# Numerical Simulations of Ohmic Breakdown Phenomena in a Tokamak

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## 1. Introduction

The ohmic breakdown is a fundamental method to produce plasmas in a tokamak. Main mechanism of the ohmic breakdown is the electron avalanche which is continuously ionizing neutral gas molecules by accelerated electrons under sufficient electric field. In the tokamak, toroidal electric field could be produced by time-varying current of central solenoid. Then seed electrons in neutral gas are accelerated along magnetic field line to make electron avalanche. Stray magnetic fields, however, produced by central solenoid current and eddy currents, impede this process by making open magnetic field configuration in the tokamak. Since electron can be lost easily following open magnetic field line before sufficient avalanche, appropriate cancelling of stray magnetic fields is required for reliable breakdown.

In this sense, previous study about the breakdown phase focused on estimation of the field quality. Based on Townsend avalanche theory, “Conventional empirical condition” [1] and “Field-line-following analysis” [2,3] methods are widely used to estimate the quality of given magnetic and electric fields. They could predict qualitative characteristic of breakdown from the estimated field quantity, but it is difficult to account for real dynamic plasma properties during the breakdown phase.

In this research, particle simulation is performed to study the dynamic plasma evolutions during early phase of the ohmic breakdown scenario.

## 2. Drift-kinetic PIC(Particle-In-Cell)-MCC(Monte Carlo Collision) code development

The electron avalanche, the main mechanism of the ohmic breakdown, is very dynamic phenomenon. For example, various particle-impact reactions, ionization and excitations, occurs during the breakdown. Many physical characteristics change in very wide range due to exponential growth of plasma density by the electron avalanche. In addition, plasma equilibrium and neutrality are broken by external electric fields. It results in poloidal electric fields produced by space charge in the tokamak. Therefore, particle simulation is the most appropriate method to study these dynamic phenomena.

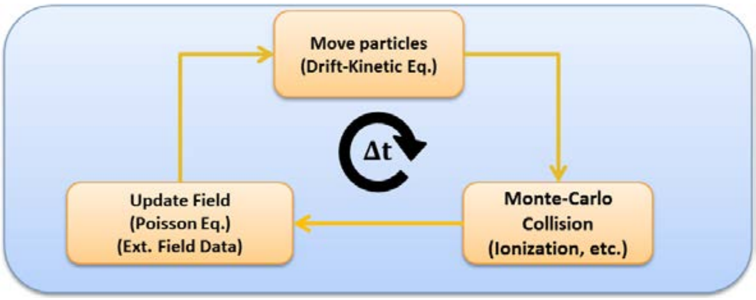


Figure 1. Numerical scheme of the developed drift-kinetic PIC-MCC code

A drift-kinetic PIC(Particle-In-Cell)-MCC(Monte-Carlo Collision) code is developed to simulate the dynamic plasma evolutions during breakdown phase. Numerical scheme of the developed code is shown in figure 1.

Since plasma temperature is low during the breakdown phase, gyro radii of charged particles are much smaller than the system size and the field gradient length. Therefore, moving of charged particles could be calculated from drift-kinetic equation [4] rather than exact Newton's law to reduce huge amount of computational cost.

To include atomic physics well, 6 species (electron, $H_2^+$, $H^+$, $H_3^+$, $H_2^0{}_{(fast)}$, $H^0{}_{(fast)}$) and total 26 collision reactions among plasma particles and background neutral gas molecules are considered [5]. And MCC method is used to simulate those collision reactions during the breakdown phase [6].

Fields are updated every step for self-consistent particle simulation. Time-varying external electric and magnetic fields are updated from input data. In addition, electrostatic electric fields produced by the space charge in the tokamak are calculated from Poisson's equation assuming the first-wall as a grounded conductor boundary.

## 3. Simulation results of KSTAR breakdown scenario

The developed drift-kinetic PIC-MCC code is applied to a reference breakdown scenario of KSTAR 2010 campaign [7]. The electron and $H_2^+$ ion densities are set to be $10^8$ #/$m^3$ and their temperatures are the room temperature (0.03 eV) at t=30 ms as initial conditions.

Figure 2 shows the simulation result of average density and temperature of two main species, electron and $H_2^+$, from 30 ms to about 33 ms. It can be decomposed into four phases where dominant mechanism is different.

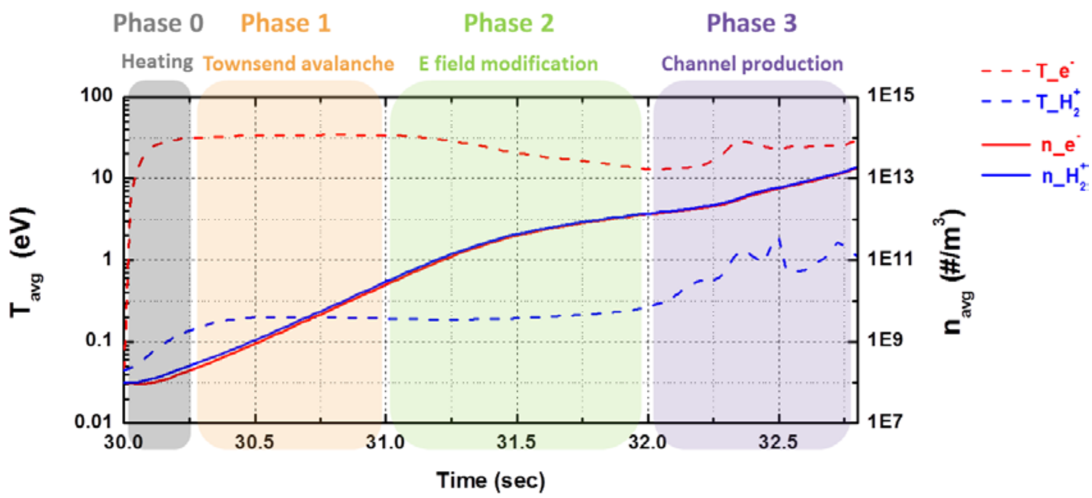


Figure 2. Particle simulation result of the reference breakdown scenario of KSTAR 2010 campaign. Average densities(Solid line) and temperatures(Dash line) of two species, electron(red) and $H_2^+$ Ion(blue), are presented.

First, heating of background electrons occurs during phase 0. External electric fields accelerate seed electrons to have enough energy to ionize neutral gas molecules. The growth rate of electron temperature decreases gradually due to electron energy loss by collisions with neutral gas molecules. Then electron temperature is saturated about 30 eV at the end of phase 0.

Dominant mechanism of the phase 1 is the Townsend avalanche. Maintaining electron temperature, electron and ion densities increase exponentially with a constant growth rate which corresponds to the first Townsend ionization coefficient, $\alpha = \mathrm{Apexp}(-\mathrm{Bp/E})$.

Phase 2 shows very interesting phenomena which cannot be explained by previous approaches. 2-D plasma effects need to be taken into account. As shown in figure 3, positive space charge is accumulated in the tokamak since electrons move to the wall along open field lines much faster than $H_2^+$ ions. As a result, high potential is grown up during the phase 2 and the produced poloidal electric fields change the electric field map to have totally different configuration. Average electron temperature decreases gradually due to reduction of $\mathrm{E_{para}}(=\vec{E}\cdot\hat{b})$ which leads to decrease of the density growth rate. The poloidal electric field becomes high enough to induce fast $\vec{E}\times\vec{B}$ drift motion of plasmas so that moving direction of electrons and ions are changed.

During phase 3, some electric channels are produced along the open magnetic field lines connecting walls due to the $\vec{E}\times\vec{B}$ drift motions. Since magnitude of $\mathrm{E_{para}}$ is higher than phase 2, electron temperature resumes to increase with the density growth rate. But the density growth rate is still lower than phase 1 because of the space charge effect. As convective loss of electrons and ions to the wall is stimulated by the $\vec{E} \times \vec{B}$ drift, plasma-wall interaction could be important in this phase.

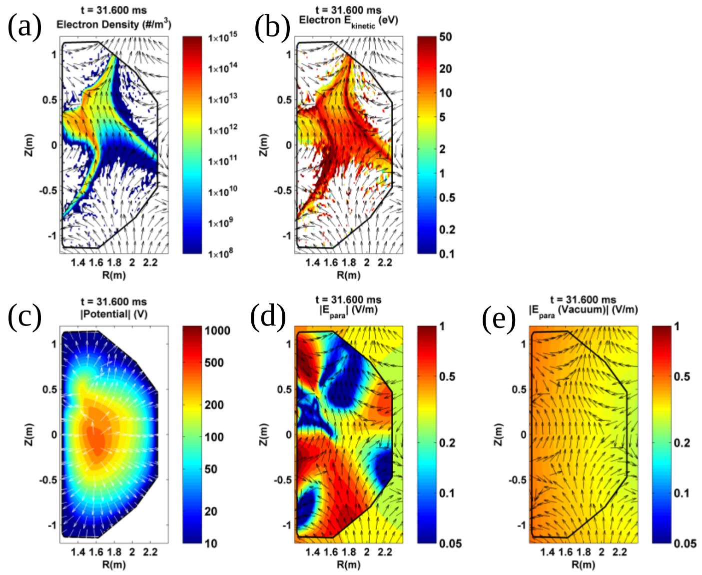


Figure 3. Several 2-D simulation results at t=31.6 ms.
(a) Electron density, (b) Electron kinetic energy, (c) Potential, (d) $E_{para}$ and (e) external $E_{para}$

## 4. Summary and future work

A drift-kinetic PIC-MCC code is developed and applied to simulate dynamic plasma evolutions during the ohmic breakdown phase of KSTAR. In the simulations, crucial effects of the electric field produced by space charge are observed; $E_{para}$ reduction and $\vec{E} \times \vec{B}$ drift.

This space charge effect will be compared with experimental measurement of VEST(Versatile Experiment Spherical Torus) device in Seoul National University. The drift-kinetic PIC-MCC code will be upgraded including more physical models such as wall-particle interactions and validated against experimental results of plasma breakdown in various devices.

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