Status of the PIP-II Cryoplant

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Abstract. The Proton Improvement Plan-II (PIP-II) is an essential upgrade to the Fermilab accelerator complex featuring a new 800-MeV Superconducting Radio-Frequency (SRF) linear accelerator (Linac). The Linac contains 23 SRF cryomodules with the SRF cavities operating at 2 K, a high temperature thermal shield at 40 K and low temperature intercepts at 4.5 K. The PIP-II cryoplant will provide the necessary cooling for the cryomodules and the cryogenic distribution system interconnecting cryoplant and cryomodules. This paper describes the evolution of the PIP-II cryoplant conceptual design and specifications, including the expected heat loads, required cooling features and the integrated design. The cryoplant capacity margin analysis and fast cool-down mode will also be discussed.

1. Introduction

The Proton Improvement Plan II (PIP-II) is currently being designed and constructed at Fermilab’s accelerator complex. It features a brand-new superconducting radio-frequency linear accelerator to provide powerful high-intensity proton beam (800 MeV, 1.2 MW) for the most intense high energy beam of neutrinos to the international Deep Underground Neutrino Experiment at Long Baseline Neutrino Facility (LBNF). The acceleration in the superconducting modules of the PIP-II Linac consists of the half-wave resonators (HWR) operating at 162.5 MHz, two types of single spoke resonators operating at 325 MHz (SSR1 and SSR2) and two types of elliptical 5-cell cavities at 650 MHz (LB650 and HB650) [1]

Cryogenics plays a vital role in the PIP-II design. The Linac consists of 23 SRF cryomodules (of 5 different types) with the SRF cavities operating at 2 K. Additional cooling capacity is required at 40 K for high temperature shield, at 4.5 K for low temperature intercepts as well as liquefaction capacity to fill the 10,000 L Dewar for fast cooldown operation of the cryomodules.

2. PIP-II Cryogenic system

Figure 1 is the block diagram of the PIP-II Cryogenic system. It consists of two major systems: the helium cryogenic plant (CP) and the cryogenic distribution system (CDS) which collectively provide the required cryogenic cooling capacity to the Linac. The cryoplant contains the warm compression system, the cold box, gaseous and liquid helium inventory, purification and recovery system. It provides the required cooling capacity at three nominal temperature levels: 40 K for the high temperature thermal shields and intercepts, designated as HTTS; 4.5 K for the low temperature intercepts, designated as LTTS; and 2 K for the
SRF cavities and magnets, where applicable, within each cryomodule. The combined 4.5 K supply is divided into two streams as it enters the cryomodules, one that is directed to the Joule-Thompson (JT) heat exchanger preceding the cavity supply and another directed to the LTTS. Each cryomodule also has a dedicated cooldown valve and JT valve to supply cryogenics to each cryomodule string. The cryogenic distribution system interfaces with the cold box at the cryoplant building to provide helium supply and return at cryogenic temperatures, its scope also includes the supply and return of warm gaseous helium from cooldown and relief applications, as well as supply of gaseous nitrogen and instrument air to the Linac.

The cryogenic system is expected to operate for 20 years with an estimated continuous operation of 2-5 years without a scheduled shutdown. The expected availability of cryoplant is 98%.

![Cryogenic system block diagram](image-url)

**Figure 1.** Cryogenic system block diagram
3. Cryoplant cold box

The cryoplant cold box will feature an integrated design including up to 9 heat exchangers, 4 turbine expanders and 4 cold compressors to provide the required cooling capacity without liquid nitrogen precooling.

Figure 2 is the proposed schematic of the cold box which is based on 4 pressure levels: very low pressure (VLP) level, low pressure (LP) level, medium pressure (MP) level and high pressure (HP) level. The helium gas returning from the cold box is first compressed from VLP and LP to MP through oil flooded warm compressors, and combines before going being compressed to the HP level by the second stage compressor.

![Figure 2. Schematic of the Cold box](image)

The HP helium from warm compressors enters the cold box at 310K and 20 bara. Then it flows through heat exchangers, in which it is cooled against the MP stream (6 bara), the LP stream (1.1 bara) and the VLP stream (0.6 bara). The HP stream flows through the air adsorber at 80 K level to remove any air pollutants. At around 20 K, it is fed to the H2/Ne adsorber to remove any trace amount of hydrogen and neon.
The HP helium stream will be partially expanded through a total of 4 turbine expanders to provide the required cooling for HP stream at around 55 K, 20 K, 11 K and finally 6 K level. Downstream of the final expander, the HP helium either enters the 10K L Dewar (liquefaction mode) or subcooled in a 4.5 K LHe bath to become supercritical helium for the cryomodules and the LTTS.

LTTS helium gas returns to the cold box at around 9 K and 2.4 bara. The VLP helium from 2 K load returns to the cold box at above 0.027 bara and around 4 K. It is then compressed through a set of 4 stage cold compressors and flows through heat exchangers to recover enthalpy before returning to the VLP compressor.

4. Heat Loads

The required capacity of the Cryoplant is based on a detailed analysis of all the heat load contributions with appropriate safety factors. Safety factors that represent the uncertainty of the predicted cryogenic heat loads for each component are defined to minimize the risk of undersizing the cryogenic plant, which can lead to operational issues and costly upgrades.

The PIP-II Cryoplant uses the following formula for calculating the required capacity:

\[ Q_c = F_o (F_s Q_s + F_D Q_D) \]

where,

- \( Q_c \) is the required plant capacity;
- \( Q_s \) is the predicted static heat load;
- \( Q_D \) is the predicted dynamic heat load;
- \( F_o \) is the operational safety factor;
- \( F_s \) is the static heat load safety factor;
- \( F_D \) is the dynamic heat load safety factor

The operational safety factor (\( F_o \)) is used to provide a capacity buffer to reliably operate the plant through system transients and potential performance degradation between maintenance periods. Therefore, the operational safety factor improves the availability and reliability of the cryogenic system. The static (\( F_s \)) and dynamic (\( F_D \)) safety factors represent the uncertainty in the static and dynamic heat load predictions, respectively. Table 1 lists the PIP-II cryogenic plant safety factors at each temperature level.

| Temperature (K) | \( F_o \) | \( F_D \) | \( F_s \) |
|-----------------|-----------|-----------|-----------|
| 2 K             | 1.2       | 1.2       | 1.5       |
| LTTS            | 1.2       | 1.2       | 1.5       |
| HTTS            | 1.2       | 1.2       | 1.5       |

The summary of the estimated heat loads of the cryomodules and CDS at each temperature level are listed in Table 2 and 3. These numbers are based on expected performance of the latest cryomodules and CDS designs in PIP-II Cryogenic Heat Load Analysis Physics Requirement Document (PRD).

|                  | HTTS (40 K supply/Return) [W] | 4.5 K Supply [W] | LTTS (4.5 K Return) [W] | 2 K (isothermal) [W] | 2 K (Non-isothermal) [W] |
|------------------|-------------------------------|-----------------|------------------------|---------------------|-------------------------|
| Dynamic          | 893                           | 0               | 49                     | 1431                | 0                       |
| Static           | 3643                          | 9               | 482                    | 225                 | 7                       |
| Total            | 4536                          | 9               | 531                    | 1656                | 7                       |
Table 3. Summary of CDS total heat loads

| HTTS Supply (40 K Supply) [W] | HTTS Return (40 K Return) [W] | 4.5 K Supply (4.5 K Return) [W] | LTTS Load [W] | 2 K load (non-isothermal) [W] |
|-----------------------------|-----------------------------|-----------------------------|----------------|-----------------------------|
| Nominal                     | 170                         | 1548                        | 79             | 70                          | 257                          |
| Total                       | 1718                        | 149                         | 257            |                             |                             |

Applying the safety factors, the maximum required capacity is shown in Table 4. The 2 K heat loads consist of the isothermal load, which is applied to the bath of liquid helium in the helium vessel of the cavities and the non-isothermal load, which affects the 2 K vapor return temperature.

Table 4. Maximum Capacity Mode Specification

| 2 K Load [W] | Isothermal | non-isothermal |
|--------------|------------|----------------|
| 4.5 K Supply [W] | Total | 159 |
| LTTS Load [W] | Total | 1065 |
| HTTS Load [W] | Total | 10936 |

5. Modes of operation

The major steady modes of operation of the cryoplant for PIP-II include: maximum capacity mode (2 K), nominal design mode (2 K), 4.5 K standby mode and Helium liquefaction mode. The maximum capacity mode represents the maximum refrigeration capacity at 2 K to handle the highest total heat loads including all the safety factors. The nominal design mode represents the design condition to handle all dynamic and static heat loads but without considering the safety factors. The 4.5 K standby mode is design for extended shutdown periods to keep the cryomodules cold and with positive pressure, which reduce the operating cost and the risk of contamination. The only heat load is the static heat in leak of CDS and cryomodules. The dedicated Helium liquefaction mode is required for acceptance test and transition operation mode.

5.1 Fast Cooldown

The cryogenic plant is capable of cooling the 2 K circuit of a single cryomodule from 40 K to 5 K by supplying up to 80 g/s of 4.5 K flow for a minimum duration of 30 min. The cool-down flow is returned via the cool-down return line. Prior to fast cool-down, liquid helium is reserved in the 10,000 L dewar. The reserved liquid is boiled off during the fast cool-down using a heater with a 2,500 W capacity. This provides additional cold return gas to the cold box heat exchangers to supplement the liquefaction capacity. During the fast cool-down, the plant maintains the Linac in a 4.5 K standby mode. Table 5 summarizes the loads during 4.5 K standby mode and fast cool-down.

Table 5. 4.5 K Stand-by Mode during Fast Cooldown

| 2 K Load | Isothermal | 440 |
|----------|------------|-----|
| LTTS Load | Total | ≥1150 |
| HTTS Load | Total | ≥7000 |
6. Cavity Performance and capacity margin

Cavity $Q_0$ (quality factor) value affects the dynamic heat load of the cavity. Lower $Q_0$ will increase the dynamic heat load and has negative impact on the cryoplant capacity design margin. The high $Q_0$ values are achieved with the fast cooldown of the cavities. It will be further decreased without the fast cooldown. Table 6 shows the impact of following scenarios on the cryoplant capacity margin: (1) High $Q_0$ for both LB650 and HB650 MHz cavities (baseline). (2) LB650 Lower $Q_0$ at 1.6E10. (3) Lower $Q_0$ for both LB650 and HB650 MHz cavities. Scenario 1 is the baseline case where the overall margin is 34%. Based on the $Q_0$ scenarios analyzed, the Cryoplant 2 K isothermal capacity of 2,500 W is justified, as well as the need for fast cooldown capabilities.

| Scenario       | $F_o$ | $F_s$ | $F_d$ | $Q_c$ (W) | Comment                              |
|----------------|-------|-------|-------|-----------|--------------------------------------|
| Scenario 1     | 1.2   | 1.5   | 1.2   | 2466      | baseline                             |
| Scenario 2     | 1.2   | 1.5   | 1     | 2477      | All dynamic margin applies to LB650  |
| Scenario 3     | 1.2   | 1.5   | 1     | 2470      | All dynamic margin applies to 650 MHz|

7. Summary

Cryogenics plays a vital role in the PIP-II accelerator. The conceptual design of the cryogenic system is complete. The cryoplant capacity margin analysis under different scenarios shows currently specified cooling capacity and cooldown requirement are justified for PIP-II future operation. The preliminary design of the cryogenic system is well underway.

8. Reference

[1] 2017 Fermi National Accelerator Laboratory Report (The PIP – II Conceptual Design Report vol 0) ed V. Lebedev

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