Cryogenic design for a liquid hydrogen absorber system

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Muon ionization-cooling is under investigation at Fermilab and several other High Energy Physics Laboratories. A test area (MuCool Test Area) is being built at Fermilab to run components of a cooling cell together under a high power beam test. The first stage of the MuCool Test Area will ensure the feasibility of a liquid hydrogen absorber and cryogenic system. The main requirement of the system is to keep the density fluctuation in the liquid hydrogen absorber lower than 2.5%. Helium refrigeration can provide up to 500 W of cooling capacity at 14 K. This paper describes the cryogenic design of the system.

INTRODUCTION

Future Muon Collider and Neutrino Factory will require a cooling system to reduce the muon beam's transverse emittance. The current design uses ionization cooling as the beam passes through number of liquid hydrogen absorbers, alternating with accelerating radio-frequency cavities and embedded within a focusing magnetic lattice [1].

A preliminary feasibility study will be conducted at Fermilab with one liquid hydrogen (LH_2) absorber at a new MuCool Test Area. The LH_2 absorber is inserted in a hydrogen loop and housed in a containment vessel to fit the bore of a 5 T solenoid magnet. The first stage of the MuCool Linac Test Area operation under construction will validate the mechanical and thermal design of the liquid hydrogen absorber system.

TEST FACILITY DESCRIPTION

The cryogenic test facility is composed of a hydrogen cryoloop and helium refrigeration provided by an onsite cryoplant. The hydrogen system is distributed between a manifold room and the experimental hall. Figure 1 shows the flow schematic of the test facility. Hydrogen gas bottles stored in a separate manifold room supply the hydrogen gas. Pneumatically controlled valves regulate the cool down and the operation condition. Transfer lines equipped with the appropriate regulation valves, instrumentation and safety devices transfer H_2 gas to the containment vessel during the cool down. Gaseous hydrogen is then liquefied via a He/H_2 heat exchange process, where the helium is supplied and regulated between14 K and 20 K. During normal operation about 25 liters of liquid hydrogen flows in a close loop at 0.12 MPa. The available helium refrigeration capacity is 500 W at 14 K.

The test facility of the liquid hydrogen absorber system under development at Fermi National Accelerator Laboratory can be compared to other experiments using LH_2, like E158 hydrogen target system under test at Stanford Linear Accelerator Center (SLAC) [2-3] and SAMPLE experiment at Bates [4]. Although, these three experiments have different physics goals, the test facilities house a similar cryo-system and have to satisfy similar safety requirements. Operating parameters like LH_2 capacity, flow rate, pressure and temperature are the main differences for such experiments.

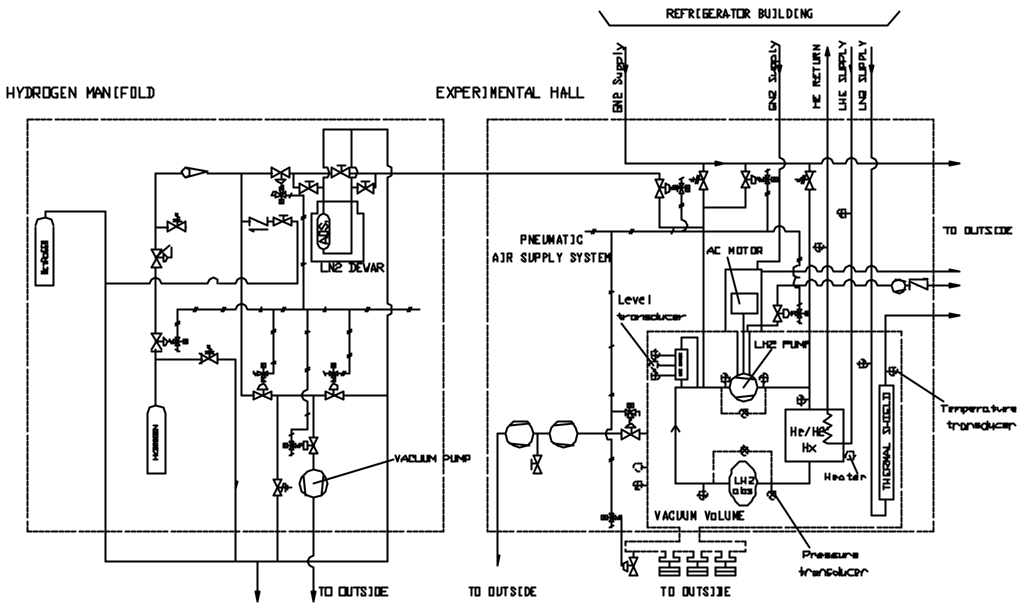

Figure 1 Flow schematic of the MuCool Test Area

LIQUID HYDROGEN ABSORBER SYSTEM

Cryo-loop

The hydrogen loop consists of the liquid hydrogen absorber, He/H_2 heat exchanger, LH_2 pump, transfer lines, safety devices and instrumentation. Figure 2 shows the conceptual design of the LH_2 system in the cryogenic solenoid magnet.

The LH_2 absorber is composed of an aluminum manifold and two non standard thin aluminum windows, with tapered thicknesses near the edge. The future MuCool experiment will require windows, which are as thin as possible in order to minimize the Coulomb multiple scattering in the material. It has been empirically determined that the thickness of the absorber and containment vessel windows should be less than 200 µm [5-6].

The He/H_2 heat exchanger regulates the temperature of the hydrogen system so that the LH_2 density fluctuation in the liquid hydrogen absorber remains less than 2.5%. We chose to regulate the LH_2 temperature between 17 K and 18 K. A 500 W heater mounted on the outer shell of the heat exchanger is used to balance the heat transfer of the hydrogen system, while keeping a constant helium refrigeration capacity of 30 g/s.

During operation the hydrogen is circulated by a mechanical pump at a flow rate up to 550 g/s. This 2 HP LH_2 pump was designed and built by Caltech as a spare pump for the SAMPLE experiment [4]. The MuCool Linac Test Area LH_2 pump is loaned by the SAMPLE collaboration.

The transfer lines connecting the absorber, heat exchanger and pump are equipped with safety devices and relief valves venting outside the experimental hall.

Containment vessel

The hydrogen cryo-loop is housed in a cryostat and is inserted in the 44 cm diameter bore of a cryogenic solenoid magnet. The LH_2 loop is thermally insulated in the vacuum vessel by a thermal shield and G10 supporting system. The thermal shield is actively cooled at liquid nitrogen (LN_2) temperature and wrapped with 30 layers of multilayers insulation. The containment vessel windows are shaped like the LH_2 absorber windows to minimize multiple scattering. The vacuum vessel volume is 52 times larger than the hydrogen cryo-loop capacity in order to withstand the expansion of the saturated liquid hydrogen. Therefore the vacuum vessel volume, being 1300 liters is distributed around the cryo-loop and through pipe venting outside the experimental hall. A pumping system composed of a roughing pump and a turbo-molecular pump will provide an insulation vacuum of 10^{-4} Pa.

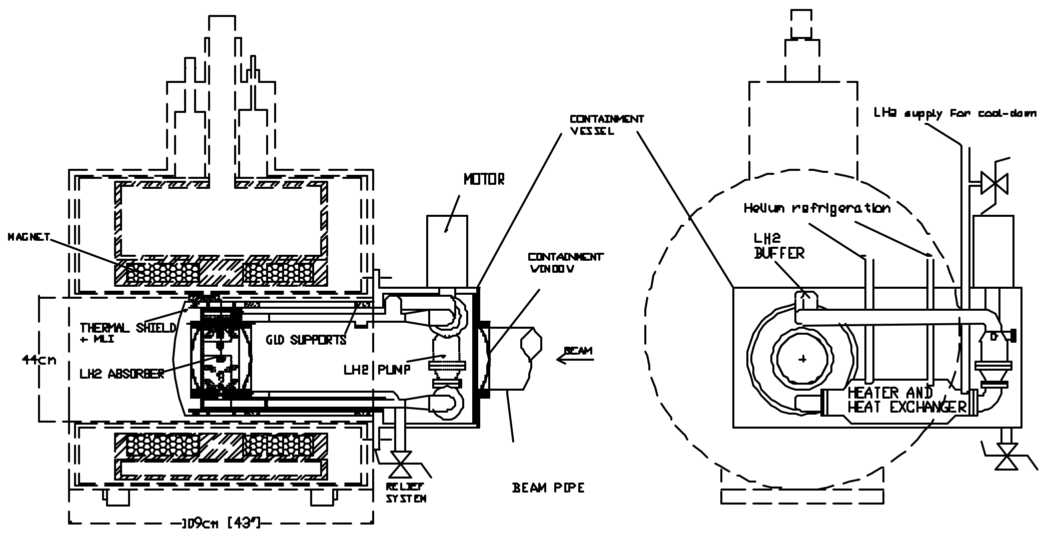

Figure 2 Conceptual design of the MuCool Test Area cryostat

CRYOGENIC DESIGN

Design of the liquid hydrogen absorber system is completed with respect to the thermo hydraulic behavior of hydrogen flow, thermal calculations, heat exchanger and safety relief valve calculations. The design is based on the American Society of Mechanical Engineers code (ASME) and the Fermi National Accelerator Laboratory safety recommended requirements for hydrogen. The associated controls and instrumentation are based on the US National Electrical Code (NEC) safety requirements for hydrogen. The use of hydrogen is challenging and implies stringent safety controls. A safety Programmable Logic Controller (PLC) is considered. More than 150 temperature sensors, pressure elements, valves within the cryostat are chosen and installed regarding the safety requirements. Additional requirements are radiation hardness for the instrumentation as well as structures to withstand forces during potential quenches of the magnet. Oxygen deficiency detectors and flammable gas detectors are installed in both the experimental hall and the hydrogen manifold.

To satisfy safety requirements for the hydrogen system, the relief valve system is redundant. Relief system is composed of fast acting valves, AGCO type valve and parallel plates. The operating pressure of the hydrogen cryo-loop is 1.2 atm. The hydrogen cryo-loop is set to open at 10 psig (0.17 MPa). The containment vessel (vacuum vessel) is sized for a Maximum Allowable Working Pressure (MAWP) of 25 psig (0.27 MPa). Parallel plates designed at Fermilab will be used.

The helium refrigeration system will ensure the cooling of the heat deposited by the beam (up to 150 W) and by the static heat load from the cryo-system. Insulation vacuum of 10^{-4} Pa, low thermal conductivity supporting system and multilayer superinsulation minimize the heat load to the liquid hydrogen system. The heat load to the 17 K LH_2 absorber is about 6 W due to radiation and conduction through multilayer insulation, 17 W due to radiation from the two containment vessel windows and 0.2 W due to conduction though the G10 supporting system. The heat load due to solid conduction from the motor shaft of the LH_2 pump is about 50 W. A safety coefficient of 2 was used for the refrigeration system sizing. Therefore, the total static heat load from the cryo-system to be extracted by the helium refrigeration system at 17 K is less than 150 W. Hence, the helium refrigeration system will ensure less than 300 W. The cryostat thermal heat load to the 77 K temperature level is calculated to be 69 W. Hence, nitrogen cooling ensures a cooling up to 140 W. Table 1 summarizes the heat load calculated for the current conceptual design of the cryostat.

A motor drives the pump via a long metallic shaft coupled to the rotating pump shaft, with one cold and one warm bearing to keep the heat load from the motor at a minimum. Being located outside the vacuum vessel, the motor is sealed in a container in order to prevent air leaking into the cryostat. This container is cooled by a flow of nitrogen gas. The shaft inside the cryostat is contained in a vessel, which is continuously pumped to limit the hydrogen and nitrogen leaks, which limits the heat load to the cryo-loop and the risk of nitrogen freezing in the cryostat. The motor runs between 10 and 60 Hz.

Table 1 Static heat loads calculated for the current conceptual design

Heat load (W)	80 K	17 K
Mechanical Supports	67	6
Superinsulation	1.5	0.2
Cryostat windows	-	17
LH2 pump	-	50
Total	68.5	73.2

The main limiting factor for the thermo hydraulic hydrogen flow is the density change for the LH_2 inside the absorber. For subcooled hydrogen, the allowable density change in the LH_2 absorber should be less than +/-2.5 %, which corresponds to a temperature gradient less than 4 K. In order to keep some margin with the hydrogen boiling point, hence large density change, the cryo-loop cryogen will be subcooled. The heat exchanger is designed for 500 W, for a nominal temperature gradient of 1 K at 17 K and for the maximum helium flow available by the cryo-plant being 30 g/s. The pressure drop in the helium side will be accommodated by the refrigeration cryo-plant. An extrapolation to 1 kW would be possible with a larger LH_2 temperature gradient and an average temperature of 20 K. The He/H_2 heat exchanger is composed of a copper coil housed in a 500 mm x 150 mm diameter stainless steel outer shell. The copper tube is wrapped around a solid aluminum core in order to reduce the total volume of liquid hydrogen.

The design of thermo hydraulic hydrogen flow schematic inside the containment window is also dictated by the LH_2 pump characteristics. The pressure drop admissible by the pump has been measured [4], being 0.5 psig (0.1 MPa) for a 550 g/s flow of liquid hydrogen. Therefore the cryo-loop including the absorber, heat exchanger and transfer lines is designed to fulfill this allowable pressure drop. In order to reduce the pressure drop in the system, two 25 mm diameter pipes are used to supply liquid hydrogen to the absorber volume and three pipes are used for the return to the LH_2 pump. The connecting transfer lines to the heat exchanger pump and absorbers are 50 mm diameters. Less than 0.4 psi (2.8 10^{-3} Pa) of pressure drop is estimated for a 550 g/s liquid hydrogen absorber system flow at 0.12 MPa and 17 K.

CONCLUSION

A cryogenic design for a liquid hydrogen absorber system has been developed at Fermilab. The requirements are based on ASME code and Fermilab safety requirements and US NEC standards. The cryogenic design is based on its ability to maintain a temperature gradient of 1 K at 17 K and 0.12 MPa within a structurally safe containment vessel. The high-powered beam test at the MuCool Test Area using protons extracted from the Fermilab Linac is scheduled to run in 2005 with cryogenic operations beginning in 2003.

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