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"INFORMAL PREPROPOSAL"

DEVELOPMENT OF A "FERMILAB NEUTRINO HYBRID SPECTROMETER (FNHS)" FOR NEUTRINO PHYSICS AT THE TEVATRON

by the DESIGN GROUP of the
"Workshop on Bubble Chamber Neutrino Physics
at Tevatron Energies"

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(A). Introduction and Abstract

It is important to continue visual-detector studies in neutrino physics in the Tevatron era with emphasis upon a high-resolution vertex detector coupled with external complete particle identification and energy measurement. A nearly ideal yet practical detector (the "FNHS") is described, whose core is a small cylindrical bubble chamber as a vertex detector, coupled closely to external electronic devices which detect, measure, and identify charged and neutral hadrons, electromagnetic showers, and muons.

Excellent momentum measurements can be made with a modest magnetic field (0.5 Tesla) which extends over both the bubble chamber and the dE/dx detector. The large acceptance for charged particles (95% for $p > 1.5$ GeV/c) is combined with good π/K and π/proton discrimination from dE/dx and time-of-flight. A lead-proportional tube electron/gamma detector collects 95% of the electromagnetic energy and resolves π^o photons. A hadron calorimeter detects neutrons and K^o_L. This system provides excellent event-energy determination for charged-current events in wide-band beams. Neutral-current events rely on precise hadron momentum and energy vectors. The use of hydrogen/deuterium and secondary particle identification and reconstruction permits kinematic fits on the majority of events produced. The bubble-chamber optics includes high-resolution lenses.

The physics dividends of FNHS depend upon (a) better detection of decays of charmed particles and other short-lived particles, with identification of decay products; (b) detailed studies of neutrino production of single and

multiple strange particles, both charged and neutral, with the ability to separate $\Delta S = 1$ processes from associated production in a large sample of events; and (c) complete reconstruction of the hadronic final state of neutrino interactions. Specific examples of such classes of events are discussed and detection efficiencies are estimated.

The emphasis is upon complete kinematic analysis of a substantial number of events: about 10,000 neutrino charged-current events from H_2, 30,000 events from D_2, or 66,000 events from light neon within a 2-meter diameter x 4.0 meter long fiducial volume, assuming 2.5×10^{18} 1-TeV protons on target 1400 meters away, with a horn beam. (The horn beam is useful since "low-energy" events as well as high-energy events with hadron particle identification are of interest.) It appears practicable to operate the FNHS in parallel with the 15-foot bubble chamber, using the same neutrino beam.

A formal proposal should await a complete design which would enable reliable cost and engineering time estimates. This "preproposal" includes only crude estimates of costs. There are indications that laboratories interested in the Neutrino Hybrid System may be able to contribute manpower and/or partial funding to the project, if the bubble chamber and magnet are supported by Fermilab.

(B) Evolution of the Concept of a Fermilab Neutrino Hybrid Spectrometer (FNHS)

The very substantial number of bubble-chamber experts attending the Tevatron Neutrino Bubble-Chamber Workshop at Argonne on October 29-30, 1979, numbering 63 and representing at least 24 different groups, attest to widespread interest in pursuing neutrino bubble-chamber physics at Tevatron energies. Even though the success of e^+e^- colliding beam machines has encouraged many physicists to "jump on the bandwagon" of colliding beam machines in general, many others feel that fixed-target high-energy physics should also be pursued vigorously by a variety of experimental techniques. This is especially true of neutrino physics, since it takes fixed targets to provide neutrino beams.

In the past, important discoveries in neutrino physics have been made using the bubble-chamber technique (e.g., neutral currents, muon-electron dileptons, neutrino-electron scattering, charmed baryons). It seems probable that new discoveries will be made using Tevatron neutrino beams with an improved system at Fermilab.

At Argonne the various Working Groups were charged to consider and recommend improvements which should be made to the existing 15-foot Bubble Chamber/EMI-IPF hybrid system in order to make maximum use of Tevatron neutrino beams. Certain improvements were obvious: (a) high-resolution optics to improve detection of short-lived decays; (b) some upgrading of EMI electronics (long recommended but not yet implemented) to improve maintenance and reliability; and (c) extension of the prototype IPF for greater coverage. (CERN is going ahead on a 360-degree IPF for BEBC.)

A more difficult problem was encountered in trying to improve the 15-foot as a hadron calorimeter, especially at high energies. The primary problem is

π^o-photon detection. The measurement of gamma energy is essential to improving the measurement of total hadron energy and momentum. If E_H can be precisely measured, then the incident neutrino energy can be determined from $(E_\mu + E_H)$ directly in wide-band beams. "Heavy" neon converts most photons, but then the events become complex to measure and the energy resolution of "neutrals" is poor. Furthermore, many groups wish to work with hydrogen/deuterium and also detect π^o photons. Several ingenious ideas have been put forward for gamma detection within the chamber (e.g., internal plates; a solid-argon ion-chamber;(1) and a novel idea(2) of a visual "matrix" calorimeter of lead-wall cells which "bubble" with tracks). Unfortunately, all such methods reduce available fiducial volume within the bubble chamber. Only the matrix-cell method seems capable of resolving electrons from negative-pion charge-exchange reactions. If an internal "gamma catcher" with good electron identification can be developed, it certainly should be considered for the 15-foot. However, our Working Party on "Gamma Detection" was led to consider external detectors.

Another important limitation on neutrino physics achievable with the 15-foot Bubble Chamber is the lack of secondary particle identification. The EMI identifies muons and heavy liquid usually identifies electrons and photons emerging from neutrino interactions. However, it is equally important to clearly identify strange particles (both neutral and charged) as well as pions and protons in the final state. Neutral strange particles can often be identified in the bubble chamber by their charged decay modes; the bubble chamber excels in detecting $K^o_S \to \pi^+\pi^-$ and $\Lambda \to p\pi^-$. However, it is almost impossible to detect charged kaons in flight in the bubble chamber; above 1 GeV/c it is essentially hopeless to distinguish between pions and protons by bubble density. Thus a whole gamut of interesting physics reactions involving strangeness change (i.e., $\Delta S = 1$ and $\Delta S = -\Delta Q$) is only rarely detected. Two examples of $\Delta S \neq 0$ reactions are:

$$\nu_\mu \, p \rightarrow \mu^- \pi^+ \pi^+ \Lambda^o$$

$$\nu_\mu \, p \rightarrow \mu^- + K^+ + (cus)^+$$

$$\hookrightarrow \Sigma^+ \overline{K^o}, \; \Xi^o \pi^+$$

These are difficult to detect since one can always assume that a charged K^+ (or K^-) is associated with the neutral strange particle. Only in rare cases (in hydrogen) have $\Delta S = -\Delta Q$ reactions been identified using kinematics; these cases have proved to be very significant. Charm decay ($c \rightarrow s$), "bottom" decay ($b \rightarrow c \rightarrow s$), and "flavor cascades" ($t \rightarrow b \rightarrow c \rightarrow s$) involve strange particles. Thus it would be a great advance to have a detector capable of detecting all strange particles (including K_L^o and $K_S^o \rightarrow 2\pi^o$), not only at Tevatron energies but also for neutrinos produced by 400 GeV protons!

The Working Group on "external particle identification" struggled vigorously to find some way to utilize Cerenkov counters, dE/dx chambers, or time-of-flight counters with the 15-foot Bubble Chamber. They considered moving the coils apart to provide acceptance outside the chamber, so that external particle identification would be possible. However, the present 15-foot Bubble-Chamber geometry, as well as the wall thicknesses of the Dewar and vacuum chamber, defy practicable solutions to this problem. Furthermore, the cost of making such changes appears to be comparable to the cost of building a new bubble chamber.

At Argonne our Bubble-Chamber Workshop was challenged to "try some unfettered thinking" about new ways of applying visual detectors to Tevatron neutrino physics. We rejected the idea of building "10 hydrogen bubble chambers in series," and we set aside the proposal of a liquid argon bubble-chamber, ARGONAUT, as being "too far out." But the Working Group Leaders did finally come to the conclusion that there were many physics advantages to coupling newly-developed electronic particle identifiers (such as ISIS) to a smaller diameter bubble-chamber vertex detector, designing the entire system as a unit. External electron and photon detectors can be added, which promise to provide good spatial and energy resolution. Muon identification is improved. We have given the name "Fermilab Neutrino Hybrid Spectrometer," or FNHS, to this system.

Before describing the conceptual design of the FNHS in more detail, we first list very briefly the physics goals of the experiments to be performed with FNHS, which cannot be done well by other neutrino detectors of mass $\geq$ 1 ton:

(a) Detection of short-lived decays from charmed particles, tau leptons, and possible new particles, and study of their associated hadronic states;

(b) Detection of strangeness-changing and charm-changing neutrino interactions;

(c) Study of quark and gluon fragmentation functions, especially into strange particles;

(d) Electron neutrino interactions: study of muon-electron universality;

(e) Neutrino and antineutrino charged-current structure functions for the proton and neutron; in x and Q^2 intervals not available to counters.

(f) Neutral current x-distributions with resolution in "x" not available to counter techniques;

(g) The opportunity to observe, visually, the production of "new physics" in complex events.

More detail on the physics applications will be discussed in Section (D), after describing the conceptual design of FNHS.

(C) Conceptual Design of the FNHS

We view the FNHS as a unique detector of neutrino interactions, based upon a bubble chamber as a high-resolution vertex detector, plus external electronic detectors to identify and measure the momenta and energy of muons, electrons, photons, pions, protons, neutrons and K_L^o, and strange particles (charged and neutral) separately in each event. Although the yield of events is limited by the mass of the bubble-chamber target, complete reconstruction of each event extracts a maximum of information from the sample. Hydrogen and deuterium may be used as a target, as well as light neon-hydrogen mixtures, thus exploring the most fundamental neutrino-nucleon interactions. The mass resolution of the final hadronic state will be good enough to detect hadronic resonances and other new final states of matter produced in weak interactions.

The starting point is to match the cross-sectional area of the fiducial volume to the Tevatron beam profile: higher proton energy on target means higher energy neutrinos which are more strongly collimated. The useful diameter is roughly a factor of two less than the 15-foot Bubble Chamber, i.e., 2.0 meters is adequate to contain the high-energy neutrinos. Using the same axial length (3.8 meters) as the 15' BC, we obtain a total volume about 1/3 of the 15' BC; i.e., about 10 m^3 fiducial volume. This smaller chamber has thinner windows, which means less conversion and nuclear interaction and thus better particle identification and total energy measurement. The smaller volume of the bubble chamber makes it possible to run the FNHS chamber without expensive additions to the existing refrigeration system at the 15' BC.

The yield of events in this smaller chamber, although not high by counter standards, is still quite respectable for a "typical" run of 2.5 x 10^{18} protons of 1 TeV from a wide-band horn beam on the three proposed liquid fillings: liquid hydrogen (0.059 gm/cc), liquid deuterium (0.12 gm/cc), or "light" neon (0.25 gm/cc). NUADA programs have been run to calculate the expected yield from the 10.5 m^3 fiducial volume, as follows:

	H2	D2	Light Neon
Neutrinos, CC	10,300	30,900	66,000
Neutrinos, NC	4,100	12,400	26,400
Antineutrinos, CC	3,400	5,100	11,000
Antineutrinos, NC	1,400	2,000	4,400
Total Events	19,200	50,400	107,800

These yields are aided by the rising cross section of higher-energy neutrinos. The number of events is well-matched to the estimated analysis capacity of the (rather large) collaborations of bubble-chamber specialists who are interested in the FNHS. The emphasis of FNHS is to fully analyze each event, and these numbers far exceed the total number of fully-measured events produced in one year by any of the present Fermilab collaborations.

The external particle identifiers are arranged in order of increasing density, as shown in Figure 1; i.e.,

(1) a dE/dx and momentum-measuring array of drift chambers and proportional-wire readout, similar to ISIS (or TPC); this follows the bubble chamber directly and is immersed in the same magnetic field;

(2) a time-of-flight scintillator wall to resolve ambiguities in dE/dx for slower particles;

(3) a "gamma-catcher" wall which detects and measures the energies of electrons and photons with sufficient precision to determine the

total e.m. energy in the forward direction and with good enough position resolution to match π^o photons;

(4) a "neutral hadron calorimeter" behind the gamma catcher, which detects neutrons/K_L^o and measures both energy and position;

(5) a "muon identifier," which identifies non-interacting particles with sufficient position accuracy to separate "pion punch-through" from genuine muons.

In addition, Figure 1 shows "side gamma catchers" which are designed to detect wide-angle photons with sufficient position accuracy (but modest energy resolution) so that $K_S^o \rightarrow \pi^o\pi^o$ events will be detected most of the time.

This sequence of detectors has the same logical sequence as the e^+e^- solenoidal magnetic detectors, except that the center-of-mass system is moving strongly forward in the laboratory...and the detectors are correspondingly peaked forward! The c.m. solid angle coverage is very much the same in both cases.

Vital to large solid-angle coverage in FNHS is the use of a modest magnetic field (B = 0.3 to 0.5 Tesla) for momentum measurement. The B-field is large in volume, covering both the bubble chamber and the dE/dx drift chamber, yet the stored energy is modest. Good momentum measurements are achieved by maintaining the product $B \cdot L^2$ high through the long path-length (L) followed by emerging charged particles. Contrary to the 15' BC philosophy of "bending as much as possible" within the bubble chamber, the main goal in FNHS is to get 95% or more of the charged tracks out of the BC into the dE/dx detector for particle identification. The low bending narrows the required transverse dimensions of the dE/dx detector, the muon identifier, and the magnetic field. It also preserves all of the bubble-chamber target volume as "fiducial volume" since the charged track can be "seen" in the dE/dx detector as well as in the bubble chamber. "Potential length" cuts are minimal, since one needs only to see the vertex and resolve the emerging tracks.

Similarly the hadron interactions and e.m. conversions in the exit windows of the bubble chamber will usually be detected and analyzed in the downstream dE/dx volume, since the FNHS will "view" both sides of the window wall.

The low momentum ($p \leq 1.5$ GeV/c) charged hadrons deflected substantially by the B-field will be analyzed within the bubble chamber. Identification of slow pions and protons by interaction and decay will occur within the chamber.

Particle identification for charged particles makes use of the combined information on velocity and dE/dx provided by the time-of-flight counter wall and the proportional readout of the drift chambers. (See Section (E) and Appendix A for a quantitative analysis.) Preliminary results indicate that very good discrimination is possible between pions, kaons, and protons over a wide range of momenta, due to frequent ($N = 400$) ionization sampling of the charged tracks and precise time-of-flight ($\sigma \leq 0.3$ ns).

Electrons and photons will produce e.m. showers in the "gamma catcher," which is modeled after the "MAC" shower detector at PEP. Frequent depth sampling provides discrimination between electron-and hadron-induced (charge-exchange) showers. Photons are easily distinguished from charged tracks by upstream drift-chamber information. The shower detector provides two-dimensional position information adequate to resolve all but the highest energy π^o gammas. It also provides good energy measurement, collecting more than 95% of the total photon energy produced in the typical neutrino hadronic final state. (However, side-gamma catchers are needed to catch the wide-angle gammas from some π^o decays.)

The "MAC" design merges into a hadron calorimeter behind the gamma catcher, using thicker absorbers between layers of proportional tubes. We expect to detect and resolve neutral hadrons (neutrons and K^o_L), separated from charged hadrons due to the distance from the vertex.

The muon identifier is an array of iron absorber, interspersed with several planes of drift chambers to measure positions of penetrating tracks. We know that the flux of such tracks is low in a neutrino beam. Our experience with the EMI system indicates that muon identification will be very good in the "slow" (1 ms) spills used for the bubble chamber.

Some quantitative design information on this FNHS design is provided in Section (E), plus Appendices. This includes Monte Carlo estimates of charged-particle acceptance of the dE/dx detector, the gamma catcher energy and number acceptance, and momentum accuracy. These estimates are preliminary but still informative enough for this Preproposal. More detailed Monte Carlos and other design calculations are planned in order to refine this "preproposal" into a Formal Proposal for a FNHS Facility.

We feel that the concept of FNHS is clear enough to explain how we expect to do "new physics"...not previously possible...with this facility. In the next section we discuss the new physics experiments which FNHS enables one to do.

Before ending this section, it should be made clear that the conceptual ideas outlined here are <u>not new</u>: they were clearly enunciated by H. Wachsmuth and W. Venus in an informal proposal at CERN[3] made in 1975. This proposal was never acted upon, probably due to the fact that BEBC and Gargamelle systems already existed and were just coming into use in high-energy neutrino physics at the SPS. The Wachsmuth-Venus proposal was an idea "before its time" then, but it is very relevant to today's planning for Tevatron physics!

(D) Physics Interest in the FNHS

The FNHS will be a facility capable of doing experiments not possible for other detectors. It will be able also to undertake experiments complementing those planned for electronic arrays at the Tevatron; e.g., extending the range of x- and Q^2 in neutrino deep inelastic scattering due to the ability of the bubble chamber to detect, identify, and measure all hadrons($\geq$ 0.1 GeV).

The FNHS will be the only neutrino detector capable of identifying and measuring the momentum or energy of all outgoing particles, both charged and neutral. Thus, for the first time at Fermilab, complete reconstruction of neutrino events produced in hydrogen/deuterium will be possible. High-resolution optics will enable the FNHS to detect short-lived decays from charmed particles and probably heavier-quark states. The FNHS is designed to detect, identify, and measure the energy of individual electrons, gammas, muons, neutrons, and K_L^o as well as charged hadrons.

Although limited in statistics when compared with counter experiments, the FNHS yield is still "respectable": i.e., the number of charged-current neutrino interactions in a typical run of 2.5 x 10^{18} protons of 1 TeV are 10,000 from hydrogen, 31,000 from deuterium, 66,000 from light neon. This event yield is well-matched to the analysis capability of interested user groups. The advantage of the technique is in the detailed analysis possible for each event.

In subsections to follow we discuss briefly important physics investigations to which the FNHS can make a unique contribution; i.e.,

(a) Search for $\Delta S \neq 0$ and $\Delta C \neq 0$ in neutral-current interactions;

(b) $\Delta S = +\Delta Q$ and $\Delta S = -\Delta Q$ in charged-current interactions;

(c) Examples of heavy-quark production, identified through decays in flight or unusual final states;

(d) Studies of hadron jets in neutrino interactions to investigate gluon bremsstrahlung and related QCD effects;

(e) Fragmentation functions, especially for hadronization into charged strange particles; tests of QCD and higher twist effects;

(f) Charged-current structure functions for high X and low Q^2 where low-energy hadrons must be detected; complementary to counter experiments;

(g) Proper measurement of the neutral-current structure functions, based on zero-constraint fits of NC events using full knowledge of final hadronic state;

(h) "Long-shots," such as tau-neutrino detection and/or evidence for neutrino oscillations, probably better done with beam-dump bubble-chamber experiments.

$\Delta S \neq 0$ and $\Delta C \neq 0$ in Neutral-Current Interactions. According to the "standard model" of weak interactions, the flavor of the struck quark can be changed only in charged-current interactions. Thus the hadronic state produced from a nucleon in neutral-current interactions must have zero net strangeness, charm, beauty, etc. Definite evidence for either $\Delta S \neq 0$ ($\Delta C \neq 0$, etc.) in neutral-current transitions would be an exciting hint of possible fundamentally new phenomena and would require drastic revision of the standard model.

The present upper limit on $\Delta S \neq 0$ in NC neutrino interactions is still that set by the Gargamelle collaboration(4) from a Proton Synchrotron exposure. The result was that

$$\frac{\sigma(\nu N \rightarrow \nu\Lambda(\Sigma^o)X)}{\sigma(\nu N \rightarrow \nu X)} \leq 0.54\% \quad \text{(90\% C.L.)}$$

This result was aided by the low level of associated production of strangeness at low neutrino energies ($E_\nu \leq 10$ GeV). However, this particular reaction is only <u>one</u> channel, and this one channel is already an appreciable fraction of the total charm production (∿5% of CC). Thus a detector able to detect and identify <u>all</u> final-state strange particles should be able to set a much lower limit. A detailed study is being made of the statistics of background subtraction, with experimental detection efficiencies included.

The present best upper limit on $\Delta C \neq 0$ in NC neutrino interactions is that of the CDHS collaboration[5] which measured the ratio of yields:

$$\frac{\nu_\mu N \to (\nu_\mu)\mu^+ X}{\nu N \to \mu^- X}$$

which is analyzed (together with NC/CC) to yield:

$$\frac{\Gamma(\text{NC with } \Delta C = 1)}{\Gamma(\text{NC total})} \leq 2.6\% \qquad 90\%\ \text{C.L.})$$

for $E_\nu > 100$ GeV (and $\lesssim 200$ GeV in practice). With higher neutrino energies and more complete detection of charmed final states in the FNHS, we hope to be able to set lower limits on charm-changing reactions.

<u>$\Delta S = +\Delta Q$ and $\Delta S = -\Delta Q$ in Charged-Current Interactions</u>. In charged-current interactions we will be able to measure the relative rates of $\Delta S = +\Delta Q$ (strangeness production) and $\Delta S = -\Delta Q$ (charm production) with a new level of precision and free from associated production backgrounds, to the extent that FNHS succeeds in identifying all final-state strange particles. We will thus be able to study the dynamics of single strangeness and charm production, the corresponding resonance structure, and the fragmentation functions involving charm and

strangeness. Charmed baryon and charmed meson production and decay should be detectable in substantial yields at Tevatron higher energies, such as $F^+ \rightarrow \nu_\tau + \tau^+$, cascading to $\tau^+ \rightarrow \bar{\nu}_\tau + A_1$, etc.

The statistics are quite reasonable: 10% of all CC interactions are expected to involve charm production (i.e., $\sim$3000 events in a deuterium exposure). If the F/D ratio is 20%, this should provide 500 charmed baryons and 2500 charmed meson events. Even after putting in branching ratios, the high detection efficiency of the FNHS should result in many events of each type.

A search for the more exotic baryons, such as those with quark structure csu, csd, css, etc., will be made. Only a few events totally reconstructed may be sufficient to prove the existence of a particle or a process.

Lower upper limit than now exist should be possible for such exotic processes as $\Delta S = 2$, with good strange-particle identification.

Search for Heavy Lepton and Quark Production and Decay. This search for rare events will most probably be made using the light neon filling, which provides about 66,000 CC events in the standard exposure. Assuming 10% charm production, F/D = 1/5, and a 3% branching ratio for $F^+ \rightarrow \nu_\tau \tau^+$, we would then expect to have 33 $F^+ \rightarrow \nu_\tau \tau^+$ events to occur within the FNHS bubble chamber. Observation of these decays with the high-resolution cameras (1/3 the total volume) should be able to detect visible decays of 1/5 of the total: i.e., a few events. Much larger yields of D^+, D^o, and F^+ decaying into all modes will in principle be available for detection: a schematic representation of the yields of produced and high-resolution camera-detected events is as follows:

H.R. cameras

66 K CC → 6600 charm → 5500 D^+, D^o ——→ 400 D^+, D^o

66 K CC → 6600 charm → 1100 F^+ ——→ 80 F^+

1100 F^+ → 33 τ^+ ——→ 3 $F^+ \to \tau^+$

Based on the Albright and Shrock estimates(6) of the Cabibbo-like mixing angles θ_1, θ_2, θ_3 and the observed charm excitation function scaled in neutrino energy as M^2_{quark}/E_ν, with M_b = 5 GeV and M_t = 18 GeV, we estimate that we should observe:

$$\nu + (\bar{u},\bar{c}) \to \mu^- + \bar{b} \qquad \text{(20 events)}$$

$$\bar{\nu} + (u,c) \to \mu^+ + b \qquad \text{(6 events)}$$

$$\nu + (d,s,b) \to \mu^- + t \qquad \text{(30 events)}$$

With good spatial resolution, we should be able to observe cascade decays, such as (t) → b → c → s, with accompanying muons and strange particles.

Studies of Hadron Jets in Neutrino Interactions. The bubble chamber is presently the only detector capable of observing jets produced by neutrinos.

Neutrino production of "jets" of hadrons has certain advantages over e^+e^- production. In e^+e^- reactions a photon produces a $q\bar{q}$ pair which produces jets, but the axis is unknown a priori and must be sought by a maximization procedure. In charged-current neutrino reactions a $W^\pm$ strikes a quark in a nucleon, and the jet axis is the known direction of the W^+. The interacting quark and the diquark pair then produce jets. Furthermore, both the quark and diquark are identified in neutrino interactions. For example, in a neutrino-proton interaction a W^+ strikes a valence d quark with a probability $\sim$0.95. The quark content of the diquark system is thus "uu," and the resulting quark is also "u"; i.e.,

$$W^+ + uud \rightarrow uu + u$$

By contrast in e^+e^- neither the quark content nor the jet axis is known a priori.

The higher energies available at the Tevatron will be much more favorable for the production of jets. Recent results from 15' BC E-546 studies, as well as BEBC result, show clear indications of the "asymmetric seagull" effect, and even hints of "three-jet" structure at high W^2. A deuterium run in the horn neutrino beam would produce several thousand events with $W^2 > 400$ GeV^2. Each jet in a three-jet event would have an average energy $\sim$6 GeV. This is large enough so that there would be sufficient multiplicity of particles to define each jet.

The additional information provided by jets in neutrino interaction makes it possible to test the quantum number of the partons in a fundamental way.(7) Furthermore, jets can be studied in which the quark content is a diquark. For example, p_T of the individual hadrons relative to the jet axis could be examined to see if the p_T distribution is the same as in jets from single quarks. Since the FNHS will be able to identify all particles, the quantum numbers of individual jets can be studied.

Fragmentation Functions - QCD and Higher Twist. As is well known, the simple quark-parton model predicts that fragmentation functions factorize such that there is no Q^2 dependence, i.e. $D = D(z)$. On the other hand, QCD makes definite predictions of the Q^2 dependence of these functions. These predictions can be tested in principle by measuring the fragmentation functions or their moments over a wide Q^2 range. In particular, in neutrino (antineutrino) scattering, we can determine the fragmentation functions which describe the hadronization of u(d) quark into all hadrons, i.e. $D_q^{\pi^+}$, $D_q^{\pi^-}$, $D_q^{K^+}$, $D_q^{K^-}$, etc., where $q = u$ or d.

At present, only bubble-chamber experiments have been able to make these determinations. However, in the Fermilab 15-foot chamber and in BEBC it is not possible to separate fast K^+, K^-, p from π^+, π^-. Thus determinations of $D_q^{\pi^+}$ and $D_q^{\pi^-}$ suffer from contamination. In the proposed FNHS we would be able to make this separation and thus obtain clean samples of π^+ and π^-. In addition, because of the ability to detect π^o's, we should be able to remove those $\pi^\pm$ which come from fragmentation into resonances such as $\rho^\pm$ and ω. The resulting pure fragmentation functions $D_q^{\pi^+}$ and $D_q^{\pi^-}$ will make it possible to search for small QCD and other effects with confidence, particularly in the non-singlet fragmentation function $D_q^{\pi^+}-D_q^{\pi^-}$.

With regard to K mesons, we can only at present observe a combination of K and $\overline{K}$, by observing K_S^o decays. With the FNHS we will obtain the fragmentation functions $D_q^{K^+}$ and $K_q^{K^-}$.

The observation of baryon fragmentation functions is of particular interest. Most baryons are expected to come from the hadronization of the recoiling diquark, thus backward in the hadronic center-of-mass. However, a higher twist process, the direct scattering of neutrinos by diquarks in the nucleon, may make an important contribution to the production of fast forward baryons. This process is expected to have a $1/Q^4$ dependence. As has been pointed out, it may be quite difficult, from structure functions alone, to separate QCD from higher twist effects. Thus the observation of the Q^2 dependence for fast forward baryons would be of particular interest.

In present bubble chambers the only observable fast baryons are Λ^o's. In the FNHS not only would the Λ's be observed, but it would also be possible to separate from them a substantial function of Σ^o's. This may enable us to separate transverse from longitudinal contributions to the deep inelastic amplitudes. At present it is clear that the information on the Q^2 dependence of strange baryon production is inadequate. One also would hope to be able to observe the Q^2 dependence for the production of fast forward neutrons and protons, completely impossible with present techniques, but quite possible in the FNHS. It is interesting to note that fast forward neutrons from a higher twist process would only be produced in νn reactions, and not in νp reactions. On the other hand, for antineutrinos, fast forward protons would be produced in $\bar{\nu}p$ reactions, and not in $\bar{\nu}n$ reactions. These comparisons would be easily made in a deuterium exposure.

<u>Charged-Current Structure Functions (high X, low Q^2)</u>. Measurement of charged-current inclusive structure functions will continue to be an important part of the bubble-chamber neutrino physics program, even at higher neutrino energies provided by the Tevatron. However, the emphasis in FNHS will be on the unique contributions to structure function analysis which FNHS can make in x, Q^2 regions not readily accessible to counter experiments. The counters with massive targets have better statistics for most of the range of X- and Y-variables. However, bubble chambers can contribute in an important way in two areas of charged-current structure-function analysis:

(a) High X- and low Q^2 region, where the hadron energy is too low for counter hadron calorimeters for good measurements;

(b) Structure functions on protons and neutrons (i.e., hydrogen and deuterium targets).

In (a) it is interesting to note that a FNHS run with only "modest" statistics (66,000 CC events from light neon) will contribute new physics. For large X, the FNHS results would span a larger range of Q^2 than is accessible to counters. This is illustrated in Figure 2, where FNHS predictions for $0.6 < x < 0.7$ are superimposed on the CDHS results. Note that the CDHS experiment does not report data for $Q^2 \leq 35\ (\mathrm{GeV/c})^2$, or $E_H \leq 28$ GeV, whereas the bubble chamber is quite capable of good resolution in hadron energy down to a few hundred MeV!

The FNHS system, with its improved π^o and neutron/K_L^o detection, should provide even better neutrino energy resolution than before...and better than any existing counter hadron calorimeter in the low hadron energy range.

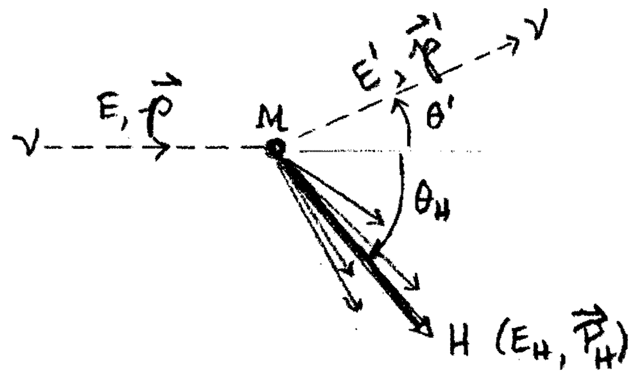
The ability to detect strange particles provides the opportunity to study the structure functions of the "strange sea" (i.e., the strange quarks in the sea) by selecting events involving strange particles. (This study has been started by the E-545 deuterium collaboration, with interesting preliminary results.[8]

Proper Measurement of the Neutral-Current Structure Functions. Although the standard theory is able to predict the neutral-current (NC) structure functions from the measured charged-current (CC) structure functions, it is an important experimental task to measure these structure functions as accurately as possible. As more than one leading theorist has emphasized, experimenters should ask about the New Orthodoxy, "How Can it Fail?" We must check critical parts of the "orthodoxy" with as many different and careful experimental methods as possible.

The greatest difficulty with NC events is, of course, that detection of the outgoing neutrino is essentially impossible. Hence the final-state hadronic system must be relied upon to provide the key variables E_H, $\vec{P}_H$ (or θ_H and P_H) with sufficient accuracy to determine x, Q^2, and y, E_ν. Since the final hadronic state consists of a number of hadrons (both charged and neutral), the problem is to sum E_H and $\vec{P}_H$ with sufficient accuracy. In principle, a NC event, fully and accurately measured in the hadronic system, is a 0-C kinematic fit. However, the kinematic variables (x, Q^2, E_ν, y, ν) are sensitive to errors in hadron energy and angle, particularly at high "y." Counter experiments, which do not resolve individual hadrons, have a fundamental problem since the "energy flow" vector does not also define the total momentum. Most counter experiments have used narrow-band beams to define the neutrino energy (to 10% - 20%) and have used an "effective x," or x', to approximately represent the true kinematic variable $x = Q^2/2M\nu$ ($\nu = E_H - M$ = energy transfer to hadron state, and $y = \nu/E$). For example, the CHARM experiment's resolution in "x'" is very wide, with a broad non-Gaussian tail. It can be shown that the error in x for a narrow-band ($\Delta E_\nu/E_\nu = \pm 10\%$) experiment with a "no-leakage" hadron calorimeter has $\Delta x/x \geq 40\%$ for $y > 0.8$.

Can one do better with FNHS? Can one increase the yield from the bubble chamber, relative to NBB counter experiments? We have examined this problem in some detail. We find that FNHS is competitive, using a wide-band beam to increase the yield an order of magnitude. All kinematic variables of NC events can be determined in a 0-C fit using complete reconstruction of the final hadronic state.

To see how this is done, let us review briefly the kinematics. Conserving energy and momentum separately (momentum <u>must</u> be measured as a vector, independent of <u>energy</u> flow), we have:[(3)]



$$E + M = E' + E_H \quad (1)$$
$$p_x = p'_x + P_{Hx}$$
$$0 = p'_t - P_{Ht}$$

Define $\ell = E'\,(1 - \cos\theta') = E' - p'_x$. It can be shown that

$$\ell = P_{Hx} - (E_H - M) = Mxy$$
$$Q^2 = 2\ell\,(P_{Hx} - \ell) + \ell^2 + P_{Ht}^2 = 2E\,(E' - p'_x) = 2E\ell$$

Thus for $\ell << P_{Hx}$ and $\ell^2 << P_{Ht}^2$, which are well satisfied except at extreme limits, it can be shown that:

$$\frac{\Delta Q^2}{Q^2} \simeq \frac{\Delta x}{x} \simeq y \cdot \frac{\Delta \ell}{\ell}$$

and

$$\frac{\Delta E}{E} \simeq (1-y)\,\frac{\Delta \ell}{\ell}$$

Since $\ell = M \cdot x \cdot y$, a typical value is $<\ell> = 100 \rightarrow 200$ <u>MeV</u>--a very small value. For good accuracy in the kinematic variables, $\Delta\ell$ must be even smaller! In "lucky" cases (e.g., the "BNL event"), $\Delta\ell \simeq 8$ MeV. However, confusion of a 5 GeV proton with a 2 GeV pion makes $\Delta\ell \geq 117$ MeV! It is clear that FNHS's ability to identify particles is crucial to good NC analysis. Also $\ell(P_{Hx}, E_H)$

is the important variable which _must_ be well measured; momentum and energy must be _separately_ determined. Once "ℓ" is known, then one can evaluate _all_ the kinematic variables:

$$Q^2 = P_H^2 - (E_H - M)^2$$

$$E = Q^2/2\ell$$

$$\nu = E_H - M$$

$$x = Q^2/2M\nu \qquad \text{and} \qquad y = \nu/E$$

We plan a Monte Carlo simulation of a neutral-current experiment, with realistic errors on $\vec{P}_H$, E_H to determine $\Delta\ell$, Δx, Δy. However, it should be obvious that the FNHS's ability to identify particle mass and momentum (thus $\vec{P}_H$, E_H separately) is qualitatively superior to the "energy flow" devices used in counter experiments.

(E) Practical Design of FNHS: Present Status

The present status of the practical design of the FNHS is not far beyond the conceptual stage, due to the scattered location of the interested parties and strongly competing commitments (e.g., teaching, ongoing research). Nevertheless, a small group of interested physicists (called "the FNHS Design Group") have committed a fraction of their research time,since mid-December 1979, to a "physicist design" of the FNHS. V. Peterson (Hawaii) has acted as coordinator of this Design Group, and there have been three Design Group meetings at Fermilab (December 13, February 22, and April 14-15) to bring together ideas from various contributors. In these all-day discussions new ideas have emerged and the initial design has been modified several times. We believe that the present design is fairly stable.

However, it will take extended and concerted effort to complete the design and prepare a reliable cost estimate. Our goal is to complete the design during the 1980 Fermilab Summer Study.

Layout of the FNHS: Figure 1 is a plan view of the FNHS, approximately to scale, showing the primary components. The bubble-chamber vertex detector (BC) is cylindrical in shape with hemispherical end caps. Directly behind the BC is the dE/dx detector (called "ISIS" for short) which is wide enough to intercept 95% of the charged prongs (above 1.5 GeV/c) emerging from the bubble chamber. ISIS is also deep enough to provide 4 meters of path length in the gas to permit good momentum measurements and ionization sampling. A modest magnetic field (vertical) of 0.5 Tesla is superimposed over both the BC fiducial volume and ISIS.

After ISIS comes a single plane of scintillator counters (marked "TOF") for time-of-flight measurements, then the "shower detector" (SHW) for photon and electron detection and energy measurement. Next is a hadron calorimeter (HAD) to detect neutrons and K_L^o. Finally a large volume of steel, with several planes of drift chambers interspersed, forms the Muon Identifier (MUI).

The overall length of the FNHS is $\sim$15 meters. The maximum width is about 8 meters. The maximum height will be determined by the Bubble-Chamber system and the magnet. However, it is clear that the entire FNHS is compact enough to be positioned either in front of the 15' BC or directly behind it.

The following paragraphs describe briefly the various components of FNHS. More detailed write-ups are available for some of the components (see References).

Bubble-Chamber Vertex Detector: The fiducial volume of the BC is defined by a 2.0 meter diameter cylindrical body, with overall length between hemispherical end caps of 4.0 meters. The total fiducial volume is thus 10.5 m^3 (0.62 tons of LH2, 1.25 tons of LD2, 2.63 tons of ρ = 0.25 gm/cc light neon). The actual Dewar volume is about 25% greater, or 13 m^3; this is considerably less volume than the 15' BC ($\sim$40 m^3 liquid volume) and thus the demands for cooling and expansion are much less.

Figure 3 is the side view (elevation) of the FNHS BC, including both the Dewar and the vacuum chamber, optics ports, and piston assembly. The neutrino beam enters from the right; the exit vacuum window (left side) is close to the liquid.

Figure 4 is an end view (elevation) of the chamber, providing another view.

Figure 5 is a sketch of the optics for FNHS BC, including both the 4 low-resolution cameras and 4 high-resolution cameras. The low-resolution cameras will view the entire fiducial volume in stereo. The high-resolution cameras are designed to resolve to 140 microns (or less) over a depth-of-field of $\sim$50 cm (each lens). Overlapping depths are planned for the high-resolution lenses, so that (on a statistical basis) we expect to be able to apply high resolution to 1/3 of the events.

The use of low-density liquids and smaller volume lowers the static operating pressure. The hemispherical BC windows are also of smaller diameter than the 15' BC. Thus the window thicknesses on the Dewar can be reduced substantially from the 15' BC; a preliminary estimate is 0.15" of stainless steel. (The vacuum chamber walls would be of the same thickness, namely 0.15" SS.) Thus the Dewar (vacuum chamber) windows are 0.22 (0.22) radiation lengths thick and 0.037 (0.037) collision lengths thick. We hope to be able to reduce the conversion thickness (0.44 r.ℓ.) by use of special metals (e.g., titanium). However, it should be noted that interactions in these windows can be detected in ISIS in most cases, so that the information is not lost by "absorption."

dE/dx Measurement in ISIS: The method of "particle identification by ionization sampling" (ISIS) has been tested in the CERN EPI development, the Oxford ISIS device, the USA development of CRISIS, and LBL's TPC. The method of sampling ionization many times by drifting the tracks along the B-lines (electric field parallel to B) has been shown to work well. (Drift distances up to 200 cm have been used successfully.) The ionization samples are read out at the end of the drift-chamber volume by an array of crossed X- and

Y-wires of a proportional chamber. Analysis of the mean ionization is done using a truncated distribution to reduce the effects of the Landau tail. The resulting r.m.s. uncertainty in mean ionization obtained by CRISIS, ISIS, and TPC in test setups with pions and protons may be summarized as follows:

Detector	Test Beam	N = (# Wires)	σ_I/I	σ_x (RMS)
CRISIS (prototype)	π^-(40 GeV/c) p(100 GeV/c)	64	6.0%	N.A.
TPC (prototype)	π^-,e^-(1.8 GeV/c)	192	2.7%	100 ± 3μ

Since we plan to have 400 samples per track in FNHS dE/dx detector, we expect to do at least as well in measuring mean ionization of each track. The overlapping of tracks sometimes causing problems in hadron beam experiments should not occur in this lower-intensity neutrino beam.

Figure 6 shows the variation of ionization with momentum for proton, kaon, and pion tracks in a typical gas used for ionization measurements. Above about 5 GeV/c the separation in ionization between pions and kaons is 16%, and for kaons and protons it is 10%, for a given momentum. Since these differences are large compared with the standard deviation of measurement, the dE/dx discrimination for 5 to 50 GeV/c tracks should be very good.

Below 5 GeV/c we can "rescue" ISIS in particle separation by using <u>time-of-flight</u>. Appendix A provides an analysis of the combined power of t-o-f + dE/dx in discriminating between pions, kaons, and protons, given the momentum, for "state-of-the-art" measurement accuracy in t-o-f (i.e., σ = 0.25 nsec) and dE/dx. The result is that rejection of pions can be made better than 100 to 1 for kaon candidates at most momenta, and protons can be identified in a background of pions which is two orders of magnitude greater.

Appendix A contains early Monte Carlo results of simulated FNHS events, which show the spatial pattern of charged and neutral particles; decay and interaction are included. Also shown are the bubble density, ISIS output, and time-of-flight predictions for various momenta charged particles, with likelihood plots to demonstrate particle identification. Particle identification is excellent below 50 GeV/c.

Momentum Measurement by BC + ISIS is much improved over the present 15' BC, even with a much weaker magnetic field in FNHS, due to the much longer path length for measurement (average path = 6 meters). The standard formula for the fractional momentum accuracy is

$$\frac{\sigma_P}{P} = 90 \frac{\delta}{B \cdot L^2 \sqrt{N}} \cdot P ,$$

where N = number of points measured, P is in GeV/c, δ = position accuracy (meters), the magnetic field B is in Tesla, and the track length L is in meters. If we assume B = 1.0 Tesla, L = 6 m, and $\delta = 2 \times 10^{-4}$ m (200 microns), we find

$$\frac{\sigma_P}{P} = 0.049 \frac{P}{\sqrt{N}} \ (\%)$$

or 3.3% for P = 300 GeV/c and N = 20 wires measuring position. This is better than the 15' BC momentum accuracy with 3.0 Tesla field (and restricted fiducial volume)! This formula ignores multiple scattering, but with hydrogen in the chamber and gas in ISIS, we expect multiple scattering to be small.

In view of this promising result, we have concluded that the magnetic field strength, B, can be reduced to about B = 0.5 Tesla, increasing the above momentum uncertainty of a 300 GeV/c track to about 7%. Further studies of the FNHS system will refine the calculations of momentum determination to include multiple scattering in the windows, etc.

The acceptance of FNHS for charged tracks, of course, increases with lowered magnetic field, since the primary spreading of exiting tracks is due to magnetic bending. Figure 7 shows the results of a Monte Carlo calculation of the acceptance of ISIS as a function of magnetic field, for the charged prongs (above 1.5 GeV) produced by a 1000 GeV horn beam.

The detection of π^o photons is to be handled by placing a (lead sheet + proportional tube) shower detector (SHW) behind the time-of-flight counters. This detector is similar to the "MAC" shower detector at PEP,[9] which has 30 layers of proportional tubes between 0.5 r.ℓ. lead sheets. The photons will undergo total absorption in the 15 radiation lengths, and the energy resolution is $\sigma_E/E = 0.18/\sqrt{E}$, where E (GeV) is the photon energy. Position accuracy is $\sigma_x \simeq 1$ cm ($\sigma_y \simeq 2$ cm), which is $\sigma_\theta = 1 \rightarrow 2$ milliradians viewed from the BC center. A great advantage of the SHW over 15' BC gamma detection is excellent measurement of the total photon energy; SHW captures 95% of the π^o energy, on the average, although only 45% of the photons in number. This is a good match to the 95% of charged particles (over 1.5 GeV/c) accepted by ISIS. Details of the shower detector are published,[10] and cost estimates are available (see Section (F)), based on recent MAC experience.[11]

The problem of detecting low-energy wide-angle photons, matching with a high-energy forward gamma to reconstruct a $\pi^o \rightarrow 2\gamma$, is more difficult. One solution is to place additional shower detectors at the sides of ISIS and the bubble chamber, as shown in Figure 1. Position resolution is more important than energy resolution so only a few layers (but $\geq$ 5 r.ℓ.) are needed. This problem is being studied in detail, in particular to detect $K_S^o \to 2\pi^o$.

It should be noted that the SHW, plus ISIS, provides an excellent detector for electrons, since the incoming charged track's position will be well known and the spatial resolution of the SHW is adequate to separate showers from photons and electrons. The usual problem of negative pion charge exchange "faking" an electron can be handled by the combined information from time-of-flight, SHW, and a counter in the hadron calorimeter: time-of-flight will resolve e/π slow tracks, and high momentum pion interactions will penetrate to the drift chamber behind the shower detector.

The "MAC" e.m. shower-detector design is readily adaptable to the hadron calorimeter, substituting iron for lead as the absorber. Again using "MAC" design experience, we plan 35 layers, each 0.2 collision lengths ($\sim$20 gm/cm^2) apart. We are in the process of calculating the detection efficiency of this "HC" for neutrons and K_L^o.

Muon identification will be accomplished by demanding penetration to one or more depths in the solid iron absorber behind the hadron calorimeter, depending upon momentum. Position accuracy for the drift chambers depends upon the expected multiple scattering at various depths, but a few mm or better is all that is required. At present, we extrapolate from our EMI experience and assume that four layers of drift chambers, at 0.5, 1.0, 2.0, and 3.0 meters, of iron will be sufficient.

Much further calculation is needed in order to fully "design" the FNHS system. However, we have done enough to believe that it is an eminently practical device which offers great advantages for future neutrino physics.

(F) Rough Estimate of the Cost of FNHS

The present status of the design of the FNHS is preliminary. The design so far is the product of poorly-coordinated efforts of a few physicists working in their spare time. A realistic estimate of cost should involve at least some time by experienced design professionals reviewing our preliminary design.

Nevertheless, the Fermilab Director has requested at least a "ballpark estimate" of FNHS cost. We have done our best, drawing upon the available experience of those involved in the design and construction of similar detectors. The level of reliability is that of "physicist opinion," rather than a well-documented engineering estimate.

The estimated cost listed below does not include engineering design time; neither does it include the time of the physicists who will be actively involved in overseeing the development of FNHS. Electronic costs are usually "per channel," which includes construction of modules but not assembly or debugging. Mechanical construction time is indicated (where known).

Table 1 lists the main components of the FNHS and the principal items contributing to cost. The basis for estimating is briefly described as follows:

Bubble Chamber: Extrapolated from experience in building the 15' BC, scaled up to account for inflation. No refrigeration equipment is included (about half the cost of the 15' BC installation), since it is judged that the present FNAL installation is adequate to refrigerate both the 15' BC and the FNHS chamber.

Low-Field Magnet (5 m x 5 m x 7 m volume of 0.50 Tesla field over both the bubble chamber and ISIS): Conventional magnet design; we will also work out a superconducting design (to save power). A great deal of magnet expertise exists at Fermilab and at Argonne, so that the magnet should be built locally. The present design involves a large volume (175 m^3) "box" magnet powered by 400 turns of 5000-amp copper coils. The iron weight is ∿600 tons; the copper is 175 tons, and the power required is 2 MW.

<u>ISIS</u> (one large gas volume, 4 m x 4 m x 4 m; drift distance = 2m; 2 x 400 sampling wires, plus 10 position wires with 500 "pads" each wire): The most directly applicable cost figures come from the MIT construction of CRISIS. TPC costs are much higher, per unit volume and per wire, due to cylindrical shape and high pressure. ISIS costs may be less. Electronics readout costs dominate

<u>Time-of-flight Counter Wall</u> (scintillator counters, total area = 4 m x 5 m of ½"-thick plastic): Numbers scaled from purchase of counter materials for an experiment at PEP-14.

<u>Electromagnetic Shower Detector (SHW)</u>: The cost estimate for SHW is scaled from the MAC e.m. shower detector at PEP, which uses proportional tubes between ½ r.ℓ. lead sheets. Using extruded aluminum tubes (½" x ½") with a single stainless-steel wire centered in each tube, MAC built a 34-layer sextant-divided solenoidal shower detector for $35,000 in materials (excluding electronics) and ∿1½ man-years in technician labor.[(11)] The mean cross-sectional area of the MAC detector normal to the photons is about 9.3 m^2; the weight of lead (type-metal) is about 3.2 metric tons.

The "forward" SHW in FNHS has a cross-sectional area of 5 m x 4 m = 20 m^2, and we propose to use the same thickness (34 layers, 17 r.ℓ.). Thus we scale the MAC costs by a factor of 20/9.3 = 2.15. Since much of the cost of MAC is in technician labor, we include this @$25,000/man-year (including overhead).

The MAC shower detector "ganged" radial sections of cells (over 3½ to 6 r.ℓ.) to reduce the number of readout channels without diminishing angular resolution. This reduced the electronics cost by an order of magnitude. We propose to adopt the same method.

Hadron Calorimeter: Again following the MAC design, we plan 35 planes (5 m x 4 m area) with 1"-thick iron absorbers interleaved with the same aluminum-extrusion proportional tubes. This provides $\sim$700 gm/cm^2 iron thickness, or 140 tons of iron. If 4-m long tubes can be used, (400/8) = 50 extrusions per layer are needed: thus 35 x 50 = 1750 8-cell extrusions are required. Ganging channels longitudinally over each collision length, the number of readout channels is $\frac{1}{7}(1750) \times 8 = 2000$.

Muon Identifier (3 m x 6 m x 3 m of steel, interspersed with three 3 m x 6 m planes of drift chambers): The price/ton cost of steel is a recent Fermilab number for steel requiring no surface machining. The drift chamber estimates come from a recent set of chambers built for use in the Neutrino Lab. Readout and digitization of drift chamber x output was assumed to cost the same/wire as the ISIS readout.

Table 1

Rough Estimate of Basic FNHS Costs

Subsystem (Detail)	Amount	Subtotal
(1) Bubble Chamber (with optics but without refrigeration):		
(a) Chamber body, including cooling loops.	$850 K	
(b) Vacuum tank, including vents, superinsulation. .	850 K	
(c) Main vacuum system	150 K	
(d) Expansion actuator	600 K	

Subsystem (Detail)	Amount	Subtotal
(e) Chamber piston, including Z-section.	400 K	
(f) Optics windows and invar supports.	500 K	
(g) Camera lenses (4 low- and 4 high-resolution) . .	300 K	
(h) Window vacuum system	150 K	
(i) Film transport and data box system	300 K	
(j) Scotchlite, flashtubes, and power supply	100 K	
(k) Transfer lines, valves, air controls	200 K	
(l) Wiring and tubing to control room.	200 K	
(m) Instrumentation system	200 K	
(n) Other items.	200 K	
		$5,000 K
(2) Magnet (175 m^3 of 0.50 Tesla field):		
(a) Steel of magnet quality (600 tons @$250)	150 K	
(b) Coil (copper, 170 tons @$1000, plus winding) . .	340 K	
(c) Mounting and bracing, etc.	50 K	
(d) Power supply, wiring, etc.	150 K	
		$ 690 K
(3) ISIS, dE/dx Device (1 big box: 4 m x 4 m x 4 m):		
(a) Mechanical construction.	$200 K	
(b) Electronics (5400 channels @$75)	400 K	
(c) Interface to computer.	25 K	
		$ 625 K

Subsystem (Detail)	Amount	Subtotal
(4) Time-of-flight Counter Plane (4 x 5 m^2):		
(a) Plastic scintillator, ½" thick (200 $ft.^2$). . . .	$ 6 K	
(b) Light pipes.	7 K	
(c) Phototubes, 2" diameter (48 @$150, w/bases). . .	7 K	
(d) ADCs (48) and fast electronics	65 K	
(e) Cabling and interface to computer.	15 K	
		$ 100 K
(5) Electromagnetic Shower Counter (after MAC):		
(a) Lead sheets (41 tons @$1400)	60 K	
(b) Aluminum 8-cell extrusions (4000 @$5).	20 K	
(c) Other items (plastic, wires)	30 K	
(d) Electronics (3200 channels @$50)	160 K	
(e) Mechanical support, technician time.	80 K	
		$ 350 K
(6) Hadron Calorimeter (MAC design):		
(a) Steel absorber (140 tons @$250).	$ 35 K	
(b) Aluminum extrusions (1750 @$10).	20 K	
(c) Plastic, wires, connectors	20 K	
(d) Mechanical support, technician time.	60 K	
(e) Electronics (2000 channels @$50)	100 K	
		$ 235 K
(7) Muon Identifier (6 m x 3 m x 3 m):		
(a) Steel (400 tons @$250)	$100 K	
(b) Mounting of steel.	20 K	

Subsystem (Detail)	Amount	Subtotal
(c) Drift chambers	120 K	
(d) Electronics readout and interface.	100 K	
		$ 340 K
Total estimated basic cost of FNHS		$7,340 K

This is about twice the cost of a "typical" Tevatron counter experiment. Since FNHS is a facility to be used for many experiments and by many user groups, we consider this cost "reasonable." Much of the small-scale construction and assembly effort can be provided by user groups involved with FNHS development.

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(11) Bill Ash, private communication.

FIGURE CAPTIONS

Figure 1: Schematic (plan view) of the FNHS, to scale, showing the main components of the system. See text for details.

Figure 2: CDHS charged-current structure function $F_2(x)$ values, plotted vs. Q^2 for various intervals of $x = Q^2/2M\nu$. Superimposed are predicted FNHS results for high X and low Q^2, with statistical errors from a standard run, which demonstrate the ability to cover a wide range of Q^2 and X.

Figure 3: Elevation (side) view of the FNHS bubble-chamber vertex detector, showing the Dewar, vacuum chamber, and optics. Bot low-resolution and high-resolution lenses are shown. The downstream windows (left end) are close together to minimize the distance to external detectors (ISIS).

Figure 4: End view of the FNHS bubble chamber, showing piston and "Z" section as well as other major components.

Figure 5: Top (plan) view of the FNHS bubble chamber, showing layout of optics ports. Four low-resolution and four high-resolution cameras are planned.

Figure 6: Ionization loss in argon + 20% CO_2 at atmospheric pressure for pions, kaons, and protons, as a function of momentum.

Figure 7: Acceptance of the ISIS 5m (wide) x 4 m x 4 m dE/dx detector for charged particles above 1.5 GeV/c produced by a 1.0 TeV quadrupole-triplet beam in a cylindrical bubble chamber 4.0 meters long. Decays in flight and interactions in the liquid and window are ignored for this calculation.

FIG. 1

F.N.H.S. SCHEMATIC

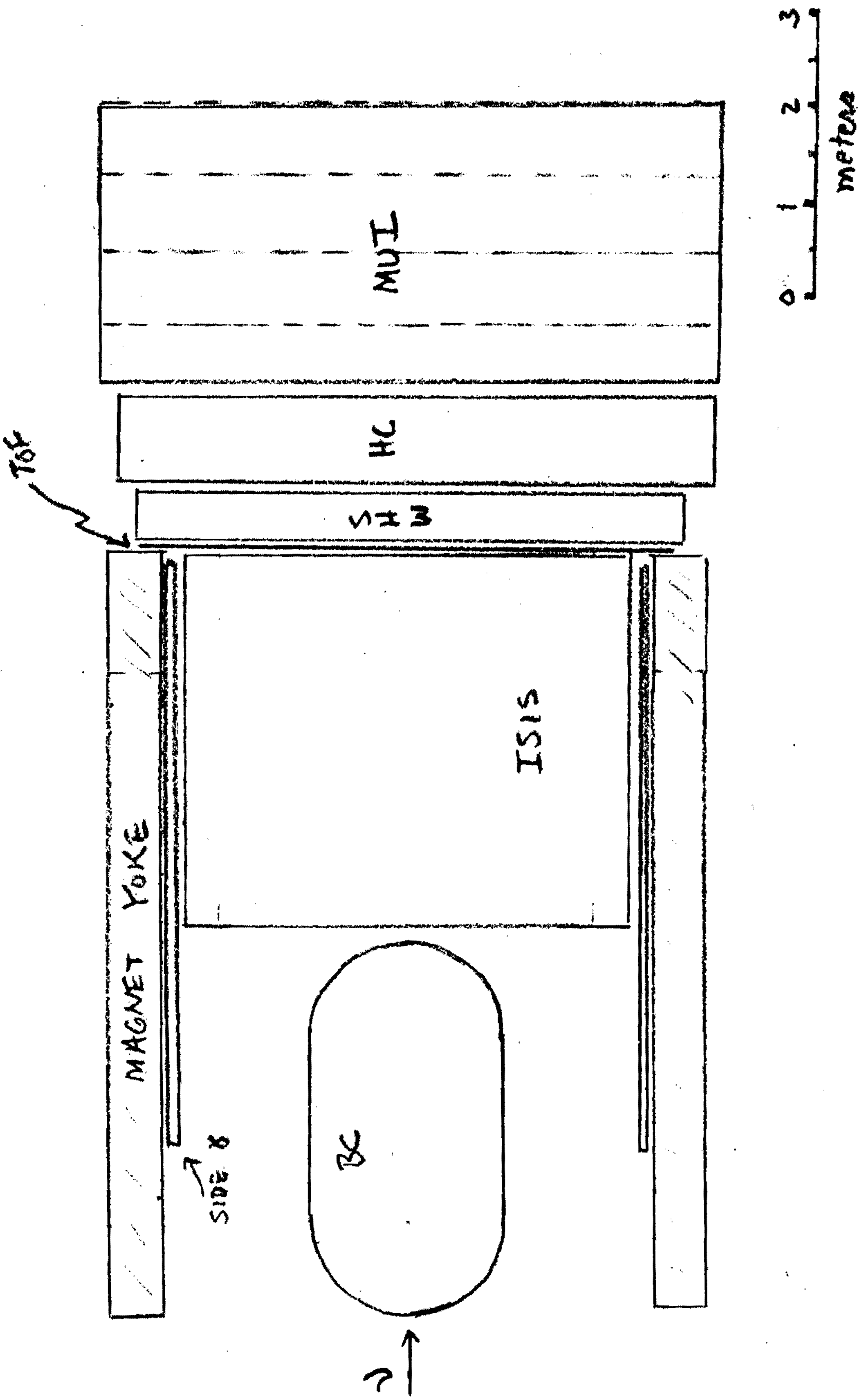
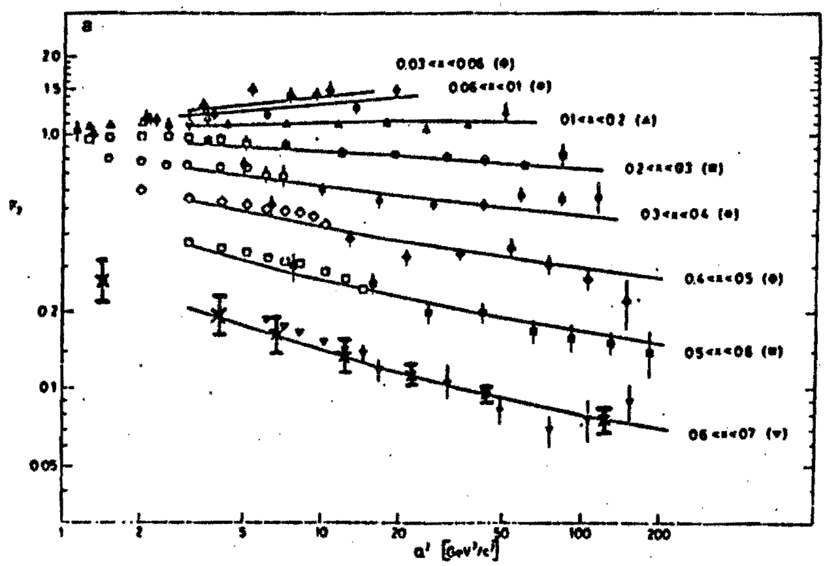


Fig 2



Ẋ expected results on $F_2(x, Q^2)$ at large x from the proposed experiment

The solid points are neutrino data from de Groot et al. (Phys. Letters 82B (1979) 456) and the open points are derived from eD scattering.

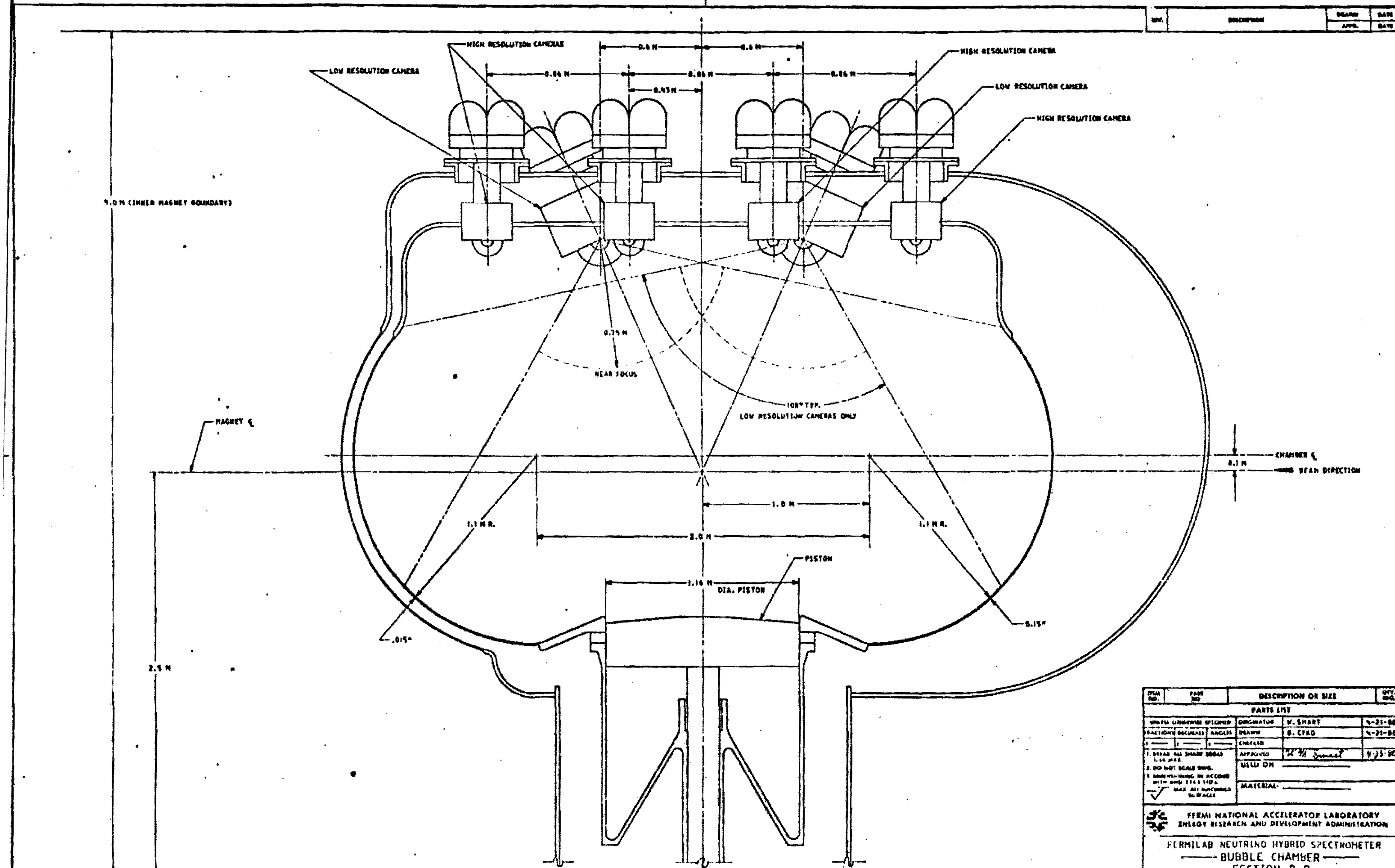
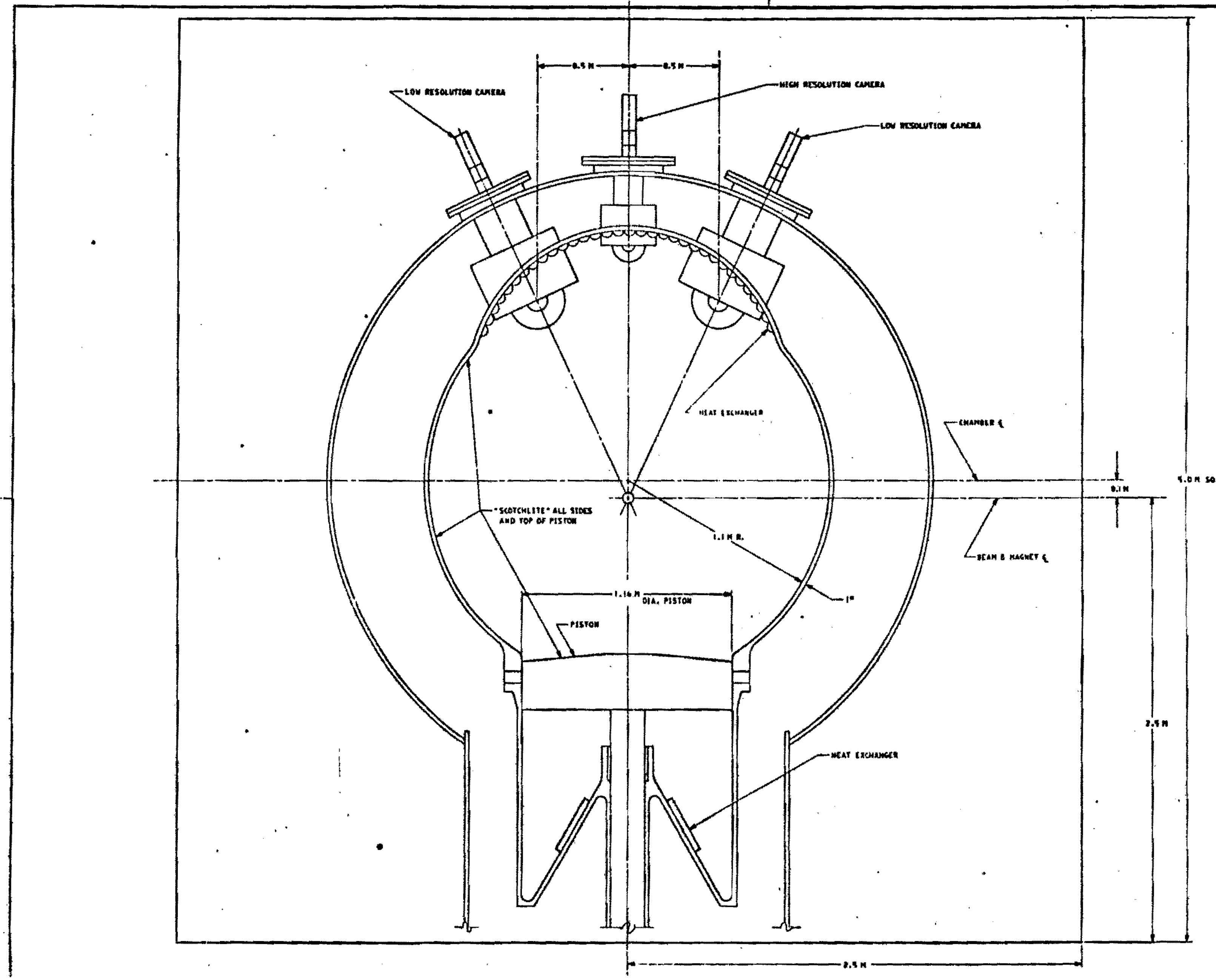

HIGH RESOLUTION CAMERAS
LOW RESOLUTION CAMERA
HIGH RESOLUTION CAMERA
LOW RESOLUTION CAMERA
HIGH RESOLUTION CAMERA
0.6 M
0.6 M
0.86 M
0.86 M
0.86 M
0.43 M
0.75 M
NEAR FOCUS
108° TYP.
LOW RESOLUTION CAMERAS ONLY
MAGNET ℄
CHAMBER ℄
BEAM DIRECTION
0.1 M
1.0 M
2.0 M
1.1 M R.
1.1 M R.
PISTON
1.16 M
DIA. PISTON
.015"
0.15"
2.5 M
DESCRIPTION OR SIZE
PARTS LIST
ORIGINATOR
DRAWN
CHECKED
APPROVED
USED ON
MATERIAL
DO NOT SCALE DWG.
FERMI NATIONAL ACCELERATOR LABORATORY
FERMILAB NEUTRINO HYBRID SPECTROMETER
BUBBLE CHAMBER
SECTION B-B
FNHS.MD-102

FIG. 3



HIGH RESOLUTION CAMERAS:

LARGE WINDOW O.D. = 18.0 CM
SMALL WINDOW I.D. = 7.2 CM
NOZZLE DIA. = 50.0 CM

LOW RESOLUTION CAMERAS:

LARGE WINDOW O.D. = 30.0 CM
SMALL WI... I.D. = 12.0 CM
NOZZLE DIA. = 50.0 CM

ITEM NO.	PART NO.	DESCRIPTION OR SIZE	QTY. REQ.

PARTS LIST

ORIGINATOR	V. SMART	4-18-80
DRAWN	A. CYRO	4-18-80
CHECKED		
APPROVED	W. W. Smart	4 23 80

UNLESS OTHERWISE SPECIFIED

1. BREAK ALL SHARP EDGES .03 MAX.
2. DO NOT SCALE DWG
3. DIMENSIONING IN ACCORD WITH ANSI Y14.5 1973
MAX. ALL MACHINED SURFACES

USED ON

MATERIAL

FERMI NATIONAL ACCELERATOR LABORATORY
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

FERMILAB NEUTRINO HYBRID SPECTROMETER
BUBBLE CHAMBER
SECTION A-A

SCALE: 1/10 M | DRAWING NUMBER: FNHS.MD-101

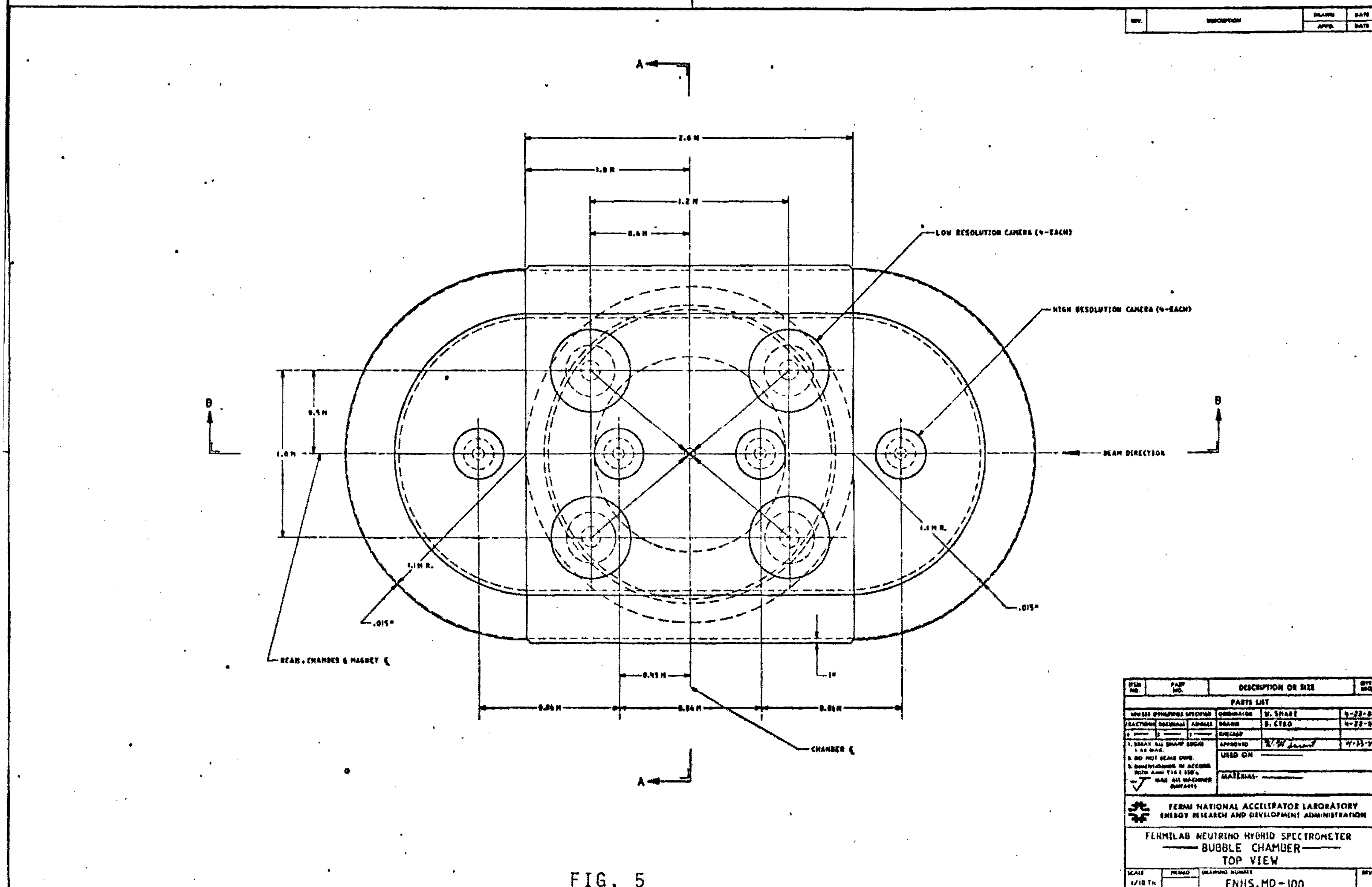
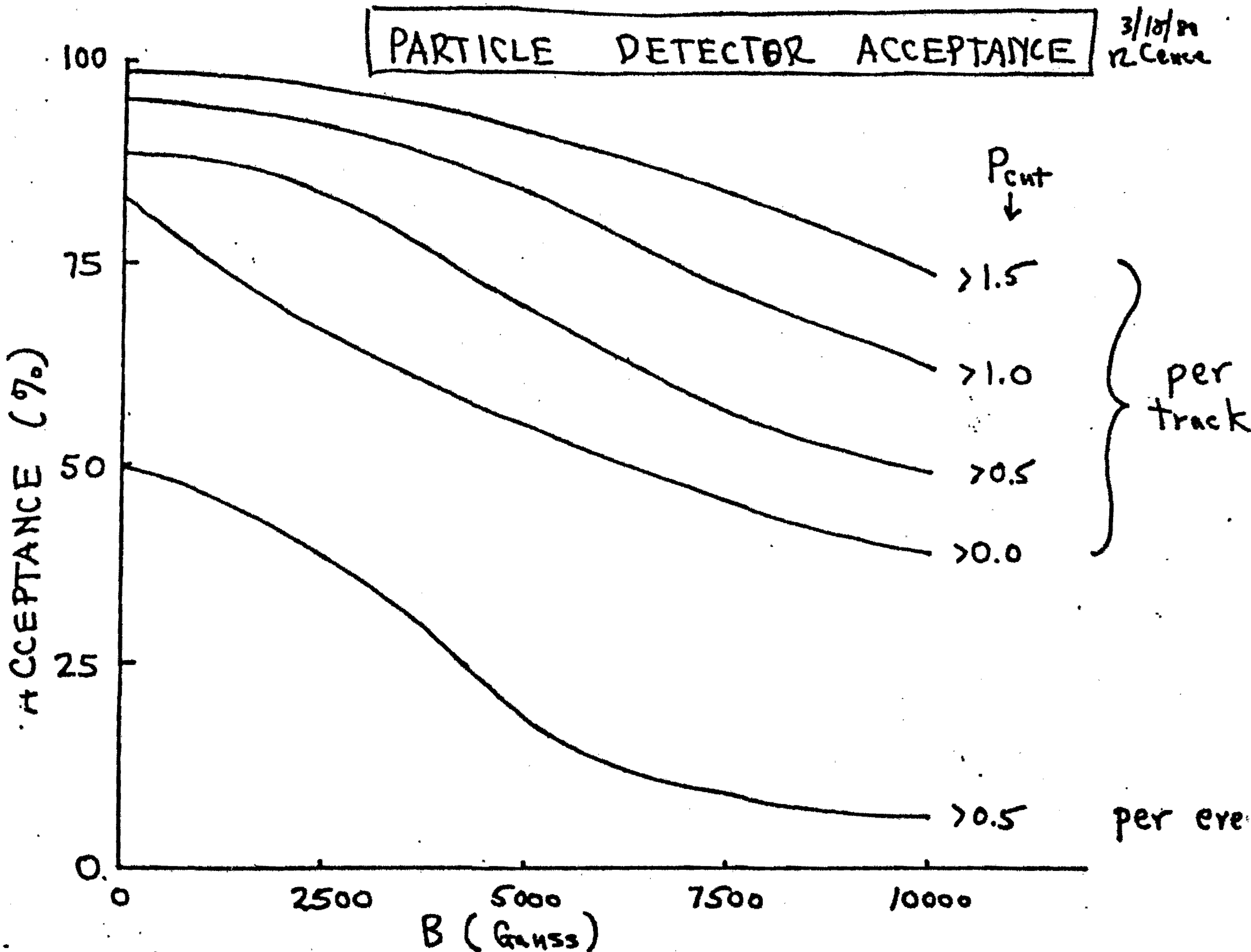
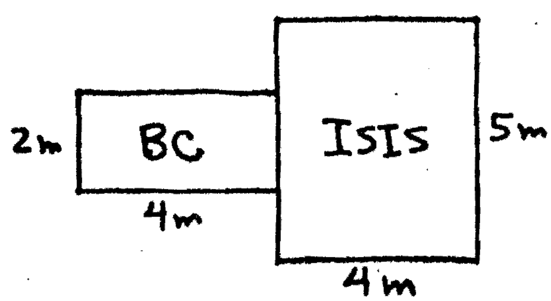

A
2.6 M
1.2 M
0.6 M
LOW RESOLUTION CAMERA (4-EACH)
HIGH RESOLUTION CAMERA (4-EACH)
B
0.5 M
1.0 M
BEAM DIRECTION
1.1 M R.
.015"
BEAM, CHAMBER & MAGNET ℄
1"
0.86 M
CHAMBER ℄
DESCRIPTION OR SIZE
PARTS LIST
ORIGINATOR
DRAWN
CHECKED
APPROVED
USED ON
MATERIAL
2. DO NOT SCALE DWG.
FERMI NATIONAL ACCELERATOR LABORATORY
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
FERMILAB NEUTRINO HYBRID SPECTROMETER
BUBBLE CHAMBER
TOP VIEW
SCALE
1/10 TH
DRAWING NUMBER
FNHS.MD-100

FIG. 5

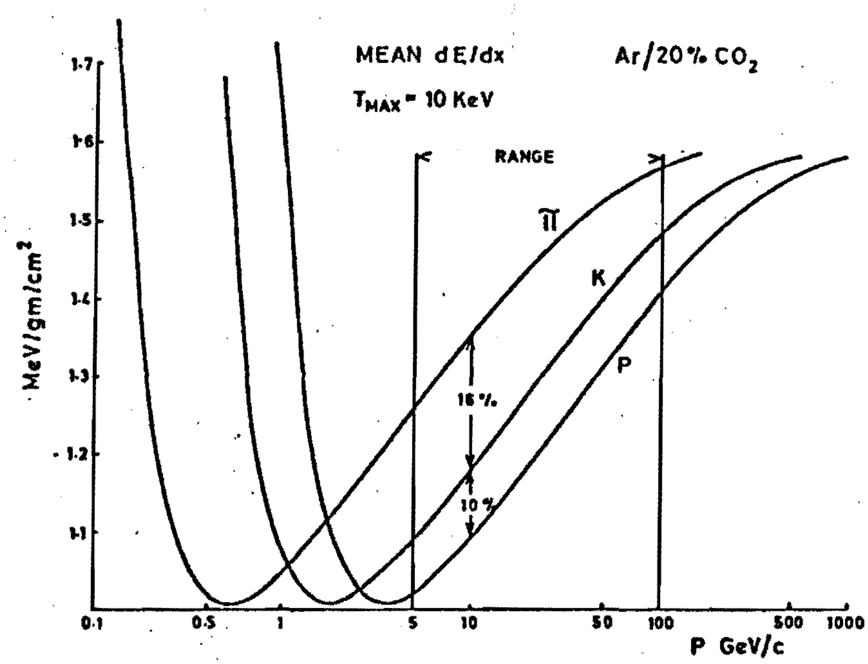


1 TeV
Quad-Triplet
ν beam



A track is accepted if it reaches the back of ISIS.
B-field includes bubble chamber.

FIGURE 6



[redacted]. The ionisation loss in argon + 20% CO_2 at atmospheric pressure for π, K and p based on the formula of Sternheimer and Peierls[13]).

Fig. 7