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PULSED X-RAY SOURCE FOR NON-INVASIVE DIGITAL SUBTRACTION ANGIOGRAPHY

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Abstract

In recent years synchrotron radiation from electron storage rings has been found to be a highly effective source for iodine K-edge Digital Subtraction Angiography (DSA). The intense radiation available at 33 keV photon energy used in DSA provides maximum sensitivity to intraarterial iodine and essentally eliminates contrast due to nonvascular body structures. Arteries can be visualized with high resolution in spite of their constant motion. So far, high energy storage rings are required to produce hard X-rays at 33 keV in sufficient intensity. For a dedicated source a lower energy and therefore smaller storage ring at reduced cost would be desirable. In this paper the potential and limitations of low energy storage rings as dedicated radiation sources for DSA are discussed. With high field pulsed magnets in a 1.2 to 1.5 GeV storage ring of about 10 m diameter the required photon intensity can be provided for DSA. Several photon beam lines can be installed at such a ring and of the order of 10,000 patients per year and beam line could be screened.

Introduction

For several years it has been known that synchrotron radiation from electron storage rings can be used as a possible diagnostic tool to uncover signs of atherosclerosis especially in coronary arteries (1). Early detection and location is essential to the success of cadiovascular surgery. Radiographic imaging procedures known as angiography are available for diagnosis but pose too high a risk for the patient to be useful as a screening method of symptomatic patients (1).

In contrast, the use of high intensity X-rays available from electron storage rings permits a safer and non-invasive method of angiography that can be used both as a medical research tool and a method for routine assessment of cadiovascular symptoms in a large number of patients. In this method use is made of the different absorption by iodine atoms of quasi-monochromatic X-rays just above and below the K-edge at 33.16 keV. Only storage rings can provide sufficient intensity of 33 keV radiation to allow the short exposure times required because of the movement of the heart due to its beating and during the respiratory cycle.

Logarithmic subtraction of two digital radiographs at X-ray energies just above and below the iodine K-edge eliminates most of the contrast due to nonvascular body structures. By DSA an iodine contrast sensitivity can be achieved which is four to five orders of magnitude larger (1) than for soft tissues or bone structures. The high risk of catheterization needed for coronary angiography would be replaced in DSA by the administration of a low concentration of iodine into a vain.

While the development of DSA is not yet completed and is being pursued by various research groups it is the intension of this paper to assess the possibilities of DSA from an accelerator point of view. In particular, it is interesting to contemplate the characteristics and limitations of electron storage rings dedicated and optimized for the production of 33 keV radiation. Such a facility could provide typically 2000 to 3000 hours of beam time per year in each of several photon beam lines. The time available for continuous storage ring operation between injection of a new particle beam is of the order of ten hours and injection itself takes about half an hour. Under these conditions it is conceivable that of the order of 10,000 patients per year and beam line could be screened.

Radiation Source Characteristics

For iodine K-edge Digital Subtraction Angiography, DSA, quasi-monochromatic radiation of hard X-rays at 33 keV switchable between just below and above the iodine K-edge must be available. The integrated photon intensity necessary for a single exposure is of the order of (1),(2)

$$N \geq 8 \cdot 10^7 \ photons/mm^2. \tag{1}$$

Assuming an exposure time of 10 msec that requires a photon flux of:

$$\frac{dN}{dt} \geq 8 \cdot 10^9 \ photons/sec/mm^2. \tag{2}$$

The radiation must cover the entire cardiovascular system or an area of about 150 by 150 mm^2.

Undulator Radiation for DSA

The most ambitious and ideal radiation source would be the quasi-monochromatic pinhole radiation from an undulator magnet in a storage ring. In such a source the radiation is highly concentrated at a characteristic photon energy ϵ_o which for a weak undulator is given by:

$$\epsilon_o = C_{ph} \ E^2/\lambda_u \tag{3}$$

with $C_{ph}=4\pi\hbar c/(mc^2)=0.948$ keV cm/GeV^2, E the particle beam energy and λ_u the undulator period length. Since the undulator gap g for the electron beam should be not greater than half the undulator period we get for the minimum storage ring energy to produce 33 keV radiation from an undulator:

$$E_o(GeV) \geq 2.6\sqrt{g(mm)} \tag{4}$$

Obviously high storage ring energies are required to accommodate conventional designs of undulators surrounding the electron beam with a gap of at least 15 to 20 mm. For DSA, however, a mode of operation is possible where the electron beam is switched for the duration of the short 10 to 20 msec pulse into a very small gap undulator. While such a small aperture would severly reduce the particle beam lifetime in a continuous mode of operation this is acceptable on a pulsed basis where the electron beam still spends most of the time outside the undulator. A gap of about 2 to 4 mm is conceivable and the associated storage ring energies would therefore be 3.7 to 5.2 GeV. Clearly, a ring like the 6 GeV synchrotron light facility under discussion (3),(4) could serve as an undulator source for 33 keV radiation. The radiation is emitted in an angle of $\pm 1/\gamma$ or $\pm$ 120 μrad to $\pm$ 85 μrad for these examples and the photon beam reaches a diameter of 150 mm at a

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distance of 625 m to 882 m. That distance, if desired, could be reduced, for example, by defocussing optical elements or asymmetric diffraction methods (5). Due to the finite electron beam size the photon energies are spread over $\Delta\varepsilon/\varepsilon = \pm\ 10\%$ and a monochromator will still be needed for the DSA. Much smaller electron beam sizes than contemplated for a national 6 GeV synchrotron light source must be achieved to make the undulator radiation directly useful for DSA.

By the use of stronger undulators of say K=1.4 (where $K=\gamma\delta$ and δ the deflection angle of one undulator pole) higher harmonics of the fundamental undulator radiation can be produced allowing the use of lower energy storage rings with energy E:

$$E_k(GeV) \geq 2.6\ \ (1+K^2/2)\ \sqrt{g(mm)/k} \qquad (5)$$

where k is the order of the harmonics. Not much, however, is known experimentally about the characteristics of these harmonics in the presence of a finite electron beam size. Specifically energy distribution and the radiation pattern must be determined experimentally before it is possible to assess the potential of direct quasi-monochromatic undulator radiation for DSA. For example, theoretically a narrowing of the spectral line width for higher harmonics is predicted but has not been observed yet. It might be very well that this narrowing is not evident for the relatively large beam sizes in existing storage rings, but would show up in smaller beam size storage rings.

Wiggler Radiation for DSA

Since it is difficult to produce quasi-monochromatic synchrotron radiation without having to use a monochromator it seems obvious to use the intense radiation available from wiggler magnets for DSA. A wiggler magnet acts like a very strong undulator where more and more radiation harmonics are created which eventually overlap to form the continuous broad synchrotron radiation spectrum well known from bending magnets. The advantage of wiggler magnets over bending magnets comes from the fact that all wiggler poles line up to form one source such increasing the photon flux by a factor equal to the number of magnetic poles. In addition the field in a wiggler magnet is not related to the geometry of the storage ring and therefore can be chosen freely to optimize the desired spectral characteristics of the photon beam.

Most of the radiation spectrum is contained in the range up to the so-called critical photon energy ε_c defined by:

$$\epsilon_c = \frac{3}{2}\ \hbar\ c\ \gamma^3/\rho = C_c\ E^2\ B \qquad (6)$$

where ρ is the bending radius and B the field strength of the wiggler magnet and $C_c = 6.64 \cdot 10^{-8}$ GeV^{-1} $kGauss^{-1}$.

The photon flux from a wiggler with N_w magnetic poles is given by:

$$N = C_N \cdot E \cdot \Theta \cdot I \cdot N_w \cdot S(x)(\Delta\epsilon/\epsilon) \qquad (7)$$

where $C_N = \frac{4\ r_e}{9\hbar c e} = 3.99 \cdot 10^{13}\ sec^{-1}\ GeV^{-1}\ mrad^{-1}\ ma^{-1}$,

Θ the angular deflection of the particle beam per wiggler pole as accepted by the experiment, I the electron beam current, $\Delta\varepsilon/\varepsilon$ the photon energy spread after the monochromator and S(x) a mathematical function (fig.1) defined by

$S(x) = \frac{9\sqrt{3}}{8\pi}\int_x^\infty K_{5/3}(\bar{x})d\bar{x}$ with $K_{5/3}$ a modified Bessel function.

From figure 1 it is evident that the critical photon energy ε_c should be of the order of 33 keV to avoid severe loss of photon intensity. The critical photon energy is proportional to $\sim E^2 \cdot B$ and for a given storage ring energy the photon flux at 33 keV as given by equation (7) depends very strong on the magnetic field used in the wiggler magnet. Would one use a 20 kGauss wiggler magnetic field strength in a 1 GeV storage ring the critical photon energy would be only 1.32 keV, $X = \varepsilon/\varepsilon_c$ would be 25, and $S(25) = 5.4\ 10^{-11}$. Indeed this is too small a number to promise a useful photon flux.

In figure 2 the photon flux from several storage rings are shown as a function of the wiggler magnetic field strength. In the calculation of the photon flux from equation (7) it was assumed that the photon beam accepted is Θ =10 mrad wide, the number of wiggler poles is N_w = 8 and the photon energy spread is $\Delta\varepsilon/\varepsilon$ = 0.1 % or 33 eV. Obviously these assumptious are rather arbitrary. The storage ring energies required for conventional magnetic fields up to some 20 kGauss are rather high requiring large and costly facilities. In contrast a 1.2 to 1.5 GeV storage ring dedicated to DSA can be build on a circumference of only 30 to 40 m (5). Very high magnetic fields, however, are required to obtain the desired total flux of at least 2×10^{14} photons/sec (eq. 2) over an area of 150 by 150 mm^2 from a low energy storage ring. Wiggler magnets with magnetic fields of at least 150 kGauss are required. Such fields can be realized on a pulsed basis in small volumes. Judging from figure 2 lower fields seem to be sufficient for the minimum photon flux but in a real storage ring some safty factor in the design photon flux is required for two reasons: first there are always some losses in the monochromator and other optical elements. Secondly, it must be realized that during the lifetime of the electron beam of say 10 hours the intensity drops to about 30% of the initial intensity and with it also the photon flux. Therefore, a safety factor of three to five in the design seems to be prudent.

Magnetic fields in excess of 150 kGauss with a duration of 10 msec and longer have been developed in various high field laboratories (7),(8). Particularly it has been shown that magnets that can sustain many pulses at 150 kGauss are technically feasible (7),(8). The small high field volume is perfectly acceptable since the electron beam has only a very small cross section. A row of pulsed magnets of alternating direction across the particle beam would act like a wiggler magnet. Each such magnet deflects the particle beam by an angle of 10 mrad which would give a photon beam 150 mm wide in the deflecting plane at a distance of 15 m. For a storage ring energy of 1.2 GeV that deflection requires a magnetic field length of only 3 mm. In practical pulsed magnets the field diameter will actually be somewhat larger. Seven such magnets plus two magnets of half the deflection on either end of this row gives the photon flux as calculated for figure 2. To minimize the gap of these magnets it is intended to switch the electron beam into the pulsed wiggler only for the duration of the pulse.

The photon beam from the pulsed wiggler is still a flat beam with a large opening angle (10 mrad) in the deflecting plane of the magnet but has only a very small divergence of the order of $\pm$ 500 μrad in the other plane. This flat beam is well suited for energy filtering in a monochromator. To get the wide photon beam exposure in both planes additional techniques need to be applied. At present the patient is moved across the photon beam (1) which is a slow process and generates additional complications due to the movement of the heart. More sophisticated X-ray optical methods seem to be available to generate a wide beam. One method could be the use of asymmetric diffraction where the reflecting plane is inclined to the crystal surface (6). By this method of glancing incidence a narrow beam can be converted to a wider beam. Factors of the order of 5 to 10 seem possible, however, it is not clear yet what the maximum beam size could be. Another technique is to use defocussing crystal reflection techniques to disperse the beam.

More elaborate schemes could be considered by using several pulsed wiggler magnets separated by ordinary bending magnets. This way the radiation from the wiggler magnets is aimed at slightly different directions and if done properly a large area can be exposed by radiation. Since each of the pulsed wiggler systems will not occupy more than about half a meter of space in the storage ring one can think of having five to ten such systems operating to cover the large area of 150 by 150 mm^2. Obviously the X-ray optical system becomes more elaborate but could be a steady system without moving parts.

The monochromatization at two distinct photon energies is usually done by rotating or oscillating crystals in the monochromator. Here too, the method of dynamic diffraction (6) can generate simultaneously two or more beams separated in energy and space. By gating the one or the other beam both photon beam energies are available as desired without moving critical optical elements.

Conclusion

To make Digital Subtractive Angiography, DSA, available for screening of a large number of patients it is important to have the proper radiation sources available at hospital centers around the country. Small and relatively inexpensive storage rings would serve this need best. In this paper a technique is discussed which uses pulsed high field wiggler magnets to obtain 33 keV radiation for DSA in a storage ring of only 1.2 to 1.5 GeV. Such a storage ring can be build with a circumference of 30 to 40 m and could accommodate several radiation beam lines. The available intensity is high enough to allow for some operational safety and inefficiencies. More research and development, however, is necessary to develop X-ray optical systems to generate a monochromatic photon beam spread over an area of 150 by 150 mm^2.

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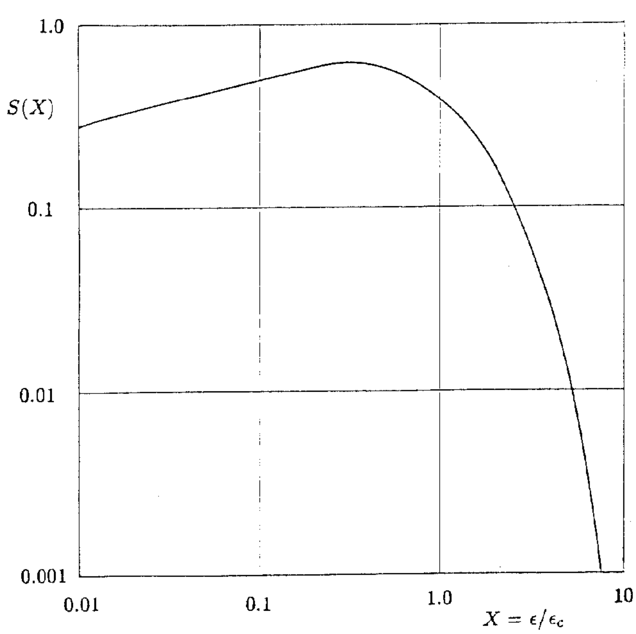

Figure 1: Characteristic Function of a Wiggler Magnet Synchrotron Radiation Spectrum

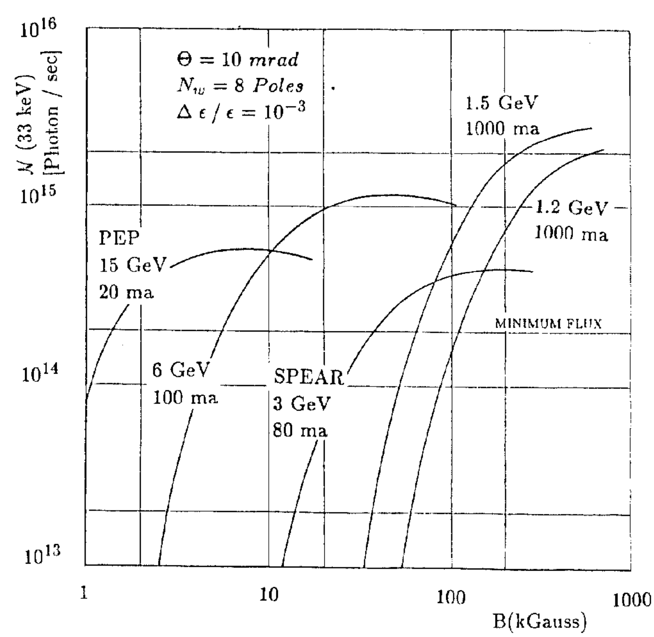

Figure 2: Photon Flux at 33 keV as a Function of the Wiggler Field Strength for Various Storage Ring Energies