Physics based design of a multi-purpose non-axisymmetric active coil system for the Divertor Test Tokamak

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Edge-Localized-Modes (ELMs) are local Magneto-Hydro-Dynamic (MHD) instabilities that appear in fusion relevant plasmas during the so-called H-mode operation. Type-I ELMs in particular are large bursts that can damage the plasma facing components causing large heat and particle fluxes. Applying 3D resonant magnetic perturbations (RMPs) with non-axisymmetric coils is a promising method to mitigate or suppress type-I ELMs [1,2]. Controlling these instabilities is a crucial task in particular for the upcoming DTT device [3,4], whose construction is starting in Frascati (Italy) with the main mission of developing reactor-relevant power exhaust solutions. A set of in-vessel non-axisymmetric coils is being developed for DTT, with the main purpose of ELM mitigation and Error Field (EF) control. Provided that these two first requirements are satisfied, the system design shall retain enough flexibility to accommodate other use cases identified in the research plan development and machine lifespan. The main design choices in terms of coil system topology (number, periodicity and position) lead to the implementation of a 9 (in toroidal direction) x 3 (in poloidal direction) system, refer to Figure 1 for a more detailed representation of the system. The present design takes into account geometrical and technical constraints, assembly procedures, integration with other in-vessel components, but also reflects the main physics driven functional specifications. In particular, the ELM control function is considered in this work. For this function, external fields produced by the coils should interact mainly with plasma in the pedestal region and avoid resonant and non-resonant amplification effects with core plasma. This calls for high toroidal mode number n ($n \geq 2$) field distributions in order to maximize the coupling to external q profile regions, while tailoring capabilities for poloidal mode number m spectrum are required to adapt to different plasma scenarios. A set of 27 independent power supplies will allow the required flexibility. Slow (f<10Hz) rotation of external fields is suggested to avoid localized plasma-wall phenomena during operations.

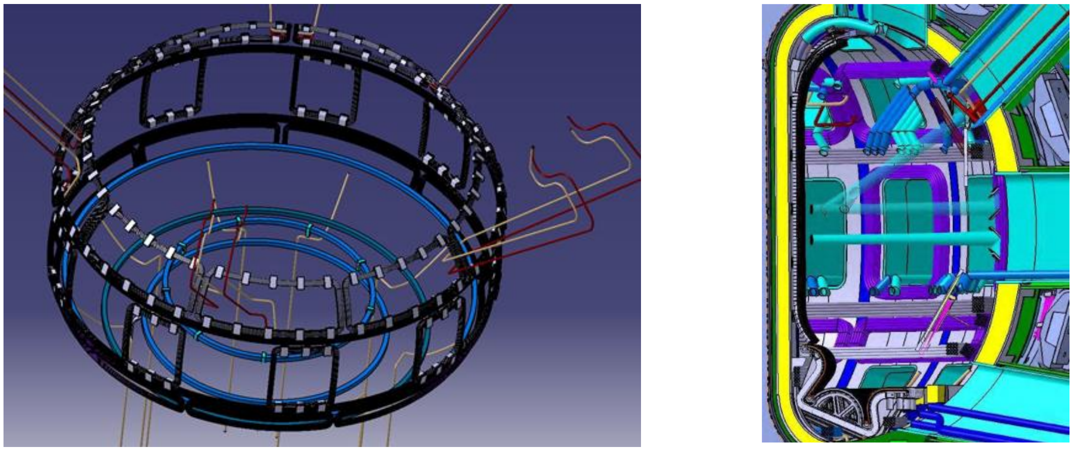

Figure 1: present conceptual design of the DTT non-axisymmetric coil system

The order of magnitude of the non axi-symmetric magnetic fields needed to fulfil the main high level requirements has to be mainly driven by physics considerations. As an output of such studies, the maximum coil current requirement can be inferred.

From the point of view of ELM control, a first assessment has been carried out using linear plasma response modelling to evaluate the effect of RMPs on edge stability. Given a target scenario obtained from integrated modelling of the full power phase [4], plasma response calculations are carried out by the MARS-F code for n=1,2,3 toroidal mode numbers. MARS-F solves linearized resistive MHD equations in two-dimensional toroidal geometry starting from an equilibrium solution calculated with the CHEASE solver. A finite element approach is used along the radial direction while the code is spectral in the poloidal angle. MARS-F includes a module for modelling external fields, such as RMPs from saddle coils, using surface currents with an analytical delta-like description in the poloidal angle while the RMP current varies as $e^{in\phi}$ along the toroidal angle. As reference, in Figure 2 an n=3 vacuum field distribution is plotted on a rectified torus at r/a=1 for a total coil current of 20 kAt.

The first metric implemented in MARS-F to evaluate the RMP effect on ELM control is the maximization of the magnitude of the normal displacement of the plasma surface near the X-point, ξ_x. A similar parameter has been introduced to interpret ELM mitigation and suppression experiments in MAST and ASDEX-U [6], and model ELM control in EU-DEMO [7].

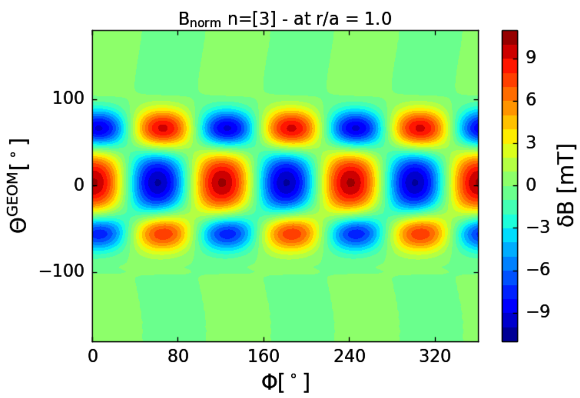

Figure 2: n=3 vacuum field (B_{norm}) distribution at r/a=1 as produced by a current of 20 kAt on each coil. Array phasing between equatorial and upper arrays is $\Delta\phi_{E-U}$= 160° and the same phasing is assumed between equatorial and lower arrays, $\Delta\phi_{E-L}$= 160°.

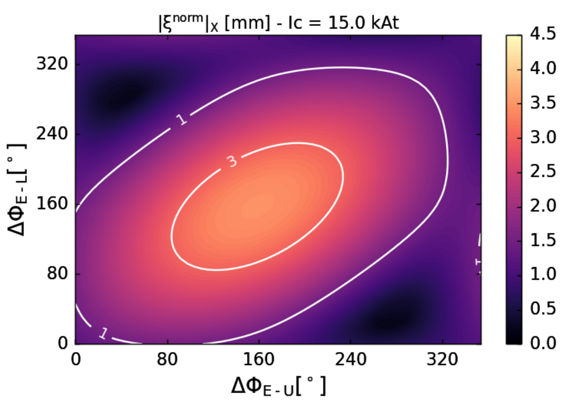

Figure 3: normal displacement of the plasma surface near the X-point for an n=3 field distribution and a current of 15 kAt on each coil.

As written above, the target plasma is a DTT (R_0 = 2.14 m, a = 0.65 m) single-null, H-mode scenario with plasma current I_p of 5.5 MA, toroidal field B_t of 6 T, q_{95} approximately 2.7 and an additional heating power of 45 MW (full power). The full description of such a scenario can be found in [5]. In order to optimize the current distribution with respect to the chosen metrics, a 2D phase scan was performed. The final result of such a calculation in terms of the normal displacement of the plasma surface near the X-point, ξ_x, for the n=3 case is provided in Figure 3. ξ_x values compatible with empirical observations of ELM suppression in MAST and ASDEX-U [6] can be found in our modelling results for currents of the order of 15 kAt.

The metric based on plasma displacement can be considered a relatively innovative approach to ELM control. Historically, ELM control by RMPs has probably been mostly studied with other parameters, such as the so-called Chirikov parameter (σ_{Ch}) in vacuum approximation, which is often used to characterize the magnetic field line stochastization given by magnetic islands overlapping, thought to be associated with the ELM mitigation by the RMP field. With the radial component of the perturbed magnetic field calculated by MARS-F, both the vacuum Chirikov parameter and the plasma response corresponding quantity can be obtained. Although the vacuum approach is probably the most common in present literature, plasma response is strikingly important for the final RMP effect. In particular, RMP screening by resistive plasma response and toroidal flow yields a substantial amplitude reduction of the resonant components of the perturbation. This significant reduction in the resonant field amplitude, compared with the external field, is mainly due to the strong shielding effect coming from the toroidal plasma rotation. Therefore, the resistive plasma response leads to a significant reduction in the Chirikov parameter. For this reason, the total perturbed magnetic field (i.e. sum of vacuum and plasma response components) is used in this work to calculate the Chirikov parameter. Simulations summarized in Figure 4 suggest that a total current of 20 kAt on each coil already provides sufficient stochastization level over a wide range of phasings for the reference scenario used in input. As support to the general discussion on coil technical specifications, it is worth mentioning here that a study on EF correction based on the same statistical approach as in [8] suggests an order of magnitude for current of 20 kAt in each coil for that function. In summary: depending on the perturbation periodicity and adopted metric, the total coil current required for ELM control ranges from 15 kAt to 20 kAt. Further uncertainties due to scenario variations are not considered in this study. These considerations are presently contributing to the definition of the corresponding power supplies [9].

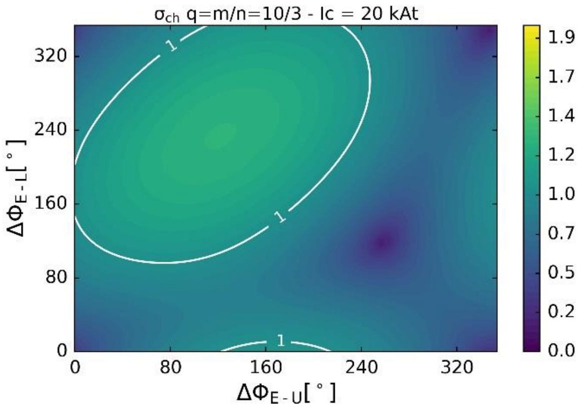

Figure 4: Chirikov parameter for an n=3 field distribution calculated on the q=10/3 surface with the total perturbed field (plasma response + vacuum) and a total current of 20 kAt on each coil.

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