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CRYOGENIC CORRECTION COIL TESTING

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ABSTRACT

The lattice of the Fermi National Accelerator Laboratory's Energy Saver/Doubler contains a group of superconducting correction windings with each quadrupole which are housed in an element referred to as a "spool". There are 192 spools in the ring plus 12 special power spools which contain the main buss 5000 ampere power as well as correction elements. There will be constructed and tested 260 spools including spares of each of the eight different types. There have been 243 individual spools tested to date. During last fiscal year 188 spool tests were conducted at the test facility[1]. The spools were tested for a) high voltage integrity, b) critical transport current, c) cryogenic heat load, d) cryogenic operating characteristics, e) thermometry calibration and at another facility, magnetic field quality. Data are summarized for 288 cryogenic tests of the 246 different spools, 488 coil sets, and 1464 correction magnets.

INTRODUCTION

The eight different Energy Saver/Doubler spool types are designated by the notation TSA-ØØØ (Tevatron Spool type "A", serial number ØØØ). The correction coil package[2] types are explained in Table I. Correction coil packages are in three catagories, DSQ (dipole, sextupole, and quadrupole); OSQ (octupole, sextupole, and quadrupole); and DDQ (dipole horizontal, dipole vertical and quadrupole).

Table I
Spool Correction Elements Series

SPOOL TYPE	DSQ COILS INNER	DSQ COILS MID.	DSQ COILS OUTTER	OSQ COILS INNER	OSQ COILS MID	OSQ COILS OUT
	DSQI					
A	2P	6P	4P	None		
	DSQII					
B	S-2P	6P	4P	None		
	DSQI			OSQI		
C	2P	6P	4P	8P	S-6P	S-4P
	DSQII			OSQI		
D	S-2P	6P	4P	8P	S-6P	S-4P
	DSQI			OSQII		
E	2P	6P	4P	8P	6P	4P
	DSQII			OSQII		
F	S-2P	6P	4P	8P	6P	4P
	DSQI			OSQIII		
G	2P	6P	4P	8P	6P	S-4P
	DDQ COILS					
	DDQI					
H	2P	S-2P	4P	None		

Notes: S-Skew
2P-Normal Dipole (Horizontally bending)

Because correction elements and beam steering devices must operate in all field configurations it is necessary for the coils to be tested with all different polarities and currents. The grouping of three elements in a given package means that there are four possible polarity combinations and an infinity of Lorentz force patterns (vector cross-products of currents and fields to obtain the resulting forces) as the coils are ramped. The coil package to be qualified as a candidate for accelerator use must pass all four of the operating configurations.

The Tevatron spool types B, D and F contain pairs of "safety" leads which will carry a 5000A current for a short time to bypass a quenching string of main magnets so the machine may be ramped down without depositing the stored energy of the entire magnet ring into the cryogenic environment. The spools also contain two carbon resistors which act as low temperature thermometers for cryogenic monitoring of the liquid helium. The thermometer calibration is cross checked in the assembled spool. An insulating vacuum compartmentalizing barrier and beam tube vacuum measuring ports are also located in the spools. The main buss quench stopper and associated voltage taps (2) are located in the single phase helium box of the spool. The function of the quench stopper is to prevent a quench from moving from one cell to another along the main buss or starting at a safety lead. Many of the, as yet, only partially understood problems of operating a superconducting accelerator will be overcome by the versatility and performance range of the correction coil packages.

SPECIFICATIONS

The designed magnetic field values and corresponding measurements (shown in parenthesis) are given in Table II.

Table II
Magnetic Field Strength
and Inductances[3]

	D	S	Q	O	S	Q	D	D	Q
∫Bdl	.465	.135	.17	.081	.107	.17	.465	.53	.17
(T-m)	(.475)	(.157)	(.19)	(.84)	(.112)	(.19)	(.475)		(.19)
	.61	.18	.22	.105	.141	.22	.61	.69	.22
B(T)	(.62)	(.19)	(.25)	(.107)	(.148)	(.25)	(.62)	(.73)	(.25)
L	722	520	374	212	353	374	722	965	374
(mh)	(755)	(603)	(489)	(221)	(390)	(489)	(755)	(981)	(489)

The maximum operating current specified for the correction packages is 50 amperes in each of the coils. The minimum (standoff) voltage requirements are given in Table III.

Table III
High Voltage Test Limits and Acceptance Criteria

5μ amps = Maximum leakage current
(kV) = Maximum Voltage tested

	Atmosphere N_2	(SPT) He	Liquid He (10 psig)
Buss→Buss or Grd	3kV(3)	1.5kV(3)	3kV(3)
Coil→Coil or Grd	1kV(2)	0.5kV(2)	1kV(2)

There are 77 electrical measurements made on the typical spool, not including superconducting measurements or approximately 22,000 measurements have been taken. (This number does not include those taken by "Quality Control" during fabrication). These are recorded on a summary page which is then transcribed

*Operated by Universities Research Assoc., Inc., under contract with the U.S. Dept. of Energy.

into the computer. The original summary page is then filed away.

The superconducting performance specification requires that all current permutations for each configuration not quench for 30 seconds through one complete cycle (ie, coil polarities +++,++-,+-+,+--). The vapor cooled correction coil leads must be able to have the gas turned off with 50 amperes in all 6 coils 2 minutes without quenching an element.

PROCEDURE

The spools are electrically checked for continuity and high voltage insulation in a STP nitrogen atmosphere when they arrive at the Spool Piece Test Facility. The spools are connected in series as shown in Figure 1. At all five inter-spool connections and at the beginning and end of the spool string there are rings with calibrated carbon resistor thermometers immersed in the single phase liquid helium. These resistors are used to monitor cool down, warm up and obtain heat load data.[4] The resistors are also used to obtain intermediate temperature high voltage insulation data as well (77K helium data).

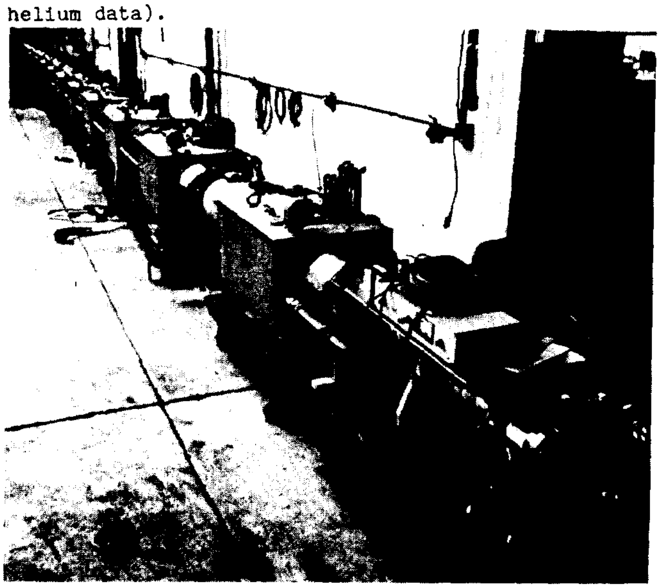

Figure 1. A Photograph of Spool Piece Facility Run #25 showing in order right to left, turnaround box, TSC 112, TSC 164, etc.

The liquid helium is pumped from a storage pump-dewar to a feed can and in turn to the single phase circuit of the spools.[5] It then goes through a "JT" valve in the turn-around box (last unit in Figure 1) and returns back to the feed can. There it can go either through or by pass a heat exchanger on its way to a satalite mode helium refrigerator which reliquefies it into the pump-dewar. One or more additional CTI 1400 helium liquefiers supply liquid to the pump-dewar. It is also possible to transfer liquid helium from external dewars into the feed can two phase return circuit. All of the electrical checks are completed when the system is circulating liquid, and then the correction coil packages are powered. All the coils of a package are individually powered to 75A. They are then powered in various polarity permutations a maximum current 60 amperes initially in each element. Qualification means that no element quenches during these polarity permutations at a qualifying current.

There have been several special tests ran for different spools, for example, the power spools TSHØØØ have their busses shorted together and the performance of the "AMI"[6] vapor cooled leads are tested with various gas flows through them using auto controllers and various power cycles. The range of stable operation is determined. The performance of a percentage of safety leads have been measured. The heat load of the run is determined during the warm up period since it was found that the longer strings are much more stable after being cold for a day.

The heat load is determined by warming the spool string up to 5K at the first spool and returning all gas back through an ambient temperature flow meter and measuring the temperature gradient across the string (Maximum spool temperature allowed is <20K). Once the string is warm the original electrical measurements are repeated to insure that nothing has changed during cryogenic testing.

Results

The summary of the test results for 288 spool tests were: 15 spool tests failed the high voltage insulation test between correction coils or correction coil to ground; 15 spools failed the high voltage insulation test between main (5000A) busses or to ground; 29 coils out of 1464 individual coils tested failed to qualify at operational current (superconducting, because of a large redundancy of coils in the spools only about 10 spools were rejected). During the 35 Spool Piece Test Facility Runs completed, there have been 4,641 quenches or 3.23 quenches per correction magnet which can be distributed to 4.9 quenches in the average coil from the DDQ package, 3.63 quenches from a coil in a DSQ package and 2.69 quenches from a coil in an OSQ package. The average qualifying current for the various packages are 58.4 amperes for the OSQ packages, 55.3 amperes for the DSQ packages, and 56.5 amperes for the DDQ package.

The heat load data is summarized in Table IV.

Table IV
Spool Heat Load (watts) at 4.2K
with a lead tower gas flow of 32cfh helium (STP).

TSA-	4.5±0.5 watts
TSB-	6.5±0.5 watts
TSC-	6 ±0.5 watts
TSD-	8.5±0.5 watts
TSE-	6 ±0.5 watts
TSF-	8 ±0.5 watts
TSH-	16 ±2.0 watts*

*This is with a 5kA power lead gas flow of 266 cfh helium (STP) for the pair (0.374 g/sec).

The TSH spools are basically similar to the TSA spools with the major exception of the 'AMI' 5000 Amp vapor cooled power lead pair. During a special test run, the load of power spool TSHØØ2 for various conditions were measured, The data are shown in Table V.

Table V
Spool TSH002 Heat Loads[7]
for Various Powering Cycles (Watts)
1 min. cycle = 20sec. up, 5sec. Max. current, 20sec. down, and 15sec. at 0 Amps.

Current (Amps) cycle (sec.)	Total lead/ pair flow cfh helium	Heat Load Watts	Maximum Volts	Time Stable (min.)
0 DC	320	12±2	0	∞
3500 DC	320	34±2	175	15
3500 1min cycle	320	18±2	75	Stable
5000 1min cycle	320	15±2	120	Stable

The size of the correction coils made it advisable to measure the energy input to the coils during a quench (superconducting to normal transition) to determine if high temperatures would result when the coils were quenched at operating levels. A correction package was modified to contain an internal heater and one on the input power leads. An adiabatic calculation done for the correction coil conductor predicted a value of 3.2 kA^2sec (KITS) for the wire to reach the solder melting temperature. The correction coils developed resistance at the rate of 0.6 mΩ/sec with 40 amperes/turn in the correction element. The rate of resistance increase would cause the coil to shut itself off under these conditions without overheating. During the course of the testing, some of the coils absorbed 3.4 KITS and without damage. It was interesting to note that, infact, after the "initiated quench" testing was over, the coils operated at higher fields than previously. In order to reach 3.4 KITS four correction coils from different spools were connected in series and then shorted after the quench was initiated in one, so that three of the coils would dump their energy into the fourth quenching coil.

The energy loss/cycle was measured for the coils electrically over a powering cycle.[8] The magnetization curve for the quadrupole coil of a DSQ set is shown in Figure 2. The area with in the curve represents 16.7 Joules.

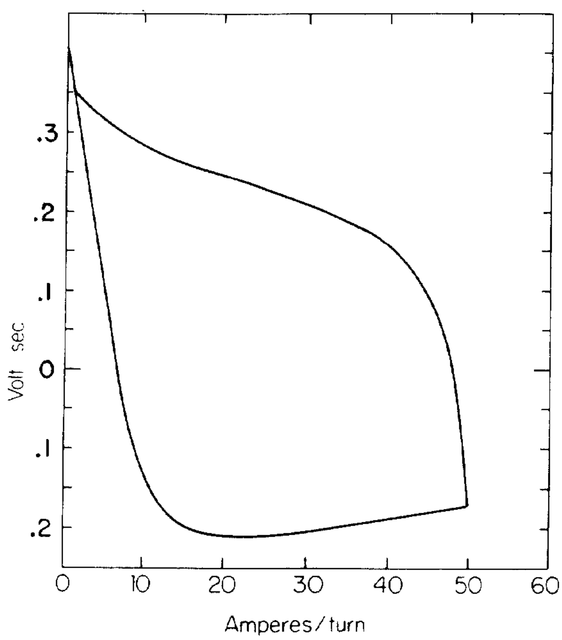

Figure 2. The energy loss curve for a quadrupole coil of a DSQ set. Area equals 16.7 joules. This is primarily due to the magnetization loss of the superconductor.

This loss is dominated by the hysteresis since the eddy currents only account for a fraction of a joule.[9]

One of the purposes of the quench stopper was experimentally checked by shorting the buss leads on both ends of the spool and mounting a heater on either joint. At currents up to 5 kiloamperes, it was not possible to propagate the quench from one end of the buss to the other buss past the quench stopper.

The harmonics of the Correction Coil elements as measured on an early coil DSQ and OSQ sets are given in Table VI.

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Table VI
Measured Harmonics[10]
for two sets of
Correction Coil Packages
(% at Measuring Radius)

*Normal / Skew

	D	S	Q	O	S	Q
Dipole*	99.96 / -2.9	-0.2 / 0.92	-2.5 / 1.1	2.5 / 1.0	-0.2 / 0.92	-0.1 / -0.14
Quadrupole	0.17 / -.005	-1.8 / -2.	100. / -0.6	-4.0 / 1.0	-1.8 / -2.0	-0.5 / 100
Sextapole	-1.2 / -0.13	99.99 / 1.4	0.51 / 0.07	-1.3 / 1.7	99.99 / 1.5	0.04 / 0.04
Decapole	-1.2 / 0.44	-/-	-/-	-/-	-/-	-/-
Octupole	1.0 / .15	-04.5 / 0.46	-0.5 / 1.3	99.97 / 2.6	-.22 / -.06	-.007 / 0.03

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