The 100 kA VLHC Transmission Line Magnet Superconducting Cable Test Facility

G.W.Foster, V.S.Kashikhin, E.Malamud, P.Mazur, A.Oleck, H.Piekarz, J.Fuerst, R.Rabehl, P.Schlabach, J.Volk

Fermi National Accelerator Laboratory, Batavia, IL, 60510, USA

Abstract – **A superconducting transmission line magnet test facility was built and commissioned Fermilab. The test facility is capable of generating a 100 kA current in a 17-meter length short-circuited superconducting loop, as well as driving 15m long test magnets. The current is excited by a room temperature primary winding and iron yoke operated as a current transformer. This approach avoids the expense and difficulty of 100kA current leads, and allows the facility to be Dewar-based. The loop has a replaceable superconductor section 4m long for testing various types of VLHC transmission line cables. The system design, 3D magnetic field analysis, magnetic force distribution and test results are discussed.**

I. Introduction

The Transmission Line Magnet [1,2] is a warm-iron single-turn 2-in-1 double-C magnet built around an 80-100kA superconducting transmission line. It is being developed at Fermilab as a cost-effective approach to the Very Large Hadron Collider (VLHC). To minimize costs and simplify cryogenics the transmission line uses NbTi conductor operated at 6.5-7K maximum temperature. Other conductors including NbAl [3] will also be tested. The system described here was built to test superconducting transmission line samples as well as to drive short ~15m prototype magnets.

A superconductor test facility (Fig.1) has been built and commissioned which is capable of generating a 100 kA current in 17-m length short-circuited loop. This is a scale-up of a smaller prototype[4] which attained 43kA. A conventional room temperature magnet with large iron core was used as current transformer. The current transformer has a water-cooled copper primary winding of 96 turns of 2.4kA and a short-circuited single turn superconducting secondary. The primary coils and yoke were obtained by converting an existing BM-109 beam line magnet from an "H-magnet" configuration to a toroidal configuration. This Test Facility was constructed during 1998-9 and tested at slightly above the design current of 100kA. The Test Facility passed two successful test runs and the results of these tests are discussed below.

II. Principle of Operation

The superconducting current transformer principle on which the test loop operates is that *the total flux connected with the superconducting winding is permanently frozen in at the time that the loop becomes superconducting.* Since the iron yoke which links both the primary and secondary windings is relatively easy to magnetize, any changes in the amp-turns of the primary must be compensated by equal and opposite change in the amp-turns of the secondary. In an ideal case the total current (ampere-turns) in primary should generate the same current in the secondary (superconducting) loop. The 96:1 primary:secondary turns ratio allows a current step-up from 1.5kA to over 100kA. Since no flux can escape from the superconducting secondary, the system is DC coupled and the secondary current can be maintained indefinitely.

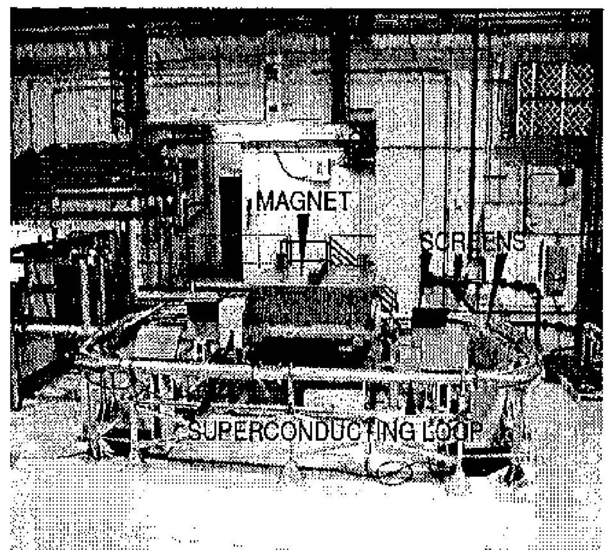

Fig.1. 100kA Superconductor Test Facility

The maximum value of secondary current depends on the flux frozen into the short-circuited loop. There are many possible variations of the initial conditions and correspondingly in the values of primary and secondary currents. The system is excited from an external beam line power supply through a reversal switch. This allows us to prepare the iron core in a state of reverse saturation prior to the point when the secondary becomes superconducting, thereby maximizing the flux swing and the efficiency of the transformer.

In reality because of imperfect coupling between the primary and secondary coils, and the large fringing flux generated by superconducting loop, the secondary current is lower than a total ampere-turns of primary. The fringing flux appears as a load inductance on the secondary. Load inductance will limit the length of transmission line magnet which can be powered from this facility to approximately 10meters.

Manuscript received September 27, 1999.
This work was supported by the U.S. Department of Energy.

III. Facility Design

The Superconductor Test Facility consists of the following components:

- A current transformer with a room temperature primary winding.
- Superconducting 17m length loop.
- Magnetic screens.
- Power supply with maximum current of ~2kA.
- Cryogenic system (LHe pump, heat exchanger, dewars, etc.)
- DAQ system.

Below we discuss only the magnet system design and the test of its components.

A. Current Transformer

The current transformer is a conventional BM109 magnet with a window frame iron core and two water-cooled coils. The coils have been reconfigured to drive the flux around the perimeter of the iron yoke instead of across the window frame gap. Both coils are connected in series and generate the circulating magnetic flux in the iron core.

The current transformer has the following parameters:

maximum current	2400 A
maximum voltage	110 V
resistance	0.0458 Ω
number of turns in both coils	96
water temperature rise	32 °C
number of parallel water circuits	12
water pressure drop	140 psi
water flow	40.8 gpm
weight	36 tons
Yoke Dimensions	
- width	2.057 m
- height	1.3 m
- length	1.83 m
- air gap for cryostat	0.177 m

The secondary winding of the current transformer is a superconducting loop. The magnetic field energy at total current in primary 150 kA is 153 kJ. The magnet inductance is 0.13 H and time constant is 2.8 sec. Both the time constant and inductance will be significantly affected by iron saturation effects and eddy currents in the solid ferromagnetic core.

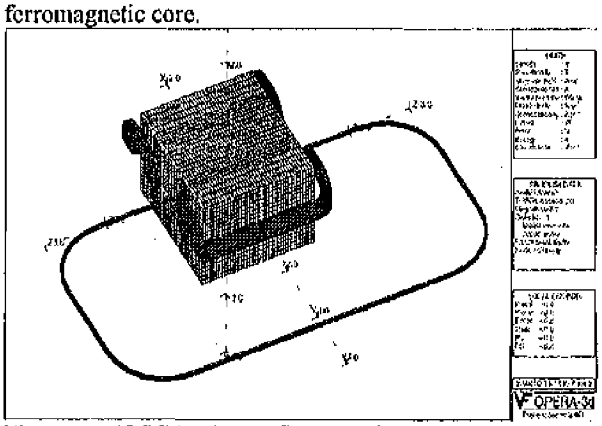

Fig.2. 3D TOSCA Magnet System View

B. Superconducting Loop

The superconducting loop is a transmission line cable designed to carry high currents. It consists of 18 SSC inner cables wound around a perforated copper tube. All cables strapped to the copper tube by several layers of copper tape. Conductor prestress and mechanical stability are provided by outer stainless steel jacket which is clamshell-welded around the conductor to form the cable in conduit structure. Dimensions of the loop are shown in Fig.2.

The SSC cable has the following parameters:

superconducting material	NbTi
copper / superconductor ratio	1.3
number of strands	30
width	12.5 mm
thickness	1.6 mm

Superconducting loop at maximum current:

maximum current	100 kA
perimeter	17 m
cross-section area	18.5 m^2
copper cross-section	463 mm^2
NbTi cross-section	235 mm^2
stainless steel cross-section	114 mm^2
self inductance	$1.6\ 10^{-5}$ H
magnetic field energy	80 kJ
(without current transformer)	
magnetic flux	1.6 Wb
maximum flux density on the conductor	1.0 Tesla
force on the conductor	64 kg/m
(two parallel conductors with distance 3.14 m)	
resistance at 20° C	0.74 mΩ
time constant at 20° C	22 msec

These parameters are correct when the current transformer is not excited and the loop parameters are defined by a self-inductance.

C. Magnetic Field Calculations

From the point of view magnetic field calculations the geometry shown on Fig.1 is unavoidably three-dimensional. The main difficulties of the calculations were to define the currents in primary and secondary by the analysis of the magnetic flux balance. The current transformer core is circuited and very quickly saturates. The entire system generates high fringing fields, which also should be calculated. These fields cause rather large forces into superconducting cable. OPERA 2D and TOSCA codes were used for the 3D field calculations.

The geometry and lattice for calculations are shown on Fig.2. The boundary conditions on the central vertical plane of the system helped to reduce twice the number of non-linear equations. There were 65520 elements and 70596 nodes in the lattice. OPERA 2D code was used for the checking 3D field calculation results. As mentioned above, the relationship between primary and secondary currents depends on the value of the trapped flux in the superconducting loop. Table 1 shows the calculated currents and energies for various values of flux initially frozen into the secondary winding.

Table 1 – Parameters for different values of frozen flux.

N	I1 kA	I2 kA	Total Energy kJ	Energy In iron kJ	Energy In air kJ	Initial Conditions *
1	150	-100	120	43	77	Zero initial currents and fields. Zero flux through loop area at max. currents
2	100	-100	75.5	1.5	74	-50 kA initial primary current & non-superconducting secondary (non-SCS)
3	150	0	153	142	11	Non-Superconducting Secondary
4	0	-100	160	94	66	-150 kA initial primary and non-SCS

The flux density component By distribution in ¼ of magnet system area is shown on Fig.3.

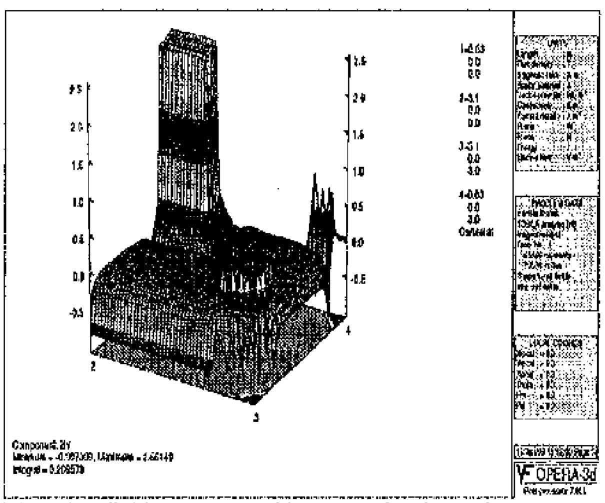

Fig.3. By field component histogram for the variant 1.

The current transformer core is saturated (2.53T) in spite of negative 100kA demagnitization current of the loop. The integrated flux connected with the loop is close to zero and it means that current transformer capable of generating the specified current 100kA in the superconducting loop.

IV. Magnet System Construction

The magnet system was built on the base of a conventional magnet having a large cross section of iron core to generate the maximum flux connected with superconducting loop. Both coils of this window frame dipole magnet were reinstalled and reconnected in such a way to produce a circuited in iron core magnetic flux. The transmission line superconducting loop goes through the magnet air gap and is short-circuited outside the magnet. The superconducting loop is attached to an aluminum support frame. Inside the loop ferromagnetic screens were installed to reduce magnetic forces applied to the superconducting cable. Three-dimensional calculations showed that without these screens the force might be more than 200kg/m, especially in the areas of the magnet ends. An optimal position of screens was calculated to minimize these forces. Because superconducting cable shrinks during cooling, the outer vacuum tube was made flexible at the corners. Two dial indicators connected through the bellows monitored the position of the superconducting cable. Another two indicators monitored the motion of outer vacuum tube. The superconducting cable is supported inside vacuum tube by 36 G-11 spiders having special configuration to reduce a heat leak.

The liquid He circulation is provided by He pump. The LHe flows through the loop, passes through a heat exchanger and returns in a pump dewar. The most complicated place in the loop is the T-piece, where LHe inlet and outlet connect with the inner LHe channel. This part of loop should pass the superconducting current but have low longitudinal thermal conductivity to lower the heat of He inlet from the outlet. Another constraint is that this part should have enough thermal mass to absorb heat during a quench. These constraints were satisfied by a structure of copper discs soldered to the superconducting cable, with G10 spacers separating these discs.

Three Hall probes were installed around the superconducting cable for current measurement. Inside the cable inner pipe 10 voltage taps were mounted. These quench detection leads were run inside the superconducting pipe so that they developed no inductive voltage as the magnet ramped, and no bucking circuit was required. One set of leads circumnavigating the circumference of the loop measured the total resistive voltage during quenches, again without need of a bucking circuit. The quench initiation system includes two heaters and a capacitor with charge/discharge system. Quenches were recorded by a LabView based DAQ system which also performed the system monitoring functions.

V. Low Temperature Tests

The Superconductor Test Facility was tested in August 1999. There were two runs to commission the cryogenic system. Here we discuss only the results of the last whole system run, when the nominal current 100kA was achieved. System cool down plus 5 induced quenches used a total of about 1000 liters of LHe. At various points the current transformer was either initially demagnetized, or driven into negative saturation to avoid hysteresis effects. The power supply reversal switch was used to stay at the main BH curve of material. The test results are shown in Table 1.

As can be seen from the Table 1, the transformer coefficient was rather stable at 91.25 +/- 2.25%. The ideal coefficient equals 96 (the number of turns on the primary winding). The lower observed value is presumably due to load inductance, iron hysteresis, and imperfect coupling.

The variations are probably due to the rather rough estimation of the secondary current from the Hall probes.

Table 2 – Cool-down and quench history.

Time	D1, mil	D2 mil	Bfi, G	I1, A	I2, KA	Ktr
11:35	16	-4.5	0.1	0	0	
13:37	16.1	-4.1	-208.5	100	-8.95	89.5
13:40	17.5	-3.5	-414.5	200	-17.8	89.0
13:42	19.2	-2.5	-629.6	300	-27.8	92.7
13:43	21.5	-1.0	-842.8	400	-36.2	90.5
13:45	22	0	-949.8	450	-40.8	90.6
14:14	19	-4.0	-7.7	0	-0.33	
14:42	22	0	-935.5	450	-40.2	89.3
Q 14:47	19	-4.0	5.4	0	0.22	
15:39	31	3.0	1190	-560	51.1	91.2
Q 15:42	19	-3.5	-	0	-	
16:24	32.5	6	-1372	650	58.9	90.6
16:45	36	7.5	-1763	830	75.7	91.2
Q 17:07	16	-3.5	6.9	-	-	
17:18	36	7.0	1802	-830	77.4	93.2
17:20	37	6.5	1957	-900	84	93.3
17:25	37	6.0	2352	-1080	101	93.5
Q 17:26	24	-3.0	-7.55	0	-0.32	
17:52	36	6.2	-1737	800	74.6	93.2
17:55	37	5.0	-2352	1080	101	93.5
Q 18:00 7.5K	6	-3.5	3.7	0	0.16	

I1 - primary current.
I2 - secondary current.
Q - quench.
D1, D2 – dial indicators of SC cable displacement.
Hfi - Bfi field component in horizontal plane.
Ktr = I2/I1 – current transformer coefficient.

Hall probes were used to measure the azimuthal component magnetic field $B\phi$ the around superconductor at various primary currents (see Table3).

Table 3- Variation of $B\phi$ around the conductor.

Angle, grad. R= 85.6 mm	I1=100 A I2=9 kA $B\phi$, G	I1=450 A I2=41 kA $B\phi$, G	I1=1080 A I2=101 kA $B\phi$, G
0	208	955	2349
45	217	980	2375
90	228.4	1013	2334
135	229.5	1030	2473
180	225.5	1028	2472
225	221.2	1005	2442
270	214.6	977	2375
315	208.3	957	2348
Bfi, average, G	219.1	993.1	2396
K=Bfio/Bfiav	1.053	1.04	1.02

These measurements showed a rather large field $B\phi$ fluctuation around an average value. At low currents this fluctuation is 5.3% and decreases to 2% at maximum current. Possible causes include a non-homogeneous current distribution between 18 parallel SC cables, inaccuracies in the mechanical positioning of the Hall probes with respect to the cold mass, or stray fields. Nonhomogeneities in the curent distribution is expected to have a small influence on the field quality of the transmission line magnet since the field is shaped mainly by iron poles. Any effects will be averaged out by the spiral wrapping of the superconducting cables in the conductor.

Measurements of a 100kA quench are shown on Fig. 4.

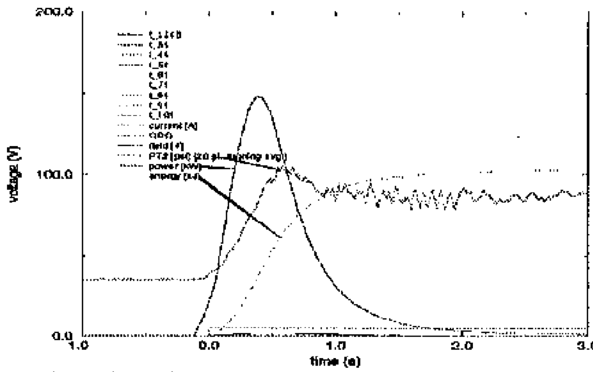

Fig.4. Quench voltage, current, resistive power, energy deposition and pressure over a 3 sec time period.

As follows from these measurements the maximum power was 150kW, pressure 100psi and dissipated energy 100kJ. These are in good agreement with calculation of the stored energy from the 3D codes, which indicate that 77kJ of air space energy and 23kJ from the iron core were dissipated in the loop during quench. (see Tab.1)

The pressure rise during quench was also in good agreement with calculations based on the time structure of the observed energy release. During 4 heater-induced quenches and a final 100kA quench induced by gradual temperature rise to 7.5~8K, the pressure stayed below 140psi and the pressure rise time before relief valve opening was in adequate agreement with the safety pressure relief calculations.

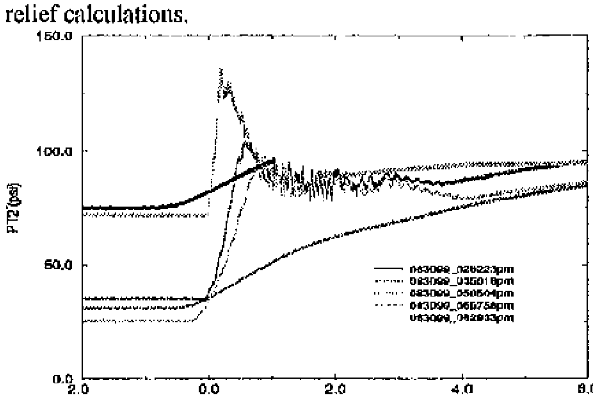

Fig. 5. Pressure rise for various quenches.

VI. CONCLUSION

The 17m Superconductor Test Facility works well at its design current of 100kA, and is ready for testing 4m superconducting cable samples and 10m test magnets.

REFERENCES

1. "The Pipetron a Low-Field Approach to a Very Large Hadron Collider", Snowmass '96, see also WWW.VLHC.ORG
2. G.W.Foster, V.S.Kashikhin, I.Novitski, "Design of 2 Tesla Transmission Line Magnet for the VLHC", (Presented on MT16 Conference).
3. E. Malamud et. al. PAC '99
4. "Design and Operation of an Experimental Double-C Transmission line Magnet, G. W. Foster, P. Mazur, T. Peterson, C. Sylvester, P. Schlabach, PAC '97.