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Tunable Compact Monochromatic X-ray Synchrotron Radiation Source Based On Inverse Compton Scattering for Advanced Radiological Applications.

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Abstract: *In radiological facilities, radiation protection of patients and physicians are the main concern of the radiation protection program that could be enhanced by adopting new advanced diagnostic/therapy techniques. The main purpose of such technique is to minimize the dose delivered to the healthy tissue in patient and/or minimize the dose delivered to the physician during diagnostics/treatment process. In that context, there were a plenty of research papers proved the feasibility of successful use of monochromatic X-ray synchrotron radiation in radiological applications. However, high brightness monochromatic X-ray synchrotron radiation is traditionally obtainable exclusively in giant facilities like 3rd generation light source when ultra-relativistic electron beam (GeV) passes through an insertion device such as an undulator. This unfortunately limits the dissemination of the radiological applications of X-ray synchrotron radiation within the synchrotron facilities only. Many research efforts have been conducted during last decade to develop a compact system that offers the opportunity to produce high-brilliance X-ray synchrotron radiation with a laboratory-scale via Inverse Compton Scattering (ICS). Unfortunately, so far, no system has been produced in commercial scale due to some technological difficulties related mainly to the linear accelerator (LINAC) which is the main core of that system. In this paper we propose a compact (≈ 1 m) traveling wave X-band LINAC that operates at $5\pi/6$ mode and produces up to 50 MeV for ICS source. This X-band LINAC has been proposed in specific since it has been designed and fabricated already in cooperation with CERN-PSI-ELETTRA and based on cutting edge technologies such as mode launcher and alignment monitors that overcomes the most known shortcomings; this nominates such X-band LINAC as a best solution for ICS source. The LINAC resonance cavities have been simulated using SUPERFISH code; the beam dynamics has been simulated using ASTRA code. The X-ray that is produced by collision between the electron beam with Table Top Terra Watt (T^3W) laser has been simulated using CAIN code. The simulation results show that many advanced radiological applications could be adopted such as Dynamic Intra Venous Coronary Arterio Graphy, early diagnosis of breast cancers and therapy for cancers using Auger Cascade Radiotherapy.*

Keywords: *Inverse Compton Scattering, X-band linac, mode launcher, Tunable monochromatic X-ray, synchrotron radiation,*

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I. Introduction

X-RAY has many useful applications in different research fields such as solid state physics, biology, microscopy and in radiological applications. The usage of X-ray sources in radiological facilities is usually associated with exposure to wide spectrum of X-ray energies although only a narrow band of the X-ray spectrum is used in diagnostic/treatment process, while the remained spectrum is considered to be parasitic and non avoidable. In some radiological applications this parasitic portion contributes significantly to the total dose delivered to the patients and physicians. An example of such situation is the Coronary Arterio Graphy (CAG) in which the coronary artery is visualized by contrast agent (iodine) injected into the artery by a catheter that inserted into the artery. The useful X-ray energy in this technique is 33.169 KeV only which is equivalent to K-edge attenuation of the iodine (Z = 53) at that X-ray energy; any other energies in spectrum emitted from X-ray tube spoil the image's clearance and quality in one hand and maximize the dose delivered to both patients and physicians on the other. For that reason, adopting advanced diagnostic/treatment techniques that could eliminate such parasitic radiation are highly encouraged. In that context, X-ray form non conventional sources (e.g. synchrotron facilities) are proposed for advanced radiological techniques since quasi mono chromatic X-ray radiation could be easily generated in these facilities with the possibility of tuning X-ray energy to fit for desired radiological use. For example, the aforementioned CAG could be conducted by means of monochromatic synchrotron radiation that is produced when the electron beam from a storage ring passed through magnetic undulator. The electron beam energy and the undulator parameters are tuned mutually to generate very narrow band of the desired X-ray energy 33.169 KeV. Hence a monochromatic X-ray just above this energy will give high contrast ratio and very clear image. This technique enables the physicians to visualize the coronary artery dynamically [1, 2] with about 30 shots/sec with ***intravenous injection*** of the contrast agent (Iodine). This technique is conventionally known as Intra Venous Coronary Arterio Graphy (IVCAG). The dynamic visualization was possible due to the high flux of the X-ray photons, about 10^{11} photons/second. The disadvantage of this technique is the limitation of its use inside synchrotron facilities only which are big and expensive to be used publicly; accordingly a numerous number of patients can not use this technique. During last decade, and due to advances in Laser and RF linear accelerator (LINAC) technologies, many institutes and research centers conducted intensive research to construct affordable and compact system that can generate monochromatic X-ray by means of interaction of an electron beam from a LINAC and a high power laser beam; a scheme that is known as Inverse Compton Scattering ICS. The most suitable proposed ICS systems are those using X-band (12 GHz) LINAC since such LINACs satisfy the compactness conditions where 50 MeV electron beam could be achieved in 1 meter long LINAC.

Up to date, not any one of the prototype systems proposed worldwide has been adopted to be produced in commercial scale due to some technological difficulties related mainly to the core of the ICS system (i.e. the X-band LINAC) such as voltage breakdown at the input and output accelerating cells and the instability of the RF power source at X-band range.

In this paper we propose a very advanced compact (≈ 1 m) traveling wave X-band LINAC that operates at $5\pi/6$ mode and produces up to 50 MeV. This X-band LINAC has been proposed in specific since it has been designed and fabricated already through a cooperation between CERN, Paul Sherrer Institute (PSI) and Italian synchrotron facility ELETTRA. The design is based on cutting edge technologies such as mode launcher that overcomes the voltage breakdown problem, and alignment monitors that help in driving the beam exactly long the LINAC axis. Many units of such LINAC have been already fabricated and tested and now are fully functional at the aforementioned facilities without any problems; this nominates such X-band LINAC along with its RF system as a best candidate for ICS source.

This paper is organized as follows: The theoretical background of the ICS is introduced in section II; the description of the X-band CERN-PSI- ELETTRA like LINAC is introduced in section III; the simulation of LINAC cavities using SUPERFISH code and tracking the beam dynamics using ASTRA code along the LINAC will be presented in section IV. Section V will be devoted to the simulation of the X-ray generation by head on collision between the 50 MeV electron beam with Table Top Terra Watt (T^3W) laser using Monte Carlo CAIN code. Some radiological examples based on ICS are presented in section VI. Finally, the overall conclusion will be drawn in section VII.

II. X-ray Generation via Inverse Compoton Scattering ICS

Production of monochromatic synchrotron radiation (X-ray) became feasible by means of collision between high energy electron beam with high power and short laser pulses as shown in Fig. (1). In such collision the magnetic field of the laser pulse acts as an undulator for the electron beam that collides with and forces the electron beam to undulate rigorously yielding to x-ray emissions. The physical mechanism involved in such process is known as "Thomson scattering" or inverse Compton scattering.

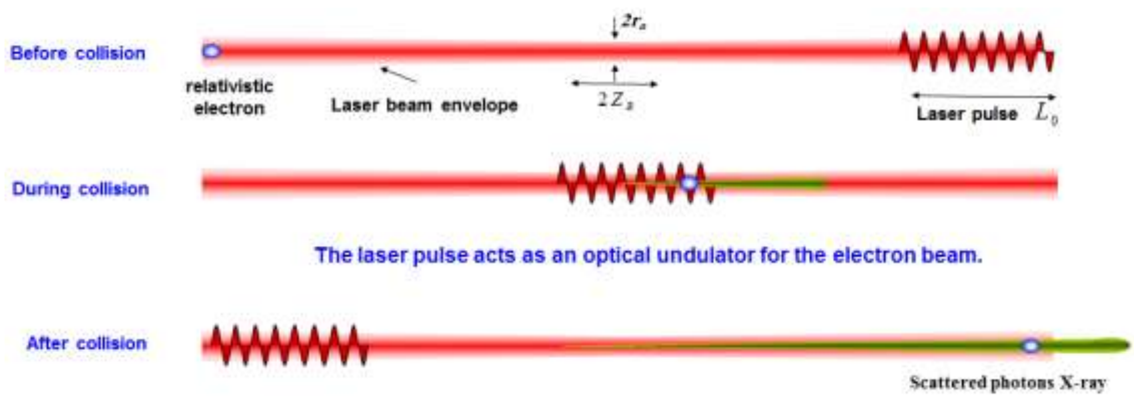


Figure (1). Generation of monochromatic X-ray radiation form Inverse Compton Scattering.

X-ray parameters from laser-electron collision.

For simplicity, suppose that the electron and laser beams are described by Gaussian temporal and spatial distribution in the transverse and longitudinal coordinates, hence the rms pulse length of the emitted X-ray radiation is given by [3]:

$$\tau \approx \tau_L \left[1 + \left(1 + \frac{\sigma_x^2 + \sigma_y^2}{4\tau_L^2 c^2} \right) \varphi^2 \right]^{1/2} \qquad (1)$$

Where σ_x and σ_y are the electron beam sizes in the transverse plane and τ_L is the rms laser pulse duration and ϕ is the angle between the electron beam axis and the laser beam axis at the collision point. Equation (1) states that the pulse duration of the emitted X-ray is mainly determined by the angle ϕ and the laser pulse duration. For head on collision for example the pulse duration of the emitted X-ray is equal to that one of the incident laser. The energy of the emitted X-ray is introduced by [3] as:

$$E_P[KeV] = E_0 \frac{2\gamma_0^2}{1 + \gamma_0^2 \theta^2}(1 - \cos\varphi) \qquad (2)$$

Where E_0 is the energy of the incident laser, θ is the scattering angle from the axis of collision, and γ_0 is the Lorentz factor of the electron beam. In case of orthogonal collision, i.e. ϕ is 90^0, "(5)" reduces to:

$$E_P[KeV] = E_0 \frac{2\gamma_0^2}{1 + \gamma_0^2 \theta^2} \qquad (3)$$

From which the angular frequency in orthogonal collision is given by:

$$\varpi = \frac{2\gamma_0^2 \omega_0}{1 + \gamma_0^2 \theta^2} \qquad (4)$$

Where ω_0 is the angular frequency of the incident laser, in case of head on collision, i.e. ϕ is 180^0, "(2)" reduces to:

$$E_P[KeV] = E_0 \frac{4\gamma_0^2}{1 + \gamma_0^2 \theta^2} \qquad (5)$$

From which the angular frequency in head on collision given by:

$$\varpi = \frac{4\gamma_0^2 \omega_0}{1 + \gamma_0^2 \theta^2} \qquad (6)$$

It is clear that the energy of the emitted X-ray in head on collision is twice that of the orthogonal collision. If the angle ϕ is 0, "(2)" is reduced to zero, which means that no X-ray emitted if the laser beam and the electron beam are propagating in the same direction. With a little mathematical manipulation, "(2)" could be reduced to:

$$E_P = 4\gamma_0^2 E_0 (1 - \gamma_0^2 \theta^2) \qquad (7)$$

For ($\theta = 0$) i.e. along the axis of collision the energy is a maximum and is given by:

$$E_P = 4\gamma_0^2 E_0 \qquad (8)$$

In other words the highest energy of the emitted X-ray photons are observed along the axis of collision, and as the angle of observation increases the energy of the emitted X-ray photons along this direction becomes lower. The maximum observed energy is determined by the incident laser and electron energies. Accordingly, to get very narrow band width of emitted X-ray, high electron energy and high laser energy are essential.

The spectral flux within the spectral width $\Delta\omega/\omega$ is a very important factor to be determined. The number of X-ray emitted photons per second is given by [4].

$$F\,[\text{photons/s}] = 8.4 \cdot 10^{16} \cdot f \cdot \left(\frac{L_0}{Z_R} \right) \cdot I_b\,[\text{A}] \cdot P_0\,[\text{GW}] \cdot \left(\frac{\Delta\omega}{\omega} \right) \qquad (9)$$

Where L_0 is the interaction length, Z_R is the Rayleigh length of the laser and is given by ($Z_R = \pi r_0^2 / \lambda_0$) where r_o is the laser spot size, I_b is the electron beam current, P_0 is the laser power, and finally f is the filling parameter and it is given by:

$$f = \begin{cases} r_0 / r_b & r_0 < r_b \\ 1 & r_0 > r_b \end{cases} \qquad (10)$$

Where r_b is the electron beam transverse size.

III. CERN-PSI- ELETTRA X-band like LINAC type

The proposed X-band LINAC in this paper is similar to the CERN-PSI- ELETTRA X-band LINAC [5,6]; the LINAC is ≈ 1m long (73 cells) integrated with two alignment monitors to manipulate the beam alignment which is very crucial in case of Free Electron Laser. Such components are not important in (ICS) source and hence such alignments monitors are omitted in the LINAC design proposed in this study. Also, CERN-PSI- ELETTRA X-band LINAC has two specific couplers that are based on SLAC mode launchers design [7] and this option has been considered in our case. The main function of this coupler is to convert the rectangular waveguide TE_{10} mode into the circular TM_{01} mode. In this way the couplers substantially reduce the surface field at the edges of the coupling irises to avoid RF breakdown. Every coupler has two opposite openings to feed/extract the RF power to/from the X-band LINAC symmetrically so that the electron beam quality will not be affected during its passage through mode launchers. The mode launchers are connected to the accelerating cells via two matching cells. The LINAC design employs a large iris, $5\pi/6$ phase geometry to minimize the group velocity of RF power along LINAC which in turn minimizes the voltage breakdown; voltage breakdown is inversely proportional to group velocity of RF power along LINAC. Figure 2 shows a cut view of the CERN-PSI- ELETTRA X-band structure; the proposed LINAC will be similar to such one except the exclusion of alignment monitors. The outstanding relevant 12 GHz high power RF source has been developed and manufactured at SLAC National Accelerator Laboratory, USA [8]. Such RF source along with the X-band LINAC represent the most practical and stable X-band accelerating system ever developed.

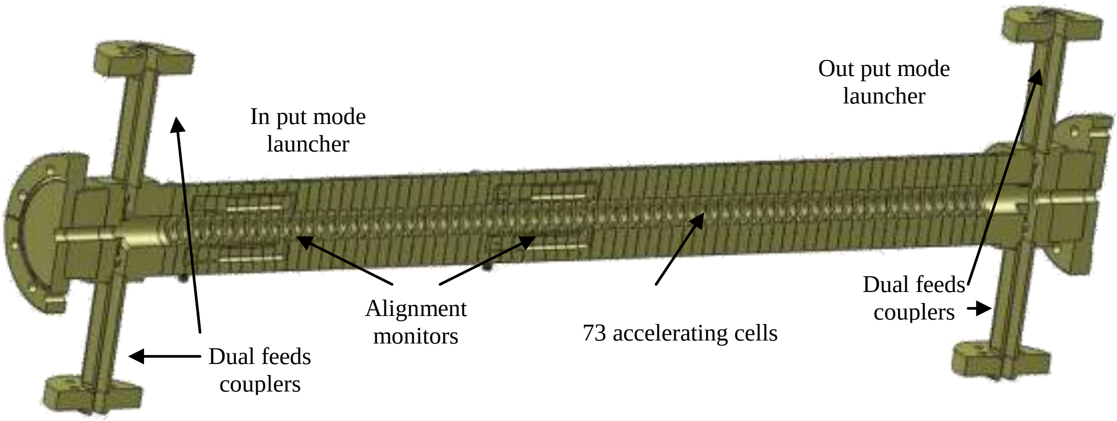


Figure (2): Cut view of X-band structure showing the mode launchers and wakefield monitors.

IV. Beam dynamics along the X-band LINAC

The target for X-band LINAC in our case is to accelerate 4-5 MeV electron beam delivered by RF electron gun up to 50 MeV. To investigate the beam dynamics in this accelerating case, all LINAC cells have been simulated using SUPERFISH code [9] from which the electromagnetic field distributions along the whole LINAC is extracted and stored in specific file formats. Files form SUPERFISH code have been prepared to be used by ASTRA code [10] to track the electron beam along the X-band LINAC. The injection phase of the electron beam has been optimized for optimum electron beam parameters that fit to the collision with high power laser. The final electron beam energy is tuned by reducing the RF power fed to the X-band LINAC or by varying the injection phase.

V. X-ray generation

CAIN [11] is a stand-alone FORTRAN Monte-Carlo code to simulate the interaction involving high energy electron, positron, and photons. Such code will be used to simulate the head on collision of the electron beam accelerated by X-band linear accelerator with a Mode locked Ti:Sapphire laser. Table 1 represents the assumed electron beam parameters from X-band linear accelerator with RF gun at maximum energy could be delivered by the X-band LINAC. The same table represents the parameters for an available commercially Mode locked Ti:Sapphire laser with long laser pulse. Figure 3 represents the angular distribution of emitted X-ray photons from the electron collision with Mode locked Ti:Sapphire laser at different electron beam energies. The outmost right below figure represents the energy spectrum of the emitted X-ray photons at such energies. From Fig. (3), it is clear that the maximum photon flux obtained along the axis of collision is 1.3×10^8 photons/pulse. Multiplying by the repetition rate of the laser pulse the final flux is 1.3×10^9/sec.

Table (1). Electron and laser beams parameters assumed in their head on collision

X-band linear accelerator	Beam energy tuned up to	: 50 MeV
	Beam bunch width	: 5 psec.
	Beam size (horizontal)	: 32 μm
	Beam size (vertical)	: 32 μm
	Beam emittance (horizontal)	: 2 π mm mrad
	Beam emittance (vertical)	: 2 π mm mrad
	Charge/bunch	: 2 nC/ bunch
	Number of bunches/pulse	: 10^4 bunch/pulse
Ti:Sapphire laser	Wave length	: 800 nm
	Laser pulse length	: 5 ps.
	Energy/pulse	: 5 J/pulse
	Laser spot radius	: 32 μm
	Repetition rate	: 10 pps

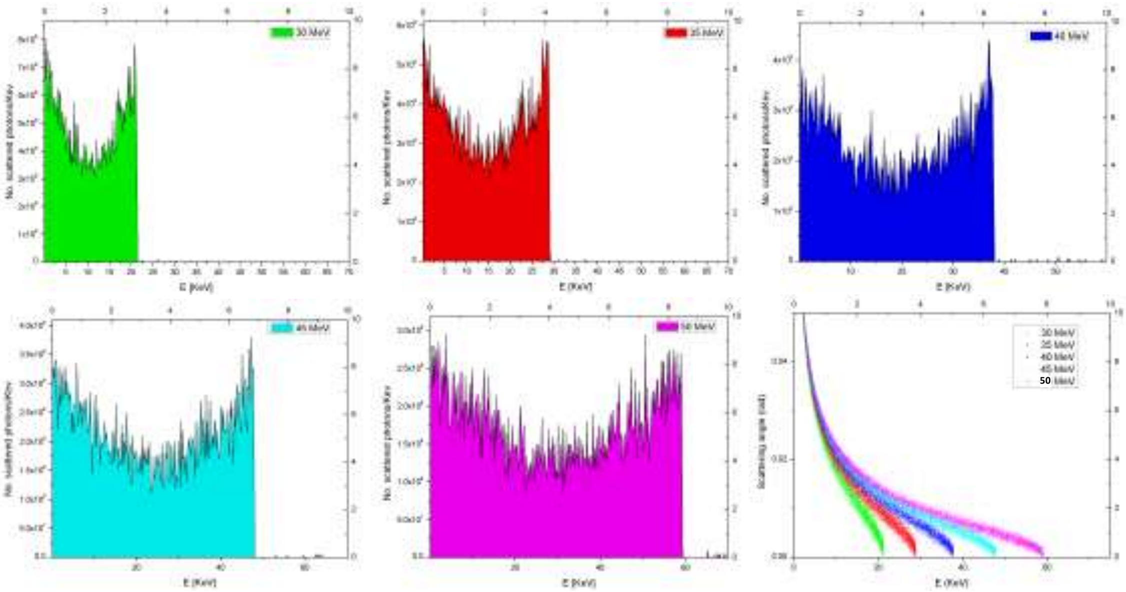


Figure (3). Emitted X-ray photons from electron pulse collision with Ti:Sapphire laser pulse. The first 5 sub figures represent the angular distributions at different energies. The last sub figure represents the energy spectrum at such electron energies

VI. Some radiological examples based on ICS

In section I we have mentioned the Intra Venous Coronary Arterio Graphy (IVCAG). In which the monochromatic X-ray just above 33.169 KeV the absorption of X-ray energy is very low for the most known elements in the human body such as Oxgen, Carbon and hydrogen while the absorption for Iodine is very high as shown in Fig. (4); this will give high contrast ratio and very clear image and stenosis could be easily visualized as shown in Fig. (5) [12]. This technique enables the physicians to visualize the coronary artery dynamically [1, 2] with about 30 shots/sec with ***intravenous injection*** of the contrast agent (Iodine). This technique is conventionally known as Intra Venous Coronary Arterio Graphy (IVCAG).

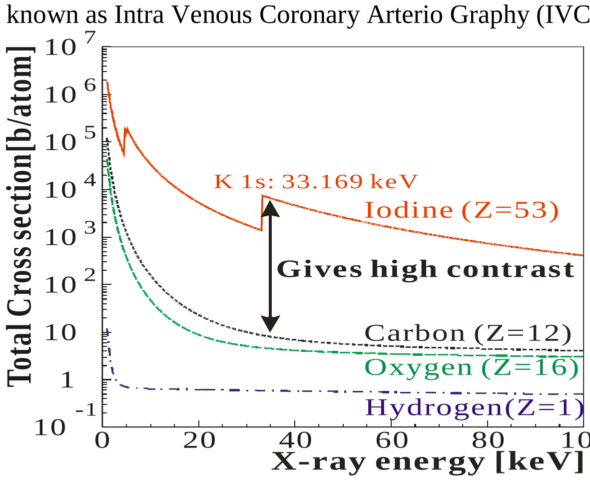


Figure (4). Absorption of X-ray energy by different elements and K-edge absorption of Iodine (Z=53).

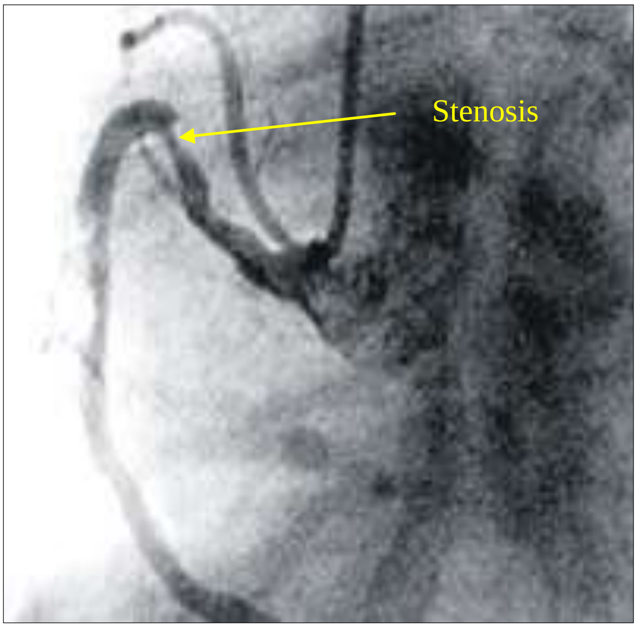
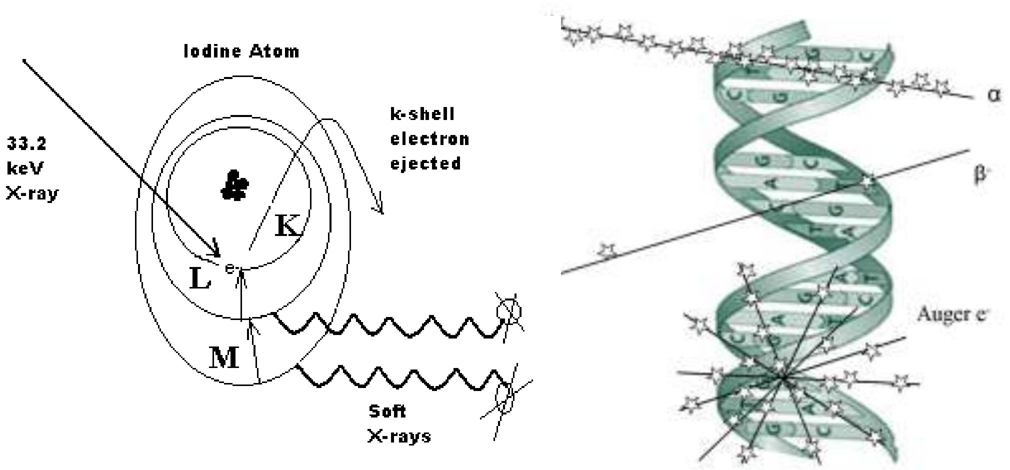


Figure (5). The Intra Venous Coronary Arterio Graphy (IVCAG) using monochromatic X-ray [12].

Frank E. Carroll et al. carried out several imaging using tunable monochromatic X-ray from 10-50 KeV at Vanderbilt University. He visualized "lesions" in breast-equivalent materials of differing glandular percentages using 24 KeV X-ray which were not seen on the polychromatic image taken using molybdenum anode with molybdenum filtration X-ray tube [13]. This means that mammography is feasible without compression. He also tuned the X-ray energy from 16 KeV to 29 KeV to switch between the details of bone and soft tissue in finger phantom and in real entire mouse. More details about imaging by monochromatic X-ray radiation in medicine and their advantages could be found elsewhere [14].

Auger cascade radiotherapy [15] is another important application of tunable monochromatic X-ray radiation. Figure (6) represents the basic principle of cancer therapy using Auger cascade principle while Fig. (7) represents an example showing the treatment of prostate cancer through Auger cascade.



K-shell electron ejected.
L-shell electron replaces it and gives off a soft X-ray.
M-shell electron replaces L-shell electron giving off an even softer X-ray and so on.

Figure (6): Auger cascade for cancer therapy

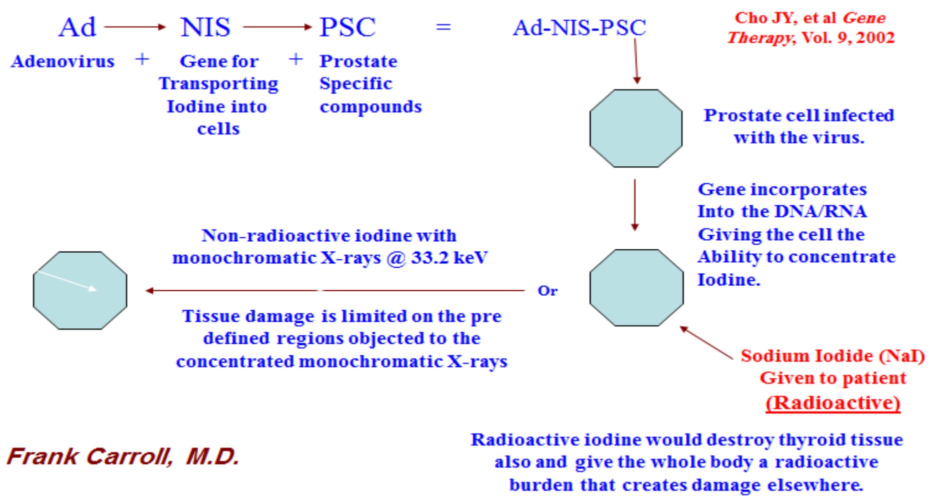


Figure (7): Auger cascade for prostate cancer therapy

VII. Conclusion.

Adopting new advanced diagnostic/therapy techniques is essential to enhance the radiation protection for both of patients and physicians as well. One of such technique was the use of monochromatic X-ray for different radiological applications at giant synchrotron facilities which are not available for the majority of patients worldwide. An affordable and compact monochromatic X-ray source is then highly required which became later feasible using Inverse Compton Scattering technique. The different prototypes of ICS-based X-ray monochromatic sources were suffering form some technological difficulties in X-band LINAC which is considered to be the core of the ISC X-ray source. A newly developed X-band LINAC has been proposed that is already designed, fabricated, tested and many units of them are fully functional without any problems which made it the best candidate for stable and powerful ICS source. This was confirmed using CAIN code simulation and the results indicate that the resultant parameters of the generated monochromatic X-ray satisfy the main requirements of many advanced radiological applications such as Dynamic Intra Venous Coronary Arterio Graphy, early diagnosis of breast cancers and therapy for cancers using Auger Cascade Radiotherapy.

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