Size matters: ITER breakdown and plasma initiation revisited

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Breakdown and plasma initiation are a well-established part of operations of present day tokamaks and hence, usually gain little interest. As a result, some misconceptions about this first and important stage in a Tokamak discharge exist. This paper revisits a number of key aspects of plasma initiation, aiming to clarify concepts and improve understanding, in view of ITER first plasma operation. The paper will show that size matters and that breakdown and plasma initiation differs in larger devices.

Firstly, breakdown is only a small and short part of the total plasma initiation phase, which also includes the preparation, plasma formation burn through phase and finally the initiation of control. The breakdown phase is usually described by Townsend avalanche discharge physics and its typical characteristics can be used to determine its duration and the level of ionization or plasma current that can be achieved by it [1]. This 0D description neglects the finite size and therefore the self-inductance of the system (initial plasma torus). This paper will show that for a Townsend discharge in a toroidal system of finite size, the system inductances, reduces the internal electric field and slows down the avalanche at high levels of ionization. This effect scales with the system L/R-time and it can be shown that this parameter scales with the size of the torus cross-section. Thus, it is more relevant in larger devices, such as ITER, and should be included in the breakdown study.

Secondly, it is a misconception that breakdown ionises the prefill gas and that burn-through only relates to impurity radiation. The Townsend avalanche only achieves ionization fractions of about 3%. Thereafter, Coulomb collisions dominate and further ionization is achieved by consumption of Ohmic heating. Low-Z impurity line-radiation can indeed, affect this process, but even without it the plasma has to burn-through the ionization of the main species [2]. The paper will show why the main species burn-through will limit the range of possible prefill pressures for Ohmic breakdown, being especially relevant for plasma initiation in a large vessel, such as for ITER first plasma operation.

Thirdly, tokamak plasma initiation at low prefill pressure is thought to increase the chance that the electron energy runs away, forming a highly energetic runaway-electron discharge. The paper will show that the traditional criterion derived from the establishment of a constant electron drift during the Townsend avalanche phase [1] is insufficient to predict the formation of a runaway discharge. The importance to first establish closed-magnetic flux surfaces is stressed, allowing the electrons to be better confined. At this stage, a high current should have been established and Coulomb collisions and plasma physics prevail. Hence, a criterion for the runaway formation during plasma initiation based on the classical critical-electric field balancing generation and losses against the development of the thermal plasma is derived. This criterion depends on the electric field and density at this stage during the plasma initiation, and these are not necessarily the same as the pre-breakdown electric field and prefill pressure.

All these aspects are discussed in view of ITER first plasma operations, which will make use of a toroidal electrical field of only 0.3V/m, aiming to breakdown in a vacuum vessel of 1700m^2, to achieve a minimum 100kA of plasma current. The paper clarifies typical parameters expected for ITER first plasma operations such as the duration of the avalanche and burn-through phase, lasting roughly ~20ms and several 100ms, respectively, and the narrow pre-fill pressure range for Ohmic plasma initiation, between 0.5 and 1mPa.

[1] B. Lloyd, et al., Nucl. Fusion **31** (1991) 2031.
[2] H.T. Kim and A.C.C. Sips, Nuclear Fusion **53** (2013) 083024.