Design of Modulated X-Ray Tube Using Velocity Modulation

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Abstract
A theory of new modulated x-ray tube is proposed. The concept of modulation based on velocity modulation technique. The incident electrons are formed as an electron beam, and by using a bunching cavity, this beam can be modulated. The incident electron bunch will produce a modulated x-ray when strikes the target.

Introduction
The modulated x-ray may well have many useful applications in different fields, medicine, communication, medicine, etc. Some of these applications are:
1. The electron beam can be used as a probe in electron probe microscopy (EPM) [1]. In using the modulated electron beam the probing will survey different depths. Then one can get three dimensional information.
2. In communication filed, the microwave signal can not pass through plasma or any other medium without interaction, which cause an attenuation [2]. Carrying the microwave signal by x-ray give a good possibility to transmit this signal via any absent medium with negligible effect.
3. The microwave ray is easy to be absorbed by wet medium (like living soft tissues, as muscles and fatty tissues). In order to deliver the heating effect of microwave beyond these tissues to hard tissues like bone (that is covered by muscles and fatty tissues). The modulated x-ray can carry this effect via many layers of these soft tissues.

The ordinary x-ray tube of two electrodes supply continuous and characteristic radiation the intensity of radiation is independent of time.

In 1966 Vainshtein and Takemenn [4] built x-ray tube of three electrodes. One of them was an access to introduce a signal (sinusoidal), the signal was over wide range of frequencies. The detected x-ray was modulated. It was shown that when modulation frequency is chosen properly, sensitivity of recording weak intensities can be increased. In 1980 A. John improved flash x-ray by using the grad-1 interaction [4]. Banuz and Dila proposal a pulsed x-ray system as a measurements technique for fluorescent lifetime [5]. In this model, the modulation based on using of pulsed laser and photocathode to generate pulsed electrons.

In the present attempt we are going to design a model of modulated x-ray tube. The theory of this new tube follows the modulation technique that can deal with the electron beam; that modulation technique is the velocity modulation [6]. Accordingly the modified tube can supply a modulated intensity.

The Tube
The intensity of ordinary x-ray radiation is dependent on both of the current and voltage of the electron beam of the tube in addition to the property of the target. For continuous radiation, the continuous intensity is [7]

$$I_{cont} = A!ZV_n$$

where

- $I_{cont}$ is the continuous intensity.
- $A$ is a proportionality constant.
- $i_e$ is the electron current.
- $Z$ is the atomic number of the target.
- $V_n$ is the cathode emission voltage.
- $m$ is a constant and approximately equal 2.

It is obvious that both of the current and voltage play an important role in the nature of the generated radiation. Therefore, this role will be empirical to generate the modulated x-ray.

The concept of this new model is depicted in Figure 1. Unmodulated electron beam passing through a cavity. When an external A.C. signal is applied on the cavity, the electrons will gain or lose energy. In other word, a velocity modulation takes place. When the modulated electron beam strike the target, a modulated x-ray will produce.

![Diagram](image)

Figure (1): The concept of the modulation technique.

The modulation
The velocity modulation was proposed by Varian Broth [8] to produce microwave, and it was
Theoretical study by Webster [9]. The model is for nonrelativistic electrons and confined by an external magnetic field. The model proposed two considerations: purely ballistic where no space charge effect and particle-like where processes are controlled by space charge. In the present work we will adopt the concept of medium-like model. Figure 2 shows the general structure of the proposed tube.

**Figure (2):** The structure of the modulated x-ray tube. 1-electron gun, 2-cavity, 3-electron beam, 4-solenoid magnetic field, 5-target, 6-cooling way, 7-x-ray window, 8-envelop.

The mean steps of its work as follows:
1. It is important to use a magnetic field to construct an electron beam of finite radius (b) and its D.C. current is $I_e$.
2. Inserting a cavity in the path of the beam, to change the energy of the electrons that pass through it. The cavity is excited by a signal generator. Let the signal like $V = V_0 \sin \omega t$.
3. The energy of electron after leaving the cavity is:
   $$ eV = eV_0(1 + A \alpha \sin \omega t) \quad (2) $$
   Where
   $A$: Coupling factor
   $\alpha = V_0 / V_0$: excitation ratio

In case of finite radius beam in a metal drift tube, the modulated current along the z axis of the tube is [6]:

$$ i(z) \sim -\frac{V_0}{\omega F} \frac{\sin \frac{F \omega z}{U_a}}{F \omega_p} \quad (3) $$

Where
$F$: reduction factor
$U_a$: DC electron velocity
$\omega$: angular frequency of the signal
$\omega_p$: angular plasma frequency of the electron beam
The angular plasma frequency is related to the DC property of the tube.
4. The electrons that leave the cavity are modulated and form an accumulation called bunch of electrons. This bunch arises in a certain position far from the cavity. This is the optimum position $z_{opt}$ [6]:

$$ z_{opt} = \frac{\alpha U_0}{2 \omega_p} \quad (4) $$

4. The target that produces the radiation should be placed in this position, to receive the bunch of electrons, that have different energies.
5. The generated x-ray will be modulated according to these bunches. If we regard the continuous radiation (eq.1), and by using eqs. 3, 3 and 4, the modulated intensity ratio is:

$$ \frac{I_{mod}}{I_{cont}} = \frac{\alpha \sin \omega t}{\cos \omega t - \alpha \cos \omega t} \quad (5) $$

Where:
$I_{mod}$: The modified intensity.
$I_{cont}$: The ordinary continuous intensity.

This ratio is controlled by $\alpha, \omega / F \omega_p$. According to eq.5. Figure 3 shows the modulated intensity of the radiation for electrons of $U_a = 1.26 \times 10^4$ V, $\omega$: $2.12 \times 10^3 \times 10^{-15}$ m, $\omega_p = 2.5 \times 10^6$, with a frequency of $10^6$ Hz, which is within the limit of classical approximation. For the case of $\omega = 2.12 \times 10^3$, $V_e = 1.2 \times 10^4$ V, $U_a = 2.297 \times 10^3 \times 10^{-15}$ m, $\omega_p = 2.5 \times 10^6$, these values are within the range of what are used in x-ray and microwave tubes [6]. A similar result may be obtained in dealing with the problem via the concept of the total energy loss over the time during bremsstrahlung process.

If the carried wave is microwave of frequency of order of $10^6$ Hz, whereas x-ray (carrier) frequency of order $10^{11}$ Hz. So the ratio of tuning variation is of order $10^6$. This ratio allowed the modulated electron to deliver its energy and produce x-ray before a significant change in the information takes place.

**Figure (3):** The ratio of the modulated x-ray intensity to the continuous intensity for different values of $\alpha$, according to eq.5.
Design Consideration

The design parameters of the tube depend on the drift region $x_0$ and the radius $b$. Eq. 4 controls the $x_0$ whereas the radius is controlled by the reduction factor $F$. The relationship between $F$ and the normalized beam radius $B = \frac{m \beta \mu}{e} \sqrt{V_0}$ is depicted in Figure 4 [10]. The figure shows various curves of different $n$, where $n$ is the ratio of tube radius $(a)$ to the beam radius $(b)$. The radius of the uncollimated beam $(b)$ is related to the applied magnetic field $(B)$, where this field is considered as a Brillouin field [11].

\[ B = 7 \times 10^4 \left( \frac{1}{b^2 \sqrt{V_0}} \right) \]  

(8)

Where $I_n$ is the D.C. electron current.

![Figure 4: Space charge reduction factors for cylindrical beams in cylindrical tunnel [10].](image)

Conclusion Remarks

1. The ratio of $I_{read} / I_{ref}$ is larger than unity for the case of $\theta > \theta_r$.
2. The minimum x-ray wavelength is [from eq. 2]
\[ \lambda_{min} = \frac{12040}{\nu_0} \left(1 + \frac{\pi \nu_0}{\nu} \right) \]  

(7)

So the output is a spectrum of different wavelength rays; note Figure 5.
3. The modulated x-ray looks as a pulse train as $\nu$ increases.

![Figure 5: The variation of minimum wavelength (in $\AA$) with the single time, according to eq. 7.](image)

References


الخلاصه

تم أجراء دراسة لпредел حساسية الموجات الإلكترونية المختلطة التي تؤدي إلى انتاج اشارة عالية في إحداثية التحمل في إنتاجية الموجات الإلكترونية. وهي هذه الخصائص التي تم الحصول عليها معرفة كثيرة من الاستخدامات المختلفة في الطرق الفيزيائية، ويستخدم يقوم البرمجة لإعطاء الأمثلة على القدرة الفيزيائية. وتم تحصيل الإشارة على الموجات الإلكترونية في إحداثية الموجات المختلطة على اليو تم تمكين تفاعل هيئة مجهولة المعقدة.