BEAM INDUCED ENERGY DEPOSITION AND RADIATION FIELDS IN MUON STORAGE RING ARCS AND STRAIGHT SECTIONS

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Feasibility of a Neutrino Source Based on a Muon Storage Ring
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OUTLINE

- MARS model of MuSR arc magnets and cells
- Power density, power dissipation and residual dose in the arc magnets due to muon beam decays
- Optimization of shielding beam tube
- Conventional radiation in and around the arc tunnel
- Neutrino-induced radiation around the arcs and straight sections

Large Acceptance 50-GeV Muon Storage Ring for Neutrino Production: Lattice Design, CJ2.0 *

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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

General: tungsten shield thickness	cm	1.0
beam-stay clear	cm	1.0
intermagnet spacing	m	0.75
Dipoles:		
dipole length	m	2.4
dipole bend	rad	0.0859
dipole field	T	6.0
beam size (6σ, max), WxH	cm	8.0x5.3
dipole full aperture**, WxH	cm	12x9.3
sagitta	cm	2.67
Quadrupoles:		
quadrupole length	m	1
arc quadrupole strength	m^{-2}	.31
arc quadrupole poletip field	T	3.6
beam size (6σ), WxH		
F quad	cm	9.2x2.6
D quad	cm	4.2x6.2
arc quadrupole bore**	cm	14
Sextupoles (overlay on quad field)		
horiz. sextupole strength	m^{-2}	0.64
vert. sextupole strength	m^{-2}	1.26
horiz. sextupole poletip field	T	.52
vert. sextupole poletip field	T	1.03
Arc FODO cell parameters:		
cell length	m	9.8
cell phase advance	deg	90
β_{max}	m	16.2
$D_x(max)$	m	1.3
total number arc cells		31

**aperture = beam size + liner thickness + beam-stay-clear

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

drift length	m	65.8
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: Parameters of cells in return straight of 50-GeV muon storage ring

cell length	m	50.78
quadrupole length	m	1
quadrupole strength	m^{-2}	0.056
quadrupole poletip field	T	0.84
quadrupole bore	cm	18
cell phase advance	deg	90
β_{max}	m	86.3
rms divergence	mr	0.73
number of cells		12

Table 5: 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
natural chromaticity		-23.9/-23.9

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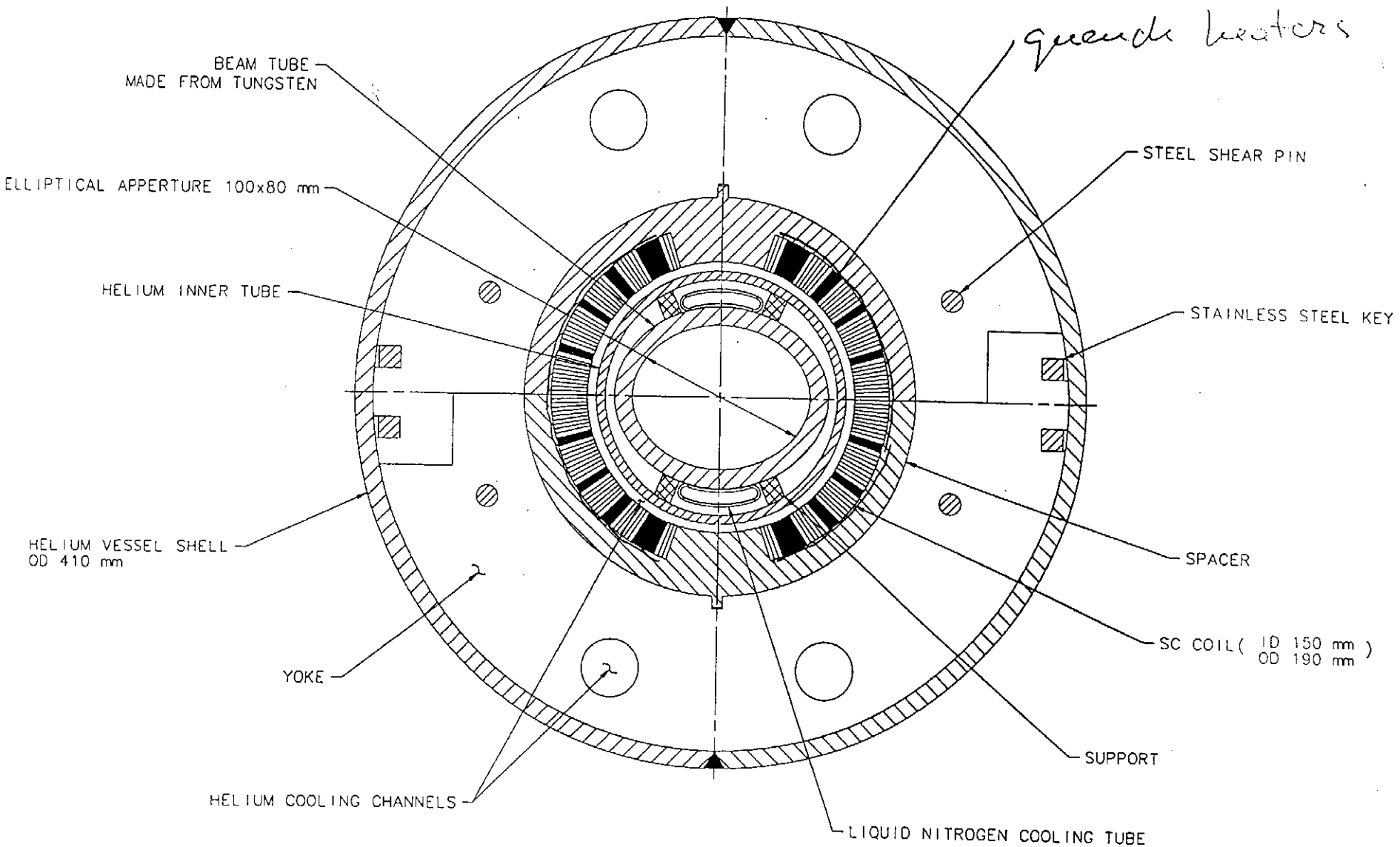
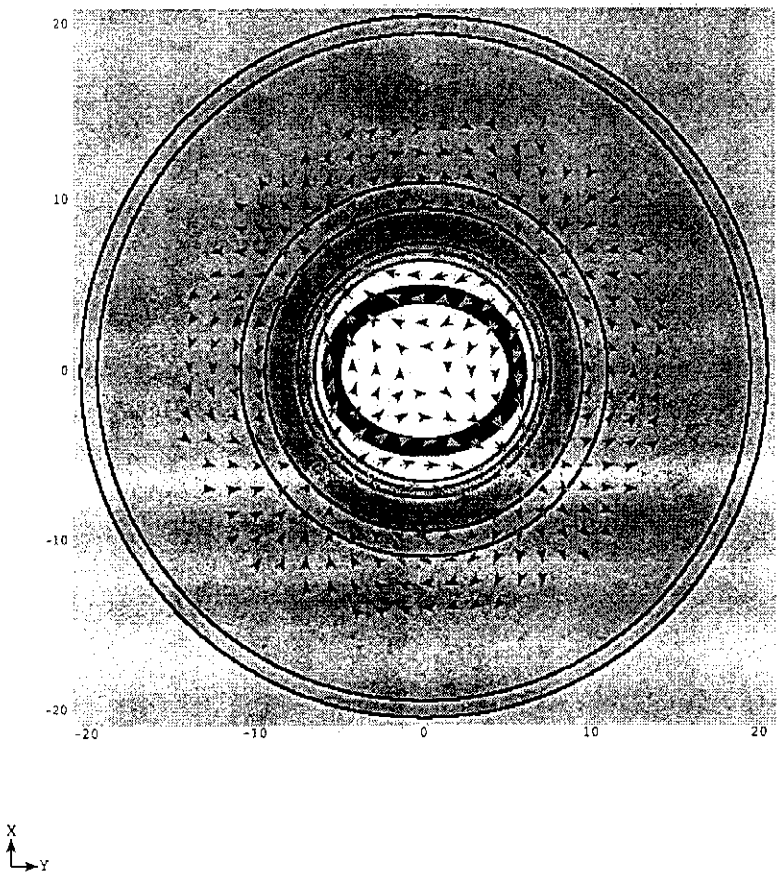
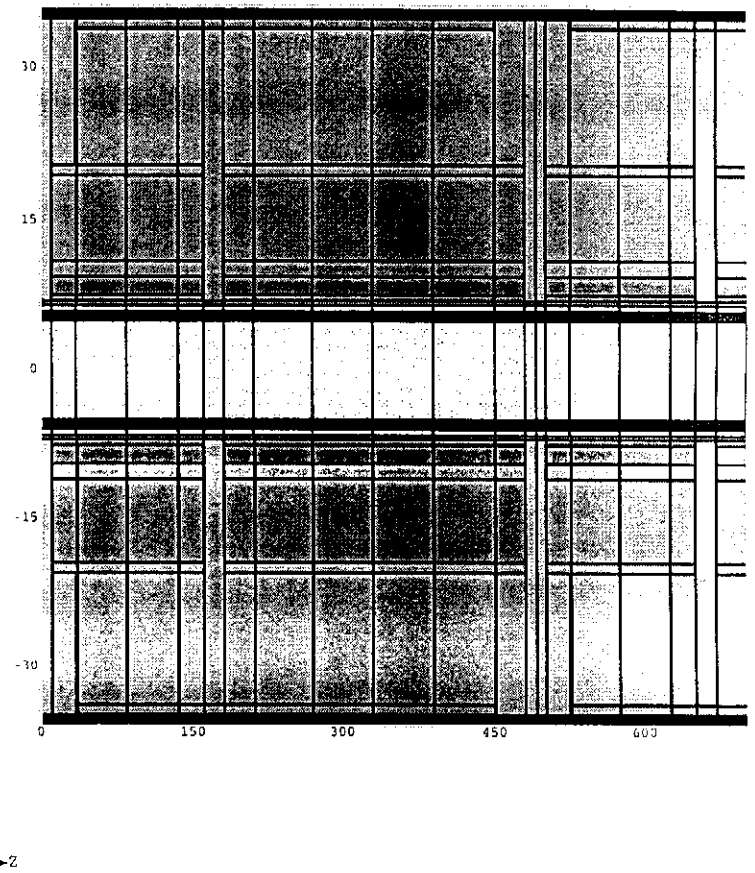
MuSR DIPOLE CROSS SECTION



MARS MODEL OF THE MUSR ARCS

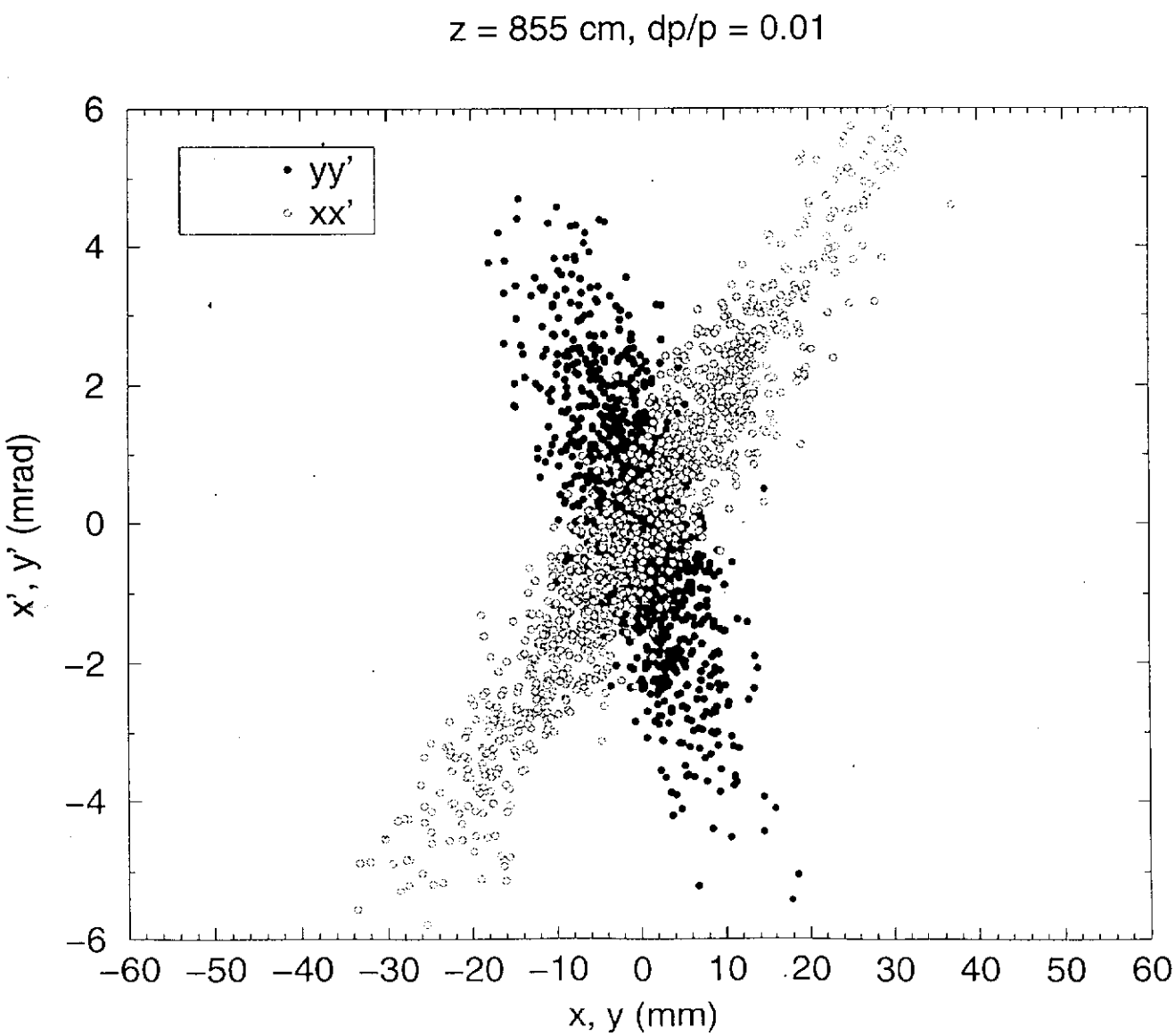




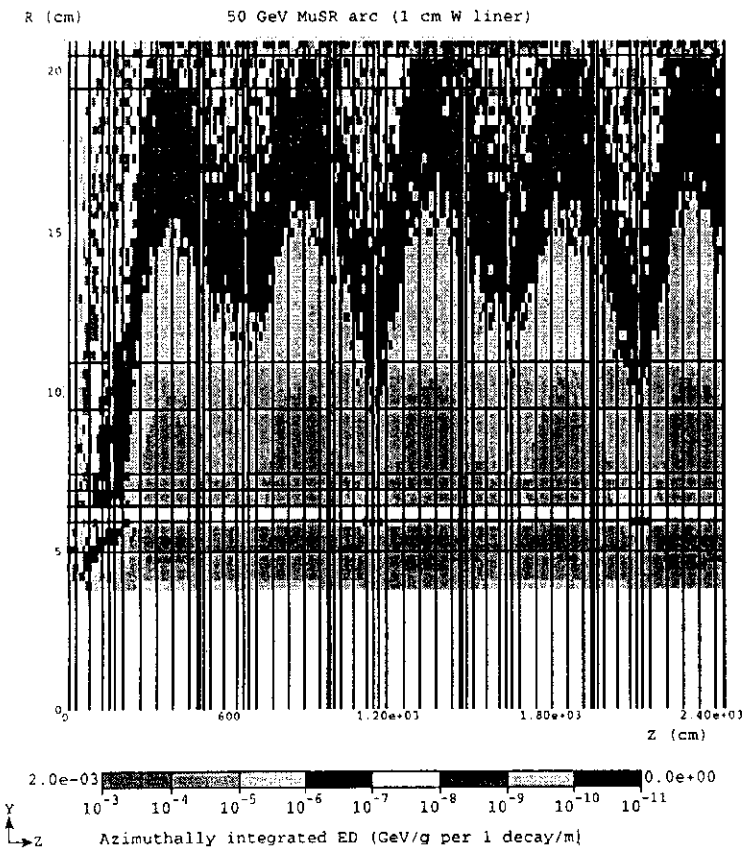
Arc quadrupole (left) and FODO cells (right).

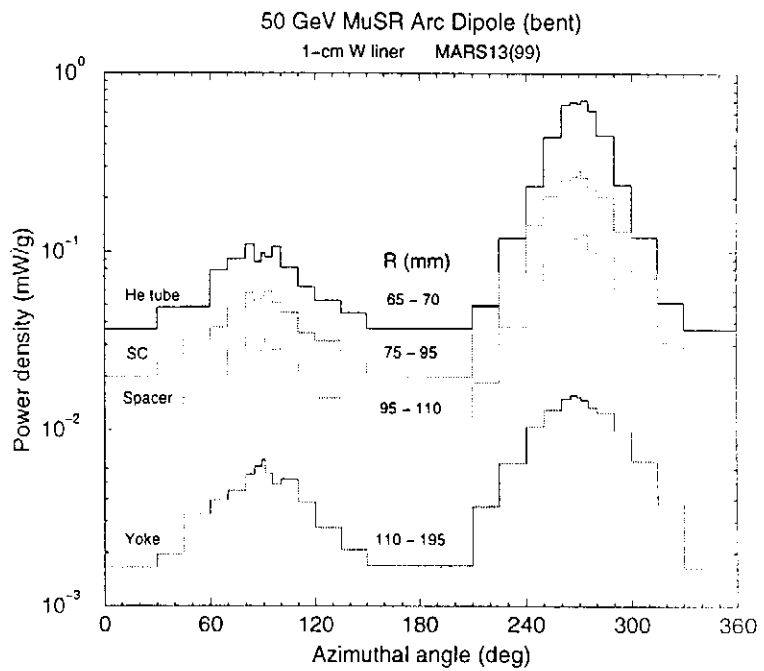
MARS SIMULATIONS

- 50-GeV muon storage ring, CJ2.0 lattice
- Arc FODO cells 9.8 m each,
  45 T/m 1-m quads and 6 T 2.4-m dipoles
- Muon decay rate =
  $2 \cdot 10^{12} \times 15 \times 165 \times 3.21 \cdot 10^{-6} = 1.6 \cdot 10^{10}$decays/m/s
- Forced muon decays and shower simulation with MARS
- 240 kW beam $\rightarrow$ 84 kW power dissipation in 1750 m μSR
  $\rightarrow$ 47.8 Watts per meter on average
- Tungsten *vs* copper *vs* aluminum liner
- Power density (quench stability), power dissipation (heat load on cryo) and residual dose rate (hands-on maintenance)


z = 855 cm, dp/p = 0.01
yy'
xx'
x', y' (mrad)
x, y (mm)
6
4
2
0
−2
−4
−6
−60
−50
−40
−30
−20
−10
0
10
20
30
40
50
60

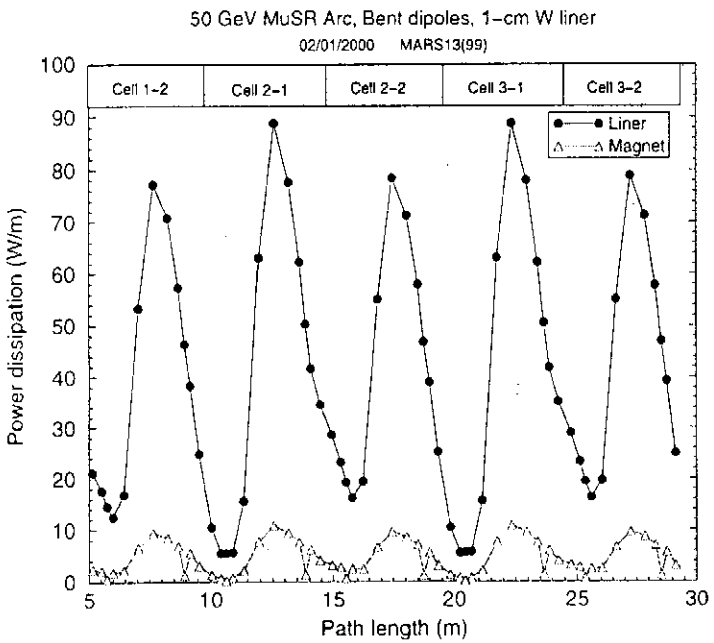
POWER DENSITY IN ARC MAGNETS

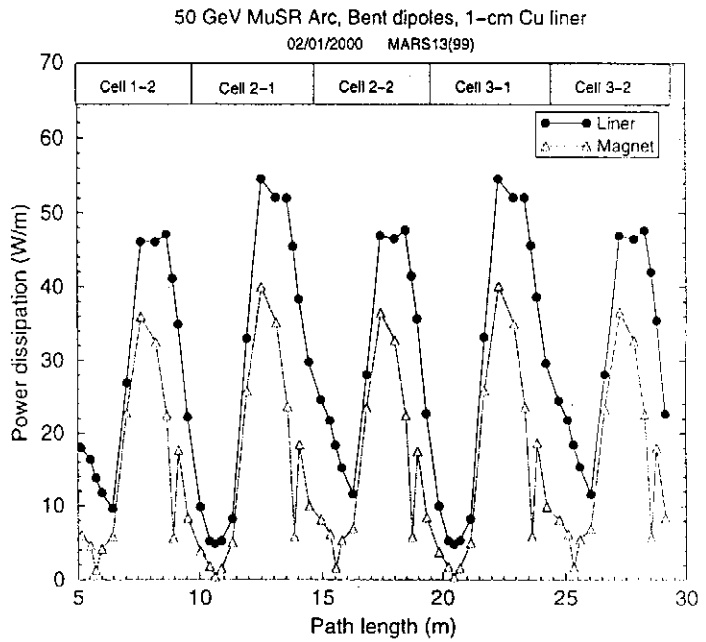




Longitudinal distribution of energy deposition in the arc magnets (left) and azimuthal distribution of power density in the arc dipole (right).

POWER DISSIPATION IN ARC CELLS





Longitudinal distribution of power dissipation in the arc magnets with tungsten (left) and copper (right) 1-cm bore tubes.

POWER DISSIPATION (AVERAGE)

Table 1: Power dissipation (W/m) averaged over 50-GeV μSR arc magnet components with a 1-cm thick liner made of tungsten, copper and aluminum: liner (100×80 mm ID), SS He tube (65<r<70 mm), SC coil (75<r<95 mm), rest of the magnet (r>95 mm) and sum in the magnet (r>65 mm).

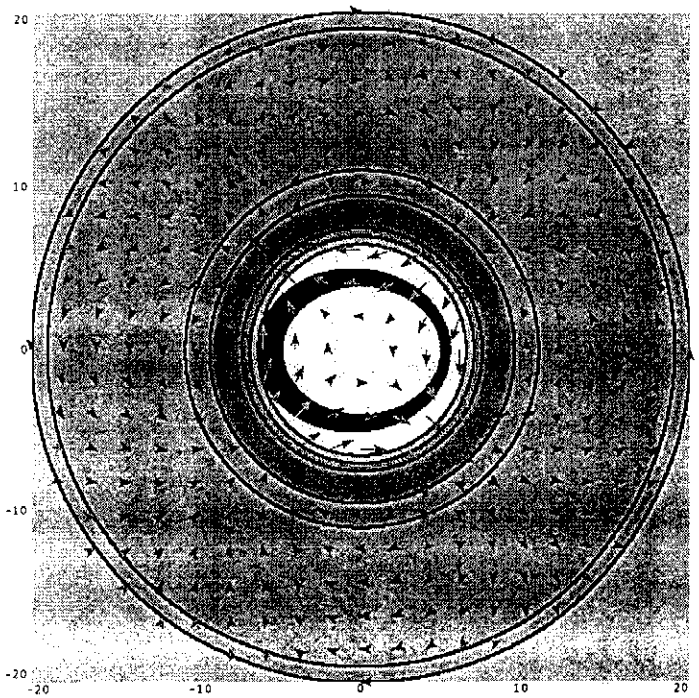
Material	Liner	Tube	Coil	Rest	Sum at r>65 mm
W	42.75	1.09	1.46	2.53	5.08
Cu	29.88	4.83	5.37	6.36	16.56
Al	5.25	11.63	15.08	13.94	40.65

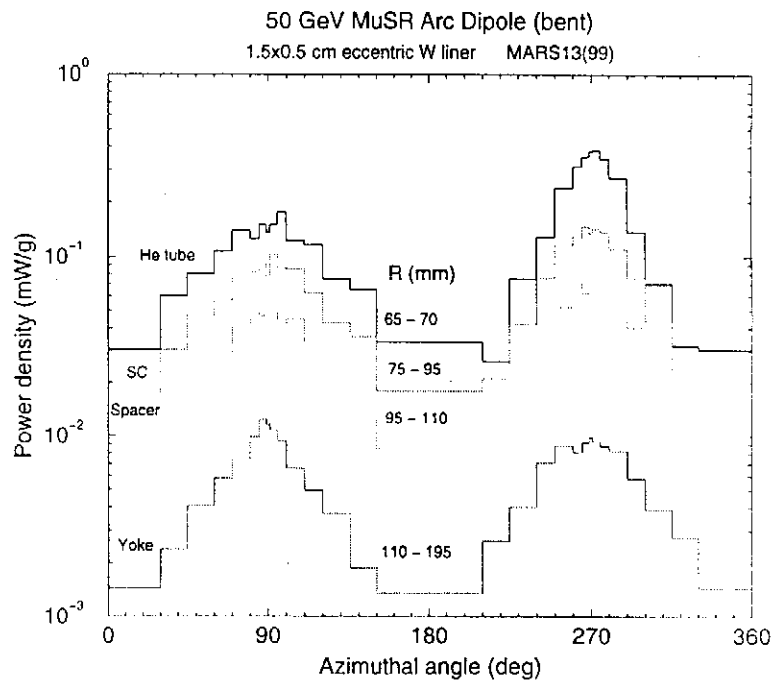
RESIDUAL DOSE ON MAGNETS

Table 3: Longitudinal maximum of residual dose rate at contact (μSv/hr) after 30 day irradiation and 1 day cooling with a 1-cm thick liner made of three materials for a 50-GeV μSR arc.

Material	Liner	SC coil	He vessel	Outer vessel
W	13.1	6.4	5.0	3.2
Cu	80.5	12.3	9.1	4.8
Al	187	32.0	15.0	5.6

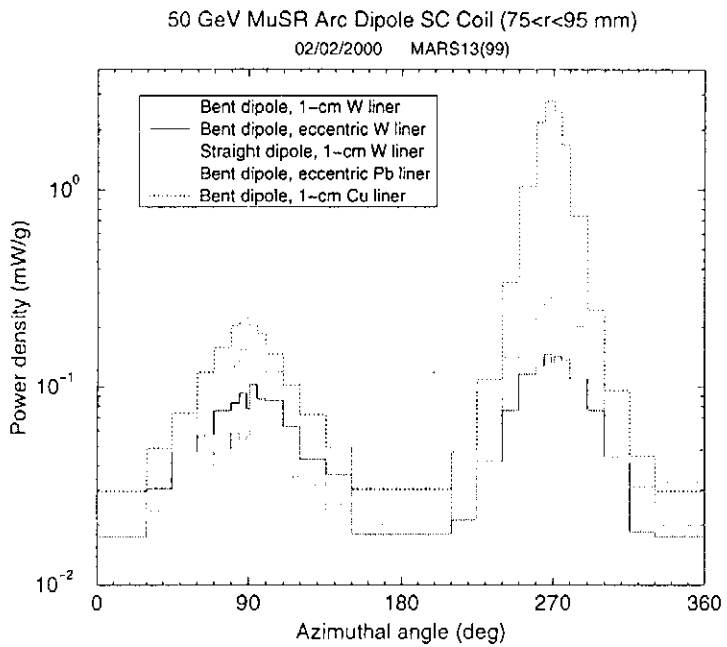
ECCENTRIC BORE TUBE

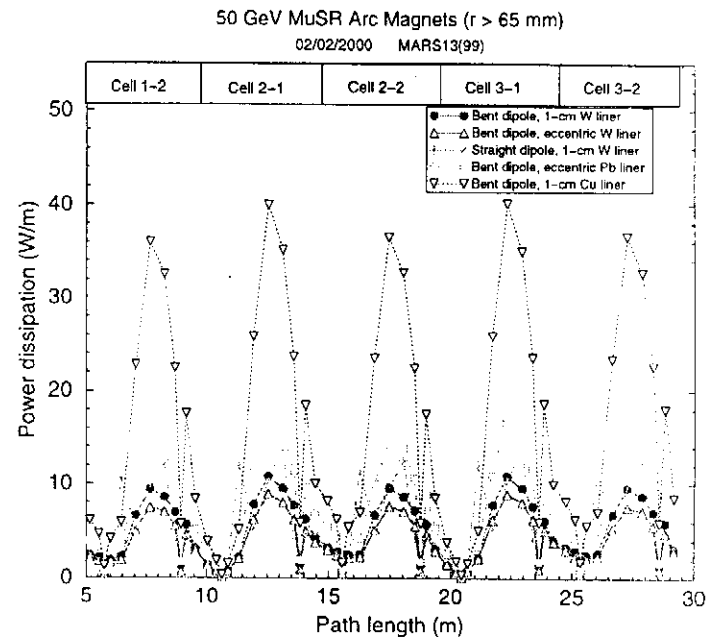




Arc quadrupole (left) and power density in the bent arc dipole (right).

BORE TUBE OPTIMIZATION-1



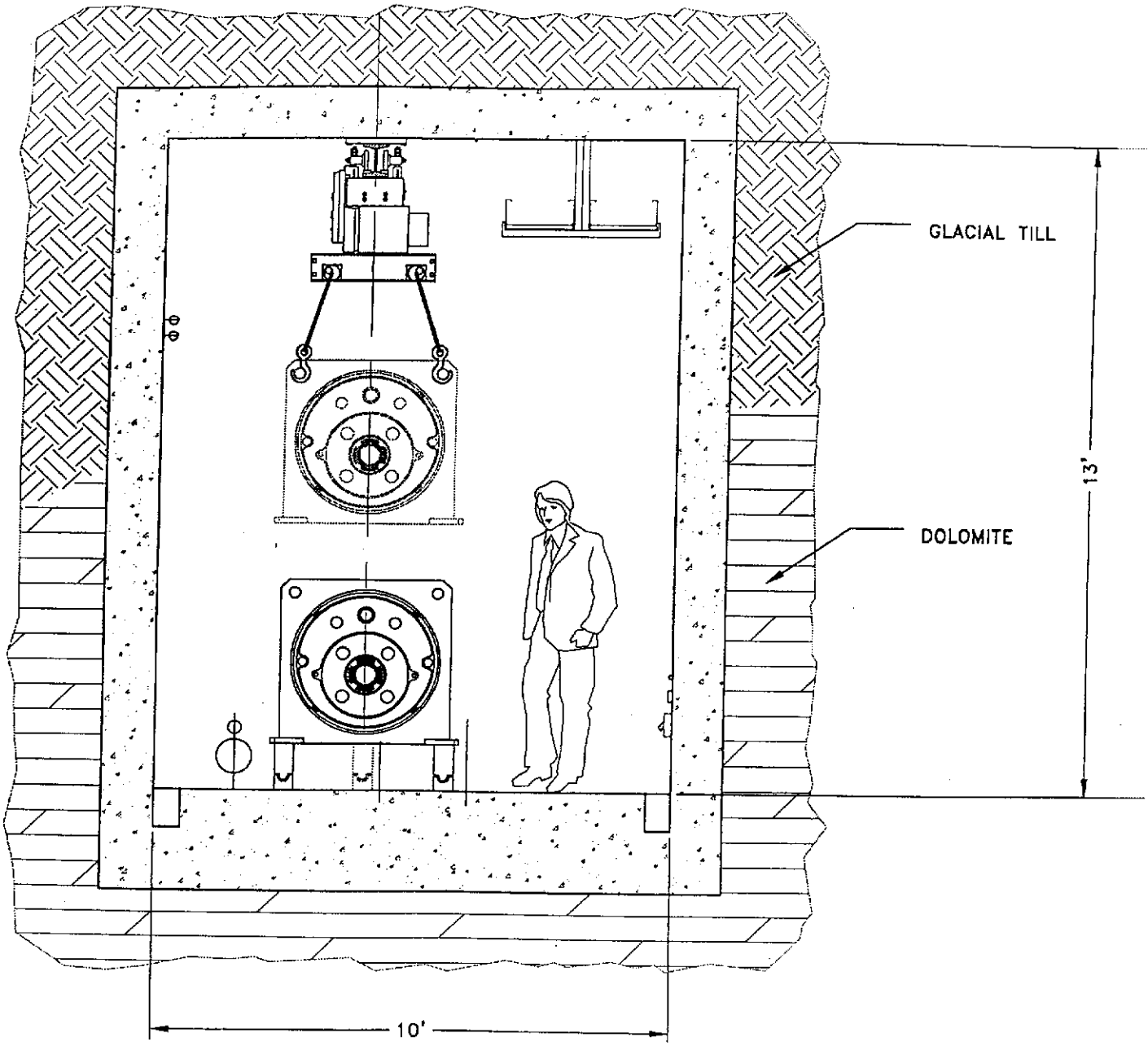


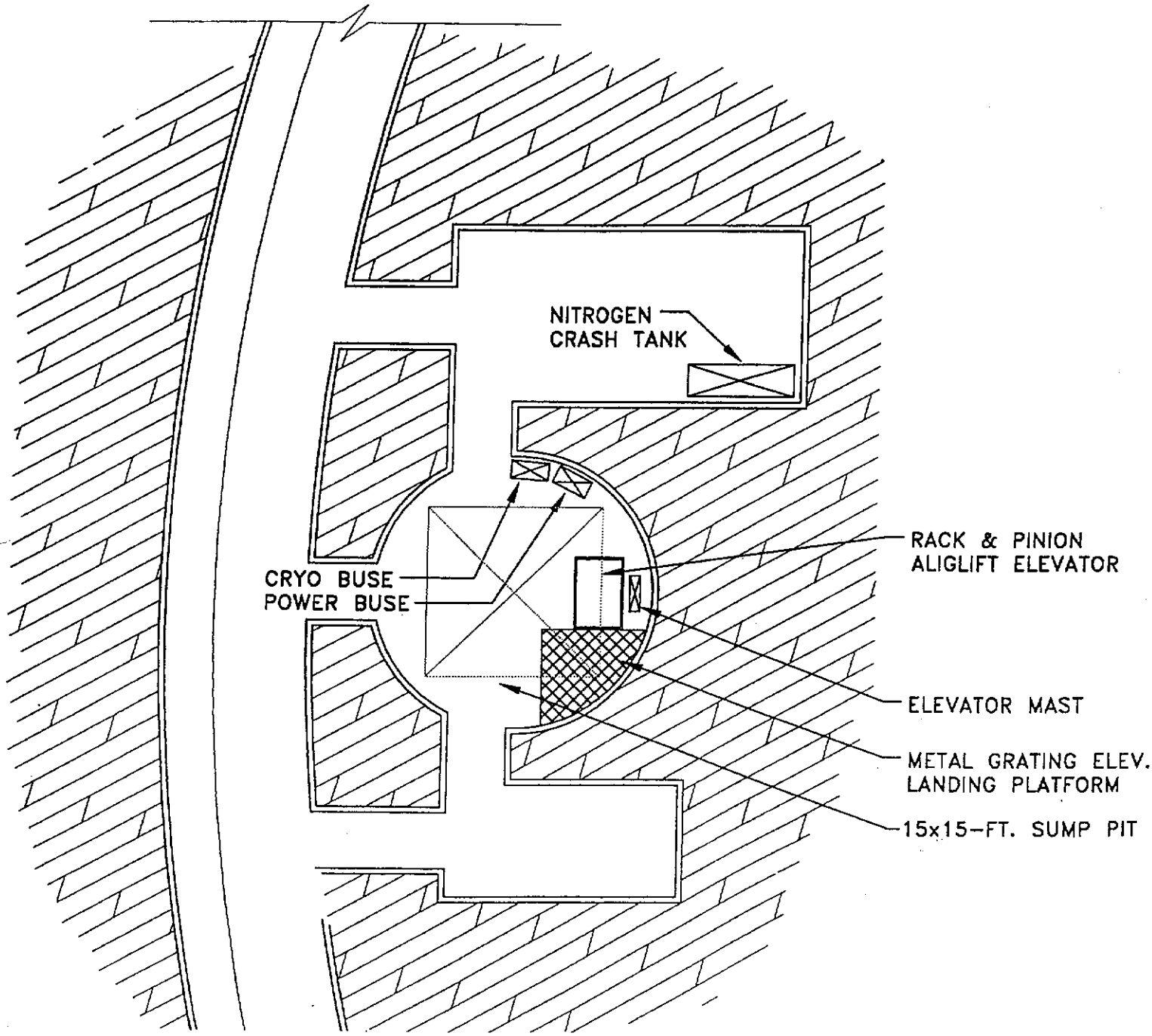
Power density in the arc dipole SC coil (left) and power dissipation in the arc magnets (right): comparison of five scenarios.

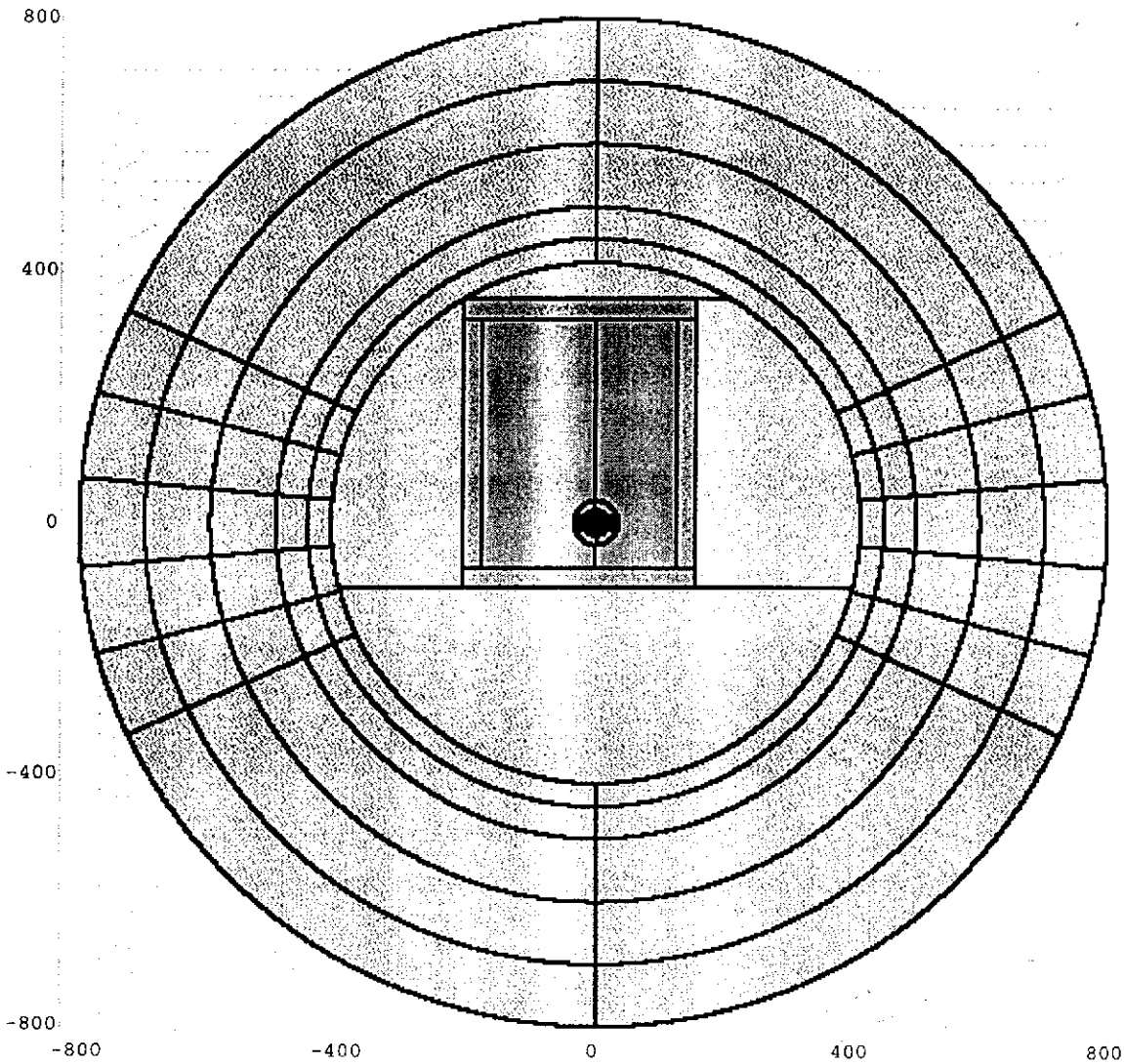
BORE TUBE OPTIMIZATION-2

Table 1: Peak power density P_{max} (mW/g) in SC coils and peak power dissipation $\mathcal{P}_{max}$ (W/m) in a bore tube and in the magnet (r>65 mm) for a 50-GeV μSR arc.

Dipole	Bore tube	P_{max} (mW/g)	$\mathcal{P}_{max}$ (W/m)	$\mathcal{P}_{max}$ (W/m)
		SC coil	Bore tube	Magnet
Bent	1-cm W	0.285	88.75	10.84
Bent	1.5x0.5 W	0.147	90.45	8.875
Straight	1-cm W	0.424	109.7	13.87
Bent	1.5x0.5 Pb	0.352	81.92	16.68
Bent	1-cm Cu	2.790	54.61	40.11

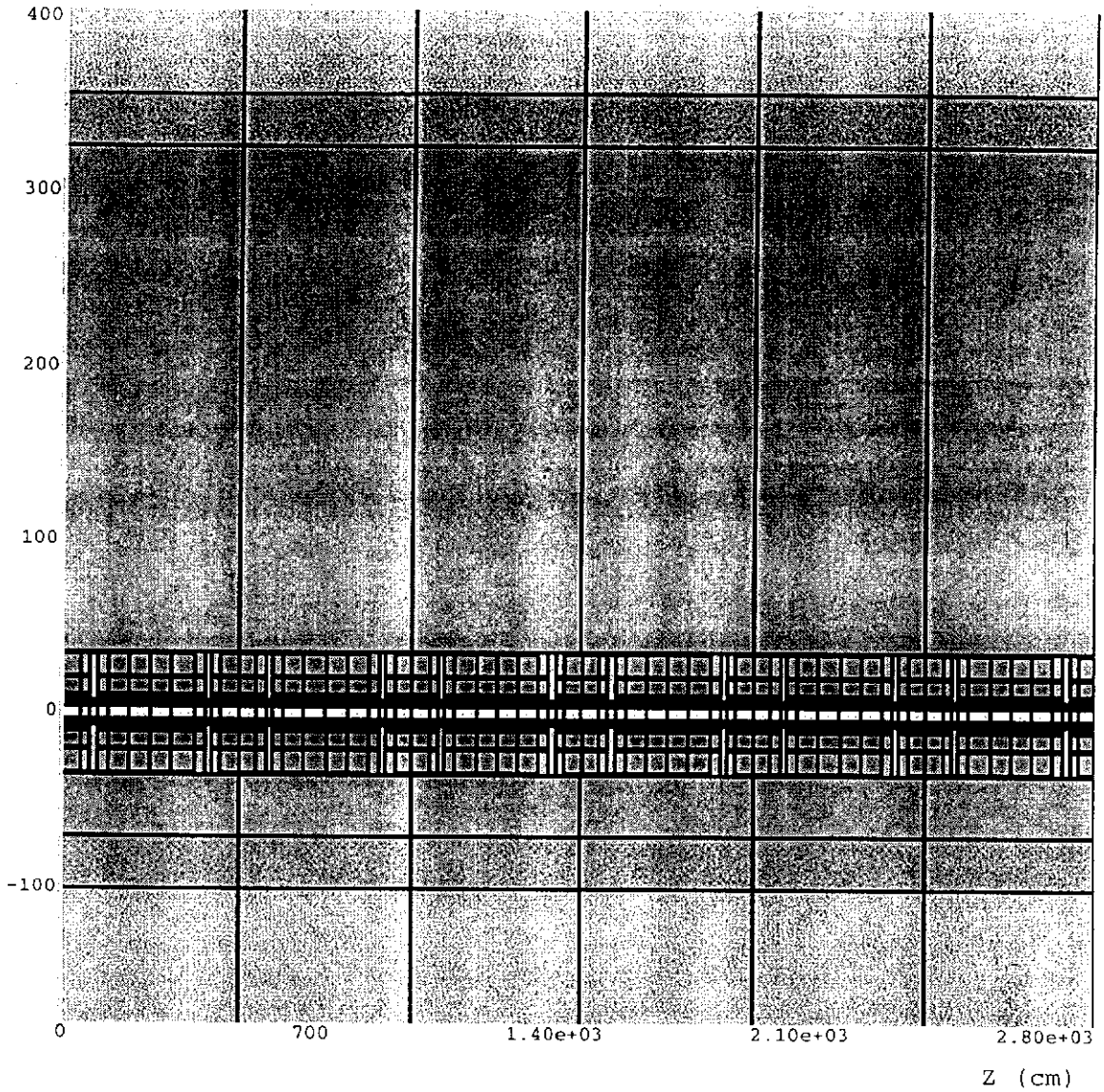

GLACIAL TILL
DOLOMITE
13'
10'

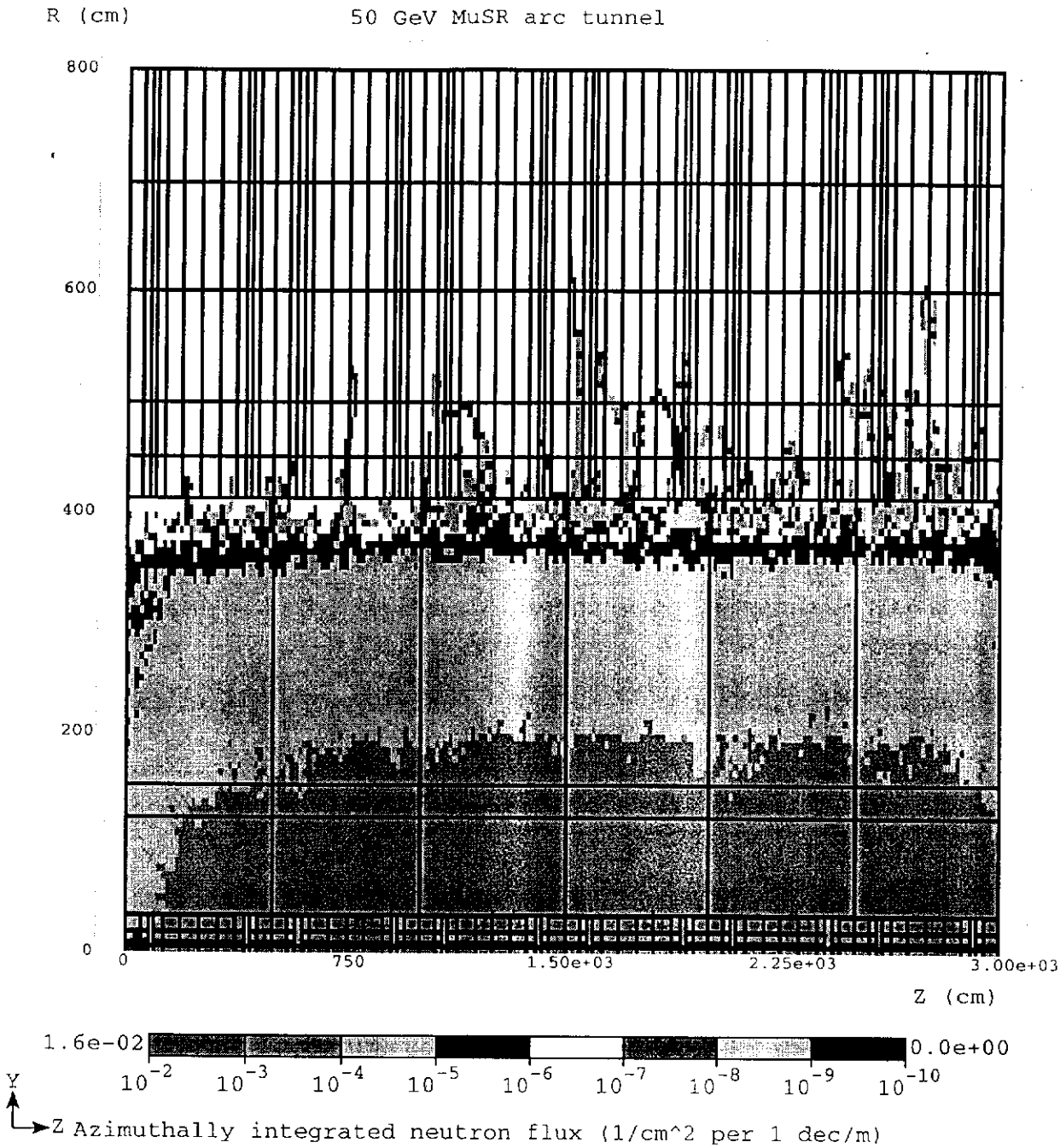

NITROGEN
CRASH TANK
CRYO BUSE
POWER BUSE
RACK & PINION
ALIGLIFT ELEVATOR
ELEVATOR MAST
METAL GRATING ELEV.
LANDING PLATFORM
15x15-FT. SUMP PIT

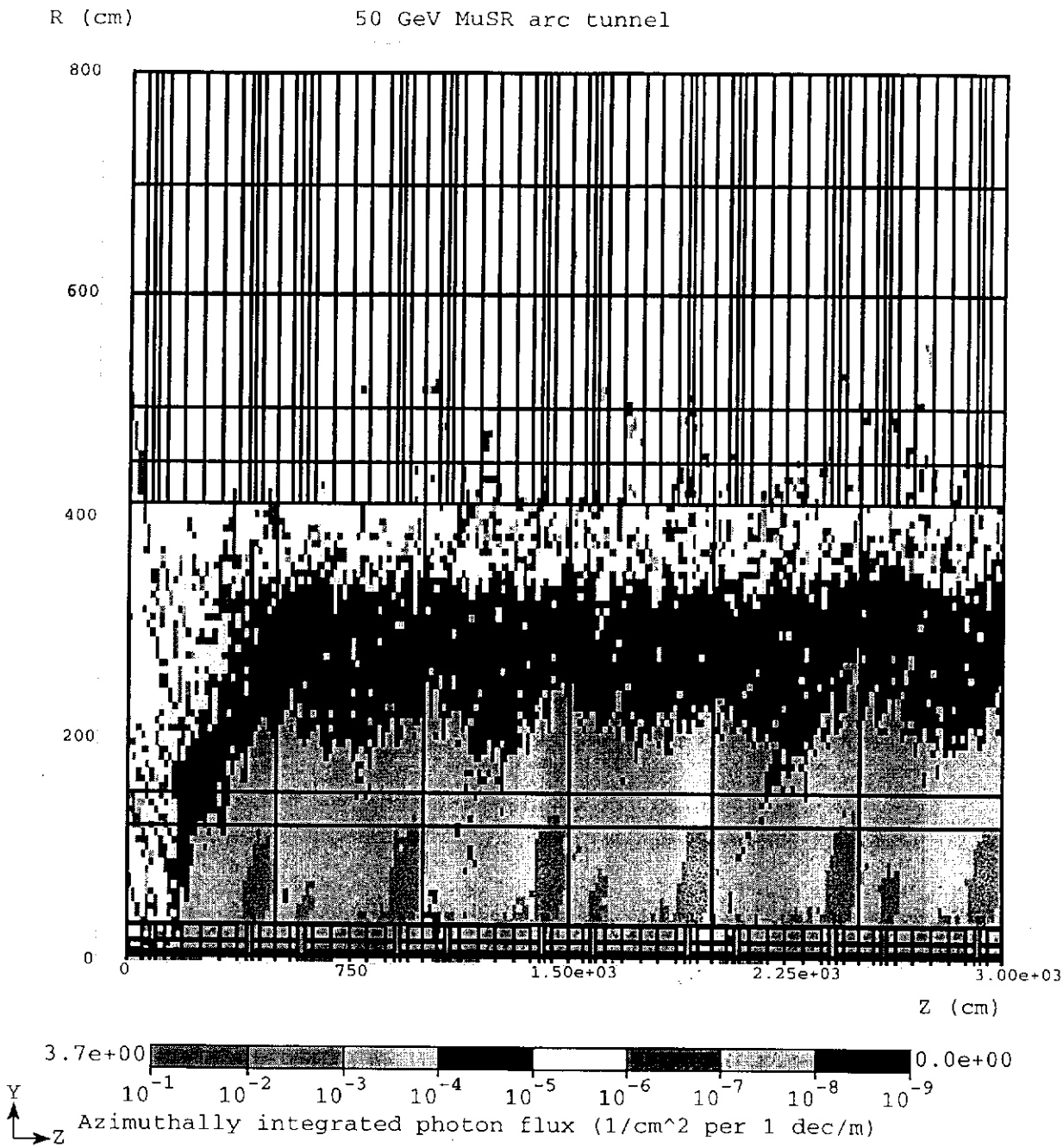

800
400
0
-400
-800
-800
-400
0
400
800

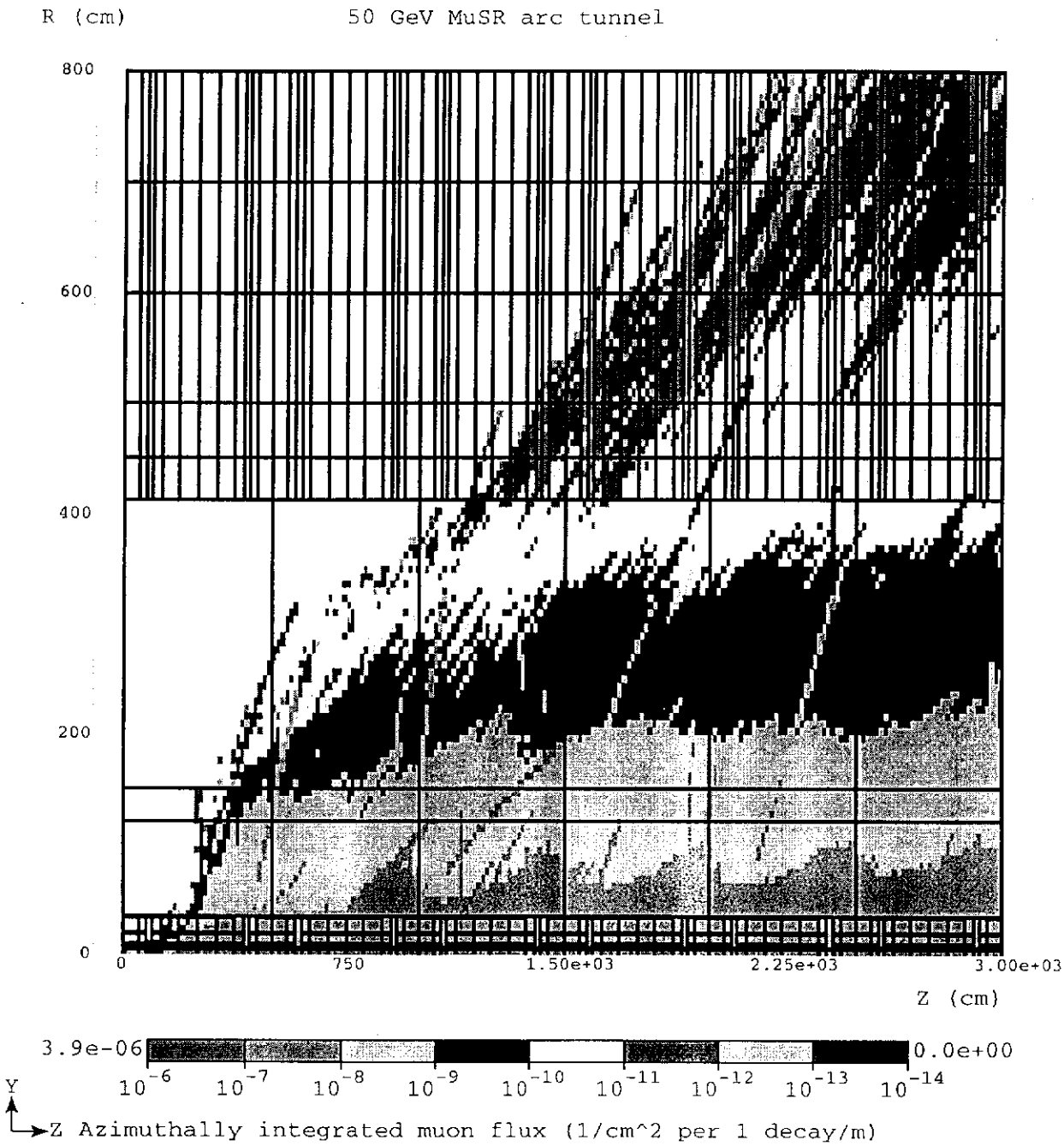
X
Y

MuSR arc tunnel

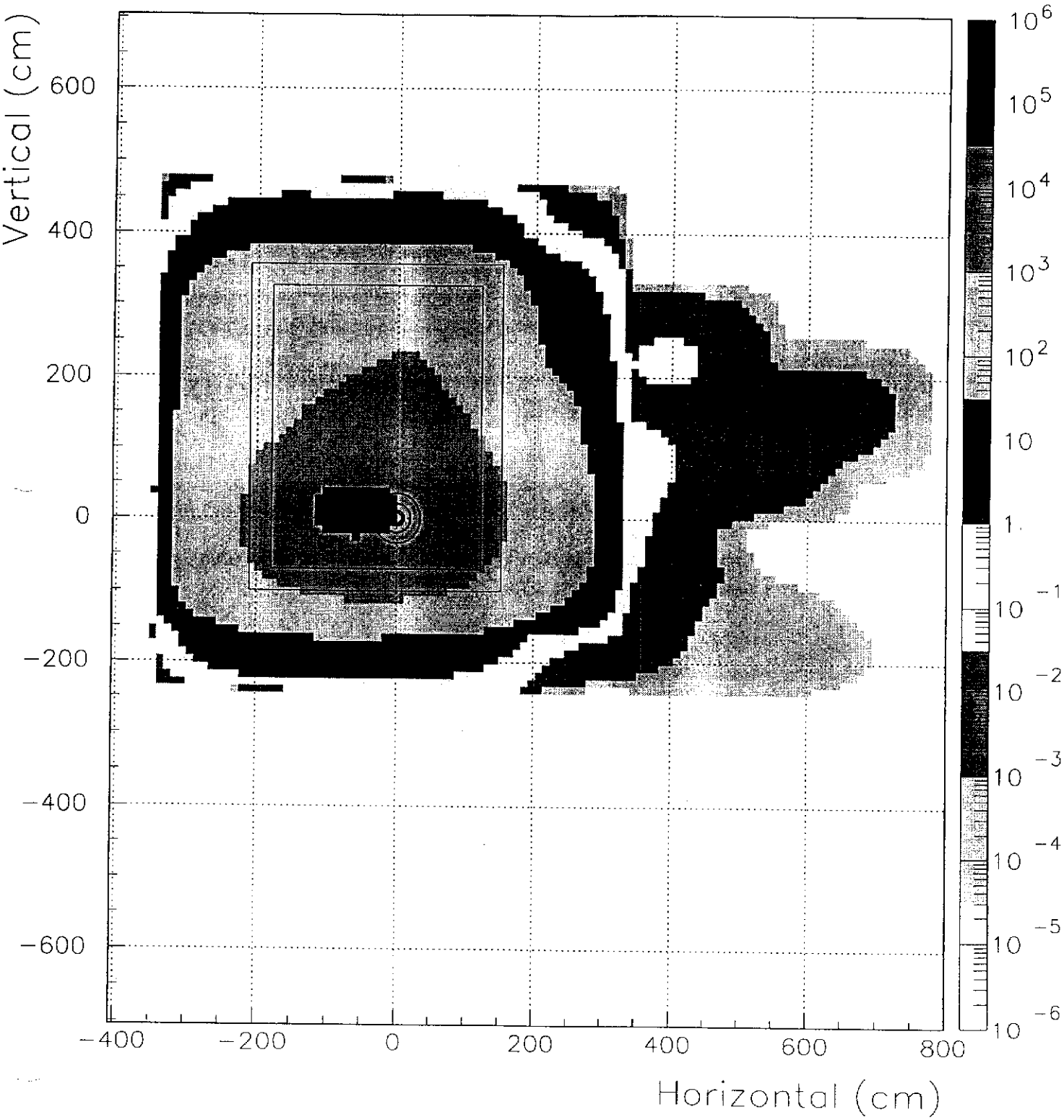



R (cm)
50 GeV MuSR arc tunnel
800
600
400
200
0
0
750
1.50e+03
2.25e+03
3.00e+03
Z (cm)
1.6e-02
0.0e+00
10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10}
Y
Z
Azimuthally integrated neutron flux (1/cm^2 per 1 dec/m)


R (cm)
50 GeV MuSR arc tunnel
800
600
400
200
0
0
750
1.50e+03
2.25e+03
3.00e+03
Z (cm)
3.7e+00
0.0e+00
10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9}
Azimuthally integrated photon flux (1/cm^2 per 1 dec/m)
Y
Z

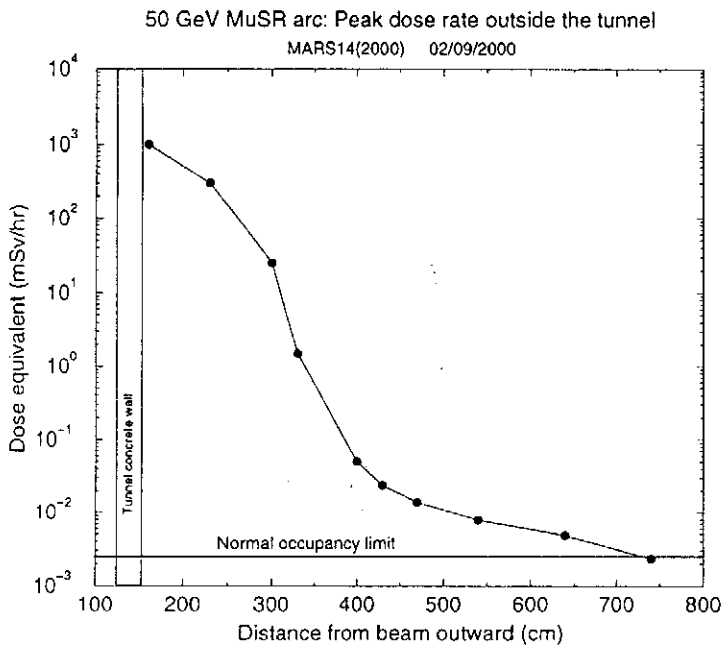

R (cm)
50 GeV MuSR arc tunnel
800
600
400
200
0
0
750
1.50e+03
2.25e+03
3.00e+03
Z (cm)
3.9e-06
0.0e+00
10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12} 10^{-13} 10^{-14}
Y
Z Azimuthally integrated muon flux (1/cm^2 per 1 decay/m)

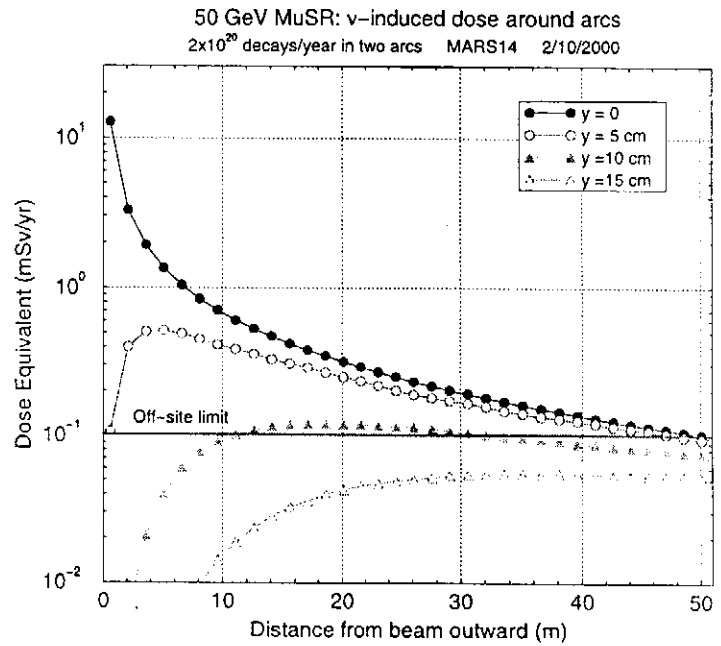
z0/02/08 18.50



50 GeV MuSR arc tunnel. Dose rate (mSv/hr)

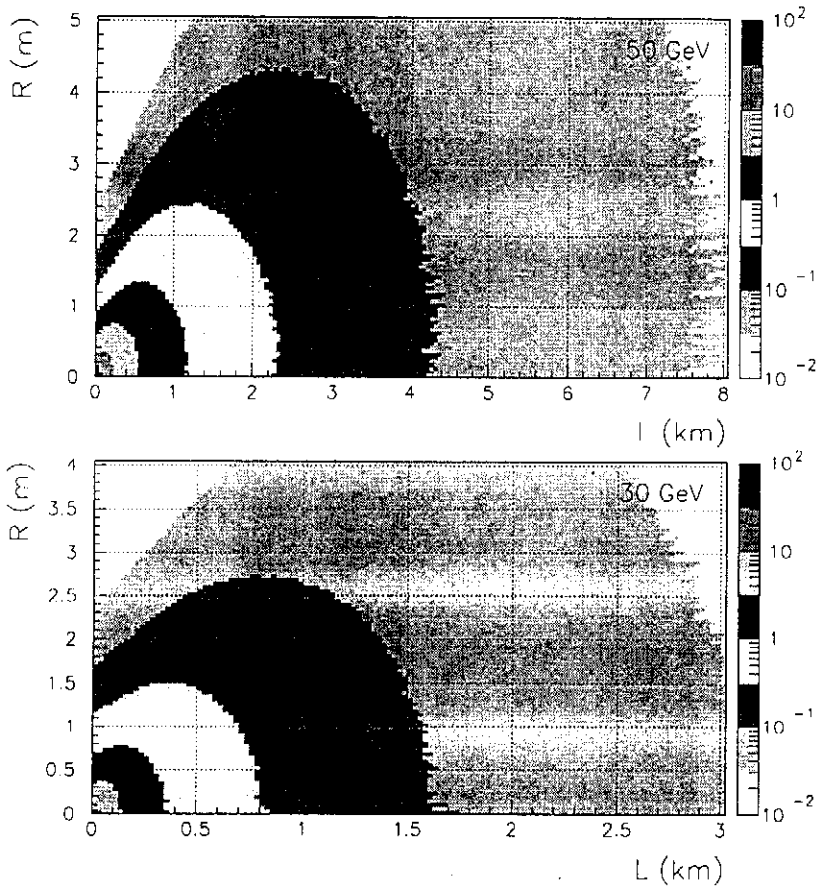
DOSE OUTWARD FROM ARC TUNNEL

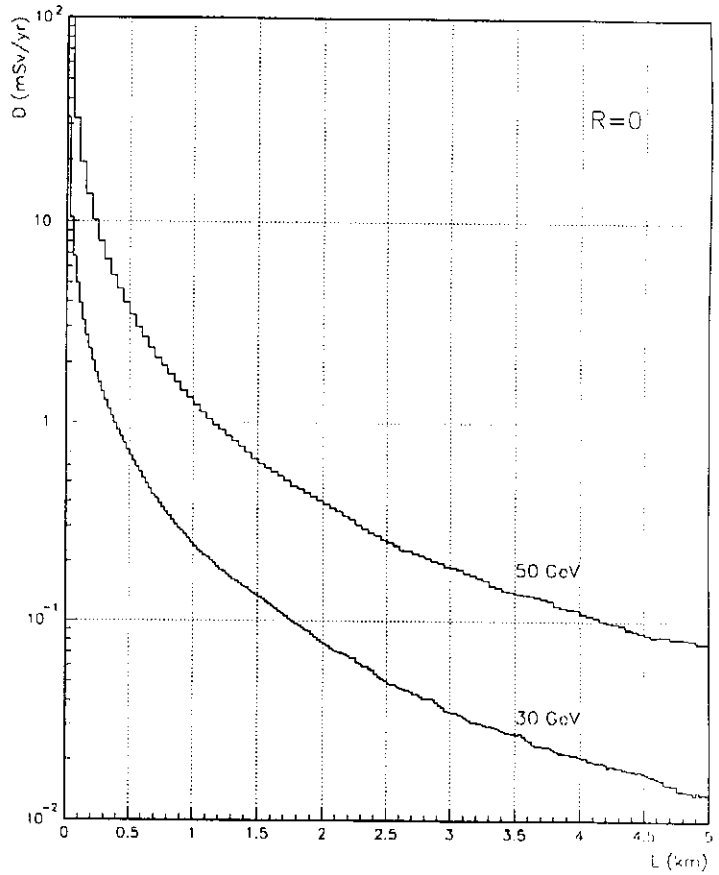




Dose distribution radially outward from the arc tunnel enclosure: conventional in mSv/hr (left) and neutrino-induced in mSv/yr (right).

DOSE DOWNSTREAM OF THE STRAIGHTS





Dose downstream of a 600-m long straight section with 2×10^{20} decays/yr at 30 and 50 GeV MuSR: isodose contours in mSv/yr (left) and axial dose (right). Off-site limit is 0.1 mSv/yr.

SUMMARY-1: MAGNETS

- Radiation load to the superconducting coils of the arc magnets due to 50 GeV muon beam decays is reduced to the tolerable levels by a tungsten (or even lead) eccentric bore tube. The later can be made of a 1-mm thick SS pipe (100×80 mm elliptical aperture) and a 1-mm thick SS pipe (122×102 mm elliptical aperture) shifted inward by 5 mm with a space between filled with a tungsten/lead type material.

- With the optimal bore tube, the peak power density in the coil is 0.15 mW/g and the peak power dissipation in the bore tube (nitrogen temperature) and in the rest of the magnet (helium temperature) is about 90 and 9 W/m, respectively. Averaged over the arc length values are about two times lower. Residual dose rates on the magnets are also quite acceptable.

SUMMARY-2: RADIATION ENVIRONMENT

- Normal occupancy limit D_1=2.5 μSv/hr is provided by 2 meters of dolomite type shielding below, above and radially inward from the arc tunnel enclosure walls. Six meters of such a shielding is needed to provide D_1 radially outward. Power supply rooms and other underground enclosures should be placed inward from the arc tunnel.

- Neutrino-induced radiation in the arcs:
  off-site limit D_2=0.1 mSv/yr is provided at 50 meters radially outward from the beam orbit. The height of such a "dangerous" disk is only $\pm$10 cm from the orbit plane.

- Neutrino-induced radiation downstream of the straight sections:
  off-site limit D_2=0.1 mSv/yr is provided at 4.2 km for a 50 GeV MuSR and at 1.8 km for a 30 GeV MuSR. The maximum half-width of a 0.1 mSv/yr isocontour is 4.3 m and 2.7 m at 50 and 30 GeV, respectively.