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SPRED SPECTROGRAPH UPGRADE: HIGH RESOLUTION
GRATING AND IMPROVED ABSOLUTE CALIBRATIONS

By

B.C. Stratton, R.J. Fonck, K. Ida,
K.P. Jaehnig, and A.T. Ramsey

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PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

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B.C. Stratton, R.J. Fonck, K. Ida, K.P. Jaehnig, and A.T. Ramsey

Plasma Physics Laboratory, Princeton University, Princeton, NJ 08544

Abstract

Two improvements to the SPRED multichannel VUV spectrographs used on the TFTR and PBX tokamaks have been made: 1) A new 2100-g/mm grating covering the 100-320 Å region with 0.4 Å resolution (FWHM) has been added to the existing 450 g/mm grating (100-1100 Å with 2 Å resolution), and 2) the TFTR SPRED has been absolutely calibrated using synchrotron radiation from the NBS SURF II facility, while the PBX system has been calibrated using conventional branching ratios along with line ratios from charge-exchange-recombination-excited lines. The availability of high resolution spectra in the 100-320 Å range provides improved measurements of metallic ion emissions and, when the instrument views across a neutral beam as in PBX, allows carbon and oxygen densities to be measured via charge exchange recombination spectroscopy.

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I. Introduction

Time-resolving multichannel spectrographs¹⁻³ which are capable of observing a wide region of the spectrum during a single discharge have become widely used for tokamak plasma spectroscopy. The SPRED spectrograph¹ is one such instrument. SPRED instruments are currently in use on the TFTR, PBX, and JET tokamaks.

As originally designed, SPRED used interchangeable 450-g/mm and 290-g/mm gratings covering the 100-1100 Å and 155-1700 Å regions, respectively, with 2 Å and 3 Å spectral resolution (FWHM). The gratings are mounted on an exchanger mechanism which allows one of them to be selected for use during a discharge. The 100-300 Å region is densely populated with lines; only the strongest lines are free of significant blending in spectra taken with these gratings. This region is important for measurement of metallic impurity lines and for charge exchange recombination (CXR) spectroscopy⁴ of carbon and oxygen because it contains the OVIII 102.4 Å (n=3-2) and 292.8 Å (4-3) lines and the CVI 182.2 Å (3-2) line. Thus, there has been a need for a higher dispersion SPRED grating to cover this wavelength region. This paper describes a 2100-g/mm grating which has been successfully used along with the 450-g/mm grating in the PBX and TFTR SPRED spectrographs. This grating allows the 100-320 Å region to be observed with 0.4 Å resolution (FWHM), which is sufficient to resolve many of the blends.

Absolute intensity calibration of the instrument is needed for measurements of impurity densities, radiative losses, and impurity transport. The TFTR SPRED has been calibrated using synchrotron radiation from the National Bureau of Standards (NBS) Synchrotron Ultraviolet User Facility (SURF II),⁵ and the PBX SPRED has been calibrated using CXR-excited line ratios^{6,7} and conventional branching ratios.⁸ Thus, the sensitivity of

SPRED has been well determined for both the 450-g/mm and 2100-g/mm gratings. The results of these calibrations and the details of the calibration procedures are discussed herein.

II. Description of the Spectrograph and the 2100-g/mm Grating

The SPRED system is described in detail by Fonck, Ramsey, and Yelle;¹ only a brief description of the instrument and details of the 2100-g/mm grating are given here. Aberration-corrected type IV gratings^{9,10} on a toroidal substrate yield a virtually astigmatism-free image; the groove curvature and density vary across the grating surface in such a way as to provide a 40-mm-wide flat focal field. The gratings, which are manufactured by the J-Y Optical Systems Division of Instruments S.A., Inc., are produced by ion etching holographically formed grooves into a glass blank and overcoating with gold. The grating blank is a toroidal surface with radii of curvature 919 mm in the plane of dispersion and 102.5 mm in the direction perpendicular to the plane of dispersion. The ruled surface of the 2100-g/mm grating is 5-mm high by 22-mm wide, but the exposed area is masked to 3 mm x 13 mm to optimize the spectral resolution. The angle of incidence for the 2100-g/mm grating is 71.9° while it is 70.6° for the 450-g/mm grating. Since the reflectance of the gold overcoating drops rapidly at wavelengths near 100 Å for angles of incidence in the 70-75° range,¹¹ the 2100-g/mm grating was designed to operate at a slightly larger angle of incidence than the 450-g/mm grating to assure that useable signals could be obtained down to 100 Å. A 2-mm x 25-μm entrance slit is used.

The detector is an image-intensified photodiode array consisting of a CuI-overcoated microchannel plate (MCP) coupled to a 1024 element photodiode

array (Reticon 1024SF) via a phosphor screen and a tapered fiber-optic bundle. The MCP has a 40-mm diameter active area which is positioned on the flat focal field of the gratings.

The data shown in Fig. 1 demonstrate the performance of the 2100-g/mm grating and, in particular, its utility for CXR spectroscopy. These spectra were taken during a neutral-beam-heated discharge in PBX¹²: the spectrum in Fig. 1a before neutral beam injection (NBI) and the spectrum in Fig. 1b during NBI. Because the spectrograph views across one of the neutral beams, the CXR-excited OVIII 102.4 Å, OVIII 292.8 Å, and CVI 182.2 Å lines, as well as several $\Delta n \geq 2$ transitions in OVIII and CVI, are strong in the spectrum during NBI, but are not found in the spectrum before NBI. Figure 1c, which is the difference of the spectra before and during NBI, shows the CXR-excited lines even more clearly.

III. Synchrotron Radiation Calibration of TFTR SPRED

The NBS SURF II electron storage ring is described in detail by Madden and Ebner.⁵ The flux onto an area (photons/sec-Å) as a function of wavelength at the electron energy of 284 MeV peaks near 110 Å and can be calculated to 2% or better from the measured beam current,¹³ which was typically ~40 mA. The flux onto the entrance slit of the spectrograph was calculated using an NBS computer code. The spectrograph was mounted on a gimbal at the end of the calibration beamline with its entrance slit 11.5 m from the point tangent to the electron orbit. The gimbal allowed the instrument to be translated vertically and horizontally in a plane normal to the incoming radiation and rotated about vertical and horizontal axes in this plane. The instrument was aligned with respect to the incident radiation by systematically using the four gimbal motions to maximize the signal on the detector.

Calibration results for the 450-g/mm grating are shown in Fig. 2. The brightness (photons/sec-cm²-sr) of a line is obtained by integrating over the line profile, subtracting the background signal, and multiplying by the inverse sensitivity at the appropriate wavelength. The total error in the inverse sensitivity is estimated to be $\pm 30\%$.

Several effects complicate this calibration. First and higher order contributions to the signal must be separated. The ratio of first to third order efficiencies (estimated from tokamak line radiation) is approximately 15, and the ratio of first to second order efficiencies is approximately 50. Thus, the signal is primarily due to light diffracted into first and third orders. Because both the grating efficiency and the SURF II flux drop rapidly below 100 Å, order overlap is a problem only at wavelengths longer than 300 Å. As a result, higher order corrections are not important for the 2100-g/mm grating over most of its wavelength range. Using the fact that the spectral distribution of the flux is strongly dependent on electron energy, the first and third order efficiencies were derived from data obtained at energies of 284 MeV and 140 MeV.¹⁴ The area on the 450-g/mm grating illuminated by synchrotron radiation was 2 mm x 80 μm. Because the grating mask height is 3 mm, most of the grating height was illuminated; however, little of the exposed grating width (dispersion direction) was illuminated. It was therefore necessary to map the grating surface in this direction by using the gimbal to rotate the instrument around the entrance slit.¹⁵ Data taken at 15 different positions and averaged together were used to obtain the final calibration curve. Since synchrotron radiation is highly polarized in the plane of the electron orbit and the grating acts as a partial polarizer, the signal depends on the orientation of the instrument with respect to the plane of the electron orbit. To account for this effect, the instrument was

calibrated in two positions: with the entrance slit perpendicular and parallel to the electron orbit. The results were averaged to obtain a calibration applicable to unpolarized light.

IV. CXR Calibration of PBX SPRED

CXR preferentially populates excited levels, for example $n=5$ in the case of O^{+8} , which are not significantly populated by electron impact excitation. The relative intensities of the lines emitted as the captured electron cascades down to the ground level can be calculated with reasonable accuracy using CXR cross sections, radiative decay rates, and calculations of the neutral beam particle energy distribution. The calculated and measured line intensity ratios are then combined to obtain the relative sensitivity of the instrument. The CXR calibration procedure is described in detail by Isler and Langley.⁵

The east and northwest neutral beams on PBX provide near perpendicular injection. SPRED views across the east beam. Data were obtained using both the 2100-g/mm and 450-g/mm gratings with only the east neutral beam on and only the northwest beam on, both at the same injected power level and plasma parameters. The injected species was hydrogen at power levels of 1.0-1.5 MW per neutral beam, and the plasmas were deuterium. The following lines were used for calibration: CVI 182.2 Å ($n=3-2$), CVI 521.6 Å ($4-3$), OVIII 102.5 Å ($3-2$), and OVIII 292.8 Å ($4-3$). Part of the rise in the intensities of these lines as the beams turn on is due to CXR excitation by the enhanced wall and halo thermal neutral populations in the plasma and to changes in the impurity ionization balance which increase the number of electron-excited ions in the spectrograph field of view. To obtain line intensities due only to prompt CXR excitation, line intensities measured with only the northwest beam on were

subtracted from those measured with only the east beam on. The calculated relative intensities were obtained using the cascade-corrected CXR cross sections of Fonck, Darrow, and Jaehnig⁴ assuming no l-mixing and a beam attenuation code.

Absolute sensitivity measurements were made using the branching ratio method.⁸ A 0.6-m spectrograph which viewed the same plasma region as SPRED and was absolutely calibrated using an NBS tungsten ribbon lamp observed the visible lines. The following line pairs were used: OVI 150.1 Å - 3811.4 Å, CIV 312.4 Å - 5801.5 Å, HeII 243.0 Å - 4685.8 Å, HeI 522.2 Å - 3964.7 Å, and HI 1025.7 Å - 6562.8 Å. The resulting calibration for the 2100-g/mm grating is shown in Fig. 3; the sensitivity curve is nearly flat over most of the wavelength range covered by the grating.

Acknowledgments

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Figure Captions

- Fig. 1. PBX SPRED spectra obtained with the 2100-g/mm grating. a) before NBI; b) during NBI; c) difference of spectra showing prominent CXR-excited carbon and oxygen lines.
- Fig. 2. TFTR SPRED calibration curve for 450-g/mm grating measured using synchrotron radiation at the NBS SURF II facility. Microchannel plate voltage: 600 V. Phosphor voltage: 4000 V.
- Fig. 3. CXR calibration curve for PBX SPRED using 2100-g/mm grating. Microchannel plate voltage: 800 V. Phosphor voltage: 4000 V.

Fig. 1

Fig. 2

Fig. 3

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