A Generalized External Circuit Model for High Order Electrostatic IFE-PIC Codes

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In this paper, we integrate the Generalized Verboncoeur Method (GVM) with the particle-in-cell (PIC) framework using an iterative immersed finite element (IFE) method to simulate plasma interactions with external circuits in both 2D and 3D cases.

The GVM extends the original Verboncoeur method(OVM) by enabling self-consistent simulations of nonlinear, multi-loop circuit-plasma coupling, overcoming limitations in OVM[1, 2]. We utilize the iterative immersed finite element (IFE) method[3,4,5,6] to develop a GVM-based approach for coupling plasma with boundary conditions. Through this iterative IFE method, GVM can be directly coupled with the plasma field via the surface electric quantity on the driving electrodes, enabling the GVM model to integrate with 2D and 3D plasma models. Furthermore, building upon the newly developed coupling boundary conditions, we supplement the discussion on circuit cases within the GVM framework.

Several numerical experiments are performed to demonstrate the convergence and applicability of the proposed Generalized Verboncoeur Method with the Iterative Immersed Finite Element (GVM-IIFE) approach. As shown in Fig. 1, these results collectively confirm the reliability and versatility of the coupled GVM–IIFE framework. Under both vacuum and plasma loading, the 2D 3V solution reproduces the canonical 1D GVM voltage waveforms with negligible discrepancy, demonstrating that the multidimensional implementation preserves the original model's accuracy. The steady state potential map clearly captures the development of a DC self-bias, while the predicted bias amplitude varies with the driving RF voltage in excellent agreement with independent experiments and prior simulations. Together, these benchmarks validate the correctness of GVM-IIFE and show that the proposed solver can simulate realistic plasma–circuit systems with both geometric fidelity and quantitative accuracy.

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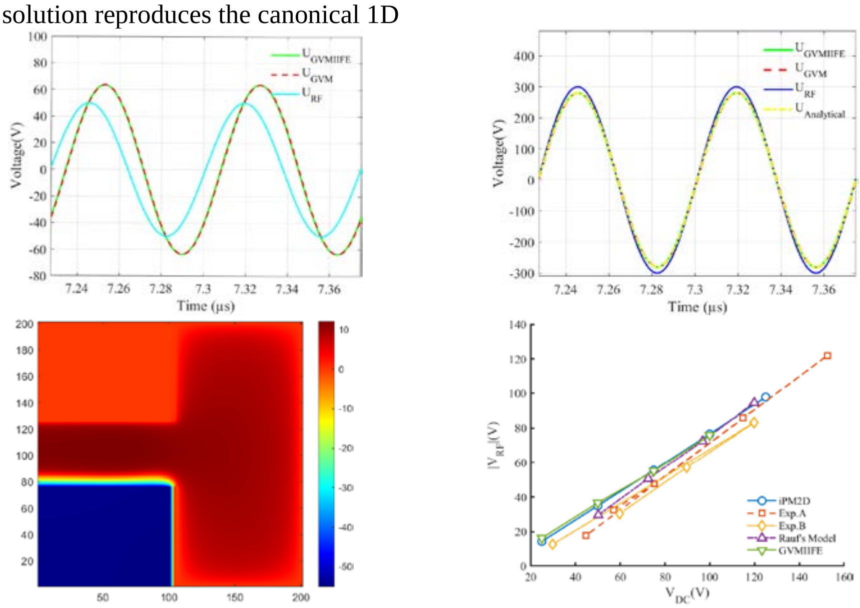

Figure 1. Validation of the GVM-IIFE solver. Top-left/right: electrode-voltage waveforms from the 2D3V versus the 1D GVM reference under plasma and vacuum loading.Bottom left: steady-state potential map at an RF amplitude of 75 V, clearly revealing the dc self-bias.Bottom right: DC bias versus RF amplitude predicted by the 2D3V compared with experimental data and prior literature.