Memory effect in repetitively nanosecond pulsed discharges: contribution of both volume and surface charges

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In repetitively nanosecond pulsed discharges (NPDs), the initial condition for each pulse is crucial for discharge evolution from the breakdown to the post-breakdown periods, which is generally called the memory effect. As far as we know, the initial condition for one pulsed discharge is strongly influenced by the previous pulse and the time interval between pulses (ΔT), i.e., the time duration of the afterglow period [1]. In this work, the contribution of residual charges both in volume and on surface is investigated.

Firstly, in fast ionization wave (FIW) discharge driven by nanosecond high-voltage (HV) pulses operated in moderate pressure helium (30 mbar), the temporal evolution and spatial distribution of the axial electric field (E_z) along the propagation direction of FIW are obtained using a capacitive probe [2]. By increasing the pulse repetition rate, i.e., decreasing ΔT and increasing the initial electron density (n_{e0}) in volume, the peak E_z when the breakdown happens decreases, while E_z after the breakdown, maintaining the FIW propagation, increases, showing the modulation of E_z during different discharge periods by residual electrons.

The effect of n_{e0} is also quantitatively verified by the unique temporal evolution of the optical emission from excited atoms and ions. It is found that the peak emission intensity of He II n = 4 state, with an excitation threshold energy ($\varepsilon_{\mathrm{thr}}$) as high as ~ 75.6 eV, decreases with n_{e0}. This is due to that the generation of high energy electrons is strongly dependent on the peak E_z. For He I 3^1P state with $\varepsilon_{\mathrm{thr}}$ ~ 23.1 eV, its emission intensity has a rapid increase during the breakdown period with all different ΔTs and n_{e0}s. However, with the increase of n_{e0}, its intensity after breakdown presents a mode transition: continuous decay, first decay and then increase (with a local minimum), and continuous increase. This clearly illustrates the effect of n_{e0} on E_z after breakdown and generation of moderate energy electrons.

Subsequently, the evolution of electric field in two kinds of NPDs, i.e., surface ionization wave (SIW) generated with a surface dielectric barrier discharge (SDBD) geometry and atmospheric pressure plasma jet (APPJ), is measured using the electric field induced second harmonic (E-FISH) generation method [3, 4].

In SIW, it is found that the residual charges on the dielectric surface, which decay with the increase of ΔT, generate a retarding electric field in the opposite direction to that during SIW propagation. The existence and direction of electric field generated by residual surface charges are also verified by a Kelvin electrostatic probe, which reveals the distribution of surface potential after the SIW discharge.

As a comparison, in APPJ with a metal target, there is no electric field before the HV pulse is applied. However, with a dielectric target, there is already an electric field before imposing the HV pulse, whose strength decays with the increase of distance from the dielectric target. The residual surface charges, with the same polarity as the HV pulse, are accumulated when the head of APPJ touches the dielectric target and also generate an electric field in the opposite direction to that during APPJ propagation, similar as the SIW case.

Based on the above observations, it is proposed that using bi-polar, i.e., positive-negative alternating, nanosecond HV pulses can enhance the energy coupling in repetitively NPDs with dielectric barriers, taking the advantage of residual surface charges. In this case, the electric field generated by the present pulse is in the same direction as that generated by residual surface charges left by the pervious pulse. This concept is preliminarily verified in SDBDs, where it is found that the coupled energy per pulse increases by about 25% when ΔT is reduced to 2 μs.

Furthermore, the effect of ΔT on the generation of active species in APPJ is also explored. The absolute density of hydrogen atom at the ground sate is measured with the two-photon absorption laser induced fluorescence (TALIF) method. It is found that the peak H atom density with ΔT = 1 μs is higher than that with ΔT = 10 μs by a factor of more than four. This is explained by the accumulation of H atom between pulses, which can only be activated with ΔT comparable with its lifetime.

To summarize, this work gives a systematic introduction to the memory effect in repetitively NPDs, via which both the understanding of the complex mechanism lying behind transient discharges and their performance in applications are hopefully improved.

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References

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