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Event: SPIE Medical Imaging, 2021, Online Only

Characterization of Compact Alumina Vacuum Sealed X-ray Tube for Medical Imaging: Interpretation with Simulation program

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ABSTRACT

We developed a compact vacuum X-ray tube using an alumina body instead of glass. A filament is implanted as a cathode which follows Richardson-Dushman equation. After aging the filament to eliminate impurities on the filament which improves performance of filament before tubing, tube current was obtained from anode voltage of 6kV, 3mA to 40kV, 3.15mA. The pulse high voltage generator is designed and developed to make the tube less stressful. With the ceramic X-ray tube, X-ray images of human breast and teeth phantom were successfully obtained, verifying the potential of the compact alumina vacuum sealed X-ray tube in X-ray application for medical imaging.

Keywords: Alumina, aging process, filament, thermionic emission X-ray, focal spot

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1. INTRODUCTION

In modern times, X-ray imaging is used for early diagnosis, quality control, non-destructive testing, and security scanning. The X-ray imaging equipment typically consists of an X-ray generator and an image sensor. Most commercial X-ray generators use thermal ions using filaments. Filaments have been widely used as cathodes for X-ray tubes [1]. Although some X-ray tubes have metal and ceramic envelopes, most of the X-ray tubes have glass envelopes. Ceramic-to-metal seals have a number of properties that allow for robust, durable compacted seal and high electrical insulation [2]. Brazing of ceramics is a process to join ceramic to metal and ceramic has its potential applications in metal-ceramic seals or vacuum tubes [3]. Furthermore, ceramic-sealed X-ray tubes have a longer tube life than glass-sealed X-ray tubes because of the deleterious effects of tungsten deposits from the release of tungsten vapor from the filament and the target, which can easily accumulate on glass during operation [4]. When the size of the tube decreases, thermal properties of the tube envelop becomes very important, as problems associated with bonding and heat storage start to arise [5]. In this study, we report a compact-sized alumina-sealed X-ray tube for portable medical imaging. The alumina envelop is used to alleviate the heat problems associated with small-sized tubes. Additionally, we seal the tube via a brazing process, which supports higher temperature and throughput than conventional welding.

2. MATERIALS AND METHODS

2.1 CST simulation of E-gun and X-ray tube

Prior to manufacturing the X-ray generator, if you test in advance by entering specific values for various variables through a simulation program, you can save cost and efficiently check the performance. The simulation program used for the test is CST STUDIO SUITE. This program is an electromagnetic field analysis software and includes a variety of functions. Electromagnetic phenomena cannot be seen or felt. Also, since phenomena do not appear intuitively, when an

Medical Imaging 2021: Physics of Medical Imaging, edited by Hilde Bosmans, Wei Zhao, Lifeng Yu, Proceedings of SPIE Vol. 11595, 115953C · © 2021 SPIE
CCC code: 1605-7422/21/$21 · doi: 10.1117/12.2582295

electromagnetic compatibility problem occurs, it is difficult to determine where and what problem is caused. So, the electromagnetic field analysis software helps you to identify and optimize the path through which the generated noise components affect, especially in what part, through visualized electromagnetic field results quickly and accurately [6]. This allows you to optimize device performance.

Using commercialized simulation software called CST (Computer Simulation Technology) PARTICLE STUDIO [7], various modelling of X-ray tube based on cathode to anode distance, shape, and size of the focusing cup and the length of filament were drawn and simulated. Based on those results, an optimized parameter for fabrication of ceramic based X-ray tube was obtained. The optimized parameter was confirmed by the producing the smallest focal spot on the anode as seen in Figure 1 (a). As can be seen in Figure 1 (a), the position of the electrons starting from the cathode is similar to the size of the filament. The electrons move to the anode due to the difference in electrical potential, and the position of the electrons found on the monitor immediately below the anode is proportional to the size of the filament, but it can be seen that it exists in a smaller area. The length of the filament used is 8.6±0.3mm, the number of turns is 23 times, and the cold resistance value is 112±30mΩ. When the axis of the filament, which is the cathode, was viewed in the long direction, it was confirmed that electron trajectories were converged as seen in Figure 1 (b).

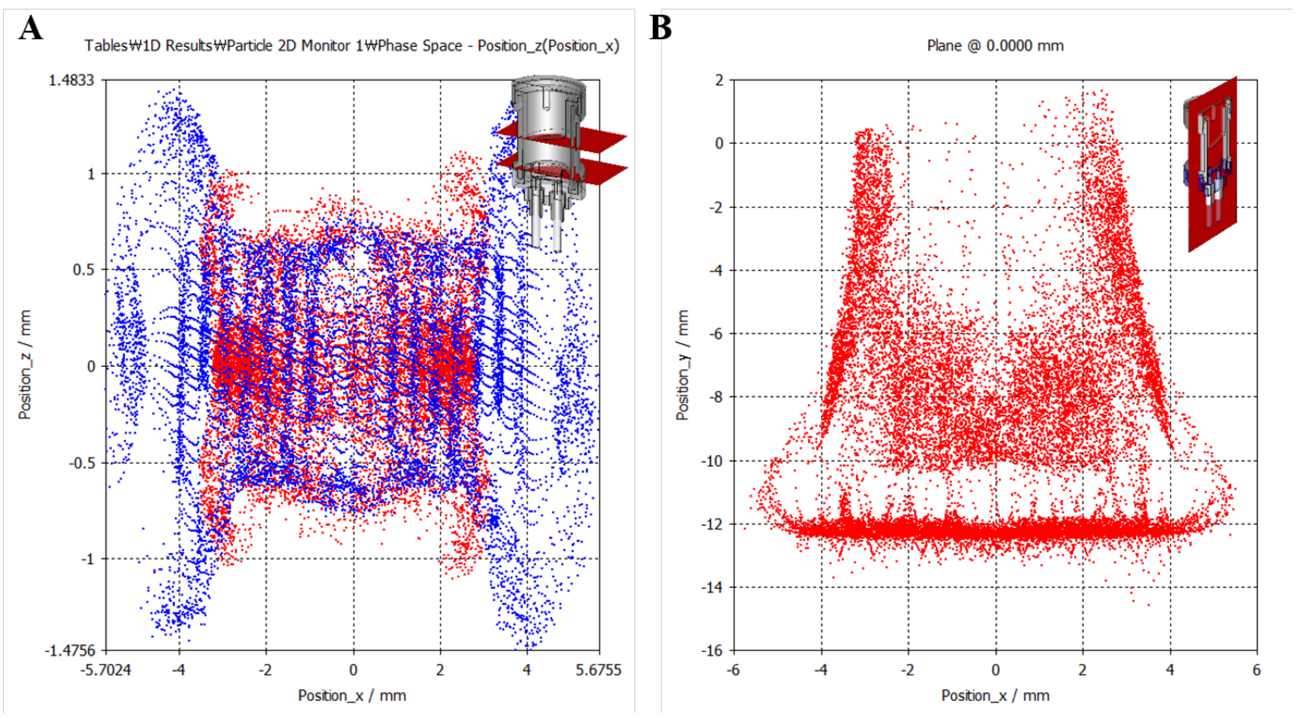

Figure 1. (A) Particle monitor position x abscissa versus z ordinate and (B) Particle monitor position x abscissa versus y ordinate.

One of the important factors characterizing the X-ray generator is the focal spot size, which indicates how small the electron beam is focused on the target [8]. As a general optical principle, the smaller the focal size, the point where X-rays are generated, the higher the resolution of the subject's shadow image. Depending on the purpose of the X-ray tube, the electron beam optical structure of the tube is designed and manufactured so that the focal size is greater than 1mm and the size is less than 1μm. Electrostatic lenses can focus electron beams with a focal size of around 1mm under voltage and current conditions required for non-destructive testing, but magnetic lenses are sometimes used to create focused beams of less than 1μm. The following figure, which is seen as in Figure 2 (a), (b), depicts the process of calculating the actual focal spot and effective focal spot that appear when the tube is driven using a simulation program.

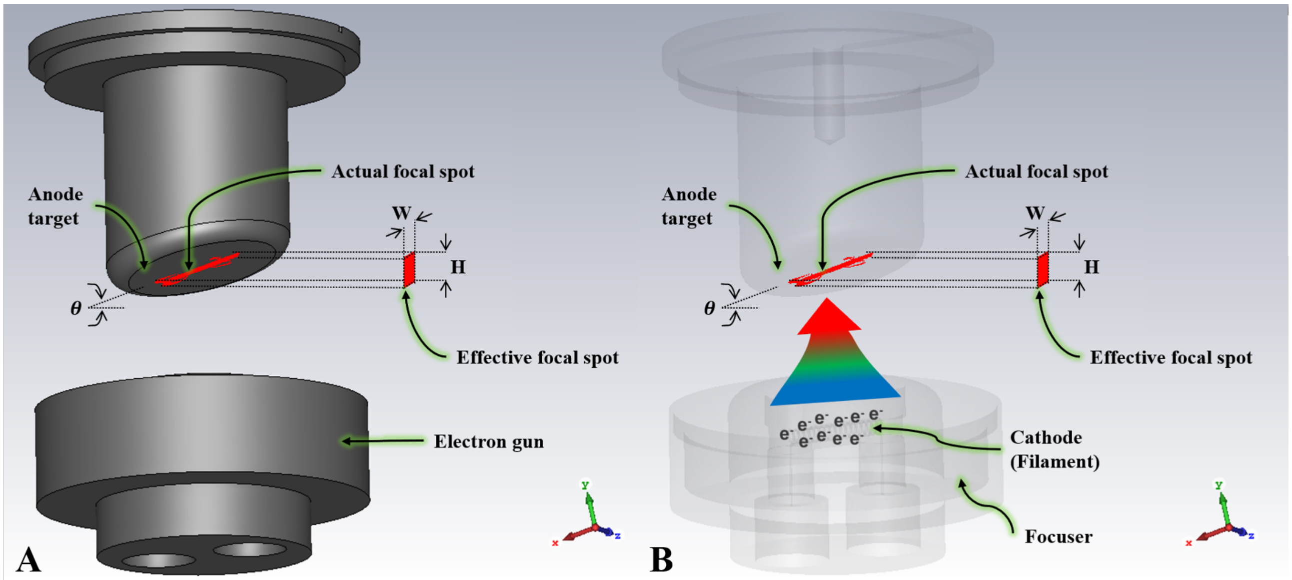

Figure 2. (A) Three-dimensional model of an electron gun and anode to describe the focal spot, (B) Schematic diagram drawn with a transparent structure

In radiography, the line focus principle explains the relationship between the actual focal spot on the anode surface and the effective focal spot size. As the actual target angle theta decrease, so does the effective focal spot. The angle of the anode target of the manufactured X-ray tube is 12.5 degrees. Therefore, the height of the effective focal spot is equal to the value obtained by multiplying the height value of the actual focal spot by sin (12.5 degrees).

2.2 Aging process and I-V Characteristic

Before brazing the ceramic body and the focusing lens, the filament undergoes the aging process for better performance in I-V characteristic [9]. To increase the performance of the filament serving as the cathode, an aging process was performed in a high vacuum state. As can be seen in Figure 3 (a), the tube current slightly exceeded 2mA before the aging process, but after the aging process, the tube's performance was improved by exceeding 5mA at the same filament voltage. As a result of the tube test, it was possible to obtain tube current at high tube voltage from 5 kV to 40 kV which is shown in Figure 3 (b).

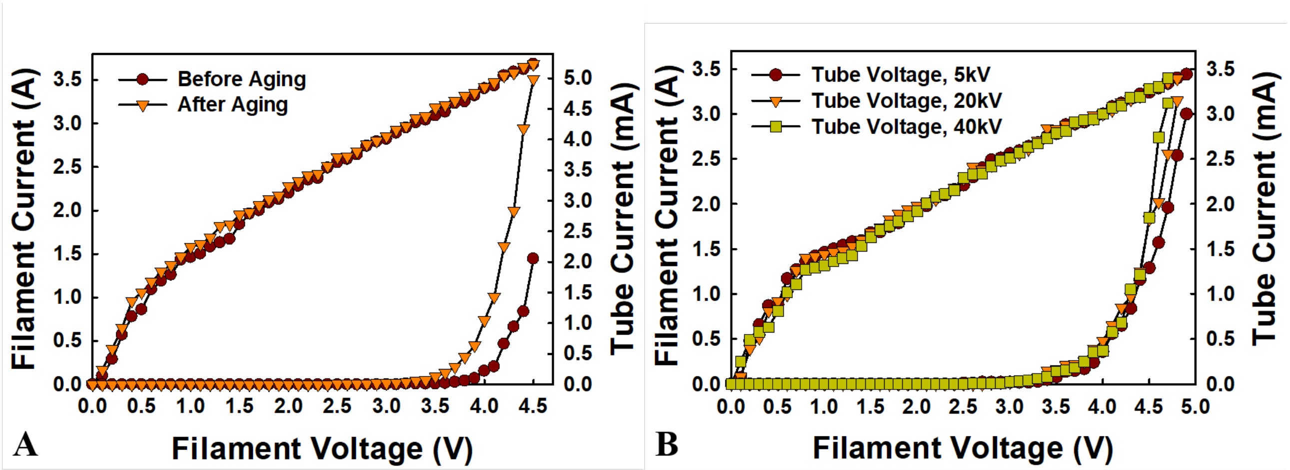

Figure 3. (A) Filament electron gun thermionic emission current-voltage characteristic: comparison according to aging process (B) Filament tube thermionic emission current-voltage characteristic: comparison according to tube voltage

To lessen the stress on the anode, the power supply that applies the tube voltage was pulsated. When the tube voltage band was from 30 to 50 kV, it was confirmed that the pulsing driving of the tube current in the output mode was 1 to 11 mA as seen in Figure 4 (b). Experiments were conducted with continuous and pulse (30 Hz, 0.5 duty) by output mode, respectively.

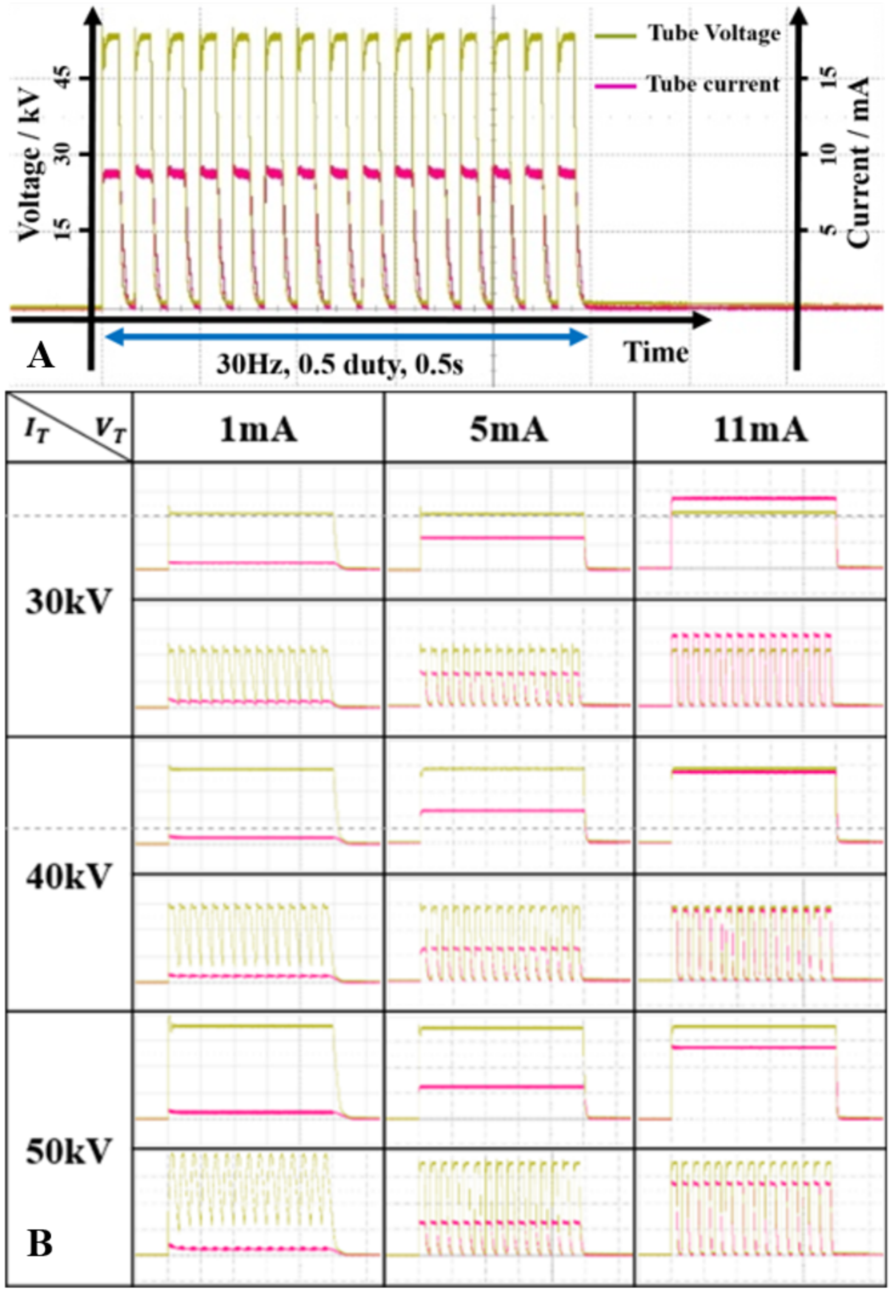

Figure 4. (A) Waveform of filament type tube when output mode is pulse of 30Hz, (B) Waveform of filament type tube when output modes are continuous and pulse of 30Hz

2.3 X-ray Image Acquisition

When X-rays were generated in front of the breast phantom using the tube, X-ray images were acquired. Optical image of the breast phantom is shown in Figure 5 (a). The X-ray image is acquired when the tube voltage is 35kV, tube current is 4.1mA and X-ray exposure time is 0.4s. The acquired X-ray image is shown in Figure 5 (b).

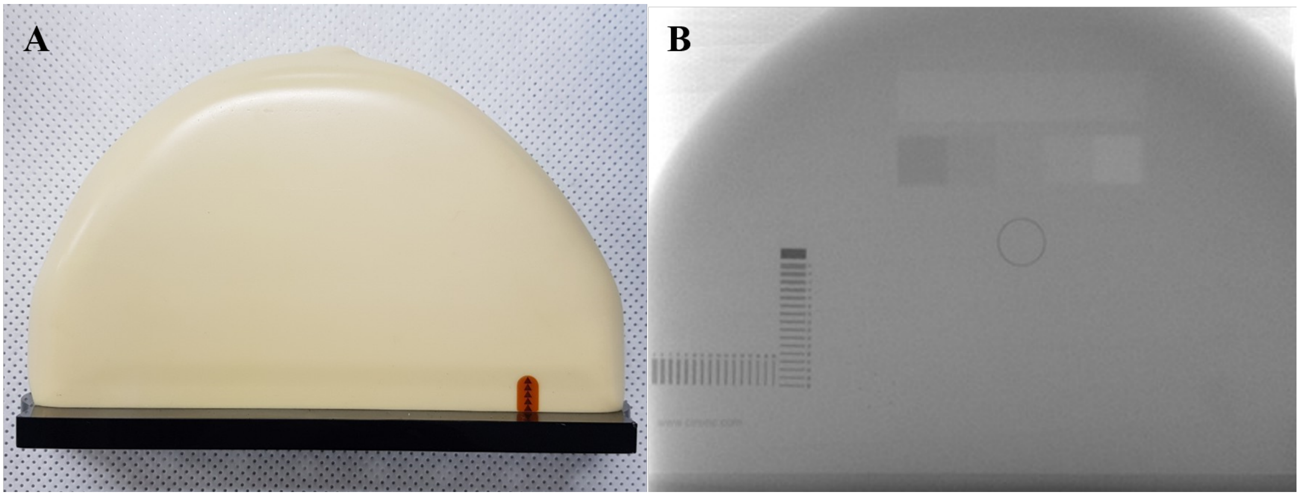

Figure 5. (A) Optical image of breast phantom, (B) X-ray image of the breast phantom.

3. RESULTS AND DISCUSSION

3.1 Focal spot size

The actual focal spot is the size of the area on the anode target that is exposed to electrons from the tube current. And its size depends on the size of filament producing the electron stream. There is a difference between the actual and effective focal spot size. The actual focal size is measured on the target itself. Therefore, actual does not change even if the angle of the target is changed. As the target size increases so does the effective focal spot, while the actual focal spot stays the same. As shown in Figure 6 (a), when an electrical potential of 4kV is given to the anode 40kV and the filament emitting hot electrons, the focal size generated on the anode target is calculated and expressed through a CST simulation program.

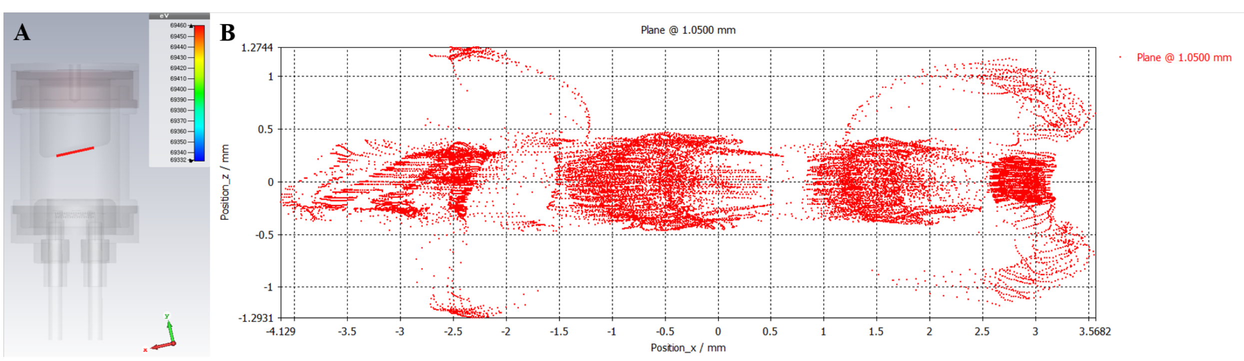

Figure 6. (A) Actual focal spot from CST program, (B) Table expressing the actual focal spot as a position

The filament used length is 8.6±0.3 mm, coil diameter is 0.92±0.025 mm. As can be seen from Figure 6 (b), the actual focal size caused by hitting the anode is about 7.6972mm horizontally and 2.5675mm vertically, which is proportional to the size of the filament.

4. CONCLUSION

Compact alumina vacuum sealed X-ray tube was demonstrated for portable medical imaging. We reported a design of developed X-ray tube with filament as cathode. By using the fabricated X-ray tube, we obtained the X-ray images for breast phantom.

ACKNOWLEDGEMENT

This research was conducted with the support of the 2020 Kyung Hee University [2020 University Innovation] Undergraduate Research Support Project. Also, this work was supported by the Bio & Medical Technology Development Program of the National Research Foundation (NRF) funded by the Ministry of Science & ICT (NRF-2018M3A9E9024942, NRF-2016M3A9E9942010), the Creative Convergence Research Program funded by the National Research Council of Science & Technology (CAP-18-03-ETRI)

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