Trichel pulses in a negative corona discharge in air at low pressure

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Abstract. Most works focused on the Trichel pulses at an atmosphere pressure in the past. In this paper, the characteristics of Trichel pulses at low pressure (several Torr) in air used by a needle-to-plane discharge structure are investigated. The current-voltage \( (I-V) \) characteristics, the images of discharge and the time evolution of the current and voltage of Trichel pulses are measured under different conditions. Results show that Trichel pulses exist in the negative differential resistance of \( I-V \) curves, and disappear when the discharge transits to the abnormal glow discharge mode with an abrupt contraction of discharge area around the needle tip. The pulses are consisted of a very short rising time (about 10 \( \mu s \)) and a short durations time (tens of \( \mu s \)) separated by longer inter-pulse periods (more than 100 \( \mu s \)). The frequency of pulses can be tuned continuously from a few kilohertz to more than ten kilohertz by adjusting the averaged current and the pressure. It increases with the increase of averaged current at the same pressure, and rises as the pressure increasing at the same averaged current. These results will be helpful to understand the mechanism of Trichel pulses.

1. Introduction

Trichel pulses are an interesting phenomenon with regular voltage and current pulses, existing in the direct negative corona discharge [1-2]. Trichel reported this phenomenon firstly in 1938[1]. He argued that the pulses of discharge seemed to derive logically from space-charge formation and subsequent clearing. He predicted the build up of a strong negative space charge away from the point and positive space charge near the point. The positive space charge enhanced the field near the point. While the field beyond the space charge was decreased, so that almost no ionization could take place. The positive ions moved toward the point, and the region of enhanced field near the cathode would become too narrow to sustain the discharge and, finally, the ionization process stopped.

In the following work, Trichel pulses were investigated extensively both from experimentation and theories [3-5]. Loeb et al [6] stated that the Trichel pulses existed only in the electronegative gases. He also found the time of negative ion drift to the anode was much longer than the pulse period. Lama and Gallo [5] investigated the dependence of pulse frequency, charge per pulse, and time averaged corona current with the applied voltage, needle tip radius, and needle to plane spacing. Cross et al [7] pointed out that the corona current, point material, and pressure also had important influence on the pulses. He stressed that the first pulse was distinctly different from the regular pulse. The Trichel pulses also have been investigated by simulation. In 1985, Morrow [8-9] proposed a one-dimension model for the

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development of Trichel pulses. Continuity equations for electrons and positive and negative ions in a one-dimensional form were numerically solved together with Poisson’s equation. Recently, some two-dimensional models have developed to simulate the Trichel pulses [10-11].

In the last, most work focused on the Trichel pulses at the high pressure (more than 100 Torr). Few works have been done at the low pressure (below 20 Torr). In this work, we report the Trichel pulses at low pressure in air used by a needle-to-plane discharge structure.

2. Experimental set up
The experimental setup is schematically shown in figure1. A needle electrode of 0.12 mm radius of curvature is utilized and connected to a negative dc high voltage supply. The needle is placed 10.0 mm away from the plane electrode. The plane electrode is grounded. The discharge system is located in a sealed vacuum chamber, with the pressure ranging from 1 to 50 Torr. A ballast resistor \( R_1 = 4 \text{ M}\Omega \) and a measurement resistor \( R_2 = 50 \text{ k}\Omega \) were connected in series at the cathode side and the anode side, respectively. An oscilloscope (Tektronik TDS3054B) is used to read out temporally the resolved potential, \( V_1 \) and \( V_2 \), and the discharge current \( I \) can be deduced through \( V_1 - V_2 \). An Ampere-meter is connected in series with the anode to measure the averaged discharge current. A digital CCD camera (Canon A950) is used to record the plasma images.

![Figure 1. Schematic of experimental setup.](image)

3. Results and discussion

3.1 I-V curves and discharge images
Figure 2 shows the I-V characteristic at three gas pressures. For all pressures, the I-V curves show three stages as the current increasing, where \( V = V_1 - V_2 \).

![Figure 2. The I-V characteristics of negative corona discharge at different pressure.](image)
In stage 1, the voltage quickly increases with the averaged current, and the I-V curve shows a high positive slope. The highest averaged current is no more than 15 μA. This stage should correspond to the pre-discharge. When we increase the voltage continuously, the averaged current increases quickly to about 15 μA and the discharge transits to the second stage. In stage 2, both the current and the voltage are unstable and self-pulsed, the Trichel pulses appear. The pulses are very regular in behavior, which will be discussed below. The averaged voltage decreases when the averaged current increases. When the averaged current reaches about 140 to 160 μA depending on the gas pressure, the pulse disappears abruptly. Then, the voltage has a weak increase with the averaged current rising. This stage corresponds to the abnormal glow discharge.

The images of discharge at different averaged current have been obtained for the pulsing stage and stage 3 at 8 Torr. It can be seen that the images show a round structure around the tip of needle with a higher brightness, and a conical structure from the tip of needle to the anode plane with a very lower brightness. In the pulsing stage, as shown in figure 3 (a), (b), (c) and (d), the brightness of discharge images falls gradually far away from the center of images, and has no abrupt change. Moreover, the brightness and the areas of discharge rise continuously with the increases of averaged current. When the averaged current rises to about 175 μA, the brightness of discharge has an abrupt increase compared with that in stage 2, which correspond to the location in which the pulsing stage transits to the abnormal glow stage. While the diameter of discharge falls obviously, from 0.6 cm at 150 μA to 0.4 cm at 175 μA. Furthermore, we can see that there is an apparent abruption of brightness from the centre to the border of discharge. The dot line shows the boundary between the two parts. This great increase of brightness means that the ionization and excitation rates are significantly enhanced. Subsequently, the brightness of discharge increase with the current again.

![Figure 3. The discharge images at different averaged current. (a) 50 μA, (b) 100 μA, (c) 125 μA, (d) 150 μA, (e) 175 μA, (f) 200 μA, (g) 250 μA and (h) 300 μA.](image)

3.2 Typical current and voltage curves
As mentioned above, the Trichel pulses appear in stage 2. Both the discharge current and discharge voltage oscillate. These oscillations are highly reproducible and can be tuned continuously from a few kilohertz to more than ten kilohertz by adjusting the averaged current.

Figure 4(a) and (b) show the typical time evolution of the voltage and the current of the Trichel pulse for pressure $p = 8$ Torr at averaged current $30 \mu$A. The pulse is very stable with frequency of $5.0 \text{ kHz}$ in figure 4. The regular current pulse has a shorter rising time of $t_r = 11 \mu$s, a longer decay time of $t_d = 35 \mu$s, and a great long waiting time $t_w = 154 \mu$s, respectively. The peak current is about $212 \mu$A and the lowest current is nearly zero, corresponding to a lowest voltage of $565 \text{ V}$ and a peak voltage of $295 \text{ V}$. The shape of pulses in the present is similar to that obtained at high pressure, but has a smoother structure. This shows that it is easy to get stable pulses at lower pressure. In addition, the peak value of current in the present is much lower than that of pulses produced at high pressure. The peak current is on the order of several milliamperes at high pressure [7]. This difference originates from the difference of particle density. Higher pressure leads to higher particles density, and more electrons can be produced. Therefore, higher peak current appears at high pressure.

![Figure 4: Typical waveforms of (a) current and (b) voltage of Trichel pulse at averaged current of 30 $\mu$A for $p = 8$ Torr.](image)

### 3.3 The influence of averaged current on the Trichel pulses.

Figure 5 shows the Trichel pulsing frequency as a function of the averaged discharge current at $8$ Torr, $10$ Torr, and $12$ Torr. For all the investigated pressures, the self-pulsing frequency is nearly proportional to the averaged current and increases with the rising in pressure.

Figure 6 shows the current waveforms of Trichel at different averaged discharge current. All of the current pulses have the same shape for different averaged current. It is seen both the peak and the lowest current increase with the rising of averaged current. The increase of peak current is because that the electric field increases with the averaged current. The lowest current should correspond to the direct component of the pulses. It means that the direct component of current become stronger with the increase of averaged current. It is noticed that all of the current pulses have the same rising time. The decay time has a weak increase, while the waiting time has an obvious decrease with the increase of averaged current. This indicates that the formation mechanism of the discharge should be the same for different conditions. The result in figure 6 also indicates that the change of frequency is caused by the change of waiting time of current pulses.
3.4 Discussion

As discussed above, the averaged current has important influence on the Trichel pulses. This can be explained as the following. The rising of current originated from the positive space charge layer to enhance the electric field. And the quench of current is caused by the build up of the negative space charge. In the other words, the decay time of current depends on the time used to concentrate enough negative ions. The high current means the stronger positive space charge layer. Therefore, this requires that more negative ions be created to yield field that quench the discharge, a longer time for the formation of the negative space charge is necessary. In another, the waiting time between two pulses depends on the time used to clear the negative ions. As the current increasing, the field rises, which enhance the velocity of ions to the anode. So the negative ions can reach the anode in a shorter time, the waiting time decreases. Because the frequency of pulses mainly depends on the waiting time, the frequency of pulses increases as the averaged current rising.
4. Conclusion

Trichel pulses at low pressure in air used by a needle-to-plane discharge structure are investigated firstly.

1. Regular voltage and current waveforms can be obtained at the negative differential resistance of I-V curves.
2. Both the brightness and areas of discharge have an obvious change when the discharge transits from the Trichel pulsing stage to the abnormal glow stage.
3. The pulses are consisted of a very short rising time, a short duration time, and a longer inter-pulse periods.
4. The frequency of Trichel pulses increases with the increase of averaged current at the same pressure. As the current increasing, the rising time is invariable nearly, the decay time increase weakly, and the waiting time decrease greatly.

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