DESIGN AND OPERATION OF AN EXPERIMENTAL "DOUBLE-C" TRANSMISSION LINE MAGNET

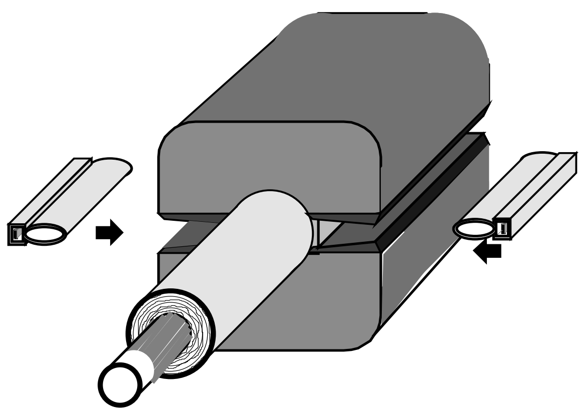
G.W. Foster, P.O. Mazur, T. Peterson, C.D. Sylvester, P. Schlabach,
Fermi National Accelerator Laboratory, PO Box 500 Batavia IL 60510

Abstract

The "Double-C" transmission line magnet is a warm-iron warm-bore single turn 2-in-1 superferric magnet designed to provide a significant reduction in magnet costs for future hadron colliders. Construction and first operational tests of a prototype magnet system are described.

1 INTRODUCTION

The transmission line magnet development program[1] has the goal of demonstrating a magnet with construction and operating costs (per Tesla-meter) which are an order of magnitude below current (cosine theta) superconducting magnets.



1.1 Transmission Line Magnet Design

Fig. 1 - The Transmission Line Magnet is a single-turn warm iron superferric magnet built around a superconducting 75kA DC transmisssion line.

A "Double-C" magnet yoke placed around the transmission line provides twin gaps with opposite bend fields for two counter-rotating proton beams. Alternating gradients of the iron pole tips eliminate quadrupoles and most costs associated with magnet ends. The current is returned in a cryogen distribution line located nearby.

Other design features include:

- Crenelated iron pole tips[2] which maintain acceptable field quality up to ~2 Tesla in an alternating-gradient design.
- An peak operating field at the conductor of ~0.8T. This translates to a very high current density and/or a high allowable operating temperature. Superconductor costs (for today's NbTi conductors operated at 7K) are in the range of $1M/TeV.
- A very simple and low heat leak cryogenic structure[3] from the transmission-line geometry. This translates into low cryogenic operating costs.
- A small cold mass (0.7kG/m or ~7 tonnes/TeV).
- An absence of large cold-to-warm magnetic forces due to the symmetry of the "Double-C" design.
- An Invar cryogenic pipe for the center conductor which eliminates bellows for thermal shrinkage.
- An inexpensive warm-bore vacuum system [4,5] using extruded aluminum and NEG pumping.
- Low Magnetic Stored Energy (60MJ/TeV). This translates into small power supplies for ramping and a simple quench protection system [6].

2 PROTOTYPE SYSTEM

In the last year a proof-of-principle 50kA Transmission Line Magnet system was constructed. To avoid the cost and complexities of high current leads, a current transformer approach with a floating superconducting secondary loop was used. The "Double-C" iron structure was mounted on the 5m long secondary loop which served as both the experimental transmission line and the curent return.

2.1 Current Transformer

The current transformer yoke was the iron structure from an accelerator magnet. The primary windings were the 24 turn x 2.5kA water-cooled copper windings of that magnet. The copper windings were driven by a 15V 2.5kA conventional SCR power supply.

Under ideal conditions a single turn shorted secondary should develop 24 x 2.5kA = 60 kA according to the turns ratio of the current transformer. Nearly ideal coupling can be expected as long as the iron yoke of the transformer does not saturate. The current at which the yoke saturates depends on the inductance of the load plus the stray inductance of the secondary loop. Calculations of the expected electrical and magnetic behavior of the prototype are detailed in [7].

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2.2 Superconducting Secondary

The superconducting secondary consisted of 7 turns of surplus SSC dipole inner coil cable, and was located in a loop cryostat 5m long which serves as the prototype transmission line. The SSC Cable was looped through the cryostat 7 times and then spliced to itself by soldering over a length of ~40cm. This approach reduced the effective resistance of the joint by a factor of seven, since the current only passes through the splice every 7^{th} time around the loop. An L/R decay time of order 10 hours is expected for the current in the superconducting secondary.

The superconductor was supported inside the 2.5cm diameter helium cryopipe at ~10cm intervals by UHMW form-fitting spacers which were clamshelled around the conductor and tied in place by twisted steel wire. Less than 10% of the cross sectional area was available for helium flow.

The superconducting line is supported in symmetric positions and accurately centered in both the transmission line magnet and drive transformer to avoid large magnetic forces. The drive transformer has a pair of copper primary coils which are placed on either side of the superconducting secondary to maintain the symmetry. In the “Double-C” magnet the conductor experiences nominally zero force but a decentering “negative spring constant” of approximately 100 kgf per mm of displacement per meter of transmission line. In the drive transformer the decentering force is about half of this.

2.3 Cryogenic System

The system consisted of a loop cryostat cooled by a convective “bubble pump” from a 30” high x 12” diam. LHe filled Dewar at one end. Liquid Helium enters the loop from the lower end of the Dewar, is heated (and perhaps vaporized) by the heat leak along the length of the transmission line loop. Bubbles travel upward in the U-turn region at the far end of the loop, and 2-phase flow is forced back out the top (return) half of the loop and back into the Dewar. The flow is convective and needs no special pumps, etc. for a system of this size.

The loop cryostat consists of a 2.5cm diameter Helium-filled stainless cryopipe with a 180-degree bend at the far end (5m from the Dewar). The 180-degree bend used a rigid U-tube 60cm in diameter. The cryopipe was enclosed in a vacuum jacket consisting of 2.5” stainless pipe and a 4” diameter flexible stainless bellows hose in the region of the U-turn. The cryopipe was superinsulated and supported from the vacuum jacket by G-10 “spiders”. The spacing of the supports was ~30cm along the length of the cryopipe and ~15cm in the region underneath the test magnet where conductor forces are greatest.

Helum was provided to the system from a 500L Dewar. Liquid level in the experimental Dewar was monitored by a superconducting liquid level probe which was also used to control the automatic transfer system.

2.4 Instrumentation

Temperature measurements were made 3 places along the loop cryostat and two places inside the Dewar using. Pressure in the Dewar was logged and there were 4 voltage taps on the 7-turn winding for quench detection and studies.

Current in the secondary was monitored with a Hall probe fixtured ~10cm away from a clear section of the drive conductor. A secondary Hall probe was used to monitor the field in the gap of the test magnet as well as various stray fields which were monitored for safety reasons.

Rapidly changing data (currents, voltages, pressures) were logged with a Sony DAT data logger. Slowly changing data (temperatures and fill levels, etc.) were logged using a computerized slow-scan system from Fermilab’s Magnet Test Facility.

3 PRELIMINARY TEST RESULTS

The initial running of the prototype took place a few days prior to this conference (PAC97).

3.1 Cool Down of Loop Cryostat

Cooldown began by initiating a transfer of liquid helium into the dewar at room temperature. A liquid level was quickly established and regulated ~60cm above the bottom line of the loop cryostat (i.e. near the level of the return line of the loop). Cooldown of the loop was initially very slow. After 3½ hours the far end of the loop cyostat was still at room temperature as the “cold wave” propagated slowly down the lower half of the loop. Shortly after this the cold wave reached the far end of the loop, travelling at ~2m/hr. as it passed the temperature transducers at the turnaround. The cooldown of the top (return) half of the cryoloop was much faster, taking only ~1/2 hour for the entire 5m return leg to reach 4.3K.

The system operated very stably after initial cooldown had been achieved. Recovery following quenches was also rapid (<2 mins), indicating that the convective flow, once established, has significant excess capacity to keep the system cool.

3.2 Electrical and Magnetic Measurements

The magnet was cooled down with the power supply off, so that nominally zero flux was trapped in the superconducting loop. The primary was then energized to various DC current levels and the currents and magnetic fields were observed. At low excitation (10kA of secondary current) the expected 24:1 current transformer ratio was observed. The transfer function between transmission line curent and B-field in the gap of the Transmission Line Magnet structure was measured to be 25kA/Tesla and agreed with calculations. Stray fields were recorded for ES&H reasons and agreed with estimates based on 2-d calculations.

In the initial running of the prototype the iron size of the coupling transformer yoke limited the circulating current in the secondary to 25kA. This behavior was calculated in advance, and served the useful side purpose of limiting the maximum energy which could be transferred to the cryogenic system until preliminary tests were completed. A larger transformer yoke is under construction which should allow us to reach the full 50kA/2T design goal in the next run.

3.3 Quench Behavior

At full current in the prototype, the SSC Cable used for the conductor is being run at a small fraction (~20%) of the nominal short-sample current carrying limit at 4.3K and 1 Tesla. However, there were (and are) concerns due to the fact that the conductor is very loosely clamped in the transmission line cryopipe, which could make the device prone to quenches induced by mechanical motion of the drive conductor. Thus the quench behavior is interesting even at the half-current tests run to date.

A conservative calculation [8] indicated a final conductor temperature following a quench of less than 300K, and hence no protection was necessary. Nonetheless quench detection and protection circuitry was included in the prototype to permit quench studies and protect against unforseen circumstances.

Two 60cm long stainless heater strips were embedded between cables of the superconducting loop and connected to Tevatron Quench Heater Firing Units to allow manual initiation of quenches. The heater units had 2/3 of the capacitance removed to limit the energy delivered to the heater tapes. In practice it was not possible to induce a quench by firing the heater tapes with the secondary current at 10kA or below. At ½ current (25kA) firing the heater tapes induced a quench which blew off only ~ 3 liters of LHe. No spontaneous quenches have been observed.

4 SUMMARY AND FUTURE PLANS

The first goal of the next run is operation of the system at the full 50kA design current. This requires a larger transformer yoke which is currently under fabrication. If still higher current is to be achieved, a polarity reversing switch on the copper primary would allow a 4 Tesla swing of the iron in the transformer yoke and a doubling of the load inductance which can be driven. The ultimate current limit of the existing setup is ~60kA given by the ideal turns ratio of the coils.

The full-current quench behavior and decay time will be studied, as well as any effects from decentering conductor forces in the Double-C magnet iron.

The present Double-C magnet iron test structure does not have contoured pole tips and hence no precision magnetic field quality measurements are planned. An interesting measurement which can be made is the ramp rate dependence of the sextupole arising from eddy currents in the solid-iron Double-C magnet yoke. This measurement is important since we anticipate substantial cost savings from using solid extruded/cold drawn steel yokes instead of laminations for the full scale machine.

A potential follow-on use of the test setup will be to evaluate persistent-current switches to extend the range of the transformer coupling technique to longer (higher inductance) prototypes. If feasible, this technique could allow dewar-based operation of prototype magnets with lengths up to ~100m.

5 ACKNOWLEDGEMENTS

The authors thank the Fermilab Technical Divison (especially B. Bianchi, J. Garvey, J. Sim, D. Sorensen, and D. Validis) and the staff of the Magnet Test Facility for their support during this project. Thanks also to M. May, D. Snee, and J. Volk of the FNAL Beams Division for fabrication Double-C magnet structure and the coupling transformer. Alvin Tollestrup is thanked for useful discussions in the initial stages of this project.

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