Design and implementation of a high-resolution, high-efficiency optical spectrometer

S. B. Utter,[a] J. R. Crespo López-Urrutia,[b] P. Beiersdorfer, and E. Träbert
Lawrence Livermore National Laboratory, Livermore, California 94550-9234

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We present the design, implementation and testing of a high-efficiency, high-resolution transmission grating spectrometer for measurements of near-ultraviolet to visible-range spectra of light from an electron beam ion trap, where geometry is constrained. The system consists of two 5 in. diameter $f/4.6$ achromatic lenses, a 6 in. diameter transmission grating ion-beam etched in fused silica, and a thinned, backilluminated CCD detector. The simple design minimizes the number of optical components, each with optimal throughput and high efficiency. Using a 30 μm wide entrance slit, a resolving power $(\lambda/\Delta\lambda)$ of 15 400 at $\lambda \approx 3850$ Å has been demonstrated. The features and limitations of the instrument have been explored and an *in situ* calibration technique for use on the Livermore EBIT-II and SuperEBIT electron beam ion traps has been developed. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1510574]

I. INTRODUCTION

Much current understanding of the physical world has come from atomic spectroscopy. Precisely measured spectra can be used to answer questions related to a variety of physical phenomena in such fields as atomic physics, astrophysics, plasma diagnostics, nuclear physics, etc. Atomic transitions with optical wavelengths are regularly used as indicators of plasma parameters such as temperature and density in a variety of plasma devices. Precision measurements require instrumentation which can efficiently collect and disperse this radiation, while remaining uncomplicated and versatile.

Among the various light sources applied to the study of multiply charged ions, the electron beam ion trap[1] has matured into a superior tool which allows systematic observation of the spectra of ions in nearly any charge state. Measurements on the SuperEBIT electron beam ion trap at Lawrence Livermore National Laboratory have been made on ions up to Cf^{96+}.[2,3]

Typically, the radiation emitted in electronic transitions of highly charged ions is in or near the x-ray region of the electromagnetic spectrum. Therefore, historically, most of the spectroscopy performed on electron beam ion traps has been focused on the study of hard x ray, soft x ray, and EUV radiation. However, there are low-lying levels in the ground configurations of many highly charged ions, and their decay leads to the emission of low-energy photons. This scenario has first been confirmed when identifying some of the then-mysterious visible spectral lines in the spectrum of the solar corona.[4] Subsequently, such lines have been used in the diagnostics of hot low-density plasmas.[5]

Electron beam ion trap measurements of optical radiation in the UV through visible band, of transitions that connect low-lying fine structure levels, were first reported by Morgan *et al.*[6] who employed a scanning spectrometer. Further studies at various electron beam ion trap (EBIT) facilities mostly used moderate-resolution monochromators equipped with reflection gratings, either as scanning instruments[7–9] or with multichannel detectors.[10,11] Additional measurements employed a prism spectrometer with a multichannel detector.[12,13] One measurement used an interferometer[14] to study the profile of a single line. Bieber *et al.*[9] arranged a complex optical set-up for precise wavelength determinations of a few spectral lines. The other measurements gave preference to spectral coverage over resolution and precision.

Although the survey instruments have proven to work well for measurements of intense transitions, the spectra regularly are much more complex than can be disentangled at this level of spectral resolution. Prism-based survey instruments have been shown to be excellent for finding and identifying fine structure ($M1$) transitions in highly charged ions,[13,15] but the nonlinear calibration curve and the low resolution hindered detailed physics studies on such lines.

Furthermore, it is often the case that a transition of interest is so weak that single-photon counting is required over extended periods of time. Examples are the hyperfine transitions in the ground states of high-Z hydrogen-like ions,[16–18] the equivalent of the 21 cm line of atomic hydrogen that is so widely exploited in radioastronomy. Therefore, optical efficiency is also of great importance.

In order to address the need for higher resolution and concurrently higher detection efficiency, we designed and built two new optical spectrometers for use on the Livermore EBIT-II and SuperEBIT electron beam ion traps. The design goals included not only precision and collection efficiency, but also versatility and reasonably simple handling. Furthermore, the limited space near the electron beam ion trap suggests an elongated design that also places the detector away from the strong magnetic fields near the trap, which differs from the traditional V shape of most grating spectrometers. While additional mirrors might remedy the geometric con-

[a]Present address: Spectra-Physics, Mountain View, CA 94039.
[b]Present address: Max Planck Institute for Nuclear Physics, D-69117 Heidelberg, Germany.

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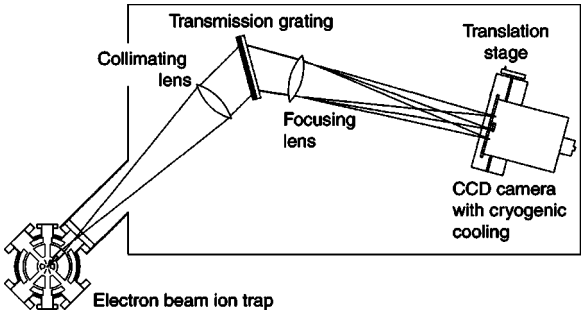

FIG. 1. Diagram of the TGS optical system.

straints, the number of optical components better be minimized to prevent additional light losses. Out of these considerations a custom-optics transmission grating spectrometer (TGS), optimized for the low-light environment of an electron beam ion trap light source, was designed and built (in two slightly different versions).

II. INSTRUMENT LAYOUT

The TGS has been designed around its key element: a highly efficient fused silica transmission grating. This type of grating was developed at LLNL[19] to be used in high-power ultraviolet laser systems (i.e., with frequency-tripled Nd:glass laser light at $\lambda \approx 3510$ Å) where transmission efficiency is critical, because thermal loads on the optical elements have to be minimized. Each grating consists of a pattern of deep near-rectangular grooves with a 350 nm spacing. The equally wide grooves and ridges are etched into a 6 in. (152 mm) diameter, 1/4 in. thick quartz plate by techniques of interference lithography.[20,21] An antireflective coating was deposited on the grating's back surface. The geometry of highest diffraction efficiency (optimized for the aforementioned third harmonic of the Nd:glass laser) requires incoming and outgoing light ($-$first order) both at 30° from the grating normal. Then the $+$first order falls into the grating surface, where the light wave coincides in spatial frequency with the grating pattern. Measurements of gratings manufactured in this way have exhibited efficiencies of nearly 94% (for one polarization) into diffraction order $m=-1$ at 30° incident angle and better than 85% (averaged over both polarizations or for unpolarized light) at incident angles from 25°–35°.[19] This high efficiency of diffraction into a single order is decisive for the high throughput of our instrument.

The TGS optical layout, shown in Fig. 1, is quite simple. Each spectrometer component is rigidly mounted to a portable lightweight aluminum optical table, and black-anodized, aluminum-sheet walls and top lids shield the enclosure against ambient light. Light is collected by a 5 in. (≈ 130 mm) diameter $f/4.6$ achromatic planoconvex collimator lens with the source positioned at the focus. The parallel light is then transmitted through the grating, and the diffracted rays are collected by a second lens identical to the first. The light is focused at the surface plane of a thinned, backilluminated, cryogenically cooled CCD detector to provide a one-to-one image of the light source. The CCD camera chip has a size of about 25 mm square and a pixel spacing of 25 μm. Edge or bandpass filters may be inserted to provide reduction of background signal, especially in the red from the electron gun filament glow. At each spectrometer setting, a wavelength range of about 130 Å is being covered by this multichannel detector. For changes of the wavelength setting, the CCD camera is being moved sideways on a translation stage shown schematically in Fig. 1.

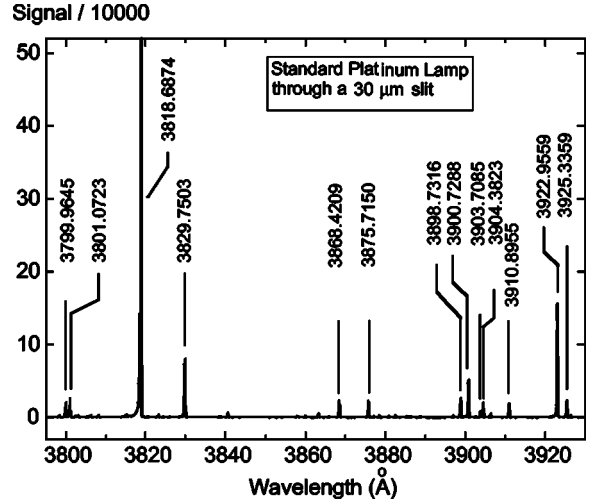

FIG. 2. Spectrum obtained from the average of thirty 10 ms exposures using a Pt/Ne lamp for the source. The marked lines are those used to determine the spectrometer's optimal resolving power and spectral dispersion.

III. SPECTROMETER PERFORMANCE

The TGS performance was tested offline using standard spectral lamps shined through a narrow slit—a 30 μm $\times$1 cm rectangular aperture—mounted onto the entrance port of the spectrometer housing. Figure 2 shows a spectrum obtained using a Pt/Ne hollow-cathode lamp as the light source.

The Pt/Ne lamp was chosen because it has well-characterized spectral features, making it the calibration source of choice throughout the near UV and visible. The lamp was developed as the primary calibration source for several astrophysical satellites such as the International Ultraviolet Explorer satellite as well as the Goddard High Resolution Spectrograph and the Faint Object Spectrograph of the Hubble Space Telescope.[22] A complete listing of all of the Pt/Ne lamp features can be found online.[23]

The TGS spectral dispersion was determined empirically using thirteen of the strongest lines in the range shown in Fig. 2. The centroid positions of the lines were determined by a Gaussian least-squares fit using the PEAK FIT MODULE of the MICROCAL ORIGIN software package, allowing for optimization of the line positions, peak heights, and widths; the widths were constrained to be the same for all features. These positions were then fit with a third-order polynomial to yield the dispersion relation.

A second series of spectra was obtained using the same setup, but using a Gd/Ne lamp as the source (see Fig. 3). Again, the line positions were determined [in units of channels (pixels) of the detector] and converted to wavelengths using the dispersion relation obtained with the Pt/Ne lamp. Sixty-six spectral features were fit. The FWHM was found to

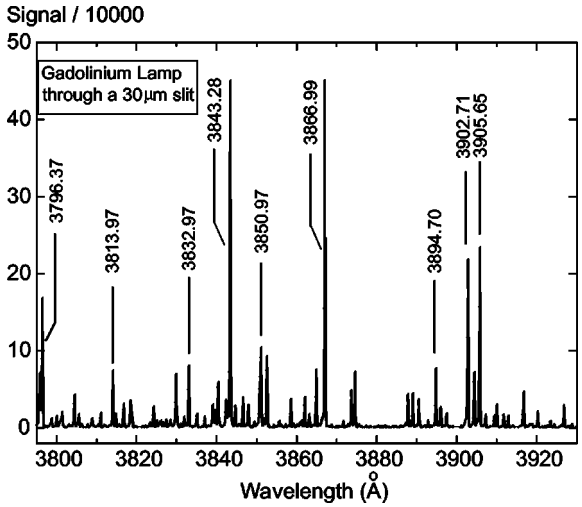

FIG. 3. Spectrum obtained from the average of thirty 10 ms exposures using a Gd/Ne lamp for the source. 66 lines were measured of which 32 were found in standard reference tables.

be 1.9 channels, or equivalent to 0.25 Å at the center of the spectrum. Of these measured lines, 32 spectral lines were found in the standard tables published by the National Institute of Standards and Technology.[24] The standard deviation of the difference between the measured and published wavelengths for the 32 lines was determined to be 0.010 Å, or about one part in 400 000, demonstrating excellent agreement between the measured and standard wavelengths.

IV. APPLICATION

The off-line tests show that the new instrument is capable of wavelength determinations within 2.5×10^{-6}. Even better accuracy may be obtained with a smaller entrance slit and a detector with a higher spatial resolving power. For spectroscopic work on the Livermore electron beam ion traps, it has become customary to avoid additional optical elements and apertures, and to directly use the source itself as the "entrance slit" by placing the narrowly confined volume in which the electron beam excites ions in the object focus of a given spectroscopic system.[11,13,25–29] This light source has a length of about 2 cm (viewing is limited by slots in the trap drift tubes, cooling shrouds and viewports) and a width of about 70 μm.[30] Light collection is optimized in this way, and we employ this geometry also for the present spectrometer. The sideways extent of the light source is wider than the slit width in the test with the spectral lamp, and this will reduce the spectral resolution accordingly.

As a first test of the overall improvement the TGS offers over instruments previously used for optical measurement on the LLNL electron beam ion trap experiment, observations of a well studied transition from highly charged Kr[8,10,31–33] (near 3841 Å) were made simultaneously with the TGS and a prism spectrometer. The two spectro/meters each recorded data using similar cryogenically cooled CCD detectors. The quantum efficiency of such CCDs is about 55% at the wavelengths studied here. A direct comparison of the data taken

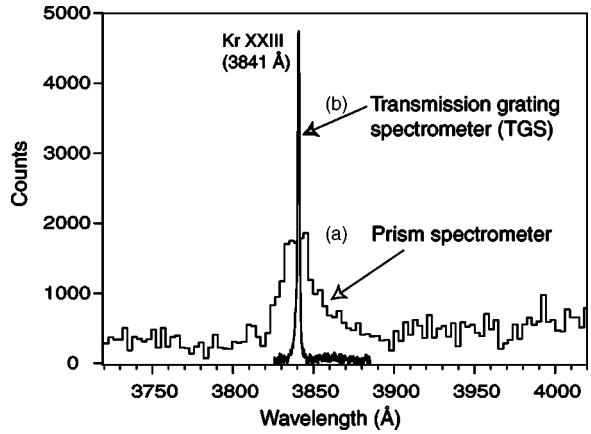

FIG. 4. Si-like Kr^{22+} ion line at 3841 Å as measured with (a) a prism spectrometer and (b) the present TGS.

with the two spectrometers (Fig. 4) emphasizes the increased spectral resolution as well as the improved collection efficiency. These data show that use of the TGS has improved the spectral resolution (FWHM) of the strong Kr^{22+} line by a factor of nearly 7, while improving collection efficiency by more than a factor of 3, an attribute to the increased optical collection solid angle.

The actual gain in spectral resolution is much higher than is indicated by the Kr^{22+} ion line in Fig. 4: the TGS spectrum (Fig. 5) contains a fair number of weaker lines of notably smaller width. These lines arise from low-charge Kr ions. Their widths are consistent with the instrumental resolution in combination with the 70 μm width of the electron beam. The decays observed are prompt (typical level lifetimes in the nanosecond range), and therefore the emitters cannot move notably from their location at the time of excitation by the electron beam. By contrast, the prominent line originates from a slow magnetic dipole transition in Kr^{22+}. The upper level of this transition has a lifetime of almost 7 ms,[33] and during such a time span, a highly charged ion (possibly also more energetic after so many ionizing collisions with electrons) can map out a volume exceeding that of the electron beam. Hence the larger line width results from

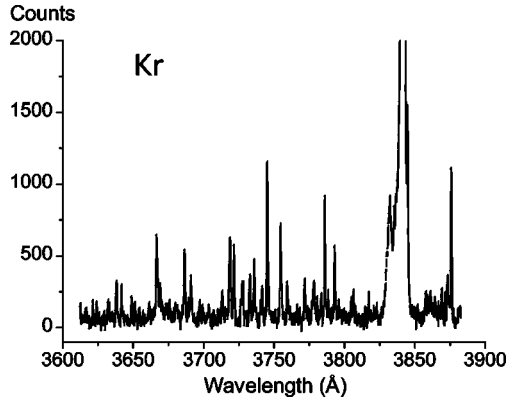

FIG. 5. Same Si-like Kr^{22+} ion line at 3841 Å as observed with the TGS and shown in Fig. 4, but displayed with a truncated intensity scale in order to show the plenitude of weaker lines nearby. These weak lines are much narrower; their width represents the instrumental resolution combined with the width of the electron beam. The dominant line is broadened because the ion cloud is much wider than the electron beam.

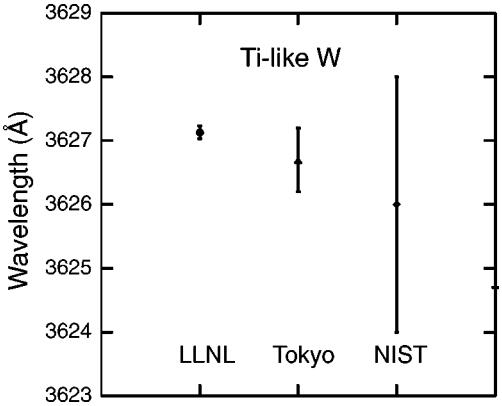

FIG. 6. Wavelength determination of a prominent fine structure transition in the Ti-like ion W^{52+}. The three experimental data are from the electron beam ion traps at LLNL (Ref. 35), Tokyo (Ref. 36), and NIST Gaithersburg (Ref. 37). The LLNL experiment employed the presently discussed TGS spectrograph.

the fact that the volume of the ion cloud inside the trap is much larger than that of the electron beam. That property can serve as an indicator of the emitter type when performing line identifications.[33]

The same weak lines that demonstrate the instrumental resolution in the spectrum shown in Fig. 5 provide an *in situ* wavelength reference. In fact, their appearance in the spectra of Ne, Ar, and Kr can be optimized by avoiding the excitation of any lines from high-charge state ions of these elements. This is achieved by the "inverted trap" mode[15] in which the electron beam ion trap drift tube voltages are set so that ions are not trapped, but expelled along the magnetic field lines. Then any observed light can only originate from freshly injected atoms that are excited or ionized in a single pass through the electron beam. Double ionization is possible, but much less likely to take place because of a much smaller cross section and the short time interval available, and triple ionization is less likely again. It is therefore no surprise that the spectral lines observed with such settings are mostly recognized as originating from singly charged ions. The wavelengths of some of these lines have been measured to high accuracy.[24,34] This makes for a very convenient method of *in situ* wavelength calibration for the TGS.

The new spectroscopic capabilities the TGS offers have meanwhile been applied to a number of spectroscopic studies. Among these are the $3s^2 3p^6 3d^4$ $J=2-3$ transitions in the Ti-like ion W^{52+}[35] and a measurement of the ground state hyperfine transition in the hydrogenlike (single-electron) ion Tl^{80+}.[18] In Fig. 6 the result of the former measurement is compared to data from other electron beam ion traps. The superior performance of the present spectrograph is evident in that the result is more precise by a factor of 5 than the measurement from Tokyo,[36] and more precise than the NIST Gaithersburg data by a factor of 20.[37] These measurements demonstrate that the TGS is rapidly becoming the instrument of choice for high-resolution, high-signal-to-noise measurements of optical lines at the Livermore electron beam ion trap.

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