

# A Test of a 2 Tesla Superconducting Transmission Line Magnet System

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**Abstract** — *Superconducting transmission line magnet test system for an injector accelerator of a staged VLHC proton-proton colliding beam accelerator has been built and operated at Fermilab. The 1.5 m long, twin-aperture, combined function dipole magnet of 2 Tesla field is excited by a single turn 100 kA transmission line superconductor. The 100 kA dc current is generated using dc-dc switching converters powered by a bulk 240 kW supply. A pair of horizontally placed conventional leads facilitates transfer of this current to the magnet transmission line superconductor operating at liquid helium temperature. Fabrication of magnet components and magnet assembly work are described. The magnet test system and its operation are presented, and the performance is summarized.*

**Index Terms** – Accelerator magnets, system test, superconducting transmission line magnet

## I. INTRODUCTION

In a quest for understanding the fundamental interactions of elementary particles, a higher and higher energy of collisions between quarks is required. This in turn leads to the design of larger and larger circular (for protons) and linear (for electrons) accelerators. As the useful dynamic range of magnets in the proton accelerators is rather limited the desired energy of proton collisions is achieved through accelerating beams in a sequence of circular accelerators, each operating in its most suitable magnetic field regime. In the VLHC design [1], the injector accelerator (VLHC Stage 1) was to produce 20 TeV proton beams to be injected to the VLHC second stage of 120 TeV proton beams. With the circumference 230 km for VLHC, the 2 Tesla magnets are needed in the first stage, and the 12 Tesla magnets in the second one. With a very limited space in the accelerator tunnel, the goal was to design the Stage 1 magnet that would use a smallest possible

space, and could be manufactured in a large scale at a very low cost. A first proposal of such a magnet design has been discussed in [2]. In this paper we present a new mechanical design of the magnet and a new design of its drive conductor, including the fabrication and assembly work of both. We describe and discuss the assembly and the performance of magnet test system which comprises of the prototypes of all the basic components envisioned in [1] for the VLHC Stage 1 magnet and its operation.

## II. FABRICATION OF TEST MAGNET COMPONENTS

### A. Magnet Mechanical Design

The conceptual mechanical design of the VLHC Stage 1 main arc dipole magnet is shown in Fig. 1. The magnet features 2 pole gaps between top and bottom half-cores with

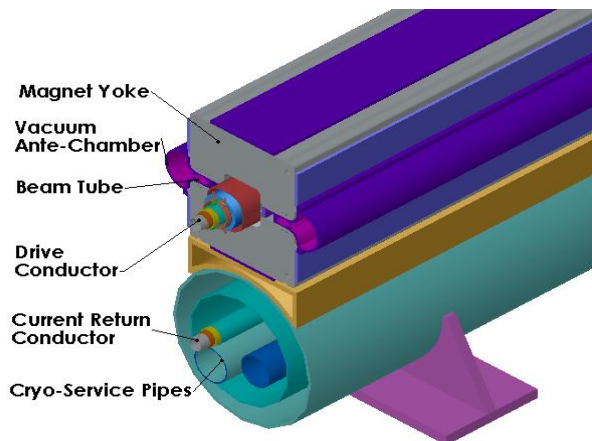


Fig1. The VLHC Stage 1 arc dipole magnet as proposed in [1].

magnetic field induced by a 100 kA dc current from a single conductor line located in the center of the half-cores assembly. As the magnetic fields in the pole gaps are of opposite directions to each other, same charge particles circulate in the opposite directions, a requirement for the accelerator with the colliding beams. The VLHC Stage 1 magnet is a combined function gradient dipole with two half-cell versions (focusing and de-focusing) interchangeably placed along the accelerator ring. The half-cell VLHC magnet is 64 m long and it features beam gaps of 2 cm height which satisfy the VLHC Stage 1

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accelerator design. The small beam gap sets a strain on the beam pipe vacuum system design. With the warm beam pipes the necessary vacuum level can only be achieved with the ante-chambers attached to the beam pipe along its entire length as shown in figure 1. The magnet assembly is supported by a large vacuum pipe which also houses the return conductor and the multiple cryogenic support pipes.

### B. Magnet Transmission Line Superconductor

With such a small pole gap it is the size of the conductor assembly that significantly determines the magnet cross-section. Consequently to minimize the cost of the laminations we minimized as much as possible the cross-section area of the transmission line conductor. With the standard 0.65 mm NbTi strand, 288 strands are needed to sustain the 100 kA current at the temperatures of up to 6.5 K (2 K safety margin relative to the 4.5 K of the liquid helium coolant). Multiple Rutherford cables, or 288 strands arranged in a single braided cable can be used. In tests, both arrangements produced nearly identical results but due to simple assembly work we have chosen the braided cable shown in Fig. 2. A perforated

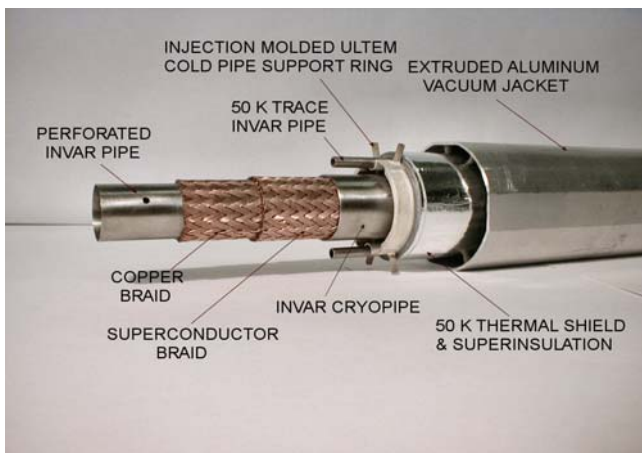


Fig.2. Transmission line superconductor assembly as used in the magnet test.

invar pipe of 25 mm diameter serves as a liquid helium flow channel. The copper braid (48 crossing bundles of five, 0.6 mm wires) is placed directly on the invar pipe and provides a copper balance for the superconductors. The conductor braid is arranged in 48 crossing bundles of 6 strands each, and it fits tightly on the copper braid. The invar cryopipe is slid over the conductor braid and then the inner invar pipe is swaged-up by  $\sim 1$  mm with by passing through a sequence of the carbide steel balls to firmly secure the conductor inside the cryopipe. The conductor cryostat, however, of at least 80 mm in diameter is needed to provide space for the cold pipe support rings, the 50 K shield with two trace tubes, and the aluminized Mylar multilayer super-insulation. The cold pipe support rings with 4 pegs position the conductor centrally in the cryostat of a near hexagonal form helping to prevent conductor axial rotations. A molded ULTEM material was chosen for the fabrication of the support rings due to very low cost of

production. At liquid helium temperature, however, the pegs shrink by about 0.1 mm (or  $\sim 5\%$ ) each. A compression of 200 kg/m on the pegs is needed to compensate for that shrinkage, and so to insure the conductor support inside the cryostat after the cool-down. This pressure is generated by squeezing the conductor cryostat's top and bottom walls with the half-cores during the magnet assembly procedure (see below). A very careful design of the support rings was needed to achieve the required pegs compression without breaking the pegs during the magnet assembly process which uses at least 20 times higher compression force. The liquid helium liner and the cryopipe are both made of invar (36% Ni steel) to minimize the conductor line shrinkage due to cool-down from room temperature to 4 K. The vacuum jacket is extruded aluminum thus allowing for a formation in a near hexagonal form which prevents axial rotation of the support rings, and fixes the position of conductor cryostat inside the magnet half-cores.

### C. Magnet Half-Cores

It was shown in the magnetic design study [2] that with the 80 mm x 80 mm center space for the conductor area the minimum half-core lamination size to produce good quality of magnetic field in a 20 mm x 20 mm pole gap is in the range of 12 cm (height) x 24 cm (width). This makes the total magnet cross-section area of about 26 cm x 24 cm. In the test magnet the field saturation effects were controlled by set of 4 holes of specific shapes and sizes [3] placed in each of the magnet poles. The necessity of having these holes and the overall subtle profile of the magnet poles were used to justify fabrication of the half-cores out of 1 mm thick laminations.

## III. MAGNET ASSEMBLY TECHNIQUE

The necessity of leaving the outside space for the vacuum ante-chambers does not allow for using the outer walls of the half-cores to weld fixtures that would hold the magnet assembly together. As a result of this situation, the interior area of the half-cores (where the conductor cryostat resides) must be used for welding of the half-core connecting plates as indicated in figure 3. We found in tests that with the laser welding the damaged area of the lamination due to generated heat is small (2 mm wide x 3 mm deep) and it can be precisely controlled even in mass magnet production. Consequently, the sensitive areas at the magnet poles are not affected. The magnet assembly is as follows: (1) two connecting 316L steel plates are welded into a dent on each side of the bottom and top half-core, (2) the half-cores with conductor line and 316L steel spacer bars (20 mm height x 8 mm wide) are stacked

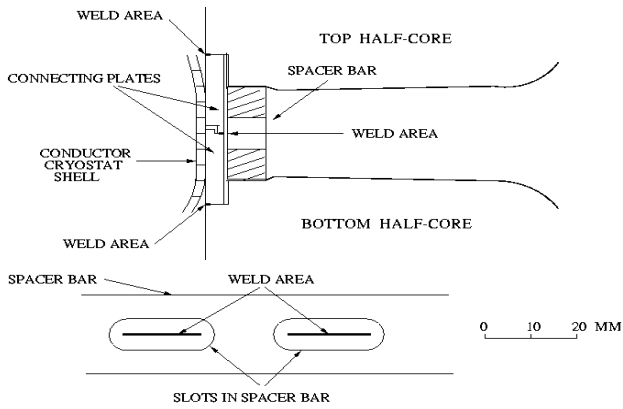


Fig.3. Arrangement to weld the top and bottom half-cores into a magnet.

together with a help of a key feature in both top and bottom connecting plate, (3) the whole magnet assembly is placed inside a 5 Ton/m press which is made of two 40 mm thick plates with bolts spaced every 120 mm, and (4) the half-connecting plates are welded together through the staggered slots in the spacer bar. The actual welding of the magnet is shown in Fig. 4. In addition to holding the magnet together



Fig.4. Welding of magnet assembly. Magnet is stationary; laser gun operation allows for automated skip welding through the spacer bar slots and bypassing the press fixture bolts.

the fusion welding of the half-connecting plates induces a significant pre-stress on the spacer bars. This pre-stress is a result of the metal shrinkage in the welded area, and the goal is to induce a stress that leaves the spacer bars in the compression saturation state. This in turn will make negligible potential vertical changes of the pole gap while energizing the magnet. The tests using compression sensors and torque measurements of the press bolts have shown that the welding indeed has induced additional compression of  $\sim 10$  Ton/m, leading to a total tension on the spacer bars of  $\sim 15$  Ton/m, and thus well inside the saturation zone. Consequently, the additional tension of  $\sim 3$  Ton/m induced by energizing the magnet to a 2 Tesla field is not expected to compress spacer

bars any further.

#### IV. MAGNET TEST SYSTEM AND ITS OPERATION

The test system arrangement comprises of a 1.5 m long test magnet, the 100 kA dc current supply, the 100 kA current leads, the cryogenic support system, and magnetic field measuring instrumentation. The power supply, the current leads and their operation are presented in [4–5], while the instrumentation and magnetic field measurement results and analysis are presented in [3] and [6]. A simplified schematic of the current flow to energize the magnet is shown in Fig. 5. The bulk 240 kW power supply provides 600 A  $\times$  400 V output current which is split in the Filter unit into ten output lines of 60 A  $\times$  400 V. These lines are fed to ten Rectifiers, each producing 10 kA  $\times$  1.5 V currents. These currents add-up to 100 kA current in large 2 copper half-moons (for input

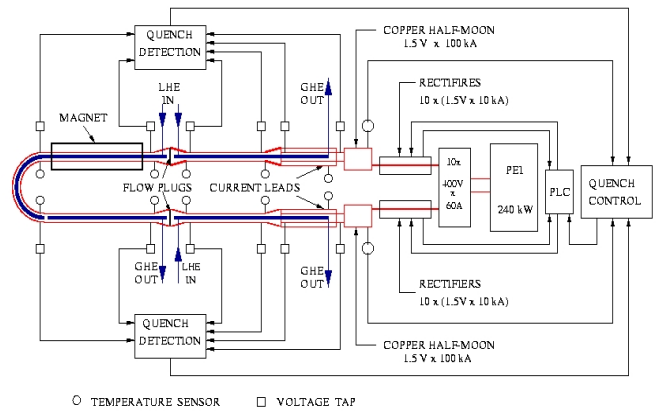


Fig.5. A very simplified schematic of magnet current flow arrangement (red lines), and power supply controls with quench detection system (black lines). The three two-phased liquid helium flows for cooling conductors and current leads are also indicated (blue lines).

and return currents) which form the warm ends of the current leads. There are two flow plugs in the conductor lines between the magnet and the current leads allowing for three independent liquid helium flows (two for each current lead, and one for the magnet conductor loop) as indicated in Fig. 5. The conductors between the flow plugs and the current leads are bent at 90 deg. angle (not indicated on the figure), so the magnet is positioned perpendicularly to the leads. This minimizes pulling force on the conductor ends at the current leads resulting from the considerable shrinkage of the lead's copper rods during the cool-down process. At the flow plugs we use an assembly of nine Rutherford cables instead of the braided cable. The flow-plug Rutherford cables are placed over a larger diameter of perforated pipe allowing for liquid helium in and out of the cooling channel, and also for the instrumentation lines to pass through. There are 4 conductor splices, all between the braided and 9 Rutherford cables and 2 splices between 9 Rutherford cables and current leads cold ends. The cool-down of the magnet conductor and the current

leads is monitored by multiple temperature sensors. The voltage taps are placed about 2 m apart along the entire current path. The cryogenic system is connected to the conductor lines and current leads through ceramic breaks for electrical isolation. We found that short (5 seconds) injections of up to 500 A current did not raise conductor temperature much even with only room temperature gaseous helium flow as the cooling medium. Consequently we used the periodic current injections to monitor the voltage rise on the taps to measure the resistance of the conductor loop and the leads. Eventually passing to the superconducting state in the conductor loop was observed, and the sequence of magnetic measurements at various currents has began. The total resistance of the system (transmission line conductor 12 m, and each lead 1.65 m) at room temperature was found to be 1720 micro-ohms. When the system was cold (30-50) K, but not superconducting, the total resistance was 18 micro-ohms. In the superconducting state there was only resistance of leads of  $\sim 0.5$  micro-ohms each, generating total dissipating power of 4 kW at 90 kA current. As about 6 g/s liquid helium flow per lead was required to keep the cold end of the current lead in the superconducting state the warm ends grew ice balls with no current flow. Consequently, matching 4 kW heaters were placed at the half moons to minimize growth of the ice-ball which otherwise would affect the entire vacuum of the magnet test system due to multiple O-ring seals at the warm ends of the current leads. A two-phase liquid helium flow into



Fig.6. A view of the magnet test system. From left to right: 180 deg. return conductor, magnet with field measuring instrumentation, liquid helium feed & instrumentation tower, and 90 deg. bent conductor followed by current leads and assembly of rectifiers.

the magnet conductor loop and current leads was supplied from four 500 l dewars which allowed for 1 hour of tests at the superconducting state after 3 hours of cool-down. In the VLHC design the supercritical helium at 4.5 K, 4 bar pressure, and 60 g/s flow will be used providing at least 20 times more cooling power. As the magnet was energized to higher currents the power dissipation at the leads was raised the warm-ends temperature which affected the resistance of the

system and so the load to the power supply. This made the programming for the desired current value of the next test a time consuming process. In order to save the overall time, we conducted tests using very quick ramping times of 2500 A/s, and short flat tops of (5-10) s, which were sufficient to perform magnetic measurements. This allowed for taking some 20 magnetic field data points for the values of the superconducting current between 5 kA and 100 kA during one cool-down session. Magnetic measurements with 102 element hall probe station and tangential coil were performed simultaneously in all tests.

## V. SUMMARY

A prototype of a superconducting transmission line magnet system consisting of a 1.5 m long test magnet, 100 kA dc current supply and 100 kA current leads was built as envisioned in [1]. All subsystems operated successfully well into the 100 kA range exceeding safely exceeding the magnet normal operating current of 90 kA [4-5]. The test magnet was energized multiple times to the field of 2 Tesla, and no distortion of the welded joints at the half-core connecting plates was detected suggesting that the magnet assembly technique employed was successful. The transmission line superconductor performed as expected with the maximum observed current of 103.8 kA. All quenches at this current range were occurring consistently at the magnet return conductor line where the liquid helium cooling was least effective. As shown in [3] and [6], the measured magnetic field properties that extend up to 10<sup>th</sup> order of harmonic multipoles are within the range expected for the VLHC Stage 1 accelerator magnet, both at the full field of 2 Tesla, and at the beam injection field of 0.1 Tesla.

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