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Results and analysis of the hot-spot temperature experiment for a cable-in-conduit conductor with thick conduit

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A B S T R A C T

In the design of future DEMO fusion reactor a long time constant (∼23 s) is required for an emergency current dump in the toroidal field (TF) coils, e.g. in case of a quench detection. This requirement is driven mainly by imposing a limit on forces on mechanical structures, namely on the vacuum vessel. As a consequence, the superconducting cable-in-conduit conductors (CICC) of the TF coil have to withstand heat dissipation lasting tens of seconds at the section where the quench started. During that time, the heat will be partially absorbed by the (massive) steel conduit and electrical insulation, thus reducing the hot-spot temperature estimated strictly from the enthalpy of the strand bundle. A dedicated experiment has been set up at CRPP to investigate the radial heat propagation and the hot-spot temperature in a CICC with a 10 mm thick steel conduit and a 2 mm thick glass epoxy outer electrical insulation. The medium size, ∅ = 18 mm, NbTi CICC was powered by the operating current of up to 10 kA. The temperature profile was monitored by 10 temperature sensors. The current dump conditions, namely the decay time constant and the quench detection delay, were varied. The experimental results show that the thick conduit significantly contributes to the overall enthalpy balance, and consequently reduces the amount of copper required for the quench protection in superconducting cables for fusion reactors.

1. Introduction

The development of future DEMO fusion reactor design following ITER has been started as several independent projects all over the world. This is an opportunity to revise the superconducting cable design used in fusion magnets in past decades, and to come up with an up-to-date conductor solution. One promising option is to use a flat Nb_3Sn cable based on the react-and-wind technology, as proposed in [1] for the European DEMO toroidal field (TF) magnet. This cable is designed with a thick steel conduit, the main purpose of which is the mechanical support against huge electromagnetic forces acting on the coil. As a side effect, the heat capacity of the relatively big amount of steel can reduce the temperature rise during a quench, i.e. the hot-spot temperature. The steel heat capacity can be exploited especially because the decay time constant in case of an emergency current switch-off is quite long (∼23 s), and the heat can thus well diffuse through the steel jacket.

In order to investigate the benefits of the thick conduit, we prepared an experimental setup in the CRPP laboratory, in which current can be transferred through a conductor during quench lasting tens of seconds.

2. Experimental setup

The setup of the hot-spot temperature experiment, sketched in Fig. 1, is based on a modified current-lead test facility Jordy at CRPP laboratory of EPFL, Switzerland [2]. The short section of superconductor, which connects the current leads, was modified and instrumented for the hot-spot experiment. The experimental setup is placed into an evacuated tank, and cooled with supercritical helium. The conductor under investigation, shown in Fig. 2, was made of the medium-size NbTi CICC with inner diameter 16.5 mm, denoted as sample #2 in [3]. The original 1 mm thick jacket was replaced in a central part, 250 mm long, by a 10 mm thick steel conduit. The main characteristics of the modified conductor are summarized in Table 1.

The current is driven by a 10 kA power supply with maximum voltage of 2 V. The aim of the experiment was to initiate a quench in the center of the thick-conduit sample, and to keep the current passing through the sample until it reaches the temperature of ∼150 K. Three measures were done in order to provoke the quench in the required position: (1) the NbTi cable was locally heated for

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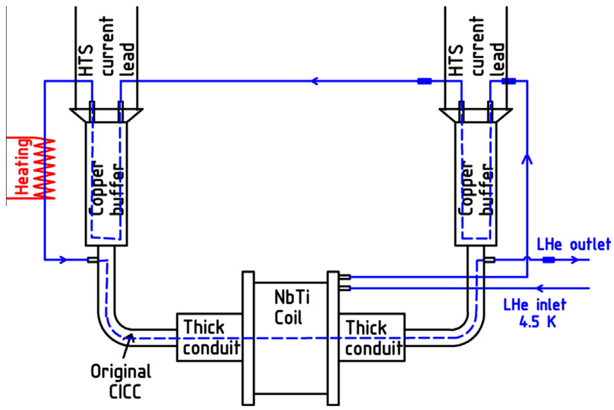

Fig. 1. Schematic sketch of the hot-spot experimental setup.

1 h to 450 °C, in order to degrade its critical temperature in the central location; (2) a 40 mm long NbTi coil was wound around the central conductor location, which allowed us to set a field of up to 1.5 T in cable center; (3) an electric heater was installed on the helium inlet, heating up just a short part of the cable, as illustrated in Fig. 1.

The cooling of different experimental components is done within one cooling circuit with supercritical helium (4.5 K) at the inlet. The cold helium is first brought to the NbTi solenoid, then to the copper buffers that restrict the heat propagation from the sample to the current leads, and finally through a heater to the sample.

The sample instrumentation with four voltage taps and 10 Cernox temperature sensors is shown in Fig. 3. The voltage is measured over three equidistant sample regions and allows us to verify that the quench is initiated in the central sample region, in which case the voltage VT2/VT3 has to rise before VT1/VT2 and VT3/VT4. The temperature sensors are located in helium on the inner surface of the steel conduit (T1 and T2), inside the steel conduit, namely 3 mm away from helium (T3 and T4) and 6 mm away from helium (T5 and T6), on the outer conduit surface (T7 and T8) and finally on top of the 2 mm thick glass epoxy insulation surrounding the steel conduit (T9 and T10). While the sensors T7–T10 are placed at the central longitudinal location, the sensors T1–T6 are shifted by ±25 mm upstream and downstream, as indicated in Fig. 3.

Fig. 2. CICC conductor [2] used in the hot-spot experiment. The original 1 mm thick steel jacket shown on the photograph was replaced by a 10 mm thick one.

3. Theoretical approach

3.1. Simulation approach

The heat propagation in a conductor is usually calculated using numerical methods, often with the help of special dedicated thermo-hydraulic programs. Most of these programs are based on the so-called 1-D models, in which heat diffusion is treated only in longitudinal direction, while the transverse heat diffusion in a given material is ignored [4]. The transverse heat propagation is approximated by introducing separate material "components", where each component is characterized by its own temperature (homogeneous in the whole component), and the transverse heat propagation between different adjacent components is modeled with the help of heat transfer coefficients. We use program Thea [5] from Cryosoft for this purpose (see Table 2). Details on the governing physics equations, providing consistent treatment of thermal, hydraulic and electric transients, are given in [5,6].

In principle, a complete simulation of the quench propagation in the conductor, i.e. the simulation that calculates ohmic heating in the cable, heat propagation between the cable, helium and jacket and the corresponding temperature increase, is possible. All the materials used in the cable, their cross-sections, the current passing through the conductor, etc. are known. In practice, such a full simulation requires a good knowledge of hydraulic properties of the cooling circuit, perimeter of strand bundle directly touching the steel jacket, and it is also sensitive to some assumptions, namely the friction coefficient of helium flow in the strand bundle and the heat transfer coefficient between the strands and helium. All these things in our experimental setup are not known, or are known with only limited precision. In addition, neither the pressure drop over the sample, nor the change of the helium mass flow rate during the quench were measured, as there was no flow meter and only one pressure sensor relatively far away from the sample. Results of the full simulation are therefore subject to a big uncertainty, in which the dominant role play the unknown friction factors, heat transfer coefficients and especially the thermal-hydraulic behavior of the cryoplant cooling circuit.

3.2. Simulation of transverse heat diffusion

In Thea, the conductor under investigation is in longitudinal direction divided into as many "elements", as required. In the transverse direction, however, the conductor is typically divided in a few components, where the whole steel jacket would be just a single component, the glass–epoxy insulation the other component, etc. Such a coarse transverse division would forbid us to observe temperature diffusion in the transverse direction.

In order to overcome this limitation of the 1-D program, we artificially divide the 10 mm thick steel conduit into 10 virtual concentric cylindrical shells (pipes). Each shell corresponds to one Thea component. Such a jacket, for better visualization divided just into two concentric shells, is illustrated in Fig. 4. The heat transfer coefficient, h_{wall}, of a cylindrical shell with inner diameter d_i and outer diameter d_j can be calculated as

$$h_{wall} = \frac{2k_{steel}}{d_i \ln (d_j/d_i)},$$

Table 1
The conductor used in the hot-spot experiment.

NbTi Strand	288 strands; ∅ = 0.70 mm; Cu:non-Cu = 1.05
Cu wires	48 wires; ∅ = 0.70 mm;
Overall cable RRR	140
Steel conduit	Inner ∅ = 16.5 mm; thickness = 10 mm