# Simulation of the JT-60SA Supercritical Helium Toroidal Field Coil Loop During Fast Safety Discharge Using Simcryogenics. Comparison With Experimental Data and Extrapolation to Higher Currents

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***Abstract:***
***The JT-60SA fusion experiment is under commissioning at Naka, Japan (2023). When a fast safety discharge (FSD) of the toroidal field coils (TFC) current occurs, the procedure is to close the supercritical helium (SHe) supply of the magnets from the auxiliary cold box to release the heated and pressurized helium of the coil and its structure into a quench tank to avoid over-pressurizing the loop. To restart normal operation, the evaporated helium must be re-liquefied to return into the loop. This can take up to 48 hours. The maximal pressure reached in the loop during FSD has to be predicted to assess the necessity to open the quench relief valve (QRV). If opening the QRV is not necessary, it will save time during the commissioning and during future operation. Simcryogenics [1] is used to model the whole cryo-magnetic loop 1 dedicated to supply SHe for the TFC Winding Pack (WP), the TFC structures and CS structures. It means that the piping, Cable in Conduit Conductor (CICC), TFC structures and CS structures, which belong to the TFC loop, are modeled thermally and hydraulically. The heat loads that are generated during FSD and that are applied to the simulation are issued from an ad-hoc simulation. This paper presents the comparison between experimental and predicted behavior of TFC FSD at 15 kA and 18 kA and extrapolates it for higher current, such as the nominal current of 25.7 kA. This paper gives the value of the FSD current for which the TFC loop helium must be released into the quench tank, meaning that the loop pressure would be expected to lead to the safety valve opening.***

***Index Terms*—Cryogenics, superconducting magnets, simulation, AC losses, eddy current.**

## INTRODUCTION

The JT-60SA fusion experiment [2] is under commissioning at Naka, Japan. This paper interest is about its cryo-magnetic system. The cryogenic system [3,4] is composed of a warm compression station ensuring helium compression from 1.05 to 15 bars, a refrigeration cold box providing a supercritical helium flow of about 400 g/s at 5 K, 5 bars and an auxiliary cold box ensuring final expansion of supercritical helium into liquid to a large liquid helium buffer (7 $m^3$). The liquid is to be evaporated by the heat loads coming from the magnets and structures, through immerged heat exchangers.

The 18 Toroidal Fields Coils (TFC) are kept cool (with supply temperature around 4.4 K) by the cryogenic system through the so-called “loop 1”. This study is focused on this cryo-magnetic loop 1 that ensures the circulation of supercritical helium into the TFC WP, the TFC structures and CS structures cooling channels.

This paper is structured as follows: Section I presents the modeling of loop 1, while Section II discusses the simulation setup with applied boundary conditions. Section III presents the simulation results, and in Section IV, we make a prediction about an event that occurred on August 23, 2023. Finally, the conclusion ends the paper and outlines our future work.

## I. MODELING OVERVIEW

The loop 1 is a supercritical helium closed (almost, see later) loop that is dedicated to supply the 18 TFC Winding Pack (WP) (the TFC WP is composed of 12 pancakes (CICC) hydraulically in parallel) and the TFC / CS structures, as **Fig. 1** sketches it. The modelling is made with the CEA tool Simcryogenics **[1].**

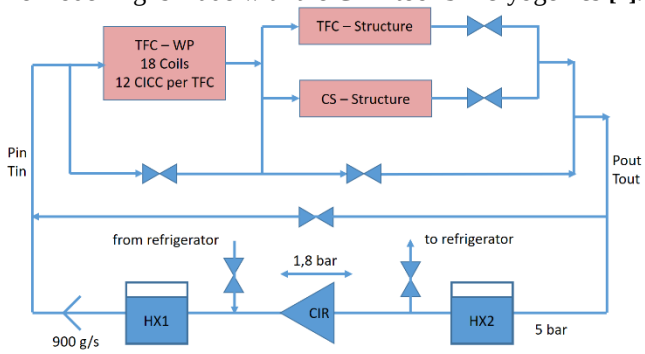


**Fig. 1.** JT-60SA loop 1 overview, CIR stands for circulator, ensuring around 900 g/s supercritical helium flow rate. HX stands for heat exchanger, removing the heat generated by the circulator and that coming from the magnets/structures. The heat exchangers are immerged into a liquid buffer helium bath at 4.3 K nominally. Valves allow some of the SHe flow to be bypassed.

The total volume of supercritical helium contained into the loop 1 is around five cubic meters (for a mass inventory of around 700 kg). In the model, there is 82 meters of piping

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(separated into 4 pipes of different length in series, with decreasing cross-section as they approach the magnet) from HX1 to the TFC WP, 50 meters between the TFC WP and the TFC structure (4 pipes in series) and 115 meters from the TFC structure to the HX2 (4 pipes in series). Others details about the loop modelling can be found in [5].

To simulate the behavior of the loop 1, several boundary conditions and parameters need to be imposed and hypotheses to be made. The next section describes them.

## II. SIMULATION SETUP

The simulation setup section is divided into two subsections; the heat loads definition and the thermal-hydraulics parameters starting with the heat loads, driving the pressure and temperature behavior of the loop.

### A. *Heat loads*

To simulate the FSD, the heat loads generated by the FSD itself (due to eddy currents and AC losses) must be known. The model used for evaluating both transient loads [6] is consistent with [7] where particular cases were compared with past experiments. From [7], the experimental enthalpy flux difference has been re-calculated in this paper: $(\dot{m}_{in}h_{in} - \dot{m}_{out}h_{out})$ between the inlet and the outlet of the WP and the structure (the sum of the 18 TFC WP and 18 TFC structures), observed during a 15 kA FSD. It is shown in **Fig. 2.** The balance of the CS structure is not represented here, as there are no loads on neither the CS WP nor the CS structures.

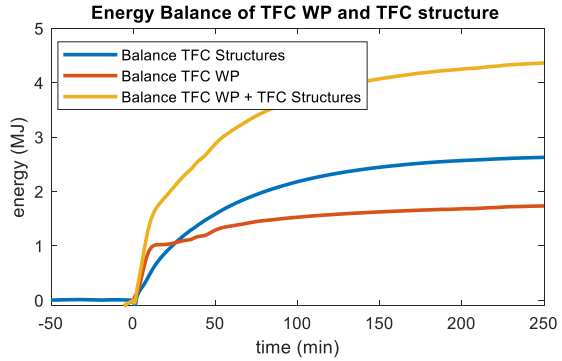


**Fig. 2.** Experimental enthalpy flux differences between the inlet and the outlet of TFC Structure, TFC WP and the sum of both, for a 15 kA FSD. The plots start at 0 J at the time of the FSD.

**Fig. 2** gives the total energy that was deposited in the TFC WP and the TFC structures by the FSD. The calculated heat loads that are considered for the study are illustrated by **Fig. 3**. The total energy is adapted regarding the experimental data.

It can be noted that energy deposited on the TFC WP by AC losses is smaller than the energy balance of the TFC WP presented on **Fig. 2**. It means that a part of the energy deposited on the TFC structure goes into the TFC WP by heat conduction (about one third).

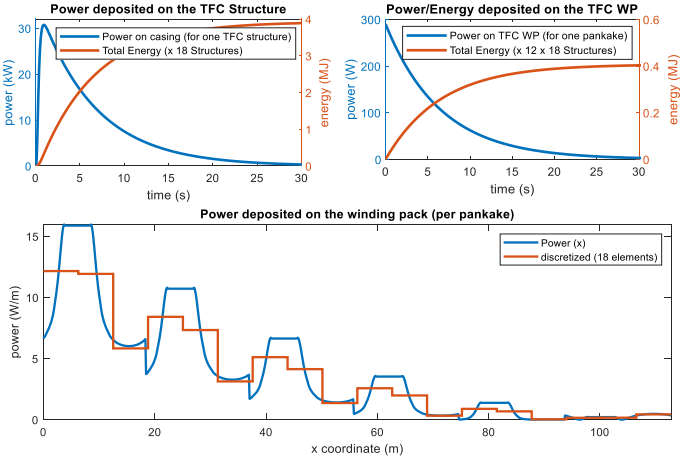


**Fig. 3.** Heat loads to be used by the model. The TFC structure (top-left) is considered to have a homogenous load along its length for a total of almost 4 MJ deposited for the 15 kA FSD while the load on the TFC WP is considered as x-dependent (bottom) with a total of 0.4 MJ (top-right) for the 15 kA FSD.

### B. *Thermal-hydraulics*

To simulate the behavior of loop1, several thermal-hydraulic boundary conditions and parameters have to be imposed, and hypotheses to be listed. Without detailing, the length and the cross section of every piece of piping, the following can be stated:

- Pipes are considered to have no mass (i.e thermal capacity of the wall is negligible with respect to the one coming from helium),
- The circulator imposes a flowrate to the loop, proportional to its inlet density (volumetric flowrate is imposed),
- The circulator stays active during the FSD, at constant speed
- Equivalent hydraulic circuits in parallel are modelled once and the result is multiplied,
- Loop outlet (outlet from the coils point of view) pressure is regulated at 5 bars (the pressure is regulated using the valves “from/to refrigerator” that can be seen on Fig. 1), except during the FSD when the loop 1 is isochoric (both valves are closed)
- Inlet temperature of the loop (inlet is from the coils point of view) is imposed as it went in the experiment (see **Fig. 5**), because the control (HX1 and HX2 temperature) of buffer effect is not well modeled so far
- Heat exchangers (HX1 and HX2 of **Fig. 1**) are considered perfect. The outlet temperature of the supercritical helium is equal to the temperature of the liquid.
- Heat load due to eddy currents are deposited into the TFC mass’s structure (stainless steel)
- Heat loads due to AC loses are deposited into the superconducting strand of the CICC
- Thermal contact between the TFC structure and its cooling channel is calculated with the Dittus–Boelter correlation and then ¼ of the cooling channel is considered in thermal contact with the TFC structure

The most important thermal parameter is the thermal resistivity between the TFC structure and the TFC WP. It is illustrated by the blue arrows on **Fig. 4.** This adjustable unknown parameter is used to make the simulation to fit the experimental data.

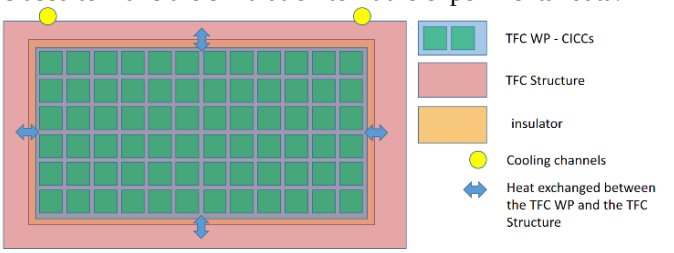


**Fig. 4.** Illustration of a cross section of the TFC magnet (schematic view). The thermal resistance is to be adjusted for the simulation to fit the experimental data.

As previously stated, there is only one pancake (one CICC) that is modeled and the result is multiplied by 12 to represent the whole TFC WP. It means that this pancake represents an "averaged one", in a smeared modelling approach. The AC losses and the transfer from the TFC WP and the TFC structure are different between central and lateral pancakes but the heat load that is applied is also an average one.

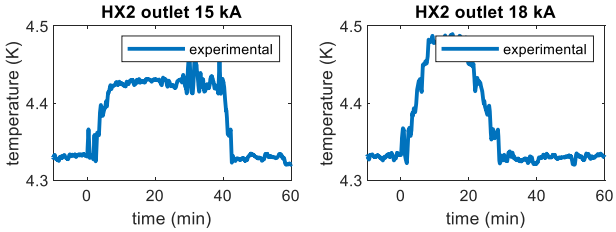


**Fig. 5.** Inlet temperature of loop 1 for the simulation of the 15 kA and the 18 kA FSD.

## III. SIMULATION RESULTS

This section presents the simulation results obtained thanks to the model described in section 1 and the simulation setup presented in section 2. The thermal resistance unknown parameter between the TFC WP and the TFC structure has been adapted to fit the experimental data. It is nevertheless considered the same for the 15 kA and the 18kA FSD. **Fig. 6** presents the comparison results between experimental data measured during integrated commissioning and Simcryogenics simulation model, for both the inlet and the outlet pressure of the loop 1, and some temperatures, during the 15 kA and the 18 kA FSD.

The model shows a good capability to reproduce the FSD trends. The closer the temperature is to the exchanger, the more its "peaks" behavior is attenuated. It is more the case in the simulations than the experiments. It is due to numerical diffusion and can be overcome using a more refined mesh for pipes. Since the objective of this study was to predict the pressure rise, such a simulation with smaller mesh is not presented.

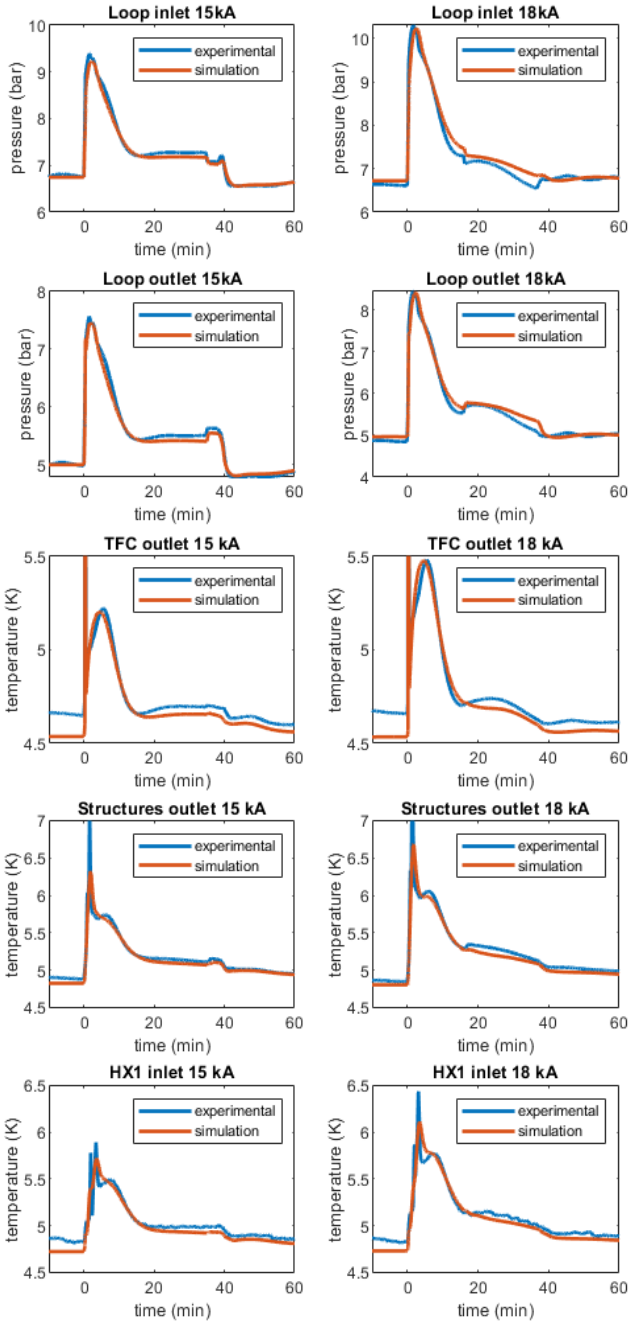


**Fig. 6.** Simulation results of the 15 kA and 18 kA FSD. Both simulations have been performed with the same parameters, only the heat loads due to the FSD has been changed, as they are not the same for 15 kA and for 18 kA.

## IV. PREDICTION RESULTS

The model of the loop 1, associated with the simulation setup described in section 2 has shown its ability to reproduce the behavior of pressures and temperatures during a FSD. It has been decided to use the model to predict the maximal inlet pressure during a FSD at 20 kA as the experiment was going to be conducted at the time of the study. The result is given by **Fig. 7**, where three plots can be found. The blue plot is the experimental result (obtained after the prediction). There is two simulation plots, *a priori* (yellow) and *a posteriori* (red). The *a priori* plot has been obtained before that the 20 kA FSD takes

place, with a guess regarding the behavior of loop 1 inlet temperature. The *a posteriori* plot has been obtained correcting the inlet temperature and pressure at the beginning of the FSD. The thermal resistivity between the TFC WP and the TFC structure stays the same.

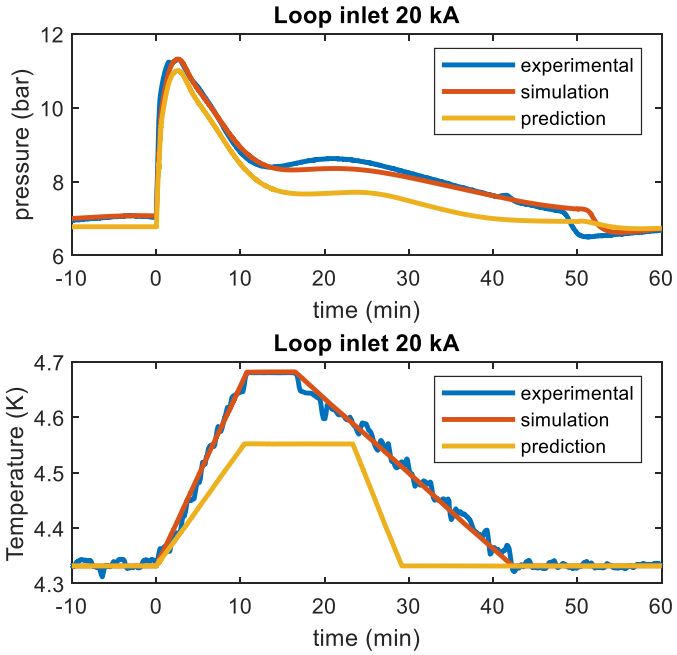


**Fig. 7.** Prediction and simulation of the inlet pressure of the loop 1 during a 20 kA FSD (top) and of the inlet temperature (bottom). The blue line are the experimental results while the yellow line are the predictions. The maximal pressure reached is correctly predicted (there is a 0.3 bar deviation due to a higher loop 1 inlet pressure at the time of the FSD) but the behavior afterward is not. The red line simulates a posteriori the pressure behavior, correcting the inlet temperature of the loop according to the bottom of the figure and the loop 1 outlet pressure.

The prediction was made before the experiment and it permitted to decide to set the quench relief valve to a set point of 12 bars, allowing the loop to not be disconnected.

The model showed its capability to predict the pressure behavior if the shape of the loop 1 inlet temperature is correct. The maximal value is nevertheless predicted correctly and a parametric study has been conducted to obtain the maximal pressure value as a function of the magnet current intensity when the FSD occurs. The result is presented on **Fig. 8**.

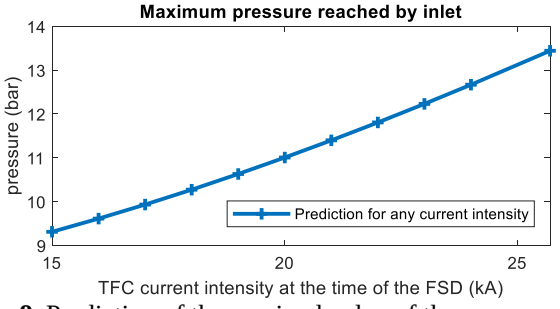


**Fig. 8.** Prediction of the maximal value of the pressure of the loop 1 inlet as a function of the intensity of the current at the time of the FSD for a pressure return of five bar at the time of the FSD.

**Fig. 8** shows that for the nominal TFC current intensity of 25.7 kA, the maximal pressure reached by the loop 1 is expected to be 13.4 bars. It means that the quench relief valves set point could be set at 15 bars, 3 bars below the design burst pressure of the rupture disk.

It is worth mentioning that the pressure is captured and well predicted because of the heat conduction being estimated.

## V. Conclusion and Future Work

The fast safety discharge of the current flowing into the 18 toroidal field coils has been modeled and simulated from the thermal-hydraulics point of view. The Simcryogenics model, associated with heat load estimation, shown great capabilities to reproduce the 15, 18 kA fast safety discharges events and to predict the 20 kA (that has already been confirmed) and the 25.7 kA ones (waiting to be compared with experimental data). The fast safety discharge at the nominal current intensity of 25.7 kA is predicted to make the loop inlet pressure to reach 13.4 bar, below the expected burst pressure of the rupture disk.

The simulation of the FSD takes less than 10 minutes to compute, leading to the possibility to use the simulator “on the fly” during commissioning activities and future operation, to perform predictions for others purposes.

During the prediction/simulation process, the behavior of the thermal buffer behavior revealed to be crucial for the pressure prediction. The pressure/temperature rise of the thermal buffer during fast safety discharge will be further investigated to have a better prediction of the loop 1 behavior. Following that on-going work, the second supercritical helium loop of the JT-60SA cryomagnetic system (dedicated to the Central Solenoid and Poloidal field coils) will be modeled using the same spirit, toward having a global predictor/simulator of the cryomagnetic system.

A tuning parameter has been used to fit the experimental data. This parameter is linked to the ground insulation thermal conductivity. In future work, Simcryogenics will include a feature to calculate the thermal conductivity of the ground insulation (based on [] for example) instead of using a tuning parameter, to ensure the code does not rely on an unknown parameters to predict the behavior of the loop. It will help Simcryogenics to become a predictive tool like the 4C code [8] or the supermagnet software suite [9].

## VI. Acknowledgement

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