Transition radiation in multilayer nanostructures as a medical source of hard-X-ray radiation

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Abstract: We show that periodic nanostructure made of alternating layers of Ag and Mo can serve as an efficient source of hard X-ray transition radiation for medical applications, which uses low energy electrons.

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One of the promising hard-X-rays medical applications is a so called bi-chromatic X-ray contrast diagnostics [1] whereby the absorption edge of a dye of interest is "bracketed" by two (usually very broad) bands of radiation. The X-ray source for that application explored so far was synchrotron radiation of a large accelerator, which makes it impractical for wider use. To make it compact and practical, one needs to develop an X-ray source with narrow radiation lines of higher brightness and much lower electron energy of an accelerator. An ideal way to go would be the narrow-line resonant transition radiation (TR) of electrons traversing a multilayer solid-state structure, proposed in [2]. Since the main domain of interest is hard X-ray beyond e. g. 20 KeV, the only effect that may provide any noticeable contrast of refractive index between layers, is the narrow-line change of refractive index in the close vicinity of absorption lines (so called atomic edges) of *K*, *L*, or *M* shells of one of the alternating layer elements (the so called *radiator* [2]).

We report on results of research efforts aimed at developing a new X-ray source using low-energy electrons. The starting point is our earlier work [2], which has theoretically demonstrated feasibility of generating intense X-ray TR by few-MeV electrons traversing solid multilayer structures. The most dramatic difference of those results from the main body of work on X-ray TR is the possibility to use electron beams of 5-10 MeV energy to generate X-rays in 30-50 KeV range, whereas the conventional technology based on foil stacks needs electron energy three orders of magnitude higher. As a result, widely available and relatively inexpensive industrial and medical electron accelerators could be used instead of electron synchrotrons of the national-facility kind, and can be thus developed into practical, low-cost sources of X-rays for numerous applications.

The requirement of sufficiently hard X-rays suggests relatively heavy atoms with respectively high *K*-shells as the choice for a *radiator*. Currently the most used element for a dye is *Iodine* for which we identified several "bracketing" radiator elements. We aimed to design a future experiment, thus, for our calculations we have chosen as a radiator an element widely used in the X-ray technology (e. g. for X-ray and EUV mirrors), whose properties are well known and which is readily available, *Molybdenum*, ($Z = 42$), and which has *K*-shell at ≈ 20 KeV. Our original approach in [2] aimed mostly at soft X-ray domain, and it was based on choosing the layer of heavy atoms as "radiator" with a chosen *K*-shell transition, and the layer of light atoms as a neutral "spacer". However, during our detailed calculations we realized that the above approach is good in the soft X-ray domain, but it does not produce desirable results in the hard X-ray domain. The major drawback is that in the $20 - 50$ KeV X-ray domain the TR spectrum with such pairs shows a spectral *dip* at the chosen *K*-shell, instead of spectral *peak*. Our search through the elements in periodical table and spectral data for each one of them, resulted in locating a few candidates of spacers for any given "radiator" to produce strongly pronounced resonant *peak* of TR with the contrast better than two orders of magnitude. Surprisingly enough, these new spacer candidates as a rule are *heavier* than the radiator. One of the criteria/stipulation on these candidates is that they have to be technologically viable and accessible, which narrows down the field of candidates, but still leaves at lest two candidates for each radiator element. As our calculations show, by far the most efficient spacer for Mo radiator is Ag. Thus, we consider a periodic nanostructure, composed of alternating Ag and Mo layers, bombarded by electrons of $E_0 = 30$ MeV energy. TR differential efficiency at the

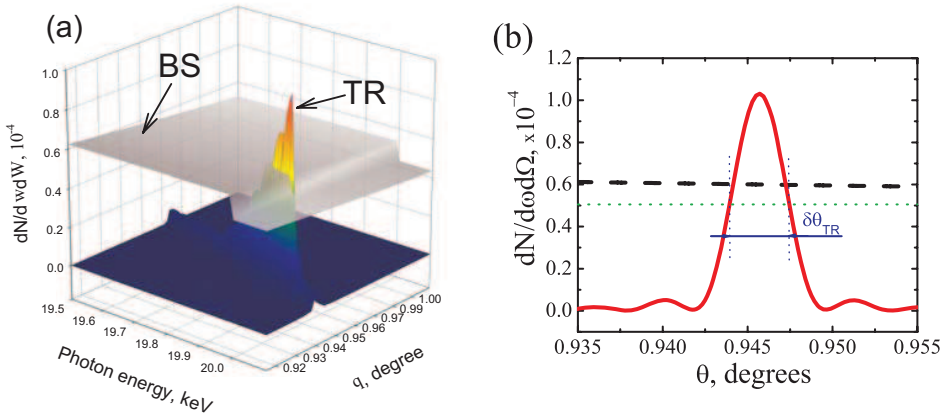

Fig. 1. a) Bremsstrahlung (BS) and transition radiation (TR) radiation efficiency in number of photons per 1 eV per steradian per electron for 250-period Ag-Mo nanostructure in the photon energy range around the K-shell photoabsorption edge of Mo (b) TR (solid) BS (dashed line) radiation efficiency at 20 keV photon energy in number of photons per 1 eV per steradian per electron for 250-period Ag/Mo nanostructure. Dotted line marks the half-maximum

first mode for the M-period structure (each period has one Ag and one Mo layer of equal width) can be calculated as [2]

$$\frac{d^2N}{d\omega d\Omega} = \frac{4\alpha(\beta\Delta\epsilon)^2}{\pi^2\omega}|G|^2 e^{-(M-1)(\sigma+\rho)}\frac{\cosh\left(M(\sigma-\rho)\right)-\cos\left(2MX\right)}{\cosh\left(\sigma-\rho\right)-\cos\left(2X\right)}, \sigma = \frac{(\mu_{Ag}+\mu_{Mo})l}{4\cos\theta},\ \rho = \frac{l}{2L_{cr}}, \qquad (1)$$

l is the period of the structure, $\alpha = 1/137$ is the fine structure constant, μ is the absorption coefficient, G is the radiation pattern for single interface, X is a half-phase difference between the periods [2], $\bar{\epsilon}^{1/2} = (\sqrt{\epsilon_{Ag}} + \sqrt{\epsilon_{Mo}})/2$ is the average square root of the dielectric constant of the nanostructure materials, $\Delta\epsilon = \epsilon_{Ag} - \epsilon_{Mo}$, θ is the emission angle, $\beta = v/c$, v is electron velocity, c is the velocity of light. Parameter L_{cr} characterizes losses due to electron-atom collisions. For the Ag-Mo nanostructure $L_{cr} \approx 1.7cm$ [2] and it is several orders of magnitude larger than the photoabsorption length in the energy range under the study (proximity of K-shell photoabsorption edge of Mo). Optimized with respect to TR intensity period of the nanostructure $l \approx 221nm$ and the resonant angle $\theta_{TR} \approx 16.51mrad \approx 0.9457°$ [2].

As our investigation shows, at such a high energies of photons and electrons one of the most important factors in attaining an efficient source of resonant TR based on atomic absorption edges, becomes filtering out the Bremsstrahlung (BS) radiation. In the soft X-ray domain BS is significantly weaker than TR, whereas for hard X-ray it should be taken into account. We calculate BS differential efficiency in the Born approximation with screening taken into account in accordance with the Thomas-Fermi model[3].

Figure 1a shows the calculated differential efficiency of TR and BS for 250-period Ag-Mo nanostructures in the photon energy range around the K-shell photoabsorption edge of Mo. One can see clearly the strongly pronounced resonant TR line, with contrast between the wings and the center easily reaching two orders of magnitude. Once again, those calculations include everything: the varying with the frequency attenuation of radiation, density of materials, etc. However, the contribution of BS radiation is significant and one has to use very high angular selectivity and coherence of transition radiation and use strong spatial filtering. For instance, the radiated photons could be detected through a pinhole, opening a small solid angle around the TR peak. Radiation efficiency of BS and diameter of a circular pinhole, suitable for experimental observation of TR, would be $d = R\delta\theta_{TR}$, where $\delta_{TR} \approx 6.1 \cdot 10^{-5}$ rad and R is the distance from the Ag-Mo structure to the pinhole (see also Fig. 1b). For example, if $R = 200$ cm the diameter of the pinhole $d \approx 0.012$ cm. Thus, calculations done by us for the Mo/Ag couple at 20 KeV show that the TR-line can be well resolved when both spatial and spectral filtering is used.

References

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