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COHERENT AND INCOHERENT COMPONENTS OF A SYNCHROTRON RADIATION SPOT PRODUCED BY SEPARATE CAPILLARIES

Sultan B. Dabagov [1,2], Augusto Marcelli [2], Violetta A. Murashova [1],
Nikolai L. Svyatoslavsky [3], Rustem V. Fedorchuk [1], Mikhail N. Yakimenko [1]
[1)] *P.N. Lebedev Physical Institute RAS, Moscow, Russia*
[2)] *INFN - Laboratori Nazionali di Frascati, P.O. Box 13, I-00044 Frascati, Italy*
[3)] *Center for Photochemistry RAS, Moscow, Russia*

Abstract

In this work the focusing properties of soft X-ray synchrotron radiation by separate capillaries are discussed. It is shown that a not negligible fraction of the synchrotron radiation beam transmitted by the capillary has a mode representation. Experimental and theoretical data are discussed to explain the superposition pattern of the X-rays in the focal plane due to the interference phenomena of electromagnetic radiation propagating through separate capillaries.

Keywords: synchrotron radiation optics, capillary optics, wave propagation

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1 INTRODUCTION

Recently, the phenomena of the interference of X-rays has been observed when glancing reflections of X-rays in the capillary lenses occur [1]. Other experiments of synchrotron radiation (SR) focusing by capillary macrosystems [2,3] showed a radiation redistribution at the focal plane of the optical systems. Although the mechanism of the multiple total external reflection of the radiation from the inner wall of a single monocapillary or a capillary system may explain the transmission of an X-ray radiation beam and the change of its geometrical configuration, namely, bending, focusing, collimating, etc. phenomena, the interpretation of the pattern redistribution is possible only in the framework of the wave theory. A wave theoretical model describing the characteristics of soft X-ray quanta into a capillary structure was recently proposed [4]-[7]. The model shows that the interference and diffraction of X-rays can not be neglected when X-ray radiation diffuses into a capillary ”waveguide”. Results of both experimental and theoretical researches on the wave properties of a SR beam travelling into capillary of definite geometry have been also discussed in Refs.[8]-[15].

Because of the complex geometrical structure of the capillary lenses, the study of the SR beam behaviour at the focal plane, when systems of simple geometry are considered, represents an ideal test of the theoretical model proposed via comparison with the available experimental data.

2 WAVE PROPAGATION INTO A CAPILLARY

Let us start considering X-rays that travel into a ”waveguide” represented by a hollow tube of inner radius r_0. Because X-rays may be considered as very short electromagnetic waves, we may solve the wave equation to define the wave’s distribution. The trajectories of X-ray photons into channels in the multiple reflection regime are spiral curves with different curvature radii. The values of the curvature radii of the trajectories vary from a minimum value which is equal to the waveguide channel radius r_0, to a maximum value defined by the waveguide curvature radius r_{curv}. Hence, for isotropic X-ray radiation the beam will be continuously distributed through all permitted trajectories.

We may consider now a particle travelling into a channel along the trajectory with radius $r_0 \leq r_1 \leq r_{curv}$. As it is well known [16,17] the wave equation for an electromagnetic wave with wave vector $k = \omega/c = 2\pi/\lambda$ into a media of dielectrical parameter ε is

$$\left(\Delta + k^2\varepsilon\right) \vec{E}\left(\vec{r}\right) = 0 \qquad (1)$$

The waveguide is represented by a hollow cylindric tube, and the field, in which the wave spreads, is described by the parameter

$$\varepsilon = \begin{cases} 1 & , \quad r < r_1 \\ \varepsilon_0 & , \quad r \geq r_1 \ , \end{cases} \tag{2}$$

where $\varepsilon_0 = 1 - \delta + i\beta$ (δ and β are real values describing the radiation polarizability and the attenuation, respectively) is the complex dielectrical function of the media (i.e. the glass of the capillary).

When solving the wave equation we are mainly interested to the edge region which, in fact, defines the wave guiding character inside the channel ($r \simeq r_1$):

$$r = r_1 + \delta r, \quad \delta r \ll r_1 \tag{3}$$

Using the asymptotic methods and the expansion in a set of unknown parameter [18, 19], it is possible to write the radiation field as

$$E(r, \varphi) = A(r_1, \varphi)\ u(\delta r) \tag{4}$$

where the function $A(r_1, \varphi) \equiv f(\epsilon) \approx f_0(\epsilon_0) + f_1(\epsilon_1) + \ldots$ determines the reflection coefficient of the electromagnetic wave from the waveguide wall, i.e. $R(\varphi) = |A(r_1, \varphi)|^2$. In the coordinate system of the guide, the wave equation at the edge region is

$$(\Delta + \varepsilon_{eff})\ u(\delta r) = 0 \ , \tag{5}$$

where ε_{eff} is an "effective field" parameter depending by ε, k and by the function A. Solving this equation we obtain the expression for the relative radial part of the wave function u

$$u_m(\rho) \propto \begin{cases} \Phi_m(\rho) & , \quad \rho > 0 \\ \alpha \Phi'_m(0)\, exp(\alpha\rho) & , \quad \rho < 0 \quad (\alpha > 0) \end{cases} \tag{6}$$

where $\Phi_m(x)$ is the Airy function.

The expression (6) characterizes the waves that propagate close to the waveguide wall, or in other words, the equation describes the grazing modes structure of the electromagnetic field. The solution (Eq.(6)) shows also that the wave functions are damped both inside the channel wall and going from the wall towards the center (Fig. 1). It should be underlined here that mode propagation takes place without a wave front distortion. A more accurate analysis of these expressions allows also to conclude that almost all the energy of the wave is concentrated in the vacuum region and, as a consequence, a small attenuation along the waveguide walls is observed.

Concerning the allowed modes of the electromagnetic field an estimation of the typical radial size of the main grazing mode ($m = 0$) may be obtained if we consider that

$$\gamma \equiv (\lambda / < u_0 >) \simeq \left(2\pi^2 \lambda \middle/ r_1\right)^{1/3} \ll 1 \ , \tag{7}$$

and as a consequence, we can underline that the typical radial size $< u_0 >$ may overcome the wave length λ, whereas trajectory curvature radius r_1 may overcome the inner channel radius r_0.

If we suppose that only the mode with $m = 0$ is transmitted by the capillary, it is possible to consider the wave superposition of the radiation emerging by two different capillaries. The computer simulation results are presented in Fig. 2 for two different cases: a simple superposition of the distributions behind different capillaries at the focal plane (left panel), and a superposition of waves from different capillaries (right panel). The right panel exhibits a strong redistribution with a clear maxima and the typical sizes of the spots ($\sim 10 \div 30\, \mu m$) significantly exceed the wave length of the radiation. Moreover, the redistribution pattern calculated does not change if the higher modes are taken into account, and only a broadening of the spots is observed.

This pattern is very difficult to observe in the real case because of the complex character of the radiation distribution into a capillary. In fact the distribution is defined by the diffuse component of the radiation beam plus the portion of the radiation travelling through the channel in the mode regime. Because SR travels through a capillary only for a few modes, experimental observation of pattern redistribution may be successful and only when the diffuse part of the radiation is significantly suppressed. In addition, the pattern of the redistribution is typically smeared out when optimal allignment is not achieved.

3 EXPERIMENTAL RESULTS AND DISCUSSION

A set of experiments to test the validity of the theoretical model were carried out using the layout described in Refs.[2,12] and schematically presented in Fig. 3. The distance between the center of the experimental chamber and the radiating orbital point was about $7\, m$. At this distance the vertical FWHM of the beam at $\lambda = 10\, \mathring{A}$ was equal to $\sim 1\, mrad$. All the channel elements were held in vacuum at about $5 \times 10^{-6}\, Torr$. A set of different thicknesses Al-filters removeable in vacuum, placed into the chamber, was used to select a narrow spectral line. A device to control the angular capillary system adjustment with an accuracy of $\leq 2\, mrad$ was also placed at the exit of the chamber.

In this setup a system of two identical curved capillaries, positioned in the electron orbital plane with mirror symmetry, replaced the capillary lenses. The scheme of the experiment is shown in Fig. 4. As suggested by the theoretical calculations, the system parameters were set to transmit SR in a mode with wave length in the range $8 \div 13\,\mathring{A}$ (such spectrum is obtained with the Al-filter inserted before the capillary system). The capillaries were $l = 110\,mm$ long, have an inner diameter of $d_0 = 2r_0 = 100\,\mu m$, and a curvature radius of $r_{curv} = 2\,m$. The distances between the capillaries centers were $a = 8\,mm$ at the entrance, and $b \approx 4\,mm$ at the exit. A mutual installation and adjustment of the capillaries was performed to provide at the entrance, the minimum possible angles between the SR beam direction and the tangents to the capillaries longitudinal axes. A special diaphragm was also positioned before the system of capillaries to allow the SR to go through only one of the two capillaries successively, or through both capillaries at the same time. When successive opening of the capillaries happens, the SR travelling through each capillary illuminates the film at the same place. This gives us the experimental possibility to compare the intensity distributions in both geometries.

The radiation behind the capillaries was detected by films (KODAK DEF392, SB392) placed at different distances from the exit. The films were processed and analysed using a photometer and a densitymeter.

The expected pattern redistribution is a superposition of the radiation beams from different capillaries. The behaviour of such geometry was checked by detecting radiation in the transverse plane at different distances from the exit of the capillaries with an accuracy of the relative distance along the SR axis of about $0.1\,mm$. The region of an almost complete superposition of the beams (at the focal spot) was determined at the distance of $69.2\,mm$ from the exit, to compare with the theoretical value of $70\,mm$.

The digitized data of this image, i.e. the microphotographs of the focal spot, is presented in Fig. 5. Both in the case of the simultaneous transmission of the radiation through the capillaries (a) and in the case of successive transmission (b) a specific macrostructure corresponding to the typical distribution of the radiation from separate capillaries is observed. A redistribution of the spot, when both capillaries are opened at the same time, occurs if we compare the distribution obtained with the separate capillaries. The change of the pattern is more evident in the 3D intensity distribution at the focus position (Fig. 6).

As underlined above [8,10], the radiation emerging by the capillaries consists of both a diffuse and a mode components. While, the typical macrostructure of the spot is given by the diffuse homogeneous component, the mode component of the radiation is that responsible of the intensity redistribution.

The lack of positional markers on the films does not allow to make a precise alignment of the 3D distributions in the two cases. Then, to obtain a quantitative estimation only a linear scanning along the marked directions was performed using a microphotometer. Thus the microphotogram alignment may be carried out only for one parameter. The distributions of the radiation intensity along the marked direction are compared in Fig. 7

(a, b). The effective size of the microphotometer slit was 100 x $10\,\mu m^2$. A difference between the microphotograms may be clearly detected with a fitting procedure of the curves that demonstrates when both capillaries are opened at the same time (a), that both change of the amplitudes and the widths of the functions fitted under fixed capillaries displacement are observed. Taking into account a constant relative displacement of the fitting functions, one may determine the residual intensities of the radiation at the focal spot in the two cases. Results are shown in Fig. 7(c), where the interference term in the case of the two interacting SR beams. Within the experimental errors, the integration of the curves (a) and (b) gives the same result, i.e. a total zero energy as confirmed by the integral of curve (c). The asymmetry of the maximum of the curve (c) may be due to an incomplete superposition of the beams emerging by both capillaries and by a possible mismatch of the optical system respect to the incoming beam. The best result of the fitting procedure returns a wide diffuse background in both cases (a, b). As a consequence, within the errors of the procedure, we may detect a mode regime of SR travelling through the capillaries. A wave superposition process is then responsible of the redistribution of the radiation intensity, or, in other words, these experimental results confirm the predicted existence of an interference phenomena between electromagnetic radiation propagating through a system of separate capillaries of sizes significantly larger then the wave length of the radiation.

4 CONCLUSION

Different experimental observations of X-ray radiation travelling through capillary systems have been carried out in the last years, and all show the presence of a coherent component superimposed to the incoherent diffuse radiation transmitted. Although, in some case this portion may give a substantial contribution, the coherent component is usually neglegible, and the observation of wave phenomena looking at the radiation beam redistribution behind a capillary structure is a complex task. However, an enhancement of the weak coherent contribution is possible when correlation among diameter, length and curvature radius of the channels, number of capillaries and degree of symmetry of the system are considered. Additional enhancement of the coherent contribution may be obtained using the alternate arrangement of capillary systems in the vertical plane.

The presence of the mode propagation of X-rays into capillaries where transmission parameters are defined by the geometry of the optical system, allows us to figure out development of the X-ray wave capillary optics. This field may be very interesting and useful for many new applications (like the technique to transfer the information, in X-ray microscopy, in research on weak coherent X-ray sources, etc.)

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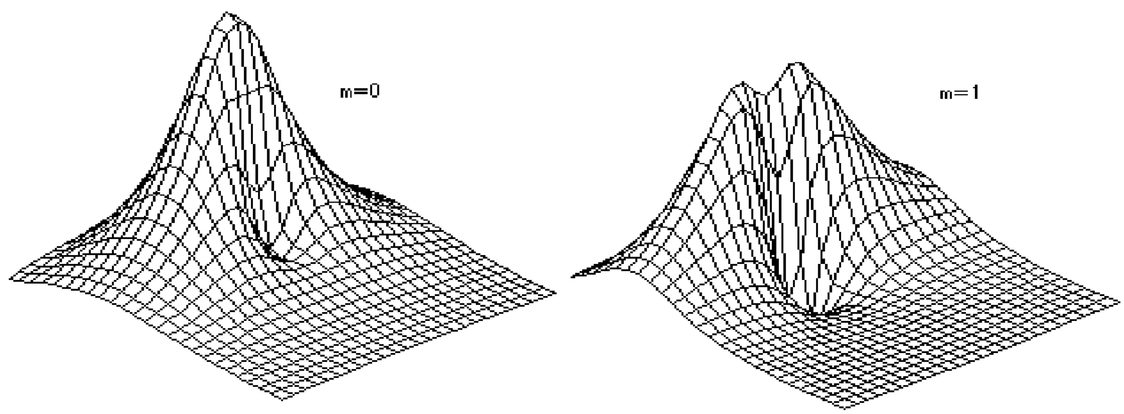

Figure 1: *The typical X-ray distributions inside a curved capillary for the first (main) 2 modes. The intensity of the distribution for the mode* $m = 1$ *is increased 10 times for comparison.*

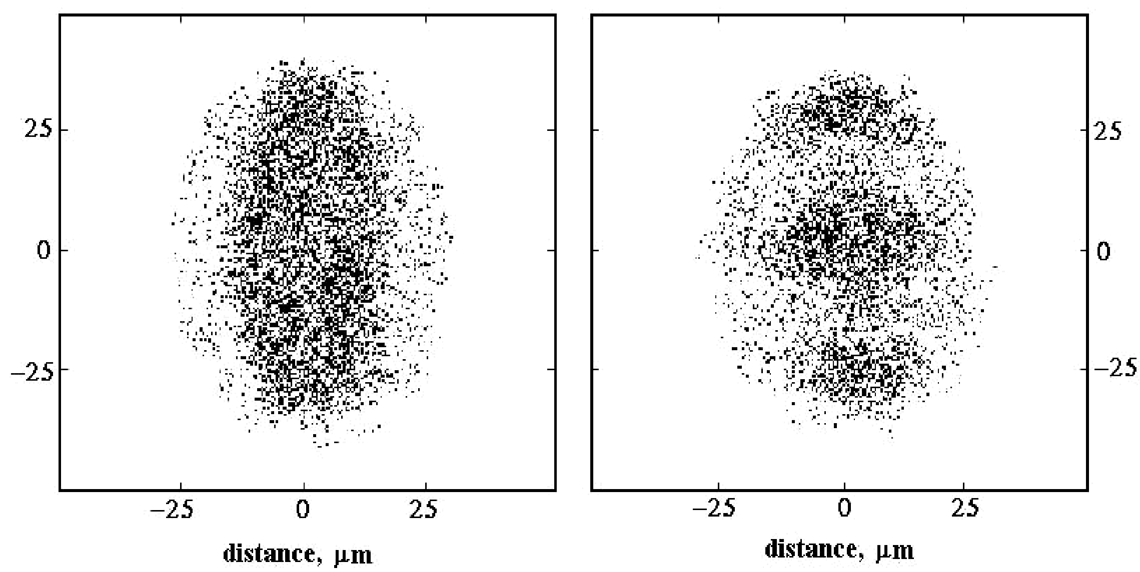

Figure 2: *The theoretical simulations of the intensity distributions behind two identical curved capillaries at the focal plane. The left distribution is the result of the superposition of the radiation distributions from separate capillaries; the right one represents a wave superposition. Calculations refer to the mode with* $m = 0$. *The sizes are in arbitrary units but the same for both panels.*

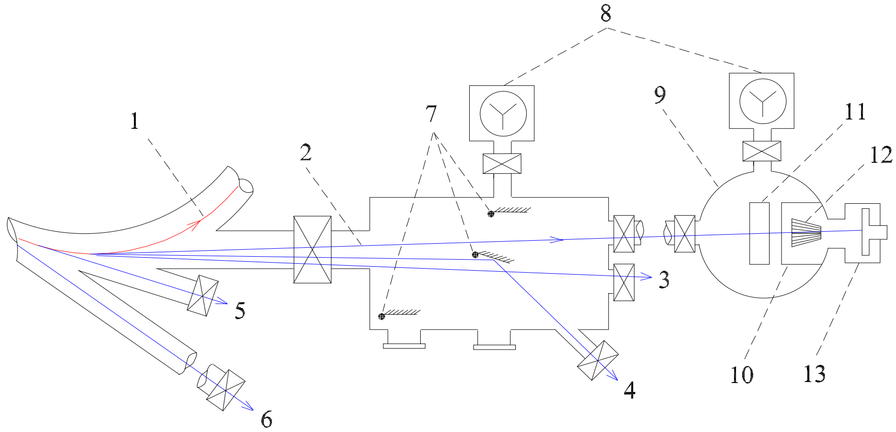

Figure 3: *The sketch of the SR experimental layout: 1 - electron orbit; 2, 3, 4, 5, 6 - SR beams; 7 - mirrors; 8 - vacuum pumps; 9 - experimental chamber; 10 - adjusting device; 11 - filter holder; 12 - capillary system; 13 - detector.*

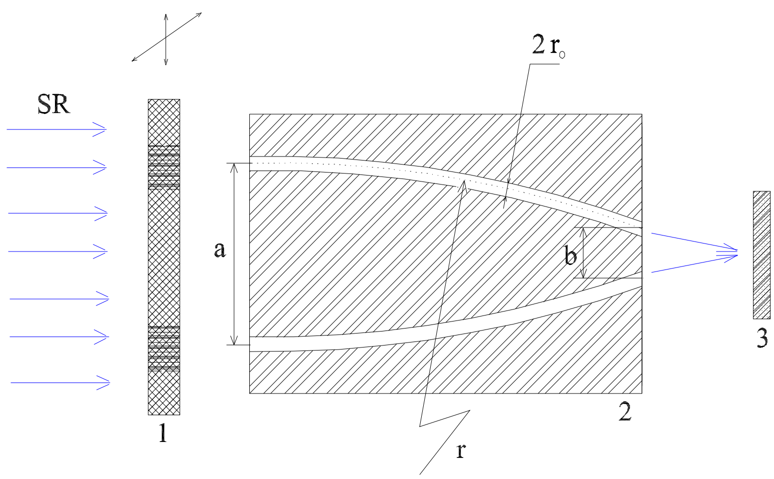

Figure 4: *Focusing scheme by a capillary system consisting of two separate capillaries (1 - system of filters and diaphragms; 2 - holder of the capillary system; 3 - detector).* a *and* b *are the distances between the capillary centers at the entrance and at the exit, respectively;* $r \equiv r_{curv}$ *is the curvature radius of the capillaries;* r_0 *is the capillary channel radius.*

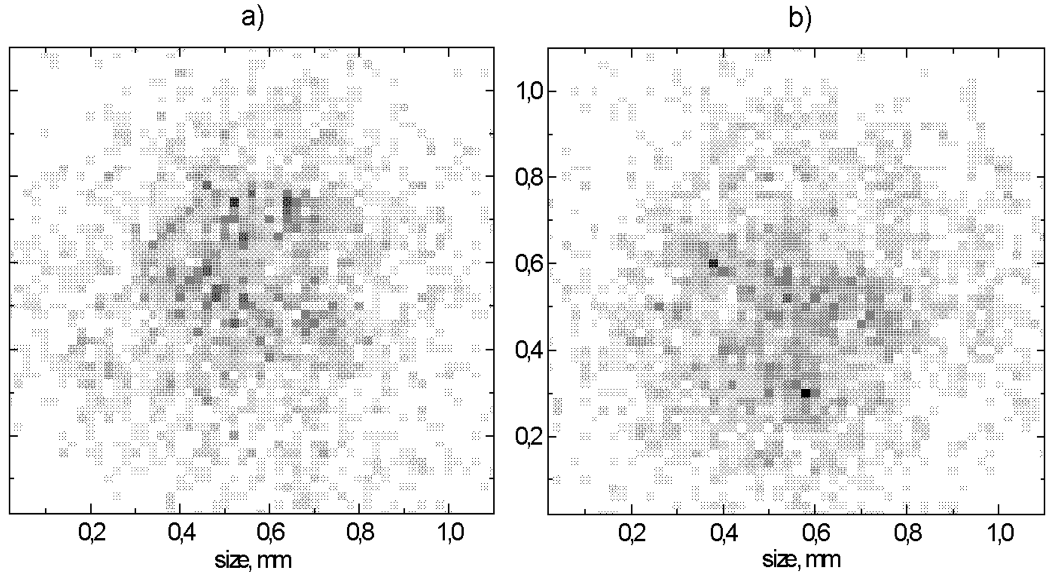

Figure 5: *The digitized microphotographs of the beams superposition at the focal plane. The X and Y scales are the same and given in mm.*

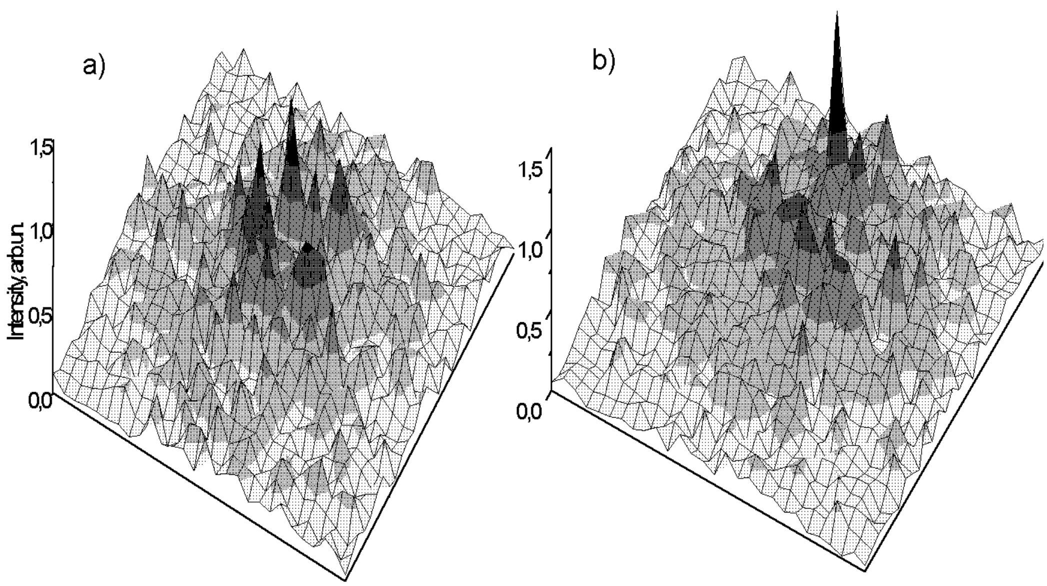

Figure 6: *3D intensity distributions corresponding to the digitized microphotographs of Fig. 5. The X and Y scales are the same of Fig. 5, the intensity axes are plotted as arbitrary units.*

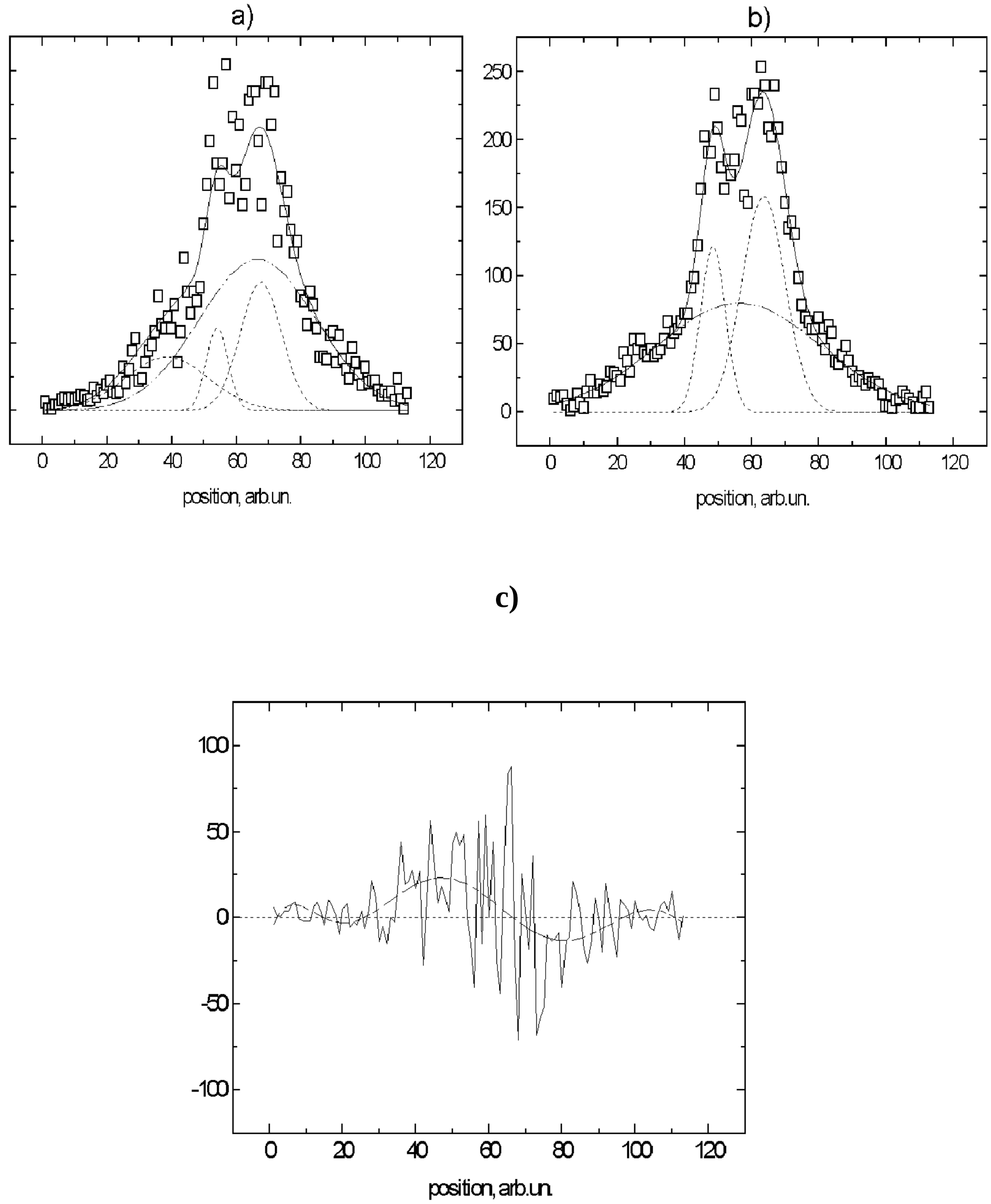

Figure 7: *The intensity of the film along the marked direction shown in Fig. 6 (a, b - open squares). Curves are obtained by a fitting procedure. The difference of the curves (a) and (b) is reported in panel (c). The intensity values are the same for panels (a), (b), and (c), and given in arbitrary units.*