JT-60SA TFC02 complementary quench tests in CTF: thermohydraulical analysis and smooth quench criticality

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Introduction

In the framework of JT-60SA tokamak commissioning (Japan, 2021), 20 **Toroidal Field Coils** (**TFC**) were tested at the **Cold Test Facility** (**CTF**), at CEA-Saclay (France, 2018).

- quench acceptance test (quench temperature up to 7.5 K at nominal current)
- complementary tests on spare coil TFC02 with different quench conditions:
  - reduced current (at 75% and 50% of nominal current)
  - delayed quench detection (increased holding time τ_h= 0.5 s, instead of $\tau_{h,nominal}$= 0.1 s)

Numerical simulations of these tests were performed using SuperMagnet code coupling:

- THEA (Thermohydraulic and electrical 1-D physics of Cable In Conduit Conductor, CICC)
- Flower (Hydraulical model of external cryogenic network)

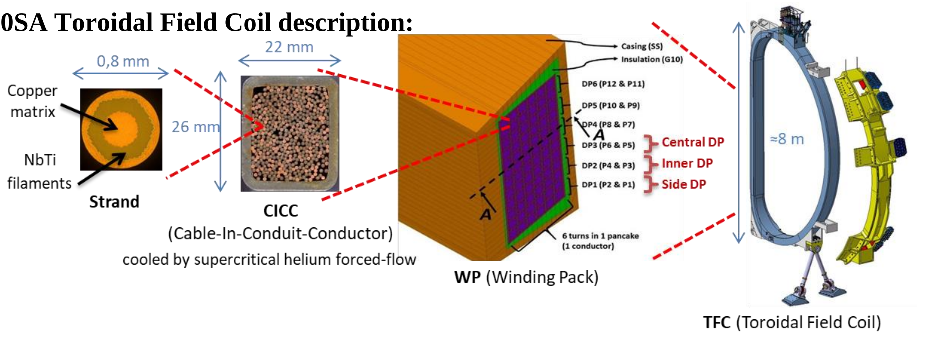
TABLE I

TFC02 COMPLEMENTARY QUENCH TESTS MAIN INITIAL PARAMETERS

TFC02 Tests	I (kA)	B_{max} (T)	$T_{cs,min}$ (K)	τ_h (s)
Acceptance	25.7	3.05	7.42	0.1
Delayed detection	25.7	3.05	7.42	0.5
75 % I_{nom}	19.5	2.29	7.83	0.1
50 % I_{nom}	12.9	1.52	8.24	0.1

TFC installed in Cold Test Facility

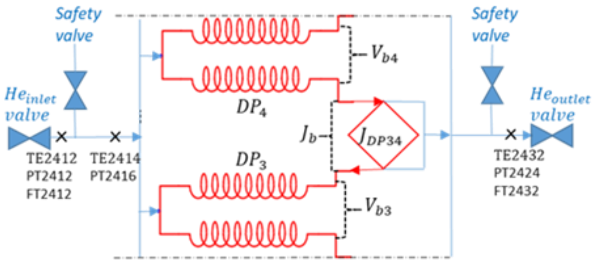
JT-60SA Toroidal Field Coil description:



1. Estimation of experimental normal length propagation

CTF instrumentation, namely double-pancake voltage and helium flow measurements, allow:

- Determination of resistance and normal length evolution in each CICC
- Analysis of the helium flow (P, T, $\dot{m}$) at winding pack inlet and outlet



Fast Safty Discharge (FSD) induces voltages

$$V_{b,DP}(t) = \underbrace{L_{DP}\frac{dI(t)}{dt} + M_{DP}\frac{dI_p(t)}{dt}}_{V_{DP,inductive}} + \underbrace{R_{DP}(t)\; I(t)}_{V_{DP,resistive}}$$

$$\gamma_{DP}(t) = \left(\frac{V_{b,DP}(t)}{V_{pickup}(t)}\right)_{\substack{Pure\\ discharge}} = \left(\frac{V_{DP,inductive}(t)}{V_{pickup}(t)}\right)_{quench}$$

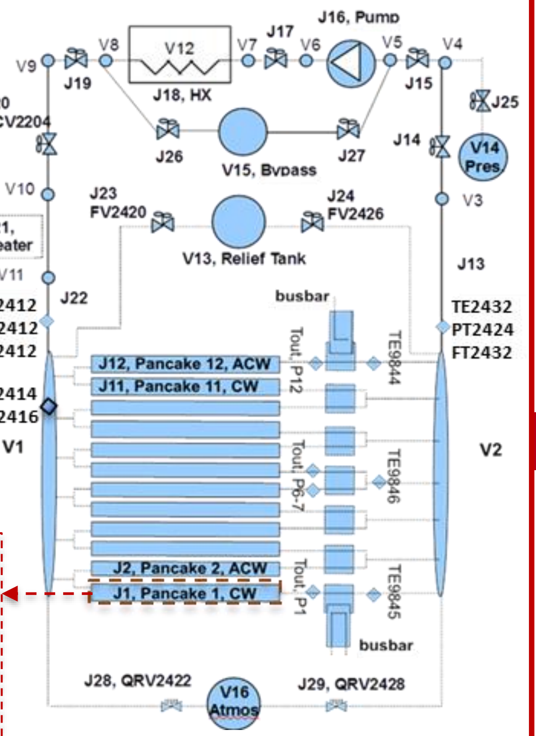
CICC quench propagation heuristic model

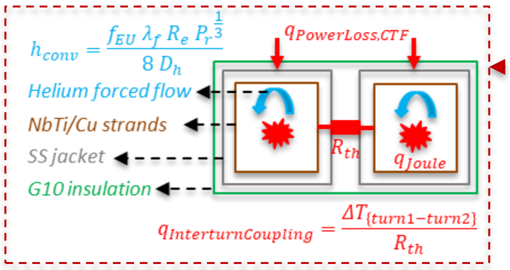
$$\left.\right\} \begin{array}{c} R_{DP}(t) \\ \downarrow \\ \displaystyle\int_0^{NL_P(t)} \frac{\eta_{Cu}(B(t,x),T(t,x),RRR)}{A_{Cu}}\, dx \geq R_P(t) \\ \downarrow \\ NL_P(t) \end{array}$$

2. Numerical quench model

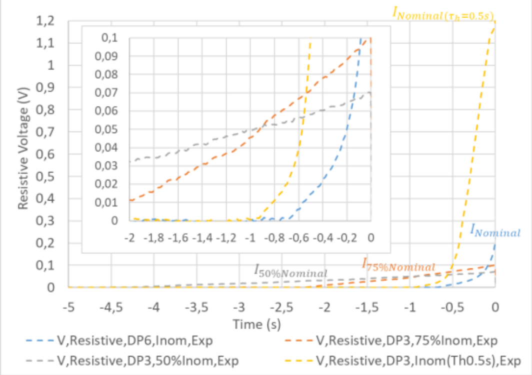
Model developed with **SuperMagnet** (L. Bottura, CERN) coupling THEA and Flower codes:

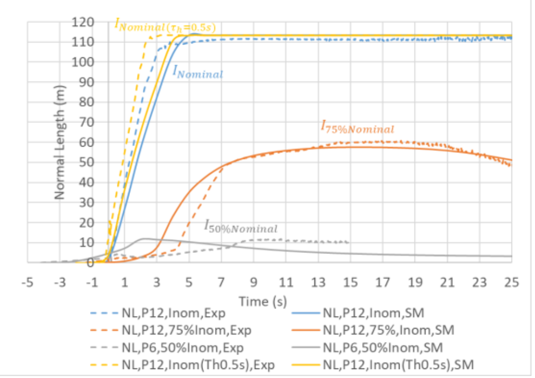
- Flower models the cryosdistribution
- THEA models the 12 CICC (helium,conductor, jacket)
- Magnetic field profiles calculated with TRAPS code
- Friction factor correlations from experimental measurements
- Primary quench detection features: voltage threshold $V_{detect} = 0.1$ V and holding time τ_h = 0.1 s or 0.5 s
- FSD: current exponential decay ($I(t) = I_0 e^{-t/\tau}$) with τ = 8 s





3. TFC02 complementary quench tests results



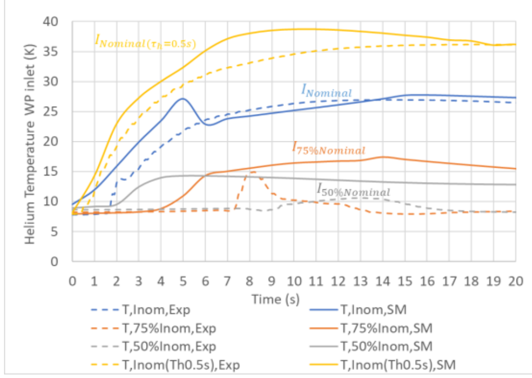


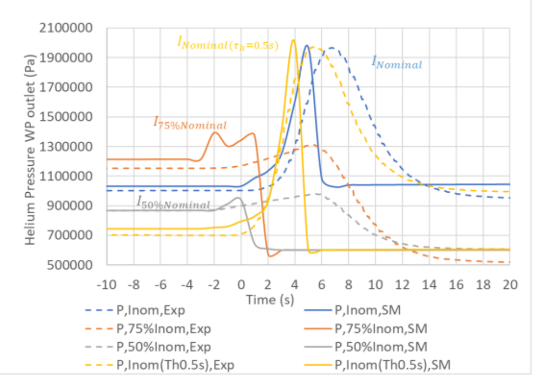
- *Early quench development:* Quench initiation of the whole coil and quench detection (t = 0 s taken at FSD start) for each quench test are analyzed with experimental DP resistive voltages:

$V_{Resistive,DP6,Inom}(0)$= **0.24 V** $V_{Resistive,DP3,75\%Inom}(0)$= 0.11 V
$V_{Resistive,DP3,Inom(\tau h=0.5s)}(0)$= **1.19 V** $V_{Resistive,DP3,50\%Inom}(0)$= 0.07 V

- *Propagation during current fast discharge:* Both experimental and calculated maximal normal lengths reached for each test show that **reduced current** induces slow quench propagation with **conductors not fully quenched**:

$NL_{max,Inom}$ = 113.2 m $NL_{max,75\%Inom}$ = **60.7 m** $NL_{max,50\%Inom}$ = **11.7 m**





- *Helium temperature*: Delayed quench detection (at nominal current) increases Joule energy dissipated before FSD, increasing CICC temperature by 10 K compared to acceptance test
- *Helium pressure*: Quench tests at reduced current induce low pressure rise and do not open quench relief valves, whereas at nominal current the pressure threshold of 20 bars is reached

4. Discussion on smooth quench criticality

Experimental results comparison with SuperMagnet and analytical approach:

- T_{cond} calculated with 0-D energy conservation equations on helium, conductor and jacket:

$$\frac{dT_{cond}(t)}{dt} = \frac{\frac{\eta_{Cu}(t)\,NL(t)}{A_{Cu}}\, I(t)^2 - h_{conv}\, P_{w,cond}\, L\,(T_{cond}(t) - T_{He}(t))}{L\;(A_{Cu}\,\rho_{Cu}\,C_{Cu}(t) + A_{NbTi}\;\rho_{NbTi}\,C_{NbTi}(t))}$$

- Quench velocity v_q provided by A. Shajii analytical scaling laws : $v_q(t) = \frac{dNL(t)}{dt}$

Nominal current:
Long coil-High pressure rise Regime

$$v_q(t) = 0.766\left(\frac{2\,D_h}{f}\right)^{\frac{1}{5}}\left(\frac{r\,NL_{ini}\,\alpha_0\,J_0^2}{c_0}\right)^{\frac{2}{5}}\frac{1}{t^{\frac{1}{5}}}$$

Reduced current:
Long coil-Low pressure rise Regime

$$v_q(t) = \frac{r\,\rho_0\,NL_{ini}\,\alpha_0\,J_0^2}{2\,p_0}$$

TABLE II

SUMMARY OF CALCULATED AND EXPERIMENTAL QUENCH VELOCITIES, TEMPERATURES AND EARLY QUENCH PROPAGATION TIMES

TFC02 Tests	Acceptance	Delayed detection	75 % I_{nom}	50 % I_{nom}
$v_{q,NLmax,Exp}$	**25.6 m/s**	**32.1 m/s**	**3.9 m/s**	**0.7 m/s**
$v_{q,NLmax,SM}$	22.7 m/s	22.1 m/s	3.2 m/s	1.6 m/s
$v_{q,analytical}$	16.1 m/s	12.8 m/s	3.6 m/s	0.6 m/s
$\tau_{da} = \tau_{h} + \tau_p$	**0.61 s**	**0.92 s**	**2.12 s**	**4.18 s**
$T_{He,max,Exp}$	**26.3 K**	**36.9 K**	**14.9 K**	**10.5 K**
$T_{He,max,SM}$	27.7 K	38.7 K	17.4 K	14.3 K
$T_{cond,max,SM}$	32.6 K	38.9 K	17.5 K	16.6 K
$T_{cond,max,analitycal}$	44.25 K	40.8 K	19.1 K	12.4 K

“smooth” quench occurs at reduced current
↓
Low quench propagation velocities
↓
Quench propagation time τ_p for reaching V_{detect} increases

CICC $T_{cond,max}$ are:
- mainly affected by τ_h at I_{nom}
- lower at reduced currents even if τ_p is larger

Conclusion

Numerical model validation:

- Large scale model of one JT-60SA TFC with its cryodistribution in CTF allowed simulating the quench transient phenomenon.
- Simulation results were compared to experimental measurements of TFC02 complementary quench tests and were found in rather good agreement.

Main results:

- Delayed detection at nominal current significantly increases the Joule energy dissipated before the fast current discharge and thus induces large CICC temperature rise.
- Smooth quench at reduced current are characterized by slower quench propagation velocities, inducing not fully quenched coil, lower temperature and pressure rises.