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ARTICLE

High charge and pulse duration tunable electron gun system for pulsed X-ray source

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A highly charged and pulse-duration-tunable thermionic electron gun suitable as a pulsed X-ray source for stroboscopic X-ray imaging was developed. An iridium-cerium alloy cathode was used as the thermionic cathode, which enabled the gun to be driven even at a vacuum level of 7×10^{-5} Pa owing to high resistance to poisoning. The pulse duration of the electron beams can be seamlessly varied from 50 to 500 μs in a temporal top-hat shape by applying a negative high-voltage pulse to the cathode generated by a direct-switch method using a semiconductor switch. This electron gun, with a diameter of 34 mm, generated a maximum emission current of 1.2 A at a cathode voltage of only -18.4 kV.

Keywords: iridium cerium; electron gun; pulsed X-ray source

1. Introduction

X-ray radiography is a widely used diagnostic technique with applications in medical and industrial imaging, homeland security, and materials research. In terms of industrial applications, X-ray radiography has several benefits, including a high spatial resolution and the ability to visualise details, such as defects, pores, and contamination in objects without destruction. Recently, the increasing maturity of image recognition using artificial intelligence technology [1-3] has led to a demand for faster and more accurate radiography for inline inspection and non-reversible events [3,4]. Therefore, X-ray radiography systems must provide X-ray images with high signal-to-noise ratios and short exposure times. In radiography, pulsing an X-ray beam to match the speed of a moving object has several advantages: reduction of (1) the heat load on the X-ray target and (2) leakage dose of X-rays. Pulsed X-ray sources utilising several electron sources, such as thermionic emitter [5-7], field emitter [8-10], and photoemitter [11,12], have been reported. The shorter the exposure time, the higher the X-ray intensity required; consequently, a highly charged electron beam is essential for the same tube voltage in stroboscopic radiography using pulsed X-rays. Recently, a compact pulsed X-ray source [13,14] using an explosive electron emission effect (EEE) [15] has been developed, operating at a maximum tube current of 240 A and a pulse duration of approximately 50 ns [14]. Notably, however, the amount of bunch charge per single pulse is only comparable to the conventional pulsed X-ray tube[5]. Maximising the intensity of an X-ray pulse by adjusting the pulse duration of an electron beam according to the speed and size of the moving object, while keeping the pulse duration sufficiently short, is important for rapid stroboscopic imaging.

We have been developing a compact pulsed X-ray source capable of generating sub-millisecond X-ray pulses, shorter than those emitted by industrial X-ray sources, to expedite the line-inspection of products. This study presents the development of a highly charged, pulse-duration-tunable thermionic electron gun suitable as a pulsed X-ray source. This electron gun was designed to obtain a high current density at a low temperature by employing an iridium-cerium alloy cathode rather than a tungsten filament, which is used in industrial electron beam applications. The pulse duration of the electron beams can be varied by applying a negative high-voltage pulse generated by the direct-switch method using a semiconductor switch to the cathode. This electron gun achieved to generate a maximum emission current of 1.2 A at a cathode voltage of -18.4 kV.

In Section 2, we present the simulation results and design of the electron gun. Section 3 presents the details of the experimental results for the developed electron gun on the test bench at AIST.

2. Gun design

A conceptual illustration of the pulse duration tunable electron gun system for the pulsed X-ray source is shown in **Figure 1**. The cathode, which is negatively biased in pulses with respect to the anode, thermionically emits electron pulses that are synchronised with the bias voltage. The high-voltage pulse power supply for driving the electron gun is based on direct switching using a high-voltage semiconductor switch. A high-voltage capacitor is

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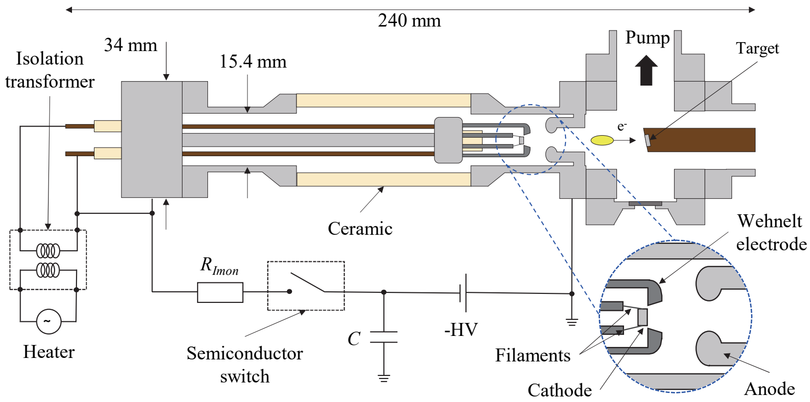

Figure 1. Conceptual illustration of the pulse duration tuneable electron gun system for the pulsed X-ray source. The exact geometry of the electrodes in a practical electron gun is shown in Figure 2(a). The scales indicate the value of the practical electron gun.

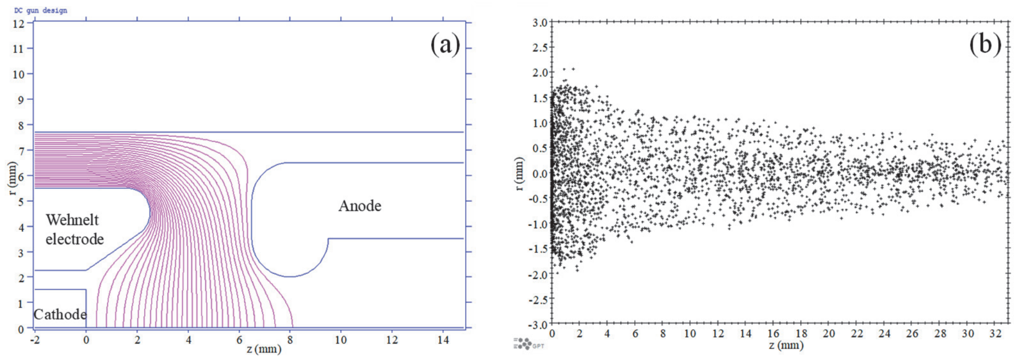

Figure 2. (a) Electrical field distribution of the electron gun. The horizontal axis is the beam axis, and the vertical axis represents any radial direction; units are millimeters. These red lines indicate the electric lines of force. Figure (b) The beam trajectories from the electron gun to the X-ray target. The horizontal axis (r = 0) is the beam axis, and the vertical axis represents any radial direction; units are millimeters. Each black cross dot represents a macro-electron bunch. The position of z = 0 is the emission surface of the cathode and z = 33 is the center position of the x-ray target, respectively. The X-ray target was grounded.

connected in parallel to the electron gun to store electrical energy when the switch is off. When the semiconductor switch is turned on, a high negative voltage is applied to the cathode, resulting in the generation of an electron beam. The pulse duration of the electron beam could be adjusted by controlling the on-time of the semiconductor switch.

The thermionic cathode material was chosen from an iridium-cerium alloy [16, 17]. Iridium-cerium cathodes have been reported to thermally emit electrons at low temperatures compared to tungsten cathode [16]. According to Reference 16, comparing the temperatures at which thermal electrons are generated at current densities above 10 A/cm^2, tungsten cathode requires more than 2,400°C, whereas iridium cerium cathode does only approximately 1,500°C. It has also been reported that the electron beams can be obtained at a current density of more than 18 A/cm^2 at 10^{-4} Pa [17], which shows a high resistance to poisoning. Furthermore, iridium cerium cathode has a lower evaporation rate at a working temperature of 1,500°C compared to LaB_6 cathode [16]. Based on the abovementioned performance, we consider that an iridium-cerium cathode will be ideal for high-charge electron guns in pulsed X-ray sources.

The internal structural design of the electron gun is determined by the electrical-field distribution and the requirements of the beam dynamics. The electron gun geometry was optimized to minimize the beam spot size on the target under the premise of ensuring that the internal electric field intensity of the electron gun is maintained within a safety range. The distance between the cathode and the target was set to 33 mm to make the X-ray source as compact as possible, assuming the use of a commercially available insulated tube and a vacuum chamber. The electric field distribution inside the electron gun was calculated using Poisson Superfish code [18]. The electron beam trajectories were calculated using a General Particle Tracer code. The cathode was set at a high voltage of −25 kV considering the safety margin to prevent some high voltage breakdown. The maximum beam current was set as 1 A. The beam divergence resulting from the space–charge effects was considered in the beam trajectory simulation. The gun structure and electric field distribution are shown in **Figure 2 (a)**. The simulated beam trajectories along the designed electron gun are shown in **Figure2 (b)**. With a cathode diameter of 3 mm and a Wehnelt electrode with a slope angle of 55 °, the electron gun allowed a 1 A electron beam to focus on the target to a beam diameter of approximately 1.0 mm.

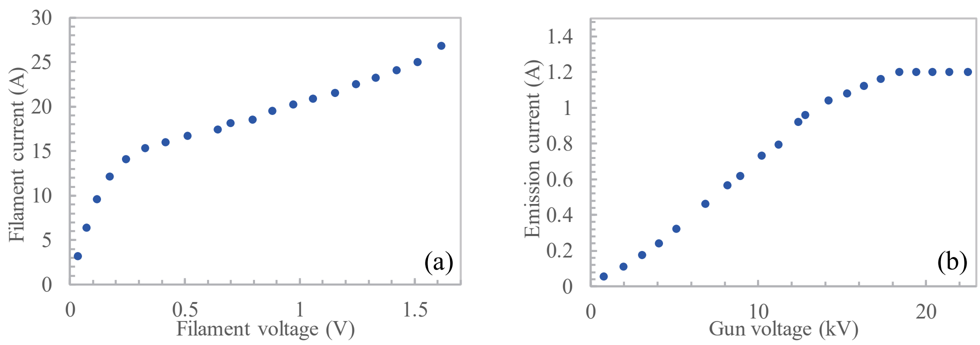

Figure 3. (a) Voltage-current characteristics of the filaments. (b) Dependence of the emission current on the gun voltage. The heater power was 43 W.

3. Experimental results and discussions

A practical electron gun, including an iridium cerium thermionic cathode, Wehnelt electrode, anode, insulator, and feedthrough with a diameter of 34 mm and length of 120 mm was developed based on the above gun design. Electron beam testing of the electron gun was performed on a test bench. A maximum accelerating voltage pulses of 22.5 kV was applied to the cathode using a high-voltage semiconductor switch (HTS 1401-10-LC2). A 64 nF high-voltage capacitor was used for charging. A high-voltage resistor of 2.500 kΩ is connected in series with the electron gun. The emission current was measured by monitoring the voltage drop before and after passing through the resistor. A vacuum of less than 10^{-4} Pa was maintained on the test bench using a 3 l/s ion pump and a getter pump. An AC voltage of 50 Hz was applied to the filaments for cathode heating via a 45 kV isolation transformer. The voltage-current characteristics of the filaments are shown in **Figure 3(a)**. To avoid filament breakage, the filament current was limited to 30 A or less.

The transmission ratio of the electrons emitted to the target was measured. In this measurement, an electrically floating stainless-steel target with a 3 mm diameter, which detected the transmitted electrons was set in place of the X-ray target. The ratio of the detected current at the stainless steel target to the emission current was determined as the transmission ratio of the emitted electrons. Consequently, the transmission rate of the emitted electrons is approximately 80 %.

The dependence of the emission current on gun voltage is shown in **Figure 3(b)**. In this figure, the horizontal and vertical axes indicate the gun voltage (kV) and emission current (A), respectively. This result was obtained when the cathode was heated to a maximum input power of 43 W, which enabled the stable operation of the electron gun. In general, at low voltages, the beam current increases in proportion to the 3/2 power of the gun voltage following the Child-Langmuir law. This is called the space-charge limited region. As the gun voltage is further increased, the beam current is dominated by the Schottky effect. As a result, the slope of the current- voltage curve decreases. This region is called the temperature-limited one. Figure 3(b) shows that the increasing trend of the emission current changed slowly when the gun voltage exceeds about 14 kV. This trend indicates that the electron emission is in the temperature-limited region for gun voltages above approximately 14 kV. Finally, a maximum emission current of 1.2 A was achieved at an gun voltage above 18.4 kV. The vacuum level during this experiment was of the order of 7×10^{-5} Pa. Using iridium-cerium alloy as the cathode, thermionic emission at a high current density was achieved, even under poor vacuum conditions. At electron gun voltages around 20 kV, it is expected that the beam current jitter caused by the gun voltage jitter is suppressed owing to the operation in the temperature-limited region. On the other hand, we must precisely control the heater power in order to stabilize the beam current if the current fluctuation is caused by a change in the environment, e.g., vacuum pressure or room temperature.

The dependence of the emission current on pulse duration was measured. For this measurement, the heater current and gun voltage were fixed at 25 A and 20 kV, respectively. The turn-on time of the semiconductor switch was varied to control the pulse duration of the emitted current. The waveforms of the emission current at each turn-on time are shown in **Figure 4**. The pulse duration of the electron beam was varied from 50 to 500 µs, and the repetition rate was 1 Hz. Even when the pulse duration was extended from 50 µs to a maximum of 500 µs, the emission current remained approximately constant in pulse at 600 mA.

This electron gun successfully suppressed the decrease in the beam current relative to the voltage drop of the charging voltage within the pulse by operating in a temperature-limited region. Consequently, the pulse duration of the electron beams could be varied from 50 to 500 µs in a temporal top-hat shape. This performance suggests that higher electron charge can be obtained for pulse duration longer than 50 µs compared with the pulsed X-ray sources based on EEE [14]. In other words, for stroboscopic imaging with an exposure time of 50 to 500 µs, a higher X-ray dose can be expected by using this electron gun system at the same tube voltage [5,14]. This is an advantage of the temporal top-hat shape, and the wide-range tunability of the pulse duration allows the selection of the optimum pulse duration for the X-ray beams according to the speed of the moving object.

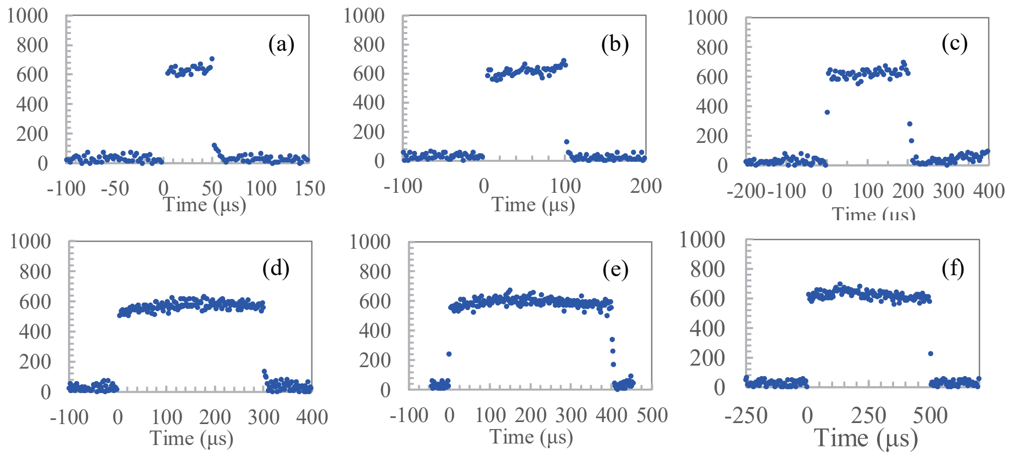

Figure 4. Waveforms of the emission current at each turn-on time (T_p). (a) pulse duration, T_p = 50 μs, (b) T_p = 100 μs, (c) T_p = 200 μs, (d) T_p = 300 μs, (4) T_p = 400 μs, (f) T_p = 500 μs. The time zero (t = 0) in these graphs corresponds to the turn-on timing of the semiconductor switch.

However, the voltage drop increases because of the capacitance limitation of the charging condenser when the amount of beam charge in a pulse further increases owing to an increase in the beam current or extension of the pulse duration. Consequently, it may be difficult to emit an electron beam in the temperature-limited region, resulting in a decreased emission current within the pulse.

4. Summary

This study presents the design and development of a high-charge and pulse-duration tunable thermionic electron gun system. Using the iridium-cerium thermionic cathode, emission currents of more than 1 A were obtained, even at a vacuum level of 7 × 10^{-5} Pa. Pulsed electron beams of 50 ~ 500 μs duration could be generated by applying a negative high-voltage pulse generated by a direct-switch method using a semiconductor switch to the cathode. This high charge generation and tunability of the pulse duration may enable the generation of a higher-intensity X-ray than that emitted by conventional pulsed X-ray sources [5,14] when used at the same tube voltage for stroboscopic imaging with the exposure times of 50–500 μs. However, to increase the repetition rate, the improvement of the high-voltage generator is required for considering the capacitance of the charging condenser and the current capacity of the power supply. Currently, X-rays are generated by using this electron gun system and radiographs are recorded with a single X-ray pulse. Through these tests, we will clarify the scope of application of this electron gun system in stroboscopic X-ray radiography. In addition, the obtained maximum bunch charge of this electron gun system is equivalent to the required parameter for an electron accelerator-driven neutron source [19] and an X-ray free electron laser [20]. Thus, it can be expected to be applied to not only X-ray sources but also electron accelerators.

References

[1] Y. LeCun, Y. Bengio and G. Hinton, Deep learning, *Nature* 521 (2015), pp. 436-444.
[2] V. Chandola, A. Banerjee and V. Kumar, Anomaly detection: A survey. *ACM Computing Surveys (CSUR)*, 41 (2009), pp. 1-22.
[3] I.E. Parlak and E. Emel, Deep learning-based detection of aluminum casting defects and their types. *Engineering Applications of Artificial Intelligence* 118 (2023), 105636.
[4] S. Shevchik et al., Supervised deep learning for real-time quality monitoring of laser welding with X-ray radiographic guidance, *Scientific Reports*, 10 (2020), p.3389.
[5] J.W. Jack and T. Smith, A pulsed X-ray generator. *Journal of Physics E: Scientific Instruments*, 6 (1973), pp. 162-164.
[6] K. Wang et al., A sort of pulsed microfocal x-ray source. Proceedings SPIE 6279, *27th International Congress on High-Speed Photography and Photonics* (2007), 627914.
[7] P. Kandlakunta, R. Pham, R. Khan and T. Zhang, Development of multi-pixel x-ray source using oxide-coated cathodes. *Physics in Medicine & Biology*, 62 (2017), N320.
[8] H. Kato, B.E. O'Rourke and R Suzuki, Development of an Xray tube for irradiation experiments using a field emission electron gun. *Nuclear Instruments and Methods in Physics Research* A807 (2016), pp. 41-46.
[9] Y. Zhang, Y.M. Tan and L.Z. Wang, Electron emission and structure stability of carbon nanotube cold cathode driven by millisecond pulsed voltage. *Vacuum* 172 (2020), 109071.
[10] S. Lai et al., X-ray ultrashort pulse emission characteristic of carbon nanotube cold cathode X-ray source by pulse driving mode. *Vacuum*, 207 (2023), 111658.
[11] G. Timofeev and N. Potrakhov, Pulsed X-ray source based on photo X-ray tube, *IOP Conference Series: Materials Science and Engineering* 387 (2018), 012079.

[12] H. Xuan et al., Light-controlled pulsed X-ray tube with photocathode. *Chinese Physics* B 30 (2021), 118502.
[13] A. Komarskiy, S. Korzhenevskiy, A. Chepusov and O. Krasniy, The pulsed X-ray radiation source based on a semiconductor opening switch with the focal point diameter of 0.5 mm and its application. *Review of Scientific Instruments* 90 (2019) 095106.
[14] K.A. Alexandrovich et al., Pulsed X-ray source with the pulse duration of 50 ns and the peak power of 70 MW for capturing moving objects. *Journal of X-Ray Science and Technology* 29 (2021), pp.567-576.
[15] Y.D. Korolev and G.A. Mesyats, Physics of Pulsed Breakdown in Gases Ekaterinburg 1998; URO Press.
[16] G. Kuznetsov, High temperature cathodes for high current density. *Nuclear Instruments and Methods in Physics Research* A 340 (1994), pp. 204-208.
[17] G.I. Kuznetsov, IrCe Cathodes For EBIS. *Journal of Physics: Conference Series* 2 (2004), pp. 35-41.
[18] J.H. Billen and L.M. Young, Poisson/superfish on pc compatibles. *Proceedings of the 1993 Particle Accelerator Conference*, IEEE (1993), pp. 790-792.
[19] B.E. O'Rourke et al., Design and construction of an electron accelerator for a pulsed neutron facility at AIST. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* 464 (2020), pp. 41-44.
[20] K. Togawa et al., CeB_6 electron gun for low-emittance injector. *Physical Review Accelerators and Beams* 10 (2007), 020703.