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Multi-scale approach to the thermal-hydraulic modelling of the ITER superconducting magnets

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***Abstract*— Superconducting (SC) magnets for ITER require the forced flow of supercritical He at ~ 4.5 K and ~ 0.5 MPa, giving thermal-hydraulics (TH) a key role in the multi-physics arena of SC magnets. Here we introduce a multi-scale approach to the problems of ITER magnets TH modelling, taking into account that the TH relevant space scales range from the 10-100 m of magnet size/Cable-In-Conduit Conductors (CICC) length, down to the 10^{-2} m of the transverse size of a CICC, while the relevant TH time scales also cover several orders of magnitude. On the "macro-scale", the entire system (winding + structures + cryogenic circuit) is considered; this requires the treatment of the "meso-scale", where single CICC are treated, weakly thermally coupled inside a winding as needed. The constitutive relations needed by the 1D meso-scale models, i.e., friction factors and heat transfer coefficients, may in turn be derived analyzing a limited portion of the CICC on the "micro-scale", with detailed 2D-3D Computational thermal-Fluid-Dynamics (CtFD) models. At each scale, different issues related to code development, benchmarking/validation and application arise and are considered in the paper. The choice of developing a code in-house is compared to the commercial codes and/or freeware. The reciprocal benefits obtained from these codes by the ITER magnet R&D program (which led, e.g., to the realization and test of Model and Insert coils, as well as many short samples), and vice versa, are discussed. Several examples of the multi-scale approach to the TH modelling of superconducting (SC) magnets will be presented in the paper, based on the experience developed during the last 15 years within our group, in collaboration with laboratories in the EU, Japan, Russia, South Korea, and the US. It is argued that the intrinsic modularity of the multi-scale approach leads to significant benefits. It is also argued that the effort towards verification&validation of the existing TH models of the ITER SC magnets has been rather limited so far, sometimes notwithstanding the existence of a significant experimental database; therefore it is recommended to launch a systematic initiative in that direction in the next future with particular attention to the assessment of the *predictive* capabilities of the existing TH codes. These capabilities are going to be more and more relevant for the ITER nuclear device, for operation and safety studies in particular, but at this time there is hardly any evidence on these capabilities in the published literature.**

***Index Terms*—ITER, superconducting magnets, thermal-hydraulics, computational modeling.**

I. INTRODUCTION

THE multi-scale approach to the thermal-hydraulic (TH) modeling of the ITER superconducting (SC) magnet system [1] is introduced in this Section. The main aim of this approach is twofold: 1) to make tractable some computational TH problems of relevance for the ITER SC magnet system; 2) to provide a conceptual framework to better understand what has been done so far and what remains to be done, highlighting the role and importance of modularity and flexibility in the development of complex computational tools.

The multi-scale approach as discussed in this paper is summarized in Fig. 1. The figure can be read both from the right to the left (i.e., top down), and from the left to the right (bottom up). In the top-down reading, we may observe that system models (i.e., concerned with what we define as the *macro* scale) require as one of their ingredients the modeling of the winding down to the single CICC (i.e., what we define as the *meso* level), which requires in turn the knowledge of constitutive relations for the heat, momentum and mass transfer across the CICC. These can be obtained from the detailed Computational thermal-Fluid Dynamics (CtFD) analysis of short portions of CICC (i.e., what we define as the *micro* level). The detailed discussion of this approach will be developed in subsequent Sections from the bottom-up point of view.

The development of the ITER SC magnet R&D program during the last 15 years or so has motivated the parallel development of computational tools, in particular for the analysis of thermal-hydraulic (TH) transients, corresponding to the evolving needs of the different phases of the program, see table 1.

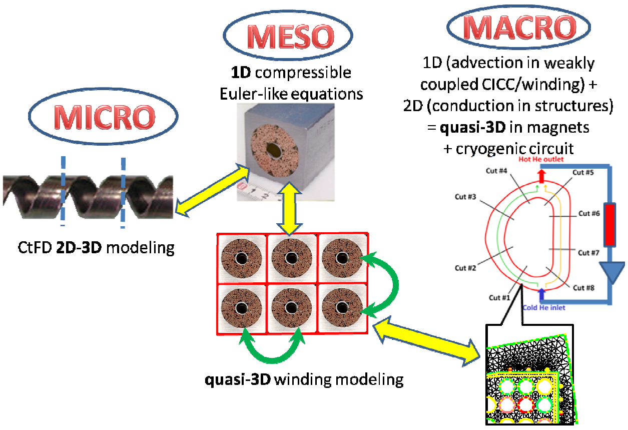

Figure 1. The three relevant scales for the thermal-hydraulic modeling of the ITER SC magnets.

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TABLE 1. Relation between ITER Magnets R&D program and development of TH computational tools

Experiments	TH computational tools	Scale
Short conductor samples	Characterization, input data, multi-physics	Micro to meso
QUELL, ITER Insert Coils	Single-CICC	Meso
ITER Model Coils	Multi-CICC/Winding	Meso to macro
ITER, JT60-SA, KSTAR, EAST	System codes	Macro

In the Table we consider, for the sake of brevity, just a few highlights of the R&D program of the ITER SC magnets, especially relevant from the point of view of TH modeling:

- Over the last 15 years, several tens of short samples were tested in SULTAN at PSI Villigen, Switzerland, originally focusing on the combined joint-conductor performance (the series of so-called full-size joint samples, see e.g. [2], [3], [4]) and later concentrating of the conductor strictly speaking, which provided at the same time important input data but also new challenges to the micro-to-meso scale models.
- In the mid '90s, the first (albeit still sub-size) cable-in-conduit conductor with a central channel was tested in the Quench Experiment on Long Length experiment at PSI Villigen, Switzerland [5]; this posed the problem of how well established models for CICC without central channel would work in the new, ITER-relevant geometry.
- In the beginning of the last decade, the two ITER Model Coils, i.e., the CSMC and the TFMC, were tested, at JAEA (then JAERI) Naka, Japan and KIT (then FZK) Karlsruhe, Germany, respectively [6], [7]. The interpretation of the test results, relying only on measured values outside of the coils, required the development of new computational tools able to correlate the (measured) conditions outside with the (unknown) conditions inside the coils.
- In the last decade, Insert Coils using different combinations of superconducting/jacket materials were tested inside the bore of the CSMC [8], [9], [10], [11], sometimes confirming the need of further development and continuing validation of tools which had till then proven to be quite reliable (this was the case, e.g., when tools validated for Nb3Sn conductors faced the issue of modeling NbTi conductors).

In order to answer the questions related to the development of the R&D program, computational models at different levels of detail were developed, implemented in numerical codes, validated and applied to the study of different types of TH transients. The development started from single-CICC models [12], [13], used to study, e.g., stability, quench propagation, etc., inside QUELL and the ITER Insert Coils, but quickly moved to multi-conductor models suitable for the analysis of the TH behavior inside the winding of a coil [14], which were aimed at that time in the first place at the interpretation of the ITER Model Coils test results. During the last years, with the growing interest for the ITER design and future operation, the TH model development has gone up to the system level, attempting to include the different SC magnet sub-systems and their sometimes bulky structures, together with the cryogenic circuit feeding them [15], [16], [17].

The possible use of a computational tool, as well as its interaction with the experiment, often changes in time, moving from the (predictive) simulations in support to the design of the experiment and to the definition of the test program, to the validation (i.e., the comparison with the experiment) of the model against the collected data and, finally, to the interpretation of the test results (sometimes confusingly mixed with the validation). This approach typically faces two difficulties: 1) the tools which are used to predict might not have confirmed predictive capabilities; 2) the validation of the tools, even when it exists, might be so specific and/or limited in scope that it might not allow a general conclusion on the qualification of the computational tools. Benchmarking the computational tools by comparison against each other, in the absence of an adequate experimental data base, allows definite conclusions only if one of the two is already validated, otherwise it will give just a good (or bad) feeling about the quality of the numerical solution.

A possible solution to these issues is that, similarly to what already happened in other communities [18], [19], [20], as the need of validated tools is increasingly realized and appreciated, then a set of systematic exercises of benchmarking and validation is promoted and supported for a selected list of TH transients, in order to confirm which are, if any, the reliable tools currently available for the different tasks. Below we propose a possible roadmap to confirm the reliability (or predictive capacity) of the available tools for the TH modeling of the ITER SC magnet system.

TH is of course just one of the many important pieces of physics contributing to the understanding of a SC magnet. Since other phenomena, like electromagnetism and (for Nb3Sn at least) also thermomechanics, are sometimes as essential as TH, multi-physics codes have been developed over the last 10 years or so, trying to include the above phenomena under the same umbrella, see e.g. [21], [22], [23]. We consider however the multi-physics aspects somewhat beyond the scope of the present paper, so that we shall only briefly touch on that in the following.

II. THE MICRO SCALE

A. *Need for CtFD Analysis*

As we shall see below in Sec. III, CICC models at the meso scale typically require in input friction factors and heat transfer coefficients between the different CICC components (in more general terms, transverse constitutive relations for the mass, momentum and energy fluxes).

While in principle these could be measured, it was noted some years ago that the experimental database was neither comprehensive nor free of contradictions [24], [25].

Therefore, we proposed to develop a *computational* database, supporting and possibly extending the experimental one, based on computational experiments performed with sophisticated CtFD tools (the commercial ANSYS-FLUENT code, in our case) on 2D or 3D discretizations of small portions of a CICC. As an example, a pipe delimited by a single pitch of the spiral was considered to study the friction in the CICC central channel; assuming periodic conditions, the mass flow rate (or the pressure drop) was imposed and the pressure drop (or the mass flow rate) was computed. In this case the validation of the model was not an issue, as a large amount of relevant data from e.g. compact heat exchangers was available in the published literature and could be used to validate the model before it was applied to the situation of our specific interest, namely the CICC.

B. *Constitutive Relations for the CICC*

The CtFD analysis of the CICC has provided several relevant contributions for the TH in an ITER CICC: understanding the reason for the non-monotonic dependence of the pressure drop in the CICC as a function of the gap size of the spiral delimiting the channel [26]; deriving a new general correlation for the friction factor in the central channel, *as a function of the gap size*, instead of ad-hoc ones different for each gap size [27]; reproducing by "microscopic" simulation the friction in the simplest cable bundle (made by *three* strands) [28] – this microscopic simulation, i.e., not relying on a macroscopic porous medium assumption, being unfortunately impossible so far to extend to a cable with a realistic number of strands; reproducing the coupled heat and momentum transfer at the interface between the two cable regions and proving that the Colburn analogy between the two mechanisms is *not* applicable in the case of a CICC [29]; confirming the relation assumed in meso scale codes, which relates the mass flux between cable bundle region and central channel to the pressure difference between the two [30].

C. *CtFD Application to HTS Current Leads and CS Inlets*

CtFD analysis on the micro scale has proved very useful for the ITER SC magnet system also beyond the CICC applications discussed so far. Here we shall present two examples.

In a collaboration between KIT and our group at Politecnico di Torino, a 3D CtFD model for the meander-flow heat exchanger used in the HTS current leads has been developed [31], [32], validated [33], and applied to the parametric study and optimization of the heat exchanger geometry. This was used, in analogy to the CICC analysis, to provide constitutive relations to a global 1D model aimed at maximizing the performance of the current lead [34]. In this case the Star CCM+ commercial code was used.

In a collaboration between the US ITER Project Office and our group at Politecnico di Torino, a 3D CtFD model of the three CS inlet designs at that time under consideration was developed [35]. Purpose of the work was to comparatively assess the three designs from the point of view of their capability to give a uniform flow among all petals at the shortest possible distance from the inlet, in order to guarantee an adequate cooling of that particularly critical portion of the magnet. For this study we used the open-source code Open Foam, which proved its flexibility in the generation of grids including for the first time tiny geometrical details (but essential for the problem at hand), like the 0.1 mm thick wrappings around each petal (the wrappings were not included in the studies described in the previous sections IIA, B), as well as the twist of the petals (previously modeled as straight). The resulting nonuniform distribution of the mass flow rate among the petals was then used as boundary condition for a 1D model of the entire first turn of the CS.

In both cases the results of the micro-scale models where then used in input to meso-scale models adopted for the global description of the current lead and of the first turn of the CS coil, respectively.

III. THE MESO SCALE

A. *Evolution of the Single-CICC Models*

Single-CICC models take advantage of the fact that the transverse size of the CICC ($O(10^{-2}$ m)) is typically much smaller than its longitudinal size ($O(10\text{-}10^{2}$ m)). 1D models along the CICC can then be developed under the assumption that the relevant thermal-hydraulic variables are uniform over suitable portions of any given cross section of the CICC.

The first such model to gain widespread use was implemented in the commercial Gandalf code [12] in the mid '90s. It described the 1D compressible flow separately in the central channel and in the annular cable region, *but assuming the same thermodynamic state in both*, thermally coupled to the heat conduction problem inside the different solid components of the CICC.

Of course, depending on the time scale of the transient of interest, the assumption of same temperature and pressure for the helium in the central channel and in the annular cable region could be satisfied or not. This was the principal motivation behind the development of a new tool, the Mithrandir code [13], which building on the Gandalf experience removed the assumption of same thermodynamic state in the two helium regions and solved for different temperature and pressure in both regions.

A somewhat striking example of the different results of the two models came from the analysis of the heat slug propagation tests in QUELL [36], [37], [38]. The apparent inadequacy of the model implemented at the time in the Gandalf code, for this kind of transients, motivated then the further development of that code to include a model similar to that in Mithrandir and in particular no more assuming a perfect (instantaneous) thermal-hydraulic coupling between central channel and annular cable region.

B. *The Traditional Modeling Targets: Stability and Quench Propagation*

Stability and quench propagation are arguably the most studied issues by single-CICC computational TH models, the first studies dating back to the end of the '70s – early '80s [39], [40].

Within the framework of the ITER magnets R&D program, it may be observed that, on the one hand, during so-called stability tests, e.g., performed during the Insert Coils test campaigns by means of inductive heaters, direct/exclusive heating of the strands was never really achieved, and the heaters were rather acting like resistive ones. This means that the experimental database for the validation of stability models of the CICC is not broad. On the other hand, comprehensive stability studies for the ITER CICC showed that, even under the most conservative assumptions, the computed stability margin is typically far above the expected disturbances [41], [42], [43].

Quench propagation studies continue to be a hot topic to this date, especially in view of their role in the design of the quench protection system for the magnets. Single-CICC models are used to compute various quantities of interest, typically including the propagation of the normal zone, the evolution of the voltage across the conductor, the hot spot temperature and the pressurization, the possibility of induced backflow at the conductor inlet. Restricting again the scope of our discussion to the framework of the ITER magnets R&D program, QUELL provided, in agreement with its mission, a significant database for the quench propagation in a sub-size Nb3Sn CICC with a central channel. Different TH codes in use at that time showed good agreement with the measured data [44], [45]. The Mithrandir code was then used also for the simulation of the quench propagation in both the CS and the TF insert coils [46], [47], showing in both cases a very good agreement with the measurements.

While at that time we thought the Mithrandir code could be considered "validated", for the purpose of the analysis of quench propagation in a full-size ITER conductor, the first attempts to simulate the quench initiation and early propagation in the Poloidal Field Conductor Insert (PFCI), a NbTi solenoid, were not giving results very close to the measurements. Indeed, there was evidence from the experiment that the peculiar sensitivity of the NbTi critical current density to the magnetic field, combined with the large magnetic field gradient on the CICC cross section typical of high-current ITER conductors, could lead to a local initiation and initial propagation inside a certain most critical petal, while only eventually the propagation should become uniform in the cross section. For that task, the Mithrandir code, assuming uniform strand temperature on a given cross section was clearly inadequate. However, when a different model, implemented in the M^3 code and allowing the separate TH treatment of each petal was adopted [48], the agreement between simulation and experiment was again good [49].

C. Multi-Physics Applications

The meso scale models implemented in the Mithrandir and M^3 codes have also built the basis for the development of the TH module of the multi-physics code THELMA. Indeed, pure TH models of a CICC (or even of simpler conductors) are applicable and relevant only if the current distribution is uniform or, at least, constant. This assumption constitutes however a strong restriction in some cases, so that coupling with electromagnetic models, allowing the current to redistribute among the cable elements, and, at least for Nb3Sn, with thermomechanical models, providing a description of the strain state inside the SC filaments, becomes necessary to achieve an adequate description of the SC system. Among the many different applications of the THELMA code we recall here just two: 1) the analysis of the effects of bending on the performance of a single Nb3Sn strand [50]; 2) the analysis of the so-called sudden quench in short samples of ITER CICC based on NbTi [4].

In the first case, the model was used in a somewhat degenerate way, bundles of filaments substituting the bundles of strands typically used in the discretization of the CICC cross section. The model was able to reproduce with good accuracy both the j_C and the n degradation [51]. In the second case, the model was able to capture in a self-consistent way the phenomenon of the precursors (voltage spikes) of the sudden quench [52], which is the result of the tight coupling between current redistribution and TH phenomena.

D. Multi-CICC (Winding) Models for the Analysis of the DC Performance of the ITER Model Coils

The need for a tool to interpret the DC performance tests of the ITER Model Coils, i.e., to determine the conditions inside the coil starting from the measured values outside the coil, led to the development of the M&M code [14]. The model implemented in the code takes into account the thermal (inter-turn, inter-layer, inter-pancake) coupling between adjacent conductors inside the winding. Since this coupling is relatively weak (i.e., the corresponding timescale is relatively long), because of the poor thermal conductivity of jacket and insulation, compared with the heat transfer along each conductor (characterized by a typically much shorter timescale), the originally 3D problem can be solved as a set of coupled 1D problems thanks to the separation of the two time scales, as such heavily building on the previous development of single-CICC models.

The M&M code was used to investigate systematically the results of both the CSMC tests [53] and those of the TFMC [7]. In particular, using as only fitting parameters the cable n value and an ad-hoc additional strain ε_{extra} on the SC filaments, it was possible to simultaneously identify the increasing degradation of the performance at increasing Lorentz load IxB, as well as to estimate the current sharing temperature T_{CS} for the different operating conditions, thanks to an excellent agreement between computed and measured V-T characteristics. (It may be interesting to note that a degradation with the Lorentz load IxB was already present in the performance of the short samples of the Nb3Sn conductors later used for the Model Coils [54], [55], but it went unnoticed until after the Model Coil tests; on the contrary, however, the short sample of the PF Conductor [4] showed a behavior which was not always confirmed in the PFCI, e.g., at high current the quench in the PFCI was sudden, as in the short sample, but not premature [56].)

IV. THE MACRO SCALE

A. *The 4C Code*

The 4C code [16] was originally developed under EFDA contract with the explicitly defined target of providing “backup and supplement for Vincenta”. The code couples three modules: 1) the winding module, based on the Mithrandir/M^3/M&M suite of meso scale models; 2) the structures module, based on a finite element (2D) discretization of an arbitrary number of cuts of the magnet structures at given poloidal locations, using the Freefem++ shareware (the strategy of the cuts was originally adopted in Vincenta, which however uses on each of them a structured, finite difference grid); 3) the cryogenic circuit module, based on the open-source Modelica language [57].

B. *Benchmarking, Validation and Applications of the 4C Code*

During the last couple of years the 4C code has undergone a first tour of successful benchmarking, verification and validation exercises and it has been applied to very different magnets and very different types of transients, as summarized in Fig. 2.

Sensitivity to some input data, like e.g. the thermal resistance between different magnet components, was studied parametrically.

To the best of our knowledge, obviously based only on the published literature, no other TH system code for the ITER SC magnets has undergone at this time a comparable series of tests fully confirming its reliability.

V. THE FUTURE ROLE OF BENCHMARKING AND VALIDATION: RELIABLE TH SIMULATION OF THE ITER SUPERCONDUCTING MAGNET SYSTEM

The multi-scale approach presented in this paper allows with its intrinsic modularity to progressively validate the building blocks of larger scale models. As demonstrated in the previous Sections, this was done for the different modules of 4C: the CtFD models at the micro scale were validated and then used to provide the constitutive relations for the transverse transport in the CICC needed at the meso scale. The single-CICC or multi-CICC models at the meso scale were validated in turn in a variety of transients and for different conductors/magnets, providing a reliable winding model at the macro scale. At the latter scale, also the cryogenic circuit module was separately validated, while the structures module was validated in combination with the other two.

Figure 2. Benchmarking, validation and applications of the 4C code so far, highlighting for each experiment the issues addressed and the major laboratories with which these exercises were carried out. Clockwise from bottom left: CEA Grenoble supercritical helium loop HELIOS [58]; KSTAR SC magnet system [59]; the TFMC monument at KIT; one non-planar coil of the W7-X stellarator [60]; one TF coil of the JT60-SA tokamak [61]; a pair of ITER TF coils.

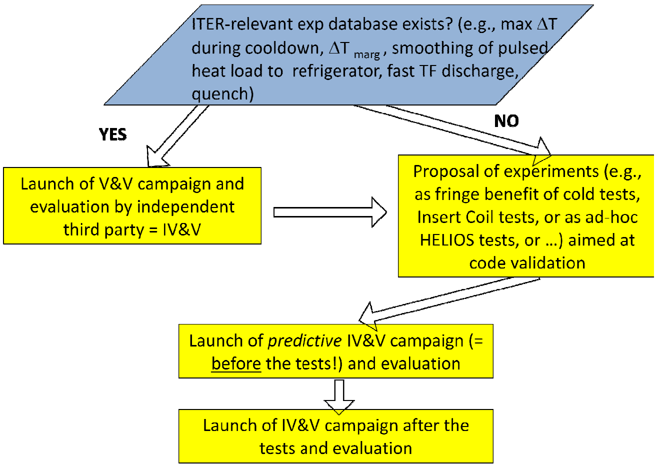

Figure 3. A possible roadmap to confirm the reliability of existing TH codes for the ITER SC magnets system.

Now the question arises: which, if any, of the existing tools for TH analysis of the ITER SC magnet system can we consider reliable, and for which type of transients? We believe that a confirmation of the actual *predictive* capabilities of the codes, e.g. for the design of the ITER operating scenarios, should be more and more needed, also considering the nuclear nature of the ITER device. At present, however, this predictive capability is not confirmed for any of the available tools, to the best of our knowledge based on the published literature. Note in this respect that some attempt was made in the past of building a database for benchmarking and validation of TH codes [74], but quickly fell into oblivion.

In Fig. 3 we propose a roadmap to approach the problem in a reasonably systematic way.

VI. CONCLUSION

A multi-scale approach to the TH modeling of the ITER magnet system has been introduced, which makes the computational problem tractable and highlights the modular structure of the computational tools, maximizing their re-usability and supporting the V&V of the higher-scale tools by the previous (and often simpler) V&V of their lower-scale components.

As an example of multi-scale approach, the published evidence for the successful validation (compatibly with uncertainties in the input data) of the Mithrandir/M&M/4C suite of TH codes, against experimental data for different transients and from different conductors, magnets, facilities and tokamaks, has been surveyed.

It has been argued that the *predictive* capabilities of the presently available tools for the TH modeling of the ITER magnet system should be important, especially considering the nuclear nature of the ITER device and the related safety issues, but at this time they cannot be generally confirmed from the literature.

A roadmap for benchmarking, validation and qualification of the predictive capabilities of the available TH codes has been proposed.

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