Nuclear Instruments and Methods in Physics Research A 729 (2013) 322–326

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Time-resolved K-shell line spectra measurement of z-pinch plasmas

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ARTICLE INFO

Article history:
Received 18 January 2013
Received in revised form
5 July 2013
Accepted 5 July 2013
Available online 16 July 2013

Keywords:
z-Pinch
Plasmas
K-shell line emission
Spectrometer

ABSTRACT

A Johann-type crystal spectrometer integrated with x-ray PIN diodes has been developed for measuring the time-resolved K-shell line spectra of the imploding Al wire array. In this spectrometer, the PIN diodes are mounted on the Rowland circle of the cylindrical bent crystal with an appointed position to collect the line emissions from z-pinch plasmas. The spectrometer with four typical channels, which are keyed to the Al ion hydrogen-like (H_α, 0.7171 nm and H_β, 0.6052 nm) and helium-like (He_α, 0.7757 nm and He_β, 0.6634 nm) resonance lines is designed and fabricated. Example data from the experiment on the Yang accelerator are shown and the time-dependent electron temperature is determined from the signal ratios of Al ion H_α line to He_α line using the collisional and radiative model.

1. Introduction

Wire array z-pinch plasmas are powerful and efficient soft x-ray radiators used for research in inertial confinement fusion (ICF), radiation physics, laboratory astrophysics and other high energy density sciences [1,2]. The phases of the pinch are: initial ablation, melting and vaporization of the wires, coronal plasma expansion, merging of the individual plasmas, a subsequent implosion exhibiting Rayleigh–Taylor instabilities, and finally, the stagnation phase (pinch) [3]. During the final stagnation phase, most of the energy is in the kinetic energy of the ions which is then thermalized with the electrons and finally converted to the x-rays as in the form of bremsstrahlung continuum and line emissions. The knowledge about the features of the plasmas, such as the electron temperature and the electron density, are considered as keys to understand the pinch dynamics and radiation generation [4].

As the electron temperature and density of the z-pinch plasmas can affect the structure of the x-ray spectra, both the continuum and the line emissions may be used to estimate the electron temperature and/or density. There are many methods to measure the spectra with temporal resolution by integrating all kinds of spectrometers with the time-resolved detectors. A direct method is to use the time-resolved x-ray detectors, such as the x-ray diode (XRD [5] or PIN [6,7]) or the photoconduction x-ray detector (PCD [8,9]), fitted with different transmission filters to measure the continuum x-rays in different energy bands. The analysis of the relative intensities in each band can give a time-dependent electron temperature or density [10]. The disadvantages of this technique are the limited availability of different filters, complicated retrieval algorithm and poor accuracy owing to little difference of the responsivity function between each filter [11]. In the past few decades, analysis of K-shell line spectra using population kinetics models has gradually been recognized as an effective method to estimate the ionization state distribution, electron temperature and electron density of low-to moderate-atomic number z-pinch plasmas. There have been many computing codes [12,13] with sufficient accuracy developed to estimate the electron temperature and density by comparison of the relative intensities of different K-shell lines [14–18]. It suggests that the measurement of the K-shell line spectra by integration of the time-resolved detectors into a crystal spectrometer may be another way for getting the information about the z-pinch plasmas.

In this paper, a cylindrical bent crystal spectrometer with Johann [19] or Johansson [20] geometry, fitted with the x-ray PIN diodes positioned along the Rowland circle, was built for measuring the K-shell line spectra of the imploding wire array z-pinch plasma. The silicon PIN photodiode has the advantage of flat response, insensitive to surface contamination, low voltage biasing requirements, sensitivity to low energy photons, excellent detector to detector response reproducibility, and ability to operate in poor vacuum experiments [21–26]. Combination of the focusing x-ray spectrometer with this high-sensitive detector should give a reasonable signal to noise ratio on the low-current pulse generator.

2. Spectrometer geometry

Fig. 1 shows the scheme of a Johann-type spectrometer in the central plane (the plane contains the center of the source, crystal and detector). The cylindrical bent crystal with arc length l, width w, and radius r is placed with a distance c from crystal center (C_2) to source center (O). The angle between the line of crystal center to

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http://dx.doi.org/10.1016/j.nima.2013.07.025

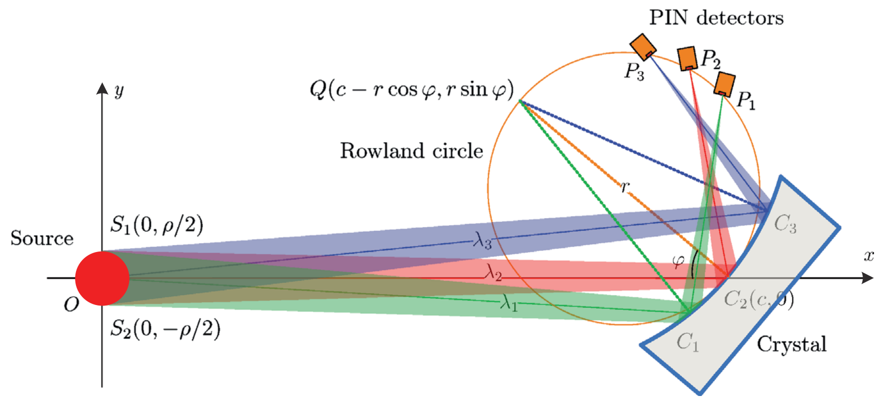

Fig. 1. The geometry of the Johann-type crystal in the central plane (the plane contains the center of the source, crystal and detector). The x-rays emitted from a cylinder-like z-pinch plasmas are dispersed by the spectrometer and collected by the PIN diodes positioned on the Rowland circle in a narrow spectral band.

source center (OC_2) and the line of crystal center to crystal curvature center (QC_2) is φ. The PIN diodes are arranged along the Rowland circle to collect the x-rays emitted from the source. If one builds a Cartesian coordinate with the origin at the source center and the x-axis at the line of crystal center to source center, the equation for the crystal profile can be written as follows:

$$(x-c+r\cos\varphi)^2+(y-r\sin\varphi)^2=r^2 \tag{1}$$

where $r[\sin\varphi-\sin(\varphi+l/2r)]\le y\le r[\sin\varphi-\sin(\varphi-l/2r)]$, defining the range of the crystal profile. Accordingly the equation of the Rowland circle tangential to the crystal center is given by the following:

$$(x-c+r\cos\varphi/2)^2+(y-r\sin\varphi/2)^2=r^2/4. \tag{2}$$

The x-rays emitted from the source are dispersed by the crystal following condition $2d\sin\theta=n\lambda$. Here, n is a positive integer that denotes the order of diffraction, d is the crystal lattice constant, and θ is the incident angle relative to the crystal surface (Bragg angle). The Bragg angle θ of the ray from the source point $S(x_S,y_S)$ to an arbitrary point $C(x_C,y_C)$ on the crystal surface in the xOy plane and the cross point $P(x_P,y_P)$ of the reflected ray with Rowland circle is calculated by the following:

$$\sin\theta=\frac{\overline{SC}^2+\overline{QC}^2-\overline{SQ}^2}{2\overline{SC}\,\overline{QC}}=\frac{\overline{PC}^2+\overline{QC}^2-\overline{PQ}^2}{2\overline{QC}\,\overline{PC}}, \tag{3}$$

where $Q(c-r\cos\varphi, r\sin\varphi)$ is the curvature center of the crystal and $\overline{QC}\equiv r$ for the Johann geometry. Since the point $C(x_C,y_C)$ and point $P(x_P,y_P)$ also satisfy Eqs. (1) and (2), respectively, the combination of these two equations with Eq. (3) can give the dispersion relationship between the wavelength λ and the detecting position (x_P,y_P) along the Rowland circle. For an ideal point source, the dispersion relationship may be one to one correspondence (if the intrinsic rocking width of the crystal is not considered), but for a real source with finite volume, a point on the Rowland circle would collect the x-rays emitted from the source in a narrow spectral band, as shown in Fig. 1.

The bandwidth resulting from the source size is one of the main contributions affecting the energy resolution of this spectrometer, especially for the source with large volume, such as the z-pinch plasmas, and it can be estimated from two independent directions. Assuming that the source is a cylindrical shape with radius ρ and height h and with the layout as shown in Fig. 1, the bandwidth in the radial direction is estimated by the difference of the Bragg angles corresponding to the two points at the up and down edge of the circle in the xOy plane, while in the axial direction the maximum Bragg angle deviation is as follows:

$$\Delta\theta=\theta-\sin^{-1}(\sin\theta\cos\delta), \tag{4}$$

where $\delta=\tan^{-1}[h/2(\overline{PC}+\overline{OC})]$ if the crystal is wide enough to cover the whole cylinder-like source. The bandwidth in the axial direction can be very small to be ignored if the distance between the crystal and the source is greatly larger than the height of the z-pinch plasmas (i.e. $\overline{OC}\gg h$).

Another contribution to the bandwidth comes from the active area of the detector. Since the actual detector is not an ideal point, it will occupy a finite area around the point on the Rowland circle which will collect the x-rays with different wavelengths in a bandwidth. This bandwidth is estimated by the following:

$$\Delta\lambda=(\mathrm{d}\lambda/\mathrm{d}l_{\mathrm{arc}})\Delta l_{\mathrm{arc}}, \tag{5}$$

where $\mathrm{d}\lambda/\mathrm{d}l_{\mathrm{arc}}$ is the linear dispersion along the Rowland circle and Δl_{arc} is the arc length of the Rowland circle from the crystal central point (C_2) to the detecting point (P).

An alternative scheme is the Johansson-type spectrometer, which is developed from the Johann geometry with a bent crystal achieved by processing the crystal surface to tally with the Rowland circle to reduce the aberrations. In this scheme, the crystal profile equation is the same with the Rowland circle and $\overline{QC}=r$ is only satisfied in the crystal central point. Eqs. (1)–(5) still can be used to compute the wavelength and the bandwidth of the spectrometer.

3. Parameters design and evaluations

The Johann-type spectrometer described here is designed to measure the K-shell line emission of the Al wire array z-pinch plasmas on the "Yang" accelerator. A Quartz (100) crystal ($2d=0.8512$ nm) of arc length 70 mm, width 15 mm, and radius 130 mm, placed at 600 mm to the z-pinch load with $\varphi=35^\circ$ is employed to disperse the x-ray beam. Four PIN diodes with 1 mm^2 active area and 1 ns temporal resolution, shielded by 2 μm Ti fiol are positioned on the Rowland circle to collect the Al ion hydrogen-like (H_α and H_β) and helium-like (He_α and He_β) resonance lines respectively. Each PIN diode constructs an individual signal channel. The detail parameters for them are listed in Table 1. The reason to select these four lines is that they can be separated on the Rowland circle with enough space to place the PIN diodes without interference with each other.

For comprehensively understanding the properties of the spectrometer, the dispersive characteristics of the Johann and Johansson spectrometer with parameters designed above are all graphically shown in Figs. 2 and 3. It can be seen that the dispersion of the wavelength λ vs. the arc length l_{arc} for the Johann and Johansson spectrometer is all nearly linear but the linear dispersion ($\mathrm{d}\lambda/\mathrm{d}l_{\mathrm{arc}}$) for the Johansson geometry varies fast as