On X-Ray Channeling in $\mu$- and $n$-capillaries

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Abstract

In this work X-ray propagation in micro- and nano-size capillaries has been considered in the frame of a simple unified wave theory. It is shown that the diminishing of the channel sizes completely changes the mode of beam transportation, namely, we obtain the transformation of surface channeling in microcapillaries to bulk channeling in nanocapillaries (nanotubes).

Keywords: X-ray channeling, nanotubes, capillary optics

I. INTRODUCTION

Starting from the mid 1980s the interest for the problem of X-ray passage through capillary systems increased, because of the development of a new technology for the manufacturing of X-ray optics of grazing incidence [1]. Nowadays capillary optics represents a well-established X-ray and neutron optical instrument that allows experiments to be performed quite efficiently on a much smaller scale than conventional X-ray devices. These optical elements consist of hollow tapered tubes that condense neutral particles by multiple reflections from the inner channel surface [2,3]. Moreover, capillary optics relies also on the ability of a
tapered and/or bent capillary channel to act as an X-ray waveguide [4], in other words, an optical element may be considered as a whispering-gallery X-ray device.

As well known, a whispering gallery device is a multiple reflection one with a large number of bounces [5]. The total subtended angular aperture of the device is determined by the number of bounces $N$ and the glancing angle $\theta$, and equals $2N\theta$. While the reflectivity of single bounce light from a substance with the complex dielectric function $\varepsilon = 1 - \delta + i\beta$ ($\delta$ and $\beta$ are the parameters of polarizability and attenuation, respectively) is defined by

$$R_1[sp] \simeq 1 - 2 \text{Re} \left( \left[ \frac{1}{\varepsilon} \right] (\varepsilon - 1)^{-1/2} \right), \quad (1)$$

where $s, p$ are the indexes of radiation polarization, the integral reflection may be estimated by taking the $\theta \to 0$ limit -

$$R[sp] \simeq \exp \left( -R_1[sp] N\theta \right) \quad (2)$$

Evaluations made by these relations have shown that the whispering galleries offer high efficiency with narrow band pass [6].

Application of wave theory to the radiation passage through capillary structures opens up new prospects for the study [7–9]. As will be shown below, capillary optical systems act in such a way that radiation propagating in channels consists of two portions: one is scattered by the laws of ray optics, the other one is captured in bound modes by a surface potential. Moreover, when the channel size values approach the transverse wavelength of radiation, the bulk channeling of photons occurs similarly to the channeling of charged particles in crystals [10]. At present, the technology of capillary system manufacturing allows structures of the deep submicron level to be produced [11]. For example, as examined samples one may consider the carbon nanostructures (nanocapillary systems) [12], in the fabricating of which a big progress has been achieved in recent years [13].

A graphitic nanotube [14–16] may be considered as a small-size (nano-size) capillary. The wall surface of it is formed by carbon atoms, the distance among which is estimated to be $1 \div 2 \text{ Å}$. The typical diameter of a single nanotube is about tens of nanometers (the channel
diameter / wall thickness ratio may reach two orders of magnitude), and the length of such a structure may be of submillimeter order. All these features of the nanotube structures result in the utilization of wave propagation theory instead of the ray approximation one, and consequently, nanotubes may be considered as X-ray waveguides. This allows the well known channeling theory to be applied for describing X-ray beam propagation inside these structures [17,18].

Nanotube research has been developed rapidly over the last decade following the bulk production of C60 and structural identification of carbon nanotubes. The discovery of a third carbon allotrope Buckminsterfullerene (C60) in the mid 1980s initiated and led to the development of elongated cage-like structures (known as nanotubes) in 1990s. Since 1991 [19], there has been a lot of study on carbon nanotubes to understand their formation and properties. In 1992, reports appeared on the bulk synthesis of nanotubes formed as an inner core cathode deposit generated by arching graphite electrodes in an inert atmosphere. The products exhibit different degrees of crystallinity and various morphologies (e.g. straight, curled, hemitoroidal, branched, spiral, helix shaped etc.).

Indeed, carbon nanotubes stick out in the field of nanostructures, owing to their exceptional mechanical, capillarity, electronic transport and superconducting properties [20]. They are cylindrical molecules with a diameter of order 1 nm and a length of many microns. They are made of carbon atoms and can be thought of as a graphene sheet rolled around a cylinder [21].

It is well known that nanotubes can be manufactured of different diameters - from a fraction of nm up to microns, of different length - from tens of microns up to millimeters, of different materials - usually carbon but also others [22]. There are various applications of nanotubes. Recent examples include use of nanotube as (I) gas storage components for Ar, N2 and H2 (II) STM probes and field emission sources (III) high power electrochemical capacitors (IV) chemical sensors (V) electronic nanoswitches (VI) magnetic storage devices etc.

Different carbon nanotubes have been manufactured and investigated by X-ray absorp-
tion near-edge structure (XANES) at the carbon K edge. The surface structure and bonding properties have been studied by characteristic pre-edge features while structural features of these nanostructured systems have been identified looking at the variation in the multiple-scattering region of the XANES spectra [23].

Simulations of particle beam channeling in carbon nanotubes have been recently performed, in order to evaluate the possibilities for experimental observation of channeling effects in both straight and bent nanotubes, considering different charged particle species, such as protons of 1.3 and 70 GeV, and positrons of 0.5 GeV [24]. There the capabilities of a nanotube channeling technique for charged particle beam steering have been discussed, based on earlier Monte Carlo simulations [25].

In this work a unified description for X-ray propagation (note that the same theory is valid for neutrons) through capillaries of various diameters is presented.

II. QUANTUM-WAVE DUALISM

As it has been shown recently, the propagation of X-ray photons through capillary systems exhibits a rather complex character [26]. Not all features shown in the experiments can be explained within the geometrical (ray) optics approximation [27–29]. On the contrary, the application of wave optics methods allows us to describe in details the processes of radiation spreading into capillaries.

The propagation of X radiation through capillary systems is mainly defined by its interaction with the inner channel walls. In the ideal case, when the boundary between hollow capillary and walls represents a smooth edge, the beam is split in two components: the mirror-reflected and refracted ones. The latter appears sharply suppressed in the case of total external reflection. The characteristics of scattering inside capillary structures can be evaluated from the solution of a wave propagation equation. In the first order approximation, without taking into account the roughness correction \( \Delta \varepsilon (r) = 0 \) (\( \Delta \varepsilon \) is the perturbation in dielectric permittivity induced by the presence of roughness), the wave equation in the transverse
plane to the propagation direction reads

\[
(-\nabla^2 + k^2 \delta (r_\perp) - k_\perp^2) \ E (r_\perp) = 0 ,
\]

(3)

where \( E \) is a function of the radiation field, and \( k \equiv (k_\parallel, k_\perp) \) is a wave vector.

Due to the fact that the transverse wave vector may be presented as \( k_\perp \approx k\theta \) under the grazing wave incidence \( (\theta \ll 1) \), an "effective interaction potential" is estimated by the expression

\[
V_{\text{eff}} (r_\perp) = k^2 (\delta (r_\perp) - \theta^2) = \begin{cases} 
-k^2\theta^2, & r_\perp < r_1 \\
-k^2\theta^2 + k^2 (\delta_0 - \theta^2), & r_\perp \geq r_1 ,
\end{cases}
\]

(4)

where \( r_1 \) corresponds to the reflecting wall position. From the latter the phenomenon of total external reflection at \( V_{\text{eff}} = 0 \) follows, when \( \theta \equiv \theta_c \simeq \sqrt{\delta_0} \) - the Fresnel’s angle.

When we introduce a curvature in the reflecting surface, the effective potential obtains an additional contribution. This term, that corresponds to the additional "potential energy", can be seen physically in the following way. Due to the reflecting surface curvature a photon receives an angular momentum \( kr_{\text{curv}}\varphi \) of the "centripetal force", where \( r_{\text{curv}} \) is a curvature radius of the photon trajectory. The latter is supplied by the "centrifugal potential energy" \( -k^2 r_\perp / (2r_{\text{curv}}) \)

\[
V_{\text{eff}} (r_\perp) = k^2 \left( \delta (r_\perp) - \theta^2 - \frac{r_\perp}{2r_{\text{curv}}} \right).
\]

(5)

The situation is explained in the scheme in Fig. 1. Because of the variation in the spatial system parameters, the interaction potential has been changed from the step potential with the potential barrier of \( k^2\delta_0 \) to the well potential, with the depth and width defined by the channel characteristics.

In the following we briefly discuss a solution of the wave equation in the case of an ideal reflecting surface (i.e. without roughness), when the reflected beam is basically determined by the coherently scattered part of radiation (for details see Refs. [30,31]). The evaluation of the wave equation with the boundary conditions of a capillary channel shows that X-radiation may be distributed over the bound state modes defined by the capillary channel.
potential (see below). It is important to underline here that the channel potential acts as an effective specular reflecting barrier, and then, the effective transmission of X-radiation by the hollow capillary tubes is observed. While the main portion of radiation undergoes the incoherent diffuse scattering, the remaining contribution (usually small) is due to coherent scattering that represents a special phenomenon, extremely interesting to observe and clarify [33].

Let us estimate the upper limit of curvature radius \( (r_{\text{curv}})_m \) (which is defined by capillary/system of capillaries bending), at which the wave behaviors are displayed under propagation of radiation in channels [7], by considering a photon with the wave vector \( \mathbf{k} \) channeling into capillary with curvature radius \( (r_{\text{curv}})_i \) (\( i \)-th layer of capillaries). At small glancing angles, \( \theta \), the change of the longitudinal wave vector, \( k_{||} \), under reflection from a capillary wall is negligibly small; but mainly one changes the transverse wave vector, \( k_\perp \),

\[
k_\perp \simeq k \theta \ (\theta < \theta_c).
\] (6)

Correspondingly, from this relation it follows that the transverse wavelength will much exceed the longitudinal wavelength that provides the interference effects to be observable even for very short wavelengths. Indeed,

\[
\lambda_\perp = \frac{\lambda}{\theta} \gg \lambda
\] (7)

quantum mechanical principles say that, in order to display the wave properties of a channeling photon, it is necessary that typical sizes of an ”effective channel” \( \delta_i \), in which waves have been propagating, be commensurable with the transverse wavelength, i.e. \( \delta_i(\theta) \simeq \lambda_\perp(\theta) \) (Fig. 2). This condition may be rewritten in the following form:

\[
(r_{\text{curv}})_i \theta^3 \sim \lambda,
\] (8)

from which we obtain \( (r_{\text{curv}})_m \sim 10 \ cm \) for a photon of \( \lambda \sim 1 \ \text{Å} \) wavelength. So, from this simple estimate we can conclude that the relation (8) provides a specific dependence for surface bound state propagation of X-rays - surface channeling - along the curved surfaces (for instance, in capillary systems) (see also [32]).
III. PROPAGATION EQUATION

A. Surface channeling

Since the waveguide is a hollow cylindric tube, if the absorption is considered to be negligible, the interaction potential, in which a wave propagates, is determined by Eq.(5) with the radiation polarizability parameter \( \delta_0 \simeq \theta_c^2 \). Solving the wave equation we are mainly interested in the surface propagation, which, in fact, defines a wave guiding character inside the channel \( (r_\perp \simeq r_1, \rho \ll r_1) \) [9]

\[
E(r) \simeq \sum_m C_m u_m(\rho) e^{i(kz+m\varphi)},
\]

\[
u_m(\rho) \propto \begin{cases} A_{i_m}(\rho) \cos \phi, & \rho > 0 \\ \alpha A_{i'_m}(0) e^{\alpha \rho}, & \rho < 0 \quad (\alpha > 0) \end{cases}
\]

where \( A_{i_m}(x) \) is the Airy function, and \( \alpha \) is the arbitrary unit characterizing the capillary substance. Evidently, these expressions are valid only for the lower-order modes and in the vicinity of a channel surface. The expression (9) characterizes the waves that propagate close to the waveguide wall, or in other words, the equation describes the grazing modal structure of the electromagnetic field inside a capillary (surface bound X-ray channeling states) (Fig. 3). The solution shows also that the wave functions are damped both inside the channel wall and going from the wall towards the center. It should be underlined here that the bound modal propagation takes place without the wave front distortion. The analysis of these expressions allows us also to conclude that almost all radiation power is concentrated in the hollow region and, as a consequence, a small attenuation along the waveguide walls is observed.

As for the supported modes of the electromagnetic field, estimating a characteristic radial size of the main grazing mode \( (m = 0) \) results in

\[
\bar{u}_0 \simeq \sqrt{\frac{3}{2\pi^2}} \frac{\lambda^2 r_1}{2},
\]
and we can conclude that the typical radial size $\pi_0$ may overcome the wavelength $\lambda$, whereas the curvature radius $r_1$ in the trajectory plane exceeds the inner channel radius, $r_0$: $\pi_0 \gg \lambda$ (for example, $\pi_0 \gtrsim 0.1 \mu m$ for a capillary channel with the radius $r_0 = 10 \mu m$).

**B. Bulk channeling**

Above we have considered the transmission of X-ray beams by capillary systems of micron- and submicron-size channels. Obviously, in that case we deal with surface channeling of radiation due to the fact that the channel sizes are larger than the radiation wavelength at least by three orders of magnitude. However, the situation sharply varies in the case when the sizes of channels become comparable with the radiation wavelength. In practice it means, that the angle of diffraction for the given wave, determined as $\theta_d = \lambda/d$ (being $d$ a capillary diameter), becomes comparable with a critical angle of total external reflection. In other words, the transverse wavelength of a photon approaches the diameter of a capillary: $\lambda_\perp/d \sim 1$. In this case channeling of photons (note, not superficial (surface) channeling!) in channels of capillary systems should occur, i.e. we actually deal with a X-ray waveguide optics similar to a light waveguide one. Under the condition of the ordering channels in the system cross section, the capillary nanostructures are similar to crystals in relation to the charged particles, flying by under small angles to the main crystallographic directions.

As the analysis of the wave equation shows, the task cannot be analytically resolved for the real nanotube potential. For the sake of simplicity, let us consider the problem in the radial approximation for the periodic field of a multilayer waveguide with the size $d_0$ of a central channel and the distance $d$ between the layers composing a waveguide wall. An interaction potential of the radiation in such a waveguide system may be presented as follows:

$$V(r) = \sum_n V_n(r) = k^2 r \left[ 1 + \Delta \sum_n \delta \left( |r| - \frac{d_0}{2} - nd \right) \right],$$

where $\Delta \equiv \bar{\delta}_0d$ is the spatially averaged polarizability of the wall substance.

Taking into account the boundary conditions and because of the potential symmetry, one
may conclude that for the central channel $|r| \leq d_0/2$ the solution of the propagation equation in the transverse plane will be defined by the simple expression

$$E_0(r) = \begin{cases} a \cos(k_r r), & \text{even mode} \\ a \sin(k_r r), & \text{odd mode} \end{cases}$$  \hspace{1cm} (12)$$

Then we define the equation solution for the 1st layer $d_0/2 \leq |r| \leq d_0/2 + d$ by superposition of the opposite-directed waves $E(r) = b e^{ik_r r} + c e^{-ik_r r}$. As it has been done in the previous section, we make the mathematical assumption that all the modes of the total energy operator constitute a complete set of functions in the sense that an arbitrary continuous function can be expanded in terms of them. Then, we have a wave function $E(r)$ at a particular instant in time that obeys the continuous boundary conditions at the walls. In other words, we impose on the solutions the requirements that the wave function $E$ and its transverse derivative $E_r'$ be continuous at the wall-channel boundary

$$\left\{ \begin{array}{l} E \left( \frac{d_0}{2} + d - 0 \right) = E \left( \frac{d_0}{2} + d + 0 \right), \\
E_r' \left( \frac{d_0}{2} + d \right) = e^{i\xi d} E_r' \left( \frac{d_0}{2} \right), \end{array} \right.$$  \hspace{1cm} (13)$$

where $\xi$ is the quasimomentum determined by the Bloch theorem: $E(r + d) = e^{i\xi d} E(r)$ - for the periodical potential function $V(r) = V(r + d)$. From these expressions we obtain the dispersion relations for even and odd waves

$$\left( \begin{array}{c} \tan \frac{k_r d_0}{2} \\ \cot \frac{k_r d_0}{2} \end{array} \right) = \left( \begin{array}{c} -\frac{k^2 \Delta}{k_r} + \frac{\cos(k_r d) - e^{i\xi d}}{\sin(k_r d)} \\ \frac{k^2 \Delta}{k_r} - \frac{\cos(k_r d) - e^{i\xi d}}{\sin(k_r d)} \end{array} \right),$$  \hspace{1cm} (14)$$

that allow the eigenvalue/eigenfunction problem to be solved.

Now it is interesting to write the wave functions of the supported modes for the narrow channel $\{k_r d_0, k_r d\} \ll 1$

$$E_n(r) \propto \begin{cases} \cos(k_r r) e^{ikz}, & -\frac{d_0}{2} \leq |r| \leq \frac{d_0}{2} \\ \cos(k_r r) \frac{e^{ikz}}{\sin(k_r d)} \sin \left( k_r \left| \tilde{r} \right| \right) - \sin \left( k_r \left| \tilde{r} - d \right| \right) \sin \left( k_r d \right), & -\frac{d_0}{2} + nd \leq |r| \leq \frac{d_0}{2} + (n + 1) d \end{cases} \hspace{1cm} (15)$$
where $|\vec{r}| \equiv |r| - \frac{d_0}{2} - nd$. In this case we see that the Eqs.(14) may be solved only for even modes. However, it is more important to underline that the even mode exists for any ratio between the channel size and the layer distance. The spatial distribution of the mode has a maximum at the centre of the channel, and due to the leak through the potential barrier of wall layers we observe the propagation of radiation in substance. The radiation intensity for the successive layer decreases following an exponential law and is characterized by a local maximum far from the layer wall (the radial wave function distribution for the case of quasidistant layer system is shown in Fig. 4).

Because of the small wall thicknesses of nanotube channels (less than $\lambda_\perp \lesssim 100$ Å) we have to note that part of the radiation, channeling inside a nanotube structure, will undergo “tunneling” through the potential wall barrier. A simple analysis of the radiation propagation in systems both for the case of macroscopic channel and for the case of totally isotropic spatial structure, shows the presence of the main channeling mode (the main bound state) for any structure, whereas the high modes may be suppressed for specific channel sizes. Hence, nanotubes present a special interest as waveguides, which allow the supported modes to be governed. Moreover, there is a special interest in studying the dispersion of radiation in a nanosystem with a multilayered wall. As follows from the analysis of the general equation of radiation propagation considered above, at any correlation between the channel size and the interlayer distance at least one mode (bound state) should be formed in such a structure. In that case the diffraction of waves reflected from various layers of the channel wall should be observed, hence affecting the radiation distribution at the exit of system.

Evidently, the efficiency of these structures for applications have to be analyzed, despite the importance of the nanotube X-ray waveguide phenomenon from the fundamental point of view. The problems associated with X-ray and neutron channeling in capillary nanotubes (single- and multi-wall systems) present a special interest and will be analyzed in a subsequent paper.
IV. CONCLUSION

The reduction in the channel size of capillary structures, as well as the discovery of a new class of natural nanosystems - i.e. carbon nanotubes - puts the problem of passage of X-ray quanta through these systems on a new qualitative level.

In the present work the general unified theory, allowing us to describe processes of radiation passage through capillary systems in a wide range of channel diameters, is offered. Our analysis shows, that in the case of micron diameters the surface channeling of quanta presents in the mechanism of propagation (the part of radiation is distributed, being trapped by the bent surface of the channel), that can influence essentially the angular radiation distribution behind capillary systems. A decrease in size up to the nano-level results in a transition from surface channeling to bulk channeling. Thus, all radiation is involved in the process of the modal propagation, as opposed to the surface channeling when only part of the radiation is subject to the bound spreading.

Recently, it has been demonstrated that for specific cases a decrease in the angular divergence of X radiation after passing through capillary systems may be observed [34]. We have found strong differences between the observed and expected FWHM (full width at half maximum) values. From the general ray approach estimations, a FWHM value of at least $2\theta_c \approx 0.9^\circ$ for 4 keV synchrotron radiation photons is expected. This width exceeds both the experimental (FWHM$_{exp}$[4 keV] = 0.28°) and Gaussian fitted (FWHM$_G$[4 keV] = 0.22°) values. An analogous feature takes place also in the case of harder radiation. Such a behavior indicates an essential redistribution of radiation scattered inside the channels. The obtained discrepancy in experimental and theoretical results is not reproduced within the framework of the ray approximation and may be explained using the wave approach method, in order to describe the angular distribution of the reflected beam.

The discovery of a new class of ordered systems like nanostructures (fullerenes, nanotubes) opens up interesting opportunities for studying coherent effects of the radiation interacting with nanosystems. The interest is not limited to fundamental research, on the contrary, there
is a big potential for using the nanosystem samples, in order to develop new technological ideas (nanotube benders, nanosystem detectors, nanosystems as a source of electromagnetic radiation, nanotube undulators, etc.). For instance, recently new types of undulators for new generations of X-ray sources (FEL) have been studied, based on the manufacturing of a crystal undulator obtained by making a periodic series of micro trenches on the crystal surface (stripe distortion potential) [35], a research that which might result in the future creation of undulators based on nanostructures.

The main purpose of the present work is fundamental - i.e. to study the processes accompanying the X-ray transmission by capillary structures - in spite of the fact that capillary optics applications are covering larger and larger areas in X-ray physics and chemistry, biology and medicine. X-ray and neutron research activities over the last ten years demonstrated that capillary optics is a powerful instrument to guide neutral particle beams. Capillary/polycapillary optics can be applied in numerous branches of X-ray research, e.g. spectroscopy, fluorescence analysis, crystallography, imaging techniques, tomography, lithography, etc. [11].

**ACKNOWLEDGMENTS**

This work was partly supported by the NANO experiment of the Commissione Nazionale V of the Istituto Nazionale di Fisica Nucleare and by the Russian Federation Federal Program "Integration".
REFERENCES

[1] M.A. Kumakhov, and F.F. Komarov, Phys. Rep. 191., 289 (1990).

[2] P. Engström, S. Larsson, and A. Rindby, Nucl. Instr. Meth. A302, 547 (1991).

[3] D.J. Thiel, D.H. Bilderback, A. Lewis, and E.A. Stern, Nucl. Instr. Meth. A317, 597 (1992).

[4] E. Spiller, and A. Segmüller, Appl. Phys. Lett. 24, 60 (1974).

[5] A. Vinogradov, V. Kovalev, I. Kozhevnikov, and V. Pustovalov, Sov. Phys. - Tech. Phys. 30, 335 (1985).

[6] N.V. Smith, and M.R. Howells, Nucl. Instr. Meth. A347, 115 (1994).

[7] S.B. Dabagov, Research Report of FIROS for 1992 (Nalchik-Moscow, 1992) (in Russian).

[8] S.B. Dabagov, and M.A. Kumakhov, Proc. SPIE 2515, 124 (1995).

[9] Yu.M. Alexandrov, S.B. Dabagov, M.A. Kumakhov, et al., Nucl. Instr. Meth. B134, 174 (1998).

[10] J. Lindhard, Kgl. Dan. Vid. Selsk. Mat.-Fys. Medd. 34(14), 1 (1965).

[11] M.A. Kumakhov, Proc. SPIE 4155, 2 (2000).

[12] E. Burattini, and S.B. Dabagov, Nuovo Cimento B116, 361 (2001).

[13] R. Saito, G. Dresselhaus, M. S. Dresselhaus, ”Physical Properties of Carbon Nanotubes” (Imperial College Press, London, 1998).

[14] S.Iijima, Nature 354, 56 (1991).

[15] P.M. Ajayan, and S. Iijima, Nature 361, 333 (1993).

[16] S. Iijima, and T. Ichihashi, Nature 363, 603 (1993).

[17] N.K. Zhevago, and V.I. Glebov, Phys. Lett. A250, 360 (1998).
[18] G.V. Dedkov, Nucl. Instr. Meth. **B143**, 584 (1998).

[19] S. Iijima, Appl. Phys. Lett. **80**, 2973 (2002).

[20] M. Bockrath, et al., Nature **397**, 598 (1999); Z. Yao, et al., Nature **402**, 273 (1999); S. Bellucci and J. Gonzalez, Eur. Phys. J. B **18**, 3 (2000); ibid. Phys. Rev. B **64**, 201106 (2001) (Rapid Comm.), cond-mat/0103558; A. Yu. Kasumov, et al., Science **284**, 1508 (1999); M. Kociak, et al., Phys. Rev. Lett. **86**, 2416 (2001)

[21] T.W. Ebbesen, Phys. Today, **49**, 26 (1996).

[22] Z.Y. Wu, J. Zhang, K. Ibrahim, et al., Appl. Phys. Lett. **80**, 2973 (2002).

[23] S. Bellucci, S. Botti, Z.Y. Wu, et al., "X-ray absorption near-edge structure study of carbon nanotubes grown without catalyst", Europhys. Lett. (submitted).

[24] S. Bellucci, V.M. Biryukov, Yu.A. Chesnokov, et al., "Channeling Of High Energy Beams In Nanotubes", Nucl. Instr. and Methods (to be published), presented at the COSIRES conference in Dresden, Germany, June 23-27, 2002, physics/0208081.

[25] V.M. Biryukov and S. Bellucci, "Nanotube diameter optimal for channeling of high-energy particle beam", Phys. Lett. B **542**, 111 (2002), physics/0205023.

[26] S.B. Dabagov, M.A. Kumakhov, S.V. Nikitina, et al., J. Synchrotron Rad. **2**, 132 (1995).

[27] N. Artemiev, A. Artemiev, V. Kohn, and N. Smolyakov, Phys. Scripta **57**, 228 (1998).

[28] S.B. Dabagov, and A. Marcelli, Appl. Opt. **38**, 7494 (1999).

[29] S.V. Kukhlevsky, F. Flora, A. Marmai, et al., Nucl. Instr. Meth. **B168**, 276 (2000).

[30] S.B. Dabagov, V.A. Murashova, N.L. Svyatoslavsky, et al., Proc. SPIE. **3444**, 486 (1998).

[31] S.B. Dabagov, A. Marcelli, V.A. Murashova, et al., Appl. Opt. **39**, 3338 (2000).

[32] Chien Liu, and J.A. Golovchenko, Phys. Rev. Lett., **79**, 788 (1997).
[33] S.B. Dabagov, A. Marcelli, V.A. Murashova, et al., Proc. SPIE 4138, 79 (2000).

[34] G. Cappuccio, S.B. Dabagov, C. Gramaccioni, and A. Pifferi, Appl. Phys. Lett. 78, 2822 (2001).

[35] S. Bellucci, S. Bini, V.M. Biryukov, et al., "Experimental Study For The Feasibility Of A Crystalline Undulator", Phys. Rev. Lett. (submitted), physics/0208028.
Figure captions

Figure 1: The change of the interaction potential between the flat surface (A.) and the curved one (B.). For simplicity, in calculations the real potential (B.) may be replaced by the model potential (C.).

Figure 2: Illustration of X-ray reflection from the inner capillary surface. At glancing angles $\theta$, when the cross size of a beam $\delta_i(\theta)$ becomes comparable with the transverse wavelength $\lambda_\perp(\theta)$, the radiation is grasped in a mode of surface channeling.

Figure 3: The radial distributions of the main bound mode of radiation inside a capillary channel for various channel diameters. The decrease of diameter ($2r_0$) results in a spatial displacement of the distribution away from the channel wall towards the center. The wall surface position is shown by the dotted line.

Figure 4: The typical radial wave function distribution for a periodic multilayer waveguide, where $d$ is the distance between the layers composing a waveguide wall.
A. flat surface

B. curved surface

C. model.
wave intensity, arb. un.

arbitrary radial distance

$|u_0(x)|^2$

$r_1 > r_2$

$r_1$

$r_2$
