DOE/ER/03064--T2

BUDGET PROJECTIONS
1988, 1989, and 1990
for
Research in High Energy Nuclear Physics

by

A Faculty Group in
THE DEPARTMENT OF PHYSICS
HARVARD UNIVERSITY
Cambridge, Massachusetts

April 1988

Contract DE-AC02-76ER03064
Between the Department of Energy
and the
President and Fellows of Harvard College

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DISCLAIMER

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HARVARD UNIVERSITY HIGH ENERGY PHYSICS
Contract DE-AC02-76ER03064

1. Introduction

Research programs in experimental high energy physics are carried out at Harvard under the general supervision of a departmental faculty committee on high energy physics. Professor R.F. Schwitters is currently chairman of this committee. The committee members are: G.W. Brandenburg, S. Geer, R.J. Glauber, K. Kinoshita, R. Nickerson, F.M. Pipkin, J. Rohlf, C. Rubbia, R.F. Schwitters, M. Shapiro, K. Strauch, R. Vanelli, and R. Wilson. Of these individuals, Professors R.J. Glauber, F.M. Pipkin, C. Rubbia, R.F. Schwitters, K. Strauch, and R. Wilson are the principal investigators with whom a number of junior faculty members and post-doctoral research fellows are associated. Dr. Brandenburg (Associate Director, High Energy Physics Laboratory) administers the High Energy Physics Laboratory and is in charge of the Computer Facility. Professor Rubbia is currently on leave of absence and will leave Harvard on December 31, 1988 to become the Director General of CERN. A reduced UA1 effort will remain at Harvard after Professor Rubbia's departure. Harvard is planning to make one or two senior faculty appointments in experimental high energy physics sometime in 1988-89.

The principal goals of the work described here are to carry out forefront programs in high energy physics research and to provide first rate educational opportunities for students. The experimental program supported through HEPL is carried out at the major accelerator centers in the world and addresses some of the most important questions in high energy physics. Our educational efforts are concentrated in graduate education, where we are currently supporting 15 research students. In addition, undergraduate students work in projects at HEPL during the academic year and over summers. Many of these students have gone on to graduate school studying physics at Harvard and elsewhere.

These budget projections cover all of the Harvard based high energy physics experimental activities. The "umbrella" nature of this contract greatly simplifies support of our essential central technical and computer services and helps us to take advantage of new physics opportunities and to respond to unexpected needs. The funding for the operation of the HEPL facility is shared equally by the experimental groups.

Harvard supports our high energy physics research program in many ways. The University pays the full salary of tenured faculty for the academic year from non-contract funds. The University has contributed significantly to special travel expenses incurred by faculty members. It has also provided startup funds and support for special projects. Non-tenured faculty have either one-quarter teaching and three-quarter research or half-time teaching and half-time research appointments. Postdoctoral Research Associates have full-time research appointments (the research appointments are paid by this contract). The University provides full support for the tuition of first and second year graduate students. Finally, the partial salaries of five HEPL staff members are supported by Harvard.

Our activities greatly benefit from the existence at Harvard of several very strong theory groups, which are supported by the NSF and the University, in addition to Professor Glauber's group, which is supported under this contract. Our theoretical colleagues give exceptional stimulation and guidance for our experimental activities. The Physics Department also invites several Loeb Lecturers each year who provide the Cambridge community with fresh points-of-view in all areas of physics.

2. Facilities

A. High Energy Physics Laboratory

The High Energy Physics Laboratory is the focus of the high energy experimental physics activities at Harvard University. The building, originally part of the Cambridge Electron Accelerator (CEA), has offices for faculty, postdocs, students, engineers and administrators. It houses a machine shop, an electronics shop, a high-bay equipment assembly area, a test laboratory, the VAX computer and an IBM analysis facility. The test laboratory is equipped with appropriate NIM and CAMAC electronics, a CAMAC interface to the VAX, and several microcomputers with CAMAC interfaces. The electronics shop has a printed circuit board CAD system, which is heavily used for the layout of specialized detector readout boards.

Even though data are taken at the accelerator centers (FNAL, CERN, Cornell, and DESY), detection equipment is built at Harvard and much of the data are analyzed in-house. The ability to make strong technical development and construction contributions to experiments permits us to be effective partners in collaborations; this ability constitutes a very important part of our program. It also permits us to make essential hardware contributions to non-accelerator connected experiments such as proton lifetime measurements. Our excellent shop and assembly facilities were inherited from the Cambridge Electron Accelerator (CEA); our dedicated technical staff originated at the Harvard Cyclotron Laboratory many years ago.

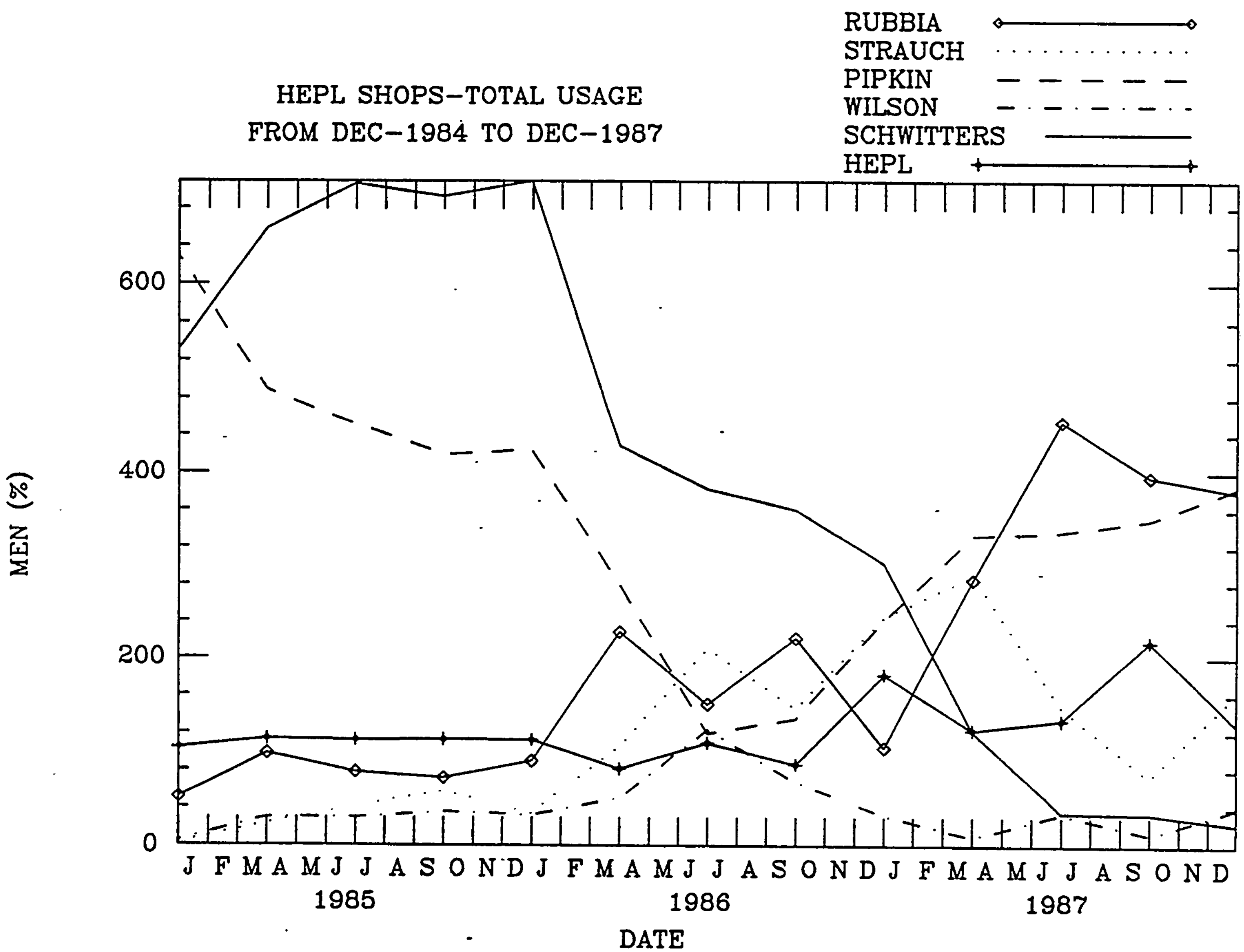
The engineering staff consists of one electronics engineer, two mechanical engineers, and a computer system manager. The technical staff consists of three electronics technicians, three machinists, and three mechanical technicians. The administrative staff (whose salaries are all or mostly paid by the university) consists of the Associate Director, a bookkeeper, and a secretary. No engineer or technician is assigned to a given group; instead the staff works on group initiated projects as need arises.

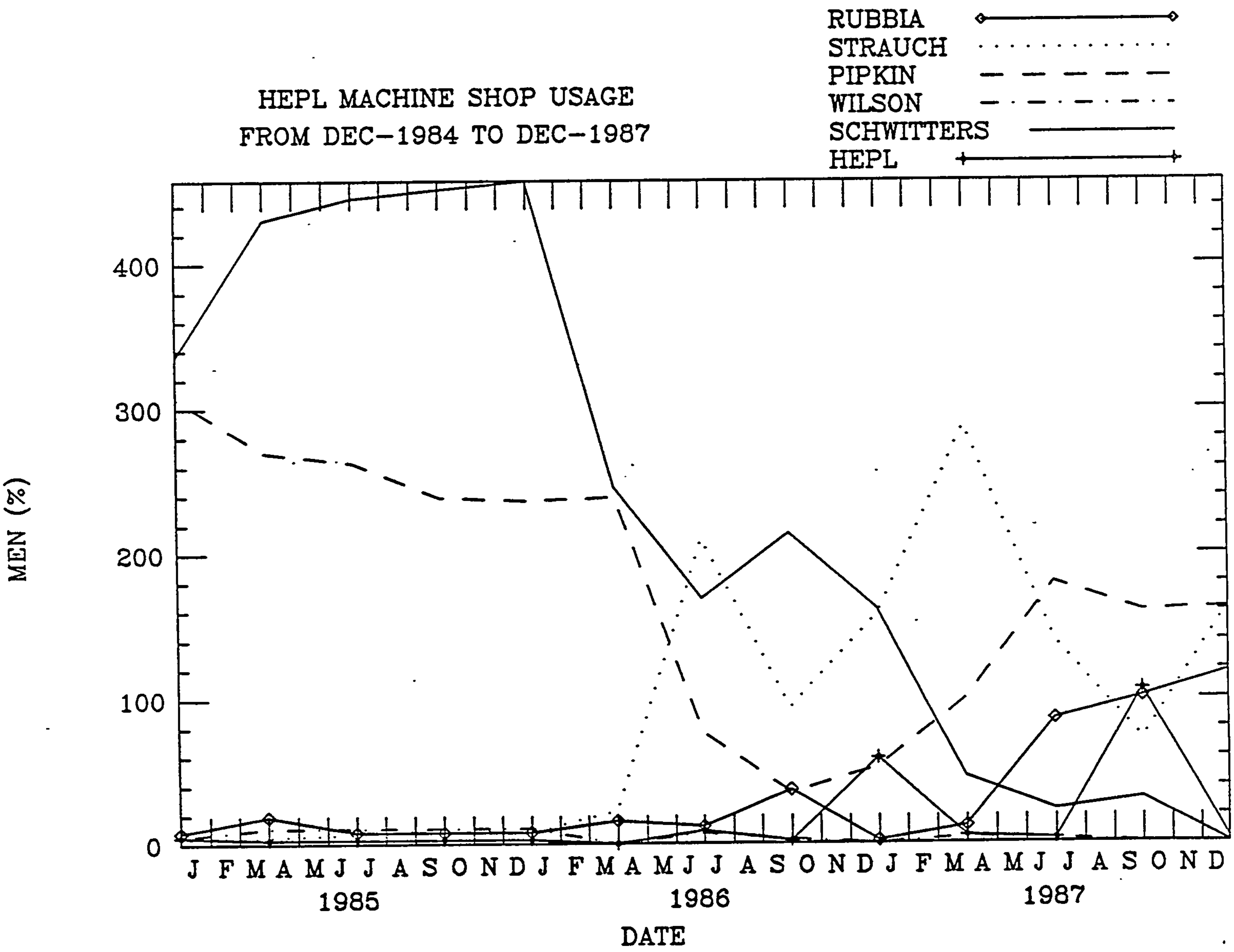
The HEPL shop facilities have been used to build equipment for numerous experiments. The major effort during 1978 and half of 1979 was devoted to the CLEO experiment at Cornell. The equipment built included the TOF system, two high-pressure Cerenkov counters, and the end-cap shower counter system. During the same period a proportional tube muon detector was built for the Crystal Ball experiment at SLAC. The period 1980 through 1983 saw the design and completion of the major components for a proton lifetime experiment at the Park City mine. A luminosity monitor for the Crystal Ball detector in its new home at DESY was also designed and built in the spring of 1982.

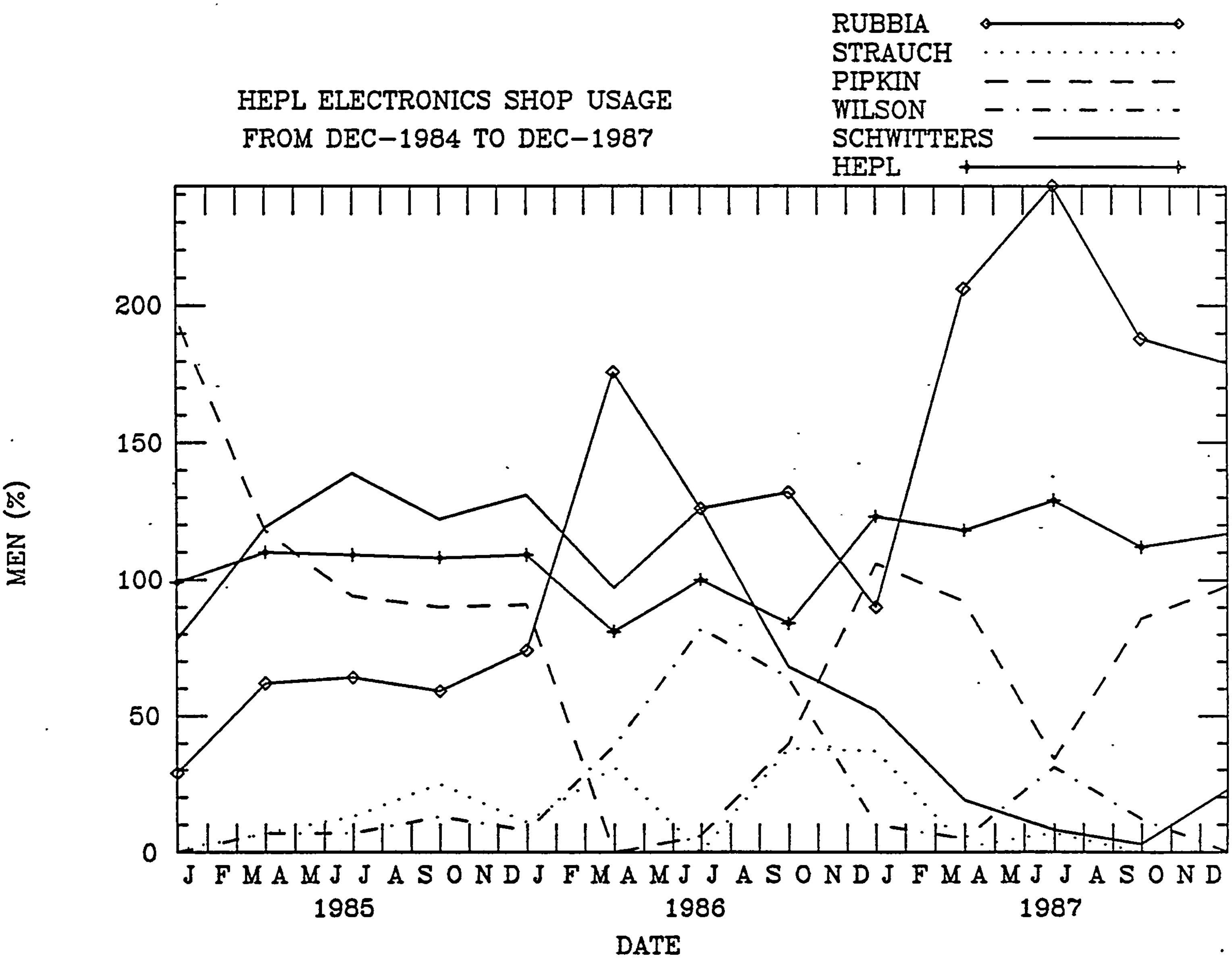
The figures on the following pages illustrate the allocation of the HEPL resources to the different groups for the last three years. The machine shop completed large electromagnetic calorimeters for both the Collider Detector at Fermilab (CDF) and the Tevatron Muon experiment (E665) during the period 1984–1986. (E665 is a joint project of the Wilson and Pipkin groups, but has been included primarily in the Pipkin group totals in the figures.) Since then the shop has been busy constructing the upgraded CLEO TOF system and building hardware for both L3 and UA1 at CERN. The electronics shop is designing and building readout electronics for CDF, CLEO, E665, and UA1 and is prototyping electronics for future experiments. More details on schedules and on future plans can be found in the sections of this report for the individual groups.

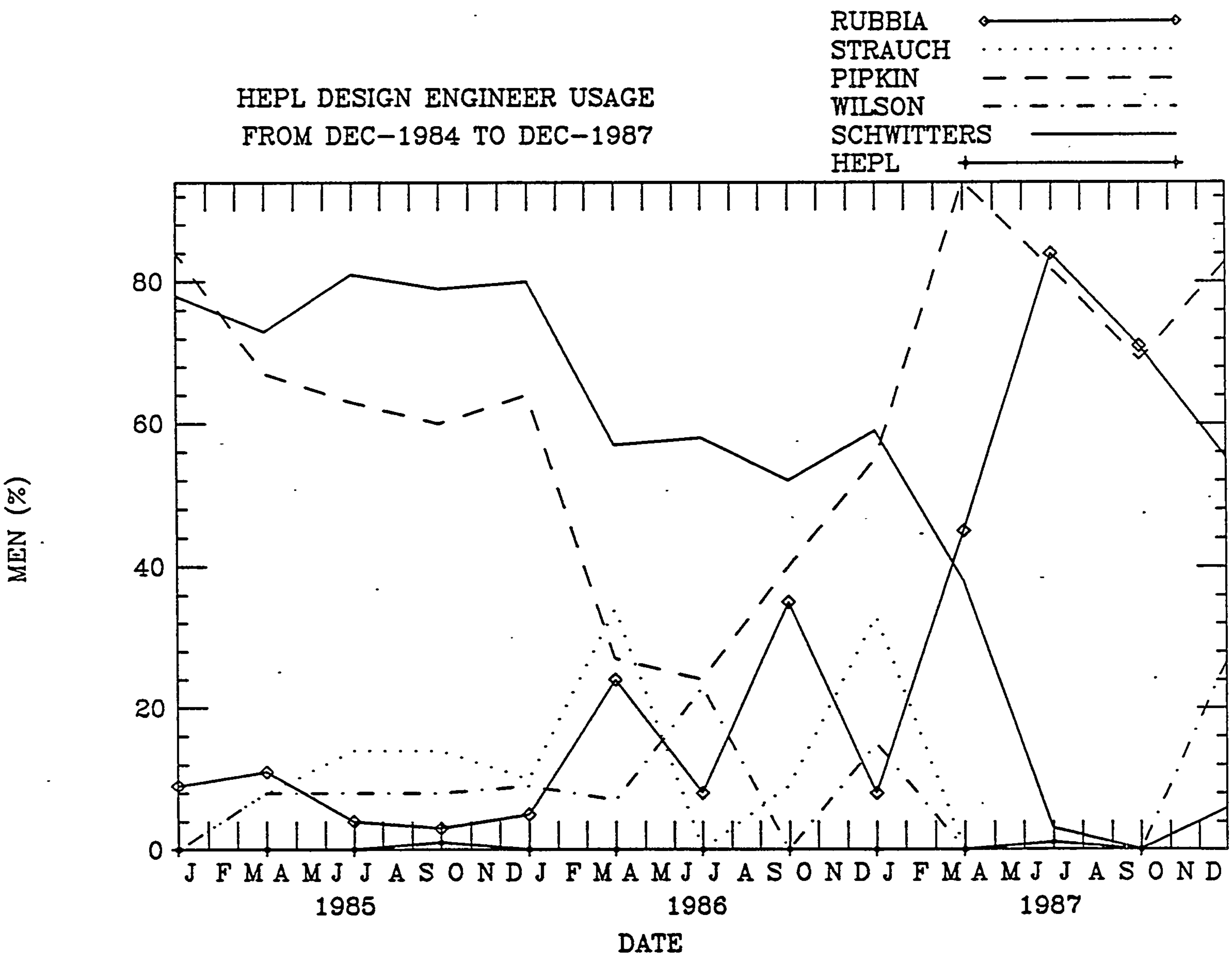
We have always had an active program of detector R&D at HEPL involving several of our physicists. This work has resulted in new calorimeter designs and in advanced readout systems in recent years. Although this effort has not been funded as a part of the SSC R&D program, its results have been generally useful for future collider experiments. Starting next year we are instituting a separate Detector R&D Group which will include two members of our engineering staff, J. Oliver (electronics) and E. Sadowski (mechanical design), on a part-time basis. We are also hoping to hire a new postdoctoral physicist who work with them. This work is described in section 9.

In an adjoining building is the Harvard Cyclotron laboratory with an external beam of 160 MeV protons. It is available at cost for testing counters and for detector development. Over the years several of our groups have taken advantage of this convenient facility.


RUBBIA
STRAUCH
PIPKIN
WILSON
SCHWITTERS
HEPL
HEPL SHOPS–TOTAL USAGE
FROM DEC–1984 TO DEC–1987
MEN (%)
600
400
200
0
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
1985
1986
1987
DATE


HEPL MACHINE SHOP USAGE
FROM DEC−1984 TO DEC−1987
RUBBIA
STRAUCH
PIPKIN
WILSON
SCHWITTERS
HEPL
MEN (%)
0
100
200
300
400
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
1985
1986
1987
DATE


HEPL ELECTRONICS SHOP USAGE
FROM DEC-1984 TO DEC-1987
RUBBIA
STRAUCH
PIPKIN
WILSON
SCHWITTERS
HEPL
MEN (%)
200
150
100
50
0
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
1985
1986
1987
DATE


HEPL DESIGN ENGINEER USAGE
FROM DEC-1984 TO DEC-1987
RUBBIA
STRAUCH
PIPKIN
WILSON
SCHWITTERS
HEPL
MEN (%)
0
20
40
60
80
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
1985
1986
1987
DATE

B. Computer Facility

We feel very strongly that it is essential for our physicists to have access to substantial computing resources at HEPL if they are to play leading roles in exploiting the physics potential of the major detectors they have helped to build. Indeed, for the vitality of high energy physics, it is extremely important that graduate students and post-doctoral researchers be able to participate fully in data analysis while resident at their home universities so that they may exchange ideas with their theoretical colleagues and scientists in other disciplines. This is particularly true at Harvard where our outstanding theory group has a deep interest in connections between experiment and theory.

All HEPL experimental groups are participating in a variety of forefront high energy experiments that will require large data analysis efforts at Harvard. Harvard is one of the few places where data from both the CERN and FNAL proton-antiproton colliders are being analyzed. The Harvard CDF Group led by Professor Schwitters is involved in a major data analysis effort aimed at looking into the completely new mass scale made available by CDF at the Tevatron collider. Likewise the Harvard UA1 Group under Professor Rubbia (and Professor Geer starting in 1989) is carrying out a major analysis effort of data from CERN. These two experiments offer promising opportunities for making truly fundamental discoveries in physics over the next several years.

Professors Pipkin and Wilson are participating in the Fermilab Muon program, a major new fixed target experiment at the Fermilab Tevatron, which began running in 1987. They are also involved in the upgraded CLEO detector at Cornell's electron-positron facility, CESR, which will allow very detailed studies of hadrons composed of bottom-type quarks. Professor Strauch and his group are members of the L3 Collaboration, which is building a very large detector for the LEP colliding beam facility at CERN. LEP is expected to begin physics running in 1989, but much computing is needed before then for detector simulation and program development. There is also a continuing need for computing by theorists and other researchers in the Harvard Physics Department that is currently being served by the HEPL VAX facility.

In 1985 we added a VAX 8600 processor and formed a VAX Cluster with the existing VAX 11/780. Both computers were acquired with funds from the Department of Energy and the Harvard Physics Department. In early 1987 the 11/780 was exhanged with Fermilab for an equivalent MicroVAX II workstation. Last year the 8600 was upgraded to an 8650 CPU with a total of 56 megabytes of memory. The system currently has 3000 Mb of disk storage, two 800/1600 bpi tape drives, four 1600/6250 bpi tape drives, 24 CRT terminals, five modems, and a line printer. A range of peripherals are attached: a CAMAC interface, two laser printer/plotters and an interactive display system. We have recently added two video cassette drives which can hold up to 2.5 gigabytes of data on each cartridge.

Two MicroVAX workstations are transparently connected to the system via ethernet. One MicroVAX is the replacement for the 11/780 and wll be used to offload network functions from the 8600. The second is a color system which is intended for interactive analysis and was purchased for the CDF group using Physics Department funds. (A third MicroVAX is currently is use by the CDF group at Fermilab.)

The VAX system is housed in the HEPL building; in addition to the machine room, several terminal rooms are provided for convenient user access. Our VAX is linked via Fermilab and DECNET to most other U.S. high energy groups and is also connected to LEP3NET and BITNET. A diagram of the current configuration of the VAX system is shown at the end of this section.

The VAX system has performed admirably. Many analysis programs have been written, installed, and used including those for the following experiments: the CCM Muon Spectrometer, CLEO, Mark II, Crystal Ball, the Park City Proton Lifetime Experiment, and CERN UA1. The UA1 group uses the interactive display system (Megatek) to scan the events which are analyzed on their emulator facility. Currently there is extensive DST analysis and Monte Carlo production underway for CDF and CLEO, and software development is proceeding for Tevatron Muon.

In 1985 the UA1 Group acquired an IBM 4361 computer with DOE funds which is also housed at HEPL. The machine serves as the manager of an emulator "farm" (3081E's), and is used for CERN UA1 data analysis. This facility is described in the section 8.

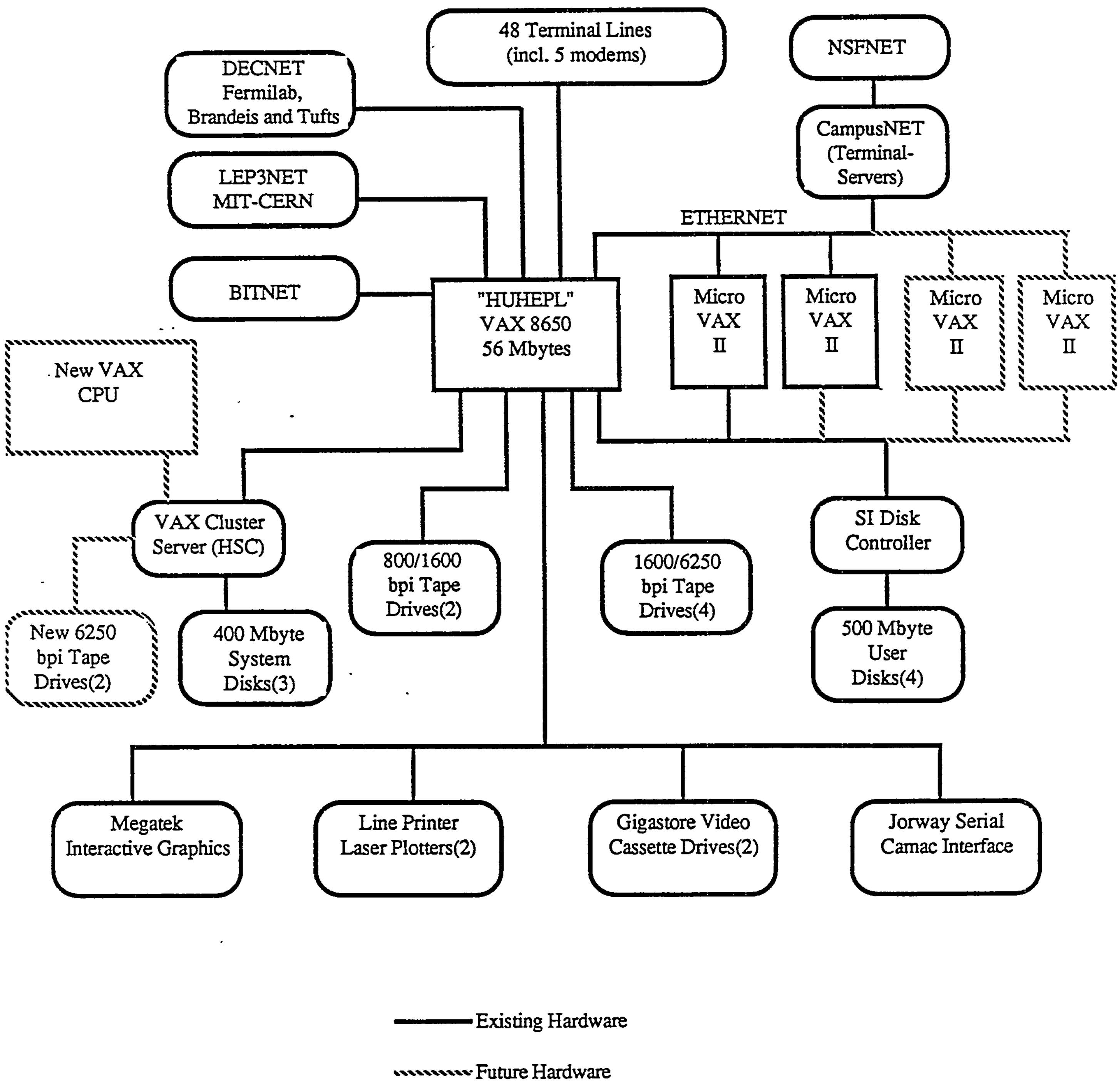
Our goal continues to be the acquisition of a facility with the equivalent computing power of at least ten VAX 780's. With the VAX 8650 we are more than halfway to this goal. The increase in capacity is estimated from UA1 experience and simulations of CDF. These are very complex detectors providing millions of events, each containing as much as 100 kilobytes of information, that must be reconstructed and examined in detail. For example, Fermilab is acquiring new VAX computers along with the Amdahl acquistion that will provide a capacity equivalent to 25 VAX 780's just for CDF data reconstruction. CDF will also make use of the Fermilab ACP system for event reconstruction and DST preparation. Any institution intending to make a significant contribution to CDF data analysis will need ten VAX 780 equivalents for this purpose alone.

For 1989 we are requesting $80K of equipment funds to further upgrade the VAX facility. With this support, we first plan to acquire two new 6250 bpi tape drives which can be attached to the VAX Cluster controller. Of our current six tape drives, two are obsolete 1600 bpi drives, and the remaining four 6250 bpi drives are six years old and overworked. A large fraction of our system manager's time is spent maintaining these drives. Two new drives will alleviate this situation and will provide greatly enhanced performance.

Our second objective is to acquire an additional pair of MicroVAX workstations. These and the two workstations already at HEPL will be coupled with the 8650 to form a "local area cluster". With this configuration we will obtain the intermediate goal of ten VAX 780 equivalents and will also have a very significant interactive analysis capability.

In 1990 we will have five experiments actively taking data. This will necessitate the doubling of our computing power, probably by the addition of several MicroVAX III processors to the existing cluster.

HEPL COMPUTER FACILITY
April 1988



C. Energy Sciences Network (ESNET)

Since the fall of 1986 Dr. Brandenburg has devoted a considerable portion of his time to improvement of computer networking services for the Harvard facility and for high energy physics in general. In 1986 it was decided by DOE management to provide a unified network with high band-width lines to all researchers in the energy sciences (ESNET). Dr. Brandenburg was named along with Dr. Stu Loken of LBL to represent the interests of high energy physics on the ESNET Steering Committee. In subsequent meetings of this committee it was decided that 56 kbaud trunk lines connecting LBL to FNAL to BNL to MIT will be an integral part of phase I of ESNET. These lines are to become the backbone of the High Energy Physics Network (HEPNET) and are coming into operation in early 1988. There will also be a branch trunk line running from FNAL to CERN. Harvard will connect to this network at MIT as soon as it is available and all of our experimental groups will make heavy use of the circuits to FNAL, CERN, and beyond.

Since the spring of 1987 Dr. Brandenburg has also served on the HEPNET Review Committee which was established to review the overall networking needs of the field of high energy physics. This committee is now finalizing its report which will be submitted to DOE.

This work has entailed at least one trip per month; the travel relating to ESNET has been reimbursed by the Scientific Computing Staff at DOE. The remaining costs have been absorbed by the Harvard HEPL budget. This effort will continue through 1988 until phase I of ESNET is successfully implemented.

3. Proton-Antiproton Colliding Beam Program at Fermilab

(Professors Schwitters and Shapiro; Drs. Brandenburg, Baden, Franklin, and Phillips; Mr. Brown, Mr. Carey, Mr. Feldman, Mr. Kearns, Mr. Ng, Mr. St. Denis and Mr. Trischuk)

Since 1980,when Prof. Schwitters accepted a part time appointment at Fermi National Accelerator Laboratory to lead the design and construction of the Collider Detector at Fermilab (CDF), the primary physics activity of the Schwitters group has been focussed on the Tevatron Collider program. Given the special relationship of the Harvard group to CDF, our students and post docs are in a strong position to exploit the physics opportunities provided by Tevatron I. The physics potential of 2 TeV proton-antiproton collisions at Tevatron I is tremendous. We are producing and studying the properties of the weak vector bosons, searching for new kinds of heavy quarks and leptons and making systematic studies to test the theory of strong interactions, QCD. We are in a position to look for entirely new phenomena such as Higgs boson production, supersymmetric particles, Centauro events, and all manner of other exotic possibilities.

The CDF collaboration consists of ten U.S. university groups including Harvard, two national laboratory groups outside of Fermilab, and major support from Japanese and Italian high energy physics groups. The entire enterprise is being managed through the Fermilab CDF department, but all of the collaborating institutions are expected to contribute substantial effort to the construction and running of this apparatus. Equipment funds for this purpose were assigned to Fermilab and divided among the participating institutions according to a formal agreement procedure with Fermilab. The construction phase of CDF was completed in FY87; funding for upgrades and improvements will be managed in a similar manner, but with tighter coupling to the Fermilab Research Division and PAC decision process on a project-by-project basis.

The design philosophy was to build an apparatus capable of detecting the production of quarks and leptons in proton-antiproton collisions provided by the Tevatron. Quarks are manifested as jets of hadrons. Therefore the apparatus must be capable of detecting dense clusters of hadrons, isolated leptons, and missing energy due to neutrinos. It is also highly desirable to measure the energies of all hadrons through calorimetry and momenta of charged particles by magnetic analysis over as much of the solid angle as is feasible. This has become more apparent following the CERN Collider studies of events where there is a large imbalance in transverse momentum. These general considerations set the overall scope of the detector.

The final design for CDF has a central magnetic spectrometer built around a solenoid magnet with charged particle tracking, shower counters, and hadron calorimetry. Since the expected physics of proton-antiproton collisions yields particles at very small angles with respect to the beam line, it is necessary to augment the central detector with forward-backward arms capable of tracking charged particles and measuring hadron energies and electromagnetic energies through calorimetry. Many of the components of this apparatus were built with a high degree of modularity for ease in assembly and to provide the granularity that is desirable for detecting jets of hadrons and leptons. This modularity also allows for construction by several different groups. The Harvard group constructed the electromagnetic shower calorimeter for the small angle regions ($2^\circ - 10^\circ$).

CDF had a short test run in the fall of 1985 and the first engineering run in the spring of 1987. A long physics run is scheduled to start in May 1988. The total integrated luminosity from the engineering run was about 30 nb^{-1}. We hope to gain a factor of 30 in integrated luminostiy during the 1988/89 run.

The commitments of the Harvard group to CDF include: 1) the production, testing, and calibration of the Forward/Backward Electromagnetic Shower Counters, 2) developing software for data reduction of the Forward Shower Counters, and for general purpose use by online and offline analysis programs 3) development and testing of front-end electronics for all the "gas" calorimeter systems of CDF , and of parts for the trigger/timing system and 4) participation in the physics analysis. The Harvard commitments to CDF are described in the following paragraphs.

A. Forward/Backward Electromagnetic Calorimeters

Our group in collaboration with the Brandeis University group designed, constructed, tested, and installed a large electromagnetic shower counter system for use in the small angle region (2° –10°) of the CDF colliding beam detector at Fermilab. The system uses proportional tube calorimetry with lead sheets as the radiator. The proportional tube planes are constructed using a novel technique which combines aluminum tubes and cathode pad readout. The total system (both forward and backward regions) has approximately 3000 independent pad towers which are read out in two depth segmentations.

The forward and backward calorimeters are symmetrical; each is approximately 10 feet square and 2.5 feet deep and has 30 layers of lead and proportional tube planes. The thickness of each layer is 85% of a radiation length. Each proportional tube plane is divided into quadrants, and the pad geometry is radial around the beam.

For rigidity we use extruded aluminum channels to form three walls of the proportional tubes, each of which has a cross section of 7 mm. by 10 mm. A large circuit board forms the fourth wall of all the tubes and has cathode pads etched on its outside surface. The inside surface is silk-screened with a layer of resistive epoxy (30 MΩ/sq.). This epoxy not only bonds the cathode pad board to the aluminum tube walls, but also keeps the surface from charging up and changing the electric field configuration. The cathode pad signals are read out via a ribbon cable harness and are then ganged longitudinally into projective towers. The anode wires are 2 mil gold-plated tungsten, and are read out in groups of 24 for diagnostic purposes.

The proportional tube planes and cathode pads are fabricated as individual sealed chambers for each layer of each quadrant. All 240 required chambers have now been built and tested in a high energy electron beam at Fermilab. The proportional tubes were filled with a 50-50 mixture of Argon and Ethane and were operated at a high voltage of 1900 volts corresponding to a gas gain factor of 5000. The response of the calorimeter as a function of energy was linear up to 200 GeV and the measured energy resolution was approximately 3% at 100 GeV. Depending on whether the beam was incident near a tower boundary or a tower center the measured position resolution varied from 2 mm. to 4 mm.

During the 1987 engineering run, the shower counters performed well. The chambers were a standard part of the CDF readout and were included in the electromagnetic energy and jet triggers. Data from the forward calorimeters is now being used in the measurement of the jet scattering angles and in the analysis multijet events. Electromagnetic clusters in the forward calorimeter are also being used in the study of the Z^0 vector boson.

In the Fall of 1987, a spare quadrant of the Forward calorimeter was placed in a test beam at Fermilab and our group was heavily involved in the commissioning of the test beam data acquisition system. The test beam effort has produced a new (more accurate) set of calibration factors for all of the CDF gas calorimeters. These factors have already been used at Harvard in the analysis of the 1987 collider data and have improved the quality of that data.

B. Software Development

The Harvard CDF group has played a significant role in the management of the enormous body of code used on CDF. The group made significant contributions to the definition of the data structures used for offline analysis. A macro expander used to maintain site dependent code within a single source file was entirely designed and implemented at Harvard. The main analysis driver, used for online calibration and offline reconstruction and physics analysis, was written by a member of our group.

Several members of the Harvard group have been involved in CDF efforts to define the standard CDF reconstruction package. A large portion of the calorimetery reconstruction code has been written by our group. This includes the code to perform offline calibration corrections and to clean-up of the data sample (eg remove noise and remove energy deposits not associate with the $\bar{p}p$ interaction). The jet cluster algorithm currently used by CDF was developed at Harvard. We have been involved in the maintanace of the reconstuction package as a whole and in the development of procedures to validate the quality of the results of this package. Members of our group have also been involved writing and maintaining the code used online to monitor the quality of the data being written to tape.

C. Electronics Development

Our group (with major participation by Craig Blocker, now at Brandeis) developed the "front-end" electronics for all the gas-tube calorimetry in CDF. This consists of 24 preamplifier and charge-sensitive integrator channels, which are multiplexed on a single board. This board, called the CARROT for Charge Amplifier for Rabbit Read-Out and Trigger, is designed to interface with the RABBIT (Redundant Analog Bus-Based Information Transfer) System designed at Fermilab. The Japanese group from Tsukuba had the CARROT cards produced by Japanese industry.

A board has also been designed for electrical checkout of the gas-tube calorimeters. This board is used as a temporary replacement for an anode wire readout board. Instead of reading out anode signals, it induces a variable size voltage step on the anode wires under Rabbit system control. This in turn induces signals on the cathode pads which are readout by the CARROT cards. Any bad connections or dead channels can thus easily be found.

A third electronics project has been an upgrade of the Analog-to-Digital Conversion (ADC) board in the RABBIT system. The present ADC requires 17 microseconds to convert each channel of data, which will introduce significant dead time into the experiment when TeV I is operated at full luminosity. We have designed and prototyped an ADC board that will have the dynamic range and precision required by CDF and will convert in one-fifth the time of the present ADC. We have produced 50 of these ADC boards.

Other projects included the development of a FASTBUS interface for the master clock generator, which provides timing information to the RABBIT system. In order to carry out this project and other future FASTBUS development projects, we developed a minimal FASTBUS system in our electronics shop. We also designed and produced a system for fanning the precision timing signals from the CDF master clock system in the counting room to the front-end electronics in the B0 collision hall.

Fermilab is studying ways to increase substantially the luminosity of the Tevatron Collider. We are investigating the impact of possible machine improvements on CDF electronics that would come from such an upgrade. Because of the basic "sample and hold" nature of CDF front-end electronics, and because of long collection times in some detector components, there are likely to be profound changes in CDF electronics when the major luminosity upgrade takes place. Given our experience with all aspects of CDF electronics, the Harvard group expects to take on major responsibilities in this upgrade.

D. Physics Analysis

At present, the Harvard analysis effort has two main thrusts: the study of QCD (the theory of the strong interactions) via the production of high transverse momentum jets and the study of the weak intermediate vector bosons (the $W^{\pm}$ and Z^o). Our group currently includes seven graduate students, four of whom plan to write PhD theses on the 1987 data sample. Their work includes the following studies:

1. Measurement of cos θ^* distribution in two jet events. The study of the scattering angle of jets with respect to the beamline provides an important test of the standard model. The distribution of this scattering angle can be predicted by QCD and is sensitive to the evolution of the proton structure functions with momentum transfer (Q^2). Deviations from the QCD prediction could be an indication either of unexpected Q^2 dependence of the structure functions or of the presence of a substructure inside the quark. Along with the measurement of cos θ^*, we hope to measure the proton structure function itself (averaged over all parton types) and compare this to QCD predictions.

2. Measurement of the relative production cross sections for two and three jet events. Three jet events are produced in $\bar{p}p$ collisions via the initial or final state emission of gluons. The study of the ratio of the two and three jet cross sections therefore is sensitive to the value the gluon coupling constant. We hope to study of dependence of this ratio on the total energy in the jet system.

3. Study of the angular distribution of jets in multi-jet events. The high center-of-mass energy of the Tevatron and the large solid angle coverage of the CDF detector together make our experiment quite sensitive to multi-jet events. In the current data sample we have approximately 1000 clean events with four or more jets with transverse momenta above 15 GeV/c. The multi-jet sample is important for two reasons. First, it allows us to study QCD in a new and different kinematic range. In particular, the sample should be contain many events with either initial or final state gluon radiation. Second, the sample should allow us to place a limit on (or measure) the cross section for multi-parton interactions within the proton. This measurement will provide information on the joint probability of finding two partons with momentum fractions x_1 and x_2 inside the proton simultaneously.

4. Study of the rate of W and Z production in $\bar{p}p$ collisions. The W,Z production cross section can be predicted by QCD models. A measurement of this rate therefore provides a standard model test.

The majority of the analysis described above is being performed at Harvard using the HEPL VAX system. At present we are using the VAX 8650 both for jet reconstruction and for final physics analysis in both the jet and W,Z channels. We are currently studying ways to improve the quality of calorimeter reconstruction and therefore have re-analyzed a large fraction of the calorimeter data on a timescale of every few weeks. Currently, the complete 1987 calorimeter data sample can be analyzed (producing jet four vectors) in two jobs, each taking about 16 hours of CPU time. We are also starting to do Monte Carlo simulation at Harvard and are investigating the possiblity of producing large quantities of simulation data on our MicroVAX work stations.

Our ability to perform CPU-intensive analysis at our home institution has meant that our graduate students can reside in the Boston area while they are working on their thesis analysis. This fact has allowed us to profitably interact with other members of the Harvard Physics department (both theorists and other experimentalists). We believe that such cross-fertilization has improved the quality of our work.

The 1988/89 run will result in a substantial increase in the amount of data available and will increase our sensitivity to new physics. We intend to extend our analysis effort as this data becomes available. In particular, we expect activity in the following areas:

1. The study of the di-jet invarient mass spectrum. This spectrum could provide evidence for the production of new particles

2. The search for heavy quark production. We intend to be involved in the CDF effort to search for the top quark. This study will need a good knowledge of both lepton and jet reconstruction efficiencies.

3. The high statistics study of multijet events and the measurement of the four and five jet cross sections. The work we are currently doing on multijet physics will be substantially improved by the added statistics of the next run.

4. The high statistics study of W and Z production. Again, the large data sample will provide us with the ability to make more sensitive tests of the standard model.

E. Upgrades of the CDF Detector

We have studied the feasibility of adding a transition detector system in the forward region of CDF to enhance the identification of electrons. A possible system was designed and a set of four prototype drift chambers were constructed. These will eventually be tested in a beam at Fermilab. However, the experience of our engineering run has indicated that extending the muon coverage of the detector is a more pressing issue. Although there is the potential for electron identification at all angles currently, muons can only be identified in the central region, $\theta > 55^\circ$, and in the forward region, $2^\circ < \theta < 10^\circ$.

Therefore we are participating in discussions about designs and timetables for upgrades to the current muon detectors. Our group is particularly interested in designing and building an extension of the central muon system. This would utilize the steel in the yoke and hadron calorimeters to extend the existing coverage from $\theta \approx 55^\circ$ down to within 30° of the beam. This would be accomplished using two concentric rings of drift chambers covering the region $30^\circ < \theta < 55^\circ$. The rings would have "spokes" consisting of individual drift chamber cells approximately five feet long and six inches across. There would be two such rings at both ends of the detector and each ring would contain approximately 1200 drift tubes. We are proposing to build these drift tubes in the HEPL shops with funding provided through the CDF management. We would plan to have the two outer rings ready for the 1989 CDF run and the inner rings for the following run.

F. Timetable

1988

In 1988, the Harvard CDF group will concentrate on the acquisition and analysis of new data. We are currently in the process of re-certifying the forward calorimeter hardware for our long physics run. We do no anticipate any difficulties in meeting the schedule run start-up in May. Members of our group are involved in plans to upgrade the online and offline software to allow reconstruction of all CDF data with rapid turn-around. We expect to maintain a significant post-reconstruction analysis at HEPL. We will be designing drift tubes for the extended central muon system and begin the necessary tooling for their production.

1989

The emphasis will continue to be on CDF data analysis and running. At HEPL we will be consructing and testing drift tubes for the extended central muon system.

4. e^+e^- Colliding Beam Program at CESR

(Professors Pipkin, Wilson and Kinoshita, Drs. Bowcock and Procario, Mr. Wasserman, Mr. Wolinski and Mr. Xiao)

<u>1987</u>

A. Improvement in CESR Storage Ring

The storage ring is now being operated routinely with seven bunches with an integrated luminosity greater than 2 pb^{-1}/day, with several days exceeding 4 pb^{-1}. An instantaneous luminosity of $10^{32}cm^{-2}sec^{-1}$ has been achieved. A new design for the cavity windows has been developed and this has reduced the problem of short lifetime for the windows at higher power levels. It is planned to modify the remaining cavities with the new window arrangement so one can run with two operating cavities in the ring. Steps will then be taken to shorten the bunch length and take further advantage of the microbeta insertion to increase the available luminosity. At the end of 1989, it is anticipated that CESR will run with only one interaction region; this will provide higher luminosity for the CLEO II detector. It is expected that these improvements will increase the luminosity by at least a factor of 7 to nearly $10^{33}cm^{-2}sec^{-1}$.

B. Improvements in the CLEO I Detector

The CLEO collaboration has undertaken several modifications to improve the detector's performance. These changes, affecting the areas of tracking, dE/dx and triggering, will carry over to the CLEO II detector.

The original CLEO drift chamber was replaced in 1986. The new chamber contains 51 layers of sense wires compared to the original 17. In 11 of the layers the wires are oriented at a slight angle to the beam line which, in conjunction with the remaining parallel wires, provides a "stereo" measurement of position z, in the direction parallel to the beam line. Cathode pads on the inner and outer surfaces of the chamber provide additional measurements of z. In comparison, the original chamber contained 8 "stereo" layers. In the layers of wires oriented parallel to the beam axis the pulse heights as well as arrival times of signals are recorded to enable reconstruction of the specific ionization in each drift cell.

Significant improvements have been realized from the new chamber, both in tracking and ionization measurements; the momentum resolution for muon pairs is now measured to be 1.4%, an improvement of approximately a factor of two, and the resolution in dE/dx is 6.4% for Bhabha electrons, compared to the previous 10%. The higher density of sense wire layers in this chamber has increased the geometric acceptance of tracks from 80% to ~90%.

Good resolution in tracking at the innermost parts of the detector is important for isolation of secondary from primary interaction vertices for reduction of background in identification of long-lived particles and for improvement of CLEO's ability to reconstruct B mesons and for the measurement of the lifetimes of the charmed mesons. To this end, a 3-layer "straw" inner vertex chamber constructed from carbon filament drift tubes has been inserted just outside the beam pipe (inside the 10-layer vertex detector, which was installed in 1984 and remains unchanged).

One relatively trivial way to improve position resolution in drift chambers is by replacing the chamber gas by a denser gas, effectively lowering the average electron drift velocity while limiting diffusion. One such "slow" gas which has been used to apply this principle is dimethyl ether (DME), which is substituted for more common gases such as 50% argon-50% ethane. The high chemical reactivity of this gas has thus far presented a practical barrier to its widespread use in drift chambers. In the fall of 1987 the CLEO collaboration conducted a brief test of several weeks, replacing the inner vertex chamber gas (argon-ethane) with DME but otherwise collecting data normally, to evaluate the potential improvement to tracking resolution and to assess its impact on the chamber materials. The preliminary conclusion of that test is that the resolution could be improved from the 90μm obtained currently with the argon-ethane to 37 μm. Extended use of DME in test chambers similar to the CLEO inner vertex chamber has revealed no evidence of long-term damage to chamber materials. Based on the promise shown by the results of this study, data are currently being collected with DME in the inner vertex chamber, and the current run in the $\Upsilon(5S)$ region of ~70 pb^{-1} will serve as a more complete test and a learning ground for future runs.

High triggering efficiencies with tolerable rates are achieved relatively simply in e^+e^- annihilation experiments by requiring evidence for one or more particles scattered (or produced) at wide angles to the beam direction. At CLEO, at least one hit in the time-of-flight counters, in combination with two or more charged tracks in the drift chamber, has been minimally required of all triggers to restrict the trigger rate to tolerable levels, less than a few Hz, with high efficiency, 70% for two-jet events and 90% for B $\bar{B}$ events. Because of such high efficiencies the detailed understanding of the trigger in CLEO has thus far been relatively unimportant. However, with the current emphasis on improvement of efficiencies and increase in data collection at CLEO, the precision of measurements will improve to the point where triggering will need to be further studied and understood. Better understanding of the triggers will also benefit analyses of events with low particle multiplicity for which efficiencies are lower, such as tau pairs and searches for invisible Υ decays. A trigger study initiated by the Harvard group involved collection of data for at least one run with a trigger which was unrestrictive in the evidence it required for tracks in the drift chamber. Trigger efficiencies were evaluated by comparing events found in full analysis which did and did not pass the standard trigger. The major impact of this study was a revision of our efficiency for triggering on tau pairs.

Another way to approach this problem is to install a trigger with greater acceptance and easily understood response. A possibility which has been discussed but never implemented is a trigger on tracks in the inner tracking chambers without further requirements of calorimeter or time-of-flight hits. Such a trigger would raise the efficiency for various types of interesting events which produce low numbers of low momentum tracks which have little or no efficiency for penetrating to the outer detector to trigger it. Until recently the timing configuration at CLEO did not allow sufficient time to enable any track recognition in the primary trigger, which contained only time-of-flight and calorimeter energy requirements. A new configuration has been installed which allows sufficient time for track recognition in the primary trigger and introduces the possibility of triggering on tracks without requiring hits elsewhere. To trigger effectively in this mode it is important to develop an algorithm which has a well-understood response to low-momentum tracks (>100 MeV/c) and good random noise rejection.

The Harvard group has designed a trigger system for the drift chamber using a new algorithm for finding tracks which is more general than that of the conventional memory-based track finder. Track-finding efficiencies are based on transverse momentum rather than on detailed geometry of drift cell configurations. It is also designed to be used at the lowest level, without requiring hits in other parts of the CLEO detector. The hardware was built by the Harvard group and tested in the CLEO system in the fall of 1986. The test revealed a source of noise in the drift chamber data acquisition system which was aggravated by the incremental load from the trigger. The rate from this noise was intolerable with the full trigger system installed, so data runs were taken with only parts of it installed, a possibility designed into the hardware. These tests demonstrated that the trigger itself is workable, and this work will be published. Modifications being made to the drift chamber electronics should reduce this noise. Plans are being made to have both this trigger and another purely tracking trigger available at the beginning of operations in 1989.

C. Work on the CLEO II Detector

i. Hardware

Substantial progress has been made on the CsI shower counters for the CLEO II detector. A prototype for one end cap was constructed and it was installed in the CLEO II detector in fall 1986. This module provided operational experience with the CsI counters. The performance obtained to date is excellent; energy resolution on electrons in Bhabha events is found to be 1.7%, and the resolution on the mass of the π^0 mesons found in the endcap is ~10 MeV. The system was stable to 1% over a five-month period. This degree of stability is adequate for maintenance of resolution, since we expect to calibrate internally every month.

The evaluation of the crystals from the several potential suppliers was completed and the crystals for the final detector were ordered. To date, all of the 7,200 CsI crystals, 32,000 photodiodes and 30,000 preamps ordered for the CsI calorimeter have been delivered. The container for the barrel CsI counters is being assembled at Cornell. The container for the end cap counters is being designed and built at Harvard.

One of the future goals of CLEO II is the insertion of a high resolution vertex chamber with a small inner radius, to enhance our ability to measure secondary vertices. Although the final design of this detector is not yet determined, it is likely to require a beam pipe with inner radius around 2.5 cm. The feasibility of reducing the beam pipe to such small radii in the interaction region is a question not easily answered without direct experimental evidence. Questions such as compatibility with accelerator parameters, susceptibility to synchrotron radiation, heating of local components, vacuum quality and detector noise are important to know before the final insertion of such a device. To answer these, we will insert a small 3-layer prototype chamber with inner radius 2.3 cm inside the current vacuum chamber in the interaction region. The design of this chamber follows many of the probable final design parameters. Insertion will occur after all regular datataking is complete and will be followed by two to four weeks of beam tests in April 1988.

At Harvard, we completed the tests for development of the barrel time-of-flight counters for the CLEO II detector. Data were taken with different configurations of scintillator, light pipes, and phtomultipliers using an IBM-PC interfaced to a CAMAC crate. We were able to obtain a resolution of 110 ps with a counter which is an exact prototype of the counters that will be used in the CLEO II detector. This is as good a performance as has been reported in the literature and is adequate for CLEO II. An article summarizing the counter tests has been published in Nuclear Instruments and Methods. Tests were also made of microchannel plates. They did not have good enough resolution for the CLEO II detector. The light pipes and counters that will be used in CLEO II are being constructed. A new design for the electronics to record the data from the time of flight counters has been developed and is now being tested. The time of flight counters will be finished in the summer of 1988 and installed in the fall of 1988.

ii. Software

The greatly expanded capabilities of the CLEO II detector will be fully exploited by the effective design and management of processing software. A new topic of crucial importance will be the reconstruction of photon and π^0 momenta in the CsI calorimeters. However the reconstruction algorithms and software for the general aquisition and processing of the data are not yet in existence. With the large volume of data we expect to analyse from CLEO II it is vital that this software be reliable, have a low maintenance overhead and be available at the earliest possible date to help uncover problems during the commissioning of CLEO II.

Given the complexity of the detector and the effort required to process large quantities of data, we wish to minimize programming errors which require time consuming reprocessing of the data. It is apparent that the traditional approach of CLEO to software development is inadequate to deal with the task of rewriting the CLEO software for the upgrade. We have decided to use a well tested systematic approach to software development that deals specifically with the problems of writing code within a large collaboration. The technique is called Structured Analysis and Structured Design and is a discipline within Computer Science that is sufficiently developed to support sophisticated software development tools (e.g. Teamwork^{TM}) that act as the environment within which we can develop our software. Harvard has played a leading role in the introduction of these new techniques at Cornell and we are contributing in a major way to their implementation.

As well as code development for the CLEO upgrade Harvard has also been principally responsible for the development and maintenance of the new Monte Carlo software necessary to model the behavior of the new drift chamber (DRII). The VAX 8650 at Harvard has been an invaluable resource for testing of programs and generation of events. The coupling of this to the Cornell computing system via PHYSNET has been especially valuable.

D. Highlights in Physics Results

New and published CLEO results for 1987 are listed below. The results are all from data taken in 1985-6.

(1) Inclusive branching ratio of B to K^+, K^-, K^o, $\bar{K}^o$

(2) Limit on the mass of the tau neutrino

(3) Limit on B^o $\bar{B}^o$ mixing and τ_{B^o}/τ_{B^+}

(4) Search for production of magnetic monopoles

(5) Limit on rare exclusive decays of B meson

(6) Measurement of the inclusive decay channel $B \rightarrow DX$

(7) Measurement of the inclusive decay channel $B \rightarrow D^*X$

(8) Measurement of the ratio of inclusive decay channels $B \rightarrow DX$ and $B \rightarrow D^*X$

(9) Measurement of D^+, D^o and F^+ lifetimes

(10) Measurement of τ lifetime

(11) Study of $\pi^+\pi^-$ transitions from the $\Upsilon(3S)$

(12) Evidence for charmed baryons in B meson decays

(13) Limit on flavor-changing neutral-current decays of the b quark

(14) $\Gamma(b \rightarrow ul\nu)/\Gamma(b \rightarrow cl\nu)$ from the end point of the semileptonic B decay spectrum

(15) New measurements of the B mass by reconstructing $B \rightarrow D\pi$ and $D^*\pi$

(16) Production of η and ω mesons in τ decay and a search for second-class currents

(17) Observation of D^{*+} polarization in semileptonic B meson decay

(18) Measurement of total continuum charm cross section

(19) Measurement of Λ_c production from e^+e^- annihilation

(20) Search for $B \rightarrow \rho^o l \nu$

(21) Search for neutral Higgs in B decay

(22) Measurement of D $\bar{D}$ correlations to infer a lower limit on the total charm cross section

(23) Measurement of D^{**o} production from e^+e^- annihilation

(24) Search for charm-changing neutral currents

(25) Search for $B \rightarrow \pi l \nu$

At Harvard we have made good use of the DECNET link to Cornell and a major part of the data analysis was carried out at Harvard using the VAX 8650. Some of the analyses which have been motivated and carried out by members of the Harvard group are:

(1) Measurement of D $\bar{D}$ correlations to infer a lower limit on the total charm cross section

(2) Search for $B \rightarrow \pi^+ l \nu$

(3) Measurement of total continuum charm cross section

(4) Search for production of magnetic monopoles

(5) Identification of π^o in the CsI endcap

(6) Identification of leptons from B decay

(7) Identification of D^{*o}

<u>1988</u>

A. Program for CLEO II Detector

A major part of CY 1988 will be devoted to the installation of the CLEO II detector. The datataking with CLEO I has ended, and the present detector is being disassembled. The major rebuilding will come with the replacement of the present magnet by a new magnet with a larger superconducting coil. The new solenoid has a diameter such that the time-of-flight counters and the CsI electromagnetic calorimeter are located inside the solenoid. The photon detector will be made of 8000 CsI crystals, each of which is viewed by four photodiodes. The time-of-flight counters will be located immediately outside the drift chamber in front of the shower counter. The central drift chamber will be 95% surrounded by CsI counters and time-of-flight counters. The present schedule calls for the completion of the installation of the new detector before the end of CY 1988.

The construction of all of the new components for CLEO II is underway. The construction of the light pipes, the assembly of the scintillation counters for the barrel time-of-flight system and the design and fabrication of the electronics for the new time-of-flight system will be carried out at Harvard. Each counter will be set up and tested at Harvard.

A study is now being made of the detailed requirements for CLEO II. The time-of-flight counters are critical for the trigger and for the rejection of cosmic ray triggers. The seven-bunch operation has forced us to redesign the electronics so as to minimize the reset and gating requirements. We are also studying techniques for handling multiple hits without a loss in time resolution.

B. Physics Program

During the past year we collected a data sample with an integrated luminosity of 60 pb^{-1} at the $\Upsilon(3S)$, 21pb^{-1} at the $\Upsilon(1S)$ and 230 pb^{-1} at the $\Upsilon(4S)$ resonances, plus 100 pb^{-1} at a continuum energy between the $\Upsilon(3S)$ and $\Upsilon(4S)$ resonances. The current run, just completed in March 1988, is at the $\Upsilon(5S)$ energy, where we expect an integrated luminosity of ~70 pb^{-1}. The CLEO detector during this time included the new central drift chamber, the inner 3-layer straw vertex detector and the crystal endcap calorimeter.

One of our goals in the last phase of the CLEO I experiment is to extract physics results from this rich data sample. The preparation of the calibration software and the development and modification of the tracking programs for the new central tracking system are essentially complete. We are currently processing the $\Upsilon(1S)$ and $\Upsilon(4S)$ data through the detector analysis programs which produce the final data summary tapes for physics analysis. The data at the $\Upsilon(3S)$ was originally run with a preliminary version of the tracking codes and therefore will be reprocessed with the modified programs in the near future. The major aim will be a study of the decay of B mesons.

A topic of fundamental interest is the degree of mixing of the neutral B^o meson: $B^o \leftrightarrow \bar{B}^o$. The surprisingly high level of mixing recently reported by the ARGUS collaboration for B^o's observed in $\Upsilon(4S)$ decays suggests that, with the data now available, it is possible to study this phenomenon in detail. This is important since the presence of mixing introduces the possibility of observable effects due to CP violation.

Another topic brought to the limelight in 1987 is the coupling of the b quark to u. We will continue efforts to search for evidence of $b \rightarrow u$ decays in the inclusive leptonic and exclusive hadronic decays. Examined especially closely will be the mode $B \rightarrow p \bar{p} \pi$ reported earlier this year by ARGUS.

1989

A. Hardware

Projects expected to be completed in 1989 include a new gas microprecision vertex detector, using a smaller diameter beam pipe than before. The design of this detector will be finalized after the completion in April 1988 of a test run using a small beam pipe and a simple prototype chamber. By using the dense gas DME, it is hoped that this detector will achieve a position resolution of 40 μm. We expect to install it in CLEO II by the end of March 1989.

The initial choice of a gas microvertex detector over silicon has been made on several grounds: the gas detector is an extention of existing technology that we know well, and induces less multiple scattering, particularly of low energy particles which are important for identification of B decays. However the Harvard group continues to monitor the progress in development of silicon detectors, since they are ideal for vertex detection in colliding beam experiments, if their thickness is small enough that multiple scattering is unimportant. The rapidly advancing technology may soon enable production of 50-100 μm thick silicon drift detectors with two dimensional readout. Although funding during 1988 does not permit active experimentation, we expect to keep close track of the work being done elsewhere so that during 1989 we may start active development and modification for use in the CLEO II detector.

B. Physics Program

The physics program will start in April 1989. The laboratory plan is to start with a run of 300 pb^{-1} on the $\Upsilon(3S)$, followed by the removal of the North Area experiment and lattice modification, then a run on $\Upsilon(4S)$. The run on the $\Upsilon(3S)$ will be useful primarily to the North Area detector. However, by using the tracking trigger, we expect to be sensitive to the decay $\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(1S) \rightarrow \pi^+\pi^-\nu\,\bar{\nu}$. By comparison with the analogous reactions where $\Upsilon(1S) \rightarrow e^+e^-$, $\mu^+\mu^-$ we should have a reliable count of the number of neutrinos with mass below 5 GeV.

The CLEO II detector will enable us to explore many phenomena that can only be touched upon with the present detector. The location of the time-of-flight counters inside the coil, together with the dE/dx in the drift chamber, will provide particle identification over almost all the solid angle. The excellent γ-ray resolution from the CsI counters will enable us to identify π°'s and thus to reconstruct events with neutral particles. This will significantly increase the efficiency with which we can reconstruct B's.

For example, the first year of running on the $\Upsilon(4S)$ allowed us to fully reconstruct 12 B decays. With the measurement of π^0 mesons, and the improved solid angle and efficiency for particle identification, we expect to increase the reconstruction efficiency by a factor of at least 10. With the expected increase in luminosity we anticipate 3000 reconstructed B's for the 1000 pb^{-1} luminosity that can be obtained in one year. Efficiencies for reconstruction of B meson decays to charm may be further increased by identification of secondary vertices; the majority of B's are known to decay to charm, and the charmed daughter travels from the primary event vertex an average of 100 μm before decaying. The installation in CLEO II of a vertex detector with the ability to distinguish the charm vertex from the event vertex can improve the efficiency of B reconstruction and of background rejection, most notably for decays with high track multiplicity.

The increased rate for B^o, $\bar{B}^o$, B^+ and B^- detection will make possible precise measurements of rare B decay channels, study of B $\bar{B}$ mixing, search for B_sB_s and studies of other interesting phenomena. One will be able to measure the ratio of $(b \to u)/(b \to c)$ by observation of charmless decays of B mesons in addition to the present method, which uses leptonic decays. In the ~1500 events containing a reconstructed B^o we expect to observe ≈300 leptons from semileptonic B^o decay, of which ≈30 will be of the same sign as would be produced by the reconstructed decay, due to mixing of $B^o \leftrightarrow \bar{B}^o$. Although this method is statistically somewhat weaker for measuring mixing than the dilepton method, it requires no assumption about the relative production of charged and neutral B mesons in $\Upsilon(4S)$ decay.

In addition to vastly improved capabilities for full reconstruction of B mesons, we will have improved efficiencies for the identification of leptons from semileptonic decays. Here the largest gain is from improving the discrimination between electrons and pions. We will benefit from the drift chamber installed in 1986, which provides 41 measurements of dE/dx for each track, but the major gain will be from the CsI shower detector to be installed in CLEO II. With an integrated luminosity of 10^3 pb^{-1} we can measure mixing at a level ≈5% in CLEO II.

It is urgent to increase the funding for this project to allow another research associate to be appointed in 1989 to take full advantage of the exciting opportunities presented by the CLEO II detector

5. Muon Scattering at FNAL

(Professors Pipkin, Wilson and Nickerson, Ms. Conrad, Mr Michael and Mr Schmitt)

The Harvard group has constructed, in collaboration with a group from the University of Maryland, an electromagnetic calorimeter for use in the forward spectrometer of the Tevatron muon experiment. The calorimeter is constructed using twenty planes of proportional tubes of the design first developed by Iarocci at Frascati for use in the Mont Blanc proton decay experiment. The Harvard group also refurbished the frames for the E98 spark chambers for use as drift chambers. We are now, in conjunction with UCSD, responsible for planning and design of the triggger electronics and construction of the second level trigger electronics.

<u>1986</u>

In the summer of CY 1983 the Maryland group supervised at Frascati and CERN the construction and stringing of the 400 modules required to construct the electromagnetic calorimeter. The modules were shipped to Harvard in September 1983. The mechanical design of the calorimeter was completed in early CY 1984 and the construction of the aluminum boxes required to house the chambers was started. At Harvard half of the chambers were modified so that they could be operated vertically. All the chambers were sealed to eliminate residual leaks due to compromises in the design. Each chamber was then tested at six positions with a source and the calibration data recorded. A specially constructed test set up was used to measure the resistance of the graphite coating in the profiles so that the individual modeules could be located advantageously in the detector.

The cathode pads for the readout were manufactured by a firm near Boston and shipped to Maryland for attachment of the cable harnesses. They were then shipped back to Harvard where the pads were fastened to the chambers. The electronic amplifiers attached to the chambers were designed and constructed at Harvard.

In January 1985 the aluminum boxes for containment of the chambers and the support structure were completed. The aluminum boxes and the chambers were shipped to FNAL at the end of January. The edge connectors for the chambers were shipped to FNAL in February. The installation of the iron absorber at FNAL was completed in April and shortly thereafter, the structure for the support of the calorimeter modules was erected. The Harvard group then started the insertion of the Iarocci tubes and the electronics in the aluminum boxes. Each of the planes was carefully tested prior to hanging.

In March of CY 1985 the construction of the lead radiator modules was started at Harvard. Each module consists of a sheet of aluminum to which is bonded a lead sheet. The modules were completed in June 85 and shipped to FNAL in July 85.

The assembly of the 16 planes with summed anode readout was completed in July 85 and some test data were obtained when the muon beam was completed and operated in a test mode. The tests were terminated at the end of August when one of the magnets in the accelerator failed and the running period for fixed target experiments was prematurely terminated.

Near the end of the run an attempt was made to hang the lead modules. While the third module was being hung the hanger for the module twisted unexpectedly and collapsed. This brought to our attention a serious deficiency in the design. The hangers were shipped back to Harvard and rebuilt with a new design so as to eliminate the transverse instability.

The rebuilt hangers for the lead modules were shipped to FNAL in April 1986 and the lead is now properly hung. The assembly of the four planes of individually read-out anode wires was completed and the chambers were hung in the summer of 1986. During the latter part of 1986, the electronics were completed, the installation of the cabling was started, and work began on the software to readout the FASTBUS data acquisition system. A system was set up to supply gas to the chamber, and to monitor the gain for the gas mixture.

Also during 1986 code for the Monte Carlo simulation of showers was written and installed in the E665 offline environment. An event display for viewing individual events in the calorimeter was written, and work on pattern recognition software was begun. In addition extensive hardware and software development for the calorimeter FASTBUS system was performed by the Harvard group.

1987

The first quarter of 1987 was devoted to bringing the calorimeter into operation. The cabling was completed and all wires, pads and associated electronics were tested.

As a result of unanticipated delays, the Harvard group agreed to help the group from UCSD in an attempt to finish the Level-II trigger processor in time for the run. Despite this effort the intended trigger processor was not ready and data taking during the 1987 run was triggered on a beam-veto based system. Harvard played a major role in bringing this system into operation.

The beam was commissioned by early July and proved to have properties closely matching those predicted by monte-carlo calculations. During beam tuning and up until mid-August the apparatus was brought into operation and the trigger improved. Data taking then commenced and continued until mid-January 1988.

Three different targets and two beam energies were used. Alignment, empty target and various test data were also recorded. The number of muons and the luminosity in the different runs were as follows:

Target	Energy (GeV)	Muons ($\times 10^{11}$)	Luminosity (pb^{-1})
D_2	500	2.5	2.4
H_2	500	1.5	0.6
Xe	500	1.5	1.1
D_2	100	0.26	0.25
Xe	100	0.35	0.47

For about half the data, the large RICH counter for forward hadron identification was not operational; all the other detector systems performed reasonably well.

In addition to the muon data taking there was a short (1 week) period in January when the beam was converted to an electron test beam. This enabled us to collect calibration data for the calorimeter, for the wide-angle Cherenkov counters, and for the time of flight counters.

A total of 600K streamer chamber pictures were taken of which approximately 170K have good deep inelastic scattering (DIS) events. 3400 tapes of electronic data were recorded; a total of 2 x 10^7 triggers of which 1.4 x 10^6 are DIS events.

1988

The first part of 1988 will be devoted to careful analysis of both the muon and calibration data recorded during the 1987 run. The electromagnetic calorimeter performed well qualitatively and detailed analysis is underway to understand its quantitative performance.

With the data in hand we expect to find many events with a radiated gluon jet in the final state; a substantial fraction of those identified should have W^2 comparable to PETRA energies. These, and all other final state studies will be particularly interesting for the data with the RICH counter operational since it provides much better particle identification than has been available in previous experiments.

The steamer chamber pictures will allow a detailed study of diquark fragmemtation and facilitate study of the forward-backward $<p_t^2>$ asymmetry (seagull plots). Information on diquark fragmentation in particular will be valuable as it is currently quite sparse.

In view of the recently reported discrepancy between BCDMS and EMC structure function data (especially at low x) an attempt will be made to extract structure functions from the E665 data taken in 1987. However this was not a primary goal of this first data taking period and it is not clear if this will be sufficiently precise to resolve the discrepancy.

During the spring of 1988 we expect to work extensively on analysis. Preparations for hardware modifications and repairs to the calorimeter will proceed in parallel at Harvard using both mechanical and electronic shop facilities. In addition we will design and manufacture the last parts of the second level trigger electronics.

In the summer and fall we will continue our analysis effort, but the emphasis will shift to making the planned changes and repairs to the calorimeter. We will complete, commission and test the level-II trigger system during this period.

During 1988 we also propose to design and construct the first module of the STAC target, which is described in the final section "Future plans", and we may build a new veto counter system to replace the existing one which has severe limitations at low scattering angles.

1989

The second data taking run for E665 will be in mid1989. During this run there will be a strong emphasis on A dependence studies. A series of interchangeable nuclear targets plus D_2 will alternately be put into the beam.

Measurements by the EMC group at CERN showed that the structure functions for nucleons in heavy nuclei such as iron were not the same as those of free nucleons (D_2). This effect was later confirmed by SLAC measurements and by neutrino data. We plan to use the higher beam energy available at FNAL to make more definitive measurements at low x where our higher Q^2 will reduce the confusion with shadowing. We will also be able to study the low to high Q^2 transition; it is still not clear what combination of x and Q^2 is relevant to shadowing phenomena.

During 1989 we will also continue our effort on the STAC target development and construction. In addition we plan to start work on the central e-m detector described in future plans below.

The Harvard contribution to the E665 collaboration is limited by the available manpower; this makes it difficult to simultaneously analyze the present data and to prepare for the new runs. Funds for another research associate are urgently needed.

Future Plans

At an internal group meeting held in February 1988 it became clear that in addition to the 1989 A dependence studies, there is well defined physics for at least three more data taking runs. The order of these runs was not specified and they require PAC approval. The three areas for future runs are as follows:

(a) Structure Function Measurements

Structure functions are important both for what we learn about the nucleon and as ingredients for a detailed understanding of some of the data from other kinds of experiments, such as $\bar{p}p$ colliders. Recently a large discrepancy between the EMC and BCDMS F_2

measurements has come to light. At low x this is as large as 12%. The scaling violations are also quite different; the quoted value of the scaling parameter, Λ, is ~60-90 MeV for EMC and ~220 for BCDMS, a 2-3 σ difference. The gluon distributions extracted from the EMC data are strongly correlated with the value of Λ and are extensively quoted in the literature. The final D_2 data from EMC is now published and suffers from quite large systematic errors. It was not possible to take advantage of the pure non-singlet distribution $F^p{}_2 - F^n{}_2$ in extracting Λ.

As a group we concluded that there was a clear need to remeasure the proton and neutron structure functions. We can double the Q^2 range of existing data and cover the entire Q^2, x range of all previous experiments, including those at SLAC, in a single experiment. We should be able to obtain D_2 data with the same quality as the H_2 data. With a long liquid target run we expect a large number of exclusive ρ° and ϕ, especially with our very low Q^2 trigger (<0.5 GeV^2). This would allow careful study of the transition between vector dominance and parton scattering. ψ/J production would be copious enough to allow photon gluon fusion studies, and some fraction of the target could be used for a continued study of final state hadrons. We anticipate that after the 1989 run we will understand the apparatus well enough to be able to control systemataic effects to the requisite 1% level.

(b) High Statistics Final State Hadron Measurements

During the 1987 data taking run 170K pictures with DIS events in them were taken. In principle this saturates our picture measuring capability for >5 years. Selective measurement will be employed but the implied limitation on the statistical power of any one data set is clear. The group proposes to replace the streamer chamber with a time projection chamber (TPC). A TPC would have a factor of ~10^4 improvement in dead time over the streamer chamber and would obviate the need for film.

Because dE/dx particle identification would be possible and high statistics could be collected and analyzed, a data run with a TPC would provide a unique data set; no previous experiments would be directly comparable. The potential for studying diquark fragmentation and for complete reconstruction of large numbers of final states makes the group enthusiastic about a TPC data run.

Havard does not currently envisage being involved in the construction of the TPC chamber; however to complement the large improvement in the vertex spectrometer we would propose replacing the central region of the current photon detector with a higher-rate, better resolution device. Among other things, this could allow us to measure Primakoff π^0 production.

The current electromagnetic calorimeter is gas-lead sampling. Because the beam passes through the detector the central region suffers severe gain non-uniformity. The replacement device would be of one of several new technologies now being tested and we would regard it as an SSC prototype. It would need to function in a high rate environment with energy and spacial resolution better than calorimeters currently typical in large-scale systems. A major part of this project would be the development of hybrid or semi-custom semiconductor chips to perform rapid analogue data manipulation for trigger purposes and fast data sparcification for read out. We believe Harvard is well equipped to undertake such a project and that a 10^7 s^{-1} muon beam is a good proving ground for the technology.

(c) STAC Target

In late CY 1984 a review of the muon experiment was carried out by a group at FNAL under J. Bjorken. One of the suggestions that came out of this meeting was that the muon apparatus should also be used to study multimuon processes. Since the withdrawal of E640 there is no planned experiment at FNAL to study multimuon production by muons.

To fill this vacuum, the Harvard group has proposed the construction of a long uranium target such that the total hadron energy and the direction of the energy flow can be measured with precision. The calorimeter would be a uranium/scintillator sandwich following a design that Harvard and ORNL have been studying. The target would be 4m long (2m of uranium sheets lcm thick) and 30cm square. A preliminary design and cost estimate has been completed and a "letter of intent" was submitted to FNAL in 1987.

In order to be cost effective the calorimeter will measure the direction of energy flow by comparing the light output from the two sides of a scintillator. The choice of scintillator as the detector rather than a liquid ionization detector is based upon the need for speed of response; a scintillator/uranium calorimeter has been extensively tested both by Monte Carlo calculations and by experiment. At Harvard we are presently engaged in testing scintillators and believe that we can get enough light to provide adequate spatial resolution. A similar calorimeter has been built by an ORNL/BNL group for a heavy ion experiment at CERN. Preliminary tests with a 61 GeV proton beam look good.

At the time the new instrumented target is ready, it is anticipated that there will be a 900 to 1000 GeV proton beam, with a muon beam of 700 GeV. It will also be possible to have a polarized beam, with mainly lefthanded muons, of lower energy. The effective luminosity of the beam and target will be about 10^{34} cm^{-2} sec^{-1}. This will, for some purposes, make it competitive with HERA. Among the experiments that it is proposed to do with this instrumented target are the following.

(1) A study of the weak charged current interaction, $\mu p \rightarrow \nu N$, which we will make by measuring the energy and direction of the recoiling hadron jet. The ratio of the charged current exchange to neutral current (photon or Z^o) exchange, will vary from 10^6 to 10^{10} depending upon the square of the four momentum transfer Q^2. These measurements will be carried out with both the normal, lefthanded, spin state of the muon, and with the abnormal right handed state. This will enable us to measure, or provide an upper limit for, the right handed weak currents, independent of the mass of the neutrino. We anticipate in an ordinary length run being able to set a limit to the Z' mass of 500 GeV. We will be able to measure the ratio of the charged current to the neutral current in a way which has a completely different set of systematic errors from the neutrino experiments.

(2) We will look for multiple muons, and hence be sensitive to the decays of charmed mesons. In particular we expect that $\bar{c}c$ pairs will be present in 2% of all inelastic muon scattering events, and a month run will give 10,000 charmed mesons decaying into muons.

(3) We will observe the decays of D^o and $\bar{D}^o$ mesons and search for D^o $\bar{D}^o$ mixing.

(4) We will observe muons from B decay, and separate them from muons from D decay by the p_t. For example, we will have several hundred events from B^o $\bar{B}^o$ decay, of which a hundred will be mixed (like sign pairs) if the results from Argus are correct.

(5) We will search for τ production.

(6) We will search for various exotic particles such as smuons.

The plan is to finalize the design and start construction in CY 1988. The run period will depend upon the FNAL schedule.

6. The L3 Experiment

(Professor Strauch, Drs. McBride and Schmitt, Ms. Wang)

The annihilation of high energy electrons and positrons has proven to be one of the most powerful probes into the nature of the fundamental properties of matter. The first observations of large hadron production at high energies were made at the Cambridge Electron Accelerator; the subsequent discovery of the ψ/J at BNL and SLAC opened a whole new field of investigation. Our group was part of the original CEA team. From 1976 to 1987 we were members of the Crystal Ball collaboration using SPEAR at SLAC and then DORIS at DESY to investigate a wide variety of phenomena involving the properties and decays of charmonium ($\bar{c}c$) and bottomium ($\bar{b}b$) states including the identification of two new particles $\theta(1640)$ and $\iota(1440)$. In the more recent studies at DESY, our group was particularly active in the analysis of the inclusive reaction $\Upsilon(2S) \rightarrow \gamma X$ and two photon reactions $e^+e^- \rightarrow e^+e^- X$ where $X= \pi^0, \eta, \eta'$. Two photon production of π^0 and η were studied for the first time.

When CERN decided to build LEP, our group joined in 1980 in the planning of a LEP experiment with MIT colleagues (Professor Ting's group) with whom we had previously collaborated in the ISR experiment I-209. Out of these discussions evolved the "Magnetic Hall" concept of the L3 experiment which was formally approved as one of four LEP experiments in September 1982. The L3 experiment is a collaboration of groups from Sweden, Fed. Republic of Germany, German Democratic Republic, Hungary, the Netherlands, USSR, Switzerland, France, Italy, Spain, India, China and the U.S. The U.S. participants come from CIT, Michigan, Carnegie-Mellon, Johns Hopkins, Rutgers, Princeton, Northeastern, MIT and Harvard. The L3 detector is a general purpose detector with emphasis on accurate identification and energy measurement of photons, electrons and muons. LEP will produce many Z^0: at $L = 10^{31} cm^{-2} sec^{-1}$ one Z^0 is produced every 3 seconds! We will measure its width, R_{peak}, its decays. We will look for new particles (Higgs?), old and new flavors (top?), study jets, measure lifetimes, measure R, study QED-weak interference, and of course look for the unexpected.

During previous collaboration with the MIT group, we jointly developed a new type of drift chamber to measure the momentum of high energy muons. For reasons of effectiveness and efficiency, we are again working with our local colleagues (and others) on the building and testing of the precision muon detection system of L3 .

After the completion of the first octant of muon chambers and its successful test at the Harvard High Energy Physics Lab in September of 1985, the focus of activities of the muon group shifted to CERN. Professor Antreasyan moved to CERN in April of 1986. Dr. McBride moved there in September of 1986. Their first responsibility has been to set up a testing program for the chambers after they are produced and before they are installed into the octants. Close coordination with the chamber builders has led to an increasingly successful construction and testing schedule and to the production of satisfactory chambers.

At CERN our group is now very much involved in

(1) Instrumentation of the chambers after they are placed into an octant.

(2) Testing of the full octants after they are instrumented.

The HEPL Machine Shop has been and is producing a variety of chamber and octant parts such as cable trays, piping for chamber gas, mountings for printed circuits, stands etc. The HEPL Electronics Shop has completed 16 VME based ADC modules (972 channels in total) which are being used in the CERN chamber tests and will be incorporated into the muon chamber monitoring system for the L3 experiment. In addition, they built DAC boards for the high voltage control system used for chamber testing.

In 1986, the HEPL VAX 8600 was linked to MIT as part of the LEP3NET network, which has been a great aid in communication between HEPL and CERN.

<u>1987</u>

Since the start of this year, the L3 program is our only activity besides completion of papers for the Crystal Ball program. Dr. Peter Schmitt joined the group at the beginning of the year replacing Dr. Irion who had left in June 1986. Professor Antreasyan resigned from Harvard in February, but continues working on L3 as a member of one of the Italian collaborating groups.

About 30 inner and outer chambers have been tested and, when necessary, have been repaired. 3 octant instrumentation stands have been built to equip 3 octants simultaneously with cables and alignment systems. By the end of the year, 5 octants had been fully assembled and instrumented; one octant was partially instrumented. Octant tests had been completed for 3 octants. These accomplishments are the result of much effort in designing and developing the installation of instruments and chambers in the octants.

Ms. Wang has been testing the precision chamber bridges built at MIT in Cambridge. This task was completed at the end of 1987 and Ms. Wang joined Drs. McBride and Schmitt at CERN in January 1988.

Because of the amount of FY87 funding, the devaluation of the dollar and the resulting increase in cost of working in Switzerland, we were not able to replace Professor Anteasyan at this time. This has brought our preparation for analysis of the future data to a near standstill since clearly the first priority must be the construction of the detector and we cannot reduce our responsibilities in this area.

<u>1988</u>

We and our colleagues are more than busy instrumenting muon octants and testing them. The installation of the octants and instrumentation in the pit will be the major focus of the last few months of 1988 and the first few months of 1989. Since completion of the octants in time is the first priority, we are supporting one technician at CERN on a temporary basis.

<u>1989</u>

This promises to be an exciting year. Installation of the L3 detector (first phase) should be completed. LEP is scheduled to start colliding beams on July 14, 1989. Bringing the detector into operation will occupy much of the year. At this time it is clearly impossible to predict how much data will be taken. We must prepare for the analysis of data; for this reason we add one Research Associate to our budget request for CY1989.

1990

This is scheduled to be the first full year of operation of LEP and L3. We will continue to help fine-tune the detector; our main activity will be analysis of data at CERN and at Harvard. We request $80K in this year for purchase of an Apollo workstation and related equipment as the Harvard component of the Cambridge L3 analysis effort. This should be an exciting year!

7. International Union of Pure and Applied Physics Activities

(Professor Strauch and Ms. Rykles)

Members of the Harvard High Energy Physics group have in the past participated and continue to participate in the activities of various DOE and NSF committees concerned with High Energy Physics. Prof. Strauch's activities as U.S. delegate on the IUPAP C11 Commission on Particles and Fields are specifically mentioned here because they involve considerable effort and substantial administrative assistance by Ms. Rykles, assistance which is supported by this contract, and because of the significant extra cost of the required travel.

During FY82-87 these activities involved primarily: 1) The organization of the U.S. Delegations to various IUPAP-sponsored conferences: 1982 HEP Paris conference; 1983 Photon-Lepton Symposium at Cornell; 1983 Accelerator Physics conference at FNAL; 1984 HEP conference at Leipzig; 1985 Photon-Lepton Symposium at Kyoto; 1986 HEP conference at Berkeley; 1986 Accelerator Conference at Novosibirsk; 1987 Photon-Lepton Symposium at Hamburg. 2) Preparation for future conferences: 1989 Lepton-Photon Symposium at SLAC; 1990 HEP Conference in Singapore; 1991 Lepton-Photon Symposium at CERN. 3) Coordination of IUPAP activities with HEPAP and DPF-APS.

During 85-87 Prof. Strauch served as Secretary of the Commission and during 1987-90 he is Chairman of the Commission. This has added the following tasks to the previously listed responsibilities: 1) Preparation of C11 meetings and minutes. 2) Coordination with the parent IUPAP organization. 3) Coordination with ICFA which was founded and is sponsored by the C11 Commission. This amounts to a surprisingly large amount of work and substantial travel to all C11 and ICFA meetings.. To carry out these duties the special administrative support must be continued, and substantial travel funds are essential.

8. The UA1 Experimental Program

(Professors Rubbia, Rohlf and Geer*, Drs. Bauer, Pancheri, and Sumorok, Mr. Jessop*, Mr. Kroll, and Mr. Schwartz) (*remaining in 1989)

A. Introduction

The UA1 experiment was proposed in 1978, and took its first data at the CERN proton-antiproton collider in the fall of 1981. The first physics publication appeared in Physics Letters in December 1981, based on an integrated luminosity of 20 μb^{-1}. Since then UA1 has accumulated a total integrated luminosity of 700 nb^{-1}, and produced 43 journal publications addressing some of the most important physics questions in particle physics today.

Harvard officially became an institution in the UA1 experiment in 1984 under the leadership of Prof. Carlo Rubbia. Prof. Rubbia is leaving Harvard to become Director General of CERN, necessitating a re-organization of the UA1 activity at Harvard in 1989.

Assistant Prof. Geer joined the UA1 experiment in 1979, was involved in its construction, and the subsequent mainstream analysis of the data, playing a co-ordinating role in the analysis of W and Z^0 physics in UA1, the dominant role in writing 6 UA1 papers, and making major contributions to a further 5 UA1 papers. He joined Harvard in 1983, participated in the proposal, installation, and use of the UA1 emulator farm at HEPL, and is now involved in the design, construction, and testing of the position detector for the upgraded UA1 calorimeter at the new CERN ACOL facility.

The calorimetry used in the UA1 detector was unprecedented at the time of its conception. This detector has been the first device in which a 4π calorimeter geometry has been used to identify neutrino emission, crucial for the discovery of the W particles. However, the device has two fundamental limitations : (a) a response difference for electromagnetic and hadronic showers of about 40 percent, which represents the main uncertainty in jet - and missing-energy measurements, and (b) large systematic errors in the energy determination introduced by the scintillation technique of ionization measurement. The upgraded UA1 calorimeter is designed to overcome these limitations by using uranium for the interaction medium and sampling the ionization directly with a pure room temperature liquid. The upgraded calorimeter is built of uranium plates sandwiched between boxes containing 2,2,4,4 tetra methyl pentane (TMP). The amount of uranium required for the UA1 calorimeter is 300 tons in the form of 10,000 plates of 2mm and 5mm uniform thicknesses. The fabrication of these plates to proper specification requires special skills not readily found. Harvard has been responsible for the procurement of the uranium for the UA1 experiment. A large effort has been made to find a cost-effective means for producing these plates in private industry.

The choice of a room temperature liquid for the active medium of the calorimeter has posed new technical challenges. The purity of the liquid against certain contaminants such as chlorine must be kept to several parts per billion in order to be able to drift electrons for times of several micro-seconds. Methods have been developed by the UA1 group in collaboration with private industry (J. Wiley Organics, Columbus, Ohio) to produce large quantities of pure liquid. A technique has been developed by the UA1 group to contain the liquid in ultra-clean stainless steel boxes which have been sealed by high technology laser welding. The position detector boxes for the UA1 calorimeter, which are the responsibility of the Harvard, MIT, and UCLA groups in UA1, are being made by Hutchinson Technology, Minnesota.

Finally, our detector development will almost certainly have an important impact on the design of detectors for future colliders.

B. Physics from the Old UA1 Detector

In the last few years the UA1 experiment has studied proton-antiproton collisions at a center-of-mass energy $\sqrt{s} = 0.63$ TeV, tested many of the central features of the Standard Model, and placed new limits on the existence of additional fundamental particles.

In the electroweak sector of the Standard Model UA1 has (i) verified the existence of the Intermediate Vector Bosons which mediate the weak interaction, (ii) verified that the production rates of the $W^{\pm}$ and Z^0 at the collider are in agreement with expectations, and therefore that the W coupling to $\bar{d}u$ and $\bar{u}d$, and the Z^0 coupling to $\bar{u}u$ and $\bar{d}d$ are as expected, (iii) verified lepton universality to $\pm$ 10 % [the W decays with equal probability to $(e\nu)$, $(\mu\nu)$, and $(\tau\nu)$, and the Z^0 decays with equal probability to (e^+e^-) and $(\mu^+\mu^-)$], (iv) verified that the $W^{\pm}$ and Z^0 have the expected angular distributions, that they are spin-1, and that parity is violated in W production and decay, and (v) measured the $W^{\pm}$ and Z^0 masses with a precision of ±3% and verified that they are in agreement with theoretical expectations based on low energy phenomenology. At Harvard Prof. Geer and Prof. Rohlf have between them made major contributions to all of these important results.

In the QCD sector of the Standard Model UA1 has (i) verified that the differential jet cross-section, measured as a function of the jet transverse-momentum, agrees with QCD expectations over a region in which the cross-section falls by ten orders of magnitude (this provides strong confirmation that partons exist in the proton with the properties and interactions specified by the theory), (ii) verified that the two-jet angular distribution is similar to the distribution expected for Rutherford scattering, from which we can deduce that the proton contains partons void of detectable structure down to distances ~ 5×10^{-17} cm (the detailed shape of the distribution shows that the two-jet rate, monitoring the strength of the strong interaction, decreases with increasing Q^2, and therefore with decreasing separation between the partons), (iii) verified that events containing three-jets exist with a rate and kinematic properties in agreement with QCD expectations, demonstrating the existence of initial state gluon bremsstrahlung off the incoming partons, and final state bremsstrahlung off the outgoing partons, and hence testing the theory to third order in the strong interaction coupling constant α_s, (iv) verified that four-jet events exist (currently being analysed), and (v) verified that production rates of c- and b-quarks are in agreement with QCD expectations.

In the search for new fundamental particles UA1 has (i) excluded the existence of a new charged lepton with mass ≤ 41 GeV/c^2 (90% CL), (ii) determined that the number of light neutrino species in the universe is ≤ 8 (combining with UA2 data we obtain ≤ 5 neutrino species), (iii) excluded the existence of further, more massive, W- and Z-like bosons having standard couplings to the fermions, with masses less than 220 GeV/c^2 and 166 GeV/c^2 respectively, (iv) excluded the existence of the supersymmetric decay $W \rightarrow e_S \nu_S$, where the supersymmetric leptons both have masses less than 26 GeV/c^2, and the supersymmetric photon (photino) is assumed to be light, and (v) excluded the existence of supersymmetric quarks and gluons with masses less than about 70 GeV/c^2. At Harvard Profs. Geer and Rohlf have between them made major contributions to all of these limits.

Finally, the UA1 collaboration has observed two events in which an exceptionally high transverse momentum lepton-neutrino pair has been produced in association with two jets, and two further events in which a large missing transverse energy has been produced in association with two jets. These events are the four events in the UA1 data samples with the largest validated missing transverse energy. We do not currently understand the origin of these events.

C. Physics with the New UA1 Detector

The next phase in the operation of the CERN SPS Collider with the new Antiproton Collector Ring (ACOL) will produce more than a factor of 30 increase over the present integrated luminosity, and open a new era in the study of Intermediate Vector Bosons and other physics uniquely accessible at hadron colliders. Possible new generations of heavy leptons and quarks, the number of neutrino families, the top-quark mass, B-meson mixing and the search for the Higgs Boson still remain to be thoroughly explored in the mass range of existing accelerators. By 1990 we expect more than 10,000 $W \rightarrow e\nu$ events in the UA1 detector. Furthermore, in view of the success of the development work of the Uranium-TMP project at CERN and of the prospects for new physics in the upgraded UA1 detector, the CERN management has decided to continue the proton-antiproton collider program beyond the beginning of LEP. We believe that the future physics program with the UA1 detector at the CERN Collider will provide valuable information on many fundamental questions which are presently unanswered.

We have reached the point where our measurements are limited by systematics, as well as by statistics. To test the theory in more detail we need a second generation detector in addition to an increase in statistics. In the coming 2 - 3 years, with the expected improvement in both the luminosity of the collider due to ACOL, and in the UA1 detector, we expect :

a) An increase in the statistics of the UA1 data samples by a factor of 30.

b) An improvement by factor of 10 in the precision of the absolute energy scale of the calorimeter energy measurement.

c) An improvement by a factor of 50 in the spatial granularity of the central UA1 calorimeter (improving the measurement of lepton isolation and measurement of complicated jet topologies).

With these improvements we anticipate having a rich physics program with UA1. In the electroweak sector of the Standard Model we expect to (i) test lepton universality to ± 2 %, (ii) observe and measure all of the so far unobserved decay modes of the W (in particular, the improved jet energy resolution together with the improved statistics should enable us to observe the decays of the weak bosons to two quarks), (iii) confirm, or exclude the existence of the decay $W \rightarrow \bar{b}t$, and measure, or place a limit on the mass of the top quark, (iv) measure the total widths of the W and Z^0 with a precision of $\pm$ 200 MeV, and therefore determine whether there are any additional W or Z^0 decay modes not predicted by the theory, (v) measure the mass difference (m_Z-m_W) with a precision of 100 - 200 MeV/c^2, providing us with the first test of the one-loop radiative corrections in the theory (in particular this measurement would reveal the existence of a large number of unobserved very heavy fermions if they exist), and (vi) confirm the existence of $B^0 - \bar{B}^0$ mixing.

In the QCD sector of the Standard Model we expect to (i) measure the differential jet cross-section as a function of jet transverse-momentum over a region in which the cross-section falls by eleven orders of magnitude, and improve the precision of the measurement by a factor of two compared to the current collider results, (ii) measure very low energy jets using the improved UA1 jet energy resolution, and determine the momentum distribution of partons in the proton at low momentum fraction x (critical for predicting cross-sections at SSC energies), (iii) improve our measurement of the two-jet angular distribution such that (a) QCD effects (which should produce an excess of jets at large angle) can be measured, and (b) quark substructure can be probed down to ~ 10^{-17} cm, (iv) measure the rate and properties of multi-jet events, enabling a test of the theory to higher orders in α_s (a particularly clean test of higher-order QCD is to compare the experimental measurement of jets produced in association with the weak bosons which decay leptonically with theoretical predictions : in this process final state gluon bremsstrahlung cannot occur, enabling initial state bremsstrahlung to be cleanly separated), and (v) perform a detailed study of non-perturbative phenomena such as the transition between high p_T and soft physics. This last physics goal has already been begun with the accumulation of 3 million minimum bias events in the fall of 1987, which are currently being analysed.

In addition to the above, the UA1 collaboration will be able to search for (i) heavy charged leptons with masses ≤ 60 GeV/c^2, (ii) heavy quarks with masses ≤ 80 GeV/c^2, (iii) new neutrino species, (iv) new W and Z bosons with masses ≤ 300 GeV/c^2, (v) Higgs boson(s), (vi) Supersymmetric quarks and gluons with masses ≤ 150 GeV/c^2, and (vii) further exceptionally high transverse momentum lepton-neutrino pairs produced with two jets, and hence to clarify whether the examples seen to date are the result of new physics or of an unlikely statistical fluctuation.

D. The Position Detector

The upgraded UA1 detector is a second-generation device designed for precision calorimetric measurements. The absolute measurement of the mass of the W and Z in the new calorimeter will be limited by systematic effects. These effects are largely understood and have led to a design which minimizes the error on the absolute calibration. A further systematic error on the energy measurement is due to the pile-up of additional particles. In order to control this effect we need to measure precisely the position of an electron in the calorimeter and compare it with the position as measured by the central detector tracking chamber. Agreement between these two position measurements tests the quality of the energy determination. Furthermore the ability to see additional electromagnetic showers will allow a more precise estimate of electron energies and isolation. To achieve these goals in March 1987 the US teams in UA1 have proposed, and are now constructing, a position detector for the upgraded UA1 U-TMP calorimeter. The position detector will also enable the detection of lower energy electrons by reducing the $\pi^{\pm}$ plus overlapping $n\pi^0$ backgrounds. It should be possible to reconstruct individual π^0s. For instance a 4 GeV/c P_T π^0 would give two photons separated by 7 cm in the central calorimeter. The validation of single photons will also become possible. Such a capability is extremely useful in trying to understand exotic events such as $Z^0 \rightarrow e^+ e^- \gamma$. The ability to reconstruct a π^0, or at least measure the opening angle of the two photons from a π^0, offers the possibility of checking the absolute energy calibration of the calorimeters, and allows cell to cell variations to be monitored.

The position detector design is based on a standard UA1 TMP calorimeter cell, the central anode plane being suplemented by the addition of two (orthogonal) strip planes to measure the position of clusters of energy deposited in the calorimeter. This is a straightforward extension of the liquid ionization chamber technology. The position detector will be placed after about four radiation lengths of absorber in order to collect a large charge over a wide range of electron or photon shower energies. The two orthogonal sets of strips are contained in a single (double thickness) calorimeter box. The width of an individual strip is a compromise between the spatial resolution and the number of channels. We have choosen a strip width of 7 mm with a pitch of 9 mm. An individual electromagnetic shower has a width comparable with the strip pitch and hence is typically sampled by two adjacent strips. Interpolation of the pulse heights will give an estimate of the centroid of the shower considerably better than the strip pitch. A prototype position detector box, manufactured by Hutchinson Technology, and filled with TMP at CERN, was successfully operated in an electron test beam at CERN during the summer of 1987 and yielded a spatial resolution approaching 1 mm for high energy showers. Two further prototype boxes have been filled and were successfully tested in electron and pion beams at CERN during the fall of 1987. The final cleaning and assembly for the position detector (at CERN) will be similar to that for the TMP gondolas and bouchons, involving equipment for final cleaning, quality control, testing, and TMP filling.

The mechanical design and manufacture of the position detector boxes have been the responsibilities of Prof. Rohlf and Dr. Sumorok at Harvard, and the cleaning and filling of the boxes with TMP the responsibilites of Prof. Geer and Dr. Bauer. All members of the Harvard group have participated in the beam tests at CERN.

A single minimum ionizing particle will give approximately 3000 electrons to be collected by the strip electrode or a charge of about 0.5 fC. The number of ionizing particles in the peak of a 128 GeV shower, for example, is about 1000. Assuming that this is a reasonable maximum shower energy, and allowing a factor of 2 for fluctuations, the readout electronics should have a full scale capability of 1 pC. Hence a dynamic range of greater than 2000 is needed to be sensitive to a single minimum ionizing particle. The charge on each strip has to be integrated, amplified and stored. The stored charge is overwritten by the next beam crossing unless there is a decision from the trigger logic to record the event. The large number of channels necessitates the multiplexing of the stored strip charges to an ADC close to the magnet. Following this the readout electronics will have automatic gain correction and pedestal subtraction from the digitized signals and zero channel suppression as only a small fraction of the strips will contain hits. It is planned to read out these recorded hits through the standard UA1 data acquisition readout system based on VME. For integrating, amplifying and storing the charge from the strips we will use integrated components in the form of a VLSI semi-custom array chip which contains a large assortment of transistors, resistors and capacitors on a 5 mm^2 array. A custom designed mask connecting the components is made to complete the circuit. In order to minimize the noise a discrete JFET is used on the input of the amplifier. An amplifier based on this technology has been built and tested and gives a noise figure as a function of the input capacitance of less than 10 electrons per pF. This amplification stage will be followed by an analog storage cell, currently available as a 32 channel device on a single VLSI chip called a Calorimeter Data Unit (CDU). This device has a dynamic range of 4000 to 1. The stored charge can be multiplexed out at a rate of 1 MHz. The device allows up to 4 charge samplings per channel and presently various algorithms are being evaluated in order to optimize the application of the device. The analogue signals will be digitised by a 12 bit ADC and then sent to the control room for processing on a VME board. The readout for the position detector has been designed at HEPL by Dr. Sumorok in collaboration with Dr. Oliver.

E. The Emulator Farm

The UA1 collaboration already uses a large fraction of the computer time available on the CERN IBM central computers. In the ACOL era UA1 computing needs will rise substantially. To obtain the massive CPU power needed, in the summer of 1985 Harvard and MIT proposed to construct a "farm" of 3081/E's at HEPL. The facility was envisaged to consist of ten emulators managed by a small IBM mainframe, which would control the reading and writing of events to disk or tape. Such emulator facilities can take over the mass computing involved in event reconstruction or large-scale Monte Carlo calculations. The 3081 emulators provide one of the most cost-effective means of obtaining the desired computing power.

The first stage of the emulator facility has been built and operated by Harvard and MIT. An IBM 4361 was installed September 1985. The first emulator arrived in January 1986, and entered production in March, the intervening time being spent adapting the UA1 event reconstruction program to the 3081/E, and changing the controlling hardware and software to make it useable for large-scale off-line work. The second emulator arrived in late March, and by early April both 3081/E's were used for production. The present configuration consists of two 3081/E's each with 2.5 megabytes of memory, controlled via an IBM 4361 MOD-4 with 4 M-bytes of memory running VM/CMS. Until recently, the emulators communicated with the 4361 via a Device Attachment Control Unit (DACU) connected to a CAMAC crate, capable of handling a sustained data transfer rate of 50 K-bytes/sec. About 1.1 gigabytes (out of 2.1) of IBM 3370 disk space is available to hold events going into and coming out of the emulators, which has allowed the facility to operate unattended for periods of time of up to about 14 hours.

In 1986 one-third of the UA1 jet data samples recorded in 1985 were processed on the farm. By mid-May we had finished the jet data, and were processing at a rate of about 82,000 events per month with two 3081/E's. During the fall of 1986 the standard UA1 Monte Carlo program ISAJET, together with the full detector simulation software, was installed on the emulators. Two large CPU intensive Monte Carlo studies of background processes relevant to the understanding of UA1 analysis topics were subsequently started at the Cambridge Facility. Typically the HEPL VENUS was used for event generation, the emulators for reconstruction (the main computing load), and the IBM 4361 for final analysis. The Monte Carlo studies performed in 1986 and 1987 at the farm are (i) simulation of heavy flavour processes that can fake large-transverse-momentum W production, (ii) simulation of backgrounds to top-quark signatures in UA1, and (iii) simulation of exotic resonance production followed by two-jet decay in the UA1 detector. Each of these processing and Monte Carlo tasks have led to at least one physics publication, and in some cases more than one publication, enabling the Harvard and MIT physicists involved in the analysis to play a decisive, and often co-ordinating, role in extracting physics from the UA1 data. This demonstrates the feasibility and importance of doing processing with emulators as an integral part of the UA1 analysis effort. In the fall of 1987 UA1 recorded 3 million minimum bias events. We plan to reconstruct a fraction of these events on the farm during 1988.

Our experience with emulators has fully matched our expectations. However, realization of the attractive cost-performance of the facility is contingent upon the construction of a large system. The slow CAMAC-DACU interface was intended as a temporary device since it precludes this. The transfer bottle-neck has now been eliminated by installing a VME to IBM Channel Interface (VICI) built in a CERN/IBM project with MIT participation. A VICI-equipped farm controlled by an IBM 4361 can accommodate well over ten 3081/E's before saturation. A ten emulator system could process about 6 x 10^5 UA1 jet events/month. The current size of a UA1 raw data event is about 180 K-bytes. After the UA1 detector has been upgraded there will be a modest increase in the size of a raw data event (200 K-bytes) and a corresponding increase in the size of a fully reconstructed event (400 K-bytes). The total integrated luminosity expected for the UA1 experiment is between 20,000 and 30,000 nb^{-1}, more than 30 times the current UA1 integrated luminosity. With the planned improvements in the trigger and data acquisition capabilities of the experiment the UA1 collaboration will need to process about 30 M events, representing 600 months of 3081E CPU time. In addition to the data processing needs of the experiment, past experience in UA1 indicates that a similar amount of CPU time is needed for large Monte Carlo calculations essential for understanding and interpreting the data. We therefore conclude that the UA1 experiment will require 1000 months of 3081E CPU time. This exceeds the present UA1 computing capacity by a factor of 10. The experiment will also require the equivalent of 150K magnetic tapes, to be able to record and analyze data taken at ACOL. Ten emulators would be capable of processing 600K UA1 events per month, which would enable about one third of the future UA1 data to be processed in the United States over a period of two to three years. Therefore in the future we will wish to increase the size of the emulator farm to 10 emulators. The UCLA group proposes to join Harvard/MIT in the upgrade phase of the farm.

F. Future Timetable

1988

Construction and installation of the position detector. Understanding of a completed calorimeter module at a test beam. Reconstruction of the large minimum bias data sample taken in the fall of 1987.

1989

Data taking. Understanding of the new calorimeter, including the position detector. Production on the farm.

1990

Data taking. Production on the farm and analysis at HEPL.

9. Detector R&D for High Energy Colliders

(J. Oliver and E. Sadowski plus physicists as noted)

Although we are confident that there is new fundamental physics to be learned at the TeV mass scale, we have no certain prediction as to how this physics will manifest itself. To be sensitive to new physics signals SSC detectors must have a wide and general detection capability. We do know, however, that the basic observables, even at SSC energies, are quarks and leptons. This implies a 4π detector geometry with good electron, muon, and jet detection. Furthermore, the relevent scale of energy and momentum measurement will become 1 TeV at the SSC.

It is clear from various detector studies at Snowmass and elsewhere that there are many unresolved problems in the areas we are proposing for study. In particular calorimetry is likely to play an even greater role and command considerably more resources at the SSC when compared with existing colliders. Given the long lead times necessary for constructing SSC detectors, it is essential that this kind of R&D activity begin as soon as possible.

The primary technical contribution to detector R&D from the HEPL facility will be the electronic enginneering support of Dr. John Oliver and the mechanical engineering support of Mr. Ed Sadowski, both of whom will spend half of their time on these projects. We also hope to hire a postdoctoral physicist to coordinate these activities, and we expect participation from several other HEPL physicists. We have included general M&S funds for Detector R&D in the budget to cover the costs of travel, tooling, and other supplies. We are also requesting $50K of equipment funds in both 1989 and 1990 for this work. These funds would be used to acquire a mechanical design CAD system as well as prototype components and test equipment. In addition we have submitted proposals to the DOE SSC Detector R&D program. Some of our specific detector R&D interests are described in the following paragraphs.

A.Warm–Liquid Calorimetry Studies (Prof. Geer and others)

Calorimetry will be an extremely important part of SSC detectors, just as it is now at existing hadron colliders. The main issues will be 1) good energy resolution with uniform response to electromagnetic and hadronic interactions, 2) good segmentation, 3) good hermiticity (few cracks and holes), 4) fast response times, and 5) radiation resistance. Because of the first requirement, we believe that the material of choice will be depleted uranium. About 12 interaction lengths will be needed to contain a 1 TeV jet. We believe that an attractive readout medium for an SSC calorimeter would be warm liquids along the lines of those tested for the UA1 calorimeter upgrade. This technology provides a very promising choice for SSC calorimetry. Such liquids as TMP, TMS, and double-TMS have good electron mobility. They have also been shown to be extremely resistant to radiation. In summary, we regard the existing programs at the present hadron colliders as the best available testing grounds for SSC detector development. We feel we need to maintain a vigorous R&D program now on detector development in the area of warm liquid uranium calorimetry, specifically directed toward SSC problems, in order to properly design an SSC detector in a timely fashion.

The physics goals together with the SSC accelerator parameters place some rather stringent requirements on detector design. The goal of good jet measurement leads us to the choice of uranium calorimetry together with a hydrogenous detection medium in which ionization is detected directly. This allows an equalization of electromagnetic and hadronic shower response and good uniformity of the detector to keep systematic errors of energy measurement low. Furthermore, the device must be as fast as possible due to the high collision rate of 1.4 events every 16 nsec. The detector must also be radiation resistant. For these reasons, we believe that the ionization collection in tetramethylsilane (TMS) would be the most suitable. At field strengths of 100KV/cm the drift velocity in TMS is 6×10^6 cm/sec which is an order of magnitude greater than that for liquid Argon. At this voltage an electron will traverse a 1 mm gap in TMS in 16nsec, well matched to the requirements of an SSC calorimeter.

The ionization yield Q in room temperature liquids, calculated by Onsager, depends on the field through a linear relation, $Q = Q_0 (1 + \alpha E)$, where E is the electric field strength, α

= 0.0567 cm/KV and Q_0 is the free electron yield at zero applied field. In comparison with the new UA1 TMP calorimeter a SSC TMS calorimeter operated at the higher field would yield more than an order of magnitude more charge for a similar deposit of energy. The present UA1 calorimeter readout electronics are extremely low noise giving only one electron per picofarad of detector capacitance. The increased charge from a TMS calorimeter would enable a more integrated approach to the readout electronics to be used. Such technology as VLSI allows a very cost effective approach in providing for a very large number of channels with some degradation in signal to noise over discrete component electronics. The increased signal would more than compensate for any increase in the noise.

We propose to do the following research and development in order to develop a warm-liquid device for SSC calorimetry:

1) Develop a high-voltage feed-through to operate at 10KV. The challenge of this development involves making a feedthrough which is both small in diameter because the TMS gap is only 1mm thick, and short to avoid any large cracks between adjacent boxes. The feedthrough must be vacuum and voltage tight and not poison the high purity TMS liquid. The feedthroughs would have a specially developed metal collar which is brazed onto a ceramic insulator and then laser welded onto the steel frame of the box.

2) Build a calorimeter stack of uranium and stainless-steel boxes with a similar design to our position detector (1 cm electrodes) but using the new feed-throughs mentioned above. The boxes would be filled and tested with TMS to make use of its higher electron mobility relative to other liquids. We would operate the TMS at about 0°C, for safety considerations. Note that TMP was chosen for the UA1 upgrade because of its much higher boiling point even though it is slower and has a smaller electron yield than TMS.

3) Develop fast analog front-end electronics based on new high-performance VLSI technology operating at 100MHz. The electronics would store the charge from many beam crossings until a trigger decision is taken. Subsequently, the relevant bucket of charge would have to be readout and digitized for each calorimeter cell. We request equipment funds for development of such electronics as fabrication of initial prototypes requires tooling charges.

B. Mechanical Design Studies of Calorimeters (Prof. Schwitters and others)

The purpose of this R&D project is to study mechanical designs of calorimeters suitable for general purpose detectors at high energy colliders such as the SSC. The study will include "paper" designs of possible configurations and construction and testing of prototypes that appear to have promising design features.

The challenge is to develop calorimeter designs that have high performance in terms of spatial and energy resolution, that cover the maximum solid angle with a minimum of dead regions, that are geometrically well matched to the intended physics to relieve some of the burden on the offline analysis, and that are reliable and relatively inexpensive to build. All of this must be accomplished within the very high rate environment of the SSC.

The goals of this effort are principally mechanical; we intend to draw on the extensive work available on the basic energy detection mechanisms in calorimeters. The signal detection problem is intimately tied to the mechanical design, however, and we will include in these studies careful attention to the connections to front-end electronics. This activity is very well matched to expertise at the Harvard High Energy Physics Laboratory. We have a mechnical designer and shop staff that are highly experienced in innovative detector design and prototyping. We also have an electronics engineer and support staff with extensive experience in low-level analog circuitry. It is important that these two areas of the detector art exist under the same roof where they can be brought together for attacking this problem.

The starting point for these studies will be to use heavy metal plates (probably lead) in a tower geometry with a liquid as the ionization sampling medium. We plan to begin with liquid argon, but will study designs involving room temperature liquids. Again, Harvard is a convenient place to study designs involving room temperature liquids because of the experience available from our UA1 colleagues. The choice of sampling material does not appear to be critical to making progress on "generic" mechanical designs. Similarly, there may be reasons to consider materials other than lead for the plates, but this can be done after experience is gained with the mechnical design questions. Modular construction techniques will be pursued. Thus, the general mechanical starting point will be something like the SLD LAQ calorimeters. The electrical connections will have to be different, however.

C. Hybrid Calorimeter for E665 (Prof. Nickerson and others)

A planned E665 upgrade is to replace the central region of the current electromagnetic calorimeter with a high-resolution, high-speed detector. Such a detector would be located directly in the muon beam, which would pass through the active area of the device. In the current configuration a 10^7 μ/sec beam deposits around $10^7 GeVs^{-1}$ in the central $24cm^2$ of the detector. This environment is therefore a good testing ground for SSC techniques. We propose to use one of the new technologies currently being developed as the basis for this upgrade; currently we are considering both warm liquid detectors and "hybrid" lead-plastic-TMAE techniques. Both methods have shown promise and we propose to choose a design for the E665 upgrade based upon development done both at Harvard and elsewhere.

An important feature of the new device will be the attendant electronics. We require fast analogue manipulation of the signals for trigger purposes and low per-channel cost. Electronics involving custom built chips seems to be indicated and we propose developing active summing circuits with very low input impedance and built-in redundancy. This kind of circuit has worked well in the current E665 calorimeter, keeping output signals fast, and holds promise for quite general applicability in the future.

D. Silicon Vertex Detector (Prof. Wilson and others)

Solid state detectors are ideal for vertex detectors in colliding beam experiments if their thickness is small enough that multiple scattering is unimportant. For experiments on B decays no presently existing detectors are thin enough. During 1988, funding does not permit active experimentation in this area. We expect, however, to keep close track of the work being done elsewhere on silicon detectors. It seems likely that 50 - 100 μ thick silicon drift detectors with two dimentional read out will be developed by manufacturers, and during 1989 we will want to start active development and modification for use in the CLEO II detector. This development, will of course be useful elsewhere.

E. Cylindrical spark counters for TOF measurements (Prof. Kinoshita and others)

We propose to develop prototype narrow gap spark chambers with high time resolution for use as time of flight counters. Our innovative cylindrical design possesses many advantages over the traditional planar construction.

The development of detectors to measure precisely the space-time trajectory of charged particles has essentially not progressed beyond the plastic scintillator, which was developed in the 1950's. The plastic scintillator combined with photomultiplier readout has a combination of features for time-of-flight which is hard to beat --- fast risetime, low mass, low expense, reliability, robustness. It has become one of the standard features of experiments at colliding beam storage rings, an absolutely essential if somewhat inconspicuous workhorse in triggering and particle identification. In spite of these commendable attributes, the scintillator-photomultiplier system has several shortcomings which render it somewhat inconvenient to use in colliding beam environments. First, phototubes are very sensitive to magnetic fields. A second inconvenience is lack of segmentation. In any case, it is difficult to imagine the improvement of timing resolution using plastic scintillator to below ~100 ps.

It is possible to obtain better time resolution using narrow-gap spark counters. The concept of this type of spark counter for high resolution measurement of time of flight is not new. In the 1970's Pestov and coworkers in Novosibirsk embarked on a program of developing the planar spark counter (PSC) into a practical detector for high energy physics. Using these methods, groups at SLAC and KEK have built a number of PSC prototypes. Its development has been somewhat slower than expected, thus earning it a reputation as a temperamental detector. The counters are very sensitive to dust and impurities in the gas. However, we would like to emphasize that a great deal of development on these questions has already been completed.

The basic components of a PSC are a conducting cathode and a resistive anode separated by a gap of order 0.1-1.0 mm, filled with a gas at up to 10 atm pressure and electric fields $\sim 10^5$ V/cm. In principle, it should be able to achieve time resolutions of order 10 ps or less. In practice, it is the electronics to read out the signals which have limited the resolution of test counters. The best published time resolution is 24 ps which, according to the investigators is easily achievable for small counters. For larger counters the resolution is degraded by complications of signal propagation.

We propose to investigate the development of a spark counter of novel geometry which may rectify these shortcomings while preserving the good time resolution of PSC's and with less mass and greater efficiency than traditional scintillator/phototube technology. We believe that the potential benefit of achieving 10 ps resolution in time-of-flight is very large and is sufficient justification for an initial study into the feasibility of this project.

The cylindrical spark counter (CYSPAC) is based on the principle of the narrow-gap spark counter but has some features which remove many of the shortcomings of the planar spark counter which have prevented its wider use in high energy physics experiments. The configuration we propose to investigate is cylindrical, unlike the planar configuration used in the SLAC-Novosibirsk-KEK version. The two electrodes are thus concentric cylindrical tubes with a very narrow gap, 100-1000μm. The diameter of the outer cylinder can be as small as a few mm, and the detectors would be configured much like a drift tube tracking system.

The advantages of this configuration over parallel plates are several. First, there is no need for a separate pressure vessel, since the cylindrical shape of the outer tube is optimal for withstanding the 10 atm or so of pressure. This eliminates some extra bulk and dead space. Second, the electrodes need not be thick in order to withstand deformation by the electrostatic force in the gap, since the cylindrical symmetry ensures approximate uniformity of stresses so that the net force is not large. Third, we eliminate any anode strip readout, which is unnecessary since the detector itself is narrow. Fourth the cylindrical symmetry of the detector will probably reduce the dependence of signal propagation speed on the lateral position of the track in the detector, simplifying calibration corrections.

Using some of the funds allocated to detector development at HEPL we have started to investigate some of the questions discussed above and to search for the best materials. We have designed and constructed a pressure vessel to produce sparks onto test materials from a tungsten carbide spark point, which will enable us to study the long term effects of sparks on the surface quality of materials and on the quenching gases. Inspection of the surfaces with a scanning electron microscope, a facility available in the Division of Applied Sciences at Harvard, should yield valuable information about suitability of various materials and alloys as CYSPAC electrodes. A simple system for mixing of gases is under construction.

We have also considered possible designs for the endplates to hold the CYSPAC module together. We are currently investigating the use of precision molded endplates that incorporate the HV feedthroughs and serial gas supply.

For the assembly of CYSPAC parts we will require a small ultra-clean CLASS 100 environment into which we will build the cleaning and assembly/fabrication mechanisms. This will be incorporated into an existing clean room environment at the Harvard High Energy Physics Laboratory. This is the most critical part of this project, since it is the only feature of the detector which has not been tested.

As an initial test of timing properties we will set up a system to trigger on cosmic rays. Ten short (~20 cm long x ~2 cm O.D.) CYSPACs will be placed in a three-layer array in conjunction with drift chambers to localize the tracks and trigger scintillators. The fast electronic TDC's will be built in the Harvard electronics shop. We also plan to test the equipment at varying rates using a proton beam from the Harvard University Cyclotron.

A conservative goal for the CYSPAC would be a timing resolution of 50 ps, although we would ultimately hope to achieve ~10 ps. Even the worst-case figure, considered straightforward by PSC researchers, would expand physics capabilities and/or reduce cost and bulk in many situations. We believe that the rapid and successful development of this system will enable significant advances for many physics experiments.

10. Theory

(Prof. R. Glauber)

We have recently demonstrated the first conclusive evidence of the existence of strong spatial correlations between the nucleons in in a nucleus. The evidence we have presented in a recent Physical Review Letter, which has been summarized in the Search and Discovery columns of Physics Today (March 1988 issue, pp. 21-23), is based on the analysis of measurements of pion double-charge-exchange processes made at Los Alamos. The theory we have developed of the mechanism of these processes has been applied successfully now to measurements in ^{14}C, ^{18}O, ^{26}Mg, and most recently to a succession of three calcium isotopes, ^{42}Ca, ^{44}Ca, and ^{48}Ca. There are now ten measurements of the cross-sections of the calcium isotopes at 35 Mev, and all of them are in good agreement with the theory.

The double-charge-exchange process,which is detected as a transition between isobaric analogue states, is quite sensitively dependent on the spatial correlation between the pairs of valence neutrons that are converted to protons. It is necessary, in order to take these correlations into account, to sum the double exchange amplitude over intermediate nuclear states that may be quite inelastic. Earlier theories, by failing to do that, had implicitly omitted the correlation effects entirely. The measurements, which are presently confined to the low energies of 35 and 50 Mev, will shortly be extended to energies as high as 300 Mev. It will be necessary to develop the theory somewhat further to deal with the absorption processes that will become much more important at those higher energies.

We have continued the phenomenological analysis of the measured high energy p p and p $\bar{p}$ cross sections that we have begun in connection with the measurements made by the UA4 group at CERN. The calculations, which are based on a simple multiple diffraction model, now provide interesting, and in most cases quite accurate fits to the experimental momentum transfer distributions measured at all energies from 630 GeV (COM) down to 13.7 GeV. They cover, in other words, the range of SPS Collider, ISR and Fermilab measurements. The calculated results fit the experimental ones, including the total cross section, accurately enough in fact that they bring to light what we can only presume are various systematic experimental errors. Among these are a systematic misdetermination of several percent in the central slope of the differential cross section. We find that the determination of this slope has a strong bearing on any attempt to measure, by means of coulomb interference effects, the ratio of the real part of the forward scattering amplitude to the imaginary part. Indeed a measurement of that ratio for $\bar{p}$ p scattering at 546 GeV that has just been reported represents a much larger value than had been anticipated from earlier measurements at lower energies. Our theory indicates that the newly measured ratio may be in substantial error due to the misleading slope measurements. A preliminary report of this conclusion was presented to the International Conference on Elastic and Diffractive Processes at The Rockefeller University in October, 1987, and a longer paper is in preparation. It now seems possible to apply the same model to the discussion of diffraction dissociation processes. We propose to analyze first, in this way, the integrated cross-sections for diffraction dissociation.

When hadrons are scattered from non-spherical nuclei they excite inelastic rotational transitions. Determining the influence of these transitions on the angular distributions of scattered particles has been a long-standing problem of the fundamental collision theory. Procedures based on numerical solution of the Schrödinger equation must take many angular momentum channels into account and are correspondingly unwieldy. We have developed, in collaboration with G. Fäldt of the University of Uppsala, Sweden, a considerably more direct method for treating such problems, based on the theory of diffractive scattering. We are investigating this method currently in order to extend the range of earlier work on rotational inelasticity.

Quantum electrodynamical measurements carried out at a level of accuracy great enough to probe the fundamental quantum field fluctuations can now be improved in accuracy by using specially prepared states known as "squeezed states". We have developed, together with M. Lewenstein, a research fellow, a theory of the generation of such states in ordinary electrically polarizable media. Since the media are not homogeneous in structure in general, it has been necessary to develop new methods for treating the quantization of the electromagnetic field. Photons emitted by one atom in a medium of identical atoms are virtually trapped within the medium. The resonant character of the atomic absorption and rescattering cross-sections implies that a photon will be absorbed and reemitted a great many times before leaving the medium. We have found, in collaboration with a former student, S. Prasad of the

University of New Mexico, that these trapping effects lead to interesting changes in radiative lifetimes and spectral profiles. We are now extending the theory to include various other effects that influence spectral line profiles.

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12. Budget Tables

Our budget projections for the three year period 1988-1990 are contained in the tables on the following pages. The CY1988 figures represent actual funding. The operations budgets, which appear first, contain two columns for 1989. The CY1989A column, assumes an increase of 3% over the 1988 funding. The CY1989B column as well as the CY1990 column present the operations budgets that are required for the effective functioning of each group and the HEPL facility. The overhead rate of 68% used for 1988 is assumed to be the same for 1989 and 1990.

Our equipment fund requests are summarized in the last table. Descriptions of the various items may be found in the text. The first two items, Detector R&D and VAX Facility Upgrade are intended to benefit all the experimental groups at Harvard, while the remaining items are attached to specific projects.

Budget removed JC

HEPL Equipment Funds

	CY1988	CY1989	CY1990
HEPL Detector R&D		50,000	50,000
HEPL VAX Facility Upgrade	60,000	80,000	100,000
CLEO II Barrel TOF System	180,000	25,000	25,000
E665 Hybrid Calorimeter		50,000	200,000
LEP3 Analysis Workstation			80,000
UA1 Position Detector	100,000	100,000	100,000
TOTAL Requested Equipment Funds	340,000	305,000	555,000

Other Equipment Funds:

	CY1988	CY1989	CY1990
CDF Muon System Upgrade*		700,000	500,000
E665 Uranium STAC Target**		300,000	300,000

* Under discussion – funds to be transferred from Fermilab CDF management

** Under discussion with E665 Collaboration – to be funded through Fermilab