The CEA JOSEFA test facility for subsize conductors and joints

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Abstract— **The JOSEFA (JOint Subsize Experiment FAcility) experimental test facility, installed at CEA/Cadarache is devoted to perform tests at cryogenic temperature on subsize superconducting conductor and joint samples under parallel or transverse magnetic field.**

This facility was built in 1993 to investigate the performances of joints of cable-in-conduit conductors at subsize level and further upgraded in the framework of European tasks. The samples of hairpin type using subsize ITER conductors are cooled by a circulation of supercritical helium in a temperature range from 5 to 15 K and tested at a maximum current up to 10 kA. Two different helium bath cooled magnets allow to apply DC or AC transverse magnetic field up to 3.5 T or longitudinal magnetic field up to 7.5 T. A sliding system with a 240 mm stroke on the sample cryostat allows to test separately in the same sample either the conductor or the joint performances. The paper reports on how, through the conductor and joint development tasks, the facility performances were successfully increased and tested. The ITER TFMC joints using Nb3Sn conductors were first developed on this facility. The last developments, performed on ITER PF NbTi conductors and joints proved this facility to be a versatile and useful tool for superconducting magnet developments and showed the interest of possible upgrading to finalise conductor design.

I. INTRODUCTION

The JOSEFA (JOint Subsize Experiment FAcility) experimental test facility, installed at CEA/Cadarache is devoted to perform tests at cryogenic temperature on subsize superconducting conductor and joint samples under parallel or transverse magnetic field. This facility was installed in 1993 in the framework of Task MJOI and further upgraded in the framework of NET and EFDA contracts in order to increase its possibilities.

II. GENERAL LAYOUT

The main part of the joint test facility JOSEFA is a magnet cryostat inside which is installed a dipole or a solenoid magnet cooled by a LHe bath. These magnets can be supplied by different DC or pulsed power supplies through specific current leads.

Inside the magnet bore, a sample cryostat is inserted and is equipped to receive the subsize sample to be tested. The sample is a hair pin constituted of two parallel conductor legs electrically connected at bottom by a joint. This sample is connected on top to the DC external power supply.

The cooling is performed by circulating supercritical helium coming from a neighbouring source in parallel through the sample legs and the current leads. The helium flow through each sample leg can be heated separately by the way of specific resistive heaters.

Initially designed to test the joint samples, the facility was further upgraded to allow test of the subsize sample in conductor position (lower position) or in joint position (upper position) with regard to the transverse magnetic field (dipole configuration). A sketch of the facility is presented in Fig.1.

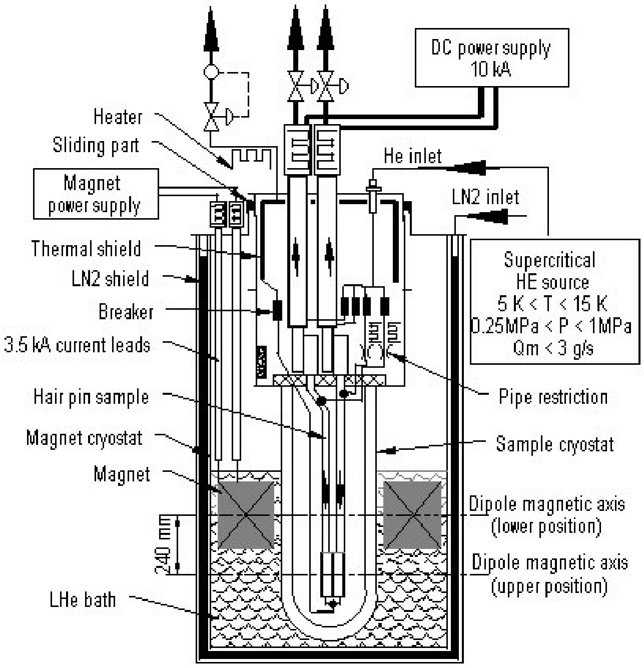

Fig. 1. Sketch of the JOSEFA facility

The command control system of the facility uses a Programmable Logic Controller which allows to control the cryogenic parameters such as temperature, pressure, heaters power and flow rate in the sample. The magnet power supply and the sample current are monitored separately by specific control command panels. A data acquisition system records the cryogenic and sample parameters as well as the values of currents in the sample and in the magnet.

III. MAGNETS

Two different magnets can be installed into the facility cryostat : The “Marius” dipole, to provide a transverse magnetic field on the sample, or the “Madeleine” solenoid, to provide a parallel magnetic field on the sample. These two configurations being possible without the need of a special adaptation.

The Marius dipole is a pulsed NbTi dipole, cooled in helium bath, producing a transverse magnetic field up to 4 T (corresponding to a current of 4 kA through the magnet) inside a 74 mm diameter useful bore, with a field homogeneity better than 90% over a length of 440 mm. The maximum pulsed field rate at 2T is 2.5 T/s. This magnet was built at CEA/Saclay in 1979 as a model of the superconducting dipoles for the UNK project [1]. The current leads of the dipole are optimized for 3 kA DC. They are made of a copper tube (30×20 mm) cooled by meshed washers.

The Madeleine solenoid, is a pulsed NbTi solenoid, cooled in helium bath, built at CEA/Cadarache in 1991, and producing a vertical magnetic field up to 7.5 T (corresponding to a current of 1.5 kA through the magnet) inside a 93 mm diameter useful bore, with a useful length of 332 mm [2]. A maximum pulsed field rate of 0.5 T/s limited by the power supply was successfully tested. Two 1.5 kA current leads connected to the solenoid were designed and manufactured using a 1 600 mm long and 108.3 mm2 cross section copper braid.

IV. SUPERCRITICAL HELIUM SOURCE

The test facility includes a supercritical helium source linked to the test cryostat through a vacuum insulated transfer line (Fig.2). The supercritical helium source is essentially made up of a vertical helium tank (volume 206 l, diameter 0.290 m, height 3.12 m, max pressure 1 MPa). This tank is initially filled with liquid helium. The supercritical helium is obtained by pressurization of the tank using an helium injection at 80 K into the upper part.. The supercritical helium is extracted from the lower part. An electric heater included in the extraction line allows adjusting the temperature of the helium flow. An 80 K thermal shield around the tank is cooled by a thermal siphon connected to a liquid nitrogen tank positioned in the upper part of the cryostat. This liquid nitrogen tank also contains the small pre-cooling heat exchanger for the pressurizing helium. The pressurization of liquid helium needed to obtain supercritical helium ($P > 0.227$ MPa) leads to an increase in temperature ($T > 5.2$ K). The 80 K helium injected in the upper part acts as a piston. The evolution of the temperature must, therefore, follow that of an isentropic compression. The maximum helium mass in the tank is about 25 kg corresponding to an autonomy higher than three hours for an average helium flow rate of 2 g/s. During this time, the temperature of the supercritical helium remains essentially constant (P = const.). The thermal losses measured in the tank are about 1W. These losses and their location do not induce convective movements, thus the helium remains stratified.

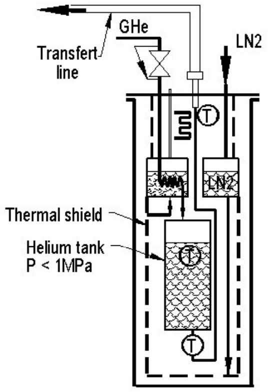

Fig. 2. The supercritical helium source

V. TEST CRYOSTAT

The test cryostat is made of two parts :

- A 400 mm diameter, 2000 mm height outer part which contains the superconducting magnet used (solenoid or dipole) maintained at 4.2 K in a liquid helium bath (≈ 150 l).
- A sample cryostat inserted into the magnet bore. It is maintained under vacuum by a cryopump made by sticking coconut charcoal on the wall in contact with the helium bath. The sample cryostat is able to receive samples with a maximum diameter of 72 mm and a maximum length of 952 mm without the sample connections to the current leads which are located in the upper part of the sample cryostat. The maximum effective total sample length including the connections is 1160 mm. The upper part of the cryostat is equipped with a 240 mm stroke sliding part at the top. This allow to test the sample in two positions, the lower and upper positions, to test separately under transverse magnetic field the conductor or the joint, respectively.

The supercritical helium inlet located at the upper part of the sample cryostat supplies as well the two current leads as the sample. The sample temperature can be independently adjusted by two 24W heaters, one for each sample leg.

All the inlet and outlet tubes are equipped with insulating electrical breakers. The helium exiting the sample is used to cool a thermal shield in the upper part of the cryostat.

To minimize the thermal flux between the current leads and the sample, the sample helium inlets are located 0.1 m beneath the sample/current lead connection. At the exit of the cryostat, the sample flow rate is regulated by a valve placed downstream from an electric heater.

VI. POWER SUPPLIES

A. Magnet power supply

The magnet electrical circuit can use two different available power supplies. A (2 kA/ ± 15 V) power supply used for AC losses characterisations by producing calibrated trapezoidal current shape between 0 and 2 kA with fast controlled ramping up and down (± 2 kA/s). A (3.5 kA/ + 3 V) power supply devoted to DC measurement with slow ramping up and ramping down through a diode. The magnet discharge is performed through a dump resistor (Rd ≤ 0.1 Ω).

B. *Sample power supply*

The space available in the test cryostat being very limited, two compact 10kA current leads were manufactured using a previously developed technology [3]. The electrical connection between the current leads and the sample is ensured by bolted connections on flat copper surfaces of 180×60 mm. To maintain a sufficient contact pressure at cold temperature, the bolts are equipped with titanium washers. For a 10 kA current, the contact resistance is lower than 3 nΩ. The power developed at the connection is then of 0.3 W, extracted mostly by the current leads.

The sample current is provided by a 3 V, 10 kA water cooled power supply controlled with a constant or variable dI/dt up to 1000 A/s. The supply is connected to the current leads through copper braids and copper bars.

VII. SAMPLES

Two types of sample have been tested in the facility. Both types are hair pin samples with two parallel legs connected at bottom through an overlap praying hand joint, and two upper terminals used to connect the sample to the 10kA current leads. In the first (historical) type, one of the legs contains an overlap (shaking-hand) joint or a butt (or a scarf) joint to be tested, the other leg is a return bus, and the lower joint is located outside the field area [4], [5]. In the second (recent) type, the sample is shorter and the lower praying hand joint can be tested under magnetic field, no joint are located on the legs [6]. The orientation of the transverse field with respect to the joint can be changed simply in the first type, by tilting the joint leg upside down, while in the second type, two samples are needed to do so.

The facility allows testing of simplified (and cheapest) samples cooled in helium bath (at 4.2 K) which has turned out to be very useful for parametric studies on joints. In this configuration, however, the sample current is limited to 3.5 kA by vapour cooled current leads.

In more relevant samples, the cooling is insured by supercritical helium flowing into the two legs from the top of the sample to the bottom. The helium outlet is located on the intermediate (shaking-hand) joint in the first type samples , while two outlets (one on each half-joint) are connected together at the bottom of the second type samples.

A sample housing constituted of a 64 mm inner diameter steel tube insure the straightness and the orientation of the sample. This tube also allows to keep the mechanical torque applied to the sample depending on the field orientation. The sample with its housing tube has to fit into the 72 mm diameter tube insert cryostat. Of course, a complete set of instrumentation can be installed on the sample.

VIII. COMMAND AND CONTROL

A Programmable Logic Controller surveys all the cryogenic parameters of the test facility. This system allows to operate at a fixed temperature under various magnetic fields and with different currents through the sample. The regulation system acts from the sample temperature order on four parallel circuits: the temperature of the cold ends of the two current leads and the two sample legs temperature. Informative living panels on a display screen allow to survey the whole process.

IX. DATA ACQUISITION

During tests, all data (temperatures, pressures, flow rate, voltages ...) can be visualized in real time and recorded through 48 available channels. Four wires (temperatures, Hall probes) as well as two wires sensors (pickups, voltages) can be used.

Each channel is filtered and amplified separately before a 0 - 10 V data acquisition. The ADC resolution is 12 bits and the maximum acquisition frequency is 1 kHz. Higher acquisition frequencies (up to 50 kHz) can be reached but on a limited number of channels.

X. OPERATION

One of the main interests of this test facility is its low helium consumption and short operating time, associated with the little personnel needed. to carry out the tests. In addition, a dismantling of the sample from the facility and a re-installation of a new sample for test can be performed without warming up of the magnet. Table 1 summarize the main operating parameters.

TABLE I
JOSEFA OPERATING PARAMETERS

	Consumption (LHe liters)	Time (days)
Cooling down	800	3
Operation	500	1
Sample exchange	100	1
Warming up	-	2

XI. EXPERIMENTAL RESULTS

The experimental campaigns in the JOSEFA facility have followed the evolution of the joint concepts for the NET and the ITER coils [7]. The first test campaigns were devoted to parametric studies on joints using Nb_3Sn conductors with samples of the first type tested in helium bath, then with supercritical helium circulation [4]. Resistance, pulsed field losses as well as stability of scarf and overlap shaking-hand joints were thus investigated [5].

The following campaigns were devoted to test the first original proposal of the CEA twin box concept using copper-steel explosion bonded plates in a praying-hand joint configuration. Parametric joint samples were again first tested in helium bath.

From the test results, key parameters such as cable void fraction (20%) and copper sole RRR (300) were fixed and two samples with two different transverse field orientations of the magnetic field with regard to the conductors plane were fabricated and tested. These samples were cooled by circulating supercritical helium. Joint resistance, pulsed field losses and stability were investigated in view of application to the ITER TF and CS coils.. All these samples made use of a square conductor containing 144 twisted Nb$_3$Sn strands inserted in a steel jacket.. Tests in parallel field were driven by plan to put the joint inside the bore of the CS coil of ITER, they show no extra loss contribution. DC resistance as well as quench temperature and loss time constant of the joint summarized in Table 2 were measured and led to a confirmation of the validity of the design. From these experiments, the estimated value of the full scale joint DC resistance was Rj < 1 nΩ at B = 6.6 T for a 20% void fraction. This result was well in line with the value gained on full size joint samples of 1.2 nΩ under the same conditions but with a void fraction of 25%. This joint design was finally retained for the ITER TFMC magnet [6].

TABLE II
SUMMARY OF NB3SN SUBSIZE JOINT PERFORMANCES IN ⊥ AND // MAGNETIC FIELD

	B⊥	B//
DC resistance (nΩ)	1.8 + 0.17B	1.9 + 0.19B
Tq at B=2T, I=10kA	12.5 K	>12.4 K
Tcs (theory)	12.9 K	13.8 K
$n\tau$	2 s	0.09 s

The last developments were performed on NbTi conductors and joints for the ITER PF coils. Subsize conductor having 108 strands compacted inside a square steel jacket were used . This study has called for adding the sliding system in the facility to be able to test both conductor and joint on the same sample. Two different strands having different resistive barriers were used for these samples. AC losses and stability measurement have brought useful information for the choice of the PF conductor strands [8]. A proposal of joint based on the CEA twin box concept was successfully qualified and later confirmed by a full size joint sample test [9]. This design constitute a candidate for the ITER PF coils joints.

A new program is now running to study the influence of joint manufacture (controlled) defaults on the current distribution inside the conductors as well as on the conductor voltage/current characteristic, using different strand coatings and different void fractions.

XII. CONCLUSIONS

The JOSEFA facility has proved to be a versatile and powerful tool for the qualification of joint designs for the NET and then the ITER coils. After successive upgrades carried out in the framework of EFDA tasks following the ITER R&D program, it is now available for testing under transverse (two possible directions) or parallel magnetic fields subsize conductors and joints within a single sample. The present facility capabilities are summarised in Table 3.

The experimental results gained since about 10 years on this facility have shown it to provide a simple way to investigate and test at low cost parametric and relevant solutions for joints and conductors, of large superconducting magnets needed in big fusion machines.

To enlarge the investigation range of the samples and to improve the measurement accuracy, further upgrading of the facility are now considered:

- increasing of the dipole magnetic field up to 4 T by the use of a 4 kA pulsed power supply.
- full separate test of each sample leg by controlling each leg mass flow rate.
- improvement of s/n ratio by the use of a new data integrated acquisition system allowing to remove the external amplifiers and conditioners.

TABLE III
JOSEFA FACILITY MAIN CHARACTERISTICS

Sample cryostat 72 mm diameter, 952.5 mm long
Maximum sample length 1 160 mm
Sample cryostat stroke 240 mm
Sample DC current ≤ 10 kA
5 K ≤ Sample temperature ≤ 15 K
0.25MPa ≤ Supercritical helium pressure ≤ 1MPa
Sample mass flow rate ≤ 3 g/s
DC transverse field ≤ 3.5 T
Pulsed transverse field ≤ 2 T with a ramp rate ≤ 2 T/s
longitudinal field ≤ 7.5 T with a ramp rate ≤ 0.5 T/s

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