<<Research Paper>> Journal of the Korean Vacuum Society Vol.15 No.1, January 2006, pp.103~109

Design of X-ray Target for a CNT-based High-brightness Microfocus X-ray Tube

Aamir Ihsan, Seon Kyu Kim, Seong Hwan Heo, and Sung Oh Cho*

Department of Nuclear & Quantum Engineering, Korea Advanced Institute of Science and Technology, Daejeon 305-305

(Received August 24, 2005)

A target for a high-brightness microfocus x-ray tube, which is based on carbon nanotubes (CNT) as electron source, is designed. The x-ray tube has the following specifications: brightness of 1×10^{11} phs/s.mm^2.mrad^2, spot.size ~ 5 μm, and average x-ray energy of 20~40 keV. In order to meet the specifications, the design parameters of the target, such as configuration, material, thickness of the target as well as the required beam current, were optimized using computer code MCNPX. The design parameters were determined from the calculation of both x-ray spectrum and intensity distribution for a transmission type configuration. For the thin transmission type target to withstand vacuum pressure and localized thermal loading, the structural stability and temperature distribution were also considered. The material of the target was selected as molybdenum (Mo) and the optimized thickness was 7.2 μm to be backed by 150 μm beryllium (Be). In addition, the calculations revealed that the maximum temperature of the transmission target can be maintained within the limits of stable operation.

Keywords : Microfocus, X-ray tube, CNT, High-brightness, X-ray target

Ⅰ. Introduction

Microfocus x-ray tubes have become popular now-a-days because they provide high quality imaging of micron level size components. The basic elements that govern the quality of x-rays are the brightness and focal spot size. The modern x-ray sources are being designed with an emphasis on the focal spot size, because the resolution is largely governed by the focal spot size [1]. Microfocus X-ray machines with micron size focal spots can provide an enhanced flaw detection capability with greater reliability than that attained with conventional radiographic equipment [2]. A micron sized focal spot also helps to increase the brightness of x-rays. High brightness of x-rays is desirable for fast x-ray imaging with high spatial resolution. Radiation facilities like synchrotron can produce x-rays with brightness higher than 10^{15} phs/s.mm^2.mrad^2 and several free electron lasers (FEL) are being constructed which are capable of generating x-ray brightness higher than 10^{22} phs/s.mm^2.mrad^2 [3-4]. However, quite huge size of these facilities constrains their lab-scale applications. The conventional x-ray sources providing lab-scale applications have limited brightness less than 10^8 phs/s.mm^2.mrad^2.

These conventional x-ray sources use thermionic emission, where electrons are emitted from hot filaments [5]. Now the carbon nanotubes (CNT) have proved themselves as excellent field emitters, because of high electron

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* [E-mail] socho@kaist.ac.kr

emission efficiency at low voltage due to their high aspect ratio [6]. X-ray tubes using CNTs as electron source have also been developed recently [7-8]. However the brightness is limited. Compared to thermionic emission, cold field emission has various advantages, for example the quality of electron beam is greatly improved. The generated electron beam has high current density and lower emittance. Moreover the field emission x-ray radiography has been of immense interest in the x-ray technology field, since it can miniaturize the entire tube structure [9]. Based upon these considerations, we present here the design of a target for a CNT based high brightness microfocus x-ray tube which is under development.

II. Basic Schematic

We have designed the target of a CNT-based high-brightness microfocus x-ray tube which is presented here. Figure 1 shows the basic schematic of the CNT based microfocus x-ray tube. It has the following specifications: brightness of 1 X 10^{11} phs/s.mm^2.mrad^2, focal spot size ~ 5 μm, and average x-ray energy of 20~40 keV. The electron beam is generated by the CNT cold field emitter. It is desired that the diameter of the electron beam while striking the target should be less or equal to 5 μm, in order to produce an effective focal spot size of 5 μm. An electron optical system is employed to focus the electron beam at the focal spot on the target. The electron optical system mainly consists of grid, anode, variable aperture and double solenoid focusing lens system.

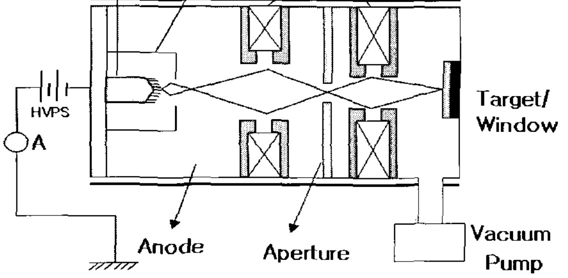

Fig. 1. Schematic of the CNT based microfocus x-ray tube

III. Design Scheme and Methods

The designing of the target of the CNT based high brightness microfocus X-ray tube is a challenging job from the viewpoint of high-brightness. It requires special considerations of target design parameters which are mainly based upon the x-ray output or intensity. Although the x-ray intensity is the most important one but carrying out the x-ray spectrum calculations alone is not enough. The target designed on the basis of x-ray intensity calculations for certain geometry must also be feasible from the real engineering point of view. Thus our design scheme is primarily focused on the calculation of X-ray spectrum while considering mechanical strength of the structure and heat loading.

3.1 Design Parameters of the Target

We employed a transmission type configuration for the designing of the target of the X-ray tube as shown in Figure 2. Transmission type is selected because it not only provides inline geometry but also helps in limiting the focal spot size by using thin targets [1]. Micron level thickness of target limits the spreading of electrons inside the target itself and the effective focal spot size is also limited. However the thin target requires a low Z backing material to ensure the structural integrity. Moreover transmission configuration allows keeping a small focus-object distance which provides high magnification. On the contrary, the focus-object distance

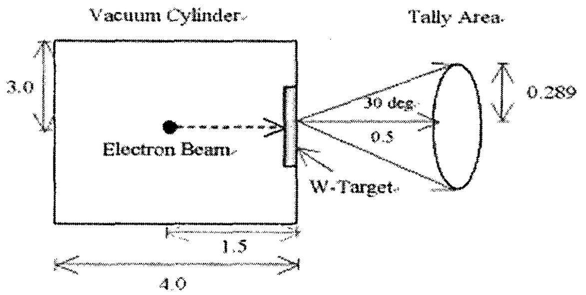

Fig. 2. Basic simplified schematic of transmission type geometry.

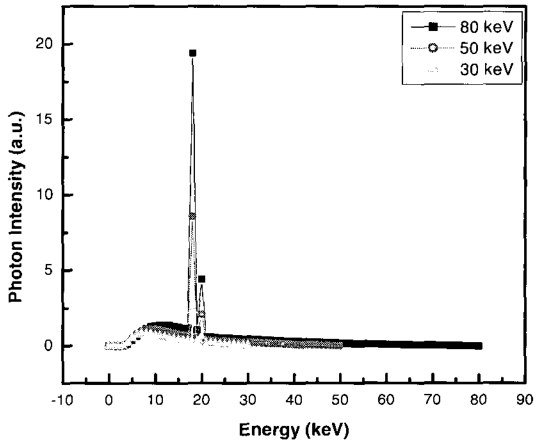

Fig. 3. Comparison of x-ray spectrum at different electron beam energies for molybdenum target.

cannot be minimized below a certain value in case of the reflection targets. It is because that the target exists inside the vacuum chamber and is apart from the x-ray window.

To meet the design goals we considered various design parameters which include the incident electron beam energy, target material and its thickness. The right combination of these parameters would result in the desired level of brightness and average x-ray energy. For this purpose x-ray spectrum was calculated by Monte-Carlo simulations using MCNPX code [10]. To determine the incident electron beam energy, we modeled the calculation scheme with computer code MCNPX for arbitrary target geometry with molybdenum target. The target was bombarded with different electron beam energies, e.g., 30, 50 and 80 keV. A comparison of x-ray spectra corresponding to different electron beam energies is shown in Figure 3. The comparison of x-ray spectra suggests 80 keV incident electron beam energy as suitable with small value of beam current and the average x-ray energy within the desired range.

After the incident electron beam energy was chosen, we determined x-ray spectrum for molybdenum and tungsten transmission type targets with 80 keV incident electron beam energy. Table 1 shows a brief comparison between the results obtained for molybdenum and tungsten transmission type configurations. This comparison is based on the values of brightness level, average energy and the required beam current to achieve the desired value of brightness. The brightness is normal-

Table 1. Comparison between tungsten and molybdenum transmission type targets.

Target Thickness (μm)	Brightness phs/s.mm^2.mrad^2 (X 10^{-04})		Beam Current Required to Produce Brightness of 10^{11} (μA)		Average X-ray Beam Energy (keV)	
	W	Mo	W	Mo	W	Mo
1.0	3.46	1.58	46.20	100.97	22.4	18.09
2.0	6.29	3.31	25.44	48.31	22.9	19.3
3.0	7.41	5.02	21.60	31.88	23.5	19.61
4.0	7.09	6.44	22.58	24.84	24.8	19.69
5.4	5.95	7.6	26.90	21.06	27.3	19.87
7.2	4.77	7.89	33.55	20.28	30.40	20.41
10.8	3.50	7.04	45.71	22.71	35.0	21.68
16.0	2.60	5.89	61.52	27.15	39.4	22.89
21.5	2.12	5.11	75.35	31.29	42.1	23.62
27.0	1.81	4.51	88.35	35.50	44.0	24.2

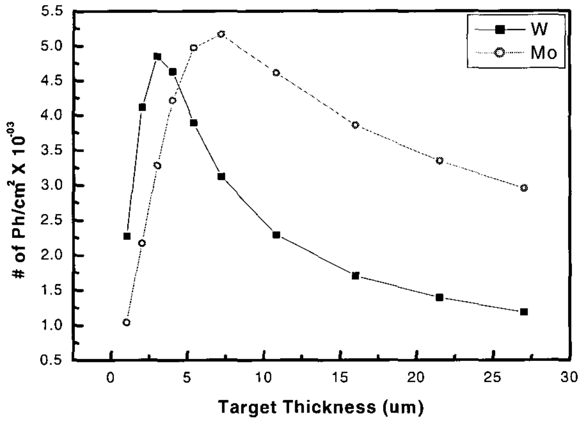

Fig. 4. Comparison of photon intensity as a function of target thickness for tungsten & molybdenum transmission targets.

ized to one electron and maximum value is obtained for 7.2 μm thick Mo. Using this value of brightness produced per electron, the beam current required to produce the desired brightness(1×10^{11} phs/s.mm^2.mrad^2) is determined. The results show that the beam current is minimum (20.28 μA) for 7.2 μm thickness of molybdenum to produce the desired brightness ~ 10^{11}. A graphical presentation is also shown in Figure 4. The comparison clearly indicates the benefits associated with the choice of molybdenum as the transmission type target of the x-ray tube.

3.2 Consideration of Engineering Problems

In the transmission type x-ray tube, thin target foil is used to limit the focal spot size and in order to provide structural stability we considered a thick backing material with the target. To minimize bremsstrahlung production low Z backing like Beryllium is preferred. This laminated configuration of target and backing is also serving as a vacuum separator. The required thickness of the backing material to withstand the pressure difference is calculated on the basis of the pressure gradient. It should be such, that the structural failure due to pressure difference must not occur and the maximum value of stress due to the pressure difference should not surpass the tensile strength of target or window material [11]. For a pressure loaded disk supported around its circumference, the maximum stress and midpoint deflection are defined as [12]:

$$s_{max} = K_s(pr_o^2P/t^2),\ K_s = 0.398$$

$$y_{max} = K_d(pr_o^4P/E_mt^3),\ K_d = 0.212$$

where ro is the radius of the disk, P is the pressure difference, t is the thickness of the disk and E_m is the elastic modulus. Based on these equations we calculated the maximum stress, s_{max}, borne by beryllium backing for different thickness at the operating temperature. For r_o = 0.5cm, P = 101.3 MPa, the minimum thickness of Be for which the maximum stress is less than the tensile limit, is found 150 mm. s_{max} is 140.66 MPa, whereas the tensile strength of Be at 538 K (max operating temperature) is around 200 MPa [13]. The calculation results therefore, suggest that the molybdenum foil must be backed with beryllium having a minimum thickness of 150 mm. The effect of backing layer on the x-ray brightness was also considered. Table 2 shows the results of the brightness produced per electron, and the required beam current to produce the desired level of brightness (1×10^{11} phs/s.mm^2.mrad^2) with the backing configuration and its comparison with that of an unbacked one.

Another point of concern is the thermal loading and heat dissipation. The electron beam when impinges upon the target, most of the energy imparted by electron beam is converted into heat. In the case of thin transmission type foil, electron beam strikes the central region whose diameter is just 5 μm, and whole of the heat energy is deposited in this small area. The accumulation of heat in the micron size area may cause localized melting of the target. That is why the consideration of the thermal loading and efficient

Table 2. Results of x-ray spectrum calculation with beryllium backing.

Be Thickness (μm)	Brightness phs/ s.mm$^{2.}$mrad^2 (X 10^{-04})	Average X-ray Beam Energy (keV)	Required Beam Current (μA) (for brightness 1011)
0	7.89	20.41	20.28
150	7.71	20.77	20.74
200	7.68	20.84	20.84
250	7.65	20.89	20.92
300	7.62	20.93	20.99
400	7.58	21.01	21.12
500	7.53	21.08	21.24

removal of heat from the target are so important. Fortunately, not all of the energy carried by the electron beam is converted into heat. Its effective value depends upon the energy which is transmitted through the target. The total power of the electron beam with 80 keV beam energy and a beam current of 21 μA is about 1.68 watt. The bremstrahlung power is calculated about 0.00338 watt. The stopping power of 80 keV electron beam in molybdenum is about 2.913 keV/μm. Based on this, the transmitted electron energy is estimated about 57.99 keV. Therefore the real or effective contribution to thermal loading by the 80 keV electron beam is just 22 keV. Hence for real thermal loading calculations, the incident power is about 0.462 watt.

We calculated the maximum temperature at the foil centre as well as the temperature distribution in the interior of the target and the backing. The temperature distribution in a bare molybdenum foil (without backing) is determined both by analytical and computational techniques, whereas the temperature distribution within the molybdenum target along with beryllium backing layer is evaluated by computer simulation. Computer code FLUENT [14] was used for the simulation of this thermal problem.

For analytical calculations, the temperature of the focal spot is estimated by assuming that when the target is so thin that electrons penetrate through it, as in this case, then the energy is supplied to the metal throughout an approximately cylindrical volume [15]. Assuming that this supply is uniform along the path t (thickness), and that the front and rear faces of the target are at the same temperature T_1, the flow of heat is purely radial and is given as:

$$E_R = k(T_1 - T_2)2pt / \ln(r_2/r_1) \qquad (1)$$

Where r_1 is the radius of focal spot at temperature T_1, r_2 is radius of foil at temperature T_2 and E_R is the rate of dissipation in watts. Assuming that T_2 is maintained at 300 K, equation (1) gives the temperature of the focal spot as 858 K.

Keeping the outer edge of the target foil at 300 K, simulation by FLUENT code showed the maximum temperature at the focal spot as 851 K and 538 K for bare Mo foil (without Be backing) and Mo foil with Be backing respectively. The melting point of Mo and Be are 2883 K and 1563 K respectively [13]. The

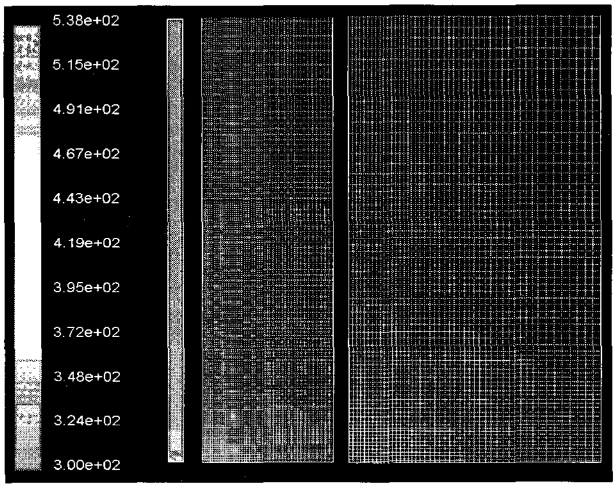

Fig. 5. Axial symmetric temperature profile for 7.2 μm Mo target backed with 150 μm Be layer after being irradiated by 80 keV electron beam

axial symmetric temperature profiles for the backing configuration determined by the FLUENT code are shown in Figure 5 with some enlarged views.

IV. Conclusion

We have designed the target of a CNT-based microfocus X-ray tube having the brightness ~ 10^{11} phs/s.mm^2.mrad^2, spot size ~ 5 μm, and average x-ray energy of 20~40 keV. The target specifications or parameters are designed on the basis of calculations performed for X-ray spectrum and the consideration of thermal loading and structural mechanical stability. The calculations suggest that 80 keV electron beam will produce X-rays with the desired energy. Table 1 shows that molybdenum transmission target with an optimum thickness of 7.2 μm exhibits maximum brightness and the beam current required to produce the desired level of brightness is also found minimum with this molybdenum thickness.

The laminated transmission configuration provided required stability of the structure to withstand the pressure difference. As depicted from Table 2, the results seem to be very favorable from the point of view of x-ray generation. With 150 μm beryllium backing, there is very minute increase in the beam current to produce the brightness ~ 10^{11} (approx 2%) as compare to that without backing. Even with 500 μm beryllium backing, the increase in beam current is just 0.96 μA. The calculations for thermal loading and heat dissipation also revealed the possibility of a safe operation and the melting of target will be avoided.

It is therefore concluded that the transmission type laminated configuration composed of a 7.2 μm molybdenum foil backed with beryllium with minimum thickness of 150 μm will serve as the target for this high-brightness CNT-based microfocus X-ray tube. An 80 keV electron beam with a current of 20.8 μA will be needed.

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≪연구논문≫ 한국진공학회지 제15권 1호, 2006년 1월, pp.103~109

탄소나노튜브를 이용한 고휘도 마이크로빔 X-선원 발생부 설계

Aamir Ihsan · 김선규 · 허성환 · 조성오*
한국과학기술원 원자력 및 양자공학과, 대전 305-701

(2005년 8월 24일 받음)

전자빔원으로 탄소나노튜브에 기초를 두고 있는 고휘도 마이크로빔 X선원용 타겟이 설계되었다. X-선원은 다음과 같은 제원을 따른다. 1×10^{11} phs/s.mm^2.mrad^2 고휘도, 5 mm의 빔의 크기, 20~40 keV 평균 X-선 에너지. 제원을 만족시키기 위해서 구성, 물질, 타겟의 두께와 필요한 빔전류와 같은 타겟의 설계 변수들은 MCNPX code를 통해서 최적화되었다. 설계 변수들은 투과형 타겟 구조를 위해 X-선원의 스펙트럼과 세기의 분포의 계산으로부터 결정되었다. 진공압력과 국소화된 열의 누적을 견디기 위한 투과형 타겟 구조를 위해서 구조적인 안정성과 온도 분포도 또한 고려되었다. 타겟 물질은 몰리보덴으로 선택되었고 최적화된 두께는 2 mm로서 150 mm 두께의 베릴륨이 붙여져 있다. 부가적으로 투과형 타겟의 최대 온도가 안정적인 작동의 한계 내에서 유지될 수 있다는 것을 계산을 통하여 알게 되었다.

주제어: 마이크로빔, X선관, 탄소나노튜브, 고휘도, X선 타겟

* [전자우편] socho@kaist.ac.kr