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THE 4C CODE AS A CANDIDATE TOOL FOR THE QUALIFIED ANALYSIS OF SUPERCONDUCTING MAGNETS TOWARDS THE LICENSING OF NUCLEAR FUSION REACTORS

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Abstract

The failures in the superconducting magnet system of a tokamak, which stores a large amount of energy, could compromise the confinement barriers, namely the Vacuum Vessel (VV) and the cryostat. For this reason, a careful investigation of the magnet system operation in any condition is required already during its design phase, to guarantee the safety of the reactor. Numerical models of different levels of sophistication have been used for decades now to perform dedicated simulations of the superconducting magnets cooled by supercritical He. However, to the best of the authors' knowledge, none of them is qualified so far 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, for the thermal-hydraulic analysis of superconducting magnets in a fusion reactor, has undergone an impressive series of verification and validation exercises over the years. Thanks to this unique qualification history, the 4C code is proposed here as a scientific computing tool to be qualified by the licensing authorities, to then reliably used it in safety analyses of future nuclear fusion plants.

1. INTRODUCTION

The superconducting magnet system of a tokamak is not a safety class component. However, it stores a large amount of energy, and in the case of the toroidal field (TF) coils directly envelops the first confinement barrier, namely the Vacuum Vessel (VV), and is surrounded by the second one, i.e. the cryostat. As a result, the catastrophic failure of the magnet system (e.g. the structural collapse of the casing, or the ejection of the coil from the torus) could damage safety-relevant components and could ultimately lead to the release of radioactive material in the environment. Safety analyses have already been carried out e.g. for ITER [1]-[2], and this possibility has already been investigated in [3]: strong asymmetric loads on the magnetic system can induce severe damages to their structure, up to the collapse of the coils on the VV. As a result, a careful investigation of the magnet system operation in both normal and faulted conditions is required already during its design phase, to ensure that the integrity of the safety relevant components is never compromised. Numerical models are typically used to perform the deterministic safety analysis (DSA) of the superconducting (SC) magnets cooled by supercritical He (SHe), see e.g. the THEA/SUPERMAGNET Suite [4], the VINCENTA/VENECIA suite [5], TACTICS [6] and the 4C code [7]. Among the available scientific computing tools (SCTs), however, none is licensed by the safety authorities to be used for the DSA. On the other hand, several public and private initiatives aiming at building the first nuclear fusion power plants in the next decade demand for such a qualified tool.

The Cryogenic Circuit, Conductor and Coil (4C) code [7], for the thermal-hydraulic analysis of the superconducting magnet system of nuclear fusion reactors, has been undergoing a continuous development over the last 15 years at the Energy Department of Politecnico di Torino, Italy. Recently, other pieces of physics have been added, including electromagnetic phenomena [8], electrical circuits [9], [10] and mechanics [11]. Most importantly, the 4C code already underwent a long series of verification and validation (V&V) exercises [12]. In this work, the 4C code is therefore proposed as an SCT to be used in nuclear safety analyses of future fusion reactors.

General guidelines for the qualification of SCTs used in the nuclear DSA are described by both the ASN (*Autorité de Sûreté Nucléaire* – Nuclear Safety Authority) / IRSN (*Institut de Radioprotection et de Sûreté Nucléaire* – Radiation protection and Nuclear Safety Institute) and the IAEA (International Atomic Energy Agency). In particular, the ASN/IRSN guide 28 ("Qualification of scientific computing tools used in the nuclear safety case – 1st barrier", [13], [14]):

— Provides recommendations to be implemented in order to ensure that an SCT is qualified in accordance to ASN's requirements.

— Specifies the contents of the file to be produced by the licensee for transmission to ASN regarding the SCT qualification.
— Indicates that the scope of utilization of each SCT is to be defined according to the identification and ranking of the principal phenomena.
— States that qualification of an SCT is achieved after the successful accomplishment of: verification, validation, quantification of uncertainties and transposition from the validation range to the scope of utilization. The transposition consists in identifying the geometrical and physical differences between the validation experiments and the real application case, to confirm that the model capabilities assessed by means of comparison to the former are maintained also in a range relevant for the latter [13].

On the other hand, the IAEA document "Deterministic Safety Analysis for Nuclear Power Plants" [15] addresses the ways of performing DSAs to achieve their purpose in meeting safety requirements. Based on the guidelines presented in both documents, we propose the following procedure for the qualification of the SCT for the tokamak magnet system, see *FIG. 1*:

(1) Identification and ranking of the principal phenomena challenging the safety of the machine.
(2) Definition of the intended scope of utilization of the SCT according to (1), and choice of the appropriate SCT.
(3) Definition of the Verification and Validation (V&V) matrix to qualify the SCT.
(4) SCT qualification by V&V and uncertainty quantification (UQ) [16].
(5) 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 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 predictive capability of the models. This step may be based on experimental data different from the validation ones, sensitivity analyses or expert assessment [14].

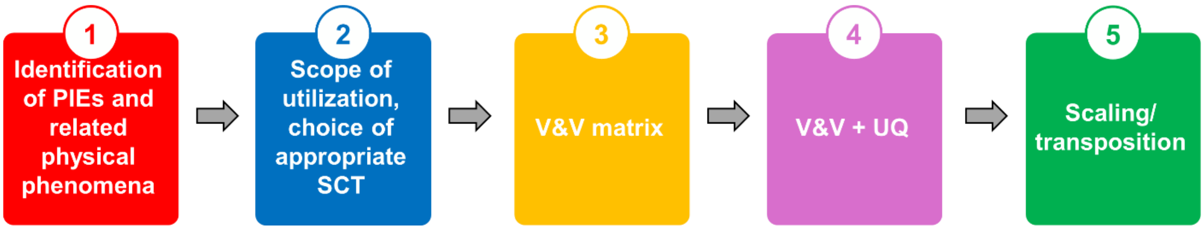

FIG. 1. Schematic of the roadmap for the qualification of scientific computing tools used in nuclear safety analyses.

Moreover, again according to [15], each SCT should be adequately documented by:

— Code manual for developers and users to facilitate the review of the models and correlations employed, ensuring that they are not applied outside their range of validity;
— Documentation of V&V activities;
— Error reporting and corrective actions.

Finally, the development and maintenance of the SCT should include:

— Acceptance testing, including non-regression (to ensures that newly introduced changes do not reintroduce previously resolved issues or alter the expected behaviour of the software) and interface tests;
— Update of the documentation;
— Version control;
— Portability on different platforms.

In view of the potential safety-relevance of the magnet system of a tokamak highlighted above, this work presents, in the next Sections, the different steps in *FIG. 1* for the DSA of the magnet system of a tokamak, following these general guidelines for the qualification of SCTs.

2. IDENTIFICATION OF THE POSTULATED INITIATING EVENTS AND RELATED PHYSICAL PHENOMENA

According to [15], "the postulated initiating events (PIEs) should include only failures that lead to the challenging of safety functions and ultimately to threatening the integrity of barriers to releases of radioactive material". The PIEs should be identified using analytical methods (e.g. hazard analysis, failure modes and effects analysis – FMEA – as that reported in [17] for the magnet system of the EU DEMO), lists from safety analyses of similar plants, experience for similar plants and results from probabilistic safety analyses, as those presented in [18]-[20].

A catastrophic failure of the magnet system that could severely damage the containment barriers (VV and cryostat) could be initiated by a short circuit or an unmitigated quench [1], therefore identified as PIEs: the resulting asymmetry in the current distribution could indeed cause strong non-symmetric loads on the magnetic system, leading to its partial or total collapse if the thresholds adopted to design the coil casings are overcome. DSA of a short circuit already performed [10] shows that it can be caused by a fast discharge (FD) of the current in the magnet system, triggered e.g. to protect it from a quench, in case of simultaneous loss of electrical insulation (one of the PIEs identified in [17]). The latter can also be due to, or enhanced by the loss of vacuum (LOVA) in the cryostat, following e.g. an in-cryostat loss-of-coolant accident (LOCA), another PIE already identified in [17]. On the other hand, electric arcs are not infrequent in the operational experience of similar plants, as recently similar accidents happened in both magnet testing facilities [21] and tokamaks [22]. In conclusion, the PIEs most relevant for the potential damage to the containment barriers are: unprotected quench, FD, in-cryostat LOCA.

The damage that can make the magnets collapse is caused by electro-mechanical forces,. The PIEs are however related to additional physical phenomena, as the thermal-hydraulic, electrical and electro-magnetic aspects involved in the quench initiation and propagation, but also the electrical and thermo-mechanical aspects involved in the loss of integrity of the insulation. These physical phenomena possibly arise during both slow, operational cooldown transients as well as fast, fault transients like a quench or a fast current discharge.

The (possibly time-dependent) variables to be evaluated for the different physics involved are:

— Electrical: current, voltage, inductance, electric resistance.
— Magnetics: magnetic field and eddy currents.
— Mechanical: displacements, mechanical stress, strain, Lorentz forces.
— Thermal-hydraulic: mass flow rates, pressure, temperature.

3. SCIENTIFIC COMPUTING TOOL (SCT)

In view of the PIEs identified above, the SCT needed for the DSA should be able to cope with the different physical phenomena to simulate the transient initiated by the PIE.

Restricting the scope of utilization of the SCT to the thermal-hydraulic phenomena, one of the reference tools used for the thermal-hydraulic simulation of transients in the whole magnet system of a fusion device at a conductor, magnet or system-level is the 4C code [7]. It has a modular structure. Each module, suitably coupled to the others (see *FIG. 2*), describes a sub-system, namely:

— The SC winding with its cooling paths, where the jacket and conductor temperature, the SHe pressure, speed and temperature 1D distributions are computed along both the bundle and the hole of each hydraulic channel.
— The bulky structures, where the temperature map on a selected set of 2D cross sections is computed, approximating with finite elements the 3D heat conduction problem.
— The casing cooling channels, where the 1D SHe pressure, speed and temperature distributions are computed along each channel.
— The external cryogenic circuit for the SHe, if needed including also the entire He refrigerator.

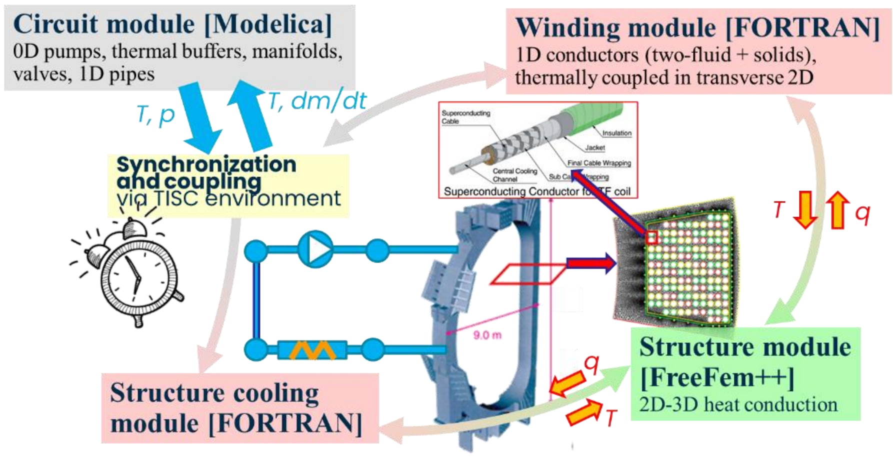

FIG. 2. Schematic view of the modules of the 4C code.

Even if the scope of the present work is restricted to thermal-hydraulic phenomena, it must be highlighted that in view of the need to address DSAs, recently some new modules have been added to the 4C code to cope with additional physical phenomena, namely:

— The electrical model of the power supply circuit [10].
— The electro-magnetic model of the coil [8].
— The thermo-mechanical model [11], potentially from a local (conductor-level) to a global (magnet level) scale.

Therefore, the 4C code is now a suite of modules that can be selected depending on the transient to be analysed. The qualification of the additional modules is however beyond the scope of this work, focussed on the thermal-hydraulic phenomena.

4. VALIDATION MATRIX

The validation matrix should be based on data collected in different facilities and in different conditions; in principle it should include [15]:

— Basic tests, i.e. simple experiments which might not be directly related to PIE as e.g. hydraulic characterization (namely, the measurement of the hydraulic impedance) or calorimetry tests to assess the energy deposited by different sources (e.g. static heat loads, AC losses, …); these tests can often be carried out at a conductor scale.
— Separate effect tests, i.e. experiments for which the driver, the instrumentation and the diagnostics allow to turn on or off or to isolate the different physical phenomena; typically the conductor or magnet scale is involved.
— Integral effect tests, i.e. experiments where the different physical phenomena are simultaneously present, but the boundary conditions are different from the operational ones. These tests can be carried out also at the large scale (e.g. the entire magnet system during the tokamak commissioning).
— Plant level tests, i.e. experiments involving the operation of the entire plant, with all the possible feedbacks and/or control loops. They involve the entire magnet system.

The list of the experimental facilities providing data for the thermal-hydraulic validation matrix used in this paper is reported in TABLE 1. Note that, due to two accidents, the electric arc and LOCA (and loss of vacuum) at the ITER CSM test station and JT-60SA can also be added to the validation matrix.

TABLE 1. FACILITIES CONSIDERED FOR THE THERMAL-HYDRAULIC VALIDATION MATRIX ([&] indicates forthcoming facilities)

Facility	Type of test	Transients	Scale
SULTAN [23]	Basic, separate effect	Normal operation, current ramps, quench	Conductor
ITER CSMC Insert Coils [24]-[25]	Basic, separate effect	Normal operation, FD / current ramps, quench	Conductor
ITER CSMC [26] ITER TFMC [27] ITER CSM cold test station [28] ITER TF coil cold test station[&] DTT coil cold test station[&] CFETR CSMC [29]	Basic, separate effect, integral effect	Normal operation, cooldown, FD / current ramps, quench	Magnet
W7-X [30] K-STAR [31] EAST [32] JT-60SA [33]	Integral effect, plant level	Normal operation, cooldown, FD / current ramps, quench	Magnet system
HELIOS [34]	Basic, separate effect, integral effect	Normal operation, LOCA, LOVA	Primary cooling circuit

5. SCT QUALIFICATION

This process ensures that an SCT is capable of correctly representing the various physical phenomena it is required to simulate, and includes the verification, the validation and the uncertainty quantification [13].

The verification ensures that the numerical methods are correctly implemented [15]. The 4C code has been verified according to ASME standards, as described in [35]: suitable numerical convergence analyses have been carried out, as well as the solution verification by means of the method of the manufactured solution [16], checking the order of accuracy of all 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 standalone.

The validation of the SCT ensures that the implemented models adequately represent the real system: the output of the code is compared with experimental data [15]. 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-downs to very fast discharges of the current, see *FIG.* . In particular, the different time scales include:

- Fast transients: fast current discharge of the ITER Toroidal Field (TF) Model Coil from 25 kA [36] and 80 kA [37]; quench in the ITER Central Solenoid Insert (CSI) coil tested in 2015 [38].
- Intermediate time-scale transients: operation of the SHe cryogenic circuit, validated by means of dedicated pulsed experiment in the HELIOS facility at CEA Grenoble in isochoric [39]-[40] and isobaric conditions [41]; AC loss measurements in the CSI [42]; current sharing temperature measurements in the ITER CS Model Coil (CSMC) [45].
- Long transients: cooldown of a W7-X non planar coil [46] and of the ITER CSMC and CSI [47], including the coupling with the refrigerator [48].

In parallel with the validation effort, also a benchmark campaign was carried out against different tools, namely a thermal-hydraulic model of the ITER TF magnet developed at the Chinese Academy of Science [50] and the circuit model of the VINCENTA code [5], involving respectively the whole code (as in the case of the ITER TF coils cooldown [49]) and/or the cryogenic circuit module in standalone [51]. Other benchmark activities between 4C and THEA™ (Thermal, Hydraulic and Electric Analysis) of CryoSoft [52] have been carried out within EUROfusion magnet work package [53], contributing to the design of the magnet system of the European DEMOnstrator (EU DEMO).

Two predictive validation exercises have also been successfully carried out, using data collected in the HELIOS facility [54] and during the ITER TF Insert coil tests [55], where the quench propagation was simulated.

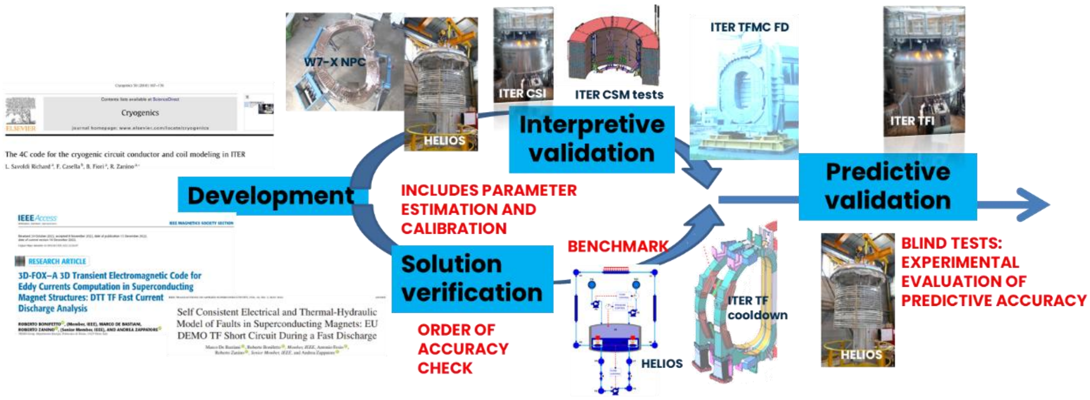

FIG. 3. 4C code qualification: V&V roadmap.

TABLE 2. TESTS CONSIDERED FOR THE 4C CODE VALIDATION (* indicates that also predictive validation was performed)

Facility	Transient	Parameters	Relevance for the DSA
SULTAN	Normal operation [43]	Hydraulic characteristic	Hydraulic impedance to compute pressurization
ITER CSMC Insert Coils	Quench [38], [55]*	Voltage, temperature, pressure, mass flow rate	Direct
ITER CSMC	Normal operation [45]	Temperature	Conductor performance to compute quench initiation
	Cooldown [47]	Temperature	Temperature distribution to assess heat transfer in the coil
ITER TFMC	FD [36]-[37]	Temperature, pressure, mass flow rate	Direct
ITER CSM cold test station	FD [44]	Temperature, pressure, mass flow rate	Direct
W7-X	Cooldown [46]	Temperature	Temperature distribution to assess heat transfer in the coil
HELIOS	Normal operation [39]-[41], [54]*	Temperature, pressure, mass flow rate	Controls to predict the real circuit operation

The validation exercise on the LOCA (and loss of vacuum) accident already started, but is still in progress [56]. The same is true for the V&V of the new modules: the verification process already started, comparing the results with classical model problems as the Felix brick problem [8].

As a result of the validation process, the uncertainty should be determined in the SCT range of validation, so that the uncertainty can be considered in interpreting any results of the DSA [15]. However, for the time being a detailed uncertainty quantification is still missing for the 4C code: it will be completed by means of suitable parametric analyses for the different transients, to assess the sensitivity of the validation results.

6. SCALING AND/OR TRANSPOSITION OF THE VALIDATION RESULTS

Thanks to the fact that all the experiments of the V&V matrix have been carried out on full-scale conductor samples and in thermal-hydraulic conditions relevant for the real coil operation, the transposition of the validation results is typically straightforward; when the experiment was carried out on a full size coil (e.g. the ITER model coils and Central Solenoid modules), only the electro-magnetic and mechanical operating conditions should be properly scaled with the support of other tests (e.g. the performance measurement in different conditions, see [57]). In particular, the parameters that could require a proper scaling when evaluated in the real (tokamak) operation of the magnet with respect to its test conditions are:

— The inter-turn and inter-layer thermal coupling not present in the insert coils.
— The quench propagation speed and the hot spot temperature, if the experiments were carried out at magnetic field and current density values different from the operational ones.
— The energy deposited in the magnet if the current evolution in the test is not that of the real system.
— The pressurization of the system, if the He volume is not preserved with respect to the real system.

7. CONCLUSIONS AND PERSPECTIVE

The need for a qualified scientific computing tool for the deterministic safety analyses needed to demonstrate the adequacy of the engineering design of future nuclear fusion reactors, with special reference to the superconducting magnet system, has been assessed.

The qualification (verification, validation and uncertainty quantification) roadmap of such tools has been presented and discussed in compliance with the IAEA guidelines, focussing on the thermal-hydraulic analyses as scope of utilization of the tool and on the 4C code as reference scientific computing tool.

The 4C code verification and validation has been reported and discussed in compliance to the IAEA guidelines. Further actions need to be taken towards its final qualification, with special reference to the uncertainty quantification of the thermal-hydraulic model and the verification, validation and uncertainty quantification of the other models, namely the electric, electro-magnetic and mechanic modules.

As a last ingredient, the documentation of the 4C code must be upgraded to include the developer and user manuals; acceptance tests must also be prepared and full portability should be ensured. After that, the 4C code will be the first scientific computing tool qualified to be used in the DSA of the magnet system of future tokamaks.

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