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Development of X-ray tube for low power X-ray applications

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Abstract: **The X-ray tube remains one of the few vacuum tubes that has not been replaced by solid-state technology, alongside magnetron tubes and other high-voltage vacuum tubes used in radar systems. While many vacuum tubes are readily available online at reasonable prices, X-ray tubes are not produced in the same quantities and are often difficult to obtain, making them quite expensive. This situation is particularly problematic given that X-rays are valuable not only for large-scale industrial and medical imaging but also for small-scale research in fields like physics, chemistry, and electronics. A more affordable and compact X-ray tube would greatly benefit small-scale research efforts. This paper explores the development of such a tube.**

Keywords: **X-ray tube, solid-state technology, radar systems.**

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1. INTRODUCTION

Finding an X-ray tube can be quite challenging, as most available options are designed for specialized equipment that produces high-power X-rays [1]. Conversely, tubes that come with their own operating units tend to be prohibitively expensive for small-scale research, and none can be customized to meet specific experimental needs.

This highlights the potential benefits of developing a compact X-ray tube. The primary challenge in creating a small X-ray tube lies in maintaining a high vacuum; beyond that, the construction is relatively straightforward [2]. Essentially, an X-ray tube functions as a specialized vacuum diode, making it one of the simplest types of vacuum tubes to build.

The two fundamental components are the cathode and anode, designed to generate a directed beam of X-rays (Figure 1). These components must be housed within a glass bulb maintained at very low pressure.

1.1 The cathode

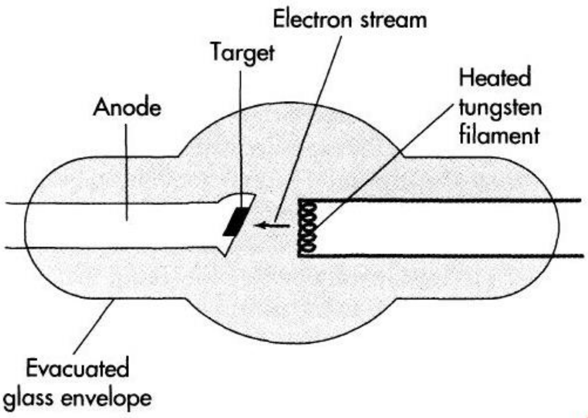

Figure 1. Schematic representation of a standard x-ray tube.

When selecting a cathode for our X-ray tube, we primarily have two options: hot cathodes and cold cathodes.

Hot cathodes consist of a metal, typically tungsten, that is heated to a temperature that facilitates electron emission. To enhance performance, the tungsten can be coated with a mixture of barium, strontium, and calcium oxides. While this configuration is commonly used in commercial X-ray tubes, it presents challenges for a compact design. The lower internal resistance associated with hot cathodes results in increased electron flow, necessitating a higher power supply to accommodate the current draw.

Through experimentation, it was found that a cold cathode is more suitable for the miniature tube. This choice is largely due to the small size and reduced distance between the cathode and anode. The cold cathode is still made of a thin tungsten filament, but it is used for vacuum formation, not for thermionic emission. Cold cathodes require significantly less power to generate X-rays, making them ideal for portable X-ray units. This low power requirement eliminates the need for expensive high-voltage power sources, enhancing the tube's practicality for small-scale applications.

1.2 Anode

These tubes have low power consumption compared to standard models, resulting in reduced anode power dissipation. This enables the use of thin metal anodes without the need for external cooling. Such anodes simplify the glasswork required for tube construction and offer the added benefit of allowing the use of various materials, which can produce different X-ray spectra.

In some experimental tubes, an additional grid is incorporated, connected to the anode and positioned halfway between the anode and cathode. This grid enhances the acceleration of electrons emitted from the cathode.

2. CONSTRUCTION PROCESS

The bulb of the X-ray tube is constructed from borosilicate glass tubing, chosen for its excellent thermal shock resistance, making it easier to work with. Tungsten wires are used to supply power and secure all the essential components inside the tube. While the diameter is flexible, 0.5 mm is ideal for creating sturdy yet manageable electrodes.

To achieve effective vacuum seals, the wires must bond properly with the glass. They should have a smooth, circular profile and must not be sanded, as a rough surface can create air pockets that compromise the vacuum over time.

2.1 Preperation of metal to glass seals

During the production of tungsten wire, certain gases can become trapped within the metal. When the tungsten is sealed in a vacuum, these gases cannot escape. However, when binding the tungsten to glass, the elevated temperatures can cause gas bubbles to form, compromising the seal. To outgas the tungsten wires, they are heated to a white-hot temperature using an oxy-propane flame. Once outgassed, a borosilicate glass tube is placed over the wire and returned to the flame for fusion. The optimal fusion occurs when the glass reaches yellow-hot or white-hot temperatures.

2.2 Inspection of the Seals

Seals are typically inspected using helium leak detectors, but for a more streamlined and reliable production process, alternative methods can be employed. Visual inspection under magnification allows for the detection of cracks or potentially harmful air bubbles. The surface of the tungsten should be clearly visible, with no noticeable refraction or gaps. While some air bubbles are acceptable as long as they are not connected to the metal, the most crucial indicator of a secure seal is the colour of the tungsten surface within the glass. A hermetic seal is indicated by a golden hue. Pure yellow-gold seals occur at higher sealing temperatures, while brown-gold seals are also considered hermetic. Conversely, seals that appear black or silver are generally faulty and likely to leak air.

2.3 Achieving high vacuum

X-ray tubes require a high vacuum for proper operation, but the equipment needed to achieve this vacuum can be quite costly. Therefore, an alternative vacuum production method is implemented. This approach involves using simple mechanical vacuum pumps to create a rough vacuum, followed by the introduction of a chemical compound to further enhance the vacuum.

Before connecting the assembled tube to the vacuum pump, a piece of sodium metal is added inside. The vacuum pump is then activated to achieve a rough vacuum of around 2 Pa. At this point, a gentle flame is applied beneath the section of the tube containing the sodium. The sodium will melt and begin to boil rapidly. Heating should continue until all the sodium has evaporated, filling the tube with sodium vapours. Shortly after, a current is passed through the tungsten filament, heating it to yellow or white-hot temperatures causing the sodium, that has condensed on the relatively cooler filament, to evaporate and coat the inside of the tube. Once this process is complete, the tube is disconnected from the vacuum pump and allowed to cool.

The tube is left to sit for one or more days to allow the sodium to react with any residual air. However, when high voltage is later applied, a plasma forms without generating X-rays, indicating that the tube still contains too much air.

To effectively react the air with the sodium, the following process is employed: the tube is connected to a 300V DC power supply with a 5 kΩ resistor to limit the current to 60 mA. One side of the filament is grounded, while the anode connects to the positive terminal. Initially, nothing should occur. Once current flows through the filament wire, it is heated to a white-hot state, allowing the tube to pass current due to thermionic emission and producing a faint blue plasma. The anode heats up due to electron bombardment, causing the sodium to vaporize. This ionized air and sodium mixture should react at this point. Afterward, the power is disconnected, and the tube is left to cool and stabilize.

The precise chemical reactions occurring during this process are not fully understood, but it is speculated that they lead to the formation of sodium azides and nitrates due to the presence of nitrogen and oxygen. Another theory suggests that the condensing sodium vapor captures air, though this would have a less significant impact on the vacuum. The vacuum at this point should be sufficient for producing low power X-rays.

The first tube produced using this method had sodium that was not fully boiled, resulting in incomplete coating of the entire tube. Subsequent improvements led to better vacuum conditions. This design also allows for clear visibility of the internal components, as well as the additional grid electrode that this tube features (Figure 2).

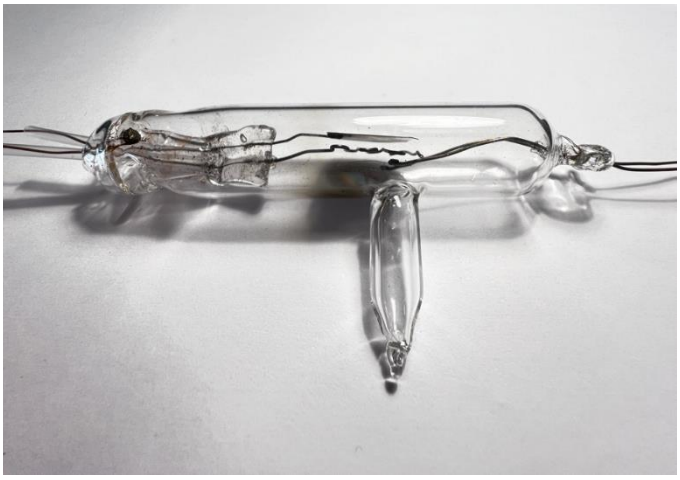

Figure 2. First prototype of X-ray tube.

The second tube was created with sodium boiled to fully coat the entire tube, resulting in a stronger vacuum. This tube utilized the process outlined in this paper (Figure 3).

Figure 3. Second prototype of the X-ray tube.

The third tube benefited from refinements in the process, allowing for a reduced amount of sodium, which made the tube transparent. This decrease in sodium also permits higher voltages to be applied, as the risk of internal arcing is minimized. Additionally, the tube features an anode plate tilted at a 45-degree angle to the tube's axis, effectively directing the X-rays outward (Figure 4).

Figure 4. The final prototype of the X-ray tube.

3. EXPERIMENTAL DATA COLLECTED ON ONE OF THE X-RAY TUBES

3.1 Method

The X-ray tube was tested by measuring radiation exposure at various distances in relation to the input power. This input power is assessed by monitoring the power consumption of the high-voltage supply. Because of the inefficiency of the supply all listed powers must be multiplied by a constant $\eta<1$ for accurate calculations.

3.2 Measurements of X-ray dispersion over distance

The tube was powered and Geiger detector of 1 cm^2 was used. In the table below (Table 1) an overview of the measured results is given.

Legend:

- Average distance of anode plate from detector – d (*cm*)
- Power applied on tube – P (*W*)
- Detected radiation – R ($\mu Sv/h$)

If the X-ray beam is rotated by 45°, the radiation on the detector decreases by over 90% which means that most of the produced X-rays are directed along one direction.

Table 1. Measurements of X-ray dispersion over distance.

P (W)	d (cm)	R (mSv/h)
2,75	2	70
3,75	2	111,86
3,75	3	40,17
3,75	4	27,06
4,05	2	232
4,05	3	72

4. DISCUSSION AND CONCLUSION

The developed tube provides the required X-ray output for low-power applications. The outlined method allows for the replication of the development process, making it accessible to those interested in small-scale research that needs support.

X-ray tubes require a high vacuum for proper operation, but the equipment needed to achieve this vacuum can be quite costly. In this paper an alternative vacuum production method is shown. This approach involves using simple mechanical vacuum pumps to create a rough vacuum, followed by the introduction of a chemical compound to further enhance the vacuum.

This approach to creating an X-ray tube suitable for low-power applications could represent a significant advancement for fields such as materials science and medical research, where compact and easily accessible X-ray sources are highly beneficial.

REFERENCES

[1] Hongfei Zhang, Weibiao Zhou, Chapter Eight - Low-energy X-ray irradiation: A novel non-thermal microbial inactivation technology, Editor(s): Fidel Toldrá, Advances in Food and Nutrition Research, Academic Press, Volume 100, 2022, Pages 287-328, ISSN 1043-4526, ISBN 9780323990820

[2] Wuhrer, R. , Moran, M. Low voltage imaging and X-ray microanalysis in the SEM: challenges and opportunities 2016 IOP Conf. Ser.: Mater. Sci. Eng. 109 012019 DOI 10.1088/1757-899X/109/1/012019