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**ABSTRACT.**
Key aspects of physics for plasma burn-through in tokamaks are investigated with DYON code, modelling the plasma formation during the initiation phase of tokamak discharge. The simulation results are explained with the Radiation and Ionization Barrier (RIB) and the Critical Degree of Ionization $\gamma(t_{RIB})$, obtained by an analytical derivation. The required electric field for plasma burn-through, the burn-through criterion, is compared to the Townsend Avalanche Criterion, and the resultant operation space available for plasma formation in Joint European Torus (JET) is presented.

## 1. Introduction

Tokamak start-up consists of the plasma break-down phase, the plasma burn-through phase, and the ramp-up phase of plasma current $I_p$ [1].

The Townsend avalanche theory[2][3] is generally used to calculate the required electric field for plasma break-down at a given prefill gas pressure and effective connection length as shown below,

$$E \geq \frac{1.25 \times 10^4 p}{\ln(510 p L_f)}, \tag{1.1}$$

where $L_f$ and $p$ are the effective connection length along the magnetic field lines and the prefill gas pressure of the vacuum vessel, respectively. The required electric field for plasma break-down in International Thermonuclear Experimental Reactor (ITER) has also been calculated with the Townsend criterion in [1].

However, the Townsend avalanche theory is not sufficient to explain non-sustained break-down discharges where $I_p$ does not increase as it specifies the condition for electron avalanche. In order for $I_p$ to increase, sufficient ionization of prefill gas(deuterium), the plasma burn-through, is necessary. Otherwise, most heating power is lost through radiation and ionizations of the remaining neutrals, so that it prevents electron temperature from increasing in the $I_p$ ramp-up phase[2].

The required loop voltage for plasma burn-through, the burn-through criterion, is generally higher than that for plasma break-down in present tokamaks[1]. Therefore, when designing a new device or determining the operation space, the burn-through criterion must be considered as well as the Townsend criterion. In 2009, more than 100 shots in Joint European Torus (JET) failed during the burn-through phase. These start-up failures can be prevented by understanding key physics aspects of the burn-through phase.

Furthermore, for ITER start-up, due to the engineering issues resulting from the use of superconducting central solenoid coils and a continuous vacuum vessel, the allowable toroidal electric field is limited up to $0.35[V/m]$ [4]. Tokamak start-up using a low electric field limits the operation space available of prefill gas pressure, magnetic error fields, and impurity content[5]. For reliable start-up using a low electric field, ECH-assisted start-up is planned in ITER[4]. The required ECH power can be estimated by understanding the burn-through conditions (or requirements).

Despite the increasing importance of the burn-through criterion, the theoretical investigation has not been published extensively since the complicated plasma surface interaction during the burn-through phase makes a theoretical approach difficult. For the sake of simplicity, uniform temperature and density (0D treatment) and pure deuterium plasma (no impurity) are assumed to investigate the criterion for plasma burn-through. Under the given assumptions, the key aspects of physics determining whether $I_p$ increases are investigated using the DYON code[6] in section 2, and the Radiation and Ionization Barrier(RIB) and the critical degree of ionization $\gamma(t_{RIB})$, determining the criterion for plasma burn-through, are derived in section 3. In section 4, the effects of prefill gas pressure and impurities on plasma burn-through are investigated, and the criterion for plasma burn-through in JET, computed with the DYON code, are compared to the Townsend Avalanche Criterion. Section 5 provides conclusions.

## 2. Conditions for Plasma Current Ramp-up

The DYON code[6], a new plasma burn-through model, has been used for the numerical calculations presented in this article. The plasma parameters assumed in the simulation are given in Table 1. The initial degree of ionization is calculated to be 0.002 according to [6][7]. In order to simulate both successful $I_p$ ramp-up and failure cases, two different prefill gas pressures are assumed, $5 \times 10^{-5}[Torr]$(Success), and $7 \times 10^{-5}[Torr]$(Failure) as shown in Figures 1, 2, and 4.

The plasma current $I_p$ can be calculated with the circuit equation

$$I_p = \frac{1}{R_p}(V_l - L_p \frac{dI_p}{dt}) \tag{2.1}$$

where $R_p$, $V_l$, and $L_p$ are the plasma resistance, the loop voltage, and the plasma inductance, respectively. In order for $I_p$ to increase for a given $V_l$, which is approximately constant in the $I_p$ ramp-up phase, $R_p$ must be decreasing. According to Spitzer resistivity, $R_p$ decreases with increasing electron temperature $T_e$[8], i.e. $R_p \propto T_e^{-\frac{3}{2}}$. Therefore,

$$\frac{dT_e}{dt} > 0 \tag{2.2}$$

is a necessary condition for $I_p$ ramp-up.

Whether or not $T_e$ increases is determined by the equation of electron energy balance,

$$P_e = \frac{3}{2}\frac{d(n_e e T_e)}{dt} = \frac{3}{2} e T_e \frac{dn_e}{dt} + \frac{3}{2} e n_e \frac{dT_e}{dt}, \tag{2.3}$$

where $P_e$ is the net electron heating power, determined by the ohmic heating power $P_{Oh}$ and the total electron power loss $P_{Loss}$, i.e. $P_e = P_{Oh} - P_{Loss}$. As separated into the two terms in Equation (2.3), the net electron heating power $P_e$ is consumed by increasing $n_e$ or $T_e$, i.e. $\frac{3}{2} e T_e \frac{dn_e}{dt}$ or $\frac{3}{2} e n_e \frac{dT_e}{dt}$.

Figure 1(a) describes the simulation result of the power consumption for successful $I_p$ ramp-up(blue) and failed(red), and Figure 1(b) indicates the corresponding plasma

currents. As shown, $P_e$ is positive for the successful case, and goes to zero in the failed case during the $I_p$ ramp-up phase. Whereas the power consumed by the increasing $n_e$(chain lines) is dominant in the burn-through phase, it is small enough to be ignored in the $I_p$ ramp-up phase as shown in Figure 1(a). Therefore, $P_e$ in the $I_p$ ramp-up phase can be approximated to be $P_e \approx \frac{3}{2} e n_e \frac{dT_e}{dt}$. Accordingly, in order for $T_e$ increases, $P_e$ must be positive in the $I_p$ ramp-up phase, i.e.

$$P_e > 0. \tag{2.4}$$

In this simulation, the deuterium recycling coefficient $Y_D^D$ is assumed as 1. In the case that $Y_D^D$ is higher than 1, the power consumed by the increasing $n_e$ would be somewhat higher than 0. However, Equation (2.4) is still a necessary condition for the increase in $T_e$ unless the power consumed by the increasing $n_e$ exceeds $P_e$.

Figure 2 shows $P_{Oh}$ and $P_{Loss}$ in the cases of $I_p$ ramp-up success(blue) and failure(red), respectively. In the successful case, $P_{Oh}$(blue solid line) exceeds $P_{Loss}$(blue dashed line), i.e. positive $P_e$ in the $I_p$ ramp-up phase. However, $P_{Oh}$(red solid line) and $P_{Loss}$(red dashed line) are overlapped in the failed case, hence $P_e$ is zero. Figure 2(b), which is enlarged from Figure 2(a), shows that the behaviours of $P_e$ in the burn-through phase are clearly different in the two cases. It should be noted that whether $P_e$ in the $I_p$ ramp-up phase is positive is determined by the change of $P_e$ during the burn-through phase.

## 3. Radiation and Ionization Barrier (RIB) and Critical Degree of Ionization

The total electron power loss, $P_{Loss}$ consists of the three power losses, i.e. radiation and ionization power loss $P_{rad+iz}$, equilibration power loss $P_{equi}$, and convective transport power loss $P^e_{conv}$. They are calculated as shown below[5][6].

$$P_{Loss} = P_{rad+iz} + P_{equi} + P^e_{conv}$$

$$P_{rad+iz} = V_p \times \mathcal{P}_{RI}(T_e) n_e n_D^0 \tag{3.1}$$

$$P_{equi} = V_p \times 7.75 \times 10^{-34} (T_e - T_i) \frac{n_e \ln \Lambda}{T_e^{3/2}} \left(\sum_A \sum_{z \geq 1} \frac{n_A^{z+} z^2}{M_A}\right), \tag{3.2}$$

$$P^e_{conv} = V_p \times \frac{3}{2} \frac{n_e e T_e}{\tau_e}, \tag{3.3}$$

where $n_D^0$ is a deuterium atom density, $n_A^{z+}$ is an ion density of which the electric charge is $z+$, $V_p$ is a plasma volume, $M_A$ is an ion mass in $[amu]$, $\tau_e$ is the electron particle confinement time, and $\mathcal{P}_{RI}(T_e)$ is the power coefficient of radiation and ionization, obtained from ADAS data[9].

In contrast to $P_{equi}$ and $P^e_{conv}$, which are proportional to $n_e$, $P_{rad+iz}$ has the maximum value at a certain degree of ionization since $n_D^0$ decreases as $n_e$ increases. The peak value of $P_{rad+iz}$ is defined as the *Radiation and Ionization Barrier* (RIB), and the degree of ionization at the RIB is defined to be the *Critical Degree of Ionization* for plasma burn-through, $\gamma(t_{RIB})$.

The RIB is of crucial importance since the required $P_{Oh}$ for $I_p$ ramp-up is mainly determined by the RIB. As will be seen, the magnitude of $P_{rad+iz}$ is dominant in $P_{Loss}$ during the burn-through phase. This implies that $P_{Loss}$ has the maximum value at $\gamma(t_{RIB})$. Hence, once the $P_{Oh}$ exceeds the $P_{Loss}$ maximum, $P_{Loss}$ decreases significantly as ionizations proceed. This enables $T_e$ to increase, so that ionizations continue to proceed up to 100%.

In the burn-through phase, the density of deuterium atom $n_D^0(t)$ decreases as ionizations proceed, thereby increasing $n_e(t)$. If the deuterium atom density within a plasma volume decreases, neutral particles flows into the plasma volume from the ex-plasma volume, giving a dynamic fuelling effect. This effect impedes the decrease in neutral density within a plasma volume as much as the ratio of plasma volume to total neutral volume(= Vessel volume $V_V$). The reduction of neutral density in $V_p$ is $\frac{V_p}{V_V} n_e(t)$. Hence, in the case that the deuterium recycling coefficient $Y_D^D$ is 1 without gas pumping and puffing, $n_D^0$ in Equation (3.1) is

$$n_D^0(t) = n_D^0(0) - \frac{V_p}{V_V} n_e(t). \tag{3.4}$$

where $n_D^0(0)$ indicates the initial density of deuterium atom, which is proportional to the prefill gas pressure. By substituting $n_D^0$ in Equation (3.1) with $n_D^0(t)$ in Equation (3.4), $P_{rad+iz}(t)$ can be written as a negative quadric function of $n_e(t)$,

$$\begin{aligned} P_{rad+iz}(t) &= V_p \mathcal{P}_{RI}(T_e) n_e(t) \Big( n_D^0(0) - \frac{V_p}{V_V} n_e(t) \Big) \\ &= V_p \mathcal{P}_{RI}(T_e) \Big( \frac{V_V n_D^0(0)^2}{4V_p} - \frac{V_p}{V_V} (n_e(t) - \frac{V_V n_D^0(0)}{2V_p} \Big)^2 \Big) \end{aligned} \tag{3.5}$$

Therefore, as ionizations proceed, $n_e(t) n_D^0(t)$ varies as shown in Figure 3(a) and has the maximum value,

$$\frac{V_V n_D^0(0)^2}{4V_p} \tag{3.6}$$

when $n_e(t)$ is equal to

$$\frac{V_V n_D^0(0)}{2V_p}. \tag{3.7}$$

The power coefficient $\mathcal{P}_{RI}(T_e)$ is a function of $T_e$ as shown in Figure 4(b). The product of $n_e(t) n_D^0(t)$ and $\mathcal{P}_{RI}(T_e)$ results in the change of $P_{rad+iz}$, thereby the change of $P_{Loss}$ in Figure 2. The increase in $P_{Loss}$ during the $I_p$ ramp-up phase in Figure 2 results from the increase in $\mathcal{P}_{RI}(T_e)$.

The degree of ionization in the burn-through phase can be calculated with

$$\gamma(t) = \frac{n_e(t)}{n_e(t) + n_D^0(t)}. \tag{3.8}$$

The degree of ionization at the RIB, $\gamma(t_{RIB})$, is then obtained by substituting $n_D^0(t)$

and $n_e(t)$ with Equation (3.4) and (3.7) as shown below.

$$\gamma(t_{RIB}) = \frac{\frac{V_v n_d^0(0)}{2V_p}}{\frac{V_V n_d^0(0)}{2V_p} + \left(n_D^0(0) - \frac{V_p \frac{V_v n_d^0(0)}{2V_p}}{V_V}\right)} = \frac{V_V}{V_V + V_p} \tag{3.9}$$

The plasma volume is limited by the vessel volume, i.e. $V_p \leq V_V$. This implies that $\gamma(t_{RIB})$ is always higher than 50%. In the case of JET, where $V_V$ is $100[m^3]$ and initial plasma volume $V_p = 14.8[m^3]$ for a major radius $R = 3[m]$ and minor radius $a = 0.5[m]$, the critical degree of ionzation $\gamma(t_{RIB})$ is 87.1%.

The simulation result of $P_{rad+iz}$ are shown in Figure 4(a). $P_{rad+iz}$ in the successful $I_p$ ramp-up case(blue) has a maximum and decreases abruptly after the peak. This is consistent with Equation (3.5), since $n_e n_D^0$ decreases with increasing $n_e$ after the peak point as shown in Figure 3(a). $P_{rad+iz}$ falls with increasing degree of ionization from $0.08[s]$, $t_{RIB}$, when the critical degree of ionization is achieved. Accordingly, $T_e$ begins to increase from $t_{RIB}$, and the increase becomes steep after $P_{rad+iz}$ falls sufficiently around $0.015[s]$ as shown in Figure 4(c). Because the neutral particles are strong sinks of electron energy, the increase in $T_e$ is impeded until the neutrals are sufficiently ionized.

As shown in Figure 4(b) the degree of ionization in the successful case(blue) approaches 100% over 87.1% which is the $\gamma(t_{RIB})$ calculated using Equation (3.9). On the other hand, the degree of ionization in the failed case does not exceed 87.1%. Hence, $P_{rad+iz}$ does not falls abruptly, and $P_e$ approaches 0, thereby resulting in the failure of the $I_p$ ramp-up.

## 4. Criterion for Plasma Burn-through

### *4.1. Prefill gas pressure effects on RIB*

Figure 5 shows simulation results of (a)plasma current, (b)degree of ionization, and (c)electron power losses for different prefill gas pressures. $I_p$ ramp-up is delayed until almost 100% degree of ionization is achieved at the low prefill gas pressures($1 \times 10^{-5}$, $3\times10^{-5}$, and $5\times10^{-5}[Torr]$), and the delay increases with increasing prefill gas pressures. $I_p$ ramp-up fails at a prefill gas pressure over $7 \times 10^{-5}[Torr]$. This indicates that for a prefill gas pressure of $7\times10^{-5}[Torr]$ and above the given loop voltage is not sufficient to achieve the critical degree of ionization, $\gamma(t_{RIB})$, as shown in Figure 5(b). The critical prefill gas pressure for the plasma burn-through with the given $20[V]$ loop voltage exists between $5 \times 10^{-5}[Torr]$ and $7 \times 10^{-5}[Torr]$.

As shown in Figure 5(b), $I_p$ increases at the low pressures, hence the peak values of $P_{rad+iz}$ shown at the low pressures in Figure 5(c) indicate the RIB, which increases with increasing prefill gas pressure as shown in Figure 5(c). Since neutrals are strong radiators, the larger number of neutrals at a high prefill gas pressure results in higher

$P_{rad}$. In addition, at a high prefill gas pressure, there are more neutrals to be ionized, thereby increasing $P_{iz}$.

The increase in RIB at the high prefill gas pressure can also be seen in Equation (3.5). Equation (3.5) implies that the maximum $P_{rad+iz}(t_{RIB})$ is

$$P_{rad+iz}(t_{RIB}) = \frac{V_V \mathcal{P}_{RI}(T_e) n_D^0(0)^2}{4}. \tag{4.1}$$

As shown in Equation (4.1), $P_{rad+iz}(t_{RIB})$ is proportional to the square of the initial density of deuterium atom $n_D^0(0)$. $n_D^0(0)$ is proportional to the prefill gas pressure $p$, hence $P_{rad+iz}(t_{RIB})$ is also proportional to the square of $p$ under an identical $T_e$ at the $t_{RIB}$. Since $\mathcal{P}_{RI}$ is a function of $T_e$, a numerical calculation is required to calculate $P_{rad+iz}(t_{RIB})$.

In Figure 5(c), $P_{iz+rad}$ is dominant in $P_{Loss}$ during the burn-through phase, and the peak of $P_{Loss}$ coincides with the RIBs. Therefore, the required electric field for plasma burn-through is mainly determined by the $P_{iz+rad}$.

### *4.2. Impurity effects on RIB*

Impurities results in a significant increase in $P_{iz+rad}$ during the plasma burn-through phase. In order to calculate RIB with impurities in the plasma, Plasma Surface Interaction(PSI) effect should be modelled in the numerical calculations.

The DYON code for plasma burn-through in the carbon wall JET has been validated, showing good agreement with the experimental data[6]. For the carbon wall, chemical sputtering is dominant, and the chemical sputtering yield is weakly dependent on the incident ion energy[10]. Hence, the sputtering yields in the carbon wall JET are assumed to be constants. In the case of oxygen ions, they are recycled as a monoxide, $CO$, at the wall with a sputtering yield close to 1[11]. Oxygen sputtering is also included for the carbon wall JET. The details of the sputtering model used in this article are in [6].

The effect of beryllium sputtering due to a deuterium or beryllium ions is important for JET experiments after the ITER-Like Wall(ILW) project where the first wall components are replaced to beryllium. For the beryllium wall, physical sputtering is dominant due to its low threshold energy[12]. A physical sputtering yield is a function of incident ion energy and the formulae have been given in [13],[14].

The Bohdansky formula for physical sputtering yield[13] is given as

$$Y = Q \times S_n(\epsilon) \times g(\delta) \tag{4.2}$$

where $Q$ is yield factor and $S_n$ is nuclear stopping cross-section which is given by

$$S_n = \frac{3.441\sqrt{\epsilon}\ln\epsilon + 2.718}{1 + 6.355\sqrt{\epsilon} + \epsilon(6.882\sqrt{\epsilon} - 1.708)}. \tag{4.3}$$

$\epsilon$ is defined to be $E_0/E_{TF}$ where $E_0$ and $E_{TF}$ are the ion wall-impacting energy and the Thomas-Fermi energy, respectively[13],[14]. The ion wall-impacting energy $E_0$

can be calculated as $2eT_i + 3eT_e$, assuming that ion's energy gain within a sheath is approximately $3eT_e$[15]. The function $g(\delta)$ is defined to be

$$g(\delta) = (1 - \delta^{2/3})(1 - \delta)^2, \tag{4.4}$$

where $\delta$ is defined to be $E_{th}/E_0$[15]. $E_{th}$ indicates the threshold energy for physical sputtering. In the case of a deuterium and a beryllium ion bombardment on a beryllium target, the parameters required to calculate beryllium sputtering yields are given in Table 2. Since beryllium is an effective oxygen getter[8], oxygen should be small enough to ignore in the ILW. Based on this, the oxygen content is assumed to be 0 in the predictive simulations.

The simulation results of the RIB in JET are shown in Figure 6. In the case of the carbon wall, the second peak represents the RIB for carbon burn-through. As can be seen in Figure 6, the RIB for carbon burn-through is critical for $I_p$ ramp-up since it is much higher than the RIB for deuterium burn-through. However, the RIB for beryllium burn-through does not appear. Hence, in the beryllium wall, the RIB for deuterium burn-through is the only RIB to be overcome for $I_p$ ramp-up. This is due to the relatively low atomic number of beryllium, thereby resulting in low power coefficient $\mathcal{P}_{\mathcal{RI}}$ compared to carbon. Furthermore, the physical sputtering yields are also low due to the low $T_e$ during the deuterium burn-through phase. Therefore, the burn-through criterion in the ILW will be reduced compared to the carbon wall experiments.

### *4.3. Criterion for plasma burn-through*

The cyan solid lines in Figure 7 are the minimum electric field for plasma break-down, drawn analytically by using the Townsend criterion in Equation (1.1). The Townsend criterion shows that there is an optimum range of prefill gas pressure where the lowest toroidal electric field is available.

The black, red, and blue solid lines in Figure 7 represent the simulated minimum electric field for plasma burn-through without or with impurities. For the simulation, plasma minor radius is assumed to be $0.9[m]$. Other conditions assumed in the simulation is the same in Table 1. The required electric field for plasma burn-through increases monotonically as prefill gas pressure rises since the RIB is greater at a high prefill gas pressure.

In tokamak experiments, there can be significant impurity influx from the wall[4]. If the Plasma Surface Interaction (PSI) effect is included, the required electric field for plasma burn-through would be higher, thereby reducing the operation space available. As shown in Figure 6, the RIB for carbon burn-through is much greater than for deuterium burn-through. Hence, the required loop voltage in the carbon wall is significantly higher than for pure deuterium plasma. This results in the smaller operation space available in the carbon wall as shown in Figure 7. However, the RIB for beryllium burn-through is not significant as shown in Figure 6, and the RIB for deuterium burn-through is similar with the RIB calculated assuming pure deuterium plasma. This implies less loop voltage would be available for plasma burn-through in

the ILW, i.e. larger operation space available compared to the carbon wall as shown in Figure 7.

The recycling coefficients and the sputtering yields in the carbon wall JET can vary due to the effects of deuterium retention and carbon migration in the wall. In addition, the ratio of the plasma volume to the vessel volume, which is related to dynamic neutral gas fuelling from the ex-plasma volume as shown in Equation (3.4), is also different in each discharge shot. The criterion for plasma burn-through is also appeared to be changed with different conditions in the DYON code, i.e. steeper with higher recycling coefficient(or sputtering yield) or smaller plasma volume.

## CONCLUSION

When determining the tokamak operation condition such as a prefill gas pressure, loop voltage, and magnetic stray field, the Townsend criterion is generally used. However, the Townsend criterion is the condition only for electron avalanche, i.e. the plasma breakdown. In order for $I_p$ to increase, successful burn-through of deuterium and impurities is also necessary.

In this article, key aspects of the physics in the burn-through phase are investigated with the DYON code. The criterion for plasma burn-through is explained with the Radiation and Ionization Barrier(RIB) and the critical degree of ionization $\gamma(t_{RIB})$ obtained through an analytical derivation. Once the critical degree of ionization is achieved, ionization of neutrals can proceed up to 100% degree of ionization, thereby resulting in the increase in Ip. Hence, POh must exceed PLoss maximum at $\gamma(t_{RIB})$.

The $P_{Loss}$ maximum is dominated by the RIB. Since the RIB increases with the increasing prefill gas pressure, the required loop voltage is also high at the high prefill gas pressure. The required electric field for plasma burn-through is calculated by the DYON code, and the operation space available for JET is computed. The limitations set by the burn-through criterion will reduce the operational space with respect to those based on the Townsend criterion for an electron avalanche.

The RIB is significantly affected by plasma surface interaction. According to the simulation results of the DYON code, the PSI effects result in much smaller operation space for the carbon wall than for pure deuterium plasma. However, the RIB in the ILW is not much higher than in pure deuterium plasma. This results in larger operation space available for successful plasma initiation in the ILW than in the carbon wall.

Modelling of the evolution of plasma volume and sophisticated PSI treatments including the effects of deuterium retention and beryllium migration is required for a quantitative computation of the operation space available for ITER start-up.

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| | |
|---|---|
| Initial electron temperure $T_e(0)$ | 1[eV] |
| Initial ion temperature $T_i(0)$ | 0.03[eV] |
| Initial degree of ionization $\gamma$ | 0.002 |
| Deuterium sputtering yield $Y_D^D$ | 1 |
| Plasma major radius $R$ | 3[m] |
| Plasma minor radius $a$ | 0.5[m] |
| Internal inductance $l_i$ | 0.5 |
| Loop voltage $V_l$ | 20[V] |
| Vacuum vessel volume | 100[$m^3$] |

*Table 1: Plasma parameters assumed for the burn-through simulation.*

| Incident ion on Be target | D | Be |
|---|---|---|
| $E_{th}$ [eV] | 9 | 25 |
| $E_{TF}$ [eV] | 282 | 2208 |
| Q | 0.1566 | 0.7517 |

*Table 2: Parameters for beryllium sputtering due to a deuterium or beryllium ion bombardment.*

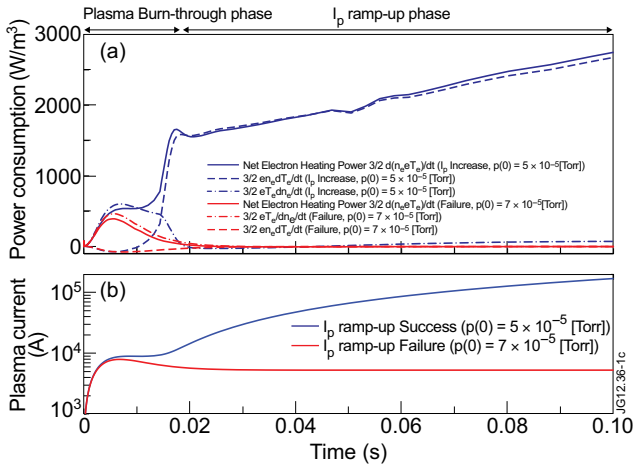


*Figure 1: The colors of lines in (a) and (b) indicate successful $I_p$ ramp-up(blue) and failure(red). The solid lines represent the net electron heating power $P_e$. The dashed lines and the chain lines are the amount of $P_e$ consumed by increasing $T_e$ and increasing $n_e$, respectively. The corresponding plasma currents $I_p$ are represented by the blue solid line ($I_p$ ramp-up) and the red solid line(non sustained break-down) in (b). In order for $I_p$ to increase, $P_e$ must be positive in the $I_p$ ramp-up phase.*

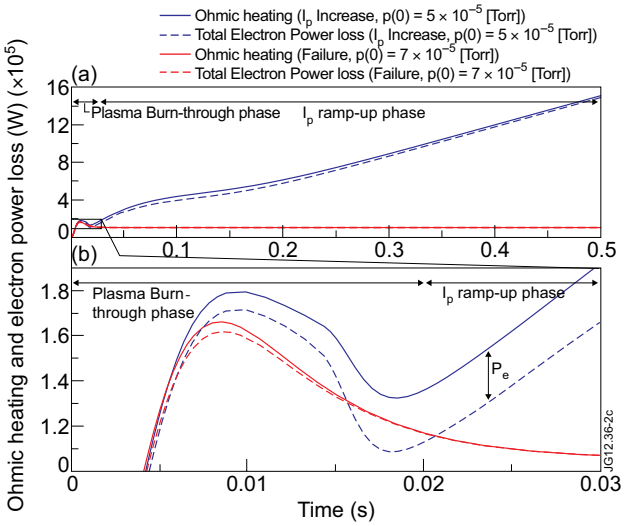


*Figure 2: The solid lines and the dashed lines in (a) show $P_{Oh}$ and $P_{Loss}$ in successful(blue) and failure(red) cases, respectively. (b) is an enlarged figure from the burn-through phase in (a). Whether the net electron heating power is positive in the $I_p$ ramp-up phase is determined in the burn-through phase.*

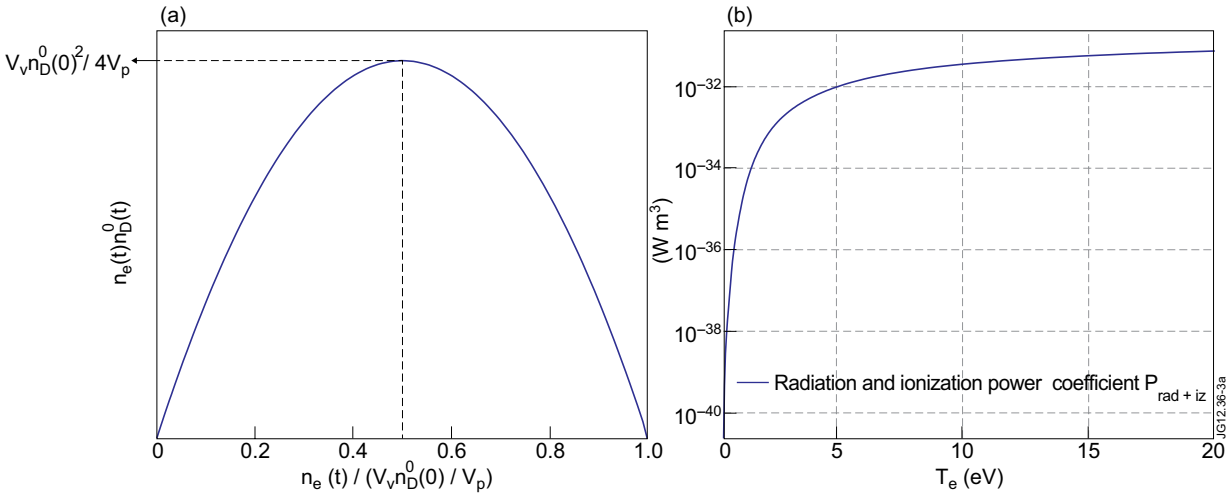


*Figure 3: As shown in (a), $n_e n_D^0$ can be substituted by $n_e(t)(n_D^0(0) - n_e(t))$ in the case of a recycling coefficient (= 1.0). Therefore it has a maximum value as ne(t) approaches Equation (3.7). PRI is strongly dependent only on $T_e$ as shown in (b). The combined term $n_e n_D{}^0 P_{RI}$ behaves as in Figure 4(a).*

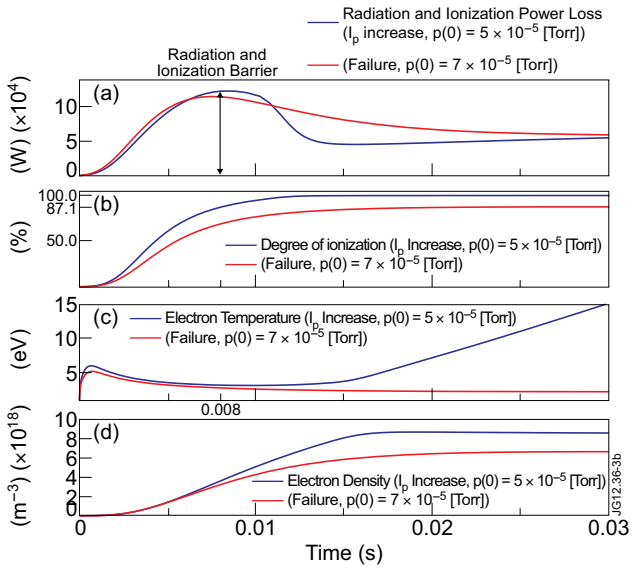


*Figure 4: The blue line and the red line in (a) indicate the case of successful $I_p$ rampup and failed ramp-up, respectively. (a) shows $P_{rad+iz}$. The corresponding degree of ionization is indicated in (b). The critical degree of ionization $\gamma(t_{RIB})$ is 87.1% as calculated using Equation (3.9). Whether or not a degree of ionization can go over $\gamma(t_{RIB})$ is critical for $I_p$ ramp-up. (c) and (d) describes electron temperature and density, respectively.*

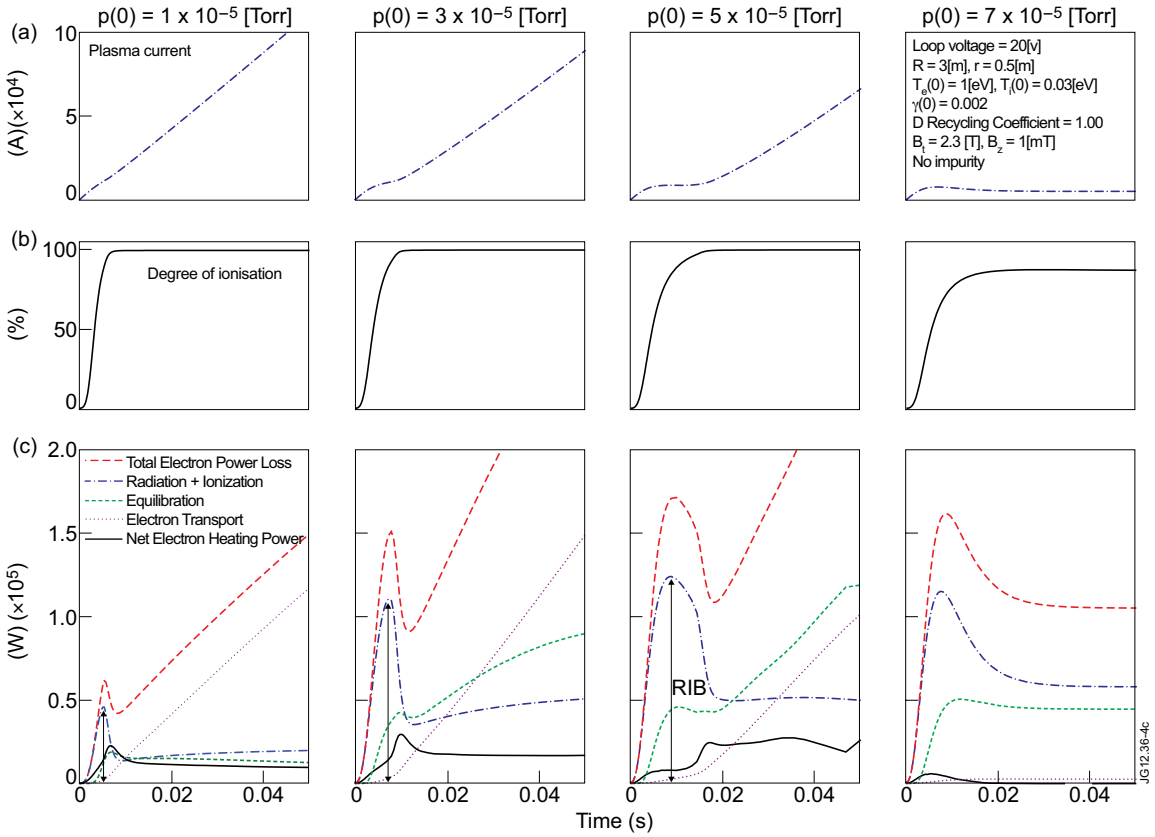


*Figure 5. The figures show (a)the plasma current, (b)the degree of ionization, and (c)various electron power losses at different prefill gas pressures, $1 \times 10^{-5}$, $3 \times 10^{-5}$, $5 \times 10^{-5}$, and $7 \times 10^{-5}$[Torr]. The assumed loop voltage and plasma parameters are shown in Table 1. Under the given condition, a critical prefill gas pressure for $I_p$ rampup exists between $5 \times 10^{-5}$] and $7 \times 10^{-5}$[Torr]. Prefill gases are almost fully ionized in the cases of successful $I_p$ ramp-up while they are not fully ionized in the cases of failure. The colored solid lines in (c) indicate $P_{Loss}$(red), $P_{equi}$(green), $P^{e}_{conv}$(cyan), and $P_{rad+iz}$(blue), respectively. As shown in (c), $P_{rad+iz}$ is dominant in $P_{Loss}$ during the burn-through phase, and its peak values coincide the RIB. The RIB increases with increasing prefill gas pressure. Therefore, The higher the prefill gas pressure, the larger the maximum for PLoss.*

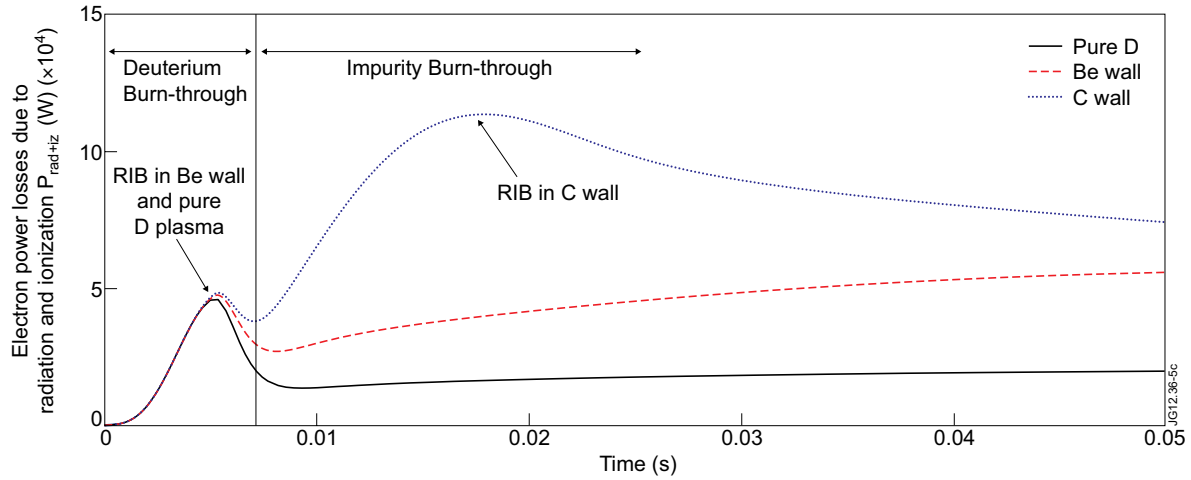


*Figure 6: Each line indicates the radiation and ionnization power losses in carbon wall(blue), beryllium(red), and pure deuterium plasma(black). In the case of carbon wall, the RIB is determined by the second peak, which results from carbon.*

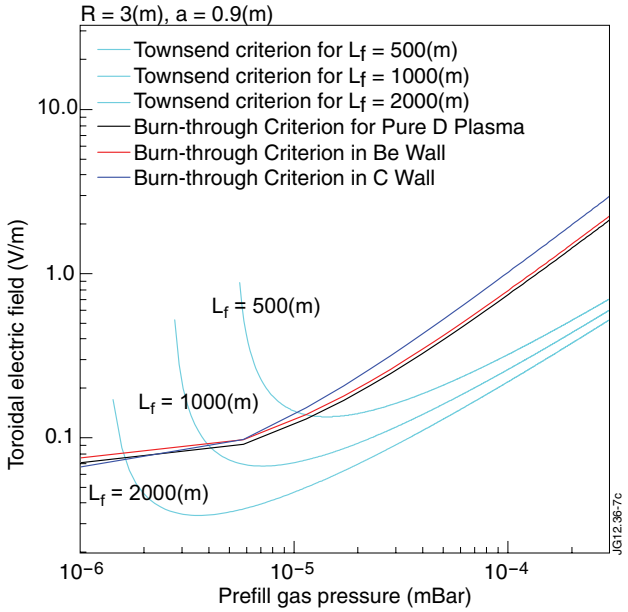


*Figure 7: The cyan solid lines show the Townsend criterion at different effective connection lengths, as indicated with 500, 1000, and 2000[m], respectively. The black, red, and blue solid lines indicate the burn-through criterion, i.e. the minimum electric field for plasma burn-through in the case of pure deuterium plasma(black), beryllium wall(red), and carbon wall(blue), respectively. For the burn-through simulation, the major radius and minor radius of the plasma are assumed to be 3[m] and 0.9[m]. The area above both the burn-through criterion and Townsend criterion represents operation space available for successful start-up in JET.*