Particle-In-Cell modeling of Inductively Coupled Plasmas for the ITER NBI source prototypes

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The ITER experiment will employ two Neutral Beam Injection (NBI) systems to achieve the temperatures required for the deuterium-tritium fusion reaction to occur. Each injector relies on a negative ion source, in which a low-pressure deuterium plasma is sustained by radio-frequency (RF) power through inductive coupling. The performance of the sources, in terms of power coupling efficiency and plasma uniformity, depends critically on the dynamics of the inductively coupled plasma (ICP). Understanding the impact of the ICP dynamics on the source performance requires a self-consistent kinetic description that can capture plasma–field interactions on the RF timescale.

In this work, a self-consistent inductive coupling model has been implemented in GPPIC, a 2D–3V Particle-In-Cell Monte Carlo Collisions (PIC–MCC) code written in C++/CUDA and under development at Consorzio RFX. The code, originally electrostatic and 2D Cartesian, has been extended to a 2D axisymmetric cylindrical geometry and developed to solve self-consistently the electrodynamic part of Maxwell's equations. This development enables the kinetic study of low-frequency ICPs without relying on simplified power deposition models.

A central aspect of the study is the analysis of density scaling, a numerical technique commonly adopted in PIC simulations to manage the high computational cost associated with the kinetic description of high plasma density and volume. In this approach, the vacuum dielectric constant in Poisson's equation is artificially reduced, effectively representing a plasma of lower density. The results demonstrate that such scaling alters the plasma response to the external RF fields.

Although a fully stable solution has not yet been achieved, the developed code successfully reproduces key features of low-frequency ICPs, such as plasma oscillations at twice the RF frequency and ponderomotive plasma compression. Therefore, this work represents a crucial step toward a self-consistent and kinetic description of RF plasma dynamics in negative ion sources, directly supporting the optimization of the ITER NBI source.

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