-purpose device, which is expected to play an important role in the research of laser fusion driver technology, high temperature explosion simulation, laser driven inertial confinement fusion physics, astrophysics and other research fields:

(1) Research on laser fusion driver technology. The United States took the lead in achieving laser fusion ignition on the NIF device, which greatly enhanced human confidence in achieving laser fusion power generation. The next generation of fusion lasers need to have four characteristics[29]: high repetition rate, high electro-optic conversion efficiency, high life and compact. This is almost consistent with the characteristics of excimer laser, which brings development opportunities for excimer laser. In addition to the continuous research on high repetition rate and high electro-optical efficiency, excimer laser also needs to explore new key technologies such as pulse compression.

(2) High temperature explosion simulation research. High temperature explosion involves very complex radiation transport process[30], and it is difficult to achieve high energy density and high temperature by traditional experimental means. High power laser is clean, high power density, low electromagnetic interference, and the initial energy density of the explosion source is flexible and adjustable, so it has unique advantages in carrying out high temperature explosion simulation. Using this device is expected to carry out 0~ tens of eV intense radiation explosion environment simulation research.

(3) Laser-driven inertial confinement fusion physics research. In view of the fluid hydrodynamic instability[31-33] and plasma-induced instability[34] faced in the research of laser-driven inertial confinement fusion in recent years, the United States proposed a broadband solid laser solution. The characteristics of excimer laser target surface uniformity can effectively suppress the fluid hydrodynamic instability, and the characteristics of wide frequency band can effectively suppress the plasma instability. Therefore, two kinds of instability studies can be carried out by using this device, which provides support for breaking through the difficult problem of inertial confinement fusion research.

(4) Frontier research in astrophysics. By using multi-beam pulse stacking, the device can shape an arbitrary laser waveform, so as to control the proportion of shock loading and isentropic loading to adjust the material temperature, so as

to achieve a wide range of pressure and temperature. Theoretical calculation and experimental results show that the pressure and temperature achieved by the device are between 0~ 100 GPa and 0~ tens of eV respectively, which can provide good conditions for frontier basic research such as astrophysics.

ACKNOWLEDGMENTS

This research was supported by the Fund of State Key Laboratory of Laser Interaction with Matter (Grant No. Z091230702, Z091240703), and the Fund of National Key Laboratory of Environmental Simulation and Effects of Intense Pulse Radiation (Grant No.NKLIPR2422).

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