Multi-Solution Impedance Matching in Capacitively Coupled Plasmas

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Impedance matching in capacitively coupled plasma (CCP) systems is critical for efficient energy transfer, especially in industrial applications like semiconductor manufacturing. However, the nonlinear interactions between the plasma and external circuits pose challenges for traditional optimization methods, which either require favorable initial conditions or suffer from convergence issues, often yielding only a single set of control parameters even when successful. [1,2]

To address these limitations, we propose a novel inverse-reasoning optimization method that shifts the process from the control parameter space to the plasma impedance space.[3] In this method, new control parameters are inversely derived from the impedance space by temporarily fixing the plasma's steady-state impedance and applying an optimization algorithm to minimize the objective function, effectively decoupling the parameters from their historical paths. This path-independent approach ensures robust performance regardless of initial conditions and inherently explores multiple saddle points, providing a comprehensive distribution of well-matched solutions.

In this work, we applied our method to a numerical CCP system with an L-type matching network, using a one-dimensional implicit PIC/MCC simulation to model the plasma load. As shown in Fig. 1, the optimization process demonstrated the method's effectiveness, achieving stable matching after six iterations with 10 random initial conditions and 4 optimization objectives, with the reflection coefficient converging to near-zero values, and both electron density and power absorption efficiency reaching satisfactory levels. Finally, the method identified 40 well-matched saddle points, with control parameters like C_{m1} and L converging tightly while C_{m2} showed a broad distribution, highlighting its ability to explore multiple well-matched solutions for enhanced flexibility in industrial applications. Furthermore, we validated the equivalence of different inverse-reasoning algorithms and confirmed the method's universality across varying discharge conditions.

References

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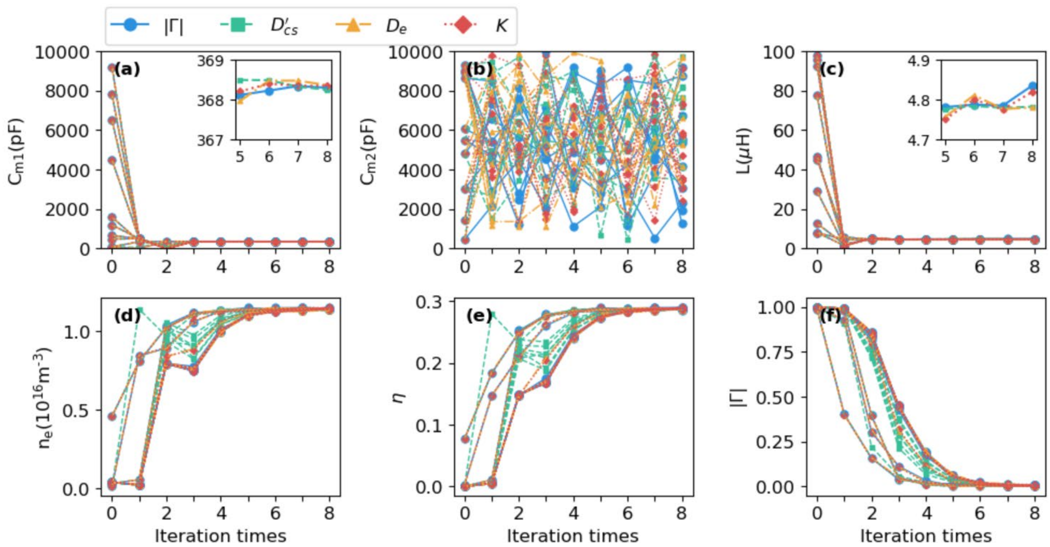

Figure 1. Changes in IMN components and plasma performances at each optimization iteration for different optimization objectives. (a), (b), (c): Values of three IMN components: C_{m1}, C_{m2}, and L. (d) Electron density at the center of the electrode plates. (e) Power absorption efficiency of plasma load, defined as $\eta = P_{CCP}/P_{source}$. (f) Magnitude of reflection coefficient.