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महिपा चरण-I के लिए निम्नतापिकी

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एलएचपी 50 शीत कोष्ठ और ऊष्ण पंपन प्रणाली के साथ एसएचपी 20 शीत कोष्ठ स्थापना का एक दृश्य

सारांश

इस शोध-पत्र में, पऊवि के 1 GeV प्रोटॉन त्वरक कार्यक्रम के प्रारंभिक चरण, मेहिपा चरण-1 को समर्थ बनाने के लिए अभिकल्पित उप-वायुमंडलीय हीलियम निम्नतापिकी संयंत्रों (एसएचपी) के विकास का वर्णन किया गया है। मेहिपा चरण-1, प्रोटॉन कणपुंज को 40 MeVतक तीव्र करने के लिए एकल स्पोक अनुनाद (एसएसआर-बी.)क्रायोमॉड्यूल्स के भीतर रखे गए अति-चालक त्वरण गुहिकाओं का उपयोग करता है। 2 K प्रशीतन के लिए त्वरक की प्रचालन आवश्यकताओं को बड़े पैमाने पर निम्नतापिकी प्रौद्योगिकियों अर्थात उप-वायुमंडलीय हीलियम निम्नतापिकी संयंत्रों (एसएचपी)हेतु एक चरणबद्ध निम्नतापिकी कार्यक्रम द्वारा समर्थित किया जाता है। इस ढांचे के भीतर, यह लेख एसएचपी 20 के विकास को प्रस्तुत करता है, जो 2 K निम्नतापिकी प्रशीतन पर 20 W है, जो प्रारंभिक अति-चालक (एससी) त्वरक घटक (एससी गुहिका) विकास एवं स्वदेशी 2 के निम्नतापिकी क्षमताओं की स्थापना के लिए अभियंत्रित है। इसके अलावा, मेहिपा चरण-1 की प्राथमिक निम्नतापिकी मांगों को पूरा करने के लिए अभिकल्पित 2K संयंत्र पर 500 W के एसएचपी 500 की एक रूपरेखा भी प्रस्तुत की गई है। विशेष रूप से, एसएचपी 500 में पऊवि प्रोटॉन त्वरक विकास कार्यक्रम के बाद के चरणों (मेहिपा चरण-1 की आवश्यकताओं से परे) में प्रत्याशित बढ़े हुए निम्नतापिकी भार को कम करने में समर्थ एक उन्नयन योग्य संरचना है।

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Cryogenics for MEHIPA Phase-I

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A view of the SHP20 cold box installation along with LHP50 cold box and warm pumping system

ABSTRACT

This article presents the development of sub-atmospheric helium cryogenic plants (SHPs) designed to support MEHIPA Phase-1, the initial phase of 1 GeV proton accelerator program of DAE. To accelerate the proton beam to 40 MeV, MEHIPA Phase-1 utilizes superconducting accelerating cavities housed within single spoke resonator (SSR-B) cryomodules. The operational requirements of the accelerator are supported by a phased cryogenic program for large-scale cryogenic technologies namely sub-atmospheric helium cryogenic plants (SHP) for 2 K refrigeration. Within this framework, this article presents development of the SHP20, a 20 W at 2 K cryogenic refrigerator, engineered for initial superconducting (SC) accelerator component (SC cavity) development and the establishment of indigenous 2 K cryogenic capabilities. Furthermore, an outline of the SHP500, a 500 W at 2 K plant, designed to meet the primary cryogenic demands of MEHIPA Phase-1, is also presented. Notably, the SHP500 features an upgradable architecture capable of mitigating enhanced cryogenic loads anticipated in subsequent phases (beyond requirements of MEHIPA Phase-1) of DAE proton accelerator development program.

KEYWORDS: *MEHIPA, Proton linac, Radioactive ion*

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Introduction

The cryogenic requirements for the MEHIPA Phase-1 system are fulfilled by SHP cryogenic plants, which are connected to the MEHIPA cryomodules (CMs) via a Cryogenic Distribution System (CDS). Fig.1 presents a schematic of the cryogenic infrastructure required for MEHIPA Phase-1. The warm accessories such as helium compressors, warm pumping system and helium buffers are not shown in the figure although they are important components of helium infrastructure required to operate the cryogenic systems. The refrigeration requirements for the MEHIPA cryogenics are detailed in [1, 2]. The SHP cold box provides the supercritical helium stream required for 2 K refrigeration and for the cooling of low temperature thermal shield/thermal intercepts and 35 K helium stream for cooling of high temperature thermal shield. Moreover, the sub-atmospheric (VLP) return stream, required to maintain sub atmospheric pressure and 2 K bath temperature in the cryomodules using Cold Compressors (CC) or Warm Pumping System (WPS), is directed back to the SHP cold box. The cold box is connected to the application cryomodules through cryogenic transfer lines, a distribution box, various bayonet cans, a turnaround box and U-tubes as shown schematically in Fig.1.

The Cryogenic Distribution Box (CDS-DB), operating in tandem with the turnaround box, manages the routing of helium streams during system cooldown and warmup procedures. Specifically, the CDS-DB serves as the interface between the cold box and the CMs, with the multiple cryogenic transfer lines originating from the cold boxes routed to the CMs through it. It also accommodates future system upgrades by offering the flexibility to integrate multiple cold boxes and distribute flow via dedicated valve operations. Furthermore, the turnaround box enables independent cool down and warm-up of individual CMs while adjacent CMs remain operational at their targeted cryogenic temperatures. To support future expansions, the cryogenic infrastructure is also equipped with specialized bayonet cans configured for SSR-A CMs.

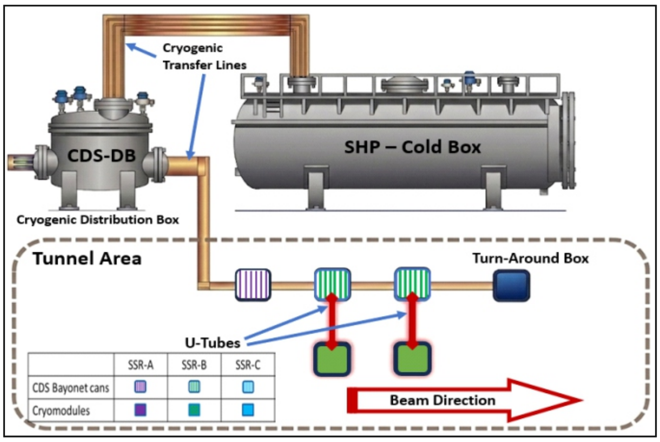

Fig.1: Schematic of cryogenic infrastructure for MEHIPA phase-1.

SHP20: 2 K Refrigeration System

SHP20 is the first in the series of sub-atmospheric cryogenic refrigeration plants conceived and developed by BARC with a rated refrigeration capacity of 20 W at 2 K. The SHP20 is developed with the intention of mitigating anticipated cryogenic load requirements during initial SC accelerator/cavity development activities and to establish and demonstrate 2 K cryogenic capabilities at BARC. SHP20 is not a standalone refrigeration system, rather, it works only in tandem with BARC developed helium liquefaction/refrigeration plants, namely, the LHP100 or LHP50. Important components of the SHP20 coldbox, along with internal construction, are shown in the process flow diagram (Fig.2).

The SHP20 cold box components are engineered for stringent thermal and structural performance [3]. Its process

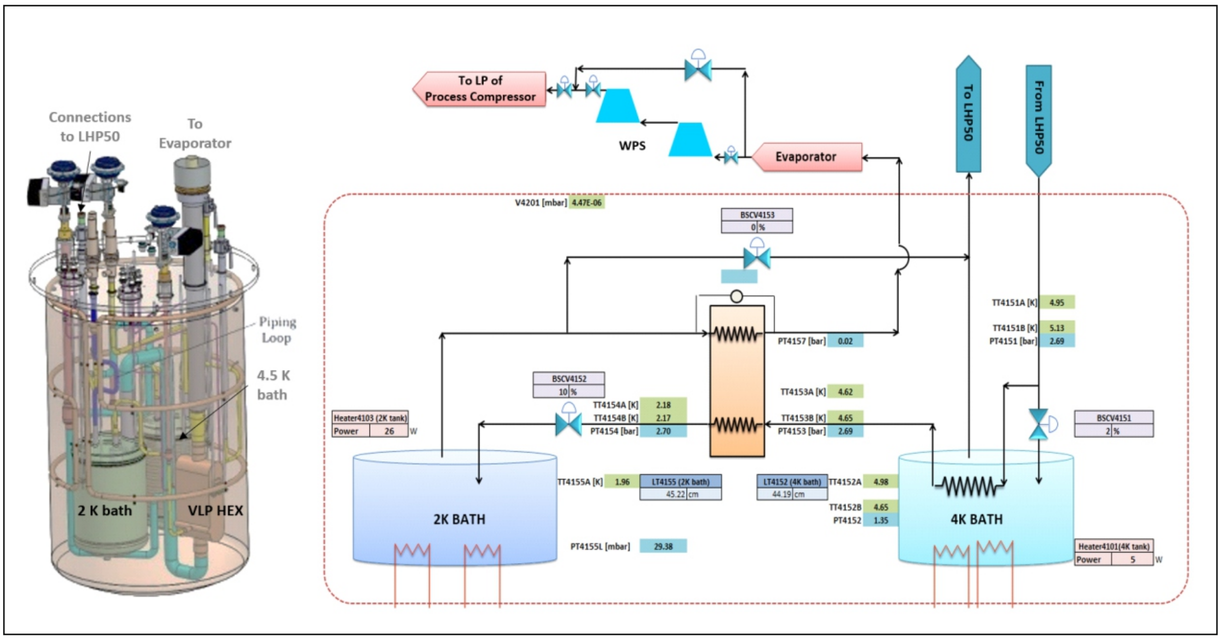

Fig.2: Schematic of SHP20 cold box internals and process flow.

Fig.3: Bird's-eye view of the SHP20 cold box installation along with LHP50 cold box and warm pumping system (WPS).

piping is constructed from SS 304L/316L as per ASME B31.3, utilizing strategic physical routing, rather than flexible joints, to absorb thermal stresses down to 2 K. A liquid nitrogen (LN2) cooled, 1 mm thick ETP copper thermal shield intercepts radiant heat from the vacuum vessel to protect the low-temperature core. Internal inventory is managed by two 45 L liquid helium (LHe) vessels equipped with cartridge heaters (to simulate heat load) and individual superconducting wire level sensors. One of these vessels is a 4.5 K pre-cooler with an immersed copper coil for supercritical helium stream, while the other is a sub-atmospheric 2 K reservoir. To maximize the post-expansion liquid fraction and refrigeration capacity, a brazed aluminum plate-fin heat exchanger (VLP HEX), designed for high-throughput PIP-II cryomodules [4], is integrated. This custom heat exchanger utilizes 3 mm offset strip fins in both channels, specifically optimized for minimal very low-pressure (VLP) stream pressure drop to maintain downstream pumping efficiency and stable 2 K bath temperatures. For process monitoring and control, about 20 nos. temperature sensors (carbon ceramic, silicon diode, and PT-100 types) are deployed via direct-fluid, thermo-well, and surface-mounting configurations. At critical nodes such as the VLP HEX cold stream exit, redundant sensors (primary and spare) are installed via thermowells with their lead wires thermally anchored to the process piping using cryogenic tape, grease and nylon rope. Fig.3 presents a bird's-eye view of the SHP20 cold box installation along with LHP50 cold box and warm pumping system (2 K helium vacuum pumping system).

Fig.4 presents key operational parameters during a long duration operational trial of the SHP20 refrigeration system. The objectives achieved through operating SHP20 cold box in multiple runs include the following:

- Establishing concurrent operation of SHP20 cold box with helium liquefier and warm pumping system.
- Achieving operational efficacy of the indigenously developed VLP heat exchanger essential for large capacity 2 K refrigeration systems.
- Establishing reliable instrumentation and control strategies for maintaining 2 K temperature (with metered heat load) over longer duration.

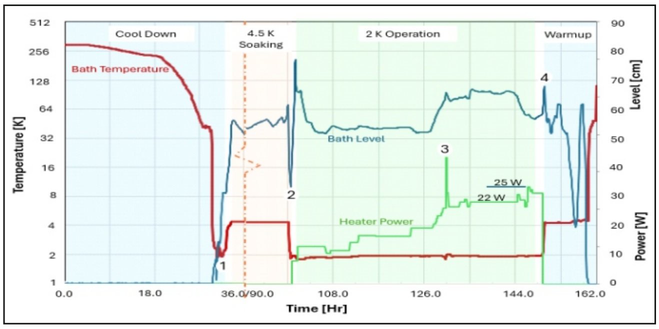

Fig.4: Transient profiles of the 2 K bath temperature, liquid level & applied refrigeration load during the SHP20 long-duration operational trial.

As illustrated in Fig.4, the cooldown of the SHP20 cold box was conducted gradually over a 30-hour period in conjunction with the LHP50 helium liquefier. The sub-atmospheric cycle was initiated, through operation of the WPS, during this cool down phase, successfully establishing a 2 K bath temperature at the conclusion of the cycle (designated as Point 1 in Fig.4). Thereafter, to ensure steady-state operation and accurate refrigeration capacity measurements, the WPS was disengaged and a prolonged thermal soak of the entire system was performed at 4.5 K. This soaking period was necessary to mitigate transient parasitic heat loads originating from the high-thermal-mass radiation shields integrated into the system. Following the completion of the thermal soak, the warm pumping system (WPS) was again operated to depressurize the helium bath and decrease its operating temperature. Transient liquid level fluctuations occurred during this pump-down phase (Point 2). The system was subsequently maintained at 2 K for the ensuing 50 hours. During this interval, the system's refrigeration capacity, which is bounded by the throughput limits of the installed WPS, was evaluated by systematically ramping the internal electric heaters. This operational phase also verified the efficacy of the active level control loop via heater modulation (Point 3), where a rapid surge in the 2 K liquid level was successfully stabilized by increasing the heater power output. Thereafter, a steady-state refrigeration capacity of 22 W was continuously maintained at a constant liquid (2 K) level for 9 hours. By maximizing the volumetric capacity of the WPS, it was possible to demonstrate a peak system refrigeration capacity in excess of 25 W. The experimental run concluded with the disengagement of the WPS, marked by an abrupt rise in the liquid level (Point 4), and followed by a controlled warm-up of the cold box to ambient temperature using a warm helium gas stream from the LHP50.

2 K Refrigeration System SHP500

The SHP500 is a 500 W at 2 K cryogenic plant engineered to meet the primary cryogenic requirements of the MEHIPA Phase-1 SC accelerator. Notably, the plant incorporates a scalable architecture designed to accommodate the enhanced cryogenic loads anticipated in subsequent phase of MEHIPA. Table 1 outlines the primary

Table 1: Client process requirements [1, 2].

Parameters Descriptions	MEHIPA Phase-I	MEHIPA
Maximum total CMs heat load at 2 K	225 W	900 W
CDS load to the supercritical lines	30 W	70 W
Supercritical supply temperature	5 K	5 K
Maximum total LTTS load to cryomodules	100 W	200 W
Maximum LTTS return Temperature	9 K	9 K
Maximum total HTTS heat load in CMs	1200 W	1700 W
CDS heat load for the HTTS lines	60 W	220 W
HTTS supply temperature	35-37 K	35-37 K
Maximum HTTS return temperature	45 K	45 K
Minimum supercritical supply pressure	2.6 bar(a)	2.6 bar(a)
Minimum HTTS supply pressure	10 bar(a)	10 bar(a)

process requirements established for the design of the SHP500 cryoplant. These client-side cryomodule refrigeration requirements [1, 2], paired with the projected heat loads from the cryogenic distribution systems (CDS), are detailed in Table 1 for both the MEHIPA Phase-1 and MEHIPA configurations. The thermodynamic process of the SHP500 is designed with operational flexibility - Mode 2 represents a reduced-capacity mode tailored to sustain baseline MEHIPA Phase-1 operations, whereas, two identical SHP500 plants operating in Mode 1 (the full-capacity mode) can seamlessly meet the anticipated enhanced MEHIPA refrigeration requirements in the future. Furthermore, the cryogenic distribution box (CDS-DB) detailed in Section 1 and Fig.1 serves a dual purpose: it guarantees the seamless integration of future plant upgrades and provides the necessary operational latitude for intermediate capacity adjustments, mitigating risks associated with potential heat load calculation uncertainties in the MEHIPA Phase-1 SC accelerator.

As shown in Fig.5, the SHP500 refrigeration architecture utilizes a three-stage thermodynamic cycle to simultaneously sustain the High-Temperature Thermal Shield (HTTS: 37-45 K), the Low-Temperature Thermal Shield/Intercepts (LTTS: 4.5 K to 9 K), the sub-atmospheric 2 K cryomodule bath, and the Cryogenic Distribution System (CDS) heat loads. In the first stage, a HP1 compressor (25 bara discharge, 3.5 bara suction) drives a 10 K Brayton cycle with two turboexpanders (expansion stages) in series. The HTTS stream is extracted from downstream of the first turbine at 37 K. In the second stage, a HP2 compressor (13 bara discharge, 1.01 bara suction) powers a Claude cycle, generating 4.5 K liquid helium via sequential expansion through a turboexpander (TEX3) and a Joule-Thompson valve (JT1, state point 7 in Fig.5) expansion stages; a pre-JT1 bypass stream feeds a sub-cooler to deliver supercritical helium to the cryomodules and LTTS. Finally, a

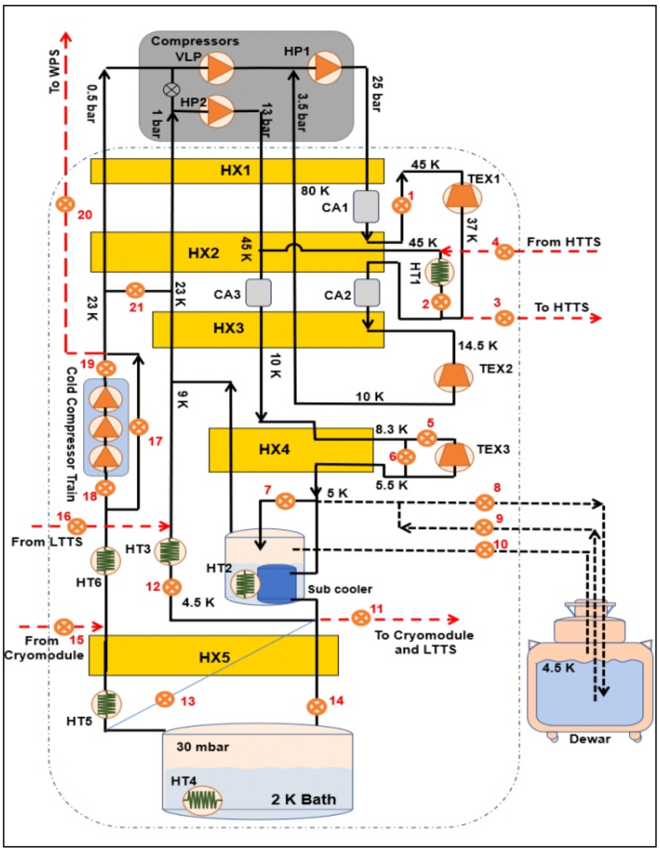

Fig.5: SHP500 process schematic.

combined cold compressor (CC) train and VLP compressor (sub-atmospheric suction pressure) regulates the cryomodule bath sub-atmospheric pressure to maintain the required ~ 2 K target temperature. For lower 2 K refrigeration load requirements, CC train and VLP compressor may be bypassed in favour of the WPS.

Recuperative cold recovery across the cold box is executed via compact plate-fin heat exchangers (PFHEs: HX1–3), a Joule-Thomson heat exchanger (HX4), and a VLP heat exchanger (HX5). For process stability and fast cool down operations, an external large-capacity liquid helium Dewar is integrated with the internal 4.5 K bath to provide thermal damping. Process regulation is managed by 21 cryogenic control valves, while three charcoal adsorbers (CA-1–3) positioned downstream of HX1 and 2 remove residual oxygen, nitrogen and neon impurities. In isolated standalone mode, a dedicated test loop, comprising HX5, two heaters (HT-4 and HT-5), and control valve CV-14, acts as a 2 K load and hydraulic resistance simulator to independently verify thermal efficiency and control automation. Similarly, heater HT2 serves as a 4.5 K bath load simulator for standalone, client-free 4.5 K refrigeration testing while damping user-side thermal and pressure transients.

Conclusion

To conclude, this article reports successful development and subsequent operational validation of the SHP20 2 K helium refrigeration system, which features a rated refrigeration capacity of 20 W at 2 K. During extended operational trials, it was possible to maintain a 2 K steady bath temperature and constant liquid level with a 22 W refrigeration (heater) load for over 9 hours. The peak refrigeration capacity, successfully demonstrated over a shorter duration, exceeded 25 W. This campaign successfully verified the concurrent, integrated operation of an indigenously developed helium liquefier, the 2 K refrigeration cold box, and the downstream warm pumping system. Furthermore, the trials validated the hydrodynamic and thermal performance of the custom-developed, very low-pressure (VLP) plate-fin heat exchanger, which serves as a critical milestone for high-capacity sub-atmospheric cryogenic infrastructure. Finally, the engineering and operational strategies detailed herein establish a robust development pathway for mitigating the primary cryogenic heat loads of the MEHIPA Phase-I accelerator utilizing the SHP500 cryogenic plant.

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