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SELFIE: ITER superconducting joint test facility

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ABSTRACT

In the frame of a contract with ITER Organization (IO) on magnets assembly support, CEA designed and built a superconducting joint test facility called SELFIE (ITER SELf-FIEld joint test facility). This facility is installed at CEA Cadarache and started to operate in 2022.

This project was initiated by IO for quality control of critical assembly activities. Indeed, the magnet superconducting joints assembly is a special process, for which the performance cannot be verified until the full Tokamak is at cryogenic temperature and obviously repair cannot be envisaged once the machine is assembled. Therefore, the quality control of these joints assembly relies on procedures and qualification of the workers in charge of their implementation.

As the joints assemblies will span over three years of the ITER construction, the qualified workers will have to assemble periodically some Production Proof Samples (PPS) joints to train and keep their certification valid. The purpose of SELFIE is to test these PPS in a timely manner.

The tests scope is the measurement of the PPS resistance (few nOhms). For that purpose, PPS integrated in ITER conductors length (~200 kg weight and 3600 mm length) are tested in a liquid helium bath (4.2 K), at nominal current (up to 70 kA), in self-field. The current is provided by a superconducting transformer integrated in the same cryostat as the sample.

CEA finalized the preliminary design in 2019, complying with the requirement to achieve a full test sequence within one week (controlled cool down, test and warm-up), with an optimised operation cost. The detailed design phase was started in April 2020 followed by the manufacturing phase up to mid 2021. SELFIE integration and installation were achieved in December 2021 and the cold commissioning done in January 2022. This paper presents the SELFIE test facility and the first results.

1. Introduction

Some ITER tokamak assembly activities are quite critical and need a special qualification process before being implemented on the machine (proven procedures and workers training). It is the case for the Central Solenoid (CS), superconducting (Sc) joints assembly for which the related procedure was developed and qualified in representative constrained environment conditions [1]. As the successful implementation of such procedure can only be controlled by resistance measurement at cryogenic temperature, ITER Organization put in place a risk mitigation program, which consists to train the subcontractor operators in charge of these joints assembly on an ITER relevant environment mock-up. As the coil assembly is along several years [2], operator's ability to perform joints are regularly checked through Production Proof Samples (PPS) tested in full operating conditions on a dedicated test facility called SELFIE.

The test performed on SELFIE aims to measure the superconducting joints sample resistance (few nΩ) in cryogenic condition (liquid helium bath at 4.2 K) at 70kA in self-field. This paper describes the SELFIE test facility and presents the first results.

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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2. Production proof samples tested in SELFIE

Two types of superconducting joints are assembled on ITER site see Fig. 3:

- **The “Main Busbar (MB) joints”** are used for the connection between the feeders and each ITER coil (300 in total on the machine), see Fig. 1.
- **The “Coaxial Compacted Joints (CCJ)”** are used for the connection between the extension leads and each CS module (12 in total). These joints, more compact are exclusively developed for the CS, see Fig. 2.

Due to their vertical position and the restricted space available for their implementation, the joints assembly is complex. A dedicated representative mock-up called CJEM (Coaxial Joint Environment Mock-up) has been designed and built especially for workers training [1].

Once assembled on the CJEM mock-up, the Production Proof Samples (PPS) produced are integrated within **a test sample** complying with SULTAN[1] [3] standard for SELFIE testing purpose, see Figs. 4 and 5:

- Two legs made of ITER Cable-In-Conduit Conductors (CICC): 3.6 m ~ 200 kg.
- Two upper terminals for sample current supply.
- One bottom joint for the current loopback.
- The PPS is mounted in the middle of one of the two test sample legs (red circle in Figs. 4 and 5).
- *SULTAN (Switzerland – EPFL/SPC): reference test facility involved among others in the ITER magnets CICC development, and production quality control.*

3. SELFIE test facility description

3.1. General

SELFIE was designed for fast and simple operation in order to optimize the cost per test (helium consumption, manpower and test duration). The SELFIE tests are performed in a liquid helium (LHe) bath at 4.2 K and 70 kA, in self-field (no background magnetic field). This facility is meant to be close to the ITER site and to guarantee exclusive availability for ITER needs during the assembly phase.

3.2. The superconducting transformer

A dedicated superconducting transformer [4] integrated in the same LHe bath as the sample, provides the sample current. This quite compact equipment, including the Controller, Protection and DAS system, was designed and manufactured by the Foundation SuperACT in collaboration with the University of TWENTE. It is able to provide up to 70 kA at the secondary in steady state during 10 min for a maximum resistive load of 12 nΩ . The primary current is provided by a standard bipolar power supply (8 V/ ±240 A).

Some mechanical reinforcement systems (pre-stressed stainless-steel wires and clamps) have been implemented to withstand the electromagnetic forces involved during current cycles (hoop and radial stresses), see Fig. 6. For accurate current measurement, the secondary terminals are equipped with two Rogowski coils mounted in opposite direction towards each other. Some embedded heaters are wrapped around each secondary terminal in order to be able to cancel the secondary current during primary energization / de-energization phases by forcing a short length of resistive zone in the superconductors. The transformer main features are listed in Table 1.

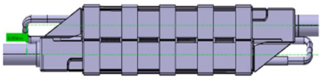

Fig. 1. Main Busbar joint (Twinbox type).

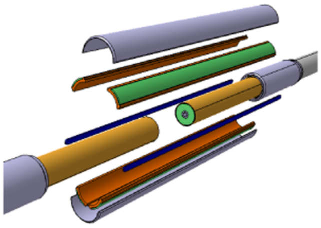

Fig. 2. CS module joint (coaxial compacted type).

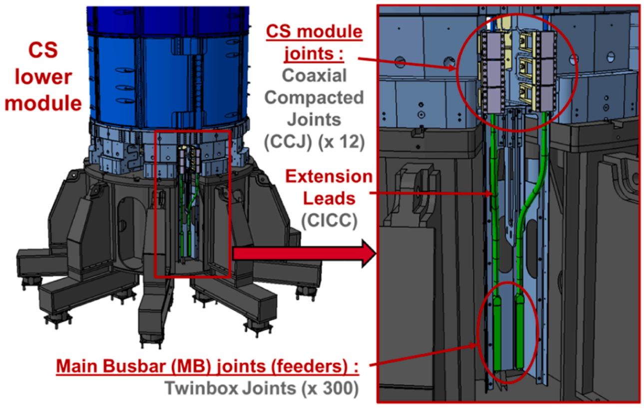

Fig. 3. Central Solenoid Sc joints environnement.

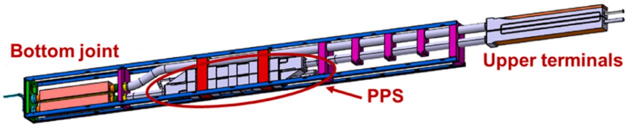

Fig. 4. Main Busbar (MB) joint test sample (Twinbox).

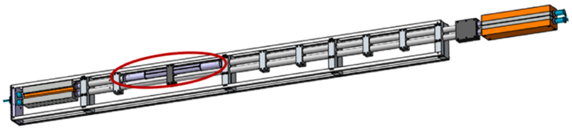

Fig. 5. CS module joint test sample (coaxial compacted).

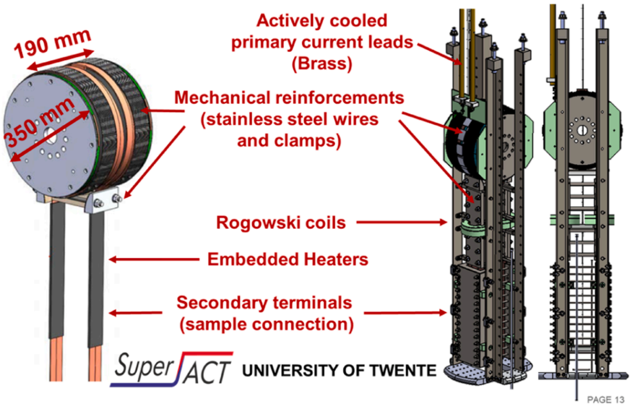

Fig. 6. Superconducting transformer integration.

Table 1
Superconducting transformer main features.

	Conductor type	Nbr. turns	I max	Self	Stored energy	B max
Primary	WST NbTi/Cu multi-filament strand 0.78 mm	**3288** 12 layers 9 mm 12.5 kg	± 240 A	3.4 H	97 kJ	3.28 T Tcs : 5.95K
Secondary	ATLAS BT Rutherford NbTi conductor 5.4 × 30 mm	**2 × 5** in parallel	70 kA	27 mH		3.1 T @70 kA

3.3. *The cryostat*

The SELFIE cryostat shown in Fig. 7, hosts the whole Test Assembly (TA) composed by **the test sample (1), the Sc transformer system (2)**, and **the supporting system from the top flange (3). A foam filler (4)** is implemented around the sample in order to optimize the LHe useful volume (∼350l). The TA is inserted inside a central **liquid Helium vessel (5)** (450 mm O.D.). The Helium vessel is surrounded by **an actively-cooled 80 K shield (6)** coupled with a 200 litres **liquid Nitrogen (LN2) guard (7)**. A **GHe subcooler (8)** is implemented inside the LN2 guard for controlled cool-down and warm-up purposes. The whole assembly is contained inside the 860 mm diameter **cryostat vacuum vessel (9)**.

3.4. *Test facility integration*

The cryostat and overall auxiliary systems required for SELFIE operation are installed in the CEA Cadarache/IRFM cryogenic Hall, see Fig. 8.

A "process valve panel" allows interfacing the cryostat circuits with Gaseous & Liquid Nitrogen (GN2 and LN2) and Gaseous Helium (GHe) networks.

A set of 5 cabinets is necessary for : **power distribution** (including Sc transformer power supply), **Sc transformer control** (Quench Detection system, data acquisition system DAS…), **Sc transformer quench protection** (Dump resistors), **the instrumentation and process control**, and **the process remote control** using Programmable Logic Controller (PLC).

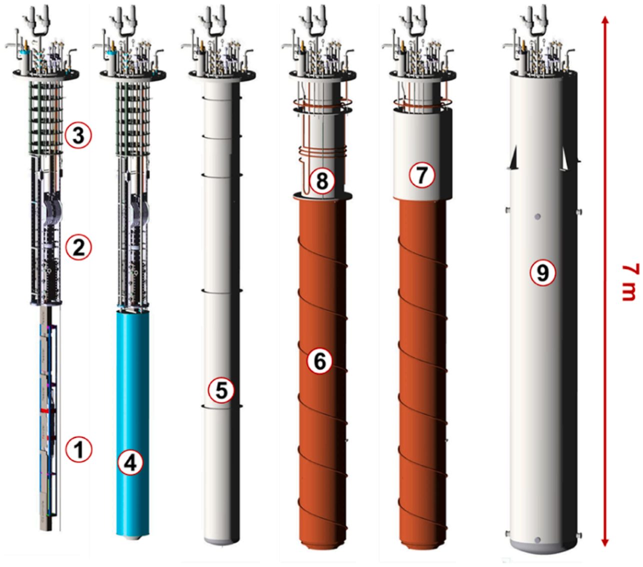

Fig. 7. Overview of the SELFIE cryostat.

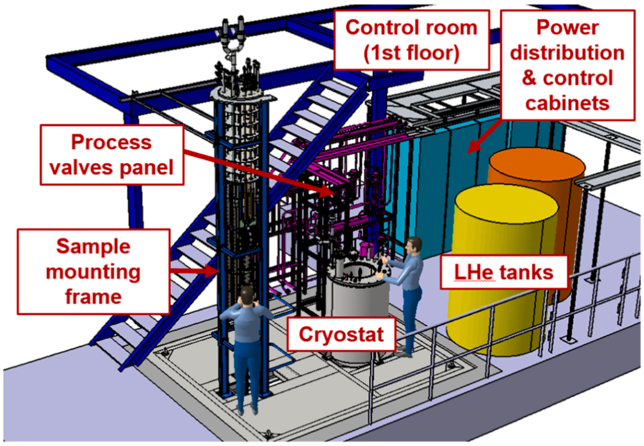

Fig. 8. Overview of SELFIE test facility layout.

A sample mounting frame enables the sample connection to the Sc transformer's secondary terminals and the instrumentation wires set-up (Temperature sensors and Voltage taps).

Two LHe tanks equipped with dedicated LHe transfer lines are used to cool-down to 4 K and to fill-up the LHe cryostat.

4. Test facility control system

Two independent control systems have been developed: one for the cryogenic process control, and another one for both the *Sc* transformer operation control and the data acquisition. Each system is monitored remotely from the control room using dedicated Human-Machine-Interfaces.

4.1. *Cryogenic process control system principle*

Based on a Programmable Logic Controller (PLC), the cryogenic process is automatically controlled for safe and optimized operation 24 h/24, 7d/w.

In particular, the Test Assembly (TA) temperature is controlled during cool-down and warm-up phases between 300 K and 80 K such to avoid any damages due to thermomechanical stresses on the Sc joints and the Sc transformer itself:

- **The overall TA DT is kept below 50 K:** at first, a GHe flow is roughly subcooled at the TA required temperature range. Thanks to the GHe subcooler optimized shape: The Test Assembly inlet temperature is roughly controlled as a function of the LN2 guard level. The TA GHe inlet temperature is then regulated accurately thanks to a GHe heater control.
- **The cool down and warm-up rates are controlled between 2 K/h and 5 K/h** thanks to a dedicated GHe flow control valve.

4.2. *Sc transformer control system*

The primary power supply control and the secondary current measurement are performed by the Sc transformer controller based on PLC. An independent quench detector module monitoring the primary voltages is able to trigger a fast discharge in case of quench event.

Overall parameters can be monitored and tuned remotely from a dedicated control software. The typical current cycle at 70 kA is shown in Fig. 9 and described below:

1: The secondary heater is switched on in order to avoid inducing high current in the secondary loop when the primary current is ramped-down to −240 A. **2:** The primary current is maintained at −240 A while the heater is kept active until the secondary current decreases to zero. **3:** The secondary current is ramped-up to the predefined set-point: 70 kA

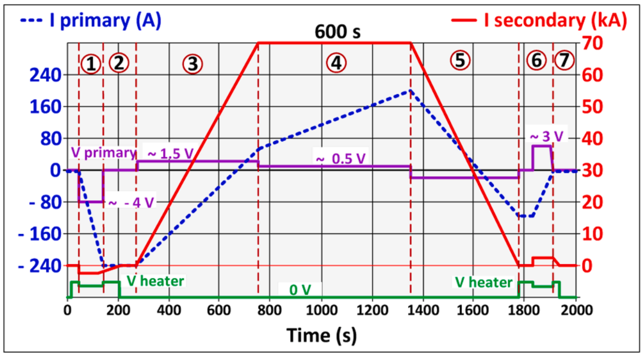

Fig. 9. Typical current cycle at 70 kA.

(secondary current control loop). **4:** The secondary current is kept constant while the primary current continues to increase slowly to compensate the secondary loop resistive effect (few nΩ). **5:** After a 10 min flat top at 70 kA, the secondary current is ramped-down to zero. **6:** The primary is returned to zero while the secondary heater is switched on again to avoid inducing too much current in the secondary loop. **7:** The heater is kept active to cancel secondary current.

5. SELFIE commissioning and first results

After 40 months of development, manufacturing and installation, the test facility was finalized and declared ready for start-up in January 2022.

For commissioning purpose, the test sample was equipped with two PPS with known resistance (coaxial compacted Sc joints already tested in the SULTAN facility [3]). The test sample was instrumented with a set of 24 Vage taps (12 Vage pairs) in order to monitor the resistance of each Sc joint including the upper terminals and the bottom joint.

After sample connection to secondary terminals and check-up of overall instrumentation wires, the TA was inserted inside the cryostat, see Fig. 10.

Fig. 10. Test assembly insertion inside the cryostat.

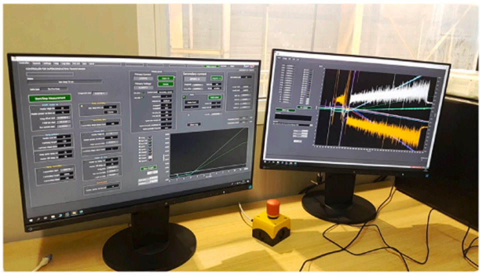

Fig. 11. Sc transformer controller and DAS monitoring.

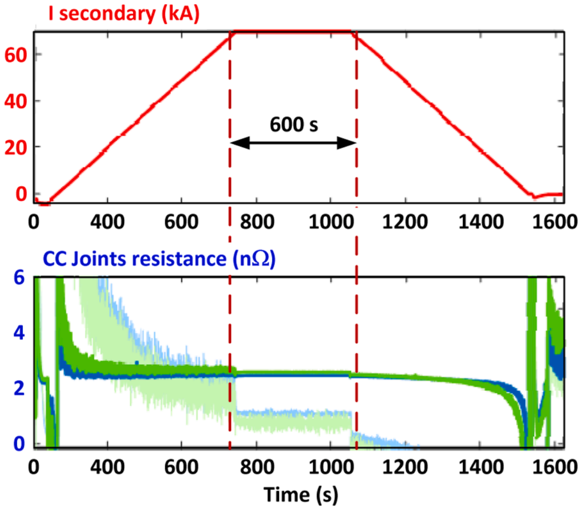

Fig. 12. First operator qualification test results.

Overall cryostat interfaces were then connected (flexible pipes and cables). One week was dedicated to tune the 300–80 K cool-down sequence. The 4 K cool-down was then performed followed by the first LHe fillings. Few days were necessary for Sc transformer system troubleshooting and parameters fine tuning: secondary heaters parameters tuning, Rogowski coils signals balancing, quench detector threshold adjustment… Few current cycles were performed: using 10 kA steps up to the nominal cycle at 70 kA while checking carefully overall acquired signals, see Fig. 11.

After data processing, both PPS resistances were calculated: the results were in full accordance with those obtained in SULTAN facility [3], that is 2.5 nΩ corresponding to a ΔV of 175 mV. These results validate the SELFIE test bench.

A first PPS (coaxial compacted joint) was realized and tested successfully in July 2022 which constitutes a green light to start the first CS Sc joints assembly operation at ITER site. Resistances measurement results are shown in Fig. 12.

6. Conclusion and perspectives

The SELFIE test facility was commissioned successfully and declared ready for operation at the end of January 2022.

The *Sc* joints resistance measurement in cryogenic condition (4 K) at nominal current (and beyond) remains the only way to check their proper assembly and to validate the IO subcontractor workers qualification before on-site assembly operation.

SELFIE will operate along the whole ITER CS assembly phase (about three years) for superconducting joints Production Proof Sample (PPS) resistance measurement in the framework of a training program initiated by IO.

Furthermore, the SELFIE facility is also available for other superconductivity R&D projects in collaboration with CEA.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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