PIP-II Cryogenic System and the evolution of Superfluid Helium Cryogenic Plant Specifications

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Abstract. The PIP-II cryogenic system consists of a Superfluid Helium Cryogenic Plant (SHCP) and a Cryogenic Distribution System (CDS) connecting the SHCP to the Superconducting (SC) Linac consisting of 25 cryomodules. The dynamic heat load of the SC cavities for continuous wave (CW) as well as pulsed mode of operation has been listed out. The static heat loads of the cavities along with the CDS have also been discussed. Simulation study has been carried out to compute the supercritical helium (SHe) flow requirements for each cryomodule. Comparison between the flow requirements of the cryomodules for the CW and pulsed modes of operation have also been made. From the total computed heat load and pressure drop values in the CDS, the basic specifications for the SHCP, required for cooling the SC Linac, have evolved.

1. Introduction
Proton Improvement Plant – II (PIP-II) has been planned at Fermilab for providing powerful, high-intensity proton beams (800 MeV, 1.2 MW) for the Long-Baseline Neutrino Facility (LBNF). The warm frontend of the PIP-II Linac provides an H- beam to the first superconducting module. The frontend consists of a 30 keV H- ion source, a Low Energy Beam Transport (LEBT) delivering up to 10 mA DC beam to the entrance of a 2.1 MeV CW Radio Frequency Quadrupole (RFQ) accelerator, and a Medium Energy Beam Transport (MEBT) [1]. The acceleration in the superconducting modules of the PIP-II Linac starts immediately downstream of the MEBT with half-wave resonators (HWR) operating at 162.5 MHz. These are followed by two types of single spoke resonators operating at 325 MHz (SSR1 and SSR2), and finally by two types of elliptical 5-cell cavities at 650 MHz (LB650 and HB650) [1]. The schematic of the system is shown in figure 1.

2. Overview of the PIP-II cryogenic system
The PIP-II Superconducting Radio-Frequency (SRF) Linac cryogenic system (figure 2) consists of three major subsystems: the SHCP that produces the refrigeration, the SC Linac cryomodules with RF cavities that utilizes the produced refrigeration and the CDS that serves as a conduit by delivering the refrigeration from the SHCP to the SC Linac. The SHCP consists of the cold box (CB) and the associated auxiliary systems such as a set of process compressors, gas management and purification system (figure 2), etc. The cryogenic system is expected to operate for 20 years, with an estimated
continuous operation of two to five years without a scheduled shutdown. The expected availability of the SHCP is 98%, which, in turn, would define the availability of the entire cryogenic system [1].

**Figure 1.** Layout of the PIP-II Linac [1].

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2.1. Basic requirements

Broadly, the cryogenic system is required to perform the following basic functions:

- Provide sufficient cooling at appropriate temperature levels to enable operation of the SRF cavities and other cryogenic components, within their respective operational conditions, for all possible operating scenarios.
- Ensure that the system supports controlled cool-down and warm-up of cryomodules.
- Maintain stable pressure (± 100 Pa) in the cryomodules to minimize microphonics.

**Figure 2.** Layout of the PIP-II cryogenic system.
- Reduce system perturbations during fault conditions.
- Provide for full segmentation of the SRF Linac and allow installation/removal of a cryomodule under cold conditions.
- Provide for proper protection of process fluids from contamination and minimize loss of cryogens.
- Ensure that the system and its components comply with the Fermilab ES&H manual [2].

2.2. Modes of operation

The major modes of operation of the cryogenic system for PIP-II would include 4.5 K standby, 2 K standby, 2 K operation in pulsed mode and 2 K operation in CW mode [1]. The 4.5 K standby mode will come into effect during extended shutdown periods, when it is desirable to keep the cryomodule string cold and all circuits at positive pressure, thus minimizing the operating costs as well as the risks of contaminating the cold circuits. During shorter shutdown periods, it is desirable to keep the cryomodule string at 2 K standby mode. During the 2 K operation in the pulsed mode of the Linac, a significant reduction of dynamic cryogenic heat loads would occur. The maximum cryogenic heat loads are encountered during the 2 K operation in the CW mode of the Linac. The heat load budget [1] of the cryomodules for both the pulsed and CW modes of Linac operation are presented in table 1. In order to minimize the cost of operation, it is necessary that the PIP-II Linac should operate in the pulsed mode with the capability to change over to the CW mode as and when required. This particular requirement, in turn, leads to wide operational heat load ranges for the cryogenic system to handle since the dynamic loads outweigh the static loads by a huge margin in the CW mode (table 1).

| Cryomodule | Static heat load, 2 K (W) | Dynamic heat load, 2 K (W) | Total 2 K heat load, pulsed (W) | Dynamic heat load, CW (W) | Total 2 K heat load, CW (W) | LTII heat load (W) | HTTS heat load (W) |
|------------|--------------------------|---------------------------|-------------------------------|--------------------------|---------------------------|-------------------|-------------------|
| HWR        | 37                       | 24                        | 61                            | 24                       | 61                        | 60                | 250               |
| SSR1       | 24                       | 46                        | 70                            | 2                        | 26                        | 176               | 332               |
| SSR2       | 63                       | 366                       | 429                           | 20                       | 83                        | 434               | 882               |
| LB650      | 22                       | 611                       | 633                           | 32                       | 54                        | 176               | 528               |
| HB650      | 16                       | 519                       | 535                           | 27                       | 54                        | 128               | 344               |
| CMs Total  | 1728                     | 267                       | 974                           |                          |                           |                   |                   |

* 4.5 – 9K LTII loads.
* Includes the intercept loads as well as 45 – 80K thermal shield loads.

2.3. Cryogenic Distribution System (CDS)

The CDS includes all the equipment required to feed cold helium gas from the SHCP to the SRF Linac components (figure 2) and return the same to the SHCP. The CDS consists of a distribution box (DB), vacuum insulated cryogenic transfer lines, valve boxes equipped with cryogen transfer tubes with bayonets (U-tubes) and a turnaround box. The use of U-tubes provide flexibility for positive isolation of tunnel components and strings of cryomodules from the SHCP during installation, commissioning, operation and maintenance, including repairs. The pressure drop and heat load budget of the CDS are presented in table 2. The operating pressures are decided from functional requirements as well as review of other large cryogenic systems [3]. The heat load values for the cryogenic valves in the transfer lines have been sourced from the catalogue of a major manufacturer [4].
Table 2. Budgeted pressure drop and heat load along the CDS.

| Circuit                  | Operating pressure (P) (MPa) | Pressure drop (kPa) | Heat load (W) |
|--------------------------|-----------------------------|---------------------|---------------|
| 2 K return, line B       | 3.13e-3                     | 0.4                 | 170           |
| 4.5 K supply, line C     | 0.22 ≤ P ≤ 0.4              | 25                  | 60            |
| LTTI return, line D      | 0.22 ≤ P ≤ 0.4              | 3                   | 50            |
| HTTS supply, line E      | 0.3 ≤ P ≤ 1.8               | 5                   | 150           |
| HTTS return, line F      | 0.3 ≤ P ≤ 1.8               | 7                   | 1800          |

The major functional and operational features of the CDS may be summarized as following:

- In steady state operation, the SHCP would supply SHe stream, at around 4.5 K and a maximum supply pressure of 4 bar, to the CDS.
- The SHe line is divided into two streams inside each cryomodule, one of which is directed to a sub-atmospheric heat exchanger (SP HX) and subsequently to a JT valve, while the other is directed to the Low Temperature Thermal Intercepts (LTTI). The LTTI gaseous helium (GHe) return stream from each of the cryomodules enters the CDS transfer line (figure 2) along the PIP-II cave and returns to SHCP via the DB at a temperature of about 9 K during normal operation.
- The sub-atmospheric (SP) GHe return stream from each of the cryomodules enters the CDS transfer line (figure 2) along the PIP-II cave and returns to the SHCP via the DB at a temperature of about 4 K during normal operation.
- The SHCP would supply high-pressure helium gas at 35-40 K to the CDS for the High Temperature Thermal Shield (HTTS). This shield flow is returned from the CDS to the CB at around 80 K.
- The CDS transfer line would make use of 25 inline bayonet cans (one for each cryomodule) and a turnaround box at the end.

2.4. Cryomodules

Superconducting cavities and focusing elements, as necessary, are grouped within the cryomodules. All the superconducting cavities are based on an operating temperature of 2 K [1], which is achieved by reducing the vapour pressure of liquid helium (LHe) to about 31 mbar in the LHe bath surrounding the SC cavities in the cryomodules. Thermal intercepts for current leads are provided at two different temperature levels, 70 K and at 5 K respectively, to help reduce the heat load to the 2 K LHe bath in the cryomodules. Each cryomodule (CM) is designed to have a single thermal shield cooled with helium gas, nominally at 45 – 80 K [1] while cold helium stream at 4.5 – 9 K is used to cool the 5 K thermal intercepts. For arriving at the SHCP specifications, the necessary uncertainty and overcapacity factors are taken into account and applied over and above the heat load budget of the cryomodules presented in table 1.

3. Simulation studies

3.1. Motivation

Due to the wide-ranging heat load mitigation requirements pertaining to different modes of operation, it becomes imperative to include a holistic simulation study involving the CDS interface with the SHCP, the cooling circuits of the CDS and all the cryomodules taken together. The main aim of the study is to determine the mass flow rate in all the cold helium lines B, C, D, E and F (figure 1) in the CDS as well as the 2 K helium flow through the LHe bath of the cryomodules. Once the flow in all these lines are computed, the cold helium supply requirements from the SHCP for different modes of operation, at different temperature levels, is automatically established thus leading to the generation of its basic specification.
3.2. Numerical model for computation

A numerical model is developed to simulate the mitigation of heat loads in the CDS and the cryomodules. The model incorporates the CDS and its interface with the SHCP cold box and the cryomodules including the SP HX set and JT valves (figure 3). First law energy balance and continuity equations are written down for the sub-atmospheric heat exchanger set (SP HX Set) of the SRF Linac cryomodules, cold helium piping circuit, liquid helium (LHe) bath inside the cryomodules and the cryogenic valves. Additionally, for SP HX set, second law limitations are imposed through the use of device effectiveness value referenced from literature [5]. Apart from the effectiveness, the pressure drop across the SP HX has also been sourced from published literature [5, 6]. It is assumed that all the SP heat exchangers in the cryomodules possess the same effectiveness and hydraulic characteristics. The set of equations so developed are solved iteratively. A computer program is written for the purpose with helium properties derived from HEPAK®. Using the numerical model, the mass flow rate of helium in the different cooling circuits of the CDS and cryomodules, along with the process point temperatures, are computed for known heat exchanger effectiveness, estimated pressure drop and heat load values for the SC Linac CMs and the CDS (tables 1, 2). Results of the simulation, for both the modes, are summarized and presented in table 3. A schematic of the proposed process along with a snapshot of computed parameters for the CW and pulsed modes of operation are shown in figures 3 and 4 respectively. The corresponding temperature-entropy (T-s) diagram for the processes are presented in figures 5 and 6.

**Table 3.** Computed flow in the different cooling circuits.

| Mode   | 2 K SHe flow (g/s) | Line B (g/s) | Line C (g/s) | Line D (g/s) | Line E (g/s) | Line F (g/s) |
|--------|--------------------|--------------|--------------|--------------|--------------|--------------|
| CW     | 97.7              | 97.7         | 128.7        | 30.9         | 23.8         | 23.8         |
| Pulsed | 17.1              | 17.1         | 48.7         | 31.5         | 23.8         | 23.8         |

**Figure 3.** Computed thermodynamic state points for heat load mitigation in the CW mode.
3.3. Results and discussions

From the results of the computation, as presented in figures 3 and 4, two important points come to light:

- The 2 K helium flow in the cryomodules vary from 97.7 g/s to 17.1 g/s from the CW to the pulsed modes of operation.
- The return line B temperature at the exit of the CDS varies from about 3.7 K for the CW mode to about 5.4 K for the pulsed mode.

Typically, for cryomodule return flows of the magnitude as in the CW mode, centrifugal compressors, which are capable of handling high flows but at lower stage pressures, are employed [7]. To take care...
of the low head characteristics per stage, a series of cold compressors (CC) are generally used to increase the pressure from about 15 – 30 mbar (depending on cryomodule LHe bath saturated temperature) to 0.5 – 1 bar. The CC operation is limited by its surge and choking limits [7] which restricts the inlet process parameters and mass flow rates. The spread of pumped down mass flow rate (a ratio of about 6) that the cold compressor train needs to handle to mitigate heat loads in both the CW and pulsed modes is much higher (almost double) than that reported in literature [7]. Moreover, the inlet temperature to the train also varies quite a bit from one mode of operation to the other. Hence, all of these may pose a challenge to the employment of cold compressors successfully and economically for both the modes of operation.

A comparison for the 2 K flow requirements of different cryomodules for the two modes of operation are also plotted in figure 7. Other than the HWR cryomodule, for which the dynamic heat load is considered to be the same for both the modes [1], all the other cryomodules need to handle flows many times lower in the pulsed mode when compared to the CW mode. This may also adversely affect the effectiveness of corresponding SP HX, which needs to handle a wide range of mass flow rates.

![Figure 7. Comparison between the CW and pulsed modes with respect to SHe flow requirements for the cryomodules.](image)

4. Conclusion

From the estimated static and dynamic heat load values of the cryomodules and the CDS, 2K flow requirements in the cooling circuits of all the cryomodules and the CDS have been computed. Thus, the basis of specifications for the SHCP that is to be procured and commissioned for PIP-II heat load mitigation, is established. However, the preliminary study reported in this article indicates that the spread of flow requirements, for the cryomodules for the different modes of operation (CW and pulsed), is quite large. Hence, economic SHCP operation using the cold compressors may get very challenging. It is clear, however, that all the systems, including the SP HX set should be designed as per the specifications of CW mode, so that the best efficiency point can be utilized through minimization of 2 K flow requirements. Based on the study presented in this article, basic specifications for the SHCP has been generated and procurement process is initiated.

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