Interaction of runaway electrons with high-Z impurities

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It is expected that runaway electrons, REs, will be generated during plasma disruptions in ITER. Uncontrolled loss of such REs can cause localized damage to the Plasma Facing Components (PFCs). Then, an adequate means to control or suppress the RE beam should be developed. Very promising recent results of experiments on DIII-D [1] manifested effective suppression of the runaway electrons with massive injection of noble gas during the runaway plateau stage of the disruption. However, experimental results can not be explained in terms of collisional drag of the RE beam employed in the classical RE avalanche model [2].

Indeed, in the analysis of [2], the dominant force opposing acceleration of REs by the electric field is the collisional slowing down by bulk plasma electrons, including free and bound. While pitch angle scattering of the RE beam in the cold post thermal quench plasma with Z_{eff}~1 plays the role of a minor correction to the evolution of the RE current. Comparison of the expected amplitude of the electric field at the current quench (based on dissipation of the total magnetic energy in the minimum current quench time) with its critical value $E_c=(4\pi e^3 n_e \ln\Lambda/mc^2)$ sets [3] the lower limit of the plasma electron density (Rosenbluth density) sufficient for the suppression of the avalanche RE generation. It is this density limit that is considered as a target for MGI suppression of REs in ITER. According to [3], this density is very high $n_{RB}\sim 4*10^{22}m^{-3}$ and is far beyond the capability of the ITER pumping system. However, in experiments, including [1], the RE current was effectively suppressed by impurity injection that produced an n_e at least one order of magnitude smaller than n_{RB}.

In addition, the measured RE energy spectra in DIII-D [1] and JET [4] were found to be significantly shifted to lower energy range compared with that expected for avalanche generated REs. Also the reconstructed RE distribution function was significantly more spread in velocity space than an extremely narrow parallel beam as follows from [2]. It was suggested in [1], that a possible explanation can be found through proper accounting of RE scattering on high-Z impurity nuclei.

In the present study we append a Monte Carlo solver of the bounce averaged Fokker Planck equation for the fast electrons, similar to the ARENA code [5]

$$\frac{\partial f}{\partial t} = \langle L_E(f_{re})\rangle + \langle C(f_{re})\rangle + \langle L_{syn}(f_{re})\rangle + \langle L_{br}(f_{re})\rangle + \langle S\rangle + \langle L_b\rangle \quad (1)$$

with a direct simulation of the RE interactions with high-Z impurities including multiple scattering in screened Coulomb fields and stopping power resulting from collisional and radiative (bremsstrahlung ~Z^2) drags. For the present report, we took the simplest equation for the electric field amplitude $E = E_c + (j_0 - j_{re})/\sigma$ as in [2].

Electron scattering on atoms is well known. Screening of the nuclei charge Ze by bounded atomic electrons is accounted for in a differential scattering cross-section

$$d\sigma = \frac{4a_B^2}{q^4}\left|Z - F(q)\right|^2 d\Omega, \qquad q = 2gp\sin(\theta/2). \quad (2)$$

by the form factor $F(q) = \int n(r)\exp(-i\vec{q}\vec{r})d^3r$, which we calculate [6] with use of the Thomas-Fermi model. For relativistic REs, $d\sigma_{RE} = \left(1 + p^2 - q^2/4g^2\right)d\sigma$. Here p is the RE momentum in units of *mc*, $g = \hbar c/e^2 = 137.37$. Then, the transport scattering cross section takes the form [6]

$$\sigma_t = \frac{4\pi a_B^2}{g^4 p^4}\left\{[Z-\xi]^2\ln\Lambda + 2Z[Z-\xi]\,I_1(q_0/Z^{1/3}) + Z^2 I_2(q_0/Z^{1/3})\right\}, \quad (3)$$

where ξ is the number of bounded electrons. Integrals I_1 and I_2 are well approximated by

$$I_k(y_0) \approx I_k(y_*) + \left[\frac{\xi - F(y_*)}{Z}\right]^k \ln(y_0/y_*); \quad k = 1,2$$

Here, y_* is some characteristic value of the argument. For relativistic electrons, i.e. large y_*, F tends to be zero. Then for pure nuclei, $\xi=0$, only the first term in (3), the standard Rutherford cross section, remains. While for atoms and lower ionization states, the third term is dominant. For Ar, the value of I_2~3 at the lower boundary of our energy domain and logarithmically grows at higher energies. For the typical CQ plasma temperatures of T_e~10eV or lower, the highest ionization state for Ar is less than 5. Then, the second and especially the third terms in (3) give about 2 orders of magnitude higher contribution to the RE beam scattering than was considered in [2], in terms of effective plasma charge Z_{eff} (the first term in (3)). Formally, the fast electron scattering on high-Z impurity nuclei in the pitch angle scattering operator [2,5] is accounted for by substitution $Z_{eff} \rightarrow \frac{1}{n_e \ln\Lambda}\sum_Z \sum_{k=0}^{Z} n_Z^k\{k^2 \ln\Lambda + \Delta_k\}$, where n_z^k is the density of ions in charge state "*k*", and $\Delta_k = 2kZI_1(x) + Z^2 I_2(x)$.

The effect from the high-Z impurities in the kinetic equation (3) is strongest in the pitch-angle scattering operator. Our calculations have shown that bremsstrahlung drag as well as additional energy losses due to inelastic scattering processes do not visibly influence the RE dynamics. Synchrotron radiation, on the other hand, as was previously demonstrated in [8], is really strong and is the favorable mechanism in suppressing the kinetic energy of REs.

Figures 1 and 2 illustrate mitigation of a 10MA RE beam in ITER-like plasma (conditions of the simulations are similar to those in [2]). After a stationary RE plateau was formed, Ar impurities with a total density $n_{Ar}=0.25n_e=0.25*10*^{20}m^{-3}$ was injected into a T_e=5eV plasma. For this temperature, the distribution of the Ar ions over ionization states is approximately: 0.4 Ar^{2+} +0.6Ar^{3+}, provided Z_{eff}=2. It is important to note that after Ar injection, the total electron density (free + bound) reached $5.5*10^{20}m^{-3}<<n_{RB}\sim4*10^{22}m^{-3}$ [3]. Nevertheless, very strong suppression (full mitigation) of the RE current and kinetic energy content is clearly seen despite having 2 orders of magnitude smaller n_e than was put as a target in [3].

Different currents in Figs. 1-2 correspond to the differences in the model used. The red curves correspond to the original model of [2], where pitch-angle scattering was accounted for in terms of Z_{eff} and synchrotron radiation was neglected. The blue curves, apparently correspond to the most dangerous situation, when strong pitch angle scattering on high-Z impurities is accounted for without synchrotron radiation. In this case, the RE current decay results in growing E and avalanche generation of new REs. This is the way to convert the maximum of the plasma magnetic energy into the kinetic energy of the relativistic electrons with a broad velocity distribution (low current) and high kinetic energy.

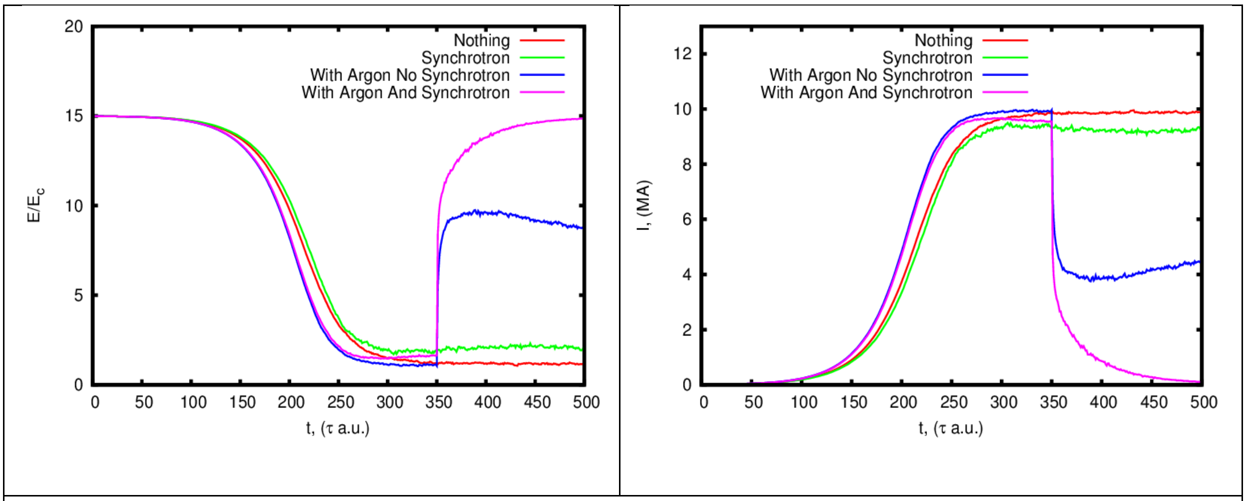

Figure 1. Evolution of the electric field (left) and RE current in an Ar mitigated CQ

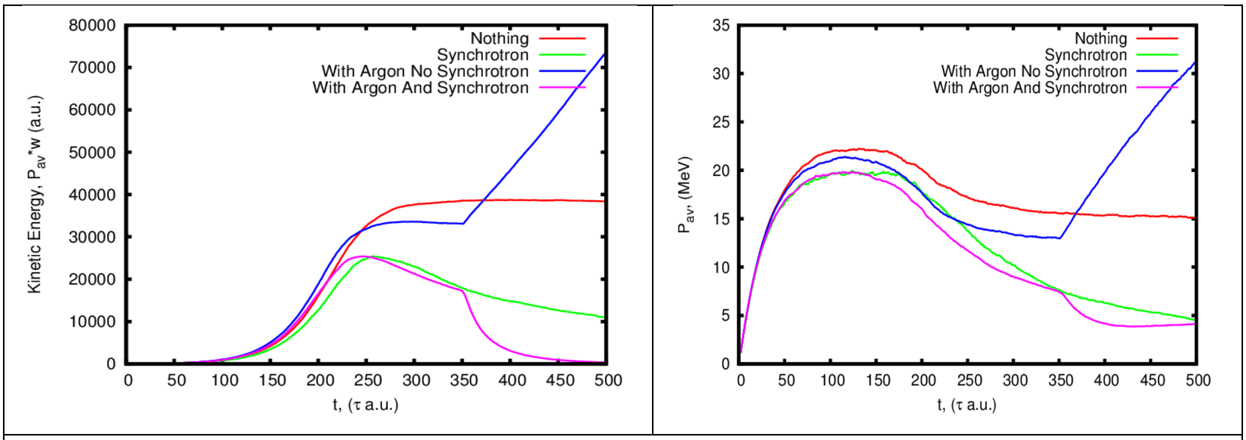

Figure 2. Evolution of the total (left) and mean (right) RE energy in an Ar mitigated CQ

Finally, the pink curves show excellent results of joint efforts of the strong pitch angle scattering on Ar nuclei provided RE current decay and synchrotron radiation, which dissipate the kinetic energy of the fast electron population as well as their mean energy. Taken together these effects a) are capable to explain the experimental findings in the mitigation of RE beams with use of a moderate amount of impurity and b) open the way to complete the conceptual design of the ITER Disruption Mitigation System including MGI with parameters within the technical limitations as a tool to suppress REs at the final stage of the current quench.

Disclaimer: The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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