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MIRA: a Multiphysics Approach to Designing a Fusion Power Plant

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According to the European strategy to fusion energy, the development and the operation of a demonstration power plant (DEMO) is foreseen as the single step between ITER and a commercial tokamak fusion power plant (FPP). DEMO is required to feature all key systems and components of an FPP and to comply with a set of general goals [Donné, 2018]. These goals include a few hundred megawatts electric power generation, a closed fuel cycle and long pulse (or steady state) plasma operation.

The conceptual design of DEMO begins with the quantitative definition of these main goals and shall proceed by selecting the major reactor parameters. The approach adopted in the EU-Programme [Federici, 2018] follows different steps, iteratively repeated until a certain grade of satisfaction, consistency and attractiveness is met (see Figure 1, black solid line path). Hence, the beginning of the actual engineering design hinges upon the verification of these conditions.

Dedicated computational tools - referred to as systems codes - are deployed to produce a reactor baseline, upon definition of reactor requirements, constraints and architectural features. The systems code output is transferred to the design codes, normally in form of a 2D reactor sketch and major reactor parameters (e.g. radial build, fusion power, major radius and magnetic field). Presently available fusion systems codes, such as PROCESS [Kovari, 2014], aim at exploring one (or more) reactor configurations that simultaneously fulfill the plasma physics operational limits, the engineering constraints and the plant general goals. In general, they rely on rather basic physics and engineering models (mostly at zero or one-dimensional level). The design codes, instead, are very detailed but run on much longer computing times and model limitations.

Due to the broad multi-physics and multi-scale spectrum involved within the design process, it is rather challenging to maintain data consistency and to keep an expedite design flow. In turns, wide modelling gaps between systems codes (0D/1D) and design codes (3D) might slow down and hinder the design loop, thereby increasing the number of iterations. To this end, the connections between system and design codes can be consolidated by complementing the systems codes by means of a more refined and intermediate system analysis tool (see Figure 1, red-dashed line path): this step is referred to as MIRA, *Modular Integrated Reactor Analysis.*

MIRA [Franza, 2019] is a high spatial resolution design tool developed at KIT, incorporating the physics and the engineering insights of the utmost domains of tokamak reactors. MIRA relies on a modular structure and provides a FPP baseline. With reference to the flowchart of Figure 2, it incorporates into a unique computing environment a mathematical algorithm for the following problems:

- 2D radial/vertical geometry and material characterization of physical components, i.e. plasma, breeding blanket (BB), vacuum vessel (VV) and toroidal field (TF) and poloidal field (PF) coils;
- 2D free-boundary plasma magnetic equilibrium;
- constrained gradient-based PF coil solver, incorporating plasma shaping requirements and coils engineering constraints for all plasma operational phases, i.e. breakdown, start of flat-top (SOF) end of flat-top (EOF);
- plasma and divertor physics modules based on one-dimensional ion, electron and impurity transport [Fable, 2018];
- quasi 2D neutron and photon core radiation transport for the evaluation of breeding (TBR), heating and shielding capabilities of all in-vessel reactor components;
- 3D magneto-static modelling of TF and PF coils elements and engineering characterization of superconducting cables;
- Plant integral modelling and power performances.

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Compared to presently available system codes, MIRA is based on a higher mathematical sophistication, engaging systems analyses up to three-dimensional space resolution. This allows scoping multiple reactor configurations with a more consolidated modelling granularity at a component level and with a holistic view of the entire plant, thereby leaving room for design modifications at higher degree.

The MIRA approach has been applied to the DEMO baselines 2015 [Franza, 2019] and 2017, generated by means of the PROCESS code. The analyses have been carried out by taking an identical set of input assumptions and requirements (e.g. same fusion power, major radius and aspect ratio) and observing the response on the key design targets and the imposed operational limits. Based on more accurate MIRA analysis, both baselines have been found in conflict with some of these limits, in particular on plasma burn time (33 % below the two-hour goal) and maximum TF ripple on the plasma boundary (13 % above its upper limit). The major causes for these discrepancies between PROCESS and MIRA are attributed to the reduced space resolution, to the modelling simplifications and to limited engineering capabilities of PROCESS. In PROCESS, the burn time is based on simple 0D magnetic flux conservation and peak magnetic field in the central solenoid (CS), whilst the TF ripple is calculated from predefined scaling laws. In MIRA, instead, the burn time derives from 2D calculation of poloidal flux profiles $\Psi(r, z)$ at SOF and EOF magnetic equilibrium configurations (see Figure 3) with plasma shaping requirements ($\partial\mathcal{D}_p^t$ target shape) and coil technological limits. The TF ripple is computed via 3D magneto-static analysis.

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The outcomes of the DEMO 2015 and 2017 baselines analyses have illustrated that modelling simplifications, affecting the state-of-the-art systems codes, affect considerably the overall design of the reactor. Therefore, the application of the MIRA approach to analyse a DEMO baseline can mitigate the lack of modelling instruments before engaging the design codes analyses (Figure 1). Accordingly, a set of active measures has been addressed to steer some identified reactor geometric variables in favour of a design point that fulfils the imposed constraining conditions. Such measures involved a parameter scan on the inboard BB radial width and outboard TF coil radial extension. Apart from fulfilling the lower and upper bounds on burn time and TF ripple, the addressed parametric studies have shown also non-trivial inter-parametric dependencies, never explored in fusion system analyses. For instance, a reduced thickness for inboard BB and TF coil leg has been identified in connection with plasma burn time, TBR requirements and coils technological limits (both in CS and TF coils superconducting cables).

In conclusion, this work poses new basis to designing a tokamak reactor and to parametrizing multiple technological solutions. Accordingly, a deeper and a more centralized multi-physics reactor analysis can speed up and improve the whole design process.

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