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摘要:近年来,人们付出很大精力研制新的具有独特性能的同步辐射装置和自由电子激光器,而飞秒激光等离子源可提供具有高峰值亮度的超短 X 射线脉冲,用来作为波荡器辐射的补充 X 射线源。此外,所有最新型的 X 射线源的诊断和应用也都需要专用 X 射线光学元件或仪器。X 射线光谱测量是激光聚变应用中最重要等离子诊断方法之一,该方法根据实验目的,可获得单色 X 射线图像或与空间或时间分辨相组合的高分辨率图像。已经研制出拥有多达 10 个环状弯晶的高精单色成像仪,用以研究激光聚变实验中的内爆过程并通过获得的数据对等离子体参数的时间分辨图做出评估。大功率飞秒激光器可提供实用的相对价格不高的大功率 X 射线脉冲源,但需要有发光效率,能量分布,以及热电子传输方面的信息来实现理想 K 层辐射线或者连续 X 射线输出的最大化,以便得到相当于同步辐射输出的峰值亮度。把这些新的射线源与弯晶光学元件相组合,可完成亚皮秒时间量级的衍射实验。激光泵浦的 X 射线探针实验已经展示了若干晶体在 250 fs 内的结构变化。作者所在研究所使用光线追踪和布拉格反射方法设计了 1D 或 2D 或 1D 与 2D 结合的弯晶 X 射线光学仪器。在仪器制备过程中,非常注重晶体完整,反射选择的优化,弯曲精确,以及成像和反射特性的测量,还使用 X 射线形貌相机和衍射仪对分析器晶体的相关特性做了测试。

关键词:X 射线光学;弯晶;X 射线诊断;激光产生等离子体;X 射线衍射

中图分类号:O434.19;TH744.15 **文献标识码:**A

Bent crystal X-ray optics

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Abstract: Much effort has been exerted both in the development of modern dedicated synchrotrons and free electron lasers with unique properties. Femtosecond laser plasma sources provide ultra-short X-ray pulses of high peak brilliance and can thus be complementary X-ray sources to the undulator based sources. All these modern X-ray sources need dedicated X-ray optics for diagnostics and applications, respectively. X-ray spectroscopy is one of the most important diagnostics of plasmas in the context of laser fusion. Depending on the aims of these experiments, monochromatic X-ray images or high resolution spectra combined with either spatial or time resolution can be obtained. Sophisticated monochromatic imagers with up to 10 toroidally bent crystals have been developed to study the implosion processes in laser fusion experiments; time-resolved maps of plasma parameters are evaluated from the data.

High-power femtosecond lasers provide a practical, relatively inexpensive, powerful X-ray pulse source. Information on production efficiency, the energy distribution and transport of hot electrons is needed to maximize X-ray output in desired K-shell emission lines or continuum ranges so that peak brilliances comparable to those of synchrotrons may be feasible. Combining these new sources with bent crystal optics enables diffraction experiments on sub-picosecond time scales. Laser-pump X-ray-probe experiments have shown evidence of structure changes in several crystals within 250 fs. These X-ray optics have been designed in our institute using ray tracing and Bragg reflection codes for the 1D or 2D bent crystals or combinations thereof. In the preparation process, extreme care has been taken over crystal perfection, selection of optimum reflections, precision bending, measurement of imaging and reflection properties. X-ray topographic cameras and diffractometers are used to check the relevant properties of the analyzer crystals.

Key words: X-ray optics; bent crystal; X-ray diagnostics; laser produced plasma; X-ray diffraction

1 Bent crystals for X-ray diagnostics of laser-produced plasmas

Hot, dense plasmas, produced at laser intensities $I=10^{14} \sim 10^{20}$ W/cm² emit strong X-ray pulses. X-ray emission shows a strong dependence on spectrum, space and time coordinates. Further, X-ray emission depends on the emission direction and may show polarization effects. One of the greatest challenges is the production of fusion energy on earth. In the industrial confinement fusion scheme D-T fuel is enclosed in small capsules to be irradiated by many laser beams (direct drive) or by laser-produced hohlraum radiation (indirect drive) eventually ignited by ultra-short laser pulses (fast ignitor scheme). To diagnose electron temperature and density during the implosion process a small fraction of argon is mixed to the D-T fuel. As shown in Fig. 1, instabilities, mainly Rayleigh-Taylor ones, occur in the compression process.

To get full information of the implosion process we need relative resolution of $10^2 \sim 10^3$ in

- * X-ray line spectra from an X-ray spectrometer
- * X-ray images, at best in a spectral line
- * Time resolved data

Fig. 2 shows three coordinates schematical-

ly, the spectrum or energy, one spatial, and the time coordinate. The right upper corner means we have high spatial resolution, we image the

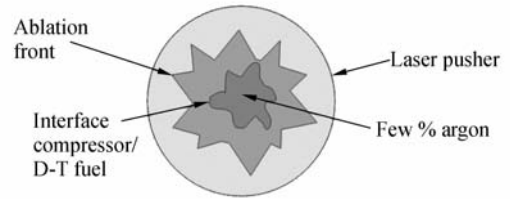


Fig. 1 Schematic diagram of target compression in the fusion

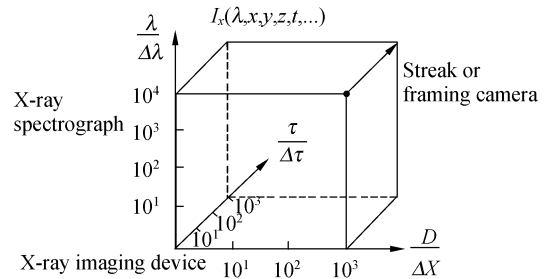


Fig. 2 Required spectral, spatial, and time resolution

source quasi-monochromatically, and we have time resolution of the process. The latter is usually realized by special detectors, streak or framing cameras. Fig. 3 shows monochromatic X-ray imaging of X-ray spectroscopy. Fig. 4 shows monochromatic X-ray imaging for a magnification factor of unity of laser-produced plasmas^[1-2]. By moving the plasma source towards the crystal, we have realized X-ray magnifications of 30. To study implosion of D-T capsules

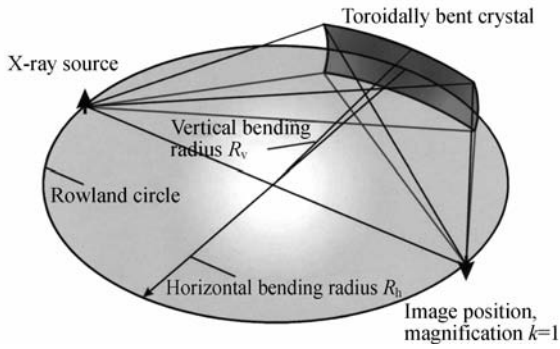


Fig. 3 Monochromatic X-ray imaging of X-ray spectroscopy

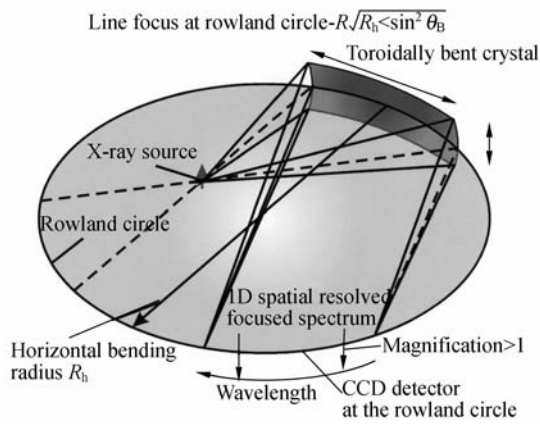


Fig. 4 Monochromatic X-ray imaging of a laser-produced plasma

at the GEKKO laser facility at Osaka, we built X-ray imaging devices with 2, 5, and 10 toroidally bent crystals^[3-4]. Ray tracing and intensity studies have been performed^[5-6], together with tests on smaller laser facilities, beforehand. All experiments were successful and gave data about the time evolution of the implosion process^[7]. Although there are more imaging devices in the X-ray range, such as refractive lenses, grazing incidence optics, zone plates, polycapillaries, use of bent crystals has a unique spectral resolution and high entrance aperture.

Parallel to the X-ray imaging devices we have developed sophisticated X-ray spectrometers with relative spectral resolution up to 10 000. They use either cylindrical crystals in the vertical dispersion mode^[8-9] or conical crystals^[10] combined with a streak camera. Such X-ray spectrometers are used in sophisticated stud-

ies to reveal the motion of radiators, the presence of strong electric fields, *etc.* They may also serve in optimization of X-ray yield for application experiments, when the source can be considered as an intense pulsed microfocus X-ray source.

2 Bent crystals for ultra-fast X-ray diffraction experiments

Titanium-sapphire lasers of moderate size and cost can easily deliver pulses of 10~100 fs duration at intensities of $10^{15} \sim 10^{18}$ W/cm² on the target. The interaction of laser radiation with matter has been reviewed for fs lasers^[11]. Based on this knowledge, a Particle-In-Cell (PIC) code was combined with a Monte Carlo (MC) code to study the yield, spectrum, focus size and pulse duration of X-ray emission. The PIC code delivers the first distributions of electrons from the surface plasma, that impinge on initially cold target regions. The basic process is, to a large part, the stopping of fast electrons (MC code) as takes place in a conventional X-ray tube. Thus, X-ray spectrum produced by fs lasers shows K α radiation of the target element. There are theoretical^[12] and experimental^[13-15] results on the optimization of the X-ray yield. Now, the peak brightness (of *e. g.* Cu K α radiation) from table-top fs lasers is comparable with that of third generation synchrotrons. However, the X-ray pulse duration is a factor 100 up to 1 000 shorter for fs laser sources, that has a unique benefit for ultra-fast diffraction experiments. The most compact, laser-based X-ray sources^[16-17] are those working at pulse rates above 1 kHz. Zhavoronkov *et al.* have reported about 6.8×10^{10} phots/s at the Cu K α wavelength from a 10 μ m X-ray focus. These short-pulse, laser-based X-ray sources have a great potential to study very fast processes in matter on a

fs scale.

A rapid change of the optical reflectivity on surfaces is known, from optical pump-probe experiments. As the X-ray diffraction pattern from single crystals depends more directly on atomic positions, the first optical-pump, X-ray probe experiments^[18] on organic crystals were performed a decade ago. Later non-thermal melting^[19] of InSb single crystals, the dispersion of acoustical and optical phonons^[20-21] were studied. A scheme of such pump-probe experiments is shown in Fig. 5. The amplified laser beam is divided in one part (90%) for production of $K\alpha$ X-rays, and the other (10%) heats or shocks the sample crystal after passing through a delay line. The X-ray pump beam is Bragg-reflected by a toroidal crystal to a spot on the sample crystal. These monochromatic and convergent X-rays impinge on the sample volume at slightly different angles. The crystal reflects these inclined beams according to its rocking curve. Thus the time-dependent rocking curve is obtained as a spatial intensity distribution on the CCD detector. Time resolution of structural changes is given by the time delay of the two split laser beams. Further, there is an alternative concept of time-resolved diffractometry for some synchrotrons, where a synchrotron pulse is shortened by the pulse-slicing technique or registration is achieved by a streak camera detector triggered by a GaAs photoconductive switch^[22].

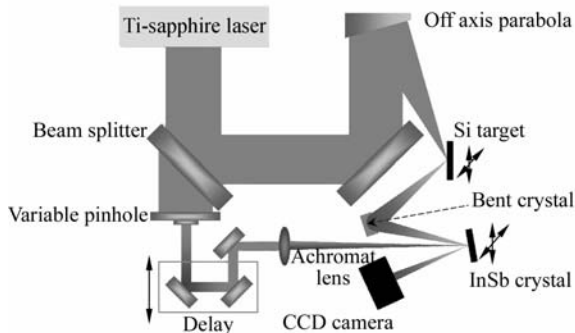


Fig. 5 Setup of an optical pump X-ray probe experiment^[13]

3 Fabrication and test of bent crystals

The design of bent crystal optics starts by using combined ray tracing^[5] and rocking curve^[23] calculations. Then we select the best available crystals suitable for the experiment by X-ray topography^[24]. As curvature radii are in the order of 0.1 m to 1 m, crystals must be extremely thin, around 70 μm in the first instance. Fig. 6 shows the fabrication steps based on optical contact of the thin, structurally perfect crystal wafer with a glass former. This technique is called bonding in semiconductor technology. It is useful that this technology using one glass former produces more than five equally-bent crystals^[4].

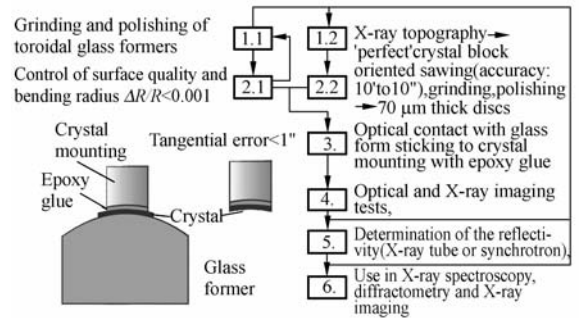


Fig. 6 Fabrication and test of toroidally bent crystals by optical-contact bending

4 Conclusions

Bent crystals known for 75 years have found new application areas. The complex process of implosion of a laser-fusion pellet was studied by a 10-crystal monochromatic imager combined with a time-resolving framing camera. Also, bent crystals are essential parts of fs laser pump X-ray probe experiments to study structural changes in the 100 fs range. Nowadays the fabrication and test of bent crystal is well understood.

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