

## Size matters: ITER breakdown and plasma initiation revisited

P.C. de Vries and Y. Gribov

ITER Organization, Route de Vinon sur Verdon, CS 90 046, 13067 St Paul Lez Durance, France

### 1. Introduction

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, provide definitions and improve understanding, in view of ITER First Plasma operation. The paper will show that size matters and that breakdown and plasma initiation differ in larger devices.

### 2. ITER plasma initiation

Breakdown is often used synonymously with the plasma initiation in a tokamak discharge. However it is only a short stage of the *plasma initiation phase*. The purpose of the plasma initiation is to ionize the prefill gas, or to create plasma, to confine it with the tokamak magnetic field configuration, and to achieve the control over it [1,2].

A possible ITER plasma initiation scenario is sketched in figure 1. It starts with (A) the preparation, when currents in the 6 poloidal field (PF) coils and in the central solenoid (CS) are ramped-up and the vacuum vessel is pre-filled with gas, (B) the development of the electric field by primarily discharging the CS, PF1 and PF6, (C) optionally pre-ionize by Electron Cyclotron (ECH) waves, (D) the breakdown or avalanche phase, requiring a small poloidal stray magnetic field in the breakdown region, (E) closed flux-surface formation, (F) plasma formation, (G) burn through and (H) the initiation of control. The order of phases E, F and G may differ depending on the detailed development of the plasma parameters. The time when the CS is discharged is chosen as  $t = 0$ s.

Size matters and the ITER plasma initiation differs from that in smaller devices, by the large size vacuum vessel and its thick conducting walls. The gas valves are positioned far ( $\sim 30$  m) from the vessel; it takes time for the gas to reach the vessel. Moreover, the pressure equilibration over the vessel volume ( $\sim 1000-1700$  m<sup>3</sup>) may take several 100 ms. Although this is not a requirement for breakdown, unevenly spread gas could complicate the measurement of the prefill pressure needed for comparison with modelling.

For small devices, with thin walls, the electric field develops near instantaneous, thus phase (B) is short. The vessel at ITER has an inductance of  $L_v \approx 5$   $\mu$ H and a resistance of  $R_v \approx 8$   $\mu$  $\Omega$ . Thus the toroidal electric and poloidal magnetic field inside the vessel develop on the order of the vessel L/R-time ( $\sim 0.6$  s). In figure 1, an electric field of  $E = 0.3$  V/m (or loop voltage  $V_{loop} \sim 11$  V) establishes in  $\sim 0.8$  s at which breakdown takes place. In the absence of plasma current, during phase (B), a large current of  $V_{loop}/R_v \sim 1.5$  MA is induced in the vessel. The PF and CS coils should provide a magnetic configuration that facilitates breakdown and then provides required stable equilibrium of the plasma with increasing current. The magnetic configuration is affected by the vessel current dynamics complicating the timing of the breakdown.

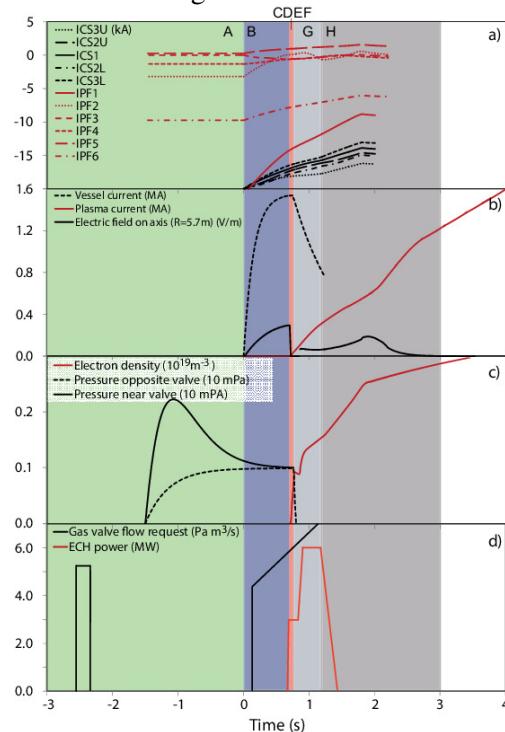


Fig. 1: A sketch of a typical ITER plasma initiation a) the currents in the central solenoid (CS) and poloidal field coils (PF), b) the current induced in the vessel, toroidal electric field and plasma current, c) the pressure at two locations in the vessel and electron density, d) the applied opening of the gas valve and ECH.

### 3. Ohmic breakdown in large tokamaks

The Ohmic breakdown phase is usually described by Townsend avalanche discharge physics. It can be used to determine the breakdown development; its duration and the level of ionization or current that can be achieved by it [1,2]. These features depend on the toroidal electric field,  $E$ , the prefill gas pressure,  $p$ , and the connection length,  $L$ , i.e. the length of the magnetic field lines from wall-to-wall, depending on the ratio of the toroidal magnetic field and the small poloidal stray-field,  $B_\perp$ . The 0D description of the avalanche process [1,2] neglects the finite size and therefore the system inductance (initial plasma torus),  $L_p$ . The system current,  $I$ , should obey the circuit equation:

$$V_{loop} = 2\pi R_o E = I \cdot R_p + L_p \cdot \dot{I} \quad (1)$$

Here,  $R_p$  is the resistance of the avalanche discharge inversely proportional with the ionization fraction and  $R_o$  the major radius. For a finite size system, part of the work of the CS is converted in the generation of the external poloidal magnetic field hence the internal electric field,  $E_{INT}$ , that drives the avalanche is reduced. The circuit equation can be rewritten as:

$$E = E_{INT} \left[ 1 + \frac{L_p}{R_p} \frac{\dot{I}}{I} \right] \quad (2)$$

During the avalanche the current growth rate depends on  $E_{INT}$ ,  $p$  and  $L$  [1,2]. The avalanching system  $L/R$ -time scales as  $L_p/R_p \sim a^2$  (a being the minor radius) and hence this effect increases for larger devices, as shown in figure 2. For ITER the internal voltage reduces towards the minimum electric field for an avalanche breakdown to develop,  $E_{min}$  [1], hence the avalanche process slows down, as shown in figure 3.

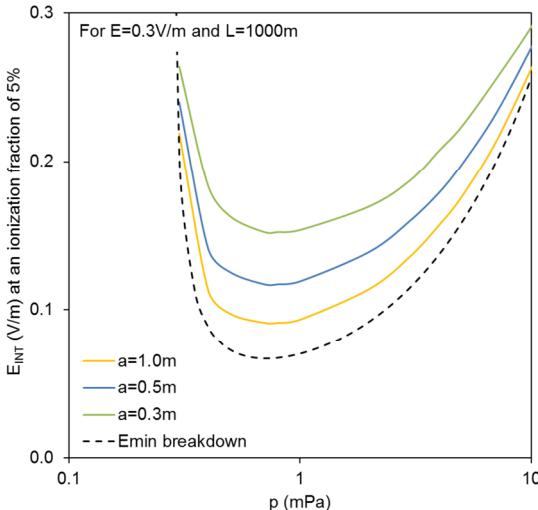


Fig. 2:  $E_{INT}$  as a function of the  $p$ , for a given  $E = 0.3$  V/m and connection length  $L = 1000$  m, for 3 different plasmas with minor radius  $a = 0.3$ ,  $0.5$  and  $1.0$  m and major radius  $R_o = 1.6$ ,  $2.9$  and  $5.8$  m. The dashed line gives  $E_{min}$  for avalanche breakdown.

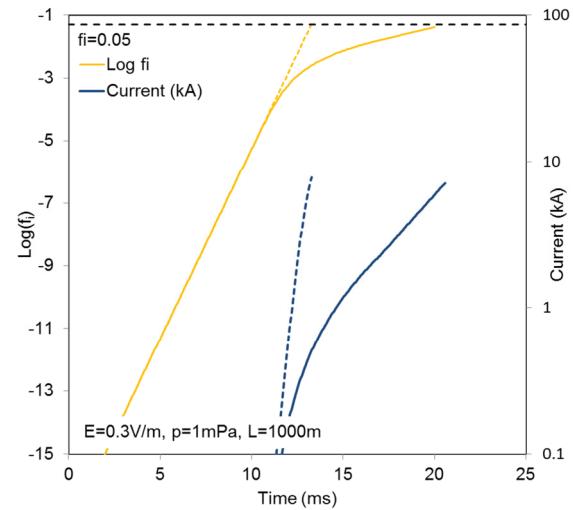


Fig. 3: The temporal development of the ionization fraction,  $f_i$ , and current for an ITER-avalanche ( $R_o = 5.8$  m,  $a = 1.6$  m), up to  $f_i = 0.05$  showing the slow-down at the end of the avalanche process. The dashed lines show the exponential development for  $L_p = 0$ .

### 3. Main-species burn-through

It is a misconception that breakdown ionises the prefill gas and that burn-through only relates to impurity radiation. If 3% gas has been ionized (at current of  $\sim 10$  kA as shown in figure 3), Coulomb collisions start to dominate, the avalanche process stops and plasma is formed. Further ionization is achieved by consumption of Ohmic heating by the plasma. Low-Z impurity line-radiation losses affect this process, but even without them the plasma has to burn-through the ionization of the main species [3]. Main species burn-through is achieved when the Ohmic power exceeds the ionization:

$$\frac{E_{INT}^2}{\eta} > W_{ion} \frac{dn_e}{dt} \sim W_{ion} \cdot S \cdot n_n \cdot n_e - losses \quad (3)$$

Here,  $\eta$  is the plasma resistivity,  $W_{ion}$  the energy to ionize,  $S$  the ionization rate coefficient,  $n_n$ ,  $n_e$  the neutral and electron densities. The latter can be simplistically expressed in terms of prefill particle density,  $n = p/k_B \cdot T$  (for a prefill gas of  $T \sim 400$  K), and ionization fraction,  $F_i$  (i.e. fraction of all prefill particles in the vessel that have been ionized). No other particle sources or sinks are considered here. For H<sub>2</sub> or D<sub>2</sub> particles:  $n_n = n \cdot (1 - F_i)$  and  $n_e = 2 \cdot n \cdot F_i \cdot V_v / V_p$  (i.e. 2 electrons per H<sub>2</sub>). The electron density is a factor  $V_v / V_p$ , larger because electrons only reside inside the plasma volume  $V_p$ , while neutrals fill the vessel volume  $V_v$ . For simplicity neutral screening by the plasma is neglected here [3]. Neglecting losses, the above power balance can be rewritten as:

$$E_{INT}^2 > 2 W_{ion} \cdot S \cdot \eta \cdot (1 - F_i) \cdot F_i \cdot \frac{p^2}{(k_B T)^2} \frac{V_v}{V_p} \quad \rightarrow \quad E_{INT} > 86 p \sqrt{\frac{V_v}{V_p}} \quad (4)$$

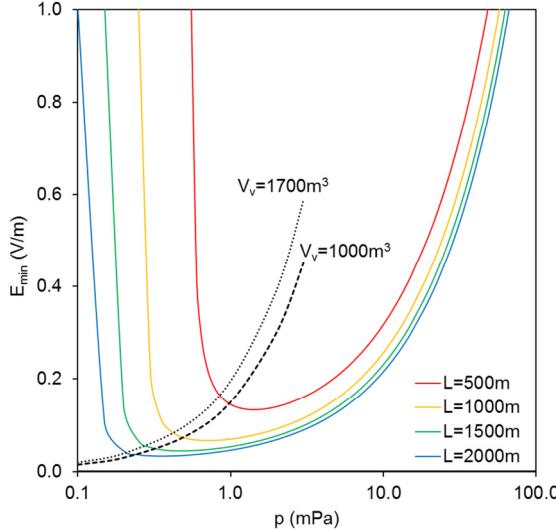


Fig. 4: The H<sub>2</sub> or D<sub>2</sub> main-species burn-through criterion for two different values of  $V_v = 1700 \text{ m}^3$  and  $1000 \text{ m}^3$  (i.e. for ITER First Plasma operations and after the installation of the ITER blanket, respectively), and  $V_p \sim 300 \text{ m}^3$ . The minimum electric field  $E_{min}$  for an avalanche breakdown is shown for values of different  $L$ .

The ionization power peaks at  $f_i = 0.5$  at which main-species burn-through is achieved. An electron temperature of  $\sim 5$  eV, determines the Spitzer resistivity,  $\eta$  and  $S$  ( $\sim 1 \cdot 10^{15} \text{ m}^2/\text{s}$ ), and assuming  $W_{ion} = 20$  eV, the main-species criterion on the right can be derived.

The criterion shows that for a given (internal) electric field the maximum possible prefill pressure is limited, depending on the assumed size of the plasma with respect to the vessel volume. In figure 4, The criterion is shown for two different vessel volumes, together with the minimum electric fields for a Townsend-avalanche. The ITER prefill pressure range is limited by the main-species burn-through and of the order  $\sim 2$  mPa. For ITER first plasma operation, when the blanket is absent and  $V_v$  larger, the pressure range is even smaller. Adding impurity radiation losses to the power balance would reduce it further [3,4], while auxiliary heating may extend it [3].

## 5. Start-up runaway electrons

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. This process is often simplistically linked to the possible free acceleration of electrons during the avalanche process at too high  $E/p$  [2]. But allowing some electrons to accelerate does not yet make a runaway discharge. The conditions for the formation a runaway discharge, i.e. when a sufficient number of highly energetic electrons dominate the discharge behaviour, are more complex [5]. It is best to first properly define such discharges and then look how these may develop.

A runaway discharge can be defined as a plasma with a negligible electrical resistance and a high streaming parameter,  $\xi$ , i.e. the ratio between electron drift velocity,  $u_e = j/e n_e$  and the thermal velocity,  $v_{th}$  [5]. The Spitzer-Härm approximation for a thermal plasma is  $\xi \ll 1$ , while for a runaway discharge it was found empirically that,  $\xi > 0.2$  [5]. Note that a Townsend avalanche in H<sub>2</sub> has  $\xi > 0.2$  if  $E/p > 33$  and thus can be regarded as non-thermal but it thermalizes as soon as Coulomb collisions start to dominate.  $\xi$  is proportional to  $I_p/n_e$ , a ratio used to empirically classify start-up runaway discharges [5]. Moreover,  $\xi \sim 5E/E_D$ , where  $E_D$  is the Dreicer electric field above which the bulk of the electrons, in a fully ionized plasma, can freely accelerate. ITER will have to use low prefill pressure and thus operate a low  $n_e$ , (i.e. high  $E/E_D$ ) thus increasing the probability to generate a runaway discharge.

For a runaway discharge to develop,  $\xi$  should increase in time. The growth of the energetic electron population is determined by the capability to accelerate *and* confine them. The latter aspect

is often forgotten and relevant during start-up. The formation of closed flux surfaces and small enough drift orbits with respect to the vessel size are important for these particles to reach high energy. Note that, free electron acceleration while magnetic field lines are still open ( $L = 1000$  m), would for  $E = 0.3$  V/m only be able to reach energies of  $E \cdot L \sim 300$  eV. Thus a runaway discharge could only develop, if the current has increased enough such that its poloidal field overcomes the stray-field, depending on the device size,  $a$ , as  $\mu_0 I / 2\pi a > B_\perp$ .

The maximum runaway growth, or increase in  $I_{RE}$  and  $n_{RE}$ , is limited by the provided flux:

$$\frac{V_{loop}}{L_p} > \frac{dI_{RE}}{dt} = \frac{I_{RE}}{n_{RE}} \frac{dn_{RE}}{dt} \quad (5)$$

The actual growth of the supra-thermal electron population is affected by collisional drag. It is important to consider all possible of collisions. For a partly ionized gas, Coulomb collisions may dominate at low energy but the drag on higher energy electrons due to ionizing collisions with neutrals can be significant. For plasma initiation, with partly ionized plasmas, this will reduce the growth rate as long as neutrals are present. Note, that this does not mean that neutrals will not avoid a runaway discharge formation. Neutral screening, when the neutral mean-free-path,  $\lambda_{mfp}$ , becomes shorter than  $a$ , will make the core opaque to neutrals, diminishing the neutral drag. In this case, runaway electron growth rates for fully ionized plasmas can be used for the core region. This happens at lower density in larger devices, but at ITER one needs at least  $p > 1\text{-}2$  mPa.

Finally the growth of the energetic tail should exceed the growth of the thermal population. The latter is significant, during the plasma formation, and  $\xi \propto I/n_e$  is expected to decrease. A runaway discharge will develop when:

$$\frac{1}{\xi} \frac{d\xi}{dt} = \frac{1}{I} \frac{dI}{dt} - \frac{1}{n_e} \frac{dn_e}{dt} > 0 \quad (6)$$

Where  $I = I_{RE} + I_p$ . Thus a runaway discharge forms, when the runaway growth,  $dI/dt$  is fast, and the increase in thermal electron density,  $n_e$ , stalls, for example (see eq. (3)) due to failure to burn-through or reduction of neutrals to ionize (e.g. if the recycling coefficient is below unity [6]). These processes should all be included in the modelling of start-up runaways [6].

## 6. Conclusions

All these aspects are discussed in view of ITER First Plasma operations, which will make use of a toroidal electrical field of only 0.3 V/m, aiming to breakdown in a vacuum vessel of 1700 m<sup>3</sup>, to achieve a minimum 100 kA of plasma current during more than 0.1 s. To obtain a self-consistent picture, ITER plasma initiation scenarios can be simulated [4]. In this paper, individual aspects are explained, to get a better understanding of the simulation results. ITER will have a large conducting vessel, that takes long to fill with the right pressure, and slows down the built up of the electric field, induces a large vessel current and yields a dynamic poloidal magnetic field configuration. The large  $L/R$ -time of the ITER avalanche discharge reduces the internal electric field and slows down initial breakdown process. EC wave ionization will be able to assist this process. ITER plasma initiation will have to use a (very) narrow prefill pressure range between 0.5 and 1 mPa of which the upper limit is determined by the burn-through criteria. It means ITER plasma initiation develops at a low density. Auxiliary heating could help increasing this range. Only a qualitative picture of start-up runaways discharge development exists. This differs from the process after disruptions and a dedicated model is needed to improve ITER predictions.

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