Overvolted Breakdown and Gas Recovery in Short Nitrogen Gaps

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Introduction

◆ Gas spark gap switches were widely used in high power single-shot devices due to their high hold-off voltage and high current capability.

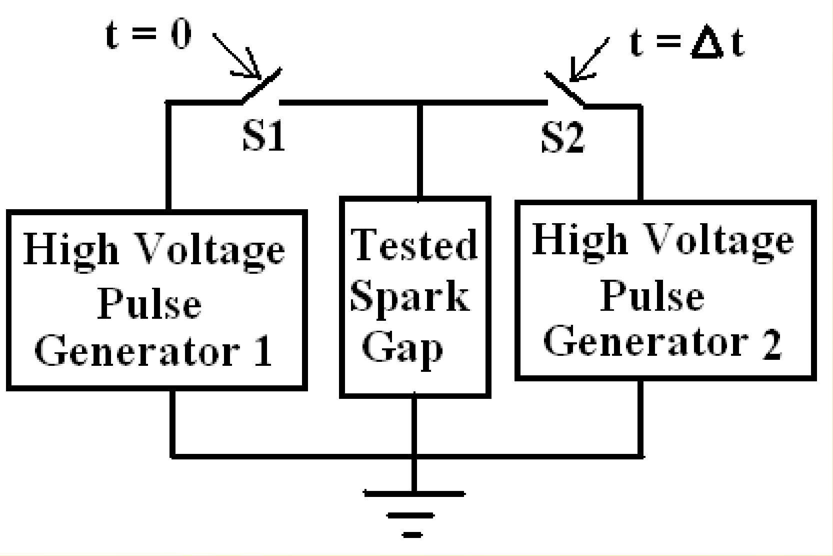
◆ Gas spark gap switches perform poorly under high repetitive operation due to their slow recovery of the hold-off voltage after breakdown.

◆ The characteristics of the overvolted breakdown and the gas recovery in short nitrogen gaps were investigated.

Experimental Methods and Devices

1. "Two-pulse method"

① Description of "two-pulse method"



Two identical high voltage pulses, with an interpulse spacing of △t, were applied to the tested gap and make it breakdown twice.

The first breakdown voltage V_{b1} determines the overvolted ability, the second one V_{b2} determines the voltage recovery R_{Vb}.

$$R_{Vb} \equiv V_{b2} / V_{b1} = f(\triangle t)$$

“Two-pulse method”

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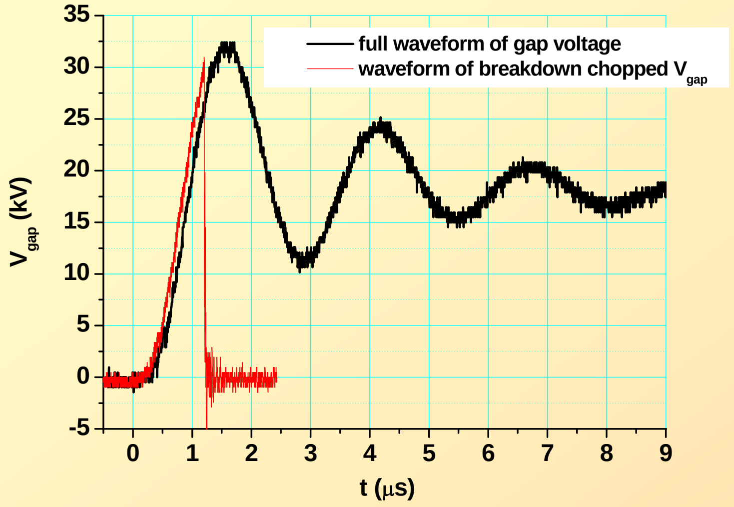
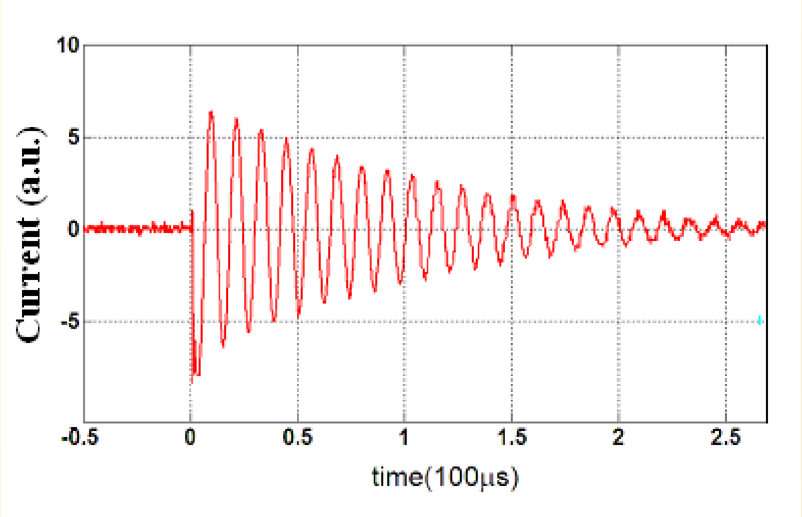
③ Typical waveforms of the gap voltage and current



Black curve --- the full waveform of V_{gap}

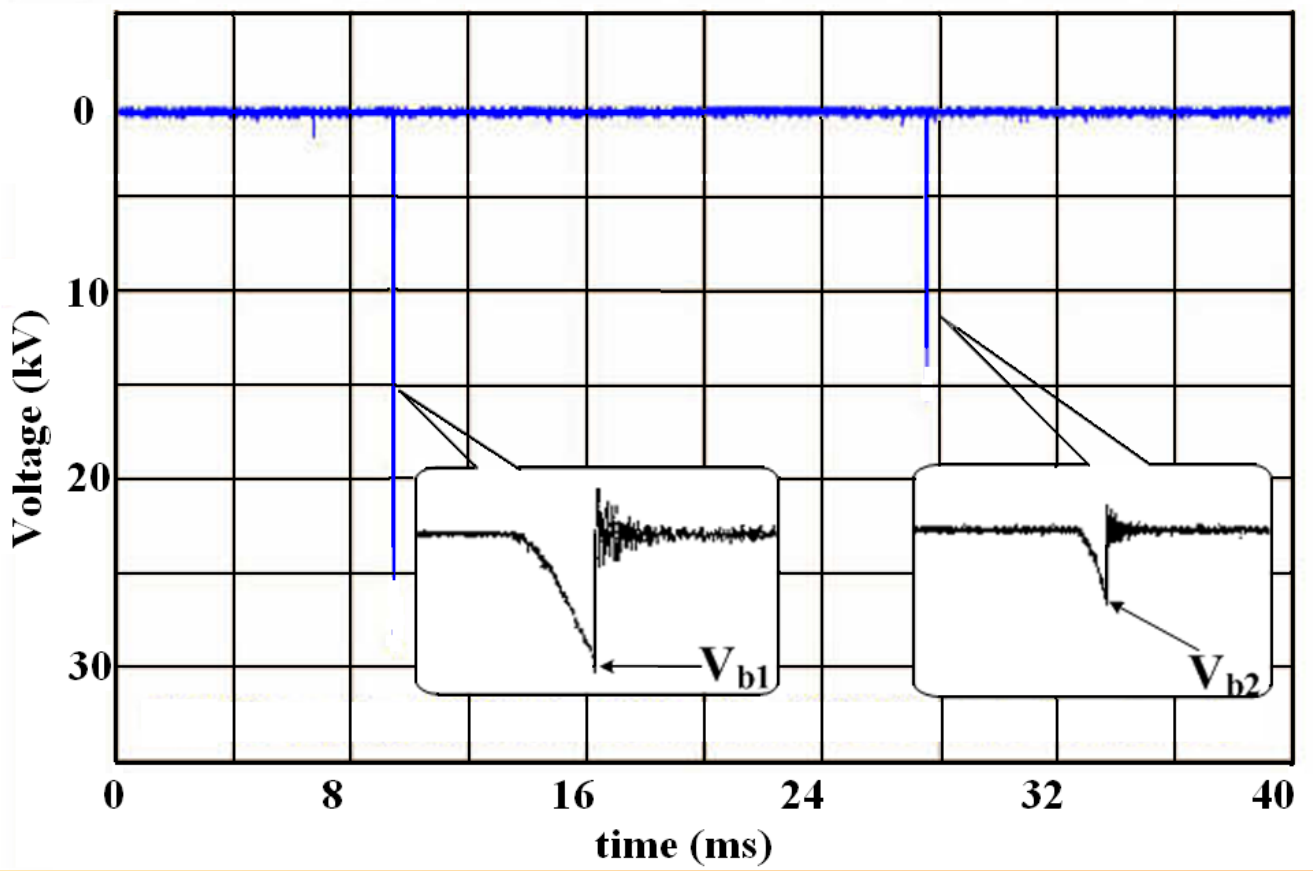
Red curve --- the breakdown-chopped waveform of V_{gap}



The spark current lasts about 260 μs.

"Two-pulse method"

④ **Typical oscillograph obtained with "two-pulse method"**



d = 0.8 mm， p = 0.4 MPa

$\triangle t = 18.2$ ms， $V_{b1} = 25.1$ kV， $V_{b2} = 14.5$ kV， $R_{Vb} \equiv V_{b2}/V_{b1} = 57.8\ \%$

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Experimental Methods and Devices

2. Mach-Zehnder Interferometry for Measurement of Gas Density

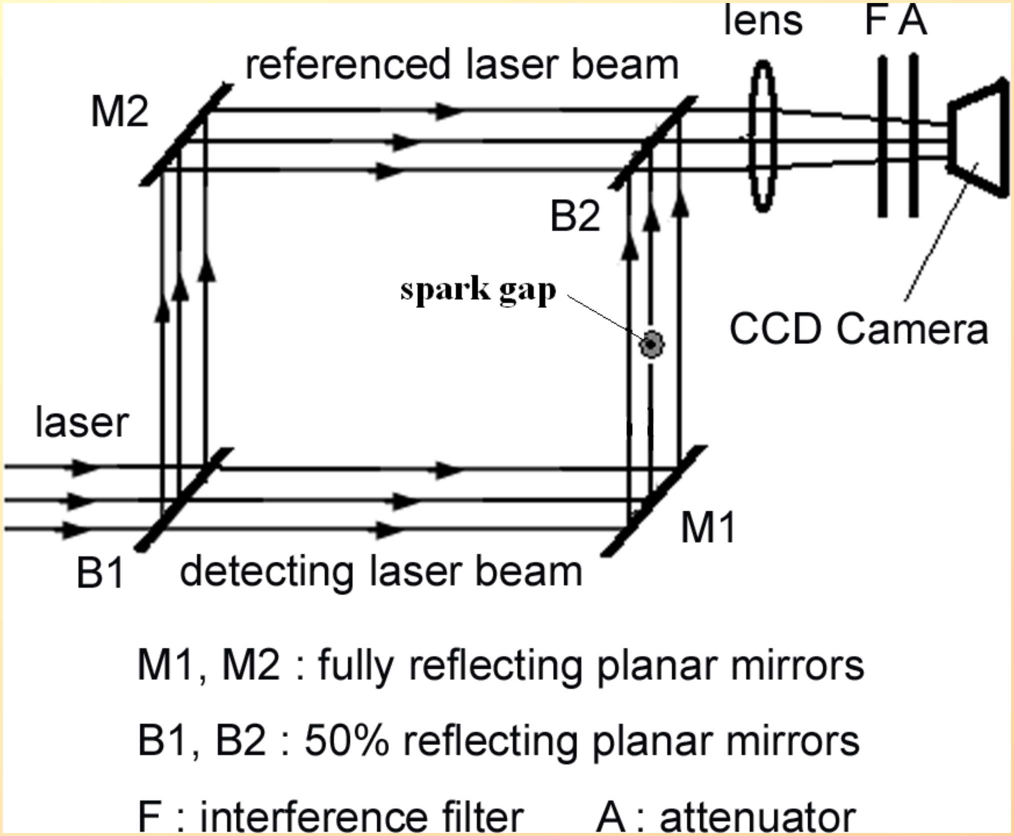
① Why do we measure gas density？

- After the extinction of the spark current, there is a hot decaying plasma channel left in the gap. The voltage recovery of the gap is determined by the gas recovery in this residual channel.

- The gas recovery includes the recovery of the electroneutrality and the recovery of the gas density. The electroneutrality recovery was believed to occur rapidly in the first few tens of microseconds. The density recovery takes much longer time and determines the gas recovery.

Mach-Zehnder Interferometry

② Optical arrangement of Mach-Zehnder Interferometer

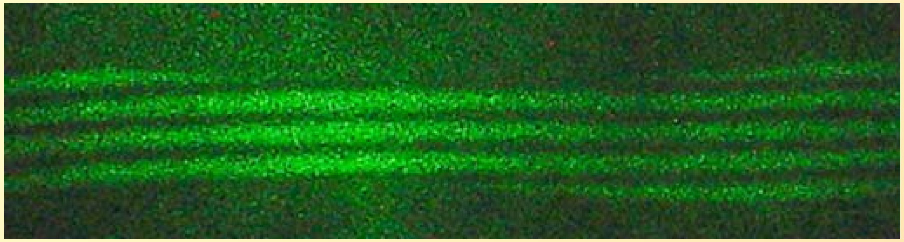


YAG laser: **wavelength of 532nm**

pulse width of 5ns

Mach-Zehnder Interferometry

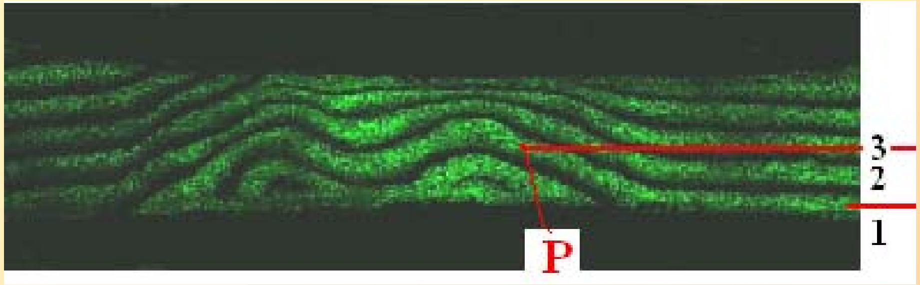
③ **Density calculation based on the fringe shift δ counted on interferograms**



Background fringes:

parallel fringes

before the discharge



Disturbed fringes by the discharge

Counting the total number of the fringe shift δ on point P:

Point P located on fringe 1 is shifted to a position of the undisturbed fringe 3, thus, δ=3-1=2.

Mach-Zehnder Interferometry

$$\delta = \frac{K}{\lambda}\int_0^L \Delta\rho \cdot dy$$

or

$$\overline{\Delta\rho} = [\int_0^L \Delta\rho \cdot dy]/\mathrm{L} = \frac{\delta \cdot \lambda}{\mathrm{K} \cdot \mathrm{L}}$$

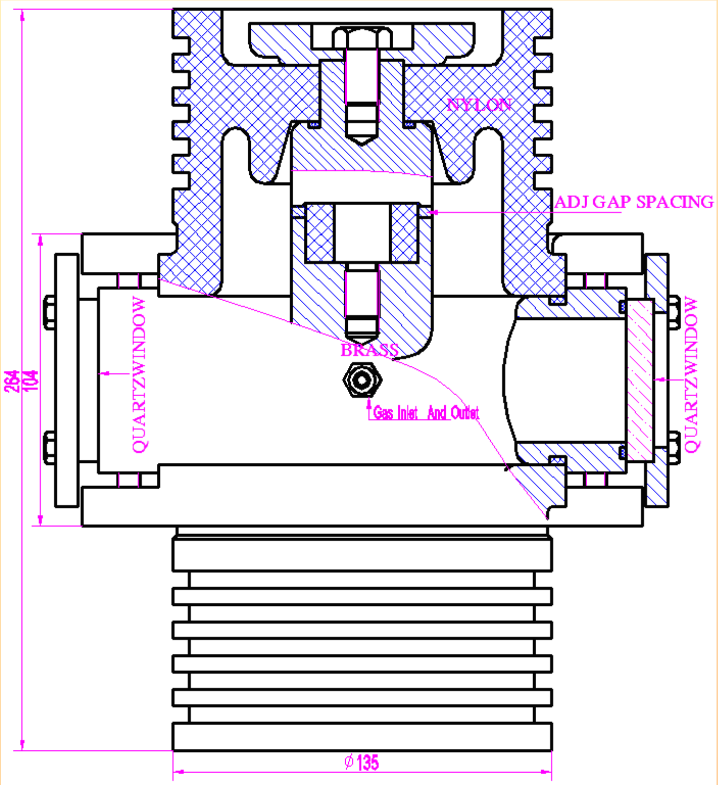
where λ is wavelength of the laser； K is Gladstone-Dale constant； Δρ is the decrease in gas mass density； y is the direction in which laser beam passes through the detecting region； L is the thickness of the disturbed-density region；

$\overline{\Delta\rho}$ **is the averaged value of Δρ over L.**

Experimental Methods and Devices

3. Tested spark gap with nitrogen as working gas

Photo of the tested gap

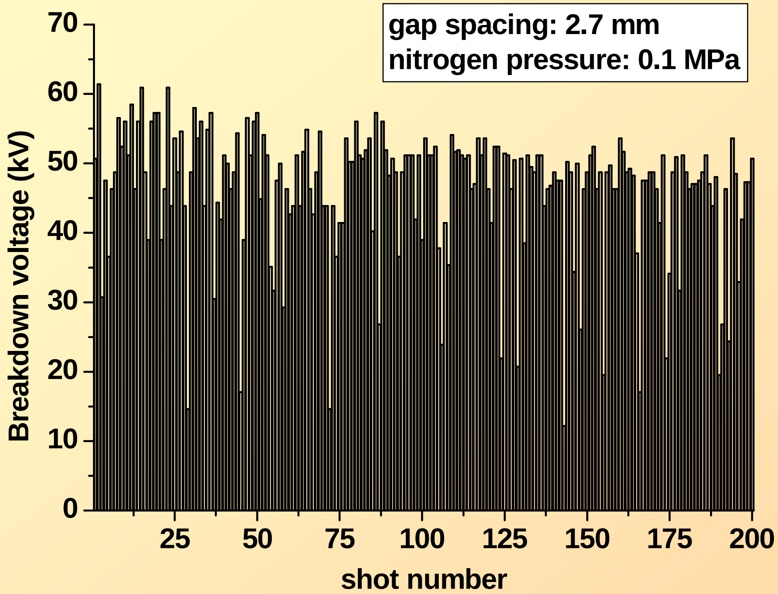


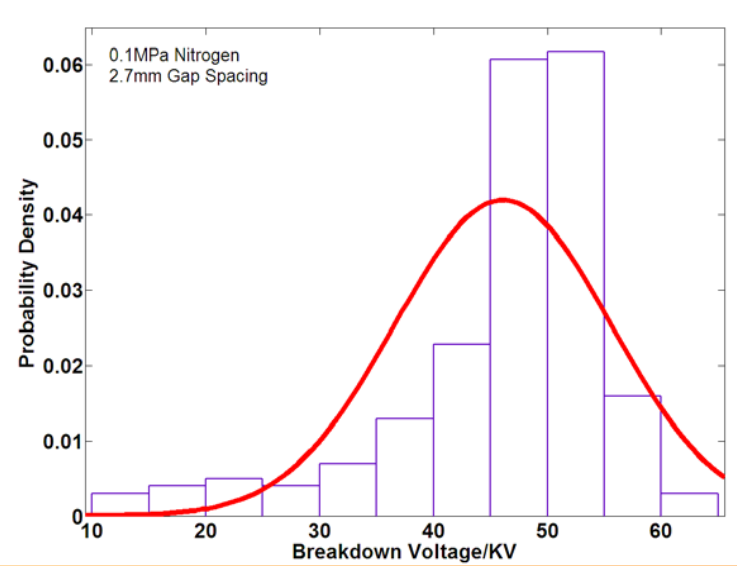
Cross section of the tested gap

Results and Discussions

1. Overvolted Breakdown （taking 2.7-mm gap for example）

① The pulsed breakdown voltage V_{b1} of a gap changes from shot to shot but obeys Gaussian distribution.





② All the pulsed breakdowns happened overvoltedly.

$$(V_{b1})_{min} = 12.2\ kV > V_{b0} = 10\ kV$$

where V_{b0} is the static breakdown voltage of the gap.

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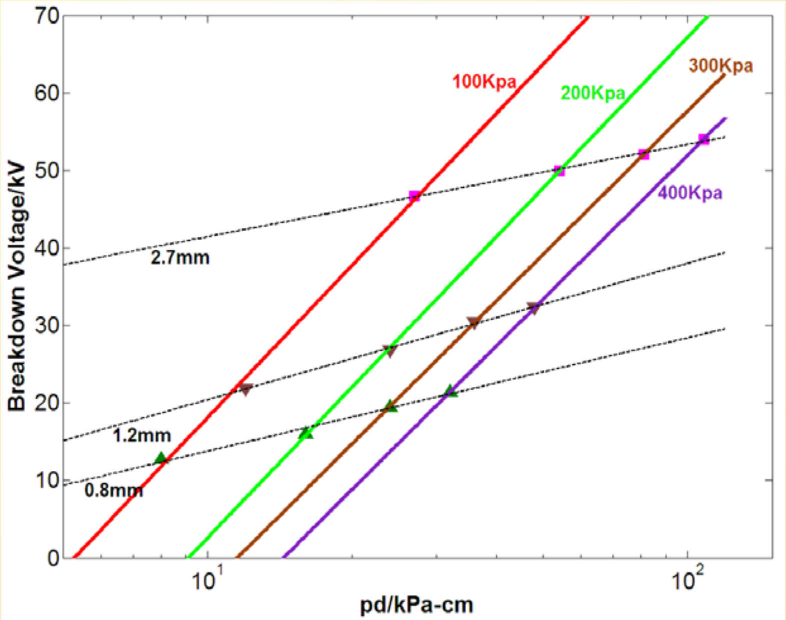
Overvolted Breakdown Voltage

③ The overvolted factor η decreases with the increase of nitrogen pressure.

For 2.7-mm gap, $(\eta)_{p=0.1\ MPa} = 4.53 > (\eta)_{p=0.4\ MPa} = 1.74$

where η is defined as $(V_{b1})_{mean} / V_{b0}$; $(V_{b1})_{mean}$ is mean value of V_{b1}.

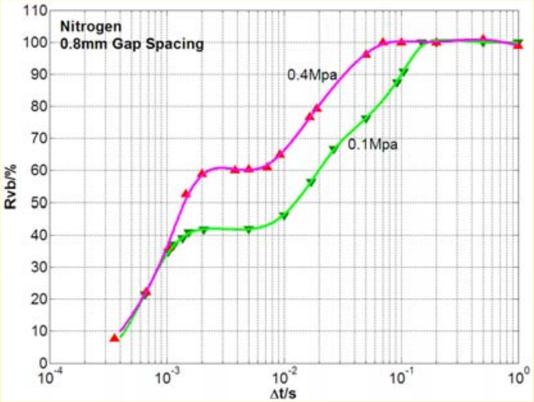
④ $V_{b1} = f(p,d) \neq f(pd)$

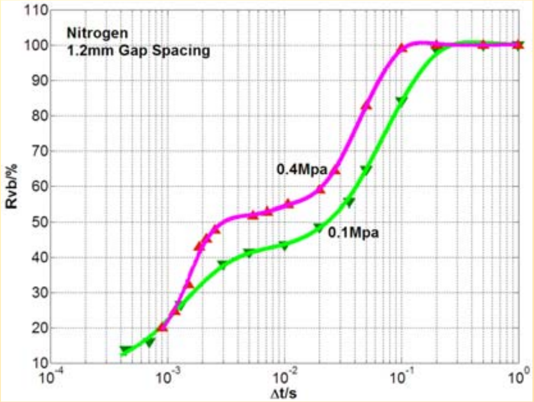


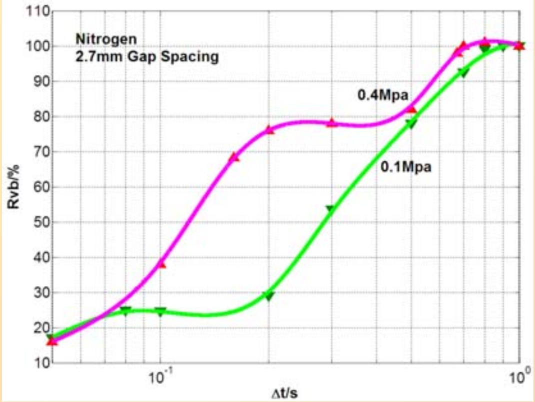
$$V_{b1} = 11.96\log(p \cdot d) + 152.63 \cdot d - 11.63$$

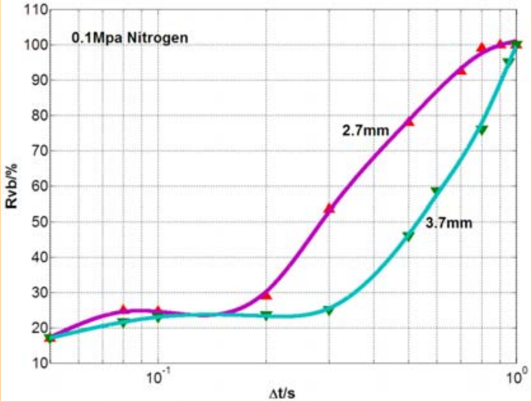
Results and Discussions

2. Voltage Recovery









- ◆ **As a whole, R_{Vb} rises up with the increase of △t.**
- ◆ **On R_{Vb} curve there is a plateau starting at V_{b2} a little bit higher than V_{b0}.**
- ◆ **Two phases of the voltage recovery: the recovery of V_{b0} and the recovery of overvolted ability.**
- ◆ **V_{b2} for a gap of higher pressure recovers faster due to more frequent collisions between nitrogen molecules, leading to faster removal of heat from the gap.**
- ◆ **V_{b2} of a shorter gap recovers faster due to easier removal of heat through the metallic electrodes.**

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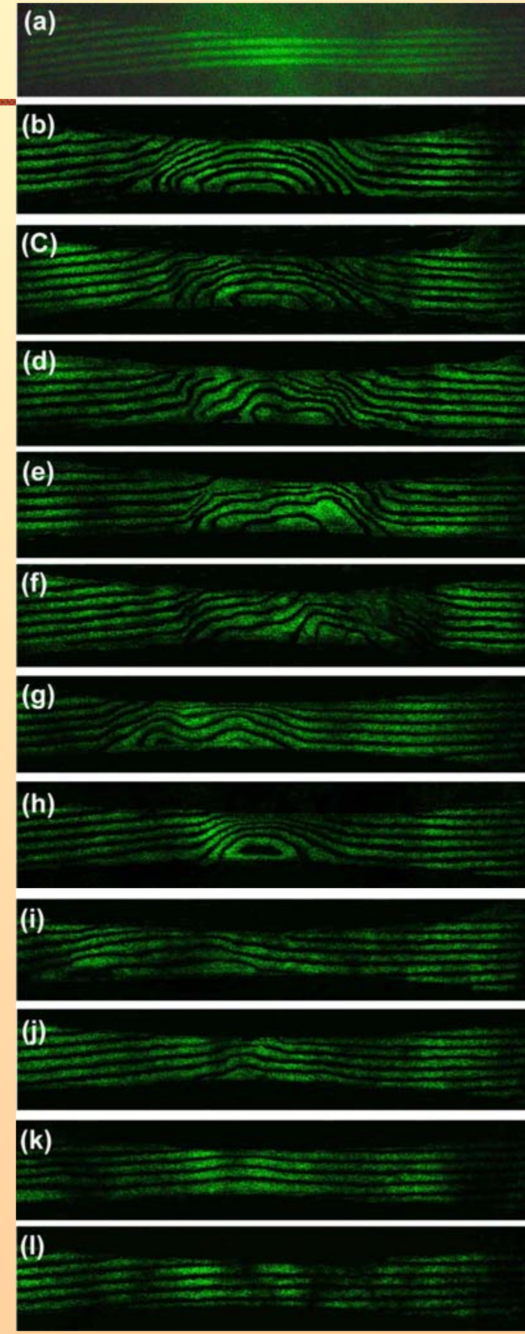
Results and Discussions

3. Recovery of Gas Density

（taking 2.7-mm gap for example ）

① Qualitative descriptions

- t = 0 was set at the beginning of the spark current. Fig.(a) is the background fringes before the discharge.
- Since the spark current lasts 260 μs， fig.(b) was at the beginning of density recovery.
- The width of the central disturbed region of fig.(b) is about 13mm, it means L=13mm.
- As the time elapses， the disturbance in the fringes gets smaller and smaller, which shows the recovery process of gas density.
- The fringes of fig.(l) recovers to parallel fringes, indicating a recovery of 50ms.



t < 0
t=266 μs
t=302 μs
t=504 μs
t=1 ms
t=2 ms
t=5 ms
t=10 ms
t=15 ms
t=20 ms
t=30 ms
t=50 ms

Recovery of Gas Density (taking 2.7-mm gap for example)

② Quantitative recovery of gas density

- δ_{max} — the largest number of the fringe shift counted on each interferogram

  δ_{max} corresponds to the point of lowest gas density that is the weakest point of electric insulation.

- Recovery of gas density R_N

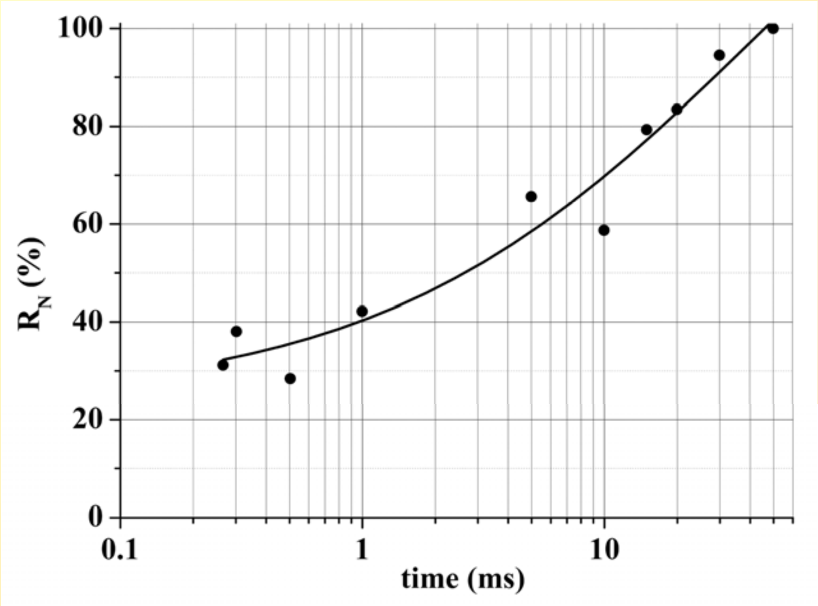
$$R_N \equiv \left[\rho_0 - \bar{\Delta\rho}(\delta_{max})\right] / \rho_0 = 1 - \bar{\Delta\rho}_{max} / \rho_0$$

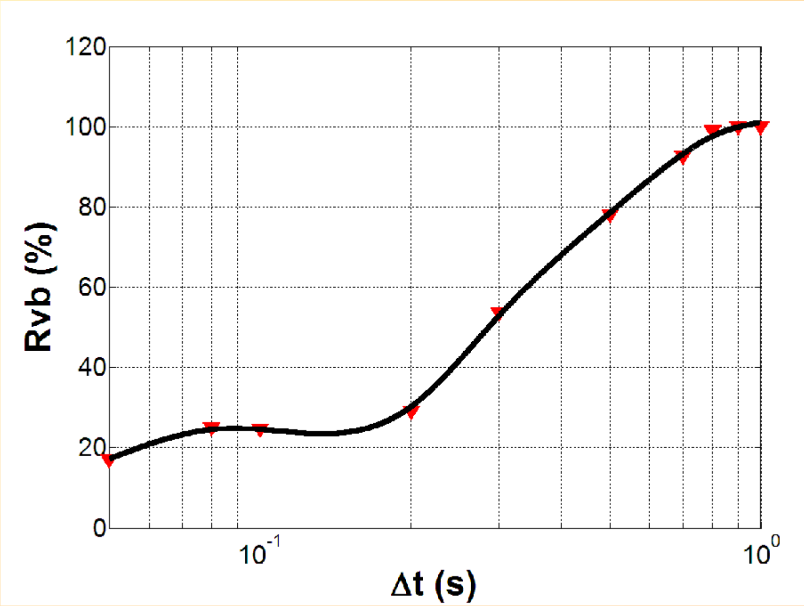
where ρ_0 is the gas density of the gap before discharge, $\rho_0 = 1.25\ mg/cm^3$ for the atmospheric nitrogen at room temperature,

$$\bar{\Delta\rho}_{max} = \frac{\delta_{max} \cdot \lambda}{K \cdot L}$$

Recovery of Gas Density (taking 2.7-mm gap for example)

③ Comparison of R_N with R_{Vb}





The recovery of the ability to be overvolted is significantly delayed compared to the recovery of the gas density.

While the gas density almost fully recovers at t = 50ms, the hold-off voltage of the gap only recovers to its V_{b0} , about 21.4% of its original value, at t = 60ms.

Recovery of Gas Density（taking 2.7-mm gap for example）

④ Reason for the delayed recovery of the overvolted ability

◆ **The reason for the overvolted breakdown of a gas gap by pulsed voltage**

For breaking down a gas gap, not only a sufficient high voltage V_{b0} but also sufficient long time t_d are needed.

$$t_d = t_s + t_f \approx t_s$$

where t_d is the breakdown delay; t_s is the time for the gap to wait for an effective discharge-initiating electron and called statistic delay; t_f is the time for the discharge channel to bridge two electrodes and called formative delay.

Thus：

$$V_b = V_{b0} + (dV/dt).\ t_d \approx V_{b0} + (dV/dt).\ t_s$$

where dV/dt is the rising rate of the applied voltage.

◆ **After the extinction of the discharge in the gap, if there exist residual and long-lived particles capable of continuously producing the seed electrons for the next breakdown， $t_s \approx 0$， $V_b \approx V_{b0}$， leading to the delayed recovery of the overvolted ability.**

Recovery of Gas Density（taking 2.7-mm gap for example ）

④ Reason for the delayed recovery of the overvolted ability

◆ **What are the residual and long-lived particles？**

For electronegative gases (SF_6), the residual negative ions that have relatively long lifetimes and produce the seed electrons through the collisional detachment.

For biatomic gases (N_2), the delayed recombinations of the residual nitrogen atoms on the cathode may produce the seed electrons.

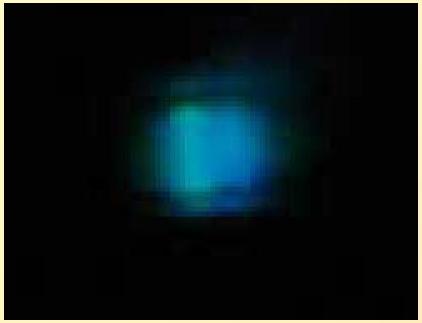
For monoatomic gases (He), the long-lived metastable atom He (2^3S) is famous for producing electrons by Penning ionization.

For gas mixture (air), it is an electronegative gas and the residual negative ions play the roles.

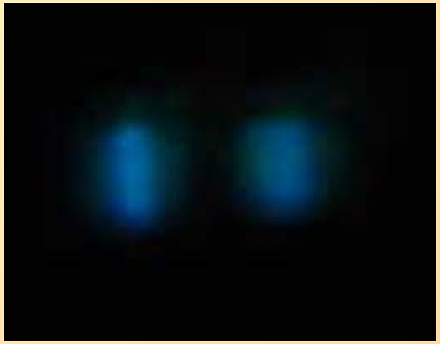
Results and Discussions

4.Location of Spark Channels

① Discharge photos obtained using an CCD camera with B gate open



△t = 100 ms



△t = 500 ms

◆ The second breakdown does not necessarily follow the path of the first breakdown.

Immediately after the extinction of the first spark current, the volume of low density centered around the spark channel has expanded to a diameter of about 13 mm. Thus, the weakest point in electric insulation may locate at any point within this expanded volume of low density.

◆ As △t gets longer and longer, the influence of the first spark channel on the second breakdown becomes less and less important.

Conclusions

- The breakdown voltage of the gaps depends individually on d and p, rather than on pd. The overvolted factor decreases as p increases.
- On R_{Vb} curve there is a plateau starting at V_{b2} a little bit higher than V_{b0}. It is this plateau that divides the voltage recovery into two phases: the fast recovery of V_{b0} and the slow recovery of overvolted ability.
- The recovery of the ability to be overvolted is significantly delayed compared to the recovery of the gas density. The reason for it may be that there exist residual and long-lived particles capable of continuously producing the seed electrons for the next breakdown.
- The second breakdown does not necessarily follow the path of the first breakdown.

Thank You !

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