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Improvement of X-ray Quality Using Multiple Electron Beams

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1. Introduction

The improvement of x-ray quality through the increase of brightness and uniformity of spatial intensity distribution is of interest because of several applications including lithography and mammography. Lithography devices require high brightness x-rays that shortens the exposure time [1]. Synchrotrons can generate x-rays with brightness higher than 10^{15} phs/mm^2.mrad^2.s and x-ray free-electron lasers can produce brightness above 10^{22} [2]. Despite the advantage of high brightness, their huge size hinders the table-top applications. Conventional x-ray tubes have limited brightness because of thermionic electron emission. Cold field emission has several advantages in comparison to the thermionic emission, including higher current density and low emittance. Due to these advantages, x-ray tubes based on carbon-nanotube (CNT) have been developed recently [3]. The low threshold field for electron emission and a high current density owing to high aspect ratio makes CNTs as the best field emitters. The brightness of x-ray tube can be increased by minimizing the effective focal spot size. Moreover, the smaller spot size is helpful in increasing the spatial resolution. That is why, microfocus x-ray tubes have now become popular for high-resolution x-ray imaging with greater brightness.

Non-uniformity in the spatial intensity and energy distribution of x-rays affects the image quality. A uniform x-ray beam improves the contrast and resolution. Subject contrast is a consequence of difference in intensity, x-ray energy and object properties [4]. In mammography, x-ray source with low energy and narrow band is preferred. In addition to digital imaging, the uniformity of intensity has a significant role in some applications. In lithography, for example, a non-uniform exposure of the open membrane surface leads to an unacceptable large distortion of the mask pattern due to stress changes [5].

A high-brightness microfocus x-ray tube is under development. In this research, we investigated several parameters of an x-ray tube that affect the beam quality. Since the intensity distribution is a bit Gaussian, therefore the x-ray produced from a microfocus x-ray tube utilizing single CNT field emitter shows limited quality. From the analysis, we propose a method of using multiple electron beams combined with a transmission target, to improve the beam quality through achieving high-brightness, increased uniformity and reduction in the energy band in a CNT-based microfocus x-ray tube.

2. Schematic Layout

A CNT-based microfocus x-ray tube has been designed with the following specifications: brightness ~ 10^{11} phs/mm^2.mrad^2.s, an x-ray spot size of 5 μm, and average x-ray energy of 20-40 keV. The achievement of this level of brightness is challenging. Figure 1 shows the schematic layout of the tube. An electron beam generated from a triode-type CNT field emitter is focused onto a transmission type target through electron optical system. The diameter of the electron beam hitting the target should be less than 5 μm to produce the required effective focal spot size.

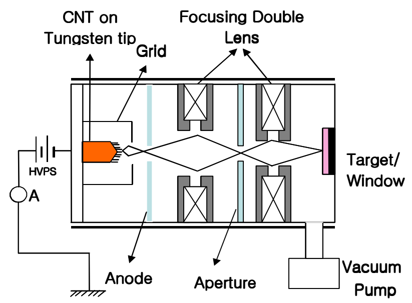

Figure 1. Schematic of CNT-based microfocus x-ray tube.

Reflection type targets with separate windows are widely used. However, the effective spot size of x-ray generated from a reflection target is larger than that of a transmission type because of the multiple scattering of electrons with the atoms in the target. Thin transmission targets limit the spread of the electrons and thus limit the effective spot size of x-ray generation. In addition, the reduction of the distance between x-ray source and object allows high magnification of x-ray images. The target is composed of molybdenum (Mo) film backed by 500 μm thickness of beryllium (Be) backing to ensure the vacuum. Target thickness was optimized as 7.2 μm to have maximum x-ray brightness using computer code MCNPX, when 80 keV electron beam strikes the target.

3. Spatial Distribution of x-ray Intensity and Energy

The characteristic parameters of the x-ray generated from the designed x-ray tube, such as total power spectrum and spatial intensity distribution were calculated at a tally region 5 mm apart from the target, using code MNCPX. The tally region has the area of 6x6 mm^2. The power spectrum is calculated for a total cone angle of 60 degrees, with an average energy of 20.41 keV. For calculation of spatial distribution the tally region was divided into 24x24 sections. Using single electron beam with uniform current distribution, the x-ray intensity distribution is more or less Gaussian with the maximum intensity region located at the centre and intensity decreases for the regions away from the centre. However with this even distribution, at the central part the region of uniform intensity is quite small and hence the corresponding cone angle is also small. Therefore different regions of decreasing intensity are formed causing non-uniformity in the whole pattern. Fluctuations in the energy profile are also exhibited.

4. Results and Discussion

The non-uniformity of the x-ray generated from microfocus x-ray tube deteriorates the quality of x-ray images. A method to increase the central cone angle that exhibits a region of relatively uniform intensity, we propose multiple electron beams. The x-ray distribution in the regions surrounding the central part can be improved if several electron beams emitted form different directions strike the same position of the target. This causes an increase in the central cone angle of uniform intensity region. Figures 2 and 3 show the calculated spatial distribution for the x-ray intensity and x-ray average energy for the single beam and multi-beam configurations respectively. One electron beam that is located on the center of the five beams strikes the target perpendicularly. The other four beams surround the central beam with the same radius and different angular positions: they are separated with each other by 90 degrees. The surrounding four beams are focused into the same position of the target with a focusing angle of 15 degrees.

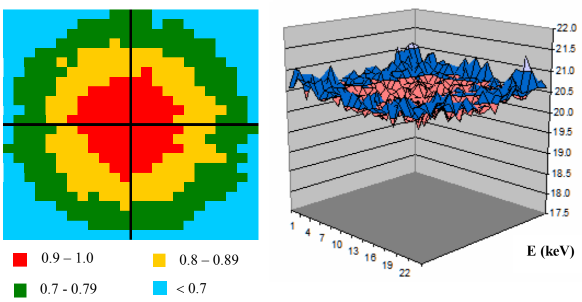

Figure 2. Spatial relative intensity distribution (L.H.S.) and energy distribution (R.H.S.) of x-ray for single electron source.

Compared to single electron beam, the central cone angle corresponding to a region of uniform intensity of x-rays and the average energy distribution got improved when the five beams are used. Since an absolute uniformity is not possible. To define the uniformity, we classified the intensity profiles into five regions of relative intensity. For comparison, we determined the central cone angle for the region that has a relative intensity of greater or equal to 0.95. For the multi-beam case, the cone angle at the central part that has relatively uniform intensity profile, exhibits an increase of about 57% in comparison to single beam case which was 14°. We also compared the cone angles for a bit broader regions of relative intensity. The central cone angles for the region having relative intensity ≥ 0.9 increases by 32% for multi-beam case compared to 25° of single beam case. For further broader region with relative intensity ≥ 0.8, the increase in central cone angle is found to be 12% compared to 43° of single beam case. Fig. 3 and 4 show the typical intensity profiles for single beam and multi-beam cases respectively, for four regions of relative intensity.

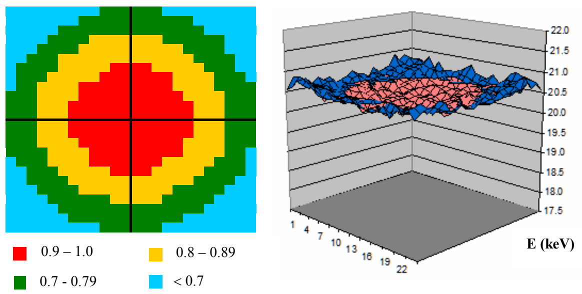

Figure 3. Spatial relative intensity distribution (L.H.S.) and energy distribution (R.H.S.) of x-ray for multi-electron source.

Secondly, the relative deviation of the x-ray energy is reduced from about 22% (single beam case) to 16% (multi-beam case). For multi-beam configuration, the reduction in the average x-ray energy band among the 24x24 sections of the tally region is about 42%. Therefore, the calculated results show that both the intensity and spectral profile of x-ray generated from a microfocus x-ray tube can be greatly improved using multiple electron beams. These two factors also have a significant effect on the spectral brightness.

Therefore, CNT-based microfocus x-ray tube with patterned multiple electron sources can generate an x-ray with a much higher brightness and an improved spatial uniformity compared to the present x-ray tubes.

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