X-ray and EUV micro-imaging systems for laser ICF diagnostics

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Abstract. Plasma imaging diagnostics plays an important role for laser ICF. Based on the urgent need to carry out high-resolution, high-throughput plasma diagnostics, grazing-incidence X-ray Kirkpatrick-Baez (KB) microscopes and normal-incidence EUV Schwarzschild imaging system were developed. The X-ray multilayer KB microscopes were successfully been applied in the physics experiments of SGII laser facility. Combined with streaked camera, the Mo-backlit implosion flow line of hollow Carbon-Hydrogen (CH) spherical target was obtained in SGII. The 4.75keV single-channel and four-channel KB microscopes were also developed for self-emission and short-pulse backlit imaging diagnostic of CH cylindrical target. In addition, according to the need of ultra-short laser pulse plasma diagnostics, the Schwarzschild imaging system working at 68eV was researched, and the physical experiments of hot electron transport with Schwarzschild imaging system were performed in SILEX-I laser facility.

1. Introduction
Laser inertial confinement fusion (ICF) is of great significance for national economy, national security, and basic research such as plasma physics[1,2]. X-ray imaging diagnostics of implosion area is an important region of laser ICF. Through X-ray imaging of high-temperature and high-density plasma implosion area, and coupled with spectrometry or time-resolved measurement devices, the diagnostics system of time, spatial, and spectrum characteristics can be formed. The basic state parameters such as irradiation uniformity, symmetry of compression, radial convergence, implosion time and velocity, electron temperature and density distribution, and other important information can be obtained to provide experimental references for structural design of the target, the optimization of laser irradiation conditions and simulation programs. The Kirkpatrick-Baez (KB) microscopes provide higher throughout and resolution than pinhole imaging. Several successful implementations such as X-ray backlighting or self-luminescence imaging implosion core area of high-energy X-ray imaging, gated monochromatic X-ray imaging (GMXI) and grating spectral imaging have been made in OMEGA and LMJ etc[3,4]. A series of ICF physics experiments such as hydrodynamic instability growth, ablation evolution, and plasma compression uniformity have been launched to obtain quantitative diagnostic information about plasma temperature \(<kT>\) and density \(<\rho R>\)[5-10]. Based on Chinese present

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situation lacking high-precision X-ray imaging devices and the urgent need to carry out high-quality X-ray space-time diagnostics, the paper carried out the research of X-ray multilayer KB imaging system and EUV Schwarzschild imaging system.

2. Optical design of X-ray multilayer KB microscopes

KB microscope as shown in figure.1 consists of two concave spherical mirrors normal perpendicular to each other[11]. The perpendicular structure plays a role to overcome the strong astigmatism. Rays from object point (A) are successively reflected at grazing angles \( (\theta_1 \text{ and } \theta_2) \) by two mirrors, and obey the Coddington equations to form a two-dimensional image \( (A') \). The KB microscope has serious off-axis aberration, and the resolution decreases obviously with the increase of object field. We have analysed the influences of geometric aberrations and optical machining tolerances on imaging quality, and the imaging quality criterion of KB microscope was established from spatial resolution, MTF and optical efficiency. The work focused on the influences of grazing incidence angle, radius of curvature, and magnification on MTF in different field of view, and provided theoretical and experimental references for the selection of initial structural parameters.

![Figure 1. Schematic of single-channel KB microscope](image)

Combing previous researches[12,13], the grazing incidence angle of KB microscopes used in China ICF diagnostics is about 1° to ensure imaging quality, optical efficiency and energy resolution. The radiuses of curvature and length of KB mirrors are about 20m and 10mm, to get better image quality and adequate optical efficiency. The magnification is about 10-15 × considering the spatial resolution of image detector, signal response threshold and other special considerations. The spatial resolution decreases near-linearly from 2 microns at central field to near 5 microns at the 200 microns object field. Base on several ICF diagnostic experiments with different types, we designed a series of KB microscopes with detailed optical parameters shown in Table.1. The 4.75keV KB microscope is a four-channel imaging system and will be coupled with X-ray framing camera.

| X-ray energy \(^a\) | Radius | Grazing angle \(^b\) | Magnification | Object distance |
|-------------------|--------|---------------------|---------------|----------------|
| 2.5keV \(^c\)    | 1839mm | \( \theta_1=1.0°; \theta_2=1.0543° \) | \( M_1=15×; M_2=14.12× \) | 171.3mm        |
| 4.75keV \(^d\)   | 20000mm| \( \theta_1=1.0°; \theta_2=1.0442° \) | \( M_1=8×; M_2=7.56× \) | 196.3mm        |
| 8keV \(^e\)      | 19500mm| \( \theta_1=1.0°; \theta_2=1.0479° \) | \( M_1=10×; M_2=9.44× \) | 187.2mm        |

\(^a\) The multilayers were designed and coated for different X-ray energies.

\(^b\) \( \theta_1 \) stands for the grazing angle of first KB mirror , and \( \theta_2 \) for the second mirror.

\(^c\) Used for imaging experiment of implosion flow line of hollow CH spherical target.

\(^d\) Used for self-emission and short-pulse backlit imaging diagnostic of CH cylindrical target.

\(^e\) Used for fast ignition Cu-Kα imaging experiments.
3. Imaging experiments of KB microscope

Imaging experiments of KB microscope is the essential issue for the ICF applications. Along with object field deviates from central field, the spatial resolution of KB microscope decreases rapidly, so the assembly and alignment must reach the positioning accuracy of about 30μm to indicate the best object field. Firstly, we must find the best object field of KB microscope through X-ray imaging experiments in the laboratory, and then the best object field was replaced by a removable pointer with an φ200μm reference ball. The ball pointer and KB microscope was connected together with high-precision industrial linear guide which ensured the repeat positioning accuracy up to 20μm.

3.1. Imaging experiments in the laboratory

We have assembled and tested KB microscopes listed in table.1. Figure.2 shows the 8keV KB imaging of 600# Au grid which simulates a resolution pattern. The object was backlit by the copper anode fine-focus of the x-ray tube operated at 45kV and the tube current of 20mA. The image was recorded by a scintillator x-ray CCD (Photonic Science: XDI-50) with 30min exposure time. The CCD pixel size (6.45μm×6.45μm) is small enough to obtain high-resolution imaging results for the magnification M=10×. The image is very clear in central field and gradually blur out with the increase of the field of view. The spatial resolution measured from figure.2, which corresponds to the distance of 20% to 80% of the minimum intensity to the maximum intensity, is approximately 2μm at central field, and better than 5μm within ±200μm object field. The ununiformed brightness is due to the x-ray source, which has been tested by directly projection. The image quality in laboratory experiments was seriously influenced by the background noise of x-ray CCD because of the long time exposure, and it will be improved in the actual ICF experiments in a 2-3ns, short-pulse time.

Figure 2. Image of 600# Au grid taken with Copper X-ray tube.

Figure 3. These Image of 2000# Au grid taken with SGII laser.

3.2. Imaging experiments in SGII laser facility

We replaced the Au grid with the ball pointer as shown in figure.2, and tested image characteristics of KB microscope in Chinese SGII laser facility. The reference ball of KB microscope was aligned to the chamber centre, and then replaced by a 2000# Au grid. The backlit X-rays were produced by Cu target driven by the ninth laser beam, and the spectral purity is improved through 4μm thickness Cu filter. The imaging results were shown in figure.3. The separation of the Au grid measured by SEM is 12μm with 5μm width. It is obvious that the clearest grid is located in the brightest region of the total field. For practical applications to ICF fast ignition experiments, the diagnostic target should be placed in this region to obtain the best image resolution and intensity.

Another two KB microscopes list in table.1 were also successfully been applied in the physics experiments of SGII laser facility. Combined with streaked camera, the Mo-backlit implosion flow line of hollow CH spherical target was obtained by 2.5keV KB microscope in SGII. The self-emission and short-pulse backlit imaging of CH cylindrical target was achieved by 4.75keV KB microscope.
4. Schwarzschild microscope for diagnostics of hot electron transport

In addition, according to the need of ultra-short laser pulse plasma diagnostics in fast ignition fusion, we also developed the EUV Schwarzschild imaging system working at 68 eV. The spatial distribution of hot electron, caused by ultra-short laser-plasma interaction, can be measured by Schwarzschild imaging system due to it is an achromatic, higher spatial resolution, larger field of view and larger collecting area system [14-17].

The physics experiments of Schwarzschild microscope were performed with 286 TW SILEX-I laser facilities. As shown in figure 4, the 30 fs, 800 nm laser pulses with energy of 4.4 J was focused by a \( f/3 \) off-axis parabolic mirror at 21° from the copper wire axis onto the edge of the target. The EUV intensity emission profile along the copper wire caused by hot electron is found by Schwarzschild microscope as shown in figure 5. As the transport distance increases, the intensity of radiation decreases.

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