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Study of Runaway Electrons in the Iran Tokamak 1 (IR-T1)

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In a fully ionized gas electrons with energies higher than certain critical energy are continuously accelerated when an electric field is applied. The resulting high energy electrons are called runaway electrons.[1] In tokamaks runaway electrons are often observed during and after a plasma disruption.[2] This issue is particularly important in the case of disruption generated runaway electrons with high energy, due to the damage first wall materials.[3] For this reason, experimental and theoretical studies are being carried out in order to determine the conditions which can provide a reduction of the effect of runaway electrons during disruptions.[4-6] Runaway electrons are generated when the accelerating electric field acting on the electrons exceeds decelerating effect that such as collisions losses.

The equation describing the motion of a test particle in momentum space were already obtained from the kinetic Fokker-Planck equation for the fast electron distribution. The dynamics of a relativistic electron in a tokamak plasma will be described using the test particle equations:

$$\frac{dP_{II}}{dt} = eE_{II} - \frac{n_e e^4 Ln\Lambda m_e \gamma}{4\pi\varepsilon_\circ^2}\left(Z_{eff} + 1 + \gamma\right)\frac{P_{II}}{P^3} - F_s \frac{P_{II}}{P} \qquad (1)$$

$$\frac{dP}{dt} = eE_{II} \frac{P_{II}}{P} - \frac{ne^4 Ln\Lambda m_e}{4\pi\varepsilon_\circ^2} \cdot \frac{\gamma^2}{P^2} - F_s \qquad (2)$$

Where P_{II} and P are the electron momentum parallel to the magnetic field and total electron momentum, respectively, γ is the relativistic gamma factor, n_e is the lineaveraged central electron density, the e is the absolute value of the electron charge, m_e is the electron mass, $\varepsilon_\circ$ is the vacuum permittivity, E_{II} is the toroidal electric field, Z_{eff} is the effective ion charge, $Ln\Lambda$ is the Coulomb logarithm and F_s is the decelerating force due to the synchrotron radiation losses. Martin-Solis and et al rewrite these equations in normalize form[7]:

$$\frac{dq_{II}}{d\tau} = D - \gamma(\alpha+\gamma)\frac{q_{II}}{q^3} - (F_{gc} + F_{gy}\frac{q_\perp^2}{q^4})\gamma^4\left(\frac{v}{c}\right)^3\frac{q_{II}}{q} \qquad (3)$$

$$\frac{dq}{d\tau} = D\frac{q_{II}}{q} - \frac{\gamma^2}{q^2} - \left(F_{gc} + F_{gy}\frac{q_\perp^2}{q^4}\right)\gamma^4\left(\frac{v}{c}\right)^3 \qquad (4)$$

Where $q = P/m_e c$ and $\tau = \nu_r t$ with $\nu_r = \dfrac{n_e e^4 Ln\Lambda}{4\pi\varepsilon_\circ^2 m_e^2 c^3}$ and $D = \dfrac{E_{II}}{E_R}$ is the normalized electron field, with $E_R = \dfrac{KT_e}{m_e c^2}E_D$, where $E_D = \dfrac{n_e e^3 Ln\Lambda}{4\pi\varepsilon_\circ^2 KT_e}$ is the Dreicer field, $\alpha = 1 + Z_{eff}$, v is the electron velocity and $F_{gc} = F_{gy}\left(m_e c/eB_\circ R\right)^2$, $F_{gy} = 2\varepsilon_\circ B_\circ^2 Ln\Lambda m_e / 3n_e$ (R is the plasma major radius and $B_\circ$ is the toroidal magnetic filed) are parameters describing the two contributions to the radiation losses coming from the guiding center motion and the electron gyro-motion, respectively. Typical plasma parameters were[8]:

$n_e \cong 2\times10^{13}/cm^3$, $KT_e = 100eV$, $B_\circ = 0.7Tesla$, $Z_{eff} = 2.3$ (therefore $\alpha = 3.3$), $R = 45cm$, $Ln\Lambda = 17$ with this parameters, we calculate $E_D = \dfrac{n_e e^3 Ln\Lambda}{4\pi\varepsilon_\circ^2 KT_e} = 88.51\, volt/m$, we use the electric field E_{II} inferred from the measured loop voltage ($E_{II} \cong \frac{V_{loop}}{2\pi R}$, which, during the flat top, when the current is stationary, can be assumed to be roughly uniform along the plasma minor radius) therefore $E_{II} \cong \frac{V_{loop}}{2\pi R} \cong 0.353\, {}^{volt}\!/_{m}$ and $E_R = \frac{KT_e}{m_e c^2} E_D \cong 0.0172$, thus normalized electric field is about $D = \frac{E_{II}}{E_R} \cong 20.5$, also we calculate $F_{gc} = F_{gy} \left({}^{m_e c}\!/_{eB_\circ R} \right)^2 \cong 2.7 \times 10^{-7}$ and $F_{gy} = {}^{2\varepsilon_\circ B_\circ^2 Ln\Lambda m_e}\!/_{3n_e} \cong 6.8 \times 10^{-3}$. The main result of this analysis for normalized electric field D>1 the critical velocity at which electrons run away is modified by relativistic effects and runaway generation occurs.

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