PROTOTYPE SSC MAGNETIZED IRON MUON DETECTOR (P757)

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INTRODUCTION

The general formula for energy loss by high energy muons in condensed matter is

$$dE/dx = I + (b + p + n) * E_{\mu}, \tag{1}$$

where the first term is due to ionization, approximately constant at high energies, and the other three terms are due to bremsstrahlung, pair production, and photonuclear effects respectively, and are proportional to the muon energy. At the critical energy the sum of the three radiation terms is equal to I. In Fe, this energy is approximately 300 GeV. The fluctuations in energy loss due to radiation are very large. This can be seen from the formula for the mean free path for the radiation of a gamma ray with energy greater than E_o:

$$\lambda = X_{RAD}/\ln(E_{\mu}/E_o), \tag{2}$$

where X_{RAD} is the muon radiation length in Fe, about 330 m. Thus while the mean free path for loss of at least 1% of the energy is 72 m, the mean free path for loss of at least 10% is 143 m, only twice as long. In one meter of Fe the latter is only half as probable as the former. These fluctuations make it impractical to consider an energetic muon trigger based on energy deposited in a reasonably thin (2 m, say) instrumented Fe calorimeter.

At muon energies well above 300 GeV, the radiation terms in Eq 1 can create electromagnetic energy above 1 GeV with a probability of a few percent per meter of Fe. This radiation can then shower with the usual 1.76 cm radiation length, resulting in a blast of ionization in a nearby tracking detector. The photonuclear term can occasionally lead to large amounts of hadronic energy. These effects will disrupt the muon tracking, and lead to erroneous momentum measurements. Since the muon spectrum in a colliding beam experiment falls very rapidly with increasing transverse momentum, measurement errors which conspire to make a muon appear more energetic than it really is are especially worrisome. It is important to determine the segmentation and total thickness of Fe required for efficient muon detection in the TeV region.

Much effort has been expended on Monte Carlo calculations of muon histories, in particular for the NA-4 muon spectrometer at CERN (1). These programs have been upgraded to muons up to 10 TeV in energy by the LHC design group (2), and can be used as a guide to detector performance. A program called MUPROP (3), which calculates dE/dx in one dimension including all four terms in Eq 1, has been used to study the energy deposited in 4.5 meters of Fe by muons of various energies. The results are shown in Table 1. Ten thousand muons were run at each energy. Above the critical energy, a constant fraction of the muons lose the same fraction of initial energy. One percent of the 700 GeV muons deposit 50% or greater in the Fe, in agreement with Eq 2.

Monte Carlo programs will be improved, and may ultimately reach the degree of complexity necessary to predict the performance of any specific SSC muon detector. However, tests of detector response to muons above the critical energy have to date only been made using cosmic ray muons (4). Good data with accelerator muons are needed to demonstrate detector performance, and to serve as a challenge to the predictive powers of Monte Carlos. Given the considerable costs of an SSC muon detector, it is important to test specific detector configurations in order to optimize the design.

The new Tevatron muon beam line (5) will provide about 10^{-5} muons per 800 GeV proton with a mean muon momentum of 500 GeV/c. About 1% of the beam will have energy above 640 GeV, and hence be of special interest for this test.

The text below will describe the test set-up, which includes a muon tagging system and a magnetized Fe spectrometer composed of 4.5 m of Fe instrumented every 0.5 m with drift chambers. Two of the 0.5 m Fe modules will be instrumented every 10 cm with scintillators for calorimetry. Because of the very high flux of the muon beam, and the rate limitation imposed by the drift chambers, two weeks of low intensity running are requested for this tet. Resources requested from the Laboratory will be given.

TAGGING SYSTEM

The proposed spectrometer will be set up behind E665 in the Muon Laboratory (6). Figures 1 and 2 show plan and elevation views of the apparatus in place at the rear of the Muon Lab. The E665 detector will have 3 m of Fe and 3 m of concrete in the muon beam as a muon identifier after their target. This material, roughly equivalent to the 4.5 m of Fe in the test spectrometer, will result in straggling of the muon energy by radiation as shown in Table 1. Re-tagging will be necessary to define the incident muon momentum to adequate precision for the spectrometer resolution measurements. To achieve this, a B2 dipole and two sets of Fenker type SWIC's will be used, as shown in the Figures. These SWIC's have 0.5mm effective wire spacing, which will give a momentum resolution $\Delta p/p = 1\%$ with the 6.5 m lever arms shown and an angular deflection of 4.5 mrad.

MAGNETS

The magnetized Fe spectrometer will be composed of nine 50 cm thick modules, each with $\int B\,dl = 1$ T m, giving a deflection $\Delta\theta = 0.47$ mrad for a 600 GeV muon. An end view of a solid Fe dipole with a vertically mounted drift chamber is shown in Fig. 3, while two views of the complete spectrometer are shown in Fig. 4. For a distance d between modules, the displacement of a muon after n modules is

$$\Delta_n = d \cdot \Delta\theta \cdot n(n+1)/2,$$

which gives a total displacement at the ninth module of 31 mm for the design spacing of 1.9 m. The projected multiple scattering angle* in 450 cm of iron for a 600 GeV muon is 0.47 mrad, so that the error from multiple scattering is 11%. A monte carlo calculation which used gaussian distributions for multiple scattering and chamber measurement errors (200 μ chamber resolution) and ignored radiation effects gave the momentum resolution as a function of p_μ shown in Figure 5. At low momenta the resolution is dominated by multiple scattering, and is momentum independent. As the momentum increases, multiple scattering becomes negligible, and the chamber measurement errors take over, resulting in $\Delta p/p \sim p_\mu$. Coincidentally, this linear rise becomes important above the critical energy for radiation effects. In this approximation the resolution for an Fe detector and an air filled solenoid are the same in the limit that multiple scattering can be

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*From the usual formula $\theta = (0.015/p(\mathrm{GeV}/c))\sqrt{X/X_{rad}}$.

neglected. The 600 GeV value obtained by fitting nine measured points to a circle was 9%. The total increase in $\Delta p/p$ over the range of momenta accessible to this test is about a factor of 1.5.

The radiative effects discussed in the Introduction will degrade the resolution at higher energies, perhaps causing a steeper rise than that shown in the figure. In addition, since the rise occurs when multiple scattering becomes negligible relative to spatial measurement errors, plural scattering may also contribute to further degradation. The objective of this test is to accumulate data on the effective resolution function for the highest energy muons available, and to check the energy dependence at two lower beam energies.

The magnets shown in Fig. 4 represent half of the total number of solid Fe dipoles used in E203/391 (7). The entire length of coil will be used, giving an open lattice appearance to the detector. The magnetic field uniformity of these magnets has been carefully studied by their previous owners. The field in the Fe is known to better than 1%. The coil operates at 4000 A and 100 V.

DRIFT CHAMBERS

The complete spectrometer will use 18 drift chambers of the type built by the Illinois group for the central muon detection system of CDF. These chambers are 10" wide by 4" deep by 8′ long, with 16 sense wires per chamber in four parallel planes. Alternate anode wires are slightly offset to resolve left-right ambiguities. The chamber resolution is 200 μ. Two chambers will be mounted verticaly in each gap between magnetized dipoles.

The drift chambers are designed to operate in the limted streamer mode and to drive CDF Rabbit system electronics, which digitizes one TDC hit and two pulse heights per wire. These measurements give the drift distance normal to the wire and the coordinate along the wire by charge division respectively. The maximum safe hit rate in this mode is 1 kHz. For the present test double hit and higher rate capabilities are both desirable. We therefore propose to operate the chambers at lower gain, in the proportional region, and to use CAMAC electronics from PREP to record the data. The system will then be able to handle 10 kHz rates without serious data loss.

TRIGGERS

For efficient data collection during the requested low intensity running, an on-line trigger tag of high momentum muons is desirable. If this is not practical, an increase in the energy of the muon beam line so that the spectrum centers at 640 GeV/c is an alternative. With a high momentum flux of about 100 Hz during the Tevatron spill, all of the muons which traverse the spectrometer could be recorded. Events in which a large amount of shower energy is deposited in one of the two instrumented modules will be flagged, as will events where the muon trajectory has scattered a distance comparable to the magnetic deflection in the bend plane. Since the modules are made of five 4" thick Fe plates, scintillators placed in between the gaps will sample electromagnetic (or hadronic) energy deposited every 6 radiation lengths. Two scintillation hodoscopes with 1/4" fingers will serve to flag large muon scatters, in order to study the non-Gaussian tail of the scattering distribution.

Drift chamber alignment will be done by triggering on halo muons which go underneath the magnets. To calibrate the instrumented Fe modules' response to energetic electrons, a radiator will be placed upstream of the tagging magnet, and that magnet will serve as a pair spectrometer for muon produced e^+e^- pairs.

RUN REQUIREMENTS

The muon beam will normally operate for E665 at 500 ± 70 GeV with a 20 sec Tevatron spill and a total muon flux of 10^7 per spill or greater. The high momentum tail above 640 GeV/c will be about 1% of the total beam, corresponding to an instantaneous rate of over 10 kHz. The spatial separation between the main beam and the high momentum tail will not be sufficient to allow the high intensity beam to miss the drift chamber spectrometer. Consequently, for a clean test we request two weeks of low intensity running near the end of the Tevatron fixed target running period which is currently scheduled to begin in January, 1987. With a total beam intensity of 10 kHz during the spill, the flux above 640 GeV/c will be 100 Hz, giving over 10^5 events per day. Runs at the two lower beam momenta, perhaps 200 and 400 GeV/c would be advantageous to document the detector response through the critical energy region.

FACILITIES REQUESTED

1. Tagging system
   a. B2 main ring dipole and Transrex supply
   b. Four Fenker SWIC chambers and read-out electronics
2. Solid Fe dipole spectrometer
   a. Rigging of nine Fe Dipoles of the coil
   b. Transrex supply
3. Data handling system
   a. PDP 11/45 computer with 6250 bpi tape drive and Bison box
   b. CAMAC interface
   c. Three CAMAC crates with branch drivers
   d. 30 units LRS 2285 24 channel CAMAC ADC's[a]
   e. 18 units LRS 4290 32 chanel CAMAC TDC's[b]
4. NIM logic
   a. Three NIM crates
   b. Four LRS 365 dual 4 fold coincidence units
   c. Six LRS 821 quad discriminators
   d. Two LRS 127FL 8/16 fan outs
   e. Two LRS 222 dual gate generators
5. High voltage supplies for 18 drift chambers and 50 PM tubes
6. Computing: 100 hours of CYBER time

a) There are are 288 drift chamber anode wires, and two ADC channels are required per wire for charge division.

b) Each wire will be connected to two TDC channels, one with common start and the other with common stop, to give double hit capability.

TABLE 1

PRELIMINARY STANEV MUON MONTE CARLO RESULTS
1000 MUONS PER ENERGY

PERCENT OF ENERGY DEPOSITED IN 4.5 METERS OF IRON
(A = 55.85, Z = 26, DENSITY = 7.86 gm/cm^3)

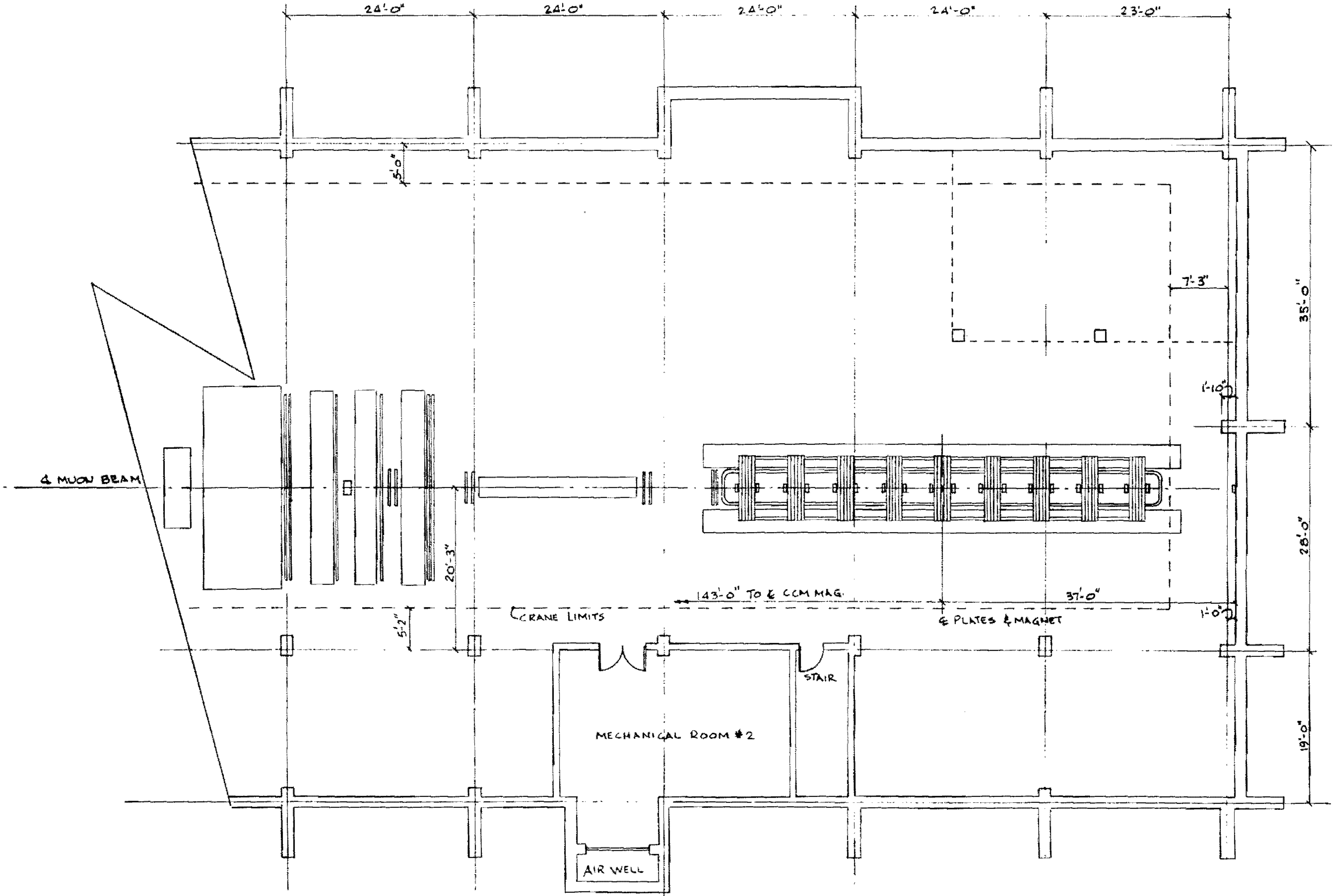
GeV	0% 10%	10% 30%	30% 50%	50% 70%	70% 90%	90% 100%
2	0	0	0	0	0	10000
9	0	0	42	1161	5172	3625
15	0	377	4962	4108	391	162
50	6332	3421	150	63	19	15
75	9021	751	129	72	14	13
100	9344	464	95	63	22	12
300	9513	296	101	51	31	8
700	9526	282	94	62	24	12
1000	9526	261	106	62	36	9
5000	9466	297	120	82	40	15
10000	9496	271	117	76	28	12

REFERENCES

1. R. Kopp, Ph.D. Thesis, University of Munich, 1984.
2. R. Voss and C. Zupancic, Report of the Muon Detection Group at the LHC Workshop, CERN, 1984.
3. T. Stanev, MUPROP-Set of program routines for Monte Carlo propagation of Muons, Bartol Technical Report 83-41, The Franklin Institute, University of Delaware, Newark, Delaware.
4. See, for example, H. Inazawa and K. Kobayakawa, Proceedings of the 17th Cosmic Ray Conference, Paris, 1981, p. 94.
5. A. Malensek and J. Morfin, The Tevatron Muon Beam Fermilab TM 1193, July 1983.
6. F. J. Hazert et al., Fermilab Proposal 665, "Muon Scattering with Hadron Detection at the Tevatron".
7. A. V. Barnes et al., Fermilab Proposal 640, "The Multimuon Spectrometer at the Tevatron".

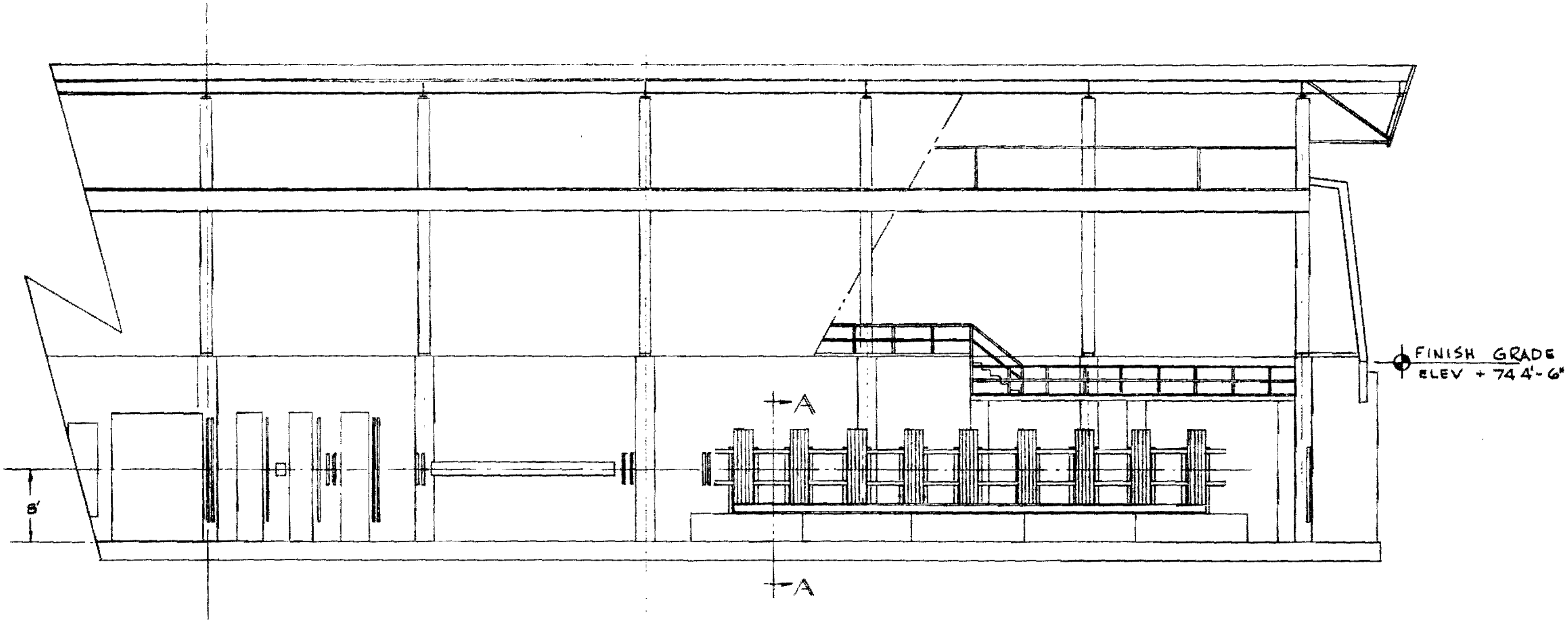
FIGURE CAPTIONS

1. Plan view of the proposed test spectrometer set up behind E665 in the Muon Lab. The tagging magnet is shown between the two experiments.
2. Elevation view of the proposed test spectrometer.
3. End view of a spectrometer module showing the vertically mounted drift chamber extending below the magnet Fe in order to use halo muons to align the drift chamber wires from one plane to the next. The magnets will be mounted on concrete blocks.
4. Detailed plan and elevation views of the spectrometer itself, showing the locations of the drift chambers and the gaps between the modules. The coils for the dipole field run continuously through slots in the Fe.
5. Calculated momentum resolution vs muon momentum resolution vs muon momentum for the nine module array, assuming gaussian widths to multiple scattering and position resolution, and no radiative effects



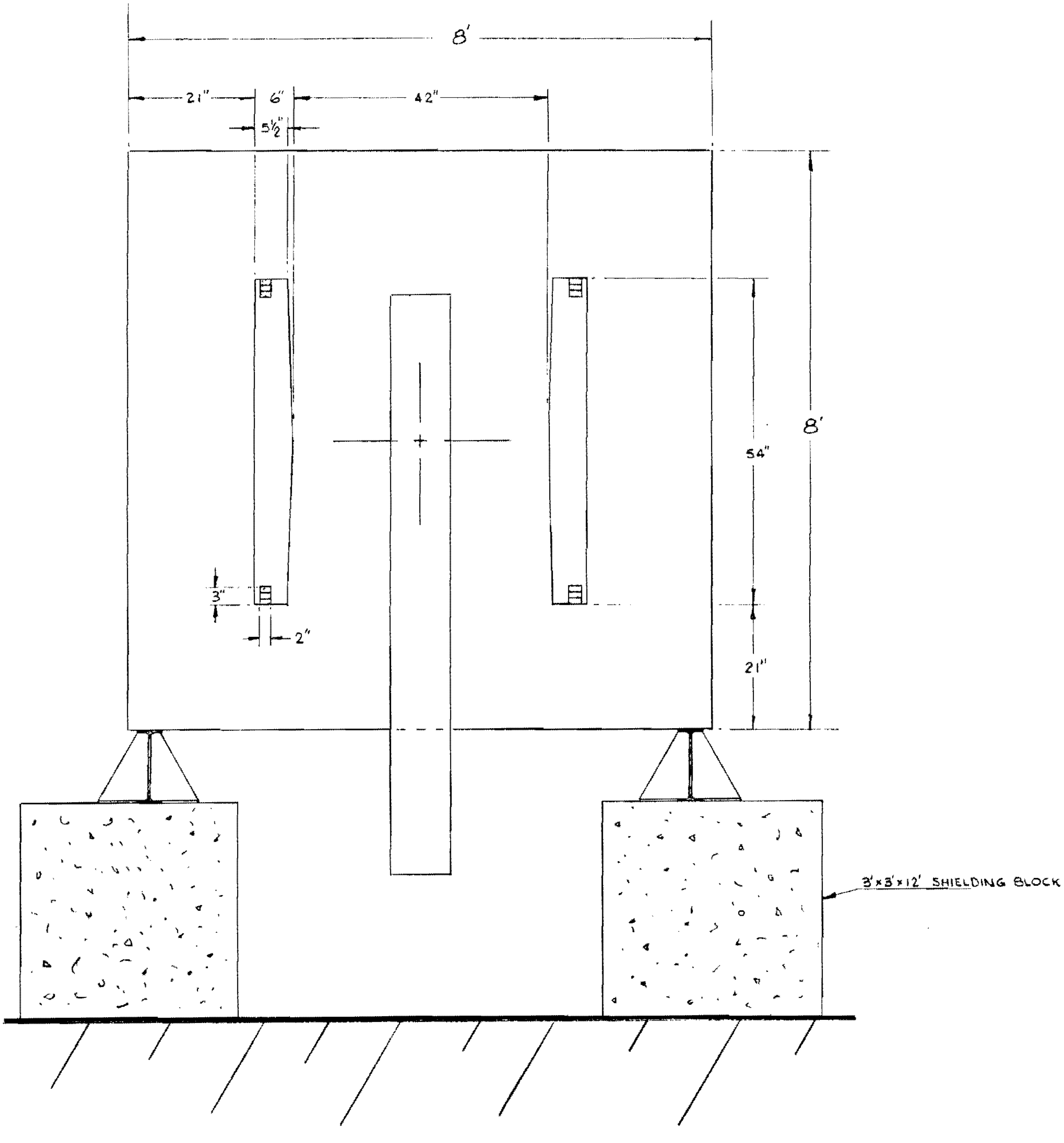
MUON LABORATORY
PLAN VIEW

Fig. 1



MUON LABORATORY
ELEVATION VIEW

Fig. 2



SECTION A-A

1/12 SCALE

Fig. 3

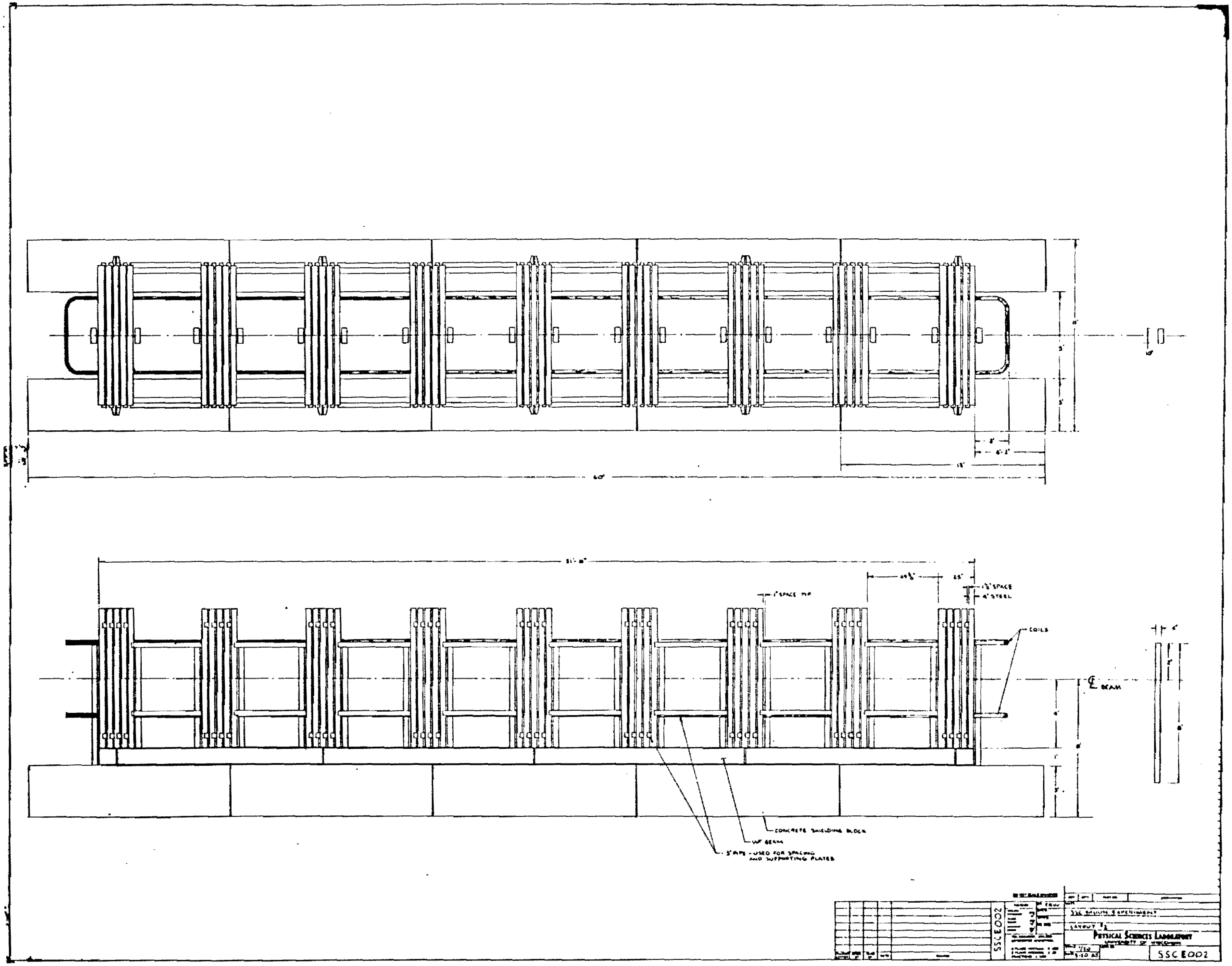

60'
51'-8"
1" SPACE TYP
25"
1½" SPACE
4" STEEL
COILS
℄ BEAM
CONCRETE SHIELDING BLOCK
WF BEAM
3" PIPE - USED FOR SPACING AND SUPPORTING PLATES
SSC MUON EXPERIMENT
LAYOUT
PHYSICAL SCIENCES LABORATORY
UNIVERSITY OF WISCONSIN
SSC E002

Fig. 4

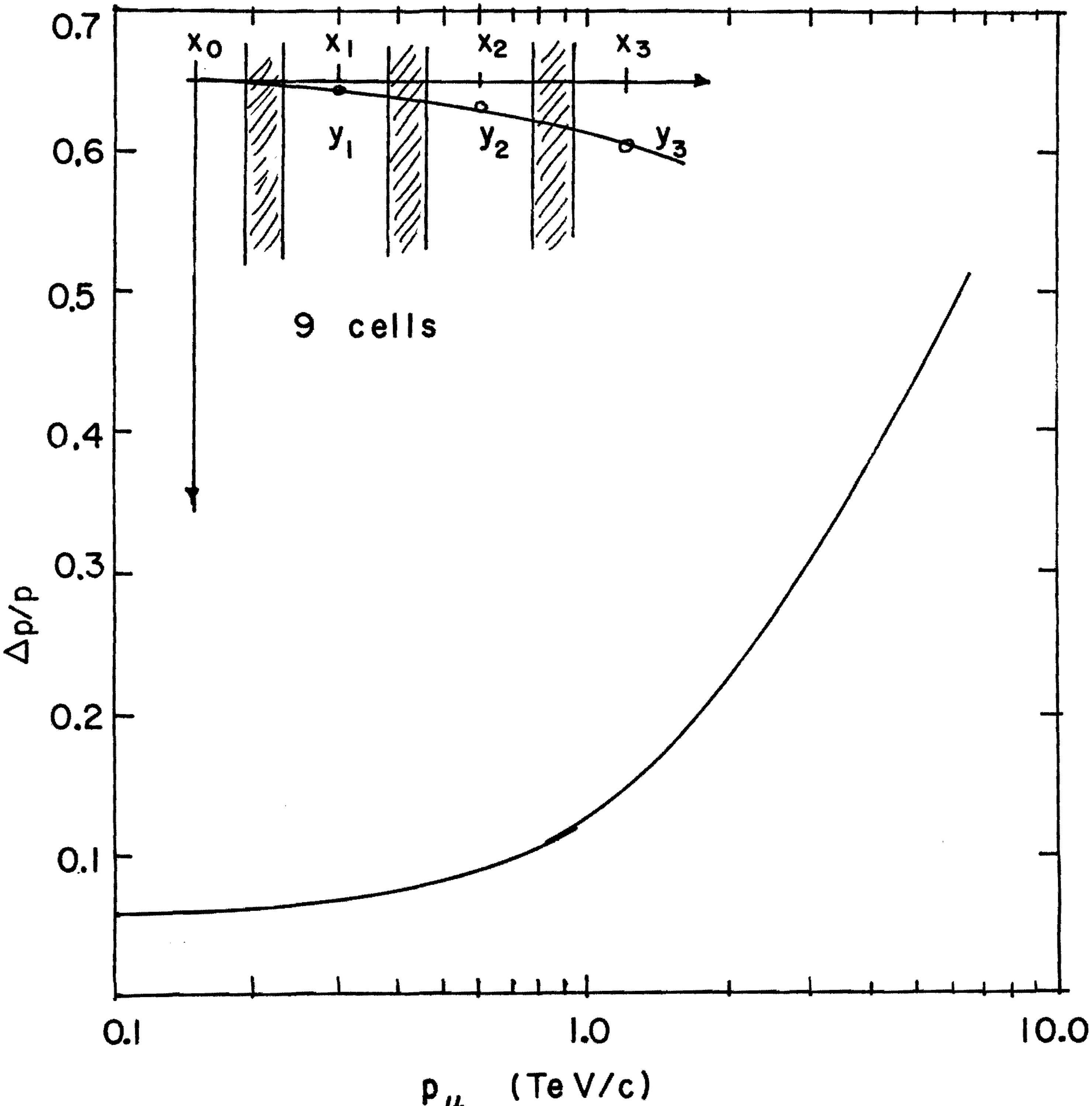

0.7
0.6
0.5
0.4
0.3
0.2
0.1
Δp/p
0.1
1.0
10.0
p_μ (TeV/c)
x_0
x_1
x_2
x_3
y_1
y_2
y_3
9 cells

Fig. 5