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Construction and Characterization of the Diode and Triode Electron Sources for EBM 300 keV/20 mA

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Abstract. The technical challenge in constructing the electron source (ES) lies in the joining of metal and ceramic tubes. Furthermore, there is a lack of available technical comparison data for the output performance between the diode and triode ES under the same experimental conditions. The research aim is to describe a simple technique for constructing the diode and triode ES for an electron beam machine (EBM) of 300 keV/20 mA, and to investigate their output characteristics. The method used is to make a flange for mounting the Tungsten filament, Pierce electrodes, and heat shield. Two or three electrodes of the NEC (National Electric Corporation) accelerator tube are removed before the flange is united into the NEC tube, becoming the ES. The ES's are investigated in terms of their electron beam profiles and beam current output for the variation of the extraction electrode voltage as well as the focusing electrode voltage. The experimental results show that for the triode ES, the focusing electrode voltage greatly affects the shape of the electron beam profile up to 3 kV. However, for the diode ES, the shape of the electron beam profile is slightly affected by the extraction electrode voltage. The beam current output increases rapidly with the increase of the extraction electrode voltage up to 2.5 kV. Above this voltage, the beam current slowly increases, and it tends to reach saturation. The diode ES provides a higher electron beam current output than the triode ES output, but the triode ES provides a better shape of the electron beam profile. The constructed ES can provide the electron beam current of 40 mA at the filament current of 18 A.

Keywords: Beam current; Beam profile; Diode and triode; Electron source; Extraction anode; NEC tube

1. Introduction

The Electron Beam Machine (EBM) is a type of electron accelerator technology that has been widely utilized in industry as a tool for electron beam processing of an object for various purposes. Prominent applications of EBM are the cross-linking of wire and cables (Seung-Tae *et al.*, 2022), surface curing of materials (Fichtner *et al.*, 2021), sterilization of medical products (Gotzmann *et al.*, 2018), and food irradiation (Pillai and Pillai, 2021). When EBM is used for sterilization, this technology has more benefits than sterilization using UV light (Widiyati and Poernomo, 2018), gamma rays (Febriasari *et al.*, 2021), or ozone gas (Abuzairi *et al.*, 2022) EBM is commonly employed for mass production due to its non-reliance on Co-60 radioactive sources, fast sterilization process, and environmentally friendly nature. The EBM has also been used to study materials sciences

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(Lee *et al.,* 2022), as well as to do vulcanization of the natural rubber latex (Reowdecha *et al.,* 2021).

One of the main components of the EBM is the electron source (ES), which generates the electron beam. The use of ES is not only for EBM but also for X-ray radiotherapy (Matejcek *et al.,* 2023), for welding (Xiaomeng *et al.,* 2021), for Electron Linac (Toonen *et al.,* 2021), and microwave tube devices (Iqbal, et.al., 2021). The ES at least consists of a filament, a cathode electrode, an anode electrode, and a vacuum chamber. Parameters of quantity and quality of the ES include the electron beam intensity and the beam emittance (Alabdullah, 2022; Eckert *et al.,* 2022).

Research Centre for Accelerator Technology has been constructing the EBM for irradiation processing of the natural rubber latex with the specification of 300 keV/20 mA. It needs the ES, which can provide the electron beam current output of at least 30 mA with a better beam diameter profile. Taufik and Darsono have carried out the simulation of the diode ES by using two NEC (National Electric Corporation) accelerator tubes for EBM latex using 3D OPERA software (Taufik and Darsono, 2014) Their results indicate that the placement of the filament against the cathode electrode and the shapes of the electrodes are the main keys to achieving a well-defined beam shape and effective electron beam transport. Another researcher has carried out a simulation design of three electrode electron guns or the triode ES (Matsievskiy and Savin, 2014). Their results show that the electrode inserted between the filament cathode and the anode functions to control electron emission from the filament and to form the beam shape. The main problem in the ES's construction is insulation between its electrodes because it is not easy to join a metal electrode with a ceramic tube, which can be used for high vacuum operation. To overcome this problem, Darsono *et al.* have reported the simulation using 3D OPERA software and the preliminary construction of the triode ES by taking advantage of the NEC accelerator tube (Darsono *et al.,* 2017). Their experimental results show that the filament position and the difference in electrode voltages are very influential to the beam shape and its trajectory.

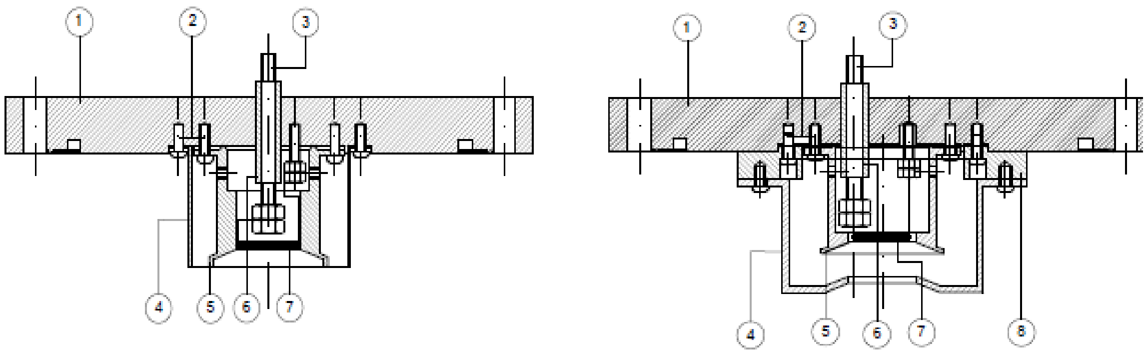
The importance and novelty of this research lie in the simplicity of the construction technique for the ES, and notably, there has been no prior investigation comparing the technical data of the output performance between diode and triode ES under the same experimental conditions. These data are very important to choose the suitable ES which will be used in the EBM of 300 keV/20 mA for irradiation processing of the natural rubber latex. Therefore, the output performance of the diode and triode ES is crucial to be investigated. This paper describes the construction and characterization of the locally made ES by taking advantage of a general accelerator tube of NEC. Two types of ES, namely the diode and the triode ES, were constructed and investigated in this research. The two ES use the electrode of Pierce type with the same specification, and they use the tungsten filament of spiral shape with the same diameter. The purpose of this research is to get the characteristic data of the ES output consisting of the electron beam profile, and the beam intensity.

2. Methods

In the construction of the ES, some important things that should be taken into account are the shape of the filament, the electrode shape, the distance between electrodes, the hole of the electrodes, and the materials used. The materials must meet the UHV (ultra-high vacuum) standard, and mechanical work must use precise machinery. The ES characterization uses the fluorescent detector to monitor a beam profile shape and uses the Faraday Cup to measure the electron beam output.

2.1. Construction of Electron Source

In this work, the construction of the diode ES is based on the simulation result done by Taufik and Darsono (Taufik and Darsono, 2014). Meanwhile, the construction of the triode ES is based on the simulation result conducted by Darsono *et al.* (Darsono *et al.*, 2017) In this work, the NEC accelerator tube of a general-purpose type 2 JA 004 150 is used as an ES chamber and as an electron acceleration. The technical drawing of the ES is depicted in Figure 1a for the diode ES and Figure 1b for the triode ES. A description of the Arabic number in Figure 1 is as the following: No. 1 is a flange, No. 2 is a screw, No. 3 is UHV power feedthrough, No. 4 is a heat shield in the diode ES and it is the focusing electrode in the triode ES, No. 5 is the cathode electrode of Pierce type, No. 6 is a feedthrough for filament holder, No. 7 is a tungsten filament, and No. 8 is Alumina ring to insulate the focusing electrode from cathode. The detailed parameter designs of the constructed ES are shown in Table 1.



(a) (b)

Figure 1 The schematic structure of the designed ES: (a) Diode ES; (b) Triode ES

Caption Figure 1(a): No. 1 is a flange, No. 2 is a screw, No. 3 is UHV power feedthrough, No. 4 is a heat shield in the diode ES and it is the focusing electrode in the triode ES, No. 5 is the cathode electrode of Pierce type, No. 6 is a feedthrough for filament holder, No. 7 is a tungsten filament

Figure 1(b): No. 1 is a flange, No. 2 is a screw, No. 3 is UHV power feedthrough, No. 4 is a heat shield in the diode ES and it is the focusing electrode in the triode ES, No. 5 is the cathode electrode of Pierce type, No. 6 is a feedthrough for filament holder, No. 7 is a tungsten filament, No. 8 is Alumina ring.

The construction was started by making a flange of DN-160 CF that matched the NEC tube for mounting the Tungsten filament, the electrodes of Pierce type, and the heat shield. For the filament's power supply input, a UHV (Ultra-High Vacuum) power feedthrough was employed to provide insulation between the anode and cathode of the tungsten filament. For the triode ES, the focusing anode electrode was inserted between the cathode electrode and the extraction anode electrode. The focusing anode should be designed so that it is in contact with the first metal ring of the NEC tube in the incident direction of the electron beam. Moreover, the focusing anode was insulated with the flange of the NEC tube using the Alumina ring. All components of the ES were made in our mechanical workshop. After completing the construction of the ES components, they were assembled into the flange of DN-160 CF. Then, this flange was mounted on the NEC accelerator tube to become an ES.

Table 1 Parameter design of the ES

No	Paramater	Diode ES	Triode ES
		Spesification	
1	Filament	Tungsten Materials, wire diameter of 0.5 mm, spiral shape of 12 mm diameter	Tungsten Materials, wire diameter of 0.5 mm spiral shape of 12 mm diameter
2	Cathode electrode	Pierce type with an opening diameter of 25 mm	Pierce type with an opening diameter of 25 mm
3	Focusing anode	None	Modified heat shield of diode ES. The electrode of Pierce type with a hole diameter of 20 mm. Alumina ring between the flange and focusing anode
4	Extraction anode	As the electrode shape of the NEC accelerator tube	As the electrode shape of the NEC accelerator tube
5	Distance filament to focusing anode	None	10 mm
6	Distance filament to extraction anode	38 mm	38 mm
7	Distance between the electrode of the NEC accelerator tube	19 mm	19 mm
8	ES Flange	DN-160 CF	DN-160 CF
9	Heat shield	Cylinder shape	Cylinder shape

The construction was started by making a flange of DN-160 CF that matched the NEC tube for mounting the Tungsten filament, the electrodes of Pierce type, and the heat shield. For the filament's power supply input, a UHV (Ultra-High Vacuum) power feedthrough was employed to provide insulation between the anode and cathode of the tungsten filament. For the triode ES, the focusing anode electrode was inserted between the cathode electrode and the extraction anode electrode. The focusing anode should be designed so that it is in contact with the first metal ring of the NEC tube in the incident direction of the electron beam. Moreover, the focusing anode was insulated with the flange of the NEC tube using the Alumina ring. All components of the ES were made in our mechanical workshop. After completing the construction of the ES components, they were assembled into the flange of DN-160 CF. Then, this flange was mounted on the NEC accelerator tube to become an ES.

2.2. Characterization

The constructed ES was characterized in terms of the electron beam profiles and beam current output. The schematic for the measurement of the beam profile is shown in Figure 2. The beam profile measurements used the method as described by Darsono *et al.* (Darsono, Suprapto, and Taufik, 2015), where phosphorescent materials were used. This approach was selected for its simplicity, ease of implementation, and cost-effectiveness in comparison to the rotating probe method (Andreev *et al.*, 2017). In our measurement, profile shapes of the electron beam formed by the interaction of the electron beam with phosphorescent materials were recorded using CCTV, which was connected to a laptop using a video capture interface USB.2.0. For the diode ES, the observation of the electron beam profile was carried out for the variation of the extraction anode voltage ($V_{k\text{-}a}$). Meanwhile, for the triode ES, the observation of the electron beam profile was carried out for the variation of the focusing anode voltage ($V_{k\text{-}f}$) as well as the extraction anode voltage ($V_{f\text{-}a}$). Both observations were carried out at the same experimental condition.

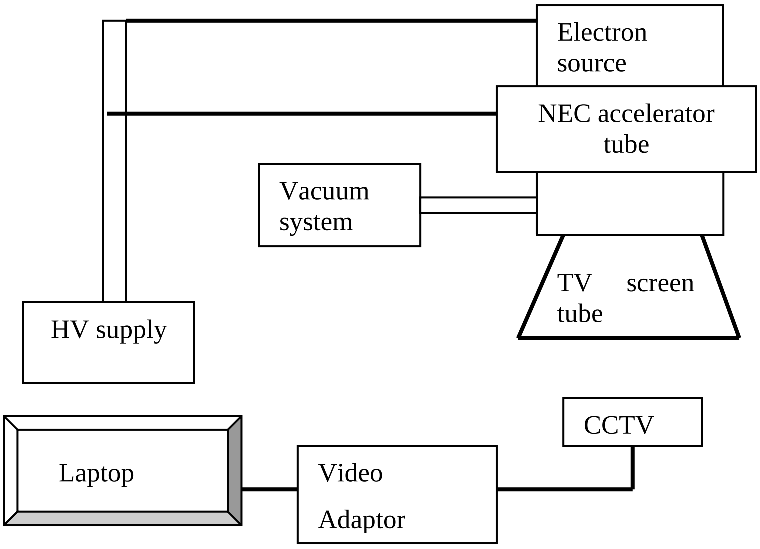


Figure 2 A schematic of the beam profile measurement of the ES

Figure 3 shows the experimental setup to measure the electron beam current output of the diode and triode ES. The beam current was measured using a water-cooled Faraday Cup. The power supply (PS) of the filament was locally made with the specification of 20 V-DC/25 A. Two regulated high voltages were used for the focusing anode voltage of 10 kV-DC and for the extraction anode voltage of 30 kV-DC. In the case of the diode ES, there are 8 electrodes used in the NEC tube, meanwhile, in the case of the triode ES, there are 7 electrodes used. Both measurements were carried out at the same experimental condition.

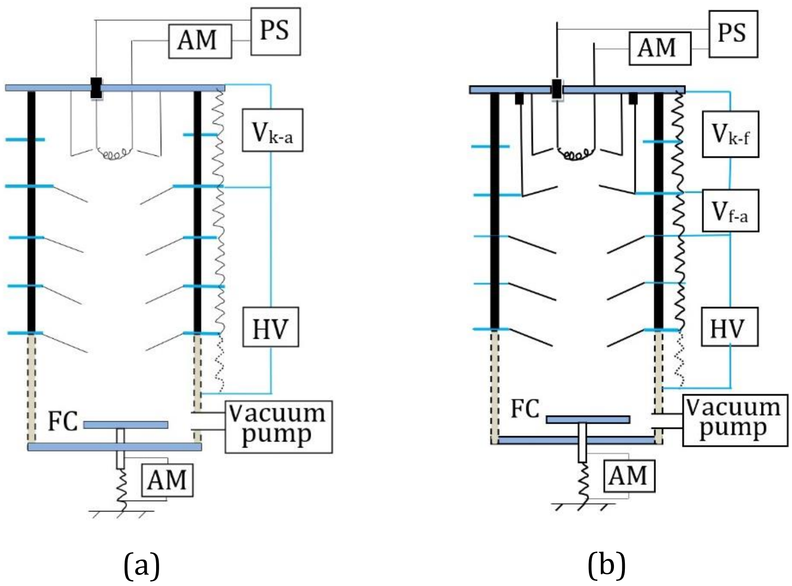
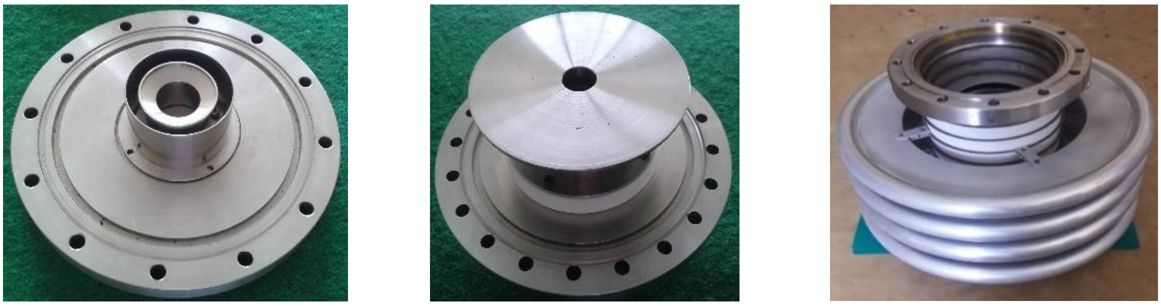


Figure 3 A schematic of the measurement of the beam current output of the ES: (a) Diode ES; (b) Triode ES

3. Results and Discussion

3.1. Construction of Electron Sources

Figures 4a and 4b show the construction results of the flange for the diode ES and the triode ES, where Figure 4c shows the NEC accelerator tube used. The white color observed on the top of the flange, as depicted in Figure 4b, represents an Alumina ring. This ring has been specifically designed to withstand the high voltage of 20 kV. On top of the Alumina ring is the focusing anode electrode. The cathode electrode of the triode ES is placed inside the tube of the focusing anode. The cathode electrode of the Pierce type can be seen in Figure 4a, located on the inner side of the heat shield.



(a) (b) (c)

Figure 4 The model of the diode and triode ES and its NEC accelerator tube: (a) The flange of diode ES; (b) The flange of triode ES; (c) The NEC accelerator tube

3.2. Characterisation of Electron Sources

Table 2 is the measurement result of the electron beam profile using the phosphorescent TV screen. The photograph image of the shape of the electron beam profile was taken in the same experimental condition for both the diode and the triode ES. The experimental vacuum condition was 3 × 10^{-6} Torr, and the filament current was 14 A. At this filament current value and fixed extraction voltage, the electron beam current in the phosphorescent TV screen ranged from 28 μA to 50 μA depending on the magnitude value of the focusing.

From Table 2, it can be said that the shape and the brightness intensity of the electron beam profile are influenced by the focusing and extraction anode voltages. At a constant extraction anode voltage, it is observed that increasing the focusing anode voltage results in improved beam profiles, indicating a more favorable shape. This case is due to the potential difference between the focusing anode and the heated filament, which forces more electrons to emit from near the filament surface. While at fixed focusing anode voltage, the greater the extraction anode voltage is, the brighter the intensity of the electron beam profile would be.

The theoretical explanation of this experimental result is the following. When the filament is heated then the electron cloud will form in front of the cathode. The applied voltage on the focusing anode will attract the electron cloud from near the surface of the hot filament. Moreover, the electron cloud can also change the configuration of the electric field so that the electron emission from the filament surface is limited. The magnitude of this electric field depends on the focusing anode voltage due to the distance of the focusing anode electrode to the cathode electrode is kept constant. In order for the electron beam to be removed or extracted from the ES chamber, a strong electric field is required in the direction from the focusing anode to the cathode (filament). In the triode ES, the configuration of three electrodes functions as the Einzel lens. For a constant extraction anode voltage, therefore, the shape of the electron beam profile is determined by the focusing anode voltage.

Furthermore, from Table 2, it can be seen that for extraction anode voltage higher than 0.5 keV, increasing the focusing anode voltage higher than 3 kV it is no longer affects the shape of the electron beam profile. However, it affects the brightness intensity of the electron beam shape. It is presumed that when the focusing anode voltage exceeds 3 kV, the electron cloud is unable to alter the configuration of the electric field, resulting in a consistent beam shape. In this condition, all electron clouds in the ES chamber are directed to the acceleration tube by focusing anode voltage; therefore, the brightness intensity increases. It can be summed that the focusing anode voltage functions to control the beam profile. This experimental result is in accordance with the experimental results which are reported by Deore *et al.* (Deore *et al.*, 2012). They measured the electron beam profile by using the transparent electron window made of flexiglass. This glass was coated with TiO_2 to measure the electron beam current, and on top of the TiO_2 thin layer was coated by ZnS(Ag) to determine an estimated diameter of the electron beam for a wide range of the focusing anode voltages.

Tabel 2 The beam profile shape of the triode ES output

Focusing voltage, $V_{k\text{-}f}$ (kV)	Extraction voltage, $V_{f\text{-}a}$ (kV)				
	0.5	1.0	1.5	2.0	2.5
0					
1					
2					
3					
4					
5					

The comparison of the shape of the beam profiles between the triode and diode ES as function of the extraction anode voltage is shown in Table 3. In this comparison, the triode ES is operated on the focusing anode voltage of 3 kV. It can be seen that the shape of the beam profile of the triode ES is better than that of the diode ES. From Table 3 also indicates that with an increase in extraction anode voltage, there is a corresponding enhancement in the brightness intensity of the electron beam profile. In simpler terms, higher extraction anode voltages result in a greater extraction of electron beam charges.

The investigation results of the electron beam current output for both diode and triode ES as a function of the extraction electrode voltages for various filament currents (I_f) are shown in Figure 5. As a note in Figure 5 D-ES represents the diode ES, and T-ES represents the triode ES. In these experiments, the data of the electron beam current output were taken in the same values of the filament current ranging from 15 A up to 18 A and also in the same vacuum condition. The magnitude value of the initial vacuum condition at off filament current was 3 × 10^{-6} Torr, then this vacuum decreased with increasing the magnitude value of the filament current.

Tabel 3 The beam profile shape of the diode and triode ES

Extraction voltage, V_a(kV)	0.5	1.0	1.5	2.0	2.5
Diode ES					
Triode ES At V_{k-f} =3 kV					

The investigation results of the electron beam current output for both diode and triode ES as a function of the extraction electrode voltages for various filament currents (I_f) are shown in Figure 5. As a note in Figure 5 D-ES represents the diode ES, and T-ES represents the triode ES. In these experiments, the data of the electron beam current output were taken in the same values of the filament current ranging from 15 A up to 18 A and also in the same vacuum condition. The magnitude value of the initial vacuum condition at off filament current was 3 × 10^{-6} Torr, then this vacuum decreased with increasing the magnitude value of the filament current.

From Figure 5, when the extraction anode voltages are increased, then the electron beam current outputs of both ES's also increase to a certain extent, and after that, it tends to be saturated at the extraction anode voltage higher than 2.5 kV. These experimental results are in agreement with similar previous studies, which show the same curve pattern of the beam current output of the ES as a function of the extraction anode voltage (Matejcek *et al.*, 2023; Darsono *et al.*, 2017; Islam *et al.*, 2016; JongChul *et al.*, 2014; Deore *et al.*, 2012; El-Saftawy *et al.*, 2012).

El-Saftawy *et al.* have investigated the extraction beam characteristics and beam diagnosis for a Pierce-type of diode electron gun with a spherical anode to acquire an electron beam suitable for different applications (El-Saftawy *et al.*, 2012). His experimental results show that at higher extraction anode voltages (acceleration voltage), the increase of the electron beam current caused by the acceleration voltage is limited, and the electron beam current seems to be quasi-saturated in this region. Deore *et al.* have reported the design, development and characterization of a tetrode type electron gun system for the generation of low energy electrons (Deore *et al.*, 2012). His experimental result shows that the beam current gradually increases with increasing the acceleration voltage at constant filament current. His results also indicate that at a given beam energy, the electron beam current can be changed over a wide range by changing the filament current. Islam *et al.* have also reported the test of the thermionic hairpin DC electron beam gun (Islam *et al.*, 2016). His experimental results also show that the beam current output increases with the increase of the acceleration potential and follows the Child-Langmuir equation, but the beam emittance decreases. JongChul, *et al.* have designed a diode-type electron source by using the EGN2w Code to calculate beam current, size, and emittance. The plate filament cathode with a 3 mm diameter was selected, and the focus electrode used Pierce type. Their findings indicate that an increase in the voltage magnitude of the focus electrode leads to a rapid rise in emitted current, particularly at higher voltage levels (JongChul *et al.*, 2014). Darsono *et al.* have also reported in the ES simulation and preliminary experiment that the electron beam profile is strongly influenced by the focusing anode voltage, and the electron beam output is strongly influenced by the anode extraction voltage (Darsono *et al.,* 2017). Matejcek, C. et.al. have designed a novel electron source for a compact x-ray tube using the software of CST Studio for microbeam radiotherapy with very high dose rates (Matejcek *et al.,* 2023). His results show that an additional negative voltage of PE (Pierce electrode) with respect to the voltage of the cathode stops extraction of the beam (beam saturation occurs). Our curve pattern of the electron beam output is also in accordance with the Child-Langmuir equation. His equation states that the electron beam intensity, which can be extracted from the ES chamber to the accelerator tube chamber, is directly proportional to the extraction voltage (V_{ext}) to the power of three-half.

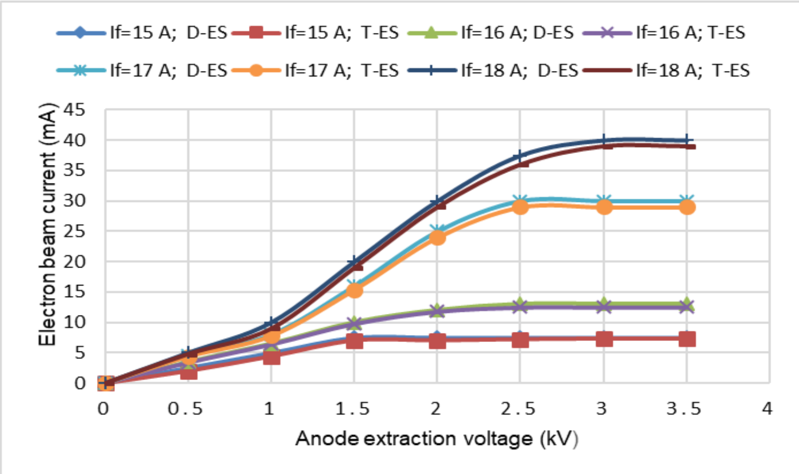


Figure 5 The effect of the anode extraction voltage on the output of the ES

Moreover, from Figure 5, it can be seen that at a fixed extraction anode voltage, the variation of the filament currents changes the magnitude value of the saturation electron beam current. In other word, at constant electrode anode voltage, the saturation electron beam current increases when the filament current increases. As predicted, in this case, the current density of the saturated electron emission, derived from the energized filament within the ES chamber, aligns with the Richardson-Dushman equation. His equation states that the magnitude of the electron cloud emitted from the filament is proportional to the square of the filament temperature, whereas the filament temperature is proportional to the increasing filament current. Our experimental results are also in agreement with similar previous investigations carried out by Deore *et al.* (Deore *et al.,* 2012), by JongChul *et al.* (JongChul *et al.,* 2014), and Matejcek, C. *et al.* (Matejcek *et al.,* 2023) Their experimental results showed that at a given beam energy or at a given electron extraction voltage, the electron beam current output can be changed over a wide range by changing the filament current.

A more detailed examination of Figure 5 reveals that the saturation electron beam current of the triode ES is approximately 10% lower than that of the diode ES. These differences might be due to the hole diameter of the focusing anode electrode of the triode ES being smaller than that of the diode ES, as depicted in Table 1. The highest electron beam current output, which can be achieved in our experiment, is 40 mA. The magnitude of the resulting electron beam current meets the specification of the ES of the EBM for irradiation processing of natural rubber latex.

Mostly, the focusing and extraction anodes are one part of the ES and are separated from the accelerator tube. However, manufacturing the ES, including the focusing and extraction anodes inside, requires an advanced technology called the vacuum brazing technique for joining the metal anode and a ceramic as an insulation material that can hold several kV anode voltage differences. The metal and ceramic joints also have to be able to withstand high vacuum. Therefore, the cost of manufacturing that kind of ES becomes expensive. Meanwhile, in our design, one or two acceleration electrodes of the electrostatic accelerator tube that have been separated by ceramic insulation are modified to focusing and extraction anodes. Therefore, no vacuum brazing process is required, and the cost of manufacturing ES becomes much cheaper. Nevertheless, our ES can be used to reduce the cost of the EBM for the electrostatic acceleration type only, which is widely used in industrial applications and in life and materials sciences (Lee *et al.*, 2022; Pillai and Pillai, 2021; Gotzmann *et al.*, 2018).

Moreover, the electron source that has been successfully constructed uses a new and simple production technique of the ES, namely by making a special flange as a main mechanical component of ES shown in Figure 1. For the diode ES, this flange is loaded with a power feedthrough that functions as a tungsten filament holder, a pierce cathode electrode and a heat shield. For the triode ES, the flange is loaded with a power feedthrough that functions as a tungsten filament holder, the pierce cathode electrode and the modified heat shield function as focusing controlled electrodes, plus an alumina ring to insulate the voltage on the pierce cathode electrode and the focusing controlled electrode. Meanwhile, the extractor electrode voltage utilizes an electrode on the accelerator tube.

The advantage of this ES's production technique is that the dimensions of the special flange of the ES can be adjusted accordingly to that of the accelerator tube to be used in the electron beam machine. The ES's production can be done anywhere with a cheap production cost as long as there is a machinery workshop. The market price of the electron source is around 26,300 USD (Kimball Physics, 2023), while the cost of our constructed ES which consists of a special flange and accelerator tube, is around 10,000 USD. Electrodes of the accelerator tube are used only 20%. The rest is used for electron acceleration. Besides the low-cost production, this ES is also very easy to maintain. Moreover, this ES is very suitable for application in low or high-energy electron beam machines. A diode-type electron source has been installed on EBM Arjuna 1.0 with specifications of 300 keV/10 mA (Nuraini *et al.*, 2021), while a triode-type SE has been installed on EBM Arjuna 2 with specifications of 300 keV/20 mA (Saefurrochman *et al.*, 2021). This ES can also be used for material evaporation (Oks *et al.*, 2017) and material polishing (Lu *et al.*, 2017) by adjusting its dimensions and using an HV pulse power source.

4. Conclusions

Two types of ES have been successfully constructed and characterized. The diode ES provides a slightly higher output of the electron beam current compared with the triode ES output, but the triode ES provides a better shape of the electron beam profile. The shape of the electron beam profile is predominantly determined by the focusing anode voltage. The focusing electrode voltage from 0 kV up to 3 kV affects the shape of the electron beam profile. The greater the filament current is, the greater the electron beam current output of the two ES would be. The magnitude of the electron beam current output is greatly determined by the extraction electrode voltage and the filament current, where the largest yield is 40 mA. For the two types of ES investigated, the experimental results show that the beam current output increases rapidly with the increase of the extraction electrode voltage up to 2.5 kV, but above this voltage, it tends to be saturated. The constructed ES meets the specifications required for EBM latex. The production technique of the ES is very simple with low-cost production, and the ES is easy to maintain.

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