A SIMULATION STUDY OF PLASMA BREAKDOWN IN THE TOKAMAK ELECTRON CYCLOTRON PRE-IONIZATION PHASE

Implementation of EC wave-particle interaction model on 2D breakdown simulation

[1]Jinwoo Gwak, [2†]Min-Gu Yoo, [3]Jeongwon Lee, [1]Yeongsun Lee, [4]Hyun-Tae Kim, and [1*]Yong-Su Na

[1]Department of Nuclear Engineering, Seoul National University, Seoul, Republic of Korea,
[2]General Atomic, P.O. Box 85608 San Diego, CA 92186-5608, United States of America,
[3]Korea Institute of Fusion Energy, Daejeon, Republic of Korea,
[4]United Kingdom Atomic Energy Authority, Culham Science Centre, Abingdon, OX14 3DB, UK

Email: yoom@fusion.gat.com[†], ysna@snu.ac.kr[*]

In this work, the electron cyclotron (EC) wave-particle interaction model [1,2], which describes an electron energy gain under the significantly low density and temperature condition of plasma breakdown, is implemented in the two-dimensional (R,Z) tokamak breakdown particle-in-cell simulation, BREAK [3]. A key energy transfer mechanism is successfully captured without adding substantial computational inefficiencies by adopting physical and numerical models. The instantaneous electron energy gain from single nonlinear interaction is predicted by analytic estimates, which were derived for room-temperature electrons by taking zero incident perpendicular energy of the electrons [1]. The key role in energy gain played by incident perpendicular energy is also captured by refining adiabatic nonlinear theory into a semi-analytic form [2]. These localized cyclotron interactions were incorporated into global particle dynamics through a probabilistic Monte Carlo-like model. Given the poloidal open-field magnetic configuration of KSTAR, the EC plasma breakdown and its two-dimensional transport are being investigated in combination with dominant $\mathbf{E} \times \mathbf{B}$ transport by self-consistent electrostatic potential (see Figure 1). A holistic understanding of this phase could contribute to inferring the EC requirements for future tokamak pre-ionization, such as ITER and K-DEMO.

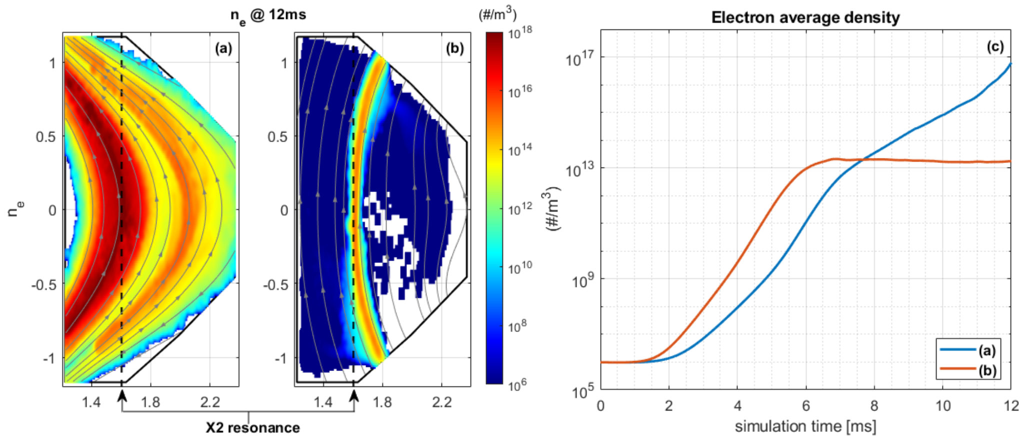

Figure 1. Particle simulation results of the second-harmonic extraordinary wave (X2) EC pre-ionization under a 2 mPa H_2 prefill in the KSTAR magnetic configuration, assuming a 170 GHz, 1 MW, 0.1 m radius, mid-plane-injected, single-pass Gaussian wave. Two different experimental magnetic configurations were considered, with the same initial and boundary conditions: poloidal fields with positive curvature (a) and negative curvature (b). The average electron densities are compared in (c), while the two-dimensional snapshots of electron densities at 12 ms are shown in (a) and (b).

The ohmic plasma initiation in tokamaks relies on the toroidal electric field to achieve breakdown, burn-through, and plasma current ramp-up, but future superconducting devices such as ITER face limitations due to constrained electric fields and stray poloidal fields. Instead, the additional injection of EC waves can relax electromagnetic requirements and even solely facilitate plasma breakdown and local burn-through when applied earlier than the toroidal electric field. It has also been demonstrated that the performance of this EC pre-ionization phase can be further improved by providing magnetic configurations such as trapped particle configurations (TPCs) that are far from widely accepted magnetic field null configurations (FNCs), which minimize stray fields [4]. Nevertheless, the underlying mechanisms remain veiled, necessitating high-fidelity simulation studies due to limited diagnostics and physical complexity. Most advanced diagnostics oriented toward fusion plasma are impractical within the relevant parametric range ($10^{6-16} m^{-3}$ for density and 0.03 eV to a few hundred eV for radiative temperature), and dominant $\mathbf{E} \times \mathbf{B}$ transport is strongly governed by self-consistent electrostatic potentials in an open-field configuration [3].

In order to investigate the creation and confinement of pre-plasma under different poloidal magnetic field configurations, we incorporated models to describe electron energy gain from EC wave-particle interaction in BREAK by prescribing the injected EC Gaussian wave. At the early stage, seed electrons interact nonlinearly with the EC wave and gain significant energy instantaneously via wave trapping, which plays a critical role in initiating electron avalanches [1]. To model the EC energy gain of electrons generated during breakdown—encompassing a broad range of incident energies and pitch angles—we implemented appropriate energy gain models based on incident velocity. For electrons with high parallel speed, which transit the Gaussian wave rapidly, energy gain was computed by numerically integrating their motion under a localized wave [1]. The equations of motion were averaged over an order of the cyclotron period, retaining only the resonant terms that dominate the interaction. For electrons with low incident perpendicular energy, analytic estimates from adiabatic nonlinear theory were adopted for energy gain [1]. For electrons with low parallel but large incident perpendicular energy, neither the analytic formula nor numerical integration is adequate. The energy gain of these electrons is addressed by refining the adiabatic nonlinear theory into a semi-analytic form, predicting the wave trapping conditions and nonlinear energy gain [2]. We confirmed the accuracy of this proposed model by calculating macroscopic energy absorption for key characteristic distributions: the secondary electron distribution for early breakdown and the Maxwellian distributions for mid-to-late breakdown (Figure 2). With the semi-analytic model, the computation time was significantly reduced by three orders of magnitude (e.g., from 64 hours to 2 minutes).

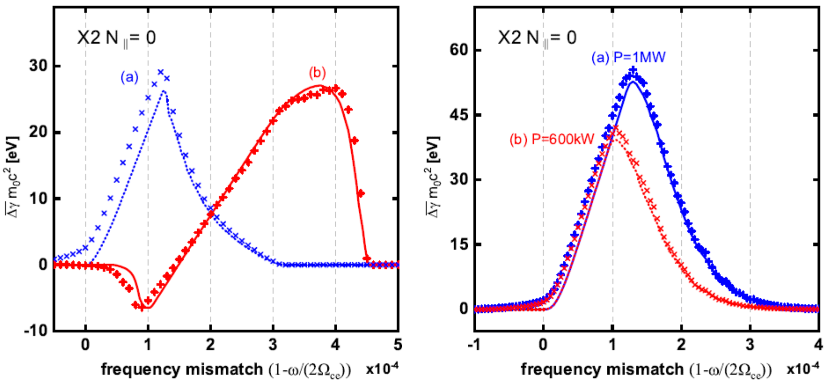

Figure 2. Total absorbed energies averaged over secondary electrons (left) and Maxwellian distributions (right, $T_\perp = 10$ eV, $T_\parallel = 2$ eV), as a function of frequency mismatch [2]. The ejected (case(a), left) and scattered (case (b), left) singly differential cross-sections from relativistic binary encounter dipole model [10] were adopted, assuming a Hydrogen atom with 100 eV incident energy. The same beam settings as in Figure 1 were used. Lines and markers indicate semi-analytic model and motion integration results, respectively.

We coupled (semi-)analytic estimates of energy gain to simulation particles by sampling a radial position from their shaping function and the corresponding frequency mismatch value, which exclusively determines nonlinear EC energy gain under given wave characteristics. For the first time, BREAK integrates the EC energy gain model with 2D transport simulations to investigate EC pre-ionization breakdown while considering plasma response. Currently, performance differences due to magnetic configurations such as TPCs and FNCs are being investigated under KSTAR geometry and wave conditions. This approach enables a more comprehensive understanding of EC breakdown, contributing to the development of predictive capability for the EC pre-ionization phase of future tokamaks and spherical torus devices.

ACKNOWLEDGEMENTS

This work was supported by the National R&D Program through the National Research Foundation of Korea (NRF) funded by the Korea government (Ministry of Science and ICT) (NRF-2021M1A7A4091135). This work was supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences under Award No. DE-FG02-95ER54309. This research has also been supported by R&D Program of "High Performance Tokamak Plasma Research & Development (code No EN2501)" through the Korea Institute of Fusion Energy (KFE) funded by the Government funds, Republic of Korea.

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