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A Storage Ring Based Inverse Compton Scattering Angiography Source?*

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Producing the 33.17 KeV photons required for coronary angiography with synchrotron radiation requires a combination of a high energy storage ring with an extremely high field wiggler. Such a source may be too big and expensive to be installed in even the largest medical center. Something other than synchrotron radiation may be needed for a practical source.¹

Inverse Compton scattering has been used in the LEGS experiment at NSLS² and elsewhere to produce high energy photons. In this process, a head on collision between a low energy photon and a high energy electron transfers energy to the photon which is then emitted in approximately the direction of the incoming electron. For a given electron energy, more higher energy photons can be produced by this method than by synchrotron radiation. This suggests that inverse Compton scattering can possibly be used for a low cost angiography source. The prospects for such a source will be examined in this paper. Unfortunately, the results will show that although it is easy to obtain the required photon energy, an extremely complicated source will be needed to produce the required number of photons.

Some requirements for an angiography source are listed in Table 1. They are based on the characteristics of the X-17 angiography x-ray beam at the NSLS. The required intensity, 2×10^8 photons/(.5 mm²)-4 msec-70 eV, is an estimate of what is required to produce a clinical quality image.

In a head on collision between a high energy electron and a low energy photon³, the photon emerges at an angle θ to the incident electron direction, with energy

$$E_\gamma = \frac{4\gamma^2\epsilon_L}{1 + \gamma^2\theta^2 + 4\gamma\epsilon_L/(mc^2)}, \quad (1)$$

where γ is the Lorentz factor for the incident electron, ϵ_L is the energy of the incident photon (L for laser, the presumed source of the photons), and mc^2 is the rest energy of the electron.

1. This report is a summary of an accelerator physics seminar presented at the NSLS on May 28, 1992.

2. C.E. Thorn, et. al., Nucl. Instr. and Meth. **A285** (1989) 447-458.

3. *Ibid.*

* This work was supported by the U.S. Department of Energy.

The highest energy photons are emitted with $\theta = 0$, at energy

$$E_C = \frac{4\gamma^2\epsilon_L}{1 + 4\gamma\epsilon_L/(mc^2)}, \quad (2)$$

called the Compton edge. This shows that 33.17 KeV photons can be produced in a collision between 417.9 MeV electrons and photons with a wavelength of $100 \mu\text{m}$. The photon beam contains all energies from 0 to E_C , distributed with differential cross-section

$$\frac{d\sigma}{dE_\gamma} = \frac{2\pi r_0^2 \epsilon_L}{E_\gamma^2 y^2} \left(\frac{2\gamma}{1+x^2} \right)^2 \left[y + \frac{1}{y} - \left(\frac{2x}{1+x^2} \right)^2 \right], \quad (3)$$

where $r_0 = 2.82 \times 10^{-15} \text{ m}$ is the classical electron radius,

$$x = \theta\gamma = \left[4\gamma\epsilon_L \left(\frac{\gamma}{E_\gamma} - \frac{1}{mc^2} \right) - 1 \right]^{1/2}, \quad (4)$$

and

$$y = 1 + \frac{4\gamma\epsilon_L}{(1+x^2)mc^2}. \quad (5)$$

Fig. 1 shows the differential cross section for the scattering of $100 \mu\text{m}$ photons off 417.9 MeV electrons. The total (Thompson) cross section,

$$\sigma_T = \int_0^{E_C} \frac{d\sigma}{dE_\gamma} dE_\gamma = 665 \text{ mb}, \quad (6)$$

is independent of ϵ_L and E_γ .

In a collision between a bunched electron beam and the light from a pulsed laser, photons are produced in an energy band ΔE , near the Compton edge, at a rate

$$R = \sigma_{Ec} \Delta E N_L F_e, \quad (7)$$

where σ_{Ec} is the differential cross section at the Compton edge, N_L is the number of laser photons per pulse, and F_e is the electron flux. It is assumed that the shape of the incident photon and electron bunches is the same in all three spatial dimensions and that the divergence of the incident beams is small compared to the divergence of the emergent photons, as given by eqn. (1) and ΔE . Eqns. 1-5 show that

$$\sigma_{Ec} \approx \frac{4\pi r_0^2}{E_c} \quad (8)$$

is independent of the incident photon and electron energies. The number of laser photons per pulse

$$N_L = \frac{E_L}{\epsilon_L} = \frac{\lambda_L E_L}{hc}, \quad (9)$$

where E_L is the total energy of the laser pulse and λ_L is the laser wavelength. In practice, E_L is roughly independent of the laser wavelength. Hence, the photons are produced at a rate

$$R = \Delta E_L \frac{\lambda_L E_e F_e}{hc} \quad (10)$$

that is proportional to the wavelength of the incident photons. This tends to drive the inverse Compton scattering source to long wavelength incident photons. However, eqn. 2 shows that the electron beam energy

$$E_e \approx mc^2 \sqrt{\frac{\lambda_L E_c}{4hc}} \quad (11)$$

increases as the square root of the incident photon energy, and with it the size and expense of the source. Together, eqns. 10 and 11 favor a source with an electron beam energy in the range from ten to a few hundred MeV and incident infrared photons.

The high energy electron beam needed in the angiography source can be supplied by either a storage ring or an accelerator such as a linac or betatron. In a storage ring, the circulating electron bunch has many opportunities to interact with the laser during the time required for the x-ray exposure. This provides a high effective flux F_e with relatively few electrons compared to the single use of a beam from an accelerator.

An example of the type of small storage ring that might be used in an angiography source was provided by the x-ray lithography source (XLS) project at the NSLS. Table 2 shows the properties of a 417.9 MeV storage ring that uses 100 μm photons to produce 33.17 KeV photons at the Compton edge. The storage ring parameters are suggested by the XLS design but the required specifications for emittance and coupling, although reasonable, are in no way similar to XLS.

The use of a storage ring as the electron beam source requires a laser with a repetition rate equal to the ring bunch frequency. The combination of laser pulse repetition rate, pulse energy, and wavelength required by the storage ring design can not be provided by a conventional laser. Instead, a free electron laser (FEL) driven by the electron beam from a superconducting linac was chosen as the source of the photons. The FEL parameters are listed in Table 3. The FEL is configured as a ring laser with the inverse Compton scattering taking place within the FEL cavity as shown in Fig. 2. Energy is recovered from the electrons after they pass through the FEL undulator by redirecting the beam through the linac.

The design of the FEL is the most uncertain part of the source. The linac beam power, repetition rate, and peak current needed have never been achieved simultaneously. Although it may be possible to build, the FEL would be complicated and at or beyond the state of the art. It does not in any way appear to be suitable for a hospital based angiography source. In choosing to use inverse Compton scattering as a source of 33 KeV x-rays, the size and expense of a high energy storage ring were exchanged for the expense and complexity of an FEL with an extremely high repetition rate. Storage rings still look like a better source of high energy photons.

Table 1
Angiography Requirements

Fundamental Requirements:

X-ray Energy	33.17	KeV
Energy Spread	70	eV
Distance to Source	40	m
Exposure Time	4	msec
Horizontal Beam Size at Patient	12	cm
Pixel Size	0.5 mm x 0.5 mm	

Derived Requirements:

Horizontal Divergence	3	mrاد (from distance to source and horizontal size)
Vertical Divergence	0.13	mrاد (from distance to source and pixel size)

Intensity	2×10^8	photons/(0.5 mm ²)-4 msec-70 eV
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By Comparison:

X-17 Intensity (Bragg monochromator)	3×10^7	photons/(0.5 mm ²)-4 msec-70 eV
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Table 2
Storage Ring Characteristics

Suggested by XLS Design:

Energy	417.9	MeV
Current	350	mA
Number of Bunches	3	
Revolution Frequency	35	MHz

Requirement:

Emittance	0.25	mm-mrad
Coupling	0.10	

At Interaction Point:

σ_x'	3	mrاد	(requirement)
σ_y'	0.13	mrاد	(requirement)
σ_x	0.083	mm	(from required divergence and emittance)
σ_y	0.20	mm	(from required divergence and emittance)
Electron Flux	2.09×10^{25}	m ⁻² sec ⁻¹	

Requires from FEL:

Wavelength	100	μm
Laser Energy/Pulse	543	μJ
Repetition Rate	105	MHz
Average Power	57	KW

Table 3
FEL Characteristics

Undulator:			
Period	10	cm	
K	1.414		
Peak Field	1.5	KG	
Number of Periods	4		
Length	40	cm	
Electron Beam:			
Energy	16.16	MeV	
Average Current	50.4	mA	
Beam Power	814	KW	
Repetition Rate	105	MHz	
Electrons/Bunch	3×10^9		
Bunch Length	1	mm	
Peak Current	144	A	
Beam Radius	2.5	mm	
Optics:			
Number of Mirrors	4		
Reflectivity	0.99		
Total Loss	0.04		
Rayleigh Length	20	cm	
Small Signal FEL Model:			
Efficiency	0.13		
Gain	0.10		
Power	102	KW

Fig. 1. Differential cross section for inverse Compton scattering, $E_e = 33.17$ KeV.

Fig. 2. Schematic view of inverse Compton scattering x-ray source.

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