A novel computation of the linear plasma response to a resonant error field in single-fluid visco-resistive MHD and application to the RFXmod2 tokamak

P. Zanca[1], L. Marrelli[1,2], D. Terranova[1,2]

[1]*Consorzio RFX (CNR, ENEA, INFN, Università di Padova, Acciaierie Venete SpA), Padova, Italy*
[2]*Istituto per la Scienza e la Tecnologia dei Plasmi (ISTP), CNR, Padova, Italy*

Email: paolo.zanca@igi.cnr.it

Magnetic confinement experiments are inevitably subject to error fields (EF), namely small amplitude static magnetic field due to coils and machine imperfections. They represent a concern when they resonate in the plasma, namely when they have the same helicity of the equilibrium field at a given radius (resonant surface). In fact, in this case they drive magnetic reconnection in intrinsically tearing-stable plasmas, and above an amplitude threshold they produce a wall locked magnetic islands, making the plasma prone to a disruption. This phenomenon is known as error-field penetration. Data analysis over a large database covering both H-mode and L-mode plasma obtains the following scaling law for the threshold of a $n = 1$ EF, normalized to the toroidal field [1]: $\left(|\mathrm{b}_{r,b}|/B_0\right)_{thr,exp} \propto n_e^{0.58\pm0.06} B_0^{-1.13\pm0.07} R_0^{0.1\pm0.07}$. However, we remark that the quality of the fit is not very good (see figure 2 of [1]), hence this scaling law should be taken with some reserve.

A research line interprets the phenomenon with linear magneto-hydrodynamic (MHD), in both one fluid and two-fluids (drift-MHD) versions [2-4]. The justification for using linear theory is that plasma rotation suppresses the EF driven reconnection before the penetration takes place. The linear plasma response is encapsulated within the delta prime (Δ'), a quantity which measures the magnitude of the current sheet induced by the plasma rotation at the resonant surface, shielding the EF penetration.

A recent work [5] re-examines the linear plasma response theory in the single-fluid visco-resistive MHD description. With respect to the above-mentioned publications, this work focuses on several basic aspects of the problem. First, the radial Fourier transform method, commonly used to solve analytically the problem, is validated by comparison with a completely different technique. In fact, a priori the problem does not fulfil the conditions to apply the Fourier transform. Second, a new analytical Δ' global formula valid in a wide range of plasma parameters is derived. This formula describes the Δ' features much better than previous asymptotic regimes modelling [2]. The comparison is illustrated in figure 1, where imaginary and real parts of Δ' are plotted as function of $Q = \tau_A^{2/3}\tau_R^{1/3}\omega$, with τ_A the Alfven time, τ_R the resistive time, ω the plasma rotation frequency at the resonant surface, for a fixed value of the Prandtl number P. Black symbols refer to our numerical estimate, green symbols to our new analytical formula, red and blue symbols to previous analytical formulas [2], which respectively refer to the so-called visco-resistive regime (VR) and inertial regime (I).

On the basis of our Δ' estimate, the EF penetration threshold is derived, pointing out the crucial role of the neoclassical poloidal flow damping within the torque-balance equation. The scaling law obtained with this procedure $\left(|\mathrm{b}_{r,b}|/B_0\right)_{thr} \propto n_e^{0.52} B_0^{-1.19} a^{-0.36} R_0^{-0.14}$ is similar to the experimental one mentioned above, and almost identical to recent two-fluids outcomes [4], showing that the choice between single-fluid and two-fluids MHD may be not crucial in this problem.

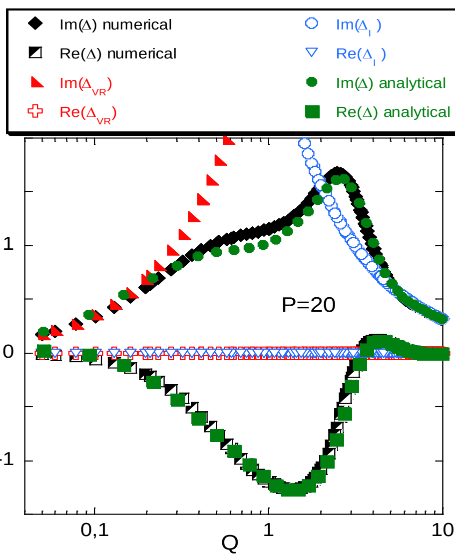

FIG. 1. Comparison between new estimates of Δ' (black and green) and those of ref. [2] (red and blue).

The new analytical formula for Δ' is also implemented in the RFXlocking code, already used to simulate the EF penetration process [6]. In the previous work [6] the VR Δ' expression has been used, but this is suitable only in a limited interval of low Q values (see Figure 1). Instead, the new Δ' formula, virtually poses no limits in the exploration of Q, and allows the investigation of a much wider plasma conditions. Therefore, a simulation work is done to estimate the EF threshold in a variety of plasma regimes, as far as density, temperature, confinement and plasma rotation are concerned.

The assumed machine dimension and layout are those of RFX-mod2 [7], the revamped RFX-mod experiment, which is predicted to start operations in the next years. At present the simulation results can be compared to the existing tokamak database, but in future they will be useful for interpretive analysis of tokamak experiments in RFX-mod2. In fact, RFX-mod2 benefits of a closer fitting stabilizing shell, which should make the tokamak plasma stable to tearing modes, the ideal condition to perform EF penetration studies. Moreover, the large number and flexibility of the active feedback coils (192×4 independent saddle coils covering the full torus) allows the application of EFs with many different helicities. Finally, the large number of magnetic sensors (suitable both for the RFP and tokamak magnetic configurations) allows a precise detection of the phenomenon. As for tokamak pulses, H-mode conditions were reached in RFX-mod in electrode edge biasing experiments [8] and this will be considered also for RFX-mod2 allowing EF penetration studies also in this improved regime.

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