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ABSTRACT

We are continuing a research program in high energy experimental particle physics and particle astrophysics. Studies of high energy hadronic interactions were performed using several techniques; in addition, a high energy leptoproduction experiment was continued at the Fermi National Accelerator Laboratory. We have joined the DUMAND Collaboration, a deep undersea astrophysical neutrino detection experiment.

We are participants in a joint US/Japan program (Project JACEE) to study nuclear interactions at energies two orders of magnitude greater than those of existing accelerators. The data are being collected with balloon-borne emulsion chambers. The properties of nuclear interactions at these high energies will reveal whether new production mechanisms come into play due to the high nuclear densities and temperatures obtained.

We carried out closely related studies of hadronic interactions in emulsions exposed to high energy accelerator beams. We are members of a large international collaboration (EMU-01) which has exposed emulsion chamber detectors to beams of ^{32}S and ^{16}O with energy 60 and 200 GeV/n at CERN and 15 GeV/n at Brookhaven National Laboratory. The primary objectives of this program are to determine the existence and properties of the hypothesized quark-gluon phase of matter, and its possible relation to a variety of anomalous observations. These activities both supplement and complement the balloon-flight program.

Studies of leptoproduction processes at high energies involve two separate experiments, one using the Tevatron 500 GeV muon beam and the other exploring the >TeV regime. We are participants in Fermilab experiment E665 employing a comprehensive counter/streamer chamber detector system. Our contribution to the collaborative effort included runtime experiment operation and maintenance, and reduction and analysis of deep-inelastic scattering data acquired.

During the past year we joined the DUMAND Collaboration, and have been assigned responsibility for development and construction of critical components for the deep undersea neutrino detector facility, to be deployed in 1991. In addition, we are making significant contributions to the design of the triggering system to be used.

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I. JACEE/SCINATT: ULTRA HIGH ENERGY NUCLEAR INTERACTIONS

A. INTRODUCTION

We are participants in an ongoing collaboration between groups of institutions in the USA and Japan for the purpose of studying cosmic-ray interactions at energies ≥1 TeV/nucleon. The scientific objectives of this program are:

- To study multiparticle production processes at energies higher than those of proposed accelerators, using balloon-borne cosmic ray detectors;
- To determine whether new channels of particle production are opened at high nuclear densities and temperatures[1,2,3];
- To interrelate our observations with data on extensive air showers (EAS), which are at present our only source of information on these phenomena at extreme energies.
- To provide theoretical particle astrophysicists with essential data on cosmic ray nucleus fluxes in the 10^{13-15} eV range, intermediate between sensitive ranges for existing ground-based[4] and spaceborne detectors.

In order to achieve these objectives, the Japanese American Cosmic Emulsion Experiment (JACEE), a project to expose balloon-borne emulsion chambers at altitudes of 3-5 g/cm^2 residual atmospheric overburden, was organized. A member of the UW group (R. J. Wilkes) is currently US spokesman for JACEE, with T. Ogata of ICRR serving as spokesman on the Japanese side. Participating scientists are listed in Appendix II-A. Eight flights have been successfully completed to date, including two long-duration flights from Australia to South America (JACEE-7 and -8). These flights provide JACEE with the largest total exposure factor ever achieved by a balloon flight experiment.

US Space Station *Freedom* will provide an ideal site for emulsion chamber experiments, offering zero overburden and long exposure times. In order to exploit this opportunity, we organized a new collaboration, SCINATT (Spectra, Composition and Interactions Above Ten TeV), including the present JACEE group with some additions (see Appendix II-B for participants), and proposed a series of space station exposures of JACEE-type detectors during the early assembly stages of the facility[5]. SCINATT was included in the first-round group of projects selected for the Space Station program[6] in June, 1989, and will be the first of seven selected projects using the ASTROMAG superconducting magnet facility[7]. Preliminary detector development and certification activity began in 1990. NASA recently indicated that test flights aboard the Space Shuttle may take place in 1995, with Space Station exposures scheduled for 1998[8].

However, budgetary concerns coupled with substantial delays in the Space Shuttle flight program may push back this schedule by several years. The principal advantage of balloon flights is that they can be carried out immediately and at low cost. As noted below, the NSBF program of long-duration balloon flights can provide exposures equivalent to those available through the space shuttle program.

Prompt extension of our exposure program is important because additional data are needed to resolve open issues regarding the character of nucleus interactions as well as for the planning of new heavy ion accelerators which will approach the JACEE energy range. Our proposed work thus provides a direct preview of the event types which will be encountered in the new machines. Such information will be essential for realistic planning of early experiments at these facilities.

JACEE has continued to evoke considerable interest from the theoretical and experimental particle physics community. For example, JACEE data were used as the focal point of recent seminal papers by Bialas and Peschanski[9] on rapidity fluctuations. These papers stimulated a flood of theoretical and experimental effort on intermittency in particle production, as described below.

B. PHYSICS MOTIVATION AND BACKGROUND

Studies of central heavy ion collisions allow us to examine the properties of hadronic matter under extreme conditions of high temperature and compression, which may lead to the existence of a previously unobserved phase transition to a quark gluon plasma (QGP) state. High energy A-A collisions offer the only known means for exploring the frontier of high baryon density[10]. Theoretical work on the quark-gluon plasma (QGP)[11] has stimulated intense experimental activity on the subject of heavy ion collisions at energies $\geq$15 GeV/nucleon.

However, the energy regime above 200A GeV is at present accessible only by cosmic ray studies, and this situation will exist for at least several years. The CERN SPS has accelerated sulfur nuclei (A=32) to energies up to 200A GeV. Facilities to accelerate Pb ions (A=207) at CERN are planned, but beams will not be available until at least 1993. The Brookhaven AGS has accelerated ions[12] up to Si (A=28) to 15A GeV, and a facility to accelerate 10A GeV Au ions is planned. No facility has yet been proposed to provide energies above $\sim$1 TeV/nucleon which will probably be needed to exceed predicted energy density thresholds for transition to the quark gluon plasma state. Even if the phase transition boundary is not reached, the copious particle production observed in central heavy nucleus collisions permits application of new techniques for exploring the properties of the hadronic interaction. Bose-Einstein correlations allow measurement of the hadronic source volume, while factorial moment analysis of rapidity density fluctuations gives insight into the chaotic character of the particle production process.

Cosmic ray experiments have observed a number of anomalies such as the Centauro events[3], described below, which are likely to be indicators of new physics at extreme hadronic matter densities. Observation of collective effects, superdense matter, or new states of quark matter would stimulate significant advances in our understanding of the hadronic interaction. There is both theoretical and experimental evidence (much of it from JACEE) for believing that the latter alternative may prove correct as higher energies are probed[10].

According to Bjorken, McLerran, Halzen, Gyulassy and others[11,13], a quark gluon plasma may be created in relativistic heavy ion collisions, perhaps even at relatively low densities, if the elementary hadrons are composed of free constituents within the strong coupling volume of a bag. If it exists, hot quark matter should be observable by studying the central collisions of heavy ions at energy densities above approximately 1 GeV/fm^3. Clues to the true situation will be provided by the present experiment, since it can determine pseudorapidities of charged particles and true rapidities of photons produced in nuclear interactions.

One possible signature for the quark matter phase transition may be a break in the $< p_t >$ vs $< \frac{dN}{dy} >$ distribution[1], as indicated schematically in Fig. I-1a. Figure I-1b, showing just such a distribution for a sample of JACEE events, shows a striking similarity to the predicted behavior. Another signature might be copious production of low-p_t photons[2]. Such events are readily identifiable in JACEE detectors.

At present, no experiment has provided unambiguous evidence of of a QGP phase transition. Theoretical estimates based on conventional QCD place the expected energy density threshold in the range 0.5 $\sim$ 2 GeV/fm^3, depending upon the assumptions used. Methods for estimating the actual energy density achieved in a given event are subject to some controversy, and it is possible that central collisions of the highest mass, highest energy nuclei thus far available at accelerators (200A GeV sulfur) produced energy densities well below threshold. JACEE data involving heavier, higher energy projectiles are subject to statistical limitations, but suggestive events have been observed. Nonetheless, the available data can provide significant new information on the conventional hadroproduction process.

The emulsion chamber technique permits measurement of pseudorapidities with precision on the order of 0.01 unit, a degree of accuracy unmatched by any other type of experiment (including conventional emulsion pellicle experiments). This, coupled with the high statistical weight of individual high multiplicity events, permits correlations studies which are impractical at lower energy densities.

Bose-Einstein correlations[14] can be used to determine hadronic source volume dimensions. Although we do not measure charge or momentum, it is possible to use two-particle correlations in space angle, in comparison with an uncorrelated background distribution generated by scrambling the azimuthal angles of real events, to estimate transverse radii of source regions, as described in more detail in Section II of this report and in a dissertation written by one of our graduate students[15]. Typical results are shown in Fig. I-2, where the source volume is estimated by Bose-Einstein correlations for a sample of JACEE A+Pb interactions (calorimeter events) with mean projectile radius $R_A \sim 3.4$ fm. The results show that the source radius is approximately equal to the projectile radius, as expected for conventional superposition models of particle production. Anomalies in the source radius are one hypothesized signal for QGP.

Bialas and Peschanski published a paper[9] on the analysis of fluctuations in pseudorapidity distributions which has stimulated extensive theoretical and experimental work aimed at investigating the chaotic character of particle production. Their seminal paper used JACEE data as an example of the utility of the proposed analysis procedure; indeed, JACEE events at the time provided the only individual interactions with sufficient statistical weight to be useful. The current situation in this active area of research is well summarized by Carruthers and at a recent Workshop on the subject, organized by R. Hwa and F. Cooper[16] where JACEE results were presented. A detailed discussion of Scaled Factorial Moment (SFM) analysis will be given in Section II. Results from JACEE are compared with EMU-01 data in Fig. I-3 (see also Appendix I). Alternative analysis procedures proposed by Hwa[17] provide a valuable approach to understanding the fractal character of particle production processes and are currently being applied by our group.

JACEE has detected several unusual events[18] which may indicate the onset of new particle production mechanisms at ultra-high energy densities. Clusters of rapidity values correspond to particles closely grouped in phase space. Rapidity values in the central region are dominated by pionization and they are not appreciably correlated with the target and projectile fragmentation regions. In some of our very high energy cosmic ray events we have found strong clustering effects in rapidity space, which may indicate cluster cooling of nuclear matter. For example, a silicon-silver interaction at 4 TeV/n produced >1000 charged particles, the highest multiplicity event thus far observed in a track sensitive target, and a calcium-carbon interaction at >100 TeV/n yielded 700 charged particles and >150 photons. These data contained evidence of non-statistical fluctuations in rapidity density, and their publication stimulated extensive interest on the part of theorists.

Other events display an anomalously high photon-to-charged particle ratio in the extreme forward direction. In one example, the rapidity range 6–9 contains 120 photons, and for normal hadroproduction we expect to find an equal number of charged particles. However, only 40 charged particles are observed in the same angular range. This represents a 7-σ effect, and from a sample of approximately 40 events with similar primary particle mass and energy, the probability of observing a statistical deviation of such magnitude is negligible.

In our latest flight (JACEE-8) we observed several events with charged-particle multiplicities $\geq$ 1000. We believe one of these to be the highest energy event ever recorded with vertex in the detector. Detailed analysis is nearly complete and results will be published during the coming contract period. Such single events provide a high-statistics measure of the rapidity distribution in and of themselves. One may speculate that the observed features suggest new characteristics for hadronic interactions at >100 TeV. In all cases certain features predicted to be associated with the hot quark matter phase may be present: extremely high rapidity density of charged particles and/or copious production of photons.

Until now the only information on individual interactions of hadrons around >100 TeV has been derived from cosmic ray experiments carried out at mountain and balloon altitudes. These experiments have reported some unusual phenomena which JACEE will continue to search for and investigate. These include (1) the Centauro events, which contain a large number of hadrons but no neutral pions[3], (2) the anti-Centauro events, which have a large number of gamma rays (presumably from neutral pion decay) but few, if any, hadrons[18,19], (3) events that exhibit abnormally large multiplicities[20], (4) events with leading clusters of particles having high average transverse momenta[21] and (5) evidence for short-lived particles[22]. The anomalies may be related to QGP production, they may be previously unanticipated results of the expected gluon dominance in hadronic interactions in the $\geq$ 10 TeV range[23], or they may signal entirely new challenges to the standard model. Detection and exploration of such new physics regimes has been a traditional role for cosmic ray interactions studies.

Ground-based observations of some of these unusual events are subject to the limitations of the experiments that reported them. The most severe limitations are (1) the charge and mass of the interacting particle were not measured, and (2) the trajectory of this particle and its interaction vertex were not observed. Instead, the characteristics of the events were determined from observations on "families" of cascades and the inferred height of the vertex in the atmosphere above the detector. While gamma-ray families from external atmospheric interactions can also be analysed, JACEE does not have these limitations for typical events with vertex in the detector. If the unusual event types mentioned above are real and if any do occur in our chamber, they will be subject to full and detailed analysis.

JACEE produces data on the primary cosmic ray spectra, including the best available measurements of intensities and particle ratios in the region just below 10^{15} eV, the critical "knee" region[24]. Studies of this type provide information on cosmic ray sources, acceleration, and interactions during propagation which will be of increasing importance as we await construction of the next generation of particle accelerators. Particle astrophysics has only recently received appropriate recognition as an important link between the particle physics and astrophysical communities[25].

C. EXPERIMENTAL TECHNIQUE

A complete description of the experimental techniques used in JACEE has been published[26], so we will provide only a brief summary here. A typical ballon flight emulsion chamber, shown in Figure I-4, consists of double-coated nuclear emulsion plates, X-ray films, etchable plastic sheets (CR39) and Pb sheets 1.0 and 2.5 mm thick. The chamber is segmented into (1) a primary charge module, (2) a target section, (3) a spacer section, and (4) a calorimeter section. All components are precision-machined to fit into an alignment box which permits spatial relationships between components to be known to better than 100 μm.

The detector satisfies four basic requirements for the proposed experiment: (1) large geometrical factor, (2) accurate charge determination, with charge resolution essentially independent of energy, (3) reliable energy measurement, with energy resolution independent of (and to some extent, improving with) energy; (4) extremely precise angular resolution ($\leq$ 0.1 mrad) for secondary charged particles.

Charges of primary particles are determined by combining grain-count and delta-ray count data from the emulsion plates with the CR39 data. Charge resolution for iron is ~2.0 units, with better resolution for lighter nuclei.

The energies of the primaries can be determined by a combination of techniques. The minimum path length through the Pb of the calorimeter section typically provides at least 6 radiation lengths for development of electromagnetic cascades. Ionisation can be determined by counting the number of tracks within a given radius at several depths. The energy resolution improves with energy from about 20% at 0.3 TeV. The energy going into minimum ionising charged tracks can be independently estimated by assuming $p_t \sim < p_t > \sim 0.4$ GeV; thus $E \sim 0.4 \csc(\theta)$. Similarly, the energies of heavy fragments can be estimated from their polar angles by well established techniques[27]. The average overall accuracy of primary energy measurement in this experiment is calculated to be better than 35%, roughly independent of energy.

In the JACEE-3 flight[28], the hybrid counter system provided independent estimates for primary charge and energy for interactions at the lower end of the energy range of interest. As will be described below, plans have been made to perform a series of flights with a hybrid superconducting magnet system, which will provide direct momentum measurements for secondary tracks.

Tracing of secondary tracks to the event vertex, and tracing the primary track to its entry point, have in past been the most time consuming aspect of emulsion chamber analysis. However, JACEE data acquisition rates have shown steady improvement, made possible by refinements in emulsion chamber design and construction and by our accumulated experience. For the most recent long duration flights, a priority list (based on ΣE_γ, the energy deposited in the calorimeter) of about 300 events was fully traced in about 6 weeks. As data accumulates, the energy range of interest can be pushed up, resulting in fewer events per stack to be traced and analyzed. On the other hand, the complexity of the individual events increases with energy. Thus the data reduction effort is reduced while the analysis time increases.

Production angles of charged tracks can be determined to an accuracy on the order of tenths of a milliradian (i.e., significant measurements can be made up to 14 units in pseudorapidity). The low density of the target section means that measurements can be made in several successive layers with negligible interference from secondary interactions and photon conversions. For the photons, true rapidity can be computed using the measured energy and the production angle determined by measuring the cascade starting point coordinates. About half of the interactions recorded occur in the calorimeter section, due to the chamber mass distribution. In some cases individual photons and the extreme forward charged particles cannot be individually resolved, so for these events corrections become more significant.

D. PROGRESS TO DATE AND FUTURE EFFORT

1. Long Duration Balloon Flights

The JACEE collaboration has performed eight successful balloon flights to date (see Table I-1). The last two flights, JACEE-7 and -8, were intercontinental long-duration flights, launched in Alice Springs, Australia and recovered in South America after 120 ~ 140 hours. These flights more than double our total exposure factor, and allow us to probe a significantly higher energy regime. This type of balloon flight yields exposures actually superior to those obtainable in space shuttle flights (due to the low level of soft background accumulation caused by geomagnetic effects), with considerably less expense in terms of both direct costs and the enormous ancillary costs involved in meeting requirements of manned spaceflight payload certification.

For a number of years, NSBF has been testing and developing flight systems for partially ballasted, circumglobar zero-pressure balloon flights. These long-duration flights typically take place in the southern hemisphere where overflight of populated areas can be minimized, eliminating the need for continuous control. In the recent flights from Australia, our 1350 lb payload was launched, floated around the globe at ~ 23 deg south latitude, and recovered in South America (Paraguay and Brasil). Satellite systems were used to track the balloons throughout flight. In both cases, local problems required storage of the payloads for several weeks due to bureaucratic delays, but the emulsions were kept in a suitable environment and no loss of data occurred[29].

An onboard computer controlled ballast drops adequate to maintain nearly constant altitude over 120,000 feet for most of the flight duration[30]. Our students and technicians in Seattle built an automatic onboard digital flight data recorder which provided a continuous record of altitude and package temperature, and was used to "turn off" the detector during temporary altitude sags by shifting a detector layer out of registration with the main chamber. An improved version incorporating a microcomputer system, which permits greater flexibility in adapting to different flight conditions, has been prepared for the 1990 flight campaign (see Table I). We expect to fly 4 standard sized JACEE detectors from Ft. Sumner, NM in September, 1990, with two detectors designed to optimize analysis of interactions and two optimized for spectral studies. In addition, we will participate in long-duration flight operations in Antarctica in December, 1990.

Supernova 1987a in the Large Magellanic Cloud generated support from NASA for several southern hemisphere expeditions in 1987–88 for balloon launches, although the JACEE experiment and a solar gamma ray experiment were the only successful intercontinental flights. The 1990–91 solar maximum will provide NASA with additional motivation for long-duration flight operations[31]. However, for the solar research activities which are the focus of interest, Antarctica is a more attractive site. A successful 72 hour flight was performed by NSF and the Air Force Geophysical Lab in 1987 at McMurdo Sound, with recovery on the East Antarctic Plateau[32]. Antarctica provides a number of advantages for long-duration ballooning in any case, including 1) continuous daylight, resulting in greatly reduced ballast requirements (ballast is primarily required at sunset to compensate for altitude loss as the helium bubble cools) and uninterrupted solar observation; 2) overland flight paths, with larger areas accessible for recovery operations; 3) negligible population density, with flights unlikely to be prematurely terminated for safety considerations; 3) absence of political boundaries, so that flight tracking and recovery remain completely in US hands. Obviously these advantages apply equally to JACEE.

While the remote location creates logistical problems, they are not substantially greater than those encountered in Australian operations and the high transport cost is borne by NSF Polar Programs for our approved experiment. The primary disadvantage to Antarctic flights from our point of view lies in the higher density of low-energy particles accumulated by our detectors due to the proximity of the geomagnetic pole. However, such backgrounds should in practice be no worse than the thermal fog accumulation encountered in JACEE-7 due to ground storage after flight, and should have little effect on our ability to analyze data for reasonable flight times. In fact, the local environment in Antarctica (extremely dry as well as very cold) is much more favorable for storage of track-sensitive materials in emulsion chambers, so that recovery delays would be much less damaging than in tropical latitudes. Details are given in a paper we prepared for a recent NSF workshop on Antarctic ballooning[35].

NASA and NSF will support an LDBF expedition in Antarctica in December 1990[33]. This operation will launch only one balloon, carrying a merged payload with four separate experiments, including two JACEE detector modules of reduced size. However, our group has provided NSBF with a JACEE gondola for use as a general purpose backup gondola, to be used for testing communications and tracking systems if the primary multi-user gondola is not flight ready during the appropriate launch window. Under such circumstances, the backup gondola will be flown carrying three full size JACEE modules supplied by our collaboration on a contingency basis.

2. Superconducting Magnetic Spectrometer

In another initiative, JACEE has reached agreement with ICR, ISAS and KEK in Japan to use a large superconducting magnet for a hybrid detector. This experiment would be extremely valuable, providing momentum and charge data for particles in the central rapidity region. The magnet was designed as a prototype for a space station experiment, and will be ideal for balloon flights due to its low weight and self-contained cryogenic system. The magnet will provide a field of nearly 2 T over an area large enough to accomodate a JACEE emulsion chamber (Fig. I-5). Construction should be complete by the end of 1990, and a test flight in Texas is planned for 5/91. Although the primary purpose of the test flight will be to test magnet performance, we will obtain a significant amount of useful data if the balloon performance is adequate. Longer flights will be carried out in 1992.

The UW group has been asked by the collaboration to supply the gondola required for this project. This involves design engineering to ensure adequate support and protection for the magnet, as well as fabrication of the gondola in our machine shop. Onboard systems control and data logging requirements will be more extensive than in previous JACEE flights and we will have to design and build a suitable computer control/recording system. Our group has extensive experience and internationally recognised expertise in this area.

3. Space Station Experiment: Project SCINATT

As noted, the proposed US space station *FREEDOM* will provide an ideal platform for emulsion chamber experiments, offering zero overburden, unlimited exposure duration, and onboard personnel. JACEE type chambers provide an excellent match to the space station requirements, since they require negligible electrical power, involve no volatile or dangerous materials, and are modular and self-contained. Moreover, during the assembly phase of the space station, it is expected that the ASTROMAG superconducting magnet facility will be operating for several months before permanent counter experiments can be operational[7]. This provides an ideal window of opportunity for our group.

The JACEE group forms the nucleus of a new collaboration which proposed an emulsion chamber experiment which was among the first round selections for the space station program[6]. Project SCINATT (Spectra, Composition and Interactions Above Ten TeV) will prepare two types of emulsion chamber, magnetic spectrometer modules (MAGIC chambers) to be installed in the ASTROMAG high-field region, and emulsion calorimeter modules (EMCAL chambers). for passive exposure nearby. The MAGIC units will contain emulsion plates spaced at relatively large intervals, as shown in Fig. I-6a. This design will allow efficient tracking while minimizing the effects of multiple scattering and secondary interactions. The EMCAL units (Fig. I-6b) are similar in design to current JACEE balloon detectors.

Support totalling about 7 M$ was requested from NASA by the collaboration over the next 10 years, of which 1.7 M$ was requested by the UW group to cover additional costs relating to detector development and certification. This funding is of course subject to Congressional approval of the overall space station program, and no funding commitment can as yet be made by NASA. However, selection for the program means that NASA has accepted the experiment for support when an appropriate budget exists. Preliminary development funding, begun in 1990, provides support for travel and other costs related to program coordination, and detector development funding should begin in 1991. It will be necessary to qualify all detector components for manned space flight, and verify in detail the performance of all detector systems, data acquisition and analysis procedures. In summary, the SCINATT project will be very similar to JACEE, with NASA covering costs specifically associated with the exposure operations, in this case including supplementary personnel, travel and equipment costs.

4. Data Analysis

During the past year, new results have been published on the spectra and composition of primary cosmic rays. These data have important implications for particle astrophysics as well as particle physics, since the observed spectra reflect interaction processes in the source environment during acceleration and the interstellar medium during propagation. Copies of papers published during the past year are presented in Appendix I. JACEE-8 is currently under analysis in our laboratory, while JACEE-7 is being worked on elsewhere. During the past contract period we have considerably increased our data reduction capabilities in Seattle. Acquisition of a computer aided microscope system from LBL (described in detail in Section II below) will greatly improve analysis throughput.

Preliminary reports of JACEE results have excited substantial demand for more data from the theoretical community. Subsequent flights will be directed to the study of the few very high energy, heavy nucleus events recorded in each chamber. Thus the analysis workload will be reduced, especially with the use of x-ray film densitometry at the earliest stages to preselect events of interest.

Recently, reorganization of emulsion chamber groups in Japan has made it likely that future cosmic ray balloon flight projects will include collaborators from the Institute of Space and Aeronautical Science (ISAS), the Japanese equivalent of NASA. This arrangement is most welcome as our group has a long-standing research relationship with the present director of ISAS, J. Nishimura. Results from our cooperative emulsion chamber experiment with Nishimura's group[34] still represent the best available data on the primary cosmic ray electron spectrum, a sensitive indicator of galactic cosmic ray propagation parameters. Emulsion chambers exposed to detect ultra-high energy nucleus interactions can be readily analyzed to extend the electron spectrum database. With the addition of P. E. Boynton to our group, we can redirect effort to the study of topics of significant current interest in particle astrophysics. Future JACEE flights will be analyzed cooperatively with Nishimura's group. The addition of ISAS expertise in balloon operations will provide a most productive cooperative program.

Table I-1: JACEE Balloon Flights

Flight	Launch Date	Launch Site	Altitude (g/cm^2)	Duration (hours)	Unit (Area/Unit) (cm^2)
Completed:					
JACEE-0	5/79	Sanriku Japan	8.0	29.0	1 (40 x 50)
JACEE-1	9/79	Palestine Texas	3.7	25.2	4 (40 x 50)
JACEE-2	10/80	Palestine Texas	4.0	29.6	4 (40 x 50)
JACEE-3	6/82	Greenville S. Carolina	5.0	39.0	1 (50 x 50)
JACEE-4	9/83	Palestine Texas	5.0	59.5	4 (40 x 50)
JACEE-5	10/84	Palestine Texas	5.0	15.0	4 (40 x 50)
JACEE-6	5/86	Palestine Texas	4.0	30.0	4 (40 x 50)
JACEE-7	1/87	Alice Springs Australia	5.5	150.0	3 (40 x 50)
JACEE-8	2/88	Alice Springs Australia	5.0	120.0	3 (40 x 50)
Planned:					
JACEE-9	9/90	New Mexico	4.5	24.0	4 (40 x 50)
JACEE-10	12/90	Antarctica	4.5	210.0	3 (40 x 50)
JACEE-11	9/91	New Mexico	4.5	24.0	1 (40 x 50) (magnet)

II. EMU-01/E-815: HEAVY ION INTERACTIONS AT ACCELERATOR ENERGIES

A. PHYSICS MOTIVATION AND BACKGROUND

1. Introduction

As noted in Section I of this report, there has been continuously increasing interest in the study of nucleus-nucleus collisions[1]. Just as in hadron-nucleus interactions, studies of the A-dependence (of both target and projectile, in this case) and energy dependence of the interaction parameters may prove valuable to our understanding of the nature of the hadronic interaction. In particular, the possible existence of a quark matter phase transition, signalled by anomalies in rapidity density distributions[2], strange-particle production ratios[3] and p_t distributions[4] is a subject of substantial current theoretical interest. Our group is in a unique position to contribute to this area of research through our participation in JACEE which complements the accelerator experiments described here.

We are participants in an international collaboration, organized by I. Otterlund, to investigate heavy-ion interactions using emulsion chambers and conventional pellicle stacks exposed to accelerator beams at CERN and BNL. The group includes participants from Canada, China, France, Germany, India, Sweden and the USSR as well as the USA, as listed in Appendix II-C. This represents, to our knowledge, the largest and most powerful collaboration ever assembled for an emulsion experiment. Exposures have been performed at BNL and CERN, using beams of mass $A = 16 - 32$ and energy $15 - 200A$ GeV, with unified and consistent experimental procedures and analysis criteria. Results have matched expectations, with data acquisition and analysis proceeding rapidly and efficiently, and a substantial body of published results (Appendix I). The combination of emulsion techniques employed provides unequalled resolution for tracking and angular distributions, combined with a minimum-bias sample of events analyzed by the same group using identical criteria.

2. Fluctuations and Intermittency

We have discussed the theoretical implications and possible experimental signals of QGP production in Section I. EMU-01, along with other accelerator experiments, has observed no unambiguous evidence of events which surpass the QGP threshold. Fig. II-1 shows the pseudorapidity ($\eta = -\ln \tan(\theta/2)$) distributions for central collisions of S ions in Au and AgBr targets, where the centrality criteria are detailed below. As shown, the data are well represented by the Lund monte carlo program FRITIOF, which reproduces only conventional physics, indicating that these distributions can be explained in terms of a relatively simple superposition picture where the number of participant nucleons is the key parameter. On the other hand, when one plots central η density versus multiplicity, as shown in Fig. II-2, some events clearly lie significantly beyond the correlation line (here well matched by the average of FRITIOF data) and merit closer attention.

A distinctive feature of central ultrarelativistic heavy ion collisions is the appearance of significant fluctuations in rapidity density. This phenomenon has been seen in both cosmic ray experiments[5] and in accelerator experiments[6]. It has been suggested that a quark-gluon plasma (QGP) phase transition could give rise to such behavior. Recent interest in this subject has been stimulated by a series of papers by Białas and Peschanski[7] discussing the method of Scaled Factorial Moments (SFM) for such analyses. The behavior of the moments may reveal fundamental features of the particle production process[8,9]. For example the factorial moments F_q of simulated events produced by a simple cascade production model showed a power law behavior[7]; one might expect an increase in F_q with decreasing $\delta\eta$ until the scale length for fluctuations is reached, at which point F_q would become independent of $\delta\eta$.

Although Bialas and Peschanski showed that individual very large events can sometimes provide adequate statistics, using a JACEE event as their example, in practice it is necessary to average over many events. In the "vertical" averaging procedure[10], one averages bin contents over the ensemble before performing the moment analysis, so the qth factorial moment is

$$\langle F_q \rangle_V = \frac{1}{M} \sum_{m=1}^{M} \frac{1}{N_{evts}} \sum_{i=1}^{N_{evts}} \frac{k_{m,i}(k_{m,i}-1)\ldots(k_{m,i}-q+1)}{\langle k_m \rangle^q}$$

where N_{evts} is the number of events in the sample, $k_{m,i}$ is the content of bin m in event i, and $\langle k_m \rangle = N_{evts}^{-1} \sum_{i=1}^{N_{evts}} k_{m,i}$ is the average content of bin m over the ensemble of events. In the vertical analysis the moments are normalized by the average multiplicity *in a given bin*, so this method removes contributions caused by variations in average bin content as a function η.

The vertical technique was applied to a sample of 135 central 200A GeV S-Au events. The $\langle F_q \rangle_V$ exhibited a rise consistent with a power law dependence upon $\delta\eta$ for bin sizes greater than 0.4 units of η but became independent of $\delta\eta$ for smaller bin sizes, as shown in Fig. II-3. But for an equal sample of events from FRITIOF, the $\langle F_q \rangle_V$ remained constant.

As Fig. II-3 shows, a rise consistent with a power law behavior for decreasing bin size is observed, implying that there are non-statistical fluctuations on scales greater than 0.4 units of η which disappear at smaller scales. Because our experimental resolution is at least an order of magnitude smaller, these results indicate the absence of intermittent behavior below this scale. This rise in the moments for $\delta\eta > 0.4$ represents a clear departure from the "conventional" physics embodied in the Lund Monte Carlo since it is absent from simulated events analyzed in the same way. These results were summarized in a recent publication (Appendix I).

3. Bose-Einstein Correlations

Due to the extremely high precision of angular measurements via the emulsion chamber technique, it is possible to employ Bose-Einstein correlations[11] to investigate the hadronic source volume dimensions. For experiments where momenta are not measured, one can derive[12] the ratio for the number of pairs of tracks of given angular separation to that of a random distribution:

$$N_{pairs}/N_{random} = 1 + \alpha \ \exp(-q_t^2 \ R^2 \ /4),$$

where q_t is the component of momentum difference $\mathbf{p_1} - \mathbf{p_2}$ transverse to $\mathbf{p_1} + \mathbf{p_2}$, and R is the radius of the source volume. The denominator is obtained by randomizing the azimuthal angles of real events, thus providing a sample of pseudo-events with η distribution identical to the real data but with completely uncorrelated space angles. Consider a pair of particles with pseudorapidities and azimuthal angles (η, ϕ) boosted to the particle pair's center of mass projected onto the beam axis. Let the space angle between particles in this frame be $\Delta\omega$ and the component of momentum difference is $q_t = \langle p_t \rangle \tan \Delta\omega$. An average transverse momentum for produced particles of 0.4 GeV/c, was used. Conversion electron pairs are excluded by imposing a cut $\Delta\omega > 4°$ (in the Lorentz boosted frame)[12].

The 200A GeV oxygen data sample for this analysis consists of 361 events with an average multiplicity of 96 charged particles. The two particle separation distribution is shown in Figure II-4a along with the minimum χ^2 gaussian fit. The hadronic emission region size is found to be 3.5 ± 0.5 fm which compares favorably with the oxygen RMS nuclear radius of $1.2 \ A^{1/3} = 3.0$ fm.

The 200A GeV sulfur data sample consists of 164 events with a gold target nucleus with an average multiplicity of 360 charged particles. The sulfur two particle separation distribution is shown in Figure II-4b. The measured hadronic emission region size of 4.1 ± 0.4 fm for the sulfur sample is not significantly larger than the sulfur RMS nuclear radius of $1.2\ A^{1/3} = 3.8$ fm.

For comparison, the same analysis was applied to 500 oxygen-AgBr interactions generated by FRITIOF[13], which produces kinematically correct decay products, but not an overall Bose Einstein correlation; the resulting two particle separation distribution lacks the characteristic peak as expected.

B. EXPERIMENTAL TECHNIQUE

The emulsion chamber technique used in the cosmic ray work described in Sect. I of this report can be directly applied to accelerator experiments, with a number of advantages over both the cosmic ray experiment and competing accelerator techniques. Since collecting area is of no importance, the emulsion chambers can be of smaller size than the cosmic ray detectors, and mechanical registration of plates can be better controlled. The smaller chambers can easily be placed inside a high-field magnet, providing magnetic spectrometry for charged secondaries. Also, noninteracting beam tracks provide an abundant supply of local fiducials, so that all track measurements can be performed with extremely high accuracy. Nuclear emulsion provides spatial resolution at least one to two orders of magnitude finer than other detector types. Finally, since the double-coated plate technique provides a vector (rather than a single coordinate) at each detection plane, the problem of track following in complex high multiplicity events is greatly simplified. This is especially important when a magnetic field is used for momentum analysis; the track-following problem can become intractable for events with multiplicity greater than 100 observed in proportional chamber systems.

Our CERN experiment, EMU-01, received exposures to ^{16}O at energies of 60 and 200A GeV in November, 1986. At the same time, our BNL experiment, E815, exposed detectors of identical design to ^{16}O at 15A GeV at the AGS. In October, 1987 both experiments received a second exposure, this time to 200A GeV ^{32}S at CERN and 15A GeV ^{28}Si at BNL. The 1987 chamber designs included some additions and improvements upon the 1986 detectors, as detailed below. We received an additional exposure to 200A GeV sulfur, using the improved detector design, in August, 1990. This will provide improved statistics on S-Au interactions, the highest available mass combination at the highest available energy. Our proposal to BNL for exposures to Au ions at 10A GeV in 1992 has recently been accepted as AGS Experiment E863; the program review committee responded very positively to results from our previous exposures (E815). Another run using Pb ions at energies up to 200A GeV at CERN is planned for 1993.

In both EMU-01 and E815, we used emulsion chambers of the type shown in Fig. II-5. A relatively thick plate, with two layers of emulsion each 250 microns thick, serves as a tracksensitive target, with some chambers including a 250 micron gold foil to provide a uniform, heavy target layer. Thin plates are used to observe secondary tracks, and graded spacer layers permit efficient use of point measurements in angular fitting procedures. The chambers have transverse dimensions 10x10 cm^2. A 5x5 cm^2 version was also prepared to fit into the gap of a standard CERN beam dipole magnet. We obtained a magnetic field of ~2T in several chambers of similar design, adequate for momentum analysis of the secondaries up to several tens of GeV. Finally, some chambers were exposed with a Pb-emulsion calorimeter (2 mm Pb plates interleaved with emulsion plates) appended to the normal front end. These chambers permit direct comparison of accelerator results with cosmic ray emulsion chamber data on ΣE_γ, the total secondary energy fraction going into electromagnetic cascades.

Plates for E815 were prepared and developed in our darkroom in Seattle. The EMU-01 plates were prepared and subsequently processed in a darkroom facility at CERN, by personnel from our lab and the Lund group. After plate processing, the target plates are scanned under relatively low (100X) magnification and interaction vertex locations are noted for later track counting and measurement.

Track coordinates are measured either on conventional digitised stages (emulsion-plane digitizers) or using an image-plane digitiser technique, originally developed in Lund[14] and adapted by our group (Fig. II-6). This "EMUPAD" measuring system consists of a digitising pad (designed for computer graphics and CAD work) coupled to an IBM PC clone microcomputer. The microscopist uses a *camera lucida* drawing tube attachment, which projects the digitising pad into the microscope field of view. The digitizer is then used to mark the points to be measured. A beam splitter is mounted on the drawing tube to merge an image of the computer monitor (as well as the digitizer pad surface) into the microscope field of view. In this way, the operator can view the emulsion image while simultaneously observing the digitizer cursor (marked by a red LED) and the computer monitor, which displays instructions as well as marking measured points in a scaled graphics display. After the first plate has been measured, predicted track locations for successive layers are displayed on the monitor (and thus on the microscope image of the emulsion plate). After measuring all previously detected tracks (or noting their absence), the operator adds any new tracks. This adds greatly to the time savings, eliminating confusion and lost measurement effort. The operator is presented with conditions equivalent to a bubble chamber measuring table, where an event map can be laid onto the image, resulting in vastly reduced confusion and remeasurement requirements. Moreover, tracking is simplified by the superimposed computer display, which identifies tracks for the operator after an initial measurement. This can be very significant when measuring complex, high-multiplicity events in the presence of a magnetic field. Results in here and in Lund indicate a factor of 5–10 in measurement throughput using this inexpensive scheme. We are presently using a system of this type for most measurements of high multiplicity events. Complete measurement of a 100 prong event takes about 2.5 hours with this device, as opposed to at least a full working day on a conventional measuring stage.

One disadvantage of the digipad system is that critical optical alignments are required. Displacement of the microscope, pad or computer monitor causes improper registration of the multiple superimposed images. An alternative approach which we are pursuing involves replacing the *camera lucida* and digitizing pad with a video camera and interface; the captured image is displayed on the computer screen and the feature to be measured is pointed out with a mouse. This method has been used at Marburg[15], and has the advantage that critical mechanical alignments of the system components are unnecessary, as image merging occurs in software. We are developing a system of this type in Seattle also.

Recently, we acquired a surplus microscope system on indefinite loan from LBL. This system includes high quality microscope optics, 0.5 micron stage coordinate digitizers on 3 axes, and a servomotor drive system. No useful software existed for this system. Our personnel repaired damaged electronics, and wrote control software to allow this system to be used efficiently as a Computer Aided Measuring System (CAMS). As presently arranged, the system uses track data from plates already measured to locate tracks automatically in subsequent plates, in a manner similar to that described for the EMUPAD system. The difference is that the CAMS device is an image-plane digitizer and is not limited to a single field of view. It will thus provide valuable improvements in measuring efficiency for large events encountered in high energy S-Au data.

Our experimental technique allows the determination of:

(1) n_s, the number of fast ($\beta \geq 0.7$) particles produced;

(2) N_h, the number of heavily-ionizing particles;

(3) the pseudorapidity distribution (-ln $\tan(\frac{\theta}{2})$) for the fast particles, with precision ~ 0.01 unit.

In addition, we can observe the decay of short-lived particles indicating the presence of charmed particles or heavy leptons. The emulsion chamber data provide high precision angular measurements of dense events in the forward and central region. The conventional emulsion pellicle stacks provide a complementary technique which can yield a minimum-bias sample of events by along-the-track scanning, and high precision measurement of projectile and target fragment charges. Both sets of data are analyzed with uniform criteria and procedures.

C. RECENT RESULTS AND FUTURE EFFORT

As indicated above, we are participating in two experiments, CERN EMU-01 and Brookhaven E815, for the study of nucleus-nucleus interactions at the highest available beam energies and masses. A list of participants in the EMU-01/E815 collaboration is provided in Appendix II. A member of our group (R. J. Wilkes) is spokesman for E815.

Scanning and measurement of the data taken is underway. The results available from the latest database distribution (6/90) are summarized in Table II-1. Data reduction and analysis has been completed on a total of >3000 events from all exposures. An exchange database system designed and implemented by our group has played a key role in the rapid progress and efficient analysis effort by EMU-01. The database defines a minimal set of event parameters required by our analysis goals, uses a simple text file format which can easily be handled by all members of the collaboration using IBM PC type computers, and can be transferred via BITNET or by mailing floppy disks.

EMU01 results have been presented in a number of published papers[16] in addition to those published during the past contract year (Appendix I). As noted in the preceding subsections, these data show no unambiguous evidence for QGP production, and the hadronic source volume derived from our own adaptation of the Bose Einstein correlations technique shows a transverse radius consistent with expectation from conventional particle production. On the other hand, as shown in Figs. II-2 and -3, we find some events which display significant deviations from the upper limit for rapidity density expected from monte carlo studies, and a sample of events with the highest energy densities (central 200*A* GeV S-Au collisions) shows evidence for nonstatistical fluctuations. These results are just in the process of publication, and preliminary presentations at conferences and workshops generated substantial interest and suggestions for further study from the theoretical community.

During the coming year we expect to perform a proportionate share of the data reduction and analysis in Seattle. The aim of the project is to provide information on nucleus-nucleus particle production features, including the question of QGP production, for each newly available projectile mass, at both BNL and CERN energies within a year of exposure. Accordingly we will improve our data acquisition rate by installing upgraded measuring and analysis equipment.

We currently have scientists from our collaborating institutions in Beijing and Hunan, P. Y. Zheng and J. F. Sun, visiting our lab for 6 months under a grant from the NSF US-China program.

Our group at UW plays a key role in this collaboration, in preparation and processing of detector modules for the experimental runs as well as in analysis effort.

Table II-1: EMU-01 Events Measured (2/90 database distribution)

Beam	GeV/Nucleon	Target	Events Measured
^{16}O	15	AgBr	960
	60	AgBr	724
	200	AgBr	1333
^{32}S	200	Au	188
	200	AgBr	416
Total			3621

III. E665: DEEP INELASTIC MUON SCATTERING AT 60-500 GEV

A. PHYSICS MOTIVATION AND EXPERIMENTAL TECHNIQUE

Experiment E665 at Fermilab is an on-going experiment for the study of muon scattering with hadron detection. The experiment consists of a powerful spectrometer directed to the study of deep inelastic scattering utilizing the world's highest energy muon beam. A primary objective for present study is the use of hadrons to study photon-nucleon interaction structure of the nucleon and hadronization. The specific topics are i) Current jet hadronization with identified hadrons, ii) Event structure relative to the virtual photon axis, iii) Target jet fragmentation and diquark fragmentation, and iv) Exclusive vector meson production. A second objective of the experiment is to measure the structure functions for nucleons and nuclei near x = 0.001.

E665 is a US-European collaboration organized to investigate the problems outlined above[1]. A list of the members of the collaboration is attached in Appendix II. Our group had constructed the open geometry magnetic spectrometer that permitted us to exploit the largest range of interesting muon physics that can be encompassed by a single experiment[2]. The apparatus combined two large magnets, the European Muon Collaboration (EMC) Vertex Magnet and the University of Chicago Cyclotron Magnet (CCM). The resulting spectrometer is as powerful as any known. The apparatus is shown schematically in Fig. III-1.

In the letter of approval (July 27, 1990), for the running of the experiment throught the 1991 fixed target running period, John Peoples conveyed the general opinions of the Physics Advisory Committee regarding the objectives of the experiment:

a) "Your emphasis on photon-gluon fusion and dijet final states is appropriate, and analysis of previous data seems sufficient- even at this early stage - to promise real results with an order of magnitude increase in statistics."

b) "It would certainly be a feather in our cap to have E-665 results on photon-gluon fusion on record before HERA because of the different kinematics."

c) "It was felt that your goals for hadronization studies were important, although some of us may not agree with the theoretical model referred to in your document."

d) "Finally, we recognize that the n/p ratio at small x is very important and hope an accurate measurment of it will emerge from your data."

B. PROGRESS TO DATE AND FUTURE EFFORT

The most recent run of Experiment E665 at Fermilab was completed in August of 1990. A number of important improvements of the experiment were made in the 1990 run. The streamer chamber within which the targets were located has been replaced with a vertex drift chamber arrangement. The streamer chamber provided excellent target fragmentation data but the experiment was hampered by the long dead-time of the chamber and the large amount of time required for the scanning and analysis of film.

As shown in Fig. III-1, the 6 planes of Vertex Drift Chambers provide excellent vertex region tracking for each event. The new target assembly allows the interchange of any of two liquid and seven solid targets between each spill. This provides substantial control of systematics in comparing results with various targets.

During our approved running for 1991, we plan to concentrate on higher luminosity studies of the hadrons from deep inelastic scattering for hydrogen and deuterium targets. The spectrometer allows a unique study of the event structure of deep inelastic events with a total hadronic energy in the c.m. of

W = 22-32 GeV. It is in this kinematic range that the first clear 3-jet event structure was observed in reactions such as the electron- positron collisions. Our results provide a new look at hard QCD processes in deep inelastic scattering and permit a unique examination of the next to leading order photon-gluon fusion process which makes a substantial contribution at x values below 0.05. The new run will allow us to obtain a good statistical sample of 2-forward jet events. It will also allow us to continue other significant studies of the hadronization process such as flavor correlations or baryon production mechanisms using the excellent particle identification of the E665 spectrometer. Lastly, we will be able to provide signficant results on the inclusive muon scattering structure functions at modest Q2 from x = 0.001 to 0.2.

A summary of our proposed beam running luminosities in the past and as proposed for 1991 are given in Table III-1.

TABLE III-1

Luminosity Summary for E665 Data Periods

Target	Trigger	Live Muons	Luminosity
1987-1988 500 GeV Data			
Deuterium	LAT	2.5E11	2.6E36
	LAT for F_2[a]	4 E10	4.2E35
	SAT	4 E9	4.2E35
Hydrogen	LAT	1.5E11	6.9E35
	LAT for F_2[a]	1.1E11	5.0E35
	SAT	1.3E10	6.0E34
Xenon	LAT	1.5E11	6.9E35
	LAT for F_2[a]	1.1E11?	5.0E35
	SAT	9 E9	4.2E34
1990 500 GeV Data			
Deuterium	LAT	2.0E11	2.0E36
	SAT	1.3E11	1.3E36
Hydrogen	LAT	4.7E11	2.0E36
	SAT	3.1E11	1.3E36
Carbon	LAT	1.2E11	2.0E36
	SAT	0.8E11	1.3E36
Calcium	LAT	2.0E11	2.0E36
	SAT	1.2E11	1.3E36
Lead	LAT	6.1E11	2.0E36
	SAT	4.0E11	1.3E36
1991 500 GeV Data[b]			
Deuterium	LAT	1.1E12	1.0E37
	SAT	0.7E12	6.0E36
Hydrogen	LAT	1.1E12	1.0E37
	SAT	0.7E12	6.0E36

[a] For the 1987-88 data, only a fraction of the data could be used for structure function analysis. For Hydrogen and Deuterium this is primarily due to restrictive beam definition cuts. For Deuterium, the trigger was substantially different for much of the accumulated luminosity.

[b] Assuming 6 x 10^{12} protons per pulse in 1991 and 0.75 x $10^{-5}\mu$ /proton. The 1991 Luminosity is based on one meter hydrogen and deuterium targets. The run was assumed to be 5 months long, including 1 month of calibration and 4 months of data acquisition at 40% overall efficiency (70% accelerator, 80% computer live time, and 70% experiment efficiency)

IV. PROJECT DUMAND

A. PHYSICS MOTIVATION AND BACKGROUND

The DUMAND Collaboration will construct a deep underwater laboratory for the study of: a) *high energy neutrino astrophysics*, principally the detection of galactic and extragalactic point sources of TeV neutrinos; b) *particle physics*, via indirect observations of UHE hadronic interactions in astrophysical objects as well as more direct observations of terrestrial interactions; c) *cosmic ray physics*, relating to muon, primary energy spectrum and composition studies; as well as c) *geophysics and ocean science* issues which are confronted incidentally.

A detailed description of the project, a $20{,}000 m^2$ effective area deep ocean neutrino detector, is found in the DUMAND II Proposal[1]. The international DUMAND collaboration, from the USA, Japan, and Europe, will construct and deploy this first long term deep ocean array over a period of three years beginning in 1991.

DUMAND-I consisted of the design, construction and operation of a ship-suspended muon counting Short Prototype String (SPS) of instruments in November, 1987. All of the necessary technology for the construction of a full array has now been developed and demonstrated in the ocean.

DUMAND-II consists of an octagonal array of 216 high sensitivity photomultiplier tubes, capable of detecting position and direction of single relativistic charged particles with a uniquely large sensitive volume and an angular resolution of 0.5 degrees. The array will be shielded by about 5 km of water to minimize the incidence of common cosmic ray particles in the detector. The project will be sited in an ocean valley approximately 25 km west of Keahole Point on the Island of Hawaii, at a depth of 4.8 km. The site has been extensively explored over the last decade, and has been found to be appropriate to our needs.

The overall concept of DUMAND-II is illustrated in Figure 1. A schematic view of the planned array is pictured in Figures 2 and 3. Its main properties are summarized in Table 1. Basically, the proposed design consists of 9 vertical strings, each with 24 photomultiplier detectors spaced 10 m apart along the string vertically for 230 m, and with the strings spaced 40 m apart horizontally in an octagonal configuration. This gives a total of 216 detectors and a neutrino induced muon detection solid angle area of $\sim 148{,}000\pi m^2 sr$ and contained mass of 1.8 megatons.

The individual strings are connected to an underwater Junction Box, which is in turn connected to a shore station (containing data processing and power supply equipment) via an electro-optical cable. In addition to optical (detector) modules, each string includes an environmental module to provide data needed for accurate location of detector elements. A preliminary array of three strings will be deployed in 1991–2.

The array planned has been optimized for the detection of high-energy muons from neutrino interactions. Calculations indicate that this gives us the best opportunity for detecting extraterrestrial neutrino sources. The detector spacings, 40m horizontally and 10m vertically, ensure that muons with energy ≥ 50 GeV which pass through from outside, will be detected with high efficiency and reconstructed in direction with better than 1deg accuracy. (The original neutrino direction will be within this error for neutrino energies above about 1 TeV. Moreover, the relatively flat spectrum sources observed in VHE and UHE gamma rays imply observed mean neutrino interaction energies greater than 1 TeV.)

The array will count downward-going cosmic ray muons at the rate of about one muon per 20 seconds, or 4.6×10^6 events per year, of which about two percent will be simultaneous multiple muons. Muons from atmospheric neutrinos (the decay products of secondary cosmic rays produced in the atmosphere) will dominate the down going muons beyond a zenith angle of about 80deg, leaving a solid angle of 2.35π sr for neutrino observations. The rate of cosmic ray neutrino induced muon events will be about 10^{-4}/sec or 3500/year. This gives a background of about one atmospheric neutrino per $(2.8\,\text{deg})^2$/year. The full DUMAND array will be about two orders of magnitude more sensitive than previous detectors located underground. We expect detectable signals from a number of point sources both inside and outside the galaxy, and from the diffuse background of neutrinos produced by cosmic rays passing through the denser portions of our galaxy. The long range goal of the DUMAND collaboration is to begin the regular observation of the universe in this new light.

In addition to opening new territory in astrophysics and astronomy, DUMAND will complement accelerator based high energy physics research. Currently existing or planned accelerator facilities offer no neutrino beam above about 600 GeV, while DUMAND explores energies above 1 TeV. The rising neutrino cross section and the enormous effective volume of DUMAND offers the best available opportunity to continue the very fruitful study of neutrino interactions energies above 1 TeV where important W-boson propogator and QCD effects are expected.

Measurement of the neutrino induced muon angular distribution (with particular sensitivity to the region near the horizon), will give a neutrino mass sensitivity in the range $0.01 \leq \delta m^2 \leq 100 eV^2$ for mixing angles $\sin^2(2\theta) \geq 0.1$. Five years of data from DUMAND will result in a factor of five improvement in statistical precision over the sum of all the present and planned underground experiments. At this moment it seems that only non-accelerator experiments have the ability to observe neutrino oscillations.

No more important issue for cosmology and particle astrophysics exists than the nature of the missing "dark matter", and DUMAND should be able to make unique contributions to that search. It must be emphasized that DUMAND will be unmatched by any other detector in the world for sheer area and volume. The catalysis of baryon decays by magnetic monopoles presents an outstanding current example. This process would give an easily recognizable signature in DUMAND. The recent history of high energy theory indicates that predictions of this sort come along every few years, and some of the objects of processes predicted may be observable in DUMAND. In searching for rare phenomena, DUMAND will be capable of setting limits several orders of magnitude better than any other detector.

DUMAND can provide information on the origins and acceleration mechanisms of the primary cosmic rays. It provides a new data channel that complements existing cosmic ray detectors at the upper end of the energy spectrum, such as extensive air shower arrays and the "Fly's Eye." The measurement of the muon energy distribution via the angular distribution of down-going muons, and observation of the spectrum of electromagnetic bursts caused by down-going muons will enable us to study the spectrum up through the UHE range.

Details of these and other physics motivations for DUMAND are provided in the DUMAND-II Proposal.

B. RECENT PROGRESS AND FUTURE EFFORT

Following preliminary discussions at the XXI International Cosmic Ray Conference (Adelaide, January, 1990), our group joined the DUMAND Collaboration in May, 1990. Two aspects of the project required additional effort urgently:

(a) Final design, development and construction of the Environmental Modules, both for the Junction Box and for the individual strings; and

(b) Design and development of the trigger processor for the shore station.

In both of these areas we provide relevant experience as well as the institutional technical capabilities required. Additional, less time-critical areas in which we are contributing include design of a suitable experimental database system, definition of astrophysical source candidates and statistical analysis procedures, and participation in the major software effort required for data acquisition, reduction and analysis.

1. Environmental Modules

The temperature, salinity, and pressure at the DUMAND site will all be stable within parts per thousand. Small ocean bottom currents will cause slow (many hour time scale) variation of string position. The anticipated maximal horizontal excursion is 5 m at the top of the string, less than one degree off the vertical, with all strings tilted in parallel. We plan to monitor string position dynamically by acoustical triangulation, which imposes stringent requirements on our knowledge of parameters affecting the local sound velocity, as well as string tilt and orientation. An Environmental Module (EM) will therefore be deployed on each string, as well as on the Junction Box (JB). Each EM will have hydrophone and tiltmeter instrumentation. Water temperature, pressure, and salinity sensors are provided in a standard commercial oceanographic instrument package, the SMARTACM, manufactured by EG& G (commonly termed a Neil Brown Unit, after the original manufacturer). Three of these units will be used, one on the JB and two on strings. Finally, the JB environmental module will be equipped with video and illumination systems to aid in initial placement and in making interconnections, as described below. A block diagram of the JB environmental module is shown in Figure 4, and the physical layout of the JB string is shown in Figure 5.

At the time of Junction Box placement we will deploy 4 battery powered acoustic transponders around the array, about 500 m from the array center. These units are designed to reply when triggered by a coded acoustic pulse. The array will contain at least 3 transponders which will produce the coded request as directed from the shore station, located near the bottom of a string. The outgoing acoustic pulses will then make a nearly horizontal path to the outlying transponders, and the returning acoustic pulses will be received by hydrophones in three locations on each string; top, middle, and bottom. The differential time between top and bottom arrival gives the tilt in that plane, and the middle gives the curvature (if any) as well as some redundancy. The timing amongst strings can be used to determine the relative position of the strings and the transponders (it is an overdetermined system), which, of course, will not change after installation. The use of a surface ship with GPS (precise satellite navigation) will yield the absolute position, and more importantly, the orientation of the transponder group relative to earth coordinates. The precision achieved should be a few meters in absolute location, and 0.1deg in azimuth. The relative string positions will be derivable to a few cm; commercially available integrated sonar systems operating on a similar principle provide $\sim$ 2 cm precision[2].

Hydrophones will be interfaced with an environmental module placed at the top of each string. Only two full EM units are required, providing precise temperature, pressure and salinity for determination of the local speed of sound, as well as processing hydrophone data. Reduced instrumentation on the remaining strings will monitor the azimuthal orientation and tilt to provide redundant information on string motion. We will also require a television monitoring system for JB deployment, equipped with some form of stereo capability (i.e., at least two cameras), attached to the JB environmental module system.

As we plan to digitize the hydrophone data at a 100 kHz rate (as in the SPS) it will also yield useful information for exploring the deep ocean high frequency (up to 50 kHz) acoustic background, and allow us to survey for possibilities involving the use of sound pulses in a future very large ($100km^3$ range) and cost-effective acoustic array[3] for observing interactions in the range above $10^{16}eV$.

While the DUMAND Collaboration includes the Scripps Institute, we have also arranged for consultation and possible collaboration with our colleagues in the University of Washington Applied Physics Laboratory

(APL) and the Department of Oceanography, who have long experience with deep underwater technology. In addition to our University colleagues, we have established contact with several private firms in the Seattle area which have extensive experience in producing commercial systems similar to the EM modules required for DUMAND. These resources will be utilised as required during the EM design, construction and testing process. Preliminary discussions with several of these local experts indicate that the EM requirements are well within current commercial oceanographic practice, and technology required for EM construction is almost entirely available off-the-shelf, excluding experiment-specific interfaces. It is essential that the final system engineering begin promptly, however. Production of a suitably tested unit for the JB is the critical path item for DUMAND, as JB deployment is currently scheduled for October, 1991.

We have hired an engineering consultant who has already begun development of the EM control system and software. We are using a GESPAC MPL4080 single-board 68000 computer, and are constructing prototype hydrophone ADC/interface modules, as well as electro-optical interfacing to the JB using the new TAXI technology. We expect to have a graduate student working full time on EM development before the end of 1990. We have excellent liaison with the Applied Physics Laboratory, and will be using their transponders and test facilities to pin down component specifications before finalizing the EM design.

2. Triggering System

The aim of the trigger system is to enable our data acquisition system to record significant events – high energy charged particles penetrating our detector array – with high efficiency and low dead time. The identification and detection of charged particle tracks in the very large sensitive volume using only a widely spaced array will require us to operate the PMTs with a threshold as low as a single photon signal. Events must be identified with high efficiency while eliminating the background which results from the high counting rates from single PMTs. We have developed algorithms which can distinguish significant events from the background at the required levels, using only well established processor technologies. The trigger system must also contain self-testing and calibration facilities to ensure the necessary level of efficiency and reliability.

The first step is a pre-trigger on a string level. There are four different pre-triggers, defined as the following combinations of nearest-neighbor hits within a string: two hits in 45 ns, three hits in 90 ns, four hits in 135 ns or five hits in 180 ns. These triggers are *inclusive*: any combination which fires a n-trigger will also fire all lower triggers. For convenience we label these four triggers "2", "3", "4" and "5". The second-level trigger for the whole array is one of the following coincidences of these pre-triggers within 1140 ns: 4–3, 3–3–2, 5–2 or 4–2–2. For example, "4–3" means the coincidence of a "4" pre-trigger on any string with a "3" trigger on any other string within 1140 ns. Additionally, every coincidence which contains at least one calibration module is regarded as a trigger.

We conservatively estimate the following rates for these triggers: 9 kHz, 160 Hz, 5 Hz and 0.2 Hz for the "2", "3", "4" and "5" pre-triggers per string. The total rate of random array triggers is expected to be 4.5 Hz. The choice of these trigger conditions is justified by Monte-Carlo simulations described in the DUMAND-II Proposal. The trigger system must be able to accommodate new trigger patterns, incomplete and damaged arrays, and possibly new physics goals to the largest feasible extent.

The trigger system planned uses an array of high-speed microprocessor modules (not to be confused with the DUMAND array of photodetectors) to do the trigger decision in software. The processor array consists of clusters of processors. Each string has a cluster associated with it which analyzes all the data from the string to find pre-triggers. Whenever a pre-trigger occurs, all the data around it are copied to the array cluster which will then analyze correlations between strings to find the array trigger. In the case of a trigger, all the data are copied into the main data recording computer. The hardware required for the trigger processor is an array of high-speed VMS-bus processor boards; organised into 9 + 1 clusters each containing three processors; connected via 9 dual-port memory boards, and one data decoder and splitter for each string.

A trigger subgroup workshop was held in Seattle in July, 1990 to finalise processor specifications and develop trigger algorithm concepts. The basic data transmission scheme adopted was one developed by a UW participant, and the UW group accepted responsibility for a number of technical tasks relating to trigger algorithm development. Proceedings of this key meeting were prepared and published by our group.

3. Planned Operations

Since joining the DUMAND Collaboration in April, 1990, we have begun work in several areas. It will be necessary to finalize the design of the EMs before the end of the year, so this area is of critical importance. With the assistance of an engineer familiar with 68000-based single board microcomputers, we selected a particular type (GESPAC MPL-4080) to serve as the controller for the EM package. This selection influenced the collaboration as a whole, and the device we suggested will also be used by other subsystem developers. We obtained a hydrophone and an environmental sensor (Neil Brown Unit) from Hawaii, and began work on interfacing these sensors to the CPU. We are presently developing subsystems to digitize the hydrophone inputs, and to handle video imaging to assist in deployment operations.

In July, 1990, we served as host institution for a DUMAND Trigger Subgroup Workshop. Members of our local group made essential contributions to the design of the data transfer system to be used by the trigger processor. We are also working on development of a database design for DUMAND in cooperation with collaborators at Hawaii and Aachen.

We expect to develop a final design and construct a prototype JB-EM in early 1991, with field testing in Puget Sound for several months before final testing in Hawaii. Deployment of the JB is currently scheduled for October, 1991.

Array dimensions	100 m diameter × 230 m high
String spacing	40 m side
Number of strings in array	8 in octagon, 1 in center
Sensor spacing along strings	10 m
Number of optical sensors/string	24
Total number of optical sensors	9 × 24 = 216
Height of first sensor above bottom	100 m
Depth of bottom	4.8 km
Sensor pressure envelope	17" (43.2 cm) O.D. glass sphere
Optical sensor	16" photomultiplier
Volume of array, contained	$1.8 \times 10^6\ m^3$
Target area for through-going muons	$23{,}000\ m^2$ horizontal, $7{,}850\ m^2$ vertical up-going, $2{,}500\ m^2$ down-going
Effective target volume for 2 TeV muons	$1.0 \times 10^8\ m^3$
Effective target volume for 1 TeV cascades	$7.0 \times 10^6\ m^3$
Muon energy threshold	20 – 50 GeV
Track reconstruction accuracy	0.5° – 1.0°
Cascade detection threshold	~ 1 TeV
Downgoing muon rate	3 / minute
Atmospheric neutrino rate for throughgoing muons	3500/yr
Atmospheric neutrino rate for contained events above 1 TeV	50/yr
Point source sensitivity	$4 - 7 \times 10^{-10}\ cm^{-2} sec^{-1}$ in a year above 1 TeV
Contained event sensitivity	$1 \times 10^{-8}\ cm^{-2} sec^{-1}$ in a year above 1 TeV

Table IV-1 Summary of the physical characteristics of the array

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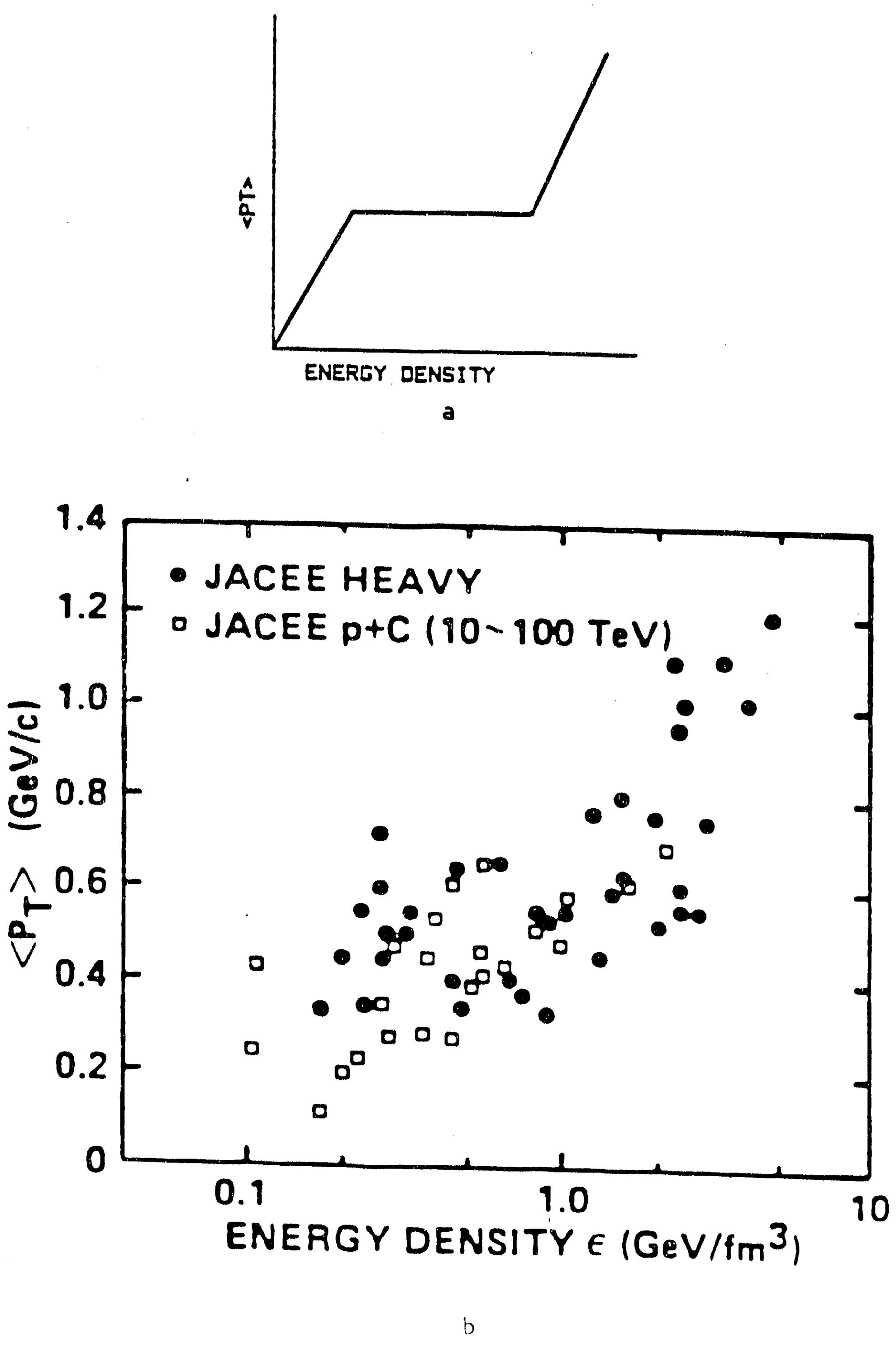


Figure 1-1 : $< p_t >$ vs energy density (proportional to $< \frac{dN}{dy} >$): a) predicted behavior for QGP phase transition; b) observed behavior of JACEE data.

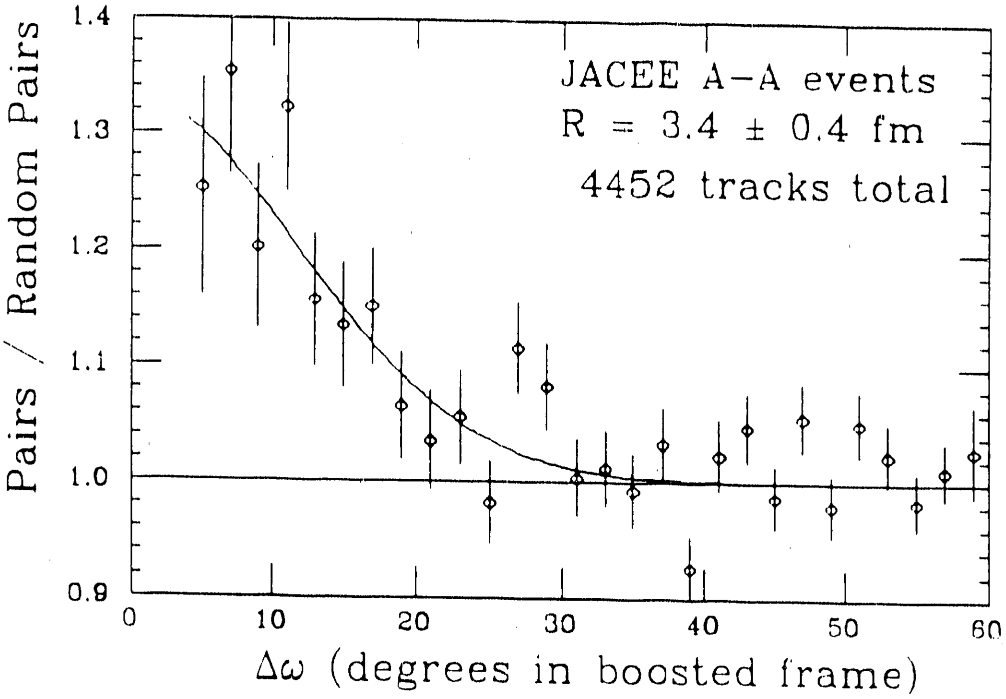


Figure I-2: Bose-Einstein correlations analysis of JACEE A+Pb data

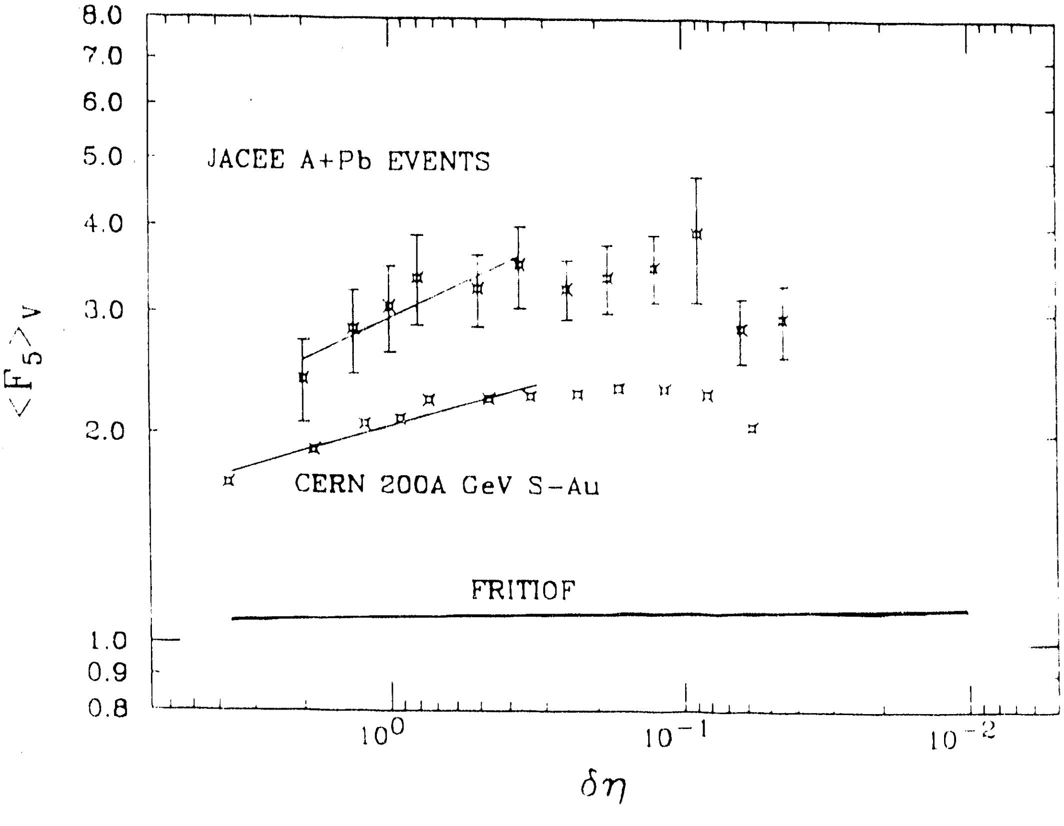


Figure I-3: Scaled Factorial Moment analysis applied to JACEE high multiplicity interactions; shown for comparison are CERN A+Au data and FRITIOF results.

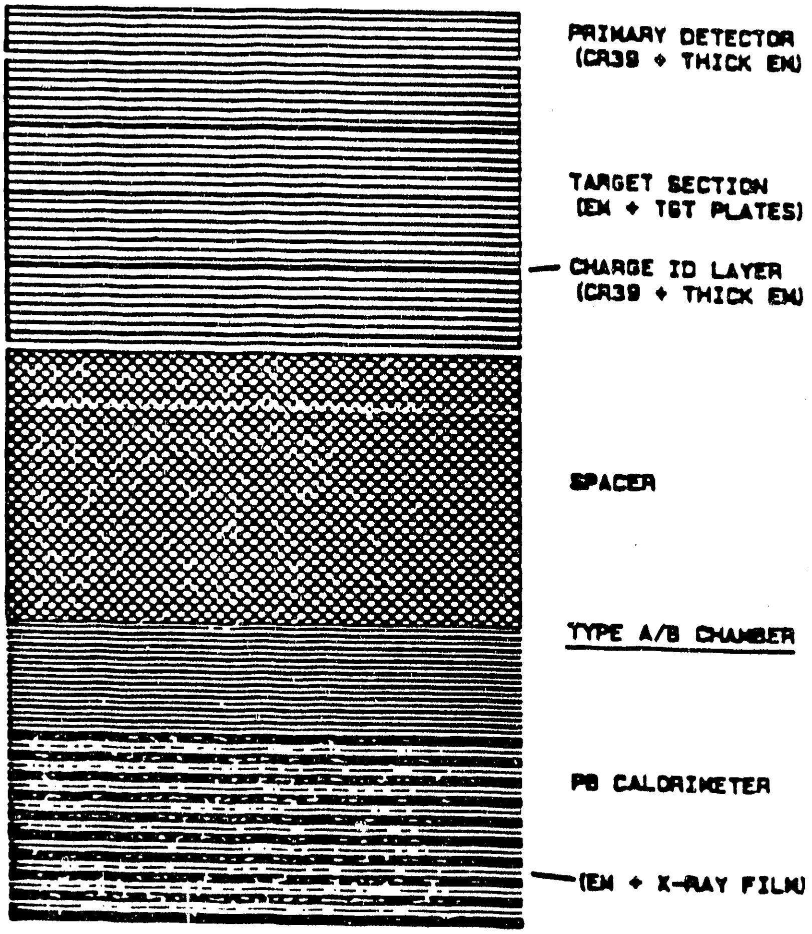


Figure I-4: Typical JACEE emulsion chamber design (JACEE-4).

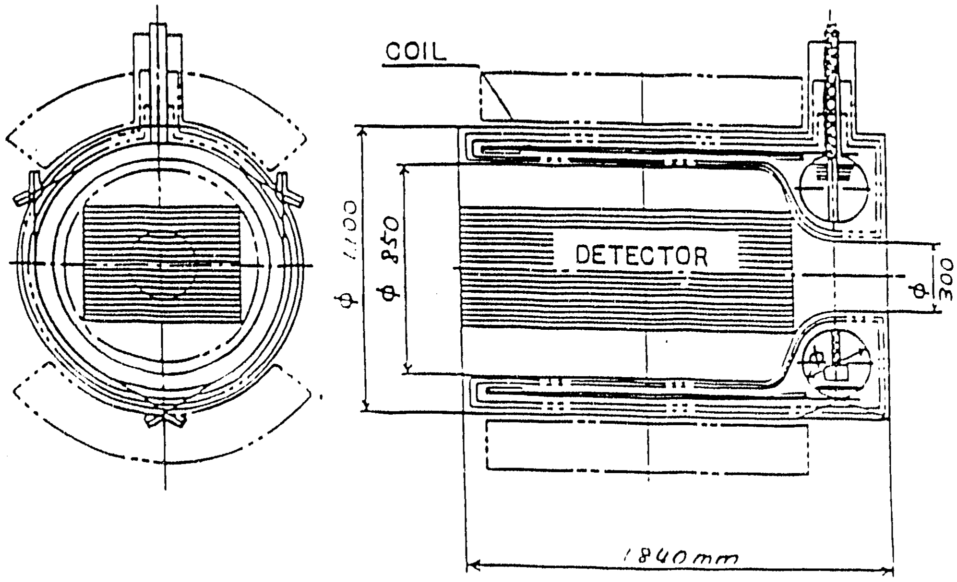


Figure I-5: Superconducting magnet for balloon flight emulsion spectrometer experiments (currently under construction at KEK).

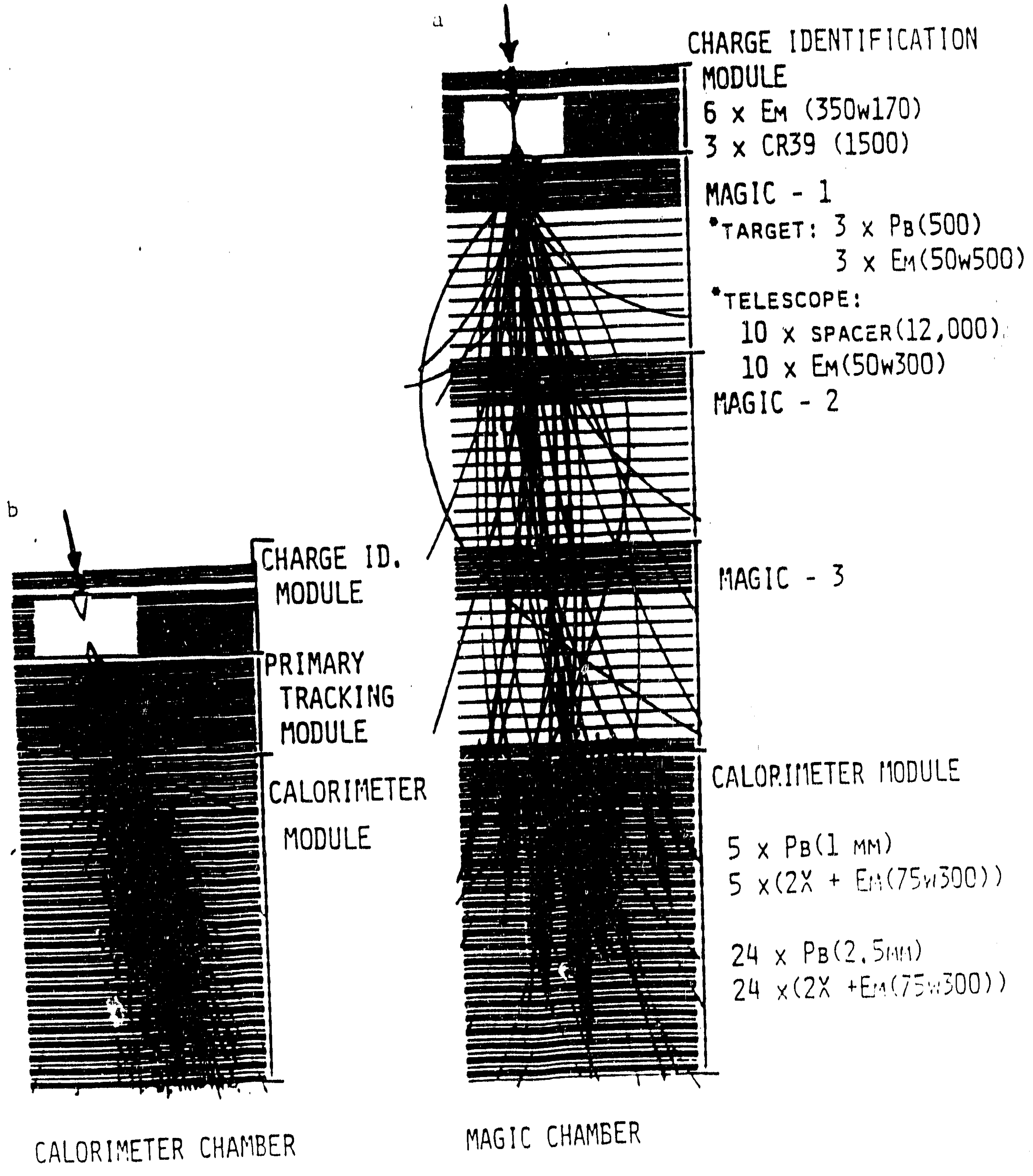


Figure I-6: Emulsion chambers for Space Station experiment (preliminary designs): (a) MAGIC modules - magnetic spectrometer chambers; (b) EMCAL modules - emulsion calorimeter chambers.

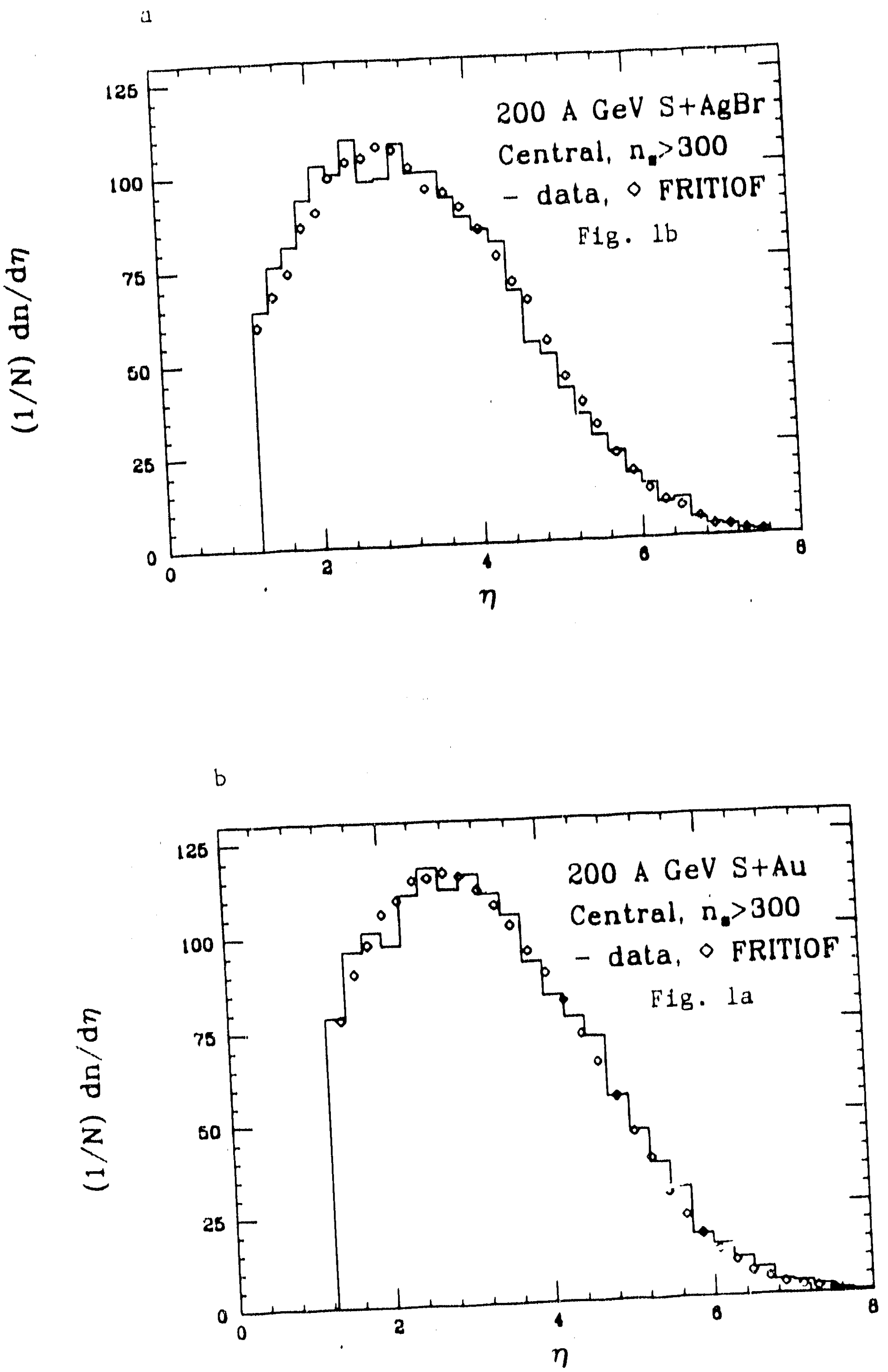


Figure II-1: Pseudorapidity density distributions for high multiplicity (> 300) central events in EMU-01 200A GeV data: (a) S+AgBr, (b) S+Au. Also shown are comparisons with predictions of Lund Monte Carlo FRITIOF.

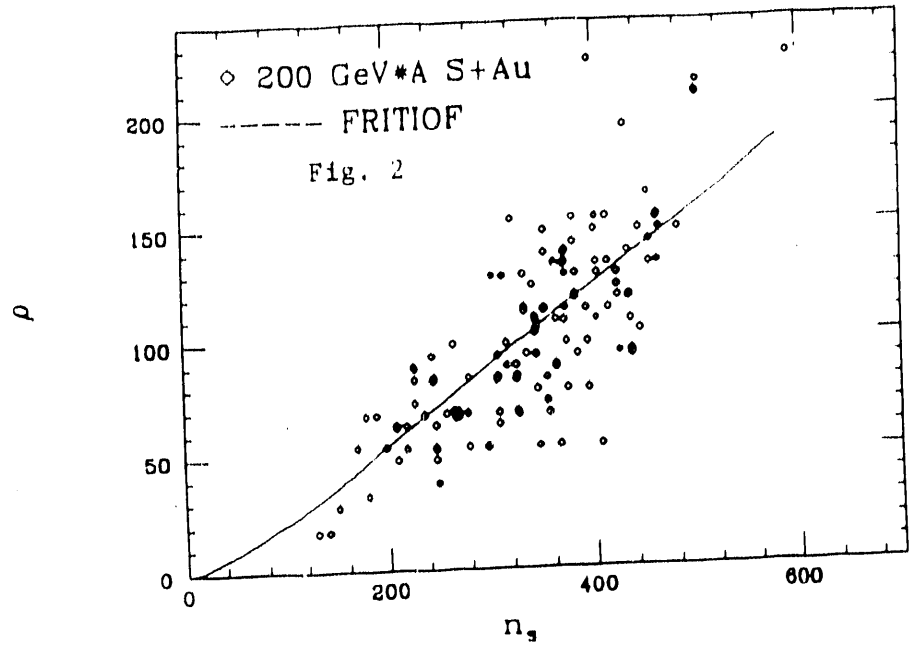


Figure II-2: Peak pseudorapidity density vs multiplicity for central S+Au interactions. Also shown is the average correlation for FRITIOF events.

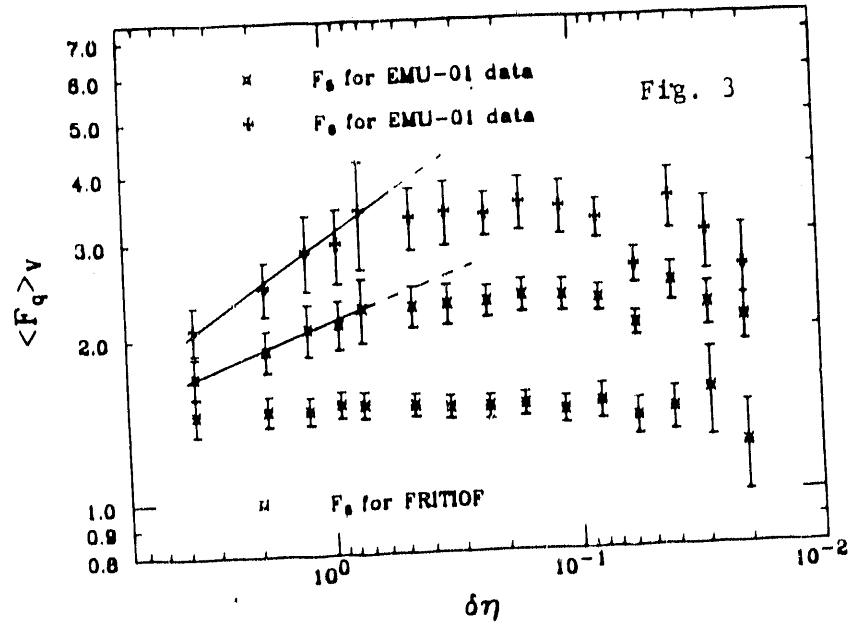
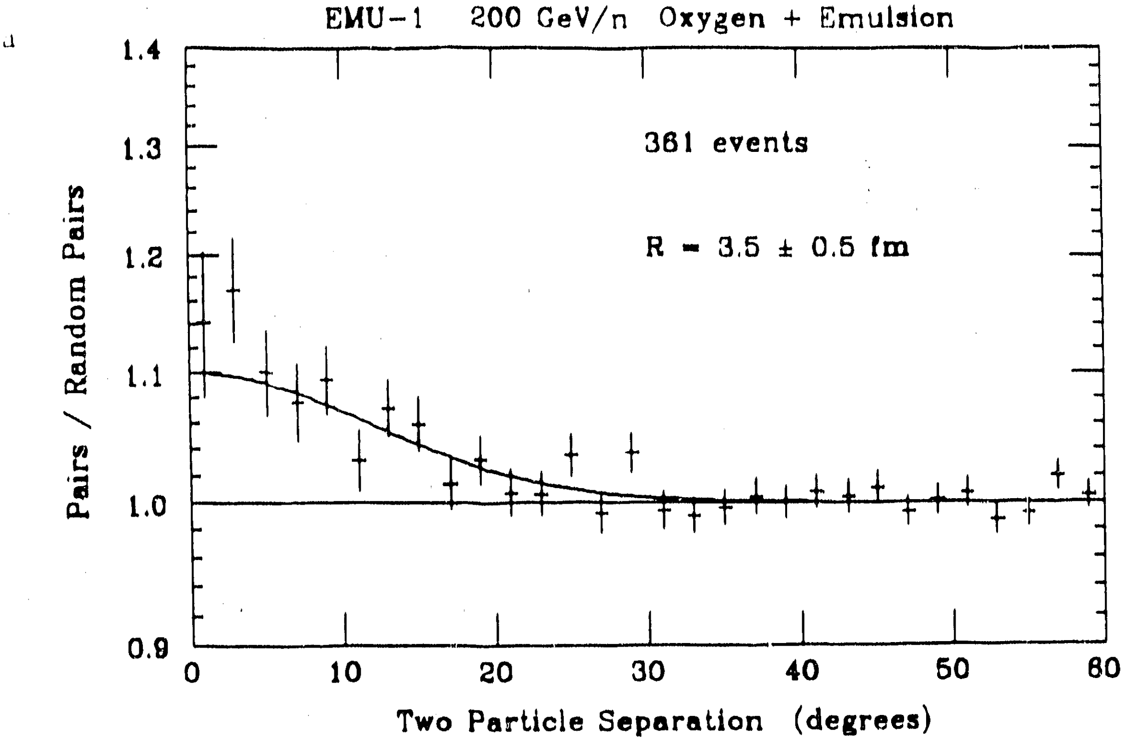


Figure II-3: Scaled Factorial Moment analysis for EMU-01 data (S+Au central events, 5th and 6th moments), compared with FRITIOF data (6th moment shown; all moments give similar results).



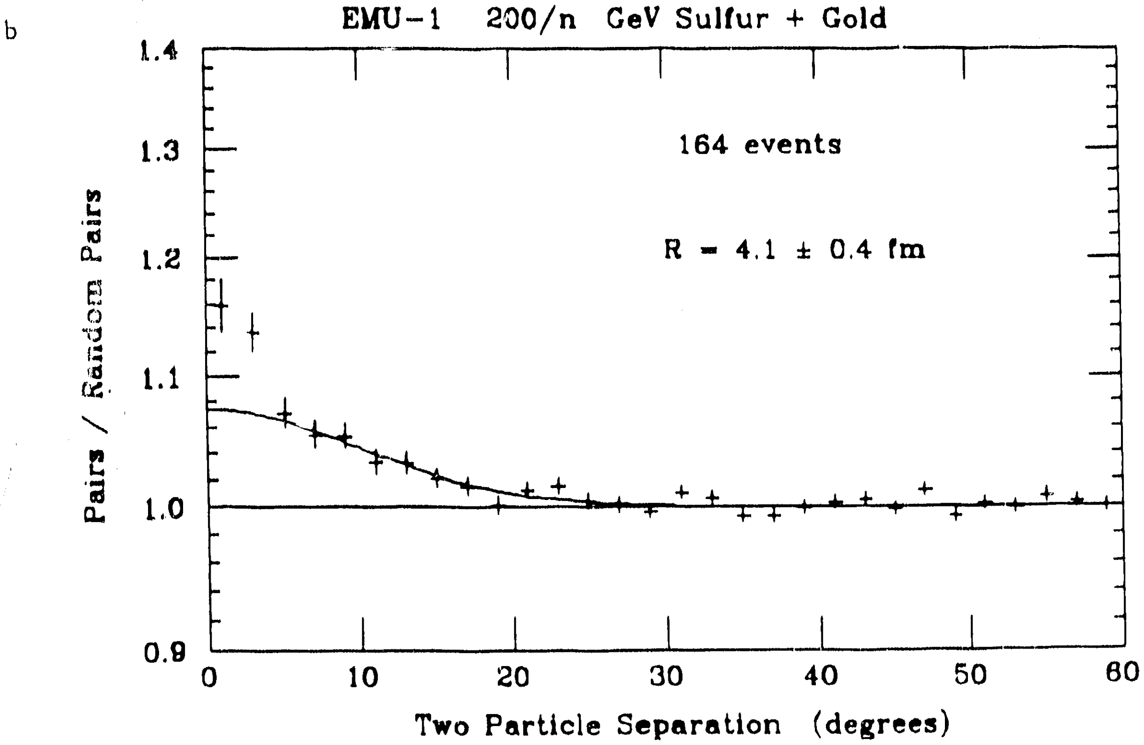


Figure II-4: Bose-Einstein correlations analysis applied to EMU-01 200*A* GeV data: (a) oxygen-AgBr; (b) sulfur-gold. In both cases fit results for source radius are consistent with projectile radius.

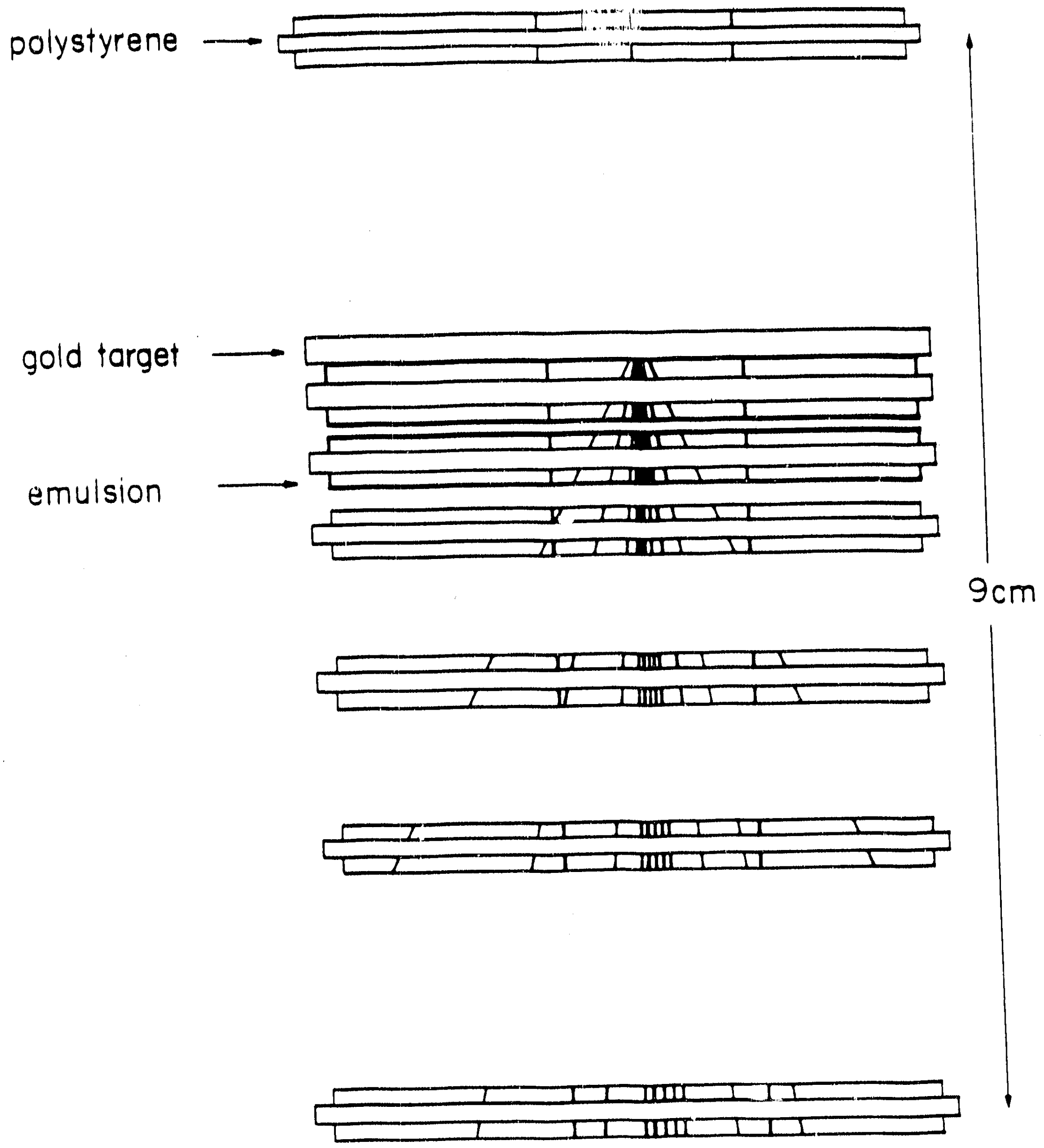
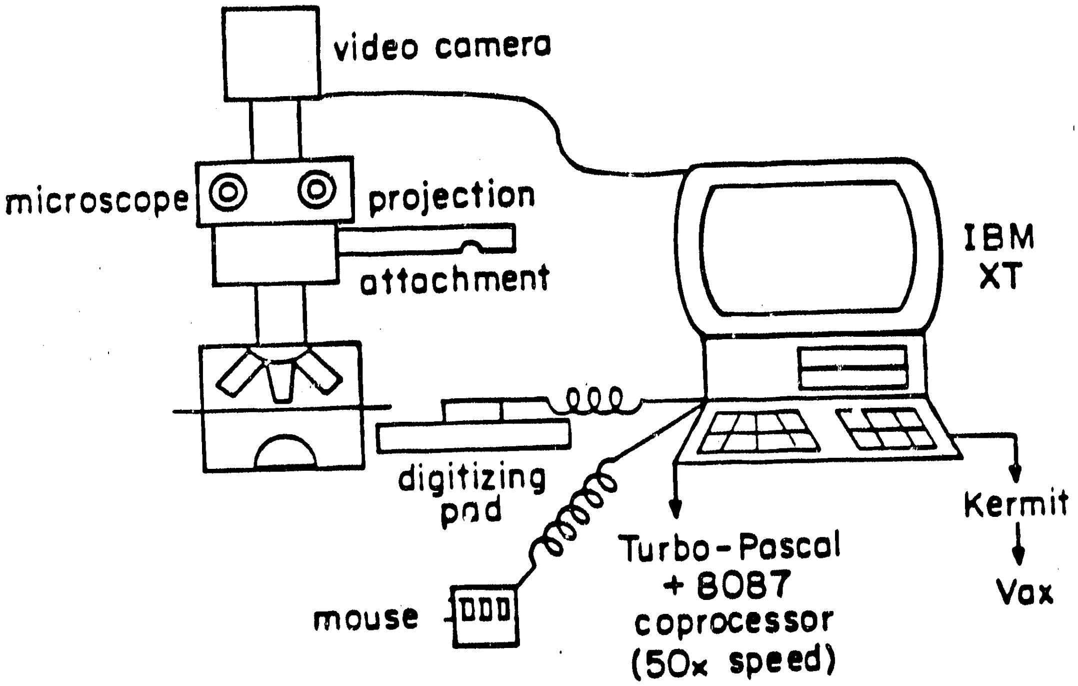


Figure II-5: Emulsion Chamber Design for EMU-01/E-815 sulfur runs.

INTERACTIVE COMPUTER-AIDED
MEASURING SYSTEM

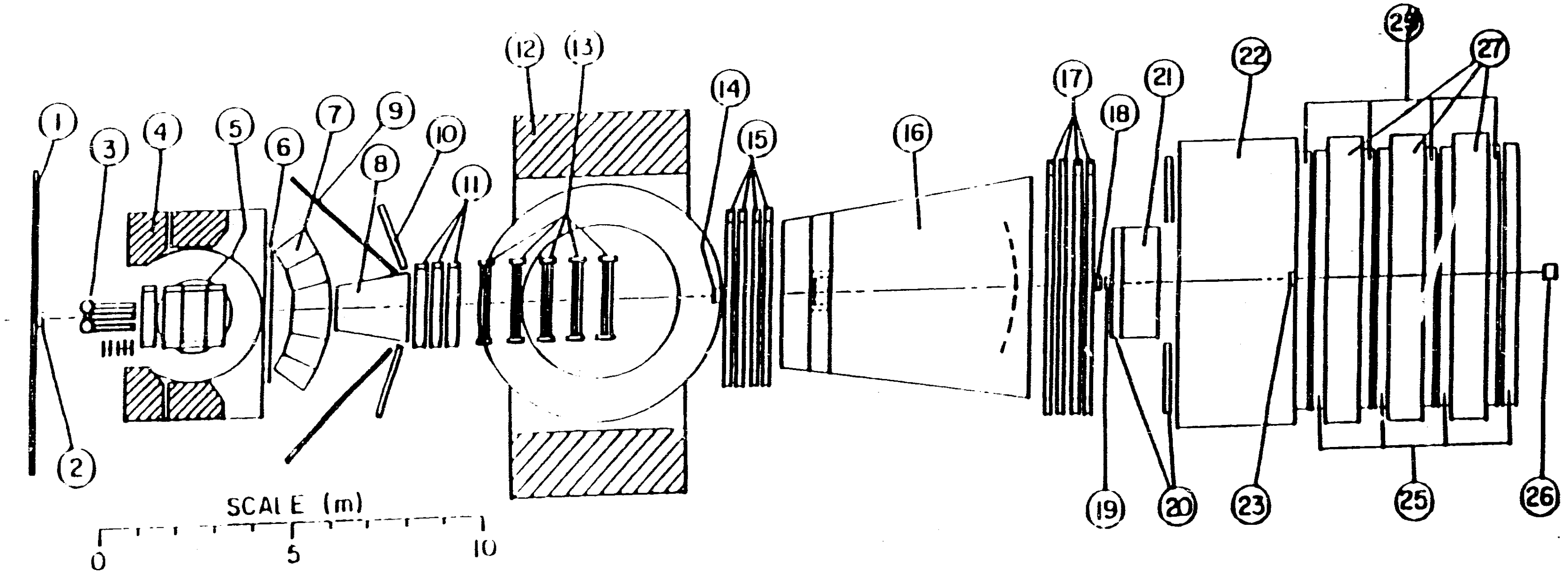


- Attachment projects digipad into microscope field of view
  → or: use video image + mouse
  = "image plane digitizer"
- Comparison with conventional stage measurements
  ("film plane digitizer")
  → no significant difference
  (can measure mult. scatt. of 2 GeV/n Fe)

Figure II-6: Computer-aided measuring system.

Figure III-1: E665 experimental arrangement.

FERMILAB E665
MUON SPECTROMETER



1. 7m x 3m Veto Counter Wall
2. Beam Tagging, Station 4
   0.13m x 0.13m MWPC 6 Planes
   0.13m x 0.18m Scintillation Counter Array
3. 1m $LH_2 + LD_2$ + Solid Targets
4. CERN Vertex Magnet
5. Vertex Drift Chambers, 6 Planes
6. 2.8m x 1m MWPC, 6 Planes
7. 144 Cell Threshold Cerenkov Counter
8. 58 Cell Threshold Cerenkov Counter
9. 4.2m x 1.6m Scintillation TOF Arrays
10. 2m x 2m Prop. Tube Arrays, 4 Planes
11. 2m x 2m MWPC, 12 Planes
12. SC Chicago Cyclotron Magnet
13. 2m x 1m MWPC, 15 Planes
14. 0.13m x 0.13m Small Angle MWPCs, 8 Planes
15. 4m x 2m Drift Chambers, 8 Planes
16. Ring Imaging Cerenkov Counter
17. 6m x 2m Drift Chambers, 8 Planes
18. 0.13m x 0.13m Small Angle MWPCs, 8 Planes
19. 0.13 x 0.13m Scintillation Counter Array
20. 7m x 3m Scintillation Counter Array
21. 3m x 3m EM Shower Calorimeter
22. 7m x 3m x 3m Iron Absorber
23. 0.23m x 0.3m Scintillation Counter Array
24. 7m x 3m Prop. Tube Arrays, 8 Planes
25. 7m x 3m Scintillation Counter Arrays
26. 0.025m x 0.025m rf Phase Lock Scintillation Counters
27. 0.9m Concrete Absorbers

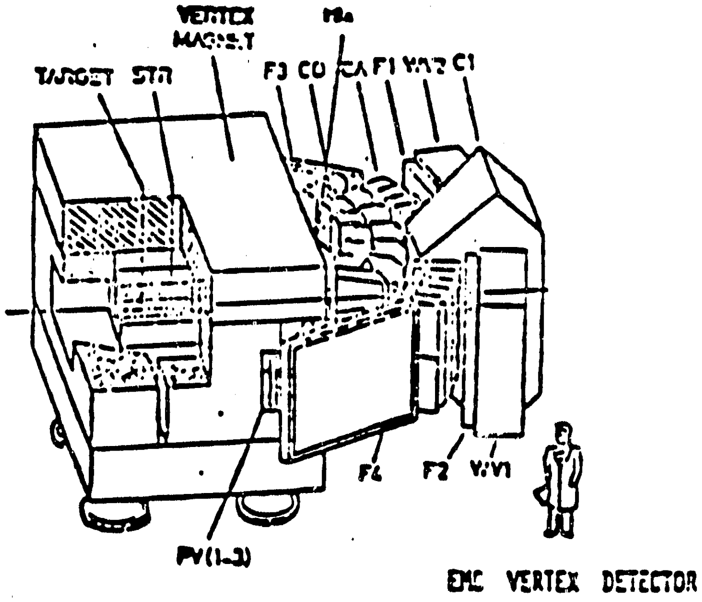


Figure III-2: EMC vertex magnet system.

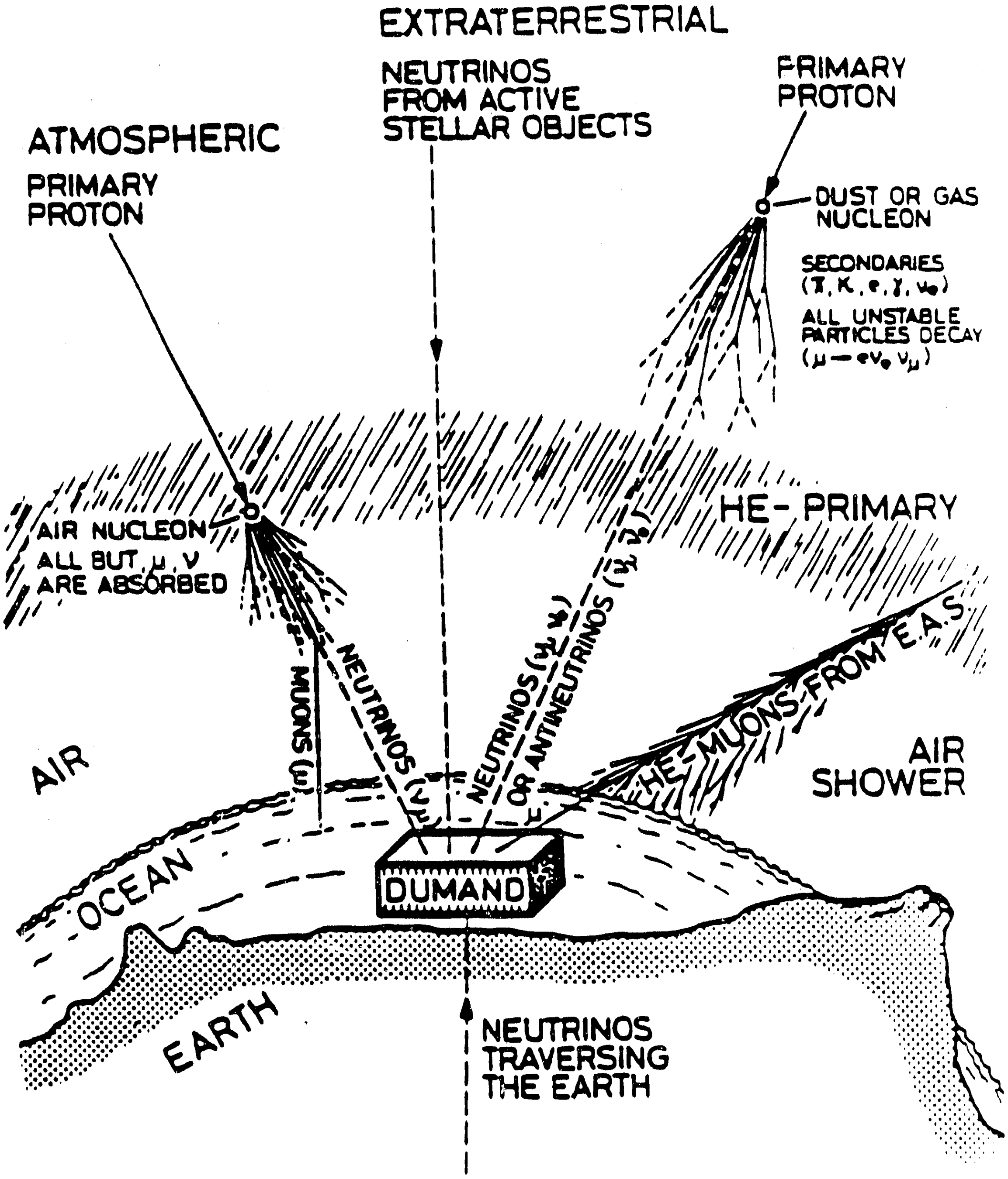


Figure IV-1: The concept of the DUMAND experiment. Cosmic ray protons (or other nuclei) of very high energy strike matter, either in the earth's atmosphere or elsewhere in the cosmos. The resulting hadronic secondaries decay into neutrinos which penetrate to the DUMAND array and are detected. Down going muons produced in the atmosphere with energy greater than ~ 3 TeV can also be detected and analyzed.

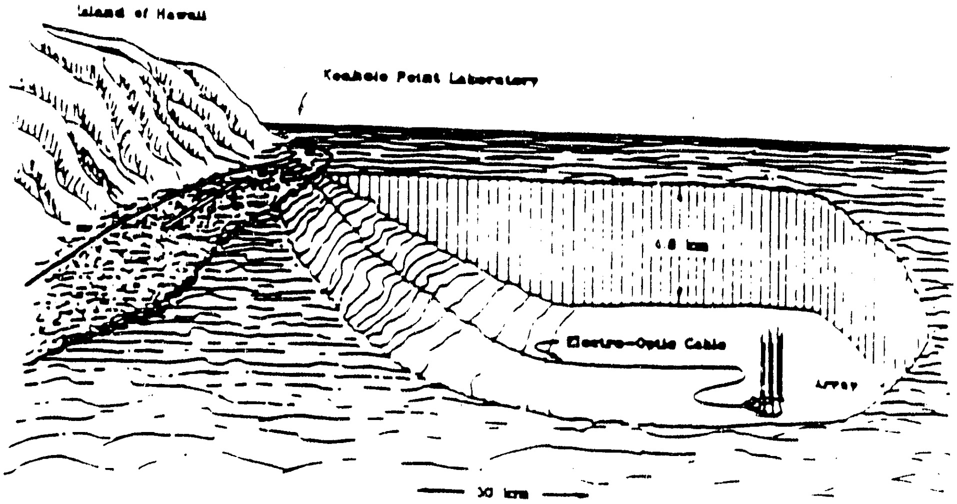


Figure IV-2: Disposition of the DUMAND detector at 4.7 km depth in subsidence basin ~ 35 km off Keahole Point, island of Hawaii. Armored cables carrying power and fiber-optics communication connect DUMAND to the shore station.

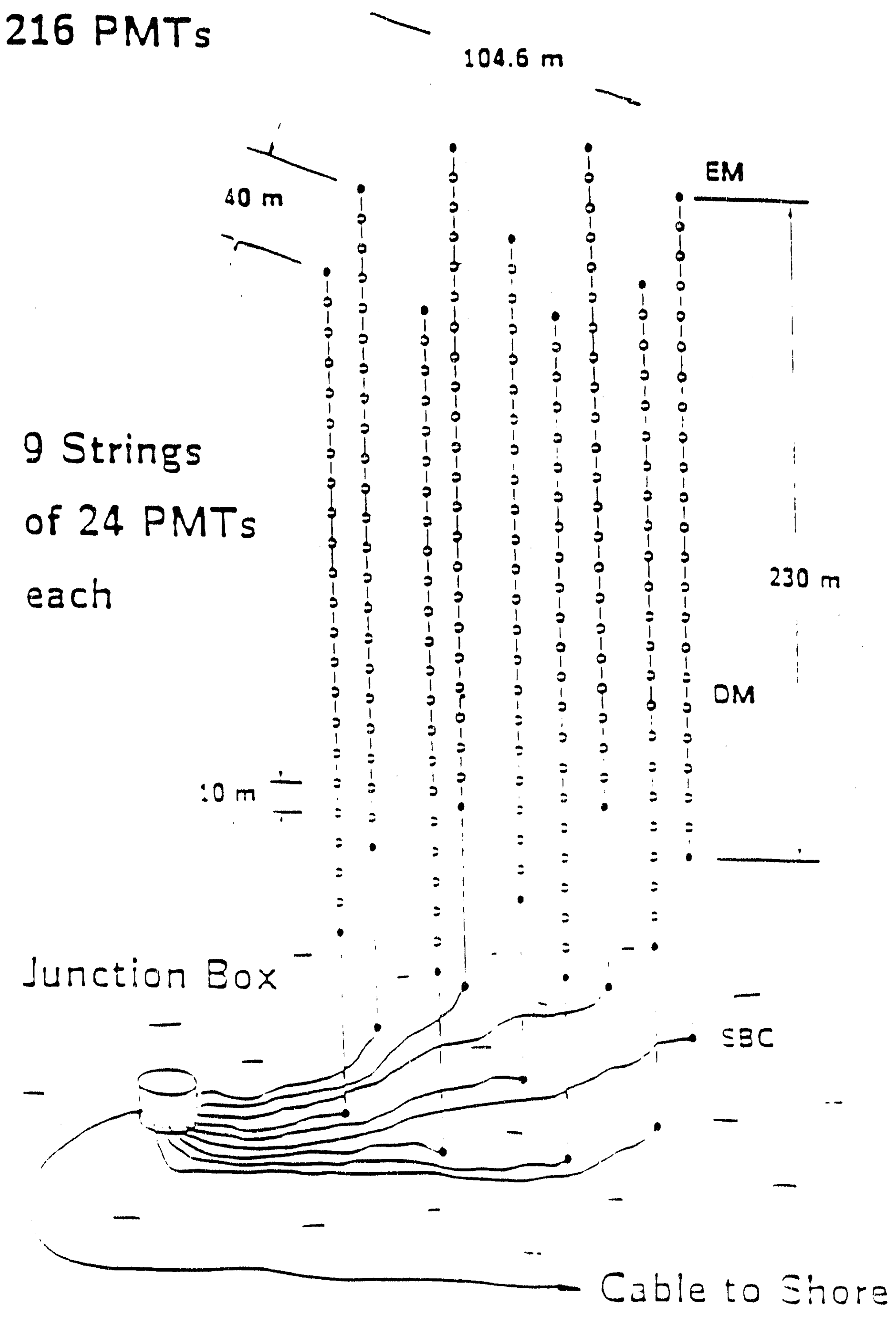


Figure IV-3: The DUMAND Octogon Array. There are 9 strings, each anchored at the bottom, and held taut by a float. They are spaced 40 m apart on the perimeter, with a ninth in the center. Along each string there are 24 detector modules spaced 10 m apart. The strings are independent — they are connected at the bottom.

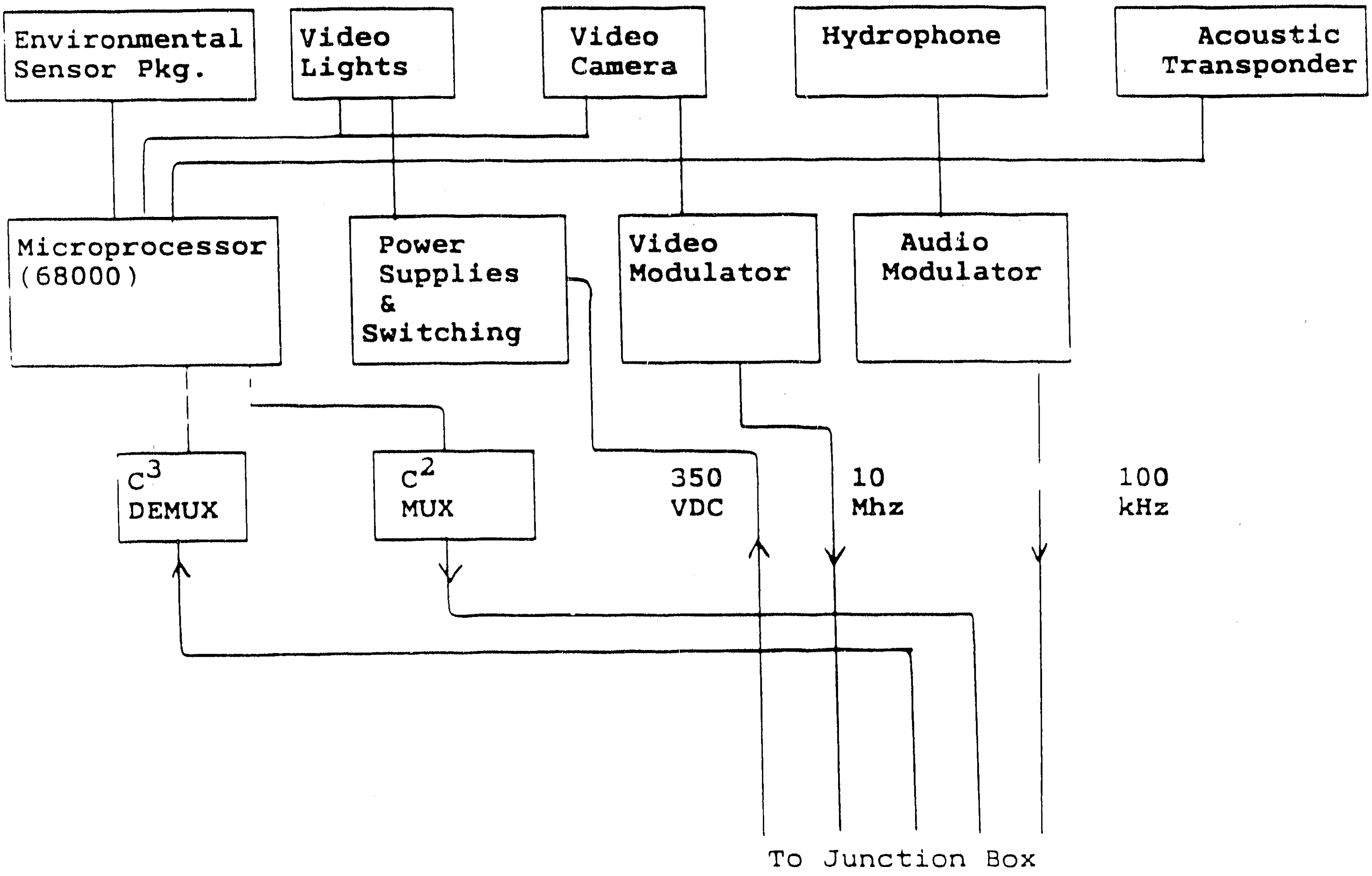


Figure IV-4: Block diagram of the Junction Box Environmental Module system.

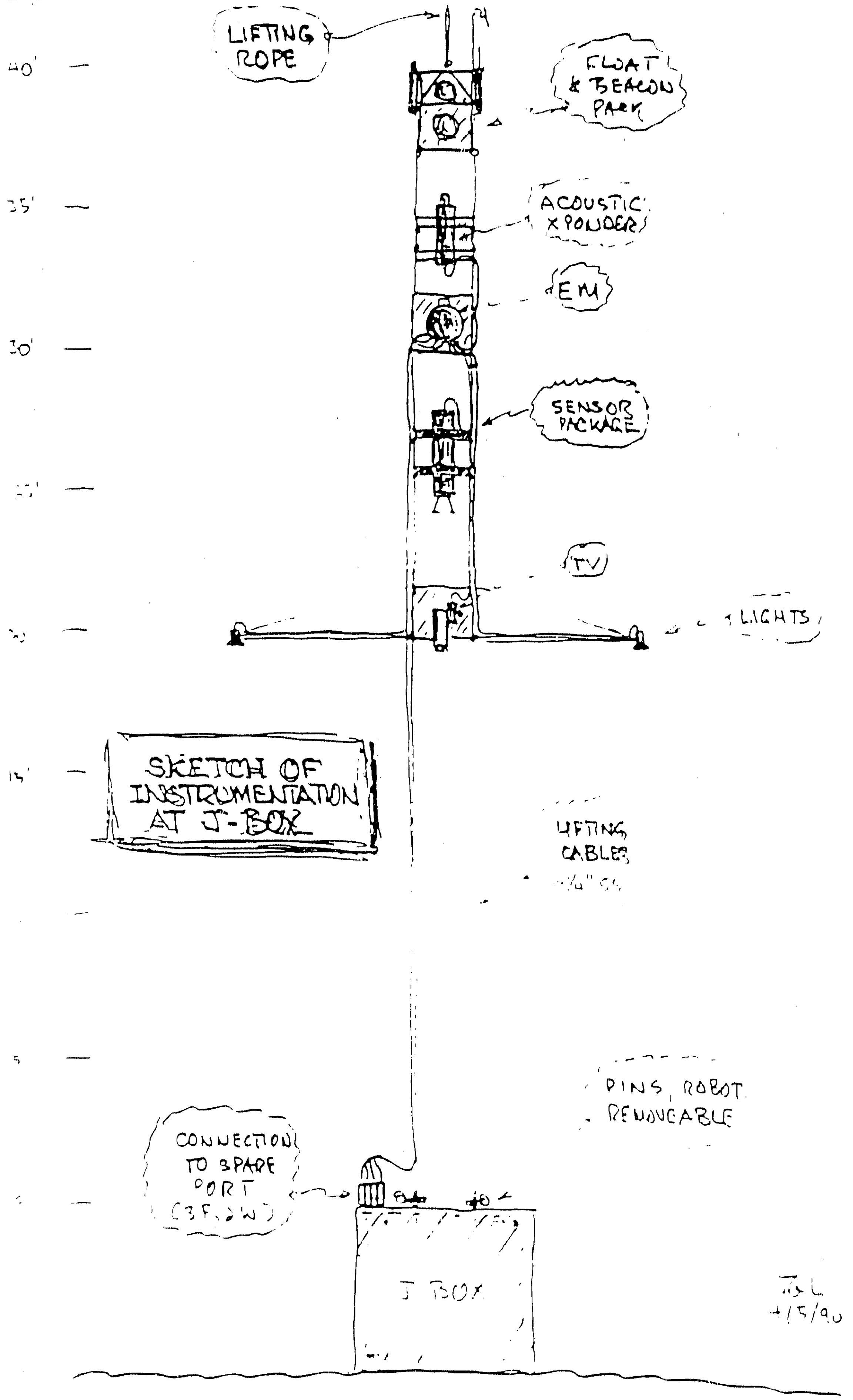


Figure IV-5: Diagram of the JB Environmental String.

APPENDIX I: Publications During the Past Year

Published Papers

1. "Rapidity Densities and Their Fluctuations in Central 200 A GeV ^{32}S Interactions with Au and Ag, Br Nuclei," (EMU-01 Collaboration) M.I. Adamovich, *et al.*, *Phys. Lett.* **B 227**(2), 285 (1989).
2. "A Study of Recoil Protons in Ultra-Relativistic Nucleus-Nucleus Collisions," (EMU-01 Collaboration) M.I. Adamovich, *et al.*, *Phys. Lett.* **B 230**(1,2), 175 (1989).
3. "A Search for Non-Statistical Particle Density Fluctuations in ^{16}O+Ag(Br) and ^{32}S+Au Interactions at 200 A GeV," (EMU- 01 Collaboration) E. Stenlund, *et al.*, *Nucl. Phys.* **A 498**, 541c (1989).
4. "Gamma Cascade Detectors for the Space Station Era," R. J. Wilkes, *Nucl. Phys.* **B 14a**, 373 (1990).
5. "A Spectrometer for Muon Scattering at the Tevatron," (E665 Collaboration) M. R. Adams, *et al.*, *Nucl. Inst. & Methods* **A291**, 533 (1990).
6. "On the Energy and Mass Dependence of the Multiplicity in Relativistic Heavy-Ion Interactions," (EMU-01 Collaboration) M.I. Adamovich, *et al.*, *Modern Phys. Lett.* **A5**(3), 169 (1990).
7. "Energy Spectra of Cosmic Rays Above 1 TeV per Nucleon," (JACEE Collaboration) T. H. Burnett, *et al.*, *Astrophysical Journal* **349**, L25 (1990).
8. "Gamma Rays at Airplane Altitudes," J. Iwai, *et al.*, in *Particle Astrophysics, The NASA Cosmic Ray Program for the 1990s and Beyond, Greenbelt, MD 1989*, W.V. Jones, F.J. Kerr, J.F. Ormes, eds., **AIP Conf. Proc. 203**, 304 (1990).
9. "Target Nucleus Fragmentation in ^{16}O+(Ag,Br) Interactions at 200 A GeV," (EMU-01 Collaboration) M. I. Adamovich, *et al.*, *Phys. Lett.* **B 234**(1,2), 180 (1990).
10. "Observation of Associated Bottom Production and Decay in a High Energy Hadron Interaction," (JACEE Collaboration) B. Wilczynska, *et al.*, *Phys. Rev.* **D 41**(11), 3336 (1990).
11. "Scaled Factorial Moment Analysis of 200A GeV Sulfur-Gold Interactions," (EMU-01 Collaboration) M. I. Adamovich, *et al.*, *Phys. Rev. Lett.* **65**, 412 (1990).
12. "Evaluation of ACT Delay Lines for SSC/LHC Applications," R. J. Davisson, *et al.*, accepted for publication in *Nucl. Inst. Meth.*

Reprints + Preprints removed

Publications that follow in this section have not been given page numbers.
Appendix II begins on page 44.

APPENDIX II: Membership of Collaborations

A. List of Participants in Project JACEE (Balloon flight experiment)

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