NON-LINEAR INTERACTION OF RUNAWAY ELECTRONS WITH RESISTIVE MHD MODES IN AN ITER VDE

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Abstract

Preliminary numerical investigations of the effects of post disruption runaway electrons on the plasma dynamics during an ITER vertical displacement event are presented. The focus is on the coupled evolution of avalanche generated runaway electrons with resistive MHD modes. The study is carried out using non-linear MHD simulations with the JOREK-STARWALL code, wherein runaway electrons are modelled as an additional fluid species interacting with the background plasma. Significant differences are observed in the mode structure and growth of the tearing modes, along with a substantial lowering of the safety factor profile during the growth of REs and altered VDE dynamics.

1. INTRODUCTION

In a tokamak disruption, sudden cooling of the plasma leads to a large toroidal electric field that can accelerate superthermal electrons to relativistic velocities and energies of the order of a few tens of MeV. Such electrons, known as runaway electron (REs) can in turn convert thermal electrons into REs even through a single knock-on Coulomb collision. This process leads to avalanching [1] and the formation of an RE beam that would carry all the toroidal plasma current by the end of the current quench, which is a significant fraction of the predisruption current. In ITER, up to 70% of predisruption current is expected to be converted to runaway current [2]. Due to their high energies, uncontrolled loss of REs can lead to deep melting of the plasma facing components, in turn leading to unacceptably long machine downtimes.

Often a disruption is accompanied by a loss of vertical position control, leading to a vertical movement of the plasma towards the first wall, that occurs on the resistive time scale or the wall time scale. This is referred to as a vertical displacement event (VDE), that leads to the eventual dumping of the plasma onto the first wall. In such a situation, the extent of damage due to the direct impact of REs on the first wall depends on two factors. These are the toroidal distribution of the RE current (that manifests as the toroidal peaking factor (TPF)) and the rate of deconfinement of REs during the VDE. Both of these factors in turn depend on the details of the non-linear interaction of REs with the plasma. Furthermore, the formation of halo currents (that lead to large mechanical forces on the surrounding structures) can depend strongly on the evolution of RE profile during the VDE. Therefore it is important to understand the coevolution of REs with the background plasma during a VDE.
which is the main objective of the present work. Detailed studies of ITER VDEs will be reported in a separate journal publication by F. J. Artola et al.

Runaway electron current in general alters the MHD behaviour both due to the pronounced central peaking [3] of their profiles as well as due to the lack of resistive decay of the REs [4]. There exist studies of RE evolution in MHD codes through the use of passive tracer particles [5, 6]. Although they provide valuable insights into the generation and transport of REs in the plasma, the back-reaction of REs onto the plasma is however neglected. Simulations with the code DINA provide self-consistent evolution of RE profile with the evolution of the axisymmetric free-boundary plasma equilibrium during VDE [7]. Linear MHD stability analysis of these equilibria shows that a variety of MHD modes can develop during the evolution [8]. However, their effect on the VDE cannot be accounted for in DINA. In this work, we take the alternative approach of a fluid model for REs that is fully coupled to the non-linear MHD. Fluid models for REs and their interaction with resistive kink modes in circular plasmas have been recently studied by Cai [9] and Matsuyama [10]. In this paper, results of our first MHD simulations of an ITER VDE with the simultaneous generation of REs are presented, along with the physical model used.

2. PROBLEM SETUP AND PHYSICAL MODEL

We consider the case of a non-stochastic, post thermal-quench ITER plasma, that is subjected to an axisymmetric vertical motion with the simultaneous generation of runaway electrons. At time \( t = 0 \), the plasma is in a state of static (velocity \( v = 0 \)) free-boundary equilibrium, with a small seed density of runaway electrons with a Gaussian spatial distribution. Furthermore, at the initial state, the total plasma current \( I_p = 14.5 \text{MA} \) and the toroidal magnetic field at the plasma axis \( B_0 = 4.8 \text{T} \). The temperature and density of the plasma are assumed to be spatially uniform and time independent, with \( T = 2.35 \text{eV} \) and \( n_e = 5 \times 10^{19} \text{m}^{-3} \). The magnetic field is expressed as \( B = \nabla \psi \times \nabla \phi + F_0 \nabla \phi \) and the velocity field is assumed to consist of only the \( E \times B \) drift given by \( v = -R^2 \nabla \psi \times \nabla \phi \), where \( \psi \) and \( F_0 \) correspond to the poloidal magnetic flux and the electric potential respectively. Runaway electrons are modelled as a separate fluid species that is subjected to an advection velocity given by

\[
v_{RE,a} = \frac{B}{B^2} + \frac{E \times B}{B^2},
\]

and secondary avalanche generation given by the Rosenbluth-Putvinski model [1]

\[
S_s = \frac{\varepsilon_c - 1}{\tau \ln \Lambda} \sqrt{\frac{\pi \psi}{3 (Z_{eff} + 5)}} \left[ 1 - \varepsilon_c^{-1} + \frac{4\pi (Z_{eff} - 1)^2}{3\psi (Z_{eff} + 5) (\varepsilon_c^2 + 4/\psi^2 - 1)} \right]^{-\frac{1}{2}}
\]

In the above equations, \( \varepsilon_a \) is the ratio of the parallel advection velocity for REs, \( B \) is the magnitude of the magnetic field, \( \varepsilon_c \) is the parallel advection velocity for REs, \( B \) is the magnitude of the magnetic field, \( \varepsilon_c \) is the magnetic field at the plasma axis, \( \nabla \psi \times \nabla \phi \) and \( F_0 \nabla \phi \) are the static (velocity \( v = 0 \)) free-boundary equilibrium, with a small seed density of runaway electrons with a Gaussian spatial distribution. Furthermore, at the initial state, the total plasma current \( I_p = 14.5 \text{MA} \) and the toroidal magnetic field at the plasma axis \( B_0 = 4.8 \text{T} \). The temperature and density of the plasma are assumed to be spatially uniform and time independent, with \( T = 2.35 \text{eV} \) and \( n_e = 5 \times 10^{19} \text{m}^{-3} \). The magnetic field is expressed as \( B = \nabla \psi \times \nabla \phi + F_0 \nabla \phi \) and the velocity field is assumed to consist of only the \( E \times B \) drift given by \( v = -R^2 \nabla \psi \times \nabla \phi \), where \( \psi \) and \( F_0 \) correspond to the poloidal magnetic flux and the electric potential respectively. Using these, the normalized visco-resistive reduced MHD equations (that we solve numerically) in the \((R, Z, \phi)\) coordinate system can be written as

\[
\frac{1}{R^2} \frac{\partial^2}{\partial t^2} \frac{\partial u}{\partial t} = \frac{\eta(\psi)}{R^2} \left[ j - c n_{re} F_0 \right] - \frac{F_0}{R^2} \frac{\partial u}{\partial \phi} - \frac{1}{R} [u, \psi]
\]

\[
\nabla \cdot \left[ \rho R^2 \nabla_\perp \frac{\partial u}{\partial t} \right] = \frac{1}{2R} \left[ R^2 \nabla_\perp u \right] + \frac{1}{R} \left[ R^2 \rho \omega, u \right] + \frac{1}{R} \left[ \psi, j \right] - \frac{F_0}{R^2} \partial_\phi j - \frac{1}{R} \left[ R^2, \rho T \right] + R \mu \left( T \right) \nabla^2 \omega
\]

\[
\nabla \cdot \left[ n_{re} E_\perp \left( \partial_{11} \psi + \partial_{22} \psi \right) + n_{re} \left( \partial_{1} \psi / \partial_1 E_\perp + \partial_2 \psi / \partial_2 E_\perp \right) + E_\perp \left( \partial_1 \psi / \partial_1 n_{re} + \partial_2 \psi / \partial_2 n_{re} \right) \right]
\]

\[
j = \Delta^* \psi
\]

\[
\omega = \nabla \cdot \nabla_\perp u
\]

\[
\partial_t n_{re} = -\frac{\varepsilon_a}{F_0 R} \left[ \left( R n_{re}, \psi \right) + F_0 \partial_\phi n_{re} \right] + 2 n_{re} \partial_2 u + R \left[ n_{re}, u \right] + \nabla \cdot \left( D_{re} \nabla n_{re} \right) + S_s
\]

where the parallel electric field \( E_\parallel \) is given by the Ohm’s law.
In the above equations, \( j \) represents the toroidal current density comprising both the thermal and RE current densities. The variables \( \omega \) and \( n_{re} \) correspond to, toroidal vorticity and the runaway electron number density respectively. The resistivity \( \eta \) is considered to be a function of poloidal flux rather than temperature. An RE advection velocity \( v_a = 10^{-4}c \) and a small value of diffusion for runaway density, \( D_{re} = 10^{-8} \) (normalized units) has been used for numerical reasons. A constant viscosity \( \mu = 3.9 \times 10^{-4} \text{kgm}^{-1}\text{s}^{-1} \) has been used. The above set of governing equations are solved using JOREK [11, 12], which is a fully-implicit non-linear MHD code based on 2D Bezier finite elements and toroidal Fourier decomposition. The effect of the field coils, central solenoid, and the vacuum vessel on the plasma response is considered too. This is done however not by including these coils and vessel explicitly into the domain, but rather numerically more efficiently by the use of non-local (integral) boundary conditions for \( \psi \) through the Green’s functions formalism. Hence the problem domain is limited to the region until the first plasma-wall interface. The JOREK code with the non-local electromagnetic boundary conditions is referred to as JOREK-STARWALL [13]. The configuration used in the present simulations is the same as that in Artola et. al. [14] and is shown in Fig. 1. The boundary conditions for \( u, \omega \) and \( n_{re} \) are however fixed in time. Although not fully realistic, they are expected to provide useful estimates of the effect of RE growth on the MHD dynamics during most part of the VDE. More realistic boundary conditions for the velocity field and the runaway current is presently under progress.

![Figure 1](image_url)  
**FIG. 1.** Configuration of the coils, central solenoid and passive components used in the present JOREK-STARWALL simulations.

3. SIMULATION RESULTS

Simulations were run with a radial-poloidal grid resolution of 170 × 240 points. Two different simulations were performed, each of them with and without the generation of runaway electrons. A purely axisymmetric simulation \( (n = 0) \) for a total time of 10.6ms and a simulation with two non-axisymmetric toroidal Fourier modes \( (n = 0, 1, 2) \) for a total time of 8.6ms. The simulations without runaway electrons would be referred to as ‘baseline’ in the remainder of the text. Due to the relatively high resistivity of the cold plasma, the plasma current starts to decay (current quench) immediately. This causes the plasma to move continuously towards a new equilibrium state, leading to the overall vertical motion of the plasma [15]. This is in contrast to a VDE caused by an inherently vertically unstable state of the plasma.

Figure 2(a) shows the plasma current decay and the simultaneous conversion of thermal current to RE current during the VDE. The decay is slowed down due to RE avalanching when a significant fraction of the current is
carried by runaway electrons. Also the saturated total RE current is about 58% of the predisruption current, which is not far from the estimated conversion ratio for ITER of about ~ 70%. The slowdown of the current decay leads to significant slowing down of the vertical plasma motion after about 7ms, as can be seen from Fig. 2(b).

The corresponding evolution of q-profiles is shown in Fig. 3. It can be seen that the conversion of thermal to RE current leads to significantly lower q-profiles. This is qualitatively similar to the observations from DINA simulations by Aleynikova et. al. [8]. Due to the decay of the total current during the current quench phase, the q-profile near the center in general tends to rise. In the presence of REs, this effect is opposed by both the near-central peaking of the RE current profile as well as the reduced total current decay rate in the later phase of the RE conversion. The profile differences at time $t = 6$ms is purely due to RE current peaking, whereas the much lower q-profile with REs at $t = 10.6$ms is both due to peaking and an overall higher total current. The corresponding current density profiles along the minor radius of the plasma (limited to the last closed surface) are shown in Fig. 4. In our case, the peaking of the RE current profile is off-axis which suggests a longer timescale of parallel electric field diffusion at the axis as compared to the avalanche timescale. Such an off-axis peaking is often observed in RE experiments. Values of $q$ lower than unity observed in this case can potentially destabilize the resistive internal kink mode.

We now turn to the non-axisymmetric simulations. In these cases, a perturbation in the axisymmetric state is applied at about $t = 7.45$ms. In the case without RE generation, this leads to the linear growth of the $n = 1$ and $n = 2$ resistive tearing modes and an eventual non-linear saturation at mode kinetic energies similar to that...
FIG. 4. Evolution of the $j$-profile over time for the axisymmetric VDE simulation with and without REs. Solid lines refer to the case with REs.

FIG. 5. a) Poloidal kinetic energy of different toroidal modes integrated over the poloidal plane. b) Poloidal magnetic energy of different toroidal modes integrated over the poloidal plane. Dotted lines refer to the case without runaway electrons and solid lines refer to the case with runaway electrons.

FIG. 6. Non-zero modes of $u$ during the non-linear phase of the mode growth at $t = 8.6\text{ms}$. a) Without REs. b) With REs.
the axisymmetric kinetic energy as can be seen from Fig. 5(a). In the case with RE generation, \((m, n) = (2, 1)\) is dominant in the initial phase of the mode growth. In addition, the \((m, n) = (2, 1)\) mode grows slower due to the lower effective plasma resistivity with REs. Furthermore, \((m, n) = (1, 1)\) mode is observed to be eventually dominant in the case with RE generation as compared to the \((m, n) = (2, 1)\) mode which is dominant in the case without REs as can be seen from Fig. 6. This is in agreement with the linear MHD analysis of Aleynikova et. al. [8]. Similar behaviour is observed with the magnetic energies of the modes as can be seen from Fig. 5b. However, we could not yet simulate the case with REs until complete non-linear saturation due to numerical issues, that are expected to be related to the fixed boundary conditions used for the velocity and runaway electron density.

4. SUMMARY

A runaway fluid model was used in the JOREK-STARWALL code to study an axisymmetric ITER VDE in the presence of runaway avalanching. Preliminary results show a significant slowing down of the vertical motion of the plasma, along with safety factors lower than unity that opens up possibilities for destabilized resistive kink modes. A transition from a \((2, 1)\) tearing mode to a dominant \((1, 1)\) mode is observed during the VDE in the presence of REs. More realistic velocity and RE boundary conditions are necessary in order to simulate the complete VDE event.

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REFERENCES