Experiments With a Radial Multichannel Pseudospark Switch for Extremely High Coulomb Transfer

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***Abstract*—Radial multichannel pseudospark switches for extremely high-charge transfer were designed, constructed, and tested. The characteristics of the switches were measured for different electrode geometries and materials in hydrogen and helium as function of gas pressure. The switches were operated in a 100-kJ capacitor bank and conducted an effective charge up to 31 C. A sealed-off radial multichannel pseudospark switch was also manufactured and tested with a 300-kJ capacitor bank. The switch was successfully tested up to 105-kA peak current and 78-C charge transfer. The experimental results demonstrated that a radial multichannel pseudospark switch with SiC electrodes and triggered by a high dielectric trigger has the capability of extremely high charge transfer under pulsed operation.**

***Index Terms*—Arc discharges, peudospark, SiC, switches.**

I. Introduction

THE PSEUDOSPARK discharge was first described in 1977 by Christiansen and Schultheiß [1]. The discharge is located at the left-hand branch of a breakdown characteristic similar to the well-known Paschen curve. Typical operational data for pseudospark switches are up to 30-kV voltage, 150–240 kA peak current, pulsewidth up to some microseconds, and maximum charge transfer of 2–3 C [2]–[5]. The capability of fast current rise resulted in the development of a fast closing switch. This medium power pseudospark switch for high repetition rate with a lifetime of 10^8 discharges (equivalent to a charge transfer of 220 kC) was especially designed for applications in a pulsed gas laser.

However, the electrode erosions of pseudospark switches are severe when the charge transfer of the switch is large. Based on the fact that the electrode erosions are related to the current density, several schemes have been reported to reduce the current density and, thus, reduce electrode erosion. Those schemes include multichannel electrode configurations or arc diffusion using external or self-generated magnetic fields [6]. Nevertheless, a pseudospark switch for extremely high charge transfer over several tens of coulombs has still a problem in its lifetime due to electrode erosion. Recently, it had been reported that a radial multichannel pseudospark switch with tungsten electrodes conducted 145 C/shot for 6130 shots [7]. This result is promising that the multichannel pseudospark switch could outperform over other switches for extremely high coulomb transfer. Recently, it was reported that SiC showed a low erosion rate compared to tungsten in a single channel or an axial multichannel pseudospark switch [8], [9].

Switching characteristics of radial multichannel switches with SiC electrodes were investigated for extremely high charge transfer. In this paper, we discussed design of the radial multichannel pseudospark switches and presented experimental results of the switches.

II. Discharges in a Triggered Pseudospark

Most of the pseudospark discharge processes are well understood [10]. There are several major processes, such as: a trigger discharge; a Townsend-like discharge; a hollow cathode discharge; a borehole discharge; a superdense glow discharge; and an arc discharge. The hollow cathode plasma expands to the area of the main borehole and more dense plasma is built up between two borehole gaps, so that the large-current conduction occurs between the anode and the cathode. Right after this transit phase, a superdense glow forms to conduct high currents of over several kiloamperes. The reason why the current density becomes high up to about 10^4 kA/cm^2 during the superdense glow process has not been fully understood yet. During the superdense glow, it is observed experimentally for the electrodes to start evaporating metal vapor, which is similar to the vacuum arc discharge [11]. Finally, the super-dense glow transits into an arc discharge, which is mainly sustained by metal vapors, and so the electrodes are eroded. When the current is more than 45 kA in the pseudospark switch discharge, the electrode erosion becomes severe because of the arc formation [12].

III. Design Consideration

It is widely known that radial multichannel switches are good for high-current conduction [13]. Fig. 1 is the simplified schematic of the radial multichannel pseudospark switch showing electrons and current paths and self-generating magnetic fields and forces.

A. Electrode Geometry

The switch hold-off voltage depends primarily on geometrical parameters of the electrodes for a given gas condition. An exact analytical formula that can predict breakdown voltage of a radial multichannel pseudospark discharge is still unknown. However, Taguchi's empirical relation for a single-gap pseudospark discharge is valuable to design a radial multichannel pseudospark switch [14]. The gap distance and the borehole diameter are typically same and selected in the range of 3–5 mm for high-voltage switches. The electrode thickness and the

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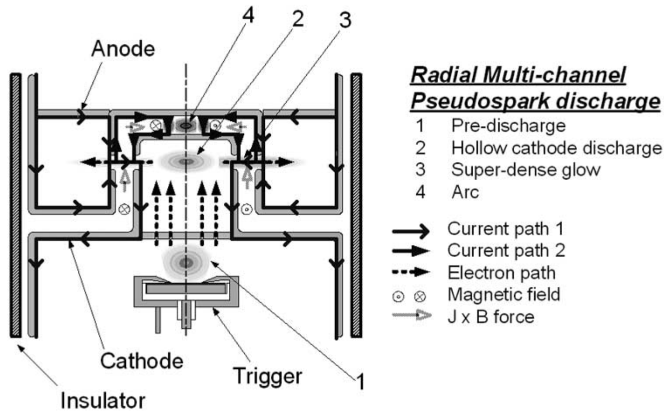

Fig. 1. Discharge process of a radial multichannel pseudospark switch.

cathode and anode cavity dimensions are not as important as the gap distance and the borehole diameter. The electrode thickness is usually selected same as the gap distance.

Metal vapor is evaporated explosively during the high-current phase. The vapor may coat the inner wall surface of the insulator near the electrode opening. Since this coating can cause unexpected self-breakdowns through the insulator surface, it is typical to use metal screen to protect the insulator from coating [15].

B. Electrode Material

In the radial multichannel pseudospark switch, the early arcs around the borehole move with velocity of 10^6 cm/s upward due to the self-generated magnetic field [16]. Hence, the arcs arrive at the center axis within around 10 μs. The arcs then pinch at the center and become very intensive. The intense arc causes severe electrode erosion. Therefore, for extremely high charge transfer switch design, it is essential either to find an electrode material with a low arc erosion rate, or to prevent the arc from pinching at the center axis.

The electrode erosion rate decreases as the gas pressure increases [17]. Since the pseudospark discharge is operated in low pressure range, it is expected that the erosion in the pseudospark is slightly lower than in vacuum arc discharges, but higher than in spark gap discharges.

It is worthy of considering the impulsivity of the material, which is introduced by Donaldson *et al.* as a parameter to determine material characteristics against arc erosion for several materials [18]. The impulsivity is defined as

$$T_{\mathrm{mp}}\sqrt{kpc}.$$

where T_{mp}, k, ρ, and c are meting temperature, thermal conductivity, mass density, and specific heat of the material, respectively. The impulsivities of carbon, tungsten, and stainless steel are, respectively, 7200, 6800, and 1970. The high impulsivity of a material means low arc erosion rate. According to Tkotz *et al.*'s report about erosion rates of several electrodes in pseudospark discharge, tungsten and graphite showed low erosion rates, whereas the CrCu's erosion rate was high [13]. However, Römheld *et al.* reported that CrCu was much better suited as electrode material than high-melting-point materials like molybdenum because melted spot size was larger and surface roughness was smaller with CrCu [3].

Recently, it was reported that SiC showed a low erosion rate as electrode material of a single gap pseudospark switch because of its negative temperature resistance characteristics [8]. The negative temperature resistance prevents cathode spots forming on the SiC electrode. Therefore, diffuse discharge is naturally formed on overall SiC surface. However, SiC absorbs hydrogen gas with a rate of 0.61 Pa/day and acts as a weak getter in a sealed-off type switch. Therefore, it will be difficult to maintain a constant internal pressure [9]. Weisser *et al.* suggested a remedy that the SiC electrodes have to be baked at temperature of 2000 K under hydrogen at a pressure of at least 1 bar for several days in a hydrogen oven. However, the successful test of this method has not been confirmed yet.

C. Trigger Unit

In order to supply sufficient electrons to each discharge channel simultaneously through boreholes in a radial multichannel pseudospark switch, several trigger schemes were developed [19], [20]. A high dielectric trigger unit showed good characteristics [21]. The high dielectric trigger unit has a finger-contacting electrode and high dielectric disk supported by a metal electrode. Wiring schemes, which decide trigger polarity, affect switch delay times and jitters [21].

IV. Experimental Setups

A schematic drawing of the switch under investigation is shown in Fig. 2. The material of the switch electrode was made of stainless steel (SS). The anode facing the cathode was a replaceable disk. SS or SiC disks were used for the test. The switch had eight equally spaced 5-mm-diameter boreholes on the anode and the cathode wall. The gap distance between the electrodes was 5 mm. For the SS anode disk, eight viewing holes were drilled that was aligned with the boreholes.

Two radial multichannel pseudospark switches were tested. The first switch (hereafter RMCPSS1) was reported detail in [22]. The RMCPSS1 had a cathode cavity with inner diameter of 42 mm and length of 45 mm. The anode cavity of the RMCPSS1 had width of 20 mm and length of 30 mm. The second switch (hereafter RMCPSS2) had a cathode cavity with inner diameter of 50 mm and length of 32 mm. The width and the length of the RMCPSS2 anode cavity were 12 and 32 mm, respectively. Electrode wall thickness of the two switches was 5 mm. A glass chamber with SS flanges was used as the switch housing. As shown in Fig. 2, the anode of RMCPSS2 is extended to prevent coating of the glass chamber wall.

A high dielectric-trigger unit was installed underneath the hollow cathode cavity. $BaTiO_3$ was used as the high dielectric material, which has dielectric constant of over 1500. The trigger unit was movable axially in order to obtain an optimum position to trigger the switch. The trigger device has two wiring connections; one for the metal fingers that contact the dielectric and one for the metal shield that holds the dielectric. Twelve 2-mm-diameter holes are drilled at the bottom plate of the cathode cavity to form a cathode baffle. The electrons generated at the trigger unit are extracted into the hollow cathode cavity through the

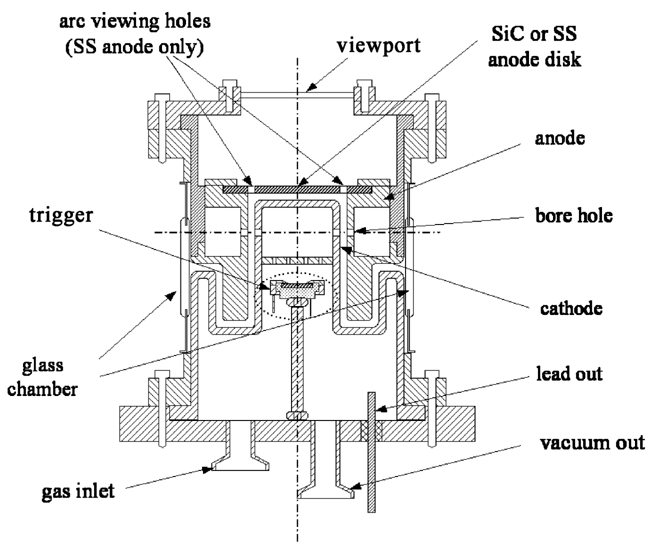

Fig. 2. Schematic of the radial multichannel pseudospark switch, RMCPSS2.

cathode baffle. The cathode and the cathode baffle are in ground potential.

Several different circuits were used for different experiments. Details of the circuits are explained in the following chapters. Voltages were measured with a 1000:1 high voltage probe (Tektonix P 6015). The discharge currents are measured with current transformers. The signals were registered with digital storage oscilloscopes (Tektronix DSA602A and Lecroy LT224) and evaluated at a PC. A charge-coupled device (CCD) camera was used to record time-integrated images of discharges.

The pseudospark switches were initially evacuated down to 10^{-5} mbar with a vacuum pump (Drytel31, Alkatel). Virgin switches were conditioned with high voltage of 36 kV for 2–3 h before experiment. Helium and hydrogen were used as filling gases of the switches.

V. Experimental Results

A. Self-Breakdown Characteristics

To obtain operating ranges of voltage and pressure of the switches, self-breakdown characteristics were studied. A test circuit to measure the characteristics is shown in Fig. 3. A 5-nF capacitor was connected in parallel with the switch. A 1-GΩ resistor was serially connected to the high-voltage probe to maintain charging voltage on the capacitor. The probe was calibrated accordingly. The self-breakdown of the switch was induced by slowly increasing applied voltage while maintaining the internal gas pressure. While increasing the applied voltage, we first observed local corona discharge. The corona discharge was distinguished by observing a small current increase of several milliamperes. As the voltage was increased further, we could observe an abrupt increase of the current due to a hollow cathode discharge in the entire discharge channels. This voltage was recorded as the self-breakdown voltage.

Fig. 4 shows the measured results of corona discharge and self-breakdown voltages as a function of internal gas pressure of helium and hydrogen. As expected, the corona voltages as well as the self-breakdown voltages were increased as the internal pressure decreased for the experimental range. Both RMCPSS1 and RMCPSS2 switches showed almost same self-breakdown characteristics. By considering that the only significant difference of the two switches was cavity volumes of cathode and anode. One may conclude that the cavity volume has a weak effect on self-breakdown characteristic. The helium shows lower self-breakdown strength than the hydrogen. To obtain a hold-off voltage of about 30 kV, the operating pressure range of the two switches can be selected from 0.04 to 0.1 mbar of helium or hydrogen.

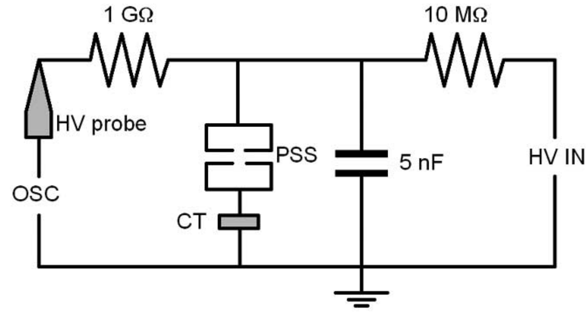

Fig. 3. Circuit diagram of self-breakdown voltage measurement.

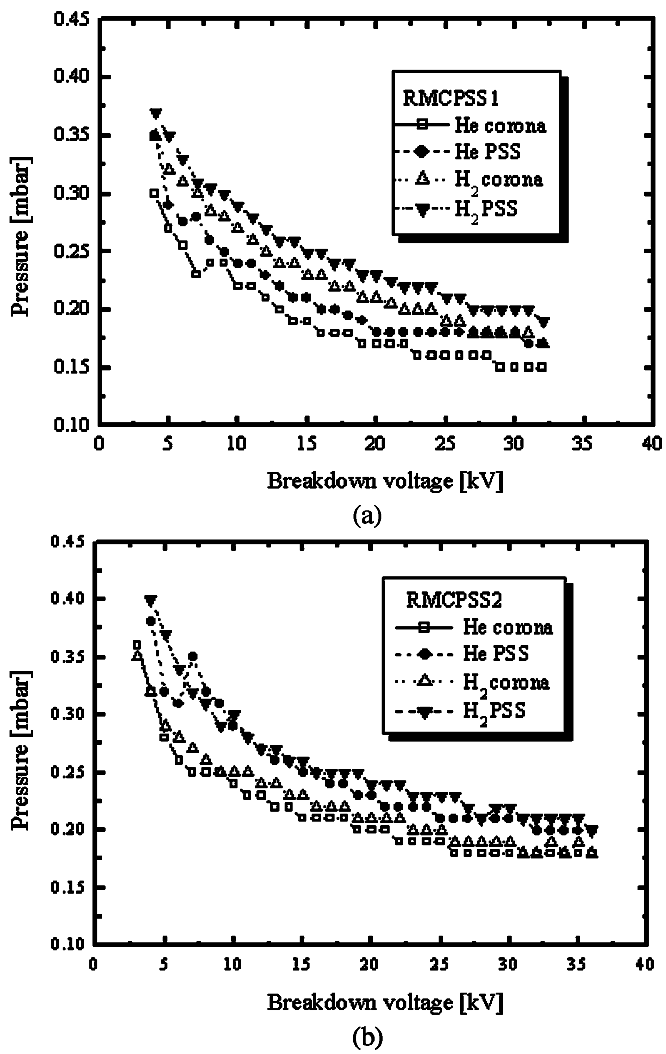

Fig. 4. Self-breakdown characteristics of the radial multichannel pseudospark switches as a function of filling gas pressure (hydrogen and helium).

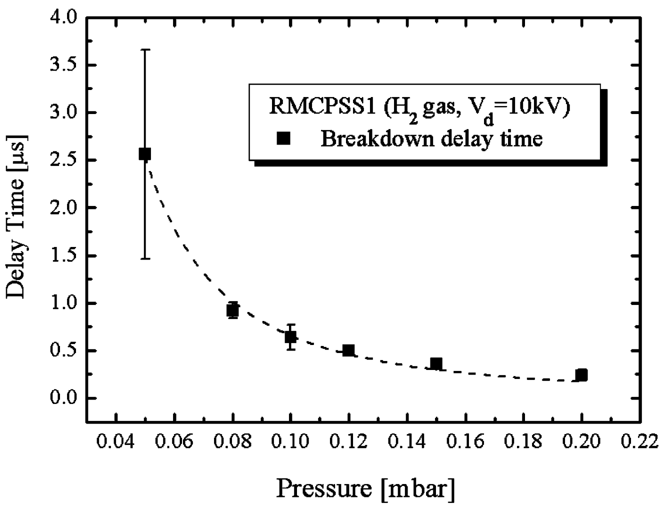

Fig. 5. Measured breakdown delay times as a function of filling gas pressure (hydrogen).

B. Breakdown Delay Time

The breakdown delay time was measured from the instance of trigger pulse to the beginning of main current pulse. Dependences of the delay time on trigger polarity and internal gas pressure were investigated. Effect of cathode cavity volume on the delay time was also studied. Six different wiring schemes of the trigger polarity were tested. We apply combinations of positive, negative, or ground potentials for the two trigger wiring connections. When the metal fingers were in negative potential against the grounded metal shield, the delay time became minimum. The result implies that electrons generated with negative potential trigger are more efficiently extracted to the grounded cathode baffle.

Fig. 5 shows dependence of the delay time on internal pressure of hydrogen. RMCPSS1 was used for the measurement. The delay time is inversely proportional to the gas pressure, and this relationship agrees well with the results given in [10].

In Fig. 6, two oscillograms are shown. The top was taken with the RMCPSS1, and the bottom was taken with the RMCPSS2. Both are taken with a same experimental condition. As shown in Fig. 6, the delay time of RMCPSS2, which has a larger cavity volume, is about 4 μs, which is about 3 μs longer than RMCPSS1. This explains that larger cathode cavity volume requires longer time to sufficiently generate pendulum electrons and, thus, breakdown.

C. High-Current Conduction Test–SS Anode

A high-current switching test circuit is shown in Fig. 7. A 16.2-μF capacitor bank was used for the test. A typical discharge waveform of the RMCPSS2 is shown in Fig. 8. The waveform was obtained with 0.9 mbar of helium and 10 kV charging. The peak and the period of the switch current (Ch 1 in Fig. 8) are 104 kA and 7.8 μs, respectively. Equivalent total series resistance and inductance of the test circuit are calculated as 55 mΩ and 83 nH, respectively.

A CCD camera was used to record switching discharge images through the arc viewing holes. Two sample images in Fig. 9 are taken with a same experimental condition of 0.09 mbar helium and 10 kV charging, but with a more opaque neutral density filter to distinguish discharge cores. As can be seen from the images, an uniform discharge was generated overall switching area.

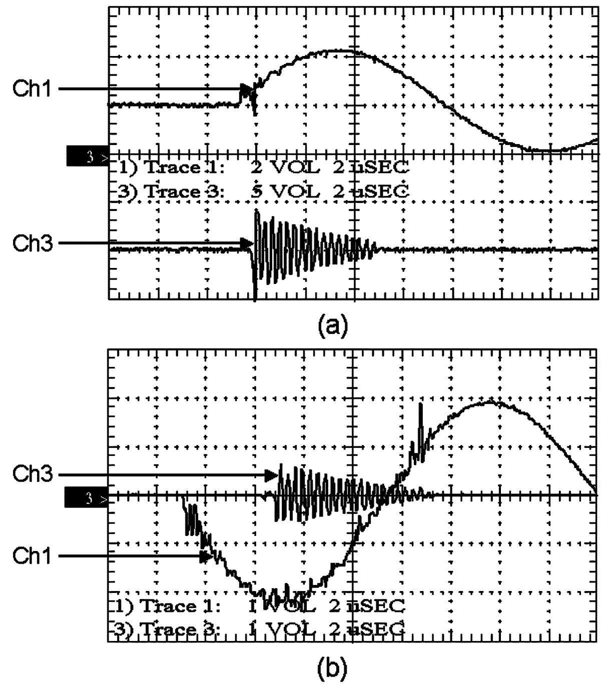

Fig. 6. Typical waveforms of triggered breakdown (10 kV, 0.1 mbar He). (a) RMCPSS1—Ch1: trigger current (40 A/V); Ch3: switch current (0.2 kA/V). (b) RMCPSS2—Ch1: switch current (0.2 kA/V); Ch3: trigger current (40 A/V), 2 μs/div.

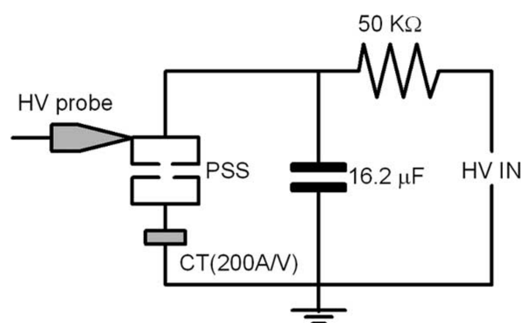

Fig. 7. Circuit used for the high-current test.

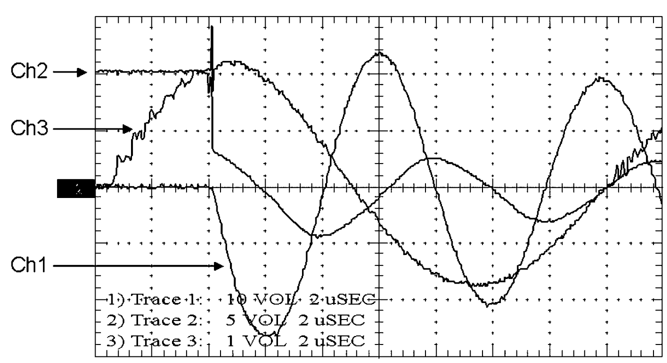

Fig. 8. Typical waveforms of a triggered discharge of RMCPSS2 at 0.09 mbar of helium and 10 kV. Ch1: Switch current (4 kA/V). Ch2: Switch voltage (1 kV/V). Ch3: Trigger current (40 A/V).

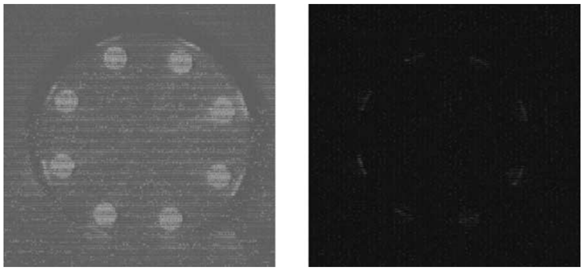

Fig. 9. Typical time-integrated discharge images of the radial multichannel pseudospark switch. In the right image, the bright circles correspond to the discharge channels formed at the boreholes. The left image is captured by using more opaque neutral density filters, which helps to distinguish discharge cores.

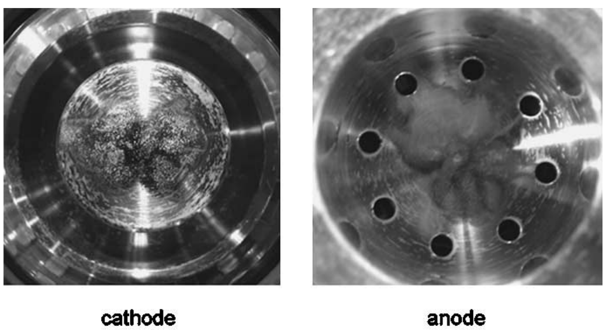

Fig. 10. Photographs of the radial type multichannel pseudospark switch.

D. Arc Erosions-SS Anode

Fig. 10 shows the cathode and the anode surfaces of the switch taken after about 50 shots of the high-current test. There were clear arc traces starting from the borehole and spread upward due to magnetic force. However, no significant arc damages near the borehole were observed. As expected, several large arc erosion damage marks were found on electrode surfaces near the axis of the switch. Taking account into these results, the radial multichannel pseudospark switch without diffusing the intense arcs is not suitable for applications requiring extremely high charge transfer.

E. High-Current Conduction Test-SiC Anode

The SS anode disk was replaced with SiC and tested with the circuit shown in Fig. 7. Fig. 11 shows a typical oscillogram of discharge current, discharge voltage, and trigger current for 0.045 mbar of helium and 20 kV charging. The peak current is measured as 208 kA. The circuit inductance and the resistance are calculated and show no difference with the results obtained with the SS anode. This implies that the SiC does not significantly differ from SS in electrical characteristics.

F. High Coulomb-Transfer Test-SiC Anode

The RMCPSS2 with the SiC anode was tested for high charge transfer. The test circuit has a 100-μF capacitor bank and a 10-μH inductor in series with the switch as shown in Fig. 12. The filling gas was helium of 0.049 mbar. Sample waveforms of the discharge current, voltage, and trigger current are shown in Fig. 13. The pulse duration is $\sim$ 100 μs long, and the peak current is $\sim$50 kA with 17 kV charging. The current is under damping for over 2 ms due to its large external inductor of 10

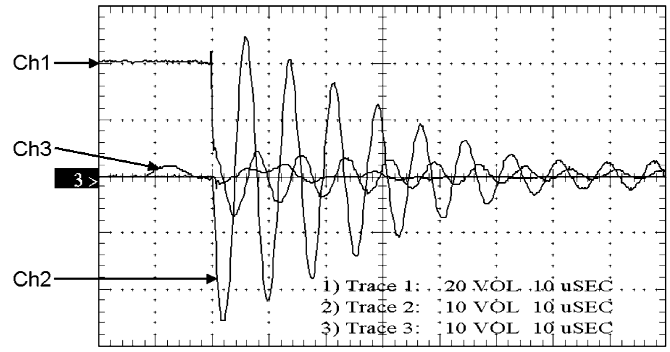

Fig. 11. Typical waveforms of triggered breakdown of RMCPSS2 with a SiC anode disk for 0.05 mbar of helium and 20 kV. Ch1: Switch voltage (1 kV/V). Ch2: Switch current (4 kA/V). Ch3: Trigger current (40 A/V).

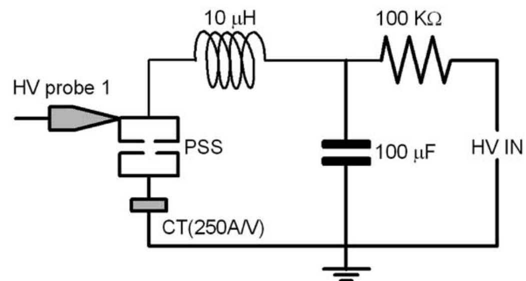

Fig. 12. Circuit for the high-coulomb transfer test.

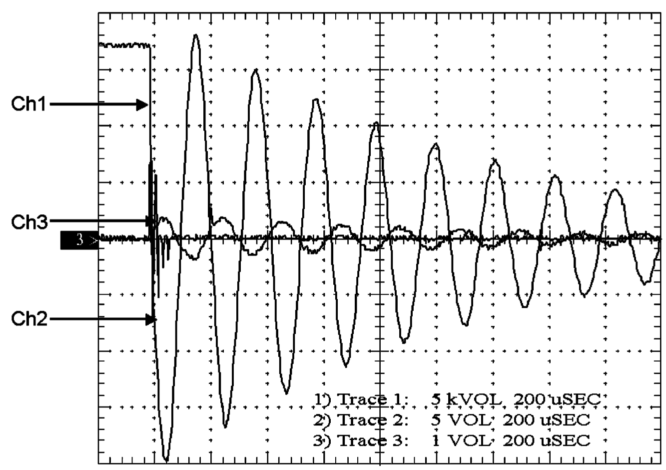

Fig. 13. Voltage and current waveforms of RMCPSS2 with a SiC anode disk tested with the circuit in Fig. 12 for He 0.049 mbar and 17 kV. (Peak current: 50 kA. Half period: 100 μS.) Ch1: Switch voltage (1 kV/V). Ch2: Switch current (2.5 kA/V). Ch3: Trigger current (40 A/V).

μH. The effective charge transfer calculated from this current waveform is about 31 C for 2.5 ms.

G. Arc Erosions—SiC Anode

After more than 200 shots of the high coulomb-transfer test of the RMCPSS2 with SiC anode, electrode status were checked and the results are shown in Fig. 14. From the inspection, we found no serious erosion marks on either SiC or the SS electrode surfaces. These results indirectly indicate uniform current distribution over the electrode surface area. This is a notable difference between the SS and the SiC anodes. The SiC surface was partially coated with the stainless steel that was vaporized

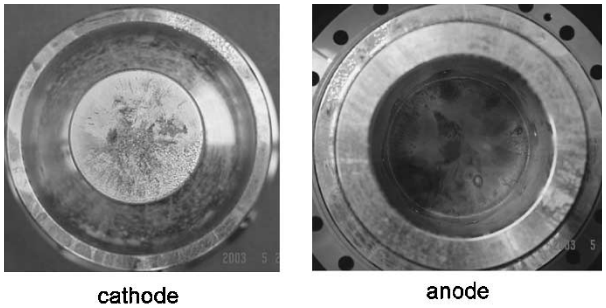

Fig. 14. Photographs of the radial multichannel pseudospark switch, RMCPSS2. Right photograph shows the SiC anode disk.

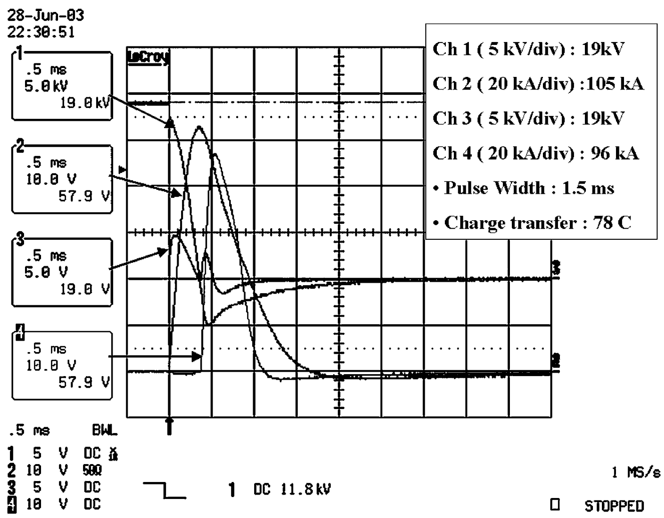

Fig. 15. Typical waveforms for extremely high coulomb-transfer experiments using the test facility of a 300 μF capacitor. Ch1: Capacitor voltage. Ch2: Switch current. Ch3: Switch voltage. Ch4: Diode current.

from the cathode. The experimental results apparently show that SiC can be used as a good electrode material for extremely high coulomb-transfer switches because of its negative temperature resistance characteristic and low arc erosion rate of about 5 μg/C [8]. Considering the erosion rate of 110 μg/C of tungsten [13], we can expect that the lifetime of a switch using SiC is much higher than that with tungsten electrodes.

H. Extremely High Coulomb Transfer

A sealed-off type radial multichannel pseudospark switch was also designed, manufactured, and tested. The main bodies of the anode and the cathode were made of OFHC copper. The cathode and anode disks were made of CrCu (Cr:25%, Cu:75%) and SiC, respectively. The disks were brazed on the OFHC bodies. Two reservoirs (ST707) were installed to control internal gas pressure of the switch. A high dielectric trigger was used. The switch dimensions were identical with the RMCPSS2. The switch was housed in a ceramic chamber. Fig. 15 shows a preliminary test result of the extremely high coulomb transfer experiment. The test circuit had a 300-kJ capacitor bank with a crowbar diode stack in parallel with the bank. A 40-μH inductor was also connected in series between the bank and the switch. The switch was successfully tested up to 105 kA peak current and 78 C charge transfer.

VI. Conclusion

Several design aspects of the radial multichannel pseudospark switch are discussed for extremely high charge transfer under pulsed operation. A high dielectric-trigger unit was adopted for the radial multichannel pseudospark switch, and it showed excellent performance in precise and stable triggering. In order to produce diffuse arc discharge, SiC anode was tested, and the results were compared with SS anode test results.

The optimum pressure range of the switch to have high hold-off voltage and smooth trigger was 0.04–0.1 mbar of helium or hydrogen. Hold-off voltage of the radial multichannel pseudospark switch was tested up to 30 kV. Breakdown delay times were varied from 0.5–4 μs for the optimum pressure range. The breakdown delay time was inversely proportional to gas pressure and the volume of the cathode cavity. The SiC showed as good electrical characteristics as the SS in pulsed high-current tests. A test switch with SiC anode successfully conducted maximum peak current of 208 kA and an effective charge transfer of 31 C/shot. SiC electrode showed no severe arc erosions after high charge-transfer tests, while SS electrode showed high erosions. No severe erosion damages were found near the boreholes and electrode cylinder walls of the switch. A sealed-off radial multichannel switch with SiC anode and CrCu cathode, which was housed in a ceramic chamber, was also tested for extremely high coulomb transfer. The sealed-off switch successfully conducted peak current of 105 kA and charge transfer of 78 C.

Considering the experimental results, it is expected that a radial type multichannel pseudospark switch with SiC electrodes and a high dielectric trigger could be a successful switch for extremely high coulomb transfer.

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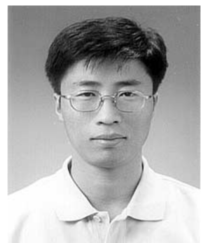

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