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X-RAY RADIATION SOURCE FOR LOW DOSE ANGIOGRAPHY BASED ON CHANNELING RADIATION

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Abstract

Angiography is one of the most reliable and contemporary procedures of the vascular system imaging. X-ray spectrums provided by all modern medical angiographs are too broad to acquire high contrast images and provide low radiation dose at the same time. The new method of achieving the narrow X-ray spectrum is based on the idea of channelling radiation application. The X-ray filters used in this method allows eliminating the high energy part of the spectrum and provides dramatic dose reduction. The scheme of the facility including the X-ray filter is discussed. The results of the spectrum analysis for the channelling radiation source and typical angiography X-ray tube are discussed. Doses obtained by the water phantom and contrast of the iodine agent image are also shown for both cases.

INTRODUCTION

The angiography nowadays is the state of the art medical imaging technique used to visualize the inside, or lumen, of blood vessels and organs of the body, with particular interest in the arteries, veins and the heart chambers. X-ray sources in angiography applications are based on X-ray tubes. These sources are well explored and provide high rates of radiation intensity. The main drawback of the tube is wide bandwidth of the generated radiation spectrum. Monochromatic radiation source application can result in better imaging, and, moreover, lower irradiation dose can be applied to a patient.

Large scale accelerators as synchrotrons, storage rings, energy recovery accelerators or LINACs can be only used to produce synchrotron and undulator radiations [1]. Compton scattering requires comparatively smaller accelerator but high power laser and high accuracy control system are strongly requested [2]. Very high CW currents up to tens of Amperes are necessary to excite the characteristic X-ray of La or Ba emitters having considerable photon flux [3]. Channeling radiation source, one of the most powerful radiation emitters by relativistic electrons in crystals is discussed below as a possible alternative of these techniques [4].

For the angiography and radiography procedure one needs a conventional total flux of $2\cdot10^7$-$2\cdot10^9$ photons/(mm^2·s) and irradiated area about 43x43 cm^2 [5]. The lower end of photon energy is estimated as 33.2 keV for angiography (the key energy to hit the peak value of iodine contrast mass attenuation). The X-ray monochromatic peak energy can be varied by means of the metal of crystal target variation of electron beam energy tuning. Standard therapy linac produced by one of the leading manufacturers can be used. Incoherent bremsstrahlung in a crystal is a serious problem that results in rather high irradiation dose. Any solution to suppress it is strongly desirable.

X-RAY SOURCE SCHEME

The monochromatic X-ray source based on the channeling radiation generated by the electrons moving inside the oriented crystals is discussed [6]. The principal scheme of the source is presented on the Figure 1. The electron beam (2) is generated in the electron source (1) and accelerated to ultra-relativistic energies in the LINAC (3) that is not considered in the work. After that electrons pass through the aligned crystal (4) placed inside the goniometer (12) and generated the monochromatic channeling X-ray radiation and broadband bremsstrahlung. The deflecting magnet (5) is used to lead the electron beam to the beam dump (11). The X-ray pass through the polycapillary optics (10) and the radiation with energy lower that 40 keV (9) is filtered and deflected to the patient (7), the rest of the radiation is propagated straightforward to the X-ray dump (6). The radiation is then detected with the panel detector (8). The electron beam deflection is done in order to eliminate the possibility of the polycalillary optics damage. The scheme of using the polycapillary optics allows fixing the main problem of such a facility – broadband bremsstrahlung spectrum that leads to unnecessary dose enhancement that is obtained by the patient. The policapillary optics is the most reliable for filtering of the high energy X-ray radiation. The possible filters are listed in the Table 1.

Table 1: Efficiency of the X-ray Transmission by Optics.

X-ray optics type	X-ray energy	
	17 keV	33 keV
Mosaic crystal	58	4.2
Log spiral reflector	35	0.04
Grazing incidence reflector	10	~0
Multilayer mirror	57	10
Polycapillary optics	60	40

RADIATION FROM CRYSTALL

The channeling is the process of the electron movement inside the crystal between the crystallographic planes (in case of the planar channeling) or near the crystallographic axis (in case of the axial channeling). We investigated the planar channeling in the crystal along the <110> plane of the diamond (Figure 2). The electron dynamics in the crystal is evaluated using the BEAMDULAC-CR [7].

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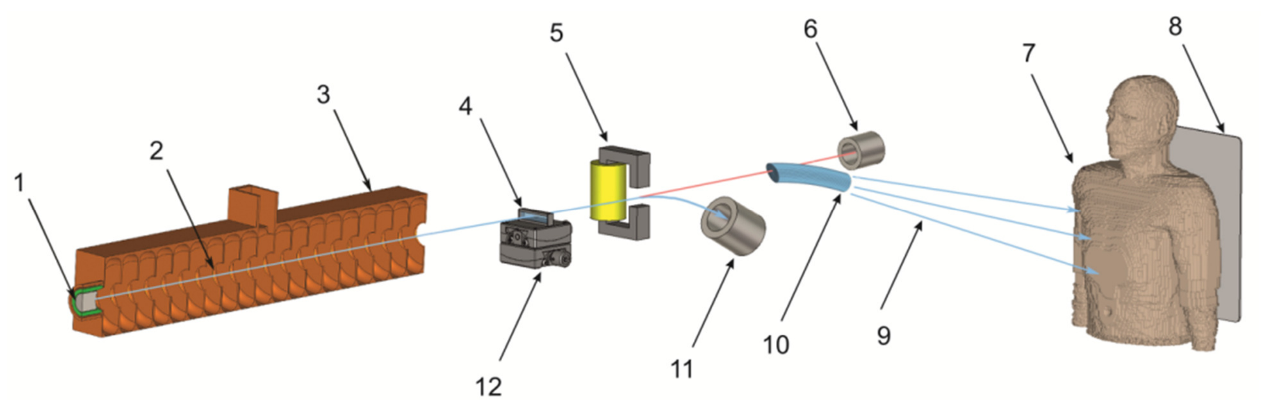

Figure 1: Principal scheme of monocrystal and polycapillary optics based X-ray source.

The investigation is held using the classical approach of the electron propagation in the transverse potential field inside the crystal [6].

Acquired spectrums of the channeling radiation from BEAMDULAC-CR are shown on the Figure 3. The photons number is based on the 10^{12} electrons in the single bunch and the diamond plate thickness of 55 µm. The graphs were evaluated for the 21 and 23 MeV electron energy and correspond to the energy spectrum of the main harmonics 33±2.4 keV (21 MeV) and 37±2.9 keV (23 MeV). The electrons dynamics in the crystal also shows that electron beam should have the divergence around 10 mrad and energy spectrum of $\Delta E/E$=1% in order to eliminate the dechanneling (travelling of the electrons from one channel to another) of the electrons. The angular distribution of the emitted radiation has narrow peak at 0 degrees relative to electron beam direction. The angular distribution is characterized by the FWHM value of 2 degrees. The acquired angular dependence reveals the theoretical proportionality of the bremsstrahlung cone opening $\theta \sim \gamma^{-1}$, where γ is the Lorentz factor of the initial electron beam.

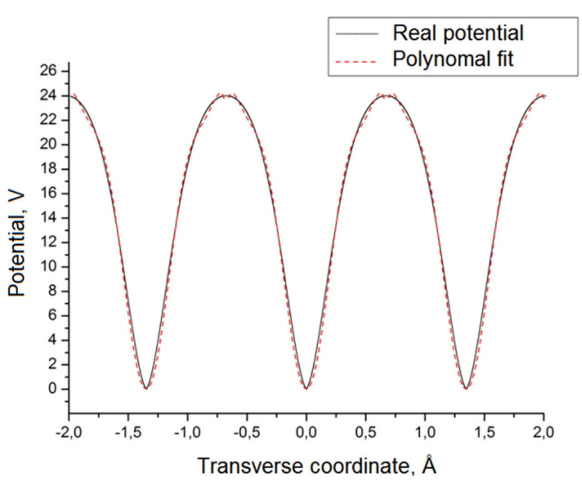

Figure 2: Potential distribution along <110> diamond crystallographic plane.

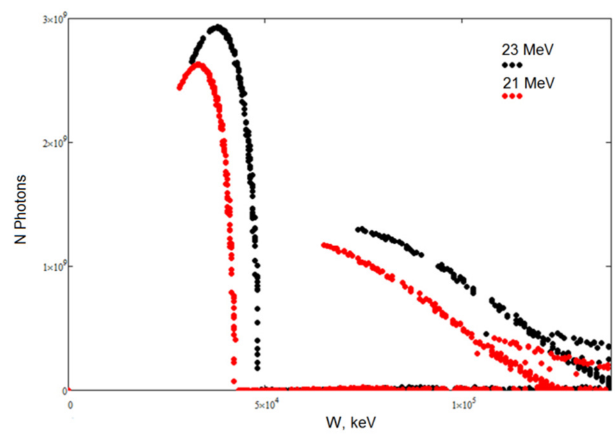

Figure 3: Spectrum of the channeling radiation.

DOSES AND CONTRAST CALCULATIONS

For estimation of the absorbed doses and image contrast the X-ray radiation attenuation in the tissue-equivalent phantom was investigated via the Beer-Lambert law. The phantom represents the water cube with the 30 cm edge and a cylindrical cavity with 1 mm diameter containing the 10 % iodine contrast agent. The photons number was calculated via the probability density curves shown on the Figure 4 using 10^{12} electrons in pulse.

The bremsstrahlung X-ray radiation generation process was investigated applying the Monte Carlo based code PyPENELOPE. The analyzed target is presented by the 55 µm thick diamond target with 3.5 g/cm^3 carbon density irradiated by the 21 and 23 MeV electron beam correspondingly.

The acquired data is presented in the form of photon emission probability (Fig. 4). The data shows that emitted bremsstrahlung X-ray radiation has broad energy spectrum with maximum intensity at the energy around 4.5 keV. Bremsstrahlung band starts from energy lower than 1 keV and spreads up to the electron beam energy.

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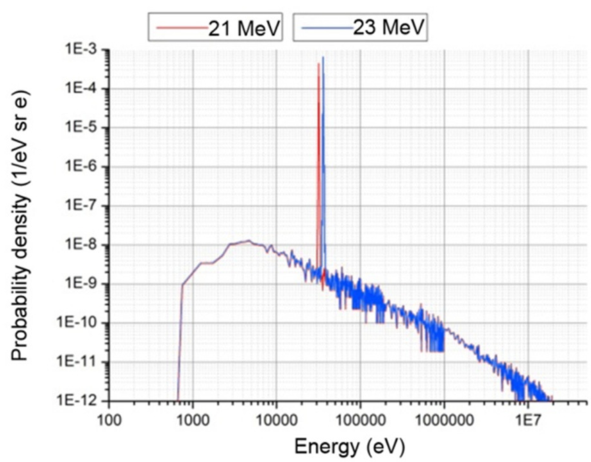

Figure 4: X-ray spectrum including the bremsstrahlung.

The image contrast will be investigated as a cylindrical cavity visibility against the background of the radiation passed through the water cube. So the contrast will be the value of the energy passed through the water vs. the energy passed through the water and iodine ratio.

Radiation energy that passed through the medium and absorbed energy together with absorbed doses rates are defined by equatios:

$$I_{pas} = \sum_{W_i} K \cdot I(W_i) \cdot W_i \cdot e^{-\mu/\rho(W_i)\cdot\rho\cdot l},$$
$$I_{abs} = \sum_{W_i} K \cdot I(W_i) \cdot W_i \cdot \left(1 - e^{-\mu/\rho(W_i)\cdot\rho\cdot l}\right), \quad (1)$$
$$D = \frac{\sum_{W_i} K \cdot I(W_i) \cdot W_i \cdot \left(1 - e^{-\mu/\rho(W_i)\cdot\rho\cdot l}\right)}{M},$$

where K – number of electron from the source, W_i – photon energy, $I(W_i)$ – possibility density of the electron emission, $\mu/\rho(W_i)$ – medium absorption coefficient (Fig. 5), ρ – medium density, l – radiation path in the irradiated object, M – irradiated object mass.

Polycapillary optics employment in case of 21 MeV channeling radiation source allows reducing dose acquired by the phantom 54 times vs. the generation system without optics and gives $4.3\cdot10^{-5}$ Sv with $2.28\cdot10^{11}$ photons. Analogous system with 23 MeV electron source gives 30 times energy reduction and gives $8.1\cdot10^{-5}$ Sv with $3.78\cdot10^{11}$ photons. The conventional 100 keV X-ray tube with W-Re anode provides $5.6\cdot10^{-6}$ Sv at $2.2\cdot10^{10}$ photons.

The contrast of iodine-filled cavity measured in these three cases shows that the 23 MeV channeling radiation source gives 3 times higher contrast image of the cavity than the conventional X-ray tube. The 21 MeV channeling source provides lower contrast of the iodine-filled cavity (0.8 of the X-ray tube image contrast) because the maximum channeling intensity peak of the radiation lies in the area of small iodine attenuation coefficients.

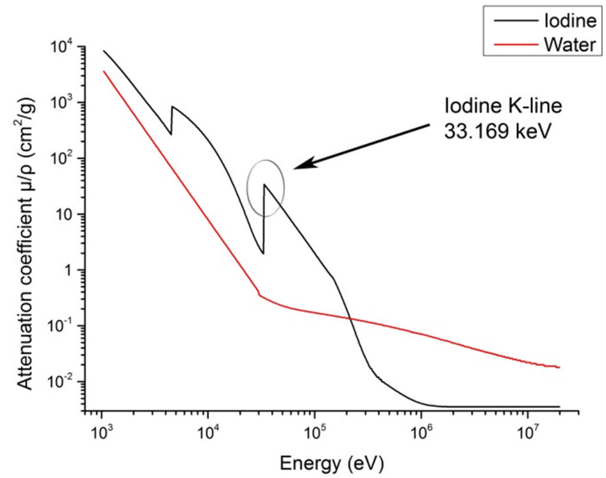

Figure 5: Mass attenuation coefficients used for doses and contrast calculations.

CONCLUSION

Principle of X-ray generation using the electron channelling through the crystal was considered. Possibility of utilizing the principle of electron channelling radiation in crystals for generating X-ray radiation was investigated. One of the possible applications of obtained X-ray radiation – angiography was discussed. Principal scheme of the estimated facility has been presented.

The presented X-ray source can provide 3 times higher contrast of the image than conventional 100 keV X-ray tube using the 23 MeV beam and 55 microns diamond plate. The polycapillary optics used the source effectively filters all the high energy X-ray radiation and transmits channeling X-ray with 40% efficiency.

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