# First principles 3D simulation of tokamak plasma breakdown.

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Plasma breakdown in a tokamak is conventionally treated as a Townsend avalanche process in which the ionisation fraction $f_i$ develops according to a simplified zero-dimensional (0D) model:

$$\frac{1}{f_i}\frac{\mathrm{d}f_i}{\mathrm{d}t} = \alpha V_{De} - \frac{V_{De}}{L}, \tag{1}$$

where $\alpha(E,p)$ is the first Townsend coefficient as a function of the toroidal electric field strength $E$ and gas fill pressure $p$, $V_{De}$ is the electron drift velocity, and $L$ the connection length. This equation describes the balance between increase of charged particles due to ionisation and their loss rate as a function of connection length [1], effectively predicting the duration of breakdown phase for given values of $E$, $p$ and tokamak dimensions. However, the 0D description of the avalanche process neglects many important processes, such as the complex drift motions of electrons in the poloidal plane due to the initial magnetic field geometry, the $\nabla B$ and $E \times B$ drifts and Coulomb collisions.

The goal of the present study is to simulate plasma breakdown with a 3D kinetic model in toroidal geometry. To our knowledge, this is the first attempted simulation to actively track the gyro-resolved charge particle orbits and drift motions under the combined action of the full magnetic, electric fields and collisional effects, thus permitting direct calculation of $V_{De}$, $L$, and $f_i$. Collision events are sampled via Monte Carlo null collision method [2], which employs collision cross section data of $e + H_2$ in elastic scattering, rotational-vibrational ($J = 0 \rightarrow 2$, $v = 0 \rightarrow 1$) excitations, momentum transfer, dissociative and non-dissociative ionisations. Each simulation case is seeded with free electrons at a number density of approximately $9\,\mathrm{m}^{-3}$, evenly distributed in a toroidal breakdown region with major radius of 5.8 m and minor radius of 1.0 m. The simulated tokamak is operating at $E/p$ value of $400\,\mathrm{V\,Torr}^{-1}\,\mathrm{cm}^{-1}$. Electrostatic potentials are computed via a mesh-free Coulomb solver which is a parallel implementation of Barnes-Hut tree traversal algorithm [3].

First results from this new model show that at the first 300 µs, the free electron number density reached $271\,\mathrm{m}^{-3}$ and the normalised growth rate obtained from numerical simulation is ∼22 % higher than the prediction of the simplified model above. This indicates that breakdown phase could last up to milliseconds with observed exponential growth. Moreover, the parallel electron drift velocity is about twice the $V_{De}$ from the 0D model; its poloidal component is also of the same magnitude. Comparison of different collision models [4, 5] demonstrates that the obtained $f_i$ and $V_{De}$ are sensitive to the scatter angle distribution assumed by the models. However, in all cases the computed electron mean connection length is comparable to the previously assumed $L$ [1]. Electron drift motions in the poloidal plane reveal that electrons tend to drift away from the breakdown region where the angular component of the poloidal magnetic field is weak. The immediate challenge is to see how $L$ is affected by self-generated electric and magnetic fields at higher $f_i$, which will introduce Coulomb collisions and formation of closed flux surfaces respectively. Future work will demonstrate how these effects can be implemented in the avalanche regime by extending the tree algorithm to include a systematic particle merging scheme.

[1] P.C. de Vries and Y. Gribov. *Nucl. Fusion* **59**, 096043 (2019). [2] H.R. Skullerud. *J. Phys. D: Appl. Phys.* **1**, 1567 (1968). [3] M. Winkel *et al. Comp. Phys. Comm.* **87**, 179-198 (1995). [4] V. Vahedi and M. Surendra. *Comp. Phys. Comm.* **83**, 880-889 (2012). [5] A. Okhrimovskyy *et al. Phys. Rev. E* **65**, 037402 (2002).