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Comparison between the predictions of the thermo-hydraulic code Gandalf and the results of a long length instrumented CICC module experiment

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Abstract

Thermo-hydraulic modeling of cable in conduit conductors (CICC) contains one main uncertainty in the heat exchange coefficient used in the different possible fluid regimes. Nowadays validation of codes, by comparison with data from experiments involving long length instrumented conductors, is one of the main technique for assessing the design tools for the large magnets foreseen in the next generation fusion machines. To this purpose, a broad disturbance scenario has to be investigated to confirm the magnet's stability versus normal and off-normal working conditions. In this paper a comparison between the predictions of the code Gandalf and the data obtained from an instrumented NbTi conductor module is carried out.

Keywords: Quench; Stability; Superconducting cable; Propagation velocity; Fusion magnet

1. Introduction

Thermo-hydraulic numerical codes have been developed to predict the behaviour of forced flow cooled superconducting magnets. Special interest is for the behaviour of large magnets in the hostile environment of a fusion machine. The only way to check the accuracy of the codes is to plan and execute experiments where the stability of a representative, instrumented, forced-flow magnet is measured as a function of all the relevant thermo-physical parameters.

2. Experimental set-up

The conductor consists of a NbTi twelve strands with a copper:no copper ratio of 5.75:1 with a CuNi 2.74 mm internal diameter jacket. The test module, a two-layer solenoid manufactured with a 35 m long conductor, is inserted into a background static field (up to 3 T) magnet.

Two concentric copper coils, magnetically coupled to it, induce AC loss along the whole length of the conductor (Fig. 1). The pulse, obtained by discharging a capacitor bank into the copper coils, can be varied in voltage to reach a maximum transient field of 1.2 T (maximum field variation 40 T/s) on the test module.

A more detailed description of the experimental set-up is given in [1].

3. Experimental conditions

In Fig. 2 typical pressure and temperature profiles are shown. The profiles are calculated with the code Gandalf [2], starting from pressures measured at the input and output and from the temperatures measured inside the module. The input temperatures are calculated by the code assuming an isoenthalpic state of the helium inside the module. The obtained values have been cross-checked with the expected critical-current values. The temperature profiles are steep, because of the helium expansion originated by the large pressure drop ΔP.

Since the conductor has no central hole, the two-fluids code has been used as a single one by imposing a zero cross-section for the hole. The length is a crucial parameter. As discussed in [1], for this kind of experiment,

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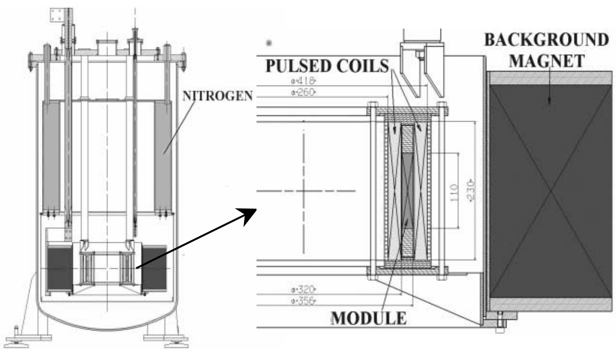

Fig. 1. The experimental arrangement.

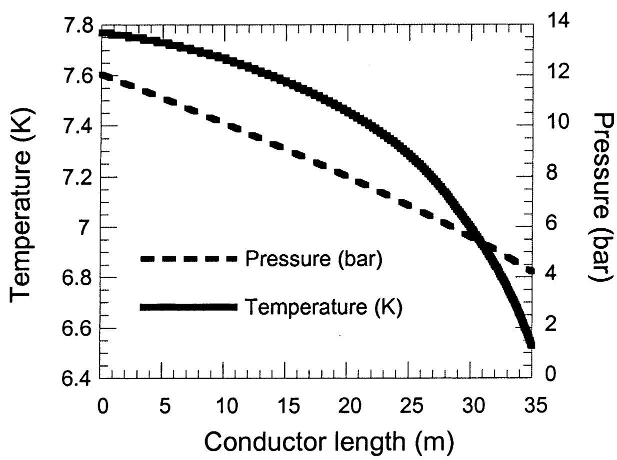

Fig. 2. Typical pressure and temperature profiles.

the usual definition of long length [3] is quite over-conservative, and due to the overall experimental conditions, our conductor fulfills the long length conditions. The mass flow is of the order of 0.2–0.4 g/s, limited by the high hydraulic impedance; however, due to the small helium cross-section, the helium speed is of the order of 1–3 m/s. Typical Reynolds numbers are then of the order of 1.5×10^4, indicating a turbulent regime and consequently a large value of the Dittus–Boelter–Giarratano (DBG) heat-exchange coefficient, that is always dominant with respect to the other relevant coefficients. The external e.m. pulse, used as the "disturbance" representative of a plasma current disruption, produces conductor heating through the AC-loss mechanism but also an additional magnetic field of the same order of magnitude of the background field that affects stability, as will be discussed in Section 6.

4. Energy calibration

The amount of energy released by the pair of copper coils onto the module conductor, as a function of the capacitor-bank charge voltage, has to be evaluated. As described in [1], the temperature increase of the conductor, due to the external e.m. disturbance, has been measured. Considering that the heat in the conductor strand is produced mainly by the AC losses, the $(dB/dt)^2$ temporal shape has been used. The helium pressures at the conductor inlet and outlet have been taken as two external time dependent functions, as measured with our sensors. The code has been run parametrically changing the input power generation distributed along the whole conductor in order to match the measured temperature increase. The corresponding energy has been plotted (Fig. 3) in order to obtain a calibration curve, i.e., a correspondence between the energy stored in the capacitor bank and that released onto the superconducting cable.

The calibration has been performed with zero transport current.

5. Stability

Once a reference temperature profile was chosen and the selected transport current supplied, stability measurements were performed. To that end, the external e.m. pulse was fired, its intensity decreased or increased depending on whether a quench was obtained or not, respectively. Measurements were repeated for different temperature profiles, transport currents (up to 1000 A), and background magnetic fields (up to 2.25 T).

Typical data are presented in Figs. 4 and 5 with comparisons to the computer code Gandalf. These run have been performed using as boundary conditions fixed pressures at the conductor ends and fixed input temperature. These conditions are representative of the actual situation, as can be inferred from the direct measurement of the respective values.

The matching between the experimental and the calculated stability curves is quite good over most of the

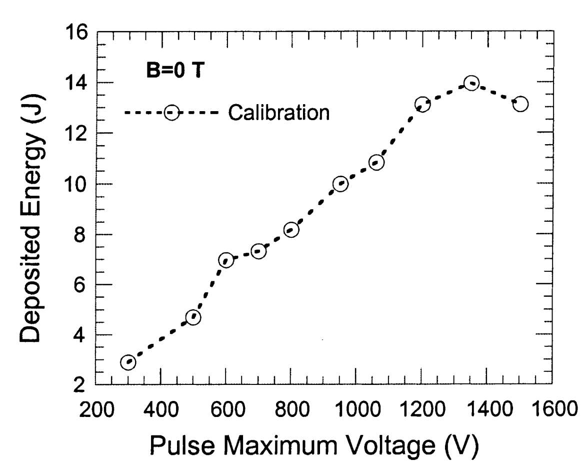

Fig. 3. The calibration curve. The energy released into the conductor by the external e.m. disturbance is plotted versus the voltage discharge of the capacitor bank power supply.

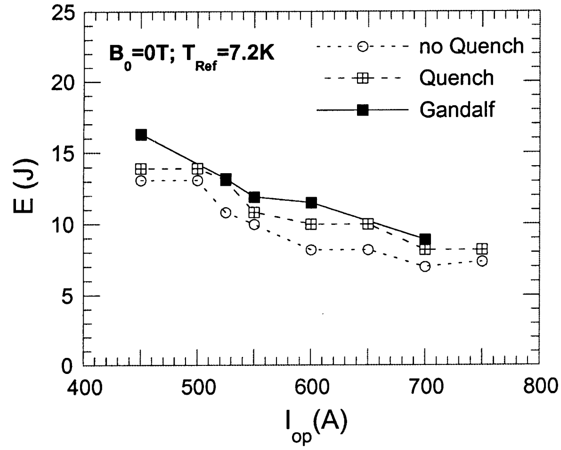

Fig. 4. Comparison between the measured and the calculated minimum quench energy at zero background magnetic field.

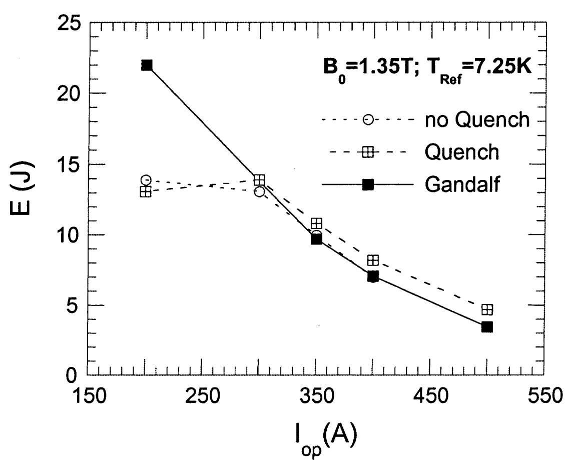

Fig. 5. Comparison between the measured and the calculated minimum quench energy at 1.35 T background magnetic field.

range. The DBG coefficient [4] is the dominant one assuming values between 3000–4000 W/m^2 K due to the high Reynolds number values. This suggests that probably, even if the helium flows through many small channels between the strands, not modelled by the code, turbulence develops, or, at least, the final heat exchange coefficient is representative of the experimental conditions. Therefore, the simple schematisation made to model the complex conductor geometry through two parameters, the hydraulic diameter and wetted perimeter, is appropriate.

Only for the point at $I_{op} = 200$ A and with background magnetic field as is shown in Fig. 5, the agreement between the code and experimental results is worse, with a 40% difference in energy. This point is the only one among that reported in Figs. 4 and 5 obtained by discharging the capacitor bank power supply at its maximum voltage, 1500 V. Looking at the calibration curve (Fig. 3) in the higher voltage region strong saturation effects are present, so that the stability decrease, with respect to the code calculated value, may be due to the saturation caused by the induced currents. This physical effect is not modelled by the code, and it could lead to a difference between measured and calculated values.

6. Quench and its evolution

The quench development during an external e.m. disturbance has been analysed in detail. The current-sharing conditions are reached since:

1. The magnetic field increase (up to 1.2 T at the maximum discharge voltage), due to the external e.m. disturbance, leads to a decrease of the current sharing temperature (Fig. 6); and
2. the induced losses increase the conductor temperature.

The consequent helium expansion takes place near the conductor extremities, leading to a velocity increase in the outlet zone, and to a velocity decrease, up to stag-

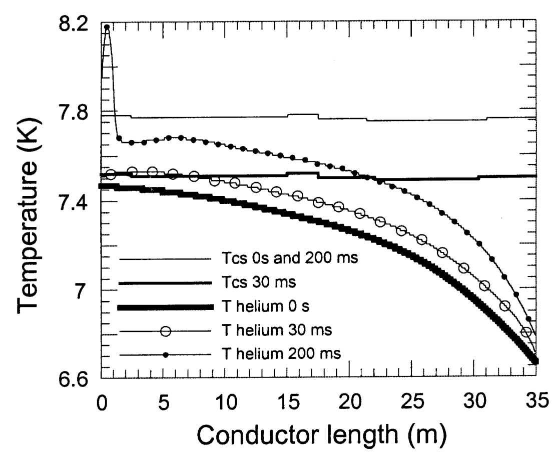

Fig. 6. Development of the quench conditions.

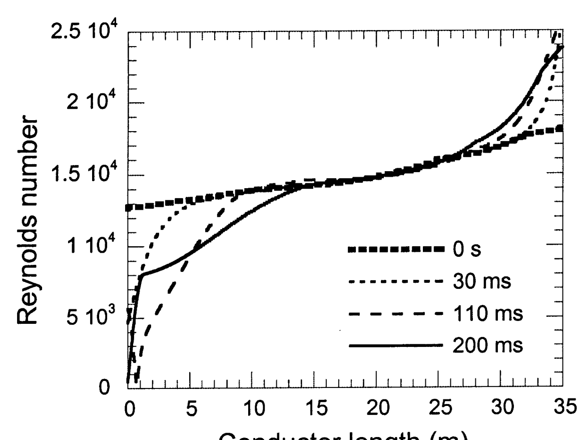

Fig. 7. Reynolds number evolution during the disturbance pulse.

nation, in the inlet zone. The helium stagnation causes a reduction of the turbulence (Fig. 7) and, consequently, of the heat exchange coefficient, up to the constant value h_{cicc} (independent of the helium flow) of 400 W/m^2 K. These conditions lead to the transition, starting, according to the code, within the first meters of the conductor. Voltage-tap measurements, due to the fast e.m. disturbance, are not reliable during the event.

7. Normal front propagation

The development of a normal zone was obtained by increasing the current in small steps at fixed temperature and background field. No e.m. disturbance was used allowing to measure the normal front propagation, by means of the voltage-taps measurements, and to compare with the code predictions. The transition starts always at the conductor first meter. This is due to the higher temperature near the inlet, the background magnetic field being rather uniform.

The results of the normal front evolution as a function of time are shown in Fig. 8.

Due to the steep temperature gradient, a "reference" temperature and current are considered: the temperature T_{ref} is the one as measured by the thermometer located at the conductor mid-length and the current I_q is the measured current at which the quench occurs. B_0 is the background magnetic field, constant within 2% along the whole conductor length.

The agreement between measured and calculated data is very good.

The normal front velocity is plotted in Fig. 9 where it is possible to see that the maximum measured front speed is about 45 m/s in the case of the highest current. The other two runs show a similar maximum front speed of about 30 m/s. This is probably due to a sort of compensation between the higher magnetic field in one case and the higher current in the other.

8. The heating steps

To check the code accuracy during slow transients, the conductor has been heated in steps. Around the helium pipe a 1 Ω heater is mounted. It has been supplied with 1, 2 and 5 A currents. In the case of 5 A, the time to reach a stationary condition was too long to be considered. This probably happens because the heater is not properly shielded and the radiated energy tends to heat up the whole cryostat. The experimental and code simulation behaviours have been represented in Fig. 10. As it can be seen, the temperature increase is represented by the code with a good accuracy. The time shift between the calculated and measured temperature inside the magnet leads to a slightly different value of the he-

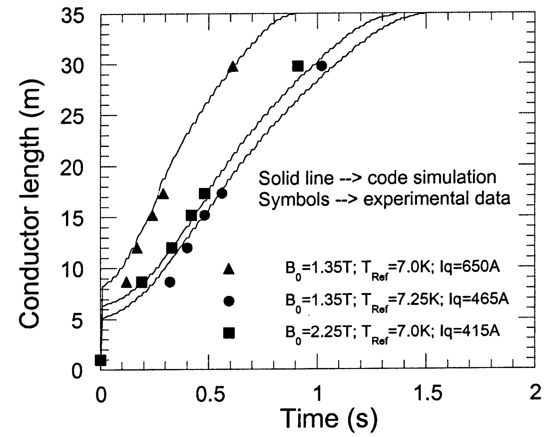

Fig. 8. Comparison between the measured and the calculated normal front evolution at different experimental conditions. In the figure are indicated the background magnetic fields, the current at which the quench occurred and the temperature measured at the conductor mid-length.

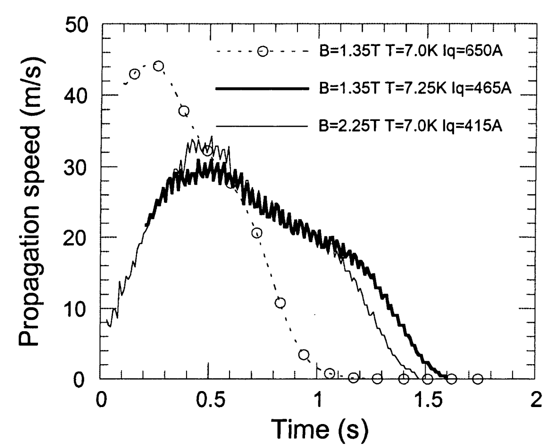

Fig. 9. Front speeds comparison. The designations are the same as in Fig. 8.

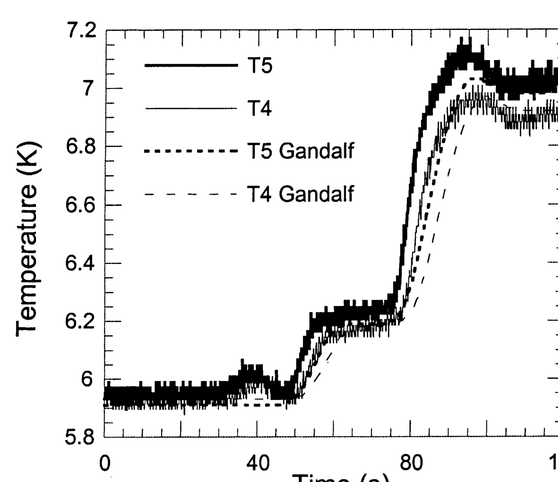

Fig. 10. Heat steps as measured at the module inlet and by the thermometers along the conductor (dashed curves). The results from the code are shown by the continuous curves.

lium flow as measured (1.0 ± 0.1 m/s) and as calculated with the code (1.2 m/s).

9. Critical currents

Critical currents are calculated by the code by means of the following expression [5]:

$$I_c(B_0, T_0) = \frac{I_{c0}}{B_0}\left(\frac{B_0}{B_{c2}(T_0)}\right)^{\alpha}\left(1 - \frac{B_0}{B_{c2}(T_0)}\right)^{\beta}\left(1 - \left(\frac{T_0}{T_{c0}}\right)^{1.7}\right)^{\gamma}, \tag{1}$$

where $T_{c0} = 9.2$ K.

We performed I_c measurements at different background magnetic fields and temperatures. Experimental data have been fitted with the above formula to find the best set of the parameters α, β, γ and normalisation coefficient I_{c0} for the conductor used in our experiment. We obtained $\alpha = 0.8, \beta = 0.8, \gamma = 2.46$ and $I_{c0} = 39,600$ $\mathrm{A} \times \mathrm{T}$.

10. Future developments

Changes in the experimental arrangements are foreseen in order to increase the magnetic field gradient and to decrease the temperature gradient along the conductor to obtain a transition starting in the central part of the magnet. It would be proper also to reduce the helium flow to change the helium regime and decrease the heat exchange coefficient. This is possible only in presence of very low conduction heat from the current leads, suggesting the use of high T_c superconductors.

The possibility to produce a pulsed magnetic field with opposite direction with respect to the background field in order to check the presence of a saturation effect, as discussed in Section 5, is under study.

11. Conclusions

A complete comparison between experimental data and simulation results has been carried out in stationary, slow and fast transient conditions.

By optimisation of the fitting parameters, critical currents are correctly calculated by the code within $\pm 20\%$.

Helium flow is in agreement within 10%. Stability and quench evolution are also in very good agreement.

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