Calibrated high-energy x-ray continuum crystal spectrometer for ICF diagnostics

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Two separate crystal spectrometers are being developed for high-energy x-ray continuum measurements at Aurora and NOVA for ICF diagnostics. Both spectrometers are required to record hard x-ray continuum over the wide energy range of 5–35 keV. Continuous spectral coverage is required with low-energy resolution $E/\Delta E$ of the order of 10 to 20. The spectrograph for NOVA will use a Laue transmission geometry while the Aurora spectrograph will use a
de Broglie curved crystal geometry. The instrumentation for Aurora will also include two discrete, time-resolved, high-energy channels for recording integrated continuum in the 40–60 keV and 60–90 keV bands. Individual component and end-to-end system calibration and alignment for both spectrographs will be done using the high-energy x-ray calibration facilities at KMS. We describe these spectrograph designs and discuss and compare the factors that affect their performance.

I. INTRODUCTION

Measurement of the high-energy x-ray continuum produced in laser-plasma interactions is an important diagnostic for determining the effect of parametric instabilities on laser-plasma coupling. In the past the primary diagnostic for studying hard x-ray continuum for energies greater than 5 keV has been nondispersive channelized detectors such as filtered scintillators or filtered x-ray diodes. For the diagnostics planned for Aurora and NOVA, continuous recording of the hard x-ray spectrum is required over a broad energy interval of 5–35 keV with moderate energy resolution $E/\Delta E$ of the order 10–20. The fact that the instrument must provide continuous energy coverage for a pulsed source requires a dispersive design using crystals as the dispersing elements.

We are developing two separate dispersive crystal spectrometers using different crystal geometries that attempt to meet the requirements for Aurora and NOVA. We discuss these designs and the factors that affect their performance.

II. INSTRUMENT PACKAGE FOR AURORA

The instrument package for Aurora includes, in addition to the crystal spectrometer, two high-energy channels for time-resolved, energy-integrated continuum measurements in the 40–60 keV and 60–90 keV energy bands. The space requirements and the requirement that data on the crystal spectrometer be acquired electronically determined the design for this instrument. Of the many crystal configurations considered, only a de Broglie[1,2] geometry was found to be sufficiently compact that the space constraints could be met while still achieving the required energy range.

The de Broglie geometry adapted for high-energy x rays is illustrated in Fig. 1. Because Bragg angles are close to grazing incidence a relatively large energy range is diffracted by the convex-curved crystal in the forward direction. The diffracted spectrum is sufficiently compressed that it can be recorded with low-energy resolution with a single, compact position sensitive detector. By close coupling the detector to the crystals it is possible to obtain the low dispersion required for high sensitivity to continuum. A feature of this geometry is that due to the convex curvature of the crystal the source is demagnified.[3] For a slitless spectrograph with resolution limited by source size this has the effect of reducing the dependence of energy resolution on source size. The main disadvantage of the de Broglie geometry at high energies is that Bragg angles are close to grazing incidence so that accurate placement of stops is critical to avoid direct beam shine through and prevent background.

The mechanical layout for the continuum spectrograph identifying the major components is given in Fig. 2. A set of stops in the collimator assembly defines the optical axis to which the crystals are aligned. The crystals are adjustable in both height and angle. The detector housing has a 0.025 cm Be window that provides both a 4 keV low-energy cutoff to block internal fluorescence and vacuum isolation for the MCP. The MCP housing is isolated from the target chamber vacuum and is pumped separately. Heavier shielding is used externally where appropriate.

The crystals chosen are PET 002 ($2d = 8.75$ Å) and LiF 200 ($2d = 4.03$ Å). Each crystal is 50 cm long and 1 cm wide, has a radius of curvature of 20.32 cm, and diffracts Bragg angles over the range of 5°–17°. Both crystals are mounted on aluminum substrates. Aluminum fluorescence from the exposed portion of the crystal mounts is blocked by the Be window on the detector housing. There is sufficient overlap in the energy range diffracted by each crystal that cross calibration is possible. These crystals were chosen because they have appropriate grating spacings for the dispersion required, minimal fluorescence, and have high mosaic integrated reflectivity at small Bragg angles.[4] Figure 3 gives the diffracted energy as a function of position along the de-

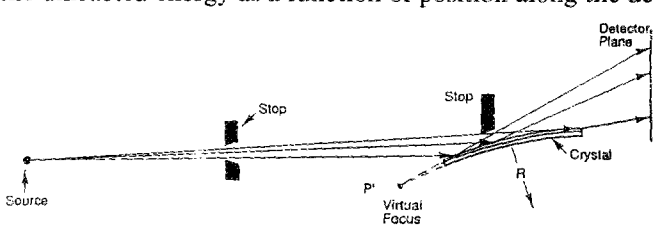

FIG. 1. Geometry for convex-curved de Broglie Bragg reflection spectrometer.

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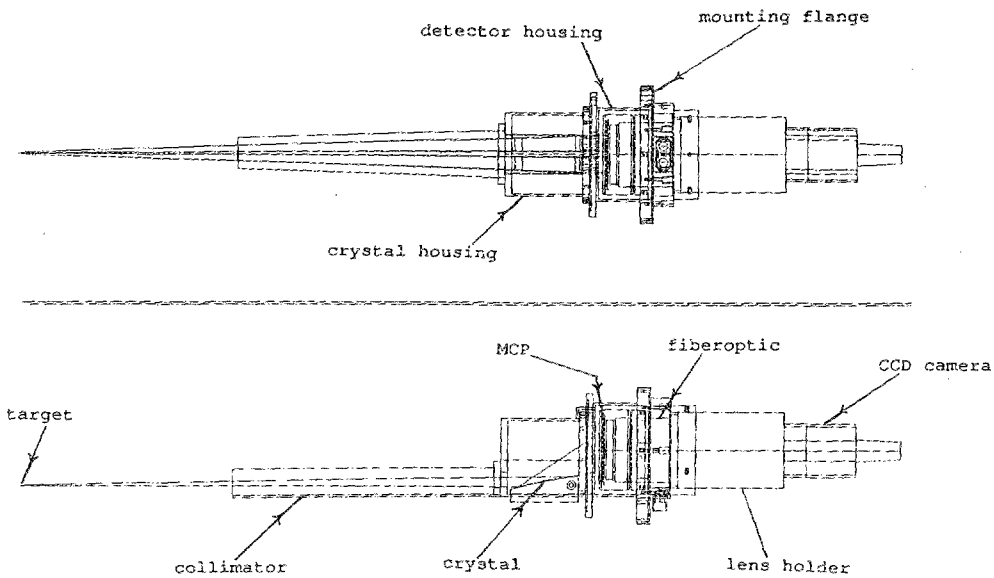

FIG. 2. Side and top views of de Broglie continuum spectrometer for Aurora showing principal components.

tector for the dispersion chosen for this design.

A multichannel plate was chosen as the detector for the continuum spectrometer because it has adequate efficiency in this energy region,[5,6] high gain, and provides two-dimensional readout. A 40:1 MCP with 12 μ channels is proximity focused to a P-20 phosphor-coated fiber optic (NA = 1, 12 μ fiber) for efficient coupling to a CCD. Spatial resolution is of the order of 50–100 μ and is more than adequate for the energy resolution required. Spectral data are transferred by the fiber optic to a camera lens and read out using a Cohu 6500 CCD camera. The TC-243 CCD chip used in the camera incorporates the frame transfer architecture with on-chip correlated double sampling for an order of magnitude increase in sensitivity over comparable CCD cameras. The camera electronics allow for synchronous triggering with the laser shot and are compatible with AT-based framegrabbers.

The two high-energy channels consist of collimated filtered scintillators for recording integrated continuum in the 40–60 keV and 60–90 keV energy intervals. *K*-edge filters define the energy band of interest while the scintillator material and thickness determine the high-energy cutoff. Cesium fluoride was chosen for its x-ray absorption efficiency and for the fact that its short decay time allows nanosecond time resolution. The scintillator is coupled to a 19 mm Hamamatsu R1450 photomultiplier tube which has good timing characteristics. The signal from the photomultipliers is sent to transient digitizers for temporal data and to CAMAC compatible charge integrators for intensity information.

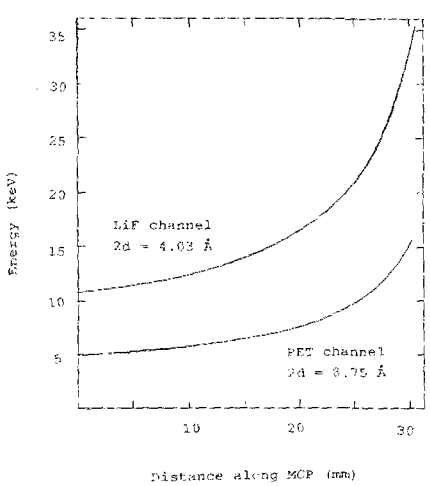

FIG. 3. Energy vs position along MCP for de Broglie spectrometer.

The entire instrument package incorporates a reentrant design with all instruments mounted on a common housing. The camera, photomultiplier tubes, and associated electronics are located in air and are electrically isolated from the target chamber ground. All instruments are to be coaligned and cocalibrated with x rays prior to installation on the target chamber using special x-ray calibration facilities constructed for the purpose at KMS.

III. LAUE SPECTROMETER FOR NOVA

A Laue transmission design is being developed for the NOVA continuum spectrometer. The energy range and resolution requirements are similar to those for the Aurora instrument with the difference that screen intensified film can be used as the detector. Eventual use with a streak camera is planned. The continuum spectrometer is the only instrument planned for this experiment port and space constraints are less severe than for the Aurora instrument.

The Laue transmission geometry has many useful features for high-energy spectroscopy. Because x rays are diffracted in transmission the small grazing angles encountered in Bragg diffraction at high x-ray energies are avoided and small diffraction angles are close to normal incidence to the crystal surface avoiding critical tolerances in stop placement for background suppression. Because the crystal focuses, ar-

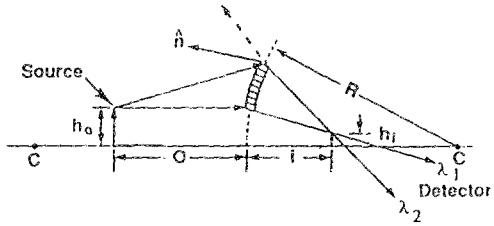

FIG. 4. Geometry for convex-curved Laue transmission. For paraxial rays, source and focus distances are related to the radius of curvature by the mirror equation $1/i - 1/o = 2/R$. Magnification is positive (noninverting).

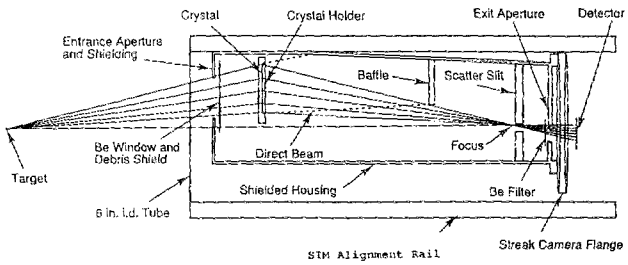

FIG. 5. Mechanical layout of a Laue transmission spectrometer for NOVA showing major components and their relation to the NOVA alignment mechanism.

bitrarily small dispersion is possible in the vicinity of the focus. This is important when the signal is weak since it maximizes the flux per unit area at the position sensitive detector. At the focus achromatic imaging is possible.[4,7] A scatter slit placed at the focus is effective in reducing background.

The Laue geometry for a convex-curved crystal is illustrated in Fig. 4. For paraxial rays the mirror equation relates the source and focus position to the radius of curvature R. The optical properties are those of a normal incidence cylindrical mirror with the virtual image of the mirror corresponding to the real image of the curved crystal. Magnification is positive (noninverting). As with the de Broglie geometry, an extended source is demagnified to increase the energy resolution, or equivalently, the effective field of view for a given resolution for a slitless instrument.

The crystals being investigated for this instrument are PET 020 ($2d = 6.08$ Å) and EddT 020 ($2d = 8.808$ Å). PET 020 is useful in this energy range because it has a large structure factor, minimal fluorescence, and very low absorption. PET 020 has been used successfully in transmission for film registration of laser-produced x rays for energies as low as 5 keV.[4,7] EddT 020 has a larger $2d$ spacing than PET 020 and will cover the required energy range with a smaller crystal. Like PET it has a large structure factor, minimal fluorescence, and very low absorption. Calculations for mosaic-integrated reflectivity show the integrated reflectivity for EddT 020 plates 0.5 mm to 0.75 mm thick to be about twice that of PET 020 in transmission and about 3 to 10 times the benchmark value of 5×10^{-5} used for estimating useful sensitivities for the continuum intensities expected at NOVA. These calculations are only upper limits because no crystal is ideally mosaic.

A configuration for the Laue spectrometer for NOVA is shown in Fig. 5. Provision is made for adjusting both the angle and position of the crystal with respect to the slit and for accommodating flat or curved crystals. Crystal dimensions are 1 cm wide and 50 cm long. The slit width is adjustable as is its distance from the detector plane to facilitate changing the focal length and dispersion of the instrument. The entire instrument mounts on an alignment mechanism for remote alignment to the target. A 0.025 cm beryllium window acts as debris shield and cutoff filter for energies less than 4 keV. A similar beryllium window on the exit port filters out fluorescent background produced by internal components. Diffracted x-ray energy as a function of position along the detector using flat EddT 020 as the dispersing crystal is given in Fig. 6. This is for a design that gives an

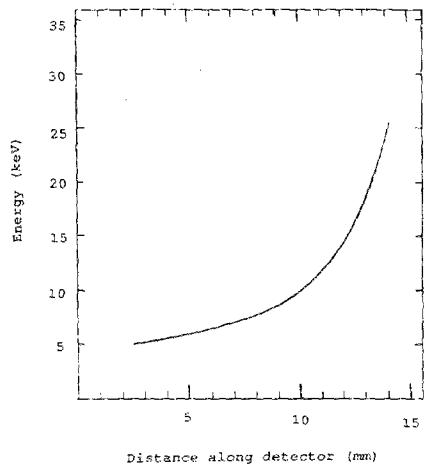

FIG. 6. Energy vs position along detector for Laue spectrometer using flat EddT 020 as the dispersing crystal.

energy resolution $E/\Delta E$ of 10 for a 300 μ detector resolution element at an energy of 25 keV.

Calculations of the sensitivity for the Laue and de Broglie geometries for the dispersion required for the instruments considered here show that for a given integrated reflectivity these geometries have similar sensitivity. Dispersion at the detector is such that the sensitivity increases strongly with energy. This lessens the dynamic range requirements for the detector when the continuum is strongly decreasing with energy.

IV. CALIBRATION

Both spectrographs are to be aligned and calibrated before delivery using the high-energy calibration facility developed at KMS for this purpose. The x-ray source is a standard 4-port, water-cooled 2.5 kW, 60 kV sealed x-ray tube with spot or line focus depending on tube orientation. Direct excitation of a tungsten anode provides x-ray continuum for spectrograph calibration. The x-ray tube is interchangeable with standard sealed tubes having anode materials other than tungsten. Fluorescence excitation is also possible for detector evaluation at discrete wavelengths. A test chamber has been built to accept the entire Aurora reentrant package with the source acting as a surrogate target for coalignment of the individual instruments. The test chamber can be pumped out for vacuum testing of critical components. Since the absolute spectral output of the source can be accurately determined with a calibrated Si(Li) detector end-to-end calibration of the efficiency of both instruments is possible.

ACKNOWLEDGMENTS

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