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On the Character of the Motion of Runaway Electrons in a Time Dependent Magnetic Field from 3D MHD Code JOREK

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Abstract. In our paper we describe our new particle tracking code and we present results of our simulations of trajectories of runaway electrons in a time dependent magnetic field computed by non-linear 3D MHD code JOREK for the case of pellet injection on Tore Supra tokamak. We show that the character of the resulting motion is not a simple diffusion process but rather a sum of a stable motion on the same radius and phases of rapid changes of radial position.

Motivation for the Study of Runaway Electrons in Fusion Plasmas

Runaway electrons (RE) created during disruptions present a serious threat for a successful operation for the future large tokamaks (ITER, DEMO). Large toroidal electric field during plasma disruption can accelerate runaway electrons up to several hundreds MeV and intensities capable to damage plasma facing components [*Ikeda et al.*, 2007]. Therefore a thorough understanding of runaway electron behaviour is needed and a reliable method(s) for their mitigation have to be found before the start of ITER operation.

A group of theoretical tools used for simulations and predictions of fusion plasma is based on magnetic flux averaged Focker–Planck equations [CQL3D — *Harvey and McCoy*, 1992; ARENA — *Eriksson and Helander*, 2003; GO — *Fehér*, 2011]. This tool estimates radial motion of runaway electrons based on assumption of a simple diffusion process with diffusion coefficient estimated usually on Rechester–Rosenbluth formula [*Rechester–Rosenbluth*, 1978]. We show in this work that this simple diffusion approximation can lead to unrealistic results because of more complicated character of runaway electron motion at least at some types of tokamak plasma.

Related work studying test particle motion in a prescribed magnetic field can be found in papers where the influence of Resonant Magnetic Perturbation is investigated [*Finken*, 2007; *Papp*, 2011, 2012]. Here the magnetic field is usually static or harmonically changing with time and it is justified by the nature of the problem. They are based on a vacuum approach which take not into account plasma response. The most similar and the only work attempting to study runaway motion in a quite realistic magnetic field, known to the authors of this paper, are papers where non-linear 3D MHD code NINROD was used [*Izoo*, 2011, 2012].

Relativistic Particle Tracking Code

General Description

We have developed a new particle tracking code computing runaway electrons trajectories in a 3D time-dependent magnetic field computed by the non-linear 3D MHD code JOREK [*Huysmans and Czarny*, 2007]. The code is written in Python 2, has an object oriented architecture and numerical integration is performed by scipy package (vode, dopr853 integration methods). Magnetic field interpolation is done by the fifth order splines from scipy.interpolate package. Input data for our code are JOREK outputs given on regular polar grid. The toroidal magnetic field $B_\varphi(R,Z)$ is supposed to be axisymetric. $B_r(R,Z)$ and $B_z(R,Z)$ components are given by a set of 10 toroidal Fourier harmonics. The code enables also a computation of full motion using relativistic Hamiltonian, but this requires a knowledge of a vector potential $\vec{A} = (0.0, A_\varphi, A_Z)$ instead of magnetic field $\vec{B}$.

Unfortunately we have to remark that our code is not capable to compute thousands or ten thousands of trajectories as would be needed for statistical analysis of runaway population as a whole. With standard desktop personal computer we are able to compute tens of trajectories in a day only. Further optimization is possible but it will need more time to perform it.

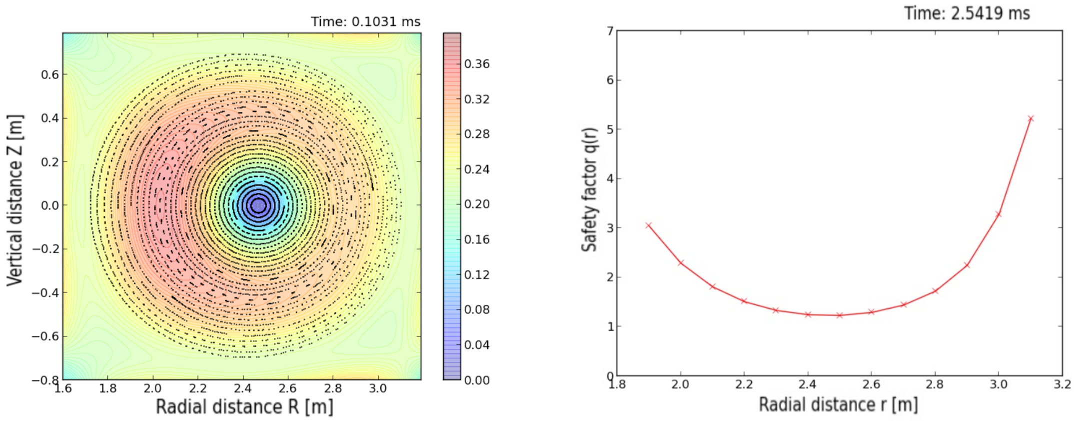

Figure 1. Snapshot of Poincare section of magnetic field lines before ergodization. Background color represents $B_{poloidal}$ magnitude (left). One time snapshot q-profile of the studied case (right).

Equation of Motion

Our code computes particle trajectories in a 3D magnetic field using relativistic guiding center equations derived by noncovariant relativistic guiding center formalism [*Carry, Brizard*, 2009, p.724] :

$$\frac{\partial \vec{X}}{\partial t} = \frac{p_{||}}{m\gamma}\frac{\vec{B}^*}{B^*_{||}} + \vec{E}^* \times \frac{c\vec{b}}{B^*_{||}} \tag{1}$$

$$\frac{\partial p_{||}}{\partial t} = e\vec{E}^*.\frac{\vec{B}^*}{B^*_{||}} \tag{2}$$

where $\vec{X}$ is the position of the particle guiding center, $p_{||}$ is the momentum parallel to the magnetic field and expressions for generalized magnetic and electric fields $\vec{B}^*$, $\vec{E}^*$ are the following

$$\vec{B}^* = \vec{B} + (cp_{||}/e)\vec{\nabla} \times \vec{b} \tag{3}$$

$$\vec{E}^* = \vec{E} - \frac{1}{e}(mc^2\vec{\nabla}\gamma - p_{||}\frac{\partial \vec{b}}{\partial t}) \tag{4}$$

where e, m is the particle charge and mass, c is the speed of light in vacuum, γ is the relativistic gamma factor of guiding center, $\mu = mv_{\perp}^2/2B$ is the magnetic moment and $\vec{b}$ is a unit vector in the magnetic field direction.

This set of drift equations satisfies Liouville's theorem for guiding centres and therefore does not create artificial attractors of the motion. In a non-relativistic limit, $\gamma = 1$, we can recover equations for the known drifts $E \times B$, grad B, curvature, polarization drift, etc. Inclusion of effects of toroidal electric field is possible as well.

Used MHD Scenario — Pellet Injection Case in Tore Supra Tokamak

In our simulation we have used a 3D MHD simulation of a pellet injection into the circular plasma of Tore Supra tokamak (main radius 2.4m, minor radius ≈ 0.5 m) lasting approximately 16.6 ms. Magnetic field in this simulation has a topology of regular nested magnetic surfaces until ≈ 11ms when ergodization starts as a consequence of pellet injection leading to abrupt disruption lasting approximately 5ms. Plasma parameters used for this MHD simulation were $\approx 5{\cdot}10^{19}$ m^{-3}, central temperature ≈ 1.5 keV, and plasma current ≈ 850 kA.

All Poincare sections time evolutions and evolutions of Poincare sections movies can be found in web page [*Paprok*, 2014].

Simulation Results

We have investigated runaway electron trajectories with different initial conditions: different magnetic moments, different initial positions and different energies in the range of 1.0–10.0 MeV, which are relevant for the Tore Supra tokamak.

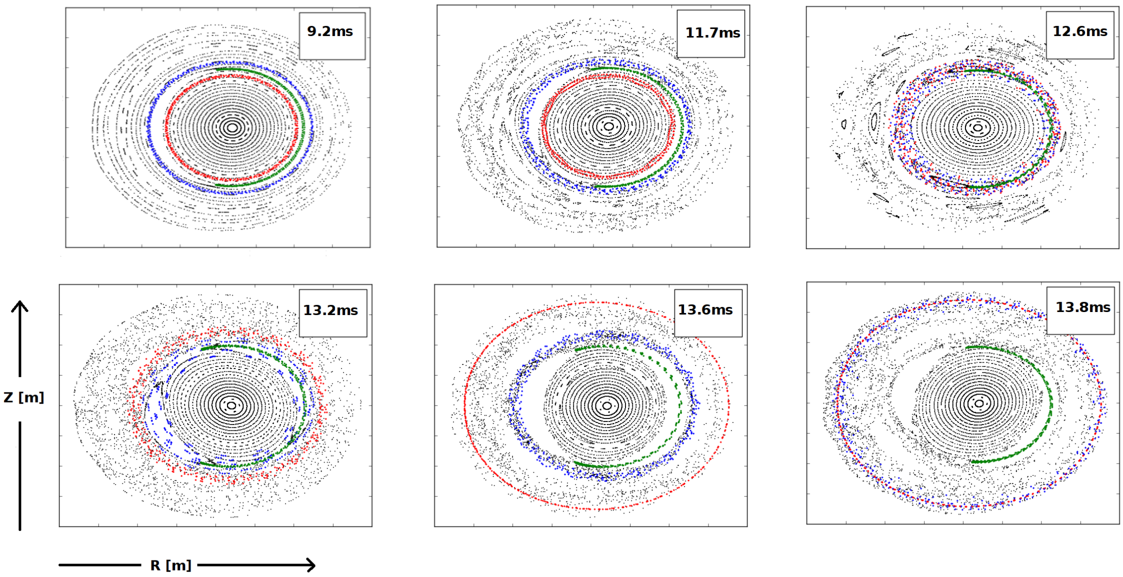

Figure 2. Stroboscopic mapping of runaways electrons positions at different times of JOREK simulation for three different pitch angles: 25°(red), 50°(blue) and 75°(green). Initial positions and energies were the same for all the particles. Black points represent Poincare sections of time dependent magnetic field.

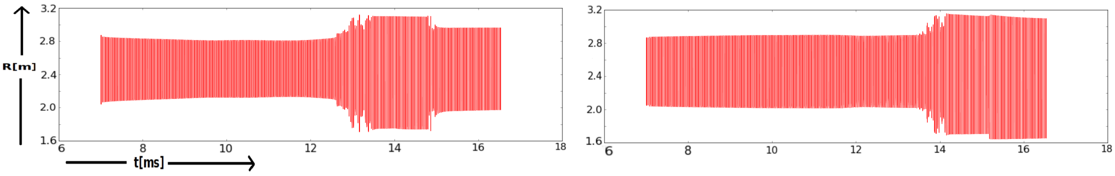

Figure 3. Time evolution of radial position of for runaway electrons with pitch angles $\alpha = 25°$ (left) and $\alpha = 50°$ (right).

Case A: Different magnetic moments, the same initial position and energy 1.0 MeV

First we have investigated the influence of magnetic moment on runaway electron motion. All particles have the same initial position $R_0 = 2.85$ m, $Z_0 = 0.0$ m, and $\varphi_0 = 0.0°$. The initial total kinetic energy for all three particles is 1.0 MeV. Pitch angle α between initial parallel and perpendicular velocities are 25°(passing particle), 50°(passing particle) and 75°(trapped particle). Resulting particle dynamics is shown in Figures 2 and 3.

In Figure 3 we see that runaway electron remains on a constant radial position for a long period of time. Once a phase of resonance with magnetic field occurs, period between 12.5–13.5 ms left figure or 13.0–14.0 ms right figure, then the radial drift velocity increase to finite value equal to $v_R = \Delta_R/\Delta_t \approx 30$ cm/1 ms $= 300$ m/s. This resonance situation can of course happen only after the magnetic field becomes perturbed enough, i.e., mainly after the ergodization starting in time ≈ 11 ms.

Case B: Approximation of a Runaway Electron Beam

To approximate runaway electron beam, which is being observed in experiments, we set initial positions on a rectangular grid 4x4 with $R_0 = (2.85, 2.86, 2.87, 2.88)m$ x $Z_0 = (0.00, 0.01, 0.02, 0.03)$m. The initial toroidal angle is $\varphi_0 = 0.0°$. Studied energies were 1.0 MeV, 5.0 MeV (shown in Figure 4), and 10.0 MeV. Pitch angle is always $\alpha = 25°$, i.e., we have a constant magnetic moment for all initial conditions.

Conclusions

From the simulations of pellet injection case follows that averaged radial runaway electron motion does not have a character of a simple continuous diffusion process, but is an aggregate of a stable motion on a constant radial drift surface and of phases of a rapid changes of an averaged radial position, ended

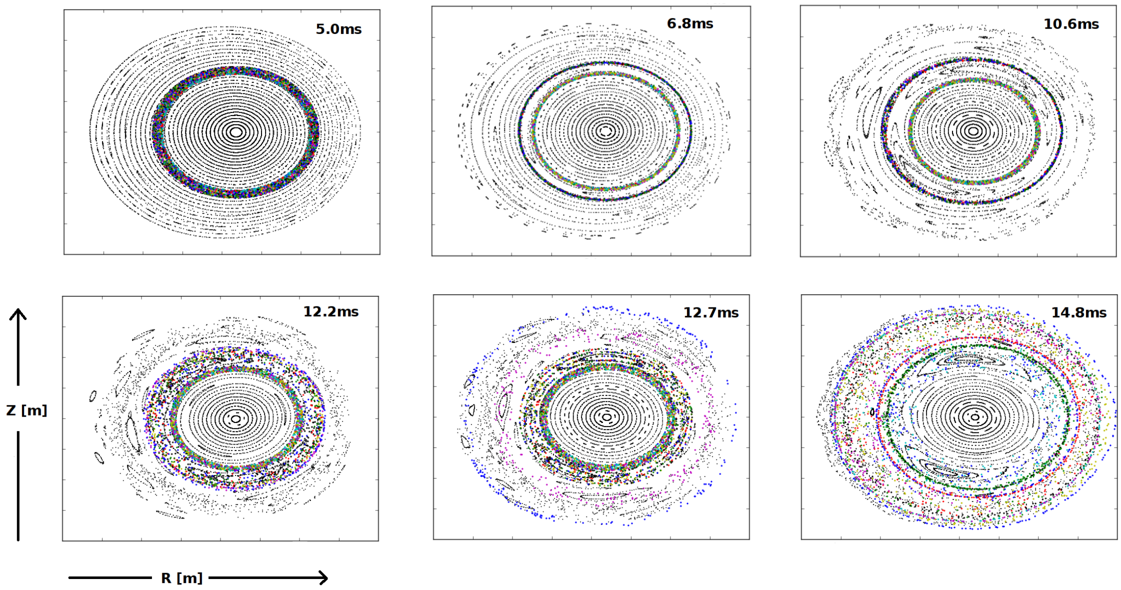

Figure 4. Stroboscopic mapping of runaways electrons positions at different times of JOREK simulation for 16 different initial positions with $R_0 = (2.85, 2.86, 2.87, 2.88)$ m, $Z_0 = (0.00, 0.01, 0.02, 0.03)$ m. Initial energy of runaways was constant 5.0 MeV and pitch angle was $\alpha = 25°$. Black points represent Poincare sections of magnetic field.

again by a stable motion. Stable motion exists even on a background of ergodized magnetic field. Rapid changes of radial position are not simply connected with reconnection processes occurring in plasma (birth and growth of magnetic islands, merge of two neighbouring magnetic island chains). Further theoretical study is needed to determine mathematically which condition(s) of the state of the magnetic field lead to a rapid motion phases and possibly investigate whether this conditions could be used for control of Runaway electron transport out of the tokamak plasma.

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