Metallic Vapor Thruster Using Field-emitted Electron Bombardments

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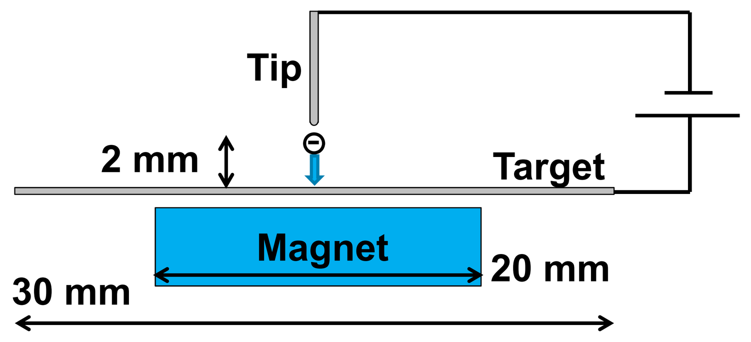
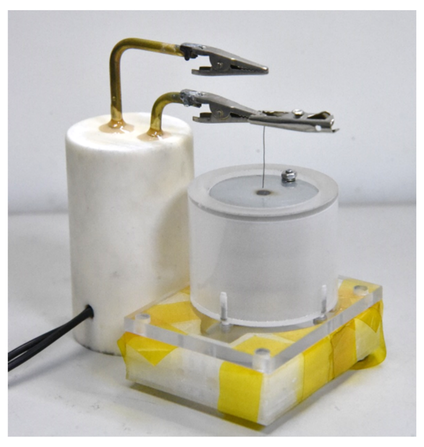
Abstract

Abstract A metallic vapor thruster using field-emitted electron bombardments (MVT-FEB), which can be used in small spacecraft such as CubeSats for precise attitude control, is being developed. The principle of E-beam evaporation, where the metal target is heated and evaporated by energetic-electron bombardments, is used. A metallic target is used as the propellant. A tungsten tip with a diameter of ~100 um is used as the electron source. The tungsten tip is normal to the target surface and a couple millimeters away from the target. A high voltage is applied between the tip and the target. The tip is the cathode while the target is the anode. Field-emitted electrons from the tungsten tip are accelerated by the electric field and collide with the center of the target. The center region of the target is heated and evaporated by the bombardments of energetic electrons. The metallic vapor leaving the target then provides the thrust. Zinc is used due to its low vapor pressure. For an electron beam with currents in the order of ~50 uA and an accelerating electric potential of 6 kV, the zinc target is heated and evaporated. The new concept of the thruster uses solid propellant which has the advantage of high density, easy to be stored, scalable in size and thrust. It is a good candidate for precise attitude control. The work is supported by the Ministry of Science and Technology (MOST), Taiwan under Award Number 107-2628-E-006-006-MY2.

Designs

- A tungsten tip with 100 um in diameter.
- A zinc target. Zinc can be vaporized easier than other metals[2].
- High voltage of 6 kV between the tip and the target.
- Magnets providing 0.15~0.25 T for guiding field-emitted electrons.





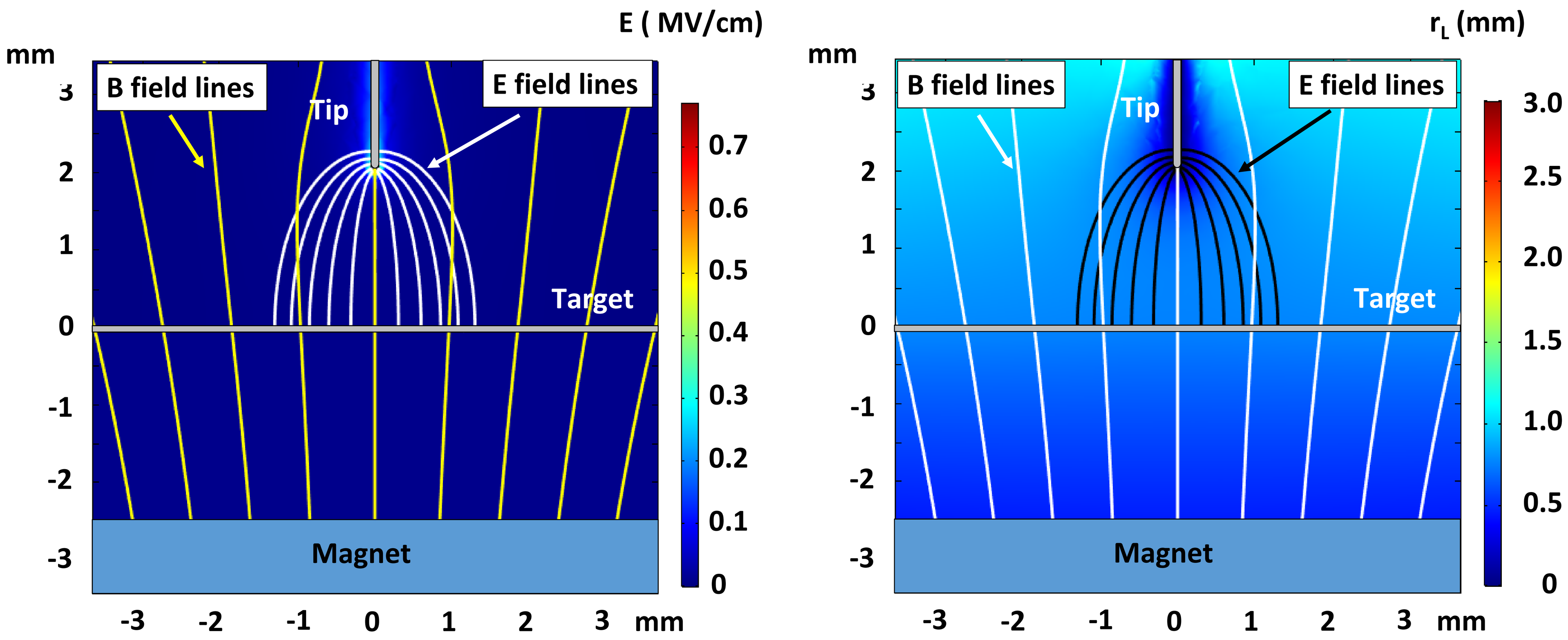
Fowler-Nordheim's theory

- Current density of field-emitted electrons[1]:

$$j = \frac{\epsilon}{2\pi h}\frac{\mu^{1/2}}{(\chi+\mu)\chi^{1/2}}E^2\exp\left(-\frac{4\kappa\chi^{3/2}}{3E}\right)$$
$$= 6.2\times10^{-6}\frac{\mu^{1/2}}{(\chi+\mu)\chi^{1/2}}E^2\exp\left(-\frac{2.1\times10^{8}\chi^{3/2}}{E}\right)$$

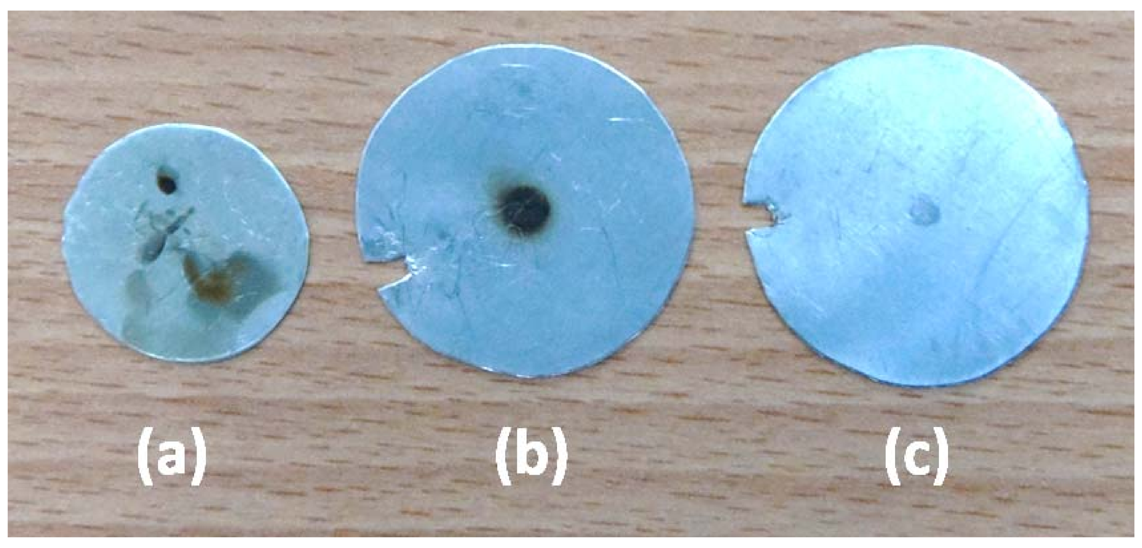
- Electric field ~10 MV/cm is needed to generate measurable current.

Simulations



- The electric field is ~1 MV/cm. Some electrons are field-emitted from the tip.
- Electron gyroradius is much smaller than the target size. Electrons follow magnetic field line toward the center of the target.

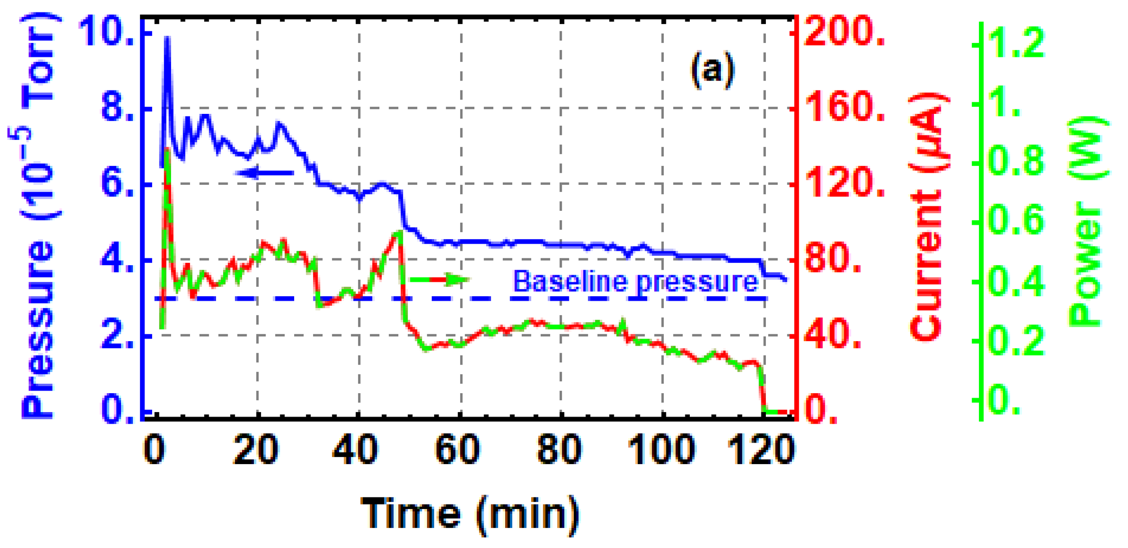
Targets after experiments

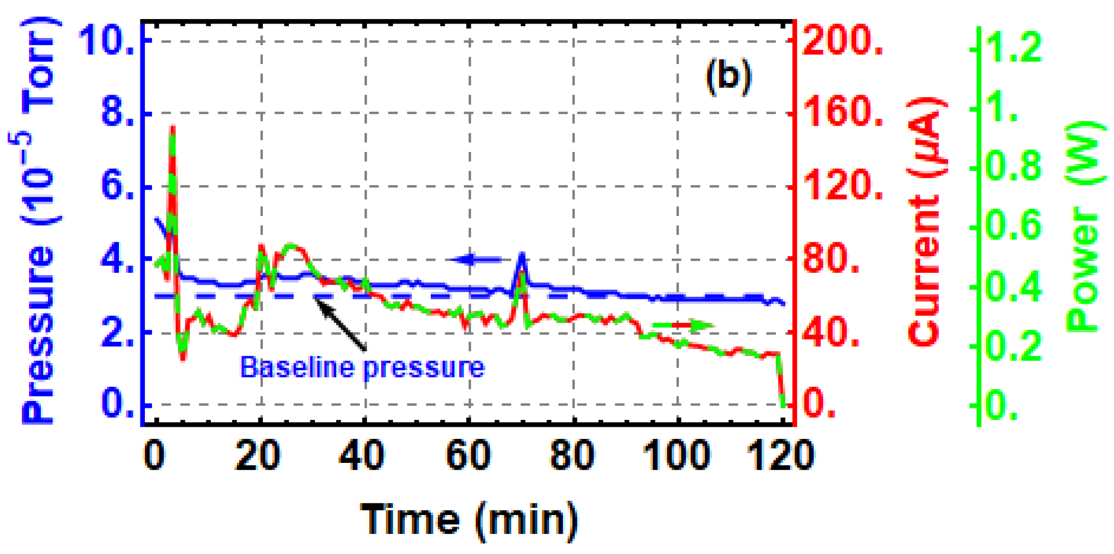


- Three different cases were tested.
  (a) The target was at 6 kV without a magnet.
  (b) The target was at 6 kV with a magnet.
  (c) A pulsed-voltage of ~5 kV was provided by a discharge of a 1.8-nF capacitor, i.e., 35 mJ in each discharge. The repetition rate of the pulsed-voltage was ~5 Hz.
- Clear burn marks on the top surface of targets in all cases. When there were magnetic fields, burn marks occur at the center of the target only.

Experimental results

- We monitored the pressure of the vacuum chamber and the field-emitted electron currents during the experiments in cases (a) and (b).





- For currents less than ~65 uA, i.e., powers less than ~0.4 W, pressures dropped back to the baseline pressure meaning that almost no vapor was generated.
- In case (c), the averaged power was ~0.2 W. Vacuum pressure was not affected.
- Although there were clear burn marks on targets in all cases indicating that targets did get heated, the mass differences of the target before and after bombarded by field-emitted electrons in all cases were within the error bar.

Discussion

- A power larger than 0.4 W is needed to generate observable evaporation.
- Field-emitted electron current is only related to the electric field strength at the tip. To increase power, either voltages or field-emitted currents need to be increased. There are four options: (1) finer tip; (2) shorter gap distance; (3) applying higher electric potential; and (4) more tips.

Conclusion

- A new concept electrothermal electric propulsions using a zinc target being bombarded, heated and thus evaporated by accelerated field-emitted electrons from a tungsten tip was tested.
- We showed experimentally that electrons heat the target and left a burn mark on the target.
- The power was not enough so that the temperature was not high enough to evaporate the zinc target.
- By increasing the power, the new concept of metallic vapor thruster using field-emitted electron bombardments can fully be demonstrated.

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Abstract

A metallic vapor thruster using field-emitted electron bombardments (MVT-FEB), which can be used in small spacecraft such as CubeSats for precise attitude control, is being developed. The principle of E-beam evaporation, where the metal target is heated and evaporated by energetic-electron bombardments, is used. A metallic target is used as the propellant. A tungsten tip with a diameter of $\lesssim 100$ μm is used as the electron source. The tungsten tip is normal to the target surface and a couple millimeters away from the target. A high voltage is applied between the tip and the target. The tip is the cathode while the target is the anode. Field-emitted electrons from the tungsten tip are accelerated by the electric field and collide with the center of the target. The center region of the target is heated and evaporated by the bombardments of energetic electrons. The metallic vapor leaving the target then provides the thrust. Zinc is used due to its low vapor pressure. For an electron beam with currents in the order of 50 μA and an accelerating electric potential of 6 kV, the zinc target is heated and evaporated. The new concept of the thruster uses solid propellant which has the advantage of high density, easy to be stored, scalable in size and thrust. It is a good candidate for precise attitude control.

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I. INTRODUCTION

Thrusters are important subsystem in spacecraft for attitude and orbit controls or deep space explorations. Electric propulsions are very attractive due to their high efficiency, small volume, and low power consumption. There are three types of electric propulsions, electrothermal, electrostatic, and electromagnetic[1]. Here we are developing a thruster in the category of electrothermal where the propellant is heated, leaves the thruster and provide the thrust.

In a conventional electrothermal thruster such as resistojets or arcjets, the gas propellant is heated electrically. A high-pressure gas cylinder so that a lot of space and weight is needed. To reduce the weight and to simplify the system, a solid propellant is used in this work. The principle of E-beam evaporation, where the metal target is heated and evaporated by energetic-electron bombardments, is used. It is called metallic vapor thruster using field-emitted electron bombardments (MVT-FEB). It is very similar to the metallic ion thrusters using magnetron electron-beam bombardments (MIT-MEB)[2] which is also presented in this conference[3]. Field-emitted electrons generated from a fine tungsten tip are accelerated and bombarding a metallic target. The target is heated and evaporated. The vapor then leaves the thruster and provide the thrust. Since the tungsten tip is not heated, all electrical energy is used to accelerate electrons and thus to heat the target. Therefore, the power consumption is very low. The thrust, however, is very little. Nevertheless, due to its low power consumption and small thrust, it is a good candidate for precise attitude control.

II. METALLIC VAPOR THRUSTER USING FIELD-EMITTED ELECTRON BOMBARDMENTS (MVT-FEB)

The MVT-FEB is simply a metallic vapor gas generator. A metallic target is heated and vaporized so that thrusts are provided when vapor leaves the thruster. The key is how vapor is generated. It is described in the following.

A. Vapor sources using magnetron field-emitted electron bombardments

The vapor is generated by a metallic target being heated by energetic electron bombardments. Field-emitted electrons from a fine tip are accelerated by electric fields and guided to the center of the target by magnetic fields. As a result, the center of the target is heated and thus the vapor is generated. The vapor source consists of four elements: (1) a tungsten tip; (2) a metallic target; (3) an high voltage between the tip and the target; and (4) a magnet.

1. **The tungsten tip**: it is used to emit electrons via field-emission. The advantage of using field-emitted electrons over thermal-emitted electrons is that no energy is needed to heat the tip. In other words, power consumption can be significantly reduced compared to the metallic ion thrusters using magnetron electron-beam bombardments (MIT-MEB)[2]. However, to generate field-emitted electron, a high electric field is needed and provided by a sharp edge, i.e., a fine tip. Tungsten is used to prevent the tip from being melted.

2. **The metallic target**: it is the propellant. The target needs to be conductive so that the electron current can flow from the tungsten tip through the target while heating the target. Zinc is chosen since it has a higher vapor pressure at the same temperature comparing to other metals[4]. In other words, it is easier to evaporate zinc.

3. **The high voltage between the tip and the target**: it is to accelerate the field-emitted electrons. Kinetic energies of accelerated electrons are transferred to the thermal energy of the target when electrons collide the target surface. A high voltage is needed so that the electric field at the tip of the tungsten is strong enough so that electrons are field-emitted.

4. **The magnet**: it is to guide field-emitted electrons to the center of the target. If electrons are not guided to a small point on the target surface, the heat is spread in a large area and is not enough to evaporate the target.

B. Design of the metallic vapor thruster

The key of the metallic vapor thruster is to generate field-emitted electrons. The current density of the field-emitted electrons can be estimated by the Fowler-Nordheim's theory[5]:

$$j = \frac{\varepsilon}{2\pi h} \frac{\mu^{1/2}}{(\chi+\mu)\,\chi^{1/2}} E^2 \exp\left(-\frac{4\kappa\chi^{3/2}}{3E}\right) \tag{1}$$

$$= 6.2\times10^{-6} \frac{\mu^{1/2}}{(\chi+\mu)\,\chi^{1/2}} E^2 \exp\left(-\frac{2.1\times10^{8}\chi^{3/2}}{E}\right) \tag{2}$$

where j is the current density in A/cm^2, ε is the permittivity, h is the plank constant, $\kappa^2 \equiv 8\pi^2 m_\mathrm{e}/h^2$ with m_e as the electron mass, χ is the thermionic work function of the material in eV, μ is the usual parameter of the electron distribution in eV, and E is the emission electric field in V/cm. In order to have measurable current, an electric field on the surface of the material needs to be in the order of 10 MV/cm. It is why a tip is used to enhance the electric field at the tip.

Shown in Fig. 1(a) and (b) are the design and a photo of the MVP-FEB. A tip with a radius of 100 μm is located 2 mm above the target surface. The tip is at ground while the target is at 6 kV. The target is made of zinc with a diameter and thickness of 30 mm and 0.5 mm, respectively. The target is placed on top of an upside-down cup made of quartz providing thermal insulation. The thermal insulation is important to keep the target hot. The thickness of the top of the cup is 1 mm. Three magnets with diameters of 20 mm stacked on each other are placed in the cup. The top surface of the top magnet is 1 mm underneath the inner surface of the top of the cup. The gap and the cup provide the thermal insulation so that magnets are not heated. The magnetic field provided by the magnets is 0.15 $\sim$ 0.25 T between the target and the tungsten tip. It is the same setup used in ref. [2] except that a heated filament is replaced by a tungsten tip.

In Fig. 1(c) is the calculated electric fields via solving poisson's equation numerically. The electric field at the tungsten tip is $\sim$ 1 MV/cm. Some electrons can be field-emitted. Electric potentials at any locations, on the other hand, represent the kinetic energies of electrons at the same location and emitted from the tungsten tip. Further, the magnetic field lines which are the same as those in ref. [2], are also shown. Therefore, the maximum of gyroradius of electrons r_L at any locations are calculated as

$$r_\mathrm{L} \leq \frac{1}{B}\sqrt{\frac{2\phi m_\mathrm{e}}{|e|}} \tag{3}$$

where ϕ and B are the electric potential and the magnetic field at that point, respectively, and e is the electron charge. The calculated gyroradius is shown in Fig. 1(d). The gyroradius between the tip and the target are much smaller than the target size. In other words, electrons emitted from the tip follow the magnetic field lines and bombard the center of the target.

III. EXPERIMENTAL SETUP

We built a prototype as shown in Fig. 1(b) to test the concept of MVT-FEB. We simply measured the field-emitted electron currents and the mass difference of the target

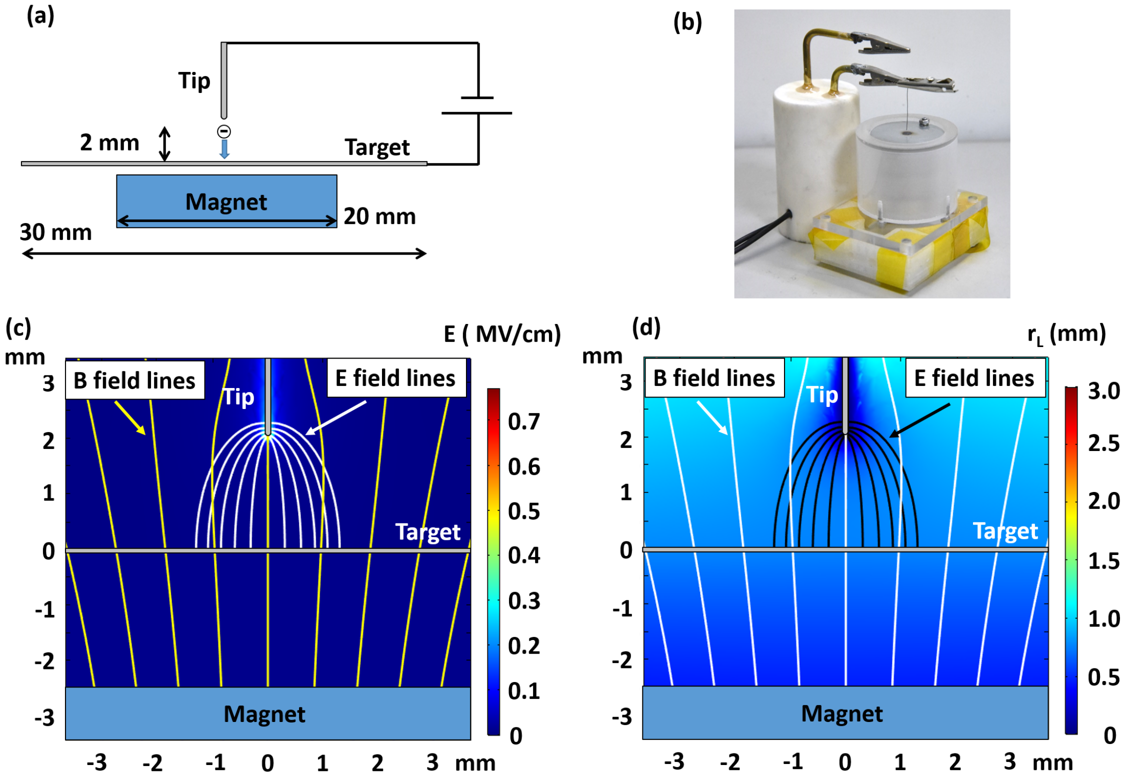


Figure 1. (a) The circuit and (b) a photo of MVT-FEB. (c) Simulated electric field in color contours, electric field lines in yellow, and magnetic field lines in yellow. (d) Calculated gyroradius for field-emitted electrons in color contours, electric field lines in black, and magnetic field lines in white. The tungsten tip is at ground while the target is at 6 kV.

after it operated for two hours. Three different cases were tested: (a) the target was at 6 kV without a magnet; (b) the target was at 6 kV with a magnet as described in section II B; (c) a pulsed-voltage of $\sim$ 5 kV was provided by a discharge of a 1.8-nF capacitor, i.e., 35 mJ in each discharge, using the circuit shown in Fig. 1(a). The repetition rate of the pulsed-voltage was $\sim$ 5 Hz. The purpose was to increase the power in each pulse while keeping the averaged power low. Note that the current is depended on the electric field at the tip according to Eq. 2. Only by changing the voltage, the gap distance and the geometry of the tip can the current be controlled.

IV. RESULTS

We first see how targets were affected by electron bombardments after experiments which are shown in Fig. 2. There are clear burn marks on the top surface of targets in all cases. In case (a) where no magnets were present, the burn mark spread in a wide range of the target surface. It is because electrons were not guided to the center of the target by magnetic fields. It shows the importance of the guiding magnetic field. In case (b) where magnetic fields were provided by magnets, there was a circular burn mark at the center of the target. Similarly, there is a circular mark at the same location in case (c) where a pulsed-voltage was used. They were direct evidence that electrons follow the magnetic field lines toward the center of the target.

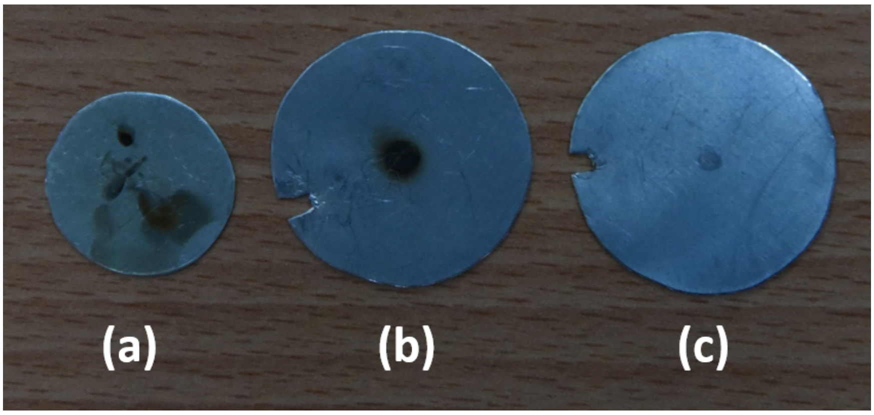
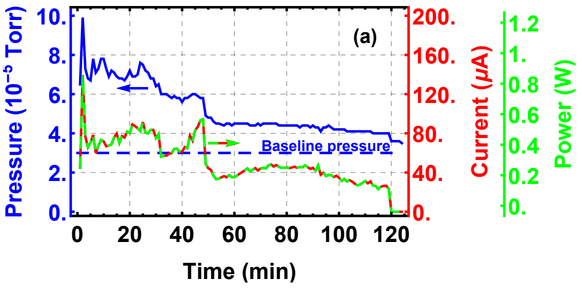


Figure 2. Targets after experiments. (a) the case where no magnets were used; (b) the case where magnetic fields were provided by magnets; and (c) the case where a pulsed-voltage was used. Burn marks are caused by accelerated electron bombardments.

We monitored the pressure of the vacuum chamber and the field-emitted electron currents during the experiments in cases (a) and (b). Currents, pressures, and calculated powers are shown in Fig. 3. Notice that the baseline vacuum pressure was 3×10^{-5} torr. Pressures higher than the baseline vacuum pressure indicated that the target was heated and evaporated. However, the amount of generated vapor was very little. For currents less than ~ 65 μA, i.e., powers less than ~ 0.4 W, pressures dropped back to the baseline pressure meaning that almost no vapor was generated. In case (c), the averaged power was ~ 0.2 W. A circular mark was also shown at the center of the target meaning that electrons did heat the center of the target. However, the pressure was not increased at all. As a result, although there were clear burn marks on targets in all cases indicating that targets did get heated, the mass differences of the target before and after bombarded by field-emitted electrons in all cases were within the error bar.



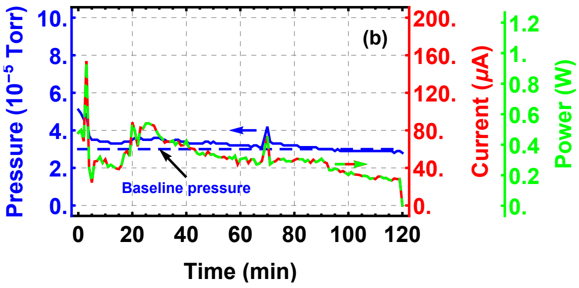


Figure 3. (a) Measurements in case (1); (b) Measurements in case (2). Blue lines are vacuum pressure while red lines are field-emitted electron currents. Dashed blue lines represent the baseline pressure.

V. DISCUSSION

We have shown that field-emitted electrons can be guided by a magnetic field toward the center of a target. A burn mark indicated that a small region of the target did get heated. However, the amount of heat was not enough to evaporate the target made by zinc. According to the experimental results shown in section IV, a power larger than 0.4 W is needed to generate observable evaporation. To increase power, either voltages or field-emitted currents need to be increased. Notice that field-emitted electron current is only related to the electric field strength at the tip. Therefore, it can be increased by (1) finer tip; (2) shorter gap distance; (3) applying higher electric potential; and (4) more tips. For option (1), it will be harder to fabricate the tip. Also, the current density will increase and the tip may not be able to handle the current and be melted. In option (2), it will be harder to build a system with a shorter gap distance. Therefore, option (1) and (2) may not be good choices. Nevertheless, for option (3), the power can be increased because both voltages and currents are increased. For option (4), the current is directly proportional to the number of tips. For example, if 5 tips are used, the power is immediately increased by 5 times and will be enough to evaporate the target.

VI. CONCLUSION

A new concept of electrothermal electric propulsions was proposed. A metallic target made of zinc was heated by electron bombardments. Electrons were field-emitted by a tungsten tip and accelerated by an electric potential of 6 kV. A magnetic field was used to guide accelerated electrons to the center of the zinc target. The zinc target was heated when accelerated electrons collide the target center and transfer their kinetic energy to heat. We showed experimentally that electrons heat the target and left a burn mark on the target. However, the power was not enough so that the temperature was not high enough to evaporate the zinc target. Therefore, we propose using a higher electric potential to accelerate electrons or using more tips so that the power can be increased leading to a higher heating capability. Therefore, the new concept of metallic vapor thruster using field-emitted electron bombardments can fully be demonstrated.

ACKNOWLEDGMENTS

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