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Ten years of cryomagnetic W7-X test facility construction and operation

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ABSTRACT

The construction, commissioning, and operation phases of the W7-X cryomagnetic test facility in CEA Saclay lasted ten years. The large diversity of equipments called, specialties involved and problems solved attest the expertise that was required to operate the test facility and test the coils. Nearly one hundred cryogenic tests were performed on the seventy W7-X coils, at a rate always increasing, using two cryostats each holding two coils.

This paper presents the test facility and its operation first, the cryogenic difficulties that were confronted with their solutions, the electro-magnetic difficulties encountered along with corrective actions, and finally the instrumentation and data acquisition aspects.

1. Test facility operation

Large Cable-In-Conduit Conductor superconducting coils require a complex multidisciplinary design that may be subject to conceptual errors or lack of quality. An integrated test of individual coils enables to mitigate the risk associated with the final tests after the stellarator or tokamak assembly [1]. Cooling down, current test, temperature margin test, fast discharge or quench, AC and DC tests were achieved systematically on the W7-X toroidal field PLanar Coils (PLC) or Non-Planar Coils (NPC). Detailed principle and content of the tests described in [2–7] led to exhaustive coil and instrumentation checks which are the safest way to reduce risk.

Human resources for this testing project add up to 55 ppy over the 4 years of construction and reception of the facility, and 48 ppy over the 6 years of operation. A team of five later reduced to four technicians, a cryogenic engineer, an electrical engineer and a quality engineer gathered full-time to constitute the test facility operating team. This team was only successful with the CEA support from control and instrumentation specialists, other cryogenic and superconductivity experts, as well as CEA Saclay helium distribution team, computer and network assistance, secretaries and hierarchy.

The test facility main equipments comprise (Fig. 1) [2] two cryostats each connected through a satellite and a common valve box, vacuum pumping groups, a He liquefier (cycle compressor, He buffer capacity, He purifier, cold box), a valve panel with atmospheric heaters, an electrical power circuit (stabilised current supply, contactor, discharge resistor, buses), Magnet Safety System (MSS), Magnet Control System (MCS), coil lifting structures and lifting means. Consumable materials, electricity, fluids and handtools are also needed and represent a large fraction of testing costs. Standard tests consist in: unloading and visual tests upon arrival, sensor checks, resistance measurements and QD wire checks, ambient temperature DC test, insertion into the cryostat and vacuum pumping, leak test, DC test under vacuum, cooling down with conductor RRR measurement, safety tests, temperature margin test, fast discharge, nominal current test, AC test, DC test at cryogenic temperature, warming up, DC test at ambient temperature, sensor checks, resistance measurements and QD wire checks, packing and loading.

Concerning safety and risk, many hazards were generated by the different aspects of the W7-X TF coil test project: heavy handling, heights, high voltage (up to 12 kV), high current (17.6 kA), cryogenic, magnetic, chemical, mechanical hazards and risk of anoxia. Main preventive measures included safety signals, controlled access, control camera, and collective protective equipment implemented from the beginning. Additionally, the 5S quality methodology was used (seiri, seiton, seiso, seiketsu and shitsuke for sorting, straightening, shining, standardizing, and sustaining). Seven human accidents occurred (physical collisions, cuts, and burns), and only one resulted in a 4 days work stop. Considering the duration of the project and the hazardous activities involved, this accident assessment is exceptionally low. All other incidents reported and

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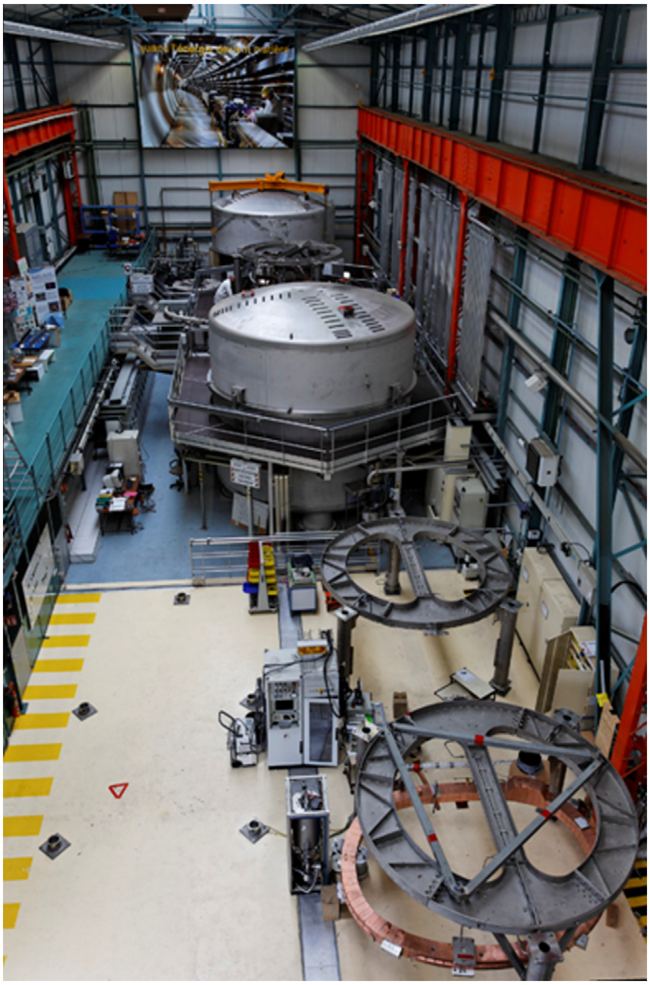

Fig. 1. Bird's eye photograph of the test facility.

Table 1
Reported estimation of test facility most recurrent modification, maintenance or replacement operations. The delay column gives an order of magnitude of the time necessary to diagnose and solve the problem.

Maintenance	Occurrence	Delay
Turbine break	3	month
Pressure/mass flow	20	week
Nitrogen leaks	16	week
Other facility leaks	19	week
Filters	12	week
Vacuum pumps	45	day
He detectors	23	day
He cycle compressor	19	day
Gasket leaks	19	day
Cold box regeneration	Countless	day
Valves	35	hour
Vacuum sensors	15	hour
Other cryogenics action	24	day
HV insulation	17	day
Fuse, relays	31	hour
Water cooling	21	hour
Heaters	15	hour
Cabling/connectors	10	hour
Other electrical action	28	day
Control hardware	45	day
Control software	43	day
Acquisition hardware	22	day
Acquisition software	30	day
Sensors except vacuum	19	day
Other electronics action	2	week

Table 2
NPC non-conformity summary (up), and PLC non-conformity summary (down): number of NCRs reported on the coils, attesting the difficulty to perform tests and their usefulness.

Visual/label check	73
Conductor bending	25
Sensors	65
Leak/pressure drop	15
Current test	15
DC/AC tests	44
NPC total NCR	237
Visual/label check	28
Conductor bending	3
Sensors	31
Leak/pressure drop	23
Current test	8
DC/AC tests	23
PLC total NCR	116

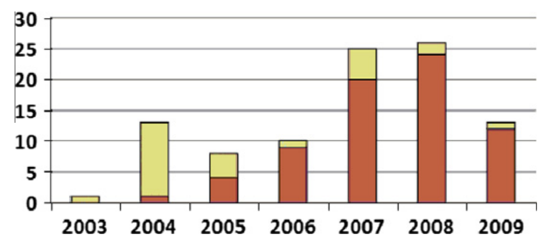

Fig. 2. Evolution of validated (dark) from tested (dark + light) serial coils over the years. Note the favourable evolution of the valid test ratio.

discussed in this paper are material incidents concerning the facility (Table 1) or the tested coils (Table 2).

The testing campaign was initiated with model coil tests in the lower and upper position of each cryostat. The test planning was optimized with the parallel preparation and warm testing of incoming or outgoing coils, while one of the cryostat was under cryogenic operation. Serial coil test rates increased beyond the planned 20 tests per year (Fig. 2), and the project of a second test facility operating in parallel was abandoned. Even with minor Non-Conformity Reports (NCR) reserves summarized in Table 2, all coils were validated and accepted after a maximum of three tests.

The 20 PLC required 33 cryogenic tests with 10 returns to the manufacturer. The 50 NPC required 63 cryogenic tests with 8 returns to the manufacturer. No coil was tested more than three times and the manufacturing of coils improved because the rate of coil failure decreased. The total number of serial coil cryogenic tests totalled 96 tests for the 70 coils.

2. Cryogenic challenges

The facility Cryogenic circuit is designed to cool down one cryostat with two coils at a time and test only one coil at a time. Fig. 3 [8] is a simple scheme of the liquid helium tanks, heat exchangers, winding and casing circuits showing the use of liquid Helium bath to obtain highly precise temperature regulation for large CICC supercritical helium mass flow rate. The cryogenic circuit design proved efficient because it allowed to provide helium temperatures ranging from 5 to 7.8 K with a precision of a few tens of milliKelvin during hours of tests. Regulation parameters required weeks to be finely tuned. The helium liquefier was a reused existing and ageing material. Preventive maintenance was performed upon installation, but its intensive use over many years of test facility operation required to replace all wearing parts initially thought to be fit for the tests.