

# Design and Construction of a High Field Cable Test Facility at Fermilab

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**Abstract**—Fermi National Accelerator Laboratory, together with Lawrence Berkeley National Laboratory, is building a new High Field Vertical Magnet Test Facility (HFVMTF) to be situated in the Magnet Test Facility at Fermilab. The HFVMTF is jointly funded by the US DOE Offices of Science, High Energy Physics, and Fusion Energy Sciences, and will serve as a superconducting cable test facility for both communities. The background magnetic field for test samples is 15 T and will be produced by a magnet provided by LBNL operating at 1.9 K in superfluid helium. The samples will be placed in the background magnetic field, cooled to between 4.5 K and a user-specified upper limit, and will be powered with a superconducting transformer at up to 100 kA. Additionally, this facility will be used to test high-field superconducting magnet models and demonstrators, including hybrid magnets, produced by the US Magnet Development Program. Currently, the various tasks of the project are at different stages of execution, from conceptual to ready-for-construction designs. This paper describes the parameters and design status of the pit construction, cryostat, heat exchanger, lambda plate, power system, and quench protection and monitoring systems of the facility.

**Index Terms**—High-temperature superconductors, Superconducting magnets, Superconducting materials

## I. INTRODUCTION

THE US DOE Offices of High Energy Physics and Fusion Energy Sciences are collaborating in the development of High Temperature Superconductors (HTSs) and are investing in an effort to build an HTS cable-testing facility. This new test facility, called the High Field Vertical Magnet Test Facility (HFVMTF), will be built at Fermi National Accelerator Laboratory (Fermilab) and will serve the U.S. DOE/HEP Magnet Development Program (MDP) [1] in the testing of magnets with 16-20 plus T accelerator dipole fields, including hybrid magnets, as well as the US DOE FES programs for testing HTS samples in very high dipole fields. For the US FES community, this facility will provide similar or better capabilities than the European test stands, FRESCA2 at CERN and EDIPO at PSI, Switzerland [2].

The Fermilab team investigated several choices for HFVMTF, and the most cost-effective proposal was selected.

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The test pit will be located close to the current Vertical Magnet Test Facility (VMTF) in Industrial Building One (IB1), Applied Physics and Superconducting Technology Division (APS-TD), in order to take advantage of its existing cryogenic and power infrastructure. The pit will be constructed such that it can be serviced by two 25-ton cranes, which will also provide support for magnet installation activities.

## II. TEST FACILITY PARAMETERS

The test facility parameters were selected after discussion within the MDP and FES communities. The minimum operating temperature of the facility will be 1.9 K for the magnet providing the background field. This requirement dictates the use of a lambda plate in the cryostat assembly. The dipole field provided by the magnet is 15 T [3]. The size of the cryostat has been established so that it can accommodate magnets with a maximum diameter of 1.3 m and maximum length of 3 m. The current limitation on the maximum stored energy in the magnet is set at 20 MJ. The recommended weight of the magnets delivered for testing should not exceed 25 US tons so that they can be easily manipulated by only one of the available 25-ton cranes. In specific situations, objects weighing more than 25 tons can be installed, with the only limitation coming from the magnet support inside the cryostat. The test facility should operate in an efficient and safe manner, minimizing the time for experiment preparation and ensuring no helium losses after possible quenches. The operational lifetime of the facility is expected to be at least 20 years.

The HTS test sample cryostat to be inserted into the magnet aperture will be similar to the cryostat at EDIPO [4], and will be capable of controlling the sample temperature within an approximately 1 K step in the region of 4.5 to 55 K.

We assume that the test facility will work independently from other test facilities in the building. To achieve this goal, a new helium cryoplant is currently being procured and will be operational in 2022. It will provide enough liquid helium to simultaneously support the operation of the superconducting radio

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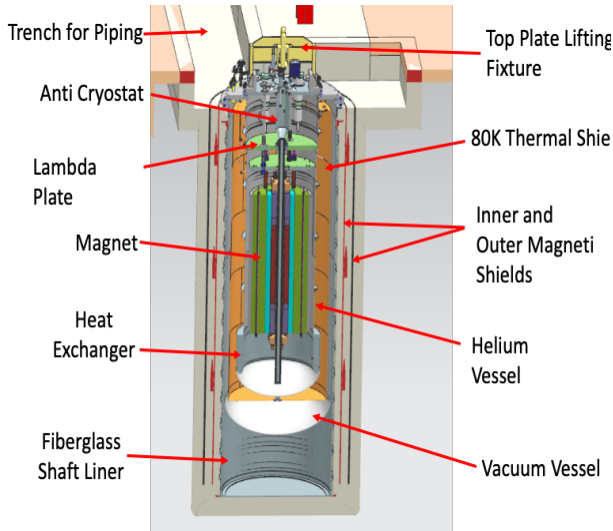


Fig. 1. Cross section of the test pit and cryostat with the magnets inside.

frequency (SRF) cavity and the magnet test programs. In order to power the magnets, we are planning to install two sets of power supplies: 24 kA for the main magnet and 15 kA for the magnet insert in case of the need for testing in hybrid configurations. For these power supplies, we will install appropriate current leads for the cryostat and corresponding current busses.

To excite HTS test samples with a current up to 100 kA, a SC transformer option has been adopted. This solution is similar to the transformers utilized in the SULTAN [5] and EDIPO test facilities.

### III. TEST PIT DESIGN

As we mentioned above, the HFVMTF pit will be constructed in Industrial Building 1. Its location has been selected based on its proximity to the VMTF pit. This proximity will allow access to all the necessary base infrastructure, including cryogenics, electrical power, cooling water, and overhead crane access.

Figure 1 shows the cross section of the pit's final design. The depth of the excavation is 20 feet ( $\sim 6.1$  m), while the inner diameter is 128 inches ( $\sim 3.25$  m). A concrete wall of a minimum thickness of 21 inches (0.53 m) will be placed around the excavation. This leaves a maximum 86-inch (2.18 m) opening for the cryostat placement. Fiberglass liner (Fig. 1) is used in the shaft as a barrier to the entry of groundwater. A set of trenches will be constructed connecting the pit to the necessary infrastructure, magnet power supplies, control system, and quench protection and monitoring racks.

The HFVMTF will be built close to other test stands having very strong limitations to exposure to the fringe fields. For example, the stands in the nearby SRF cavity test facility have a Mu-metal shield capable of intercepting only a fringe field of less than one Gauss [6]. The main dipole will be installed at a distance of 8 m from the closest SRF stand and the fringe field in this area will be on the level of 5 Gauss which is unacceptable. To protect these test stands, the most efficient options for

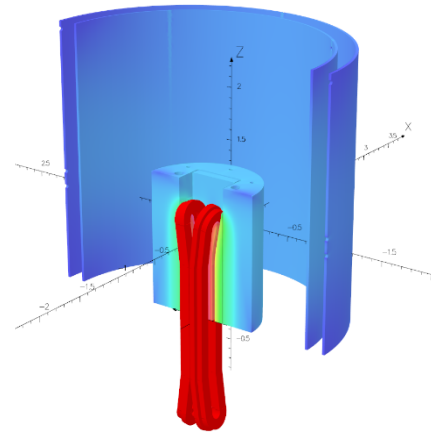


Fig. 2. Modeling configuration of the fringe magnetic field with the magnet in the center of the shield structure, producing a dipole field of 15.3 T.

suppressing the fringe field would be the placement of a ferromagnetic shield around the magnet. For this reason, we have decided to embed concentric cylindrical magnetic shields made from low-carbon steel in the concrete wall of the pit (Fig. 1).

Several shielding options were investigated, and the double-shield configuration shown in Fig. 2 was chosen. Both shields are one inch thick and made from AISI 1020 steel. Fig. 3 shows the 5 G and 0.5 G contours when the magnet is powered to an

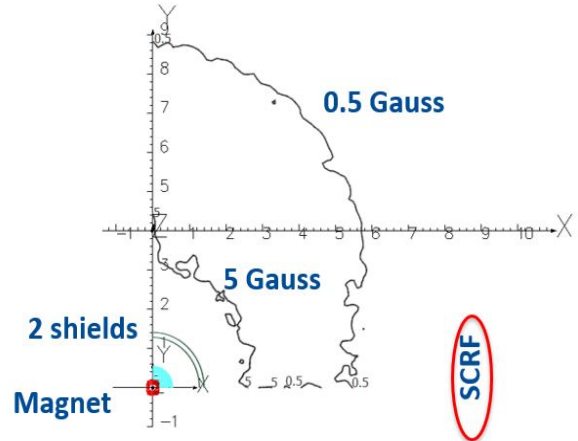


Fig. 3. Fringe field around shielded HFVMTF with magnet at center, producing at 15.3 T. The SCRf mark shows the position of the closest SRF test stand.

operational current ( $\sim 15.5$  kA) corresponding to 15.3 T [3]. One can see from Fig. 3 that the shields reduce the field to 0.5 Gauss at a distance of 6 m. It should be noted that the background field in this area is also 0.5 Gauss.

Our simulation showed that the critical issue in this design is a possible decentering Lorentz force applied to the magnet if the magnet is relatively shifted to the shielding geometrical center. It was found that this force gradient is 0.24 kN/mm which

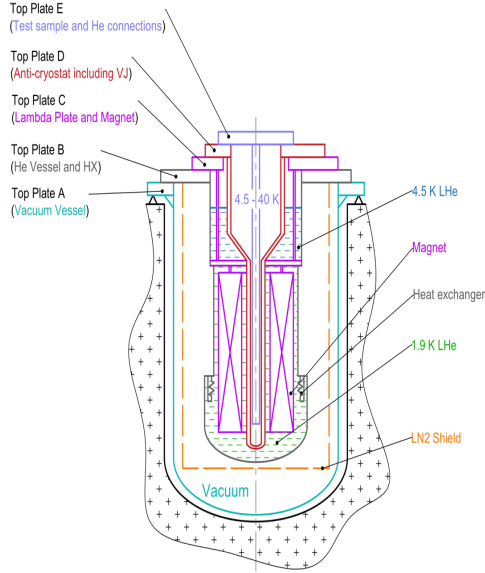


Fig. 4. Cross section of the cryostat with the magnet inside and of the HTS test sample holder.

is linear for the magnet shift of  $\pm 100$  mm relative to the shield's central axis. This implies an additional requirement for the design of the magnet support structure and the cryostat.

#### IV. CRYOSTAT DESIGN

The next step of the project includes the design, procurement, delivery, and integration of the cryostat, the heat exchanger, and the lambda and top plates. The cryostat design will be done in-house while its manufacture will be contracted to an outside party.

The current design of the cryostat is largely based on the existing VMTF cryostat, which is described elsewhere [7]. It is a double-bath system with 4.5 K liquid helium above the lambda plate and subcooled 1.9 K helium below. The lambda plate separates the upper and lower He vessels and transfers the load of the cold mass to the upper vessel wall. The wall thickness is optimized to minimize the heat load from 4.5 K helium and to provide sufficient support to the cold mass.

Two major differences between the HFVMTF and VMTF cryostats are the increase to 1.4 m in the diameter of the lower helium vessel and a different subcooling heat exchanger. The design of this liquid-to-liquid heat exchanger is based on the heat exchanger used at the magnet test facility at CERN [8]. It allows keeping the cold mass centered inside the cryostat in order to minimize the forces from an external magnetic shield. The heat exchanger transfers heat from subcooled helium to saturated helium, which will be evacuated with vacuum pumps.

The lambda plate is equipped with the combination of a check valve and a rupture disc to prevent overpressurization of the bottom part of the He vessel. The internal pressure of the

TABLE I  
HFVMTF TEMPERATURE REQUIREMENTS

Requirement	Time (hours)
Controlled cool-down 300 K to 100 K	< 200
Cool-down 100 K to 4.5 K	< 10
Cool-down, 4.5 K to 1.9 K	< 24
Controlled warm-up to 4.5 K to 285 K	< 200

helium vessel is limited to a 100 psi differential from the internal vacuum to maintain compatibility with the cryosystem.

The anticryostat (Top Plate D, Fig. 4) is designed to house a sample, a superconducting transformer, and process piping. Between test runs, the sample holder (Top Plate E, Fig. 2) can be removed and reinserted without warming up the cold mass. The sample temperature is maintained within a 4.5 to 55 K temperature range.

Cool-down and warm-up of the cold mass is controlled between 300 K and 100 K with the temperature gradient remaining below 50 K. Time and temperature requirements are shown in Table I.

#### V. QUENCH PROTECTION AND MONITORING SYSTEM

The magnet's quench protection and monitoring (QPM) system block diagram is shown in Fig. 5. It simultaneously protects two independent superconducting magnets or a magnet and test sample, their superconducting bus, and their high current vapor-cooled leads. When testing a hybrid magnet, the two branches of the QPM will simultaneously protect the LTS magnet (usually an  $\text{Nb}_3\text{Sn}$  magnet) and the HTS insert. When the system is

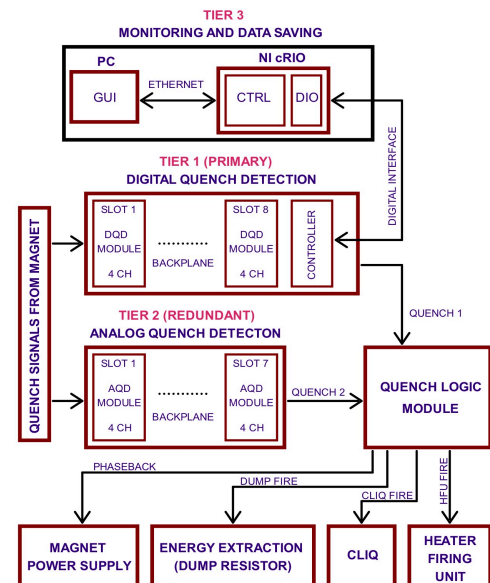


Fig. 5. Quench protection and monitoring (QPM) system block diagram.

TABLE II  
NOMINAL QUENCH PROTECTION PARAMETERS

Magnetic Length	1.7 m
Inductance	97.2 mH
Current	15500 A
Stored Energy	12 MJ
RRR	100
Cu/NCu	0.8
Quench Detection/Validation time	15 ms
Dump Resistor	130 m $\Omega$
CLIQ capacitance	40 mF
CLIQ voltage	600 V

used to test HTS samples for fusion energy R&D, the first branch will protect the main dipole magnet and the second branch the test sample.

The principle for detecting a quench in the LTS magnet and HTS insert is based on monitoring the resistive voltage growth and comparing this signal with a predefined threshold [9]. When the quench threshold is exceeded, a quench trigger is generated. The quench event trigger is used to initiate the quench protection logic, which results in energy extraction (dump resistor circuit), protection heater discharge, and CLIQ unit [10,11] discharge.

This QPM system may control 8 single-channel Heater Firing Units (HFUs) for up to 32 magnet-protection heaters, 2 dual-channel HFUs for magnet spot heaters, two Coupling-Loss Induced Quench (CLIQ) units, and the monitoring, using fast-data loggers, of 128 isolated quench characterization channels.

The HFVMTF QPM system is based on a quench detection system developed for the Mu2e experiment at Fermilab. It consists of a primary Digital Quench Detection (DQD) hardware system, a redundant Analog Quench Detection (AQD) hardware system, and a quench management system based on National Instruments' CompactRIO system [12]. The quench management system provides quench configuration, control and monitoring and quench data management. In addition, a hardware quench logic module (QLM) carries out the critical hardware-based quench logic, including protection heater control logic, CLIQ [8] control logic, power system enabling and phaseback, energy extraction system enabling and discharge control, and slow ramp-down.

## VI. QUENCH PROTECTION STUDIES

The quench protection study has been performed using STEAM-LEDET [13] on the magnet as described in Ref. [3]. The main parameters of the quench protection study are reported in Table II.

Quench protection can be provided by dump resistor only. Indeed, the calculated Hot Spot Temperature (HST), using pa-

rameters reported in Table 1, is 211 K. This result is conservative since minimum RRR and Cu/Non-Cu values have been used. The peak voltage to ground is 1 kV, assuming that the dump is middle-grounded, while peak voltage across magnet leads is 2 kV. The dump can extract 70 % of the magnet's stored energy. It is possible to reduce the voltage across magnet leads to 1 kV using a 75 m $\Omega$  dump, but this would increase the HST to 335 K and extract only 40% of the stored energy. Increasing the detection time by a factor of 3 (to 45 ms) causes an increase of ~30 K in the HST.

The dump-resistor-only quench protection system is not, however, redundant. In the case of a dump failure, the magnet is completely unprotected. In this case, a CLIQ unit can be added to the quench protection system to provide redundancy. Indeed, using the parameters reported in Table II, including those related to the CLIQ unit, the HST can be reduced to 185 K. If the dump resistor works correctly, CLIQ reduces the HST to only 25 K, but in case of a dump failure the HST with CLIQ-only protection is 330 K. Therefore, the use of CLIQ by itself can preserve the magnet from quench damage in case of dump failure. However, CLIQ can increase the peak voltage to ground up to 2 kV depending on the coil's electrical ordering and the position of the CLIQ leads. It is possible to reduce the peak voltage to ground back to 1 kV by optimizing the coil ordering and the position of the CLIQ leads. This leaves CLIQ completely ineffective when the dump resistor works correctly (no reduction of HST in that case) but allows it to be used as a backup quench protection system in case of dump failure.

## VII. CONCLUSION

Fermilab is building a new high-field cable-testing facility with a capability similar to the European facilities EDIPO and FRESCA2. This facility will serve two US national programs within the DOE Office of Science, the Magnet Development Program and the US fusion energy science program for testing HTS samples in a 15 T field. For the Magnet Development Program, this facility will make it possible to test hybrid magnets built on LTS and HTS superconductors – an important step toward the 20 T dipoles to be used in future hadron-hadron colliders.

The civil engineering of the HFVMTF pit is finalized and construction has begun. To protect SRF stands that are sensitive to fringe magnetic fields, it was necessary to incorporate a system of cylindrical carbon steel shields. The cryostat design is in the preliminary phase and it is expected that it will be finalized in the following months. The QPM system is fully designed and will be manufactured in late 2021. After this step, we will begin the commissioning of the facility.

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