Stability analysis of the ITER TF and CS conductors using the code Gandalf

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***Abstract*--The stability of the TF and CS cable-in-conduit conductors for the International Thermonuclear Experimental Reactor (ITER) has been analyzed with the code Gandalf. The energy margins, computed for a number of disturbance scenarios, are in the order of some 100mJ/ccst, well above the expected disturbances. A detailed convergence study is shown to be essential not only in principle but also in practice, e.g. dual stability was found in some cases, but disappeared when the integration time step was refined.**

I. Introduction

Cable-in-Conduit Conductors with Central Cooling Channel (C^6) are foreseen for the Torodial Field (TF) and the Central Solenoid (CS) superconducting magnets of the International Thermonuclear Experimental Reactor (ITER). A detailed thermal-hydraulic analysis of these cables, the most heavily loaded in ITER, is needed in order to design the magnets with a reasonable safety margin.

The QUELL experiment at the CRPP SULTAN facility has provided a broad and detailed quench propagation database, which has been used for the validation of Gandalf and Mithrandir [1-4]. In general, the good global agreement of the simulations with the quench propagation experiments have qualified these codes as reliable engineering tools for the design of magnet using C^6. A detailed validation of these two codes against on-going and future stability experiments in the SULTAN facility is planned.

Both the 1-fluid code Gandalf and Mithrandir, a 2-fluid code developed from Gandalf, have been used in two parallel studies [5-7] for the stability analysis of the ITER TF and CS coils. This paper reports some of the results of the code Gandalf, including a brief comparison with the results of Mithrandir.

II. Model

A. Code Gandalf and conductor data

The finite element code Gandalf is the numerical implementation of a 1-dimensional model for thermal-hydraulic, quench and stability analysis of C^6 [8]. Two simplifying assumptions of Gandalf are significant for this study: the current is uniformly distributed among the strands and the disturbance is applied uniformly in the conductor cross section. The following implementation of the stability criterion has been used: at the end of the time integration (t=TEND) the amount of Joule heating power P_j released during the last time step is computed. If P_j=0 the conductor has recovered. If P_j>0, then dP_j/dt is checked; if it is ≥0 the conductor is quenching, if it is <0 the transient is still in process and the run is restarted to a longer TEND. The choice of TEND is sometimes rather delicate, as will be discussed below.

The ITER TF and CS Nb_3Sn conductors are cooled by forced-flow of supercritical helium. In the TF coil the length of the cooling channel is XLENGT=700m, one half of the conductor length of the 2-in-hand wound pancake. In the CS coil XLENGT= 674m, the length of the innermost layer at the peak magnetic field. The analysis is performed at constant peak magnetic field B and constant operating current. In the reference scenario the heat transfer perimeter at the contact surface of helium-jacket PHTJ and conductor-jacket PHTCJ are conservatively assumed to vanish when entering heat transfer quantities. In other scenarios (a) the helium in the central cooling channel is assumed not to be available, a limiting case for most conservative estimates, (b) extra co-wound copper strands are added to the nominal Cu cross section (i.e., +72% for TF and +25% for CS), (c) nominal value of PHTJ and PHTCJ (i.e., 50% of the jacket inner perimeter) and (d) twisted cross sections of copper and superconductor (i.e., 95% of the nominal value) are used. All input data are presented in [5].

B. Disturbance scenarios

Transient inputs of energy may disturb the operation of a large fusion magnet and the superconducting cable must be able to absorb them without quenching. Disturbances can be classified in terms of “slow” (loss of coolant, increased inlet temperature, overloads from joints, radiation, normal operation AC losses, etc.) and “fast” (epoxy cracks, winding displacements, slip-stick movements of individual strands, etc.) events [9]. In ITER the disturbances are mainly caused by eddy currents driven by magnetic field changes during a plasma disruption, but can also be caused by mechanical heating.

A limited number of disturbance scenarios have been investigated; some are ITER relevant and some are only significant for code benchmark comparison. In all cases the heating input is a square wave in space and time, i.e. the external linear power Q_0 is applied directly into the strands for the time t_{dis}

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and for a length equal to the initial heated zone IHZ (see Table III). In the TF coil the scenario TF-1 simulates a mechanical disturbance; TF-2 simulates a disturbance due to AC losses extended to one turn at high magnetic field, where the losses are relevant, i.e. proportional to dB/dt. In the CS coil the scenario CS-1 simulates a mechanical disturbance extended to one full turn at high field (12m), an unrealistically long length selected for code benchmark tests; the scenario CS-2 simulates a disturbance due AC losses extended to one full turn at high field, also for benchmark tests; and finally CS-3 simulates a disturbance due to AC losses extended to the part of the innermost layer exposed to high field (150m).

III. Energy margin

The energy margin EM is given as a window between two limits, i.e. the maximum value for recovery and the minimum value for quench of the energy deposited into the strand divided by the heated volume of strands (mJ/ccst). All computed energy margins are well above 200mJ/ccst (Table I), in agreement with previous stability analysis [10] and such that the conductor design appears to be conservative compared to the expected disturbances due to mechanical effects (e.g. 10mJ/ccst) and to AC losses (e.g. 80-120 mJ/ccst) [9]. The recovery/quench evolutions of the reference case are presented and discussed in terms of the variable L_{nor}, i.e. the normal zone length (see Fig. 1 and 2).

A sensitivity study has shown that there are only marginal variations of the energy margin by vanishing of the central cooling channel (except in TF-1 where the EM reduction is 36%) or by using the nominal values of PHTJ and PHTCJ, as well as by small variations of copper and superconductor cross sections. Otherwise, there is a large increase of EM (except in TF-2 [6]) if the co-wound copper is included, i.e., a large increase of the Cu cross section.

A. TF coil

In the TF-1 scenario there is an almost instantaneous propagation of L_{nor} to the full IHZ (i.e. at t= 0.1ms, dL_{nor}/dt~10m/ms). Shortly after the end of the 1ms disturbance L_{nor} shrinks due to induced flow, i.e. higher He temperature, higher He velocity, higher heat transfer coefficient, enhanced cooling. These beneficial effects start before the end of the pulse at the IHZ leading edge, and shortly after that at the IHZ trailing edge. The recovery is only partial, i.e. the normal zone is small

TABLE I. Summary of the energy margin (mJ/ccst)

Case	TF-1	TF-2	CS-1	CS-2
Ref.	545-584	234-243	305-515	248-258
(1)	331-389	224-234	267-277	210-219
(2)	1265-1363	234-243	458-468	401-410
(3)	-	243-253	-	277-286
(4)	-	231-240	-	263-272

(1) No central cooling channel
(2) Copper: strand+extra, not twisted. (The extra Cu is not included in the strand volume for normalization)
(3) Nominal value of PHTJ and PHTCJ
(4) Copper (strand only) & superconductor: twisted.

but does not vanish (L_{nor}=15cm at t=6.5ms). At this time the helium in the hole begins to decelerate, from the center towards the edges of the IHZ and L_{nor} remains in equilibrium till t=10ms [5]. In the following 20ms the conditions for a “quench” are met. However, this quench is not irreversible, as shown by the second equilibrium, reached and maintained in the time interval 30ms<t<200ms. The subsequent collapse of the normal zone is decisive, and full recovery is completed at t=260ms. If one would have selected the final time for the time integration 10ms<TEND<30ms, then our implementation of the stability criterion would have labeled this simulation as a “quench”. The irreversible quench case has practically the same evolution of the recovery case till t=210ms. The characteristics of the TF-1 scenario are that the full IHZ becomes normal almost instantaneously, and the decision recovery/quench requires times which are orders of magnitude larger than the disturbance duration.

In case of a quench in the scenario TF-2 the conductor temperature T_{co} increases slowly during ~2/3 of the 100ms heating pulse until the conditions for normalcy (T_{co}> current sharing temperature) are met at t=75ms. Due to the combined effect of Joule and external heating L_{nor} reaches its peak (~60cm, short compared to IHZ=15m) before the end of the disturbance. In the following 10 ms L_{nor} shrinks due to induced flow. As this effect decays, equilibrium is reached (L_{nor}~20cm~constant for 110ms<t<175ms). At t=175ms the effect of enhanced cooling is practically exhausted and the Joule’s and the friction heating drive the conductor towards an irreversible quench [5]. In case of recovery only a very short normal zone is generated at the end of the heating pulse and the subsequent enhanced cooling

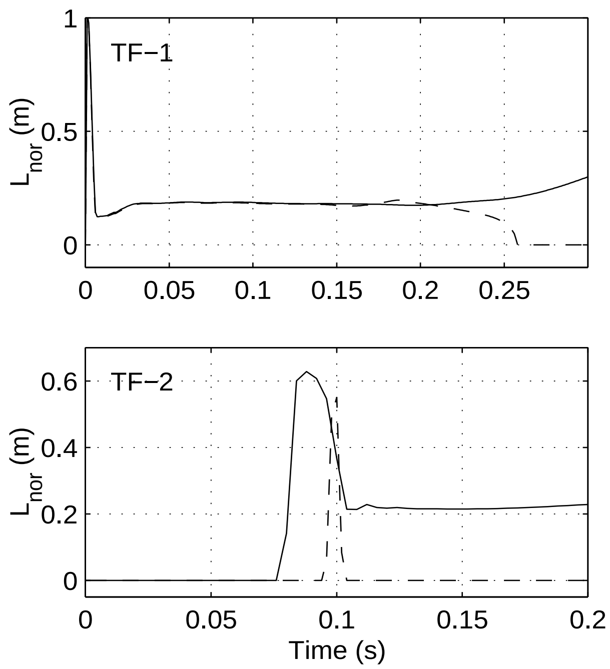

Fig. 1. Converged time history of normal zone length initiated by minimum external linear power Q_0 for quench (solid lines) and maximum Q_0 for recovery (dashed lines). The reference case of the disturbance scenario TF-1 (top) and TF-2 (bottom) is shown.

is enough for a full recovery in few milliseconds. In summary, in TF-2 the normal zone is much smaller than the IHZ, and the decision recovery/quench takes place shortly after the end of the disturbance.

B. CS coil

In the scenario CS-1 there is an almost instantaneous propagation of the normal zone to the full IHZ=12m (L_{nor}/dt~60m/ms). After a decay of L_{nor} in the next 30ms at quasi constant rate, either full recovery or equilibrium takes place. In the latter case the normal zone remains very small (<20cm) and only at t~300ms the quench becomes clearly irreversible.

In CS-2 normalcy starts at ~1/2 of the 100ms disturbance pulse and the normal zone grows in the next 20ms at the rate of 3.2cm/ms. L_{nor} then shrinks when the induced flow begins to dominate over external and Joule heating until a first and short (in time) equilibrium is reached. At the end of the disturbance L_{nor} decreases to a second equilibrium (120ms<t <220ms). At this point in time either recovery (fully completed at t=290ms) or quench take place.

The energy margin of CS-3 (367 mJ/ccst) is a numerical solution close to but not fully at convergence in space. The first normalcy begins at t=30ms (L_{nor} is ~few meters, short compared to IHZ=150m) and is followed by a quick recovery. At t=75ms the normal zone rapidly grows to ~2/3 of the IHZ (dL_{nor}/dt=22m/ms). Just after the end of the disturbance pulse the normal zone rapidly shrinks (with approximately the same rate of the growing phase) and at t=125ms there is either a full recovery or the start of an equilibrium phase (L_{nor}<5m). The quench becomes irreversible for t>200ms.

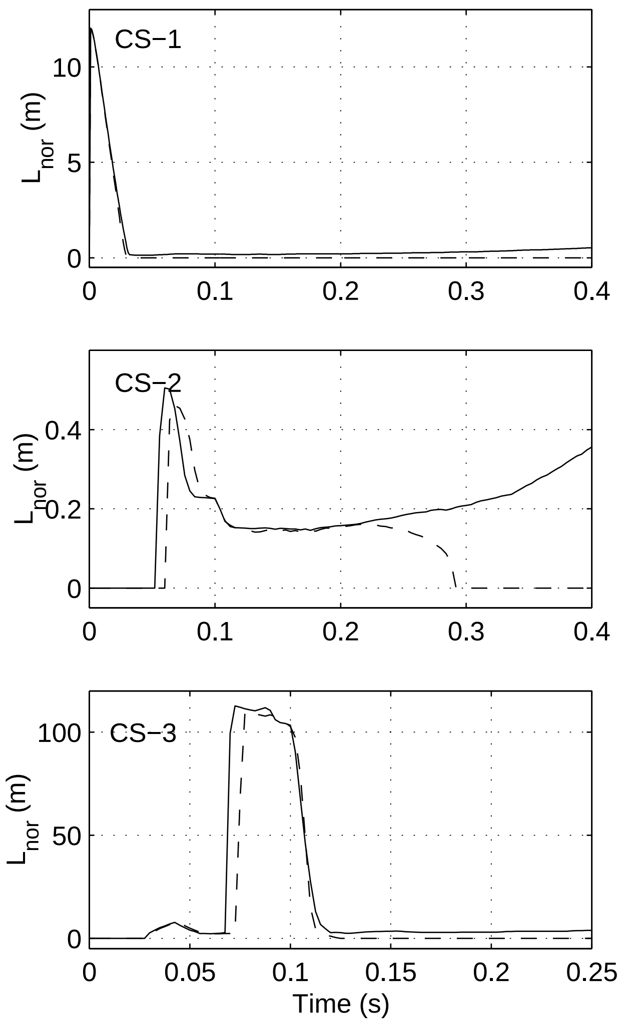

Fig. 2. Converged time history of normal zone length initiated by minimum external linear power Q_0 for quench (solid lines) and maximum Q_0 for recovery (dashed lines). The reference case of the disturbance scenario CS-1 (top), CS-2 (middle) and CS-3 (bottom) is shown. The CS-3 numerical solutions are close but not fully at convergence in space.

C. Discussion and comparison with Mithrandir

The normal zone length is either comparable with the IHZ when the helium enthalpy cannot be used and the rate of growth is in the order of several m/ms (scenarios with mechanical disturbances and CS-3), or L_{nor}<<IHZ when enough reserve of He enthalpy is available and the corresponding dL_{nor}/dt is in the order of few cm/ms (TF-2 and CS-2) [7].

A dedicated test has shown that the influence of conductor lengths far from the heater is negligible; in fact (a) the stability margins obtained using a short length of conductor (XLENGT =3•IHZ) are practically the same as the reference results and (b) the numerical solutions are insensitive to variation of the mesh outside the refined zone, which is eventually reached by the pressure wave but never by the heating wave.

For all scenarios the decision between recovery and quench requires times of few 100ms; this means that in simulations of mechanical disturbances the TEND can be orders of magnitude larger than the duration of the heating pulse [7]. In the particular case of TF-1 our implementation of the stability criterion was shown to be sensitive to the choice of TEND and this partial arbitrariness will require further work.

The energy margins computed with the 2-fluid code Mithrandir are lower than the Gandalf estimates “with” the central hole. In general, the difference between the two codes is small (see also the discussion in [7]), except for the TF-1 disturbance scenario, where the 1-fluid margin significantly exceeds the 2-fluid result. In TF-1, however, the margin appears to be still sensitive to mesh variations, but the combination of number of nodes, time step and TEND used is the finest practically affordable on our computers (e.g., 41h CPU on a SUN-Ultra-200MHz for a single threshold search). The results of the 2-fluid code are also, as expected, above the limiting cases of the 1-fluid code “without” the central hole (marginal discrepancy in TF-1 but see above). The energy margins, given as the arithmetic average between the minimum EM for quench and the maximum EM for recovery, are shown in Table II.

As a final warning, it is important to notice that in Gandalf the artificial diffusivity associated with upwind spatial discretization in the momentum equations is computed using (V+C) where V and C are the helium flow and sound speed, respectively. In Mithrandir the same quantity is computed using V only, and therefore results to be about 2 orders of magnitude lower. Although an additional dissipation sometimes gives smoother profiles, it can also artificially change the computed stability threshold. In the CS-2 case, runs performed by Mith-

TABLE II. COMPARISON OF THE AVERAGE ENERGY MARGIN (MJ/CCST)

Code	Case	TF-1	TF-2	CS-1	CS-2
Gandalf	Ref.	565	238	310	253
Mithrandir	Ref.	333	230	293	260
Gandalf	(1)	360	229	272	215
Gandalf	(2)	1314	238	463	405
Mithrandir	(2)	863	241	355	364

(1) No central cooling channel
(2) Copper: strand+extra

randir simulating Gandalf result in a threshold increase by ~25% when going from (V+C)-upwinding to V-upwinding, with all the rest unchanged.

IV. NUMERICAL CONVERGENCE STUDY

A detailed convergence study has been performed to gain confidence in the numerical solutions of the thermal hydraulic stability analysis, a complex and highly non-linear problem. The goal of the analysis is to determine the time step Δt and the space parameters, i.e. the total number of elements in the mesh NELEMS and the number of elements in the refined mesh NELREF (i.e., the mesh is refined in a 3•IHZ long region centered on the external heater, which is symmetrically located between inlet and outlet of the cooling channel), so that the stability margin does not change by a further refinement of these parameters. The test is done on a single "global" number, the stability margin, rather than on a specific variable during the transient. Fixed mesh, fixed time step and second order (in time) solution method have been used for reliability and accuracy. Time convergence has been studied by fixing NELEMS and NELREF and by decreasing Δt; space convergence by fixing Δt and one of the two space parameters and by decreasing the other. Converged solutions could be found in all scenarios except in CS-3, where unexplained spacial oscillations take place which need further investigation, and in TF-1 (see Section III-C). The resulting numerical parameters confirm that the convergence study must be repeated for each disturbance scenario and, in general, whenever an input parameter is modified, as discussed in detail in [5] (Table III).

Multiple stability occurs when the conductor is stable against small heat pulses, unstable against larger heat pulses, again stable against even larger heat pulses, and finally unstable against the largest heat pulses. Multiple stability has been observed experimentally and has been explained in terms of heating induced flow in the early stages of recovery, leading to enhanced heat transfer coefficient [11]. The multiple stability found during the convergence study of the CS-2 scenario when including the extra co-wound copper to the copper cross section is a numerical artifact rather than the reproduction of a physical phenomenon.

TABLE III. DISTURBANCE SCENARIOS AND CORRESPONDING NUMERICAL PARAMETERS FOR CONVERGENCE

Case	TF-1	TF-2	CS-1	CS-2	CS-3[a]
t_{dis} (ms)	1	100	1	100	100
IHZ (m)	1	15	12	12	150
TEND (ms)	300	400	400	400	250
Δt (s)	2.0E-6	1.0E-3	1.0E-5	1.0E-3 1.0E-4[b]	1.0E-5
NELEMS (-)	3000	1500	2000	4000	1400
NELREF (-)	1000	500	1000	2000	1000

[a] With oscillations in space
[b] Cu: strand+extra, not twisted

V. CONCLUSIONS AND FUTURE DEVELOPMENTS

The thermal hydraulic stability of the ITER TF and CS conductors has been studied with the codes Gandalf and Mithrandir in five disturbance scenarios. All simulated energy margins are of the order of some 100mJ/ccst, well above the expected disturbances. The energy margins computed with the 2-fluid code Mithrandir are, as expected, in a range delimited from below by the prediction of Gandalf "without" central cooling channel, and from above by the prediction of Gandalf in nominal conditions (except in the singular case CS-3 which needs further investigation).

A more accurate assessment of the stability margins of C^6 type conductors, including ITER's, will be possible when the thermal hydraulic codes will be validated against dedicated experiments, two of which are planned in the SULTAN facility. The simulation models should also include more realistic electromagnetic effects, e.g., current transfer. It's recommended to apply the stability analysis to a short length of conductor in order to reduce the long simulation times without loss of accuracy, and to carefully select the end of the time integration.

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REFERENCES

[1] C. Marinucci, L. Bottura, G. Vécsey and R. Zanino, "The QUELL experiment as a validation tool for the numerical code Gandalf," *Cryogenics* **38**, pp. 467-477, 1998.
[2] R. Zanino, L. Bottura and C. Marinucci, "A Comparison between 1- and 2-Fluid Simulations for QUELL," *IEEE Trans. Appl. Supercond.*, **7**, pp. 493-496, 1997.
[3] R. Zanino, L. Bottura and C. Marinucci, "Computer simulation of quench propagation in QUELL," *Adv. Cryo. Eng.* **43**, pp. 181-188, 1998.
[4] S. DePalo, C. Marinucci and R. Zanino, "Stability estimate for CICC with cooling channel using one- and two-fluid codes," *Adv. Cryo. Eng.* **43**, pp. 333-339, 1998.
[5] C. Marinucci, "Stability analysis of the ITER CS and TF conductors using the code Gandalf," Report CRPP/FT/CM/98-RE-01, pp. 1-102, May 1998.
[6] R. Zanino and L. Savoldi, "Stability modeling of ITER CS and TF CICC using the MITHRANDIR code," Report PT DE 478/IN, April 1998.
[7] R. Zanino, C. Marinucci and L. Savoldi, "Two-fluid analysis of the thermal-hydraulic stability of ITER CS and TF super-conductors," presented at ICEC-17, July 1998.
[8] L. Bottura, "A Numerical Model for the Simulation of Quench in the ITER Magnets," *J. Comput. Phys.* **125**, pp. 26-41, 1996.
[9] P. Bruzzone, "Disturbances and margins for the ITER conductors in pulsed operation," to appear in *IEEE Trans. Magn.*, 1998.
[10] M. Shimada and N. Mitchell, "Stability estimations and quench simulations for the ITER Conductors," *J. Fusion Energy* **14**, pp. 59-67, 1995.
[11] J.W. Lue, J.R. Miller and L. Dresner, "Stability of cable-in-conduit superconductors," *J. Appl. Phys.* **51** (1), pp. 772-783, 1980.