#531

A PROPOSAL TO STUDY WEAK DECAY LIFETIMES OF NEUTRINO PRODUCED PARTICLES IN A TAGGED EMULSION SPECTROMETER

We propose to tag neutrino interactions within nuclear emulsions and study lifetimes of resulting weakly decaying particles. The one-micron resolution of emulsions permits observation of lifetimes in the range 2×10^{-15} seconds to 3×10^{-12} seconds; drift chamber tagging will localize each event vertex to within a volume of roughly 3 mm^3, limiting the scanned emulsion to less than 10^{-3} of the total volume.

An existing spark chamber magnetic spectrometer system will be converted to drift chambers for more precise momentum reconstruction of charged prongs including muons, and an existing lead-glass array will aid in reconstruction of electromagnetic showers from π^o decays and rare direct electrons. Muons will be identified by range and by requiring small pulse heights in scintillation counters and single tracks in existing spark chambers placed within a thick steel wall located just downstream of the spectrometer.

A four-month run with 3×10^{18} protons should produce 3,300 neutrino interactions in the emulsion, of which at least 2,000 should be detected and analyzed.

By studying every tagged neutrino interaction we hope to directly measure more than 100 observable track length weak decays.

531

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TABLE OF CONTENTS

A. Summary of the Experiment

We propose to study the decay lifetimes of charmed bosons and baryons in a tagged nuclear-emulsion apparatus exposed to the Fermilab neutrino beam. A three- to four-month run with the double-horn beam and 3×10^{18} protons on target will yield over 3,000 events, each tagged by our counter system. We propose to scan the emulsion for every event. Assuming a conservative 60% efficiency for tagging and finding events in the emulsion, a 6% ratio of charmed-particle production to total neutrino interactions and lifetimes in the range 2×10^{-15} to 3×10^{-12} seconds, we can achieve our desired goal of 100 measured charm decays. (We note that 4×10^{18} protons, 80% tagging and a 10% ratio of charm production are all possible and would yield 320 observed decays.)

The proposed spectrometer will measure charged-particle momenta by magnetic analysis, and π^o's through conversion in the emulsion and/or the existing lead-glass spectrometer. It will thus be possible to convert decay-length measurements to lifetimes of an accuracy compatible with our expected statistics. In addition, the experiment will yield useful information on weak interaction production processes of charmed particles such as charged and π^o multiplicity, approximate x and y distributions and associated Vees. The partial measurements of the decay particles will provide information on decay branching ratios of both charmed baryons and bosons. The possibility of observing weak decays of entirely new particles such as hadrons containing heavier quarks of new flavors or heavy leptons provides further interest in this experiment.

Because of reliance on a conservative design and a large amount of existing tested equipment and techniques, we could be ready for the expected heavy period of neutrino running early in 1978, if approved in March.

B. Physics Motivation of the Experiment

The existence of charmed bosons has been established by the SPEAR results on $K(n\pi)$ final states. There are strong indications of the existence of charmed hadrons from Fermilab and Brookhaven. The observation of parity non-conservation in the D decays at SPEAR and the decaying tracks observed in the E247 neutrino emulsion experiment and the Nagoya cosmic ray and Fermilab proton exposures indicate the possibility of weak decays with lifetimes measurable in emulsion. The fact that over 1% of all neutrino interactions have di-leptons, and the strong indication that the μe events may be associated with a kaon excess provides clear impetus for studying a large sample of neutrino interactions in a tagged emulsion system. It seems particularly desirable to make use of the next major double-horn run for this purpose.

Accepting the existence of charm as a working hypothesis, we might expect the $c\bar{d}$, $c\bar{u}$ and $c\bar{s}$ bosons (D^+, D^o and F^+ in the notation of reference 1) each to decay weakly with different lifetimes. Several of the charmed baryons (such as the $\bar{\Lambda}\pi\pi\pi$ resonance discovered at Fermilab) might also be expected to decay weakly with measurable lifetimes. This reinforces the need for an emulsion experiment with statistics increased by an order of magnitude over E247, and with good ability to reconstruct tagged events.

One may also speculate that this experiment has the ability to search for leptonic decays of both chargedand neutral leptons, and weak decays from particles containing heavier quarks of new flavors, provided these occur with lifetimes greater tha 2×10^{-15} seconds and rates in excess of 1/2% of the total neutrino interaction.

C. Description of the Experiment

The experiment proposes to use a hybrid emulsion spectrometer. Emulsion, with a position resolution of better than one micron, permits direct observation of particle decays with lifetimes as short as 2×10^{-15} seconds. Drift chambers, with a FWHM resolution of better than 0.2 mm, will localize each interaction within a scanning volume of 3 mm^3 (about 10^{-2} liters when summed over 3,000 events).

Immediately downstream of the emulsion target region will be a magnetic spectrometer, an array of shower counters, and a steel muon identifier, as shown in Figures 1 and 2.

Discussion of the experiment will be divided into four sections; emulsion, electronic spectrometer, electromagnetic shower measurement and muon tagging. Other equipment which could be added as time and manpower permit will be discussed briefly in an appendix.

We plan to rely heavily for equipment and software on an existing charged-neutral spectrometer which we have operated for the past three years at ANL, and which is now in its final stage of data collection.

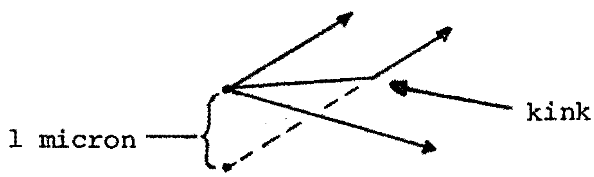
1. Emulsion:

It is assumed that 26 liters of emulsion (100 kg of AgBr loaded gelatin) will be used in the exposure. These will be divided into two planes of roughly 10 and 16 liters, each 5 cm in thickness along the neutrino beam direction. Each emulsion plane will be subdivided into a large number of elements (≈50) which can be individually removed and scanned upon the identification of interesting events within the module. A small number of modules will be developed as soon as they contain ~5 interesting events to allow an early start on the improvement of event-finding techniques.

Use of 5-cm thick emulsion planes minimizes problems due to warping of the outside ≈2 mm of emulsion during processing but eliminate the possibility of external electronic tagging of directly produced electrons. Of course, direct electrons may be identified by their highly visible shower topology as each event is scanned in the emulsion.

Charged-particle decays can be detected in the emulsions provided the decay angle exceeds 5 milliradians. For particles with multiple decay products and/or with special computer-aided emulsion-digitizing equipment, this angular resolution could possibly be halved.

In the case of decays with only a kink (single charged particle in the decay products), track intersections removed from the main event by as little as 1 micron are detectable.



Furthermore, below 1 GeV/c it becomes increasingly possible to separate known momentum kaons from pions by investigating multiple scattering and dE/dx losses within the emulsion.

In order to calibrate locations of emulsions great care must be taken in constructing a precise emulsion holder. Careful processing techniques must be used, and straight through muons must be tagged. From the results of E382, it appears that events may be found with an efficiency of greater than 60% within a fiducial volume of 1/2 mm x 1/2 mm x 10 mm (3 mm^3).[2]

Tagged muon background tracks will in addition serve to calibrate ionization standards and as a reference correcting for distortion effects. However, the integrated muon intensity should be kept well below $5\times10^4/cm^2$ to avoid undue confusion in finding the events. This is ten times smaller than the present flux (for 3×10^{18} protons) at the Wonder Building; we are thus counting on a fraction of the 10^3 reduction estimated for the muon spoiler under construction for E253. See Appendix II. for details of the emulsion stack.

2. Electronic Spectrometer:

This part of the apparatus may be divided into two major areas; target region and magnetic spectrometer.

a. Target Region:

The target, as shown in Figure 1, consists of two emulsion planes, each followed by 6 drift chamber planes, the minimum number needed to give reasonable efficiency while resolving left-right and multiple track ambiguities. Spacing the first chamber slightly away from the emulsions damages the vertex localization by a factor of 2 in emulsion volume but insures that the sense wires will not be saturated by multiple hits. We also plan to use small sense-wire spacings (0.6 and 1 cm) in the target region to help in this regard. The use of small angle stereo simultaneously removes left-right and multiple track ambiguities with a minimum number of chambers. However, assuring reconstruction in a non-uniform fringe magnetic field may require a spark-chamber or extra drift-chamber plane per emulsion layer. These matters are currently under active Monte Carlo investigation. Assuming ambiguities may be resolved, multiple scattering within the emulsion (radiation length = 2.94 cm) and curvature in the magnetic field limit precision vertex reconstruction to particles with momenta in excess of 2 GeV/c. These tracks are likely to pass deep into the spectrometer, and hence it will be possible to correct for their curvature using known momenta. A worst case uncertainty from multiple scattering of 0.5 mm FWHM will occur if the event occurs at the upstream face of the emulsion. For these events, it will be necessary to scan 10 mm^3 of emulsion, four times the volume needed if the event were to occur near the downstream face.

b. Magnetic Spectrometer:

If mass fitting is to be performed for events of interest, it will be necessary to momentum analyze charged particles from such interactions.

We plan to use the ANL SCM-104 magnet and power supply system which we have used for the last three years for precision spectroscopy. The field is well mapped and extensive on- and off-line software exists for tracing particles through the full magnetic aperture. The layout is shown in Figures 1 and 2, and a drawing of the magnet in Figures 3 and 4.

Prongs within a core of ±0.2 radians may be analyzed by this system to an accuracy of roughly $\delta P/P \cong 0.006$ P FWHM, where P is in GeV/c.

Tracks out to ±0.3 radians may also be fully analyzed, though prongs from the emulsion edges may not pass through the full magnet and will be analyzed as much as five times more crudely in $\delta P/P$ than given above. Most events will be fully visible to ±0.5 radians; a Monte Carlo is in progress which will be included as an appendix at a later date.

3. Electromagnetic Shower Measurement:

Electromagnetic shower measurements are important to our experiment in two ways. By identifying electrons originating directly from the decay vertex we can obtain information about semi-leptonic branching ratios and further confirmation of the presence of weak interactions. Secondly, it is important to measure, as accurately as possible, the energies of π^0's in either the production or decay final states.

The emulsion itself is the primary detector of electromagnetic particles. Each emulsion layer is 1.7-radiation-lengths thick and therefore direct electrons will traverse, on the average, 0.85 radiation lengths before emerging from the emulsion module in which they are produced and for energies over 1 GeV, >60% of them will have produced at least one other associated observable electron in the emulsion. Electrons which exit the first emulsion stack will virtually all (>99%) produce a shower in the second stack which will be indentifiable in the chambers alone. All tracks that produce energetic showers in the lead glass will be traced back to the emulsion and associated where possible with the appropriate primary. This complex analysis will be practical because of the small total number of events in the experiment. The probable effectiveness of this process is under study by Monte Carlo methods. The approximate probabilities given above are derived from the shower tables of Messel and Crawford. Direct electrons that do not shower in the emulsion will be well measured and identified in the lead-glass counters. Each π^o produced at a primary or decay vertex produces two decay photons and thus an average traversal length in its own emulsion stack of 1.7 radiation lengths. The probability of at least one pair production is thus ~73%. For the great majority of these the origin of the pair will be closely assignable to the production or decay vertex. All showers will be measured as fully as possible using the momentum measurements of slow electrons and positrons in the tagging chambers which are immersed in the fringe field of the magnet, the shower and direction information from the emulsions, and the energy measurements of the lead glass.

The lead-glass array will be constructed from 56 blocks, 12-radiation-length blocks used at ANL for the last three years and for which the software and gain monitoring hardware have been thoroughly tested. The central 16 blocks of 13 radiation lengths will consist of 12 blocks used in E25A and 4 new blocks to be purchased for this experiment.

4. Muon Tagging:

Muons will be tagged by demanding passage through several interaction lengths of steel without showering. The spectrometer will provide momentum information which below 75 GeV/c will be superior to that which could be obtained from conventional toroid systems.

The design for a muon range identifier is shown in Figure 2. The system consists of 3 feet of steel fully covering ±0.25 radians and 9 feet of steel fully covering ±0.15 radians. A system of wire spark chambers provides information on whether hadronic interactions took place as particles progressed through the steel. The chambers and all associated pulsing and readout electronics already exist.

At wide angles where the steel is thin, a small number of long liquid scintillation counters with end-to-end timing will be used to give additional pulse height information discriminating against showering hadrons. All phototubes, supplies, much fast electronics and all techniques exist from our previous Fermilab experiment, E12. This system is somewhat inferior to those with larger volumes of steel but is well matched to our spectrometer, which has a 2-meter path permitting decays prior to reaching the steel. In this path most kaon decays would be detected by observation of the decay angle, but most pion decays would go undetected, giving rise to a di-muon contamination above 2 1/2 GeV of about 2%, double the true signal.

D. Experimental Rates and Acceptance

1. Event Rate:

The calculation of running time is based on the rate for E53A as reported in "Neutrino Event Rates at FNAL," Howard B. White, Jr., June 18, 1976. For 400 GeV running one expects 0.8 events/20 tons/10^{13} protons at the 15-foot bubble chamber. Using a $1/R^2$ intensity variation and a realistic extended neutrino source, one expects an increase of 2.5 for this number at the Wonder Building.

The density of Ilford emulsions is 3.82 g/cm^3, corresponding to 0.111 tons for 26 liters.

For 3×10^{18} protons (a conservative integrated flux for a four-month running period) the total number of interactions would be

$$\text{Total Events} = (\text{flux})\left(\frac{\text{events}}{\text{ton-proton}}\right)(\text{tons of emulsion})$$

$$= (3\times10^{18}\ \text{protons})\left(1\times10^{-14}\ \frac{\text{events}}{\text{ton-proton}}\right)(0.111\ \text{tons})$$

$$= 3{,}330\ \text{events}$$

If we assume an efficiency of 60% for finding tagged events, the number of events "seen" in the emulsion will be

$$\text{Reconstructed Events} = 3{,}330 \times 0.6 = 2{,}000\ \text{events}$$

It appears possible to achieve more than 3×10^{18} protons and an efficiency higher than 60%, but we prefer to be conservative. Much of the uncertainty in finding events is due to uncertainties in geometric acceptance. If vertices are to be accurately reconstructed, at least two tracks must pass unobscured by other tracks through three planes in each view. Further, it is unclear how many "found" events may be reconstructed. Several Argonne physicists, including Lloyd Hyman and Brian Musgrave, have expressed interest in this proposed experiment and are constructing a Monte Carlo based on real Fermilab neutrino events to examine these and other problems. Some results will be available by the time of the open presentation.

2. Muon Background:

The price paid for working near the Wonder Building is the increased muon flux, rising from $5\text{-}10/m^2/10^{13}$ protons at the 15-foot chamber to $15{,}000/m^2/10^{13}$ protons at the Wonder Building. (E253 memo to Lundy from Booth and Skuja)

This is too high for our experiment, both from the standpoint of observing events within the emulsion and also electronic triggering. The integrated muon flux for 3×10^{18} protons is 5×10^{5} muons/cm^2, comparable to that obtained in the muon emulsion exposure E382, but 10-100 times more intense than the desired level within the emulsion.

The electron detection system should support one background muon per event within the emulsion area of 1/3 m^2. The number of "extra" muons depends on the product of muon flux and the ratio of detection system memory time to total spill time.

For a 20-microsecond spill of 10^{13} protons and a 1/2-microsecond memory, one may tolerate 360 muons/m^2, about a factor of 40 less than at present. (Of course, the tolerance level goes up linearly with the length of the spill.)

A factor of 1,000 is claimed for the spoiler using the E21 and E26 toroids in Enclosure 100, which would reduce the muon flux well below the maximum tolerable level. E253 counts heavily on such a drastic reduction in muon backgrounds, so the spoiler should be installed and operating near design well before calendar year 1978.

E. Cost Estimates

		TOTAL (in Thousands)
1.	Fermilab:	
a.	Prefab building downstream of Wonder Building with 30'x40' of floor space, utilities including 30 kw of 110 and 208 v power; 1,200 ft^2 @\$35/ft^2	\$ 42
b.	0.5 megawatts of power delivered to the magnet .75 MVA substation	25
c.	Purchase of 90'x90'x108' of steel for muon tagging (reusable after this experiment); 124 tons @\$125/ton	15.5
d.	Electronics (PREP)	40
e.	Rigging for massive equipment and steel fabrication; 15 days @\$500/day	7.5
	TOTAL	\$130.0

2. Experimenters: (Total costs are shown, but as indicated, much equipment already exists.)

a.	Magnet	
1)	SCM-104 magnet and supply	\$200 (Exists)
2)	Moving and installation	5
	TOTAL	\$200 (Exists) 5 (New Cost)
b.	Scintillation Counters	
1)	Tubes, bases, power supplies, and voltage dividers for 40 tube units	\$ 16 (Exists)
2)	Scintillation material	5
	TOTAL	\$ 16 (Exists) 5 (New Cost)

		TOTAL (in Thousands)
c.	**Lead-Glass Array**	
1)	Glass	\$ 60 (Exists)
2)	Tubes, bases, supplies, and dividers	22 (Exists)
3)	Fast electronics including CAMAC modules	15 (Exists)
4)	Calibration system	3 (Exists)
5)	4 blocks of 13 radiation lengths plus associated PM tubes, etc.	7
6)	Stand	2
	TOTAL	\$100 (Exists) 9 (New Cost)
d.	**Drift Chambers**	
1)	20 chambers @\$2.5K/chamber (Does not include the fixed cost of technical support salaries)	\$ 50
2)	Readout electronics @\$100/wire (including spares)	150
3)	Mechanical mounts	10
4)	Gas system	5
	TOTAL	\$215 (New Cost)
e.	**Spark Chambers**	
1)	6 large chambers @\$2.5K/chamber (Does not include the fixed cost of technical support salaries)	\$ 15 (Exists)
2)	Readout electronics @\$1K/line	12 (Exists)
3)	High-voltage pulsers, pulsed clearing fields, power supplies, etc.	15 (Exists)
4)	Recirculating gas system	5 (Exists)
5)	Stands @\$500/chamber	3
	TOTAL	\$ 47 (Exists) 3 (New Cost)

		TOTAL (in Thousands)
f. Electronics (in addition to that listed above)		
1) Fast electronics and CAMAC		$ 30 (Exists)
2) On-line computer SPC 16/85		120 (Exists)
	TOTAL	$150 (Exists)
g. Emulsion		
1) 26 liters @$4K/liter		$104
2) Fabrication		15
3) Developing		11
4) Support structure		4
	TOTAL	$134 (New Cost)
h. Operating Costs 6 months @$3K/month		$ 18
	TOTAL	$ 18 (New Cost)

i. Software costs are uncertain at this time but will be shared among participating institutions. At 1 minute per event, the computer time would not exceed 50 hours.

SUMMARY OF COSTS

Fermilab		$130
Experimenters	$513 (Existing)	
	$389 plus computing (New Cost)	$902

F. Time Scale of the Experiment

At the time of writing there is one published candidate for an accelerator produced visible charmed-particle decay (E247) and a small number of similar events from cosmic rays. We aim to measure, as soon as possible, a reasonable statistical sample (100-200 events) of such decays and to obtain information about the decay products. We believe that these measurements should be completed as soon as possible because of the intrinsic interest of the physics and also because complementary experiments are underway at CERN using the BEBC (Conversi, et al.)[3] and the tagged photon beam - Omega spectrometer.[4]

By designing a conservative system that makes maximal use of existing equipment, we can be ready to run by March, 1978, if the experiment is approved this March. It will take one year to complete the nineteen new drift chambers so we have already begun electrical and mechanical design and have ordered much of the necessary materials. This procedure is costing \$15K-\$20K but will make use of the month and a half until a recommendation can be made by the Program Advisory Committee on this proposal. The last month of secondary hadron beam running at the ZGS is scheduled for June, and the moving of the spectrometer can thus be started during the summer. The full apparatus should be operational by March, 1978.

The experiment requires 3×10^{18} protons on target with the horn neutrino beam or an equivalent ν yield from the quad triplet. The latter would require twice as many protons on target. With the horn beam the run could be completed in 2 1/2 to 3 months.

We feel it is essential to be ready as early as possible in order to maximize our chances of using the major horn run planned for the neutrino D_2 bubble chamber experiments which we understand may be run as early as spring, 1978.

Processing of the emulsions could be completed less than two months after completion of the exposure. It will require 3 to 6 months to couple electronic tagging information to emulsion scanning, and an additional 1 1/2 years to complete scanning, including extensive remeasurement of events with short decaying tracks.

G. Conclusions

We believe that measurements of the decay lifetimes of charmed particles will contribute substantially to our understanding of this new region of the hadron spectrum. The possibility of observing other short-lived decays provides further interest in this physics.

The scale of this experiment and the use of existing equipment will make possible its rapid preparation and its execution at very little cost to Fermilab.

We believe that the measurements we propose and the techniques for accomplishing them complement the two experiments being undertaken at the CERN SPS.

Charm searches in hadron beams and the photoproduction of ψ's and charmed baryons together with the di-lepton events from ν experiments suggest that the ratio of charmed particle to non-charmed hadron production is highest in neutrino beams. We therefore propose to use the neutrino beam to produce charmed particles in our emulsions as was done in E247. This does not appear to us to be a major new neutrino experiment but rather a parasitic use of the neutrino beam. We hope that the Program Advisory Committee will agree that these arguments suggest the need for an early decision on this proposal.

References

1. M. K. Gaillard, B. W. Lee, and J. L. Rosner, Rev. Mod. Phys. 47, 277 (1975).

2. J. Lord, private communication.

3. M. Conversi, et al., "Proposal to Investigate Di-muon Events and to Search for 'New Particles' in Neutrino Interactions in an Emulsion Stack Coupled to BEBC", CERN/SPSC/76-41 SPSC/P 70.

4. G. Diambrina Palazzi, et al., "Study of Charmed Particles Photoproduced in Emulsion Plates Tagged by the Omega Apparatus Triggers", CERN/SPSC/76-96 SPSC/P 78.

Figure Captions

1. Layout of Emulsion Target Region (scintillation counters not shown).

2. Layout of Full Experiment.

3. Excerpt from ZGS Handbook Showing SCM-104 Magnet.

4. Excerpt from ZGS Handbook Showing Magnet Field of SCM-104 Magnet.

HYBRID EMULSION EXPERIMENTAL LAYOUT

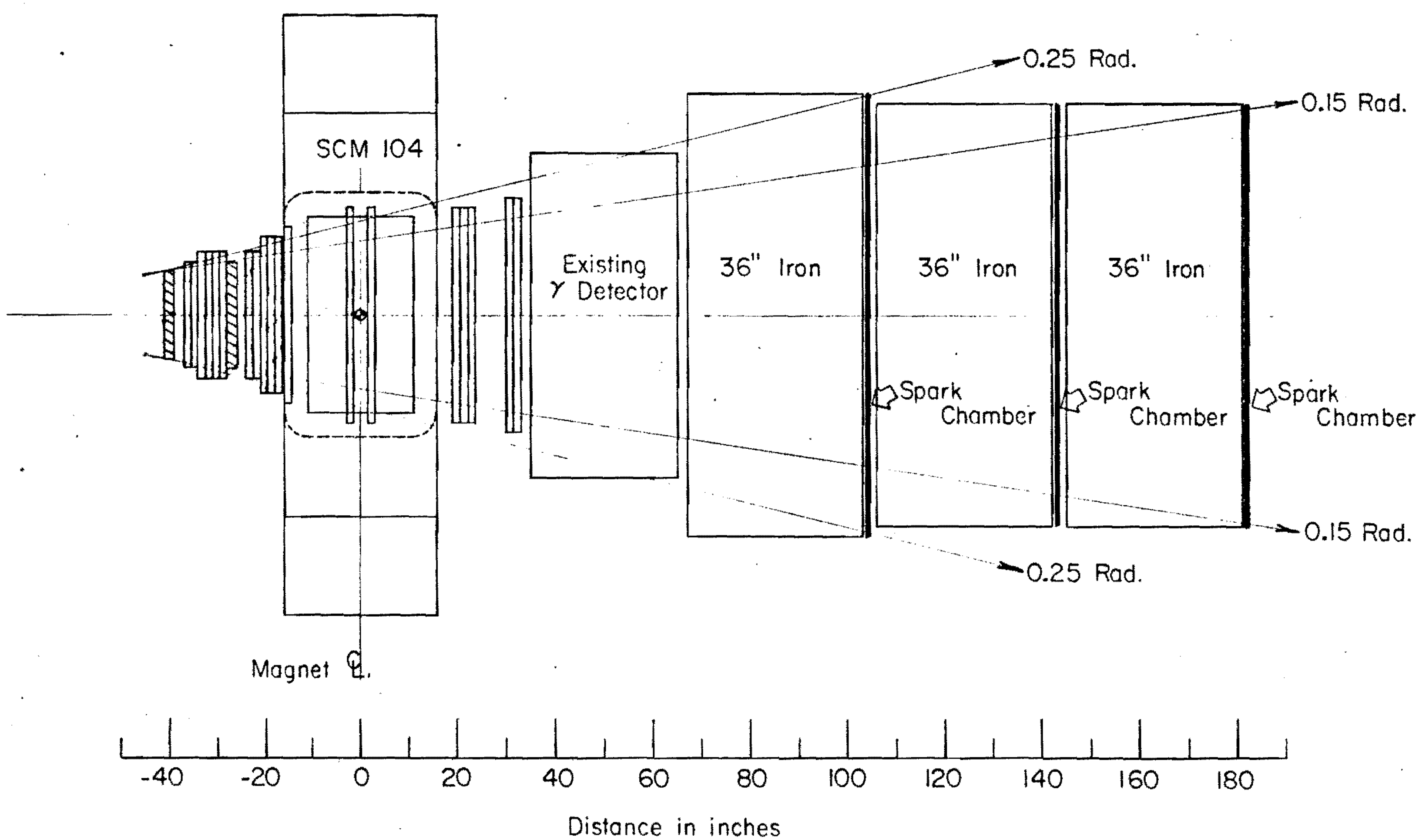
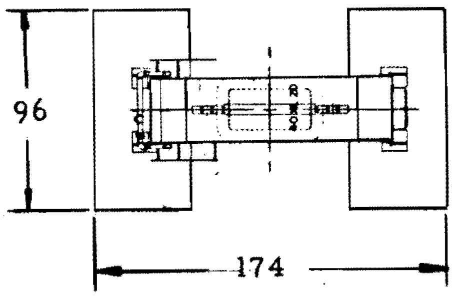
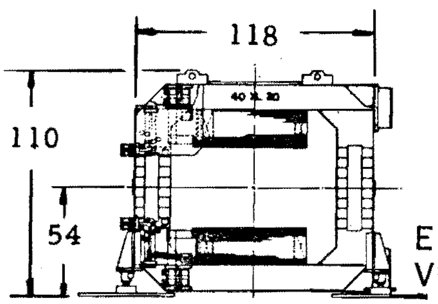


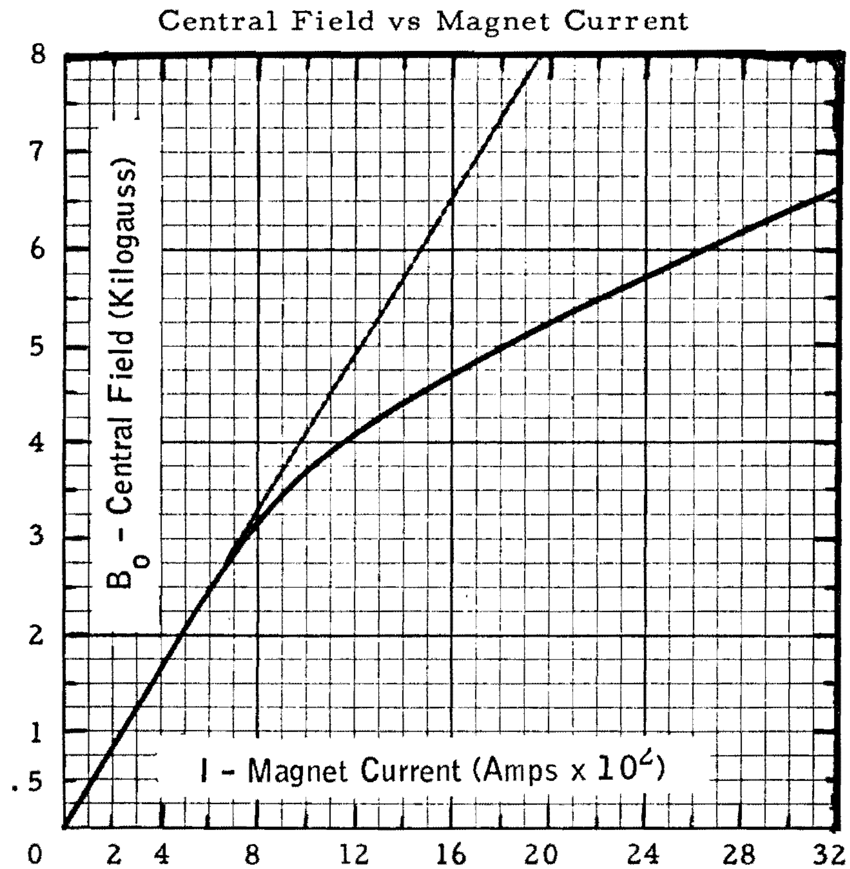
FIGURE 2.

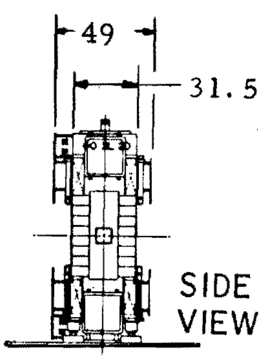


TOP VIEW



END VIEW





SIDE VIEW

FIGURE 3.

Total Weight:	36 Tons
Measured Data:	
Voltage	402 Volts dc
Current	3200 Amps dc
Power	1286 kW
Field Strength	6.6 kG
Cooling Water (Booster Pump Required)	
No. of Circuits	26
Pressure Drop	379 psi
Flow	124 gpm
Temp. Rise	72° F

Current (Amps)	Terminal Voltage (Volts)	Central Field (Gauss)	
		Up	Down
300	31	1240	1239
600	66	2457	2457
800	87	3173	3173
1000	110	3719	3722
1200	135	4091	4097
1400	157	4406	4410
1800	207	4967	4971
2200	259	5476	5480
2400	286	5716	-
2600	314	5951	5958
2800	342	6187	-
3000	371	6411	6415
3200	402	6633	-

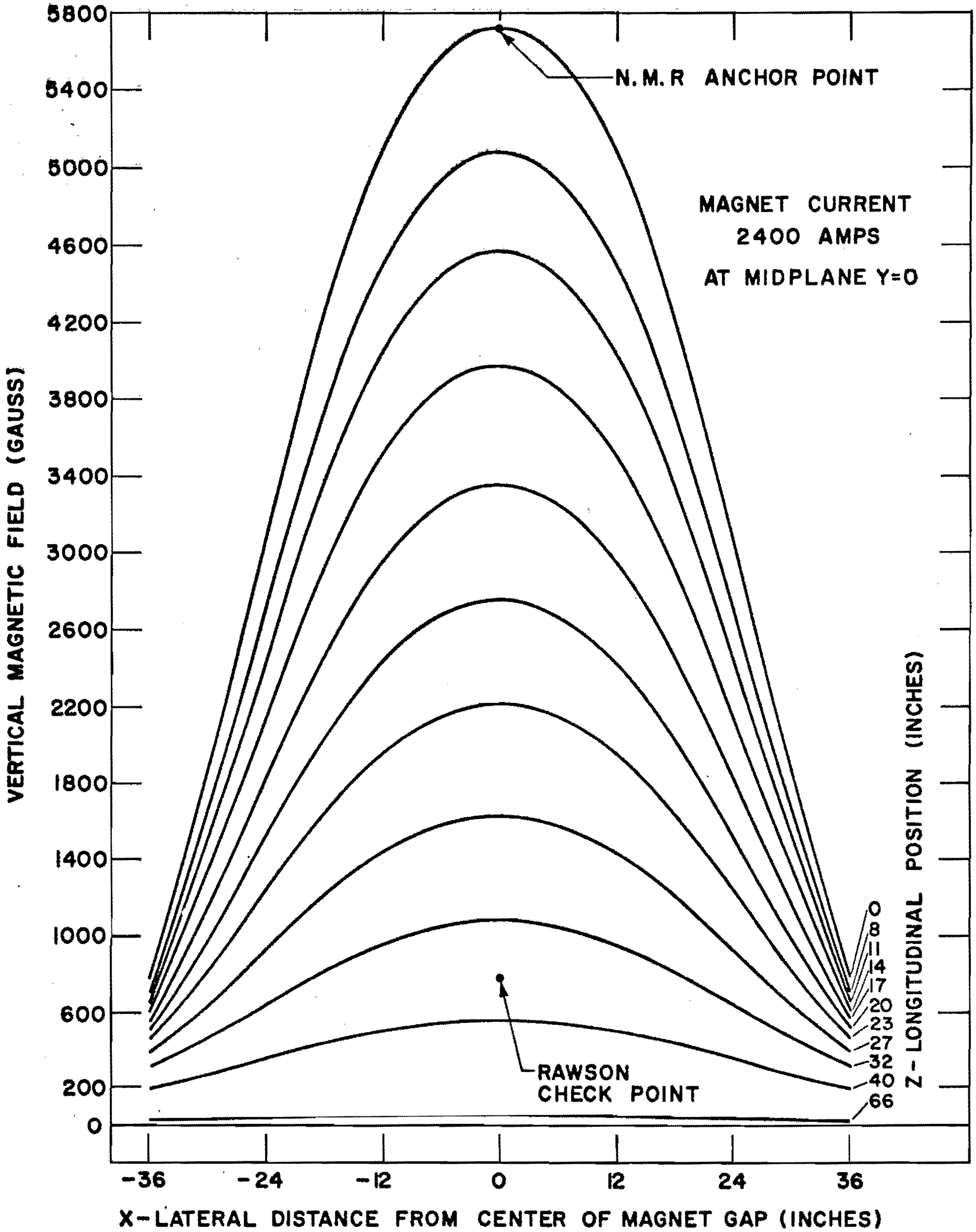

5800
5400
5000
4600
4200
3800
3400
3000
2600
2200
1800
1400
1000
600
200
0
VERTICAL MAGNETIC FIELD (GAUSS)
N. M. R ANCHOR POINT
MAGNET CURRENT
2400 AMPS
AT MIDPLANE Y=0
RAWSON
CHECK POINT
0
8
11
14
17
20
23
27
32
40
66
Z - LONGITUDINAL POSITION (INCHES)
-36
-24
-12
0
12
24
36
X-LATERAL DISTANCE FROM CENTER OF MAGNET GAP (INCHES)

FIGURE 4.

APPENDIX I.

Equipment to be Added as Circumstances Permit

Though our proposal should be judged wholly on apparatus as given in the body of the text, we have given some thought to expansion. Such expansion may be divided into four sections; more emulsion, more chambers, a hadron calorimeter and kaon-pion separation.

1) More emulsion - We will build chambers near the emulsion planes with 25% more wires than will be instrumented. By instrumenting these wires at a cost of $40K, and using emulsion planes of 25% increased thickness, the amount of emulsion used in the spectrometer could be doubled. Constructing these additional uninstrumented wires will add little to the overall cost or building time scale of the experiment as proposed.

2) At a cost of $70K, a third more chambers could be spaced through the system to aid in vertex finding and event reconstruction. These chambers should be added only after experience has been obtained in the first emulsion exposure.

3) Addition of some 3 dozen long liquid scintillator counters with phototubes on both ends would convert the upstream end of the muon steel into a hadron calorimeter of resolution $\delta E/E \simeq 2.5 \sqrt{E}$ FWHM, where E is in GeV. Demanding more than minimum energy deposition in such a calorimeter is necessary in establishing a trigger for neutral current events. We have about half the tubes, bases and supplies needed for this operation, and have experience in building and wiring such counters. This project would take about one man-year spread over six months, and would cost about $40K in addition to our present inventory.

4) A short, multi-mirror Cerenkov counter to separate kaons from pions is under consideration, but a design sufficient to permit reasonable cost estimates does not yet exist.

APPENDIX II.

Emulsion Stack Construction and Event Location

Details of Emulsion Stack Construction

Each emulsion plate, emulsion film, and paper sheet is punched out to have exact measurements of 9.500 ± 0.002 cm x 12.000 ± 0.002 cm and 4 holes with a diameter of 0.700 ± 0.002 cm on the fixed position at each corner, by a special punch press.

Thicknesses of all materials are measured and registered before setting up each chamber. They are then assembled, one by one, on a plastic stand with 3 guide poles.

The whole chamber is then tightly packed and heat sealed in a vacuum chamber with black polyethylene film, 100 μm thick and poly-laminated paper in which thin aluminum foil of 15 μm thickness is one of the constituents. With this method of packing, the emulsion layers are held with a uniform, constant pressure between thin laminated paper sheets, against a precisely machined plastic base. This method insures the flatness and parallelness of all the emulsion sheets and their precise registration.

Detection of Neutrino Interactions

Detection of neutrino interactions is made as follows.

1) Setting nuclear emulsion films on the stage of the microscope:

As described in the preceding section, all films are punched out to have an exact size and form by a punching machine. The same machine is used to make a plastic frame in which to set the film. This frame is fixed on the stage of the microscope. To follow a vertical track film by film, we only remove one sheet of film and set another in its place.

Relative setting error from film to film in this case is ±20 μm, because films and frame are punched out by the same machine, and they fit each other very tightly. In our case, a diameter of the field of the microscope is 100 μm even under the highest magnification (X1000), and this accuracy is enough to follow a single track without trouble.

2) Location of events in the emulsion:

As described above, we expect to define the search volume in the emulsion to an average of less than 5 mm^3. The dimensions of the volume for each event will depend on the number and angles of well reconstructed tracks.

For the best defined events, a volume scan will be made by 400X magnification in which a cylinder of diameter 500 μ by 10 mm can be scanned in less than one hour.

For events with less well defined volumes but for which there is a single well defined track at an angle $>5^o$ from the average direction of the background muon tracks, the reconstructed track will be followed.

Finally, there will be some events in which a heavy electromagnetic shower (>15 electron tracks) makes reconstruction particularly difficult. In these cases the downstream layer of the emulsion will be scanned for the shower and the electron tracks will be followed back to the shower origin. The initial pairs will point accurately to the original π^o decay point.

About 80% of all events will have nuclear stars with two or more heavily ionizing tracks emanating from the point of interaction. Scanning for these events is simplified by their highly visible topology.

Distortion

Distortions in our type of nuclear emulsion plates or films are generally less severe than the distortion of usual pellicles. The reasons for this are as follows.

1) The emulsion layers are perpetually supported on the plastic plates or

films, and no mounting operation is needed in which a pellicle receives the most serious distortions.

2) Unit emulsion thickness of 300 μm is thinner than that of standard 600 μm pellicles.

This thinner thickness of unit emulsion has less distortions as the lateral displacement due to shear distortion is known to vary quadratically with the thickness.

Elimination of Distortion Effect

The magnitude of distortion vector in an emulsion plate or film, in our case, is usually less than that of pellicles with equal effective thickness by reason described in the preceding subsection.

When vertical exposure is applied on these emulsions, most of the tracks we are concerned with are vertical and hence distortion effect appears more seriously than that of a horizontal track. In our case, however, there are quite a good number of vertical and parallel tracks due to incident beams, and it is very easy to estimate and eliminate the distortion effect measuring a relative position of a track referring to these beam tracks. Therefore, elimination of distortion effect is not a serious matter.

These techniques have been developed by the Nagoya University group and this appendix is based on the work of Professor K. Niu. His group is interested in joining this collaboration and negotiations are continuing. A decision will be made before the closed meeting of the Program Advisory Committee in March.

531

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A REQUEST FOR EXTENSION OF FERMILAB EXPERIMENT 531

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May 7, 1979

INDEX

I. INTRODUCTION

We wish to request an extension for Fermilab Experiment 531. This experiment recently completed a successful run in which a hybrid emulsion spectrometer (see Figure 1) was used to measure lifetimes of new long-lived particles produced in neutrino interactions. This type of experiment is a natural consequence of theories which predicted the new spectroscopy of charm and beyond. It is a crucial aspect of the simplest of these theories that the lightest of the charmed (and perhaps b and t) particles decay weakly, resulting in decay lengths typically less than a millimeter at Fermilab energies. Decay lengths as short as 10 microns are identifiable in emulsion, and charmed particles are known to be produced copiously in neutrino interactions. Many experiments have therefore exposed large volumes of emulsion to neutrino beams and have used downstream detectors to locate interactions which would take decades to find by raw scanning techniques. However, in the past, this type of experiment has been plagued with three basic difficulties: A small number of tagged events, a low efficiency for finding tagged events in the emulsion, and an inability to scan for neutral decays (such as from D^0 mesons) downstream of the interaction vertex. Our recent 350-GeV/c single-horn run resulted in 2000 ± 20% tagged interactions. Because of the high quality of our Fuji emulsion and due to successful use of the fiducial-sheet emulsion-tagging technique described on page 4, we expect to find 60% of tagged events. The emulsion was of high quality, but backgrounds (particularly from beam-associated muons) were also high, and these backgrounds increase the difficulty of scanning for downstream neutrals. Though we now have candidates for charm decays, at our present stage of analysis it is too early to make meaningful statements about the effects of these backgrounds, other than to note that they could be serious.

In the requested 350-GeV/c extension, we expect to accumulate $1\frac{1}{2}$ times the number of events, and with considerable reduction in background. In particular, beam-associated muons should be reduced by a factor of five with the addition of 10 meters of large-area steel shielding into the NØ neutrino line.

Combining past and future runs, we should be able to find 3000 neutrino interactions in the emulsion, of which 1000 would have a total energy over 50 GeV. It is hoped that from such a large sample we can identify enough kinematically-fit charm decays to yield proper lifetimes for some or all of the lightest charmed mesons (D^o, $D^{\pm}$, F) and baryons (Λ_c, Σ_c, and other states not yet identified).

Obtaining this larger sample also increases the possibility of observing the decay of a τ lepton resulting from F decay, or of finding an example of sequential B decay. Because of the latter posssibility, we wish also to expose emulsion to anti-neutrinos. The anti-neutrino bubble-chamber exposure E-390 is presently scheduled to run first in the next sequence of horn running. This run will be performed "plug in", according to Dr. M. Derrick. The second bubble-chamber exposure in this horn period will be E-53A (neutrinos), probably followed by E-180 (anti-neutrinos). According to Dr. F. Nezrick, E-180 probably will be performed "plug out", enhancing both neutrino and anti-neutrino yields. Therefore, we wish to expose 30 liters of emulsion throughout neutrino and "plug-out" anti-neutrino operation.

II. DISCUSSION OF E-531

A. Description of the Experiment

The present experimental configuration is shown in Figure 1. The apparatus consists of an emulsion target in which interactions are localized to within a few cubic millimeters by an external spectrometer, an on-line display from which is shown in Figure 2. Tracks reconstructed in the drift chambers can also be extrapolated into a doubly-coated sheet of emulsion placed just downstream of the emulsion modules; this sheet was changed many times during the experiment to minimize muon background. The increased precision of this fiducial sheet permits the following of individual minimum-ionizing tracks directly into the emulsion modules. The fiducial-sheet layout is shown in Figure 3.

Our detection equipment also determines momenta of charged tracks, distinguishes particles by fast time of flight, converts gamma rays and identifies electrons using a large lead-glass hodoscope, measures hadronic energy in a steel-plate calorimeter, and identifies muons by range. The spectrometer has a large acceptance. For example, most of the particles produced at polar angles less than 20° pass through the spectrometer, and the upstream drift chambers can momentum analyze particles with less than a few GeV/c out to 40° by making use of the fringe field of the magnet. More details of spectrometer elements can be found in the Appendix.

B. Data Taking and Emulsion Processing

Data taking began November 21, 1978, and ended February 7, 1979; we recorded a useful flux of 7.2×10^{18} protons on the production target. Our down time for repairs and changing runs was less than 10%, and the performance of the accelerator at 350 GeV/c was quite remarkable and set records for intensity and reliability. We recorded muon triggers at the tail end of each spill for calibration purposes but used 97% of the spill to record neutrino triggers. The latter were defined as the interaction of a neutral particle in the emulsion which produced three or more charged secondaries in the scintillator adjacent to the target and at least two hits in the hodoscope downstream of the analyzing magnet. Typically, we recorded 2-3 muons/pulse and 0.14 neutrino triggers/pulse.

Emulsion developing began at the University of Ottawa on February 10 and ended April 13. The average grain density was 29 ± 1 grains per 100 microns for vertical emulsion and 28 ± 1 grains per 100 microns for horizontal emulsion. (Neutrinos were incident normal to the plane of emulsion sheets for vertically mounted stacks and parallel to the plane of emulsion sheets for horizontally mounted stacks.) Background was relatively high and consisted of approximately 4×10^3 Compton electrons/mm^3, 150 ± 30 nuclear stars/cm^3, and 225 ± 23 muon tracks/mm^2 within a cone of half angle 20° about the beam direction. Ninety-eight percent of the nuclear stars have no minimum-ionizing tracks and probably result from slow neutron capture. The Compton background arose in large part from high radiation in the pouring laboratory, and steps are being taken to eliminate this source. However, the most troublesome background is the stiff muon tracks in the beam direction, which make finding and following tracks, and scanning for neutral decays more difficult.

C. Results

Event scanning began in early March, using both volume scanning and track scanning techniques. In the latter method, tracks found by the electronic spectrometer are identified in the changeable sheet, which in turn was referenced to the main stack of emulsion modules by X-ray sources, as illustrated in Figure 3. Over 170 collimated X-ray sources left 1-mm diameter darkened spots on the sheets, each of whose centers may be found to better than 100 microns using a densitometer. These sheets are scanned at Nagoya using a specially-constructed large-stage microscope. Scanners search for track patterns resembling the pictures furnished by software analysis of electronic information. Found secondaries are correlated in angle with predictions, and fiducial-sheet information is used to locate within 100 microns corresponding tracks in the neighboring emulsion stack. Subsequent track following to the interaction vertex requires less than two hours, and all tracks so located in the fiducial sheets have been connected to tracks in the main stack. Essentially all of the vertically exposed emulsion will be scanned in this fashion.

Historically, horizontally-exposed emulsion has been scanned using conventional volume scanning techniques. The spectrometer data are analyzed to predict an interaction vertex, and a certain volume is searched which encompasses that predicted location. However, it appears possible that the fiducial technique can work as well for this type of exposure, and efforts will be expended in this direction.

Results to date for the two scanning methods are listed in Table 1. As anticipated, the volume scan is less than half as efficient as track following because of the difficulty of locating interactions with zero or a small number of dark tracks resulting from nuclear breakup.

If we assume that the vertically-mounted emulsion (which comprised 60% of the total sample) will be track scanned with 75% efficiency, and that the horizontal emulsion will be volume scanned with 33% efficiency, we will find almost 60% of tagged events. If we can successfully apply track-following techniques to horizontally-mounted emulsion, our scanning efficiency could be improved significantly.

Much work remains to be done in calibrating the various counter hodoscopes, tuning the parameters of the drift chambers, and in refining algorithms for reconstructing tracks and finding vertices. Nevertheless, about 45% of the data were analyzed on the University of Toronto VAX computer during February, and 577 candidates for scanning were found and sent to the emulsion groups. A second independent program is now being written to reconstruct events and will be ready shortly. Preliminary results suggest this program is more than 90% efficient at event finding. Our first priority is to scan for events with high energy, opposite-sign leptons, or a reconstructed strange particle.

III. DISCUSSION OF THE PROPOSED E-531 EXTENSION

A. Introduction

In the extension run we hope to record 500 $\bar{\nu}$ and 3000 ν events, with improvements in background, in system dead time, in event finding and track reconstruction, and in particle identification. We will first discuss improvements, then present yields, discuss our state of readiness, and finally list our requirements from Fermilab.

B. Improvements

Lowering backgrounds will be a major experimental goal. Cosmic-ray background will be reduced a factor of two by storing all emulsion deep underground in a low-radiation area prior to running and prior to developing after completing the exposure. Compton-electron background will be reduced a factor of three by the above and by shielding against radiation from the concrete walls of the emulsion pouring room. The muon background, which is accelerator produced, can be reduced 80% by adding a 10-meter-thick steel wall upstream of the Wonder Building. This wall is of course in addition to the steel and 60-feet of concrete shielding used in our previous run. Should any of the latter be removed, the thickness of steel added would have to be increased proportionately. Reducing the muon flux will lower track density in the emulsion, reduce anti-counter overkill and reduce false neutrino triggers, which in the past were proportional to the muon rate. Since emulsion is always live, all background yields must be integrated over both fast and slow spills.

We wish to express concern over backgrounds coming from neighboring beam lines. A scintillator-counter system set up to abort the N5 hadron beam in the event of high backgrounds was activated several times during beam tuning. Though backgrounds from this source in general proved small, we found prior to running that considerable background resulted from operation of experiments in the Muon Laboratory. We therefore request that the Muon Laboratory not operate during our exposure. In the unfortunate event that the Muon Laboratory must operate simultaneously, we ask that they also be monitored by a high-background abort system. Because of our nuclear-star background, we plan to sensitize all abort systems to low energy neutrons.

Should both Muon Laboratory and N5 beams operate simultaneously with our exposure, a new source would have to be found for powering our magnet.

To improve event finding and track reconstruction, we will add an existing ninth drift chamber downstream of the analyzing magnet, and have ordered parts and electronics for three more chambers upstream of the magnet. We also intend to increase the distance between the emulsion and the present first drift chamber from six to fourteen inches. This will increase the distance between tracks (the electronics cannot resolve tracks separated by less than 2.3 mm), and also will double the drift space for neutral strange-particle decays. Part of this space could be occupied by the proposed new upstream chambers so that we do not lose "close-in" information on unobscured tracks.

We are also studying various options to improve charged-particle identification. We have exposed eighteen plates of Fuji emulsion to 0.48-GeV/c and 13.0-GeV/c π^- beams at Brookhaven National Laboratory and will evaluate the relativistic rise in our Fuji emulsion for various developing techniques, including the ones used for the past E-531 exposure. In this way it may be ascertained whether emulsions may be used for identification of particles of known momentum for both past and proposed exposures. We are also building a small prototype ionization device (similar to ISIS) which will be tested this summer. If successful, a scaled-up version could be installed in the magnet aperture.

C. Event Yield

We ask for 6×10^{18} protons of 350-GeV neutrino running and 6×10^{18} protons of 350-GeV "plug-out" anti-neutrino running. We expect the horn will be run with a peak current of 120 kiloamperes, and that the spill will be at least 1 millisecond FWHM. Excluding long shutdowns, we averaged 0.85×10^{18} protons per week during the past run; this could be boosted 12% with the increased horn current (other conditions being equal).

Table II gives integrated event yields based on our previous neutrino exposure. Rates have been increased 12% because of increased horn current and 15% because of expected smaller dead-time losses; the ratio of anti-neutrino to neutrino yield is taken from S. Mori (TM 837). Numbers based on 30 liters of emulsion are quoted as we cannot increase emulsion area without limiting solid angle for decay products. We also do not wish to increase the emulsion thickness unduly because of the effect secondary vertices from converted gamma rays would have in obscuring vertex finding for events produced upstream in the emulsion.

The numbers shown in parentheses are the wrong-sign neutrino-event yield for plug-out anti-neutrino running.

D. Time Schedule

We expect to complete the first software pass through our data in the summer of 1979, but at least two experts will continue to work exclusively on improvements and in incorporating information obtained from emulsion scanning. Scanning our complete data sample will require an additional twelve to eighteen months, but more than half should be processed prior to the next run. Three people from a force of thirty three emulsion experts would be occupied full time by another run, and and additional three would be needed during the two-month emulsion pouring and developing phases. Thus, our scanning effort would suffer only marginally in preparing for and executing a new run.

E. Estimate for New Costs Incurred in the Extension Run

	Total (in Thousands)
1. Fermilab:	
a) Continued use of the Wonder Building and the 200 tons of calorimeter and muon steel now in position	---
b) 0.5 megawatts of power (delivered primarily for our SCM 104 analyzing magnet)	$ 25
c) Continued use of PREP equipment	140
d) Installation of shielding and safety devices (if necessary) to protect against Muon Laboratory backgrounds	?
e) Installation of the ANL steel already planned for Summer, 1979	?

		Total (in Thousands)
2.	Experimenters†,††:	
a)	New scintillation counters	$ 14
b)	Three (3) new drift chambers	9
c)	One hundred (100) channels of drift-chamber electronics	10
d)	Emulsion purchase, 30 liters @$5K/liter*	150
e)	Emulsion pouring and processing	20
f)	Operating costs: 8 months @$7K/month	56
	TOTAL FOR EXPERIMENTERS	$259

†Home institution travel, software, and emulsion scanning costs are not shown..

††As the feasibility study of an ISIS-like ionization detector is not complete, its cost also is not included.

*Japanese collaborators have already received funding for the emulsion.

TABLE I

SCANNING RESULTS AS OF MAY 6, 1979

A heavy prong (N_H) is defined as a track with ionization ≥4 times minimum.

	Method: Track Following	Method: Volume Scan
Events looked for	59	71
Events found	53	31
Efficiency	.90	.44
Distribution of found events by heavy prong count:		
$N_H = 0$	30%	0%
1, 2	15%	13%
3.4	17%	16%
≥ 5	38%	71%

The track scanning method has minimum bias on N_H; thus, the above numbers indicate that if N_H is small, volume scanning exhibits reduced efficiency.

TABLE II

Emulsion Volume = 30 liters

Proton Flux = 6×10^{18} at 350 GeV both for ν and $\bar{\nu}$ running

Horn Current = 120kA

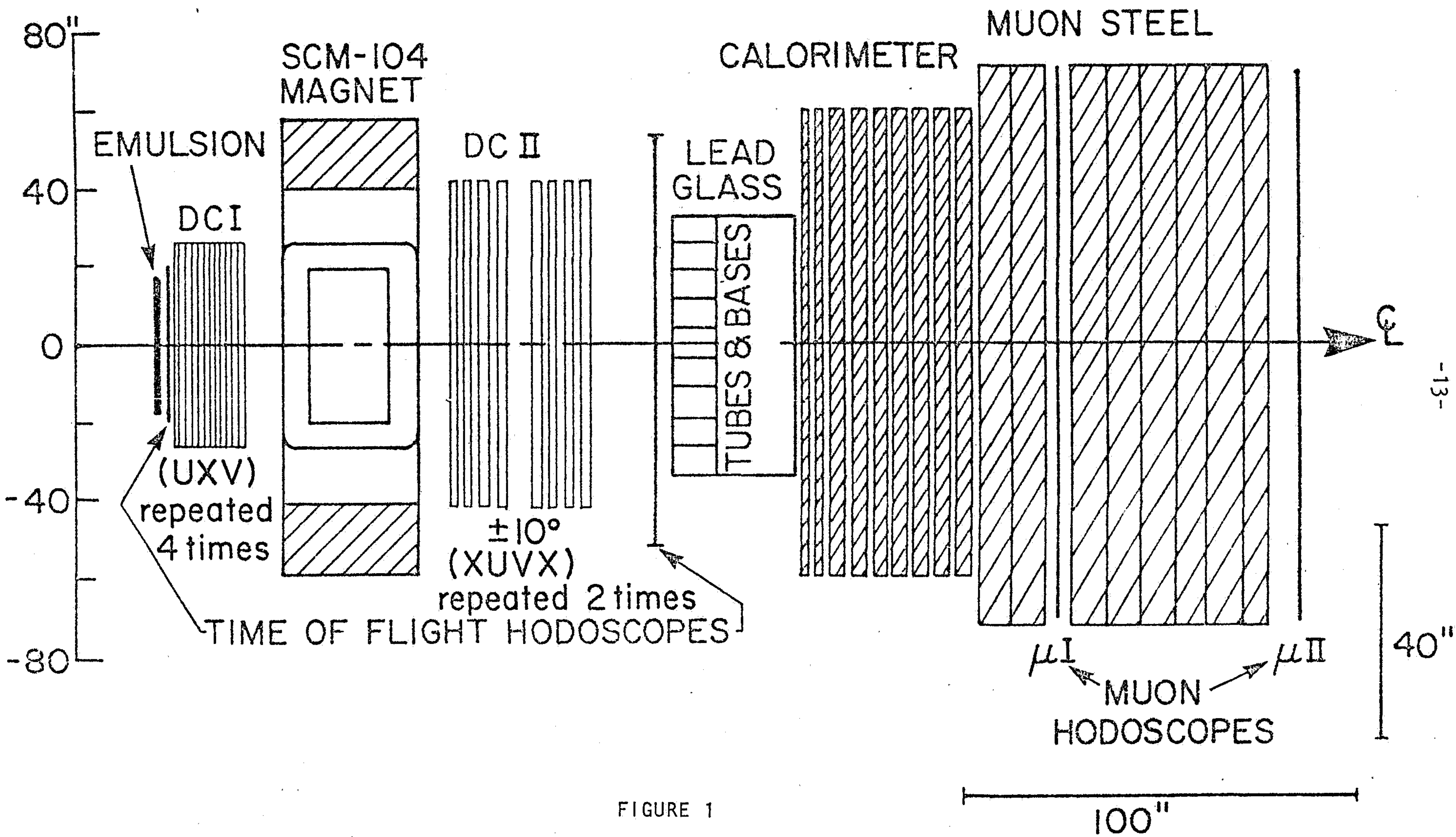
Beam	Total Events	Events for E_{Total} > 50 GeV
ν	2800	1000
$\bar{\nu}$ (Plug out)	380 (650)	75 (340)

FIGURE CAPTIONS

1. Plan view of the experiment. Neither the scintillators which fill the gaps in the calorimeter nor the anti-counters are shown.

2. Event display illustrating information available from the spectrometer. The U and V projection drift chambers are not shown for the sake of clarity.

3. Cutaway view of an emulsion package and the support structure. The beam is incident from the left. The plates in this module are thus oriented perpendicular to the beam. The X-rays are from an Fe^{55} source collimated by a metal insert.


80"
40
0
-40
-80
EMULSION
DCI
(UXV)
repeated
4 times
SCM-104
MAGNET
DC II
±10°
(XUVX)
repeated 2 times
TIME OF FLIGHT HODOSCOPES
LEAD
GLASS
TUBES & BASES
CALORIMETER
MUON STEEL
℄
μI
μII
MUON
HODOSCOPES
40"
100"
FIGURE 1

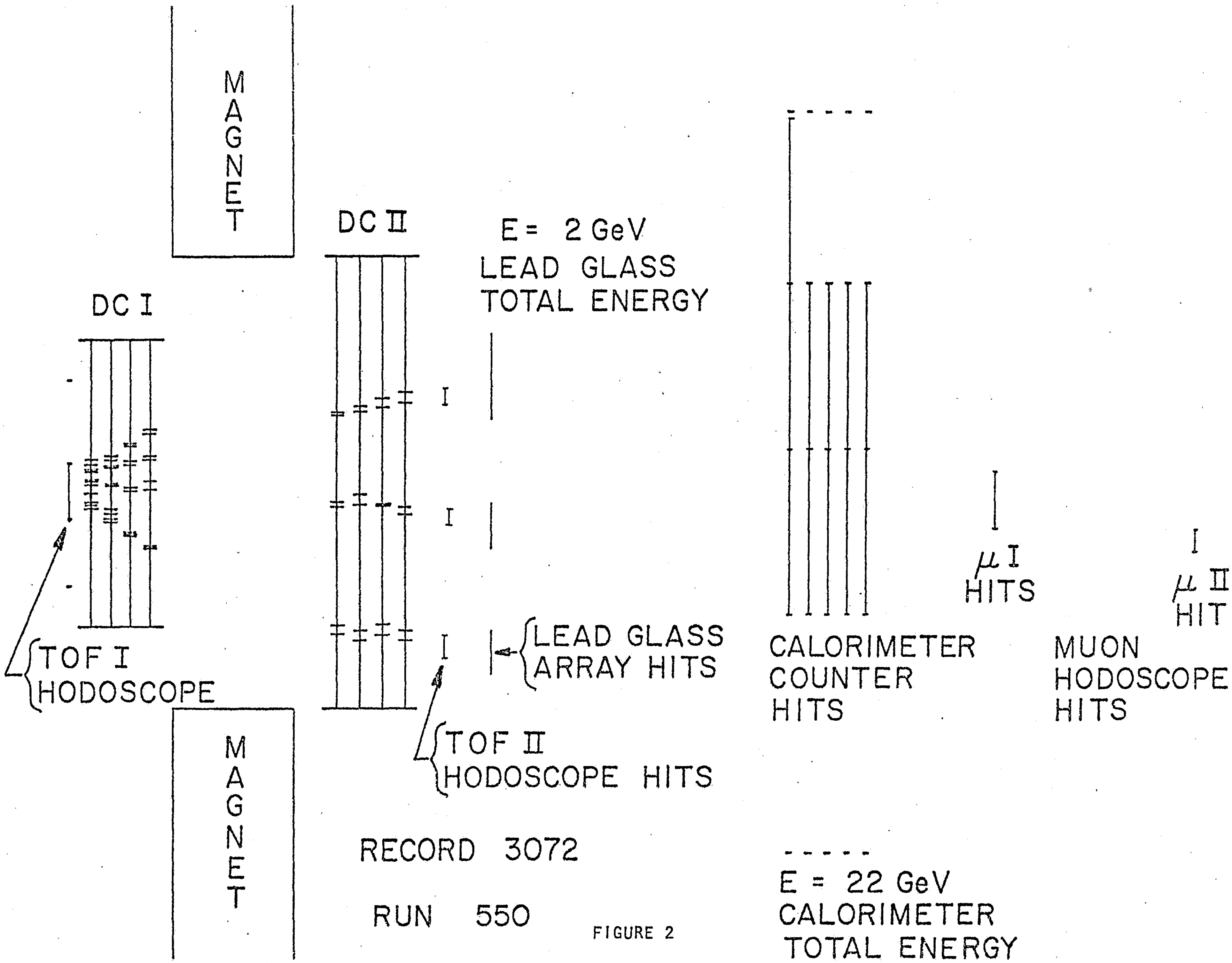

MAGNET
DC I
DC II
E = 2 GeV
LEAD GLASS
TOTAL ENERGY
TOF I
HODOSCOPE
LEAD GLASS
ARRAY HITS
TOF II
HODOSCOPE HITS
CALORIMETER
COUNTER
HITS
μ I
HITS
μ II
HIT
MUON
HODOSCOPE
HITS
MAGNET
RECORD 3072
RUN 550
E = 22 GeV
CALORIMETER
TOTAL ENERGY

FIGURE 2

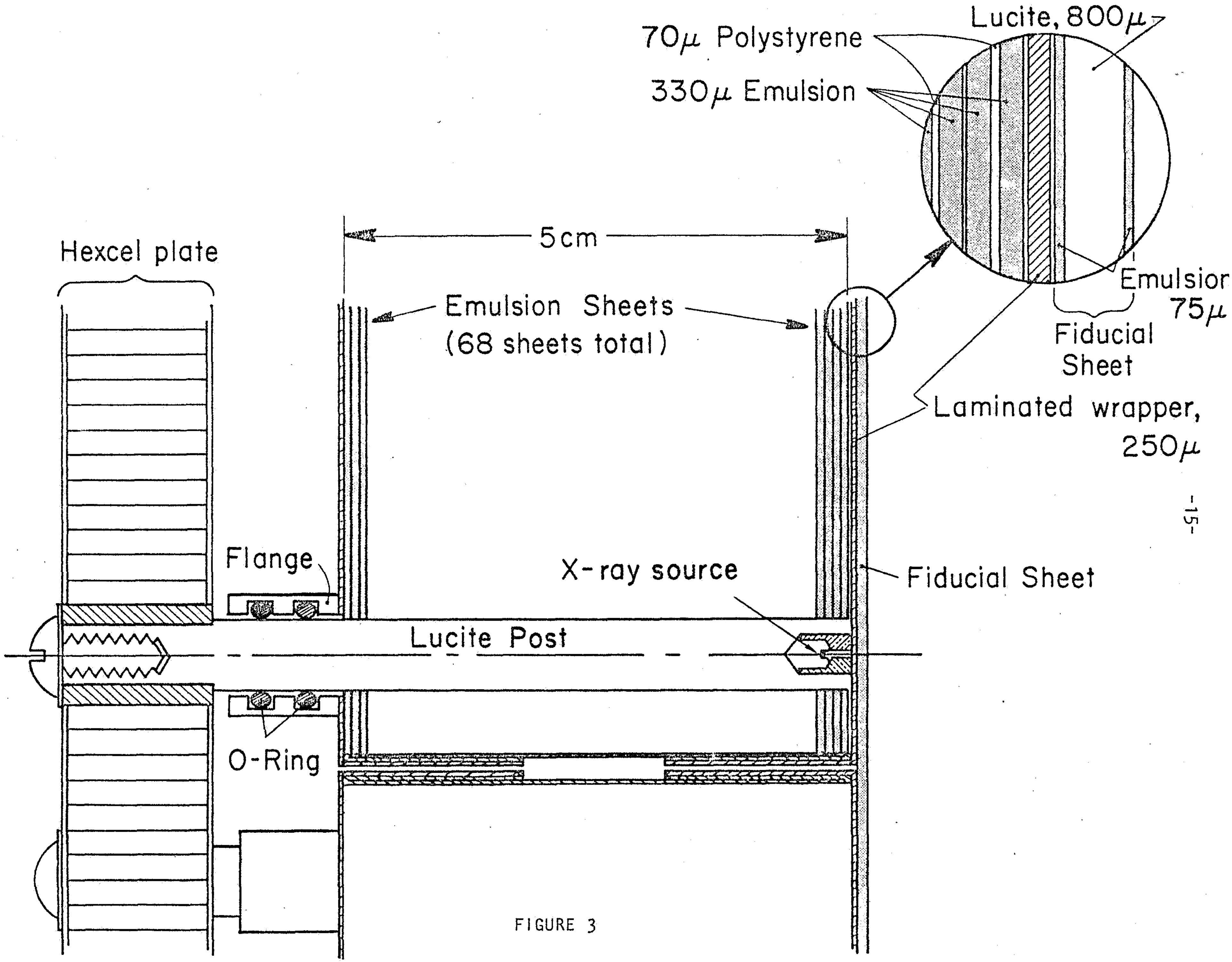

Lucite, 800μ
70μ Polystyrene
330μ Emulsion
5cm
Hexcel plate
Emulsion Sheets
(68 sheets total)
Emulsion
75μ
Fiducial
Sheet
Laminated wrapper,
250μ
Flange
X-ray source
Fiducial Sheet
Lucite Post
O-Ring

FIGURE 3

APPENDIX

Parameters of the Experimental Apparatus as of February 7, 1979

1. Veto Counters - 7 paddles, each 10 inches high by 70 inches long by ½-inch thick, each viewed by two phototubes.
2. Emulsion - 22.9 liters of Fuji emulsion with 13.8 liters mounted perpendicular to the neutrino beam and 9.1 liters parallel. The thickness of emulsion in the beam direction is 4.5 cm for the perpendicular exposure (68 sheets per module, each comprised of a 70-micron plastic sheet sandwiched between two 330-micron coatings of emulsion), and 5.0 cm for the parallel exposure (600-micron thick emulsion pellicles). The emulsion modules are followed immediately by two large fiducial sheets (75 microns of emulsion on either side of an 800-micron thick plastic sheet) which are used as an interface between the modules and the drift chambers. These fiducial sheets were changed every few days to minimize their track background.
3. TOF I - A 3/8-inch thick scintillator viewed by 12 phototubes.
4. Upstream Drift Chambers - 12 planes, each 51 inches square and placed to give 60° stereo (UXV repeated 4 times). Sense wire spacing was 4 cm. The electronics could encode a maximum of 15 hits per wire and had a typical dead time of 50 microseconds for neutrino triggers. The resolvable separation between two tracks was 2.3 mm. The observed resolution for high-momentum muons was 200 microns (FWHM).
5. Analyzing Magnet - The SCM104 on loan from Argonne National Laboratory is 31.5 inches deep by 40 inches high by 84 inches wide. The center of the magnet is 50.8 inches from the upstream face of the emulsion. $\int Bdl$ = 6 kilogauss-meters.
6. Downstream Drift Chambers - 8 planes with 10° stereo (XUVX repeated twice). Each chamber was 48 inches high by 84 inches wide.

APPENDIX (Continued)

7. TOF II - A 30-element hodoscope of scintillators each viewed by two phototubes. This hodoscope is designed to measure time of flight from TOF I. Test beam resolution was better than 0.25 nanoseconds FWHM.

8. Lead Glass - A wall of 68 lead-glass blocks, each 7.5 inches square by 11 to 14 radiation-lengths deep. The area covered is 60.8 inches by 67.5 inches.

9. Hadron Calorimeter - A simple hadron calorimeter consisting of 2 inches by 96 inches by 120 inches Fe plates sampled every 4 inches in depth by scintillators coupled to 58 DVP phototubes.

10. Muon Detector - Identifies muons by range after 47 inches and after 91 inches of steel. The two muon hodoscopes comprise 76 scintillators, each viewed at one end by a 56 AVP phototube for which pulse height and timing information are recorded. The resolution of the hodoscopes is sufficient to locate a particle to several inches in X and Y at each plane of counters. The active area of the detector is 116 inches high by 140 inches wide.