Design study of Thomson Laser-Electron X-ray Generator (LEX) for Millisecond Angiography

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Abstract. In this concept study a laser-electron X-ray generator (LEX) is considered for the medical imaging of the inner vessel structure. It is demonstrated that the modern lasers and linear electron accelerators are suitable for the design of the new generation of angiography medical equipment combining higher spatial and time resolution with the reduced patient dose. Angiography setup based on LEXG can make use of different contrast media (iodine, gadolinium) working on absorption edge due to the narrow tuneable spectrum which is not possible with conventional X-ray tubes. In the present study all estimations are made for iodine-based contrast agents. The conclusion is that modern technologies allow practical implementation of LEX for angiography based on multibunch linear accelerator and photon storage device.

1. Introduction

Initially the idea and the implementation of a laser-electron X-ray generator (LEX) based on Thomson scattering was proposed by F.E.Carroll [1,2]. Currently two LEXG are fully operational [3,4] and even commercially available [5]. In all cases these are multipurpose setups shared by many investigators. Whereas LEX setups are 10 to 30 times bigger than the conventional X-ray sources based on X-ray tubes they can provide several orders of magnitude higher brilliance which stimulates applications in traditional X-ray technologies like security [6], therapy [7] and medical diagnostics [8,9]. The present paper discusses the requirements to LEX and its components to apply it to vessels visualization with 1 ms exposure time and the spatial resolution of 0.1 mm which exceeds the current image quality in clinical practice.

Angiography in medical practice is performed by the radiography of the vessels filled with a contrast agent. Let us estimate the required number of photons for one projection of an object with the blood vessel thickness δ (figure 1). The condition of blood vessel visualization in a bulk of non-contrasted media is:

$$\sqrt{N_\delta e^{-\mu L}} < c\left[N_\delta e^{-\mu L} - N_\delta e^{-\mu L - (k-\mu)\delta}\right] \tag{1}$$

Therefore the minimal exposure for the one picture element is:

$$N_\delta(E) = e^{\mu L}\left\{c\left[1 - e^{-(k-\mu)\delta}\right]\right\}^{-2},\qquad(2)$$

where attenuation coefficients μ (outside the vessel) and κ (in the vessel) depend on an X-ray photon energy E, c is a contrast ratio defined by the particular task and by the detector, L is the body thickness. Hence the number of photons required for the 2D detector M by M pixels is:

$$N(E) = M^2 e^{\mu L}\left\{c\left[1 - e^{-(k-\mu)\delta}\right]\right\}^{-2}.\qquad(3)$$

This formula does not contain any information about the source itself. It estimates the necessary number of photons at the detector side to be able to extract small contrasted detail surrounded by attenuating material.
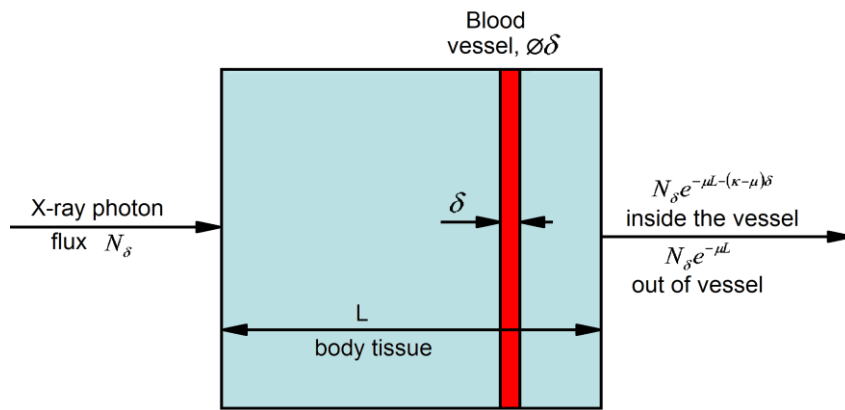

Figure 1. Exposure dose in angiography: L – total object thickness, N_δ – number of incident photons for the square $\delta X \delta$ required for one image, μ - linear attenuation coefficient of the body, κ- linear attenuation coefficient of the vessel with the contrast agent.

2. Coronary angiography. Exposure and radiation dose

For the last decades the "golden standard" for the heart vessel tree diagnostics remains a selective coronary angiography – an invasive procedure which requires artery catheterization with the subsequent injection of a contrast agent next to the investigated region. The risk of complications remains high. Noninvasive CT methods have been developed in the last 15 years [10] with the contrast agent injected intravenously prior to the study. At the same time there were attempts to improve image quality using monochromatic synchrotron radiation [11], X-ray tubes with rotating anode [12] and LEX [13]. However the time and spatial resolution of non-invasive techniques remained worse than those of the "golden standard" method [14-16]. Later in the text we present the LEX design that allows to overcome these limitations.

Let us first define the required dose i.e. the number of photons N(E) demanded for one-projection angiographic image. For that let's use formula (5) with the values typical for medical radiography patient thickness L=20 cm , vessel diameter $\delta = 1$ mm. Attenuation coefficient μ is taken for water [16], attenuation coefficients for iodine contrasted vessels κ are expressed through the mass iodine concentration η related to Hounsfield units CT_{Number} [17], which is standard in radiology diagnostics. $N(E)$ for different iodine mass concentrations η in the energy range 30-120 keV is presented on figure 2 assuming that the imaging matrix contains 0.06 megapixel (256*256) and contrast ratio is $c = 0{,}6$. Data for the calculated iodine mass concentrations correspond to $CT_{Number} = 50 \div 500$ measured by CT angiography [19, 20].

Figure 2 demonstrates that the exposure dose is minimal at the energies of 35-45 keV . These doses correspond to $\sim 10^{11} \div 10^{13}$ photons for the clinically approved iodine concentrations (several mSv) and do not exceed approved radiation exposure for angiography and coronography [21]. The optimal energy estimated is above the absorption K-edge of iodine and it is confirmed experimentally [30]. Let us consider the requirements to LEX capable of generating the required number of photons in 1 ms of exposure time.
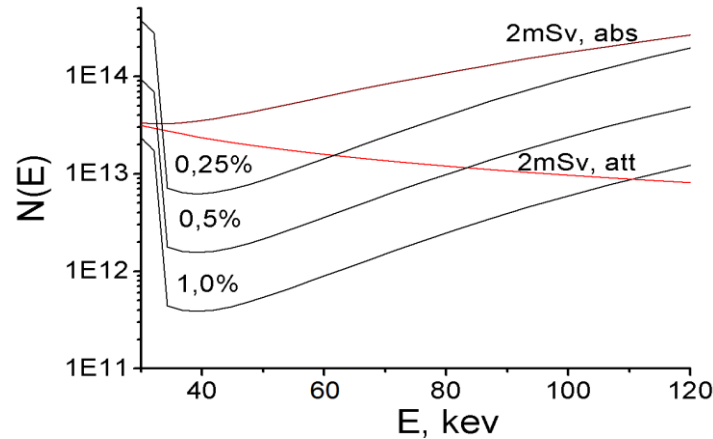

Figure 2. Number of X-ray photons required for one angiography image obtained in 1 ms (see (5)) as a function of photon energy E. Vessel thickness $\delta = 1$ mm, body thickness $L = 20$ cm, contrast ratio $c = 0,6$, matrix size 256*256 ($M =256$). Iodine mass concentration in the vessel η is indicated in percent above the curves. Red curves correspond to the dose of 2 mSv for the 75 kg men: abs – one scattering event, att – multiple scattering, photons are totally absorbed.

3. Principles of Laser-Electron X-ray Generator

The basic scheme of LEX is presented on figure3. The X-rays are generated in the photon storage as a result of Thomson scattering of laser pulses on the relativistic electron bunches produced by the linear accelerator. Electron trains have a frequency of ν_e and contain n_e bunches N_e electrons each. Photon device amplifies (resonator [22]) or stores (circulator [23-25]) laser radiation. The number of stored photons is $N_L^s = \eta N_L$, where N_L is the number of laser photons and η is the photon device efficiency. Further in our estimations we are using $\eta = 10^3$ for the resonator and $\eta = 0,25$ for the circulator, which are feasible at the current technological level [26,27]. The energy and the X-ray flux emitted by the Thomson scattering of the laser photons on electrons depend on the geometry of the colliding beams. For the head-on collision the following formula can be used [28]:

$$E \approx 4\gamma^2 E_L, \quad \Phi = n_e \nu_e N = n_e \nu_e N_e N_L^s W = \frac{1}{eE_L} I \Sigma^s W, \quad \text{where } N = N_e N_L^s W, \qquad (4)$$

Σ^s – laser pulse energy accumulated in the optical storage device, e – electron charge, I – accelerator current, E_L - laser photon energy, W – the number of X-ray photons produced at one collision. W is used for the total flux calculations as well as for the spectral and angular distributions. For the radiography the key parameter is the total flux. In this case $W \approx \sigma_T / s$, where $\sigma_T = 6.6 \cdot 10^{-25} cm^2$ – Thomson cross-section, s – interaction area. For instance for s=30 μm^2:

$$W \approx \sigma_T / s = 0.93 \cdot 10^{-19}. \qquad (5)$$

The general picture of Thomson scattering of a laser pulse on a relativistic electron bunch is different both from scattering on a bunch in a rest condition as well as from a scattering of a single photon on a single relativistic electron. Scattering diagram is elongated along the electron beam direction and concentrated in narrow angle $\delta\theta \sim 1/\gamma \approx 10$ mrad, where $\gamma = E_e/m_e c^2$ – relativistic factor and the spectrum width is 15-20%. Angular and spectral distributions are defined by the momentum distribution functions of the colliding beams. Exact formulas for W and for the LEX spectrum can be found in [28] and the previously cited literature.
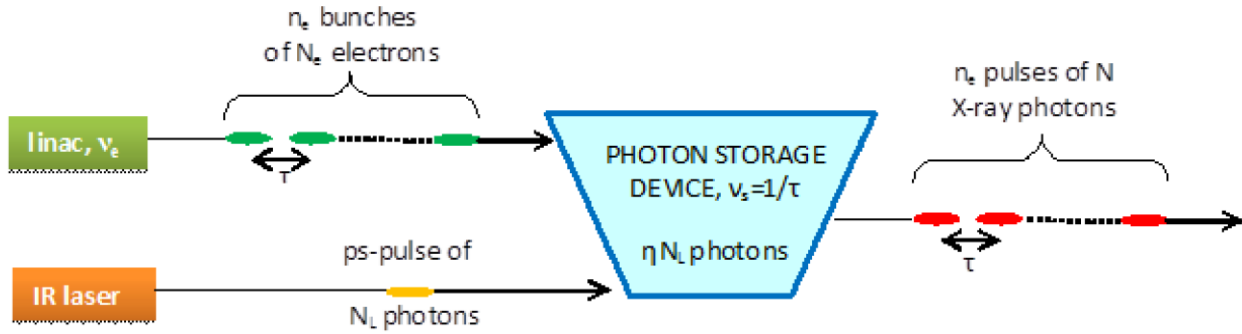

Figure 3. Basic scheme of LEX.

4. Laser-electron X-ray generator for angiography

Due to the narrow angular distribution and the spectrum almost a significant part of the flux can be used for imaging. Using (4) the total number of X-ray photons in one LEX pulse can be calculated:

$$N = \frac{Q}{e}\frac{\Sigma^s}{E_L}W, \tag{6}$$

where Q is the full charge in one bunch. According to the basic scheme (figure 3) one LEX pulse contains n_e X-ray pulses corresponding to n_e electronic bunches generated in one accelerator cycle with the duration not more than 1 ms (temporal resolution of the imaging setup). Formula (5) remains valid because all generated photons are used in the imaging. Finally, accounting for the photon-electron interaction cross-section area the total number of photons for one LEX pulse is:

$$N = \sigma_T \frac{Q}{es}\frac{\Sigma^s}{E_L}. \tag{7}$$

Therefore the LEX X-ray output is the product of the two factors: the first one is related to the electron beam, the second one to the number of laser photons accumulated in the optical storage device. Formula (7) can be used in the development of LEX for the laser and the accelerator optimization in order to achieve the exposure of $N \sim 10^{11} \div 10^{13}$ required for coronal angiography (see section II). From this point of view we analyzed the experimental setups build so far and current projects for the photon energies of 12-30 keV. Estimations were performed for the IR lasers with the pump wavelength 1.03 μm ($E_L = 1.2$ eV). The laser pulse energy accumulated in the photon storage device was taken as $\Sigma^S = 10$ mJ.. Two LEX systems with the close parameters (electron bunch charge, interaction cross-section area) are presented in table 1. demonstrating that the accelerators currently under construction provide output close to the required one for the millisecond angiography.

Table1. Total X-ray flux in 1 ms for the accelerators under development in [27,29].

Linear accelerator	s, μ^2	Q, μC	N	
			calculated see. (13)	required see section 2
[27]	3.6	0.01	$6 \cdot 10^{10}$	10^{11} - 10^{13}
[29]	100	10	$2 \cdot 10^{12}$	10^{11} - 10^{13}

4. Discussion and conclusions

Modern angiography instruments use X-ray tubes for illumination allowing to dynamically observe heart vessel tree condition with 0.01 second temporal resolution and 0.15-0.2 mm spatial resolution [15]. Based on the simplified model developed we demonstrated that LEX can outperform these parameters. In particular the LEX exposure time for one image does not exceed 1 µsec and the spatial resolution is much less than the diameter of the electron beam (10-100 µm). Another key feature of PLEX is the tunable spectrum of X-ray illumination which allows to benefit from another contrast media like gadolinium. Table 2 summarizes some of the main differences between X-ray tube and LEX regarding angiography applications.

Table 2. X-ray sources for coronal angiography.

	Source	
	X-ray tube	LEX
Directionality of illumination	-	10 mrad
Temporal resolution	10 ms	< 1 ms
Spatial resolution	0,15-0,20 mm	<0,1mm
Dynamic imaging	+	-
Safety	Low	High
Spectrum optimization for the contrast agent used	-	+

References
[1]   Carroll, F.E., Waters, J.W., Price, R.R., Brau, C.A., Roos, C.F., Tolk, N.H., Pickens, D.R., Stephens W.H. 1990 Near-monochromatic X-ray beams produced by the free electron laser and Compton backscatter, Invest. Radiol. 25, 465.

[2]   Carroll, F.E 2003 Tunable, monochromatic X-rays: An enabling technology for molecular/cellular imaging and therapy, Cell J. Biochem., 90, 502.

[3]   Pogorelsky, I.V. 2016, Progress and prospects of a Compton X-ray source driven by a high-power CO2 laser, X-Ray Lasers 2014, Ed.: Jorge Rocca, Carmen Menoni, Mario Marconi, Springer, 133-138.

[4]   The "Munich Compact Light Source", https://www.munich-photonics.de

[5]   http://www.lynceantech.com/

[6]   Albert, F., Anderson, S.G., Anderson, G.A., Betts, S.M., Gibson, D.J., Hagmann, C.A., Hall, J., Johnson, M.S., Messerly, M.J., Semenov, V.A., Shverdin, M.Y., Tremaine, A.M., Hartemann, F.V., Siders, C.W., McNabb, D.P., Barty, C.P.J. 2010 Isotope-specific detection of low-density materials with laser-based monoenergetic gamma-rays, Optics Letters, 35(3), 354-356.

[7]   Jacquet, M. 2014 High intensity compact Compton X-ray sources: Challenges and potential of applications, NIM B, 331, 1-5.

[8]   Bessonov, E.G., Vinogradov, A.V., Gorbunkov, M.V., Tur'yanski, A.G., Feshchenko, R.M., Shabalin, Yu.V. 2003 Laser electron-beam X-ray source for medical applications, Physics-Uspekhi, 46(8), 872.

[9]   Bessonov, E.G., Gorbunkov, M.V., Kostryukov, P.V., Maslova, Yu.Ya., Tunkin, V.G., Postnov, A.A., Mikhailichenko, A.A., Shvedunov, V.I., Ishkhanov, B.S., Vinogradov, A.V. 2009 Design study of compact Thomson X-ray sources for material and life sciences applications, JINST, 4, P07017, 1-14.

[10]   Mastouri, R., Sawada, S.G., Mahenthiran, J. 2010 Current Noninvasive Imaging Techniqes for Detection of Coronary Artery Disease,. Expert Rev. Cardiovasc Ther, 8(1), 77-91.

[11]   Dix, W.-R., Kupper, W., Dill, T., Hamm, C.W., Job, H., Lohmann, M., Reime, B., Ventura, R. 2003 Comparison of intravenous coronary angiography using synchrotron radiation with selective coronary angiography, J. Synchrotron Rad., 10, 219–27.

[12]   Sarnelli, A., Taibi, A., Tuffanelli, A., Baldazzi, G., Bollini, D., Cabal Rodriguez, A.E., Gombia, M., Prino, F., Ramello, L., Tomassi, E., Gambaccini M. 2004 K-edge digital subtraction imaging based on a dichromatic and compact x-ray source, Phys. Med. Biol., 49, 3291–3305.

[13]   Bessonov, E.G., Gorbunkov, M.V., Kostryukov, P.V., Maslova, Yu.Ya., Tunkin, V. G., Postnov, A.A., Mikhailichenko, A.A., Shvedunov, V.I., Ishkhanov, B.S., Vinogradov, A.V. 2008 Design Study of Compact Thomson X-Ray Sources for Material and Life Sciences Applications, Springer Proceedings in Physics, 130, 521-535

[14]   Achenbach, S. 2015 Can Coronary Computed Tomography Angiography Replace Invasive Angiography?, Circulation, 131, 410-417.

[15]   Stefanini, G.G., Windecker, S., 2015 "Can Coronary Computed Tomography Angiography Replace Invasive Angiography? , Circulation, 131, 418-426,.

[16]   Khovrin, V.V. 2016 "X-ray and MR tomography of aorta in diagnostics, planning and evaluation of surgical results" (in Russian), Doctoral Thesis, *National Center of Surgery named after academician B.V. Petrovsky, Russian Academy of Medical Sciences, Moscow, Russian Federation*

[17]   http://physics.nist.gov/PhysRefData/Xcom

[18]   Bryant, J.A., Drage, N.A., Richmond, S. 2012 CT number definition, Radiation Physics and Chemistry, 81, 358–361.

[19]   Cademartiri, F.,de Monye, C., Pugliese, F., Mollet, N.R., Runza, G., van der Lugt, A., Midiri, M., de Feyter, P.J., Lagalla, R., Krestin, G. 2006 High Iodine Concentration Contrast Material for Noninvasive Multislice Computed Tomography Coronary Angiography: Iopromide 370 Versus Iomeprol 400, Invest Radiol., 41(3), 349-53.

[20]   Komatsu, S., Kamata, T., Imai A., Ohara, T., Takewa, M., Miyaji, K., Yoshida, J., Kodama, K. 2013 Controlling intracoronary CT number for coronary CT angiography, Journal of Cardiology, 61, 155–161,.

[21]   Komarova, M.A. 2016 Image quality and radiation exposure optimization in CT coronography (in Russian), PhD Thesis, Moscow State University, Faculty of Fundamental Medicine, Moscow, Russian Federation.

[22]   Pupeza, I. 2012 Power Scaling of Enhancement Cavities for Nonlinear Optics, Springer Theses, Springer-Verlag New York,.

[23]   Bessonov, E.G., Gorbunkov, M.V., Maslova, Y.Y., Kostryukov, P.V., Tunkin, V.G., Ishkhanov, B.S., Shvedunov, V.I., Vinogradov, A.V. 2007 Relativistic Thomson scattering in compact linacs and storage rings: a route to quasi-monochromatic tunable laboratory-scale X-ray sources, in Soft X-Ray Lasers and Applications VII; edited by G. J. Tallents and J. Dunn (SPIE, San Diego, CA, 2007), Proceedings SPIE 6702.

[24]   Bessonov, E.G., Gorbunkov, M.V., Ishkhanov, B.S., Kostryukov, P.V., Maslova, Yu.Ya., Shvedunov, V.I., Tunkin, V.G., Vinogradov, A.V. 2008 Laser-electron generator for X-ray applications in science and technology, Laser and Particle Beams, 26, No. 3, 489-495,.

[25]   Gorbunkov, M.V., Maslova, Yu.Ya., Vinogradov, A.V. 2009 Optical unit of Laser-Electron X-ray Generator designed for medical applications, NIM A 608, S32-S35,.

[26]   Carstens, H., Lilienfein, N., Holzberger, S., Jocher, C., Eidam, T., Limpert, J., Tünnermann, A., Weitenberg, J., Yost, D.C., Alghamdi, A., Alahmed, Z., Azzeer, A., Apolonski, A., Fill, E., Krausz, F., Pupeza I. 2014 Megawatt-scale average-power ultrashort pulses in an enhancement cavity, Optics Letters, 39, 9, 2595-2598,.

[27]   Graves, W.S., Bessuille, J., Brown, P., Carbajo, S., Dolgashev, V., Hong, K. H., Ihloff, E., Khaykovich, B., Lin, H., Murari, K., Nanni, E.A., Resta, G., Tantawi, S., Zapata, L.E., Kärtner, F.X., Moncton, D.E. 2014 Compact x-ray source based on burst-mode inverse Compton scattering at 100 kHz, Phys. Rev. ST Accel. Beams, 17, 120701,.

[28]   Artyukov, I.A., Bessonov, E.G., Gorbunkov, M.V., Maslova, Yu.Ya., Popov, N.L., Vinogradov, A.V. 2016 Thomson linac-based X-ray generator: a primer for theory and design, Laser and Particle Beams, pp. 1–8

[29]   Shimizu, H. et al, 2015 X-ray generation by inverse Compton scattering at the superconducting RF test facility, NIM A, 772, 26-33,.

[30]   Meyer, M., Haubenreisser, H., Schoepf, U.J., Vliegenthart, R., Leidecker C., Allmendinger, T., Lehmann, R., Sudarski, S., Borggrefe, M., Schoenberg, S.O., Henzler, T. 2014 Closing in on the K Edge: Coronary CT Angiography at 100, 80, and 70 kV—Initial Comparison of a Second- versus a Third-Generation Dual-Source CT System, Radiology, 273, 373–382,.