Dynamic simulation of ITER cryogenic system under D-T operation

R Maekawa¹, S Takami², A Iwamoto³, H S Chang⁴ and D Grillot¹

¹ITER Organization, Route de Vinon-sur-Verdon 13067 St Paul Lez Durance Cedex – France
²National Institute for Fusion Science, 322-6 Oroshi Toki Gifu 509-5292 JAPAN

E-mail: ryuji.maekawa@iter.org

Abstract. Co-simulation of Cryoplant and Tokamak superconducting magnet system (referred to as Magnet) has been performed to characterize operating condition associated with control strategies. Cryoplant model, developed by EcosimPro®, consists of three identical refrigerators connected with integrated Cryoplant Termination Cold Box (CTCB) which distributes the coolant to five Auxiliary Cold Boxes (ACB) for Magnet and CryoPump (CP) cooling. Meanwhile, Magnet model, developed by Visual Modeler®, consists of Toroidal Field (TF) coil, Central Solenoid (CS), TF STructure (ST) and Poloidal Field (PF)/Correction Coil (CC). Magnet model computes thermo-hydraulic behavior of a forced-flow Supercritical Helium (SHe), with specified thermal energy deposition along the conductor in the case of Deuterium-Tritium (DT) operation as well as plasma disruption followed by the fast energy discharge of CS and PF. Global simulation of ITER cryogenic system provides its operating characteristics for complex cryogenic processes. The paper discusses the coupling of Cryoplant and Magnet models and the control strategy for Cryoplant to manage substantial dynamic heat loads.

1. Introduction

To investigate the complex plant processes for ITER cryogenic system, a development program has been launched to build-up Magnet as well as Cryoplant since 2011. Two stand-alone models [1] [2] [3] have been developed with the utilization of dynamic simulation software; Visual Modeler® for the Magnet and EcosimPro® for the Cryoplant, respectively. As for the final phase of program, co-simulation has been taken place to run the two independent models in parallel/simultaneously as exchanging/sharing process variables in a collaborative manner.

The paper describes the co-simulation system set-up and its simulation results under DT operation, including the case of plasma disruption followed by the fast energy discharge of CS and PF. Thermal energy mitigation (refer to as “the mitigation”) scheme, regulating a cold circulator speed to manage the arrival of “hot” SHe in the saturated bath, demonstrates promising result to sustain the operation of Cryoplant.

2. Co-simulation

2.1. Simulation model

The simulation model consists of two stand-alone models, Cryoplant and Magnet (consists of four subsystems). The coupling of two models is at the saturated/subcooled LHe baths in ACBs. Cryoplant model computes the process under substantial dynamic heat loads from Magnet operation, while Magnet
model calculates the energy dissipation at the LHe immersed HXs in the saturated/subcooled LHe baths as implementing complex time-dependent heat load along the conductors. Figure 1 shows a simplified cryogenic system, consisting of three helium refrigerators, Warm Compressor Station (WCS), Cold-Box (CB), CTCB to integrate the coolant from refrigerators and distributed to 5 ACBs. Magnet and CP are connected to the dedicated ACB, consisting of two LHe baths, a circulation pump and a cold compressor to fix the supply temperature.

Cryoplant side, up to ACB baths, is developed by EcosimPro® while the Magnet side, including winding pack and ACBs, is built-up by Visual Modeler®. The process simulation is based on the thermal energy deposition to Magnet and CP systems, which is absorbed by the forced-flow SHe cooling and dissipated at the saturated LHe baths in ACBs. The difference between the stand-alone Magnet model and the global model is floating pressure in the Low-Pressure (LP) return, which was fixed for the stand-alone model whereas the value is time-dependent for the co-simulation; affected by the thermal energy dissipation at the baths.

![Figure 1. A schematic of ITER cryogenic system model.](image)

2.2. Co-simulation setup

Figure 2 shows a co-simulation set-up, which consists of two workstations, represented in two rectangular boxes, connected via TCP/IP socket for data exchange. Each workstation has not only process simulation program, Cryoplant and Magnet model, but also InterFace (I/F) programs, ECOCOM and VMCOM, to exchange the process data through TCP/IP. I/F programs exchange the predefined variable for process calculation in each model. For instance, EcosimPro® has a feature to generate a stand-alone model, called “Deck”, which also generates C/C++ function-call based interface program “Application Programming Interface” (API). As utilizing API to obtain the data from Deck and provides the predefined variable for Deck to execute the simulation. Meanwhile, the predefined process variables are exchanged via I/F program (VMCOM) though VM Space. To execute the co-simulation, a coupling of two programs are realized by “Execution Control” in the Omegaland® package, which also includes Visual Modeler®. The co-simulation is defined such that the EcosimPro® is acting as a server while Visual Modeler® is assigned as a client.
Two simulation models are independently executed with an optimized time-step, the data exchange only takes place as setting the time-step, for this particular simulation which was set at 1s. Execution control is monitoring the computation in each model and triggering the data-exchange in a timely manner. There is no direct data sharing at the process simulation level nor a local scheduler to look-out the execution time. Even though discrete-time execution sometimes costs CPU load as starting the computation at different values (1 step time back value), the drastic change in each time step is limited and can be considered as a reasonable approach to execute the process simulation.

Figure 2. Co-simulation setup for Visual Modeler® and EcosimPro® running in parallel.

3. Control strategy

3.1. Cryoplant control

The control strategy of Cryoplant is relying on the self-regulation; floating process variables to sustain the operation under dynamic heat load. Although this approach has not been validated due to the lack of dynamic simulation capability, it has been considered as a known fact for the large scale refrigerator operation. Thus, it is more practical to focus on the management of power consumption at WCS in terms of operation efficiency.

As shown in figure 3, the control has been implemented to accommodate the LP flow variation with dedicated Variable Frequency Drive (VFD) at one LP unit at WCS, while the LHe level in the subcooler is regulated with level controls. LC3800 keeps the minimum level as feeding the LHe from the tank, whereas LC4310 releases the extra cooling power to LHe tank. In principle, the regulation of JT pressure via PC1600 should be sufficient to keep the LHe level in the subcooler within the upper/lower boundary defined by LC3800/4310. As the VFD is only activated as a result of increasing evaporation of LHe in ACBs, this arrangement is ideal to manage power consumption rate at WCS. [5]

Figure 3. Control logic implementation at the WCS and the cold end of refrigerator.
Table 1. List of set-point for the operation

| Component | Process value | Set-point |
|-----------|---------------|-----------|
| WCS       | HP (High Pressure) (bar) | 20.5      |
|           | MP (Medium Pressure) (bar) | 5.03      |
|           | LP (Low Pressure) (bar)    | 1.05      |
| Cold box  | JT pressure (bar)          | 5.0       |
|           | LHe subcooler level (%)   | 50/75     |
|           | HTS lead supply pressure (bar) | 4.0   |
|           | HTS lead supply temp. (K)  | 50.0      |
| ACB       | Saturated/subcooled bath level (%) | 50/60 |
|           | Subcooled bath pressure (bar) | 0.99 |

Additional control, supervision, to monitor the balance of three refrigerators [4], has been implemented to allocate the equivalent refrigeration capacity from each cold-box operation. In principle, the variation on LP flow drives operation states of CB, supervision tracking the balance in LP flow to each CB and activate the control as deviating the LP flow balance. LP flow partition in each CB is dominated by the flow impedance in HX block temperature gradients and JT flow is proportional to LP flow to compensate the balance of CB operation. In addition to this control implementation, overall refrigeration capacity can be regulated as adjusting HP set-point, as monitoring increase/decrease in the LHe tank level. Table 1 summarizes the required set-points for the system operation.

3.2. ACB control
ACB has several control logics to sustain DT operation as well as in the case of fast events; plasma disruption and the fast energy discharge of CS. The most critical control is for the protection of cold circulator/compressor operation with Anti-Surge Control (ASC) logic, as shown in figure 4. To fulfil ACBs functionality, those two components have to be operated under any circumstance. ASC has been implemented and process simulation confirm its fidelity against transient disturbance to the system operation, which includes the initial magnetization of plasmas by CS [2]. In addition to the protection control, the mitigation scheme has been implemented for ST operation in the case of plasma disruption. As having abrupt increase of thermal energy deposition to ST, the mitigation has to be activated to sustain the operation of Cryoplant; preventing too much cold gaseous helium return to Cryoplant. In this case, the control is based on the inferential control to regulate the pressure in the saturated LHe bath via cold circulator speed. In other words, as increasing the pressure in the bath, cold circulator slow-down its speed to limit the thermal energy dissipation at LHe immersed HX. [3]

![Figure 4. Simplified control schematic for ACB for Anti-Surge-Protection (ASP)](image-url)
4. Simulation results

4.1. Nominal DT operation

The nominal DT operation with 7 plasma-pulses has been simulated, as shown in figure 5 through 8, which summarize the process variation of ACBs to cross-check their functionality. Thermal energy dissipation in the saturated baths is shown in figure 5, while figure 6 shows their variation in the subcooled baths. It is apparent that major dynamic heat loads are from ST and CS operations. ST is subjected to have a substantial heat load during plasma burn due to plasma control noise and nuclear heating, while CS heat load is caused by the initial magnetization of plasmas. The timing of peak heat loads is not synchronized as CS has a relatively long hydraulic path, which takes about 15 min. for transit the cooling path.

The functionality of subcooled bath is extracting compression work at the cold circulator and setting the supply temperature to Magnet. Since the mass-flow rate in Magnet cooling is constant, the heat load on the subcooled bath is expected to be stable. However, as shown in figure 6, the heat loads to the subcooled bath showed some variations. As Cryoplant utilizes its self-regulation approach, the floating process values at LP (see the upper curve of figure 7) results in the SHe temperature variation to the subcooled bath. In figure 7, the legend “_sat” represents the saturated bath, while “_sub” implies the subcooled bath. Meanwhile, the subcooled bath pressure was kept constant as regulating cold compressor speed as shown in figure 8, demonstrating the compliance of ACB requirement for DT phase.

As mentioned earlier, the key operation of Cryoplant is to minimize its power consumption at WCS. As showing in figure 9, the performance of VFD is satisfactory as corresponding to the variation of heat load and mostly stayed at its minimum level at 50%. Figure 10 represents the variation in LP at the WCS suction, showing satisfactory regulation performance to keep its set-point at 1.05±0.02 bar.

As for CB side, figure 11 shows the mass-flow rate and the outlet temperature of Turbine 4. Although there is no active control in CB, Turbine 4 mass-flow adapts the time dependent heat load at Magnet. It
appears that the variation of JT stream is proportional to the LP mass flow rate, which is the out of phase with the temperature variation. To compensate for the temperature variation in the HX blocks, JT mass-flow rate increase with LP mass flow rate. Self-regulation of CB well balances the JT flow to sustain the operation under dynamic heat load. After 4 pulses, the process-variables profile becomes almost identical, which suggested the system is reached at the balanced operation state.

Figure 9. VFD response during pulse-operation.  

Figure 10. LP variation at WCS suction.

Figure 11. Variation of T4 mass-flow rate and temp.  

Figure 12. LHe level variation for CBs.

To understand the performance of each CB, one should look at the variation of LHe level in the subcooler, as shown in figure 12. LHe level in the subcooler has mostly stayed at its upper boundary, indicating sufficient cooling power from each CB. As a result, the control philosophy to rely on the self-regulation of CB is verified and saving power consumption with VFD demonstrated satisfactory result.

4.2. Plasma disruption followed by the fast energy discharge of CS

Plasma disruption generates substantial thermal energy to ST, 10 MJ in 1 s, which likely to initiate the fast discharge of CS. To prevent any malfunction or trip of components in Cryoplant, the mitigation scheme has been implemented to impose time delay in the thermal energy dissipation at the HX for ACB-ST in terms of circulator speed regulation. The inferential control has been employed to regulate the pressure of saturated LHe bath with a circulator speed. [3]

Figure 13 compares the heat load at the saturated bath HX of ACB-ST with and without the mitigation scheme. The no-mitigation case has been calculated as considering ideal HX in the saturated LHe without having any limitation. As a result, the maximum heat load exceeded 40 kW due to plasma disruption.

As applying the mitigation, the heat load was successfully suppressed below 20 kW, which satisfy the design value of HX at 20 kW. Figure 14 represents the speed reduction of cold circulator, imposing a delay on the arrival of “hot” SH coolant to the HX. The speed variation is within the design of cold circulator which ensures fidelity of this control approach. Note that by changing the speed of circulator,
the heat load at subcooled bath was also reduced, as shown in figure 13 with “sub_mit” line. ACB operation is robust enough to sustain ST cooling even in the case of plasma disruption.

Meanwhile, Cryoplant is successfully adapting the drastic increase of heat load (without the mitigation) as consuming the LHe in the subcooler to counterbalance the lack of cooling power (see figure 15). Similarly, VFD has sufficient capacity (the maximum is 120%) to compensate for the increased LP mass-flow rate, as shown in figure 16. Still, the sharp increase of LP pressure was registered for the saturated bath in the ACB-ST (see figure 17). On the other hand, the tracking performance of cold compressor is satisfactory to keep the subcooled bath pressure at 0.95 bar. However, as looking at the speed variation of cold compressor (see figure 18), the maximum value exceeds its design specification of 110% (as considering 100% at its nominal operation speed). This is mostly caused by the abrupt increase of discharge pressure of cold compressors. Although Cryoplant has sufficient capacity to adapt the temporary increase of heat load, cold compressor operation range was beyond its boundary to sustain the operation without having the mitigation scheme.

Figure 13. Comparison of heat load at HX.

Figure 14. Cold circulator speed variation.

Figure 15. LHe level variation without mitigation.

Figure 16. Comparison of VFD operation.

Figure 17. ACB-ST bath pressures.

Figure 18. Cold compressor operation.
Unlike the mitigation scheme for ST, CS does not have a plan to implement the mitigation to suppress
the transient increase of heat load due to its fast discharge. As comparing with nominal operation, the
heat load increased up to 13 kW after the fast discharge (at the fourth pulse), as shown in figure 19.
Since the design of HX for all ACB is approximately 20 kW, there is still some margin for the HX to
absorb additional heat load. The decrease of heat load to the negative region after the fast discharge is
caused by the fact that the supply temperature becomes less than that of saturated bath temperature,
having no heat load after the fast energy discharge of CS. The operation range of cold compressor is
verified as plotting its speed variation (see figure 20).

![Figure 19. HX heat load variation for ACB-CS.](image)

![Figure 20. Cold compressor operation for CS](image)

5. Conclusion
Co-simulation of ITER cryogenic system has been conducted under nominal operation as well as the
fast event; a plasma disruption followed by the fast energy discharge of CS. Process simulation indicates
that Cryoplant can be operated based on the self-regulation with floating process variables. Although
this approach impacts on the cold-compressor, as changing their discharge pressure, the operation range
of cold compressor is within its design boundary. It has also confirmed that the mitigation ensures the
stable operation of cryogenic system. Consequently, the current process control strategy is robust
even to sustain the drastic change in their process.

The development program to build-up a process simulation platform has been successfully executed
as benchmark against SuperMagnet® for Magnet model. Validation of Cryoplant will be performed
after starting the commissioning of Cryoplant at the end of 2020.

6. References
[1] Booth W, Bradu B, Vinuela E B, Gayet P, Maekawa R, Serio L, Chang H-S and Chalifour M.
“Dynamic simulation of the ITER helium cryogenic system under pulsed heat loads.”
ICEC 24. Fukuoka: Cryogenic society of Japan, 2012. pp 595-598.
[2] Maekawa R, Takami S, Iwamoto A, Chang H-S, Forgeas A and Chalifour M. “Process control
strategy for ITER central solenoid operation.” Cryogenics 80 (2016): 284-293.
[3] Maekawa R, Takami S, Iwamoto A, Chang H-S, Forgeas A, Chalifour M and Serio L. “Process
analyses of ITER Toroidal Field Structure cooling scheme.” Cryogenics 63 (2014): 222-
230.
[4] Palacin LG, Bradu B, Vinuela E B, Maekawa R and Chalifour M. “An optimal control approach
for an overall cryogenic plant under pulsed heat loads.” ICEC 25. Elsevier, 2015. 1141-
46.
[5] Bradu B “Consultation of He cryoplant modeling and control.” Internal report (2016).

ITER Disclaimer
The views and opinions expressed herein do not necessarily reflect those of the ITER Organization