A four-channel multilayer KB microscope for high-resolution 8-keV X-ray imaging in laser-plasma diagnostics

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A four-channel multilayer Kirkpatrick-Baez (KB) microscope is developed for the 8-keV X-ray imaging of experiments on laser inertial confinement fusion (ICF). A periodic multilayer that works at 8 keV and with a grazing incidence angle of 1° is coated on reflective surfaces to achieve a spatial resolution higher than 5 μm and an effective solid angle higher than 10−7 sr. A precise assembly is realized by a conical reference cone to couple with an X-ray framing camera. This study provides detailed information on an optical and multilayer design, assembly method, and experimental results with a Cu X-ray tube. The instrument provides a high-resolution and high-throughput X-ray image for backlit or self-emission imaging of laser plasma at Cu Kα line radiation in Shenguang series laser facilities.

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X-ray imaging is a useful method in the plasma diagnostics of laser inertial confinement fusion (ICF). The detailed spatial and temporal (∆t=35−100 ps) evolution of plasma density or temperature can be obtained through high-resolution two-dimensional X-ray framed imaging of laser-produced plasma in backlit or self-emission mode. Four-channel Kirkpatrick-Baez (KB) microscopes that provide a better spatial resolution (3−5 μm in several hundred microns field of view) and a larger collecting solid angle (∼10−7 sr) than X-ray pinhole arrays have been used in ICF experiments to observe precise physical processes, such as hydrodynamic instabilities and evolutions of distortions in the implosion of the ICF target.[1] These instruments use the total external reflection of single-layer metal coatings (e.g., Ir or Pt) on the reflective surface, and the working energies are mainly in the soft X-ray region, such as 1.25 keV (U N-band) for X-ray backlighter[2] and 2.79 keV (Cl He-like Ly α) for X-ray self-emission[3].

Friesen et al.[10] developed a single-channel KB microscope for the 8 keV X-ray imaging of fast ignition experiments in Titan laser facility. The 25.4-mm diameter reflective surfaces with a curvature radius of 20 m were coated with Pt and operated at a grazing angle of 0.5°. The actual spatial resolution is only 15 μm in the center field and 30 μm over the 300 μm object field. Multilayer coatings based on Bragg diffraction 2Dsinθ=mλ are a good solution to achieve a large grazing angle with a narrow high-throughput bandpass.[11] Marshall et al.[12,13] designed a four-channel multilayer KB microscope that is capable of imaging X-ray emission in the range of 7−9 keV. The reflective surfaces with a curvature radius of 28 m were coated with W/B4C multilayer and operated at a grazing angle of ∼0.7°. The measured peak reflectivity was up to 80% at a grazing angle of 0.72°, and an X-ray image with a 5-μm resolution over a ∼400 μm object field was obtained.

In this study, we develop an 8-keV four-channel multilayer KB microscope for X-ray imaging diagnostics in Shenguang series laser facilities. Firstly, we describe the optical design of the four-channel multilayer KB microscope and the assembly method to accurately control image separations on the image plane because of the limited detector size of the framing camera. Then, we attempt to maximize the response of 8 keV through the coincidence of the grazing angles between nominal and actual values. At last, we describe the 8-keV X-ray experiments and the imaging results of the four-channel KB microscope, followed by a brief conclusion and discussion of its possible applications.

The KB microscope consists of two perpendicular concave spherical mirrors in tandem. The imaging equation...
of each mirror in the meridian plane is given by\cite{14}

\[
\frac{1}{u} + \frac{1}{v} = \frac{1}{f} = \frac{2}{R \cdot \sin \theta}, \tag{1a}
\]

\[
u = \frac{R \sin \theta}{2 \left(1 + \frac{1}{M}\right)}, \tag{1b}
\]

where \(u\) is the object distance from the target to the mirror center, \(v\) is the image distance from the mirror center to the image plane, \(f\) is the focus distance, \(R\) is the radius of curvature of the mirror, \(\theta\) is the grazing incidence angle, and \(M = v/u\) is the magnification. The spatial resolution expressed by lateral aberration and the geometric collecting solid angle expressed by the solid angle are respectively given by\cite{9,11}

\[
\delta = \frac{3d^2}{8R} + \frac{d}{R \cdot \sin \theta} \cdot q, \tag{2}
\]

\[
\Omega = \left(\frac{d \cdot \sin \theta}{u}\right)^2 = \left[\frac{2d}{R(1 + 1/M)}\right]^2 \approx \left(\frac{2d}{R}\right)^2, \tag{3}
\]

where \(d\) is the mirror length along the optic axis, and \(q\) is the object field of view. The first term on the right-hand side of Eq. (2) is the primary on-axis spherical aberration, which determines the best achievable spatial resolution of the KB microscope, and the second term is the obliquity of the field. The values of the above-mentioned parameters should be determined by both the resolution requirement and the actual flux. The radius of curvature and the length of each mirror are selected to be \(\sim 20\) m and \(10\) mm, respectively, which are similar to those in Ref. [11], to achieve a spatial resolution better than \(5\) \(\mu\)m in the central field and a geometric solid angle of \(\sim 10^{-6}\ sr\). The reflectivity of X-ray multilayer mirrors affects the effective solid angle. Therefore, the grazing incidence angles of the X-ray multilayer mirrors were selected at \(\sim 1^\circ\), and the effective solid angle was up to \(2.5 \times 10^{-7}\ sr\) under an X-ray multilayer reflectivity of 50\%. Meanwhile, Eq. (2) shows that off-axis aberration is improved under a grazing incidence angle larger than those in Refs. [10,12]. The magnification was selected to be \(\sim 10\times\) because a small magnification would lead to a relatively high intensity in the image plane, although the actual spatial resolution was limited by the pixel size of the image detector. The spatial resolution simulated by the ray-tracing method with the use of Zemax software decreases near-linearly from \(2\) \(\mu\)m at the central field to near \(8\) \(\mu\)m at the \(\pm 200\-\mu\)m object field.

The four-channel KB microscope shown in Fig. 1(a) utilizes four concave spherical mirrors stacked in two perpendicular pairs to form four images of the ICF target. The instrument also follows Eqs. (1)–(3), but X-ray images must be separated to specific distances to couple with the microstrips of the framing camera. If common assembly methods based on optical contact are used, the image separations of the instrument are up to \(57\) mm, which exceed the maximum detector size (\(\Phi=30\) mm) of the existing framing camera on Shenguang series laser facilities\cite{15}. The assembly method of the four-channel KB microscope we used is similar to that in Ref. [16], which uses ball plungers to press the concave mirrors on the rectangular conference core. However, the rectangular reference core was improved as a conical one with angle \(\alpha\) to control the image separations (2L) at a specific value of \(20.0\) mm. The geometric relations of the four-channel KB microscope in the meridian plane are given by Fig. 1(b) with the following equations:

\[
y = R \cdot \cos \alpha - u \cdot \sin (\theta + \alpha) - \sqrt{R^2 - (d \cdot \cos \alpha + R \cdot \sin \alpha)^2}, \tag{4}
\]

\[
L = u \cdot [M \cdot \sin (\alpha - \theta) - \sin (\alpha + \theta)]. \tag{5}
\]

The best object field of the four channels must be located at the same position because of the rapid decrease in spatial resolution at the off-axis field. However, an error in the radius of curvature (\(\Delta R\)) from manufacturing leads to deviations in the best object field of different channels. This error can be compensated by a precise spatial alignment and the resulting change in the grazing angle. Equation (1b) shows that the grazing angle will have the same change of \(\sim 0.05^\circ\) if \(\Delta R/R=5\%\), which significantly influences the reflect efficiency of the 8-keV X-ray multilayer with a narrow angular width of \(\sim 0.1^\circ\). Therefore, the optical parameters of the four-channel KB microscope as listed in Table 1 were designed according to the measured results of the radius of curvature. As measured by an optical profiler (Contour GT-X3,Bruker, USA), the mean curvature radius of the four concave mirrors is 19.5 m with an root mean square (RMS) variation of 0.3 m, which corresponds to a grazing angle change of \(\sim 0.015^\circ\). The conical reference cone has a thickness of \(2\mu=13.515\) mm and a conical angle \(\alpha=1.193^\circ\) in the meridional direction and \(2\mu=15.183\) mm and \(\alpha=1.248^\circ\) in the sagittal direction. The thickness and angle accuracy \(\Delta(2\mu)\) and \(\Delta\alpha\) of the conical reference core can

### Table 1. Optical Parameters of the Four-Channel KB Microscope

<table>
<thead>
<tr>
<th>Direction</th>
<th>R(m)</th>
<th>(\theta(\degree))</th>
<th>(d(\mu\text{m}))</th>
<th>(u(\mu\text{m}))</th>
<th>(v(\mu\text{m}))</th>
<th>(\Omega_{\text{geo}}(\text{sr}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meridian</td>
<td>10.00</td>
<td>0.9730</td>
<td>182.1</td>
<td>1821.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>19.5</td>
<td>10.00</td>
<td>8.0 \times 10^{-7}</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sagittal</td>
<td>9.3</td>
<td>1.0310</td>
<td>194.1</td>
<td>1809.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1. Schematic of the four-channel KB microscope. (a) Optical structure for time-gated X-ray imaging. (b) Geometric parameters determine image separations in the meridian plane.
The reflectivities are $\sim 0.973^\circ$ and $1.031^\circ$ respectively. These angles correspond to the $\sim 300 \mu m$ object field and can fulfill the requirements of the KB microscope. The grazing angle change of $\sim 0.015^\circ$ caused by the measurement error of the radius of curvature (0.3 m RMS) corresponds to a decrease in reflectivity of $\sim 2\%$.

X-ray imaging experiments of the four-channel KB microscope in the laboratory are essential before the microscope can be used for ICF experiments. The best object field and the actual spatial resolution can be characterized by X-ray imaging results. A 600# Au grid (42.0-µm period with 6-7-µm line width calibrated by scanning election microscope (SEM)) simulated a resolution pattern and was backlit by a copper X-ray tube (8 keV) operated at 37.5 kV and a tube current of 20 mA. A scintillator X-ray CCD (XDI-50, Photonic Science, UK) with 696 × 520 pixels and 12.9 × 12.9 (µm) pixel size was placed on the image plane. The distance between four X-ray images was controlled at 20 mm by a motorized $x$-$y$-$z$ axis translation stage fixed with X-ray CCD. Figure 3 shows the imaging results of the grid obtained by the four-channel KB microscope after the assembly, in which the exposure time is 20 min with 83 gain. The ununiformed brightness is due to the X-ray source, which has been tested by direct projection. A hole with about 150-µm diameter in the grid was used as a reference of the best object field and the image separations. The actual hole separations between four channels were $\sim 20.2$ and $\sim 18.8$ mm in the horizontal and vertical directions, respectively, which were in good agreement with the designed value of 20.0 mm.

The image of the Au wire is very clear in the central field (the reference hole) and gradually blur out as the field of view increases. Figure 4(a) shows the intensity distribution of channel 2 along the horizontal direction. The actual magnification of the four-channel KB microscope can be calculated by comparison of the period of the grid imaged by CCD and that calibrated by SEM. The value is $9.68 \times$ and $9.17 \times$ in the horizontal and vertical directions, respectively. The measured spatial resolution of channel 2 is shown in Fig. 4(b), which corresponds to a distance of 10% to 90% of the minimum intensity to the maximum intensity. It is approximately 5 µm within ±100-µm object field and better than 10 µm...
Fig. 4. Image quality of a 600# Au grid obtained by the four-channel KB microscope at 8 keV. (a) Intensity distribution of channel 2 in the sagittal direction. (b) Comparison of the measured and simulated spatial resolutions of channel 2.

Fig. 5. Theoretic energy response of the four-channel KB microscope.

within ±200-µm object field. The simulated resolution by Zemax is also shown in Fig. 4(b). The image quality is influenced by the diffraction effect, figure error, and surface roughness of the concave spherical mirrors, especially for the central field. An improved spatial resolution can also be achieved by the X-ray CCD with a small pixel size.

In conclusion, a four-channel multilayer KB microscope for the high-resolution 8 keV X-ray imaging of experiments on laser inertial confinement fusion is investigated. A spatial resolution of 4-6 µm within the ±200-µm object field is achieved in the X-ray experiments. The precise control of image separations of the four-channel KB microscope is realized by a conical reference cone, which also has the ability to reflect soft X-rays lower than 3 keV. Figure 5 shows the energy response of the instrument subtended by two reflections of KB mirrors. The reflectivities at 1.25 keV (U N-band) and 2.5 keV (Mo L-band) are higher than 60% and 20%, respectively. Therefore, the instrument is also applicable to soft X-ray imaging diagnostics, such as measurements of the growth rate of Rayleigh-Taylor instability and implosion trajectory of a hohlraum-radiative-driven capsule[10,17].

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References