# Determination of spectral reflectivity of spherically bent mica crystals applied for diagnostics of relativistic laser plasmas



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# Determination of spectral reflectivity of spherically bent mica crystals applied for diagnostics of relativistic laser plasmas

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**Abstract.** Mica crystals are widely applied in x-ray spectroscopy diagnostics since their ability to effectively reflect the radiation in different orders covering a wide range of photon energy, including sub-keV range hardly accessible with other crystals. Particularly, spherically bent mica crystals are commonly used in high energy density plasma imaging spectrometry diagnostics. However, the detailed reflectivity properties of bent mica crystals are not known well. Here we propose and verify the way to calibrate mica crystal spectral reflectivity in the experiment with relativistic laser plasma. The approach is based on the comparison of dense laser plasma x-ray spectra measured by focusing spectrometers with spatial resolution equipped, with examined mica and pre-calibrated alpha-quartz bent crystals. As a result, the normalized reflectivity of spherically bent mica crystal operated in $2^{nd}$ order of reflection was experimentally evaluated for the first time versus wavelength in the range of 6.7–8.7 Å. The obtained spectral calibration curve for bent mica crystal demonstrates remarkable difference to that one calculated for flat mica crystal and given in Henke tables and has to be applied further for a correct interpretation of the measured x-ray spectra.

Calibration of x-ray reflectivity properties of crystals remains to be a relevant issue in the x-ray spectroscopy diagnostic and imaging of plasma [1–5]. Spherically bent crystals are widely applied in x-ray spectroscopy diagnostics since their ability to effectively reflect the radiation in different orders covering a wide range of photon energy, including sub-keV range hardly accessible with other crystals. Particularly, such crystals are commonly used in high energy density plasma imaging spectrometry diagnostics [6–10]. So, x-ray reflectivity properties of bent crystals define the characteristics of measured spectra and should be known for following spectral data interpretation. Particular it is important for calibration of spherically bent mica crystals, which are not monocrystalline crystals, as for example quartz, but polycrystalline crystal. In this case the reflectivity of each spherically bent mica crystals could be varied and it is necessary to calibrate each sample and if possible in the geometry of experimental conditions.

For calibration of crystal x-ray reflectivity the monochromatic x-ray source with adjusted spectral range is required. X-ray tubes and synchrotron radiation are commonly applied for crystal reflectivity calibration. However in the case of relativistic laser plasma diagnostic it is more important to know the x-ray reflectivity dependence in the wavelength range of $\delta\lambda \sim 3$–8 Å. Unfortunately there are no monochromatic x-ray sources in the same wavelength range that makes strongly difficult the experimental measurement of crystal reflectivity dependence. Thus for practical use theoretical calculations of x-ray reflectivity for different type of crystals

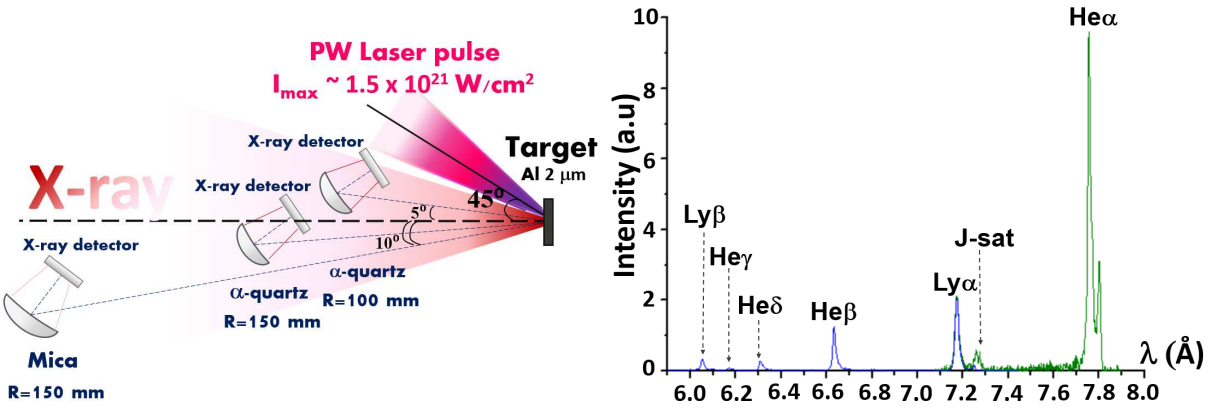


**Figure 1.** (a) Experimental setup. Laser beam focus on the target surface and heats the foil. X-ray source is generated by 1 ps 1 PW laser beam focused on 2 $\mu$m Al foil. X-ray radiation is measured by three FSSR spectrometers located on front sides of the target at 5° to the axis of the target normal. (b) United spectrum measured by two pre-calibrated $\alpha$-quartz crystal equipped spectrometers in the wavelength range $d\lambda \sim$ 6–8 Å.

were made by Henke [11] assuming of the theory of dynamic diffraction are commonly applied instead.

X-ray reflectivity ability of crystals strongly depends on geometric parameters of crystals and high lever quality of fabrication. Crystals of a-quartz are more widely applied since they have a perfect monolayers structure and x-ray reflectivity properties of bent $SiO_2$ crystals are rather well studied. Moreover the technology of $SiO_2$ spherically bent crystals fabrication is not connected with mechanical and thermal deformation leads to crystal surface defects and destructions of crystal grating. On a par with quartz, crystals of RAP(Rubidium Hydrogen Phthalate), KAP (Potassium Acid Phthalate), ACD (Acetyl-CoA syntheses) and Mica are used for imaging spectrometry diagnostics but their x-ray reflectivity properties are not well known as a technology of production is more complicated. Such bent crystals should be calibrated individually. Mica bent crystal found a wide application in x-ray spectroscopy diagnostics since there ability to perfectly reflect the radiation in different orders including sub-keV range of soft x-ray hardly reached by another type of crystals. By this reason spherically curved mica crystals are often used for diagnostic of dense laser plasma radiation and correspondently they should be calibrated with high accuracy.

Here we propose the way to calibrate mica crystal spectral reflectivity in the experiment with relativistic laser plasma. We consider the approach based on the comparison of a dense laser plasma x-ray spectra measured by focusing spectrometers with spatial resolution (FSSR) equipped, correspondingly, with examined mica and pre-calibrated alpha-quartz bent crystals.

X-ray source to be measured was generated in the interaction of intense petawatt power 1 ps laser pulse with Al 2 $\mu$m thin foils. The spectra were registered in a single laser shot in overlapping wavelength range of 6–8 Å by three FSSRs installed in front of the laser irradiated target surface at the angle about 5°–10° to the axis of target normal (figure 1a).

Spectra were measured simultaneously by $a$-quartz crystal equipped spectrometers operating in the 1$^{st}$ order of reflection (curvature radii of $R_1 = 100$ mm and $R_2 = 150$ mm correspondently, lattices spacing 2d = 4.256 Å) just as spectra were measured by the third spectrometer equipped be examined mica crystal operating at second order of reflection (curvature radius $R_3 = 150$ mm, lattices spacing 2d = 19.9376 Å). Spectra were registered by means of Image Plate detector

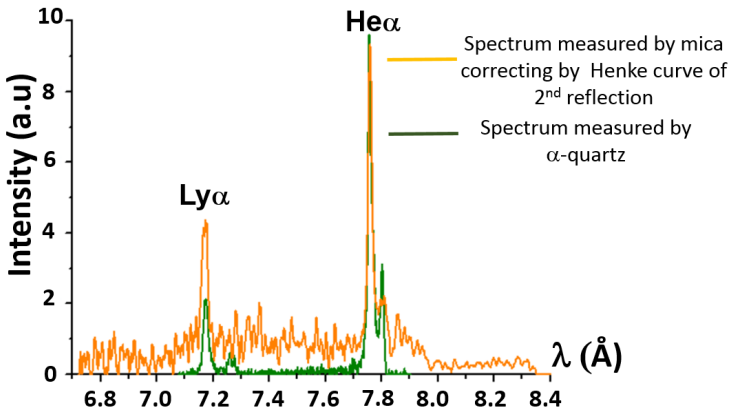


**Figure 2.** Aluminum plasma x-ray spectra measured by means of spectrometers with quartz and mica crystals. Orange curve—the spectrum measured by mica crystal in the 2$^{nd}$ reflection order in wavelength range $\sim$ 6.7–8.6 Å processed with the application of x-ray reflectivity curve theoretically evaluated for a flat muscovite crystal [11]; green curve—spectrum measured by $SiO_2$ crystal in the 1$^{nd}$ reflection order in wavelength range of 7.0–7.9 Å.

with or Andor CCD camera providing the resolution of 25 $\mu$m at the detector plane. To perform the calibration we compared the relative intensities of resonance spectral lines emitted by multicharged Al ions, as well as the shape of bremsstrahlung radiation, measured by means of quartz and mica crystals in the overlapping wavelength range $\delta\lambda \sim$ 6.7–7.7 Å.

We made the calibration applied only "well known" experimental spectra to escape the influence of some strong spectra features attributed to hollow ions generation or another physical processes connected with high laser intensity, target thickness and so on. To protect x-ray detectors from visible light we use sets of attenuating filters consisted of two layers of polycarbonate (thickness $h = 2\ \mu m$) with thin sputtering layer of Al ($h = 0.6\ \mu m$) for quartz crystal equipped spectrometer closest to the target surface and we utilized a beryllium filter ($h = 7\ \mu m$) for protection of the second quartz crystal equipped spectrometer correspondingly. In the case of mica spectrometer we used a complex attenuating filters set involving two layers of 1 $\mu$m Mylar with Al sputtering ($h = 0.3\ \mu m$), and one layer of polycarbonate ($h = 2\ \mu m$) with thin sputtering layer of Al ($h = 0.6\ \mu m$). To prevent a possible damage of crystals by debris flow from the target we have installed 6 $\mu$m Mylar film in front of the crystal aperture. The acquired spectra were then corrected taking into account the functions on filters attenuation and detector efficiency [12].

Let us note that the reflectivity of the bent $\alpha$-quartz crystal was calibrated in [12] in the considered photon energy range using x-ray synchrotron radiation source. The united spectrum emitted by laser-irradiated Al foil target is shown in figure 1b as it was measured by two spectrometers with $\alpha$-quartz crystals. The spectrum registered by each spectrometer was normalized in order to equal the intensity of Al $Ly_\alpha$ spectral line registered by both devices.

Then the united spectrum was compared with that one acquired by use of spherically bent mica crystal. Figure 2 demonstrates clearly that when both spectra are normalized on Al $He_\alpha$ spectral line intensity, the spectra in shorter wavelength range (containing Al $Ly_\alpha$ line and its satellites) differs several folds. The only way to explain such a discrepancy is appeared to be due to incorrectness in mica crystal reflectivity curve the range $\sim$ 6.7–7.7 Å, which was theoretically evaluated for a flat muscovite crystal [11] and taken into account here during the spectral data processing.

Note, that in fact mica crystal reflects x-rays well in a set of reflection orders ranging from 1$^{st}$ up to 12$^{st}$ and even higher ones [13]. However, the contribution from the 1$^{st}$ order was

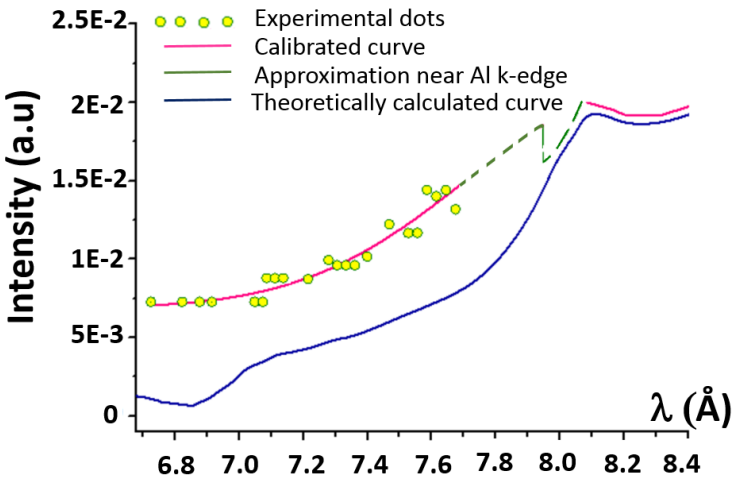


**Figure 3.** Calibrated mica x-ray reflectivity curve of 2nd reflection order in comparison with calculated curve from a theory [11].

effectively eliminated due to the crystal was protected by 6 $\mu$m thick Mylar ($C_{10}H_8O_4$) filter with absorbing more than 85% of radiation in the wavelength range of 10–12 Å, and both IP and CCD detector quantum efficiency drops for an order of magnitude for that range also. The spectra from 3rd and further reflection orders in the case of Al plasma might consists of bremsstrahlung and recombination continuum radiation, but in a given experimental conditions they were both of negligibly low intensity, as it could been seen from figure 1b. Thus it becomes possible to consider the spectrum measured by mica-equipped spectrometer as acquired from 2nd reflection order only.

In turn, by reaching the coincidence between the spectra measured by means of that questionable mica and calibrated quartz crystals it becomes possible to plot out a new reflectivity calibration for a spherically bent mica crystal working at second order of reflection and particular wavelength range of 6.7–7.7 Å. The values of the mica reflectivity efficiency versus radiation wavelength obtained by this way are given in figure 3. Experimental points were approximated such way that it is allowed us to reach the correspondence of $\delta I/I \sim 10^{-4}$ in between the spectra intensities measured by means of mica and quartz crystals.

Though for the wavelength range of 7.7–8.5 Å we do not have any experimental data, therefore we are only able to determine the implicit view of spherically bent mica reflectivity in the range, as it is shown in figure 3 by dashed curve. The most reliable explanation for the discrepancy in theoretical and a new experimental curve is in a proper accounting of a mica chemical composition ($K(Mg,Fe)_3AlSi_3O_{10}(OH,F)_2$) containing the fraction of aluminum atoms, which absorption K-edge is lying at 7.94 Å and, in turn, should influents the number of photons reflected. The expected feature in the reflectivity curve caused by this reason is also given in figure 3.

The application of different crystal reflectivity curves for the processing of the experimentally measured spectra results in a strong changes of Al $Ly_\alpha$ (7.17 Å) and Al $He_\alpha$ (7.75 Å) lines relative intensities, and so in parameters of a plasma determined by X-ray spectroscopy methods. As an example, one might consider the case when the initial reflectivity curve is applied to the measured data (see figure.4a). Then, the spectrum is modeled by atomic kinetics open-source code FLYCHK [14] choosing electron temperature and density of plasma in order to obtain the best correspondence between the experimental and modeled spectra. It was obtained for $N_e = 3\times10^{22}$ cm$^{-3}$ and $T_e = 430$ eV as seen from the figure. We have to stress that temperature values given above are supplied only as an example to demonstrate the sensibility to the spectral

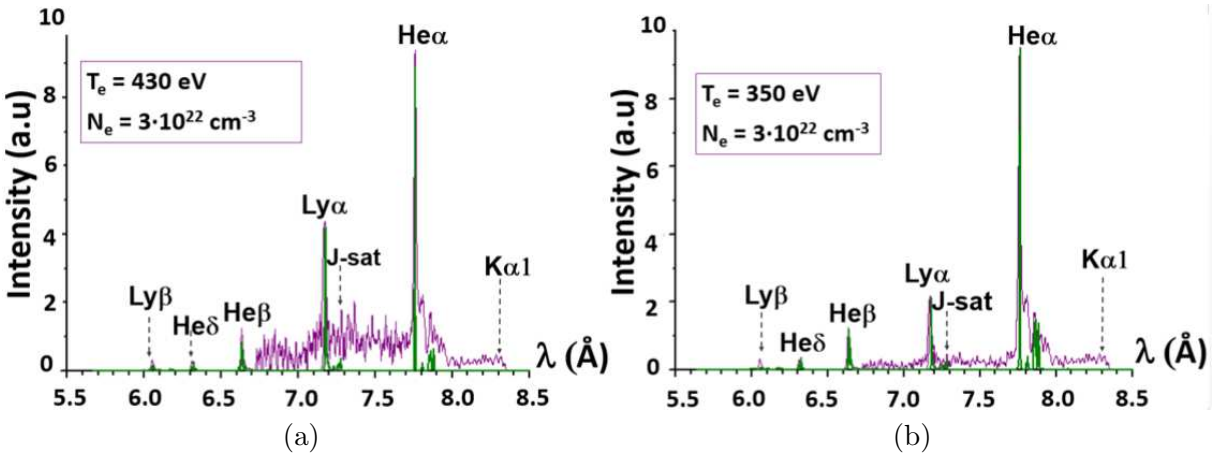


**Figure 4.** Modeling of Al plasma spectra measured by FSSR spectrometer equipped with mica spherically bent crystal. The red fitting curves represent the output of FLYCHK simulations obtained for particular electron density and temperature of plasma. (a) Experimental spectrum is evaluated using theoretically calculated mica reflectivity curve [11], simulated spectrum reaches the best correspondence for $N_e = 3 \times 10^{22}$ cm$^{-3}$ and $T_e = 430$ eV; (b) Experimental spectrum is evaluated with a new x-ray reflectivity calibration for bent mica crystal, simulated spectrum reaches the best correspondence in the assumption of $N_e = 3 \times 10^{22}$ cm$^{-3}$ and $T_e = 350$ eV.

lines intensity. Even by roughly estimation the application of calibrated mica reflectivity curve resulted in 10% temperature value change. As for the magnitude of plasma density results given above is only the illustration to x-ray diagnostic sensibility. To improve the accuracy of plasma parameters calculation we have to consider the fraction of hot electron component but that issue is outside the scope of this paper. In turn, for the case of a new x-ray reflectivity calibration curve applied, the ratio between $Ly_\alpha$ and Al $He_\alpha$ spectral line intensities is changed from 2.16 to 4.36. Correspondingly, the measured and the modeling spectra are in good agreement for the same electron density $N_e = 3 \times 10^{22}$ cm$^{-3}$ but for a different electron temperature of 350 eV, which gives the evidence of how the proper determination of a crystal reflectivity curve reflects in a precision of plasma parameters diagnostics.

The approach of x-ray reflectivity curve calibration based on comparison between spectra of x-ray radiation of dense laser plasma measured by high spatial resolution x-ray spectrometers with alpha-quartz and mica dispersive crystals allow us to obtain the new calibration for spherically bent mica x-ray reflectivity curve in 2$^{nd}$ order of reflection. We experimentally demonstrated that character of earlier calculated curve should be refined in the wavelength range of 6.7–7.7 Å. Using this way of calibration we obtained a good agreement in relative intensities of H- and He-like spectral lines of aluminum dense plasma measured by both mica and alpha-quartz spherically bent crystal. The obtained experimental reflectivity curve is now in use in studies of solid-density plasma created in the interaction of PW-power laser pulses with solid targets.

## Acknowledgments

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