High-resolution crystal spectrometer for the 10–60 Å extreme ultraviolet region

P. Beiersdorfer
Lawrence Livermore National Laboratory, Livermore, California 94550

G. V. Brown[a)]
University of Maryland, College Park, Maryland 20742

R. Goddard and B. J. Wargelin
Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138

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A vacuum crystal spectrometer with nominal resolving power approaching 1000 is described for measuring emission lines with wavelength in the extreme ultraviolet region up to 60 Å. The instrument utilizes a flat octadecyl hydrogen maleate crystal and a thin-window 1D position-sensitive gas proportional detector. This detector employs a 1-μm-thick 100×8 mm^2 aluminized polyimide window and operates at one atmosphere pressure. The spectrometer has been implemented on the Livermore electron beam ion traps. The performance of the instrument is illustrated in measurements of the newly discovered magnetic field-sensitive line in Ar^{8+}. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1781754]

I. INTRODUCTION

The extreme ultraviolet (EUV) region between 20 and 60 Å is rich in emission lines that in principle can be used for plasma diagnostics. Because of the high density of emission lines in this region, high resolution spectrometers are needed to resolve lines and to determine line shapes, for example, for ion temperature measurements from the Doppler-broadened line width. Crystal spectrometers have traditionally been used to record high-resolution spectra in the soft x-ray region below 25 Å. Above this wavelength grating spectrometers have been used, but often with limited resolution.

Barnsley *et al.*[1] described a high-resolution crystal spectrometer for the EUV region utilizing an octadecyl hydrogen maleate (OHM) crystal with a lattice spacing $2d=62.5$ Å as the dispersive element. This spectrometer was implemented on the COMPASS tokamak and provided spectra of helium-like boron with resolving power $\lambda/\Delta\lambda\approx 700$.[1] The success with this instrument has prompted us to construct a spectrometer employing an OHM crystal for use on the electron beam ion traps at the University of California Lawrence Livermore National Laboratory. The new instrument described below complements two grazing-incidence grating spectrometers described earlier[2,3] by providing high resolving power as well as single photon counting capabilities and the possibility of rejecting higher order photons.

II. INSTRUMENT DESIGN

Bent-crystal spectrometers in the von Hámos geometry have been very successful for measuring x rays below about 5 Å on the Livermore electron beam ion traps.[4] These have achieved very high resolution.[5–7] Bent-crystal spectrometers have also been used at electron beam ion traps at other institutions.[8,9] However, crystal spectrometers built for the Livermore electron beam ion traps operating in the ultra soft x-ray region between about 5 and 20 Å have used the flat-crystal geometry,[10–13] despite the fact that the flat-crystal geometry provides less throughput than bent-crystal spectrometers. Flat-crystal spectrometers are easy to set-up for observing different wavelength regions by simply rotating the crystal and detector around a common pivot point. The ease of setting up is especially important because these spectrometers must operate *in vacuo* given the rather long wavelength of the radiation observed with these instruments.

The present spectrometer operates in a wavelength range that is even longer than covered by usual crystal spectrometers and also operates *in vacuo*. We employed the flat-crystal spectrometer design described earlier.[10] No slit is needed as the photons are emitted from the cylindrical interaction region between the trapped ions and the electron beam, which has a width of about 50 μm.

Our spectrometer utilizes a 1×5 cm^2 OHM crystal.[14] It is mounted on a glass slide for stability. The distance between the source and the crystal is about 40 cm; the distance between the crystal and detector is 25 cm. The unequal distance means that a given spectral line shifts its position on the detector when the Bragg angle is changed. This only affects alignment and does not affect the quality of the observed spectra.

Charge coupled device (CCD) cameras have been successfully used for recording EUV radiation in the existing grazing-incidence spectrometers on the Livermore electron beam ion traps.[2,3] These, however, do not work well with the present crystal spectrometer because the crystal acts as a mir-

[a)]Located at NASA Goddard Space Flight Center, Laboratory for High Energy Astrophysics, Greenbelt, MD 20771.

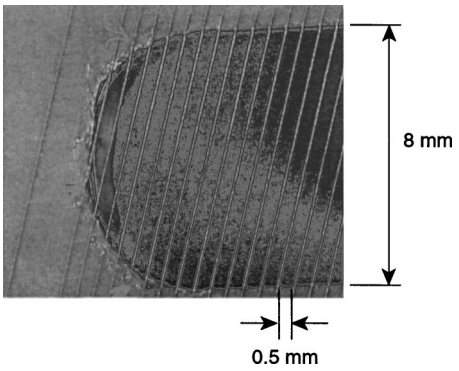

FIG. 1. Closeup of gold-coated tungsten wires used to support the 1 μm polyimide window on the proportional counter. The support wires are angled so that the blockage fraction (10%) is constant across the diffracted spectrum.

ror that directs visible light from the electron beam ion trap source onto the detector. The amount of reflected light swamps the relatively weak EUV radiation dispersed by the crystal, if a CCD camera is used. In order to reduce the high background caused by visible light blocking filters would be necessary that invariably also absorb the desired EUV radiation. No such problems occur in grazing-incidence grating spectrometers, as the light is reflected by the grating in zeroth order, while the EUV radiation is dispersed in higher orders.

We considered two types of detectors that are not sensitive to visible light: microchannel plate (MCP) and gas proportional detectors. Both have the advantage that they can detect single photons. This is important for resolving time-dependent phenomena, such as the transition from the electron to the magnetic trapping mode in an electron beam ion trap.[15] We chose to equip our spectrometer with a position-sensitive proportional counter. This type of detector has the advantage that the pulse height signal is proportional to the detected photon energy, which allows for order discrimination.[10] Unlike an open-faced MCP detector, the proportional counter needs an entrance window to contain the counter gas. This window reduces the efficiency of the spectrometer, and must, therefore, be as thin as possible.

We chose a 10 cm long, 8 mm tall single-wire proportional counter[16,17] that operates with P-10 gas (90% Ar, 10% CH_4) at a pressure of 1 atm. The gas is continuously flowing through the detector. In the past, we have used such detectors with a 4 μm thick polypropylene window.[10] For the present case, we employed a 1 μm thick polyimide foil. The foil was supported by 50 μm gold-plated tungsten wire wound diagonally (at an angle of about 13° from normal) to the detector axis as shown in Fig. 1. The spacing between each winding was 500 μm. The window is coated with 200 Å of aluminum, which provides an electrical connection to the frame.

The spatial resolution of the detector is about 200–250 μm for keV-type x-ray energies, with somewhat worse resolution at lower energies (about 500 μm for 250 eV photons). This yields a nominal resolving power of our instrument (not accounting for the resolving power of the crystal) of about 1000 at a Bragg angle of 45°. The crystal has a theoretical resolving power of up to 2000.[1] A resolving

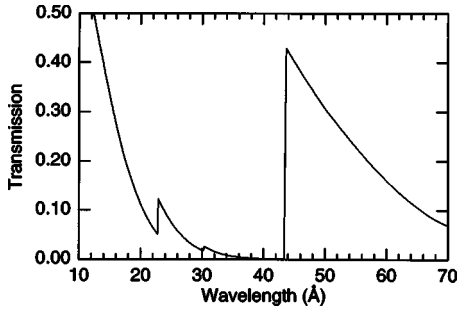

FIG. 2. Combined window transmission properties of the detector and spectrometer polyimide windows.

power as high as 1100 was estimated from spectra observed from laser-produced plasmas using film as recording material.[18] Assuming a resolving power of 1000 for our crystal, we expect a nominal resolving power of about 700 for our spectrometer.

In addition to the detector window, a 0.5 μm thick polyimide foil is used to separate the vacuum of the spectrometer (about 10^{-6}–10^{-7} Torr) from that in the electron beam ion trap (about 10^{-10}–10^{-11} Torr). Absorption by these two foils reduces the efficiency of the spectrometer below the carbon edge at 43.6 Å, but readily allows measurements above the edge or well below. The transmission of a nearly identical detector window was measured at the BESSY synchrotron in Berlin. Net transmission of our spectrometer and detector windows was derived from those measurements after scaling appropriately for foil thickness, and is shown in Fig. 2.

III. PERFORMANCE CHARACTERISTICS

Spectra are acquired in event mode, i.e., single photons are counted stamped by time and beam energy, by a personal computer interfaced to a CAMAC crate that houses the modules for data digitization, as described earlier.[19]

A spectrum of the $3s \rightarrow 2p$ transitions in neonlike Ar^{8+} is shown in Fig. 3. The spectrum was acquired on the Livermore EBIT-II electron beam ion trap in 11 min at an electron beam current of 8 mA and an electron energy of 360 eV. The rate of acquisition is fast compared to other crystal spectrometer measurements, which we attribute to the relatively high reflectivity of OHM crystals.[20]

The spectrum is of special interest because it shows not only the well-known transitions from upper levels $(2p^5_{1/2}3s_{1/2})_{J=1}$, $(2p^5_{3/2}3s_{1/2})_{J=1}$, and $(2p^5_{3/2}3s_{1/2})_{J=2}$ to the $(2p^6)_{J=0}$ neon-like ground state, labeled $3F$, $3G$, and $3H$, respectively. It also shows the $(2p^5_{1/2}3s_{1/2})_{J=0}$-$(2p^6)_{J=0}$ transition, labeled $\mathcal{B}$. This transition is normally strictly forbidden, but is enabled by level mixing induced by the ambient 3T magnetic field in which the Ar^{8+} ions are embedded.[21] The relative intensity of this line can be used as a diagnostic of magnetic field strength.

Figure 3 also shows a spectrum of the $3d \rightarrow 2p$ transitions in neonlike Fe^{16+}, i.e., transitions from upper levels $(2p^5_{1/2}3d_{3/2})_{J=1}$ and $(2p^5_{3/2}3d_{5/2})_{J=2}$ to the $(2p^6)_{J=0}$ neonlike ground state labeled 3C and 3D, respectively. It illustrates the instrument's performance in the soft x-ray region.

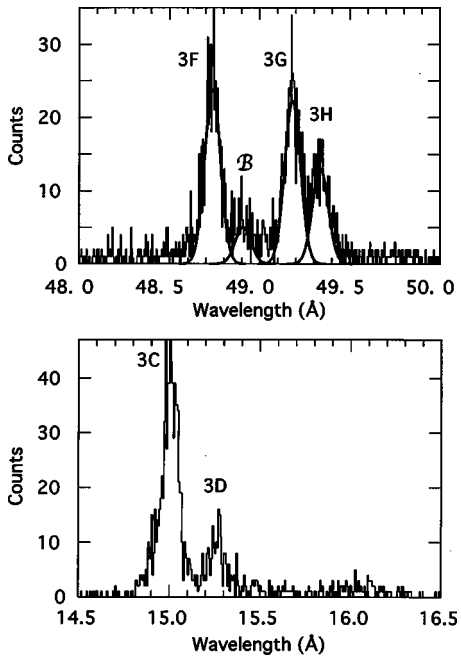

FIG. 3. Spectra obtained with the OHM crystal spectrometer on the EBIT-II electron beam ion trap: (a) $3s \rightarrow 2p$ transitions in Ar^{8+} showing the magnetic-field sensitive line $\mathcal{B}$; (b) $3d \rightarrow 2p$ transitions in Fe^{16+}. Exposure times are (a) 11 and (b) 30 mins at electron beam energies of 360 and 1250 eV, respectively.

The Ar^{8+} lines were measured at a Bragg angle of 50°. The observed line width intimates a resolving power of the OHM spectrometer of $\lambda/\Delta\lambda \approx 450$. The Fe^{16+} lines were measured at a Bragg angle of 13.7°, providing a resolving power of $\lambda/\Delta\lambda \approx 180$. The resolving power scales with the tangent of the Bragg angle. Therefore, the latter measurement implies a nominal resolving power at $\theta = 45°$ (about 750) that is twice as high as the value inferred from the Ar^{8+} measurement (375). The reason is that the spatial resolution of the proportional counter is better at the higher photon energy than at lower energy, as discussed above. This shows that the spectrometer could yield a resolving power approaching the theoretical value of the OHM crystal of 1000–2000, e.g., if higher resolution detectors are used in the future.

ACKNOWLEDGMENTS

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