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Taylor relaxation in Wendelstein 7-X

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In Wendelstein 7-X, the vacuum rotational transform, $\bar{\iota}$, has a rather small shear and does not cross any major rational surfaces. Nevertheless, during plasma operation it can be modified by electron cyclotron current drive (ECCD) in such a way that the resulting iota profile passes through low-order rational values, potentially triggering magnetohydrodynamic (MHD) events.

Indeed, W7-X plasmas are sometimes subject to repetitive collapses of core confinement, which were observed during co- and counter central ECCD [1]. These phenomena are periodic, rapid "crashes"of the electron temperature reminiscent of tokamak "sawtooth"instabilities. In some discharges these events lead to a complete termination of the entire plasma on the time scale of a few ms. These large crashes are usually accompanied by a noticeable (~0.6kA) current jump in the total plasma current. Even though the origin of these MHD instabilities is not yet clear, the fast crash is likely to involve the formation of magnetic islands and magnetic reconnection.

Since the deposition profile of ECCD is usually very localized, it results in a strong distortion of the rotational transform $\bar{\iota}$. For co-ECCD (defined as locally increasing $\bar{\iota}$), it can cause $\bar{\iota}$ to pass through unity, which is detrimental for MHD stability. Experimentally the $\bar{\iota}$-profile is rather uncertain, therefore information about the profile form has to be inferred from simulations.

To calculate the pre-crash $\bar{\iota}$-profile (Fig.1, left plot, green line), the plasma current evolution has been simulated from the poloidal flux diffusion equation using NTSS code [2]. The temperatures, the bootstrap current density, and the parallel electric conductivity have been modeled self-consistently
with the electron cyclotron resonance heating (ECRH). The ECCD current density has been calculated with the Travis ray-tracing code [3] taking into account the real launching geometry, beam size and plasma density and temperature profiles. The total plasma current evolves slowly due to the compensation of the ECCD current by an inductive plasma current. But the current density profile
variation produces a change of the $\bar{\iota}$ profile, which is a superposition of the "vacuum"$\bar{\iota}$, generated by the external stellarator coils, and the ι generated by the internal toroidal current. An $\bar{\iota}$ peak develops
in the core and crosses the $\bar{\iota} = 1$ resonance (see Fig.1, left plot, green line). Note that the rotational transform passes through unity twice. Under such conditions, linear calculations suggest that the plasma is ideally stable but unstable to resistive MHD modes.

The main question addressed in this work is what happens to the plasma configuration as a result of this instability. This question could be answered by nonlinear resistive MHD simulations. However, there is no code capable of such a simulation in the geometry of W7-X. In this work, we use a model based on Taylor relaxation [4, 5] to predict the nonlinear redistribution of the plasma current caused by these events.

The key theoretical assumption is that, in the crash, the plasma will seek to minimize its magnetic energy while keeping magnetic helicity and toroidal flux fixed. This assumption leads to the prediction of a unique plasma state, where the current flows in the direction of the magnetic field and the current density is proportional to the field strength:

$$\nabla \times \mathbf{B} = \mu \mathbf{B} \quad (1)$$

where μ is a constant. We suggest that the nonlinear result of resistive instability in W7-X may be such a Taylor-relaxed state.

It is not easy to numerically construct equilibria with prescribed helicity. We therefore scan the values of μ and solve Eq. (1) numerically to obtain a range of possible post-relaxation states. Given those, we select the one whose helicity equals the pre-quench value. The pre-quench toroidal magnetic flux and the plasma boundary shape are also assumed to be conserved during the relaxation.

To calculate the pre-crash equilibrium we use VMEC equilibrium code [6]. For the calculations of possible relaxed states, the SPEC (Stepped Pressure Equilibrium Code) code [7] is used. SPEC can find minimal-plasma-energy states, subject to the different constraints, in nested sub-volumes, by extremizing the energy functional. Relaxation and magnetic reconnection is allowed in each volume.

Our results are in agreement with the experimentally observed current «jumps» during large crashes in W7-X. Furthermore, we cross-check our results with edge diagnostic, e.g. infrared (IR) thermographic systems. We show that a sequence of several crashes (Fig.1, right plot) at the plasma edge, i.e. increase of the toroidal current, and a change in the island divertor geometry, resulting in a move of the divertor strike lines.

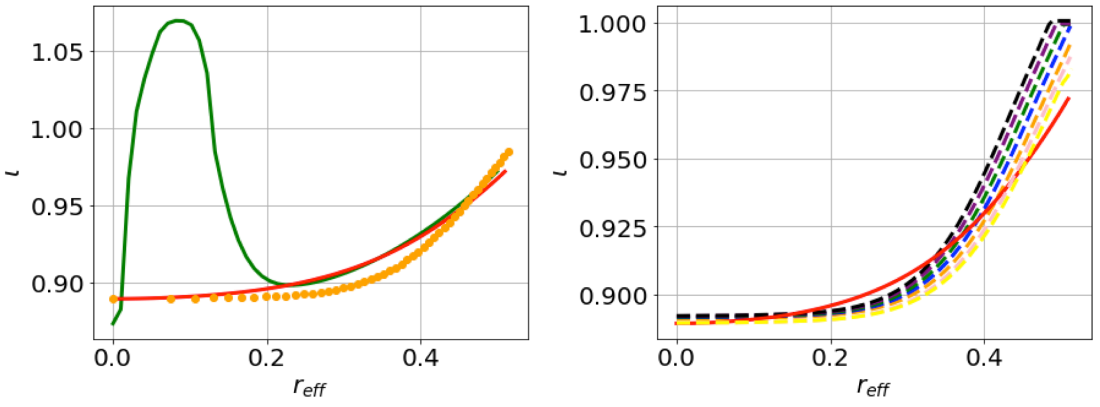

Figure 1: Left plot: prescribed pre-crash iota profile as VMEC input (green), after-crash iota profile (SPEC output, orange dots) and vacuum iota (red) versus r_eff. Right plot: After-crash iota profile (SPEC output, yellow, pink, orange, blue, green, purple and black dashed lines) and vacuum iota (red) versus r_eff.

References:

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