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# Experimental and numerical study of the different quench acceleration phenomena in the JT-60SA Toroidal Field coils

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**Abstract.** JT-60SA is an advanced superconducting fusion Tokamak jointly constructed by Japan and Europe. It takes the main missions of addressing key physics issues and providing direct operation experiences for ITER and DEMO reactors. In the framework of the JT-60SA project, the 18 NbTi superconducting Toroidal Field (TF) coils have been tested in quench conditions at CEA Paris-Saclay. In our previous study of these coils tests, a typical quench behavior has been identified and analyzed. This behavior shows for the majority of the coils (13 tests over 19), four dynamic phases including a quench initiation phase with a velocity around 3 m/s which is rapidly (several hundreds of milliseconds) followed by a quench acceleration one at around 30 m/s near the start of the current discharge. This is called "early" quench acceleration. Nevertheless, a few number of coils showed a quench acceleration with a certain delay of about 0.5s to 2s after the current discharge. This paper will propose a study of this "delayed" quench acceleration phenomenon in two steps: Firstly, a physical analysis of the experimental data of these few tests; Secondly, a numerical study with the code THEA analyzing the testing conditions impact on the beginning delay of the quench acceleration phase.

## 1. Introduction

Within the Broader Approach agreement, the 18 NbTi superconducting TF coils of JT-60SA are manufactured half by General Electric (GE) in France [1] and half by ASG in Italy [2]. In order to check the coils performance and hence mitigate their fabrication risks, these TF coils have been tested at quench conditions in a single-coil configuration in the so-called Cold Test Facility (CTF) at CEA Saclay [3, 4]. Each TF coil is composed of a stainless steel (SS) casing and a 6-Double-Pancake (DP) winding pack, separated by epoxy fibreglass insulation (G10), as presented in Figure 1. Each DP consists of two adjacent pancakes wound with the same Cable-In-Conduit Conductor (CICC) in 6 turns along two opposite directions, clockwise and anticlockwise [5]. In order to facilitate a further study of the coil quench behaviour, the 6 DPs have been classified into 3 types depending on the coil geometric symmetry, including side, inner and central DPs. Each single pancake is in a total length of 113 m. Each elementary rectangle represents the cross-section of one NbTi CICC which is multi-twisted cable composed of NbTi and Cu strands embedded in a 2 mm thick SS jacket. The CICC is then wrapped by G10 insulation in a thickness of 1 mm against the electrical short circuit. More dimensional details about the CICC can be found in Table 1 [6].



Quench experiments begin with achieving a thermal stability in the TF coil during nominal conditions (25.7 kA and 5 K). The inlet helium temperature is then increased with a first fast ramp of about 0.4 K/min followed by a slower one of about 0.05 K/min up to quench at around 7.5 K (see [3, 8] for more details). Such temperature-increasing protocol allows to initiate the quench at the TF coils inlet which is actually the peak self-field region [5] thus the minimum current sharing temperature ( $T_{cs}$ ) region. Once the coil is quenched, the resistive voltage increase is detected immediately by the Magnet Safety System (MSS) and triggers a current fast discharge (FD) with an experimental time constant of 8.3 s when the measured voltage overpasses 100 mV during 100 ms [7].

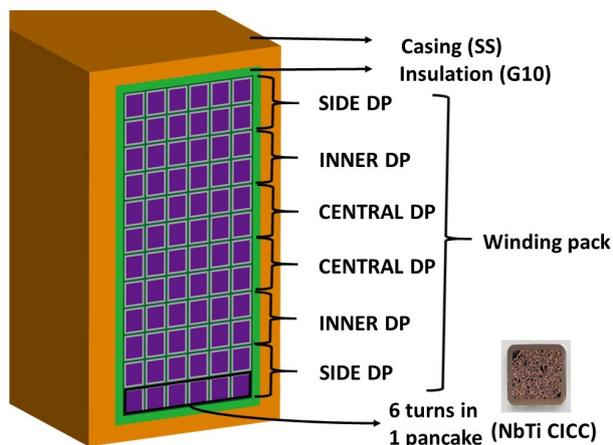


Figure 1: Cross-section of the JT-60SA TF coil, with SS = stainless steel, DP = double pancake.

Parameter	Value
CICC Dimension	26 mm × 22 mm
Void fraction	32 %
NbTi section	56.8 mm <sup>2</sup>
Cu section	180 mm <sup>2</sup>
Stainless Steel section	176 mm <sup>2</sup>
Helium section	123 mm <sup>2</sup>
G10 section (outside CICC)	100 mm <sup>2</sup>
Single pancake length	113.277 m

Table 1: Dimensional parameters of the JT-60SA TF coils CICC

## 2. Experimental analysis of the delayed quench acceleration phenomenon

The physical phenomena driving each one of the quench dynamic phases during the TF coils quench tests have been studied experimentally [8] and the most typical ones have also been analyzed numerically [9, 10, 11]. Figure 2 shows two types of the quench acceleration dynamics observed during the FD of the two quench experiments in the same TF coil number 10. One can see that the first quench test (noted as TFC10) has shown a typical "early" acceleration taking place near the start of the FD ( $t = 0$  s). This common phenomenon has already been explained with the classical preheat effect by thermo-hydraulic quench-back [8, 12] whereas the second one (noted as TFC10bis) has this quench acceleration 2 s after. Two different quench behaviors resulting from the same coil indicates that the reason could be due to the different testing conditions before reaching the quench. A further comparison has thus been made in Figure 3 between the inlet temperatures. One can see that the inlet temperature oscillation in the first test TFC10 is much smaller (around 10 mK) compared to the second one in TFC10bis of around 100 mK. As already presented in Figure 2, the test TFC10 has seen an "early" type of quench acceleration whereas the TFC10bis has a "delayed" one. Such coherence allows us to think that the quench acceleration delay could be related to the instability of the testing temperatures (caused by the temperature control loops of the cryogenic system).

Indeed, the high oscillations during the temperature-increasing phase could probably lead to a short heat peak that initiates a local quench when the general helium environment still remains "colder", i.e. generally below the cables  $T_{cs}$ . Such higher temperature difference ( $\Delta T$  more than 200 mK) between  $T_{cs}$  and helium can then lead to a lower level of the quench propagation velocity during a certain time. In order to verify this assumption, a numerical approach has been performed by implementing for the inlet temperature  $T_{in}$  a time dependent function combining the principal temperature fit  $T_{fit}$  (two increasing ramps mentioned in Section 1)

and the temperature oscillations  $T_{oscill}$  simplified to be a sinusoidal function, as written below:

$$T_{in}(t) = T_{fit}(t) + T_{oscill}(t) = T_{fit}(t) + A \sin\left(\frac{2\pi}{T_{per}} t - \varphi\right) \quad (1)$$

where  $A$  is the oscillation amplitude,  $T_{per}$  the oscillation period and  $\varphi$  the phase shift.

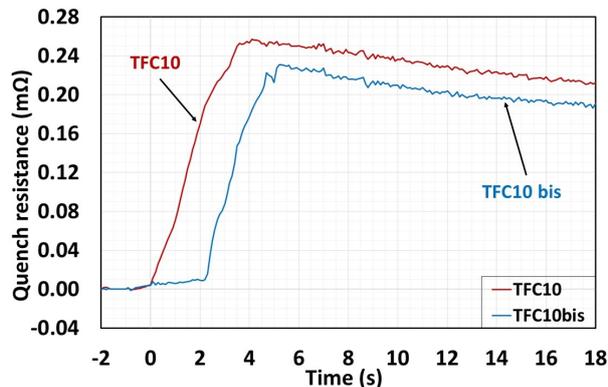


Figure 2: Comparison of the side DP resistance evolution between the two quench tests of the coil number 10. "Early" acceleration in TFC10 and "delayed" type in TFC10bis.

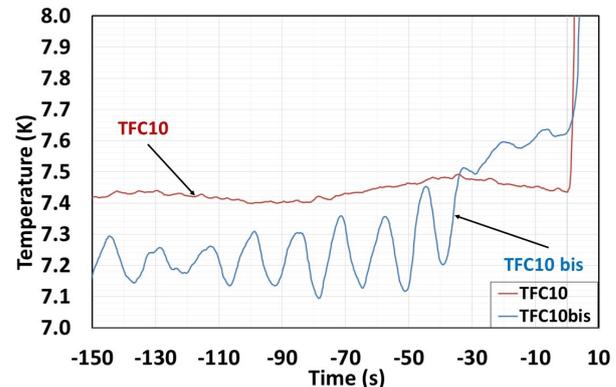


Figure 3: Comparison of the temperature oscillations between the two quench tests of the coil number 10.  $t = 0$  s indicates the start of the FD.

When analyzing all the "delayed" quench acceleration tests, two extreme amplitudes have been experimentally measured with a minimum of 35 mK (in TFC16) and a maximum of 125 mK (in TFC10bis). Such amplitude scope has led to the different delays of the quench acceleration ranging from 0.5 s to 2 s. In addition, the experimental  $T_{per}$  has been nearly constant around 20 s. In the following analysis, we will rely on a quench numerical model to study the oscillation amplitude effect on the quench acceleration dynamics by fixing  $\varphi = 0$ .

### 3. Numerical study of the impact of the testing temperature oscillations

Quench propagation in a CICC can lead to fast transient thermohydraulic phenomena including both conductive and convective transfer between conductors and helium. Such multiphysical phenomena have been extensively studied during the last decades by developing several numerical codes covering from the conductor-level ones [13, 14, 15] to the magnet-grade ones [16, 17]. In order to focus on the temperature oscillation phenomenon, a single pancake quench model developed in THEA [9] will be applied to carry out the following numerical study. This numerical model takes into account both longitudinal and transversal heat transfers in the 6-turn pancake as well as the fully transient quench state. The CICC dimensional properties (see Table 1) as well as the necessary parameters, such as friction coefficient and field map, are also used as boundary conditions in the numerical model. The delayed quench acceleration in the side DP of TFC16 has been taken as the model input for its representative dynamics (with a 2 s delay).

The parametric study has been carried out by varying the oscillation amplitude  $A$  in Equation (1) from 35 mK to 125 mK. Figure 4 shows that the beginning moment of the quench acceleration (or resistance slope change) is more and more delayed with the increase of the oscillation amplitude. One can see that for the oscillation amplitude smaller than 85 mK, there is almost no quench delay before quench acceleration while for a higher amplitude, the delay becomes significant from 0.5 s to several seconds. This then qualitatively confirms the experimental assumption about the predominant effect of temperature oscillations on the quench acceleration dynamics. The difference between experimental and numerical results could be explained by the limit of the single pancake model that cannot take into account the thermal effect from the

adjacent pancakes. One may also note that the beginning delay of the quench acceleration is in a discontinuous correlation with the amplitude increase, such as the big change of quench dynamics appearing from the amplitude 90 mK. In order to verify the local quench assumption and to better understand the above physical phenomena, spacial profiles of the helium temperature are plotted in Figure 5 for comparing "delayed" and "early" quench acceleration cases.

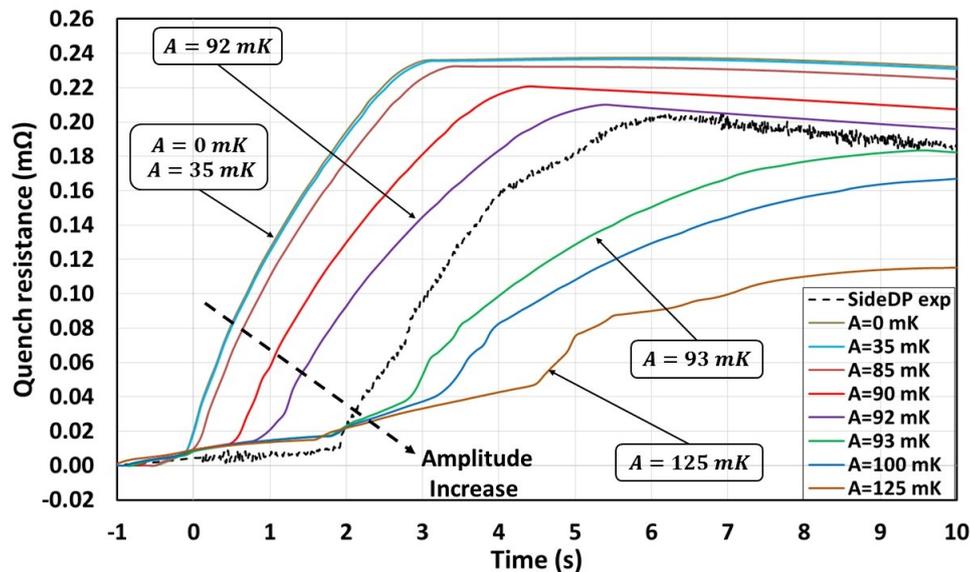


Figure 4: Time evolution of the quench resistance computed with different temperature oscillation amplitudes at  $T_{per} = 20$  s and  $\varphi = 0$  s.  $t = 0$  s indicates the start of the FD. The experimental resistance in the side DP of TFC16 is plotted in black dashed line.

Figure 5 shows that the oscillation amplitude can have a direct impact on the initial quench location and on the temperature profiles. In the "delayed" quench acceleration case with  $A = 125$  mK, the helium temperature starts to reach the  $T_{cs}$  at the pancake's inlet. Whereas the "early" quench acceleration case with  $A = 35$  mK has shown an initial quench location near the first peak field region at around  $x = 2.2$  m. Indeed, the normal zone propagation can be more reinforced in the "early" case than in the "delayed" one owing to the fact that the quench near the peak field region can propagate from two directions whereas the pancake inlet quench can only have one direction propagation. In addition, the temperature profiles have also been much modified by the oscillations as well as the temperature difference ( $\Delta T$ ) between  $T_{cs}$  and helium. If one takes the position at 1 m away from the initial quench location as an example (see  $\Delta T$  in Figure 5), one can see that the  $\Delta T$  is about 170 mK for the "delayed" case and about 50 mK for the "early" one. Knowing that the quench propagation velocity is inversely proportional to the temperature difference, a lower  $\Delta T$  will definitely reinforce the initial quench propagation and make the superconducting outer region near the normal zone faster to be quenched.

Until now, both the quench initiation location and the temperature profile show a predominant effect on the normal zone length development. We recall that when the Joule heating produced in this normal zone is high enough, the helium will be heated to expel from the quench location and will preheat the superconducting outer region in front of the quench under the helium friction effect. Such preheat effect can then lead to a quench acceleration, called thermo-hydraulic quench-back effect. The common "early" quench acceleration can take place thanks to its satisfaction of the rapid normal zone length development conditions (quench initiation at peak field region and homogeneous temperature profile). According to the numerical simulations, if no temperature oscillations appeared, i.e.  $A = 0$  mK, the initial quench location has also been around the first peak field region. This is actually in good agreement with the

small oscillation case of  $A = 35$  mK where an "early" quench acceleration can take place.

Based on the above analysis, the "delayed" quench acceleration can thus be easily explained. When the temperature oscillation is strong enough, the initial quench location can be modified from the peak field region to the pancake's inlet as well as the temperature profile getting very unstable. This leads to a slow initial quench propagation thus a slow development of the normal zone length. As the Joule heating takes longer time to trigger a thermo-hydraulic quench-back in this case, a "delayed" quench acceleration phenomenon then occurs. Finally, the discontinuous correlation between the quench acceleration delay and the amplitude increase can be explained by the abrupt switch of the quench initiation location from the peak field region to the pancake's inlet when  $A$  is higher than a "critical value" of around 90 mK.

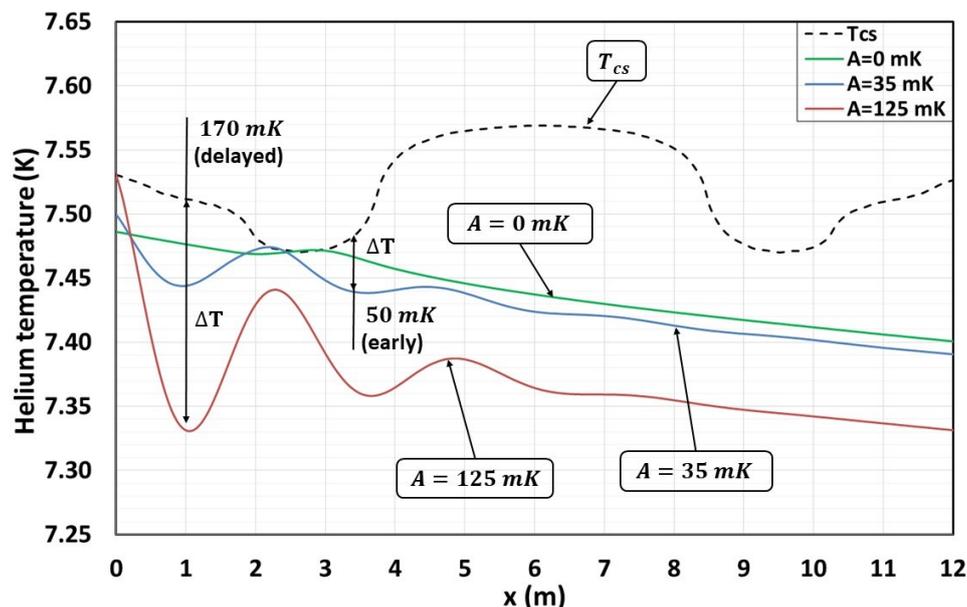


Figure 5: Helium temperature profiles at the quench initiation moment for "delayed" case ( $A = 125$  mK), "early" case ( $A = 35$  mK) and no oscillation case ( $A = 0$  mK), with  $T_{per} = 20$  s and  $\varphi = 0$  s. The temperature difference is taken at 1 m away from the initial quench location.

#### 4. Conclusion

The experimental analysis of the two quench tests on the same TF coil (TFC10) led us to study the effect of the testing temperature oscillations on the quench acceleration dynamics. A single pancake model has then been developed in THEA code to check this assumption. Analysis of the model results showed that the oscillation amplitude can have a direct impact on the initial quench location and on the temperature profiles. When the temperature oscillation is strong enough, the initial quench will probably be located at the pancake's inlet that only allows one direction propagation as well as the temperature profiles being more unstable to have a higher  $\Delta T$  between  $T_{cs}$  and helium. Both of the two effects make the normal zone length development slower leading to a "delayed" appearance of the thermo-hydraulic quench-back effect. Thereby, a "delayed" quench acceleration takes place. The opposite conditions induced by a small oscillation amplitude can then lead to the common "early" quench acceleration phenomenon.

Including the predominant effect of the oscillation amplitude, the phase shift parameter should also be taken into account in the effect of the temperature oscillations. Indeed, the phase shift can also bring a translation of the temperature profiles thus a modification on the quench initiation location and on the local temperature difference between  $T_{cs}$  and helium. This work will thus be followed by a future parametric study with the phase shift parameter in order to verify its effect on the quench acceleration dynamics.

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