Analysis of Early Quench Development in JT-60SA Toroidal Field Coils Tested in the Cold Test Facility

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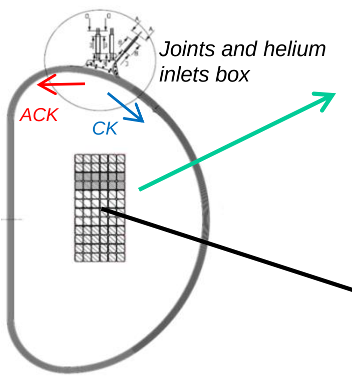
INTRODUCTION

The Toroidal Field system of the JT-60SA tokamak is composed of 18 NbTi superconducting coils. Each TF coil is composed of 6 cable-in-conduit conductor lengths, wound in double-pancakes, carrying a nominal current of 25.7 kA. These coils are being tested in the single coil configuration at the so-called Cold Test Facility (CEA/IRFU Saclay, France). The test program includes for all coils a DC operation for one hour at nominal temperature (4.7 K) and nominal current followed by a progressive operating temperature increase up to quench (around 7.5 K inlet temperature). Thanks to the accuracy of the fast Data Acquisition System at 10 kHz sampling rate which is triggered by the quench, but which allows the measurement of the six double-pancake voltage drops up to 10 s before the magnet fast discharge, it has been possible to follow the very early development of the quench at the scale of a few millimeters normal (i.e. non-superconducting) length. In addition, this early quench development over one conductor length was also simulated using the THEA code with relevant boundary conditions. Two different quenchs which occurred on two different coils are analyzed: one starting on a central pancake winding which corresponds to the peak magnetic field, the other starting on a side pancake corresponding to a more heated conductor due to heat transfer from the casing.

TF Coil and Conductor

Coil winding pack (WP)



P12	ACK	DP6
P11	CK	
P10	ACK	DP5
P9	CK	
P8	ACK	DP4
P7	CK	
P6	ACK	DP3
P5	CK	
P4	ACK	DP2
P3	CK	
P2	ACK	DP1
P1	CK	

- ❑ 6 double-pancake (DP) winding
- ❑ 12 hydraulic pancake (P) channels
- ❑ WP embedded in a thick steel casing

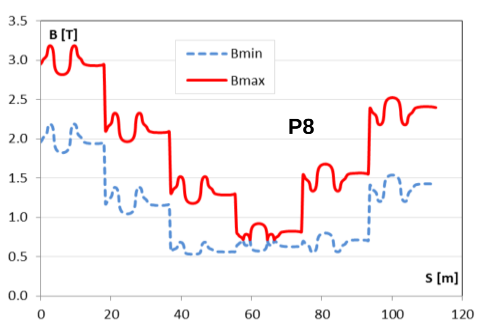
- ❖ Clockwise (CK) and anti-clockwise (ACK) pancakes according to helium flow direction from helium inlet (at inner radius)
- ❖ ACK pancakes have peak field closer to helium inlet.

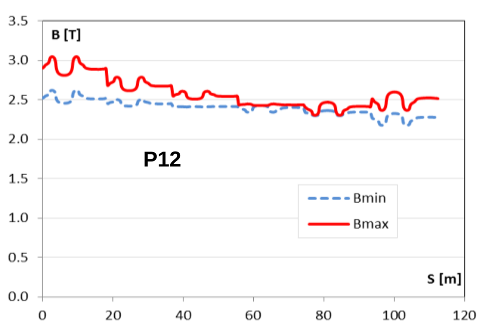
Rectangular NbTi cable-in-conduit

NbTi and Cu strand dia. [mm]	0.81
NbTi strand non-sc to sc ratio [-]	1.9
NbTi strand internal CuNi barrier [µm]	6.0
Cabling pattern	(2 NbTi + 1 Cu) x 3 x 3 x 3x 6
Cable void fraction [%]	32
Jacket thickness [mm]	2.0
Conductor size [mm x mm]	22 x 26

Operating conditions in CTF (single coil test)

Magnetic field maps (ACK pancakes)





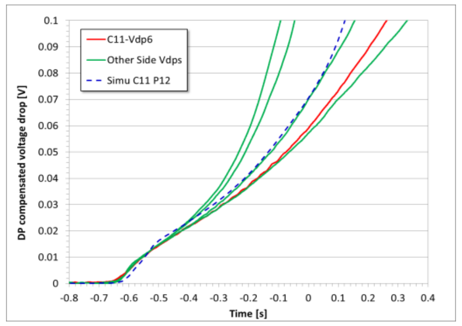
- Max. and min. fields (in cable cross-section) along P8 (DP4) and P12 (DP6)
- P12 is a side pancake (SP) and P8 a central pancake (CP)
- Mass flow = 24 g/s for 12 pancakes in parallel ≈ 2 g/s per pancake

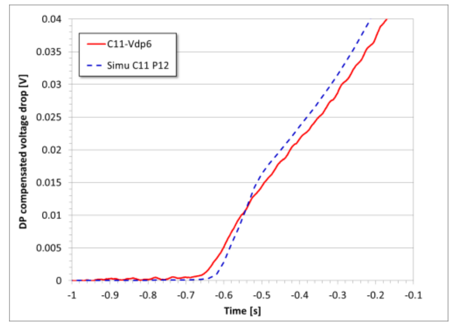
Location (pancake)	B_{MAX} [T]	T_{CSM} [K]	T_{CS} [K]
P5 to P8 inner turn	3.19	7.36	7.43
P1 & P12 inner turn	3.05	7.42	7.47
P1 & P12 outer turn	2.53	7.65	7.69
P4 & P9 inner turn	3.17	7.37	7.44

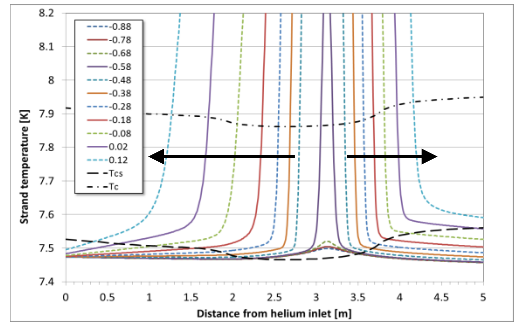
Conductor performance evaluation

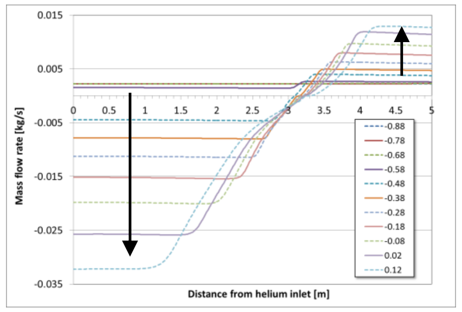
- Critical locations along pancakes lengths
- Average performer strand
- T_{CSm} for strand @ E = 10 µV/m at B_{max}
- T_{CS} for cable @ <E> = 10 µV/m averaged on cable area

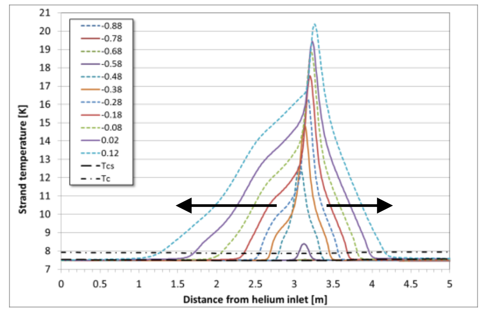
Current sharing and Quench tests vs. THEA Simulation: Side DPs (SDPs)









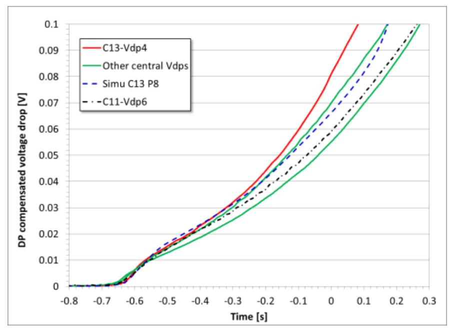


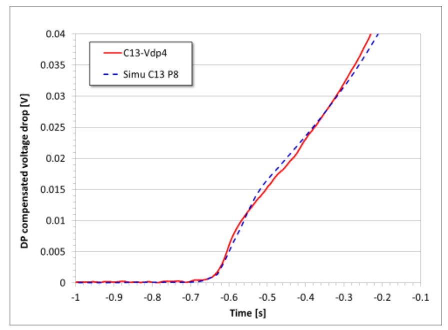
- ➢ Very close signals for all coils resistive voltage drops up to 12 mV
- ➢ Significant scattering above (up to 0.43 s in time to reach 100 mV = QD threshold)
- ❑ **Good agreement between THEA simulation (inner turn of C11 P12) and experiment**

Three phases identified in early quench develoment after a slow stable voltage increase

1. Fast voltage grow due to combination of both transtion zone extension and temperature increase (from T_{CS} to T_C)
2. Slower voltage grow (after a knee) due to only normal zone extension (with $T_C < T_{strand} < 21$ K)
3. Quench acceleration due to helium explulsion, particularly toward helium inlet (reverse flow)

Current sharing and Quench tests vs. THEA Simulation: Central DPs (CDPs)





Again, good agreement between THEA simulation (inner turn of C13 P8) and experiment

Very similar behaviour to SDPs with the same 3 phases due to very similar maggnetic field profiles along the inner turns

CONCLUSION

Twelve TF coils among twenty (18 + 2 spare coils) of the JT-60SA tokamak have been tested by a transient increase of helium inlet temperature up to quench at nominal current. All coils show quite similar results in terms of quench temperature but with quench locations varying from coil to coil. Thanks to an accurate fast DAS it has been possible to measure each double-pancake resistive voltage before the fast safety discharge is triggered.

The analysis of these signals has been complemented by a simple one-turn numerical modeling using the THEA code. Results of simulations are in good agreement with experiment, which allows better understanding the early quench development; particularly 3 phases have been identified corresponding to 3 parts of the voltage drop evolution associated with 3 physical phenomena. Little differences have been observed between central and side pancakes' quenchs which is not surprising taking into account the low normal zone extension (about 2.8 m) before the coil is discharged, which also explains why our 1-D single conductor model has turned out to be so effective in modeling the early quench development.