Lifetime extension of ferroelectric cathodes for microwave tubes

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The lifetime of a microwave tube with a ferroelectric cathode was investigated. The repeatability of the radiation output was measured as a function of the cathode lifetime. In this experimental research, two barium titanate ceramic cathodes were studied with different operating parameters. The emission current density was \( \sim 0.6 \text{ A/cm}^2 \). Current pulses of 0.5–1.5 A with \( \sim 0.5 \text{ ms} \), and Duty factor \( \sim 10^{-4} \) were used. The microwave tube used was a gyrotron operating at \( \sim 7 \text{ GHz} \). The tube was operated in a repetitive mode and even after \( \sim 10^7 \) pulses the cathode still operates and microwave radiation is obtained. The pulse charge was fairly stable during the experiments. Nevertheless, the rate of missing pulses and irregularity between successive pulses increases and becomes the limiting factor for the cathode lifetime. It is concluded that the practical limitation for ferroelectric cathode lifetime in microwave tubes in the suggested configuration is not the degradation in the pulse charge, but the growing rate of missing pulses.

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1. Introduction

Ferroelectric (FE) cathodes attract scientific interest due to their unique characteristics that include a high current density [1] and high total current [2], as well as their simple operating conditions—modest vacuum requirements \( (\sim 10^{-5} \text{ mbar}) \), cold operation, immediate operation \( (\text{no conditioning is needed}) \), long shelf lifetime, and simple storage. Different modes of FE cathode operational setups and working points were suggested; these include electron emission [3], ion emission [4], and plasma shortening [5,6]. The ferroelectric cathode was also proven to be feasible as an electron source for various microwave tubes. A cyclotron resonance maser interaction was demonstrated in 1998 [7,8], a traveling wave tube [9] was demonstrated in 2001, and a gyrotron [10,11] interaction was also demonstrated in the same year. Microwave amplifier [12] and free electron maser [13] interactions were demonstrated in 2002. Recently a magnetron [14] with a ferroelectric cathode was demonstrated.

The lifetime of the ferroelectric cathode is an important characteristic influencing future applications. Refs. [14,15] describe FE cathode lifetime experiments for \( \text{Pb(Zr,Ti)O}_3 \) (PZT) and barium titanate \( (\text{BaTiO}_3) \) cathodes. Neither experiment included a microwave tube; only the cathodes were tested. The reported results of the cathode lifetime experiments were \( \sim 10^7–10^8 \) pulses. In the case of the PZT cathode, holes began to appear on the emitting side of the ceramic material [15], whilst for the \( \text{BaTiO}_3 \) cathode, black spots developed on the emitting side [16]. The nature of these spots is explained as a surface change in the composition in very thin surface layer. The plasma produces homogenization of sample surface composition and destroys surface effects [16]. However, the influence of the FE cathode lifetime on microwave tube performance was not reported.

In this experimental work the lifetime of a \( \text{BaTiO}_3 \) FE cathode used as an electron source for a gyrotron microwave tube operating at \( \sim 7 \text{ GHz} \) was investigated. The lifetime was characterized in relation to the microwave tube performance parameters such as repeatability and missing pulses. The cathode lifetime was defined by its operational capability as part of the entire microwave tube system and not as a stand-alone electron source.

2. Experimental setup and procedure

The investigated FE cathodes were made of the ceramic \( \text{BaTiO}_3 \). A lifetime test was performed using two ceramic samples of 18 mm diameter and 2 mm thickness. The cathode configurations used are shown in Fig. 1. The non-emitting rear side of the FE ceramic was metal coated and connected to voltage driving pulses. The only difference between the two cathodes used was the structure of the front of the electrode. The front surface of the first sample was covered with a tin circle \( \sim 6 \text{ mm} \) in diameter, while the front surface of the second cathode was coated with a \( \sim 4 \times 3 \text{ mm metal rectangle} \).

The electron-gun setup used is shown in Fig. 2. The tested cathode was subjected to positive voltage pulses of \( \sim 2 \text{ kV} \), with a
frequency measurements were made. The detector output was coupled out. After 36 dB attenuation, power and axial velocity components, respectively.

A kicker made of a pair of magnets[17], placed above the entrance section. This arrangement enables high PRF operation of the electron gun. The electrons moved from the e-gun to the gyrotron tube through a small hole in the anode. The electron current was measured in the tube using a Rogowski coil. The tube was made from a standard WR-90 waveguide that was centered in a solenoid. The solenoid was activated in a pulse mode generating a 2.3 kG field in the interaction region. The current pulse duration of 150–500 ns and a rise time of less than 100 ns, applied to the electrode of the non-emitting side. The same pulse was also applied to a grid that was placed ~5 mm in front of the FE cathode. The driving pulses repetition frequency (PRF) was either 1 or 0.2 kHz for high PRF mode and either 1 or 0.3 Hz for low PRF mode.

The front electrode was connected to a DC voltage of ~ −15 kV and the cathode pulse generator was floating on the same DC voltage. The anode was connected to ground. A ~100 G constant axial magnetic field was induced by the gun solenoid in the gun section. This arrangement enables high PRF operation of the electron gun. The electrons moved from the e-gun to the gyrotron tube through a small hole in the anode. The electron current was measured in the tube using a Rogowski coil. The tube was made from a standard WR-90 waveguide that was centered in a solenoid. The solenoid was activated in a pulse mode generating a ~2.3 kG field in the interaction region. The current pulse generator was constructed from a slowly charged capacitor bank that was discharged on the solenoid every ~1–3 s. Therefore, although the gun could be operated in high PRF, the interaction that is dependent on the solenoid magnetic field could only be operated in low PRF.

The electron transverse velocity component is induced by a kicker made of a pair of magnets [17], placed above the entrance of the interaction region (Fig. 3). The kicker position, determine the electron-beam pitch factor. According to electron trajectory simulations $V_x/V_y = 2$, where $V_x$ and $V_y$ are the transverse and axial velocity components, respectively.

At the end of the waveguide the generated microwave radiation was coupled out. After 36 dB attenuation, power and frequency measurements were made. The detector output was measured by oscilloscope. Part of the radiation was directed to a tunable band pass filter (BPF) for simultaneous frequency measurements. All experiments were conducted in a vacuum of $2–5 \times 10^{-5}$ mbar. The gyrotron tube setup used is shown in Fig. 3.

Successive test cycles of 1–3 h were performed in high PRF mode. The gun current consumption was measured in high PRF mode, while the reproducibility of the electron emission current and microwave power were investigated after each cycle at low PRF. The low PRF was necessary due to limitations of the solenoid pulse generator.

The working conditions of the electron-gun were the same at low PRF and at high PRF, thus the electron beam produced in the high PRF mode had basically the same parameters as in the low PRF mode. So, although the radiation measurements were done only in low PRF, the conclusion is related also to the high PRF as far as the electron gun itself is concerned. Some differences related to the transfer from low PRF to high PRF are also measured and discussed separately. The duty factor (the pulse length divided by the repetition duration) was $< 10^{-4}$.

3. Experimental results

After the setup was operated with a repetition rate of 1 kHz (high PRF) with cathode#1 for ~1–3 h, the repeatability of the tube current during operation at ~1 Hz (low PRF) was measured as shown in Fig. 4. The current was monitored during the operation. The maximal value of the current was gradually reduced by one third between the times when Fig. 4(a) and (c) were recorded, from ~1.5 to ~1 A. The current density reduced from ~0.6 to ~0.2 A/cm². The ‘tail’ after the main pulse grew during the experiment from a maximal value of 0.5 A in Fig. 4(a) to almost 1 A in Fig. 4(c).

The microwave output was similar to the results described before in Refs. [10, 11]. The device operated in the gyro-TWT regime, with ~0.5 GHz frequency up-shift above the cyclotron frequency. The obtained frequency was ~7 GHz and the power was ~1 kW. Fig. 5 shows a result of the tube current together with the microwave detector voltage output after $4.3 \times 10^7$ pulses. This result shows that in spite of the above current reduction there is microwave radiation. As discussed below, vanishing of the radiation is not the limiting factor for the cathode lifetime.

Fig. 6(a) and (b) shows cathode#1 after almost $5 \times 10^7$ pulses, and Fig. 6(c) and (d) shows cathode#2 after the experiment without electric connection, and after $10^7$ pulses with connection. There are no holes on the ferroelectric samples. The only change that is notable is the front surface blackening around and under the front electrode.
Cathode#2 was operated at a repetition rate of 200 Hz (high PRF) and the results were taken at repetition rates of ~1 Hz (low PRF). Fig. 7 shows the repeatability of the current and microwave pulses during the progress of the experiment. Stable and repeatable current and microwave pulses can be seen in Fig. 7(a) and (b). The experiment was repeated for up to ~10⁷ pulses. After 10⁷ pulses (Fig. 7(c)) the microwave radiation still appeared, but the emitted current became unstable. As seen in Fig. 7, the ‘tail’ effect does not appear for cathode #2. It can be related to the front electrode being metal-coated rather than a solder tin layer deposition.

Fig. 8 shows the dependence of the electron-emitted charge Q per pulse vs. the number of shots for both of the cathodes. For cathode #1 the charge of each pulse is divided to the main pulse and the ‘tail’. The total emitted charge Q from each cathode during the entire experiment is ~8C for cathode #1 and ~6C for cathode #2.

An important result is that the electron current did not appear for each applied high-voltage pulse. Whilst in the first stage of the test the current pulses were obtained for every shot (at high PRF and low PRF), in the final stage, current pulses did not appear for every shot. Fig. 9 shows the current consumption of the cathode high voltage power supply during the experiment at high PRF. This graph indicates the rate of pulses missed. In the initial stage, all the pulses appeared regularly. But after ~10⁷ pulses only 10–15% of the pulses appeared.

Another interesting short-time-recovery effect was observed as follows. After every High PRF cycle the system was stopped for a while, operated in low PRF (for measurements), and turned on for the next high PRF cycle. During the high PRF the solenoid kept operating in the low PRF. So, although not recorded, the current and microwave pulses were visually monitored during the high PRF. It was clear that the pulses had the same general shape in high and low PRF. Nevertheless, the rate of the missing pulses showed a short time recovery effect. As seen in Fig. 10, immediately after the high PRF operation most of the pulses re-appeared, and after a few minutes, the missing pulses rate stabilized again to the same rate as in the former high PRF sequence.

4. Discussion

The number of pulses obtained from the cathode is significantly extended in this experiment in comparison to Refs. [15,16], where the cathodes were tested in a stand-alone configuration. The reasons are most likely because of the use of a repellent grid and a focusing magnetic field at the cathode that limit the plasma progression. Also, as seen in Fig. 8, in this configuration the current pulse charge remains stable during the experiment and does not degrade. The cathodes were still producing electron beams good enough to obtain microwave pulses after 1–5 × 10⁷ pulses, but as shown, the current does not appear in every shot. This may be considered as the main limiting factor for the cathode lifetime regarding the use in microwave tubes.
A practical limitation was obtained regarding the lifetime of FE cathodes for microwave tubes. The lifetime is apparently not limited by the reduction of the charge in the current pulse, or by the vanishing of the radiation at the tube output, but by the increasing rate of missing pulses, and by increasing of the irregularity between consecutive pulses.

The observed blackening phenomenon is similar to the one reported in Ref. [16], and their conclusion regarding surface microstructure changes is reinforced. This explains the color change. Also, the surface micro-changes in proximity to the front electrode may slightly increase the minimal voltage for the initial

Fig. 7. Repeatability of the current and microwave pulses during the experiment after $3 \times 10^6$ pulses (a), after $5 \times 10^6$ pulses (b), and after $1 \times 10^7$ pulses (c) (Cathode #2).

Fig. 8. Electrical charge vs. number of driven pulses for cathode #1 (a) and cathode #2 (b).

Fig. 9. Current consumption of the cathode HV power supply during the high PRF experiment vs. number of driven pulses.

Fig. 10. Stabilization of the consumed current when starting high PRF.
surface plasma formation. Therefore, the ignition of the plasma does not occur for every shot. According to this explanation a possible way to partially overcome this limitation is gradual increment of the trigger voltage. Regarding the short-time-recovery effect, possible explanation is related to the charge. Each pulse takes away negative electron charge from the cathode that has to be compensated. Unlike thermionic cathode, the ferroelectric cathode is not conductive and therefore, the charge compensation is slow. When the pulses are stopped after long period of high PRF operation, slowly the charge is compensated for as a surface layer. Then, when re-operating, the pulses are more easily ignited, and slowly, as the charge is lost again, the ignition becomes more difficult and the former steady state is reached again.

References