Design of the cryostat for High Field Vertical Magnet Testing Facility at Fermilab

S Koshelev 1, T Tope 1, J Theilacker 1, V Nikolic 1, G Velev 1, E Voirin 1, A J Marone 2 and P E Kovach 2

1Kirk Rd & Pine St, Batavia, IL 60510, United States
2Brookhaven National Laboratory, P.O. Box 5000, Upton, NY 11973, United States
E-mail: koshelev@fnal.gov

Abstract. High Field Vertical Magnet Test Facility (HFVMTF) is a joint project between the Office of High Energy Physics (HEP) and the Office of Fusion Energy Sciences (FES). Its construction is currently under way at Fermi National Accelerator Laboratory (Fermilab). As a part of the project a new double bath superfluid helium cryostat has been designed. The cryostat can accommodate magnets with up to 20 tonne weight and 1.3 m diameter. This paper discusses challenges and solutions for cryostat, lambda plate and heat exchanger design, and presents results of performance analysis.

1. Introduction
High Field Vertical Magnet Test Facility will serve DOE Magnet Development Program to test 16 T to 20 T accelerator dipole demonstrators and other test magnets, and the FES program to test samples of High Temperature Superconductor (HTS)[1]. The HFVMTF cryostat will be a “double-bath” system, with 4.5 K saturated liquid helium above a barrier, called the “lambda plate”, and 1.9 K, 1 atmosphere helium below the lambda plate. The 1.9 K space will be used for testing superconducting magnets. Figure 1 shows principle schematic of the HFVMTF in the HTS sample testing configuration. The primary focus of the HFVMTF cryostat is to accommodate Test Facility Dipole (TFD)[2] designed for the FES program. The TFD presents a number of challenges due to its dimensions, weight, and large aperture.

2. Cryostat design
The design of the HFVMTF cryostat is influenced by the cryostat of the VMTF[3] operated at Fermilab. Large aperture of the TFD causes fringe magnetic field to interact with an external magnetic shield if the magnet is eccentric to the shield resulting in a decentering Lorentz force. The force is proportional to the position of the magnet axis in regards to the shield axis and is estimated at 240 N/mm of offset. To reduce the force the magnet needs to be installed as close to the shield center as possible. This is achieved by a two-fold strategy. The cryostat is designed with concentric helium and vacuum vessels to minimize the eccentricity. After the installation of the cryostat the center of the magnetic shield will be located with a superconducting magnet and the whole cryostat will be shifted slightly in order to further reduce the offset between the magnet and shield axes. The concentric design of the cryostat and stricter limitations on the maximum diameter don’t allow for use of a thermosyphon heat exchanger design successfully...
Figure 1. HFVMTF principal schematic (not to scale). HTS sample is supported by Top Plate E inside an anti-cryostat (Top Plate D) within the magnetic field. The magnet is supported by the lambda plate and the Top Plate C of the helium vessel.

implemented in VMTF[3]. An investigation of 2 K heat exchanger designs showed successful use of concentric U-tube based heat exchanger design at multiple CERN facilities[4][5]. Reliability and simplicity of the design made it a perfect fit for HFVMTF cryostat. Estimated cooling capacity of the HFVMTF 2 K heat exchanger is 90 W.

Another challenge introduced by the TFD is an increased helium vessel diameter, compared to VMTF, leading to longer line of contact between the lambda plate and the helium vessel. The superfluid helium leaks account for majority of the 2 K heat leaks, therefore, special attention has been paid to the choice of the type of the lambda seal. Most commonly used types of seals in similar applications are surface-to-surface contact (flat or conical), polymer seals[6], and spring energized seals[7]. Epoxy coated surface-to-surface seals have demonstrated good performance and reliability with shorter line of contact. The difficulty of manufacturing a long surface-to-surface seal[6] presents a significant challenge that makes this choice suboptimal. The spring energized seal has shown high leak tightness, reliability, low maintenance requirements during its use at Brookhaven National Laboratory and represents the best choice for HFVMTF design.

In addition to differential internal and external pressures listed in Table 1, upper part of the helium vessel experiences the weight of the magnet as a part of the load path shown on Figure 2. Stress analysis converged on minimum required wall thickness of ∼5 mm (3/16 inch) with reinforcement rings satisfying all of these requirements.

The lambda plate is designed as a laminate of stainless steel and G10 composite to balance
Table 1. HFVMF cryostat design pressure and temperature.

| Vessel   | Internal pressure, MPa | External pressure, MPa | Design temperature, K |
|----------|------------------------|------------------------|-----------------------|
| Helium   | 0.689                  | 0.207                  | 2 — 322               |
| Vacuum   | 0.103                  | 0.103                  | 77 — 322              |

Figure 2. Load path due to the TFD.

low thermal conductivity with the required strength to bear the magnet load.

The analysis of the relief conditions identified the worst case as the vacuum loss causing the magnet quench. The single failure mode assumes that the magnet quench protection is operational at the moment of vacuum vessel failure. Despite high stored energy of the TFD, estimated in 12 MJ to 16 MJ range, the energy deposition into the helium bath is ≤50 kW. This upper boundary is determined by limited heat transfer area of the magnet and the heat transfer coefficient. The air condensation on the MLI of the helium vessel causes ~134 kW of heat transferred to the helium bath, dominating worst case scenario. Internal DN 100 helium return line is sufficient for full quench+vacuum loss flow with less than 3 % pressure drop.

3. Thermal performance
Large thermal mass of the magnet assembly requires special consideration for cooldown and warmup with regards to the requirements presented in Table 2. Both cooldown and warmup above 100 K are controlled to maintain constant temperature difference between the magnet and the gaseous helium flow. The incoming helium is passed through a liquid nitrogen precooler with a controlled outlet temperature. Below 100 K the cooldown switches to fast mode with cooling provided by liquid helium flow from the cryosystem. The warmup below 100 K is performed
with the gas helium flow precooled to 180 K to reduce the probability of accidentally exceeding magnet temperature constraints around 100 K point.

Figure 3. The TFD cooldown times for $\Delta T$: ---20 K, —30 K, ——40 K, ·····50 K.

Figure 4. Optimized transient process curves for 10 g/s flow and $\Delta T = 80$ K: - - - - cooldown, —warmup.

The cooldown and warmup processes have been analyzed using a zero dimensional model of gaseous helium flow through the annular gap between the magnet and the vessel with the assumption of perfect conduction inside the magnet. The results of the analysis show the temperature difference between the magnet and the helium flow to be the governing factor for the process time as shown on Figure 3. In collaboration with Lawrence Berkeley National Laboratory, responsible for the design of the TFD, the magnet temperature constraint has been increased to 100 K to reduce the cooldown time. The temperature difference of 80 K has been chosen to prevent exceeding the allowable 100 K limit. The major reduction of the cooldown time is achieved at 10 g/s to 15 g/s of precooled helium. To provide fast cooling to the magnet without significant disruption of the cryoplant operation flow rate of 10 g/s is chosen. The internal piping, however, is designed for 30 g/s flow for when such capacity will be available in the future. Figure 4 shows combined cooldown and warmup curves for the optimized flow with the estimated total process duration presented in Table 2.

| Process                | Required time, h | Estimated time, h |
|------------------------|------------------|-------------------|
| Cooldown, 300 K to 1.9 K | 234              | 229               |
| Warmup, 1.9 K to 285 K  | 200              | 116               |

The steady state thermal performance of the cryostat has been estimated using available VMTF values[3]. The results presented in Tables 3 and 4 are comparable with similar cryostats[5]. The cryostat requires 216 L/h of liquid helium allowing for minimum of 23 hours of continuous steady-state powered operation using full cryoplant capacity and stored liquid helium.
Table 3. HFVMTF cryostat heat loads at 1.9 K.

| Source                                  | Heat load, W |
|-----------------------------------------|--------------|
| Lambda plate leaks                      | 20.5         |
| Conduction through lambda plate         | 5.1          |
| Current leads                           | 5.0          |
| Thermal radiation from sides            | 1.5          |
| Anticryostat CF                         | 1.1          |
| Conduction through lambda seal ring     | 1.0          |
| Warmup/fill line                        | 0.9          |
| Instrument wires                        | 0.6          |
| Valves                                  | 0.1          |
| Conduction down magnet supports         | 0.0          |
| Conduction down vessel walls            | 0.0          |
| **Total heat load**                     | **35.9**     |

Table 4. HFVMTF cryostat heat loads at 4 K.

| Source                                  | Heat load, W |
|-----------------------------------------|--------------|
| Conventional leads, powered             | 63.5         |
| Conduction down vessel walls            | 24.0         |
| Helium gas conduction                   | 13.5         |
| Instrument wires                        | 6.7          |
| Thermal radiation from top              | 4.2          |
| Conduction down magnet supports         | 2.5          |
| Valves                                  | 0.7          |
| Thermal radiation from sides            | 0.2          |
| **Total heat load**                     | **115.2**    |

4. Conclusion

The cryostat presented in this paper has been designed for testing of superconducting magnets with weight up to 20 tonne and diameter up to 1.3 m at 4.5 K or 1.9 K. Lambda seal and 2 K heat exchanger designs selected for this cryostat allow to achieve it state-of-the-art performance. Optimized cooldown and warmup processes allow for simple automated operation with fast cooldown and warmup of the cold mass. At the current stage the initial design of the HFVMTF cryostat is completed and shown to satisfy the requirements of the Test Facility Dipole.

5. References

[1] Velev G V et al 2021 IEEE Trans. on Appl. Supercond. Design and construction of a high field cable test facility at Fermilab 31 1–4
[2] Vallone G et al 2021 IEEE Trans. on Appl. Supercond. Magnetic and Mechanical Analysis of a Large Aperture 15 T Cable Test Facility Dipole Magnet 31 1–6
[3] Peterson T J, Rabehl R J and Sylvester C D 1998 Adv. in Cryog. Eng.(Portland) vol 43 (Boston: Springer) pp 541–8
Benda V, Pirotte O, de Rijk G, Bajko M, Vande Craen A, Perret P and Hanzelka P 2015 *Phys. Proc.* Cryogenic Design of the New High Field Magnet Test Facility at CERN 67 302–7

Vande Craen A *et al* 2014 *AIP Conf. Proc. (Anchorage)* vol 1573 (New York: AIP Proceedings) pp 229–36

Vande Craen A, Bajko M, Benda V, Deschamps J-B, Giloux C, Lees A, Parma V, Pasdeloup F and Pirotte O 2019 *OP Conf. Ser.: Mater. Sci. Eng.* Thermal performance of the new superfluid helium vertical test cryostats for magnet tests at CERN 502 012081

Muratore J, Anerella M, Joshi P, Kovach P, Marone A and Wanderer P 2017 *IEEE Trans. on Appl. Supercond.* Design and fabrication of the 1.9 K magnet test facility at BNL, and test of the first 4-m-long MQXF coil 28 1–4

**Acknowledgments**

The authors wish to thank Arnaud Vande Craen, Pierre Minginette and Vincent Maire for sharing the knowledge of design and operational experience of HFM, Cluster D and FRESCA2 facilities. Clark Reid, Ruben Noceda, and Anton Rusy, who were responsible for the design/drafting for this project.

Work supported by the Fermi National Accelerator Laboratory, managed and operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for U.S. Government purposes.