Simulation of run-away electron trajectories during current ramp-down and ramp-up in ISTTOK AC discharges

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1. Introduction

Runaway electrons (REs) represent a fraction of the plasma current in tokamaks that can evolve to a formation of an electron beam which can impact with the inner wall elements of the vessel and cause damage potentially interrupting operations for relatively long times. It is expected that in fusion grade devices (i.e. ITER, DEMO) with long time discharges (minutes to hours) the formation of REs is unavoidable. Therefore, study of REs formation, their trajectories inside the chamber and interaction with the plasma are extremely important and are conducted in large extend in the fusion community.

ISTTOK is a small tokamak with large aspect ratio (A=5.4) and circular cross section with major radius R = 0.46 m, minor radius r = 0.085 m, toroidal magnetic field B ~ 0.46-0.48 T, central electron temperature T_e ~ 30-150 eV, average density <n> ~ 4 - 6.5×10^{18} m^{-3} and plasma current Ip = 4-6 kA. It operates in Alternating Current (AC) mode with period of around 50 ms and it is characterized by having a significant population of REs during flat-top [1] and during AC transition [2]. The present work builds upon the investigation [2] of the role of REs in contributing for the AC discharge quiescent plasma phase. The quiescent plasma phase corresponds to the time lapse during AC transition when the plasma current is zero (Ip=0) for which a plasma average density of about 20% - 25% of the plateau density (4E18m-3) is observed. Several authors attribute the existence of such residual plasma to the formation of an anti-parallel current appearing during the vanishing of the previous current half-cycle. The justification is attributed to the time the inversion electric field would take to penetrate the initial half-cycle current when its reversed. The inverted V_{loop} would start to drive an opposite current before penetrating all pre-existing current channel. In support of this scenario, most AC experiments report a finite value of Vloop during the current transition (Ip=0). This electric field drives the formation of an anti-parallel current while keeping the total Ip=0. However, in ISTTOK AC discharges no signature of formation of anti-parallel currents was found (within experimental errors) as V_{loop} is always null when Ip = 0. A complementary mechanism is proposed for the existence of the quiescent plasma. The quiescent plasma drive is attributed to ballistic runaway electrons´ coming from the first half-cycle and penetrating into the subsequent opposite half-cycle. These fast electrons will seed the background gas with primary electrons via collisions with neutrals.

In order to investigate if this is a plausible hypothesis one needs to verify: (i) if the REs can survive from one cycle to the next one during the AC transition (i.e. not colliding with the in-vessel wall), (ii) if they can deposit their energy in the plasma by collisions with neutrals – used for seeding secondary electrons and (iii) the fraction of REs that can be formed during the AC plasma conditions.

For investigating the trajectories of REs a numerical code was used (based on Boris pusher) that accounts for all the vacuum fields of ISTTOK and for the plasma current profile evolution, j, (in cylindrical approximation). In order to search the most favorable energy group of REs that can deposit their energy into the quiescent plasma a RE model was used based on the work of Knoepfel [3]. It is the combination of possible AC transit trajectories (depending on RE energy and j profile) and the effectiveness in depositing energy in the background plasma/gas mixture that would determine the energy range and radial positions of REs that are most-likely to contribute for the quiescent plasma (with typical temperature, T_e ~ 5-10 eV).

2. RE generation and damping

Runaway electrons are produced mainly from the tail of the Maxwellian distribution for which the total resulting collisional force $F_{col} = mu\nu_{col.}$ (u electron velocity and $\nu_{col.}$ the plasma collision frequency) produced by the plasma collisional force, F_p, and the neutrals collisional force, F_m, is lower than the induced electric field force eE ($E = V_{loop} / 2\pi R = 1.73E\text{-}2$ V/cm). Being in this condition the tail electrons start to be continuously accelerated by the inductive electric field.

The plasma collisional force is dependent on the electron velocity, the plasma density and Coulomb factor ln(Λ). For ISTTOK plasma parameters with $Z_{eff} \sim 2$ and regarding the velocity ratio to thermal velocity $\xi = u/u_{th}$ these relations can be written as,

$$\langle F_p \rangle = mu\; 3.6 \frac{n_e}{10^9} \left(\frac{10^3}{0.5\, mu^2} \right)^{3/2} \times \frac{ln(\Lambda)}{15} \times Z_{eff}$$

(s^{-1}, cm^{-3}, eV, kg)

$$ln(\Lambda) = 23 - ln\left[\left(\frac{n_e}{10^3} \right)^{1/2} \left(10^{-4} \times T_e\right)^{-3/2} \right]$$

(cm^{-3}, eV)

The collisional molecular force is computed from $\langle F_p \rangle$ and by the momentum transfer cross-section relation $<F_m> = Q_m/Q_p \times F_p$ each given by,

$$Q_m \cong \frac{2 \times 10^{-12}}{\sqrt{W}\left(750 + W^{3/2}\right)} \;\; ; \; Q_p \cong 1.5 \times 10^{-12}\, W^{-2}$$

(cm^2, eV)

with n_e the electron density, T_e the electron temperature, m the electron mass and W the fast electron energy. It is useful to define the critical energy W_c and the critical velocity u_c as the energy/velocity from which the electric force becomes larger than the collisional force, $eE = F_{col.}(u = u_c)$.Using the explicit collision frequency expression,

$$u_c^2 = \frac{4\pi e^3 n_e ln(\Lambda_c)}{mE} \; and \; W_c = \frac{1}{2} m u_c^2$$

Similarly, the critical field E_c is defined as the balance between electric force and the collisional force for the Maxwellian bulk distribution characterized by v_{th},

$$E_c = \frac{4\pi e^3 n_e ln(\Lambda_c)}{m v_{th}^2}$$

with the units defined above. For induced electric field values above this critical field the bulk electrons will enter the runway condition. In table 1 are presented the values of such parameters computed for a few average density and temperature values representative of the ISTTOK AC transition (from flat top to quiescent plasma conditions).

Table 1 – Representative values during AC transition using Knoepfel model

n_e (m-3)	T_e (eV)	ln(Λ)	u_c (m/s)	W_c (eV)	E_c (V/cm)	ξ_e = u_c/v_th
7.00E+17	5	1.29E+01	4.95E+06	69.75	0.4827	5.28
1.20E+18	10	1.37E+01	6.68E+06	126.70	0.4384	5.03
2.00E+18	15	1.41E+01	8.73E+06	216.60	0.4996	5.37
3.00E+18	20	1.43E+01	1.08E+07	330.19	0.5712	5.75
3.50E+18	25	1.45E+01	1.17E+07	392.17	0.5427	5.60
4.00E+18	30	1.47E+01	1.26E+07	454.56	0.5242	5.50
4.50E+18	35	1.49E+01	1.35E+07	517.36	0.5114	5.44