Design, construction, and performance test of MICE superconducting solenoids

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***Abstract*—The purpose of the MICE spectrometer solenoid is to provide a uniform field for a scintillating fiber tracker, and thus, it is also called tracker solenoid. The uniform field is produced by a long center coil and two short end coils. Together, they produce 4T field with a uniformity of better than 1% over a detector region of 1000 mm long and 300 mm in diameter. Throughout most of the detector region, the field uniformity is better than 0.3%. In addition to the uniform field coils, we have match coil 1 and match coil 2. These two coils can be independently adjusted to match uniform field region to the focusing coil field. The overall coil package is 2544 mm. We shall present the tracker solenoid cold mass design, the cold mass support against 50 ton axial load, the cryogen free system equipped with cryocooler, recondenser, Hi-Tc lead, and the vacuum vessel. Finally, we shall present performance test data of the MICE tracker solenoids.**

***Index Terms*— MICE, performance test, spectrometer, tracker solenoid.**

I. Magnet Design

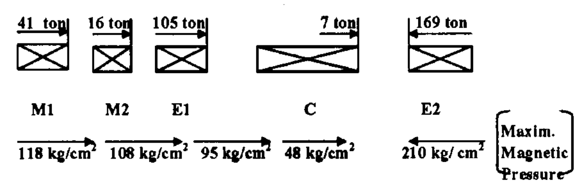
We have designed a five-coil scintillating fiber tracker spectrometer solenoid which provide a 4T uniform field over a region 300 mm diameter by 1000 m long. The uniform field is provided by a long solenoid and two end coils. Two of the five coils, M_1 and M_2 are for beam focusing match and are independently adjustable. Fig. 1 shows the on-axis field profile and Fig. 2 shows the conductor used, the peak field and the load line. The coil design parameter is shown in Table I. The axial coil force, the maximum magnetic pressure, and the maximum coil stress are shown in Table I.

The five coils bobbin is machined from a single forged 6061T6 aluminum cylinder to contain the axial load. The radial load is further supported by aluminum band of 6 to 10 mm in thickness. The helium vessel shell is made of 12.7 mm 6061T6 aluminum. Table III summarize the inductance and stored energy calculation and Table IV summaried the result of 3D quench analyses. Fig. 3 shows magnet protection design and instrumentation.

Table I Coil Design and Actual Winding Data Summary

	M1	M2	E1	CENTRAL	E2
# TURN	115	114	64	768	64
# LAYER	42	28	56	20	62
TOTAL TURN	4830	3192	3584	15360	3968
Z1 (CM)	2.3416	46.4254	90.8679	105.6851	240.8679
Z2 (CM)	22.4584	66.3746	101.9321	237.1149	251.9321
R1 (CM)	25.8	25.8	25.8	25.8	25.8
R2 (CM)	30.44825	28.86075	31.9659	28.0416	32.6263
DELTA Z (CM)	20.1168	19.9492	11.0642	131.4298	11.0642
DELTA R (CM)	4.64825	3.06075	6.1659	2.2416	6.8263

Table II. Axial Coil Force, Maximum Axial Pressure and Coil Stress



	coil	hoop stress (kg/ cm²)	compress stress (kg/ cm²)
M_1	match 1	538.8	-182.5
M_2	match 2	643.3	-124.7
E_1	end 1	834.7	-298.2
C	center	818.2	-39.6
E_2	end 2	882.7	208.9

Table III Inductance and Stored Energy

Coil	M1	M2	E1*	Center*	E2*	Total
Inductance(H)	17.47	9.59	15.39	51.58	15.91	109.94
Energy (MJ)	0.56	0.33	0.40	1.88	0.46	3.63
Operated Current	253.80	263.60	226.60	269.90	240.70	
*Total Inductance for Three Coil = 80.6700 H						

Table IV 3D Quench Analyses

Coil	M1	M2	E1	C (half)	E2
Quench time	2.4 sec	3.6 sec	4.4 sec	3 sec	4.2 sec
Maximum R	9.6 Ω	6.0 Ω	7.1 Ω	12.0 Ω	8.9 Ω
Maximum internal V	1143 V	454 V	857 V	1637 V	1094 V
Maximum temperature	135K	83K	131K	86K	155K

II. Cryostat Design

Dessign of cryostat and instrumentation is shown in Fig 4. The cryostat consists of 4.2K helium vessel, 60-80K thermal shield, and a 300K vacuum vessel. The total heat leak is shown in Table V and VI. The service tower is equipped with 3-1.5W pulsed-tube cryocoolers and 8 Hi-Tc leads to achieve zero cryogen boil off for the 5-ton cold mass magnet.

The helium vessel is designed to satisfy ASME pressure vessel code. The total liquid helium volume is about 180 liters. The helium vessel pressure rating is 45 psi. The rupture disc pressure is set at 30 psi. The relief pressure will be set at 10 psi.

The 60-80K shield is made of 6.35 mm thick 6061T6 aluminum. The shield is conduction cooled by the first stage of cryocooler. The vacuum vessel is made of 20 mm thick 304SS and is made to satisfy the ASME pressure vessel code to sustain a pressure rating of 1 atmosphere pressure. The helium vessel contains one precool tube (25 mm in diameter) and two vent tubes of 38-mm diameter each. In addition, it has a 12-mm diameter gas recovery tube and one 6-mm diameter liquid refill tube for three helium recondensers.

The service tower is designed with three vacuum insulating sleeves to allow removal of cold head for maintenance without warming up the magnet. In addition to cool the thermal shield, the first stage of the cold head is employed to cool the hot end of high –Tc lead at 60K, as shown in Photo 1. The heat leak of 60-80K shield and of 4.2K is shown in Table V and Table VI.

III. Coil Fabrication and Cryostat Construction

Photo 1 shows the coil winding fabrication and helium shell installation. The winding data is tabulated in Table I.

Photo 2 shows the cryostat assembly.

Photo 3 shows the service tower assembly with 3 cryocoolers, Hi-Tc lead, and thermal intercepts to remove I^2R and many heat sinks to the first stage of cryocooler.

Table V <u>Heat Leak to 80 K Shield</u>

(a) Heat leak through two neck tubes from 300 K through 80 K intercept = 1.888W
(b) Radiation from 300 K to 80 K for total surface area(149468 cm^2) = 10.745W
(c) Heat leak through LN2 cold mass suspension = 0.58W
(d) Heat Leak from 4.2 K cold mass suspension = 6.41W
(e) From Hi Tc lead = 91.5W

Total heat leak = (a) through (e)=111 W

Table VI Heat Leak to 4.2 K if shield is 80 K

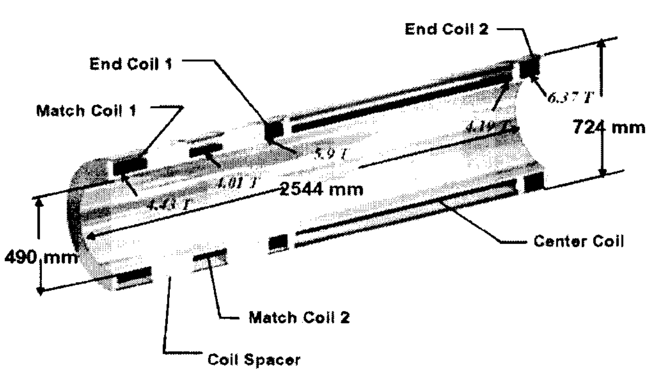
(a) Two SS neck tubes conduction from 80 K to 4.2 K =56 mW
(b) Three Cryocooler sleeve SS tube from 1st stage 60 K to 4.2 K =624 mW
(c) Radiation from 80 K to 4.2 K =31.4 mW
(d) Cold mass Suspension =308 mW
(e) Hi Tc lead – =850 mW
(f) Feedthru I^2R Joint =1440 mW

Total Heat Leak to 4.2 K 3342mW = 3.342 W

IV. Performance Test of Magnet and Cryostat

To keep thermal stress at helium shell within 10 ksi, we control cool down to 1° K per hour. After we have filled liquid helium to cover 30% of coil, we performed magnet energization test. We have energized each of five coils. Then we energized all five coils together with 10-V 500 A power supply. It takes 5 training to reach 194 A. Before airship to UK.The magnet will be warm up and then ship to Fermi Laboratory to add end iron shield to test the effect of 50 ton attractive force to complete the last 50 A energization and to perform Final Field mapping.

Fig. 1 Tracker Solenoid Peak Field And On-Axial Field Profile



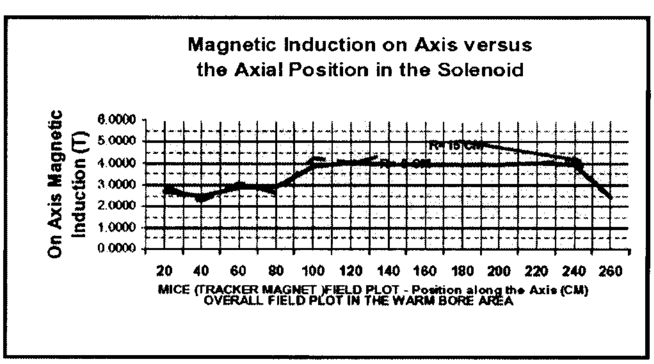


Fig. 2 Conductor, Peak Field and Load Line Design

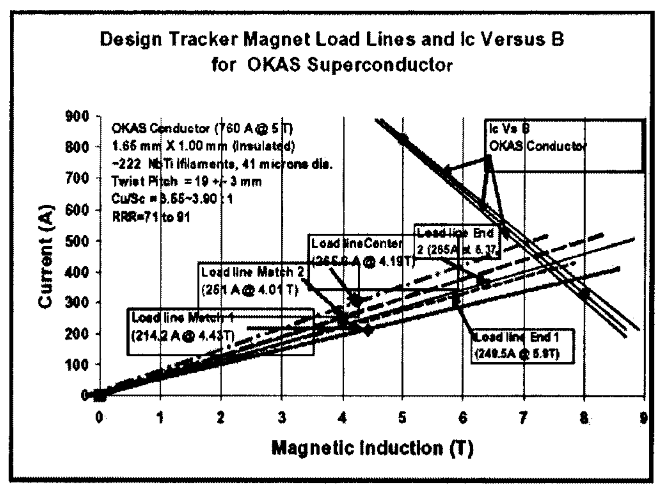


Fig.3 Magnet Protection

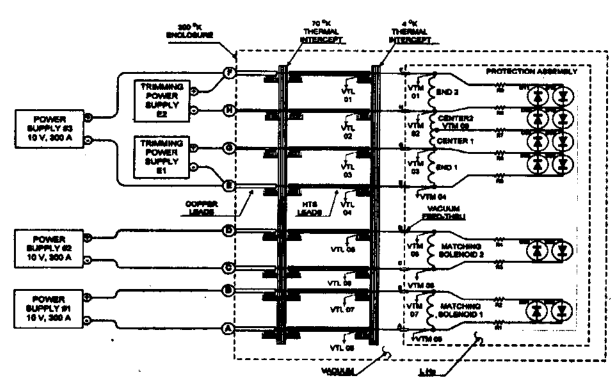
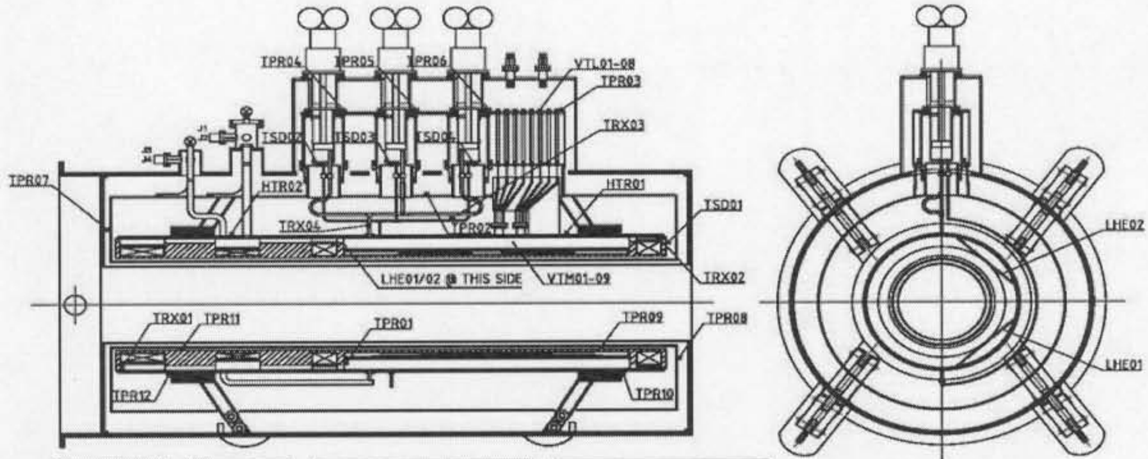


Fig.4



J1	
J1-1A	TPR01+V
J1-2B	TPR01-V
J1-3C	TPR01+I
J1-4D	TPR01-I
J1-5E	TRX01+V
J1-6F	TRX01-V
J1-7G	TRX01+I
J1-8H	TRX01-I
J1-9J	TRX02+V
J1-10K	TRX02-V
J1-1L1	TRX02+I
J1-12M	TRX02-I
J1-13N	LHE01+V
J1-14P	LHE01-V
J1-15R	LHE01+I
J1-16S	LHE02+V
J1-17T	LHE02-V
J1-18U	LHE02+I
J1-19V	COMM

J2	
J2-1A	VTM01
J2-2B	VTM02
J2-3C	VTM03
J2-4D	VTM04
J2-5E	VTM05
J2-6F	VTM06
J2-7G	VTM07
J2-8H	VTM08
J2-9J	VTM09
J2-10K	

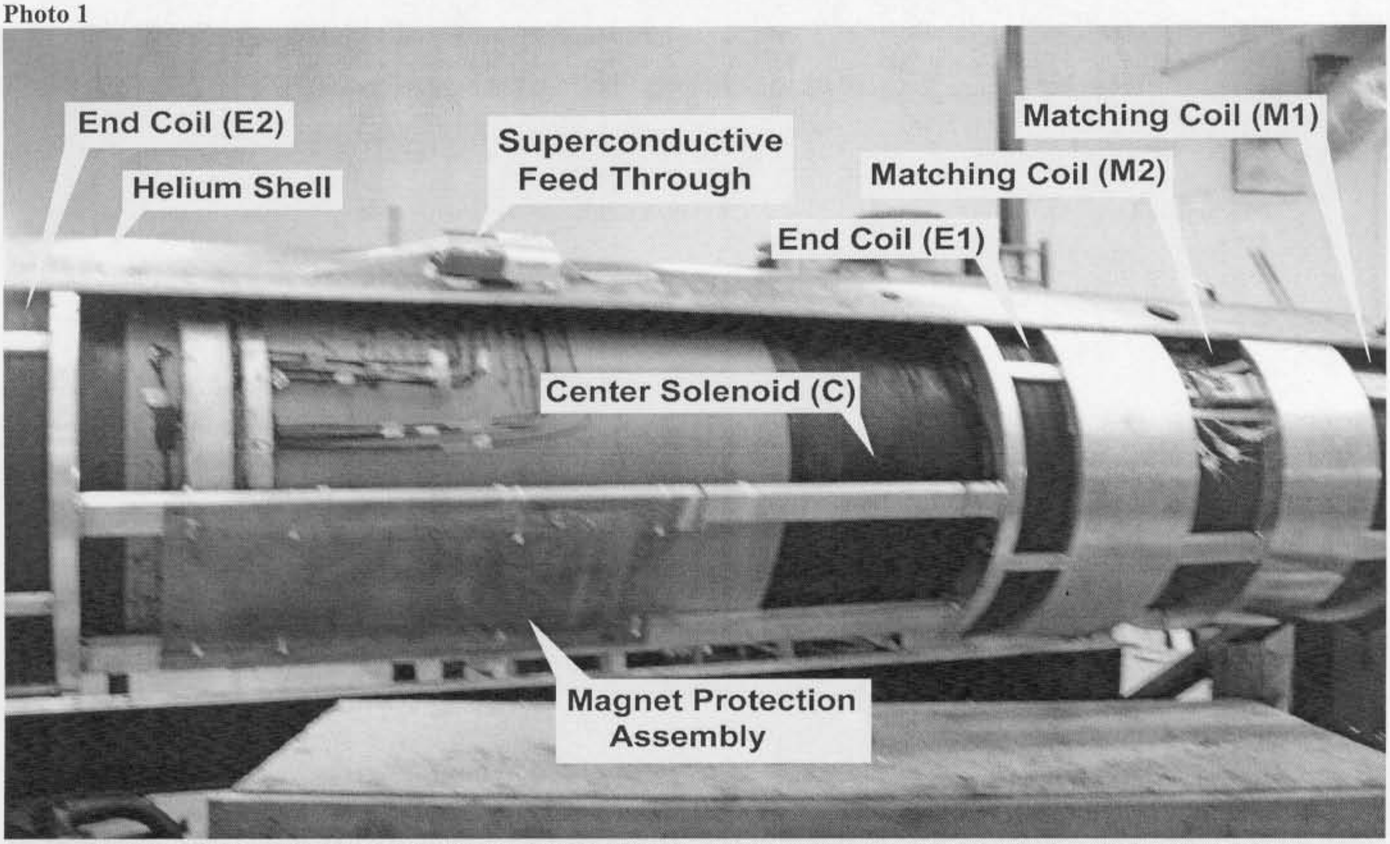
J3			
J3-1A	VTL01B	J3-21X	TPR12+V
J3-2B	VTL02A	J3-22Y	TPR12-V
J3-3C	VTL03D	J3-23Z	TPR12+I
J3-4D	VTL04C	J3-24a	TPR12-I
J3-5E	VTL05F	J3-25b	TSD01+V
J3-6F	VTL06E	J3-26c	TSD01-V
J3-7G	VTL07G	J3-27d	TSD01+I
J3-8H	VTL08H	J3-28e	TSD01-I
J3-9J	HTR01A	J3-29f	TSD02+V
J3-10K	HTR01B	J3-30g	TSD02-V
J3-11L	HTR02A	J3-31h	TSD02+I
J3-12M	HTR02B	J3-32i	TSD02-I
J3-13N	TPR10+V	J3-33j	TSD03+V
J3-14P	TPR10-V	J3-34k	TSD03-V
J3-15R	TPR10+I	J3-35m	TSD03+I
J3-16S	TPR10-I	J3-36n	TSD03-I
J3-17T	TPR11+V	J3-37p	TSD04+V
J3-18U	TPR11-V	J3-38q	TSD04-V
J3-19V	TPR11+I	J3-39r	TSD04+I
J3-20W	TPR11-I	J3-40s	TSD04-I

J4			
J4-1A	TPR02+V	J4-21X	TPR07+V
J4-2B	TPR02-V	J4-22Y	TPR07-V
J4-3C	TPR02+I	J4-23Z	TPR07+I
J4-4D	TPR02-I	J4-24a	TPR07-I
J4-5E	TPR03+V	J4-25b	TPR06+V
J4-6F	TPR03-V	J4-26c	TPR06-V
J4-7G	TPR03+I	J4-27d	TPR06+I
J4-8H	TPR03-I	J4-28e	TPR06-I
J4-9J	TPR04+V	J4-29f	TPR09+V
J4-10K	TPR04-V	J4-30g	TPR09-V
J4-11L	TPR04+I	J4-31h	TPR09+I
J4-12M	TPR04-I	J4-32i	TPR09-I
J4-13N	TPR05+V	J4-33j	TRX03+V
J4-14P	TPR05-V	J4-34k	TRX03-V
J4-15R	TPR05+I	J4-35m	TRX03+I
J4-16S	TPR05-I	J4-36n	TRX03-I
J4-17T	TPR08+V	J4-37p	TRX04+V
J4-18U	TPR08-V	J4-38q	TRX04-V
J4-19V	TPR08+I	J4-39r	TRX04+I
J4-20W	TPR08-I	J4-40s	TRX04-I

NOTE:
VTM( )=VOLTAGE TAP @ MAGNET
VTL ( )=VOLTAGE TAP @ LEAD
TPR( )=TEMPERATURE SENSOR, PT102
TRX( )=TEMPERATURE SENSOR, CERNOX
LHE( )=LIQUID HELIUM SENSOR
HTR( )=HEATER RESISTER
TSD( )=TEMPERATURE SENSOR, SI DIODE

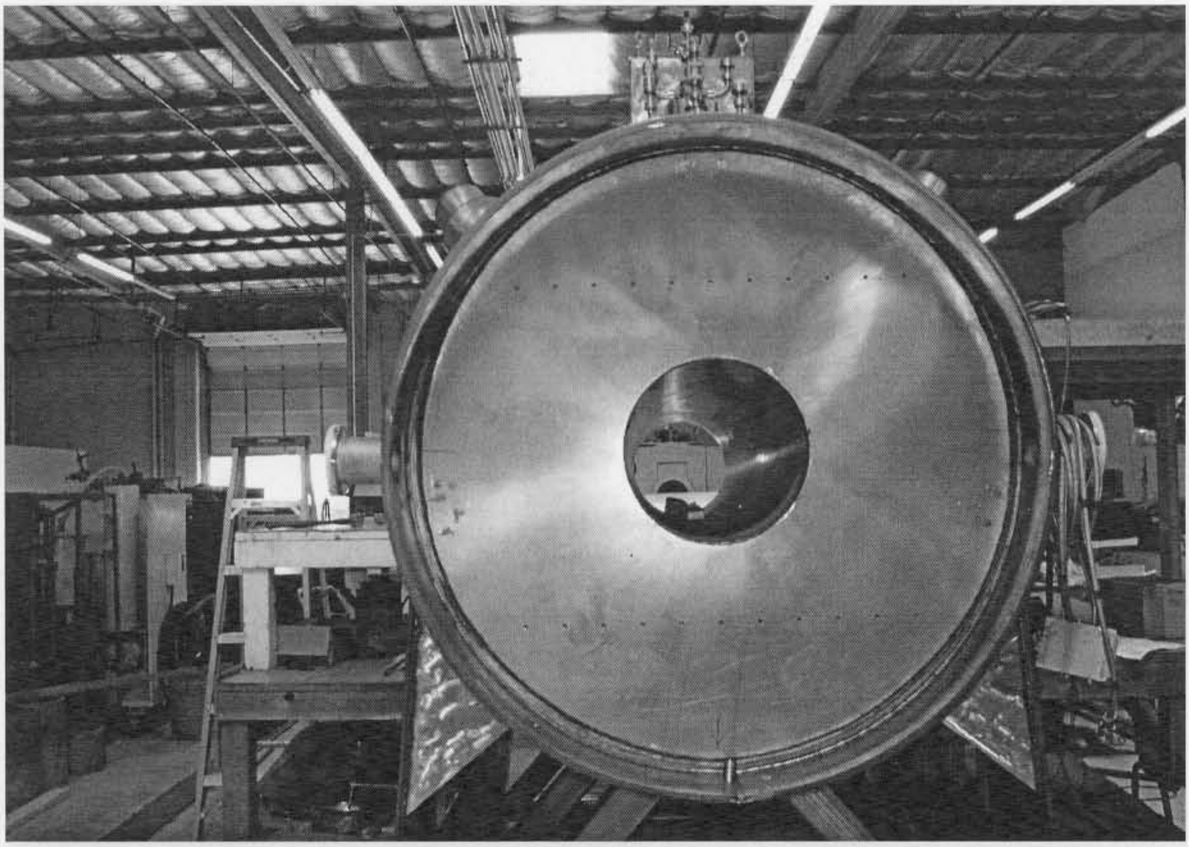
TRACKER #1 SENSOR SERIAL		
TRX01	TPR06 P13641	TSD03
TRX02	TPR07 P13605	TSD04
TRX03	TPR08	
TRX04	TPR09	
TPR01	TPR10	
TPR02 P13640	TPR11	
TPR03 P13639	TPR12	
TPR04 P13195	TSD01	
TPR05 P13209	TSD02	

Photo 1



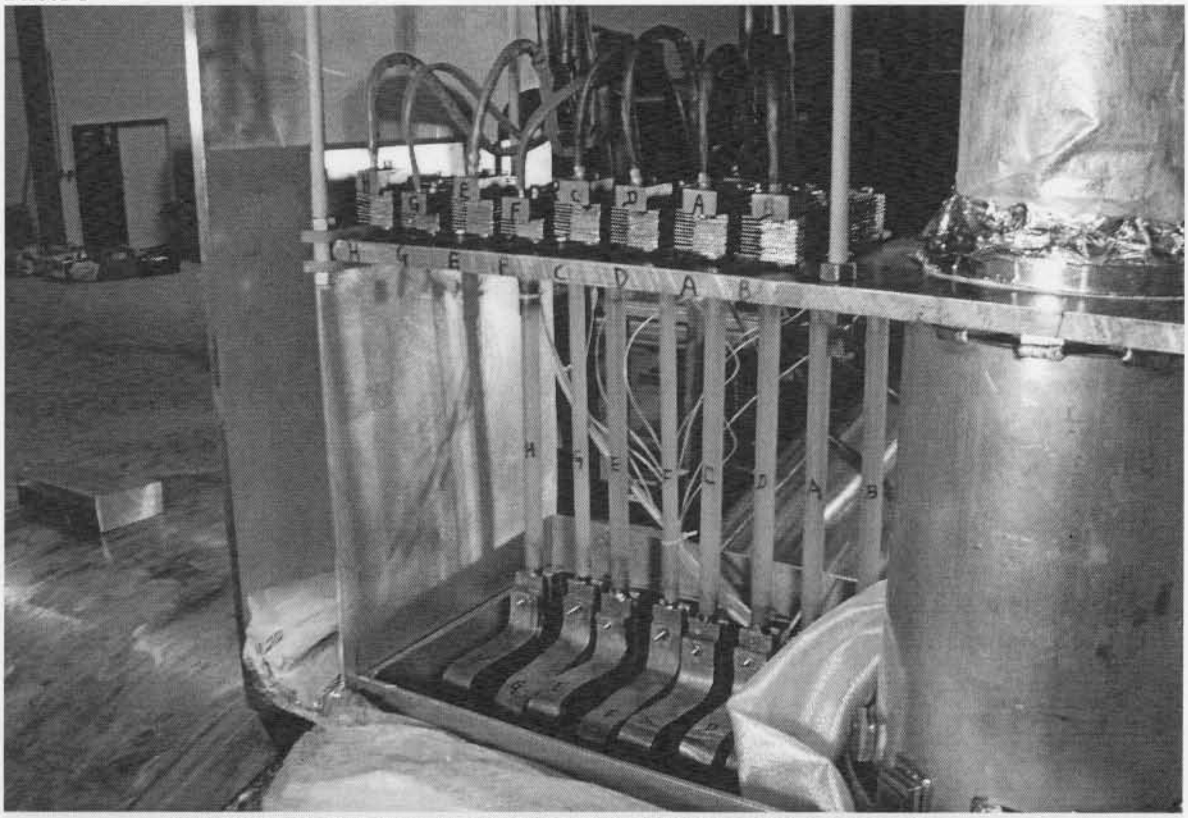
MICE COIL FABRICATION SHOWING TRACKER LONG SOLENOIDS WITH END COILS, MATCHING COILS, SUPERCONDUCTIVE FEED THROUGHS AND MAGNET PROTECTION ASSEMBLY AND HELIUM SHELL ASSEMBLY

Photo 2



CRYOSTAT FABRICATION AND ASSEMBLY

Photo 3



SERVICE TOWER ASSEMBLY SHOWING HiTc LEADS,
HEATSINKS AND ONE OF THREE COLDHEAD ASSEMBLY