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Simulation Study of Plasma Ablation Discharge under Dual Time Scales

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Low-temperature plasma ablation technology is a new type of tissue cutting technology that uses a thin layer of transient plasma generated by the tip of a surgical blade electrode to interact with biological tissue, thereby achieving precise tissue ablation. The energy transfer process in plasma ablation exhibits distinct dual time scale characteristics: microsecond-scale transient discharges dominate the formation of plasma channels, while second-scale thermal accumulation effects determine the extent of tissue damage. To further investigate the energy transfer process during plasma ablation, this paper establishes a dual time scale simulation model based on the typical physical structure of discharge occurring when the ablation surgical knife electrode is covered by bubbles. The model couples microsecond-scale transient discharges with second-scale long-term electrothermal coupling. The transient discharge model is coupled with the plasma-heat transfer module to study the regulatory patterns of voltage and frequency on spatial charge distribution and discharge modes; The long-term electrothermal model is coupled with the electrothermal-multiphase heat transfer module to investigate the effects of voltage and frequency on the spatiotemporal evolution of the electrothermal field.

Study has found that during transient discharge process, the amplitude of the voltage primarily drives the transition of discharge modes through nonlinear enhancement of the inter-electrode electric field. As the voltage amplitude increases, the electron density surges by approximately three orders of magnitude, and the discharge channel exhibits a petal-shaped charge distribution after penetration. An increase in frequency induces dielectric polarization lag and capacitive coupling effects, shortening the expansion distance of the discharge channel. At high frequencies, the enhanced charge recombination rate leads to electron density saturation, driving the discharge transition from uniform diffusion to localized strong ionization. Under prolonged discharge conditions, the Joule heating power density increases quadratically with the inter-electrode field strength. When the voltage amplitude increases, this leads to extreme temperatures at the electrode tip and an expanded thermal gradient zone, resulting in a temperature gradient distribution centered on the electrode-bubble interface; At high frequencies, the skin effect and polarization hysteresis drive the nonlinear enhancement of the inter-electrode field strength. The cumulative thermal effects result in elevated temperature extremes at the electrodes and localized thermal zone distributions at high frequencies, facilitating minimally invasive selective ablation.

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References

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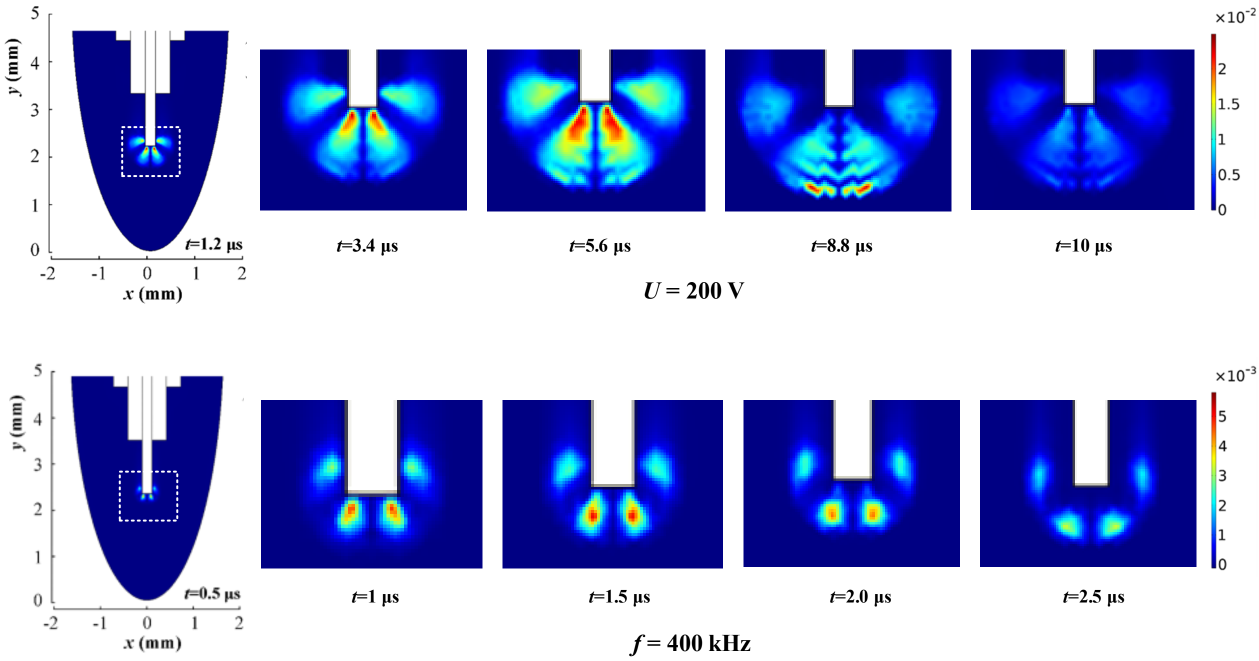

Figure 1. Changes in the space charge distribution at the electrode tip