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Exotic Sources of X-rays for Iodine K-Edge Angiography

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Digital Subtractive Angiography (DSA) has been performed to image human coronary arteries using wiggler radiation from electron storage rings. The significant medical promise of this procedure motivates the development of smaller and less costly x-ray sources. Several exotic sources are candidates for consideration, using effects such as Cherenkov, channeling, coherent bremsstrahlung, laser backscattering, microundulator, parametric, Smith-Purcell, and transition radiation.

In this work we present an analysis of these effects as possible sources of intense x-rays at the iodine K-edge at 33.169 keV. The criteria we use are energy, efficiency, flux, optical properties, and technical realizability. For each of the techniques, we find that they suffer either from low flux, a low energy cutoff, target materials heating, too high electron beam energy requirement, optical mismatch to angiography, or a combination of these. We conclude that the foreseeable state-of-the-art favors a compact storage ring design [1].

1. Introduction

Coronary angiography is presently an important medical technique, used mainly with urgent cardiac problems and surgery. Angiography on other body systems, such as the carotid, renal, and femoral arteries, is also widespread. Coronary angiography is the most challenging to radiologists because the heart is in constant motion and because it resides in a thick body cavity through which x-rays must pass. It is also challenging to the patient because it is dangerous; up to 1 in 500 patients die of complications, and up to 1 in 100 have serious complications [2]. It is dangerous partly because it is performed by insertion of a catheter into the femoral artery; the catheter is guided into the heart using x-ray fluoroscopy. It also involves a large x-ray dose. The medical world is motivated to seek a safer approach to angiography, both for urgent care and for less urgent screening and diagnosis.

A promising new technique is two-beam Digital Subtractive Angiography (DSA), which involves catheterization on the venous side of the circulation system, through the arm or the neck [2]. Coronary DSA reveals a contrast agent present in the coronary arteries during exposure to x-rays. The contrast agent in current use is iodine, with a K-edge at 33.169 keV. Two images are obtained simultaneously, one with x-rays just below the iodine absorption edge and one with x-rays just above the edge. The bandwidth of the two x-ray beams should be about 1%. For DSA sources which require a monochromator, approximately 4×10^{14} source photons/sec are desired for a few seconds [1]. When the two images are subtracted logarithmically, the background features common to both are suppressed, and the iodine patterns stand out. Two-beam coronary DSA is not practical with conventional x-ray sources because their intensity at the iodine edge is low, though another type of DSA is performed by subtracting images with and without contrast agent.

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In conventional angiography, many images are obtained; series of 100–250 images might be taken to view a given position, and perhaps eight positions are viewed [3]. The average dose per image is only 20–40 mrad, so the patient absorbs 20–40 rad per 1000 images. This low a dose per image is possible because the contrast agent is so concentrated. In venous DSA, the contrast agent is much more dilute, so that each image requires 3–5 rad, as much as a whole series of conventional images. Only a few images are acquired, but this large dose may make venous DSA usable only for patients who are more seriously threatened by heart disease than they would be by the increased risk of cancer from x-radiation. The use of higher-Z contrast agents like gadolinium (K-edge at 50.329 keV) would lower the required dose; at 33 keV only 0.7–5% of the incident radiation passes through the patient.

Synchrotron storage rings with wigglers have been used successfully to generate x-rays for high resolution, high-speed coronary DSA [2]. The image is collected in a horizontal line scan mode where the patient is moved vertically through the beam in a few seconds. The image is distended vertically but quite useful. A typical electron storage ring is both large and expensive for hospital use. Here we examine other x-ray sources that might be smaller and less expensive.

There are many 'exotic' candidate effects, including anomalous dispersion Cherenkov radiation (ADCR), channeling radiation (CR), coherent bremsstrahlung(CBS), laser backscattering (LBS), microundulator radiation (MUR), parametric x-radiation (PXR), Smith-Purcell radiation (SPR), and transition radiation (TR). We shall first discuss these effects collectively because some of their properties are shared, and then we shall consider briefly each effect by itself.

In the following, $\gamma = E_e/m_ec^2$, E_e is the electron beam kinetic energy, and $\beta = v/c$, where v is the velocity of the electron.

2. General Characteristics of Exotic Sources

There are some general considerations which apply to groups of exotic sources. As in an x-ray tube or a synchrotron, they all employ an electron beam. When the proper force is applied to an electron beam, it will emit electromagnetic radiation in the form of x-rays. Several (LBS, SPR, CR, MUR) of them force the electron beam to oscillate transversely in a periodic field; others (TR, PXR, CBS, ADCR) rely on some kind of longitudinal deceleration.

A fundamental design choice is whether to use the electron beam in a single use or multiple pass mode. Several of the effects (CR, TR, PXR, ADCR and CBS) involve inelastic collisions of the electron beam with a material target, so that they are limited to one pass. One can imagine thin targets through which an electron beam passes and is cleaned up and recycled afterwards, but the optical properties would suffer from the collision. The other effects (LBS, SPR, MUR) do not involve collisions with material targets. Here one has a choice of a storage ring or a single pass accelerator, such as a linac or betatron. In general a linac is much more expensive than a storage ring, for energies above about 500 MeV [4].

The single use mode has the advantage that it can be matched to the duty cycle of DSA; in a typical facility, x-rays might be required only a few percent of the time. In principle, single use requires less apparatus than a multipass storage ring. However, the storage ring offers the advantage that, during the time when x-rays are required, the multiple passes of the electron beam generate high effective current. In a storage ring, the beam loses an amount of energy equal to its total energy every damping time (a few milliseconds), so the energy cost of low duty cycle x-rays is high with a multiple pass machine.

Several of the exotic sources (LBS, SPR, CR, MUR) generate x-rays by a transverse oscillation of the electron beam. Special relativity requires such x-rays to have a dispersion of energy with angle Θ measured from the forward direction: $E_\gamma = E_{max}/(1 + \Theta^2\gamma^2)$. The x-rays are emitted into a cone with half angle $\Theta = 1/\gamma$. The highest energy x-rays are on the axis of the cone in the forward direction. At the edge of the cone, the energy is only 50% of the maximum energy. DSA 1% bandwidth radiation falls into a $0.1/\gamma$ cone, and since the flux varies as Θ^2, only 1% of the flux is usable. One might imagine systems where the dispersion is taken into account at different positions on the detector, because the radiation bandwidth is quite small across each pixel.

A wiggler also produces mostly unusable radiation not near the iodine K-edge, which heats the monochromator crystal undesirably. Wigglers and undulators both produce higher harmonics that fog the detector with unwanted background radiation. But wigglers can produce adequate flux for angiography, unlike any of the exotic sources.

All the exotic sources emit into a cone, but current DSA imaging requires x-rays in a flat fan pattern. This is because the detectors in use are line scan type detectors, not two dimensional area detectors. Line scan detectors are used both for reasons of flux intensity and ease of image generation. Images above and below the absorption edge are easily separated, since they are acquired by two detectors separated by a vertical gap. An area detector would require separating high- and low-energy x-rays into different detectors, and would have to have much greater flux. A line scan detector can use less flux, because it controls blurring in only one dimension. An area detector would have to acquire an image fast enough to control motional blurring in two dimensions. An intriguing possible use of line scanning is in high resolution mammography, where it is desired to image sub-millimeter grains of calcium associated with breast cancer.

No source contemplated at present has the intensity to satisfy a two dimensional detector, (about 6¥108 source photons per 250 micron square pixel) given the time limitation imposed by the motion of the heart. DSA images might someday be built up from multiple synchronized exposures with sophisticated image processing, but that option is not viable presently. A cone source might be masked or rastered to create a fan, or the cone might be compressed into a fan optically. This would require special large multilayer mirrors or capillary lenses because the incidence angle required for efficient reflection from ordinary metal mirrors above 27 keV is too small. These optics are not presently available, but research is active in this area. Radiation needs to be spread out to 15–20 cm horizontally to be usable for angiography.

The fixed target exotic sources (CR, CBS, ADCR, PXR, TR) also suffer from a natural thermal limit; only so much electron beam energy can be put into and carried away from a target with cooling. It was the problem of thermal loading of the target which led to the development of the rotating anode x-ray generator. There may an exotic source technique that uses a moving or consumable target, but in the cases of CR, CBS, and PXR, precise alignment with crystal axes, and low damage of a very high quality crystal is required.

Thermal gradients may cause the crystal to fracture. Fortunately in crystals like diamond and silicon, thermal expansion is minimized and thermal conductivity is maximized at cryogenic temperatures. An electron beam might be rastered over an expendable silicon target cooled to 100 K, where the thermal conductivity is 51 W/cm• K. The problem is that even a modest electron beam may deposit a great deal of energy; a 20 MeV, 1 milliamp electron beam carries 20 kW, which is far in excess of what may be carried away from a millimeter sized target by cooling. Material target exotic sources would generally require a much greater electron beam current to produce the intensity required.

3. Characteristics of Specific Source Systems

Anomalous Disperion Cherenkov Radiation (ADCR): Cherenkov radiation occurs when electrons exceed the phase velocity of light they create; this occurs in a medium were $\beta > 1/n(E\gamma)$; $n(E\gamma)$ is the index of refraction of the medium at x-ray energy $E\gamma$. X-rays are not usually emitted, because the index of refraction is less than unity. However, near absorption edges, there may be anomalous dispersion that allows x-rays to be produced within a narrow energy range. Since the index of refraction due to anomalous dispersion is different from unity only near the absorption edge, only the iodine edge itself would be useful. The index of refraction for a crystal with one kind of atom is:

$$n = 1 - \frac{r_0\lambda^2}{2\pi} \rho \left(f' + if''\right) , \qquad (1)$$

where ρ is the electron density, r_0 is the classical electron radius, λ is the x-ray wavelength, and f' and f'' are the real and imaginary parts of the the atomic scattering factor.

The Cherenkov mechanism works in the case of light elements like carbon, because the number of anomalous electrons ($f' \approx -9.7$) near the absorption edge is greater than the number of electrons (6) and this causes the index of refraction to be greater than unity. The mechanism will not work in the case of iodine, because it has 53 electrons and f' is only -10.6 at the K-edge. Figure 1 shows the variation of f' for iodine near the K-edge [5].

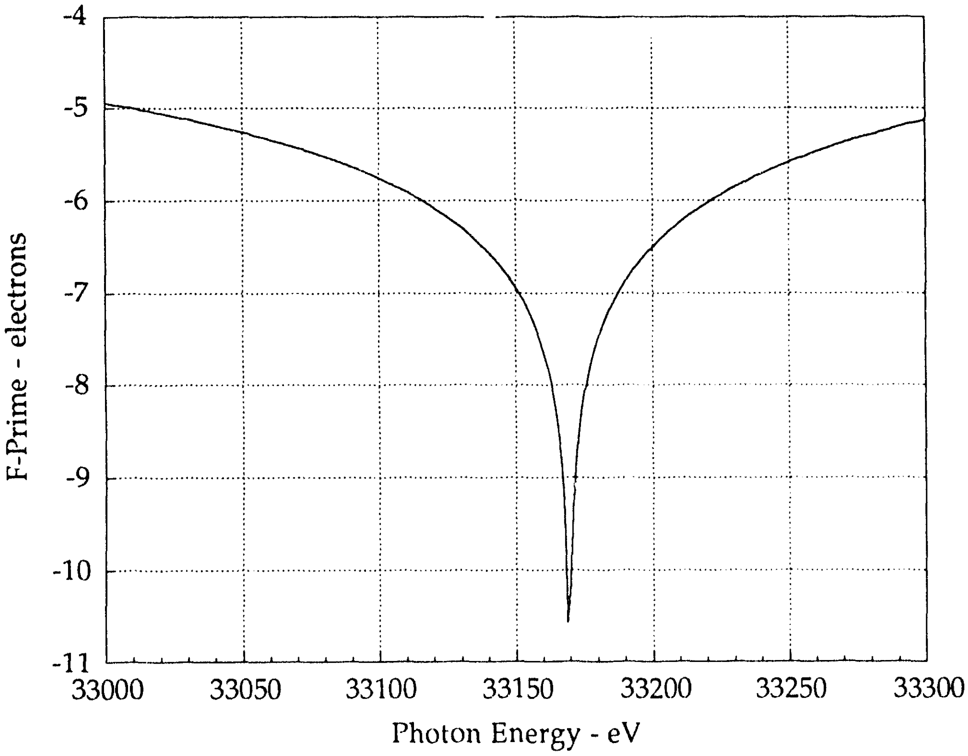

Figure 1: Plot of anomalous dispersion effect on f' at the iodine K-edge.

Channeling Radiation (CR): This is a transverse oscillation effect; it is caused by the interaction of periodic fields in a crystalline solid with an electron beam which travels parallel to lattice planes. The relativistic beam excites electronic transitions in the solid, and the resulting photon energy is Doppler upshifted by $2\gamma^2$, just as in an undulator. Channeling has been likened to an atomic scale undulator with magnetic fields of megagauss [6]. Experiments have shown that 30 keV radiation is readily obtained from crystals with electron beams on the order of 20 MeV.

In a study of channeling radiation yields at 30 keV, several crystals were used; it was determined that diamond was the best candidate for several reasons [7]. It has the best thermal conductivity (100 W/cm•K at 100 K). Channeling radiation appears in narrow spectral lines from diamond, but in broader features from higher Z cyrstals. For angiography, a narrow line is usable, though there are intense harmonic peaks present. Also, an electron beam is less subject to scattering in diamond than in higher Z crystals, so a longer penetration depth is usable. Scattering generates heat, so diamond can generate more radiation per watt absorbed.

For all its virtues, even with state-of-the-art cooling, diamond can sustain only a few milliamps of 50 MeV electron beam. With this beam, channeling radiation flux of 4.2×10^{10} photons/sec was obtained in a 5% bandwidth [6]. This is four orders of magnitude less than is required for angiography, and angiography requires a 1% bandwidth or less. The diamond target has a lifetime of only a few minutes before it is radiation damaged beyond use.

Coherent Bremstrahlung (CBS): This is an effect similar to channeling radiation, but here the electrons need not travel along major crystal axes. In CBS the electron beam excites free-free electron transitions, while in CR, the electron beam excites bound-bound transitions [7]. The effect occurs especially in crystalline superlattices where it is used as a diagnostic technique. Bremsstrahlung produces x-rays in the 33 keV range only for very low energy electrons (1 MeV); CBS may produce an order of magnitude more flux than homogeneous bremsstrahlung and CR, but it is less efficient than parametric radiation, by at least two orders of magnitude [8].

Laser Backscattering (LBS): If laser light strikes a relativisitc electron beam, the backscattered photons will have energy equal to the iodine K-edge, according to the relations:

$$4\gamma^2 E_v \approx E_\gamma \Rightarrow E_e \,(\text{MeV}) = \frac{46.5}{\sqrt{E_v\,(\text{eV})}}\ , \tag{2}$$

where E_v is the laser photon energy.

There are a number of intense laser sources; the higher the energy of the laser, the lower energy will be required from the electron beam. A KrF (4.99 eV) excimer laser could be used to generate 33 keV x-rays with an electron beam of only 20.8 MeV. The flux of backscattered x-rays is given by the luminosity expression:

$$N_\gamma = \frac{F_c\ N_v\ N_e\ \sigma_T}{4\pi\ \sigma_v\ \sigma_e}\ , \tag{3}$$

where F_c is the photon pulse-electron bunch collision frequency, σ_T is the Thomson scattering cross section (0.655×10^{-22} mm^2), N_v is the laser flux, N_e is the electron current, σ_v is the radius of the light beam, and σ_e is the radius of the electron beam. Figure 2 shows the fluxes which would result from scattering 100 micron diameter electron and laser beams:

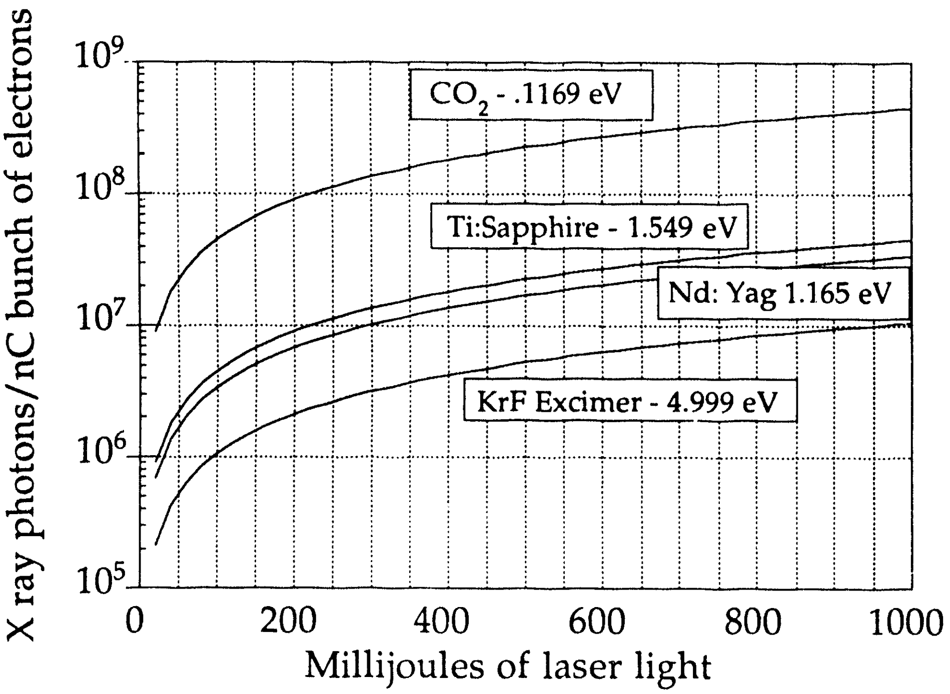

Figure 2: X-ray flux per nano-Coulomb electron pulse per millijoule pulse of laser light.

Sprangle has proposed a laser backscattering system with a 'Tabletop Terawatt' laser scattering against a 100 amp, 200 MeV betatron electron beam, which is close to the maximum practical size for a betatron [9]. In very optimistic circumstances, this source would produce about 3×10^{13} photons/sec over a 100% bandwidth, so it still has three orders of magnitude fewer photons than the 4×10^{14} photons/sec in a 1% bandwidth that are needed for coronary angiography.

Microundulator Radiation (MUR): An undulator generates a radiation spectrum consisting of a series of peaks, of which the first harmonic is the most intense. A microundulator is one with a small period length chosen to obtain higher energy x-rays. It might consist of two rows of magnets with a small gap between them, or a single row of magnets with a grazing electron beam. An undulator with a first harmonic at 33 keV would generate 66 and 99 keV harmonics, which are unwanted, just as with a wiggler. The energy of the first harmonic is given by:

$$E_f\ (\mathrm{eV}) = \frac{950\ E_e^2\ (\mathrm{GeV})}{\lambda\ (\mathrm{cm})\ \left(1+K^2/2\right)}\ , \qquad K = 0.934\ B(\mathrm{T})\ \lambda\ (\mathrm{cm})\ , \qquad (4)$$

where λ is the undulator period length. The undulator flux falls off very sharply below $K = 0.5$; taking that as a minimum value, and using an extreme superconducting value of $B_{max} = 5$ T, we obtain a period length of 1 mm. At this period length, an electron beam energy of 2 GeV is required to produce a first harmonic at the iodine K-edge. With $B_{max} = 2$ T, the electron beam would have to have more than 3 GeV. These high values of electron beam energy and magnetic fields make undulators unattractive as angiography sources, compared to wigglers.

Parametric X-Radiation (PXR): Parametric x-rays are created when an electron beam strikes a crystalline target and the virtual photons which make up the electric field of the electrons exit the crystal by means of Bragg scattering. The photons may exit on the same side of the crystal as the one on which the electron beam enters (Bragg case diffraction) or on the other side (Laue case diffraction). Parametric radiation leaves the crystal in discrete beams, just as in conventional x-ray diffraction. Each beam subtends a narrow angle, $(1/\gamma)$ and a narrow range of energy ($\Delta E/E \approx 10^{-3}$). This obviates the need for a monochromator, but it is excessively monochromatic for angiography.

PXR has been described as the most efficient exotic source of x-rays, according to an analysis by Baryshevsky and Feranchuk [8]. The efficiency of this process is at best 10^{-5} photons/electron, and single use electrons up to 1 GeV may be required [9]. To obtain the flux required for line detection angiography would require 4 amp currents, which are prohibitively costly at the energies required, and would overheat any target.

Smith–Purcell Radiation (SPR): This radiation is produced when a charged particle beam travels close to a surface, such as a diffraction grating, which has corrugations normal to the beam direction. The effect is similar to channeling or undulator radiation in that the electron beam sees an oscillating field which causes a transverse force on the beam. As with an undulator, it requires a small period motion with high field strength. The strength of the field increases as the beam gets closer to the grating. The criterion for distance d above the grating is [11]:

$$d < \frac{\gamma \beta \lambda_\gamma}{4\pi}, \qquad \lambda_\gamma = \lambda_g \left(\frac{1}{\beta} - \cos\Theta\right), \tag{5}$$

where λ_g is the grating period length, and λ_γ is the wavelength of Smith–Purcell radiation. The shortest wavelength radiation occurs for forward scattering at $\Theta = 0$. Since we require $\lambda_\gamma = .373$ Å, we have $d/\gamma = .0297$ Å. Even if an electron beam could be projected only 100 Å above the surface, it would have to have $\gamma = 3{,}369$ (1.7 GeV); such a high energy defeats the attraction of the Smith–Purcell radiation for angiography. A more realistic electron beam would be tens of microns in diameter, and would be tens of microns above the surface; it would need proportionally greater energy.

Transition Radiation (TR): Transition radiation is generated when a charged particle beam passes into or out of media with different dielectric constants. A typical experiment involves a stack of thin foils as a target. Unlike channeling and parametric radiation, it does not require a crystalline target. Transition radiation occurs in a 'formation length' over which there is a dephasing between the particle and the electromagnetic wave it creates. A stack of a few hundred foils may be used before they begin to absorb too much of the radiation produced. The radiation falls into a $1/\gamma$ cone.

Transition radiation is limited by target heating, as with channeling radiation, but it is more amenable to an expendable or moving target because there is no crystallinity requirement. The most severe limitation of transition radiation is that its intensity varies as $1/E_e$. Experiments have shown intensities on the order of 0.01 photons/electron–sr–eV at 1 keV, but the intensity is negligible at 33 keV [12]. It does not appear competitive as an angiography source.

4. Summary

Arguments as to why certain things will not work can be taken as challenges; there may be some innovation which defeats the limitations described here. However, this work provides a review of current understanding of the applicability of the various exotic sources to iodine K-edge angiography.

One-time electron beam use, angular dispersion of the x-ray energy, circular beam profile, and thermal limitations affect generally the usefulness of several exotic sources and each has its own specific show-stopping problems at the present state-of-the-art. Given these limitations, the compact electron storage ring with a superconducting wiggler would seem the most likely source of x-rays for angiography [1].

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