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Author
Underwood, J.H.

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J.H. Underwood and J.A. Koch
Materials Sciences Division

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High Resolution Tunable Spectrograph for X-ray Laser Line Width Measurements Using a Plane Varied Line Spacing Grating

J.H. Underwood¹ and J.A. Koch²

¹Center for X-ray Optics
Ernest Orlando Lawrence Berkeley National Laboratory
University of California
Berkeley, California 94720

²L-473
Lawrence Livermore National Laboratory
Livermore, California 94550

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J. H. Underwood and J. A. Koch

1 Center for X-ray Optics, Lawrence Berkeley National Laboratory, University of California, Berkeley California 94720
2 L-473, Lawrence Livermore National Laboratory, Livermore, California, 94550

Abstract

We describe a spectrograph for x-ray laser line width measurements in the range 100 - 220 Å. The design employs a plane varied line spacing grating operating in the convergent light produced by imaging the entrance slit with a concave spherical mirror. By the appropriate choice of the linear term in the grating spacing variation, two separate wavelengths can be focused at the same image distance. As a result all wavelengths within the range of interest are focused at or near the same distance. The spectrograph can be tuned by rotation of the grating to bring any wavelength within the range to the center of the focal plane and the spectra are dispersed on a surface which is "erect", or practically flat and perpendicular to the principal ray. This allows the use of a planar detector. Using a streak camera as a detector, the instrument has obtained time resolved line width data on x-ray lasers with a resolving power of 1-2 × 10^4. This paper presents the design methods used to optimize the VLS grating, the design of the tunable spectrograph and results from the instrument in operation.

Introduction

The instrument described in this paper (named the "HiRes" spectrograph to denote "high resolution") was designed to measure the spectral line width of x-ray lasers, in particular selenium and yttrium x-ray lasers. The stringent requirements of the project forced a new approach to grazing incidence spectrograph design which resulted in a unique instrument based on the use of plane varied line spacing (VLS) gratings. The properties of this spectrograph have been briefly outlined in other publications, but the principles and details of the design have not been published. These principles are of general utility and can be applied to other kinds of spectroscopic instrumentation, for example high resolution monochromators for synchrotron radiation. This instrument was the first to be designed and built using the plane VLS grating concept and thus the spectrograph serves as a prototype for verifying and evaluating them.

Design Considerations

The range of wavelengths over which the spectrograph was optimize to operate extends from ~100 to ~220 Å. This region encompasses the (2p^5 3p^3 s^1 3p^2 J=2 - (2p^5 3s^2 3p^3 J=1 (206.38 Å) and (2p^4 3p^3 s^1 3p^2 J=0 - (2p^4 3s^1 3p^2 J=1 (182.45 Å) transitions in Ne-like selenium and the corresponding transitions in Ne-like yttrium (both at 154.985 Å). For this investigation a number of design considerations must be satisfied. First, high
A resolving power is needed; a 400 eV ion temperature estimate implies an intrinsic Doppler width for the 206.38 Å laser of 36 mÅ, or $\lambda/\Delta \lambda \approx 5750$. For longer targets ($g l$) gain narrowing of the line profile would be expected to narrow the line width to $\approx 10$ mÅ at saturation, assuming that saturation intensities are reached for targets longer than 30-40 mm; this implies a minimum relative line width of $\lambda/\Delta \lambda \approx 20,000$. It is desirable to have an instrument having approximately twice this resolving power $\lambda/\Delta \lambda \approx 40,000$. Operation at a wavelength close to 200 Å requires a grazing incidence design to obtain sufficient throughput.

Secondly, a streak camera is required for the detector, to allow temporally and spatially resolved intensity measurements to be made for targets of different length. It also allows any time dependence of the measured line width to be observed within the dynamic range limitations of the system, and improves signal-to-noise for short laser amplifiers, where the laser line is not dramatically brighter than the background continuum but is considerably shorter in duration. The need for a streak camera has several design consequences. Since the spatial resolution of a streak camera is about 100 μm, the spectrum must have a linear dispersion of about 20 mm/Å to achieve a resolving power of 40,000. Secondly, the cathode of the streak camera is flat, and in order to maximize the sensitivity it is desirable to have the radiation incident normally to the cathode surface. This requires a flat focal plane which is perpendicular to the incident rays, which we call an “erect” focal plane. Another consequence of the use of a streak camera is that, owing to the large bulk and weight of the camera and its power supplies, it is preferable to access different wavelength regions by moving or rotating the grating or another optical element, rather than by physically moving the detector. In other words the spectrograph must be tunable.

Other design considerations include a reasonably sized entrance slit ($\approx 10$ μm), which again necessitates a minimum value for the linear dispersion, and an efficient grating. Stigmatic imaging is also required, i.e. the source must be reimaged at the focal plane. This is needed for three reasons: a) to provide an image at each wavelength that is resolved spatially resolved in the direction perpendicular to the plane of dispersion so that the x-ray laser source size can be measured, b) to increase the signal-to-noise at the detector by ensuring that the spectral lines are within the detector vertical aperture, and 3) to avoid a degradation of the resolution which would result from the curvature (astigmatic coma) that would result if the spectral lines were of significant height.

Figure 1 is a schematic diagram of the HiRes spectrograph as installed on the two-beam chamber at the NOVA laser facility at LLNL. The instrument can be thought of in two sections; the tunable spectrograph and the fore-optics. The spectrograph consists of the entrance slit, a spherical mirror M3 to produce a real image of the entrance slit, and a plane varied line spacing grating. The fore-optics consist of a mirror M1 to focus the source on the entrance slit, and M2 to focus the source on the detector in the direction perpendicular to the plane of dispersion.
Optical design of the spectrograph

The requirements for a high efficiency, high resolution tunable and stigmatic spectrograph with a flat and erect focal plane cannot be achieved with conventional spectrographs, in particular, with the classical grazing incidence spectrograph using a spherical grating. This type of instrument is not tunable; the spectrum is dispersed along the Rowland circle, and to fit it the detector must be long and curved. Furthermore, the spherical grating instrument can be made perfectly stigmatic at only a single wavelength, by using either a toroidal grating or a cylindrical pre-mirror\textsuperscript{15} to control astigmatism. The only optical design that meets the design criteria is the plane grating monochromator using a mechanically ruled grating whose groove spacing is not constant across its width but varies according to some prescribed formula. We draw a distinction between varied line spacing (VLS) gratings which can have an arbitrary variation of line spacing limited only by the capabilities of the ruling engine, and holographic gratings whose variation is limited by the recording geometry. Additionally, VLS gratings are usually blazed while holographic gratings are not. The VLS principle was first made practical by Harada and Kita\textsuperscript{6}, who developed an interferometrically controlled grating ruling engine to rule plane and spherical gratings with this property. Hettrick and Bowyer\textsuperscript{7} drew attention to the valuable properties of spectrograph designs in which a plane VLS grating operates in converging light. Hettrick and Underwood\textsuperscript{8,9} described how, by adding an additional perpendicular mirror to eliminate astigmatism, this principle could be used to construct scanning spectrometers, tunable spectrographs and monochromators. The instrument designed for the x-ray laser project described in this paper was built in 1988 and tested with line radiation from a Penning source\textsuperscript{2}. This effort was described only briefly in ref. (9); in the present paper the design is discussed in more detail and performance data from x-ray laser experiments is presented.

Figure 2 is a schematic diagram showing the optical principle of the tunable spectrograph. The radiation emanating from the entrance slit $E$ is refocused by the spherical mirror $M_3$ in the meridian plane to the focus $S$. The plane VLS grating is positioned in the converging beam such that $S$ is a virtual source at a distance $r$ from the center of the grating. The converging beam is essential if the spectrograph is to have an erect focal plane, i.e. one that is perpendicular to the principal ray. The sagittally focusing mirror $M_2$ forms a horizontal image of the source at the detector plane. It corrects astigmatism and reduces the height of the spectral lines to a small value; without it the resolution would be limited by spectral line curvature. It can be positioned anywhere in the optical train depending on the magnification required. In Fig. 2 it is shown between the entrance slit and the grating, but in the actual instrument it was positioned before the grating as shown in Fig. 1, and can be considered part of the "fore-optics".

To analyze the spectroscopic performance of the instrument we consider first only the rays in the meridional plane. Ignoring the size of the slit $E$ and the aberrations of $M_3$ for the moment, we consider $S$ to be a point source. It is clear\textsuperscript{10} that for any wavelength $\lambda$ and any arbitrary angle of incidence on the grating, we can choose a grating period variation that will form an image $S'$ at some other arbitrary distance $r'$ from the grating and at a diffraction angle $\beta$. The variation of the grating period along the meridian plane
can be obtained by simply inverting the grating equation. However, while an arbitrary choice of \( r' \) (for example \( r' = r \)) will give high resolving power over a small wavelength interval at the chosen wavelength, it will not necessarily be optimum for other tunings of the spectrograph, i.e. for other values of \( \alpha \) and/or \( \beta \). It is possible to choose the ratio \( r'/r \) in a way such as to optimize the resolution over a wider range. This can be done in several ways, of which three are:

1) Choose \( r'/r \) such that the spectrograph is in focus at two discrete wavelength/angle of incidence pairs \((\lambda_1, \alpha_1)\) and \((\lambda_2, \alpha_2)\).
2) Choose \( r'/r \) such that \( r' \) is stationary \( (\partial r'/\partial \lambda = 0) \) at some wavelength \( \lambda \).
3) Same as (2), but in addition allow the grating to assume a large radius of curvature \( R_0 \). This introduces another parameter which can be chosen to widens the range of tuning found by method (2).

The equations for all three of these optimizations have been derived using the method of the light path function. The equations were re-derived by McKinney using a symbolic algebra solving program. However, the first two of the equations can be derived within one page of algebra. For the instrument described here, the first optimization method was used and the relevant equation is presented in ref. (2). To minimize further confusion, we outline its derivation below.

**Optimization of \( r'/r \)**

Using the grating equation, we may derive paraxial formula for the grating variation required for point to point focusing with a plane varied line spacing grating. By "paraxial" we mean that the derivation is valid for an infinitesimal pencil of rays near the optical axis, which in this case we take to mean the principal ray through the center \( C \) of the grating: the grating is rotated about \( C \) in order to scan wavelength. Although it is conventional to use the method of the light path function to derive the properties of spectroscopic systems, we use for heuristic purposes a method based on the grating equation, which of course is exactly equivalent.

Consider a grating whose groove period varies with the ruled width \( w \), with period \( \sigma_0 \) at its center \( C \). If we express the period \( \sigma \) as a function of the ruled width:

\[
\sigma(w) = \sigma_0 + \varepsilon_1 w + \varepsilon_2 w^2 + \varepsilon_3 w^3 + \ldots
\]

where \( \varepsilon_0 = \sigma_0 \), \( \varepsilon_1 = d\sigma/dw \), \( \varepsilon_2 = d^2 \sigma/dw^2 \), \ldots

we wish to find the values of \( \varepsilon_0 \) for a grating that, at wavelength \( \lambda \), will form an image of a virtual source \( S \) at a distance \( r \) from \( C \) at a real image point \( I \) distant \( r' \) from \( C \) (figure 3). The angles of incidence and diffraction at \( C \) are \( \alpha \) and \( \beta \) respectively. We may find the first (paraxial) term simply as follows: using the grating equation in the form:

\[
n\lambda = 2\sigma(\sin \alpha + \sin \beta)
\]
Differentiating:

\[-\frac{n\lambda}{\sigma^2} \frac{d\sigma}{dw} = \cos \alpha d\alpha + \cos \beta d\beta\]  

But from figure 3:

\[r'\Delta \beta = \Delta w \cos \beta; \quad r\Delta \alpha = \Delta w \cos \alpha\]  

So that, substituting into (2) we obtain:

\[-\frac{n\lambda}{\sigma^2} \frac{d\sigma}{dw} + \frac{\cos^2 \alpha}{r} + \frac{\cos^2 \beta}{r'} = 0\]  

This eqn. provides the linear variation $d\sigma/dw$ of the grating period required to focus from the arbitrary point $S$ to the arbitrary point $S'$ at wavelength $\lambda$. We note that eq. (5) is equivalent to Eqn. (13) of ref. (11), and thus describes the focal condition $F_{2\sigma} = 0$ for the case of a grating of infinite radius (plane grating). It is the equivalent of the optical "thin lens formula" for a plane VLS grating. The sign convention is that $r, r'$ are positive for real, and negative for virtual objects or images.

We note that $r$ and $r'$ may be chosen independently. Hence, having chosen either one, we may choose the other so as to satisfy the focal condition (4) at two separate wavelengths $\lambda_1$ and $\lambda_2$. Let the corresponding incidence and diffraction angles be $(\alpha_1, \beta_1)$ and $(\alpha_2, \beta_2)$, then by using the grating equation (1) we obtain:

\[-\frac{1}{\sigma} \frac{d\sigma}{dw} = \frac{(\cos^2 \alpha_1)/r + (\cos^2 \beta_1)/r'}{\sin \alpha_1 + \sin \beta_1} = \frac{(\cos^2 \alpha_2)/r + (\cos^2 \beta_2)/r'}{\sin \alpha_2 + \sin \beta_2}\]  

with some manipulation we obtain:

\[-\frac{r'}{r} \frac{\cos^2 \beta_2 (\sin \alpha_1 + \sin \beta_1) - \cos^2 \alpha_1 (\sin \alpha_2 + \sin \beta_2)}{r (\sin \alpha_1 + \sin \beta_1) - \cos^2 \alpha_2 (\sin \alpha_2 + \sin \beta_2)} = \frac{\lambda_2 \cos^2 \beta_2 - \lambda_1 \cos^2 \beta_1}{\lambda_2 \cos^2 \alpha_2 - \lambda_1 \cos^2 \alpha_1}\]  

This equation, with sign differences which arise as a result of the use of a different sign convention appears as eq. (1) of ref. (2), and as eqn. (15) of ref. (11). Eqns. (4) and (6) are used to find an optimized value of the linear term $d\sigma/dw$ in the grating period variation.

It should be noted that, although in the present case we are applying the optimization eq. (7) to a tunable spectrograph with fixed included angle, the method applies to any kind of grating spectrograph, spectrometer or monochromator, regardless of the functional dependence of $\beta$ upon $\alpha$, i.e. the method of spectrum scanning.
The higher terms $\varepsilon_2$, $\varepsilon_3$, ..., in eq.(1) represent the corrections to the grating period that are required to achieve stigmatic focusing at finite apertures. They can be derived by equating to zero the corresponding terms $F_3$, $F_4$, ..., in the light path function, and closed form formulae have been given for them. However, the required grating spacing function can be found by a simpler method. It consists of merely solving the grating equation across the surface of the grating for one of the correction wavelengths $\lambda_c$, as shown in their eqn. (1) and Fig. 1. This leads to an explicit formula for the grating spacing as a function of $w$:

$$w = \frac{\lambda_c}{\left\{ \left[ 1 + h_0^2 / \left( t_0 - w \right)^2 \right]^{1/2} - \left[ 1 + h_1^2 / \left( t_1 - w \right)^2 \right]^{1/2} \right\}}$$

(8)

where: $h_0 = r\cos(\alpha_c)$, $t_0 = r\sin(\alpha_c)$; $h_1 = r\cos(\beta_c)$, $t_1 = r\sin(\beta_c)$.

Clearly this provides correction of all orders for this particular correction wavelength. This equation can be inverted to find the coefficients $\varepsilon_n$ in the series (1). However, (8) provides sufficient all the information required to specify a grating. The correction will be relatively good at other wavelengths, especially for small numerical apertures. For higher numerical apertures it will in any event be necessary to consider the aberrations of the optics as well as the grating, and in the absence of analytical expressions for the aberrations of the combined system it is necessary to use a numerical optimization method such as that devised by Koike et al., which uses a combination of the light path function and ray tracing methods. In this way the groove period variation can be used to correct the spherical aberration of other optics in the system, including the $M_3$ mirror. This was not done for the present case since the $M_3$ mirror works at unit magnification and has negligible spherical aberration.

Returning to equation (4), let us suppose that $r' = \infty$ and, using the derived value of $d\sigma/dw$, solve for the corresponding wavelength $\lambda_\infty$. This will be the "collimation wavelength"; at wavelengths longer than $\lambda_\infty$ the spectral images will be virtual. The corresponding value of $\alpha$ is given by:

$$\frac{r \sigma}{\sigma_0} \frac{d\sigma}{dw} = \frac{\cos^2 \alpha_\infty}{\sin \alpha_\infty - \sin(2\theta - \alpha_\infty)} = -\frac{\cos \alpha_\infty}{(1 + \cos 2\theta) \tan \alpha_\infty - \sin 2\theta}$$

(9)

This equation can be solved numerically for $\lambda_\infty$ which represents the upper wavelength limit at which the spectrograph will operate, not the horizon wavelength at which $\beta = -\pi/2$. However, motion of the focus towards infinity degrades the resolution very severely at wavelengths above 220 Å, which represents an effective upper limit to operation.

The x-ray laser spectrograph was optimized using eqn. (6); the basic specifications and operating parameters are listed in Table 1.
Gratings

Applying $d\sigma/dw$ only over the ruled width of 63 mm, we find that the groove period varies from 1/1763.2 mm at $w = -30.5$, to 1/1838.4 mm at $w = 30.5$ mm. The application of eqn. (8) to calculate a grating fully corrected at 208.44 Å makes only a small difference to the groove period variation, the corresponding figures becoming 1/1763.0 mm and 1/1837.2 mm. The values of the coefficients, $\varepsilon_n$ in eqn. (1), are:

$\varepsilon_0 = 1/1800$ mm, $\varepsilon_1 = -3.681 \times 10^{-7}$, $\varepsilon_2 = 5.66 \times 10^{-11}$ mm$^{-1}$, $\varepsilon_3 = 2.32 \times 10^{-13}$ mm$^{-2}$

To three significant figures, $\varepsilon_2$ and $\varepsilon_3$ are identical when computed for the other correction wavelength 103.09 Å. Thus the instrument is well corrected throughout its range. The 4% variation of $\sigma$ is easily within the range of modern interferometrically controlled grating ruling engines. The grating was ruled into a gold-platinum alloy coating on a plane fused silica blank with a flatness of $\lambda/20$ of 6328Å light. The rulings were made on a ruling engine developed by Hirst at the Perkin-Elmer Corporation.

The only other optical component contained within the monochromator is the $M3$ mirror. This was polished to $\lambda/20$ and a surface roughness of 50 Å. It was coated with gold for maximum reflectance at 200 Å.

Predicted spectrograph performance

Figure 4 shows the focal length of the spectrograph as a function of tuned wavelength. From zero order where $r' = r = 2958.7$ mm, $r'$ reaches a minimum of 2816 mm at $\sim 180$ Å and becomes 2958.7 mm again at $\sim 212$ Å. Thus between 0 and 212 Å the range of variation of $r'$ is 143 mm; between the two correction wavelengths, the variation is 77 mm. For best focus and highest resolution at any wavelength it would strictly be necessary to move the detector. However, a refocusing of this amount can easily be achieved by a slight change in the incidence angle of the $M3$ mirror, which introduces a corresponding change in its image distance and the virtual source distance for the grating. By this method the intrinsic high resolution of the spectrograph can be achieved at any wavelength between 0 and 212 or more Å. This refocus adjustment is required for another reason. It is very difficult for an optical manufacturer to achieve a close tolerance on the radius of a spherical mirror of the radius of $M3$; a tolerance of 0.5% to 1.0% is common. Thus a slight angular adjustment of the mirror is needed to place the focus at its nominal position. This was done during the at-wavelength alignments described below.

Figure 5 shows the resolving power calculated using the paraxial focusing eqn. (5) and the maximum beam divergence of 3 mrad. This gives a resolution figure which is somewhat pessimistic because it is measured by the extreme rays. Ray tracing yielded essentially identical results, which is hardly surprising since all grating coefficients were obtained using equation (9) which is essentially a ray trace formula. We see that, with the detector at the nominal distance $r'_0$ the desired resolving power of 40,000 is achieved only over small wavelength intervals near the correction wavelengths. These high resolution regions can be repositioned through refocusing, but for the highest resolution
measurements the aperture was reduced to 0.5 mrad to give the resolving power as shown in the second curve.

Detectors

A more important limit to the resolving power is set by the entrance slit and detector pixel sizes. During the original tests of the instrument\textsuperscript{9}, a Schumann emulsion (Kodak 101-01) was used. The fine grain of this film allowed the resolution limit of the optics to be achieved. For the x-ray laser measurements, a Kentech x-ray streak camera was used. In figure 6 we plot the resolving power as limited by a) an entrance slit of 10 μm width, the streak camera pixel size of 100 μm, and a 23 μm pixel corresponding to the use of a CCD camera for alignment. A intensified microchannel plate (MCP) detector was also used in the alignment phase, and in this case the effect of the large pixel size (also ≈ 100 μm) was reduced to a small magnitude by the use of a tilted slit in the exit plane. This technique is described by MacGowan et al.\textsuperscript{14}. It may be seen that the large pixels of the streak camera impose a the most serious limitation to the achievable resolving power of this instrument.

Tunability of the spectrograph

Although the calculations of resolution were made as if the instrument were a scanning spectrometer of fixed deviation, in actual use the spectrum is dispersed across the face of the detector and the instrument acts as a spectrograph, i.e. $α = \text{constant}$. The spectrograph can be tuned to access different wavelength regions by resetting $α$ to discrete angles $α_1, α_2, \ldots$ corresponding to discrete central wavelengths $λ_1, λ_2$. Under these conditions the focal surface is given by $r'(λ)$, with $α = α_j$. Fig. 7 shows the form of this surface for a series of values of $λ_j$. In this graph the horizontal axis represents the distance across the focal plane from the central position, at which $α - β = 2θ = 162°$ and $λ = λ_j$. For each setting the focal distance $r'(λ)$ was calculated, from eq. (5), for the range of values $λ_j ± 2$Å; the vertical axis is the difference between this value and the optimum value of $r'$, the detector distance. In other words the curves represent cross-sections of the focal surface on which each spectrum is dispersed. By definition the curves for the two correction wavelengths pass through (0,0), however the focal surface is approximately erect, i.e. flat and perpendicular to the central ray, only for the shorter of these two wavelengths. It is also precisely erect at $λ_j = 217.75$ Å. The curvature and inclinations of these focal planes cause additional deterioration of the resolution, which is unimportant for most of the laser line width measurements since the lines are so narrow.

Since each curve represents a 4 Å spectral range (except for the two longest wavelengths for which the curves are slightly truncated at the left), Fig. 7 also shows the variation of linear dispersion with $λ_j$. This varies from 4.7 mm/Å at 80 Å to 19.2 mm/Å at 220 Å.

The tuning of the spectrograph is accomplished through the use a sine bar grating drive with appropriate gauge blocks set under the ball end of the sine bar.
Fore-optics

The HiRes spectrograph was not intended for use as a slitless instrument, since it was not clear that the x-ray laser source is sufficiently small to maintain the high resolution. Hence an entrance slit was provided and fore-optics provided to illuminate it. The mirror M1 focuses the laser source on the entrance slit with a demagnification of 0.42; mirror M2 focuses the source on the detector plane with a magnification of 3.01, and thus provides the required stigmatic focusing. The use of a sagitally focusing mirror to provide stigmatic focusing reduce spectral line height and increase resolution was first used by Hettrick and Underwood\textsuperscript{15} in a tunable spectrograph employing spherical gratings.

Unlike the M3 mirror, which affects the spectral resolution, these mirrors do not need to be of the highest optical quality. They were made by bending rhodium-coated strips of float glass in a two-couple bending mechanism\textsuperscript{16,17}. This method allows the focus to be adjusted easily by altering the radius of the mirrors, and, since the mirrors can be bent into a good approximation of an ellipse, partial correction of the spherical aberration of the mirrors is possible if they are used at non-unit magnification.

Alignment

A continuous source of x-rays was needed for the final at-wavelength alignments of the optics, since it was not possible to make adjustments during the few nanoseconds of the x-ray laser pulse. This was provided by the light from an aluminum-neon plasma confined in a Penning source of the type first used to bench test the instrument\textsuperscript{2}. Due to its bulk and weight it could not be positioned in the NOVA chamber, but was positioned outside at the same distance and the x-rays reflected onto the spectrograph slit by a retractable molybdenum-silicon multilayer mirror. This mirror operated at a grazing angle of 42°, and coatings of the appropriate period were chosen to permit alignment and adjustment of the spectrograph using the Al IV $3s-2p$ lines at 161.074 Å, the Al III autoionization lines near 171 Å, and the Ne IV $3s-2p$ lines at 208 Å.

Performance

The instrument was first bench tested and evaluated using a Penning source\textsuperscript{9}. Under these optimum conditions a spectral resolving power of 35,000 was demonstrated. The instrument was then installed at the NOVA facility, and was successfully used to measure gain-dependent spectral line widths of the 206.38 Å Ne-like Se soft x-ray laser. The main results of these experiments have been published elsewhere [3]. Figure 8 shows a typical Se x-ray laser spectrum obtained with the instrument, together with the measured instrument resolution function. The instrument resolution, while a significant fraction of the total measured spectral line width, is small enough to allow deconvolution, as shown in Figure 9. The results shown in Figure 9 were the first spectral line-width measurements of a collisional-excitation soft x-ray laser, and data of this type could not be obtained with any other instrument. The instrument has also been used to measure structure in hyperfine-split soft x-ray transition line shapes\textsuperscript{18}, and has been used to measure absolute wavelengths and line overlaps with extremely high precision\textsuperscript{23}.
An interesting feature of the data obtained with this instrument are the Rowland ghosts on either side of each bright spectral line, as shown in Figure 10, which is a recording of the \( J = 2 \rightarrow 1 \) (\( \lambda = 154.985 \) Å) transitions in the Ne-like yttrium laser. The first order ghost lines appear on each side of the central line at apparent wavelengths \( \lambda' = \lambda \pm 0.085 \) Å. Using the formula:

\[
\lambda' = \lambda (1 \pm n'/nN)
\]  

where \( n \) is the spectral order, \( n' \) the order of the ghost, and \( N \) the number of grooves ruled in one turn of the screw, we see that \( N \sim 1800 \). The ghosts are thus caused by a ruling error in the grating of period 1 mm. They are weaker than the central line by a factor of about 100, and limit the useful contrast range of the instrument to approximately 100:1. It should be noted, however, that this grating was ruled in 1986, and the engine that ruled it has been considerably upgraded and improved since then.

**Other applications of plane VLS gratings**

The VLS plane grating concept provides a very powerful method for building high performance spectroscopic instrumentation. It is doubtful that the design requirements for the project described in this paper could have been met by any other grazing incidence design.

Since the erect focal planes (Fig. 7) translate into a focal distance that remains relatively constant as \( \lambda \) varies, it is clear that the VLS-PGM design is readily adapted to function as a fixed deviation monochromator or scanning spectrometer if a fixed exit slit is provided and the dispersed spectrum is scanned over it in some fashion. For example Calcott et al.\textsuperscript{19,20} retrofitted a monochromator, originally designed to use a transmission grating, by substituting a VLS grating and adding a plane mirror between the grating and the exit slit; combined rotation and translation of this mirror sweeps the spectrum across the exit slit for scanning. However, if fitting into an already existing configuration is not a design issue, spectral scanning is more simply implemented by rotating the grating as described by Hettrick and Underwood\textsuperscript{8}. Since the focal distance remains relatively constant (Fig. 4), this scanning mechanism requires no movement or minimal movement of either the entrance or the exit slit, whereas in a spherical grating spectrometer/monochromator (SGM), one or other slit must move in order to keep the spectrum in focus and obtain optimum resolution. Thus it is possible to build simple monochromators of high resolution and high throughput. VLS-PGM monochromators of this design have been constructed for the synchrotron radiation storage rings at BESSY in Berlin, Germany and at the Advanced Light Source in Berkeley, California\textsuperscript{21}. These instruments have the additional feature that the converging mirror (figure 2) operates at a demagnification of 10:1, resulting in a more compact and stable instrument. This introduces spherical aberration\textsuperscript{22}, which is then corrected by the terms higher than linear in the variation of the grating line spacing. The optimization of such a design then requires an optimization scheme such as that described by Koike et al.\textsuperscript{12}, which takes advantage of the versatility of the ray trace method and the completeness of the analytical design method. This method is
applicable not only to constant included angle designs such as described here, but can be used to construct monochromators of the variable included angle variety as well\textsuperscript{24}.

Acknowledgments

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References


10. Rowland pointed out that a theoretically perfect grating for one position of the entrance and exit slits could be ruled on any surface, plane or otherwise. See G. W. Stroke, “Diffraction Gratings” Handbuch der Physik XXIX (Ed.: S. Flügge), p.473 (1967). This result holds in general for only one wavelength, but it clearly applies to virtual as well as to real sources.


22. Often confusingly misnamed “coma”.


Table 1. Design Parameters of HiRes Spectrograph

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value/units</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Order n</td>
<td>-1</td>
<td>outside order, $</td>
</tr>
<tr>
<td>Included angle $2\theta$</td>
<td>162°</td>
<td>$2\theta = \alpha - \beta$</td>
</tr>
<tr>
<td>Virtual source distance r</td>
<td>-2958.71 mm</td>
<td></td>
</tr>
<tr>
<td>Optimization wavelength $\lambda_1$</td>
<td>208.440 Å</td>
<td></td>
</tr>
<tr>
<td>Optimization wavelength $\lambda_2$</td>
<td>103.090 Å</td>
<td></td>
</tr>
<tr>
<td>$r'/r$ from eq. (6)</td>
<td>-0.9779005</td>
<td></td>
</tr>
<tr>
<td>Focal distance $r'$</td>
<td>2893.31 mm</td>
<td>at $\lambda_1$ and $\lambda_2$</td>
</tr>
<tr>
<td>Grating period at center $\sigma_0$</td>
<td>1/1800 mm</td>
<td></td>
</tr>
<tr>
<td>$d\sigma/dw$</td>
<td>$-0.3681 \times 10^{-6}$</td>
<td>$w$ increases towards image</td>
</tr>
<tr>
<td>Grating ruled width $w$</td>
<td>63 mm</td>
<td></td>
</tr>
<tr>
<td>Ruling length</td>
<td>30 mm</td>
<td></td>
</tr>
<tr>
<td>Blaze angle $\phi$</td>
<td>4.75 ± 0.25°</td>
<td></td>
</tr>
<tr>
<td>Blaze wavelength $\lambda_B$</td>
<td>~ 144 Å</td>
<td></td>
</tr>
<tr>
<td>M3 mirror radius $R_M$</td>
<td>20,000 mm</td>
<td>spherical, concave</td>
</tr>
<tr>
<td>M3 dimensions (l x w)</td>
<td>127 x 30 mm</td>
<td></td>
</tr>
<tr>
<td>M3 mirror incidence angle</td>
<td>81 degrees</td>
<td></td>
</tr>
<tr>
<td>Slit to M3 distance</td>
<td>3128.7 mm</td>
<td></td>
</tr>
<tr>
<td>M3 to grating distance</td>
<td>170 mm</td>
<td></td>
</tr>
<tr>
<td>Maximum vertical aperture</td>
<td>3 mrad</td>
<td>Limited by aperture stop</td>
</tr>
<tr>
<td>Horizon wavelength $\lambda_H$</td>
<td>271.908 Å</td>
<td></td>
</tr>
<tr>
<td>Collimating wavelength $\lambda_\infty$</td>
<td>246.559 Å</td>
<td></td>
</tr>
<tr>
<td>Plate scale @ $\lambda = 200$ Å</td>
<td>15 mm/Å</td>
<td></td>
</tr>
</tbody>
</table>
Figure 1. Schematic diagram of the HiRes VLS-PGM tunable spectrograph. The various components are described in the text.
Figure 2. Principle of the VLS-PGM tunable spectrograph. \( E \): entrance slit; \( M2 \): horizontal focusing mirror for removal of astigmatism, \( M3 \): spherical concave mirror; \( G \): grating; \( C \): grating center; \( S \): image of \( E \) formed by mirror; \( Z \): zero order image of \( S \), \( S' \): dispersed image of \( S \). An "outside" order is shown. Note that \( M1 \) of figure 1 is not shown and \( M2 \) is shown after the entrance slit. The two configurations are equivalent.

Figure 3. Paraxial imaging by a VLS grating.
Figure 4. Focal length as a function of wavelength for the "constant included angle" condition. The vertical dot-dash line represents the "collimating wavelength".

Figure 5. Resolving power as a function of wavelength for two different values of the divergence. Horizontal line: $\lambda/\Delta\lambda = 40,000$. 
Figure 6. Slit width and pixel size limits to the resolving power. Bold: calculated for an entrance slit width of 10 μm; dash; for a 23 μm CCD pixel; dot-dash; for a 100 μm streak camera pixel.

Figure 7. Spectrograph focal surfaces for different wavelengths. Each curve is calculated over a range of ± 4 Å and is labeled with the corresponding at the center (x=0) of the detector.
Figure 8. A plot of the measured spectral line width data obtained from a 3.35 cm Se x-ray laser (solid line), along with the measured instrument resolution function (dashed line). The deconvolved laser spectral line width has a full width at half-maximum intensity (FWHM) of approximately 12.5 mÅ.

Figure 9. A plot of measured (triangles) and deconvolved (diamonds) experimental line FWHM vs. amplifier length data from the Se x-ray laser experiments. The error bars arise primarily from deconvolution uncertainties.
Figure 10. A spectrum of the yttrium x-ray laser illustrating the presence of Rowland ghosts due to periodic ruling errors in the grating. The central line was saturated on film, allowing the sidebands to be clearly visible; the actual contrast ratio was measured to be approximately 100:1.