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Issues on active control of MHD instabilities in a RFP

Background

The issue of controlling the magnetic boundary is of fundamental importance for the RFP and for future fusion reactors. To this end, part of the RFP research is now devoted to investigations about techniques of active control of MHD instabilities by means of non axi-simmetric saddle coils. In particular, the EXTRAP-T2R and the RFX-mod experiments [1] have been equipped with sets of saddle coils, located outside their stabilizing shells. Saddle loop pick-up coils, located inside the passive shell are the sensors devoted to MHD modes detection. Signals are sampled by a digital system and reference signals for saddle coils power supply units are generated [2].
Full stabilization of multiple Resistive Wall Modes have been proven in both experimental facilities [3,4], allowing plasma discharges whose duration largely exceed the stabilizing shell time.
Resonant MHD modes also play a fundamental role in the RFP configuration. In particular the RFX-mod capabilities have also been exploited in order to mitigate the effect of wall-locked resonant MHD modes. Due to their global nature, in fact, such modes (usually defined tearing modes) induce a deformation of the plasma edge that may lead to severe plasma wall interaction. Such a deformation is eliminated by an ideal shell located at the plasma boundary, in which eddy currents flow and produce the required cancelling field. Alternatively, in the intelligent shell approach [5], the ideal shell is replaced by a grid of feedback controlled saddle loops, aimed at zeroing the flux measured by corresponding sensor coils. While this approach allowed RWM stabilization, RFX-mod experiments revealed the intrinsic limitation of the intelligent shell approach as long as field cancellation is concerned as it happens when tearing modes are wall locked [6]. In fact, the discrete nature of the actuator coils inevitably produce sidebands which are aliased in the measurements. Therefore even if the measured fluxes are all identically zeroed, edge radial fields of plasma modes are not completely cancelled. The issue of sidebands was already identified in RWM codes [7], but was found not relevant for mode stabilization.
The discovery of the sidebands aliasing issue led to a change in the control algorithm: namely from the Virtual Shell, which is based on the Intelligent shell approach, to the Mode Control approach. While in the former sensor signals act as feedback variables, in the latter a real-time Discrete Fourier Transform of sensor signals is performed and the control is based on harmonic coefficients.
The Mode Control approach, in conjunction with the real time removal of sidebands aliasing from measurements (cleaning algorithm), allowed to wall unlock tearing modes in RFX-mod. Partial phase unlocking was also observed [8], even though tearing modes still tend to align their phases and produce a localized bulging. The bulging is not stationary during the discharge, but the distribution of the spatial locations where it is observed is not uniform [9]. This new control scenario allowed exploring the 1.6MA regime in which the RFP configurations frequently reach a helical topology, named Quasi Single Helicity or Single Helical Axis [10], depending on the amplitude of the helical perturbation.
The behaviour of tearing modes phases has been qualitatively modelled by a torque balance model [11], which includes: viscous torque between modes and plasma; the electromagnetic torque between modes and surrounding shell; the torque due to non linear interaction between modes; the torque exerted on the mode by the feedback controlled external saddle coils. The time evolution of the mode amplitude at the resonance is given as an input, and the code simulates their edge values and phases.

On going research

In order to understand the behaviour of such complex control architecture and the interaction with MHD behaviour, the development of simulation tools and subsequent benchmarking against experimental data is essential. To this end, several approaches are being pursued. A model of the electromagnetic boundary has been developed [[12]]: the model includes simplified transfer functions for the feedback controlled current power supply units and a multi-input multi-output (192x192) dynamical model of the transfer function matrix M(jω) from the coil currents to the flux measurements estimated from vacuum calibration measurements (black box paradigm). Mutual couplings estimated from calibration shots have been compared with predictions by the finite elements code Cariddi [[13]]. This activity revealed the necessity to further improve both the experimental estimates of the mutual couplings and to refine the RFX-mod mesh representation in Cariddi. This step is preliminary to the study of Resistive Wall Modes by integrating the electromagnetic code Cariddi with the MARS code. The development of a full simulator of RWM control system in RFX-mod will also allow testing different kinds of model-based control approaches, where standard PID controllers will be replaced by more complex state space controller, which may also take into account the 3D structure of the magnetic boundary.

A parallel approach to RWM control modeling is based on the development of a more complete physics modeling of the plasma in a simplified geometry: such a model takes into account plasma pressure, compressibility, inertial, dissipation and longitudinal plasma rotation.

The optimization of the magnetic boundary for tearing modes control is also very important. Extensive parameter scans simulations are being performed, aiming at optimizing the non axisimmetric deformation of the last closed magnetic surface. The simulations are used to determine optimal gains to be benchmarked in experiments and to further refine the simulation model.

Integration of the tearing modes torque balance model with a more accurate representation of the electromagnetic boundary is at present under evaluation.

Open issues. Direction for future research

Given the present knowledge, the R&D required for the development of the RFP configuration concerns several issues.

- Tearing modes (TM) spectrum shaping: induction of helical states.
    - Which are the control parameters that determine the transition to helical states?
    - Is it possible to keep the RFP plasma in a helical state by pre-programmed or feedback controlled axisimmetric fields?
- Tearing modes wall-locking elimination or mitigation. Error fields reduction.
    - How important is the active control of m=0 modes?
    - Is the model of wall locking adequate to describe TM phase dynamics during helical states?
    - Which are the minimum requirements for a passive boundary in order to reduce wall locking occurrence?
- Control modelling and optimization of resistive wall modes (RWM) in order to determine minimal hardware requirements. Development of simulation codes both for TMs and RWMs with 3D boundary conditions and realistic representation of power supply units.
    - Which is the optimal active coil set for RWM stabilization?
    - Which is the optimal active coil set for TMs mitigation/wall locking avoidance? Is it the same for RWMs, or can it be limited to error field corrections (based on evidences on the MST experiment [[14]]?
- Determination of the optimal magnetic boundary and plasma shape for power handling

The design of an active control system for a next step device will need to take into account the following issues:

Aliasing of sidebands is reduced by using more sensors than actuators

The lack of homogeneity of the system can be compensated by ad-hoc saddle coils

Active control of m=0 modes is best performed by toroidal windings instead of saddle coils.

Are active coils located inside the vacuum vessel (as in ITER) or inside a stabilizing shell necessary for a RFP?

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