Fermilab

Magnets for the Storage Ring

Nikolai ANDREEV

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Large Acceptance 50-GeV Muon Storage Ring for Neutrino Production: Lattice Design *

C. Johnstone, †, FNAL, Batavia, IL 60510

Table 1: Muon Storage Ring Design Parameters and Constraints

Storage Ring Geometry		racetrack
Storage Ring Energy	GeV	50
Vertical Descent Limit	m	183
Declination Angle	deg	13
Cross-sectional profile	m	813
ϵ_{rms} (normalized)	mm-rad	3.2π
dp/p (rms)	%	1
maximum poletip field	T	6.0
arc cell phase advance	deg	90

Table 2: Parameters of the large-momentum acceptance arc cells for a 50-GeV muon storage ring

intermagnet spacing	m	0.75
dipole length	m	2.4
dipole bend	rad	0.859
dipole field	T	6.0
dipole full aperture, HxW	cm	10x12
quadrupole length	m	1
arc quadrupole strength	m^{-2}	.31
arc quadrupole poletip field	T	3.6
arc quadrupole bore	cm	14
horiz. sextupole poletip field	T	.52
vert. sextupole poletip field	T	1.03
cell length	m	9.8
cell phase advance	deg	90
β_{max}	m	16.2
$D_x(max)$	m	1.3
number arc cells		31

Table 3: Parameters of the high-beta cells for neutrino production in a 50-GeV muon storage ring

drift length	m	66.3
quadrupole length	m	3
quadrupole strength	m^{-2}	0.0019
quadrupole poletip field	T	0.05
quadrupole bore	cm	33
total cell length	m	137.6
cell phase advance	deg	≈ 22
β_{max}	m	436.0
rms divergence	mr	0.20
number of high-beta cells		5

Table 4: Storage Ring Parameters at 50-GeV

Circumference	m	1752.8
Neutrino decay fraction		39.2%
Production region:		
matching and dispersion suppression	m	44.1
High-β FODO straight	m	688
$\beta_{xmax}/\beta_{ymax}$	m	435/484
$\nu_x/\nu y$		13.63/13.31
cell phase advance	deg	≈ 25
natural chromaticity		-23.9/-23.9

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† email: cjj@fnal.gov

MuSR DIPOLE CROSS SECTION

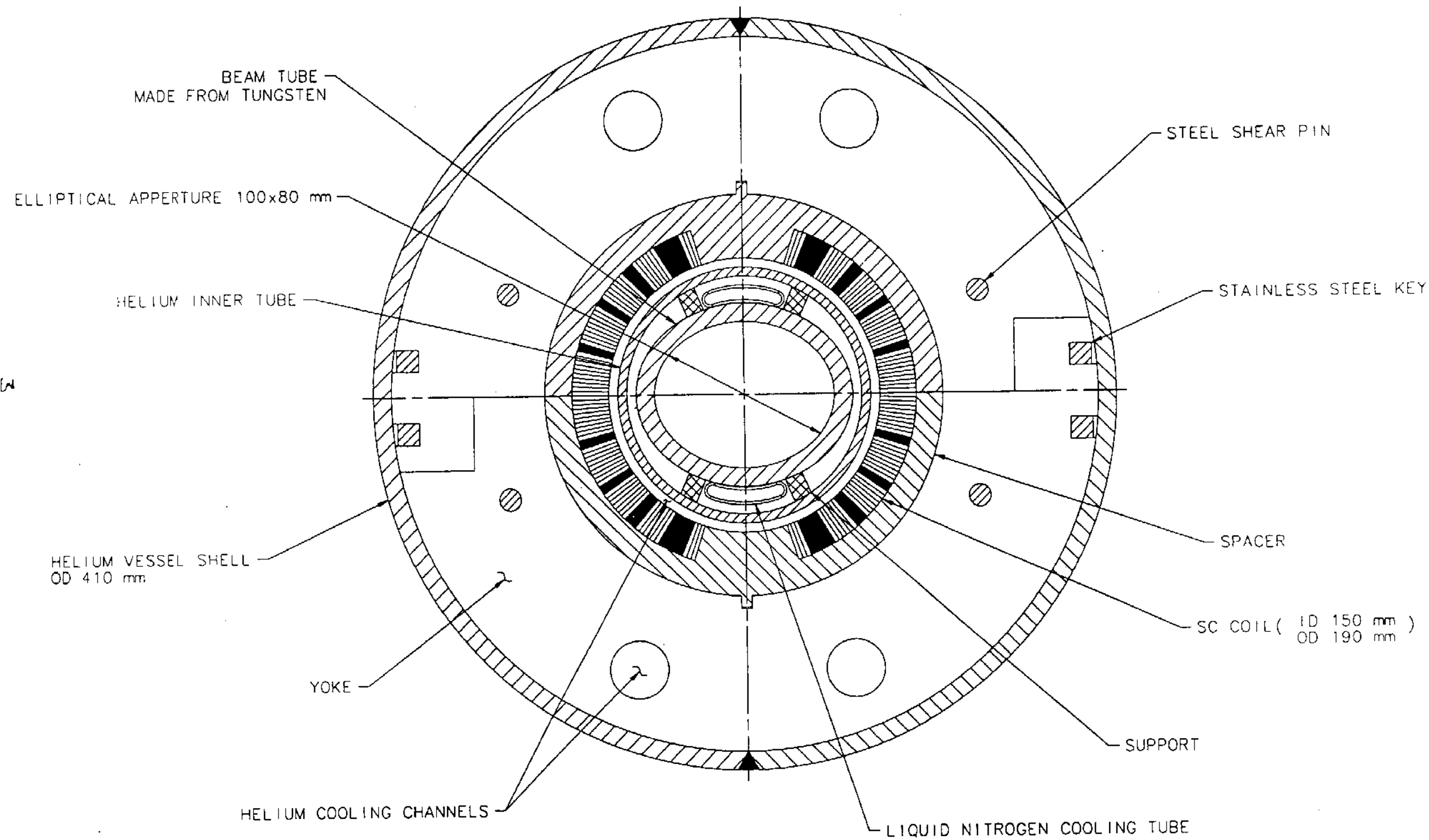


Table 1

Superconducting Dipole Parameters for MuSR

Basic parameters:

Operating field	- 6 T
Magnetic length	- 2.4 m
Operating current	- 15 kA
Operating temperature	- 4.5 K
Beam aperture (H x W)	- 80 x 100 mm
Tangsten beam tube thickness	- 10 mm
Operating temperature of beam tube	- 77 K

Coil:

One layer Cos θ type design

Turns numbers in coil	- 70
Inductance	- 12.5 mH
Stored energy	- 1.4 MJ

Structure:

Cold mass diameter	- 410 mm
Length of cold mass	- 3 m
Weight of cold mass	- 3 t

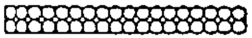
Table 4. Electrical performance data for SSC 50 mm dipole inner strand (7T,4.2K)

Production Unit	Critical Current		Current Density	
	Average Ic(A)	SDEV(%)	Average Jc(A/mm²)	SDEV(%)
-007	349	1.51	1690	1.44
-008	348	0.83	1678	0.53
-009	333	0.58	1685	0.67
-010	339	0.69	1689	0.72
-012	335	0.91	1643	0.98

Electrical performance is presented in the form of critical current data for outer dipole strand in Table 3. Over the five outer production units the average critical current ranged from 286 A to 293 A at 5.6 T and 4.2 K. The cumulative average I_c for the four outer billets is 291 A with a standard deviation of 1.49 percent.

Critical current data for inner dipole strand is presented in Table 4. The average critical currents for each of the five inner production units ranged from 333 A to 349 A at 7T and 4.2 K throughout the three billets. Throughout the five inner production units a cumulative average Ic of 340 Amps was obtained with a standard deviation of 1.66 percent.

COMPARISON OF KEYSTONE-STYLE SUPERCONDUCTOR CABLE CONSTRUCTIONS

STYLE	CROSS-SECTION	APPLICATION	NO. OF STRANDS n	STRAND DIA. d	CABLE WIDTH w	MAJOR EDGE THICKNESS t_1	MID-THICKNESS t	MINOR EDGE THICKNESS t_2	CABLE TWIST PITCH ℓ	CABLING ANGLE ψ	KEYSTONE ANGLE ϕ	PACKING FACTOR[1] P	MINOR EDGE RATIO[2] R_e	WIDTH RATIO[3] R_w
1		CERN LHC QUADRUPOLE CABLE	24	1.09 mm (.0429")	13.05 mm (.514")	2.16 mm (.0851")	1.93 mm (.076")	1.70 mm (.067")	100 mm 3.94"	14.6°	2.07°	91.7%	78.1%	99.8%
2		CERN LHC DIPOLE INNER CABLE	26	1.29 mm (.0508")	17.0 mm (.669")	2.48 mm (.0976")	2.25 mm (.0886")	2.02 mm (.0795")	120 mm 4.72"	15.8°	1.56°	92.5%	78.2%	101.3%
3		CERN LHC DIPOLE OUTER CABLE	40	.84 mm (.0331")	17.0 mm (.669")	1.65 mm (.0650")	1.475 mm (.0585")	1.30 mm (.0512")	120 mm 4.72"	15.8°	1.18°	92.0%	77.3%	101.1%
4		OLD SSC DIPOLE OUTER CABLE RHIC DIPOLE CABLE	30	.67 mm (.0255")	9.7 mm (.383")	1.27 mm (.0499")	1.166 mm (.0459")	1.06 mm (.0418")	73 mm 2.90"	16.4°	1.21°	91.0%	82.0%	100.1%
5		OLD SSC DIPOLE INNER CABLE	23	.81 mm (.0318")	9.3 mm (.366")	1.59 mm (.0625")	1.45 mm (.0573")	1.32 mm (.0522")	79 mm 3.125"	13.2°	1.61°	89.4%	82.1%	100.1%
6		NEW SSC DIPOLE OUTER CABLE	36	.67 mm (.0255")	11.7 mm (.460")	1.26 mm (.0496")	1.158 mm (.0455")	1.05 mm (.0415")	94 mm 3.70"	14.0°	1.01°	90.4%	81.4%	100.2%
7		NEW SSC DIPOLE INNER CABLE	30	.81 mm (.0318")	12.3 mm (.486")	1.59 mm (.0625")	1.458 mm (.0574")	1.32 mm (.0522")	86 mm 3.39"	16.0°	1.21°	88.9%	82.1%	101.9%
8		FERMILAB DIPOLE CABLE	23	.68 mm (.0268")	7.77 mm (.306")	1.40 mm (.055")	1.26 mm (.0495")	1.12 mm (.044")	66 mm 2.62"	13.2°	2.06°	88.0%	82.1%	99.3%
9		HERA PROJECT DIPOLE CABLE	24	.84 mm (.0331")	10.00 mm (.394")	1.67 mm (.0657")	1.475 mm (.0581")	1.28 mm (.0504")	95 mm 3.74"	11.9°	2.27°	92.3%	76.1%	99.2%
10		FERMILAB LOW β QUADRUPOLE CABLE	36	.53 mm (.0208")	9.78 mm (.385")	.99 mm (.0388")	.897 mm (.0353")	.81 mm (.0318")	76 mm 2.99"	14.4°	1.06°	93.5%	76.0%	102.5%

NOTES:

1 $P = \frac{n \pi d^2}{2w(t_1 + t_2)\cos\psi}$; 2 $R_e = \frac{t_2}{2d}$; 3 $R_w = \frac{2w}{nd}$

MuSR QUADRUPOLE AND SEXTUPOLE CROSS SECTION

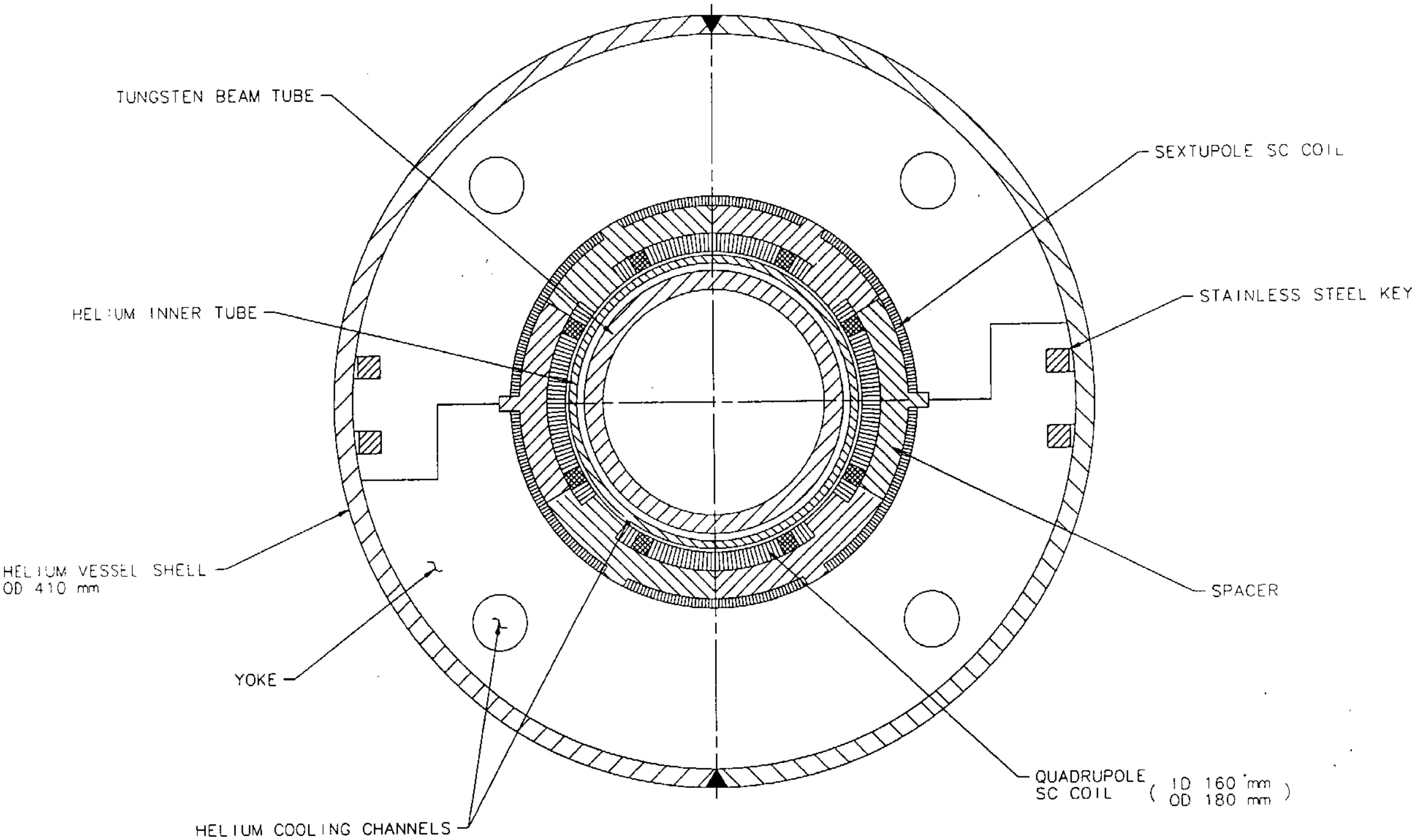


Table 2

SC Quadrupole + Sextupole Magnets Parameters for MuSR

Quadrupole parameters:

Operating field	- 3.6 T
Magnetic length	- 1.0 m
Operating current	- 10 kA
Operating temperature	- 4.5 K
Beam aperture	- 120 mm
Tangsten beam tube thickness	- 10 mm
Operating temperature of beam tube	- 77 K

Quadrupole coil:

One layer Cos θ type design	
Coil inner diameter	- 160 mm

Sextupole coil:

One layer Cos θ type design	
Coil inner diameter	- 220 mm
Horizontal sextupole poletip field	- 0.52 T
Vertical sextupole poletip field	- 1.03 T
Magnetic length	- 1.0 m

Structure:

Design concept: Collared coil assembly of the quadrupole is installed inside aperture of sextupole with common iron yoke.

Common cold mass diameter	- 410 mm
Length of cold mass	- 1.5 m
Weight of cold mass	- 1.5 t

Table 3

Arc half sell of the MuSR

Design concept:

- Common cold mass vessel for the arc half sell which will contain
- dipole, quadrupole and sextupole magnets.
- Common vacuum vessel for the cryostat.
- Two suspension posts and anchor in the middle of quadrupole.

Structure parameters:

Cold mass diameter	- 410 mm
Total length of cold mass	- 4.6 m
Beam tube length	- 4.9 m
Total weight of the common cold mass	- 4.5 t
Outer diameter of cryostat	- 800 mm
Suspension post dimension (H x W)	- 900 x 800 mm
Total weight of the half sell assembly	- 5.5 t

Cryo-loads:

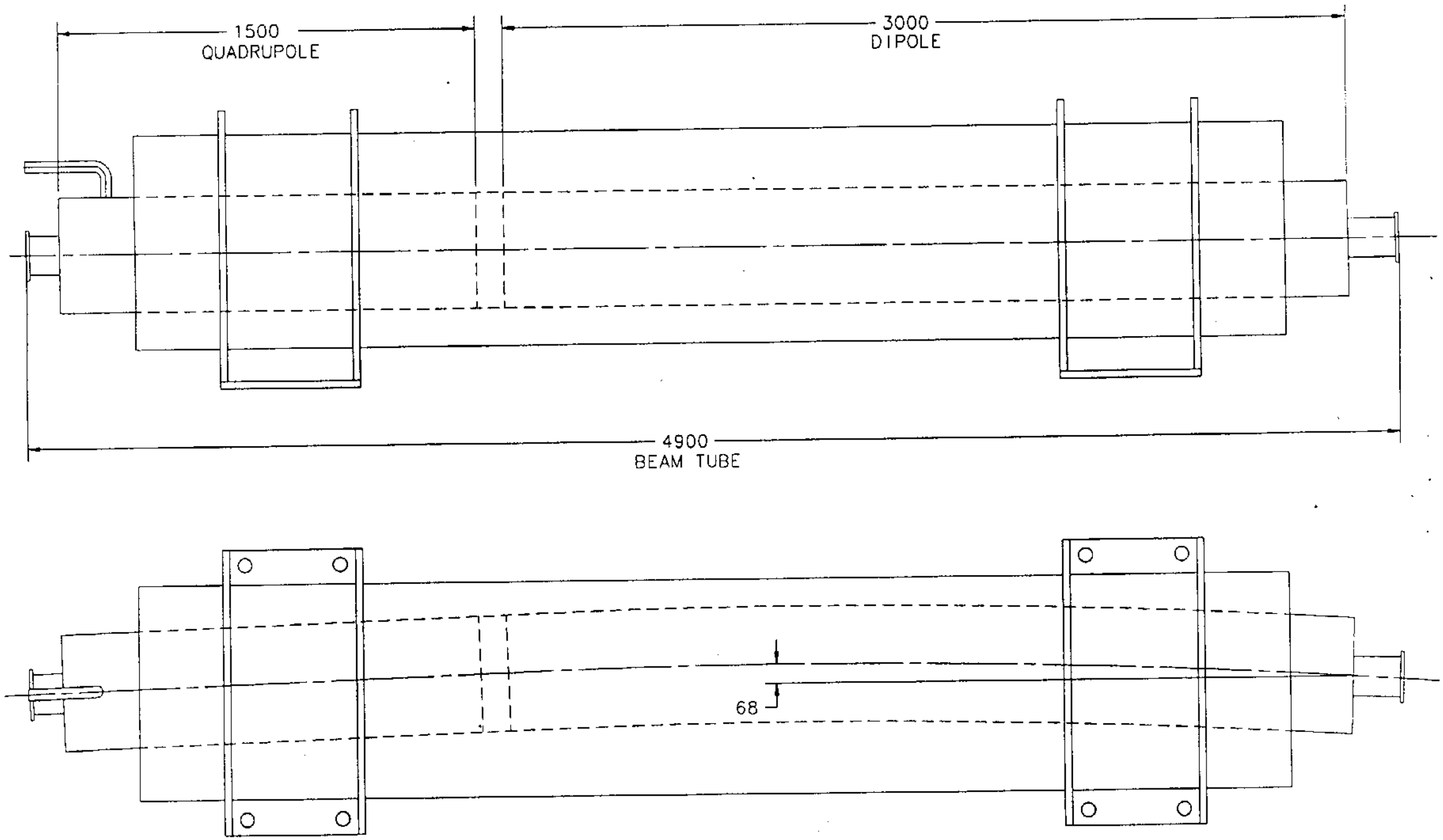
Static heat leaks:

- to He level, at 4.5 K	- 5 W/cryostat
- to N2 level, at 77 K	- 30 W/cryostat

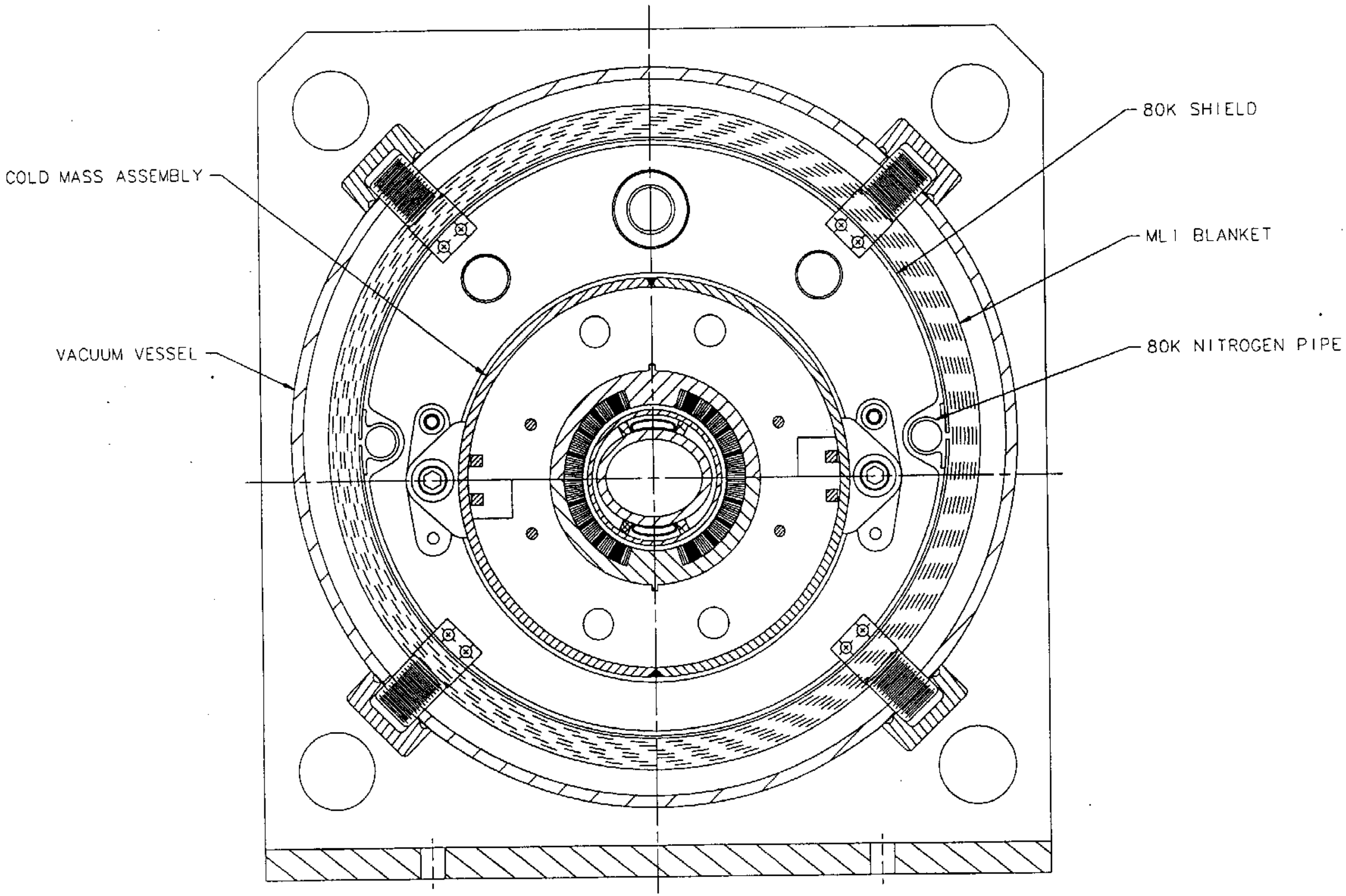
Dynamic heat losses:
(Included beam losses)

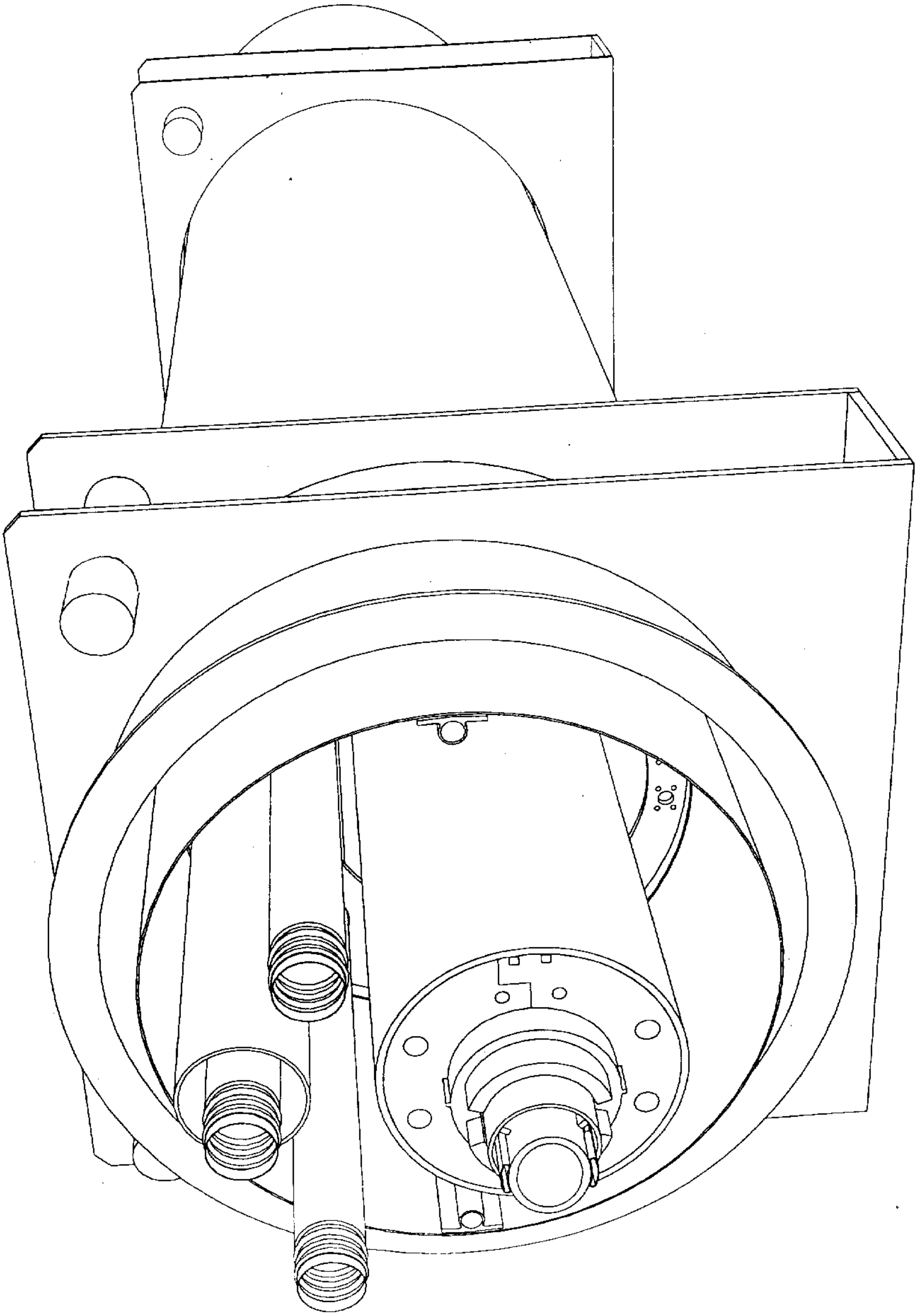
- to He level, at 4.5 K	- 7 W/m
- to N2 level, at 77 K	- 70 W/m

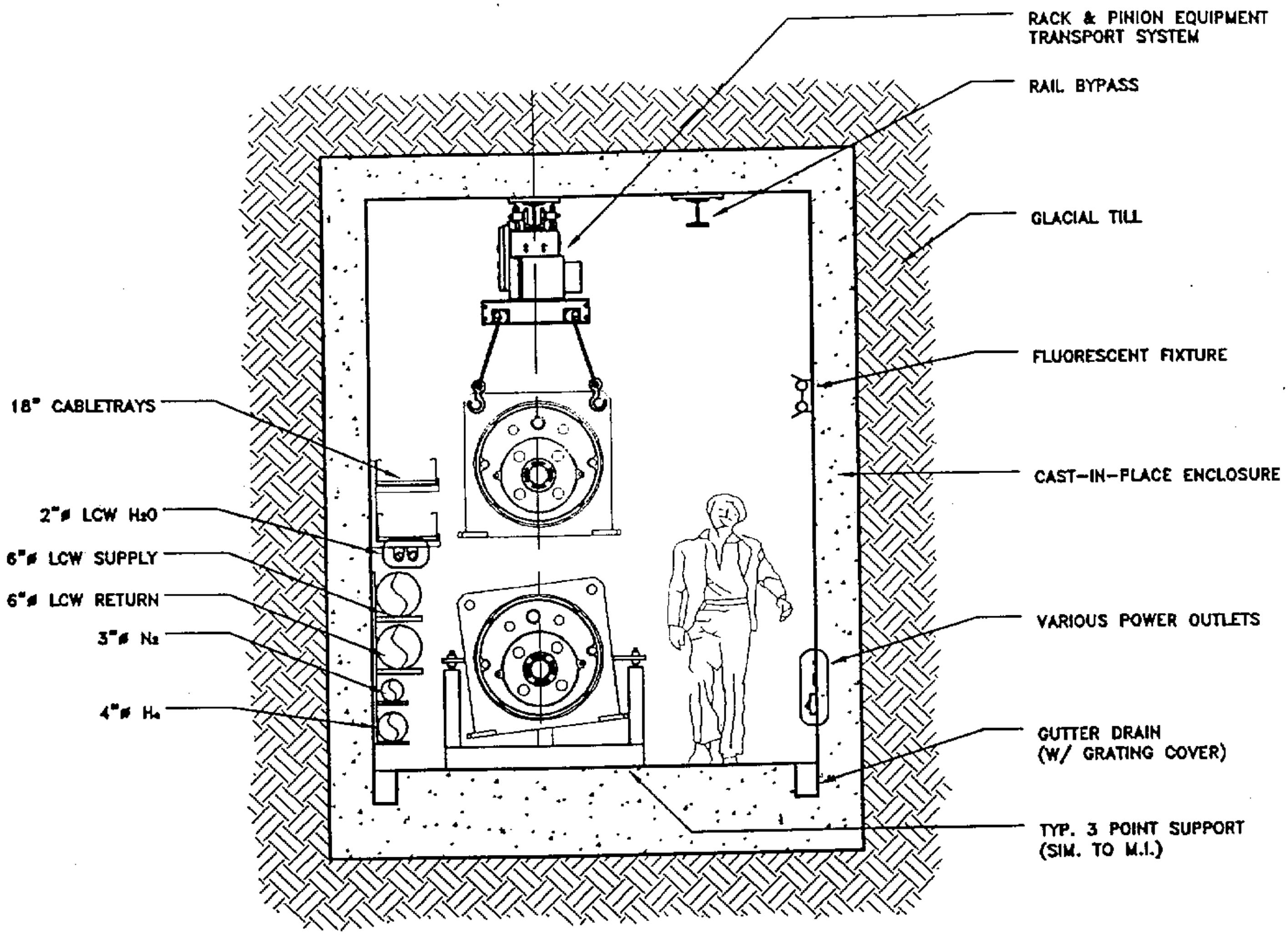
CRYOSTAT PLAN AND ELEVATION VIEW



DIPOLE CROSS SECTION



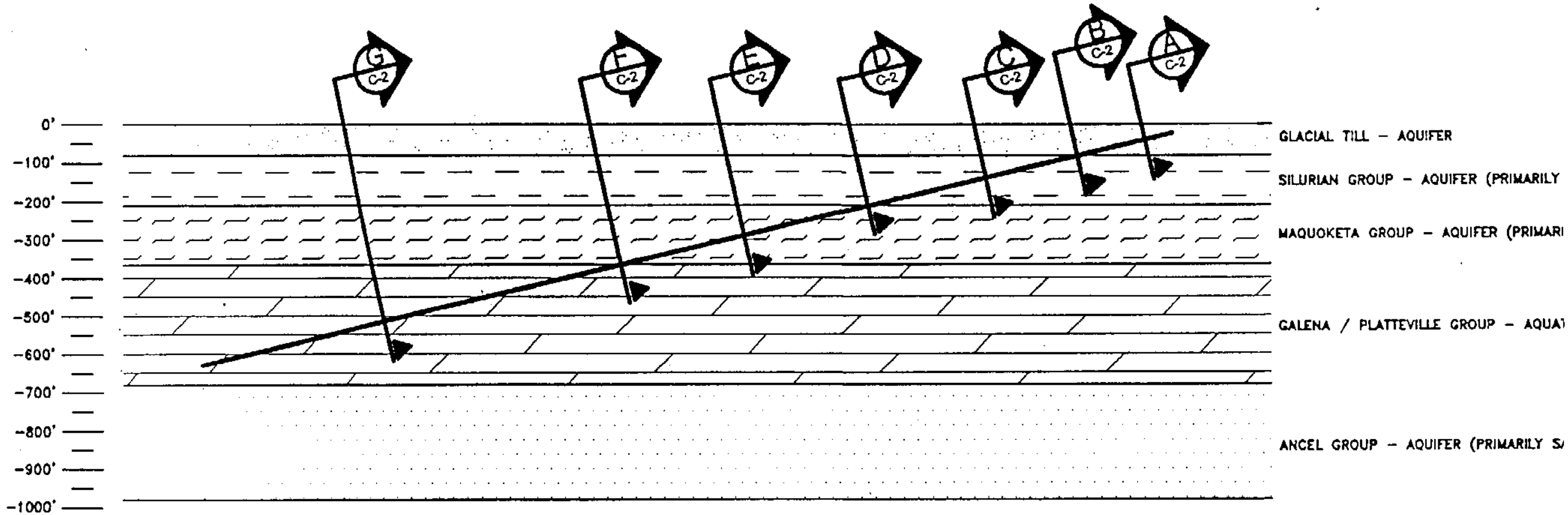




CROSS-SECTION (A / C-1)

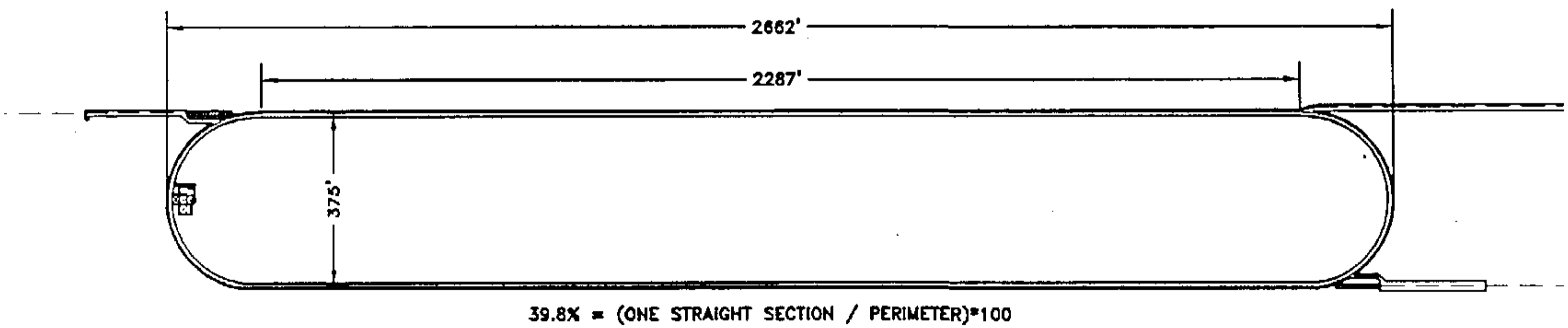
1/2"=1'-0"

APPROX. VERT. DIST. = 0' : -67'



GEOLOGY SECTION

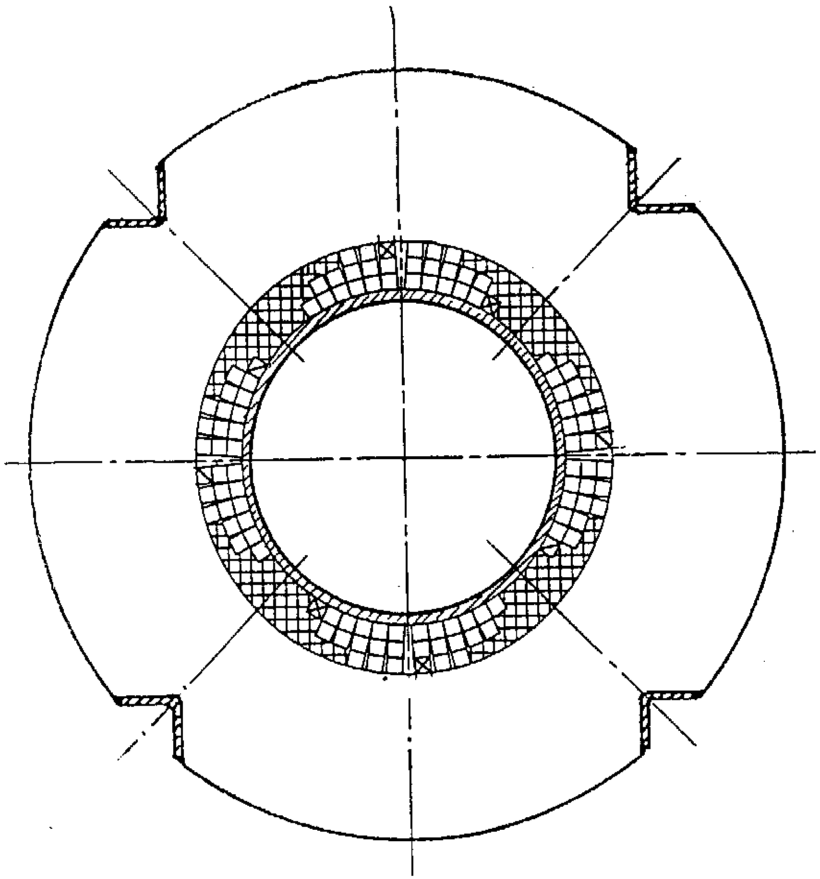
1"=200'-0"



MuSR PLAN

1"=200'-0"

Quadrupole magnet for straight section of MuSR



Basic parameters:

Quadripole poletip field	0.05 T
Gradient	0.303 T/m
Beam bore diameter	33 cm
Quadrupole length	3 m
Inner coil diameter	35 cm
Outer diameter of iron	83 cm
Number of turns	56
Copper conductor cross-section	2x2 cm2
Operating current	1750 A
Energy dissipation	50 kW/magnet

HYBRID PERMANENT QUADRUPOLES FOR THE 8 GEV TRANSFER LINE AT FERMILAB

S.M. Pruss, B.C. Brown, G.W. Foster, H.D. Glass, D.J. Harding, G.P. Jackson, M.P. May, J.-F. Ostiguy, J.T. Volk (Fermilab)

Abstract

Hybrid Permanent Magnet Quadrupoles for specialized portions of the 8 GeV transfer line from the Fermilab Booster to the new Main Injector have been built, tested and installed. These magnets use a 0.635 m long iron shell and provide an integrated gradient of 1.48 T-m/m with an iron pole tip radius of 0.0416 m. and pole length of 0.508 m. Bricks of 0.0254 m thick strontium ferrite supply the flux to the back of the pole to produce the desired 2.91 T/m gradient. For temperature compensation, Ni-Fe alloy strips are interspersed between ferrite bricks to subtract flux in a temperature dependent fashion. Adjustments of the permeance of each pole using iron between the pole and the flux return shell permits the matching of pole potentials. Magnetic potentials of the poles are measured with a Rogowski coil and adjusted to the desired value to achieve the prescribed strength and field uniformity. After these adjustments, the magnets are measured using a rotating coil to determine the integral gradient and the harmonics. These measurements are used to calibrate the production Rogowski coil measurements. Similar quadrupoles are included in the design of the Fermilab Recycler.

1 MAGNET DESIGN

These magnets serve both as necessary components of the 8 Gev transfer line and as production prototypes for the quadrupoles needed for the Fermilab Recycler. All the of Fermilab permanent magnets are of the "hybrid" type in which the field is driven by permanent magnet bricks and the field shape is determined mainly by iron pole pieces [1]. The advantage of this design is low cost due to the use of the same type of permanent magnet material (Type 8 Strontium Ferrite) as many automotive and other commercial applications. The magnets made in this way are also very stable over long time periods and are not affected by radiation. The disadvantage is the brick to brick strength variation which must be tuned out of each magnet based on measurements of assembled magnets. The intrinsic temperature coefficient of the Ferrite material (-0.18% / °C) is canceled by interspersing a "compensator alloy" between the ferrite bricks. In this application an amount of compensator about 14% of the brick in volume is required.

2 MAGNET ASSEMBLY

Assembly of these magnets from purchased parts is straightforward and requires two technicians for only two hours. The four precision pole pieces are assembled to two precision stainless steel end spacers and four aluminum spacer bars. The ferrite bricks and compensator strips are inserted along one side with one channel length having its field pointing into a pole and the other with its field pointing out of the adjecent pole. A steel flux return side is layed over the bricks and the assembly rolled 90°. This procedure is repeated for the remaining three sides, taking care to maintain the proper brick polarity. The four sides are bolted together but are not attached to the pole assembly. The flux return end pieces are installed and bolted to the sides, but again not to the pole assembly. The magnetic forces hold the pole assembly strongly to the flux return shell and prevent it from moving longitudinally. Nevertheless, we plan to have retainer spacers between the flux return end pieces and the pole assembly in the Recycler quadrupoles to prevent movement if the magnet is mishandled. A total of ten magnets were built, nine used in the beamline and one prototype/spare.

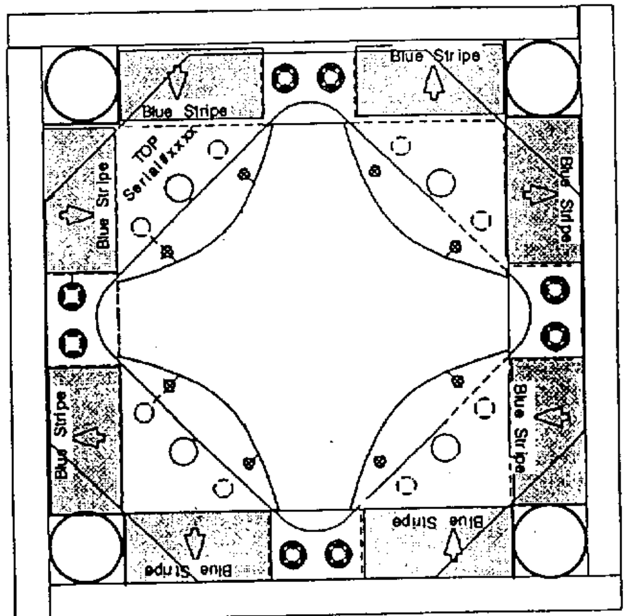


Figure 1 Magnet Cross Section, ferrite bricks are dotted.

3 ROGOWSKI MEASUREMENTS AND TRIMMING

After each magnet is assembled, the magnetic potential is measured at both ends of all four poles with a Rogowski coil [2,3]. The magnet is then put in a freezer overnight and cooled to 0° C. The magnet is removed from the freezer, wrapped in a thermal blanket in such a

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Summary

SC magnets for MuSR are quite simple, could be made from NbTi superconductor, and by well-known magnet technology.

RHIC type design of SC magnet; with one layer of cosθ coil – is one of the best solutions for the MuSR arc magnet design.

R&D magnets for MuSR could be fabricated and tested at Fermilab with some modifications of existing equipment.

5 Years R&D Program for SC Magnets of MuSR.

- **Development magnets design (dipole & quadrupole) and tooling - 2years**
- **Fabricate and test 8 short models (4+4) of dipoles and quadrupoles - 1.5years**
- **Fabricate and test one full length prototype of the arc sell for MuSR - 1.5years**