Simulations of runaway electron transport under MHD perturbations in ITER

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Massive Runaway Electrons (RE) can be produced in ITER during plasma disruptions and VDEs. It is known from present experiments and previous modelling that energy deposition by runaway electrons can be localized and their loss can result in very high energy density on the First Wall (FW) [1] leading to local severe damage of the wall and dust production. Perturbations of the magnetic field due to MHD instabilities as well as intrinsic for ITER perturbations produced by ITER ELM control coils, ripples, test blanket modules (TBMs), NBI ports etc. can affect distribution of the heat loads on the plasma facing elements due to RE loss. It is also recognized that radial transport of runaway electrons due to various MHD perturbations can significantly suppress avalanche process of RE generation [2]. Quantitative characteristic of RE transport is crucial issue in analysis of RE generation in ITER and in developing their mitigation technique.

Our approach for integrated modeling of the current quench phase of the disruption with RE includes: simulation of the overall discharge evolution by means of the DINA code [3]; development of the kinetic model for RE formation similar to that of ARENA [4]; MHD stability analysis by KINX code [5] (linear ideal MHD) and DELTAPCYL code [6] (tearing modes). RE transport and loss are studied with Orbit Following Monte Carlo code DRIFT [7] recently upgraded for calculating the drift orbits of relativistic electrons in the presence of 3D MHD perturbations.

Present report addresses evaluation of the “typical” distributions of the heat loads over the ITER FW due to loss of RE and calculation of the RE radial transport coefficients associated with perturbations of the magnetic field to be used in kinetic modeling of RE distribution function. 3D data for perturbations of the ITER magnetic field due to ripples (including ferromagnetic inserts), TBMs and NBI ports were taken from [8]. Special routine has been developed for Biot-Savart calculation of the magnetic field produced by ELM control (RMP) coils. Geometry of the RMP coils was taken from [8]. Nonlinear evolution of the magnetic islands was described in terms of extended Rutherford equation [9] for the

magnetic island width: $(\tau_R/r_s)dw/dt = 1.22 r_s^2 \Delta'(1 - w/w_{sat})$, where tearing mode stability parameter Δ' and saturated island width, w_{sat}, were calculated by DELTAPCYL code [6]. 3D geometry of the ITER First Wall was taken from [8].

ITER FW loads due to RE loss

The evolution of the ITER plasma after thermal quench was evaluated by DINA code. For the case presented here several simplifying assumptions had been made. Plasma temperature (10eV) and density ($5*10^{19}m^{-3}$) profiles were taken to be flat and not changed during the current quench phase. RE current evolution was described in terms of Rothenbluth-Putvinski semi-analytical model [10]. Under these assumptions the resulted profile of the RE current was strongly peaked near the plasma center providing wide area with $q<1$. Nevertheless, no sawtooth activity was included in the simulations. Volume uniform RE source was used in calculations of the RE loss by DRIFT code. Initial velocity distribution was taken from [10]. Then, the weights for each electron lost to the FW was taken according to calculated RE current amplitude in the "birth" point. Calculation of the RE loss during VDE was started from t=56ms (Fig.1), when the upper X-point approached FW. At this time we firstly made an estimation of the RE loss boundary, $S_{loss}(t_1)$ (with 10^4 test particle orbits calculated from volume uniform source during 0.2ms) , and then continued calculations of $4.5*10^5$ particles with source from $S_{loss}(t_1)$ to plasma boundary $S_{bound}(t_1)$ till particle hit the wall or during 0.2ms if it did not. For the following time steps we found from DINA results the moments t_{n+1}, when $S_{bound}(t_{n+1}) = S_{loss}(t_n)$ and repeated the aforementioned calculations. At this procedure we had more than 60% of initially sampled particles lost to the wall at each time step for statistically representative evaluation of the heat load distribution. Resulted heat loads during VDE then can be evaluated by direct time integration. However, for the case considered, due to highly peaked RE profile, 99% of RE are lost at the very end of the VDE. Also it should be noted that in this model case the radial current profile is ideally unstable during almost all evolution time, so that "disruption" of the moving upward plasma can take place at any moment during VDE. In the simulations we considered VDE a)without any perturbations (orbital loss only), b)with perturbations from RMP coils with currents specified for ELM mitigation in reference inductive scenario, and c) with all external perturbations:

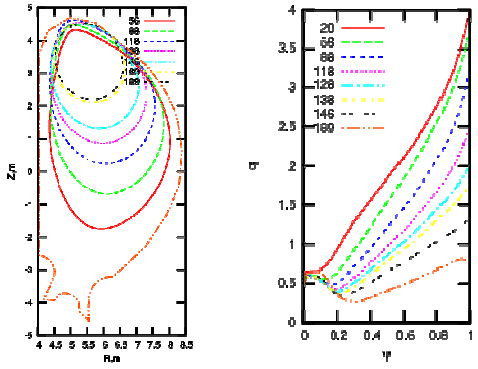

Fig.1 DINA simulations of the VDE with RE (left) and corresponding q profiles (right).

RMP+ripples+TBMs+NBI-ports. Saturated island widths calculated by DELTAPCYL code were found to be smaller than produced by RMP coils and were not included in the modeling.

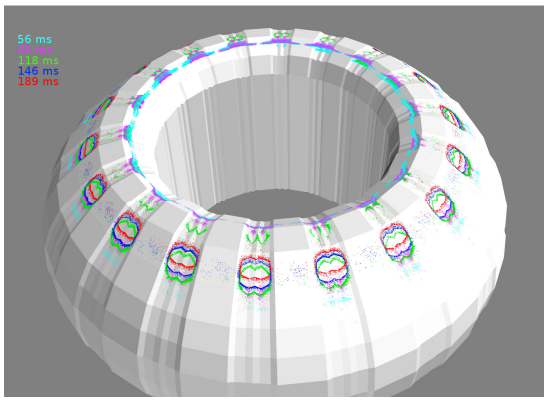

Fig.2a Incident point positions for the lost RE at different time slices of VDE.

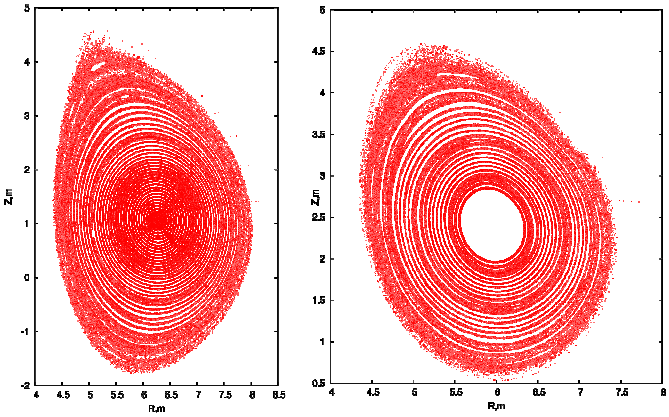

Fig.2b Poincare plots for magnetic field lines in the presence of RMP+ripple+TBMs+NBI ports perturbations at t=56ms (left) and t=128ms (right).

Results of the calculations are presented in the Figs.2,3. They can be summarized as follows:

External perturbations including those from RMP coils, ripples, TBMs and NBI ports destroy magnetic surfaces at the very periphery of plasma column (Fig.2b) and, do not affect significantly the loss of RE.

Heat load distribution over FW is determined primary by the position of the plasma with RE relative to the wall (poloidal position of the heat spot(s)) and 3D wall shaping (Fig.2a), providing an additional toroidal peaking factor of order 3, and only secondary by the structure of the external perturbation. Additional toroidal peaking factor for the heat load distribution is of order of 2 due to RMP (with dominant m/n=3/2 mode). Ripples, TBMs and NBI ports weakly contribute to toroidal peaking of the loads.

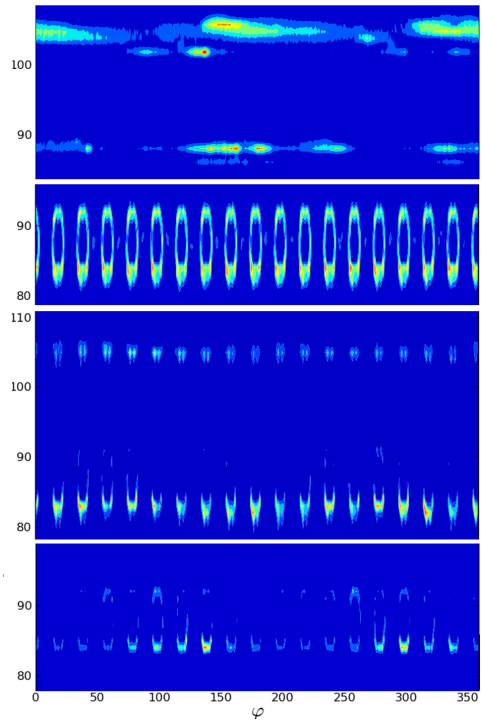

Fig.3 Heat load distributions (E_{loss}/m^2) at t=128ms for (from top to bottom)1)2D wall with RMP, 2)3D wall no perturbations, 3)3D wall +RMP, 4)3D wall + all external perturbations.

RE radial transport

Radial diffusion coefficients for RE due to RMP perturbations and magnetic islands were calculated as functions of the RE radial position, energy and magnetic moment. Series of runs of DRIFT code calculating the orbits of particle ensemble with the same initial radial

position ψ (in fact with the same toroidal momentum to exclude variation of ψ along the particle orbit), energy, and the magnetic moment $\lambda = p_\perp^2 / p^2 B$ for about 0.02ms. Time derivatives of the first and second central momentums, $\langle\psi\rangle(t)$ and $\langle(\psi - \langle\psi\rangle)^2\rangle(t)$ give radial drift velocity and diffusion coefficient (see Fig.4). The D_ρ profile for the 50MeV passing (λ=0) RE at the t=20ms time slice of the VDE modeling in the presence of RMP only is shown in the Fig.5 together with the structure of the equilibrium magnetic surfaces destroyed by RMP perturbations. As expected pure radial diffusion exists in the area of fully stochastic magnetic field and it falls to almost zero in the rest of plasma column. For fully stochastic regions radial diffusion is extremely high, exceeding 100m^2/s. This value is in a good agreement with estimation for the $D_M = \pi q R_0 \left(\tilde{B}_\rho / B_0\right)^2 \nu_\parallel$ of [11]. This estimation also correlates with our result that diffusion coefficient does not depend of the RE energy for E>1MeV. However the radial profile of the diffusion coefficient is changed with decrease of the RE energy and almost repeats the structure of the magnetic surfaces due to the shrinking of the drift orbit width. Growth of the magnetic moment results in decrease of the radial diffusion, but D_ρ still remains rather high (of few tens of m^2/s) providing almost instantaneous loss of all REs from the stochastic regions and, therefore, filamentation of their profile.

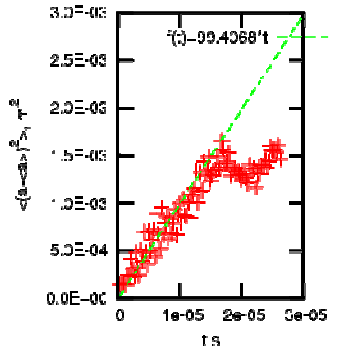

Fig.4 Typical evolution of the second central momentum in fully stochastic region.

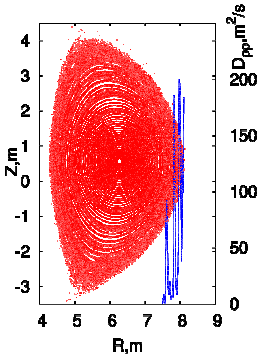

Fig.5 Magnetic surfaces and diffusion coefficient profile for t=20ms.

Acknowledgements

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