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System-scale dynamic simulation of the 400W@1.8K test facility at CEA Grenoble: experimental validation on steady state and transient configurations (towards new applications)

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Abstract. The CEA DSBT (Low Temperature System Department) commissioned in 2004 a test facility with a 400W@1.8K cooling capacity, designed to be modular to meet the needs of a wide range of studies: characterize industrial components, studies with two-phase superfluid helium, fundamental research on high Reynolds number turbulent flows… At the same time, the Simcryogenics library was developed by DSBT to simulate and optimize cryogenics plants. This tool, based on Simscape, aims in particular to generate model-based control schemes for cryogenic plants subject to high disturbances. The library is validated on numerous experimental systems. Recently, the 400W@1.8K facility was used to characterize a He-II heat exchanger for CERN and measurements have been used to extend the validation Simcryogenics: characterisation of each component, validation of the whole cryogenic model based on steady-state and transient tests between 1.8 K and 2.3 K with He-II. System-scale modelling enables to accelerate the adaptations of the facility to new needs and more specifically to anticipate cryogenic refrigeration problems for quantum cluster applications. The 400W@1.8K can thus be adapted to become a Quantum Engineering Demonstrator (QED) enabling the demonstration of key solutions contributing to the scaling up of quantum technologies requiring high efficiency cryogenic cooling.

1. Introduction

Large scale refrigerators have been developed for many applications that require to extract high levels of power at very low temperature. The main applications include particle accelerators, such as the CERN Large Hadron Collider (LHC), whose high-energy particle beams are guided around the accelerator ring by a strong magnetic field maintained by superconducting electromagnets, which must be kept at 1.9 K. Other examples are large research test facilities such as the European XFEL linear accelerator in Germany, which generates ultrashort X-rays and which needs around a hundred cryomodules at 2 K, nuclear fusion reactors such as JT-60SA in Japan or ITER in France which need high power at 4.5 K and magnetic resonance imaging. The CEA Grenoble 400W@1.8K test facility (or 800W@4.5K) was commissioned in the early 2000s with the aim of providing high cold power for various research related applications [1]. In parallel, simulation tools have been developed to reach required specifications with reduced costs and limited power consumption, such as EcosimPro® and the associated cryogenic library Cryolib [2]. CEA Grenoble has also developed its own library, Simcryogenics, well suited to these needs and in particular to the development of high-performance control techniques and the demonstration of their benefits through their implementation using simulation tools before using them on actual installations [3]. This tool is also used to study non-CEA large refrigeration tools, such as JT60-SA [4]. For all these applications, the modelling must be extensively validated on experimental data. Many validation works have already been done with Simcryogenics.

In 2022, the 400W@1.8K test facility was used to characterize a specific heat exchanger in the framework of the High Luminosity upgrade of the Large Hadron Collider at CERN [5]. This heat exchanger provides heat transfer between a He-II pressurized bath and a He-II saturated bath under different operating conditions at 1.8 K and 2 K. After these tests for CERN, new tests were done dedicated to extend the validation of the modelling of the 400W@1.8K facility with configurations at 1.8 K and 2 K, through steady states configurations and transient between steady-states.

The aim of this work is to extend the validation of the 400W@1.8K with Simcryogenics using these dedicated experimental data. The validation approach includes three parts: first, validation of each component using the steady state configurations; second, validation of the modelling of the whole system with the steady-state tests with different flowrates and temperatures between 1.8 K and 2.3 K; third, validation of the whole system model on transient configuration.

This validated modelling of the installation allows it to be adapted more quickly for new applications and to ensure that required specifications can be reached. In particular, this facility can be used for quantum applications to address the critical scalability challenges.

This paper presents first the 400W@1.8K facility to be modelled (section 2) followed by a brief description of the system-scale Simcryogenics simulation library (section 3). Section 4 describes the three steps of the validation approach. Section 5 presents the new Quantum Engineering Demonstrator concept (QED) that the 400W@1.8K installation aims to achieve. The last section concludes the paper and draws perspectives for future work.

2. Description of the 400W@1.8K Test facility

CEA Grenoble DSBT (Low Temperature System Department) commissioned in 2004 a test facility with a cooling capacity of 400W@1.8K or 800W@4.5K [1]. It has been designed to be modular in order to meet the needs of a wide range of experiments: test of industrial components (magnets, cavities of accelerators, heat exchanger), studies on thermal-hydraulics of two-phase superfluid helium, fundamental researches such as on high Reynolds number turbulent flows for example.

This facility is made up of three parts (Figure 1 left). The Warm Compressor Station (WCS) is composed of one sub-atmospheric oil ring pump (from 20 mbar to 1.2 bar) in series with two screw compressors (from 1.05 bar to 16 bar). The Cold Box aims to cool helium from ambient temperature to 4.5 K through a pre-cooling stage with nitrogen, multi-circuit heat exchangers, a cold turbine, a wet piston expander, a Joule-Thomson valve, a phase separator at 4.5 K and two centrifugal cold compressors on the Very Low Pressure line (VLP). Finally, the large Multi-Test Cryostat (CMT), 4 m high, 2.5 m in diameter, has been designed to be easily adapted for each specific need. For example, the HELIOS experiment (HElium Loop for hIgh lOads Smoothing), [6], or the specific heat exchanger HxD2 for the CERN [5], have been successively installed in the CMT.

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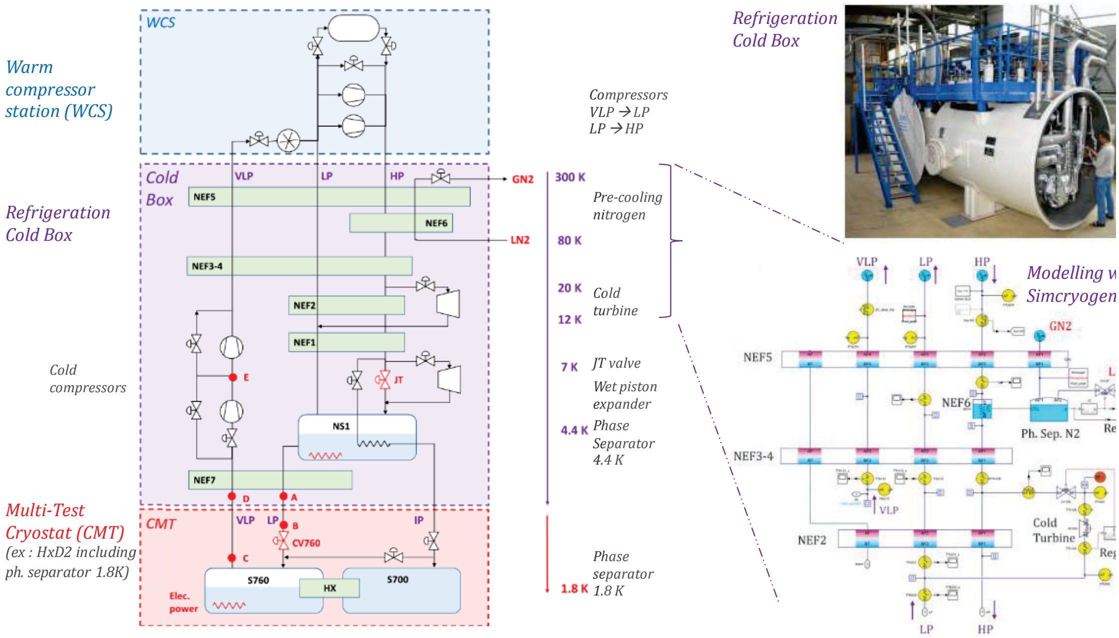

Figure 1. 400W@1.8K test facility with CMT in configuration heat-exchanger HxD2 for the CERN need (left), global view of the Cold Box (top right) and a part of modelling with Simcryogenics (bottom right).

3. System-scale simulation with Simcryogenics library

In parallel to the experimental facilities, the Simcryogenics library was developed to simulate and optimize cryoplant and its distribution to end-users. This homemade tool, based on Simscape, the modelling language extension of the Matlab/Simulink software, aims in particular to generate model-based control schemes for cryogenic plants that are subject to high disturbances (such as pulsed heat loads infusion reactors or particle accelerators).

Actually, system-scale modelling is being used in preliminary conceptual studies, experimental plan validation, and performance verification, to carry out parametric optimizations or to assess transients. System-scale modelling is moreover used for model-based control and for control strategy validation. At last, it can also be used for commissioning (offline control design, real time simulations) and exploitation (increased availability). Operator training may also be an objective, provided that a complete digital twin of the facility is developed.

Simcryogenics library is object-oriented whose physical models are detailed in [3]. It includes almost all the components commonly used in large scale refrigerators, completed by boundary conditions, constant or time dependent (mass flowrate, temperature, heat losses…), set point values for the regulations, and components for the regulation itself. The components are dragged and dropped on a Simulink worksheet and connected together. The solver (fixed or adaptative time-step) is provided by Simulink. Physical properties are calculated by interpolation. Figure 1 (right bottom) shows part of the Cold Box modelling with Simcryogenics: the three lines High Pressure (HP), Low Pressure (LP) and Very Low Pressure are represented, connected with heat exchangers (NEF5, NEF3-4, NEF2), the nitrogen pre-cooler stage, the cold turbine on the HP line, the valves, and the associated regulations. The library is validated on numerous experimental systems: WCS, cooling of superconducting magnets, cold boxes (JT-60SA), RF cavities (SPIRAL), data from the 400W@1.8K facility in the 800W@4.5K configuration. The issue of this work is to complete the validation by using new dedicated tests with a He-II phase separator.

4 Validation of the system-scale simulation with new dedicated experimental data.

In 2022, the Multi-Test Cryostat (CMT) has been modified to install the CERN HxD2 He-II/He-II heat exchanger [5]. It has been adapted to include a set of cryogenic valves and dedicated instrumentation (temperature, pressure, liquid level, electrical heaters).

After the characterization of this heat exchanger, new tests have been carried out dedicated to extend the validation of the modelling of the 400W@1.8K facility. For these additional tests, the phase separator was used with several stationary conditions with low pressure (15, 30 and 70 mbar) and therefore low temperature in the phase separator (1.8 K, 2.0 K and 2.3 K). The two lowest pressure values correspond to He-II liquid in equilibrium with its vapor whereas the highest value corresponds to He-I liquid in equilibrium with its vapor. Several values of mass flowrate entering the separator phase have been achieved (5, 7, 10, 12 and 15 g/s). Between steady-state configurations, the transient steps are also recorded and can be used for modelling validation (Section 3.3). For these tests, the pressurized bath associated with the heat exchanger and the heat exchanger itself had no effect on the experiment. They are therefore no longer represented on the schematic representation of the 400W@1.8K facility (Figure 3).

The three steps of the validation approach are presented below.

4.1 Characterisation of each component through steady-state configurations

The first step of the approach consists in using all steady-state configurations to characterize and validate each component of the facility, in particular components added during the adaptation of the CMT. Two examples of this step are presented below, one deals with the evaluation of heat losses along a pipe joining the Cold Box and the CMT, the other with the characterisation of a valve located on the same line.

First, the heat losses along the pipe joining the outlet of the NEF7 heat exchanger (point A, Figure 1) and the CV760 valve inlet located just upstream of the phase separator (point B, Figure 1) through which supercritical helium flows. The difference of enthalpy, h, between these deux points should depend linearly on the inverse of the mass flowrate, $\dot{m}$, if the heat losses, $P_{heat-losses}$, are independent of the tests (Equation 1).

$$h(B) - h(A) = \frac{P_{heat-losses}}{\dot{m}} + \Delta h_{offset} \quad (1)$$

The analysis of all the stationary tests shows that the heat losses are indeed constant (slope of the linear regression in Figure 2 (left), 14.2 W). Each point in Figure 2 corresponds to a steady-state configuration. The slight offset, Δh_{offset}, whose value is 0,09 J/g, corresponds to a temperature measurement shift at one of the points of only 0.04K.

Second, the characteristic of the valve CV760, located just upstream of the phase separator, links its flow coefficient, Cv , to its opening in percent, *opening* (Equation 2) [3].

$$C_v = \frac{C_{v,max}}{R_v}\left(exp\left(\frac{opening}{100} ln(R_v)\right) - \left(1 - \frac{opening}{100}\right)\right) \quad (2)$$

where $Cv{,}max$ is maximal flow coefficient and Rv is the rangeability. By applying a regression on the experimental values of the flow coefficient in function of the experimental value of opening, the values of these two parameters can be determined: 0.26 for the maximal flow and 50 for the rangeability (Figure 2, right). These parameters' values are valid in the range 60% to 90%.

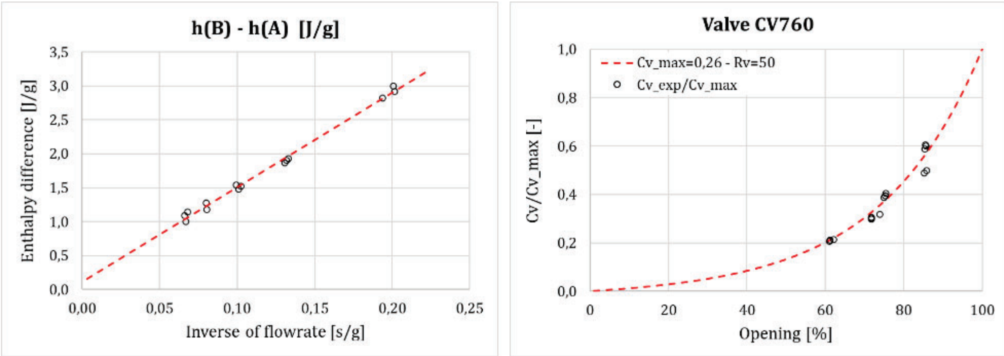

Figure 2. Characterisation of heat losses between A-B (left) and of valve CV760 (right) through steady-states configurations.

4.2 Validation of the whole modelling through steady-state configurations

Once the first step of the approach is applied for the components and the parameters values obtained are used in the modelling, the second step deals with the comparison of the results of the whole system simulation with the experimental ones for steady-state configurations.

Figure 3 shows an example for the steady-state named “30 mbar – 5 g/s”. Several boundary conditions and set point values for the regulation are needed to reach this steady-state. The boundary conditions concern helium pressure at the inlet of HP line and at the outlet of LP and VLP lines, and helium temperature at the inlet of the HP line. Nitrogen pressure and temperature values at the inlet are also boundary conditions for the pre-cooler stage. The main set point values are the flowrate in the HP line and the flowrate entering the VLP phase separator in the CMT. Other set point values concern the level in the phase separator, pressure upstream of the compressor or temperature after the cold turbine. Each set point value is used by a regulation to define the state of a component: opening of a valve, electrical power in a phase separator or flowrate through a cold compressor for example. The comparison between modelling and experimental data deals with pressure and temperature at many points in the lines, valve opening, and electrical power applied to separate phases to reach steady-state, especially in the CMT. A relatively good agreement between modelling and experimental date is reached for the steady-state “30 mbar – 5 g/s” for example (Figure 3).

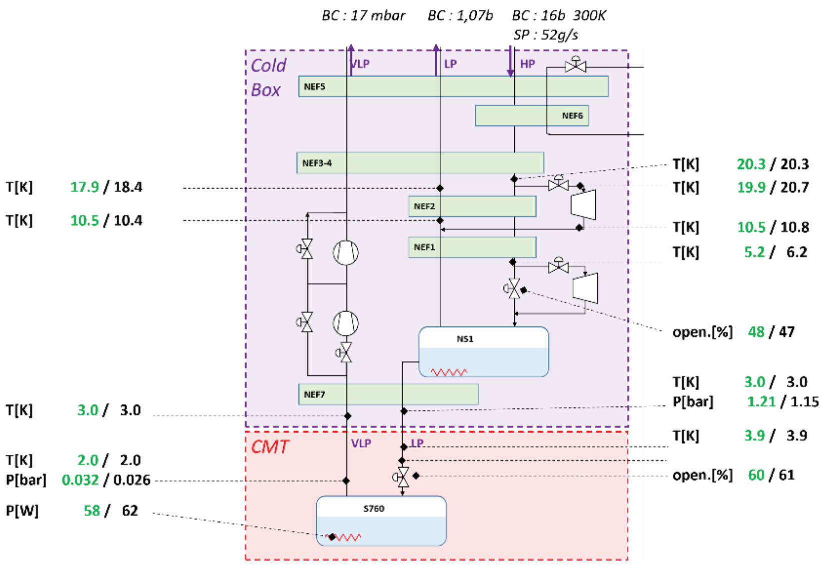

Figure 3. Validation of the whole modelling for the steady state 30 mbar – 5 g/s (in green: simulation with Simcryogenics, in black: experimental values., BC: boundary conditions, SP: set point value for regulations).

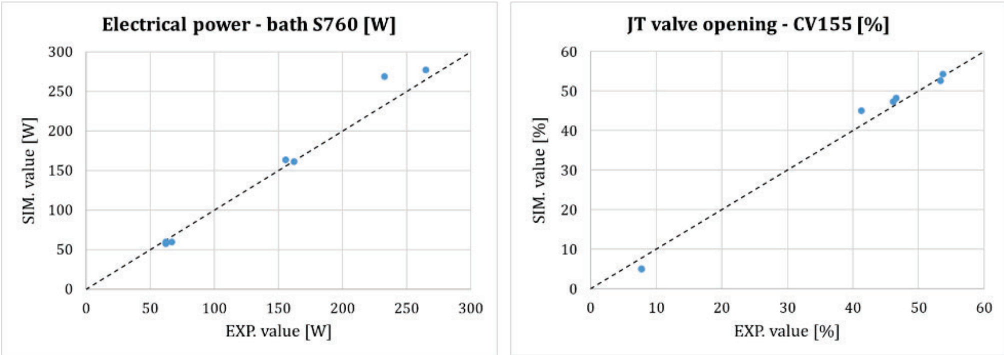

Figure 4. Validation of the whole modelling through steady-state configurations.

The modelling and experimental data for the steady-states are then collected for an overall comparison for the main points of the circuit. For example, the values are rather close for electrical power in the phase separator in CMT (Figure 4, left) or for Joule Thomson valve opening (CV155) in the Cold Box (Figure 4, right). This comparison at the main point of the circuit shows a relatively good agreement for steady-state configurations, which validates the modelling.

Moreover, specific results can be noticed for the configurations with high values of flowrate entering the CMT phase separator. Even if these configurations are out of design for the heat exchanger, they are interesting on a physical point of view. Indeed, helium should be vapor at saturation at the phase separator outlet. Nevertheless, if the heat losses along the pipe located just after the phase separator, in the VLP line, between the points C and D (Figure 1), are calculated using the same approach as the equation (1) and assuming helium is vapor at saturation at the outlet of the phase separator, the heat losses value appear to depend on the flowrate for the highest flowrate values (Figure 5, left). In a more instructive way, heat losses appear to be lower when the temperature at point D is close to the saturation temperature corresponding to the phase separator (Figure 5, right). Actually, there is probably two-phase flow, gas and droplets, at the phase separator outlet (point C, Figure 1) for the highest value of flowrate. Thus, heat losses don't depend on the flowrate, but a part of heat losses is used to evaporate droplets. These observations, obtained for out-of-design configurations, do not disturb the validation of the modelling because the thermal losses are evaluated taking this phenomenon into account.

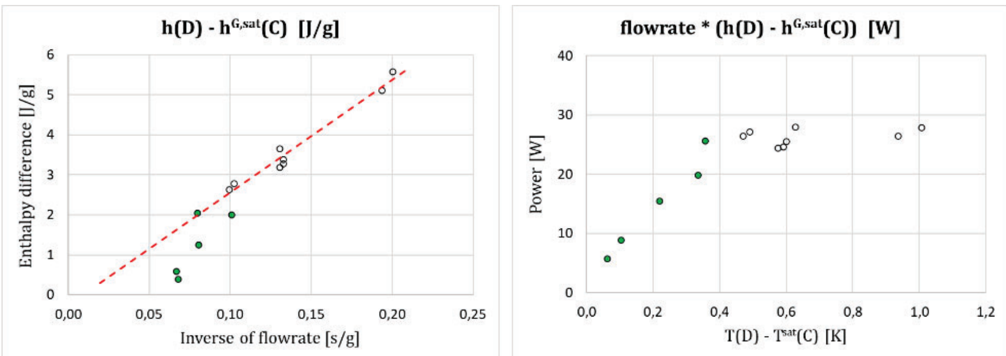

Figure 5. Characterisation of heat losses for pipe CD (steady-states conf.). Specific results for highest flowrate (green points).

4.3 Validation of the whole modelling through transient configurations

The last step of the approach deals with the validation of the whole modelling through transient configurations. Transients' states between two steady-states are used for this step. To switch from one steady-state to another, several boundary conditions and set point values must be changed.

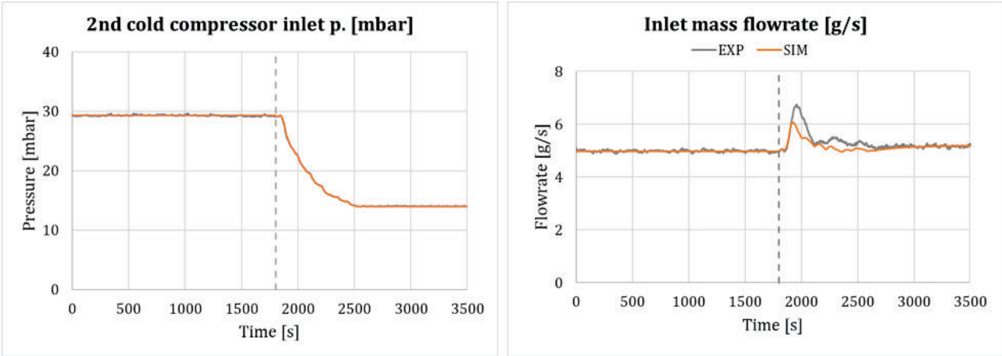

Figure 6. Transient configuration between two steady-states: examples of set point value (left) and result (right).

Figure 6 (left) shows an example of the evolution of pressure upstream of the second cold compressor (point E, Figure 1) during the transient between two steady-states: "30 mbar – 5 g/s" and "15 mbar – 5 g/s". Since the first cold compressor is shut down for this test and its bypass valve is fully open, the pressure at point E and D are practically identical. These transient experimental data are used as set point value for the modelling. The validation deals with the evolution of values at the main points during this period. For instance, the mass flowrate entering the CMT phase separator shows the same transient trends as the experimental one and reaches a new stable value after the transient (Figure 6, right). The transient modelling of the 400W@1.8K provides good trends. Nevertheless, further validation is still required to get closer to the real transient behaviour.

5. A new application for 400W@1.8K: the Quantum Engineering Demonstrator (QED)

A part of the quantum technologies needs a robust cryogenic infrastructure for low temperature (4 K) or even ultra-low temperature (20 mK). The challenge of scaling up for both quantum technologies and cryogenic devices has been highlighted through the roadmaps of several major industrial players. The aim is to include always more physical Qbits (~100 kQbit to 1 MQbit) to reach around 100 logical Qbits [7]. One way is to use a high-power helium cryostat, similar to those used for fusion reactor or particle accelerator equipment, and distribute the power at the Qubit entity level. However, new issues arise with the need for high power at different levels of temperature and the management of different needs for many Qubit entities at the same time (some are in operations while others are under maintenance for instance). In order to study these issues straightaway, without waiting for these quantum technologies to reach a high TRL, a possibility is to use already operational cryogenic facilities. An example of collaboration is set between SLAC National Accelerator Laboratory and PsiQuantum which made it possible to test quantum devices by adapting the SLAC infrastructure to provide 100 W at 2.4 K [8].

The 400W@1.8K has been designed to be easily adapted to meet varied needs. This installation can thus be adapted to become a Quantum Engineering Demonstrator (QED) leveraging the existing components and extended to multiple cryogenic satellites, hosting real Qbits or makeshift ones represented by heating elements (Figure 7). This QED would enable to evaluate without delay technological solutions on distributions issues, to define the best architectures to provide several levels of cooling temperature at the same time and adapted for each quantum device. It could contribute accelerating studies on the scaling up of quantum technologies requiring cryogenic cold.

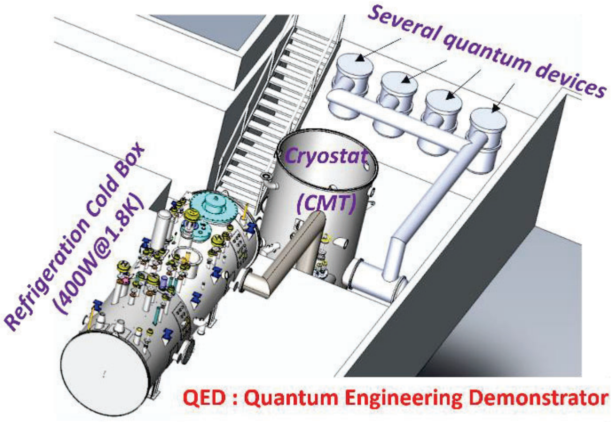

Figure 7. Using the 400W@1.8K as a Quantum Engineering Demonstrator (QED).

6. Conclusions

The present paper contributes to extend the validation of the modelling of the 400W@1.8K facility with Simcryogenics library to He-II subatmospheric configurations through new dedicated experimental data. This enables to accelerate the adaptations of the facility to arising needs and, more specifically, to anticipate cryogenic power supply problems for quantum applications. Even if the specifications of the quantum domain needs evolve, the 400W@1.8K can thus constitute a Quantum Engineering Demonstrator (QED) allowing us to address, from now on, the problems of multiple power supplies of systems not necessarily operating simultaneously. Modelling makes it possible to reduce the design phase of the adaptations and to quickly test configurations without having to wait for the construction of specific quantum-related systems.

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