The 4C code as a candidate tool for the qualified analysis of superconducting magnets in the licensing of nuclear fusion reactors

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Introduction. The failures in the magnet system of a tokamak, storing a large amount of energy, could lead to damages to the confinement barriers, namely the Vacuum Vessel (VV) and the cryostat [1]. For this reason, a careful investigation of the magnet system operation in any (normal and faulted) condition is required already during their design phase, to ensure that the safety is never compromised. Numerical models are typically used to perform dedicated predictive simulations of the superconducting (SC) magnets cooled by supercritical He (SHe). However, to the best of the authors' knowledge, so far none of them is qualified by the licensing authorities to be used for the assessment of the integrity of the 1st safety barrier (the VV). The Cryogenic Circuit, Conductor and Coil (4C) code [2] developed more than 15 years ago at the Energy Department of Politecnico di Torino for the thermal-hydraulic analysis of the ITER superconducting magnets, underwent since then an impressive series of verification and validation (V&V) exercises [3]. Thanks to this unique qualification history, in this work the 4C code is proposed as a scientific computing tool to be used in nuclear safety analyses.

Methodology. General guidelines for the qualification of scientific computing tools used in the nuclear safety demonstration are described by the IAEA [4] and include:

1) Definition of the intended scope of utilization of the code according to the identification and ranking of the principal phenomena challenging the safety of the machine.
2) Tool qualification by V&V and uncertainties quantification (UQ) [5].
3) Scaling and/or transposition of the validation results, to specify how the conclusions of the validation apply to the intended scope of utilization. This is needed because of the geometrical and physical differences between the tests used for the validation and the real geometry may have an impact on the physical phenomena, questioning the ability of the models to remain predictive. This evaluation may be based on other experimental data, sensitivity analyses or expert assessments [6].

Moreover, again according to [4], each computer code should be adequately documented to facilitate review of the models and correlations employed, ensuring that they are not applied outside their range of validity. Finally, the code must be continuously maintained, with a proper tracking of the errors and reporting of their correction status.

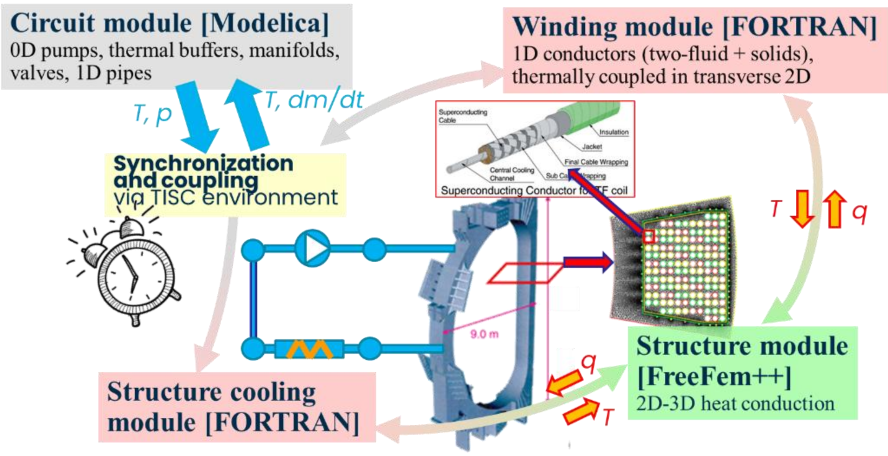

Figure 1. Schematic of the roadmap for the qualification of scientific computing tools used in the nuclear safety analyses.

Scientific computing tool. The 4C code [2] allows the system-level thermal-hydraulic modeling of transients in the whole magnet system of a fusion device. It has a modular structure. Each module, suitably coupled to the others, describes a sub-section of the system, namely the SC winding with its cooling paths, the bulky structures, the casing cooling channels and the external cryogenic circuit for the SHe, if needed including also the entire He refrigerator (see Figure 1).

Results. For the superconducting magnets of the EU DEMO fusion reactor, we started with the identification of the Postulated Initiating Events (PIEs) [6], step 1 above. A subset of the PIEs listed there can be related to physical phenomena (e.g. thermomechanical stresses) possibly arising during both slow, operational cooldown transients as well as fast, fault transients like a quench or a fast current discharge. In view of the need to address these safety-related transients, recently some new modules have been added to the 4C code to include additional pieces of physics, namely the electrical model of the power supply circuit [8] and the electro-magnetic model of the coil [9].

Concerning step 2, the 4C code has been verified according to ASME standards: the solution verification was carried out by means of the method of the manufactured solution [5], checking the order of accuracy of all the modules. Also a code-to-code benchmark campaign was carried out against different tools, involving the whole code (as in the case of the ITER TF coils cooldown) or the cryogenic circuit module in standalone. A big effort has been made to extensively validate the 4C code against measurements coming from different magnet systems and with time scales spanning from week-long cool-down to very fast discharge of the current, see Figure 2. Two predictive validation exercises have also been successfully carried out, using data collected in the HELIOS facility and during ITER TF Insert coil tests in 2017 [10], where the evolution of the quench propagation was simulated. The UQ will be initially addressed within this work, by means of suitable parametric analyses for the different transients, to assess the sensitivity of the validation results.

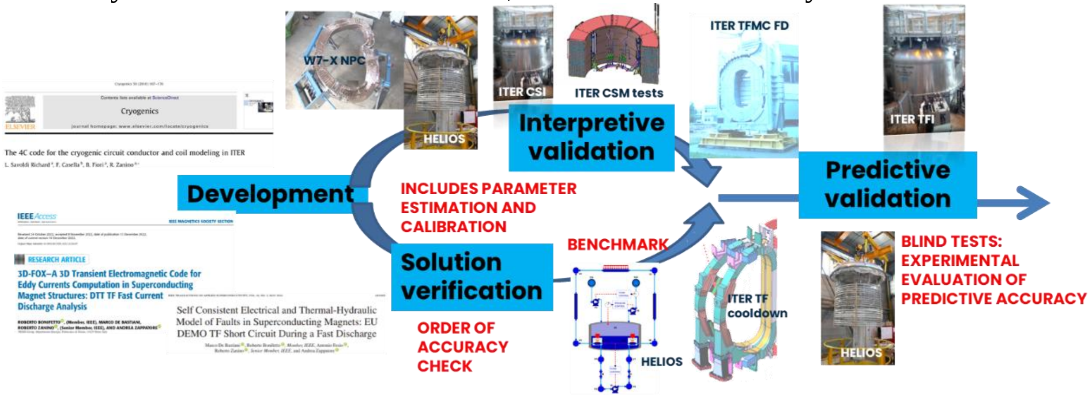

Figure 2. 4C code qualification: Verification&Validation roadmap.

The transposition of the validation results (step 3), is in some cases more straightforward: when the experiment was carried out on a full size coil (e.g. the ITER model coils and Central Solenoid modules), only the operating conditions should be properly scaled with the support of other tests (e.g. the performance measurement in different conditions); for other validations, also parameters related to the geometry must be properly scaled, by means of similitude or separate validation of other geometrical effects, as e.g. the inter-turn and inter-layer thermal coupling not present in an insert coil.

Conclusions and perspective. The 4C code is proposed as a possible scientific computing tool to be used in the nuclear safety demonstration of future nuclear fusion reactors, with special reference to the superconducting magnet system. Its qualification (verification and validation) roadmap has been presented and discussed in compliance to the IAEA guidelines. Further actions to be taken towards its qualification concern the uncertainty quantification and the transposition of the validation results, as well as the code documentation and error tracking, reporting and fixing.

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