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Developments of Pulsed Electron Beam Sources for High-Power Microwave Applications

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ABSTRACT High-current pulsed electron beam sources are the core components of high-power microwave systems. In order to meet the requirements of future applications, one needs to improve the performance of electron beam sources in terms of vacuum insulation, beam transportation, and thermal management. In this paper, we report about our recent progress in the development of high-current vacuum electron beam sources. In order to meet the vacuum maintenance requirements of high-power microwave tubes, a high-electric field ceramic vacuum interface is designed and fabricated based on the ceramic metal brazing technique. In our experiments, a stable operation of the ceramic vacuum interface is demonstrated in the 10 Hz repetition mode with withstand voltage of larger than 600 kV and pulse width of about100 ns. Besides, a cold cathode is developed using SiC nanowires, and an average beam current density of 1.2 kA/cm^2 is achieved under the electric field strength of 90 kV/cm. Compared with traditional velvet cathodes, the characteristics of the SiC nanowire cathode, such as macro-electrical stability, emission uniformity, and operating life have been significantly improved. Furthermore, a high-current electron beam collector has been developed for relativistic backward wave oscillator tubes. A spiral flume is designed in the collector to meet the requirement of both high specific energy and low flow rate. It shows that the withstand heat flow density is in the order of 10^{12} W/m^2, which is suitable for the long pulse and repetitive operation of the system. These results represent a significant step towards the practical application of long-life high-power microwave systems.

INDEX TERMS High-current sources, vacuum interface, ceramic flashover, nano-cathode, collector, thermal control, high-power microwave devices.

I. INTRODUCTION

High power microwave (HPM) systems have been developed in the past few decades, which offer innovative approaches to several existing applications in modern engineering [1]. The typical layout of a high-power microwave system is shown in Figure 1, where high-current pulsed electron beam sources are exploited to generate high-current relativistic electron beams [1]. A typical high-current pulsed electron beam source contains several parts including a vacuum interface, a cathode (emitter), and an anode (collector). The development of high-power microwave systems with high-repetition rate and long-life operation raises the requirement of high-current pulsed electron beam sources, which means their capacities in vacuum insulation, beam transportation, and thermal management should be improved. While, high-current pulsed electron beam sources will become one of the main limiting factors in developing mobile compact HPM devices.

In the electron beam source, the vacuum interface is employed to isolate the working medium (e.g. deionized water, transformer oil, SF_6, etc.) in the pulsed power drive source from the vacuum environment in the microwave source. Here, the interface can normally withstand pulsed voltage of the order of several hundred kV or even MV before emitting high-current beams, and the pulse width is about 50∼100 ns and the repetition rate is between 1∼ 100 Hz. Due to the possible surface flashover under high-power flow, the vacuum interface has become the potential limiting factor [2], [3]. Besides, vacuum interface is crucial to ensure

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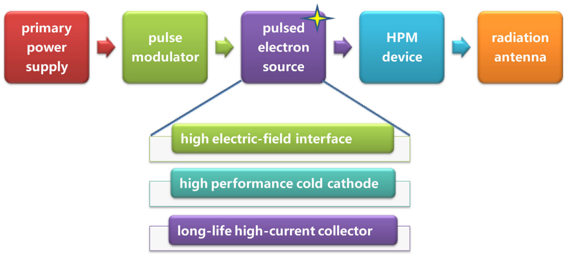

FIGURE 1. **Layout of a typical HPM system.**

the vacuum condition of the high-current beam source, the microwave source, and the radiating antenna in the HPM system [4], [5]. The strict control of the gas source is based on the use of fully enclosed microwave tube technology, requiring a ceramic-metal packaging at the vacuum interface of the high-current beam source. On the one hand, ceramic materials have the advantages of low outgassing rate, high temperature baking resistance, and easy welding property with metal. On the other hand, the hardness of ceramics is much larger than that of organic polymer materials and the shape cannot be arbitrarily adjusted, meaning there is a higher requirement of the fabrication process of ceramics. All of these result in the current low performance of the insulation of high-current vacuum interface. Thus, improving the insulation reliability of vacuum interface and avoiding the vacuum surface flashover in compact miniaturized systems is crucial when using ceramics [6], [7].

The high-current electron beam source cathode could directly affect or even determine the performance of high-power microwave devices [8]–[15]. In a single-run high-power microwave system, a high-current electron beam source should be able to provide a uniform beam density distribution in the order of kA/cm^2 [16]. In addition, in order to achieve high-repetition rate and long-term operation [17], high-current electron beam sources are required to process the quality of high intensity beam emission, as well as being resistant to ablation, small outgassing, long life, and stable and reliable at high-repetition mode [18], [19]. Therefore, the fabrication and study of high-current-density, high-stability, and high-current electron beam source cathodes are particularly urgent and critical.

Specially, the electron current is with an amplitude of several kilo amperes and current density is in the range of 10–1000 A/cm^2; the pulse duration is about 10 ns to 100 ns, the vacuum compatibility is about 10^{-5} Torr, and the lifetime is between 10^3 to 10^7 pulses, depends on the current density and repetition rate. The pulse-to-pulse instability of the emission current is about under 5% (considering the pulse voltage has an instinct jitter of 2%).

As shown in Fig.1, the high-current electron beam produced by the cathode propagates through the beam-wave interaction region and converts a fraction of its kinetic energy into microwave energy. The electron beam reaches the collector (or anode) eventually and carries most of its initial kinetic energy [11], [20]–[24]. In this scenario, the electron beam reaching the collector still contains high energy, since the energy efficiency of most high-power microwave sources is less than 30%. Moreover, the high heat flux will suddenly raise the surface temperature of the collector material, which could further cause the thermal desorption of the adsorbed gas on the material surface or even the evaporation and vaporization of the material surface. The evaporating substance can be impacted and ionized by the electron beam, which will cause the formation of secondary electrons and unnecessary plasmas [25], [26]. Besides, the local temperature of the collector may exceed its material melting point and cause erosion when a high-power microwave source is operated for a long time. In this case, the heat deposited on the collector cannot be dissipated effectively during the interval of the pulse train. This is another bottleneck for the reliable operation of high-power microwave systems. Normally, the local temperature of the collector should be controlled under the melting point of the material. For stainless steel, the safe temperature is better under 900 °C. The withstand heat flow density of an optimized collector should achieve the value more than 10^{10} W/m^2.

In this paper, technical measures to shield the vacuum triple junction and to control the surface field of ceramics are proposed and investigated. Compared to traditional electric vacuum solutions, the ceramic insulator fabricated in the paper can withstand a pulsed voltage of the order of 600 kV with the insulation path below 15 cm. Besides, nano-materials are used in the strong-field emission cathode to exploit the nanostructure effects in the SiC nanowire cathode. Beam emission density of the order of kA/cm^2 is achieved and the operating life is more than 10^5 pulses. Finally, a water-cooled collector based on a helix-channel structure is also investigated. Finite-element simulations and experimental verification show that the collector could withstand a heat flux of 10^{12} W/m^2, which meets the requirement of long-time operation of 30 Hz repetition rate for high-power microwave sources.

As a common shared technology, the parameters of the vacuum interface in this paper is suitable for typical HPM tubes, such as magnetically insulated transmission line oscillators(MILOs), relativistic magnetrons(RMs), and relativistic backward wave oscillators (RBWOs). The cathode mentioned here has potential applications in low-impedance devices, such as MILOs and RMs. While, the collector is specifically designed and tested for long-life and repetitively operated RBWOs.

II. CERAMIC VACUUM INTERFACE

Concerning the ceramic vacuum interface, the electric field along the surface is reduced by tuning the structural configuration, in order to make it as uniform as possible. Then, the field strength is carefully controlled in the area of the triple junctions of the cathode and anode, to make it below the allowable value. For ceramic-to-metal sealed components, shielding is a relevant point due to the need of using Kovar as a matching metal. To address this point, a vacuum interface structure based on ceramic-to-metal sealing for a

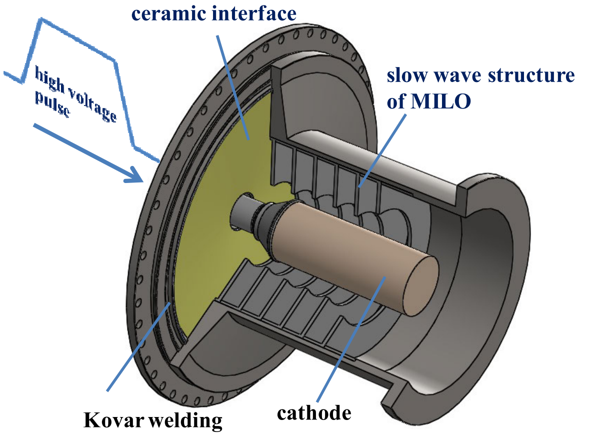

FIGURE 2. Vacuum interface based on a disk type ceramic-metal welding.

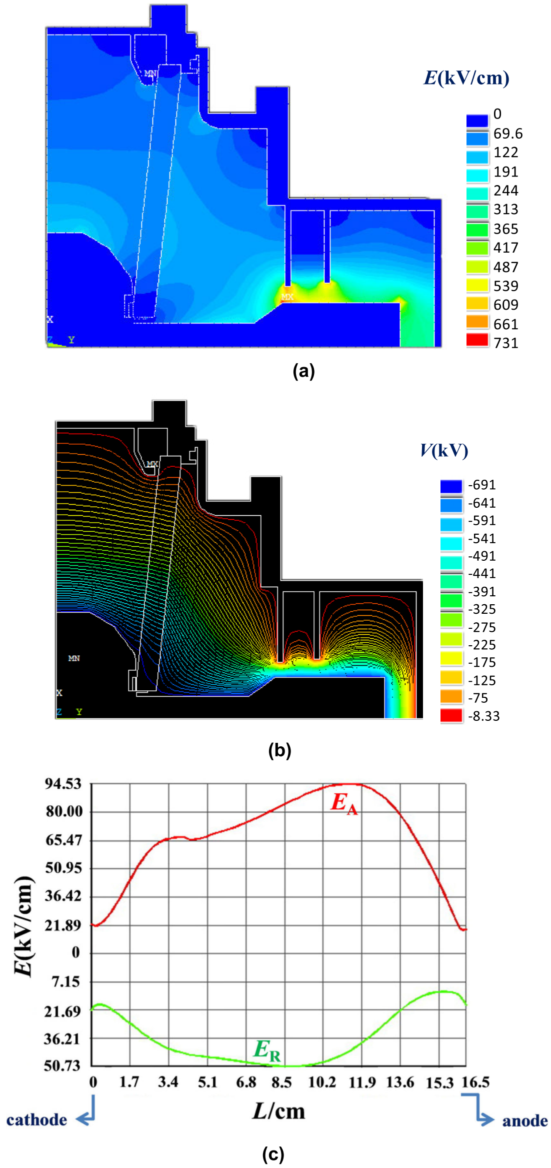

FIGURE 3. (a) Electric field distribution of the ceramic insulated interface, (b) Equipotential line distribution of the ceramic insulated interface, (c) Profile of the electrical field along the ceramic insulated interface.

magnetically insulated transmission line oscillator (MILO) is suggested, as shown in Fig.2.

The two sides of the ceramic interface correspond to liquid deionized water and vacuum, respectively. The diameter of the ceramic interface (not including the outer flange) is 300 mm. In order to verify the effectiveness of the structure, ANSYS simulation package is employed to analyze the electrostatic field and, in particular, the distribution of the electric field along the surface and the average electric field amplitude of the three junction points of cathode and anode.

In the simulation, the cathode voltage is −600 kV and the anode is with zero potential. The relative dielectric constant of alumina ceramic is 8.8 and deionized water is 81. Since the model is axisymmetric, a half-plane is taken for calculation, with the bottom edge as the axis of symmetry.

Fig.3 shows the typical results of numerical simulations:Fig.3(a) shows the electric field distribution of the ceramic vacuum interface with the local structure of the microwave generating device; Fig.3(b) shows the equipotential line distribution. It can be seen that the ceramic electric field distribution is relatively uniform. With an applied voltage of 600 kV, the maximum total field strength (E_A) is less than 95 kV/cm, and the maximum surface component (E_R) is less than 50 kV/cm.

The above-mentioned ceramic vacuum interface is assembled with a microwave source to form a vacuum high-current load, and a withstand voltage test is performed on a 30 GW pulse power source platform with a repetition rate operation. The main components of the pulse power drive source include charging power source, primary capacitor, primary trigger switch, pulse transformer, pulse forming line, main switch, variable impedance transmission line, relevant diagnostic and measuring equipments. The output pulse width is about 80ns, the maximum working voltage of the forming line is greater than 1 MV, and the repetition rate is adjustable from 1-10 Hz, which can satisfy the test requirements for the vacuum interface. Meanwhile, the diode voltage and current are measured by a capacitor voltage divider and a Rogowski coil, respectively. The typical primary discharge current waveform and forming line charging voltage waveform and the load voltage waveform of 50 pulses at 10 Hz are shown in Fig. 4(a) and Fig. 4(b).

When the vacuum interface is operated at the voltage level of 600 kV, the confidence level is 0.9 and the lower limit of the overall reliability of the insulation structure exceeds 97%.

III. SiC NANOWIRE COLD CATHODE

SiC nanowire is a semiconductor material with a wide bandgap, leading to a nanometer emission tip, large aspect ratio, high melting point, high thermal conductivity, high breakdown voltage, and good thermal and chemical stability [27]. As shown in Fig. 5(a), during the preparation procedure, polycarbosilane and ferrocene were introduced into active carbon to form homogeneous slurry, which was

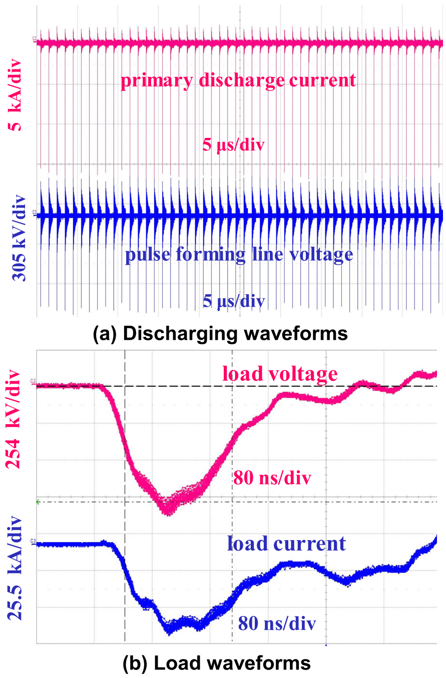

FIGURE 4. Typical performance of the ceramic insulated vacuum interface.

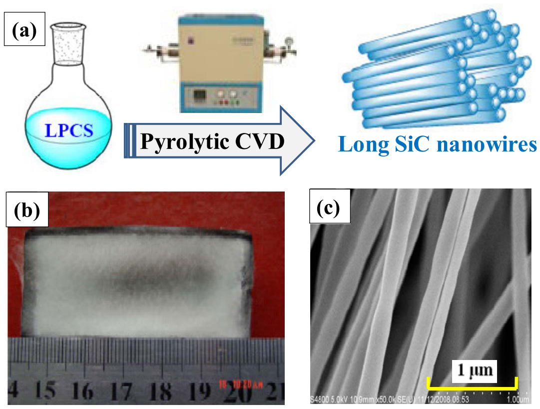

FIGURE 5. (a) Preparation of the achieved long SiC nanowires, (b) macro morphology of SiC nanowires, (c) micro morphology of SiC nanowires.

placed in a ceramic boat and pushed to the center of a tube furnace with another two empty ceramic boats. The system was heated to 1300 °C in high purity nitrogen and maintained at 1300 °C for 3 hours. Then the cotton-like centimeters-long SiC nanowires were found covering on the empty ceramic boats after the furnace cooled to room temperature, shown in Fig. 5(b) and Fig.5(c).

At first, we noticed that the micro-morphology of SiC nanowires contain a large aspect ratio. When the high voltage is applied, the field enhancement at the emission point is large, and electrons are more likely to flow by tunneling through the vacuum. Each nanowire causes a local field-enhancement point on the surface of the cathode, which is similar to the field-enhancement points generated by emitter heads in a field emission array. The density of these points along the surface is rather high, making the cathode able to work at lower average voltage and higher current density.

In addition, the silicon carbide nanowires have undergone high temperature treatment during the preparation process, and there is no obvious morphological change after annealing in Ar gas flow below 1300 °C, indicating a good thermal stability [28]. During the emission process, the SiC nanowire cathode does not cause obvious erosion, and there is only a small change in the size of the nanowire tips. This fact suggests that a stable emission performance may be obtained during long-time operation. The promising thermal and chemical stability of SiC materials also suggest that material degradation due to heating and high-temperature desorption of surface gases during multi-pulse or high-repetition-rate operation could be alleviated or even suppressed. Cathode pulse desorption and vacuum degradation during continuous operation will likely be increased and improved.

The SiC nanowire cathode performance was tested and compared with traditional velvet cathode. The pulsed power apparatus is shown in Fig. 6(a). The schematic shows the diode gap housed in a vacuum vessel (middle), typical pulsed voltage trace (left), space charge limited electron ray-tracing (top-right), and photographs of the two type cathodes (below-right).The high voltage pulse was produced by a power modulator using a spiral coaxial pulse forming line and a pulse transformer. By varying the pressure of SF_6 gas filled in the gas spark switch, the output voltage of the modulator can be adjustable from 300 kV to 500 kV, with pulse rise-time (10% to 90% amplitude) of 25 ns and pulse duration (FWHM, full width at half maximum) of 120 ns.

The generation and dynamics of the cathode plasma determine the performance of high-current electron beam cold cathode. We compared the plasma characteristics of conventional velvet cathodes and SiC nanowire, including the cathode start-up process, cathode plasma expansion, macro stability, and vacuum compatibility, in the same electric structure. The analysis is carried out for the high-current emission characteristics of SiC nanowires. Typical voltage/current waveforms and diode impedance evolution are shown in Fig. 6(b). The results show that the threshold electron field strength of the SiC nanowire cathode is 17 ± 3 kV/cm, which is about 2/3 of that of the conventional velvet cathode. At fixed rate of increase of the electric field strength, the SiC nanowire cathode has a higher startup time period than the conventional velvet cathode of 12∼17 ns.

In addition, the stability of the two cathodes under repetition rate operation has been also compared, which is shown in Fig. 7. The current density here is the average value, which is obtained by dividing the total current measured at the emission area.

During the pulse shot process, even in a low repetition rate, a large pressure gradient builds from pulse to pulse. This high pressure will facilitate the gas ionization and form uncontrolled background plasma near the cathode surface. The plasma cloud also emits ions under the electric fields. As the pulse continues, the bombardment of the cathode surface by

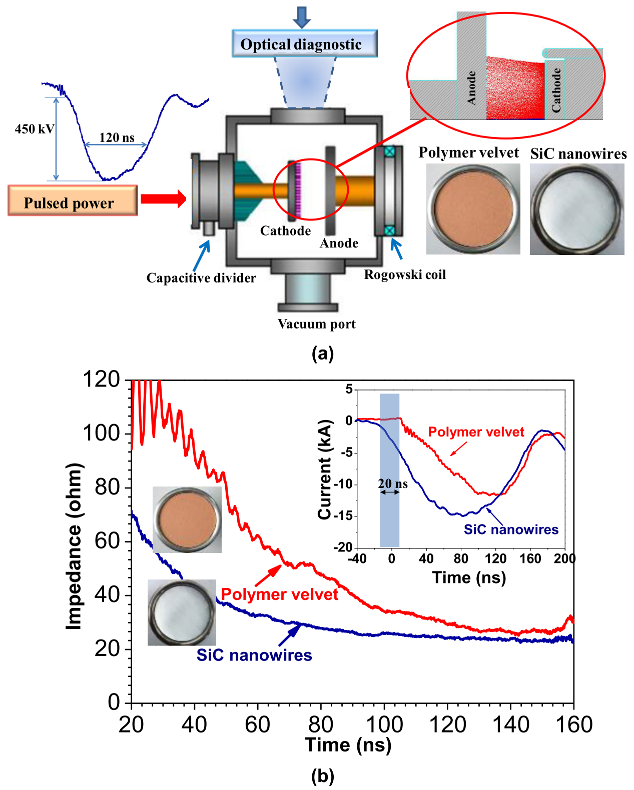

FIGURE 6. (a) Schematic illustration of the experimental arrangement for cathode performance test, (b) Current and impedance evolution of the two cathodes with same applied voltage.

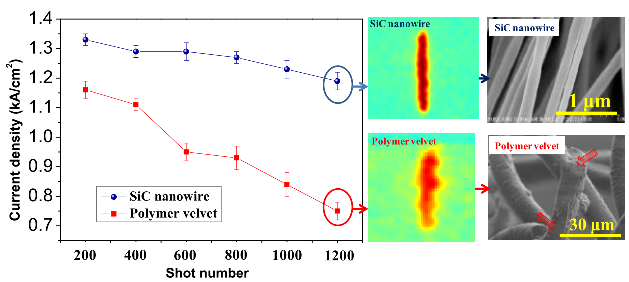

FIGURE 7. Of the stability of the two cathodes under repetition rate operation.

heavy ions may cause the degradation of the cathode microscopic morphology, such as surface erosion and sputtering of materials, which make the threshold of electron emission increase. Therefore, the variation of the beam current density can be directly reflected by the increase in the shot number parallel to different stages of microstructure changes.

At a fixed repetition rate of 20 Hz, after continuous operation of 1200 shots, the macroscopic morphology of the SiC nanowires does not change significantly, and the average beam current density drops from 1.3 kA/cm^2 to 1.2 kA/cm^2. In contrast, the morphology of the surface of the velvet cathode is distorted. The fiber surface is bent, carbonized, or even destroyed. Cathodic ablation is a complex plasma chemical process, and its main factors include current density, electron bombardment, and anode sputtering. It can be seen from

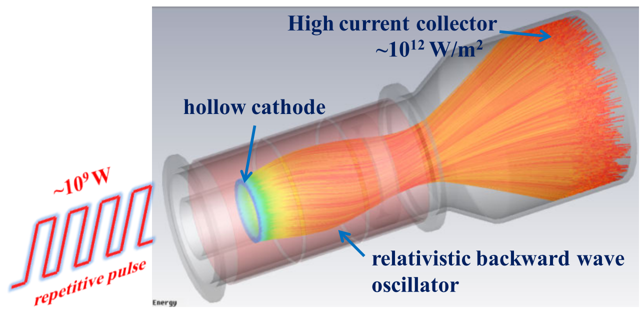

FIGURE 8. Of the hitting of the collector by high current electron beam.

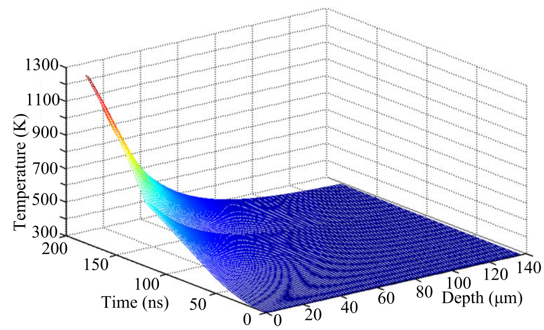

FIGURE 9. Temperature rise of the collector without special thermal control.

the experimental results that the developed SiC nanowire cathodes show a significantly better ablation resistance than traditional cathodes, and can emit beams in the order of kA/cm^2. At present, the developed SiC nanowire cathode has accumulated over 10^5 shots. It is understood that the SiC nanowires possesses the property of high temperature resistance. Thus, it can hold high-current with minor surface damage. The successful development of this cathode is promising to provide a high-current electron beam source that meets the application requirements for the high-repetition-rate operation of low-resistance high-power microwave devices.

IV. THERMAL MANAGEMENT OF HIGH-CURRENT COLLECTOR

Heating at the collector site in high-power microwave sources, such as backward wave oscillators, is originated from the electron beam of a certain density hitting on the inner surface of the collector, shown in Fig. 8. When a thermal load is applied, the energy of the electron beam entering the collector is converted into heat through collision, ionization and bremsstrahlung.

Taking 700 keV, 7 kA high current beam as an example, for collectors made of stainless steel, the local temperature of the collector could exceed the melting point of the material and cause erosion when a high-power microwave source is continuously operated at a certain repetition rate. Fig.9 shows the typical simulation results of the rise of temperature without special thermal management.

During the interval of pulse trains, the temperature variation can be treated as an adiabatic process and the temperature

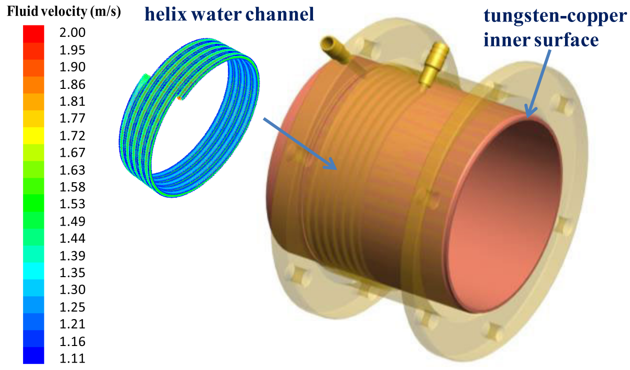

FIGURE 10. Layout of the improved high current collector with a spiral water streamline and pressure distribution.

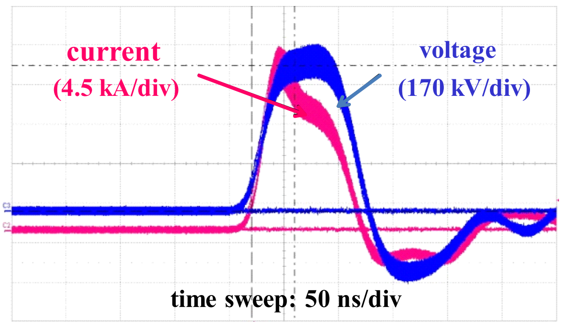

FIGURE 11. The applied pulsed power on the collector (150 ns, 30 Hz, and 300 pulses).

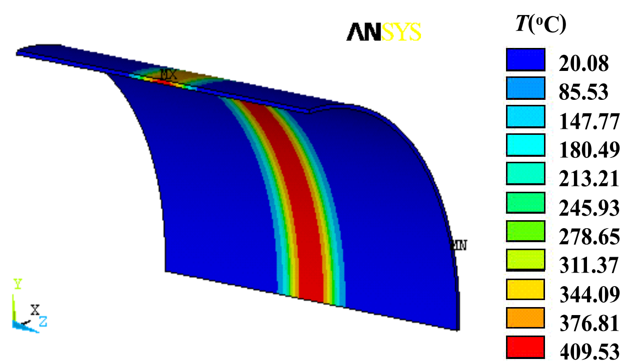

FIGURE 12. Temperature distribution of the collector after 10 s continuous operation.

rise is mainly determined by the energy deposited on the collector. While for cooling process, it is mainly affected by materials and cooling structures. In order to further optimize the thermal management of the collector, tungsten-copper with high thermal diffusivity is firstly introduced as the inner surface material of the collector. Besides, the approach of improving the convective coefficient is much significant for heat dissipation. A water-cooled collector based on a helix-channel structure is also proposed, showing that the original collector cooling channel structure in [26] has been improved. In turn, as shown in Fig. 10, it allows the fluid to run along the prescribed track to ensure a uniform flow

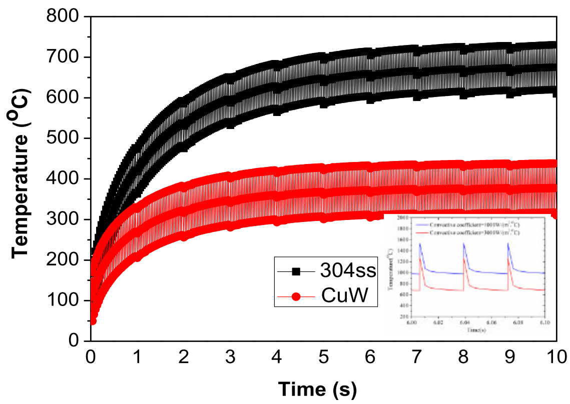

FIGURE 13. Temperature evolution of the tungsten-copper collector compared to stainless steel.

velocity in the cooling area, thereby providing the corresponding convective heat transfer capabilities.

Based on a giga-watt-level repetitive-rate long-pulse power source experimental platform (output voltage 300-700 kV, pulse width 150 ns, adjustable repetition frequency 1-30 Hz, and continuous running time more than 30 s), a preliminary repetition rate test of the improved collector has been carried out. In the experiment, the high-current beam was in the shape of a hollow ring, and the collector structure was in a hollow cylinder. Fig. 11 shows the typical voltage and current waveforms of the pulse drive source at 30 Hz and 10 s operation.

Fig.12 illustrates the simulation result of temperature distribution map of the inner surface after 10 s continuous operation. Fig.13 shows the typical experimental results of temperature evolution with different inner materials (tungsten-copper and stainless steel) during pulse loading with frequency of 30 Hz for the whole process under cooling condition. It indicates that the collector using tungsten-copper as inner surface material experiences a much lower temperature rise than that of inner surface with stainless steel and the helix-channel structure in the collector also helps reduce the temperature rise.

V. CONCLUSION

In this paper, in order to overcome the challenge of vacuum insulation, we suggested a coaxial-feed ceramic vacuum interface as a solution and carried out relevant experiments. Under the conditions of 600 kV and 100 ns repeated pulse loading, the average insulation field strength of the ceramic vacuum interface reaches up to 44 kV/cm with a stable operation. Our design methodology could be used as a benchmark for the design of ceramic vacuum interfaces with other shapes and structural parameters. In terms of high-current electron beam source, nano-materials are incorporated into the high-electric field emitters, so that the cold cathode's emission beam density can reach to the order of kA/cm^2. The beam emitting from the cathode shows better performance than conventional velvet cathodes, which indicates that this cathode could meet the requirement of the low-resistance and high-power microwave devices in the future. In terms of collector thermal management, a water-cooled collector structure with a helix-channel water channel structure and tungsten-copper material have been proposed and tested, and it is able to deal with the heat flux density up to10^{12}W/m^2, which is suitable for long-pulse microwave source (100 ns) and high repetition rate operation (30 Hz).

Future perspectives include the integration of new materials, new processes, as well as new diagnostic and design methods to further improve the performance of high-current vacuum electron beam sources, thus offering a significant reference for the practical application of long-pulse and high repetition rate operation of high-power microwave systems.

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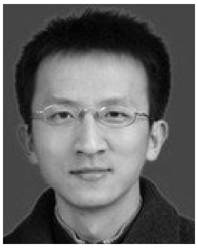

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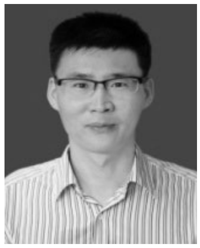

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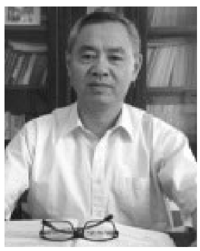

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