ELECTRON DIFFUSION AND ENERGY LOSS IN A REVERSED FIELD PINCH PLASMA.

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Introduction Plasmas confined in a Reversed Field Pinch (RFP) configuration exhibit a turbulent behaviour characterized by a relatively high amplitude of the magnetic fluctuations (b/B~1% in experiments with plasma current I~100 kA, where b is the fluctuating field and B the mean field) /1/. As a consequence a wide stochastic region takes place into the plasma, resulting in an enhanced electron energy loss. A theoretical model, the Kinetic Dynamo Theory (KDT) /2/, has been proposed to couple the diffusion of energetic electrons with the sustainment of the configuration. In this paper the main experimental results of the ETA BETA II device (a=0.125m, R=0.65m) /3/ supporting this model are summarized. A numerical code, solving the KDT model equations in cylindrical coordinates, is presented and the results are compared with the experimental data obtained on ETA BETA II at different reversal parameters.

Experimental results An important feature, common to most RFP experiments /3,4,5/, is a flow of energetic electrons in the edge region along the magnetic field lines, in direction opposite to that expected from the externally imposed electric field. On ETA BETA II, by taking the difference between the energy flux densities on the electron and on the ion drift side of a limiter inserted into the plasma (q_e and q_i respectively), the energetic electrons contribution has been derived (including non-linear effects and thermal response of the equipment /6/). The difference q_e-q_i is reported in fig.1 as a function of the parameter $\Theta = \frac{B_\theta(a)}{\langle B_z \rangle}$ (where <....> is the volume averaged value), which has been shown to be strongly related to MHD stability and magnetic fluctuations properties /7/. The fraction of power carried by energetic electrons over the total power lost by transport, $f^{ee} = \frac{q_e - q_i}{q_e + q_i}$ /3/, is reported in fig.2. It is worth nothing that f^{ee} decreases from 90% at standard Θ down to 60% at high Θ. By equating the energy loss to the wall to the energy flux density intercepted by a limiter inserted into the plasma /8/: $\int_0^x (q_e - q_i)dx' = f^{ee} \frac{VI}{S} L_{eq}$ (where VI is the ohmic input and S is the plasma surface), an equivalent collection length L_{eq} can be obtained for a limiter insertion x. Thus the magnetic diffusion coefficient $D_m=<\Delta r^2>/L$, where $<\Delta r^2>$ is the mean square radial excursion of a field line in a longitudinal distance L, has been derived by the approximation $D_m \simeq x^2/L_{eq}$ /8/. The Θ dependence of the magnetic diffusion coefficient D_m at x=2 mm is reported in fig.2: the increase with Θ is due to the larger amplitude of magnetic fluctuations, as, in quasi-linear approximation /9/, $D_m \simeq (b/B)^2\Lambda$, where Λ is the longitudinal autocorrelation length of the magnetic fluctuations ($\Lambda \simeq$ a for a RFP).

KDT modelling of RFP configurations The KDT model /2/ is based on a drift kinetic equation for the electron distribution function, with a Spitzer-like electron-ion collision term /10/ and an additional term describing the diffusion due to the magnetic field stochasticity /11/:

$$\frac{\partial f_1}{\partial t} - \frac{eE_{//}}{m}\frac{\partial f_0}{\partial v_{//}} = \left(\frac{\partial f_1}{\partial t}\right)_{coll} + \left(\frac{\partial f_1}{\partial t}\right)_{diff}$$

(where $E_{//}$ and $v_{//}$ are the electric field and the velocity parallel to **B**). This equation is solved in stationary conditions for a small perturbation f_1 of the maxwellian f_0, self-consistently with Ampere's law in force-free approximation /2/. The model assumes a isothermal and isodense plasma, and is solved in cylindrical geometry instead of slab geometry with the same boundary condition $\partial f_1/\partial r = 0$ as in ref. /2/. It is worth noting that the solutions are odd in the cosine of the angle between velocity and magnetic field, leading to the absence of particle density perturbation and of particle and energy radial fluxes, whereas there is a radial flux of parallel current density /2/. The numerical code requires as input parameters the applied electric field E_0, the on-axis magnetic field B_0, the average temperature $<T_0>$ and the average density $<n_0>$ of the background f_0, the minor radius a of the vessel and the magnetic diffusion coefficient $D_m(r)$. The main outputs of the model are the perturbed electron distribution function f_1, the magnetic field $B_z(r)$ and $B_\theta(r)$, and from them the parallel current density $j_{//}(r)$, the plasma current I and the pinch and reversal parameters Θ and F ($F=B_z(a)/<B_z>$). The fast electrons energy flux at the edge parallel to the magnetic field $q_{//}^{ee}$, as well as their temperature T^{ee} and density n^{ee}, have been calculated according to the expressions

$$q_{//}^{ee} = \int \tfrac{1}{2}mv^2 f_1 v_{//} d^3v \qquad n^{ee} = \int f_1 d^3v \qquad T^{ee} = \frac{1}{n^{ee}}\int \tfrac{1}{2}mv^2 f_1 d^3v$$

where the high energy portion of f_1 is integrated over the velocities forming an angle with the magnetic field less than $\pi/2$. In this way the contribution of energetic electrons flowing on one side has been taken into account. The experimental conditions of the Θ scanning described in the previous section have been reproduced by imposing the experimental values of the electric field and of the plasma current I. Moreover $<T_0>$=70 eV, constant, and $<n_0>\sim 3\div 5\cdot 10^{19}$, varying linearly with I, have been assumed. Finally a radially uniform D_m, 3.5 times the edge value and varying with Θ as shown in fig.2, has been used. In this way, magnetic field profiles as shown in fig.3 (for two cases of standard and high Θ) have been obtained. The parallel current density profiles relative to these two cases are shown in fig.4 and compared with the profiles which would be expected from a purely local Ohm's law with Spitzer resistivity.

Discussion Substituting the experimental values of the parameters into the code, different configurations are obtained. In fig.5 the F and Θ parameters of these configurations are compared with the experimental values, and the Bessel Function Model (BFM) curve is also reported as a reference. F and Θ are systematically lower than the experimental values and the discrepancy can be accounted by pressure profile and toroidal equilibrium effects. The energy flux density is reported in fig.6: it decreases with Θ and the absolute values are of the same order of the experimental ones (a better agreement at higher Θ could be obtained taking into account a lower $\langle T_0 \rangle$). In the same figure are also shown the temperature T^{ee} and the density n^{ee} of the energetic electrons: T^{ee} exhibits a tendency to increase with Θ whereas n^{ee} shows a tendency to decrease. In terms of relative values, $\frac{T^{ee}}{\langle T_0 \rangle} \simeq 5$ and $\frac{n^{ee}}{\langle n_0 \rangle} \simeq 2\%$, confirming previous estimates based on the assumption of a half-maxwellian perturbation f_1 /12/.

In conclusion the KDT is widely supported by experimental results of ETA BETA II. Solving the equations of the model in cylindrical coordinates and taking the experimental values of E_0, D_m, I, $\langle T_0 \rangle$ and $\langle n_0 \rangle$, the profiles of the magnetic field in RFP configuration at different Θ have been obtained. It is confirmed that energetic electrons carry most of the current density at the edge in opposition to $E_{//}$.The resulting energy flux density is in fairly good agreement with the experimental values, and it is found that T^{ee} and n^{ee} are weakly dependent on the parameter Θ.

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