Smoothed KrF laser irradiation with a wide
divergence oscillator and a phase plate

Isao MATSUSHIMA, Eiichi TAKAHASHI, Yuji MATSUMOTO,
Isao OKUDA, Susumu KATO, Toshihisa TOMIE, Yoshiro OWADANO
Electrotechnical Laboratory, 1-1-4, Umezono, Tsukuba, 3058568, JAPAN

Abstract
A focused beam profile smoothing technique for high-efficiency KrF laser fusion is reported. The technique consists of the combination of a broadband laser oscillator with wide beam divergence angle and phase plates. The wide divergence angle laser beam vanishes out the speckle patterns caused by the phase plates. Foil targets have been irradiated by the smoothed beam. X-ray radiation profiles of the produced plasmas have been observed. The results have been analyzed as the spatial Fourier spectra.

1. Introduction
Uniform target compression is required to achieve high gain in laser fusion. Various kinds of techniques have been proposed to improve laser irradiation uniformity. Kinoform Phase Plates (KPPs) and two-dimensional smoothing by spectral dispersion (2-D SSD) are recently of interest to glass laser system developers. For KrF lasers, the broad bandwidth is useful for improving the laser irradiation uniformity. For example, the induced spatial incoherence optical smoothing (ISI) technique could make a uniform irradiation profile successfully [1]. Authors have also proposed the broadband random phase (BRP) irradiation technique as a beam smoothing method for the Super-ASHURA KrF laser system [2]. This BRP technique has been extended to two-dimensional smoothing [3]. In these techniques, focused laser beams on targets are angularly dispersed by special optics. The high spatial frequency components in the speckle pattern caused by random-phase irradiation are removed by incoherent overlapping of broadband laser light. Our next idea is to combine a broadband and wide divergence angle laser oscillator with a phase plate. The requirement for the dispersion angle is reduced by the use of the phase plate. In the echelon free ISI method of NRL Nike laser system, a diffuser is used to generate the wide divergence angle incoherent laser beam. Although the echelon free ISI technique of Nike laser system is now well working, we are trying an alternative method for our Super-ASHURA laser system with a simple optical configuration.

This paper reports the beam smoothing technique with using the combination of the broadband laser oscillator with wide beam divergence angle and the phase plate. The effectiveness of this concept has been experimentally observed with the front-end pulse of the Super-ASHURA KrF laser system. Foil targets have been irradiated by the smoothed beam amplified with the two e-beam pumped amplifiers. X-ray radiation profiles of the produced plasmas have been observed with a pinhole camera. The results have been analyzed as the spatial Fourier spectra.

2. Beam smoothing
Although binary phase plates such as random phase plates or Fresnel phase zone plates (PZPs) [4] are simple and useful methods for focused beam profile control, the focused intensity distributions include highly modulated speckles from the interference between different phase-plate elements. To smooth the speckle pattern, we have proposed the one-dimensional and two-dimensional BRP irradiation techniques. In these BRP techniques, focused laser beams on targets are angularly dispersed. The high spatial frequency components in the speckle pattern caused by random-phase irradiation are removed by incoherent overlapping of broadband laser light. A similar effect is can be realized by using the combination of a broadband and wide
divergence angle laser oscillator and a phase plate as shown in figure 1. The typical fine scale pitch of the speckle pattern caused by the random phase plate is

$$w_d = \frac{2 f \lambda}{D} = 2 F \lambda$$  (1),

where $D$ is the incident beam diameter, $f$ is the focal length, $\lambda$ is the laser wavelength, and $F$ is the F-number of the focusing lens. The typical fine scale pitch $w_d$ is similar to the minimum focal spot size of a diffraction-limited beam. In other words, the focal spot profile with the random phase plate consists of many small beamlets of this size. As explained in the principle of BRP [3], the wide beam divergence has the effect of expanding the diameters of the small beamlets on the focal plane. In case of the beam divergence is $N_d$ times diffraction limited (XDL), the diameter is expanded to

$$d = N_d \frac{2 f \lambda}{D}$$  (2).

As a result of using $N_d$ XDL beam, $N_d$ times overlapping of the speckle pattern is expected.

To obtain the smoothed profile, the overlapping should be incoherent. The instantaneous focal spot intensity is highly nonuniform speckle. It approaches a smooth profile only when averaged over intervals much longer than the laser coherence time. The broad bandwidth laser reduces the averaging time for the incoherent overlapping. The typical KrF laser bandwidth is 0.3nm, i.e., the coherence time is 1ps.

In this method, the envelope profile of the focused beam is determined by the phase plate. The laser beam divergence has only the effect of expanding the diameter of the small beamlet in RPP irradiation. Therefore, the requirement for the divergence angle is reduced as compared with the echelon-free ISI, and precise image-relaying is not necessary. These are merits for the laser amplifier system design. On the other hand, the phase plates usually cause an energy loss of more than 10%, and possible shapes of the focused profile are limited by the ability of the phase plates. In comparison with 2D-BRP, this method does not require the wedged etalon. Moreover, the smoothing effect is continuous, while the wedged etalon effect is discrete.

A compact commercial KrF laser oscillator is used as the broadband and wide divergence angle oscillator. It is placed in the front-end part of the Super-ASHURA KrF laser system. The oscillator with a resonator length of 30cm generates a 20 times diffraction-limited (XDL) beam with a size of 2mm (FWHM). A telescope with two single lenses expands the beam size to 10mm. The beam is amplified by a discharge preamplifier and sent to the Super-ASHURA main amplifier chain. The main amplifier system consists of the three stages of electron beam pumped KrF laser amplifiers. The beam is expanded by a concave lens before each amplifier. A concave mirror placed behind each amplifier converges the beam. After the double-pass amplification in each of the three e-beam pumped main amplifiers, the laser beam is focused at the center of the target chamber by the focusing lens. The focal length of the lens is 1.2m. A random phase plate with a 2mm pitch is inserted in front of the lens. The envelope size of the focal spot with the RPP is calculated as 300µm for a diffraction-limited beam. The fine pitch of the speckle pattern caused by the RPP is about 4µm for the diffraction-limited beam. The broadband and 20XDL beam can reduce the nonuniformity as a result of the average of 20 times overlapped speckle pattern.
The focused beam profile has been measured with an oscillator pulse. In this measurement, the beam was not amplified but passed through the entire amplifier chain. The result is shown in figure 2. The speckle pattern of the random phase irradiation has been smoothed out clearly. The wide divergence beam expands the size of the focal spot. The observed spot size is larger than the above calculated size for the diffraction-limited beam. The uniformity of the measured profile is evaluated in spatial frequency domain by Fourier transformation as shown in next section.

![Focused beam profile](image)

**figure 2.** Focused beam profile with the broad-band wide divergence angle oscillator and the random-phase plate. Observed focal spot image (a) and intensity profile in horizontal direction (b) and vertical direction (c) at the center region.

### 3. Target irradiation experiment

Foil targets have been irradiated by the smoothed beam amplified with the two e-beam pumped amplifiers of ASHURA. An iron foil target with the thickness of 100µm is placed on a 1.5mm thick aluminum substratum. The target has been irradiated by the smoothed KrF laser beam with the energy of 12J and the pulse duration of 15 ns (FWHM). X-ray radiation profiles of the produced plasmas have been observed with a pinhole camera. The pinhole camera consists of an X-ray CCD detector and a pinhole of 10µm diameter covered with a titanium foil X-ray filter of 2µm thickness. The overall resolution of the pinhole camera is 18µm. The sensitive X-ray photon energy range is 1~10KeV. Detection of the line emissions with the photon energy of 1~2 keV area from the iron plasma is expected.

The contour plot of the observed X-ray image is shown in figure 3. The image mainly shows the smoothed profile except several hot spots. The uniformity of the measured profile has been evaluated in spatial frequency domain by Fourier transformation as shown in figure 4. The solid line is the intensity distribution in spatial frequency domain by Fourier transformation from the data indicated in figure 2. The thick dashed line is the Fourier spectrum of the X-ray image in figure 3. The thin dotted line indicates the conventional RPP irradiation using a narrow band coherent laser beam. High spatial frequency components are included in the conventional RPP irradiation which corresponds to the strong speckle pattern. These high frequency components are well reduced to less than 1%, when the broad-band and wide divergence beam is used. The high frequency components in the X-ray image are about 2%.

Irradiation nonuniformity will be reduced by thermal conduction and radiation lateral heat flow in laser produced plasmas. In general, more smoothed profile is expected in the X-ray image than the laser profile. In this experiment, the observed X-ray image includes some hot spots. High spatial frequency components of the X-ray image are not less than the laser intensity distribution. There are several possible explanations. The calculated results of X-ray spectra from iron plasma and spectral sensitivity of the pinhole camera imply that the detected X-ray intensity strongly depends on the electron temperature of the plasma. When the electron temperature increases from 200eV to 300eV, the X-ray intensity increases with the factor $10^7$. A small fluctuation in the electron temperature appears as a strong contrast in the X-ray image. Another possible reason is degrading of the laser beam in the amplification. Though self-focusing and filamentation might cause hot spots, the laser intensity is not enough strong for nonlinear laser plasma interaction.
4. Conclusion

In this paper, a beam smoothing technique for KrF laser systems has been presented. A broad band and wide beam divergence angle laser is used with a random phase plate to obtain the smoothed focal spot profile. The observed focused beam profile with the front-end laser output indicates that the speckle pattern caused by the random phase plate has been smoothed out by the effect of broad band and wide divergence angle. The amplified beam by the two e-beam pumped amplifiers has irradiated a foil target. The X-ray radiation profiles of the produced plasmas have been observed with a pinhole camera. The X-ray images show the smoothed profiles except several hot spots. The results have been analyzed as the spatial Fourier spectra. Some possible reasons for the hot spots have been discussed. The observation of the amplified laser beam profile with an adequate attenuator is undergoing.

In the above reported experimental results, a random phase plate has been used as the phase plate to control the focused beam profile. As long as random phase plates are used, the smoothed beam profile is limited to Sinc function. To obtain a flat-top style profile, a PZP [4] type phase plate has been fabricated. Although some improvement is needed, the experimental result has shown the flat-top profile essentially.

References


figure 3. Contour plot of the observed X-ray image.

figure 4. Fourier spectra of observed focal spot images with narrow-band random-phase irradiation (thin dotted line) and broad-band wide divergence angle beam (solid line). The thick dashed line is the Fourier spectrum of the X-ray image.