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Design, fabrication and installation of the refurbished K500 cyclotron cryogenic distribution system for MSU chip testing facility

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Abstract. Michigan State University (MSU) has refurbished the superconducting K500 cyclotron and installed it as the heart of a new semiconductor / electronic chip testing facility at the Facility for Rare Isotope Beams (FRIB). The K500 cyclotron consists of a superconducting solenoid and several cryo-panels (independently maintained at 4.5 K and 80 K). The refurbishment of this cyclotron required a completely new cryogenic distribution system incorporating several different modes of operation for the solenoid and the cryo-panels to satisfy the testing requirements. The cryogenic distribution has been designed using the same operational concept used for the FRIB experimental system cryogenic distribution system – which has separate lines for cool-down and 4.5 K operation. This provides flexibility for commissioning, different modes of operation, and maintenance of the K500 cyclotron without affecting other cryogenic loads on the refrigerator. The refurbishment, associated additions and modifications of a legacy system to fit new requirements presented several design challenges which were resolved during the concept design phase. Design, fabrication, and installation of all the elements of the cryogenic distribution system were carried out in-house at FRIB. This paper presents an overview of the process design, analysis, fabrication, and installation of the refurbished K500 cyclotron cryogenic distribution system.

1. Background

Michigan State University has refurbished its history-making K500 cyclotron and installed it as the heart of a new chip-testing facility for next-generation semiconductor devices at the Facility for Rare Isotope Beams. The new facility is considered as the third act for the K500 cyclotron, which made history on the nuclear science scene 40 years ago as the world's first superconducting cyclotron. It went through the first refurbishment in the late 1990s for coupling with the more powerful K1200 cyclotron in the Coupled Cyclotron Facility (CCF) [1]. CCF began operations in 2001 and was used continually until November 2020. Following the decommissioning in 2020, it is being refurbished once again to be transformed into K500 Single-Event-Effects facility (KSEE) for electronics / microchip testing.

Design of a cryogenic distribution for such a legacy equipment can be challenging due to several reasons – lack of legacy design / hardware information to retrofit the new cryogenic distribution, differences in operating philosophy *e.g.* batch fill cooling or continuously filled cooling, residual stress development in the legacy equipment during decommissioning and recommissioning etc. The present paper discusses the requirements and challenges to design a completely new cryogenic distribution system for this refurbishment effort. Starting from the process design, and cryogenic distribution layout, the mechanical design concepts and details are discussed.

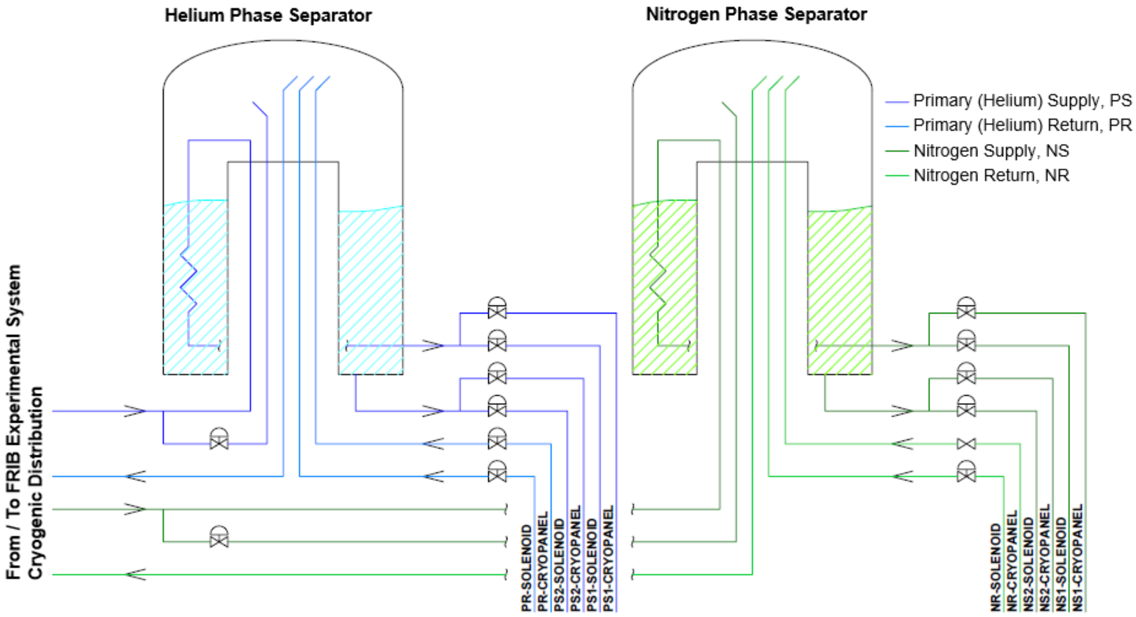

Figure 1. Simplified schematic diagram of the refurbished K500 cyclotron cryogenic distribution system with helium and nitrogen phase separator vessels.

2. Cryogenic Distribution Requirements

The K500 cyclotron cryogenic system consists of two separate cryogenic '*loads*'. These are the superconducting solenoid cryostat and a group of three cryo-panels. The superconducting solenoid cryostat is an annular ring-shaped vessel [2] with approx. 6 ft (1.83 m) diameter and holds approx. 400 liters of liquid helium (LHe). It has a liquid nitrogen (LN) cooled thermal radiation shield. However, there is no phase separator for the liquid nitrogen circuit in the existing configuration of the cryostat. This cryostat is equipped with multiple instrumentation for liquid helium level monitoring covering the entire height of the vessel. Following decades of operation, the reliability of these level monitors has deteriorated significantly and replacement of these within the legacy cryostat can pose significant risk to the integrity of the system. The cryo-panels are also LHe cooled and thermally shielded by LN. The cooling loops (LHe and LN) for the cryo-panels doesn't have any proper means for phase separation or liquid level control / monitoring. The cryo-panels hold approx. 30 liters of liquid helium and requires frequent warm-up / cool-down to aid changes in configuration of the cyclotron.

First commissioned in the early 1980s, these cryogenic *loads* (superconducting solenoid and cryo-panels) were primarily designed to be operated in a liquefaction mode, where the helium boil-off / return is warmed-up and recovered at the cryo-plant compressor [3]. The return 2-phase nitrogen was designed to be vented to atmosphere. Such an operating philosophy is simplistic but wasteful. Since FRIB already have existing large-scale cryogenics infrastructure, it is prudent to change the operating philosophy and retrofit these loads with hardware which will

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enable operating in a refrigeration mode and minimize utility consumption. The following requirements and scope of work are identified:

a) Cryogenic operation (LHe and LN) of the superconducting solenoid and cryo-panels with potential phase separation and recycle from the return flow.
b) Flexibility in operating modes to minimize risks related to existing instrumentation reliability
c) Flexibility in operating modes to minimize operational disruption due to frequent changes in configuration (i.e. during warm-up / cool-down of cryo-panels)
d) Capability to cool-down / warm-up the cryogenic *loads* independently

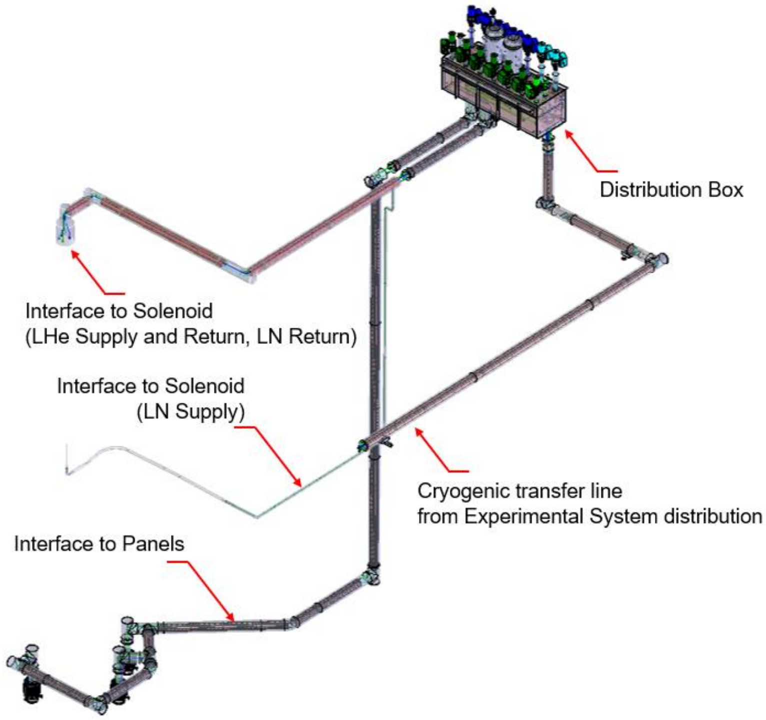

Figure 2. 3D model of the overall cryogenic distribution system for the refurbished K500 cyclotron

3. Process Design and Cryogenic Distribution Layout

A simplified schematic of the refurbished K500 cyclotron cryogenic distribution system is shown in figure 1. The cryogenic transfer line consists of four (4) cryogenic process piping headers – two each (supply and return) for primary (helium, 4.5 K) and thermal shield (nitrogen, 50 K) enclosed in a single vacuum insulated (vacuum jacketed) pipe. Cryogens are supplied from and returned to the FRIB experimental system distribution. To address the operational issues relating liquid level monitoring and phase separation in the return headers, two phase separator vessels are added in the distribution system – one for the helium circuit and the other for the nitrogen circuit.

For operational flexibility (Sec. 2; requirements b and c), each cryogenic load (*i.e.* superconducting solenoid and cryo-panels) is furnished with two different supply options – forced flow cooling from the experimental system distribution and thermal-siphon cooling from the phase separator vessel. Also, the return headers (helium and nitrogen) from each load are furnished with cryogenic isolation valves and warm return bypass valves (not shown in fig. 1) to aid in cool-down / warm-up without affecting the other.

4. Components of the refurbished K500 Cryogenic Distribution System

The overall cryogenic distribution system has several significant sub-assemblies including – distribution / valve box, phase separator vessels, interface coupling to the *loads*, bayonet box and transfer line sections and warm utility piping. An overall layout of this cryogenic distribution system is shown in fig. 2. The sub-assemblies are discussed in the following sub-sections.

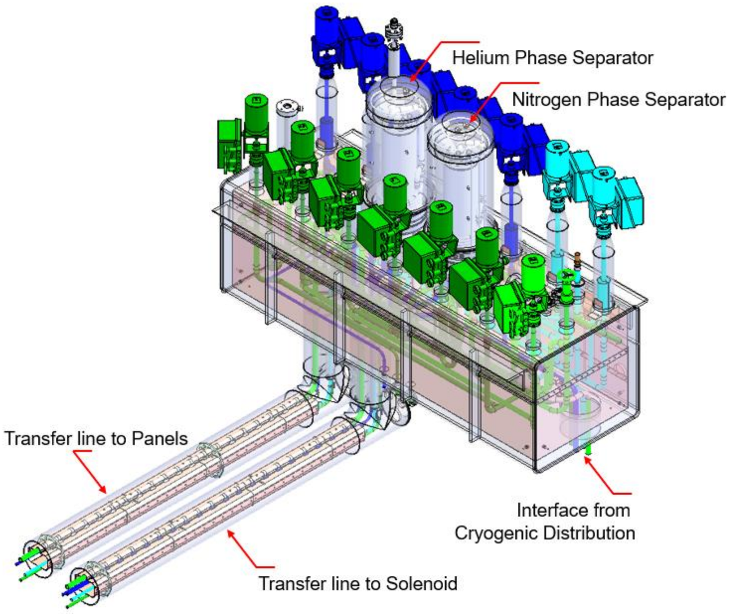

Figure 3. 3D model of the K500 cryogenic distribution box incorporating the phase separator vessels

4.1 Distribution Box

The K500 distribution box incorporates the phase separator vessels (LHe and LN), all cryogenic valves, interface to the cryogenic transfer lines to the FRIB experimental system, K500 superconducting solenoid cryostat and cryo-panels. The vacuum jacket for this box is rectangular in shape, made of 1/2 in. (12.7 mm) thick stainless steel bent plating with approx. 72 in. x 24 in. x 22 in. (1.82 m x 0.60 m x 0.55 m) dimensions. There are a total of 14 cryogenic valves housed in this box - 4 helium supply (2 each for solenoid and panels), 4 nitrogen supply (2 each for solenoid and panels), 2 helium return (1 each for solenoid and panels), 2 nitrogen return (1 each for solenoid and panels) and 2 liquid fill valves (1 for each phase separator). All valves are ½ NPS (DN15 or similar) sized and have flow coefficients (C_v) ranging from 1.0 – 3.2. The distribution box also houses an additional utility bayonet coupling for LN and associated welded interfaces to a warm gas management rack (clean-up, cool-down and warm-up). The 3D model for the K500 distribution box is shown in fig. 3.

4.2 Thermo-siphon and Phase Separator Vessels

As mentioned earlier, there are two phase separator vessels housed inside the distribution box. Both are similar in design. The 3D model for the K500 helium phase separator vessel is shown in fig. 4. The phase separators are annular vessels with an 8 NPS (DN200) outer shell, 5 NPS (DN125) inner shell. The outer shell is approx. 26 in. (660 mm) tall while the inner shell is approx. 20 in. (518 mm) tall. Each vessel can contain approx. 8.0 liters of liquid. For each phase separator, the corresponding process flow return headers are routed through the inner shell separating the return vapor superheat from the saturated liquid volume. Two ½ in. (12.7 mm) OD coiled tubing are passed through the annular space and are merged outside the phase separator vessel. This cryogenic header provides sub-cooled forced flow supply to the cryogenic *loads.* Four 0.375 in. (9.5 mm) rod hangers with G-10 sleeves are used to support each of the phase separator vessels from the vacuum shell of the distribution box. In addition, six 0.25 in. (6.3 mm) G-10 pegs are added to each vessel as bumpers minimizing potential thermal short to the vacuum jacket. In addition, each phase separators are also equipped with electric heaters to address potential liquid overflow to the cryogenic distribution return headers during operational transients.

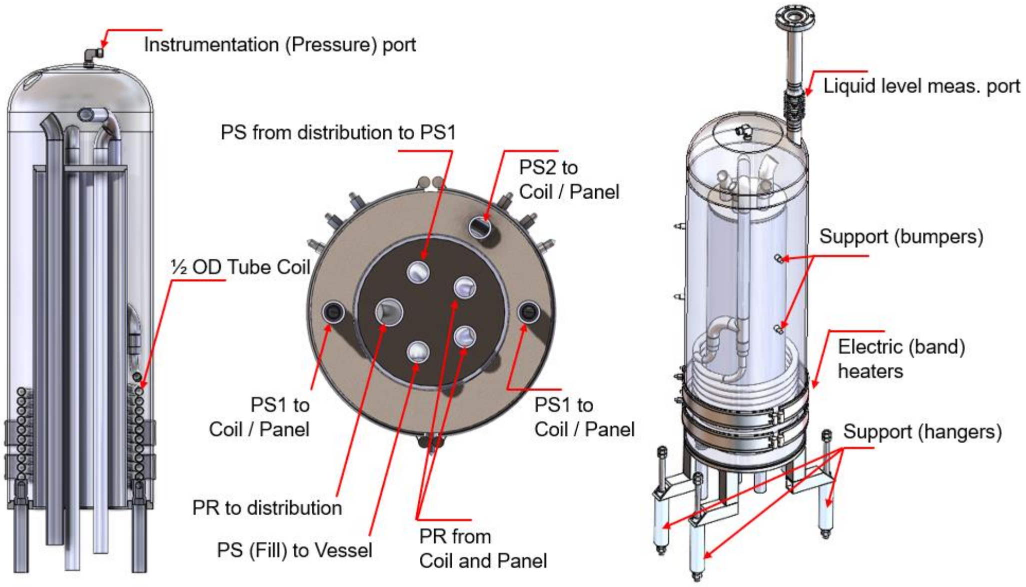

Figure 4. (left) Cross-section view, (center) bottom view and (right) isometric view of the K500 helium phase separator and associated sub-assemblies

4.3 Interface Couplings to Solenoid and Cryo-panels

Four cryogenic headers (helium supply and return, nitrogen supply and return) are routed to each of the cryogenic loads, *i.e.* superconducting solenoid and cryo-panels. Existing metal gasketed face seal tube fittings, *e.g.* VCR® are used at the interface to the cryogenic loads from the new cryogenic transfer line. This type of fitting is proven to be adequately leak tight and aids quick disconnect during maintenance and troubleshooting. There are two independent cryogenic transfer lines routed from the distribution box to each of the loads (see fig. 2). Moreover, the transfer line to the solenoid is further branched between one incorporating the helium supply, return and nitrogen returns – which interfaces at the top of the solenoid cryostat; and the other incorporating the nitrogen supply that feeds at the bottom of the solenoid cryostat. Both vacuum jacket interfaces at the solenoid cryostat are welded. The cryo-panel transfer line has three branches going to each of the cryo-panels. Due to frequent warm-up / cool-down of this load, this system can be prone to operational issues. Hence, the vacuum jacket interface at the cryo-panels is equipped with a vacuum disconnect flange for troubleshooting. 3D model of the cryo-panel transfer line, branches and the removable interface are shown in fig. 5.

Each of the major transfer lines to the loads have a 6 NPS (DN150) vacuum jacket, with ½ in. (12.7 mm) OD tubing for the process lines. Both these transfer lines have separate vacuum insulation boundaries from the distribution box. This aids troubleshooting one load (solenoid or cryo-panel) while maintaining the other at 4.5 K.

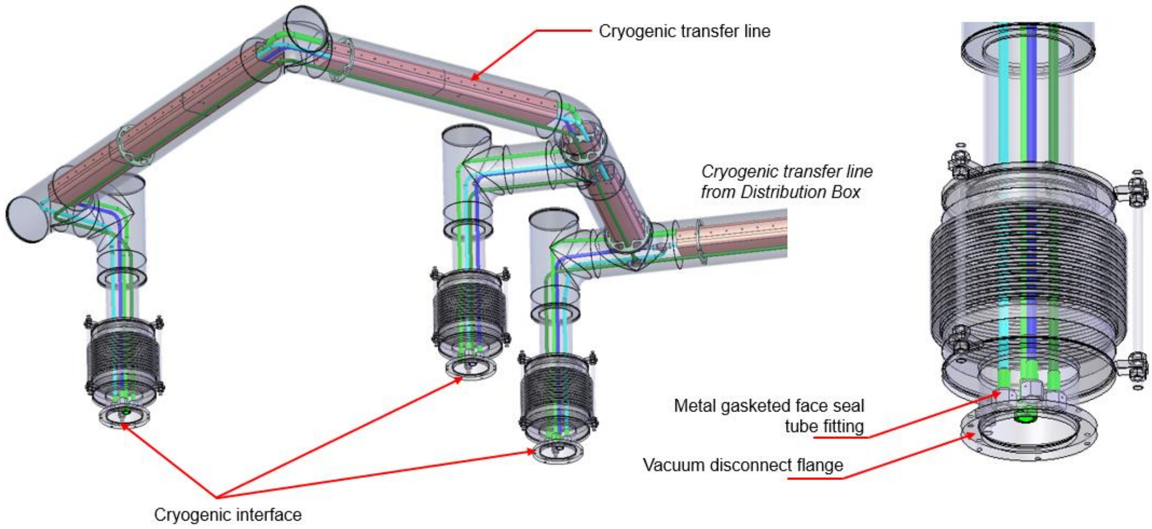

Figure 5. (left) 3D model of cryogenic transfer line to the cryo-panels, and (right) removable interface coupling to the cryo-panels including metal gasketed tube fittings and vacuum disconnect flange

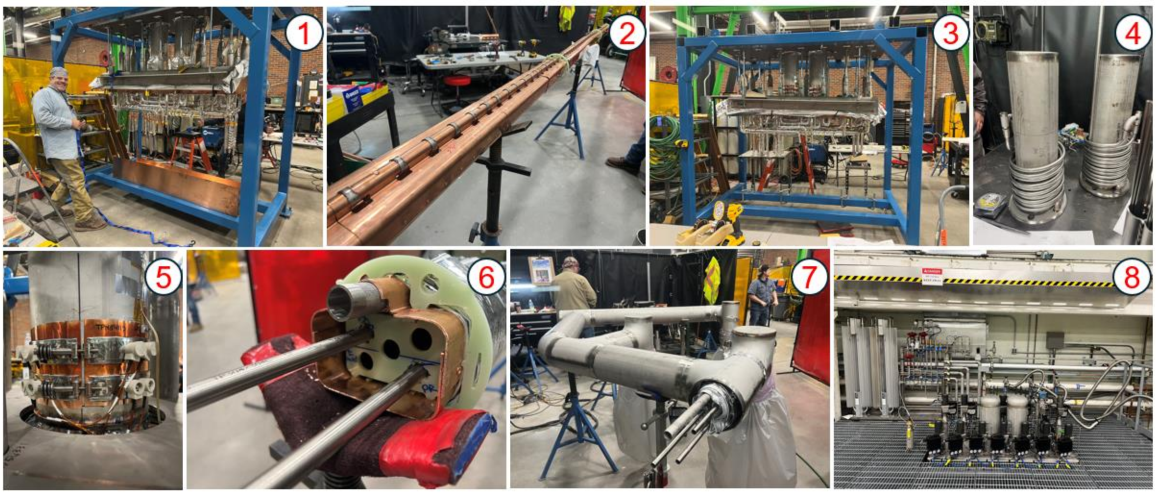

Figure 6. Different fabrication stages of refurbished K500 cryogenic distribution system starting from 1-assembly stand, 2- transfer line assembly, 3- insulated assembly on fabrication stand, 4- phase separator assembly and coils, 5- phase separator heater installation, 6- transfer line support, 7- cryo-panel transfer line assembly and 8- overall cryogenic distribution installed at KSEE facility mezzanine level.

4.4 Bayonet Interface and Transfer Line

The refurbished K500 cryogenic distribution system is connected to the FRIB experimental system cryogenic distribution via bayonet style couplings. The associated bayonet box was installed in 2020 during re-configuration of the FRIB experimental system [4], and in anticipation of a refurbishment effort for the then decommissioned loads. The bayonet box design is similar to one reported in [4] and is not discussed here for sake of brevity. The cryogenic transfer lines are housed in a 6 NPS (DN150) vacuum jacket. The main cryogenic headers are ½ NPS (DN15), except for the nitrogen return, which is ¾ NPS (DN20). This is mainly to improve the structural rigidity of the surrounding thermal shielding (copper plating), as they are mechanically and thermally strapped to the nitrogen return pipe for interception of heat.

4.5 Miscellaneous

There are additional supporting sub-assemblies connected to the refurbished K500 cryogenic distribution system. These are – warm gas (helium and nitrogen) distribution to aid clean-up, purge and cool-down, ambient heat exchangers for supporting cool-down, vacuum headers to support insulating vacuum of the cryogenic distribution. The design of these sub-systems follows conventional piping design standards and are not discussed here.

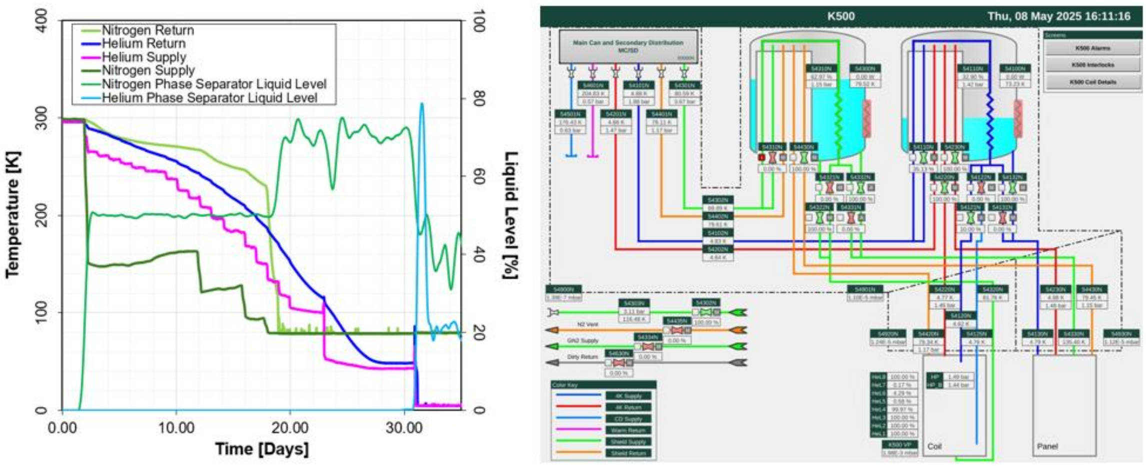

Figure 7. (left) Process temperatures and liquid level response during the first cool-down of the K500 superconducting solenoid cryostat and, (right) the cryogenic control interface for the refurbished K500 cryogenic distribution system

5. Fabrication, Installation and Operation

Following the design, fabrication of the sub-system components for the K500 cryogenic distribution began in Q2/Q3 of 2023. Installation of the entire cryogenic distribution system was completed by Q4 of 2023. Commissioning activities began Q4 of 2023. These include clean-up and purging of the cryostat, piping and associated components, controls system commissioning, checking instrumentation and valve actuations etc. Cool-down of the distribution system and the solenoid started by end of January 2024. A very slow cool-down path was intentionally followed for the first cool-down to prevent unforeseen thermal stress in the legacy equipment and associated sub-systems. The cool-down supply temperature was precisely controlled by FRIB experimental system cool-down heat exchanger [5] and instrumentation, tension links to the magnet were checked at multiple check points during the cool-down. The cool-down of the solenoid to 4.5 K took approx. 32 days. The cryo-panels were first cooled down a few months later (May 2024), and the cool-down to 4.5 K was achieved in 3 hours.

6. Summary

The refurbished K500 cryogenic distribution system has been designed, fabricated, installed and commissioned following an aggressive project schedule. Of course, the design and fabrication experience gathered from the past projects greatly helped in the successful execution and commissioning of this cryogenic distribution system. However, detailed planning, concept development and design efforts were still required due to additional challenges relating to the legacy equipment. At present, the cryogenic distribution system is being operated with the thermo-siphon circuit and without any major issues. The KSEE facility is being commissioned now with plans to be in operation by the end of AY2025.

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