6-m TGM implementation at the Wisconsin Synchrotron Radiation Center (SRC)

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We recently commissioned the SRC/Vanderbilt University 6-m toroidal grating monochromator beamline. The problems with mirror heating, signal normalization, monochromator control, and scattered light reduction have led to several innovations on this line, making for a better user interface and adding to the stability and reliability of the final image. We discuss these innovations, and how they affect the user. They include a built-in laser alignment system, a sapphire windowed gate valve, entrance mirror temperature stabilization, computer automation and control, a beam-chopper, and the capability of real-time monitoring of the photon flux during the experiment. We have used noble gas resonance lines to carefully characterize the wavelength resolution of the beamline as a function of energy over a range of beamline parameters. The results demonstrate that by limiting the horizontal width of the image at the slits, and by masking outer portions of the gratings, the flux/bandwidth ratio can be improved at the points where the exit slit location does not coincide with the Rowland circle. These same resonance lines, in conjunction with accurate measurements of the grating rotation angle as a function of scan-drive displacement, are used to correct for imperfections in the surface of the drive-flat and thus obtain a precise and accurate determination of wavelength versus scan-drive displacement.

INTRODUCTION

On 29 February 1988, the Wisconsin Synchrotron Radiation Center (SRC) commissioned the first of two new 6-m toroidal grating monochromators (TGM) as part of a cooperative effort between Vanderbilt University and SRC. A 25% block of the annual beam time is reserved for a group at Vanderbilt University headed by Norman Tolk and Richard Haglund, while the rest of the time is available to outside experimenters similar to other SRC lines. The addition of this and a second new TGM enhances SRC's pool of higher-energy beamlines.

Toroidal grating monochromators were conceived with the intention of creating high throughput monochromators with moderate to high resolution capabilities. The use of a toroidal surface provides for focusing of the light in both the sagittal and tangential planes while involving only one reflecting surface. The utilization of holographic techniques to produce the rulings provides for further refinements of the image at the exit slit and, hence, improved resolution. In keeping with the concept of high throughput and well-defined images, but few reflections, the SRC 6-m TGMs utilize only three reflective surfaces throughout the line; an ellipsoidal entrance mirror, the toroidal grating, and an ellipsoidal exit mirror.

I. BEAMLINE DESCRIPTION

The ellipsoidal entrance mirror enhances the flux through the line with its large angular acceptance of 22 $\text{mrad}_x \times 4\ \text{mrad}_y$ at only 1800 mm from the source (Fig. 1). The mirror consists of a diamond-turned aluminum block, plated with electroless nickel, superpolished, and then plated with gold through vacuum deposition. Tests conducted by Peter Takacs (BNL) on the surface finish indicate a surface roughness of about 46 Å rms. This mirror is scheduled for replacement by a slightly longer mirror with a surface roughness close to 15 Å rms.

Concerns about the thermal expansion of the mirror actually arose before it was installed on-line. Studies of image shifts were made using thermocouples to monitor temperature and a reticon system to monitor the image size and position. The system showed large and rapid shifts in the position of the image, typically 400 μm, as the temperature of the mirror increased (Fig. 2). The rapid lowering of the image at the beginning to the thermal expansion of the mirror itself, while the later rise back through the starting point was due to the transfer of heat to the aluminum support legs. Unequal lengths of the support legs, necessary to provide a 5° tilt, further complicated the results. These effects tended to cancel out over a region of 60°–70°. Using supports made of Invar proved unsatisfactory, so the strategy settled upon involved stabilizing the temperature of the mirror by providing heating and cooling. Heating is accomplished through small filaments between the mirror and its backplate. Cooling is accomplished through copper heat straps. This system reduced image shifts to less than 100 μm. Some slight shifts remain due to the fact that the filaments supply heat differently than the SR beam. We have considered exploiting this difference to actually steer the beam to the entrance slit.

Mounted just below the entrance mirror chamber is the HeNe laser for the alignment system designed to aid the SRC staff during alignment of the optical components of the line. An added benefit to the user is the fact that it provides light

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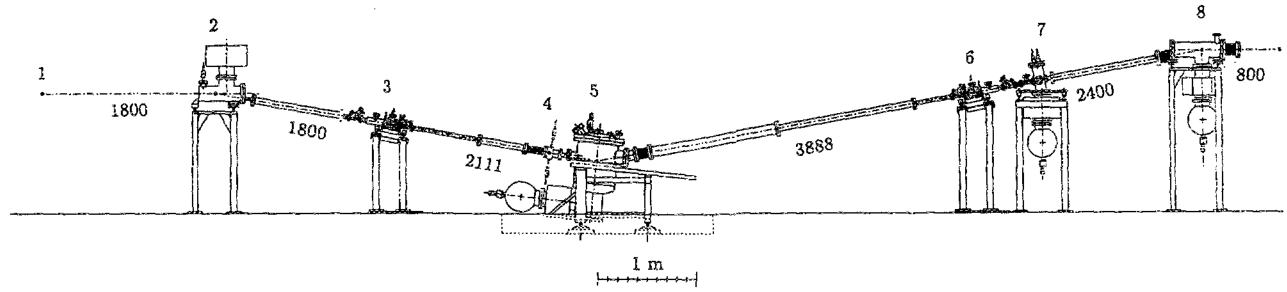

FIG. 1. Elevation view of the 6-m TGM showing distances between optical components in millimeters. 1—source, 2—entrance mirror, 3—entrance slit, 4—grating apertures, 5—gratings, 6—exit slit, 7—filter array, and 8—exit mirror.

at the final focus even when there is no beam in the storage ring. Users coming on-line during the weekend can take advantage of the alignment system and the windowed gate valve at the end of the line to align their system without beam in the storage ring, and while their system is at its most maneuverable stage.

The entrance slits were designed and fabricated at SRC utilizing flexural hinges and a tapered plunger on the vertical apertures to provide a continuously adjustable range from 8 to 5000 μm. The nonlinear taper of the plunger provides for finer adjustments at smaller settings. The horizontal apertures have seven possible settings (460 and 710 μm, 1.0, 1.5, 2.0, and 3.0 mm, and 2.0 cm). A more detailed discussion of the slit's mechanical design can be found in Ref. 1.

The three 6-m toroidal gratings are mounted on a revolving carousel. The gratings are composed of a silicate substrate with ion-etched holographic rulings coated with platinum. Characteristics of the three gratings are given in Table I. The gratings are changed *in vacuo* at the touch of a button, or by the command of a computer, in a matter of minutes. The grating change mechanism brings the gratings back into proper position with a reproducibility of better than 5 s of arc. The scan motion is provided by a sine-drive mechanism which is described in more detail in Ref. 1. Positional information is provided by a Heidenhain linear encoder mounted to the linear driver portion of the sine-drive.

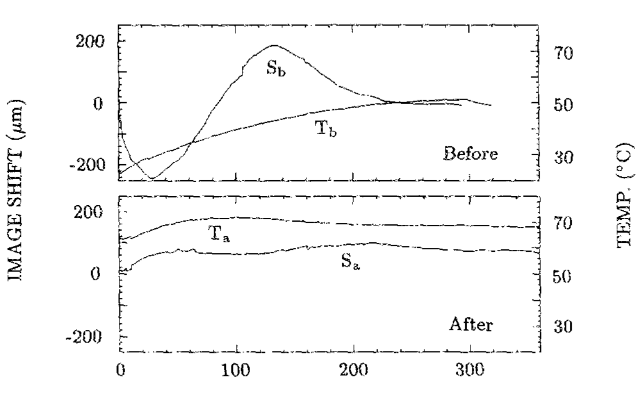

FIG. 2. These plots show the difference in the stability of the image at the focal point before (b) the installation of the temperature stabilizing system and after (a). T_a and T_b designate temperature after and temperature before, respectively, whereas S represents the shift in the image position.

During assembly, an angle-resolving laser interferometer was used to determine the reproducibility and linearity of the scan mechanism. The information was recorded by computer and available in moments, as feedback, while we were making fine adjustments to the drive-flat. The final data sets were entered into the computer control system and are used for making fine corrections to the calculated wavelengths.

Since our design of the 6-m TGM utilizes entrance and exit slits at fixed locations the resolution becomes dependent on the wavelength and is optimal when the slit location coincides with the Rowland circle. Choosing unequal arm lengths (entrance arm = 2111 mm, exit arm = 3888 mm) causes these two "optimal points" to fall within the first-order range of the grating. Aberrations at the exit slit often lead to the image appearing as a segment of arc which can either curve up ("smile") or down ("frown"). These non-horizontal wings tend to detrimentally affect the resolution, but they are easily removed by horizontally (sagitally) masking the image. The effects of such maskings can be seen in Fig. 3. Theoretically, resolution can be further improved by masking outer portions of the grating, since the aberrations induced by the toroidal grating surface are strongly influenced by the angular acceptance in the dispersion plane.[2] Adjustable apertures were placed just before the grating and Fig. 4 demonstrates that these apertures actually improve the resolution.

Light scattered within the system and reaching the exit slits can also contaminate the desired signal. This is a significant problem after the grating chamber, where zero-order light and dispersed light can reflect along the sides of the exit arm and reach the exit slit with significant intensity. The light-baffling arrangement installed on the 6-m TGM involved placing an aperture along the exit arm at the point where a reflection would direct light at the exit slit. For in-

TABLE I. Gratings.

Grating	Low energy (LEG)	Medium energy (MEG)	High energy (HEG)
Groove density	288/mm	822/mm	2400/mm
Useful range	1650–500 Å 7.5–24.8 eV	600–175 Å 20.6–70.9 eV	190–65 Å 65.2–191 eV
Optimal resolution	0.61 Å @ 1378 Å 4 meV @ 9 eV	0.18 Å @ 476.9 Å 10 meV @ 26 eV	0.055 Å @ 165.3 Å 25 meV @ 75 eV

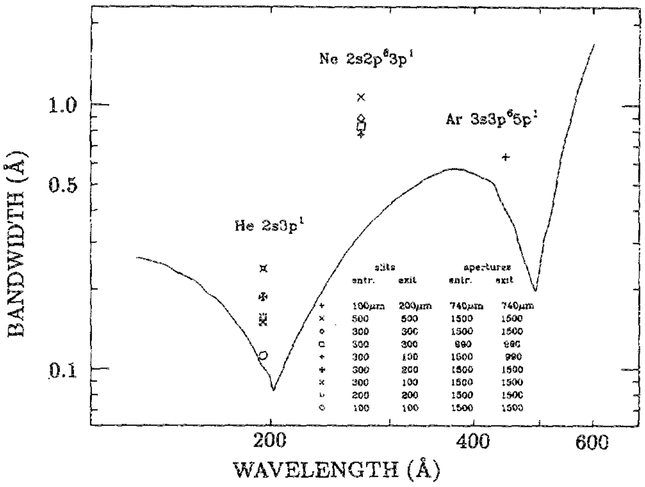

FIG. 3. Comparison of observed resolution (points) with theoretical limit (solid line) from Thiry *et al.*[7] The series of points show the effect of adjusting the slit widths and apertures at the entrance and exit slits.

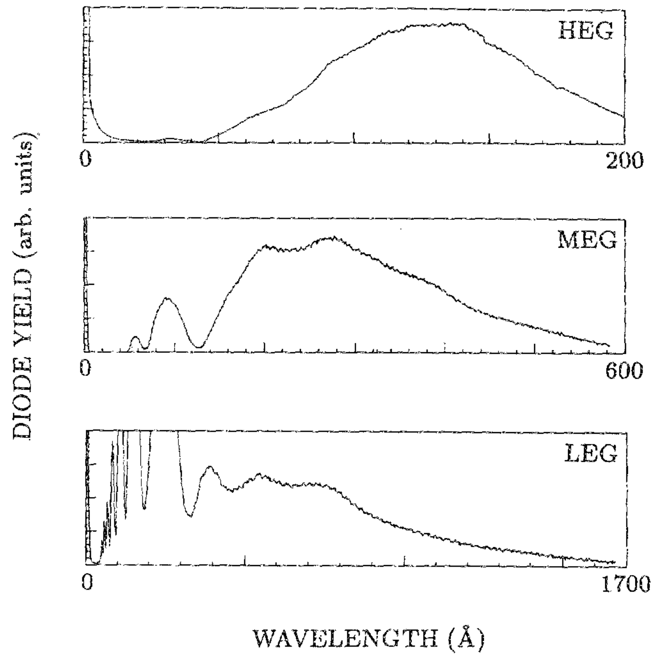

FIG. 5. These I_0 scans taken recently, with the aid of the Computer Control System, indicate the ranges covered by the three gratings. Notice the sharp drop off near zero order, indicating low levels of scattered light in the system. The undulations are typical of holographic gratings with sinusoidal rulings.

stance, midway along the arm light from the grating will reflect off the pipe and reach the aperture produced by the exit slit. Placing a fixed aperture at this location prevents the light from following this path and reaching the slit. In fact, all light making an odd number of reflections along the pipe are similarly excluded by this one aperture. Similar logic was applied to determine where to place apertures blocking light making less than ten reflections prior to reaching the slit. The success of the design is indicated by the sharpness of the zero-order image in the scans shown in Fig. 5.

One of the unique features of this beamline is the 37.8-Hz beam-chopper installed just after the exit slit. Acquired from National Electrostatics Corporation, it consists of a rotating cylinder with windows cut in it. As the cylinder rotates, the light is either blocked by the cylinder walls or passed by the windows. Synchronizing pulses indicate the beginning and end of the transmitted beam providing the experimenter with the ability to use subtractive techniques and to study temporally dependent effects.

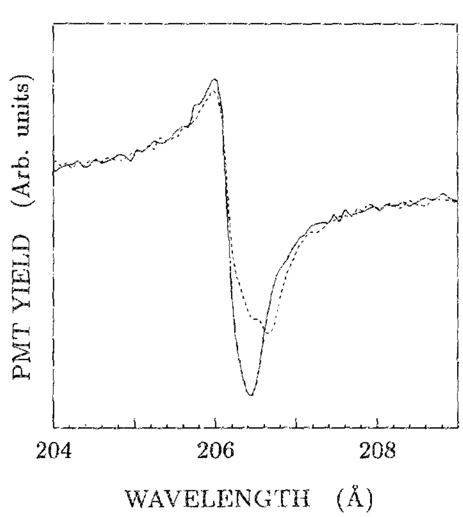

FIG. 4. Photomultiplier response at the He 206.21-Å resonance line visibly demonstrates the improvement made in the resolution when the pregrating apertures are used. Both measurements were made using 100-μm slits. Vertical and horizontal acceptances for: dashed line—4×22 mrad^3, solid line—2×11 mrad^2.

Holographic gratings are known for their higher order components in the spectra. To counteract this tendency, an array of filters has been carefully chosen to cover the entire useful range of the monochromator. The desired array and the effective ranges are displayed in Table II.

The exit mirror is similar to the entrance mirror in several respects: it is an ellipsoidal mirror of diamond-turned aluminum manufactured by Research Optics, Inc. It was also superpolished after plating with electroless nickel, but the gold was deposited by electroplating. Surface roughness for this mirror, determined by Peter Takacs, averaged 23 Å rms.

One of the most innovative and useful features of this system is the computer control package. This system grew out of a desire to remove the technical details of TGM operation from the many concerns already confronting the visiting scientist. Utilizing an IBM clone and an IBM Data Aquisition and Control Adapter (DACA) the TGM control package monitors various beamline parameters and controls various monochromator functions. Program development,

TABLE II. Filter array.

LiF 6–12 eV	Al 36.5–73 eV
In 11.8–16.4 eV	Be 55.7–111.5 eV
Sn 15.5–23.9 eV	C 142.1–284.2 eV
Mg 24.6–49.2 eV	Open
Open	Gold diode
Supplier SRC	

currently in the final stages, will allow the user the choice of two modes; MASTER MODE (fully implemented) and SLAVE MODE (under development).

SLAVE MODE will provide all the builtin capabilities of the line (including wavelength corrections, scan control, and grating selection) driven by commands issued from the user's own computer. This allows the user to continue using the system they are most familiar with, and meeting their own specific needs, while taking advantage of SRC's wavelength correction tables, etc. MASTER MODE acts as a complete data acquisition and control program. Utilizing a spread-sheet-style menu system, the unfamiliar user rapidly gains confidence in using the program to control nearly every aspect of the scan, including the acquisition and treatment of data.

II. TESTING AND RESULTS

We have used monatomic gas absorption resonance lines to both aid in the wavelength calibration of the monochromator as well as to characterize the resolution at varying slit widths and aperture settings. Measurements were made using a gas cell consisting of a small vacuum chamber with pumping manifold[3] at the end of the beamline operating between 1–100 mTorr, a sodium-salicylate-coated window to intercept the transmitted light, and a photomultiplier tube to measure the fluorescence from the window. A thin aluminum window[4] confined the gas from the rest of the beamline. We observed the transmission to vary as we scanned across the resonance according to a Beutler–Fano profile of the absorption cross section, characteristic of a monatomic gas,[5]

$$\sigma = \sigma_a [(q+\epsilon)^2/(1+\epsilon^2)] + \sigma_b ,$$

where

$$\epsilon = 2(E - E_0)/\Gamma.$$

The parameters σ_a, σ_b, q, Γ, E_0 have been published by Madden and co-workers.[6]

Lines from helium, argon, and xenon, in first and higher orders, were used in conjunction with the laser interferometer data (theta versus displacement of scan arm) to correct for ruling errors, and relative angular errors to give an accurate calibration for the medium and low energy gratings. The aluminum LII-LIII edge, at 172 Å, was used to relate the high to the medium energy grating. Helium, neon, and argon resonances at 194.78, 272.21, and 442.83 Å, respectively, were selected for further study. They are in the region of wavelengths that are transmitted well through an aluminum window, and are near resolution minima and maxima of the medium energy grating of our monochromator. Furthermore, the helium resonance lines are particularly suitable for resolution studies since they are intrinsically narrow, and the instrument resolution to a first approximation is the peak-to-valley separation in the transmission spectrum. As has been stated, the resolution of the TGM is a nontrivial function of slit width and wavelength. Thiry *et al.*[7] have described the theoretical limit of the resolution for the TGM with fixed exit slit. Our results agree well with theoretical expectation (Fig. 2). The 195-Å line, which very nearly focuses at the exit slit, showed improved resolution as the slit width was reduced, approaching the theoretical limit at 100-μm slits. The 443-Å line, near the other focused wavelength, also approached the theoretical limit. On the other hand, the resolution of the 272-Å line, far from the focus, was only slightly improved by adjustments made at the slits. The magnitude shown, twice that of the theoretical limit, is probably due to a breakdown in our simplification of the natural linewidth.

III. CONCLUSIONS

The newly commissioned 6m-TGM at the Synchrotron Radiation Center in Wisconsin and some of the problems faced during its implementation have been described. A temperature control system at the entrance mirror helps maintain a stable image focused on the entrance slit. Scattered light is almost nonexistent due to a planned system of light baffles along the exit arm of the monochromator. A builtin beam-chopper provides additional flexibility in experimental design. The laser alignment system coupled with a windowed gate valve at the end of the line greatly simplifies coming on-line and aligning at times when there is no beam in the ring and/or the user's chamber is not at vacuum and is most maneuverable. Coordinating the entire system is a dedicated microcomputer that controls the changing of the gratings *in vacuo*, and can work in conjunction with the user's system to aid in data collection and monochromator control.

Various noble-gas resonance lines have been used to ensure that the monochromator is performing as expected, and to refine the wavelength and resolution calibrations of the TGM. Results included in this paper demonstrate the expected resolution is close to that predicted by theory and that the predicted improvements in resolution, resulting from masking the grating, have been observed. Further work along these lines is proceeding as time between user allotments permits.

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[b] Currently with the Materials Science Program, Univ. of Wisconsin-Madison.
[c] On leave from Trieste Synchrotron Radiation Facility, Trieste, Italy, during this project.

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[2] W. R. McKinney and M. R. Howells, Nucl. Instrum. Methods **172**, 149 (1980).
[3] D. C. Mancini and J. W. Taylor (to be published).
[4] Model no. TF101-a, Luxel Corporation, 515 Tucker Ave., Friday Harbor, WA 98250.
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[7] P. Thiry *et al.*, Nucl. Instrum. Methods **222**, 85 (1984).