Available online at www.sciencedirect.com
ScienceDirect
Nuclear Instruments and Methods in Physics Research B 266 (2008) 3881–3887
NIM B
Beam Interactions with Materials & Atoms
www.elsevier.com/locate/nimb

On X-ray channeling in narrow guides

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Received 18 December 2007; received in revised form 17 March 2008
Available online 11 April 2008

Abstract

The fine features of X-ray propagation both in an ultra-narrow collimator and at glancing reflection from a smooth surface can be described within the unified theory of trapped radiation propagation: surface channeling in μ-guides and bulk channeling in submicron/nano-guides.
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PACS: 41.50.+h; 42.82.Et; 61.85.+p; 68.49.Uv

Keywords: X-ray waveguide; X-ray channeling; Capillary optics; Nanostructure

1. Introduction

Manipulation of matter on the atomic scale, i.e. nanotechnologies, requires new technological solutions. One of the potential tools is to use the radiation at X-ray frequencies. Advantages in both the fields of nanotechnology and X-ray propagation are mutually beneficial. For instance, the use of specially designed systems formed by nanochannels (n-channels; below in the text we use n- for nano- and μ- for micro-), like the bundles of nanotubes, porous media or artificial nanoholes, represents a great interest; X-ray propagation in n-channels is important due to the potential applications in X-ray optics. The basic feature of these structures is the presence of a hollow inner cavity, which might act as a channel for selective radiation penetration, similar to channeling of charged particles in crystals (see [1] and references therein); in this context, n-channels are similar to μ-capillaries that are in wide use as X-ray optical elements (the base of capillary/polycapillary optical elements [2]). However, diminishing the capillary internal radius from microns to nanometers results in a qualitative change of the radiation transmission character, i.e. from the surface channeling in μ-capillaries ("whispering modes") down to the bulk channeling in n-capillaries ("waveguide modes"). As shown previously in a number of papers in the both cases we deal with the trapped radiation propagation, and the correct description is based on the solution of wave equation. In the case of μ-capillaries the problem can be resolved partially by means of the ray optics approximation for the angles less than the Fresnel angle $\vartheta_c = \omega_p/\omega$ (ω is the photon energy, $\omega_p = \sqrt{4\pi n_e e^2/m_0}$ is the plasmon energy, n_e is the electron density of the cladding, and e and m_0 are the electron charge and mass, respectively[1]), but exceeding a specific angle, starting from which the wave features of radiation propagation have to be taken into account.

Below the results on coherent scattering of X radiation in μ- and n-structures and on X-ray channeling in hollow channels of various origins [3] will be presented.

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[1] Below we use the units with $\hbar = c = 1$.

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doi:10.1016/j.nimb.2008.03.238

2. Channeling formalism for X-rays

The main criterion for observing the wave features of radiation propagation in media is very simple – the transverse space where radiation is limited at propagation (no matter for either a profiled surface or a specific collimation system) should approach in size the transverse radiation wavelength: $X_{\perp} \simeq \lambda_{\perp}$, where $\lambda_{\perp} \simeq \lambda/\vartheta_{\mathrm{c}}$. For X-ray frequencies, at reflection from a flat surface (optimally, we deal with the total external reflection) as well as at X-ray propagation in a planar waveguide, the transverse dimension of a beam can be estimated as $X_{\perp} \simeq L\vartheta_{\mathrm{c}}$ (the length L is refereed to the single reflection distance); and thus we get a very simple and important expression that allows the limits for revealing the wave features at reflection to be evaluated

$$L\vartheta_{\mathrm{c}}^{2} \simeq \lambda \tag{1}$$

This makes evident why even at radiation propagation in μ-channels it is possible to observe the wave features. This relation will be examined below in detail from the viewpoint of both the wave equation solution and of the simple physical base of the phenomenon.

The modes of radiation propagation in a waveguide are revealed at interference between the incident and reflected waves forming a standing wave pattern [4]. However, it becomes constructive just for specific angles. This phenomenon, valid for reflection from a flat surface, takes place just in the vicinity of the surface. Similar phenomena can be observed at radiation reflection from a curved surface (so called "whispering modes") [5]. Strong radiation redistribution also takes place behind capillary systems (which is actually a simple example of the curved surface system); some structural features in the distribution are due to the spatial geometry of the system (typically, hexagon type in the transverse cross section). However, some fine features could not be interpreted by ray optics, and require solution of the wave equation of radiation propagation.

The history of interference phenomena observed for X-rays, from various sources, propagating in capillary structures amounts to more than 10 years. It starts from the first theoretical note regarding such a possibility for capillary optical systems [6] that was later experimentally proved [7] and supported by the phenomenology proposed [8]. The latter has shown that the fine features of X-ray propagation in μ-size channels, which have been observed behind capillary structures, can be explained in view of the radiation interference due to the various channels' curvatures. Later the trapped radiation propagation in the very vicinity of a surface was carefully studied in a number of papers [9–14] where the wave theory of X radiation propagation along a curved surface was developed (for complete citation, see references in [1]).

Regardless of the research on radiation transmission by capillary systems, which represent circular guide systems, nowadays considerable progress in studying X-ray waveguiding in planar structures (as specially fabricated waveguides consisting of the guiding and cladding layers, or ultra-narrow slits and collimators with air gap, etc.) is achieved [15–23].

The passage of X radiation through the guides is mainly defined by its interaction with the inner guide walls. In the ideal case, when the boundary between hollow channels 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 the structures of ultra-small holes of various shapes can be evaluated from solution of the Helmholtz equation. In the first order approximation, propagation of X radiation through specially designed guides, the cladding material of which is characterized by the refractive index $n = 1 - \delta(\mathbf{r}) + \mathrm{i}\beta(\mathbf{r})$ defining the guide geometry, is described by a wave propagation equation

$$(\mathbf{\Delta} + k^{2}n^{2}(\mathbf{r}))E(\mathbf{r}) = 0,\ n \equiv \begin{cases} 1, & \text{hollow core} \\ n_{0} = 1 - \delta_{0} + \mathrm{i}\beta_{0}, & \text{cladding} \end{cases} \tag{2}$$

for the electromagnetic field amplitude E, where $\mathbf{k} \equiv (k_{\parallel}, k_{\perp})$ is the wave vector of radiation, $k = 2\pi/\lambda$, $\mathbf{\Delta} \equiv \partial^{2}/\partial\mathbf{r}_{\perp}^{2} + \partial^{2}/\partial z^{2}$ is the Laplacian, $\mathbf{r} \equiv (\mathbf{r}_{\perp}, z)$. Separating a transverse part of the radiation field as $E(\mathbf{r}) = E(\mathbf{r}_{\perp})\mathrm{e}^{\mathrm{i}k_{\parallel}z}$ and neglecting absorption ($|\delta| \ll 1$, $|\beta| \ll 1$, $|\beta| \ll |\delta|$), the Helmholtz equation can be reduced to

$$[\mathbf{\Delta}_{\perp} - (2k^{2}\delta - k_{\perp}^{2})]E(\mathbf{r}_{\perp}) = 0, \tag{3}$$

where the right side term in brackets is a potential of interaction V_{eff}. Due to the fact that the transverse wave vector $k_{\perp} \approx k\vartheta$ under the grazing wave incidence ($\vartheta \ll 1$), an effective interaction potential is estimated by the expression

$$V_{\mathrm{eff}}(\mathbf{r}_{\perp}) = k^{2}(2\delta(\mathbf{r}_{\perp}) - \vartheta^{2}) = \begin{cases} -k^{2}\vartheta^{2}, & \text{guiding channel} \\ k^{2}(2\delta_{0} - \vartheta^{2}), & \text{cladding} \end{cases} \tag{4}$$

From the latter the phenomenon of total external reflection at $V_{\mathrm{eff}} = 0$ follows, when $\vartheta \equiv \vartheta_{\mathrm{c}} \simeq \sqrt{2\delta_{0}}$. One can see that Eq. (3) corresponds to the Schrödinger equation for a particle of mass $k^{2}/2$ and kinetic energy ϑ^{2}. We have used below the terminology of "channeling" [24], where a channel is formed by the effective potential of radiation interaction in a guide (a quantum well). The phenomenon is similar to channeling of small-divergent beam of charged particles traversing crystals near the main crystallographic planes or axes at angles less than the critical one $\varphi_{\mathrm{L}} \simeq \sqrt{V/\varepsilon}$, the Lindhard angle ($\varepsilon$ is the projectile energy).

As is well known from quantum mechanics, any well supports at least one quantum bound state (channeling state); the number of bound states can be estimated from the expression for the potential (4). Eq. (3) for radiation propagation in a medium with the potential (4) can be solved for the case of μ-guides as well as for the n-guides.

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