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Experimental Investigations of High Voltage Pulsed Pseudospark Discharge and Intense Electron Beams

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A high voltage pulsed discharge device which can produce intense high energy electron beam named "pseudospark" is presented in this work. This discharge device is able to hold 10s of kV voltage, kA current and 10^{10}-10^{11} A/s current rising rate. The pseudospark device is also a simply-constructed source for intense electron beam with high energy. The presented experimental investigation is focused on the discharge properties of pseudospark and the plasma-produced electron beam characteristics for current and potential applications in aerospace problems. The discharge property results show the presented pseudospark device has the hold-off voltages up to 26 kV and discharge current of 2 kA with current rising rate of 1×10^{11} A/sec. And the comparative study on various discharge configurations show the capability of pseudospark device to hold voltage and high current generation in short pulse can be further improved by the device geometric configuration, leading to higher pulsed load drive capability. The intense electron beam obtained from the multi-gap pseudospark device has a current up to 132.2 A, and electron number is varied from 4×10^{15} to 2×10^{16} in the presented operation voltage range obtained from 10s of cm^3 charged particle channel. The energy analysis on this pseudospark-produced electron beam displays the "double-hump" non-Maxwellian energy distribution. The maximum energy peak value varies from 900 eV to 6.3 keV under 4 kV to 12 kV discharge voltage. Specifically, comparison of the beam parameters obtained from pseudospark device and the electron beam requirement for a MHD channel indicates pseudospark is a promising electron source.

Nomenclature

e	=	charge of single electron
I_{max}	=	maximum magnitude of discharge current
N_e	=	total number of electrons
Q_{total}	=	total charge of electrons
I_e	=	electron beam current

I. Introduction

THE pseudospark discharge was first discovered in the late 1970's, as an axially symmetric, high voltage gas discharge operating at low pressure regime located on the left hand side of the Paschen curve as illustrated in Fig.1, which is based on the principles of a hollow cathode discharge.[1-3] The fundamental discharge configuration consists of planar anode and cathode, or multi-gap electrodes, as illustrated in Fig.2 and Fig.3. The central hole in the middle of the electrodes makes the effective distance of the discharge path a maximum in the region of the bore hole on the axial center of electrodes and cathode cavity. Thus the gas discharge is concentrated in the region around the axis of the central holes.[1] Then the high electric field (10^6 V/m) concentrated in the central axis across the electrode gap and the charge carrier multiplication taking place in the hollow cathode cause the final ignition of high voltage high current gas breakdown.

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Pseudospark discharge is a pulsed gas discharge in which the gas discharge can obtain 10s to 100s of kV voltage hold-off capability and kA discharge current during total time of discharge of 10s to 100s ns, and several ns rise time. The physical volume of pseudospark discharge chamber is at 10s of cm^3. Thus the pseudospark discharge component can obtain the 10s of kV hold-off voltage and high current rising rate of 10^{10} to 10^{11} A/s within a 10s of cm^3 volume, which makes it suitable for compact pulsed power drive.[5] Besides the high voltage high current hold-off capability, the pseudospark is a low-pressure gas discharge operated on the left branch of Paschen curve. Thus unlike high pressure spark gaps, this device is free from mercury and electrode erosion to achieve longer lift time

Another important feature of pseudospark is the plasma-produced intense electron beam. During gas breakdown, electrons are multiplied rapidly because of the hollow cathode effect. Then the electrons are accelerated by high electric field and extracted from the exit at anode side. This electron beam is a highly pinched electron beam with high current density (10^3 A/cm^2) and high energy (keV-10s keV).[6-8]

The outstanding characteristics of pseudospark discharge and the produced charge particles have been successfully applied in multiple applications. In Ref. 6, 9 and 10, single gap and multigap pseudospark discharge switches were developed and used for compact pulsed power drive. In Ref. 11-16, the intense electron beams were developed for ultraviolet and x-ray production, material processing, accelerator applications, pulsed laser oscillations, microwave generation, etc.

Furthermore, the pulsed discharge and intense beams also have wide applications in aerospace area. Electron beam fluorescence is a relevant example. The electron beam fluorescence technique for gas specie density measurement has been developed since 1968.[17] In this technique, local number density measurement using the electron beam technique is determined by a unique relationship between the local gas number density and the spontaneous fluorescence of the beam-excited atomic states.[18] In Ref. 19 and 20, the pulsed electron beam fluorescence technique was developed and the advantages of pulsed electron beam compared with DC electron beam in fluorescence technique were analyzed and validated. In Ref. 17, initial experimental study of pulsed electron beam fluorescence was obtained in a pseudospark discharge device. In Ref. 17 and 19, the results of density measurements in non-equilibrium, chemical reacting flows by such pulsed electron beam fluorescence techniques were presented.

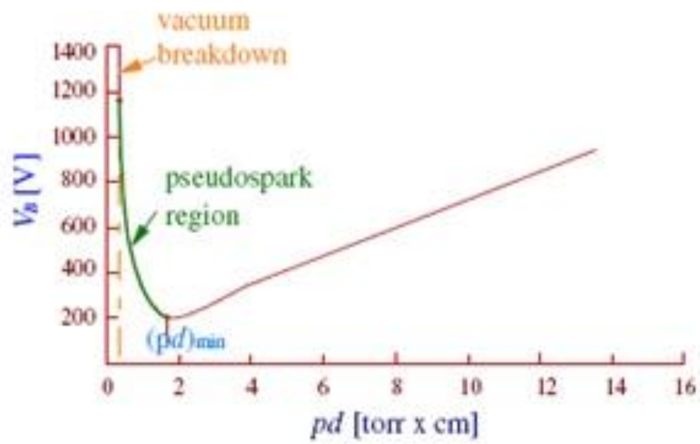


Figure 1. Pressure range for various types of discharges (Figure from Ref. 4)

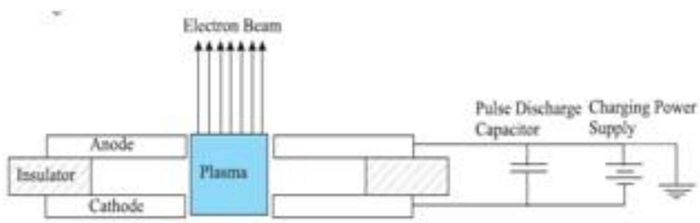


Figure 2. Configuration of single-gap pseudospark

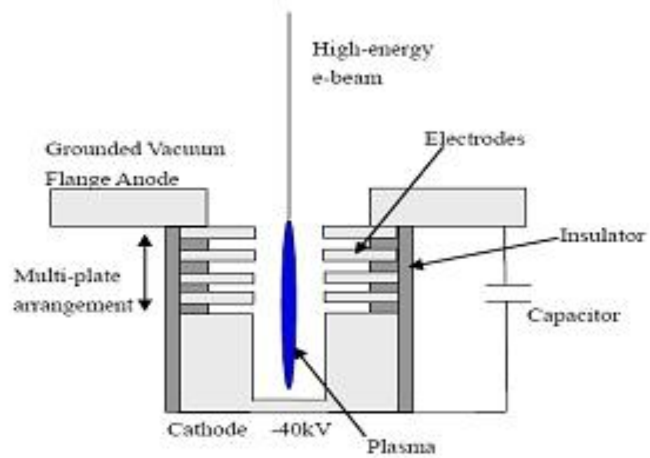


Figure 3. Configuration of multi-gap and hollow cathode pseudospark.

MHD channel is another application which requires high energy intense electron beams. In Ref. 21 and 22, the feasibility of electron beam generated plasmas in hypersonic MHD channel control was discussed. In Ref. 23 and 24, the MHD control of hypersonic flow and scramjet inlets by electron beam ionization was developed and validated. Electron beams are assumed to be the most efficient way of ionizing cold gases. Specifically, in Ref. 24, it shows that compared to low-energy (1-3 eV) electrons in conventional discharges that dissipate most of their energy in nonionizing inelastic collisions, the ionizing electrons with comparatively high energy from tens of electronvolts to thousand of electronvolts minimize the power required to sustain weakly ionized plasmas, which can be easily achieved by the presented pseudospark discharge.

However, pseudospark discharge is a highly flexible and controllable pulsed discharge and charged particle source. Since the processes and mechanisms that dominate the pseudospark discharge are complicated, the basic mechanism of discharge ignition and development, the formation of high energy space-charge-neutralized electron beams, and the experiment observations and determinations on spatial and time-dependent characteristics of pseudospark discharge and produced charged particles are still not well understood, leading to the lack of systematic experimental investigations on the controllable parameters of this type of discharge and intense beams. A typical example is presented in Ref. 17: Although the pseudospark-produced electron beam fluorescence technique showed encouraging results as a diagnostic tool, there was still significant scatter in the intensity distribution data caused by the inconsistent discharge nature and beam quality issues in the presented pseudospark device. Thus in our research work, we focus on the systematic experimental investigation of pseudospark discharge properties for multi-gap discharge configurations, and the highly time-resolved characteristics of pseudospark produced electron beams, which are the challenging subject in pseudospark discharge and transient hollow cathode discharge due to the high voltage (10s – 100s kV), short pulse duration time (1ns-10s ns), and very fast transient evolution inside a very small volume (10s cm^3). These highly time-dependent properties of the discharge process and the charge particle production are important for the application of pseudospark discharge and produced charged particles in various applications and helpful to understand, control and optimize the useful parameters of the pseudospark properties and produced charge particles. Specifically, comparison of electron parameters obtained in our presented pseudospark device, and the electron parameters required in hypersonic MHD channels listed in Ref. 21-24 are presented in our work.

This work is organized into the following sections: a detailed introduction to the current pseudospark experiment setup and measurement methods is presented in Sec II. The experiment investigation results of discharge properties from various multi-gap configurations and the comparative study results are shown in Sec III. The time-resolved characteristics of pseudospark produced electron beams are presented in Sec IV. Finally, conclusions on the experimental investigations and future work are summarized in the last section.

II. Pseudospark Experiment Setup

The pseudospark discharge chamber is shown in Fig.4. As shown in Fig.4, the pseudospark discharge chamber consists of a cylindrical hollow cathode, grounded anode, multi-gap electrodes, and stacked interelectrode insulator disks. The presented pseudospark discharge chamber has an adjustable gap number varied from 1 gap to 20 gaps. Each electrode and the hollow cathode have 22 mm diameter and 1.5 mm on-axis hole for the electron beam extraction. The gap distance between a pair of electrodes is 1.5 mm. The hollow cathode was connected to the high voltage dc power supply (100kV, 1mA) through a 20 MΩ charging resistor. Two 390 pF ceramic capacitors were connected between the anode and cathode symmetrically.

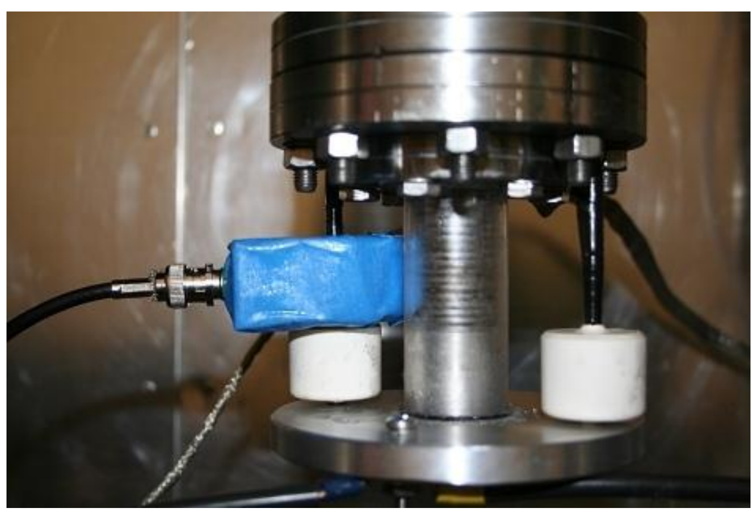
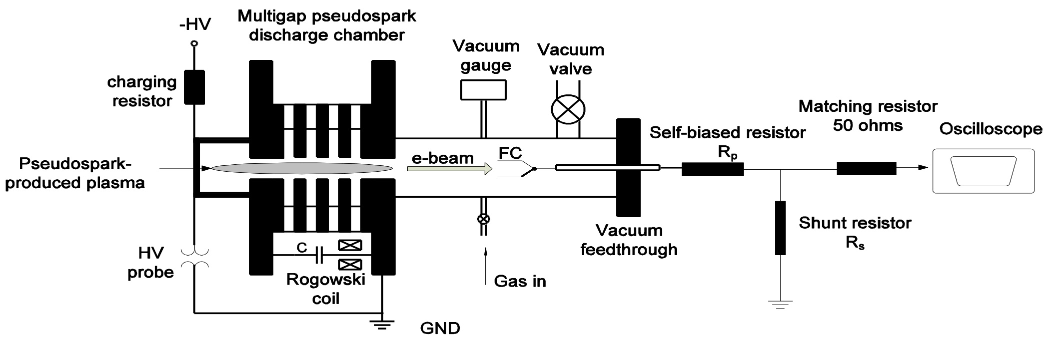


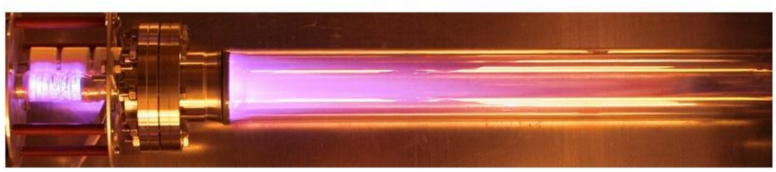
Figure 4. Pseudospark discharge chamber fabricated in APLab

The pseudospark discharge and electron beam experimental setup is shown in Fig.5. A 70 cm long drift tube was connected to discharge chamber for beam propagation study. The whole experimental system was evacuated down to 10^{-5} Torr initially by a two-stage mechanical pump and turbo pump. The operating gas was argon. Argon gas enters into the vacuum system through a mass flow controller. The mass flow rate of argon can be adjusted accurately to control the operation pressure in vacuum system. There was no external applied guide magnetic field in our experiments.

The breakdown voltage of pseudospark discharge was measured by a custom North Star high voltage probe PVM-5. A Rogowski coil located in the discharge loop was used to measure the discharge current flowing through the external capacitor. The study of pseudospark-produced pulse electron beams was realized by a movable fast response Faraday cup with adjustable impedance developed in our lab.[25] The data acquisition is realized by high speed oscilloscope with 500 MHz bandwidth, 1 G/s sampling rate. The control of oscilloscope readout and data storage is acquired by a Labview software workbench.



Pseudospark Plasma **Plasma-based Electron Beam**



20 kV Pseudospark Discharge and Electron Beam Production System

Figure 5 (a). Pseudospark discharge and intense electron beam experiment setup (top)
(b). Pseudospark discharge and produced intense e-beams obtained in the presented setup (bottom)

III. Experiments Results and Analysis I: Pseudospark Discharge Properties

As discussed in Section I, pseudospark device is a good candidate for pulsed power drive and fast switches. In the pulsed power applications, the capability of pseudospark device to hold high voltage and generate large current magnitude within short time is the main concern. In this section, the discharge properties of pseudospark in different configurations are presented and compared. According to the presented experiment results, the presented pseudospark devices have kV to 10s of kV hold-off voltage, and current rising rate is 10^{10}-10^{11} A/s. The comparative study shows that it has been proved that the multiplication of discharge gap region can improve the hold-off voltage and discharge current. The comparative study results of discharge characteristics from single-gap to 5-gaps are presented in the following section.

A. Discharge characteristics of pseudospark in single-gap configuration

Fig.6 is an example of pseudospark breakdown voltage and discharge current waveforms obtained in single-gap pseudospark configuration. As shown in Fig.6, the initial breakdown process of pseudospark operated at 4.9 kV is within 50 ns, which is the characteristic operation time of pseudospark discharge. The damping oscillation in V-I waveform is mainly caused by the inductance in the discharge loop, which is measured to be 50 nH approximately. And the negative peak discharge current is increased from 0 to 0.6 kA within 10 ns, which means in such a pulsed discharge, the current rising rate can go up to 10^{10} A/s.

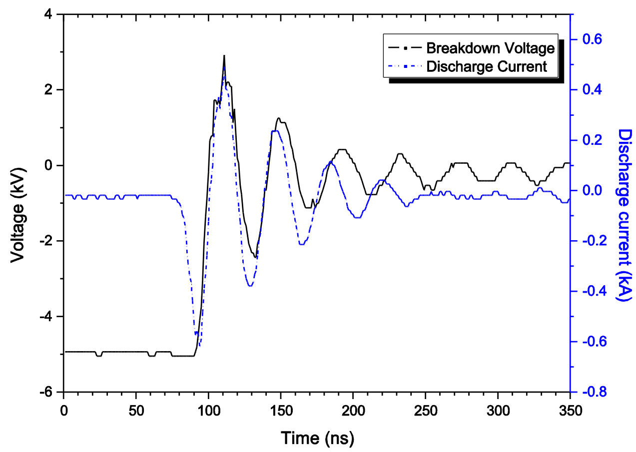


Figure 6. Typical self-breakdown voltage and discharge current waveform in single-gap pseudospark configuration.

B. Discharge characteristics of pseudospark in multi-gap configuration

The comparative studies are operated over 5 groups of different gap numbers and the discharge characteristics are determined and compared in the following sections.

1) Breakdown voltages over pressure range

Like conventional thyratron discharge, the pseudospark discharge operates in low pressure high voltage situations, where the reduced electric field (E/N) is of the order of 10^{11} V cm^2 = 10^6 Td. At such high E/N values, the mean free path of electrons and ions are comparable to the electrode spacing (mm). Therefore, most of the electrons released at the cathode reach the anode without undergoing ionizing collisions and do not contribute much to the ionization growth within the gas, which explains the increase of the breakdown voltage with decreasing pressure, since the mean free path is proportional to $(\text{density})^{-1}$, thus $(\text{pressure})^{-1}$.

Moreover, as shown in Fig.1, pseudospark has its characteristic operation pressure varied from several mTorr to Torrs, strongly dependent on the geometric dimensions of discharge configurations. Fig.7 shows two V-I waveforms obtained from the multi-gap configurations which are within the critical pressure range 70 mTorr~80 mTorr. The right traces show the stable, repetitive pseudospark discharge behavior while the left traces are unstable discharge. Our experimental investigations show that increasing gap numbers will affect both the self-breakdown voltage and stable operation pressure range, as illustrated in Fig.8.

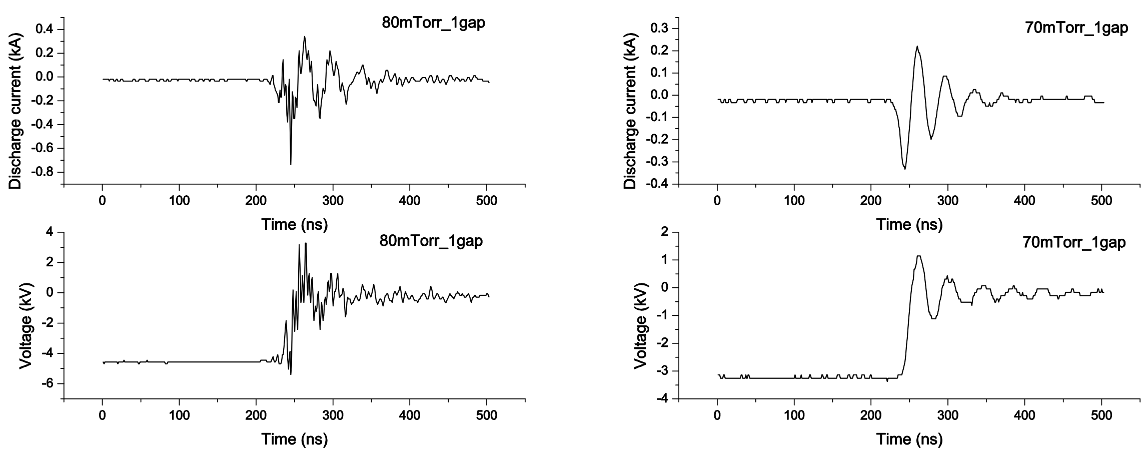


Figure 7. (a). Unstable discharge characteristics away from the pseudospark operation pressure range (left); (b). Stable discharge characteristics within pseudospark operation pressure range (right)

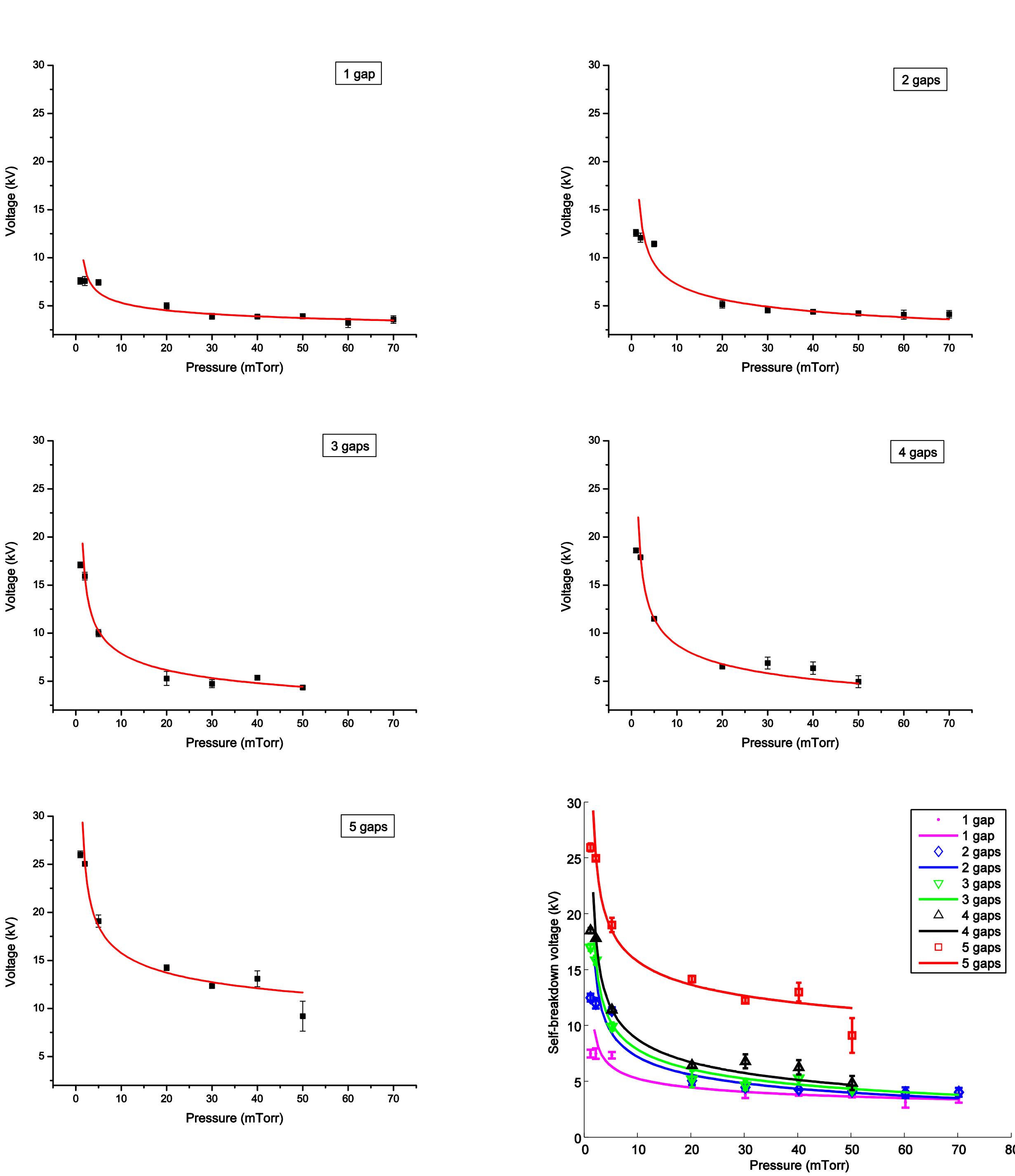


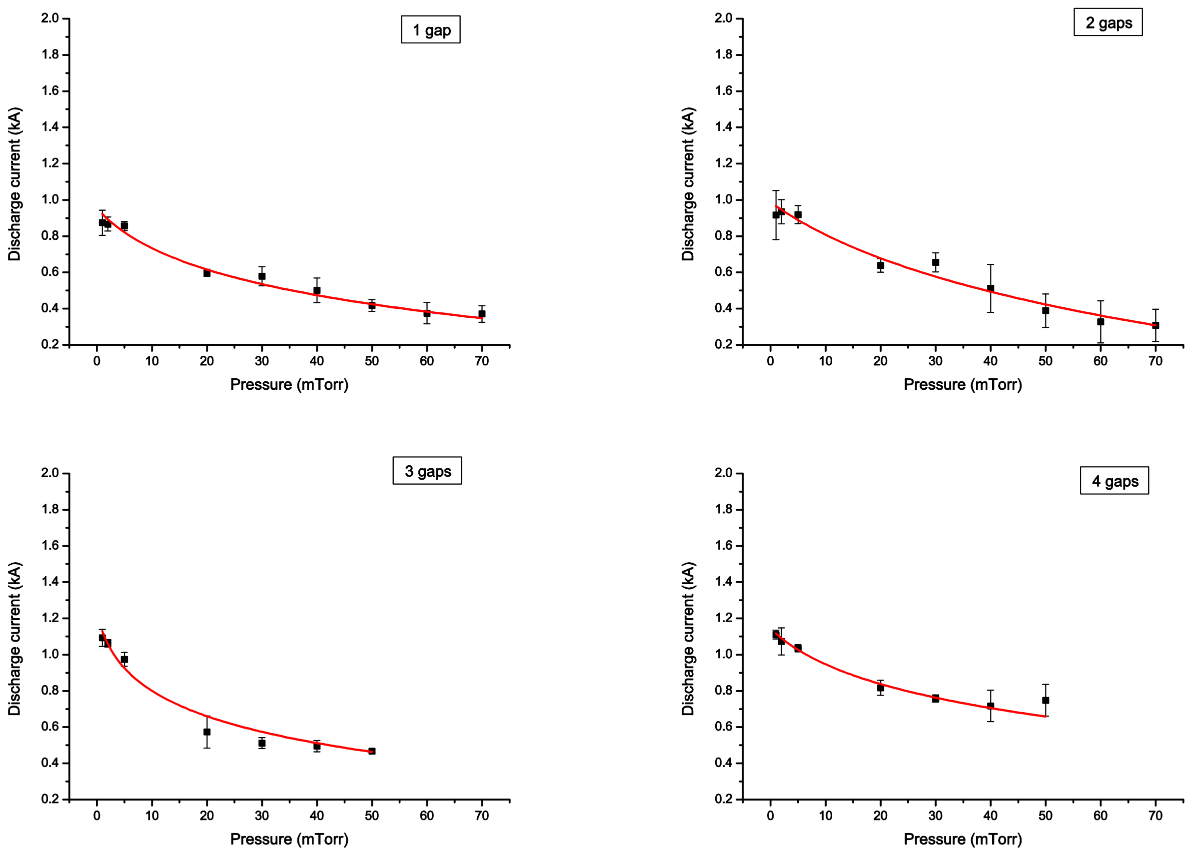
Figure 8. Self-breakdown voltage in operation pressure range obtained in various discharge configuration (single gap- 5 gaps)

Fig.8 shows the self-breakdown voltage vs. operation pressure range obtained in single gap to 5-gap configurations. All the data points are averaged over ten continuous discharge shots. It illustrates that the self-breakdown of the presented pseudospark configuration is increased with decreased pressure, which is located on the left side of the minimum point of Paschen curve. From Fig.8, the self-breakdown voltage can be increased from maximum -7.2 kV in single-gap configuration to a maximum -25.1 kV in 5-gap configuration. The breakdown voltage increase from 1 to 5 gaps is 248.61% at pressure of 1 mTorr. The minimum self-breakdown voltage in 5-gap configuration is -10.9 kV and in single-gap configuration is -3.1 kV at 70 mTorr, the maximum pressure, which is an increase ratio of 251.6%.

Moreover, the gap numbers also affect the stable operation pressure of pseudospark. For single-gap and double-gap pseudospark configurations, the maximum operation pressure is 70 mTorr. But in 4-gaps and 5-gaps configuration, the critical pressure for stable pseudospark is 50 mTorr. Our experimental results also show that the electrode distance has a critical effect on stable operation pressure for pseudospark. In the presented configuration, electrode thickness is 3 mm and can be operated up to 70 mTorr but this operation pressure *(p)* can be increased by decreasing the electrode distance *(d)*, which is qualitatively consistent with the Paschen's law: The self-breakdown voltage is dependent on the product of (*pd)*. Our experiment investigations also show that if the electrode thickness is 1.5 mm, the operation pressure for stable pseudospark can be up to 280 mTorr. The maximum pseudospark pressure reported and published to date is 1 Torr in Ref. 6. All those results show that both the hold-off voltage and operation pressure of a pseudospark device is controllable by geometric dimensions of discharge chamber.

2) Discharge current characteristics

Fig.9 is the peak value of discharge current over the investigated pseudospark pressure range, which is averaged over 10 continuous shots. Similar to self-breakdown characteristics shown in Fig.8, the maximum discharge current also increase from -0.87 kA in single-gap to -1.9 kA in 5-gaps, an increase of 118.3%. At 50 mTorr, the discharge current increases from -0.42 kA for 1 gap to -0.90 kA for 5 gaps by a factor of 114.3% at. Comparison of Fig.8 and Fig.9 shows that the increase ratio of discharge current is lower than self-breakdown voltages for various pseudospark configurations.



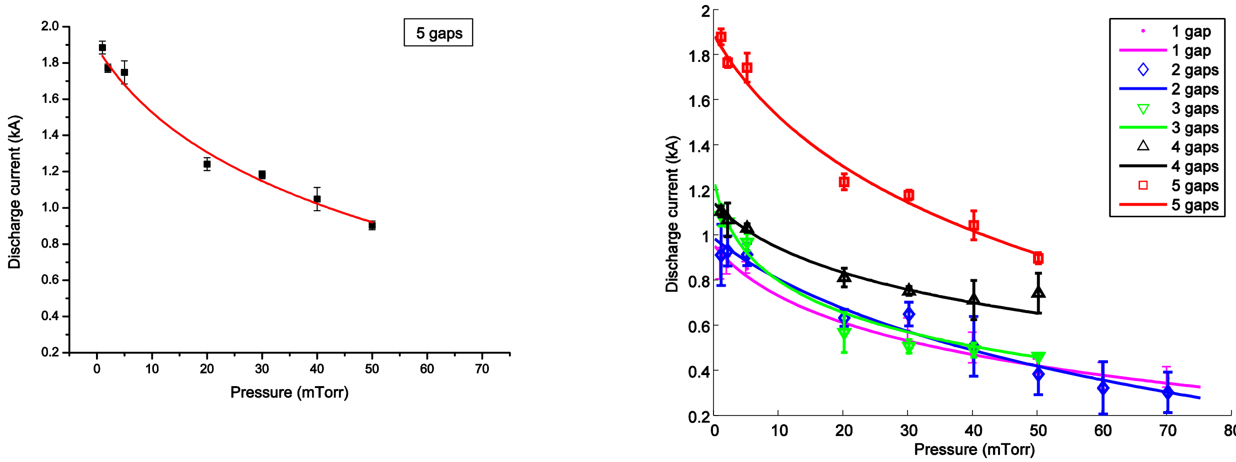


Figure 9. Discharge current obtained in various discharge configurations (single gap- 5 gaps)

3) Characteristic time and Current rising rate

The characteristic time of pseudospark is defined as the time duration of discharge current from initiation to the maximum peak current, which represents the capability and response speed of a pseudospark device to drive a pulsed power load. Fig.10 shows this characteristic time in various gap configurations. It shows that the characteristic time is not a very sensitive parameter to gap number, and is within 16 ns to 20 ns.

Current rising rate is defined as

$$\frac{dI}{dt} = \frac{I_{\max}}{\Delta t} \qquad (1)$$

The current rising rate for different gap numbers is shown in Fig.11. Multi-gap configuration still shows better power drive characteristics than single-gap configuration. A current rising rate of 1.03×10^{11} is obtained in 5-gaps configuration, which is 114.5% higher than the maximum current rising rate obtained in single-gap configuration. This high current rising rate of 1.03×10^{11} at 28kV obtained in a cm^3 small volume is comparable to the maximum current rate of present thyratrons at 30 kV.[26]

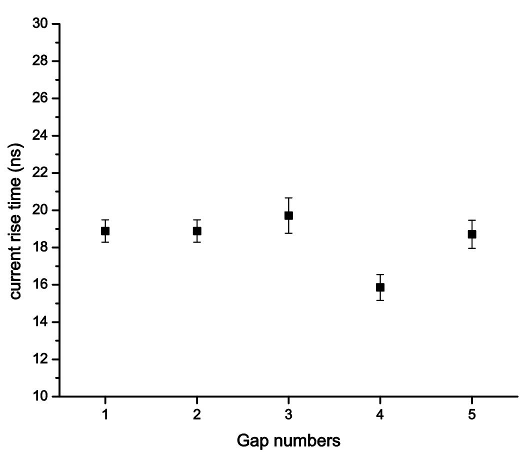


Figure 10. Discharge characteristic time (current rising time)

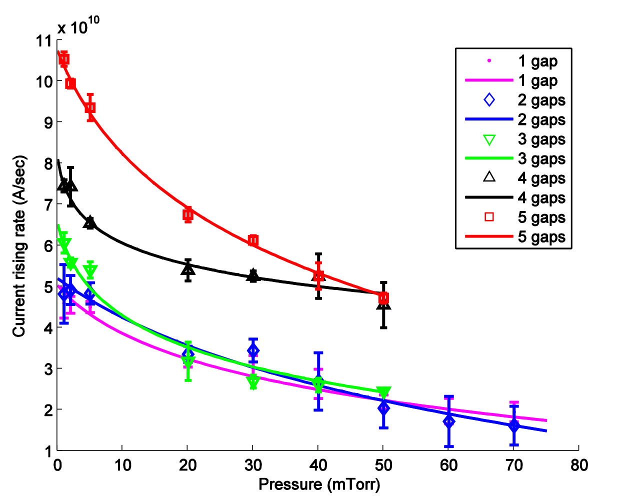


Figure 11. Current rising rate at operational pressure range obtained in various discharge configurations (single gap to 5 gaps)

IV. Experiments Results and Analysis II: Intense Electron Beams from Pseudospark

As discussed in Introduction, hypersonic MHD channel control by electron beam ionization is a potential application of pseudospark-produced electron beams. In the development of hypersonic MHD devices, how to generate an adequate non-thermal ionization is the first-order problem. In Ref. 21, the feasibility of injecting high-energy electron beams into the channel along magnetic field lines was presented and analyzed. Based on the ideas presented in Ref. 21-24, in this section, the beam parameters from pseudospark are presented, and its potential capability to work as an efficient ionization source is analyzed and discussed.

A. The characteristics of plasma-produce electron beam from pseudospark discharge

The pseudospark device which is studied for electron beam measurements has a 2 mm gap distance, 1.5 mm electrode thickness, and 12 gap stacks. Fig.12 is the pulsed electron beam measured by a fast Faraday cup electron detector (FC) and high frequency Rogowski coil F-70 current transformer (F-70 CT).[25] The pseudospark is operated at a pressure of 82 mTorr on Argon at a discharge voltage of 4 kV. Fig.12 shows that the electron beam current pulse has a peak current of 36.6 A and full width at half maximum (FWHM) of 40 ns. The electron beam is multiplied rapidly at the beginning of the first 15 ns. As shown in Fig.12, the beam current has a long-decreasing "tail" consisting of slower electrons.[27] The total duration time of the electron beam obtained from the presented pseudospark device is approximately 150 ns.

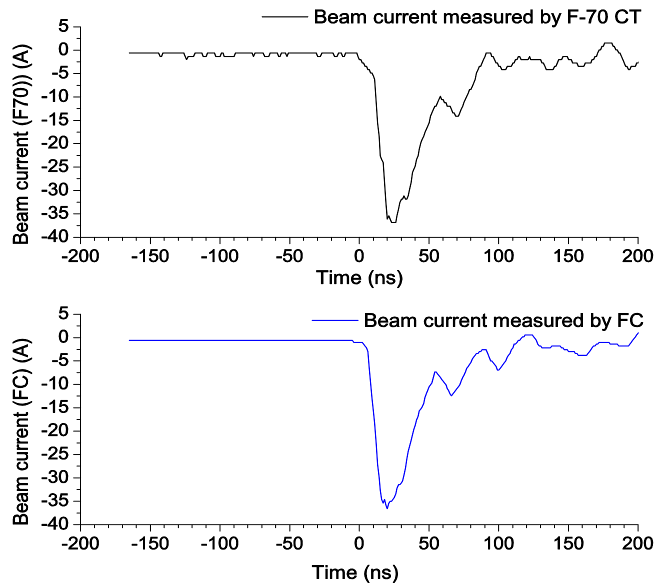


Figure 12. Pulsed electron beam current at 4 kV in a ten-gap pseudospark device

The peak electron beam current measured by the fast Faraday cup was obtained under voltages from 4 to 14 kV. Each data point is averaged over 10 continuous shots. The results are illustrated in Fig.13. As discharge voltage increases from 4 to 14 kV, the electron beam current collected by the FC increases from 36.6 A to 132.2 A.

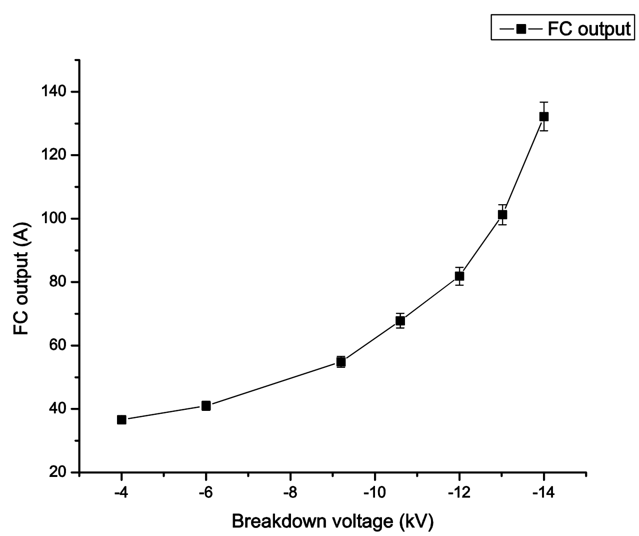


Figure 13. Pulsed electron beam current varied from 4kV to 14 kV

The total number of electrons produced from one pseudospark shot is defined as

$$N_e = \frac{Q_{total}}{e} = \frac{\int I_e dt}{e} \qquad (2)$$

where $e = 1.6\times10^{-19}\,\mathrm{C}$ is the charge of single electron.

Fig.14 is the number of electrons one single pseudospark shot can produce. The maximum number of plasma-produced electrons is 2×10^{16} from one discharge shot at 14 kV. The number of electrons varies from 4×10^{15} to 2.8×10^{16} in the presented operation voltage range obtained from 10s of cm^3 charged particle channel. Considering a rectangular shaped MHD channel with electron beam array consisting of 10 beams as shown in Fig.1 in Ref. 24, and assuming the mean value of radial dimension of MHD channel is 0.1m and longitudinal length is 2 m, the volume of the MHD generator is 2×10^4 cm^{-3}. Then the electron beam density into the MHD channel is estimated to 1.4×10^{13} cm^{-3}. Ref. 23 and 24 estimated that an electron number density at least on the order of 10^{12}-10^{13} cm^{-3} was required to impart or extract enthalpy of a few megajoules per kilogram from airflow at densities on the order of 0.1-atm density.[23, 24] And this number density of electrons can be further increased by multi-channel pseudospark device[27,28] and more electron beam array, since the electron beam from pseudospark device has small diameter of 0.5 mm to 3 mm.[2,4,7,8] Beam current density is estimated to be 10^2-10^4 A/cm^2 by assuming the diameter of electron beams has the same size as the electron exit hole, 1.5 mm.

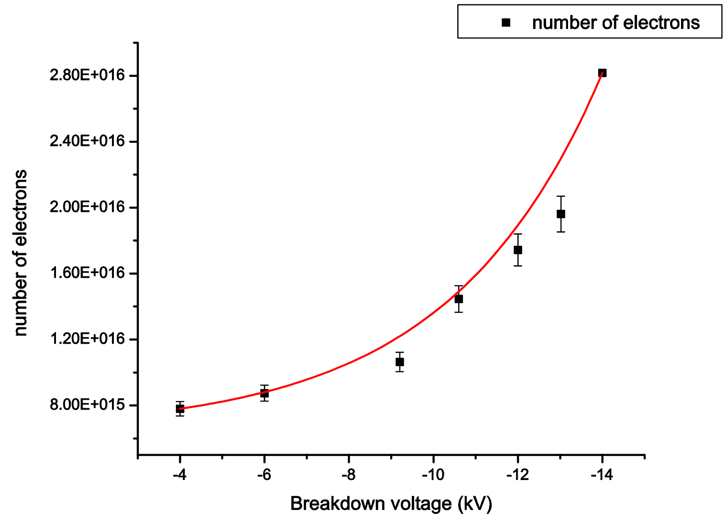


Figure 14. Number of electrons in single discharge shot varied from 4kV to 14kV

B. Energy analysis of pseudospark-produced electron beams

The energy estimation and measurement are always challenging in pulsed electron beams at ns level. Currently there is no systematic and detailed results of electron energy obtained from pseudospark. However, the determination of electron energy is important since it determines capability of ionization by electrons to sustain the plasma. In Ref. 25, a self-biased Faraday cup setup with adjustable impedance was constructed and calibrated to measure the time-resolved electron energy distribution function (EEDF) from pseudospark-produced electron beam. As discussed in Ref. 25, adjustable shunt resistance allows self-biased measurements to be quickly acquired to determine the EEDF. The calculated electron energy distributions at various times are illustrated in Fig.15.

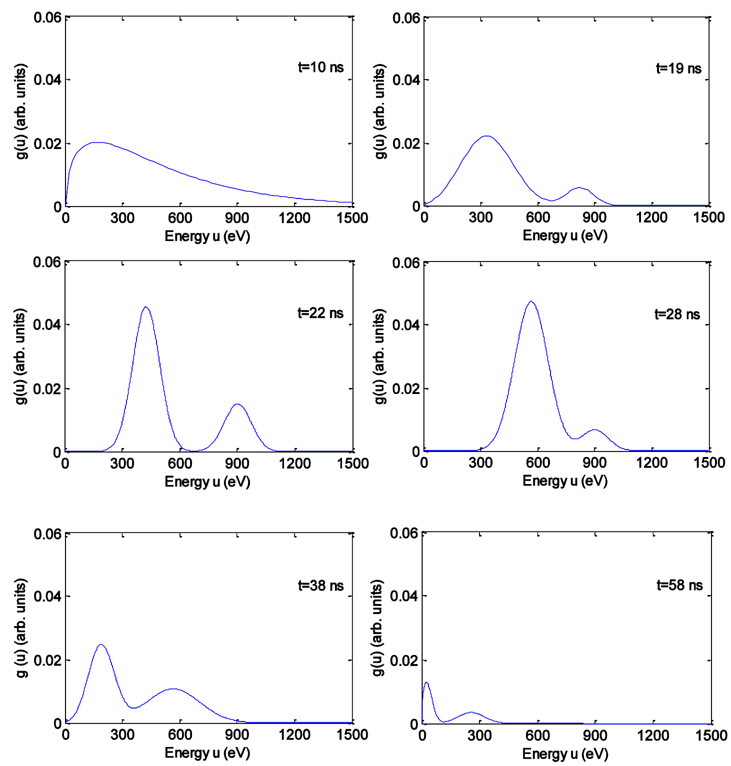


Figure 15. Temporal evolution of the EEDF obtained from pseudospark device at 4 kV

Results shown in Fig.15 indicate a "double-humped" energy distribution in pseudospark-produced electron beam. At t = 10 ns the electron energy has a temperature peak of 150 eV. After that the EEDF shows double peak energy values with low-energy peak at 300 eV and high-energy peak at 800 eV. Then both energy peaks move to higher energy level. The maximum magnitude of both energy peaks are 415 eV and 920 eV, which are much higher than the electron energy obtained from conventional glow discharge of 1-3 eV.[24] And the electron energy produced from pseudospark can be obtained into higher energy by increasing the applied voltage on discharge gaps, as illustrated in Fig.16.

As shown in Fig.16, the peak energy of electrons goes up with the breakdown voltage. And the maximum peak energy obtained in the investigated voltage range is 6.3 keV at 12 kV. In Ref. 4, 7, 13, 27, 28, it was claimed that the electron energy by pseudospark can be 50%-70% of or even equal to the applied potential on discharge gaps based on different discharge configurations. For tens to thousands of electronvolts, the power required to sustain ionized plasma can be minimized in contrast to low-energy (1-3eV) electrons in conventional discharges that dissipate most of their energy in nonionizing inelastic collisions. [21-24]

Ref. 24 also showed the beam power to sustain an electron density 10^{13} cm^{-3} in air at 1 atm, 2000 K was 27 W/cm^3 approximately. In the repetitive pseudospark discharge with a frequency of 63 Hz in this work, 27 W is equivalent to a single beam with 2×10^{16} electrons and average energy of 133 eV. The equivalent beam parameters can be obtained from pseudospark devices based on the presented experiment results. And the total energy transmitted by the beam can be further increased by increasing the operation voltage, post-acceleration voltage,[7] or from multi-channel, multi-gap pseudospark devices[4,27] or pseudospark beam gun array to meet more requirements by plasma generation in MHD channels.

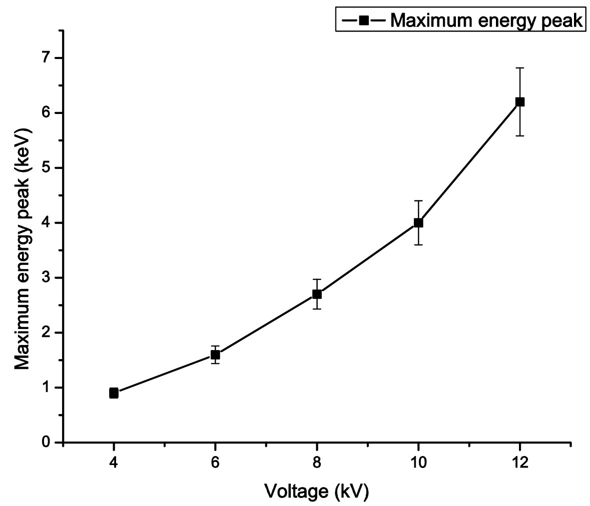


Figure 16. Maximum peak energy of electron energy obtained on various voltages

V. Conclusion

In this paper, a compact pulsed pseudospark discharge device was developed as a fast pulsed module and intense electron beam source. Special attention was paid to the current and potential applications of this discharge device and the plasma-based intense electron beam on aerospace problem. The experimental investigations showed that this device has capability to hold 10s of kV and generate kA current within 10 ns. And the comparative study results in various discharge configurations demonstrated that the power drive capability of this discharge device can be further improved by multiple gap numbers. Another specific focus in this paper is the application of intense electron beam for plasma generation in hypersonic MHD channels. The electron beam exiting from the presented pseudospark device can obtain a 132.2 A beam with electron number of 2×10^{16} from one discharge shot. The energy analysis shows that the maximum peak energy in this electron beam can be 6.3 keV at 12 kV discharge voltage. The comparison between our experimental results and electron beam requirement for plasma generation in hypersonic MHD channels presented in Ref. 21-24 indicates that the pseudospark-produced electron beam is a promising option for plasma generation by high energy electron beam ionization in MHD channels.

Certainly, further technical and engineering issues need to be experimentally determined and resolved to apply the pseudospark device in pulsed technology and plasma generation practically, such as insulator recovery time, device life time in the discharge chamber, and the ionization rate of the produced electron beams in neutral gas at various pressure. For the future work, the experimental studies of ionization by pseudospark-produced electron beam in neutral gas for various pressures, the collision loss and ionization rate, and the post acceleration of electron beam along propagation path in neutral gas are the main focuses.

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