

Absolute Calibration of Kodak Biomax-MS Film Response to X Rays in the 1.5- to 8-keV Energy Range

Introduction

X-ray film is in common use for recording the absolute x-ray fluence in high-temperature plasma experiments. The typical energy range is 1 to 10 keV, where imaging of plasma x-ray emission and spectroscopy of ionic species are often performed. Film finds use in laser-generated plasma x-ray diagnostics and in a number of related plasma-fusion-energy research fields such as in x-pinch, z-pinch, and magnetic-fusion-energy research. While directly exposed x-ray film cannot be used to time resolve the intensity of x rays, it can often be used where other means of image recording cannot.

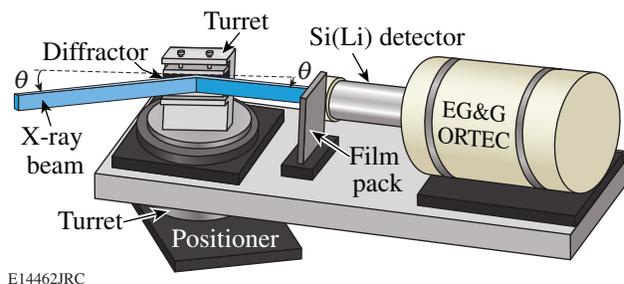
An example of such a calibrated x-ray film is Kodak direct-exposure film (DEF).¹ DEF film was absolutely calibrated² in the 1- to 10-keV energy range. The results were fitted to a semi-empirical mathematical model of the film as described by Henke *et al.*³ and extended to DEF film,² which has two emulsion layers (one on each side). Kodak has ceased production of DEF film, and absolute calibration of a suitable replacement is needed for the eventual time when the supplies of existing DEF are exhausted. The absolute calibration of a Kodak replacement film, Biomax-MS (BMS), now in production, is the subject of this work. The measurements were taken in the x-ray laboratory at the Laboratory for Laser Energetics. Also, comparative measurements of BMS to DEF film sensitivity were taken on the OMEGA laser facility⁴ and are compared to the results of Chandler *et al.*⁵

Experimental Technique

Film calibration was accomplished with an e-beam-generated x-ray source, a crystal/multilayer monochromator, a film pack, and an absolutely calibrated x-ray photon detector. The apparatus is shown schematically in Fig. 107.11. X rays are produced in a vacuum system with the e-beam striking the desired target. The beam passes outside the vacuum system through a thin Be window (8.5 μm thick) after which the remaining path of the beam is through He gas at just over 1 atm. This minimizes beam absorption. A monochromatic beam of x rays is produced by placing a crystal or multilayer diffractor in the path of the beam with the angle of incidence equal to

the Bragg angle θ_B for the wavelength desired and the detector (film or photon counter) set to the angle $2\theta_B$. The line energies produced by this method and the corresponding monochromators and angles used to produce the monochromatic beam are given in Table 107.I.

The x-ray source intensity is measured with a liquid-nitrogen-cooled, lithium-drifted silicon Si(Li) detector⁶ read out with a pulse-height analyzer. An aperture of precisely measured dimensions (4.99 \pm 0.01 by 0.47 \pm 0.01 mm, 2.35 \pm 0.06 mm²) is placed over the entrance window of the photon detector, allowing the photon flux density to be calculated from the count rate. Since the beam is truly monochromatic, all counts above the



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Figure 107.11
Schematic of the experimental arrangement used to calibrate Biomax-MS (BMS) film.

Table 107.I: Atomic line, line energy, monochromators, Bragg plane spacing ($2d$), and Bragg angles used for these measurements.

Line	Energy (keV)	Monochromator	$2d$ (Å)	θ_{Bragg} (°)
Al $K\alpha$	1.49	WB ₄ C	26.300	18.44
Ag $L\alpha$	2.98	WB ₄ C	26.300	9.10
Ti $K\alpha$	4.51	LiF(200)	4.027	43.06
Fe $K\alpha$	6.40	LiF(200)	4.027	28.76
Cu $K\alpha$	8.04	LiF(200)	4.027	22.49

noise threshold are included. Background is negligible. During film exposures, the beam intensity is measured before and at the end of the exposure. The fluence on film is determined from the average count rate and the fluence error determined from the pre- and post-exposure beam-intensity variation. Exposure times varied from as little as 2 min to as long as 3.7 h for the highest energy and density.

Film was developed by the standard method recommended by Kodak,⁷ common to both DEF and BMS. The test exposures were digitized with a calibrated PerkinElmer microdensitometer (PDS) using a 0.25-numerical-aperture (NA) lens and a $50 \times 50\text{-}\mu\text{m}$ digitizing aperture.

Absolute Measurements

A typical exposure on film is shown in Fig. 107.12(a). The exposed region of the film was limited to an image of the x-ray beam's exit aperture (nominally 1×7 mm). Figure 107.12(b) shows a lineout across the PDS digitized region. The photon detector measurements were taken in the central 0.5×5 -mm region, and the average density was inferred from a similar-sized region of the digitized density values. The horizontal gradient of the film density is due solely to the aperture, while no vertical gradient was seen in the exposures. The results of the exposures are shown in Figs. 107.13(a)–107.13(e). The DEF and BMS densities are plotted as a function of the incident fluence for the five x-ray energies used in this work [no DEF exposure was taken using Al $K\alpha$ (1.49 keV)]. The expected DEF density values determined from the Henke model² are shown with dashed lines. In general, the measured DEF density values agree well with those calculated from the model, although the

measurements are systematically lower. This is likely due to the age of the film, which has an average fog level of ~ 0.5 , considerably higher than that of fresh film (~ 0.25). This can lower the film's sensitivity.

The Henke model values are used as a basis to determine the relative sensitivity of BMS film to DEF film. At Al $K\alpha$ (1.49 keV) and Ag $L\alpha$ (2.98 keV) the sensitivities are comparable. The sensitivity of BMS drops farther compared to DEF at higher energies and is considerably lower ($\sim 2\times$ less sensitive) at the highest energy measured [Cu $K\alpha$ (8.04 keV)]. This is a consequence of the choice of emulsion (two thin emulsion layers, one on each side of the film⁸) and is expected. The BMS measured densities versus photon fluence and energy are used to determine the best-fit parameters of a mathematical model of the film response, given in a companion article in this issue (**Response Model for Kodak Biomax-MS Film to X Rays**, p. 142).⁸ The results of this model fitting are shown with solid lines in Figs. 107.13(a)–107.13(e).

Comparative Measurements

Simultaneous measurements over the energy range from ~ 2 keV to 8 keV were obtained by placing DEF and BMS film at the image planes of two images of a four-image Kirkpatrick–Baez (KB) microscope system,⁹ which uses a transmission grating for wavelength (equivalently energy) dispersion.¹⁰ The image magnification was 20 and the wavelength dispersion was $0.586 \text{ \AA}/\text{mm}$. Figures 107.14(a) and 107.14(b) show images obtained with DEF and BMS film on an experiment performed with the 60-beam OMEGA Laser System.⁴ The laser target was a 15-atm- D_2 -filled, $27\text{-}\mu\text{m}$ -thick-plastic-shell target imploded with 23 kJ of 351-nm laser light using a 1-ns square pulse shape. The grating-dispersed emission from the intense core region is indicated with arrows on the DEF-recorded image [Fig. 107.14(a)]. The exposure levels obtained with BMS film on the same target experiment [Fig. 107.14(b)] are significantly lower. The sensitivity of the two films is compared by using the known grating dispersion of this system to determine the film density as a function of energy, and by the assumption that the two imaging systems are identical. Figure 107.14(c) shows the DEF and BMS film-density energy spectra obtained from the images shown in Figs. 107.14(a) and 107.14(b). The density obtained with BMS film is seen to be significantly less than that obtained with DEF film above ~ 3 keV.

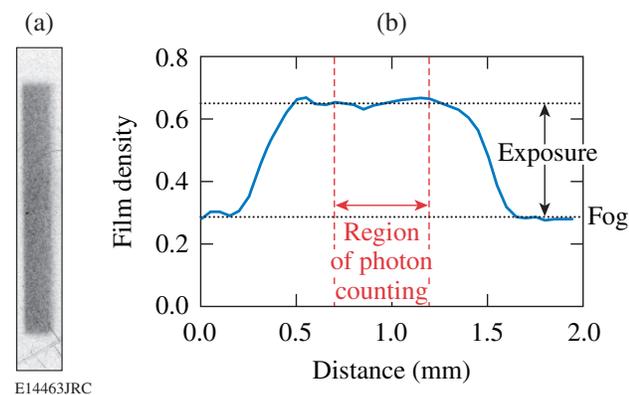
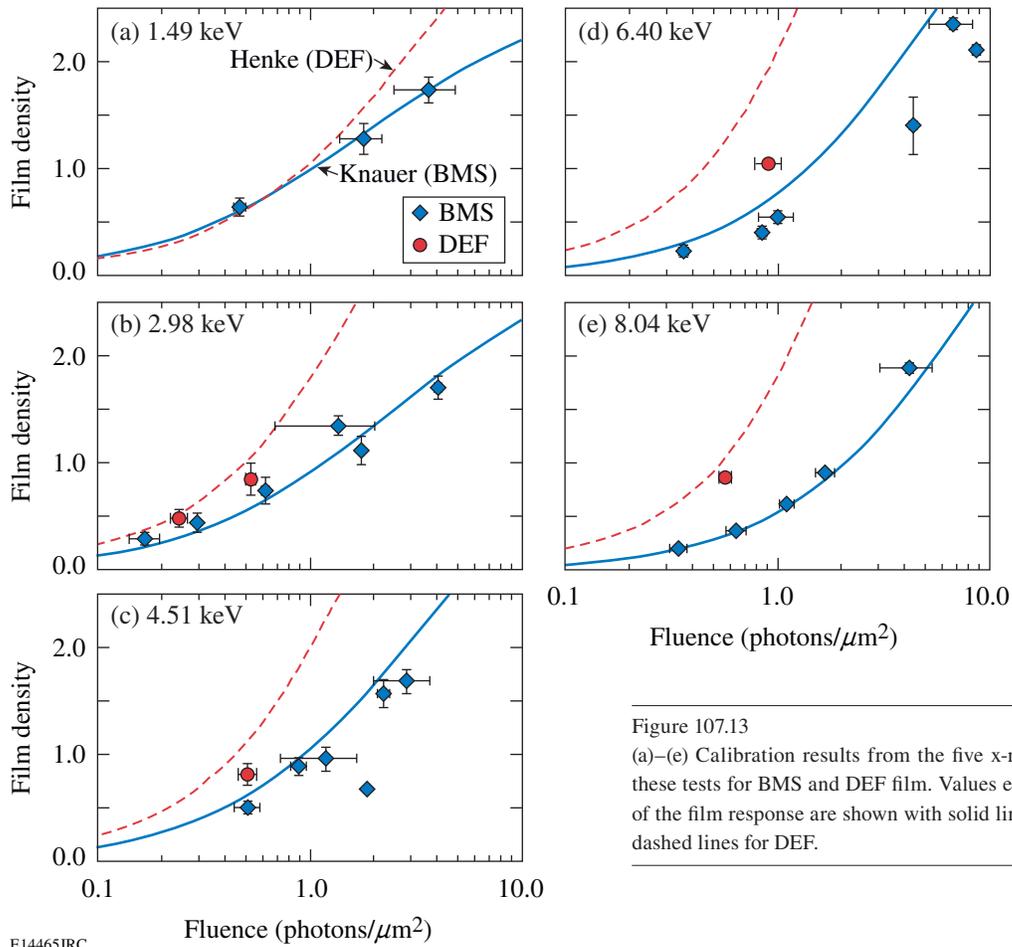


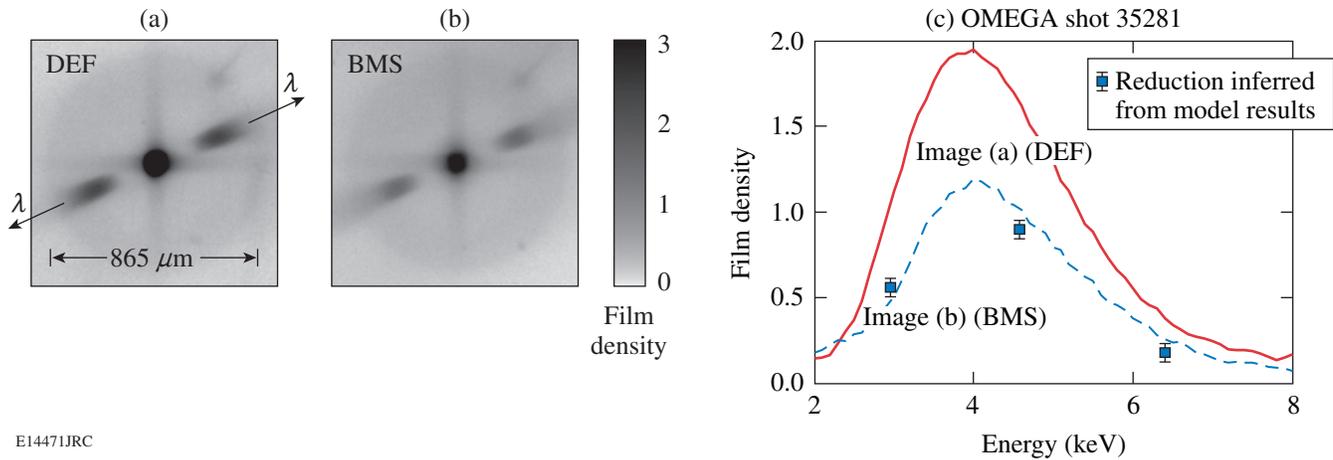
Figure 107.12

Typical exposure on (a) BMS film and (b) lineout through digitized density values. The exposure is determined by subtracting the fog level from the observed density.

Comparison of these results with the absolute measurements presented earlier is accomplished with the two mathematical models. The Henke *et al.*² model of DEF response [dashed lines in Figs. 107.13(a)–107.13(e)] is used to determine the



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Figure 107.14

Comparison of DEF and BMS film response determined by two images taken with a grating-dispersed KB microscope on a single OMEGA target shot. (a) DEF-recorded image; (b) BMS-recorded image; (c) film-density/energy spectra from DEF and BMS determined from (a) and (b).

corresponding fluence, and the Knauer *et al.*⁸ model is used to calculate the values expected for BMS film. The values determined for 2.98, 4.51, and 6.40 keV are shown as data points in Fig. 107.14(c). The error bars represent uncertainty in the film-density values of ± 0.05 . The inferred density values are in close agreement with the BMS-measured film-density spectrum at all three energies. The BMS density is less than the DEF density by approximately a factor of 2 above 3 keV. Chandler *et al.*⁵ have made similar comparative measurements of DEF and BMS film using a spectrometer and x rays from an *x*-pinch source. They find an asymptotic BMS to DEF density ratio of ~ 0.55 at the high-energy limit of their measurements (3 to 6 keV). This is in good agreement with both the absolute measurements and comparative measurements presented in this work.

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REFERENCES

1. Kodak DEF film was manufactured by the Eastman Kodak Company, Rochester, NY 14650.
2. B. L. Henke *et al.*, *J. Opt. Soc. Am. B* **3**, 1540 (1986).
3. B. L. Henke *et al.*, *J. Opt. Soc. Am. B* **1**, 818 (1984).
4. T. R. Boehly, D. L. Brown, R. S. Craxton, R. L. Keck, J. P. Knauer, J. H. Kelly, T. J. Kessler, S. A. Kumpan, S. J. Loucks, S. A. Letzring, F. J. Marshall, R. L. McCrory, S. F. B. Morse, W. Seka, J. M. Soures, and C. P. Verdon, *Opt. Commun.* **133**, 495 (1997).
5. K. M. Chandler, S. A. Pikuz, T. A. Shelkovenko, M. D. Mitchell, D. A. Hammer, and J. P. Knauer, *Rev. Sci. Instrum.* **76**, 113111 (2005).
6. An ORTEC Poptop Si(Li) detector was used for these calibrations: Model #1019P, S/N 303-T7076 with bias set to 1000 V negative as per manufacturer's calibration instructions.
7. DEF and BMS film was developed in an auto film processor using gentle agitation as follows: 5 min in Kodak GBX developer, 30 s in stop bath, and 6 min in fixer. A post rinse in photoflo and water followed.
8. J. P. Knauer, F. J. Marshall, B. Yaakobi, D. Anderson, B. A. Schmitt, K. M. Chandler, S. A. Pikuz, T. A. Shelkovenko, M. D. Mitchell, and D. A. Hammer, presented at the 16th Annual Conference on High-Temperature Plasma Diagnostics, Williamsburg, VA, 7–11 May 2006 (Paper WP41); also this LLE Review.
9. F. J. Marshall and Q. Su, *Rev. Sci. Instrum.* **66**, 725 (1995).
10. F. J. Marshall, J. A. Delettrez, R. Epstein, and B. Yaakobi, *Phys. Rev. E* **49**, 4381 (1994).