ANGIOGRAPHY X-RAY MONOCHROMATIC SOURCE BASED ON RADIATION FROM CRYSTALS

Yu.A. Bashmakov, Lebedev Physical Institute of RAS (LPI), Moscow, Russia and National Research Nuclear University (MEPhI), Moscow, Russia
T.V. Bondarenko, Siemens LLC, Moscow, Russia and National Research Nuclear University (MEPhI), Moscow, Russia
S.M. Polozov, National Research Nuclear University (MEPhI), Moscow, Russia
G.B. Sharkov, Siemens LLC, Moscow, Russia

Abstract

Nowadays angiography has become one of the most commonly used medical procedures. However the X-ray tubes are mostly used in angiography imaging systems. The problem that encounters in using X-ray tubes is low monochromaticity due to bremsstrahlung while angiography imaging requires quasimonochromatic energy spectrum for better image quality and lower dose rate obtained by the patient. The use of the monocrystaline target at the medical electron LINAC can be one of the possible ways to obtain the monochromatic X-ray radiation. This type of X-ray generator will provide monochromatic radiation with photon energy dependent on the electron beam energy. The X-ray generation mechanism, possibilities of monocrystal usage as an X-ray source for angiography and requirements for beam parameters are discussed.

INTRODUCTION

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. This method is traditionally done by injecting a radio-opaque contrast agent into the blood vessel and imaging using X-ray based techniques.

X-ray sources in angiography applications are based on X-ray tubes. These sources are well explored and provide high rates of radiation intensity. In X-ray tubes the source of the radiation is tungsten rotating anode that is irradiated by the electron beam from the thermal cathode. The main drawback of the tube is wide bandwidth of the generated radiation spectrum provided by two principles: fluorescence and bremsstrahlung. The low energetic part of the X-ray is cut-away by the alumina or beryllium filter.

Angiography principle lies in using a contrast medium that allows to clearly identify the agent in the patient body. A medical contrast medium is a substance used to enhance the contrast of structures because of the high rates of mass attenuation coefficient for X-ray radiation in specific narrowband peak e.g.: at 33.1 keV for iodine contrasts, 37.4 keV for barium and 50.2 keV for gadolinium. All bands of radiation spectrum from X-ray tube that differs from the agent attenuation energy peak penetrating patient is less attenuated by the contrast agent and therefore will degrade the clearness of the contrasted part of the image and leads to the unnecessary high dose rate delivered to the patient.

There are several methods of eliminating undesirable spectrum parts of the radiation. The most widespread is usage of X-ray tubes with filters like beryllium windows to suppress the low energy spectrum part that is absorbed in the skin and is the most harmful for the patient. Another method lies in the utilization of X-ray fluorescence method: radiation obtained from the X-ray tube illuminates the fluorescent target and irradiates the characteristic lines. The disadvantage of this method is low level of radiation intensity [1].

Another idea is based on using of the inversed Compton scattering principle. The light beam from the laser is counter-propagated against an electron beam produced by a linear accelerator. X-ray photons are generated by inverse Compton scattering that occurs as a consequence of the "collision" that occurs between the electron beam and IR photons generated by the laser. The disadvantage of this method is concerned in necessity for terawatt laser pulses with ps duration [2].

CHANNELLING RADIATION

The method of obtaining of the narrow-band X-rays lies in utilizing the principle of so called channeling radiation from crystals [3].

Channeling radiation is emitted by relativistic electrons passing through single crystals along a direction of high symmetry. The radiation is forward directed into a narrow cone with an angle of emission $\Theta\sim\gamma^{-1}$.

There are two different types of channeling dependent on the electron track – axis channeling and planar channeling. In the first case electron captured in the channel is moving along the crystal axis and experience the influence of the axially-symmetrical coulomb field of the crystal axis. In the planar channeling the particle is forced by the fields of the atoms situated on the crystalline plane.

The mechanism of channeling radiation can be described in two principal ways: classical physics model and quantum mechanics.

Electrical field formed between the crystallographic planes forming the channel can be characterized with an averaged potential $U(x)$ where x is transversal offset from the channel central plane. As a rule $U(x)$ is smooth,

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even and periodical function with period of $2d$: $U(-x)=U(x)$, $U(x+2dk)=U(x)$, where $2d$ is the channel width, k - integer number. Potential value on the border of the channel can be labeled as $U(|x|=d)=U_0$. Potential describing the electron channeling phenomenon is often called "reversed parabola" [4]. With fine accuracy it can be expressed as follows:

$$U(x)=U_0\left(2\frac{x^2}{d^2}-\frac{x^4}{d^4}\right),\quad |x|\le d \qquad (1)$$

In this field the particle with charge *e,* energy ε and rest mass of m perform small transversal harmonic oscillations relative to channel central plane. The magnitude of the oscillations is much less then channel width ($x_m << d$) and the period of the oscillations can be expressed as:

$$\Omega_n=\sqrt{2}\Omega_0,\quad \Omega_0=\frac{c}{d}\sqrt{\frac{2eU_0}{\varepsilon}}, \qquad (2)$$

here $\gamma=\varepsilon/mc^2=(1-\beta^2)^{-1/2}$ is reduced particle energy, $\beta=v/c$, v - particle velocity. It is obvious that the frequency of transversal oscillations is reduced with energy gain as $\sim\gamma^{-1/2}$ [5, 6].

Let us mention that the frequency of large transversal oscillations $x_m\sim d$ depends on their amplitude. Therewith in particle motion Fourier harmonic expansion appears higher harmonics of the fundamental frequency and the particles motion becomes anharmonic. This fact is significant for investigation of the radiation spectral characteristics

Radiation frequency of *k*-harmonic propagating with angle θ to the central plane of the channel in dipole approximation for ultra-relativistic motion ($\gamma>>1$) can be written as:

$$\omega_k=\frac{2k\Omega\gamma^2}{1+\theta^2\gamma^2},\quad (\theta<<1,\ \gamma>>1) \qquad (3)$$

Radiation frequency achieves its maximum at the zero angle: $\omega_k=2k\Omega\gamma^2$.

Based on mentioned equations maximum energy for 9 MeV electron channeling relative to (110) plane of the diamond crystal estimation value of the radiated X-ray photons can be obtained. For this case maximum value appears to be $\hbar\omega=5.90\,\mathrm{keV}$ that qualitatively matches with experimental results [7].

Power of radiation losses of electron due to channeling radiation is defined by the equation:

$$P=\frac{2e^4<E^2>\gamma^2}{3m^2c}, \qquad (4)$$

here $<E^2>$ is the mean square of electrical field along the particle trajectory.

ANGIOGRAPHY APPLICATION

Benefits provided by exploiting the channeling radiation principle consist in ability to change the X-ray energy and in the monochromaticity of the radiation.

The point is that in the case of using the X-ray tube X-ray spectrum is wide due to bremsstrahlung and K-lines of any used anodes are situated in 5 keV or more from attenuation peaks of contrast agents. In case of channeling X-ray the radiation peak can be moved directly to the attenuation peak of the agent.

The drawback of the channeling X-ray radiation is presence of the radiation background spreading from low energy level of several keV to the energy of electron beam. This radiation caused by the bremsstrahlung is still present because of electron scatter at the atoms of the crystal lattice. The radiation level is quite low, but integral radiation of all radiation bandwidth gives quite large contribution to the overall intensity.

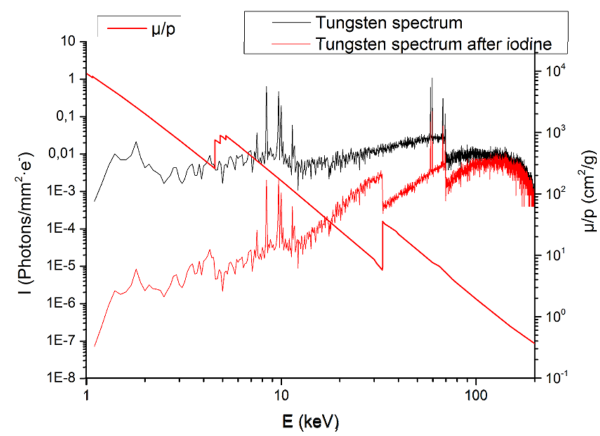

Fig. 1. Spectrum of X-ray tube with tungsten anode, spectrum after iodine contrast agent and iodine mass attenuation coefficient.

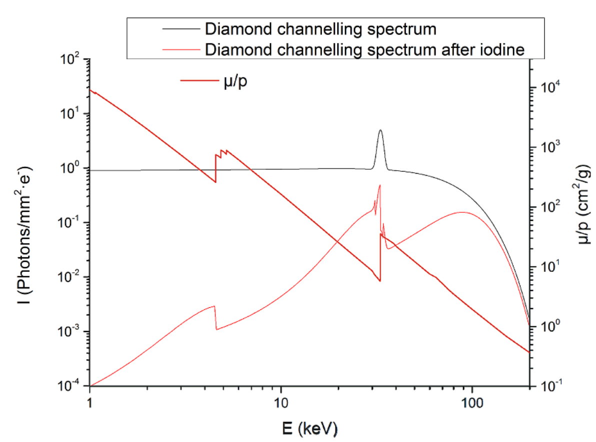

Fig. 2. Spectrum of channelling X-ray obtained from diamond crystal with 21 MeV electron beam, spectrum after iodine contrast agent and iodine mass attenuation coefficient.

The figure 3 shows the principle of image obtaining with the electron channeling mechanism. The irradiated

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object contains contrast agent. In the right part of the picture the intensity of the radiation versus the transverse coordinate is presented. The highest values of intensity correspond to the imaged part of the object without contrast. As the contrast medium has high attenuation coefficient on the photon energy adjusted to the radiated X-ray energy, the image part corresponding to the contrast agent is irradiated with the X-ray of lower intensity. Obtained image contrast is the higher the higher is attenuation coefficient of the contrast agent. For example if X-ray source with 33.1 keV photons energy is used – attenuation coefficient would be 35.8 cm^2/g and in case of X-ray tube with tungsten anode (59.5 keV) the attenuation coefficient would be 5 times less – 7.5 cm^2/g.

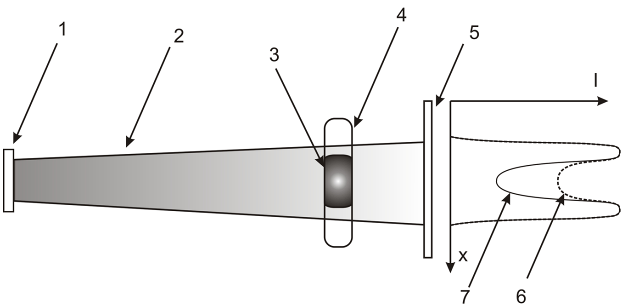

Fig. 3. Angiography image obtaining principle: 1 – X-ray source, 2 – X-ray radiation, 3 – contrast agent , 4 – investigated object, 5 – detector, 6 – intensity curve in case of X-ray intensity peak doesn't match attenuation coefficient peak of the contrast agent, 8 – intensity curve in case of X-ray intensity peak match attenuation coefficient peak of the contrast agent.

SCHEME OF THE FACILITY

The facility scheme for channeling radiation generator is constructed on the requirements for the specific types of X-ray radiation. For instance the radiation demanded for operation with the iodine medium contrast should have the energy of 33.1 keV to fit the iodine mass attenuation peak. To realize this requirement electron beam with the energy of approximately 21 MeV is required, so the electron accelerator should be used to achieve this energy level.

Channeling mechanism of X-ray generation occurs when electron travels near one of the crystal planes. The largest levels of X-ray intensity are obtained in case of (110) axis. According to this crystal must be precisely set relative to the electron beam with the goniometer having at least two axis of adjustment. Goniometer with the monocrystal must be placed inside the vacuum chamber in order to eliminate the beam scattering in the air.

Due to presence of critical angle in channeling mechanism, electrons in the beam should have angle divergence less than critical angle. Beam of this quality can be obtained with LINACs or microtrons without focusing systems.

After the interaction with the crystal electron beam should be deflected from the X-ray propagation direction. This can be made by a magnetic deflector. The deflector is turning the electron beam to the beam load that can be based on Faraday cup to produce the measurements of beam parameters and rectify the beam energy.

As the radiation obtained from the crystal contains bremsstrahlung background – some kind of filtering system should be organized to eliminate it. The low frequency bremsstrahlung can be suppressed by the beryllium windows that are opaque to the X-ray radiation with energy below about 10 keV. X-ray windows cannot suppress the high energy radiation. To eliminate the high energy tail filters like multilayer mirrors or mosaic crystals can be applied [8].

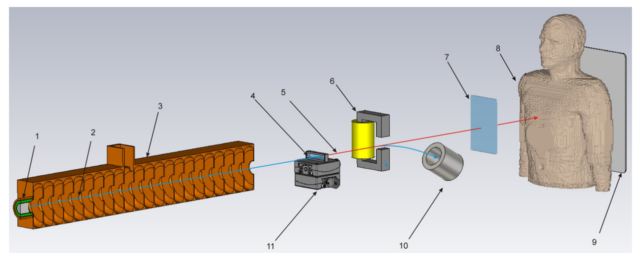

Fig. 4. Principal scheme of monocrystal based X-ray source: 1 – electron gun, 2 – electron beam axis, 3 – accelerating structure, 4 – crystal, 5 – X-ray radiation, 6 – magnet deflecting system, 7 – X-ray radiation filter, 8 – patient body, 9 – X-ray detector, 10 –beam dump, 11 – goniometer.

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.

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