Spectral instruments for x-ray and VUV plasma diagnostics

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Abstract. Spectral instruments for x-ray and VUV plasma diagnostics are described: focusing crystal spectrometer, several modifications of grazing incidence spectrometers and grazing incidence spectrometer-monochromator. Using spectroscopy methods these instruments could diagnose plasmas in a wide electron temperature range (Te ~ 30 eV-1.5 keV) and provide absolute intensity measurements of various plasma sources.

1. Introduction
X-ray and VUV spectroscopy methods are the most informative diagnostic tools for investigation of high temperature plasmas. These methods allow determining of electron temperature and density, ionization stages and charge distribution, and other plasma parameters. Investigation of these plasma parameters needs developing of special schemes of spectrometers. For these purposes a set of spectral instruments are developed for X-ray and VUV spectroscopy of plasma sources in a spectral range of λ=0.1÷100 nm:

1) High efficiency very compact focusing crystal spectrometer (XRS-1) (figure 1);
2) Various modifications of compact off-Rowland grazing incidence diffraction spectrometers (GIS-1S, GIS-2S, GIS-3S) (figure 2);
3) Grazing incidence diffraction EUV spectrometer - monochromator (GISM) with a constant angle of deviation (figure 3).

Figure 1. Scheme and external view of the focusing crystal spectrometer (XRS-1).
2. **Focusing crystal spectrometer (XRS-1)**
High efficiency very compact focusing crystal spectrometer (XRS-1) is based on von Hamos scheme. In this scheme a crystal is bent into a cylindrical surface, the x-ray source and the detector plane lie on the cylindrical axis (figure 1). The spectrometer parameters and characteristics in von Hamos geometry are described in details in Refs. [1, 2]. This type of spectrometer possess several advantages of interest: high detection efficiency, high spectral resolution, direct registration of source image and mosaic focusing. The von Hamos focusing geometry gives very high spectrometer efficiency when spectra are recorded over a wide spectral range. This property is very helpful for a study of low-intensity, small-size x-ray sources. The spectra obtained with a von Hamos spectrometer form a two dimensional image of the source for each wavelength. Another distinctive feature of the von Hamos
geometry is a mosaic focusing. It allows the use of mosaic crystals with high integrated reflectivity that is leading to high sensitivity without sacrificing spectral resolution.

The XRS-1 spectrometer includes all mentioned above properties. Cylindrical mica crystal \(2d=1.98\) nm with a radius of curvature \(R=20\) mm is installed in the spectrometer. Spectra are recorded by a CCD linear array or x-ray photographic film. A Toshiba TCD 1304 GP CCD linear array with 3724 elements 8 \(\mu\)m in width and 200 \(\mu\)m in height is used as a radiation detector. When extra wide spectral range is needed a photographic film with a length of 70 mm could be used. X-ray spectra are recorded in a spectral range of \(\lambda=0.04\div1.6\) nm for reflection orders of \(n=I-XII\). The spectrometer has very small size (40 mm diameter and ~100 mm length) and installed inside a vacuum chamber in a standard \(\varnothing\) 2” or \(\varnothing\) 60 mm optical mount.

The XRS-1 spectrometer is absolutely calibrated using a new method for formation of quasi-monochromatic divergent x-ray fluxes from laser-produced plasmas [3]. X-ray spectra of highly charged ions in absolute intensity scale and their use for plasma diagnostics are presented for laser-produced plasmas in Refs.[1,2,4] including femtosecond laser-produced plasmas [5]. HOPG (Highly Oriented Pyrolitic Graphite) crystals [2] and multilayer structures [6] can be used in the spectrometer as dispersive elements instead of the mica crystal.

3. Grazing incidence spectrometers

The GIS and GISM spectrometers are highly compact and portable VUV grazing incidence spectrometers using an off Rowland circle registration scheme. In this scheme, spectra are recorded in a in a plane perpendicular to the diffracted rays (figures 2 and 3) and thus exact focusing of the entrance slit takes place only for one single wavelength – \(\lambda_0\), which corresponds to the intersection of the plane of registration with the Rowland circle. Operating with a small angular aperture in the plane of dispersion of the grazing incidence spectrometers, reasonable resolving power is maintained to record the spectrum in a sufficiently wide spectral range \(\lambda_0 \pm \Delta \lambda\). The value \(\Delta \lambda\) is connected with observed spectral resolution \(\lambda/\delta \lambda\): the wider \(\Delta \lambda\) the lower \(\lambda/\delta \lambda\) caused by defocusing. The alignment to a different \(\lambda_0\) is produced by changing of a distance between plane of registration and grating (spectrometers GIS) and by a precision grating rotation (spectrometer GISM). Using this off Rowland circle registration scheme, significant reduction in the complexity of the setting up and alignment procedure is achieved.

Incidence angle of \(\varphi=86^\circ\) is used in the GIS spectrometers. There are three GIS modifications: GIS-1S is installed inside vacuum chamber and has an extra small size; GIS-2S and GIS-3S are installed outside vacuum chamber and have a port for differential pumping (figure 2).

In the GISM spectrometer the incidence angle of \(\varphi=(85\pm1)^\circ\) is changed by a precision grating rotation. This spectrometer has monochromator and spectrometer modes. Constant angle of deviation \((\alpha=\varphi+\psi=166^\circ\), where \(\varphi\) and \(\psi\) are incidence and diffraction angles) is used.

A set of three gratings (1-m spherical replaceable gratings with 300, 600 and 1200 grooves/mm) with different dispersion characteristics is used in all spectrometers to provide an extended range of spectral coverage. The spectral range consists of \(\lambda=2-80\) nm for GIS spectrometers and \(\lambda=4-45\) nm for GIMS spectrometer. The spectrometers are equipped by various type of CCD detectors based on CCD linear arrays, fiber optical plates and phosphor layers. The use of other types of detectors (micro channel plates, photographic films, PIN diodes, streak cameras) is also possible due to the flat field plane of registration.

These spectrometers were successfully used for VUV spectral diagnostics of laser-produced plasmas [4, 7], capillary discharge plasmas [8, 9] and high power Z-pinch plasmas [4, 10, 11]. GISM mainly intended for reflectometer purposes when it is used in the monochromator mode [8, 9]. Calibration of separated spectrometer elements (diffraction gratings and detectors) allows determination of absolute spectrometer efficiency under known device geometry.
4. Conclusion
The unique features of these spectral instruments for x-ray and VUV plasma diagnostics are a capability of their absolutely calibration for metrology applications. Using x-ray spectroscopy methods these spectrometers could diagnose plasmas in a wide electron temperature range ($T_e \sim 30 \text{ eV} \div 1.5 \text{ keV}$). The spectrometers are widely used for diagnostics and absolutely intensity measurements of various plasma sources: laser-produced plasmas including nano- and femto- second laser-produced plasmas, high power Z-pinch plasmas, capillary discharge plasmas, EUV sources intended for nanolithography.

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