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X-Ray Spectrograph for Investigation of Plasma Radiation at the Range 0.7keV–200keV

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Abstract

Results are presented on the possibilities of x-ray instrument, covering the 0.7keV–200keV wavelength range. The significant achievement is that device firstly uses unique Jogansson quartz crystal, connected by optical contact with spherical substrate. Comparison is made with widely used Johann device of cylindrical geometry. Characteristics of different dispersive elements, application of the device for analysis of emission from x-ray tube and z-pinch plasma are given.

Keywords:

x-ray spectroscopy, dispersive elements, optical contact

1. Introduction

Plasma with parameters $T_e \sim 0.1$–10keV and $n_e \sim 10^{13}$–10^{24}cm^{-3} is widely investigated by experimentalists. The purposes of such investigations are nuclear fusion, creation of coherent and incoherent radiation sources for nuclear fusion and for different applications (x-ray microscopy, lithography, biology), investigation of astrophysical plasma, etc.

X-ray spectroscopy is one of the most effective way to study parameters of hot plasma. This method provides information on electron and ion density and temperature, sizes of emitting regions, ionization stages, ion velocities, on electron velocity distribution function and on electromagnetic fields.

The essential difficulty is that plasma parameters are changed in time and space, therefore temporal (up to 1ns) and spatial (about microns) resolutions are necessary for correct investigation of plasma dynamics. High spectral (better, than 10^{-4}) resolution is needed to resolve so called satellites, which are in abundance emitted from hot plasma.

Few kinds of x-ray devices are usually used in experiments. Most of them are based on application of Bragg's x-ray crystals of different geometry. To analyze observed spectra flat and convex crystals are used, in which spatial resolution can be done with slit, oriented in dispersion direction. The width of the line depends on the size of x-ray source, therefore spectral resolution is not usually high enough.

To investigate the fine structure of spectra so called Johann, Johansson and Cauchois devices are necessary [1]. These devices use the focusing concave crystals, mounted on Rowland circle. Spectral resolution does not depend strongly on the source size, light power is very high, spatial resolution might be obtained without slit, if

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crystals have finite curvature radius in vertical direction.

The goal of this paper is to describe possibilities of the x-ray instrument, designed and fabricated in Russia within the collaboration with US firm Ecopulse.

Device uses spherical mica crystals on glue and quartz crystals of different orientations, connected with substrates by optical contact. Optical contact is widely used in optics for connection of flat surfaces, we used it to connect quartz crystals with spherical and even toroidal substrates. The new is that weave done crystal of Johansson spherical geometry on optical contact, providing high spectral resolution of device.

CCD and MCP detectors, providing temporal resolution about 1 ns supply commercial version of the device.

Metal chamber of device can be easily adopted for using Cauchois dispersive elements, this case detector is the pair of luminophor LaOBr and film.

Described instrument has high light power, high spectral (in some cases up to $\delta\lambda/\lambda \sim 10^{-5}$) and spatial (about few microns) resolutions and may be used for investigation of x-ray emission in the range 0.7keV–200keV, radiated by various plasmas (*z*-pinch, laser produced, tokamak, etc.).

2. Description of the Instrument

Optical scheme (Fig.1) of the device is similar to Johann's one. The range of reflecting angles is 20–80 degrees. This makes it possible to analyze 0.7keV–200keV energy region, using the different x-ray crystals.

Radius of Rowland circle is 250mm, curvature radius of crystal is 500mm. This value was chosen due to following considerations: the quality of the crystal strongly depends on radius of curvature, the less the radius, the worse the quality. And hence, the more the radius, the better the spectral resolution, which is determined by quality of the crystal. Geometrical spectral resolution is also increased with radius increase.

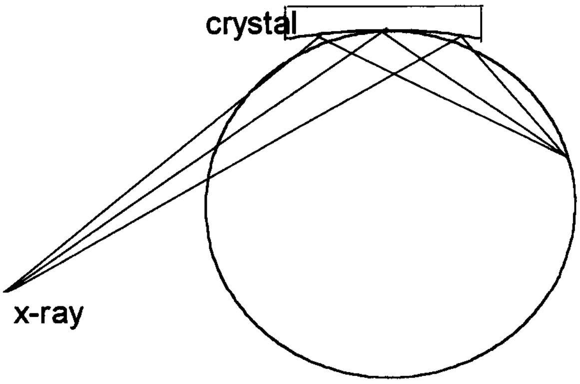

Fig. 1 Optical sheme of the device

From the other hand the geometrical sizes of the device must be reasonable. Accounting considerations, mentioned above crystal radius 500mm was taken, because both the worthwhile qualities of the crystal and geometrical sizes of the device are achievable.

The size of crystals might be up to 60mm in diameter. Special technology was developed to fabricate Johansson dispersive element and Cauchois one. So device can operate in Johann, Johansson and Cauchois optical schemes, using different crystals, mounted in the same metal chamber.

There is possibility to use two crystals simultaneously, such kind of measurements is essentially useful for polarization analysis. Film cassette permits to measure spectra in 25–30 experiments and there are also possibilities to use CCD, MCP, and frame camera to detect x-ray spectral lines.

3. The Characteristics of the Dispersive Elements

We use mica spherically bent crystal to analyze spectra in the 1–20A° wavelength region and we use different kind of quartz to measure radiation with wavelength shorter than 8.5A°. Energy resolution is one of the most important characteristics of spectrograph, used for study of infrared, visible, VUV or x-ray regions. Energy resolution of x-ray spectrograph depends on the sizes of the source, quality of the dispersive element, resolution of the detector, geometry of the device and experiment.

Quality of concave crystals is determined by reflection curve of the bent crystal (i), optical quality of the substrate, which is used for bending (ii), aberrations, which gives the concave surface of bent crystal (iii) and it also strongly depends on the method, which is used to connect crystal and substrate (iv).

i) We mainly use quartz crystals of different orientations. Quartz crystals have high reflection coefficients, they are well known as elastic, quite appropriate for mechanical polishing and burnishing. Half a width of some flat quartz crystals is about few seconds (this is the best value for x-ray crystals), therefore they can provide spectral resolution $\delta\lambda/\lambda \sim 10^{-5}$. Rocking curve of bent crystals is worse, so careful investigation of it after bending is necessary.

ii) We use concave substrates, manufactured with the accuracy not less, than 0.1mm in radius, in most of the cases the defocusing of line because of this value is less than defocusing, which comes from aberrations.

iii) Even concave surface, manufactured ideally, gives aberrations. The value of aberrations depends on the sizes and type of used surface. In the case of spherical surface with R = 500mm aberrations might be about few microns. Toroidal surface of the same aperture with $R_m = R_s \cos^2\theta$ (the θ is reflection angle), has aberrations which are several times less, than that, belonging to spherical surface of the same meridian radius [2].

iv) Connection of the crystal and the substrate by glue is very difficult to realize without inducing of local inhomogeneities of reflecting surface of crystal. The reasons are the dust between crystal and substrate and the tension of the crystal, which arises as a result of gluing.

It must be mentioned once more, that tension appears also due to bending the crystal and it's mechanical polishing. The well-known fact is that bending and polishing leads to deterioration of reflection curve [3].

We used optical contact [4] to connect crystal and substrate, when intermolecular forces realize fixation of two surfaces. This case no visible defects of the crystal surface are seen under optical microscope

Optical quality of the crystal surface is just the same as the optical quality of substrate, used for crystal fixation. We investigated the quality of cylindrically, spherically (R = 500mm) and toroidally bent crystals on optical contact by x-ray double crystal difractometry method in nonparallel low dispersive geometry of diffraction.

Analysis has shown the deterioration of reflection curve after bending. Flat quartz crystal (2d = 6.68A°) gives the value of half a width reflection curve approximately 8 seconds. The same quartz crystal, bent spherically with radius 500mm, has averaged half a width of reflection curve 95 seconds.

This value may be explained by presence of aberrations and crystal tension after bending. Chemical polishing can decrease crystal tension, and average value of half a width is decreased up to 38 seconds. So the defocusing/ widening of line after bending of crystal may be stronger, than defocusing due to presence of aberrations.

Cylindrical and toroidal crystals also have the deterioration of rocking curve similar to spherically bent. The obvious result is : the larger the radius of curvature of crystal the less is the deterioration of the rocking curve.

4. The Results, Obtained Using X-ray Tube and Plasma Focus Discharge

To check up the possibilities of the device the following experiments were carried out:

1. K alpha radiation from x-ray tube (U = 35kV, I = 80μA, size of the source is 0.4mm) were registered with spherical Johansson crystal (2d = 6.68A°) in two regimes of operation:

a) crystal was not chemically polished. Direct registration of Cr K alpha lines was used, when only the small part of crystal reflects the lines. This case the influence of spherical aberrations is minimized and quality of the crystal depends mainly on tension inside crystal, which occur due to bending and polishing. The result is shown on Fig.2a.

b) Crystal was chemically polished. Registration of Fe K alpha lines was made in fluorescence regime, when Fe target was radiated by x-rays from Cu-anode x-ray tube. This case the full crystal surface (diameter of the crystal was 30mm) reflected Fe K alpha lines. The

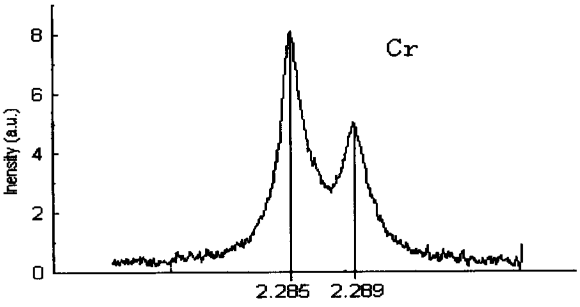

Fig. 2a K-alpha lines of Cr, registered with spherical Johansson crystal, R = 500mm, 2d = 6.68A, chemically nonpolished.

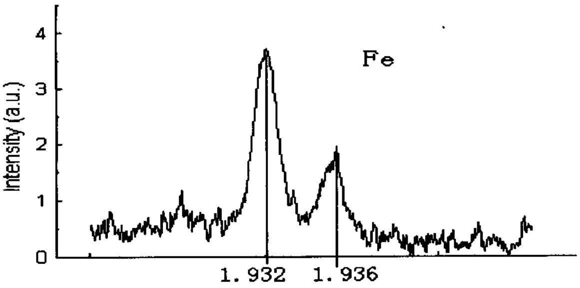

Fig. 2b K-alpha lines of Fe, registered with spherical Johansson crytsal, R = 500mm, $2d$ = 6.68A, chemically polished.

result is shown on Fig.2b.

It is clearly seen that resolution in case 2b is better, than in case 2a, in spite of the fact, those aberrations are larger for 2b case. This testifies, that crystal tension after bending might deteriorate reflection curve in more degree, than spherical aberrations.

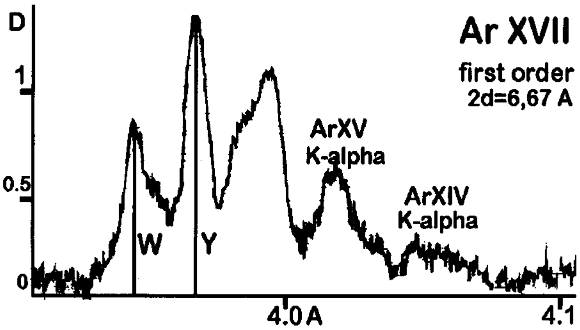

Fig. 3a He-like Ar spectra, emitted by plasma focus device. Cylindrical Johann crystal, R = 500mm, 2d = 6.68A, nonpolished.

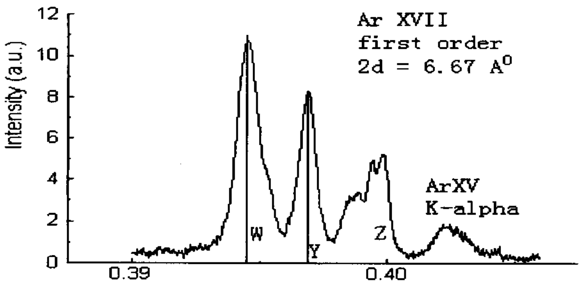

Fig. 3b He-like Ar spectra, emitted by the plasma focus device. Registration was made with spherical Johansson quartz crystal, R = 500mm, $2d$ = 6,68A, chemically polished.

2. Fig.3a,b shows He-like spectra of Ar, registered from Mather type plasma focus devices. Cylindrical Johann crystal with R = 500mm, $2d$ = 6.68A° was used in case a) and spherical Johansson crystal R = 500mm, 2d = 6.68A° was used in case b). It is clearly seen, that fine structure of spectra is essentially better resolved in the case b). For our knowledge Johansson crystal on optical contact was applied for spectra measurement in this experiment for the first time.

5. Summary

The possibilities of the x-ray device for 0.7keV–200keV energy range are described. Detailed characterization is made for unique spherical quartz crystal of Johansson geometry. Application of the device for investigation z-pinch plasma is given.

Acknowledgments

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