From Oscillation to Optimization: Understanding and Controlling Nonlinear Plasma–Circuit Coupling

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Oscillations in Capacitively Coupled Plasmas

What is it

- **In 2006, Kim *et al.* [1] first experimentally observed a stable kilohertz-range oscillation in capacitively coupled plasmas, caused by impedance mismatch arising from periodic ignition in edge gaps due to the device's special structure.**

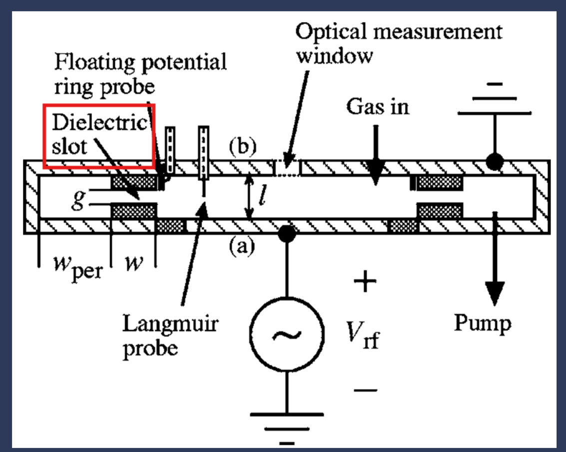

Figure 1. Schematic of the experimental setup (Kim group). Ignition occurs at the slot marked in red.

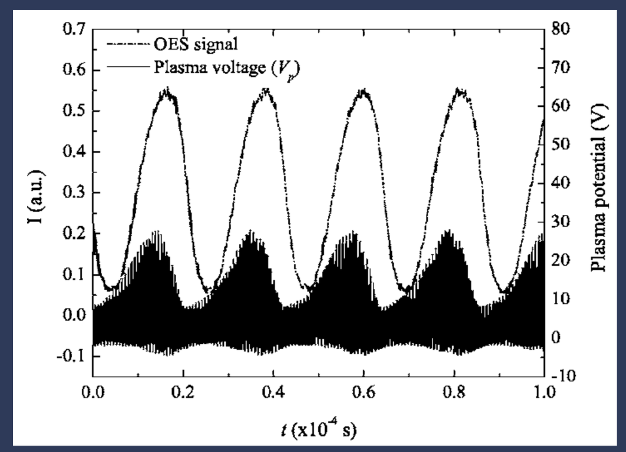

Figure 2. Observed high-frequency relaxation oscillation (~46 kHz).

- **In this study [2], we numerically demonstrate for the first time that such oscillations can be excited even in simple circuits without any special device structure, and we systematically reveal the underlying physical mechanism.**

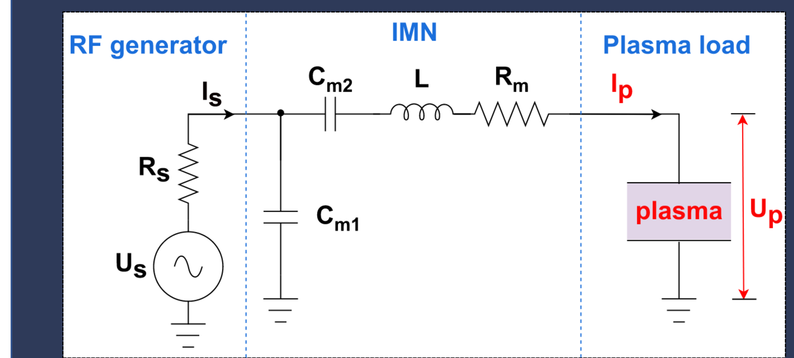

Figure 3. The simulated circuit, with only three core components: the RF power source, impedance matching network, and plasma load.

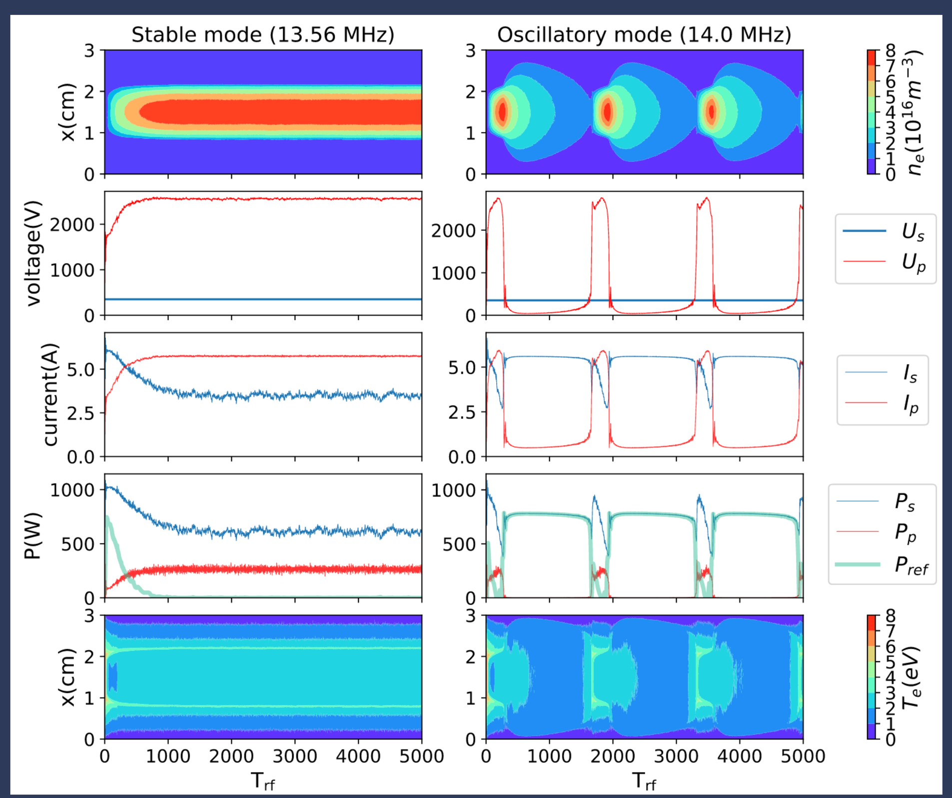

Figure 4. Two discharge modes with identical circuit parameters but different driving frequencies.
Left: f_s = 13.56 MHz, stable mode;
Right: f_s = 14.0 MHz, oscillatory mode.

Why it happens

- **The matching condition of the CCP system can be quantified by:**

$$|\Gamma| = \frac{Z_L - Z_s}{Z_L + Z_s}.$$

mode	$U_{s(\mathrm{V})}$	$f_{s(\mathrm{MHz})}$	$R_{s(\Omega)}$	$C_{m1(\mathrm{pF})}$	$C_{m2(\mathrm{pF})}$	$L_{(\mu\mathrm{H})}$	$R_{m(\Omega)}$	$D_{p(\mathrm{m})}$	$A_{p(\mathrm{m}^2)}$	$P_{p(\mathrm{Pa})}$
STABLE	350	13.56	50.0	329.6	230.2	6.32	0.5	0.03	$\pi\times0.1^2$	13.3
OSCI	350	14.0	50.0	329.6	230.2	6.32	0.5	0.03	$\pi\times0.1^2$	13.3

Table 1. Circuit configuration.

- **Special numerical configuration (OSCI) induces a transition region in |Γ|; oscillations are triggered when the system's evolution path crosses this region.**

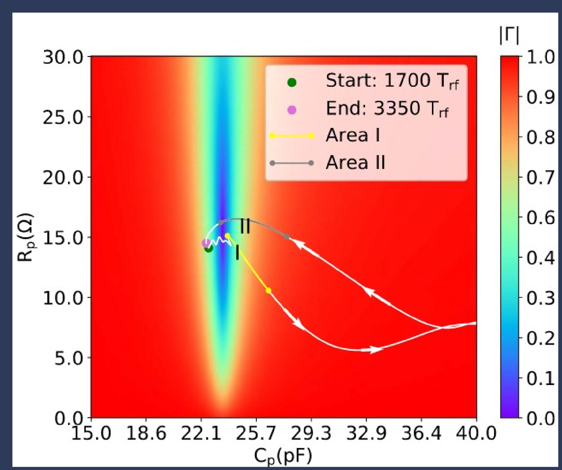

Figure 5. Distribution of the reflection coefficient |Γ| in the plasma impedance space (C_p, R_p) under the oscillatory discharge mode. The white curve shows the evolution of plasma impedance over one oscillation cycle. Areas I and II indicate regions with strong variations in |Γ|.

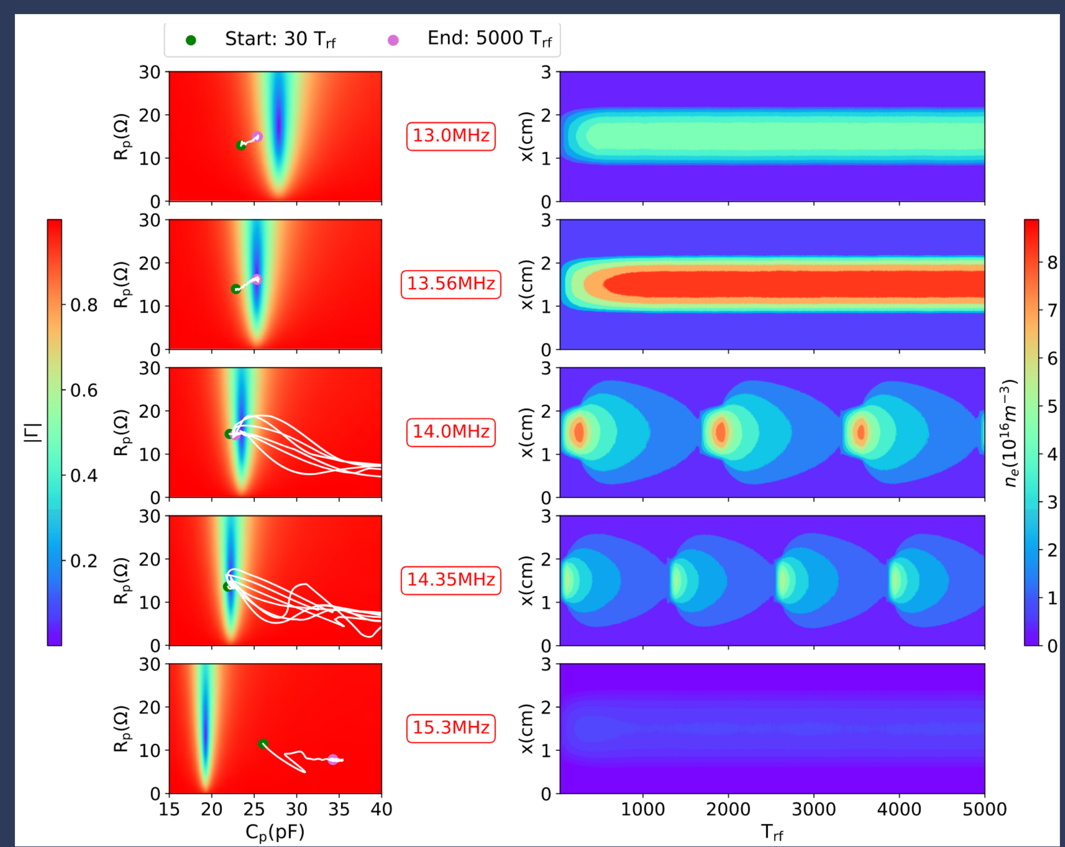

Figure 6. Effect of driving frequency on discharge stability.
Left: Increasing the driving frequency shifts the ideal matching window (blue region) toward lower capacitance.
Right: The evolution of electron density illustrates how this shift drives the transition from "stable → oscillating → stable."

- **References**

[1] Sungjin Kim et al. Journal of Applied Physics 100.10 (2006): 103302.

[2] Dehen Cao et al. Plasma Sources Science & Technology 34.7 (2025): 075011.

- **Acknowledgements**

This work was supported by the National Natural Science Foundation of China (12275095, 11975174 and 12011530142) and the German Research Foundation in the frame of Project 428942393.

Multi-Solution Impedance Matching Optimization

Oscillation to Optimization

- **The oscillation involves three key positions:**
  1. **The transition region.**
  2. **The plasma's initial position.**
  3. **The plasma's steady position.**
- **The closer the transition region is to the steady position, the better the impedance matching.**

Track the equivalent impedance (C_p, R_p)

Reverse inference to minimize |Γ| for circuit parameters.

Running with the new circuit parameters.

- **The optimization method [3] tracks the plasma's steady-state impedance in each iteration and shifts the matching window toward that position. Instead of forcing the plasma to move into the window, the window is continuously "pulled" to follow the plasma's impedance until they fully align.**

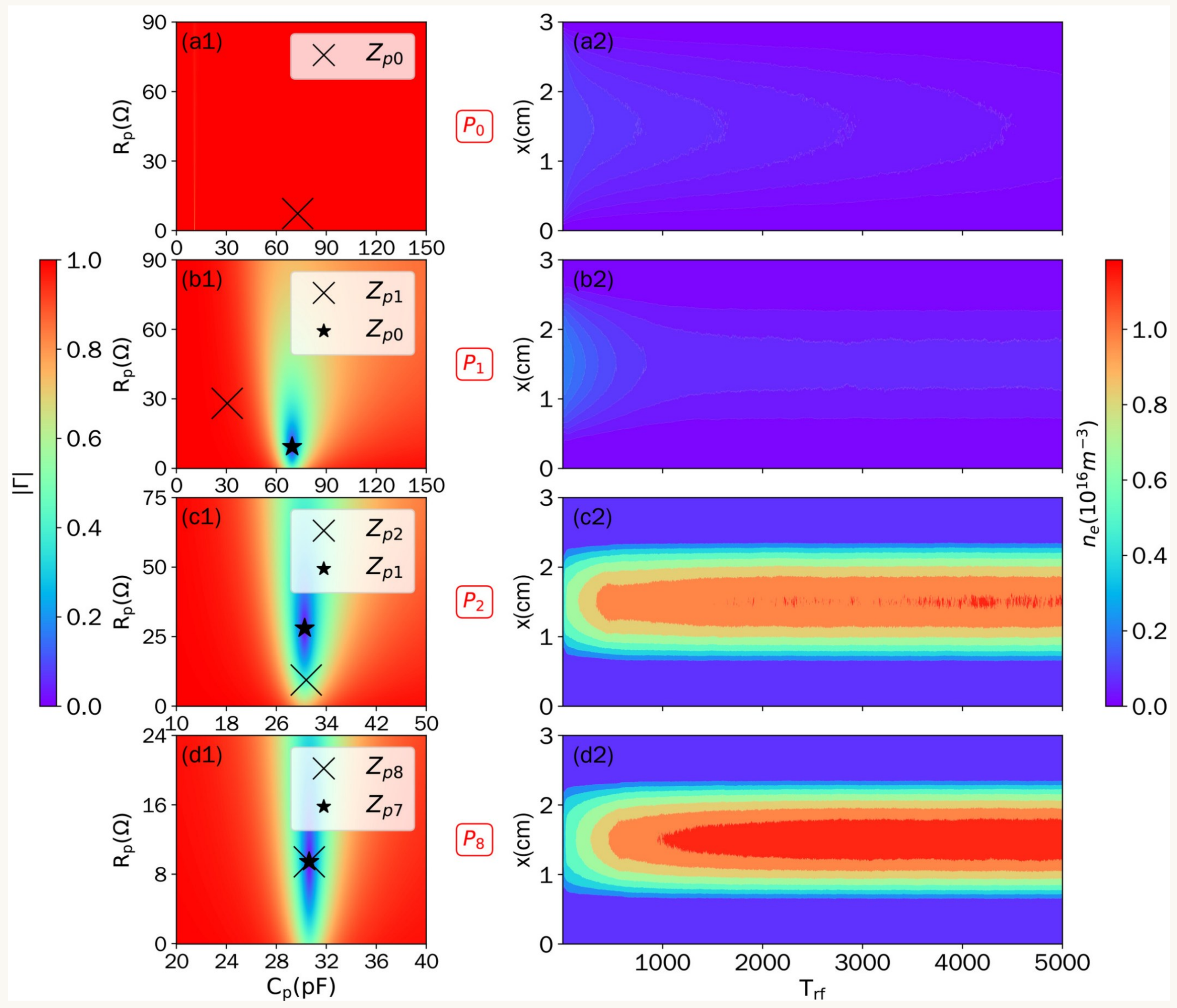

Figure 7. Iterative optimization of the matching algorithm: (a–d) show initial and successive iterations.
Left: reflection coefficient maps with the matching window (blue) pulled toward the plasma's stable point (★).
Right: corresponding evolution of electron density.

What's new

- **Initial conditions for optimization can be arbitrary.**
- **Parameters to be optimized can be arbitrary.**
- **The number of parameters optimized simultaneously can be arbitrary.**

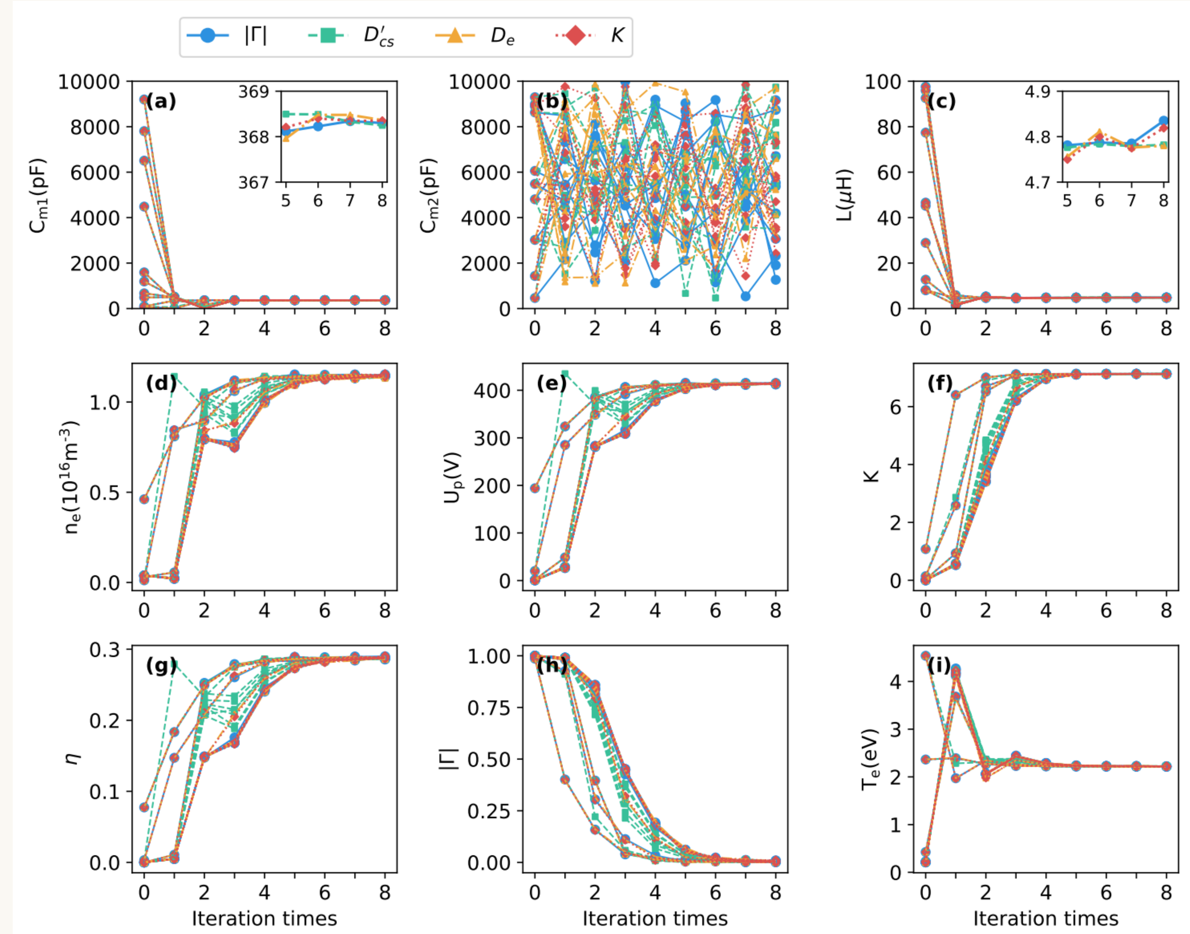

Figure 8. Optimization trajectories show rapid convergence of C_{m1} and L, while C_{m2} remains scattered; nevertheless, overall matching performance stabilizes after several iterations, indicating robust convergence despite parameter variability.

- **Can seamlessly integrate existing mature optimization algorithms.**

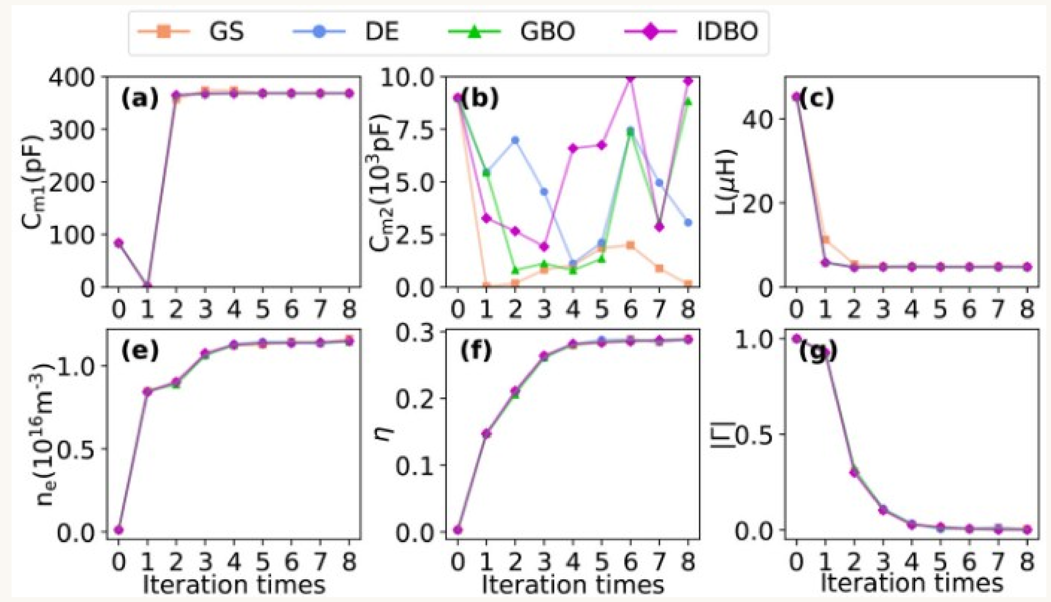

Figure 9. Comparison of different optimization algorithms shows distinct parameter trajectories but nearly identical matching performance, confirming the robustness of the proposed method.

- **References**

[3] Dehen Cao et al. Journal of Vacuum Science & Technology B 43, 042206 (2025).

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This work was supported by the National Natural Science Foundation of China (12275095, 11975174 and 12011530142).