Effects of dust on plasma discharges during tokamaks start-up phase

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1. Introduction and motivation.

Recent investigations have proved the existence of magnetic dust in tokamaks [1–3] Dust in tokamaks has been widely investigated [4], but magnetic dust can be mobilized in the vacuum vessel by the external magnetic field *before* and during the start-up stage of discharges. Recently in FTU [5] the presence of an estimated average dust density of $2-30\times10^{-3}$ cm^{-3} *before the start-up phase was documented.* The impact on tokamaks operations of flying dust, during the plasma breakdown phase, could be summarized in essentially three phases: i) perturbing the breakdown phase of discharges; ii) affecting the current ramp-up phase; iii) terminating the discharge due to the dust vaporization. In this paper we focus our attention on the first two mechanisms. This investigation could be important in the perspective of using steel components and RAFM materials in ITER and future fusion power plants [6].

2. Breakdown in presence of trace dust

The breakdown phase of discharges in tokamaks in presence of trace dust has been extensively described in [5, 7]; in this paper we summarize the general concepts and results. The classical Townsend model [8] can be extended to a plasma discharge considering a simplified 1 D steady state momentum balance and continuity equations [5] for electrons and isolated dust particles:

$$-eE - m_e\left(\nu_{en}+\nu_{ed}\right)u_e \simeq 0, \qquad u_e\frac{dN_e}{dx} = N_e(\nu_{ion}-\nu_{rec}) - N_e\overline{\nu}_{d,e} - N_e\nu_{loss} \tag{1}$$

where m_e, u_e and N_e are the electron mass, drift velocity, and density; E the applied electric field; ν_{en} and ν_{ed} are the electron-neutral and electron-dust collision frequencies; $\overline{\nu}_{d,e}$ is the frequency of absorption of electrons on dust; ν_{ion} and ν_{rec} are the ionization and recombination rates (ν_{rec} can be neglected in this case); and $\nu_{loss} \propto 1/L_{Loss}(N_d)$ represents the electrons loss rate caused by drift effects due to the multipolar magnetic field scale length at breakdown. It should be noted that $\overline{\nu}_{d,e} = N_d < \sigma_{e,d}v >$ and ν_{loss} depend on the dust density N_d [5, 7]. The effect of dust is to deplete the free electron available for the avalanche and it appears as a sink and friction mechanism in the above equations (1). In this model, the first Townsend avalanche ionization coefficient and the electron capture coefficient are represented, respectively, by: $\alpha(v) = N_n < \sigma_{ion}v >/u_e$ and $\beta(v) = N_d < \sigma_{e,d}v > /u_e$, where N_n is the neutral density; σ_{ion} and $\sigma_{e,d}$ the ionization and the electron-dust impact cross sections. Estimating u_e from the momentum equation (1), and the cross sections from ref. 69 in [5], it is possible obtain the two coefficients $\alpha(E,p_g) = Ap_g\exp(-Bp_g/E)$ and $\beta(E,N_d) \approx \overline{\nu}_{d,e}/(\mu_e E)$, where μ_e is the electron mobility, p_g is the gas pressure, and A and B the appropriate Paschen coefficients. In the tokamaks environment considered here, very different from the Townsend d.c. discharge between two electrodes, a more realistic model is that of the formation of localized 'streaming' space charge [8, 9], in a transient non-uniform applied field. Extending this criterion, the effective breakdown condition depending on the dust density through $L_{Loss}(N_d)$ is expressed by: $\alpha(E,p_g)-\beta(E,N_d) = 1/L_{Loss}(N_d)$. Fig.1a shows a plot of the effective avalanche rate for a constant pressure $p_g = 5\times10^{-3}$Pa and two values of dust densities and lengths $L_{Loss}(N_d)$, with $A \simeq 1.91\,\mathrm{Pa}^{-1}\mathrm{m}^{-1}$, $B \simeq 25.97\,\mathrm{V\,Pa}^{-1}\mathrm{m}^{-1}$ coefficients estimated for a FTU case study [5]. The intercepts with the E axis show the existence of a critical field (or loop voltage) below which the discharge does not grow in presence of dust.

3. Current ramp-up and transition to inductive discharge

The current evolution ideally occurs in three stages: the breakdown-avalanche stage, the ramp-up stage with non-linear decrease of the resistance, depending on temperature and Z_{eff}, and the flat-top regime, generally feedback controlled. In this phase with constant I and temperature the response to the loop voltage is essentially linear again. We consider the problem of the transition from the avalanche discharge to the inductive current rise, aiming at determining the value of the typical time constant and the scaling with the main parameters of the early discharge state [10]. These parameters depend on the condition of the avalanche (Meek-Pedersen condition) and on the discharge resistance which depends on the impurity content. The mechanisms retarding or inhibiting the discharge are embodied in the breakdown time constant τ_b, which does not depend on the impurity densities but on the electron "attachment" rate to dust, acting as an "extraneous body". In the Meek-Pedersen avalanche process the current grows exponentially as $I_{av}(t) = I_0(e^{\frac{t}{\tau_b}} - 1)$, where the effective avalanche rate is $\tau_b^{-1} = (\alpha(N_d) - \beta(N_d))u_e$. The rise of the current depends on the type of applied loop voltage waveform, ranging from simple primary circuit breaking to feedback control of the current or the rate of rise: the different operation leads to different matching conditions with the initial, "spontaneous" avalanche phase. In a lumped parameters description, the evolution of the plasma current in the inductive phase I_{ind} is governed by the circuit nonlinear equation for the plasma loop, inductively coupled to the transformer primary circuit.

$$L\frac{dI}{dt} + R_{p0}(Z_{eff})\big(\frac{T_0}{T}\big)^{\frac{3}{2}} I = V\big(t\big) \qquad (2)$$

where L is the discharge self-inductance and $R_p = R_{p0}(Z_{eff})\big(\frac{T_0}{T}\big)^{\frac{3}{2}}$ the plasma resistance associated with a matching condition with the avalanche current $I_{av}(t)$ at some time $t = t_m$. The avalanche value of the current can be estimated adapting the Townsend model [8], indicated as $I_0 \propto 0.5 n_0 e u_e$, where n_0 is the gas density.

Nonlinear Circuit Equation. Physical insight is gained by applying a dimensional argument to a simplified energy balance with lumped effective loss and Ohmic heating input expressed through the plasma resistivity $\eta \propto Z_{eff} ln\Lambda T^{-3/2} = \eta_0\big(\frac{T_0}{T}\big)^{\frac{3}{2}}$ obtaining the scaling of the discharge temperature with current. We consider $\frac{dNT}{dt} = \eta_0\big(\frac{T_0}{T}\big)^{\frac{3}{2}}\frac{I^2}{S^2} - \frac{NT}{\tau_E}$ where L and S are the (a priori) varying discharge self-inductance and cross section, and τ_E is an effective energy loss (confinement) time scale which during the current pinch development cannot be longer than the (single) particles confinement time, of the order of the drift time in the multipolar field. Then one obtains $\big(\frac{T_0}{T}\big)^{\frac{3}{2}} \equiv I_{T_0}^{\frac{6}{5}} I^{-\frac{6}{5}}$ where $I_{T_0} = \big(\frac{N_{e0}T_{e0}}{\eta_0\tau_E}\big)^{1/2} S$, a scaling parameter which *must* be considered adjustable, given the uncertainty of the early discharge cross section S and energy confinement time. Consequently R_p is a function of $\big(\frac{I_{T_0}}{I}\big)^{\frac{6}{5}}$, which for numerical evaluation is conveniently expressed by the smooth transition expression $R_p = R_{p0}\left(1 + (\frac{I}{I_{T_0}})^{\frac{6}{5}}\right)^{-1}$. The inductive-resistive stage of the current evolution is then governed by the single nonlinear equation

$$\frac{dI}{dt} + \frac{R_{p0}(Z_{eff})}{L}\left[1 + (I/I_{T_0})^{\frac{6}{5}}\right]^{-1} I = \frac{V\big(t\big)}{L} \qquad (3)$$

The self consistent expression of the resistance limits the influence of errors and uncertainties of other quantities, such as T, N, S, τ_E confining them in a single *fitting* parameter I_{T_0}. The effect of the Meek-Pedersen avalanche process is contained in the breakdown time scale τ_b and in the delay time scale t_m to be determined. The first avalanche stage is followed, after the matching time t_m, by the nonlinear inductive current rise with a possible reduction of the current plateau value. It should be noticed that an increase of dust density could be sufficient to quench the start-up. In this stage, where T_e is constant and very low, a perturbation of plasma resistivity due to dust atoms can be estimated from the amount of impurity atoms vaporized by plasma. The total Fe atoms carried by magnetic dust of $50-1000\,\mu$m of diameter with a density of $N_d \approx 10^{-3}$ grains/cm^3 is about $10^{12}-10^{16}$ at/cm^3. If only 1% of the total dust material is vaporized by plasma heat load, the impurity concentration become comparable to the plasma density leading to a rising of Z_{eff} and to the plasma resistivity. An increase of resistivity actually accelerates the transformer driven electric field penetration, but the consumption of the stored magnetic flux is mainly resistive leading to limitation of the plateau current.

Linear approach. From the breakdown stage the current at some time point must match the inductive stage. The matching conditions represent different choices in the tokamak operation. To gain insight it is useful to address first the linear version of eq.3, which, associated with a sufficiently realistic waveform of the loop voltage, has an exact solution. Consider the model waveform and the linear circuit equation $V(t) = V_0[e^{-t/\tau_v}+\phi_0]$, $\frac{dI}{dt} = -\frac{I(t)}{\tau_R} + \frac{V(t)}{L}$. It is convenient to use the notation $U_0 = V_0/L$, $\tau_R = L/R_{p0}$, $\gamma = 1/\tau_R$, $\gamma_b = 1/\tau_b$, $\gamma_v = 1/\tau_v$, $V_0\phi_0 = V_\infty = R_0 I_\infty$. Rewriting the equation as $U(t) = U_0 e^{-\gamma_v t} + \gamma I_\infty$, the formal solutions for the inductive current and the avalanche current are

$$I_{ind}(t) = Be^{-\gamma(t-t_m)} + \frac{U_0\phi_0}{\gamma}(1-e^{-\gamma(t-t_m)}) + \frac{U_0 e^{-\gamma_v t_m}}{\gamma_v-\gamma}\left[e^{-\gamma(t-t_m)} - e^{-\gamma_v(t-t_m)}\right], \ \ t > t_m \quad (4)$$

$$I_{av}(t) = A\left[e^{\gamma_b t}-1\right], \ \ 0 < t < t_m \quad (5)$$

where $B = I_0$ and t_m is the time of matching of the two currents (4) and (5), the Townsend avalanche current [8]. In absence of dust a purely inductive discharge, would grow from zero to a value eventually reaching the avalanche value. Imposing a certain current rate U_0 leads to match the two expressions of the current $I_{ind}(t_m) = I_{av}(t_m)$ at some time t_m, solution of $\frac{U_0}{\gamma_v-\gamma}\left[e^{-\gamma t_m} - e^{-\gamma_v t_m}\right] = A\left[e^{\gamma_b t_m}-1\right]$. After the breakdown delay, the current ramps up with the rate prescribed by U_0, possibly within a feedback loop not considered now. Another interesting scenario results in the delay of the discharge ramp-up and reduction of the flat top, when no loop voltage control is applied. The current evolution described by eq.4 in this case is associated with the conditions of smooth matching of the current and its derivative: $I_{ind}(t_m) = I_{av}(t_m)$, $\frac{dI_{ind}}{dt}\mid_{t_m} = \frac{dI_{av}}{dt}\mid_{t_m}$. The matching time is slightly different time t_m and the ramp rate is not imposed.

Nonlinear approach. For the nonlinear case one can keep similar matching conditions. In the first case of sharp matching of the avalanche current with the inductive one, the matching applies to the linearized version at $t < t_m$, and after t_m the current ramp is described by the numerical solution of eq.3. For the case of smooth matching corresponding to the exact solution of eq. of the linear problem we introduce the notation $z = e^{\gamma_b t_m} \geq 1$ and $g = z/(z-1)$; from the matching conditions, replacing, for simplicity, $U_0[e^{-\gamma_v t_m}+\phi_0]$ with a constant $\overline{U}_0$, an expression for g is obtained. Using $B = I_0 = I(t_m)$, and $\overline{\gamma} = \frac{1}{\tau_R}\left[\frac{I_{T_0}}{I_0}\right]^{6/5}$, after some algebra one gets $g = \frac{\overline{V}_0\tau_b}{LI_0} - \frac{\tau_b}{\tau_R}\left[\frac{I_{T_0}}{I_0}\right]^{6/5}$. The dependence of the matching time t_m on the main physical parameters to leading order in γ_v, is

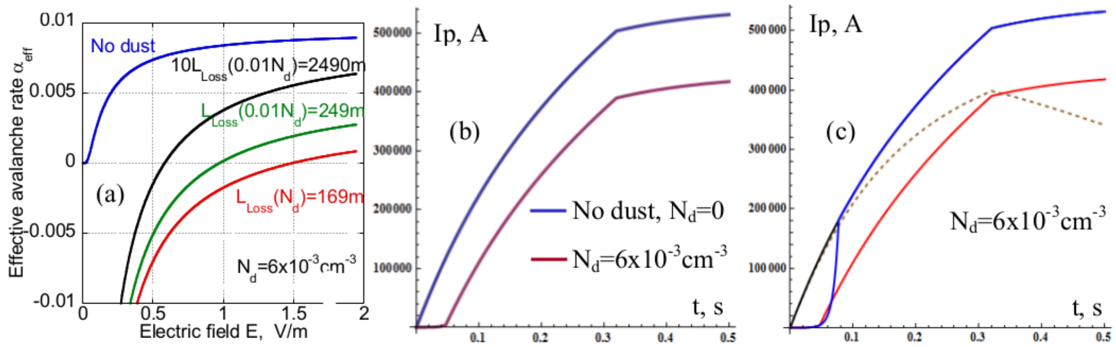

FIG. 1: (a) Effective avalanche rate $\alpha_{eff} = \alpha - \beta - 1/L_{Loss}$ vs. E at constant p_g for different values of $L_{Loss}(N_d)$. The blue line is $\alpha(E, p_g)$ *without dust effect*. (b) $I_p(t)$ with the non linear model with smooth transition, thermally evolving R_p and transition from the early Townsend avalanche stage $I_{av}(t)$ to the inductive one. Blue line, no dust. (c) Comparison of I_p for 3 models: dashed black line, no dust; blue, with dust and sharp transition from avalanche to inductive phase; red, with dust and smooth transition; dashed brown, linear case without dust.

then: $t_m = \tau_b ln[(C_V \frac{\tau_R}{\tau_b} - C_I)] - ln[(C_V \frac{\tau_R}{\tau_b} - C_I - \frac{\tau_R}{\tau_b}]$. However actually $C_V = \frac{\overline{V}_0 \tau_b}{L I_0}$, $C_I = \left[\frac{I_{T_0}}{I_0}\right]^{6/5}$ are *constants* which should be considered as adjustable parameters, given the uncertainties of the values of $I_0, I_{T_0}, \overline{V}_0, L, \tau_R, \tau_b$. Therefore the time t_m is a multiple K of the breakdown time τ_b. The nonlinear solution for this scenario is shown in Fig.1b. The behaviour displayed in (Fig.1c) reproduces well the experimental cases of *driven* recovery of the discharge after a hesitation, normally due to difficulties in "burn-through", associated to massive presence of light impurities. In the present case the hesitation and delay in take-off is due to a *totally different mechanism*: the subtraction of avalanche electrons by a sufficient density of dust particles as they charge up [11].

4. Summary of theoretical results.

Breakdown phase. Electron attachment to dust changes the conditions for gas breakdown and avalanche rate. A severe reduction of the effective avalanche rate could result in a delay, up to few 100s ms, in the plasma current ramp-up phase.

Plasma resistivity. Dust can increase Z_{eff}, by the release of impurities (Fe). In the flat-top stage where I and T are $\simeq$ constant, the behaviour is again linear, and for a given loop voltage the flat top current is reduced by an increase of $R_p \propto Z_{eff}$. The importance of this dust effect on tokamaks operations depends of course on the amount of dust presents in each discharge. The possible presence of magnetic dust in future devices should not be disregarded. ITER and future plants [12] will be equipped with superconductive coils that require low loop voltage for plasma initiation. Our discussion shows that because of dust, breakdown and ramp-up could require larger loop voltage, in contrast to technical constraints for these devices.

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