SC Strand and Cable Test Demand and Infrastructures (ITER experience)

Pierluigi Bruzzone

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE
SWISS PLASMA CENTER

OUTLINE

- The rationale of superconductor testing
- The ITER (and other projects) approach to testing
- Why FCC ≠ LHC and FCC ≠ ITER
- Available vs. Desirable Infrastructures
- Managers and Testing

The rationale of testing

The test of superconducting components has different drivers and rationale:

In the design and R&D phase: *Proof a design approach (prototypes)*

Validate a model

Qualify a supplier

Explore new operating conditions

Crucial, dedicated tests
Low to medium frequency
Lab infrastructures

Standard, routine tests
Commercial relevance
Integrated in QA
Industrial facilities

In the production phase: *Fulfillment of contractual acceptance*

Accumulation of database

Routine, pre-installation checks

The object of testing

In the scope of a project, the object of a test must be clearly identified in advance, since the need of the test is agreed.

The "test result" must drive a decision (about a design approach, a model validation, the acceptance of a supply, etc.).

A test without consequence points at a non-effective resource management in the project.

Disregarding the kind of driver and the project phase, the superconductor test is eventually a quantitative performance test.

Either an action, a criterion or a prediction must be formulated in advance of the test, to guide the result assessment and its use.

Typical kind of testing

Are ALL these tests really needed??

Straight tests on superconductors:

- **Strands**: I_c (B, T, mechanical loads, radiation), n-index, RRR, microscopy (cracks, lattice, grain size, composition), geometry (size, copper fraction, twist pitch), stress/strain, magnetization…
- **Cables**: T_{cs}(B, e.m. loads, radiation), n-index, AC loss, stability, pressure drop, insulation, geometry (size, pitches, voids), joints…
- **Coils**: cool-down, integral performance (training), field quality, quench aspects (detection, hot spot), current leads, actual engineering margin…

Supporting tests: thermal properties of fluid and structures (heat exchange friction factor, diffusivity), residual magnetization, heating systems, signal conditioning, sensors, switches, diodes, power supplies, heat treatments…

ITER in the first decade 1988-1998

The superconductor testing in ITER must be understood with the history and organization of the project. During the long design phase, ITER worked as an agency, with poor authority over the institutes able to carry out R&D.

The lack of R&D and verifications was named "**success oriented design**".

At the time when the CS Model Coil was being transported to Naka (1998),

- no full size conductor was tested
- no joint prototype was tested
- the strand test was struggling with the third round of bench mark test

On the other hand, extensive investigations were carried out by the coil manufacturers for electrical insulation (pre-preg) and Incoloy 908 (SAGBO).

ITER in the second decade 1999 - 2009

A number of technical changes occurred in the coil/conductor design, few of them triggered by the degradation observed in the Model Coils:

From Incoloy to 316LN steel

More superconductor cross section

From layer to pancake winding

Eventually, the ITER construction agreement was signed - new managers and better funding. With the procurement arrangements being placed in 2008 – 2009, the need of *urgent R&D for "mitigation of degradation" contrasted with the "frozen design" situation*.

The foggy sharing of responsibility between the central team and the domestic agencies generated a poorly coordinated test activity in 2007-2010 – a mix of frantic R&D to provide the manufacturing parameters to the domestic companies and triplicated strand acceptance tests (the company, the domestic agency and ITER/cern).

ITER in the current decade 2010…

Lot of testing is still going on during the construction phase:

- **Strand**: a very large amount of resources is spent in series production test. Despite over two decades of bench mark round robin, nobody seems to trust the I_c results of the others. The suppliers must test, the buyers (domestic agencies) re-test every strand and ITER (at cern) re-test a third time.

  Little attention is paid to the results of strand tests. *No rejection due to the I_c re-test results (same as cern LHC)*.

  For the ITER Nb_3Sn strands, the ratio of I_c at operating conditions to I_c at test conditions is <50% and not really accurately predictable. A deviation of 1-2% from the strand acceptance criterion has capital importance at commercial level, but little relevance for the actual conductor performance in operation.

ITER in the current decade 2010…

- **CICC**: Full size conductors from the industrial manufacture are tested.

The *short length* test in the SULTAN facility are full on-going since 2007. The last "*developmental*" samples (CS) were tested in 2012. The test in SULTAN is an acceptance test: for the suppliers (*qualification* tests) and for the production (sampling from the *series manufacture*). A broad performance scattering among suppliers and a limited reproducibility for the same supplier are observed. No rejection so far.

Two *long length* samples are prepared for the CSMC facility in Naka (the CS tested in 2015, the TF in 2016). The performance fully matches the short length test in SULTAN.

The *joint samples*, prepared by the coil manufacturers, are tested as qualification samples in SULTAN. One supplier had to iterate several times…

Coil Cold Tests for ITER ?

The option for cold tests of the ITER coils was debated at length. Eventually,

- the cold test for the 18 TF coils (Nb_3Sn) was discarded because a full current test in a single coil is not possible, i.e. the superconductor performance cannot be proved. Time / cost were also an argument against cold test.
- For the six PF coils (NbTi) a cold test at 77 K is foreseen (electrical insulation test). No superconductor performance test.
- For the six modules of the CS (Nb_3Sn) a 4 K performance test at the supplier is decided by the US. The cost/benefit ratio is much better and the due date is also convenient (the CS is installed at last in the tokamak).

Balance/Lessons from ITER Tests

- The systematic duplication of the strand tests, including the bench marks and reference labs, turned to a an activity with little-to-zero added value for the project: no strand improvement, no cost reduction, no rejection.
- The conductor tests started too late. The scope of the R&D could not include the overall design – only (successful) “mitigating measures”. The big potential of the conductor R&D is not adequately exploited. The series production tests have consolidated the trust in the last minute R&D and somehow replaced the missing coil performance tests.
- The approach to the coil performance test is understandable for a fusion device under enormous time pressure.

The culture of rejection could not find place in the ITER environment.

Other Fusion Projects with Superconducting Coils

- **EAST** (NbTi coils) Strand recovered from a former accelerator project, CICC short length test in SULTAN, no cold test for all coils.
- **W7-X** (NbTi coils) Strand test from suppliers, no CICC test, cold test for all coils at CEA-Saclay – no issue on superconductor performance, few electrical insulation issues.
- **KSTAR** (Nb_3Sn coils) Strand test from suppliers, no CICC test. A cold test facility was prepared but only a prototype TF and few winding sections of CS were tested.
- **JT60** (NbTi TF coils) Strand test from suppliers, CICC TF test in SULTAN, voluntary TF coil test at CEA-Saclay, no coil test for CS and PF coils.

FCC vs. ITER – Superconductor Tests

Disregarding the level of technical challenge, there are different boundaries conditions, which drive the test needs in accelerators and fusion projects.

In accelerators, with hundreds of identical, magnetically non-integrated coils, the performance test of an individual coil is the key instrument for advanced R&D and acceptance (pre-installation) test.

In tokamaks, the performance test of an individual coil is either not relevant (TF coil) or too expensive (time/cost). Anyway, no R&D (feedback) is possible on actual prototype coils.

The conductor test for ITER "replaces" the coil test both in the R&D and production phase. For accelerators, conductor tests are meaningful in the early R&D, but are bypassed by the coil test in production phase.

FCC vs. LHC – At first glance "similar", but…

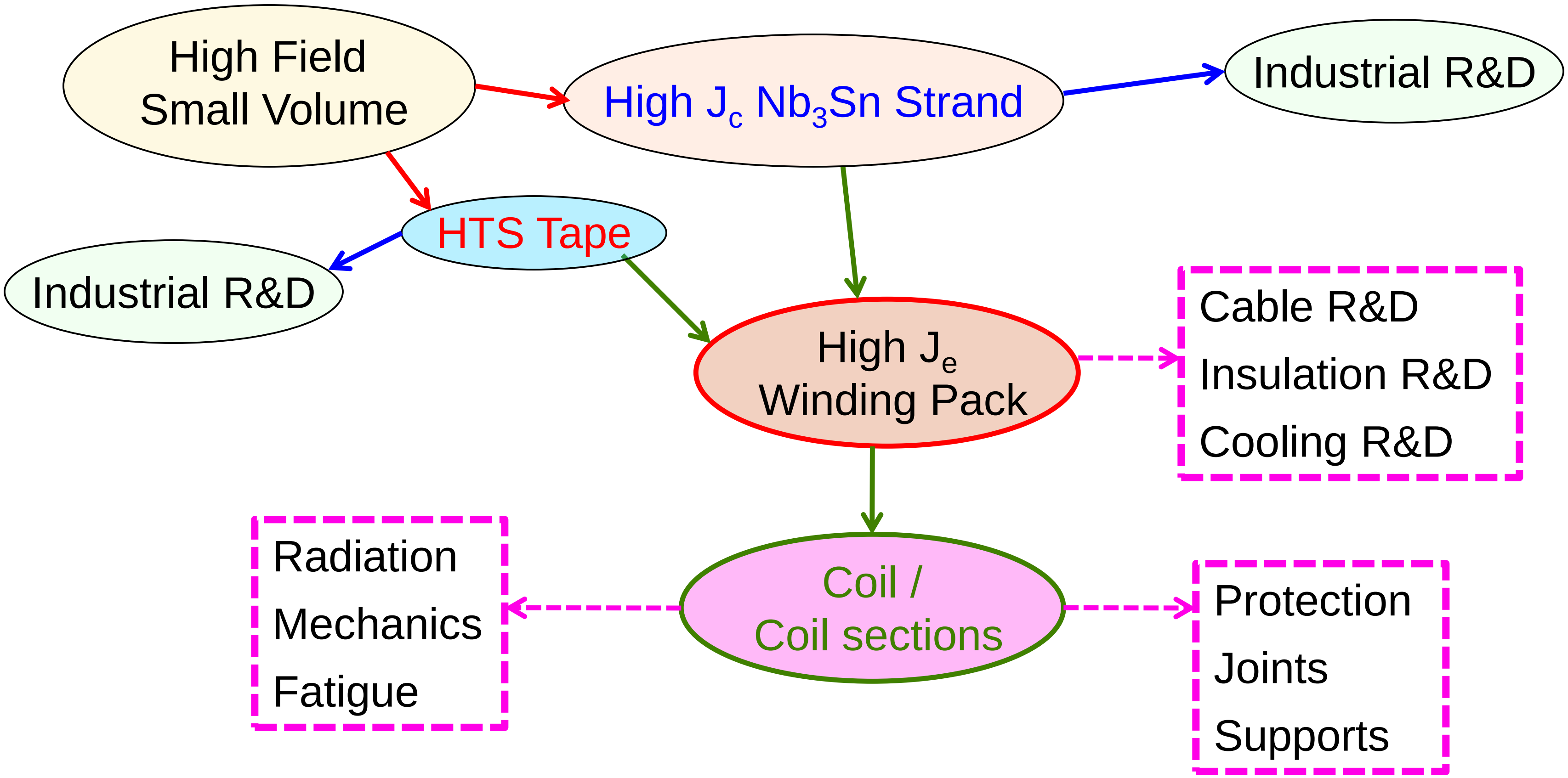
NbTi (LHC) vs Nb_3Sn or HTS (FCC)

The coil technology must be developed (no Tevatron in the background), not necessarily by cut&paste of Nb_3Sn filaments into NbTi filaments. There is room for new concepts (cables, cooling, mechanics, training, protection, safety, …)

Definitely more need for broad R&D in the conceptual design phase, including test of cable and winding concepts, as well as "supporting tests" (stability, quench protection, residual magnetization, heat exchange…) and "technology tests" (heat treatment, insulation, tolerances, joints,…)

For the production phase, the rate of pre-installation tests is much larger than LHC and calls for different logistic solutions.

The FCC Challenges from the Perspective of Superconducting R&D and Testing



Test needs for FCC

The ideal way to qualify a strand/cable for use in a coil is to test it as a coil, i.e. an *integrated test conductor&coil*. This is feasible for accelerators.

The test of **stand alone strand** is a business of the industry. Only selected specialty tests (e.g. radiation resistance, fatigue loading, elevated temperature) may be carried out at specialized labs.

The **stand alone cable** tests are crucial for the R&D, demonstration of the industrial feasibility and optimization of individual parameters.

The actual **performance test for strand and cable must be verified at winding level**. The test of a reduced size/length winding in the R&D phase is appropriate if it offers advantages in time/cost.

Test Facilities for R&D Phase - 1

Strand:

For routine tests, the supplier facilities are preferable and available at no extra cost.

For specialty tests (under mechanical load, radiation resistance, very high field, high operating temperature), several labs worldwide can cover the demand for extended characterization:

TU Vienna (neutron irradiation)
Cern + RF (proton irradiation)
Durham University
University of Geneva
University of Twente
NIST
NHMFL
NIMS

Test Facilities for R&D Phase - 2

Cable and Cable Joints:

Few facilities are equipped for <u>short length cable test</u> in high background field and high operating current:

EDIPO (SPC), 12.35 T background field, op. current up to 100 kA, operating temperature 4.3 K – 50 K, 1 day sample change

SULTAN (SPC), 11.0 T background field, op. current up to 100 kA, operating temperature 4.3 K – 10 K, 1 day sample change

FRESCA II (cern), under construction – 13T background field, 4.2K/1.9K bath

Long length cable tests and “specialty” tests on cable sections do not seem necessary as they are covered by the coil tests

> For the aim of cable R&D, the existing facilities cover the needs of FCC assuming up to 20 prototype tests per year

Test Facilities for R&D Phase - 3

Coil and Coil Sections:

For prototype coil test, the cern facilities set up for LHC can be used with modest upgrade effort for FCC, assuming that few tens of prototype/year are needed in the R&D / qualification phase.

For coil sections (winding technology R&D) a high field test facility, e.g. EDIPO, may be more cost-effective compared to a full prototype test.

Specialty, cryogenic tests, for which new set-ups are requested, e.g. dedicated to protection, stability, insulation, leads, training… must be defined case-by-case and can be allocated to the qualified labs.

Test Facilities and Test Items

The existing facilities for superconductors tests are adequate to support the basic needs of the FCC project in the next (R&D) phase.

The technical management should focus on the **test items** and the rationale to plan them, i.e. the roadmap for R&D. The infrastructure for R&D, i.e. to produce the test items, is not dramatically expensive. For FCC, the choice of "*where to do the R&D*" should **not** be driven by "*where are the infrastructure for R&D*". Industrial R&D is also an option.

Attracting and concentrating the *available technical expertise* on the field (Nb_3Sn and/or HTS magnet technology) is the mandatory condition for an effective R&D.

Non-technical value of tests

Beside the technical value of a test, there are other factors at play:

- "testing" is highly regarded as a measure of scientific rigor. Whatever you test, the more you test, the more you are serious.
- "testing" involves (lot of) money. You can make friends by allocating large test programs.
- "testing" of large objects has high visibility and is a good opportunity for public relations (thank the sponsors, make press releases).
- "testing" of prototypes allows to claim success and self-celebrate the team (crucial in some cultures)

The perspective of the (analyst) project manager (half a joke)

Why	*I must do the test to hush up those bothersome guys in the advisory board*
What	*I'll let test a detailed behavior and bench mark it by codes to bring the attention to the codes and leave the prototype alone*
When	*I'll delay the test till it will be too late to question the design and my own choices*
How	*I'll use a test configuration which can be questioned for relevance in case the results are bad*
Where	*I'll use a facility where I have good friends*
Who	*Of course, I'll be the only one good enough to understand and assess the test results!*

Tests in the Production Phase - 1

Once the R&D and Qualification Phase is completed, the challenges turns to the production **rate** and acceptance test **rate**.

Strand: For Nb_3Sn, the 100 t/y achieved by ITER did not saturate the production capability of 9 suppliers. For FCC, ≈ 1500 t/y may be required (less than NbTi). The experience shows that the scale-up of production facilities does not need long time/measures, provided that **multiple suppliers** are at play.

Strand tests only at the suppliers as quality control.

Cable: Assuming a production rate of ≈ 1000 cable units/y, 10-20 cabling machines should work in parallel, possibly at 4-5 different locations/companies (at best matching the coil manufacturers). Surely not a big challenge for cabling companies, compared for example to the market for power transmission.

No cryogenic test for stand alone cables from the series production

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Test Production Phase - 2

Coils: The challenge of up to 1500 coil test/y (even if the test is "short") may be better faced by the multiple facilities, at best at the coil manufacturers locations.

The LHC approach – 3 manufacturing companies and a single coil test location at cern, may be not adequate.

The number of coil manufacturing facilities must be optimized between 10 and 20, e.g. based on the number of parallel tools. With a coil test facility at each manufacturing locations (70-150 coil tests/y at each test facility) and an average test duration in the range of 4 weeks/coil, each test facility should have 5-8 test stations.

The set up of such large test facilities goes together with the set up of large coil manufacturing facilities. An adequate transition between R&D phase and production phase will be mandatory.

My opinion on superconducting tests

- Test yourself only what cannot be tested by the industrial suppliers. Do not duplicate tests. Make test because you need, not because you can.
- For R&D test, start early and link the test results to the design. Have the designers believe in R&D tests.
- Do not be scared by bad results in R&D tests. You learn more from failures than from "as-predicted" test results.
- For routine tests, consider the trade-off cost/benefit. Focus on tests where failure and rejection may really happen.
- Have a clear course of actions prepared for the case of failures in production tests: a non-conformity cannot be the only outcome.
- If rejection is not an option, save the money of the test.