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ABSTRACT

In the paper we analyze the generation of the runaway electrons (RE) in multicomponent JET boundary plasmas during a preemptive disruption current quench phase, when considerable amount of Ar is injected into boundary region. The impact of Z_{eff} on the onset of the RE generation as well as on growth rates of primary and secondary REs is considered for multicomponent JET boundary plasmas in CFC and the ITER-like wall (ILW) discharges. Two electron density boundaries can limit the occurrence of the REs depending on concentration of impurities. An upper density limit is related with the increase of friction force at higher densities ("Rosenbluth density limit"). Another limitation could occur due to the excitation of helicon waves by the REs, which prohibits the avalanche development and restricts for given toroidal magnetic field the RE occurrence at low densities ('Helical density limit'). These density boundaries of the RE occurrence as function of impurity concentration are derived. The important role of Z_{eff} on the RE generation in the CFC and metallic JET wall cases may explain the difference in the RE occurrence in both discharges.

1. INTRODUCTION

One of the major drawbacks of the massive gas injection (MGI) as a disruption mitigation technique is the possible generation in plasma the runway electrons (RE) of mega-electronvolt energies carrying several MA of current. These electrons carrying the kinetic and the considerable amount of poloidal magnetic energies and impacting the plasma facing components can potentially pose a serious threat. The REs are triggered by a large electric field arising due to an increase in plasma resistivity at low temperatures. We will show that the RE generation and/or amplification (avalanche conversion) in multicomponent plasmas are very sensitive to the plasma parameters like electric resistivity, the ion charge and ion concentration, plasma temperature and density. The influence of the full – metal JET ITER- Like Wall (JET-ILW) on RE could show up through boundary plasma conditions specific for metal wall case.

The REs at JET are regularly observed during disruptions with carbon plasma facing components (JET- CFC) [1]. Contrarily, for the all-Be metal JET-ILW almost no spontaneous RE beam has been observed during disruptions [2]. In order to study the impact of the JET-ILW on the RE generation process, a parametric study has been carried out to locate the boundary of the RE occurrence domain. Argon MGI has been used to explore the operational space defined by the toroidal field B_t, the fraction of argon in MGI jet and the pre-disruption plasma density n_p [2,3]. It was shown that the boundary location of this space is approximately the same in JET – CFC and JET-ILW [2]. Large Ar concentration c_z, high toroidal field B_t and low density are the best conditions to the RE generation.

It will be shown below that the qualitative agreement with the experimentally observed boundary on the B_t-c_z plane gives the model of the helical wave instability [4] as a mechanism limiting the RE occurrence at low density. At sufficiently high electron density the electric field becomes lower than the critical one (see below) and there is no avalanche multiplication. This limit (Rosenbluth density

[5]) depends on impurity concentration and plasma parameters and defines the upper boundary of the RE location on the n_p-c_z operation plane.

In the case of multicomponent plasmas, it has been recognized that energetic electrons could penetrate through the electronic shell of partly ionized heavy ions thus experiencing a non-Coulomb scattering with the bound electrons as well as a Coulomb scattering with the atomic core [6]. This effect renders qualitatively the same result as high Z_{eff} Coulomb plasmas. Since the generation rate of runaways depends on Z_{eff}, its production during the mitigation of disruptions by massive gas injection could in some cases decrease owing to an Ar impurity concentration. This effect provides a rationale for the hindrance of further RE generation in tokamak plasmas during the mitigation of thermal disruption by MGI.

In this paper we first derive the criteria for the RE occurrence in terms of the Z_{eff} dependence for different impurity concentrations. Then we will assess the density limiting boundaries and the growth rates in multispecies plasmas with C, Be and Ar impurities. Finally, the core effect on the generation suppression will be presented. Based on this analysis we will discuss in conclusion the RE occurrence in JET for different wall conditions.

2. CRITERIA FOR THE RE OCCURRENCE IN MULTICOMPONENT PLASMAS.

The Dreicer mechanism seems to be the primary driver for runaway generation in JET. The minimum electric field E_D required for the thermal electrons to run away can be derived for multispecies plasma as [7]:

$$E_D = \frac{4\pi^3 \Lambda}{T_e} \cdot n_e \cdot \left(1 + \frac{Z_{eff}+1}{\gamma}\right), \tag{1}$$

where Z_{eff} is the effective charge number, $\Lambda(n_e,T_e)$ is the Coulomb logarithm, $\gamma = \mathcal{E}/m_e c^2$ is the relativistic parameter, $\mathcal{E}$ is electron energy. In the brackets of Eq.(II.1), the second term accounts for pitch-angle scattering, which dominates for non-relativistic energies ($\gamma \leq 2$). For highly relativistic energies, however, main contribution comes from the energy exchange in electron-electron collisions. RE formation is expected when the electric field $E \geq 0.01E_D$ [1]. The electric field at given plasma current I_p can be written as $E = I_p/\sigma$, where σ is the electric conductivity. In multicomponent plasma with average charge Z_{eff} [6]

$$(Z_{eff}) = \frac{\sigma_p}{2Z_{eff}} \cdot \left(\frac{2+7Z_{eff}}{3+2Z_{eff}}\right) \cdot f^{-1}(\sigma,\beta,Z_{eff}) \tag{2}$$

where $\sigma_p = 1.96 n_e e^2 \tau_{ep}/m_e$ is the electric conductivity of a fulli ionized hydrogen plasma and $f(\alpha,\beta,Z_{eff})$ is the factor which takes into account the effect of an ion core $f(\alpha,\beta,Z_{eff}) = (1+\alpha\ln(1+9/\beta^2)-\ln(1+25\beta^2)/(2+Z_{eff}))$ for supra-thermal electrons. Parameters α and β are given in [6] and for light impurities vary in the range 0.1-0.4 and 0.2-3 correspondingly. The criterion for the RE occurrence $\eta_D = E / 0.01E_D > 1$ in multicomponent plasmas can be written as:

$$\eta_D(Z_{eff}) = \frac{I_p}{\sigma_0 S}\cdot\left(\frac{15}{\Lambda}\right)\left\{\frac{2Z_{eff}}{\left(2+Z_{eff}\right)}\cdot\left(\frac{3+2Z_{eff}}{2+7Z_{eff}}\right)\cdot\frac{f(\ ,\ ,Z_{eff})}{(1+C_zZ(T_e))}\right\}\frac{1}{n_p\sqrt{T_e}} \qquad (3)$$

where I_p is the plasma current before CQ in A, S is the poloidal cross-section in m^2, n_p is the density of protons in m^{-3}, T_e is the electron density in eV, $\sigma_0 = 1.2\ 10^3\ (15/\Lambda(n_e,T_e)$ in simens/m and $\Lambda(n,T)$=14.7--$\ln(\sqrt{n_{20}}m^{-3}/T_{e,\ keV})$. As it is seen from (3) both, higher temperature and higher density lead to a decrease in η for constant plasma current. In the case of impurity influx the rise in electron density $n_e = n_p(1+c_z*Z(T))$ and the drop in the electron temperature T_e due to ionization and radiation are expected. In the case of CFC wall the temperate drop is stronger than in the case of Be metallic wall for the same amount of impurity influx (carbon for CFC and beryllium for ILW) due to stronger radiative capability of carbon. In the case of Ar influx the RE occurrence depends on amount of ionized impurities $c_z = n_{Ar+}/n_p$. Fig.1–4 show the ratio of the fields η_D as a function of impurity concentration c_z for argon, beryllium and carbon impurities. The effective charge state in the case only one impurity species as a function of T_e and c_z is $Z_{eff}(T_e, c_z) = (1+c_zZ(T))/(1+c_zZ(T))$ (see Fig.1) , where $Z(T_e)$ is the average charge state as a function of electron temperature calculated for different species on the bases of average–ion model [8]. The ratio of the electric fields vs different impurity concentration is shown in Figs (2, 3 and 4). It is seen that for Beryllium $\eta_D < 1$ and remains independent on amount of Be influx, whereas for carbon and argon impurities one can expect the REs under some plasma conditions (the electron temperatures and proton densities).

3. DENSITY LIMITING BOUNDARIES LOCATING THE RE OCCURRENCE

We consider here two mechanisms limiting the secondary RE occurrence in multicomponent plasmas. First is related to the increase of the drag force due to the increase of the electron density. At, so-called Rosenbluth density the critical electric field is higher or equal to the toroidal field in the plasma, $E \le E_c$, where $E_c = E_D\ T_e/mc^2$. The electric field in the plasma scales inverse proportional to electric conductivity $E = I_p/S\sigma$, therefore the upper density limit for the RE occurrence can be written as

$$n_e(m^{-3}) > n_R \equiv \frac{I_p(A)}{k\cdot S(m^2)\cdot\sigma\ (Z_{eff},c_z)}\ \xi_Z\cdot c_Z\cdot n_p\,(m^{-3}) \qquad (4)$$

where ξ_z is the atomic number of impurity ions, c_z is the impurity concentration, n_p is the proton density and $k = 5.2\ 10^{-22}\ m^2 Volt$ [9]. Dependence on the average charge Z_{eff} appears from the electrical conductivity (see (2)). The inequality (4) indicates the maximum density above which the REs are not generated. In Fig.5 the limiting Rosenbluth density is plotted as a function of Ar concentration for the different electron temperatures. The low temperature the high the critical boundary above which no generation occurs.

There is another boundary which limits the RT occurrence at low plasma density. It was shown that the helicon-waves can be destabilized by secondary RE. These waves cause rapid pitch-angle scattering and isotropization of the RE in velocity space thus prohibiting an avalanche occurrence.

This destabilization occurs when the toroidal magnetic field B_t is less than some critical value, which is inverse proportional to density [4] $B_t < j_{re}T_e^{3/2}/n_eZ_{eff}$. This gives the low limit on density n_H (‘Helical density limit’), below which the RE avalance denervation is prohibited

$$n_H(m^{-3}) < \frac{4.2\cdot 10^{11}}{S_{re}(m^2)}\cdot\frac{I_{re}(A)}{B(T)}\cdot\frac{T^{3/2}(eV)}{Z_{eff}(T,c_z)}, \tag{5}$$

Here $j_{re}=I_{re}/S_{re}$ is the RE current density, S_{re} is the cross-section of the RE beam. This model limits the RE occurrence at low density and is in a qualitative agreement with the experimentally observed boundary on the B_t-c_z plane. Figure 6 shows the bride band below which no REs where observed in JET ILW experiment with Ar injection. The red line corresponds to the maximum B_t values for given Ar concentration which indicate the upper boundary for RE suppression due to helical waves instability. The higher Ar concentration the lower B_t limit is foreseen. The RE beam cross section S_{re}~4cm^2 has been chosen to fit the experimental boundary. Figure 7 shows the RE occurrence in operation n_H-c_z plane at given B_t. It is seen that with increase of Ar influx the generation of the secondary RE occurs at lower densities, and this density limit becomes lower at higher B_t. In terms of density boundaries, the RE exist in the range of densities $n_H < n < n_D$ at densities above the Rosenbluth density and below the densities, when the Helical waves become unstable. Operation domain in the (n-c_z) plane has shown in Fig. 8 for the JET-CFC case. Calculations show that for the electron boundary temperatures about 100eV the RE occur at any concentration of impurities and in a broad range of the line average density which is only limited by Rosenbluth density, which lies higher above the line average density (see dashed line). This is consistent with experimental observation. At lower temperature ≤ 50eV REs occurrence is restricted at low densities by the ‘Helical density limit’ and the REs can be generated for Ar concentration above ~ 17%.

4. REDUCTION OF RE GROWTH RATES AT HIGHER Z_{EFF} IN MULTICOMPONENT PLASMAS

The growth rates of primary and secondary RE strongly depend on ion charge state and in general drop when Z_{eff} increase. Much stronger reduction occurs, however, for another reason, namely, due to a non-Coulomb nature of the RE collisions with the heavy impurity ions [6]. The RE can penetrate deep into the electron shell of partly ionized ions like Ar, for which reason they scattered by a positive charge effectively larger than that of a shielded nucleus. This effect increases the Coulomb cross section and can be treated via an effective ion charge Z_{eff} (ε_{kin}) that depends on the kinetic energy of the incident electrons ε_{kin}. The increase of effective charge number with increasing electron energy in multi-component plasmas renders qualitatively the same result as high Z_{eff} Coulomb plasmas. Since the generation rate of runaways depends on Z_{eff}, its production during the mitigation of disruptions by massive gas injection could in some cases decrease owing to a heavy impurity concentration in the boundary tokamak plasma. As shown in [6,10] the energy dependent effective charge state in multicomponent plasmas with one ion species reads as

$$Z_{eff}(\varepsilon)=Z_{eff}(0)\cdot\left[1+\alpha\ln\left(1+\frac{\varepsilon^2}{\beta^2 T_e^2}\right)\right], \qquad (6)$$

where ε is ε_{kin} normalized on electron temperature, Te and the parameters α and β are the same as in (2) and can be found in [6,10]:

$$\beta_I=\frac{6}{T_{e[eV]}}\left(\frac{\sqrt{\xi_I}}{1-A}\right)^{4/3}, \qquad \alpha_I=\frac{(\xi_I^2-Z_I^2)}{4Z_{eff}(0)\lambda}\frac{n_I}{n_e} \qquad (7)$$

where ξ_I is the atomic number of impurity ion. Here n_I and Z_I are the most representative impurity ion density and charge state for a given temperature T_e . The representative argon, beryllium and carbon charge states Z_I as a function of the electron temperature are taken from [8].

The growth rate of primary RE depends exponentially on Z_{eff}. Replacing Z_{eff} by $Z_{eff}(\varepsilon)$ one can write

$$\gamma(\varepsilon)\equiv\frac{\partial\ln n_e}{\partial t}\propto\frac{E_D}{E}^{3(1+Z_{eff}(\varepsilon))/16}.\exp\left\{-\sqrt{(Z_{eff}(\varepsilon)-1)\frac{E_D}{E}}\right\} \qquad (8)$$

Although the dependence of $Z_{eff}(\varepsilon)$ on ε is logarithmic, the growth rate strongly decreases with increasing ε, because of exponential dependence in (8). In Fig 9 the growth rate of primary RE (normalized to $\gamma(\varepsilon=0)$) is shown as a function of the incident RE energy for different values of the electric field E / E_D. A strong reduction is observed for high energies and vor small E/E_D values.

The population of secondary RE arises due to multiplication of energetic electrons by close Coulomb collisions with plasma electrons when the electric field exceeds some critical value $E\geq E_{crit}$. The growth rate of secondary RE can be written as [1]:

$$\gamma(\varepsilon)\propto\eta^{-\frac{3}{16}(1+Z_{eff}(\varepsilon))}.\exp\left\{\frac{1}{4\eta}-\sqrt{(Z_{eff}(\varepsilon)-1)/\eta}\right\} \qquad (9)$$

where $\eta\equiv E/E_{crit}$ *and* $E_{crit}=4\pi e^3\ln\Lambda n_e^*/mc^2$, n_e^* is the electron density of bound and free electrons and $F(\eta,\varepsilon)=\{1-1/\eta+6(Z_{eff}(\varepsilon)-1)^2/(\eta^2+7.2)(Z_{eff}(\varepsilon)+5)\}^{-1/2}$ [10]. The dependence of the RE production rate (9) on ε is shown in Fig.11. It confirms a significant drop in secondary electrons production as a result of non-Coulomb collisions.

CONCLUSIONS

1) During the disruption electron densities, temperatures and impurity content strongly affect the occurrence of the RE in JET plasmas. The influx of C or Ar impurities lowers the electron temperature and increases Z_{eff} which, at given current, increases the electric loop voltage and brings about the RE occurrence. In the case of metallic ILW the radiative capability of Be impurities is not sufficient to trigger the RE generation unless the external Ar impurities are injected for disruption mitigating reasons. For the temperature drop due to radiative cooling

lowers the primary RE generation criteria of the RE generation. Higher T_e and n_e lead to a decrease in E/0.01ED for constant plasma current

2) In multicomponent plasmas Z_{eff} is an important parameter which strongly influences the RE generation rates and boundaries of the RE occurrence. The absence of spontaneous RE occurrence for metallic wall is likely related to the difference in Z_{eff} due to different impurity content in JET-ILW and in JET-C.
3) Operation boundary for the MGI-induced REs in terms of B_t versus Ar concentration, derived on the bases of helical waves instability fits the JET experimental observations.
4) The REs are suppressed above the "Rosenbluth density" and below the "Helical density". This defines the operational domain in terms of density and impurity concentration, etc. where the RE can be expected. Further justification of these boundaries, derived on the basis of physics models with the JET experimental observation will be performed.

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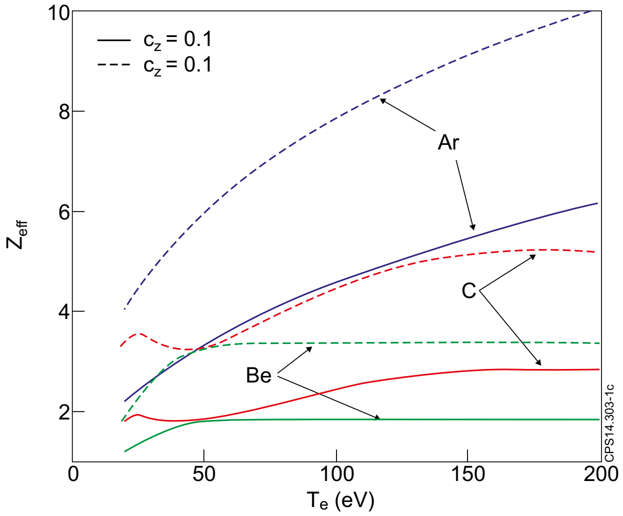


Figure 1: Z_{eff} dependence on the electron temperature for different species calculated from the average-ion model [8] vs impurity concentration. Z_{eff} for C and particularly for Ar impurities is higher than for Be at any electron temperature.

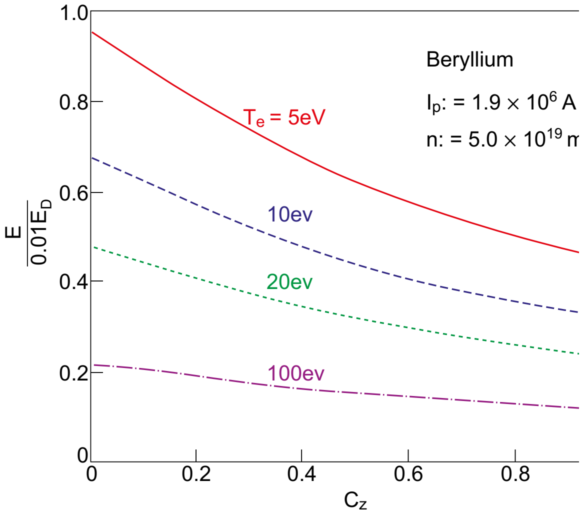
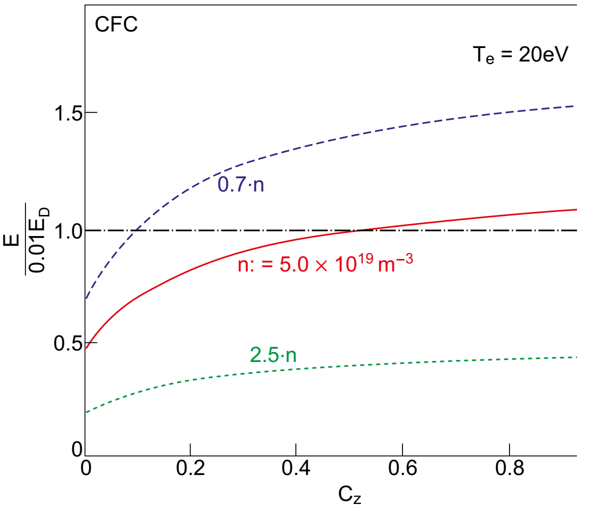


Figure 2: The ratio of the electric fields $E/0.01E_D$ versus concentration of Be in JET ILW discharge plasmas, n is the line average electron density, T_e is the electron temperature in CQ phase. No REs are generated because $E<0.01E_D$ for entire range of Be concentration and the expected electron temperatures.



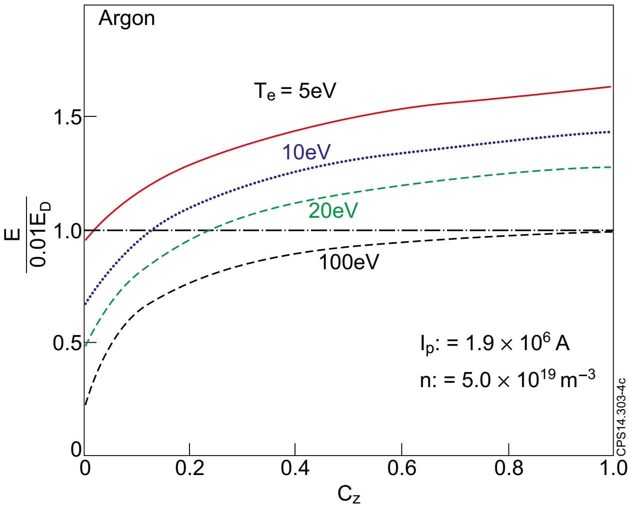


Figure 3: The same as in Fig.2 for JET CFC discharges for different carbon concentration and the electron temperatures. The RE can be trigged at densities high than $5 \cdot 10^{19}$ m^{-3} for the electron temperature of 20eV.

Figure 4: The same as in Fig.2 with Argon injected in the JET ILW Pulse No: 85948. The less concentration of Ar is required at higher temperatures for the RE onset.

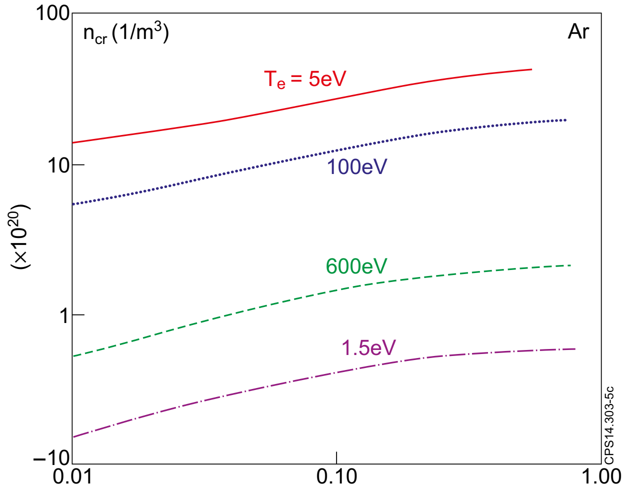


Figure 5: The limiting Rosenbluth density is plotted as a function of Ar concentration for the different electron temperatures.

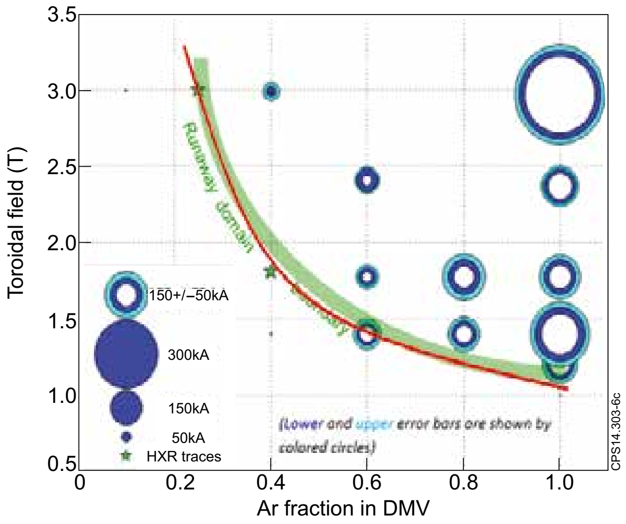


Figure 6: The experimentally observed boundary (brite band) which separates the range with and without RE on the B_t-c_z plane for ILW discharges with Ar injection fits with the theory prediction (red curve) for the RE beam cross section of about S_{re}~ 4cm^2 . Large c_z, high toroidal field B_t and low density n_e are the best conditions to generate RE.

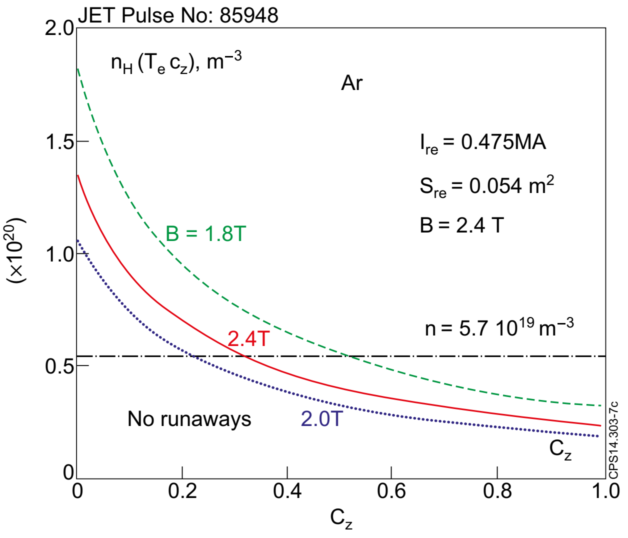


Figure 7: The low density boundary ('Helical density limit') vs. Ar concentration.

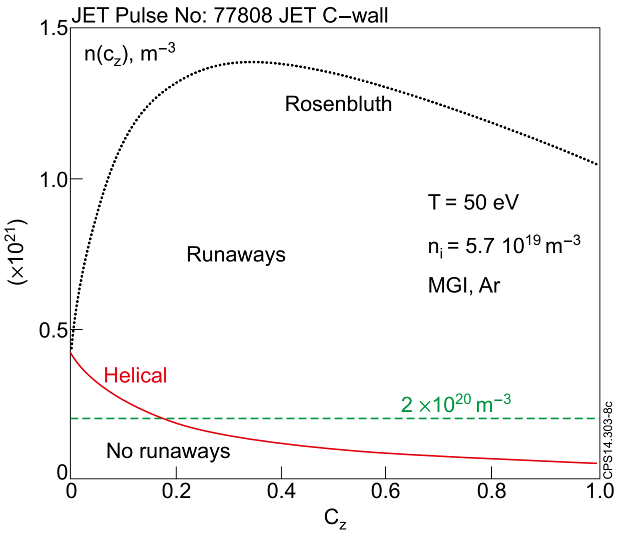


Figure 8: The RE occurrence boundaries on the density vs Ar concentration plane. JET CFC-wall Pulse No: 77808 with Ar injection. The Rosenblith density lies higher above the line average density (dashed line). The 'Helical density' limits the RE occurrence at low densities. The REs are generated for Ar concentration above about 17%.

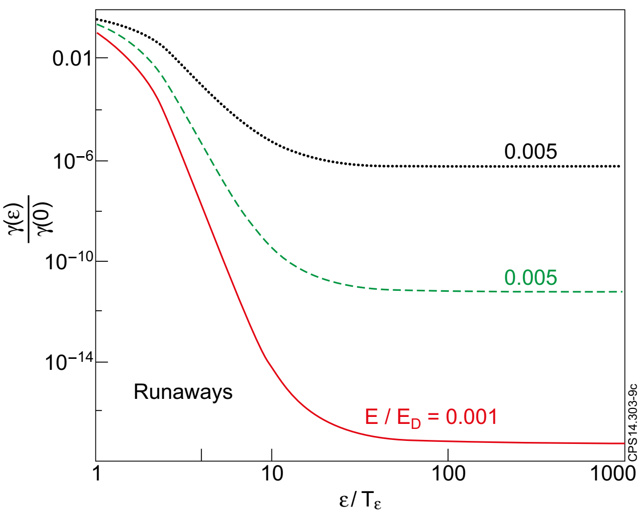


Figure 9: The growth rate of primary RE (normalized to $\gamma(\varepsilon = 0)$) versus the electron energy (normalized to T_e) for different values of the electric field E/E_D.

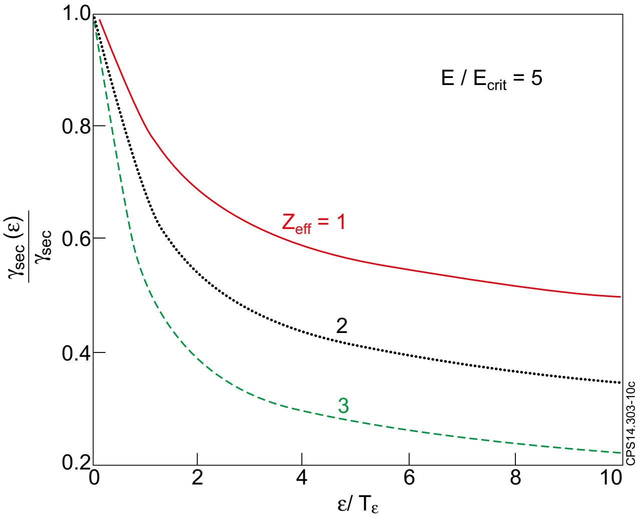


Figure 10: The growth rate of secondary RE (normalized to $\gamma_{sec} = \gamma(\varepsilon = 0)$) versus RE electron energy (normalized to T_e) for various charge state values (Z_{eff} = 1,2 and 3) for $E = 5E_{crit}$.