1 of 2

U.S./JAPAN COOPERATION IN HIGH ENERGY PHYSICS

REVIEW OF ACTIVITIES

1988 - 1993

REPORT OF THE U.S. COMMITTEE TO REVIEW
THE U.S./JAPAN PROGRAM FOR COOPERATION
IN HIGH ENERGY PHYSICS

MASTER

UNITED STATES DEPARTMENT OF ENERGY
OFFICE OF ENERGY RESEARCH
OFFICE OF HIGH ENERGY AND NUCLEAR PHYSICS
WASHINGTON D.C. 20585

**REPORT
OF THE
U.S. COMMITTEE
TO REVIEW THE
U.S./JAPAN PROGRAM
FOR COOPERATION IN
HIGH ENERGY PHYSICS**

1988 - 1993

**WASHINGTON, DC
NOVEMBER 16, 1993**

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PREAMBLE

The review committee was greatly impressed by the achievement and effectiveness of the U.S./Japan Committee for Cooperation in High Energy Physics. This collaborative program has witnessed the accomplishment of superb research, much of which would have been difficult or impossible without it. The program has provided an important catalytic function in fostering the close bond and interactions between the particle scientists of both nations, in facilitating the Japanese high energy physicists quickly arriving at the forefront of this basic field of research, and in galvanizing Japanese industry to play a vital role in the related, necessary cutting-edge technology. Especially in the last five years, we have witnessed the rapid growth of intellectual and technical leadership of Japanese scientists in key detector projects in high energy physics in the U.S., as well as in the R&D important for the development of a future linear collider.

Ours is the era of advanced science and technology. More than ever, the internationalism of science is the way to the future. The harmonious and productive collaboration between the American and Japanese scientists under this program is an excellent model for international cooperation and is highly reminiscent of what happened between the U.S. and Western Europe after the suggestion by I.I. Rabi in Florence in June of 1950. The Rabi proposal led to the establishment of CERN, which has become a citadel of basic science with a significant effect on the development of Europe over the past four decades.

However, in order to have a true internationalism of science, Asia must be an active leader in partnership with America and Europe. The present U.S./Japan collaboration program in high energy physics could well pave the way to such a global partnership.

EXECUTIVE SUMMARY

The U.S. Committee to review the U.S./Japan Program for Cooperation in High Energy Physics has concluded the following.

- ◆ The research performed under the sponsorship of this program is of very high quality and covers many key areas of high energy physics.
- ◆ The research has produced a number of important results, many of which would not have been accomplished without the support and encouragement provided by the program.
- ◆ The flexibility provided by the funds made available to the researchers makes them disproportionately valuable to the programs to which they are awarded.
- ◆ Researchers involved in the program have been very effective at making good use of the reciprocal strengths of the two communities
- ◆ The interactions between researchers in the two countries, made possible by the accord, have resulted in a number of important and identifiable intellectual developments.
- ◆ The agreement has helped promote a close working relationship between the two communities that could lead to more extensive future collaborations.

On the basis of these conclusions, we recommend that the program be continued, strongly encouraged and, if at all possible, intensified.

INTRODUCTION

The U.S./Japan High Energy Physics Cooperative Program was formally initiated in November 1979, under the terms of the "Implementing Arrangement between the Department of Energy of the United States of America and the Ministry of Education, Science and Culture of Japan on Cooperation in the Field of High Energy Physics" following the signing of the ten-year "Agreement Between the Government of the United States of America and the Government of Japan on Cooperation in Research and Development in Energy and Related Fields" on May 2, 1979.

The objective of the Implementing Arrangement was to further the energy programs of both countries by establishing a framework for cooperation in the field of high energy physics, including research, accelerator and detector instrumentation research and development, the fabrication and subsequent use of new experimental devices and facilities, and related joint efforts as may be mutually agreed. Over the years, this cooperation has been very effective and has strengthened the overall collaborative efforts and the understanding between our nations and their citizens. It has demonstrated to the world our ability to work together to attack difficult problems. High Energy Physics goes across national borders; the bond is clearly intellectual and common ground is shared for the benefit of all in a most effective manner.

This review covers the activities conducted under the aegis of the U.S./Japan Committee for Cooperation in High Energy Physics during the past five years (1988 - 1993). This was the second such U.S. review of the U.S./Japan cooperative activities; the first was held in 1987.

Charge to the U.S. Review Committee

The DOE Office of High Energy and Nuclear Physics established a U.S. review committee to conduct an in-depth review of the activities that have been carried out during the past five years, make a critical appraisal of the accomplishments that have been achieved, and provide an overall evaluation and assessment of the program. The results of the review are presented in this report which was to be completed by November 30, 1993. See Appendix I for the review committee charge letter.

Membership of the U.S. Review Committee

The review committee was chaired by Professor Stephen Olsen of the University of Hawaii and consisted of six members. See Appendix II for the full membership of the U.S. review committee.

Review Process

Individual members of the review committee made site visits to the major U.S. participating laboratories and summarized their findings at the one-day meeting held at the DOE Forrestal Building in Washington, D.C. on November 16, 1993. Laboratory representatives also made presentations on the collaborative activities at Fermi National Accelerator Laboratory (Fermilab), Stanford Linear Accelerator Center (SLAC), and Brookhaven National Laboratory (BNL).

The review committee then discussed the program and arrived at the conclusions and recommendations regarding future collaborative activities that are contained in final sections of this report, Conclusions and Recommendation. The agenda for the November 16, 1993 meeting is included as Appendix III.

PROGRAM HIGHLIGHTS

Fermi National Accelerator Laboratory

The Collider Detector at Fermilab

Collaboration of Japanese physicists in the experimental program at the Fermi National Accelerator Laboratory (Fermilab) has been a major part of the U.S./Japan Program for Cooperation in High Energy Physics since its inception about a decade and a half ago. Japanese groups participate in the highest quality experiments, and their contributions to those experiments is significant, both intellectually and materially.

The jewel of the U.S./Japan program in High Energy Physics at Fermilab is the Collider Detector at Fermilab (CDF) research with the $p\bar{p}$ collider. Japanese researchers were part of the team that originally conceived the detector, and have played a major role in its construction, its operation, and in analyzing the data from the experiment. Japanese physicists number about 10% of the collaboration, and Japanese groups provided nearly a quarter of the capital cost of the detector. Data analysis by the Japanese collaboration continues to play a crucial role in the physics results from CDF.

Over the past five years, CDF has had extensive modifications to improve its power to detect top quark and beauty mesons. These would not have been possible without Japanese collaboration. Over the next few years, extensive upgrades are planned for CDF, to enable it to take advantage of the higher luminosities planned for the collider. The Japanese groups are leading the effort, or are heavily involved, in several of these upgrades. Among them are upgrades to the data acquisition system, and the replacement of the existing plug and forward gas calorimeters with a new scintillator-based plug calorimeter.

The Japanese participation in the CDF collaboration demonstrates the value of the U.S./Japan program as a mutually profitable, high quality scientific activity. As CDF proceeds to a more incisive role in exploiting B-physics, in finding and investigating the properties of the top quark, and in the search for new particles, this will be one of the premier sources of data for high energy physics during the next decade. The scientific success of CDF, with its Japanese involvement, is a superb example of frontier joint research.

K Meson Decays

The next most noteworthy collaboration at Fermilab is KTeV ("Kaons at the Tevatron"), the new high precision study of neutral kaon decay. KTeV is the continuation of a series of important and powerful experiments. Previous experiments in the series have resulted in the publication the most accurate values of many rare K^0 and π^0 decay branching ratios, and produced the most significant upper limits on many others. The major result has been a value of the CP violation parameter $\text{Re}(\epsilon'/\epsilon)$ of $(7.4 \pm 5.2 \pm 2.9) \times 10^{-4}$. The new KTeV experiment, now under construction, will reduce the error on $\text{Re}(\epsilon'/\epsilon)$ to 10^{-4} , with corresponding reductions in the uncertainties or upper limits of the other decay modes. This increased accuracy will provide a very sensitive test of the Standard Model and the origin of CP violation.

Japanese participation in this collaboration is new, but the track record of the group involved is excellent. They are developing the photomultiplier system for the CsI calorimeter, which is the most critical piece of the apparatus. They are also working on the data acquisition system for the experiment.

This experiment, which has the highest priority in the Fermilab fixed-target program, is expected to start taking data in 1995. The scope of this research is such that important indications of very small effects "from much higher energies" should be observable. With the demise of the Superconducting Super Collider, this becomes even more important. The CDF collider program aside, KTeV appears likely to become the most prominent and productive research in the U.S./Japan program at Fermilab.

Emulsions

The unique expertise of Japanese groups in emulsions, and the techniques they developed for rapid measurement of emulsion events, has been crucial to a series of neutrino experiments starting in the 1970's. These experiments made important measurements of charm quark and bottom quark particle properties. The newly approved experiment to search for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations opens up the possibility of establishing a non-zero mass for at least one flavor of neutrino. This experiment is one of the kind of taste and ambition which should continue to characterize the collaboration. These experiments will effectively exploit Fermilab's new Main Injector.

Summary

The activities conducted under the U.S./Japan Agreement for Cooperation in High Energy Physics are an important part of Fermilab's research program, and have long been so. Japanese physicists participate in experiments which are unique in high

energy physics because of the use of the highest energy accelerator available. Their contributions include the provision of equipment, operation of the experiments, and analysis of the results. Japanese collaborators are fully involved in achieving the particle physics results that emerge from these experiments.

Stanford Linear Accelerator Center

Accelerator R&D

The SLAC-KEK collaboration on accelerator R&D started in 1979 and covered a broad range of topics including superconducting RF, surface physics, ceramic windows, and high-power klystrons. Since 1986, the program has been focussed entirely on R&D for high-energy, linear e^+e^- colliders. In 1990, the program was expanded and aimed at the development of a design for a machine in the 0.5-1.0 TeV cm energy region.

After examining a variety of possibilities, the two laboratories have converged on very similar design concepts. Both laboratories' preferred design uses 11.4 GHz accelerating structures, multi-bunch operation, and flat beams that cross at a small angle.

The R&D efforts have been coordinated to match the individual strengths of each laboratory. Both laboratories are developing high power X-band klystrons. SLAC is developing an RF pulse-compression system. KEK is developing superconducting focussing solenoids for the klystrons. While KEK investigates damped cavity structures for reducing the effects of high-order modes, SLAC is studying detuned cavities. The superlattice GaAs photocathode, developed in Japan, appears to be suitable for producing multiple bunches of polarized electrons with intensities appropriate for linear colliders.

The R&D plan includes three major facilities at SLAC and KEK, the Final Focus Test Beam (FFTB) and the NLC Test Accelerator (NLCTA) at SLAC, and the Advanced Test Facility (ATF) at KEK.

Final Focus Test Beam

This is a test facility to study the feasibility of achieving the large demagnifications needed for next generation linear colliders. It uses the SLAC linac beam, high precision final-focus quadrupoles supplied by KEK, as well as equipment from France, Germany and Russia. One of the items to be tested is a novel laser-interferometer system, invented by a KEK researcher, for measuring the sub-micron beam spot size.

Accelerator Test Facility

This is a facility being built at KEK to study technical issues associated with the injection and extraction of multi-bunch beams into and out of the damping ring

as well as the dynamics of damping and beam compression. Achieving ultralow-emittance beams for injection into the main linac is an important feature of linear collider design and must be well understood. The ATF consists of a section of S-band linac and a 1.54 GeV damping ring. The linac uses a klystron and a SLED-I pulse compression cavity from SLAC. SLAC physicists made a number of contributions to the design of the damping ring. Experiments with the ATF are expected to start in late 1996.

NLC Test Accelerator

This will be a facility at SLAC for complete systems testing of the main linac and for studying beam dynamics at current levels required for a next-generation device. It will be a complementary facility to the ATF at KEK. The components to be tested include an X-band injector, high-power X-band klystrons, energy efficient modulators, the SLED-II RF pulse compressor and a few 1.8 m long sections of accelerating structures. The beam dynamics experiments include multi-bunch beam loading compensation, multi-bunch transverse emittance growth, transverse RF field effects, and field emission. The NLCTA tests are planned to start in late 1996.

U.S./Japan funds have supported frequent visits by KEK personnel to SLAC, and the resulting interactions have produced a number of advances in the understanding of the physics of linear colliders. As a result of these interactions, the relationship between the focussing strength of the final-focus quadrupole system and synchrotron radiation levels in the detectors, the nature of beam-beam effects and various instabilities, and the effects of misalignments and imperfections are quantitatively understood.

The SLD experiment

The SLD is a large solenoidal detector studying the decays of polarized Z bosons produced by the SLAC Linear Collider (SLC). The experimental team includes scientists from three Japanese institutions supported by U.S./Japan funds. The experiment has benefitted from the recently achieved high luminosity operation of the SLC running with polarized electrons produced from a strained-lattice GaAs photocathode. The primary goal of the experiment is to use the polarized electrons to make a precise determination of the Weinberg angle based on measurements of the left-right cross section asymmetry. In addition, the special nature of the SLC interaction region permits vertex reconstruction with unmatched precision. This provides the opportunity to do a number of important measurements of the properties of heavy quarks. These features give the SLD capabilities that complement those of the LEP detectors and the ability to make a number of measurements with competitive levels of precision.

The Japanese participants in SLD have played a key role in the construction and operation of the Central Drift Chamber (CDC), used for charged particle tracking, and the Cerenkov Ring Imaging Detector (CRID), which provides particle identification. Both components are operating successfully.

SLAC has recently approved a four year extension to the SLD run, as well as the construction of a new beam polarization monitor and an upgraded CCD vertex detector. A four-year run with polarized electrons should result in the world's most precise measurement of the Weinberg angle. The new vertex detector will provide excellent capabilities for studying $B_s\bar{B}_s$ mixing.

Brookhaven National Laboratory

Over the past 15 years, the U.S./Japan program has supported a number of important programs at Brookhaven and helped generate a number of the most significant scientific and technological achievements of the laboratory. In the last five years, the physics focus of the program has been on neutrino physics, the new discipline of high energy heavy-ion collisions, the study of rare K decays, and the precise measurement of the muon anomalous magnetic moment. The latter has required the construction of the world's largest diameter superconducting magnet coil and the development of the first superconducting beam-inflection system; both technical achievements are attributable to collaborations sponsored by the program.

Neutrino Scattering

The neutrino program, started in 1979, was one of the first experimental programs supported under the U.S./Japan agreement, and has produced a number of interesting results. The initial experiment produced some of the first experimental results on neutrino-electron and neutrino-proton elastic scattering. In addition, detailed studies of quasi-elastic neutrino-neutron scattering were made that provided a measurement of the neutron's axial vector form-factor and placed useful limits on the existence of second-class weak interaction currents. Other important results from this program were negative searches for heavy neutrinos and neutrino oscillations.

Heavy-Ion Interactions

Japanese researchers supported by the U.S./Japan agreement played a key role in the initiation of the successful high-energy heavy-ion collision program at Brookhaven. The initial experiment in this area was proposed by the Tokyo group and started a program that has now become a major component of Brookhaven's research. This experiment and its follow-up experiments have mapped-out the general aspects of collisions of heavy-ions ranging from silicon to gold. One of the interesting new results is the production of K^+ mesons, which grows from approximately 11 K^+ /event in Si-Au collisions to about 50 K^+ /event in Au-Au collisions.

The success of the fixed target heavy-ion work has led the proponents to develop the PHENIX proposal for RHIC, the Relativistic Heavy Ion Collider under construction at Brookhaven. The goal of this experiment is to observe a new phase of matter called the quark-gluon plasma. This proposal has been approved and initial work on the construction of the detector is underway. Until now, support for the Japanese collaborators has been limited to R&D on imaging cerenkov counters, precision

time-of-flight counters, and beam-beam counters. It is expected that the PHENIX experiment will be an important component of the U.S./Japan program in the future.

Rare K decays

Recently, researchers from the University of Tokyo and KEK have joined Experiment 787, which is a search for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ using Brookhaven's new stopping K^+ beam. With the support of U.S./Japan program funds, the Japanese contingent is supplying CsI detectors for the endcaps which are essential for bringing the sensitivity of the experiment down to the branching ratio level expected from Standard Model processes. An observation of a deviation from this prediction would provide important information about the physics that lies beyond the Standard Model. In the absence of any indication of new physics, the measurement can be used to place important constraints on the Kobayashi-Maskawa parameters and the top-quark mass. In addition to $K^+ \rightarrow \pi^+ \nu \bar{\nu}$, any K^+ decay mode that results in one π^+ and one or more unobservable particles (photinos, majorons, axions, etc.) can be seen.

Muon Anomalous Magnetic Moment

The goal of this experiment is to measure the anomalous magnetic moment of the muon (g-2) to a precision that is 20 times that of the previous measurement made at CERN. The general method is the same as used in the CERN experiment, using muons at the "magic" momentum of 3.1 GeV/c. The experiment requires a 14 m diameter superferric muon storage ring with an ultra-precise magnetic field (uniform to 1 PPM and measured to 0.1 PPM). The magnet, which is primarily the responsibility of the Japanese collaborators, is the key improvement over the CERN experiment that provides the enhanced precision.

The in-place winding of the four superconducting coils was completed in 1991. Each coil is a stack of 24 turns of TOPAZ-style conductor wound onto an aluminum mandrel. The completed coil is the world's largest diameter superconducting magnet. Special low-carbon steel poles were fabricated in Japan and are now being machined in the U.S.

A novel 1.5 Tesla superconducting inflection magnet is also being supplied by the Japanese team. This device cancels the magnetic field seen by the beam particles as they enter the storage ring. Construction of the full 1.7 m inflection magnet started in 1993, after successful tests of a 0.5 m prototype.

In addition, KEK physicists are developing a scintillating-fiber profile monitor to track the parameters of the injected beam.

The g-2 magnet will be assembled in 1994, and measurements and shimming will be complete in 1995. The first data runs are expected to occur in 1996.

Cornell University

The activities supported under the U.S./Japan agreement at Cornell have been focussed on R&D on superconducting RF cavities for use in accelerators. The goals of the R&D are to increase accelerating fields, decrease losses, lower the impedance that the RF structures present to the circulating beams, and to understand causes for the limitations. As part of this program high current cavities for use in the Cornell Electron Storage Ring (CESR) are being studied. In addition, crab-crossing cavities, which provide transverse fields to rotate the beam bunches as they cross at a finite angle, are being developed, and a prototype RF structure for a high energy superconducting linac has been produced and its properties are being studied.

The high current CESR cavity, now under construction, uses a novel single-cell structure with a large bore diameter. Higher-order modes excited in the cavity by the circulating beam are transmitted through the bore and dissipated on room temperature ferrites situated along the beam-pipe outside of the helium cryostat. Tests indicate that this technique eliminates the effects of higher-order modes to the level where feedback stabilization systems are not necessary. A fluted structure to the beam pipe, suggested by a KEK visitor to Cornell, has proven effective for transmitting the higher-order modes to the ferrite dissipator. Cavities of this type may be used in future configurations of the KEK B-factory storage ring.

Crab-crossing cavities are needed to rotate beam bunches as they enter the interaction region so they collide head-on, in spite of the existence of a finite crossing angle. These are an important component of the KEK B-factory design. A one-third scale model has been built and tested; surface fields of 20 MV/m at a Q of 10^9 were obtained. A full-scale cavity with these performance levels would compensate for a 10 milliradian beam crossing angle; this would be adequate for the KEK B-factory.

A major effort has been initiated to study, design, and test many of the vacuum and mechanical elements of the interaction region. The issues involved include masking, radiation protection of the detector during filling of the ring, the beryllium tube at the interaction point, vacuum pumping, and mechanical supports.

The major challenges for the development of a high energy superconducting linear collider are to increase the maximum possible gradients from their current levels of 5-10 MV/m to 20-30 MV/m and to reduce costs by at least a factor of four. The Cornell R&D program has shown that high pulsed power RF processing is effective at overcoming field emission problems in cavities and the use of high purity, high thermal conductivity niobium overcomes thermal instabilities. Using these techniques, they

have reached an accelerating gradient of 25 MV/m with a Q of 2×10^9 in a 5-cell prototype cavity. Work is proceeding on ways to reduce the cost of the cavities.

Lawrence Berkeley Laboratory

Under the U.S./Japan program, Japanese physicists from Tohoku University and from KEK collaborate with the Particle Data Group (PDG) in the production of the Review of Particle Properties (RPP) and other PDG publications. The Review summarizes the status of High Energy Physics. It is the arbiter of particle properties and provides vital reviews of experimental and theoretical physics.

The Japanese have collaborated with the PDG since 1986. They participate in all aspects of the Review, including the encoding of experimental data and the writing of reviews on selected topics of interest, such as the search for the top quark. On numerous occasions these collaborators have visited Lawrence Berkeley Laboratory during the final production phases to help insure the quality of the sections of RPP for which they assumed responsibility. In recognition of their substantial contribution to the collaboration, the Japanese were chosen as the first authors of the 1992 edition of RPP.

CONCLUSIONS

The Committee was impressed by the high quality of the work sponsored by the U.S./Japan Program. The resources provided by this mechanism have stimulated strong collaborations between the U.S. and Japanese high energy physics communities, resulting in an impressive and broad range of accomplishments.

◆ Scientific Importance

The collaborations are concentrated in key areas of the U.S. national program. A prime example is the strong Japanese participation in the CDF experiment at Fermilab — currently the premier research effort at the high energy frontier — from its very inception in 1979. Funds provided under the accord have resulted in major Japanese contributions to the design, construction, and exploitation of this detector. The pioneering work on high energy heavy-ion collisions, starting with Experiment 802 at Brookhaven in 1984, was initiated by Japanese physicists supported by the accord. This experiment and its follow-ups have been extremely successful and have developed into a major thrust of the Brookhaven National Laboratory's program. Especially noteworthy is the strong partnership that has developed between SLAC and KEK for developing the technical and theoretical base for next-generation linear e^+e^- colliders, seen by many as the next logical step in e^+e^- physics. The two laboratories, working closely together, have made impressive progress on technical issues and are establishing a strong and close relationship that could form the basis of an international effort to implement such a device.

◆ Cost Effectiveness

The funds provided under the accord, although only a small fraction of total resources available on both sides, have had a disproportionate effect on the output of the two communities. They have been used to provide major components of important experiments, such as the magnet coil and the endplug calorimeters of the CDF detector at Fermilab and the final-focus quadrupoles for the FFTB test at SLAC. Moreover, the flexibility afforded by these funds make them particularly useful, providing U.S. laboratories easy access to Japanese industry and vice-versa. The importance of such flexibility is difficult to overstate.

◆ Symbiosis

Researchers participating in these joint activities have been very effective at matching the reciprocal strengths that obtain in the two communities, with the end result of significant enhancements to the scientific output. Among the many examples of this are:

- the Fermilab hybrid emulsion program (E531/653), where an effective match was made between the U.S. group's strength in electronic detectors and the Japanese group's unique ability for analyzing large volumes of emulsions;

- the CDF magnet, which was a product of Japanese industry's strong capabilities in superconductivity;

- the linear collider R&D, where SLAC's expertise in high power RF systems is complemented by KEK's strength in high precision manufacturing and alignment.

◆ Interactions

The most valuable aspect of the accord is the intellectual benefits that derive from the close contact between the two communities. Here the travel funds provided to the Japanese researchers play an essential role. As noted above, the very successful heavy-ion program at Brookhaven was primarily initiated by Japanese groups, and the CDF experiment at Fermilab was conceived by a US-Japan-Italy team. There are many developments in accelerator physics that have derived from these contacts. For example, the ingenious Laser-Compton spot-size monitor was invented by a KEK participant in the FFTB at SLAC. SLAC visitors at KEK have provided important input to the design of the ATF damping ring currently under construction at KEK. The KEK B-factory design has benefitted from the crab-crossing R&D at Cornell; a KEK participant in the crab-crossing work at Cornell made major contributions to the design of the large-aperture RF cavity being developed by Cornell for the CESR upgrade. The close interactions between SLAC and KEK accelerator theorists has produced an impressive body of work on linear collider accelerator physics, including theoretical limits on allowable focussing strengths, and a better understanding of beam-beam effects and tolerance requirements.

◆ Funding Level

The funding for the program has stayed level since its inception, while the number of activities that it supports has increased. As a consequence, some of the major past successes of the program, such as the construction of the magnet for the CDF experiment, probably could not be accomplished today. The committee is concerned that a continuation of level funding may result in a deterioration of the quality and impact of the program.

RECOMMENDATION

The Committee concludes that the U.S./Japan Program for Cooperation in High Energy Physics has produced an impressive amount of important and high quality work. The contacts between researchers provided by the accord have stimulated important new ideas, a number of identifiable advances, and has strengthened the close ties between the two communities.

Based upon this U.S. review of cooperative activities conducted under the terms of the "Implementing Arrangement Between the Department of Energy of the United States of America and the Ministry of Education, Science and Culture of Japan on Cooperation in the Field of High Energy Physics" during the period 1988 - 1993, the Committee recommends that the U.S./Japan Program for Cooperation in High Energy Physics be continued, strongly encouraged and, if at all possible, intensified.

APPENDICES

APPENDIX I

MEMBERSHIP OF REVIEW COMMITTEE

REVIEW COMMITTEE

Chairman Professor Stephen Olsen	University of Hawaii
Professor Charles Baltay	Yale University
Professor Leon Lederman	Illinois Institute of Technology
Professor T-D Lee	Columbia University
Professor Boyce McDaniel	Cornell University
Professor Jack Sandweiss	Yale University
Executive Secretary Dr. Jeffrey E. Mandula	Department of Energy

APPENDIX II

CHARGE TO THE REVIEW COMMITTEE

CHARGE TO THE REVIEW COMMITTEE

To the committee to review the activities conducted under the aegis of the U.S./Japan Committee for Cooperation in High Energy Physics during the past five years:

The U.S./Japan Cooperative Program was initiated in November, 1979, and it was last comprehensively reviewed in the spring of 1987.

The Committee is to conduct an in-depth review of the activities that have been carried out under the U.S./Japan Cooperative Program during the past five years, to make a critical appraisal the accomplishments that have been achieved, and to provide an overall evaluation and assessment of the Program. The Committee should present the results of its review to the Department of Energy in the form of a report, which should be completed by November 30, 1993.

APPENDIX III

AGENDA FOR THE NOVEMBER 16, 1993 MEETING OF THE REVIEW COMMITTEE

Tentative Agenda

U.S./Japan Committee for Cooperation in High Energy Physics

1988 - 1993 Summary Review - U.S. Side

Tuesday, November 16, 1993
Department of Energy
Forrestal Building
Room GH-027

9:00 a.m.	Executive Session	S. Olsen
9:45 a.m.	Break	
9:55 a.m.	Opening Remarks	W. Hess
10:00 a.m.	Activities at Fermilab	K. Stanfield
10:40 a.m.	Activities at SLAC	G. Loew T. Markiewicz
11:20 a.m.	Activities at Brookhaven	N. Samios
12:00 p.m.	Lunch	

Afternoon - Executive Session

1:15 p.m.	Laboratory Visit Reports	S. Olsen L. Lederman C. Baltay J. Sandweiss B. McDaniel
2:30 p.m.	Discussion of Program	S. Olsen
3:45 p.m.	Break	
4:00 p.m.	Discussion of Recommendations and Organization of Report	S. Olsen
5:00 p.m.	Adjourn	

APPENDIX IV

SUMMARY OF ACTIVITIES AT NATIONAL LABORATORIES AND UNIVERSITIES

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Introduction

The following material consists of summaries of the activities at U.S. National Laboratories and Universities conducted under the U.S./Japan Program for Cooperation in High Energy Physics during the period 1988 - 1993. It was prepared based on information provided to the Department of Energy by the Laboratories and Universities at which the activities were carried out.

Activities at Fermi National Accelerator Laboratory

Introduction

Fermilab has been a major part of the US/Japan high energy physics collaboration since its inception about a decade and a half ago. Over the past five years, there have been five collaborative experimental activities, some now completed, some still underway, and others preparing equipment for upcoming runs. The major Fermilab/Japan collaboration has been on CDF, one of the two large detectors at the Tevatron Collider, which is studying the highest energy interactions available in the world at present.

Given below are short descriptions of the five collaborative activities and a brief mention of some of the many physics results. The attached figure summarizes the funding for these projects from the US/Japan agreement over the last several Japanese fiscal years.

Emulsion

This collaboration between U.S. and Japanese physicists began in the late 1970's. The first experiment (E-531) studied neutrino interactions in a hybrid emulsion spectrometer. Among the results were the first reliable measurements of charm particle lifetimes, cross sections for neutrino-produced charm, and the best limit for muon neutrino to tau neutrino oscillations. The expertise of the Japanese groups with emulsions, and the techniques they developed for rapid measurement of emulsion events, were crucial to this success.

The technique was pursued further in E-653, a study of charm and beauty production in a hybrid emulsion spectrometer, using 800 GeV protons and 600 GeV negative pions. Again the use of an emulsion target and the associated measurement techniques, together with the use of silicon strip detectors, proved invaluable in achieving important new physics. Results have been obtained up to now on D meson decay form factors and charm production dynamics. Rare decays of the D meson to muon and muon neutrino, and to tau and tau neutrino, have been observed, the latter for the first time. Decays of charged and neutral b hadrons have been observed in the emulsion, allowing lifetimes and production dynamics to be determined; hadro-produced b pairs have also been studied. Several papers have been published on the above work, and others are in various stages of production at the present time. In

addition, the group has proposed a future experiment on neutrino oscillations using similar techniques; this could take place when Fermilab's Main Injector is complete.

Bubble Chamber

Two experiments were carried out with the Japanese-built Tohoku Bubble Chamber in beams at Fermilab. E-745 was an exposure of over half a million pictures to wide-band beam neutrinos. A unique feature was the holographic optics, developed in Japan, which gave a resolution of 70 microns; this allowed the short charm meson tracks to be observed. Several publications and theses have been based on this work.

The Tohoku chamber was modified, and then used for E-782, which had an incident high energy muon beam. High resolution optics were installed, and a downstream spectrometer provided the trigger. About 13,000 inelastic muon interactions were observed in the 300,000 pictures, and analysis is continuing.

Polarization

Several Japanese groups took part in Fermilab E-704, a study of spin effects using polarized 200 GeV/c proton and antiproton beams, which are the world's highest energy such beams. A new beam was constructed of polarized protons (antiprotons) produced from the decays of Λ^0 hyperons; this unique facility was able to provide either transverse or longitudinally polarized beam particles. Depending on the physics process to be studied, polarized or unpolarized hydrogen targets were used. Beam polarization was measured using the Primakoff effect, and also Coulomb-nuclear interference.

Spin effects in many interactions were studied. Among them were the transverse asymmetry of high- P_t π^0 production, the helicity correlation (A_{LL}) of π^0 production, the transverse asymmetry of high- x_F Λ^0 , π^+ , π^- and π^0 production, and the helicity dependences of pp and $\bar{p}p$ total cross sections. Many theorists have been subsequently interested in the large asymmetry which was observed in high- P_t π^0 production.

Analysis of this data continues, with current emphasis particularly on direct photon production. Final results of this experiment will take another one to two years of data processing and analysis.

Rare Kaon Decays

Construction is underway on the latest in the series of rare kaon decay experiments which have been carried out at Fermilab; this now has a strong participation by Japanese physicists. Previous experiments in the series have published the most accurate values of many rare K^0 and π^0 decay branching ratios, and produced the most significant upper limits on many others. The major result has been a value of the CP violation parameter $\text{Re}(\epsilon'/\epsilon)$ of $(7.4 \pm 5.2 \pm 2.9) \times 10^{-4}$. The new KTeV experiment, now under construction, will reduce the error on $\text{Re}(\epsilon'/\epsilon)$ to 10^{-4} , with corresponding reductions in the uncertainties or upper limits of the other decay modes. This increased accuracy will provide a very sensitive test of the Standard Model.

For KTeV, Osaka University is working on the development of photomultipliers for the CsI calorimeter, which is the most critical piece of the apparatus. The photomultipliers have finally met the tight specifications on linearity and are under production. Osaka has also worked on the photomultiplier bases, where it is essential that the gain is constant to high accuracy up to average anode currents of $50\mu\text{A}$. In addition work has been carried out at Osaka on the experiment's data acquisition system.

This experiment, which has the highest priority of any in the Fermilab fixed-target program, is expected to start taking data in 1995.

CDF

The CDF (Collider Detector at Fermilab) observed its first $\bar{p}p$ collision at the Tevatron Collider in 1985, carried out a test run in 1987, and had its first physics run in 1988/89 with an integrated luminosity of 4.5 pb^{-1} . The 1992/93 run delivered over 30 pb^{-1} to CDF, and some 75 pb^{-1} are anticipated in the 1993/94 run which will start in late 1993. Japanese groups have been significant contributors to the construction of CDF and the physics analysis, and are taking a major role in equipment construction in an ongoing upgrade which will allow CDF to take advantage of the higher luminosities to become available at the Collider by the end of the decade.

CDF has already provided some of the most stringent tests of the Standard Model, and only abbreviated lists of the many topics can be presented here. From the 1988/1989 run, important results have been on the mass and decay width of the W, which give information on the electroweak mixing parameter and the mass of the top; QCD studies with jets and photons; inclusive b quark production; searches for many kinds of postulated new particles, and a direct search for the top quark.

Results from the 1992/93 run are just becoming available, and considerable effort continues on analysis. At the 1993 Lepton-Photon Conference, there were many

papers on these results. Among the more significant are observation of the B_s , b-lifetime studies, and a new top mass lower limit of 113 GeV/c².

Over the next few years, extensive upgrades are planned for CDF, to enable it to take advantage of the higher luminosities planned for the Collider. The Japanese groups are leading the effort, or are heavily involved, in several of these upgrades. Among them are upgrades to the data acquisition system, and the replacement of the existing plug and forward gas calorimeters with a new scintillator-based plug calorimeter.

Summary

Cooperative US/Japan collaborative activities have been an important part of Fermilab's research program since the start of the US/Japan agreement on high energy physics. Japanese physicists have contributed to a number of experiments which are unique in high energy physics because of the use of the highest energy accelerator available. Contributions have been in many areas (equipment, analysis talent, graduate students, etc.) and the Japanese collaborators have taken a full role in achieving the forefront particle physics that has emerged from these studies. Special mention must be made of the substantial Japanese contribution to the CDF detector, one of the two major detectors operating at the highest energy frontier. The physics from CDF is at the current forefront of the field; with the upgrades already planned for the remainder of this decade, our Japanese colleagues are assured of taking part in the most exciting high energy physics research in that time period.

Activities at the Stanford Linear Accelerator Center

The SLC/SLD Program

Results and Analyses of 1993 Run

The major program at SLAC during FY1993 was the physics run of the SLD detector at the SLC using a polarized electron beam colliding with an unpolarized positron beam.

A. Machine

The system of components needed to generate and transport polarized electron beams was installed between 1990 and 1992 and successfully commissioned for the 1992 run. For 1993, the polarized electron source was upgraded with a GaAsP strained lattice cathode and two high power Ti:Sapphire lasers pumped by a pair of YAG lasers. With these improvements, the beam polarization from the source was increased by nearly a factor of three, to 70-75%.

The 1993 run began in January, with two months of recommissioning and machine development studies. The SLD physics run began in March and continued through August, although half of the machine time in July and August was devoted to the first runs of the Final Focus Test Beam and to polarization experiments. Midrun it was found that there was a significant difference between the polarization measured by the Moller polarimeter at the end of the Linac and that measured by the Compton polarimeter near the Interaction Point which could not be explained by measurements of depolarization effects through the North Arc transport. Resolving this discrepancy became the highest priority for the SLD collaboration, causing a shift away from production luminosity. During the 1993 SLD physics run, the average number of Zs logged per week was a factor of 2.5 higher than in 1992 and a factor of 25 higher than in 1991. Over 4400 Zs were logged in a single week, with peak instantaneous luminosities up to 50 Zs per hour. The SLD averaged 10,000 Zs on tape per month, almost as many as in the entire 1992 run. The biggest gains came from a switch to a flat beam mode of operation with vertical beam size much smaller than the horizontal. The beams were focused to a size of 2.6 microns by 800 nanometers at the interaction point, producing a beam area of 2.1 microns squared, smaller than the original SLC design value of 2.9. Partial control of the Damping Ring microwave instability by manipulations of the RF profile allowed a 10-20% increase in beam

intensity. Machine uptime was excellent (70-80%), and flat beam operation produced an added bonus of very low backgrounds allowing high efficiency for SLD logging. By the end of the run, over 50,000 Zs had been logged by SLD with an average polarization of 63%.

For the 1994 run, better cathodes and a possible reduction of depolarization through the SLC Arc will increase the beam polarization to about 70%. In addition, two major upgrades to the SLC will be installed. The RF impedance of the SLC damping rings will be reduced by replacing the existing vacuum chambers with smoother ones. This will allow stable operation with higher beam intensity and reduce the energy spread of the beams. The optics of the SLC final focus systems will be modified to cancel third order aberrations and provide more diagnostics to facilitate tuning. These improvements are expected to increase the specific luminosity by a factor of 2-3 and permit operation with higher currents. For the 1994 run there will be a lengthy commissioning period and a gradual learning curve before the full benefit of these upgrades is achieved. The SLD should record over 100k events in 1994, reaching a rate of 250k events per six month run for 1995.

B. Detector

The SLD took its first long physics run in 1993 with the twin benefits of much higher luminosity and much higher polarization. By the end of the run it had written to tape more than 50,000 hadronic Z^0 events produced with an electron beam polarization averaging 62%. The contrast with last year's run 11,000 with 26% polarization amounts to an improvement to the precision of the polarization-related measurements of a factor of six.

The leading result from the SLD run is the world's single most precise measurement of the fundamental parameters of the Standard Model from asymmetry measurements. The statistical errors for the left-right asymmetry, A_{LR} , and the extracted mixing angle are:

$$A_{LR} = \pm 0.0074$$

$$\sin^2\theta_W = \pm 0.0009 .$$

The precision on the mixing angle is seven times better than achieved in the previous run and exceeds the precision of any category of the LEP measurements.

The precision vertex detector, the only CCD-based system in operation at a collider, is routinely used to reconstruct primary and secondary vertices to unmatched precision in any other experiment. By itself it is providing excellent physics in heavy flavor.

Together with polarization, it provides unique measurement techniques for quark asymmetries. All detector systems have been used in several QCD studies, giving results competitive with those from LEP and also some new studies that include polarization effects.

The endcap Čerenkov ring-imaging detector, CRID, was commissioned during this run, completing all particle detection systems for the experiment. Particle identification from both the barrel and endcap systems should soon be incorporated in the mainline analysis.

Higher luminosity and longer running times, together with some increase in polarization (already near the maximum) is expected at the collider in the next running periods. This will provide a much larger and richer data sample, enabling asymmetry measurements sensitive to the mass of the top quark and Higgs boson at a level unsurpassed by other experiments; direct measurements of the time development of BB mixing; and a continuing program of precision $\{qcd\}$ studies, including some interesting avenues related to polarization effects.

Results and Analyses of 1992 Run

The SLD began its physics program in 1992, following its installation and successful commissioning at the collider in 1991. During the three-month data run, 11,000 hadronic Z^0 events were recorded on tape for analysis together with about 2000 wide-angle electron pairs and about 300 tau and muon pairs --- all produced with the electron beam longitudinally polarized at up to 26%. An additional 1000 events were collected at the beginning of the run with an unpolarized beam during machine tune up. The machine and detector work that brought about this big improvement for the 1992 running and those planned for the coming years are discussed below.

Preliminary results are already available from the 1992 data including a first measurement of a fundamental parameter of the Standard Model of the electroweak interaction, studies of the B system, and independent analyses of QCD models. These results are discussed below together with the vital physics program made available by planned increases in polarization and luminosity in coming runs.

A. Precision tests of the Standard Model

The leading result from the SLD run is the world's first measurement of the left-right asymmetry in the Z^0 hadronic cross section, A_{LR} . The basic parameter of the standard model, $\sin^2\theta_W$ may be extracted independently from this asymmetry.

The preliminary values are:

$$A_{LR} = 0.10 \pm 0.045$$

$$\sin^2\theta_W = 0.237 \pm 0.006 .$$

These values are already in league with those obtained by less direct measurements of the final states at LEP requiring about 100 times more integrated luminosity. For example, the error in $\sin^2\theta_W$ as determined by the forward-backward asymmetry in electron-pair decays of the Z^0 ranges from ± 0.006 to ± 0.010 in the four LEP experiments based on the sample available in 500,000 hadronic decays.

B. B physics

The precision vertex detector, the only CCD-based system in operation at a collider, has been used to reconstruct primary and secondary vertices, giving a handle on separating and studying the b-quark events in the total sample of hadronic decays. The first welcome result from reconstruction is that the machine collision point itself is stable to better than 10 microns short term, essentially giving an additional restraint on fits. Thus, the advantage of the very small beam spot in a linear collider can in fact be realized.

Using the vertex detector tracking to identify the large impact parameter characteristic of B decays provides an efficient method to tag Bs. This has already given a preliminary value for the branching ratio for Z^0 decay into b-quarks of

$$R_b = 0.22 \pm (0.03) \pm (0.03)$$

where the first error is statistical and the second is systematic, primarily from Monte Carlo modeling of the detector and of fragmentation. This result, which is based on the 1992 data should improve to a statistical error of about 4% and significantly smaller systematic errors, competitive with LEP.

C. QCD physics

The collaboration has completed three established analyses of the data using jet rates, energy-energy correlations, and the forward-backward asymmetry of the

correlation, extracting values for the strong coupling constant, α_S . The value for the jet rate analysis is:

$$\alpha_S(M_Z) = 0.119 \pm 0.002 \pm 0.003 \pm 0.014,$$

where the errors are statistics, systematics, and theoretical modeling uncertainties, respectively. The other analyses give comparable results.

A recent compilation of world data on the strong coupling constants based on nine techniques at six detectors at four different machines included the three entries from SLD, reporting

$$\alpha_S(M_Z) = 0.120 \pm 0.006.$$

Continuing Physics Programs

The continuing program for SLD physics is based on the unique features provided by SLD and SLC --- polarized incident electrons and a close-in 3-dimensional CCD-based vertex detector. In addition the Čerenkov Ring Imaging Detectors (CRIDs), will be incorporated in event analyses to aid in particle identification.

This program is complementary to that of the LEP with its much higher luminosity, but unpolarized and larger area beam.

The measurements outlined below are based on the projected running for 1993 and 1994 giving better than 50,000 Z^0 's per year with an electron polarization of 40%. Reference is also made to the possibility of polarizations closer to 65%, if the current R&D on new cathode materials can be successfully applied to the high-current collider guns.

A. Precision Tests of the Standard Model

The primary emphasis will continue to be the direct left-right asymmetry but with errors shrinking to the point where the comparison of the extracted value of $\sin^2(\theta_W)$ with that obtained by LEP from the precision mass measurement of the Z^0 will be sensitive to the mass of the top quark and Higgs. Assuming further that the top quark mass is known within that time, the asymmetry measurement can be used to set an upper limit on the Higgs mass. With 100,000 Z^0 's produced with a 40% polarized electron beam, the 90% confidence level upper limit to the Higgs's mass is about 1000 GeV. This would improve sharply with an increase in polarization to 65%, giving a limit significantly better than that available from LEP even under the generous assumptions

of statistically independent experiments, combining different techniques, and no systematic error limit in dealing with several million events.

Additional analyses for electroweak effects will also be available for the subsequent data by looking at the forward-backward asymmetries marked by the initial state polarization, including the application to b quark decays by themselves.

B. B Physics

In a manner analogous to that of K mesons, the neutral B mesons mix by higher order processes, involving in this case the top quark and W boson. The physical consequence is that a pure B^0 , for example, will change into $B\bar{B}^0$ over time and back before it decays. The observed decays will reflect this in like-sign dilepton in the final state, for example. The much stronger signature for this process is to observe the mixing over time directly, by dividing the sample for B decays of different time. The SLD is suited to this more sophisticated analysis by the good vertex detection to measure the decay time. Moreover, the polarization of the electron beam greatly enhances the production of the B rather than B in the forward hemisphere. Incident electrons will produce a substantial forward-backward asymmetry for $B\bar{B}$ pairs from Z^0 decays, with the forward-going jet more likely to a B than a B . This provides a very efficient B or B tag for the $B\bar{B}$ mixing measurements.

With 100,000 Z^0 s and 40% polarization, the time development of mixing can be measured for the B_d^0 system and possibly observed in the B_s^0 system.

With these same tools, a variety of other topics will be explored, including B lifetime and branching ratios, b -quark forward-backward asymmetries, and τ lifetime, all of which will be limited by systematic errors at that level rather than statistics.

C. QCD

The QCD topics, which are already being thoroughly explored with the current data sample, will be expanded to include subtle effects from the polarized beam. For example, the beam polarization coupled with the large forward-backward asymmetry produces a large correlation between quark direction and quark polarization. In the case of strange-quark production, fragmentation into final states with a λ allows a measure of final state polarization. Spin transfer in the hadronization process is then available for study, provided the statistics get to the expected level.

Higher polarization and luminosity expected at the collider in the next running periods will provide a much larger and richer data sample, enabling asymmetry measurements sensitive to the mass of the top quark and Higgs boson at a level unsurpassed by other experiments; direct measurements of the time development of $B\bar{B}$ mixing in

both B_s and B_d systems; and a continuing program of precision QCD studies, including some interesting avenues related to polarization effects.

The barrel Čerenkov ring-imaging detector, CRID, was fully operational and has successfully identified particle species in hadronic decays. The endcap CRID, which was partially installed, will be completed during the down time. Particle identification will be incorporated in the mainline analysis in the coming runs.

Combining this with the high resolution of the detector and its unambiguous determination of hits will permit competitive physics in lifetime measurements and b-tagging. Combined with the polarization information, it will provide a unique measurement of quark asymmetries similar to A_{LR} .

CRID Subsystem Progress Report

The CRID project made good progress throughout the summer of 1993. The barrel system was in full operation in the spring-summer run, while the SLD accumulated over 50,000 Z^0 events with an average polarization of greater than 60%. The CRID hardware performed reliably during the data taking and down time due to hardware failures was insignificant. The fluid systems performed well and maintained the required gas and liquid purities. The data acquisition electronics and TPCs also performed well. However, channel attrition rates approached 20% by the end of the run. Most of these losses were due to the breakage of 7 μm carbon filaments during the course of the run in a number of TPCs. There was no access permitted during the run for electronic or chamber repair, and only one access was allowed to repair a water leak. The observed Čerenkov efficiencies were consistent with those obtained in the 1992 run, and the number of Čerenkov gas photons observed increased due to a higher fraction of C_5F_{12} in the mix. Local TPC resolutions close to design values were observed.

All end cap chambers were installed on both ends before the beginning of the run, and commissioning of the systems continued throughout the run. By the end of the cycle, ethane- CO_2 mix with 23% TMAE was running into both end caps with a good lifetime performance in the ELMs. The C_4F_{10} system was operating, and some data from hadronic Z^0 events was accumulated at the run's end. Following the run, a number of special runs were conducted to observe cosmic ray muons and to study the single electron performance with the optical fiber injection system. A few early results of these studies will be discussed below.

The barrel TPC gas during the run consisted of C_2H_6 bubbled through liquid TMAE at 26° (about 3° higher than during the 1992 run) resulting in about 0.1% TMAE by volume. Due to difficulties in obtaining high purity ethane, the gas flow was typically 4 l/m, so that the gas in each TPC was changed about every eight hours. The ethane gas was purified by both a 13X molecular sieve and a proprietary oxygen removal filter called an Oxisorb. Typical oxygen levels at the exit of the TPCs were less than 0.5 ppm with water levels below 5 ppm. The electron lifetimes remained excellent (over 160 μsec) during the run. The continuing breakage of carbon filaments (seven in all) is a cause for concern, and was the dominant source of lost readout channels. As of this writing, all broken chambers have been repaired and replaced in SLD. Studies are underway to attempt to understand the mechanism causing breakage.

The barrel gas radiator during the 1993 run was typically a recirculated mixture of 76% C_4F_{12} plus 24% N_2 . The vessel volume of about 13,000 liters was exchanged approximately every six hours via a thermally driven engine. During the run, the mixture was monitored by sound velocity at several points inside the vessel and no

stratification was observed. Impurities were removed in a two-step process. The first step was a distillation process, which also provided the pressure head required for circulation, while the second step consisted of liquid phase purification through a system of filters. The transmission was directly monitored in a U.V. cell and remained high and stable throughout the run. A typical result is shown by the solid points in Fig. 1. The distillation cycle in the heat engine effectively separated out a number of contaminants with low U.V. transmission, which were frozen in the system until the tank was warmed up between cycles. The open circles in Fig. 1 shows the transmission of a particular mix of these contaminants obtained from residual liquid left in the tank after warm-up following the 1992 run.

The liquid C_4F_{14} radiator circulation and filtration system also worked extremely well during the run. The typical transmission before cleaning the liquid is shown by the dashed line in Fig. 2(a). Before the run began, the radiator was deoxygenated by N_2 entrapment. The O_2 levels were further reduced to less than 1 ppm by passing the liquid through the Oxisorb, yielding the transmission shown by the solid line in Fig. 2(a). Oxygen and other impurities were continuously removed during the run with this system. The transmission of this radiator system remained stable throughout the run, as shown for example by Fig. 2(b) for a two-month period in the early portion of the run.

Many factors can affect the overall performance of the CRID, and a significant analysis effort is required to extract particle identification information from the raw CRID hits. In general, the corrections to CRID data internal to the CRID system are now understood and are about the size expected. Many of these effects, such as drift velocity variation, charge division offsets, distortions along the edges of the TPCs, and distortions due to the magnetic field, can be monitored and corrected using the fiducial marks provided by the fiber optics pulsing system. Other effects, particularly related to relative alignment of CRID components and the CDC, are more difficult to solve and are still being studied. These issues are made more difficult by the rather high level of background noise from the SLC. Results from cosmic rays and an early look at the 1992 Z^0 data were discussed in our March report to this committee. Here, we will discuss some additional features of the performance in cosmic events and the Z^0 data.

Figure 3 shows a number of the major components which contribute to the efficiency of photon transport and subsequent conversion into observed photoelectrons. They are derived from a collection of efficiencies (1) measured during the construction period (quartz transmission, mirror reflectivity, and TMAE quantum efficiency), (2) measured by routine monitoring throughout the run (U.V. transmission of the radiators), and (3) measured in separate systems or calculations, such as absorption by field cage wires, electron lifetime, chamber inefficiencies, etc. The resulting final efficiencies are shown by the open circles in Fig. 3, which are then integrated to

estimate N_0 . Estimated N_0 's obtained in 1992 are $56\text{-}66\text{ cm}^{-1}$ for the gas radiator and $32\text{-}42\text{ cm}^{-1}$ for the liquid.

These estimates are consistent with the number of photoelectrons observed in cosmic ray and di-muon events. For example, about 18 photoelectrons are observed in a full liquid ring, and about eight are observed per gas ring in cosmic rays-- implying $N_0 = 45\text{ cm}^{-1}$ for the liquid and $N_0 = 63\text{ cm}^{-1}$ for the gas. The numbers obtained for the gas are about 8% higher in 1993 because of the increased fraction of C_5F_{12} in the gas.

Figure 4 shows liquid rings from a sample of hadronic Z^0 events in the 1992 data. Though the rings are clearly visible in these integrated plots, there is also a substantial amount of background. Much of our present effort is directed at characterizing and reducing these backgrounds. An example which illustrates our approach is shown by the different histograms in Fig. 5 which demonstrate the effect of a number of different cuts: histogram (a) includes all non-saturating hits in the chamber associated with the track; histogram (b) includes only those hits with reasonable TMAE absorption length; and histogram (c) adds cross-talk and amplifier recovery cuts. Further improvements are in progress. The local resolution on the Čerenkov angle is close to the design value (about 12 mr), however there is a global systematic error of about 10 mr which is probably dominated by a number of global misalignment effects. The present particle separation capability of the liquid system in hadronic Z^0 events is illustrated in Fig. 6. Figure 6(a) shows the reconstructed radius of the liquid rings versus $\ln P$ (in GeV/c) for a sample of events from the 1992 run. Clear π , K, and p bands can be seen. The separation of particle types in narrow momentum bands can be observed in Figs. 6(b) and (c). Figure 7 demonstrates the power of liquid radiator particle identification in extracting mass signals from the data. Figure 7(a) shows the invariant mass distribution from a sample of hadronic events taken in 1992 run where all oppositely-charged particle pairs are called kaons, while figure 7(b) contains only those pairs with at least one positively identified kaon in the CRID. The ϕ emerges cleanly from the background with particle identification, whereas it is essentially non-observable before.

Figure 8 illustrates the present status of gas ring identification in hadronic Z^0 events. A $\beta = 1$ particle gives approximately eight photoelectrons per ring, and the local resolution is close to the design value (about 4-5 mrad). However, again the systematic errors are approximately 10 mrad.

The endcap CRID subsystem has now entered the final stage of commissioning. Several milestones were reached during the summer run: the drift boxes were exposed to the $\text{C}_2\text{H}_6/\text{CO}_2$ gas mixture with TMAE; the vessels were filled with C_4F_{10} for the first time, and end cap CRID data was taken during SLD running at the Z^0 . Approximately 22000 Z^0 events were collected with the north endcap CRID and 3000 Z^0 events with the south endcap CRID. A significant effort is currently taking place on the offline software, and progress has been made in calibration and detector

response studies. Substantial effort has also gone into the geometrical description of the detector and the one-event graphics display.

The addition of TMAE to the drift gas allowed UV fiber fiducials to be observed (see Fig. 9), which shows hits in the plane perpendicular to the drift field direction for a number of chambers. This provides the first direct demonstration that the chambers work with single photoelectrons as designed and that the Lorentz-angle correction electrostatics are correctly understood. Following the run, a number of cosmic ray runs were undertaken and ring candidates of the expected radius were observed, as shown in the "typical event" of Fig. 10. Work is now underway to link charged tracks from the drift chambers to the reconstructed hits inside the endcap CRID. The endcap CRID is now undergoing final system commissioning and is expected to be fully operational by the beginning of the 1994 data taking.

Figure Captions

Figure 1. The U.V. transmission in the gas radiator measured in 1 cm of liquid--phase C_5F_{12} during routine CRID operations (solid dots) and in the material remaining in the tank after warm--up at the end of the 1992 run (open circles).

Figure 2. The U.V. transmission of 1 cm of C_6F_{14} liquid radiator: (a) typical transmission versus wavelength performance during operations (solid line), and after several days without circulation (dashed line); (b) time history of U.V. transmission for a two month period.

Figure 3. The predicted efficiency for the 1992 data as a function of wavelength for conversion of Čerenkov photons into detected photoelectrons (open circles): the major components of the overall efficiency are shown by the labeled curves.

Figure 4. Liquid rings observed for a sample of 1992 hadronic Z^0 data: (a) full rings (near 90°); (b) partial rings (a portion of the ring is totally internally reflected in the radiator).

Figure 5. Typical Čerenkov angle (θ_c) distributions with different background removal procedures: (a) before cuts; (b) after restricting the conversion length in the TMAE; (c) after also including cuts to remove hits due to electronics cross-talk and pulses created during amplifier recovery from saturated hits.

Figure 6. Particle identification performance of the liquid radiator CRID system for a sample of 1992 hadronic Z^0 data: Čerenkov angles versus log of the momentum (GeV/c); (b) a narrow momentum projection showing $\pi/K/p$ separation; (c) a narrow momentum projection below p threshold showing π/K separation.

Figure 7. The invariant mass distribution for kaon pairs for a sample of 1992 data: (a) all oppositely charged particle pairs are taken to be kaons; (b) includes only pairs with at least one positively identified kaon in the liquid Čerenkov.

Figure 8. Particle identification performance of the gas radiator CRID system for a sample of 1992 hadronic Z^0 data: (a) angles in Čerenkov angle space; (b) projected Čerenkov radius distribution; (c) distribution of the number of photo--electrons observed per ring; (d) residual of individual hits with respect to ring radius (the local resolution).

Figure 9. Time--domain projections at the chamber from the fiducial fiber system for a number of end cap chambers.

Figure 10. A single cosmic ray observed in the endcap CRID.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig 8

Fig. 9

ID= 41

Detected hits in the CRID

XTPC

5: 10

16-AUG-1993 15:47:04

Central Drift Chamber Performance

The Central Drift Chamber (CDC) was installed within the SLD detector in the Collider Experimental Hall on May 17, 1990. By September 1, 1990 100% of the chamber-mounted front end electronics, controller cards, and cable plant were installed and working. The CDC fully participated in the September 1990 and January 1991 cosmic ray runs where roughly 100,000 tracks were recorded on tape (see 1991 version of this report). During the first SLD engineering run, April 1, 1991 through August 15, 1991, 363 Z events were recorded. The chamber's performance during this period was reported in last year's version of this report. In 1992 SLD began its first physics run. It was highly successful: about 11,000 Z's, produced with electrons having an average longitudinal polarization of 22.4%, were recorded on tape. This report will focus on the performance of the CDC during this run and, in particular, on the physics results we have achieved using the CDC together with the silicon pixel (Charge Coupled Device) based vertex detector (VXD) that was operational for the first time during the 1992 run.

With the 1992 run the focus of activity within the tracking group switched from hardware to software. Improvements in this domain will constitute the majority of the report. This section summarizes the hardware improvements or changes implemented in 1992 relative to the 1991 engineering run.

The failed bypass capacitor on L8 (recall that the CDC is composed of 10 superlayers, labeled L0 to L9, each composed of 8 wire layers), was replaced before the run, and the resulting loss of efficiency in it and in its adjacent layers cured. Figure 1 shows the hit efficiency observed as a function of layer number (1-80) in 1992. The drop at the inner layers is due to lost data in high background conditions and the loss of one of four readout boards.

There continue to be two major consequences to the operation of the CDC from the varying and sometime large noise conditions that the SLC can produce. Firstly, HV trips continue to occur due to "fliers", that is single rogue beam pulses caused by misfiring klystrons or other failures in the accelerator. Diagnostic capacitive monitors have been installed on the inner layers of the CDC which dump the beams when pulses over a given threshold are detected. Thus the chamber is protected against multiple bad beam pulses. A system of ADCs were installed to monitor the state of the drift chamber HV on an event-to-event basis so that when trips do occur, the offline analysis can be aware of them and make the appropriate corrections. Secondly, photon interactions in the CDC, presumably on the guard wires, cause very large pulses which couple to many other adjacent wires. Diagnostic work indicates that this is due to the mutual capacitance of the field wires and the lack of sufficient space for decoupling resistors or capacitors on the field wire HV

distribution system. As thresholds are lowered to increase our efficiencies for low multiplicity physics, notably tau and dimuon events, these become increasingly a problem which must be dealt with offline.

The CDC continued to lose its gas tightness during the year. This is ascribed to a poor choice of the adhesive used to seal the guard-sense wire bundle blocks to the endplates. Nevertheless, the double buffered gas system provided by the covers over the electronics volume maintained the oxygen content in the gas to between 20 and 35 ppm. No loss of pulse height with drift distance was observed. After unsuccessfully temperature regulating the gas system mixing rack by cooling during the engineering run, a scheme was implemented where heaters maintained constant temperature and thus limited diurnal fluctuations in the gas mix. This required raising the water content of the gas from 2000 ppm to 4500 ppm.

About halfway through the run, the SLD data acquisition system was upgraded to allow for different types of triggers and a trigger allotted to the Photo Electron Source (PES) laser calibration system. This system measures the variation of drift velocity with pressure and temperature by measuring the variation in drift time of electrons emitted from needles internal to the CDC by pulses of UV light from a nitrogen laser. While not completely incorporated into the data analysis chain, and still needing improvements, the system was demonstrated to work. Figure 2a shows the variation in measured drift time as a function of time. Figure 2b shows the drift velocity as measured with this system versus that measured directly from the data. Once the calibration is understood we should be able to improve our measurement of v_d considerably.

The electronics failure rate during the run was acceptably low. Out of 170 mother boards in the system, 3 had failed completely by the end of the run. The double sided readout of the CDC protected us from completely losing information. The electronics were typically operated with waveform thresholds of 75 mV and the hit thresholds (for the tracking trigger, see below) of 150 mV. Analysis after the run has revealed a loss of efficiency at the center of the wires, where the pulse height divides evenly. This has contributed to the track reconstruction inefficiency and plans are to lower thresholds, to the extent allowed by DAQ dead times and buffer limits, for the 1993 run.

Two major improvements to the drift chamber data acquisition system were implemented in 1992. First, a new waveform analysis program was developed to run in the Waveform Sampling Modules (WSMs). The old algorithm was a simple threshold cut, which led to poor timing information and poor multi-hit resolution. The new algorithm much more closely follows the offline version, looking essentially at changes in the first derivative of the waveform. Second, a CDC tracking trigger, independent of the calorimeter, was installed. This worked very well, with a 99% efficiency for double tracks while it was sensitive. Unfortunately, it pointed out a

new source of SLC background. Inelastic eN interactions on the masking elements closest to the vertex provide a continuous source of low multiplicity events with tracks in the 0.2-2 GeV range. Their frequency caused this trigger to fire too often and required that it be used in a rate limited mode, thereby lowering its sensitivity to tracking events of interest. Background studies in SLC early in the 1993 run will likely allow the rate limit condition to be eliminated or relaxed.

Combined Drift Chamber - Vertex Detector Tracking Results

The analysis of the drift chamber benefited greatly from the need to extrapolate tracks accurately and efficiently to the CCD-based vertex detector. This detector is composed of 4 layers of CCD's with $22\ \mu\text{m} \times 22\ \mu\text{m}$ sized pixels, yielding local cluster resolutions of $7 \times 9\ \mu\text{m}$. The drive to extract B-meson physics led to a huge and largely successful effort in determining CDC systematics. Figure 3 shows an example of the power of the CDC-VXD combination, the xy view of a Z decaying into 2 B mesons. In part (a) the scale is such that only the CDC track fits are visible. Part (b) shows the extrapolations of the CDC tracks to the VXD region and the matching VXD clusters. If the picture is expanded even more (Figures 4a,b) the displaced vertices from the B decays are clearly visible in both views. SLD has the unique capability of reconstructing these vertices in both views, thereby eliminating combinatoric backgrounds, and having a beam spot that is small enough ($2\ \mu\text{m} \times 2\ \mu\text{m} \times 750\ \mu\text{m}$) to contribute negligibly to the systematic errors in displaced vertex driven physics.

After alignment of the CDC-VXD system the efficiency for linking good CDC tracks to the VXD is 96%. Figure 5a shows this efficiency as a function of momentum, and figure 5b shows it as a function of ϕ . The slight dips in ϕ are due to dead CCD chips in the VXD. A detailed understanding of this efficiency is one of the 2 dominant detector systematic effects in any B physics result.

On average, 15.9 tracks are found in Z events in the CDC and the overall track reconstruction efficiency is measured by the MC as 93%. The 1991 analysis had non-understood discrepancies in the track finding efficiency depending on the proximity of the track to the core of a jet. The 1992 analysis has determined the two hit timing resolution to be 80 ns. When this is taken into account in the MC, excellent agreement with the data is achieved. Figure 6 shows the number of tracks found in the data (points) and MC (histogram) as a function of the ϕ distance of the track from the thrust axis for Z events. The small residual discrepancy near the thrust axis is under study.

Many improvements to the understanding of the chamber were made and implemented in the analysis in 1992 to make this kind of agreement possible. Individual timing corrections for each wire end were found and implemented.

These came from previously non-understood subtleties in the phasing of the 8.3-ns (119 Mhz) clocking signals to the mother boards. The 4-8 ns improvements in the timing of each board lead to much improved track chi-squares.

A large effort was made to use the data itself to measure drift velocity changes and generate a run-by-run constants base of the calibration. Essentially, track chi-squared is minimized as a function of v_d . Figure 7 shows the relationship of the thus determined fractional corrections to the nominal v_d to the pressure measured in the CDC. As the CDC is maintained at constant temperature, v_d is expected to vary as 1/pressure. The overall change in the drift velocity can be as much as 2%; the scatter of points indicates that the calibration procedure tracks it to the level of about 0.4%. It is hoped that the PES system mentioned earlier will bring the knowledge of v_d down to the 0.1% level for 1993.

In 1991 an electrostatic model of the CDC was used to get a time to distance relationship in the chamber; this relationship was then corrected using the data to generate one correction function for all 80 wire layers. To achieve systematic understanding at the sub 100 μm level it was required that this procedure be enhanced to allow for individual wire layer differences (80 correction functions) and that the procedure be iterated. The major benefit was in pulling in hits which were on the tails of the resolution distribution, particularly near cell boundaries. Additionally, the procedure allowed the data to be automatically corrected for a floating field wire (1 of 18 in L5) that became detached from its HV supply as the chamber covers were closed just prior to the run.

Lastly a charge division calibration procedure was implemented which succeeded in bringing the z resolution as measured by charge division down from 3% of wire length to 2%, and more significantly, corrected the tails of that distribution.

Figure 8 shows the intrinsic (or local) resolution of the hits found on track segments within 11.5° of radial as a function of drift distance in a cell for the 1991 analysis (lines) and 1992 analysis (filled diamonds). In the linear field region the data follow the curve expected from diffusion (75 μm at 1cm and varying as $\sqrt{d}$), whereas near the guard and field shaping wires one can readily see the effect of the rapidly increasing electric field on the drift velocity in the chamber's unsaturated gas. Figure 9a shows the local resolution for those hits in the linear field region between 0.5 cm and 2.5 cm. The full width at half maximum (FWHM) of 160 μm leads to a resolution of 68 μm . While the measured intrinsic resolution of the chamber is as per design, the determination of wire by wire geometrical corrections that affect the global spatial resolution and momentum resolution eludes analysis. These are suspected to be due to tilts of the guard-sense wire bundle blocks in their slots and is currently the subject of much investigation. The current result for the global track resolution, again for those hits between 0.5 cm and 2.5 cm and track segments within 11.5° of radial, is shown in figure 9b. The full

width at half maximum (FWHM) of 200 mm leads to a resolution of 84 mm. Relative to the 1991 analysis the local resolution has improved by about 10% and the global resolution by about 20%.

It is these and other basically geometrical uncertainties that dominate the momentum resolution of the chamber. The momentum resolution is studied by looking at that relatively small sample (out of 100,000 triggers) of cosmic ray tracks that pass through the vertex area and can be broken into two parts and compared. Figure 10a shows the difference in measured $1/p$ (divided by the statistical factor of $\sqrt{2}$) for those cosmic tracks with $p > 5$ GeV/c momentum using the 1991 analysis; the fit resolution is $\sigma(1/p) = 0.0150$ (GeV⁻¹). Figure 10b shows the same quantity for the same data using the 1992 analysis; the fit resolution in this case is $\sigma(1/p) = 0.0081$ (GeV⁻¹). For large momenta, the design resolution is $\sigma(1/p) = 0.0025$ (GeV⁻¹). Figure 11 elaborates on this comparison of the momenta of cosmic ray track halves by plotting $\sigma^2(1/p)$ vs. $1/p^2$. In these variables the y-intercept measures the component of resolution due to measurement error and the slope the component of the resolution due to multiple coulomb scattering (MCS). This plot accentuates the improvement achieved in 1992; not only is the large momentum value better, but the slope is also reduced, reflecting a better treatment of MCS in the fitting procedure. Figure 12 shows the distribution of charge over momenta measured by the CDC in dimuon events; the curves are Gaussian fits to $1/p$. The mean value of $1/p$ is 0.0197 ± 0.0007 (GeV⁻¹) for the negative muons and 0.0226 ± 0.0007 (GeV⁻¹) for the positive muons, approximately equal to each other and to the expected value of 0.0219 (GeV⁻¹). Their resolutions are (0.00713 ± 0.0006) (GeV⁻¹) and (0.00678 ± 0.0006) (GeV⁻¹), respectively; which are about 3 times the design value and in agreement with what we observe in the cosmic ray analysis.

Figure 13a (b) shows the two-prong miss distance in xy (rz) for dimuon and wide-angle Bhabha events for tracks without including the VXD hits on the track. The two-prong miss distance is the separation between the extrapolations of the two tracks at their distance of closest approach. The curves are fits to the data of the sum of two Gaussians; the fits give $\sigma = 240$ μ m (xy) and $\sigma = 3.4$ mm (rz) for the dominant central parts and $\sigma = 340$ μ m (xy) and $\sigma = 4.8$ mm (rz) for the small tail component. The rz view has much poorer resolution due to the CDC z coordinate measurement using the 41 mrad stereo wires. Figure 13(c) and 13(d) show the two-prong miss distance for the same tracks where now the linked VTX hits have been added to the fits. The resolution improves by more than a factor of 15 in xy ($\sigma(\text{core}) = 16$ μ m, $\sigma(\text{tail}) = 23$ μ m) and by a factor of 70 in rz ($\sigma(\text{core}) = 47$ μ m, $\sigma(\text{tail}) = 66$ μ m). The fact that the CCD pixels have the same excellent resolution in both dimensions is what causes this dramatic improvement.

The road to B physics relies on efficiently tagging those events with a large number of tracks significantly displaced from the vertex. The impact parameter of a track is the distance of closest approach of the track extrapolation to the interaction point (IP); it

is signed by whether it is in the same (+) or opposite (-) hemisphere as the jet to which it belongs. Its quality is determined by how well one can measure the IP position and extrapolate the tracks. Figure 14 shows the xy impact parameter measured for the combined sample of dimuon and wide angle Bhabha events. The Gaussian fit has a sigma of 22 μm , which reflects essentially the resolution of the two prong miss distance divided by 2 and the error on measuring the IP, currently about 18 μm . As $c\tau = 387 \mu\text{m}$ for B mesons and 91 μm for t leptons typical decay lengths are on the order of 2 to 4 mm. The excellent resolution of the CDC+VXD system thus allows for high purity efficient tagging of B and t events for physics analysis.

Future Plans

The CDC is already taking data in the 1993 SLC/SLD physics run. All HV and electronics problems have been fixed. The prototype mother boards on Layer 0 have been replaced with production versions with better ground planes and less wire patches. The tracking trigger has been hardened against the backgrounds observed in 1992 and the waveform algorithm again improved. The first attempts at running SLC in flat-beam mode have resulted in reductions of CDC backgrounds by about a factor of two and record luminosities of 33 Z/hr.

As prospects for the future of SLC/SLD continue to improve plans are being made to allow for an extended CDC running life. Hardware to continuously monitor the charge deposition in the CDC and its effect on chamber aging is in design. The unavailability of the now out-of-date custom chips (Data Correction Units) in the WSMs and the resulting inability to service the WSMs over an extended period has led a group to form to discuss a new design for their replacement.

The major improvement in the software is expected to be the final geometrical alignment. Less specifically, we expect that as the Cerenkov Ring Imaging Detector analysis develops, it will, as the VXD has done at small radius, demand improved performance from CDC tracking and help uncover its current limitations.

Figure Captions

Figure 1: Hit efficiency vs. layer number (or radius).

Figure 2a: The variation (in ns) of the drift time measured by the PES system over a 3-month period.

Figure 2b The variation in the drift time measured by the PES system versus the correction to the drift velocity as measured directly from the data.

Figure 3(a,b): The xy view of a Z decaying into 2 B mesons. In (a) you see the CDC track fits. In (b) the scale is such that you are seeing the CDC track extrapolations and the VXD clusters.

Figures 4(a,b): The event of figure 3 on a scale where the displaced vertices from the B decays are clearly visible in both views.

Figure 5a (b): CDC-VXD linking efficiency as a function of momentum (ϕ).

Figure 6: The number of tracks found in the data (points) and MC (histogram) as a function of the ϕ distance (radians) of the track from the thrust axis for Z events.

Figure 7: The relationship of the fractional corrections to the nominal drift velocity as determined from the data to the pressure measured in the CDC in inches of water.

Figure 8: The intrinsic (or local) resolution of the hits found on track segments within 11.5° of radial as a function of drift distance in a cell for the 1991 analysis (lines) and 1992 analysis (filled diamonds). The line indicates the approximate contribution to the resolution that we would expect from diffusion.

Figure 9a: Local spatial resolution for hits with drift distance between 0.5 cm and 2.5 cm.

Figure 9b: Global spatial resolution for hits with drift distance between 0.5 cm and 2.5 cm.

Figure 10a: The difference in $1/p$ (divided by the statistical factor of $\sqrt{2}$) for cosmic ray tracks with $p > 5$ GeV/c momentum, as measured with the 1991 analysis.

Figure 10b: The same quantity as in 11(a), but measured using the current analysis.

Figure 11: The square of the rms of the $1/p$ difference distributions ($=\sigma^2(1/p)$) plotted vs. $1/p^2$ for the same cosmic ray data as measured with both the 1991 analysis and 1992 analysis. The solid curve is the design report expectation.

Figure 12: The distribution of charge over momenta measured by the CDC in dimuon events; the curves are Gaussian fits to $1/p$.

Figure 13a (b): The 2 prong miss distance in xy (rz) for dimuon and wide angle Bhabha events for tracks measured solely using the CDC.

Figure 13c (d): The 2 prong miss distance in m in xy (rz) for dimuon and wide angle Bhabha events for tracks measured using both the CDC hits and linked VXD hits.

Figure 14: The impact parameter from tracks in dimuon and wide angle Bhabha events.

Wire Eff. vs Laver

Figure 1

Photo Electric Source Drift Time Variation over Three Months

Figure 2a

Figure 2b

Figure 3

Figures 4

Figure 5

Figure 6

Figure 7

CDC Drift Distance Resolution

Figure 8

Figure 9

Figure 10

CDC Momentum Resolution

Figure 11

Q/p for Dimuons from $Z \rightarrow \mu^+\mu^-$

Figure 12

Figure 13

Figure 14

Linear Collider Research & Development

Introduction

The SLAC-KEK Collaboration on Accelerator R & D started in November 1979. As can be seen from Table 1, the program went through two phases. The first one was a broad technology phase during which the collaboration covered RF superconductivity, surface physics, ceramic windows and especially the construction of a 150 MW S-Band klystron carried out at SLAC with the help of personnel from KEK, Mitsubishi and Toshiba. After the success of this program, starting in 1986, the collaboration became entirely focussed on R&D for linear colliders. In June 1990, a meeting held at KEK between Directors H. Sugawara, B. Richter et al. led to the decision to accelerate the linear collider collaboration, to focus it on a machine with a c. of m. energy of 500 GeV expandable to at least 1 TeV, and to greatly increase the exchange of personnel between SLAC and KEK towards these ends.

In step with this chronology and these decisions, the pace of meetings and exchanges involving the two laboratories increased significantly. Table 2 shows a list of some of the meetings and workshops held at either SLAC or KEK. The number of scientists traveling to and from each laboratory increased from about 30 to 60 per year. Table 3 gives a list of international Linear Collider Machine and Physics workshops also being held during the last five years. Examples of people and topics involved in the specific SLAC-KEK annual workshops are shown in Tables 4 through 7. As a result of these numerous meetings, discussions and exchanges, the specifications and schematic layouts of the NLC (SLAC Next Linear Collider) and the JLC (KEK Japan Linear Collider) have converged greatly. Details on major topics of collaboration will now be discussed in the following pages.

Major Topics of Collaboration

A. Overall Linear Collider Design

The choice of research topics on linear colliders is largely determined by the nature of the components and sub-systems which are necessary to build the machine. Figures 1 and 2 show schematic layouts of the NLC and JLC respectively. As can be seen, these layouts are very similar. Both machines consist of electron and positron sources, injectors, damping rings, bunch compressors, pre-accelerators, main linacs, final foci, one or two detectors, and beam dumps. The main difference between the NLC and the JLC is that the JLC is somewhat longer than the NLC and thus for the same total energy requires less peak and average power. The length of the JLC linacs is also chosen so as to keep open the option of RF frequency. The preferred

frequency is X-Band (11.424 GHz) like for the NLC but the gradients obtainable with C-Band (5.272 GHz) or S-Band (2.856 MHz) can also meet the required 500 GeV c. of m. energy specification within the available length. The machine parameters are summarized in Tables 8 and 9. It can be seen that the JLC-I(X) and NLC are not too different. Certainly, the R&D done for one machine is very useful for the other. This explains why the collaboration is so symbiotic and why a healthy mixture of duplication and division of labor is most useful to both laboratories. Without covering the entire comprehensive list shown in Table 10, we will now describe some of the principal topics of research and facilities underway principally at SLAC and to some extent also at KEK. All of the R&D aspects of this work are in part supported by the collaboration.

B. RF Sources and RF Pulse Compression

Figure 3 shows a block diagram of a generic module for the main linacs. Typically, referring to Table 9, the JLC-I (X) has 3400 such modules and the NLC 1945. Much of the linac R&D of the last five years has been concentrated on the components of this module. In order to reach an accelerating gradient of 50 MV/m, each 1.8 m long accelerator section in the NLC must receive about 100 MW of peak power with a pulse length of 250 nsec. With a typical RF pulse compression of a factor of 6 and an efficiency of 67%, the RF source must produce a 1.5 μ sec pulse with a peak power just under 100 MW.

Over the last few years, several promising alternatives to conventional klystrons were explored by either SLAC or KEK, or both laboratories. These included relativistic klystrons using beams from induction linacs, lasertrons using lasers and photocathodes to produce bunched beams, and crossed-field amplifiers (similar to magnetrons). For different reasons, none of these RF sources lived up to their original expectations and the projects were all discontinued. The conventional klystron combined with a pulse compressor remained the only viable candidate. Thus, since that time, SLAC and KEK (together with Toshiba) have spent their efforts on developing X-Band klystrons and associated windows. At SLAC, a first series of eight so-called XC klystrons with a microperveance of 1.85 were built with various types of output cavities and tested up to early 1993. Efficiency, pulse length and power output did not quite meet specifications and many of the ceramic output windows (TE_{11} mode) broke. For these reasons, it was decided to go to a lower microperveance design (1.2) and for now to limit the klystron peak output power to 50MW. A recently tested tube of this new series (XL-1) has actually met these specifications, as shown in Figure 4. This tube is equipped with a new ceramic window which operates in the TE_{01} mode and thereby avoids having high currents flow across the metal-ceramic interface where most of the damage occurred with the TE_{11} mode. This new window was tested in an X-Band resonant ring where it worked nicely up to about 80 MW. The new waveguide transitions and the so-called flower petal transducer that was invented for this purpose are shown in Figures 5 and 6.

In parallel with all these efforts, two RF power compression systems were developed over the last five years, first the so-called Binary Pulse Compressor (BPC) and more recently SLED-II. Because of the excessive waveguide length required by the BPC system, SLED-II is now the preferred system. In contrast to SLED-I which uses microwave cavities to store the energy and produces exponentially decaying pulses, SLED-II uses delay lines and produces rectangularly shaped pulses. A diagram of SLED-II is shown in Figure 7, and RF compressed pulse shapes obtained this year have yielded up to 140 MW peak output with 35 MW peak input (see Figure 8). This power has been used recently to test a new accelerator structure (see later in this report).

Meanwhile, at KEK, klystron tests are proceeding in collaboration with Toshiba. Several tubes and windows have been tested. The prototype shown in Figure 9 reached 80 MW peak output with a maximum pulse length of about 100 nsec. KEK, however, is leaving it to SLAC to concentrate on the development of SLED-II.

All the collaborative RF work described here will continue during the next few years. Special emphasis will be placed on replacing the power hungry room temperature focusing solenoid in Figure 3 by a periodic permanent magnet (PPM) or a superconducting solenoid (SCS).

C. Modulators

Referring back to Figure 3, we note that another critical component of the generic module of the linac is the modulator. In the late 1980's, because of developments in the pulsed drivers for induction linacs, it was thought that their so-called magnetic pulse compression could be used efficiently to time-compress high voltage pulses down to a few hundred nanoseconds. Prototypes were successfully built at SLAC and at KEK but the results failed to meet the desired efficiency of about 80% by a considerable factor and the projects were discontinued. Efforts from then on, starting around 1990, were refocused on using conventional modulators. To increase their efficiency, a scheme was proposed (see Figure 10) which reduces the rise time by decreasing the leakage inductance of the pulse transformer by decreasing its turns ratio. The reduced voltage multiplication is made up by using the three mismatched pulse forming networks in series as shown. When the thyatron fires, a higher primary voltage appears as a difference between networks 2 and 3. One such modulator is presently under construction at SLAC, and the results should become known in the next year. Similar work is going on at KEK.

D. Accelerator Structures

The work on accelerator structures over the past five years at both SLAC and KEK proceeded along three lines: theoretical design, fabrication techniques and high-gradient tests.

The theoretical design work was driven by the desire to control single and multibunch wakefields. To increase luminosity, both SLAC and KEK have slightly decreased the charge per bunch, thereby reducing the single bunch emittance growth, while greatly increasing the number of bunches (up to 90 bunches spaced 1.4 nsec apart). The single bunch emittance growth is controlled by using short bunches and by increasing the ratio of iris radius to wavelength (a/λ). The multibunch emittance growth was first thought to be controllable only by damping the Q of the cavities in the HEM_{11} deflecting modes to under 20. Cavities constructed with four radial or azimuthal slots actually achieved such Q-values but the design of the loads needed to absorb this higher frequency power turned out to be problematic. Starting in 1991, the idea of progressively detuning the cavities so as to cause the wakefields to decohere appeared to become feasible. The criterion imposed by beam dynamics calculations dictated that the amplitude of the dipole wakefields produced by the first bunch should be decreased to one percent of its initial value by the time the second bunch arrived 1.4 nsec later (see Figure 11). Over the past two years, these studies have resulted in the design of a quasi constant-gradient 1.8 m long structure in which the first deflecting mode frequency is detuned by 10% over a truncated Gaussian of 4σ width. Such a design with 204 cells and two couplers has been developed with dimensional accuracies corresponding to $\Delta f_0 < 0.1$ MHz (accelerating mode frequency) and $\Delta f_1 < 0.6$ MHz (deflecting mode frequency). The resulting field profile can be seen in Figure 12. The corresponding RF parameters, which have been adopted for the NLC Test Accelerator structure (see later in this report), are given below:

Section length	1.8 m
Phase advance per cell	$2\pi/3$
Iris aperture radius (a)	5.72-3.91 mm
a/λ	0.218-0.149
Equivalent shunt impedance per unit length	80.7 Mohms/m
Group velocity	0.12c-0.03c
Filling time	100 ns
Attenuation parameter	0.517 nepers
Peak input power for 50 MV/m	86.5 MW

Equivalent circuit models have been developed and used to analyze the long-range wakefields in the presence of manufacturing errors, and a perturbation method has been worked out to speed up the mode calculations. The above specification of wakefield decay to 1% after one bunch can be seen to have been met in Figure 13, but recoherence appears to be excessive after about seven bunches. Figure 14 shows the result of interleaving four different families of sections over the length of the linac. These four different families are obtained by shifting the HEM_{11} frequency by one-quarter increments of the spacing in the core of the distribution. Transverse alignment tolerances which go with these structures are in the range of 10 to 20 microns. The simulations also include transient beam loading calculations which

indicate that it may be possible to obtain an 0.1% bunch-to-bunch energy spread by using a linear ramp in the klystron wave envelope.

Concerning X-Band fabrication techniques, both SLAC and KEK have gone through a considerable evolution, starting from simple machining and brazing techniques with nested copper cups and external cooling tubes to more complicated structures with integral cooling tubes, vacuum manifolds and tuning holes. The first simple X-Band design was used to make a 7-cell standing-wave structure and a 26.25 cm long constant-impedance traveling-wave structure with relatively small irises to enhance field strength for a given amount of available peak power. The specifications of this constant-impedance structure were as follows:

Effective section length	26.25 cm
Phase advance per cell	$2\pi/3$
Iris aperture radius (a)	0.375 cm
Cavity radius (b)	1.06 cm
a/λ	0.143
Shunt impedance	
per unit length	98.1 Mohms/m
Group velocity	0.033 c
Attenuation parameter	0.136 nepers
Filling time	26.5 nsec
Peak-to-accelerating field ratio	2.18

More recently, a much more sophisticated 75 cm long structure using diamond-point machined cavities made by Texas Instruments (with a 25 nanometer surface finish) has been successfully assembled (see Figure 15) and tested. In this constant-impedance structure, every cell communicates with two vacuum manifolds and has four integral water cooling tubes. The structure is also equipped with symmetrical double input and output couplers to compensate for transverse deflecting RF fields. While operation of this 75 cm long structure has been excellent (see below), the manufacturing details seem to make it excessively complex and expensive, and for the 1.8 m long structure presently being assembled, certain simplifications and improvements have been adopted. As seen in Figure 16, the cooling and vacuum manifolds are external (section B-B) and only six cells are directly pumped (section A-A). The cavities are turned on a conventional lathe (yielding a surface finish of about 0.4 μm). The specifications of this structure are given below:

Section length	75 cm
Phase advance per cell	$2\pi/3$
Iris aperture radius (a)	0.428 cm
Cavity radius (b)	1.079 cm
a/λ	0.163
Shunt impedance per unit length	87.7 Mohms/m
Group velocity	0.048 c
Attenuation parameter	0.267 nepers
Filling time	52 nsec
Peak-to-accelerating field ratio	2.29

In the early days, KEK had some of its structures assembled and brazed by Japanese industry with variable degrees of success. They are now working on some improved fabrication techniques in-house and have also successfully tested one of two identical X-Band structures made at CERN with techniques developed for CLIC. The second CERN structure will be tested at SLAC to compare results. Meanwhile, to improve ultimate alignment, individual test cavities which were precision-machined at KEK have been brought to SLAC to perform brazing experiments, following alignment in a specially designed vee-block.

The SLAC high-gradient tests have been pursued throughout this entire period, first in the Cryogenics Laboratory Area and more recently in the Accelerator Structure Test Area (ASTA) in the Test Laboratory. Comparative standing-wave seven-cavity studies were first done at S- and X-Band, and then with the traveling-wave structures described earlier (26.25 cm and 75 cm long sections). Table 11 gives the results for the seven-cavity resonant sections, and an empirical law of breakdown field versus RF frequency. Note the 500 MV/m surface field reached at X-Band. Figure 17 shows the effect on the 26.25 cm long structure (30 cavities) of progressive RF processing over three successive periods during which increasingly higher peak RF power became available. The ultimate accelerating gradient exceeded 100 MV/m with a field emitted (dark) current of about 2 mA. Subsequent tests done this year with the 75 cm long section (86 cavities) and SLED-II reached accelerating fields of 85 MV/m with less than 100 μ A of dark current. In both these cases, the dark current at 50 MV/m was negligible.

All these tests with the CERN and 1.8 m sections will be continued in the ASTA facility during the coming year. The wakefields for the 1.8 m section will be measured on the SLAC linac in such a section installed immediately downstream of the damping rings in which the spacing between a driving bunch producing the wakefields and a witness bunch traversing the section behind it will be varied continuously. The transverse displacement of the witness bunch will be studied by measuring its betatron oscillations in the linac.

E. Polarized Electron Source Work

Planning for collaborative work on polarized electron sources between SLAC and KEK started in 1990 with the goal of generating bunch trains with 1.4-5.6 nsec bunch-to-bunch separation. Progress at first was slowed down by the discovery of charge limitation (i.e. saturation) and other interbunch effects. However, following the recent success at SLC with electron beams from strained GaAs photocathodes exceeding 60% polarization at the Interaction Point, interest in polarized electron sources for future linear colliders increased greatly. Starting about one year ago, the collaboration became more active. At KEK, three parallel electron sources are being constructed for the S-Band Accelerator Test-Facility (ATF): one thermionic gun, one photocathode RF gun and one polarized photocathode gun. Meanwhile, a GaAs-AlGaAs superlattice cathode has been developed by KEK/Nagoya/NEC and tested at SLAC in the SLC Polarized Gun Test Facility. A record charge density of 12 nC/cm^2 (for a 20 mm diameter active area) in a 2.5 nsec pulse was extracted at 120 kV (see Figure 18). The polarization of this cathode, measured with a Mott polarimeter at Nagoya University, was 71%. Cross-calibration checks will now be made at SLAC.

Other collaborative studies include the possibility of a polarized RF gun (assuming the RF cavity vacuum can be kept low enough for a photocathode to survive), high voltage studies, the generation of pulse trains, current stability and beam loading tests.

We will now briefly describe the three major facilities at SLAC and KEK.

F. Final Focus Test Beam (FFTB)

Planning for the FFTB at SLAC began in 1988 and funding for the project started in 1989. A schematic diagram and the original beam specifications are shown in Figure 19. The project is the result of the first true international linear collider collaboration, with responsibilities as listed in Table 12. The FFTB Collaboration regularly came together for design review meetings and the construction was completed at the beginning of 1993 with the installation of both the Orsay Spot Size Monitor and the KEK Laser-Compton Monitor (see Figure 20). Initial tests for radiation and beam containment certification took place in the spring of 1993. Later, during the summer, hardware, alignment and background checks were performed and the first signals were observed from the two spot monitors. A flat beam with a σ_y of $1.4 \mu\text{m}$ was measured with a conventional $4 \mu\text{m}$ wire scanner.

The next FFTB runs are planned starting in early spring 1994. A rigorous R&D program will then be pursued during which it is hoped that beam spots with σ_y of 60 nm will be measured.

G. Accelerator Test Facility (ATF) at KEK

Planning and component design for the ATF started several years ago but actual installation did not begin until 1992 when the newly upgraded Tristan Assembly Hall became available. A schematic drawing of the ATF with its 1.54 GeV S-Band linac and its 1.54 GeV Damping Ring is shown in Figure 21. The linac, which is driven by ten S-Band klystrons (both Toshiba and SLAC tubes) combined with SLED-I cavities will operate at a gradient of ~ 30 MV/m. The injector has recently come into operation with a beam energy of 80 MeV and an accelerating gradient of about 27 MV/m (see Figure 22).

The specifications for the Damping Ring are shown in Table 13. A special SLAC-KEK ATF review workshop was held at KEK, June 8-10, 1992 (see Table 2) and several SLAC physicists made contributions to the design of the Damping Ring. Operation of the ring is scheduled to start in late 1996. Major goals are to study the beam dynamics of five 20-bunch trains (bunches spaced 2.8 nsec apart), their injection, damping, extraction and compression. The facility also includes the possibility of building a positron source.

H. NLC Test Accelerator (NLCTA) at SLAC

Planning for the NLCTA started in 1991, early site preparation of the housing inside End Station B began in 1992, and actual funding of the project occurred in 1993. The layout of this 540 MeV X-Band linac (later expandable to over 1 GeV) is shown in Figure 23 and the RF system parameters are outlined in Table 14. The purpose of this facility is two-fold: to serve as a complete systems test facility for the linac, and to perform a number of important beam dynamics experiments with an injector of average current (within the bunch train) comparable to the NLC. The components to be tested include an X-Band injector, 50 to 100 MW peak output klystrons, efficient modulators, SLED-II, 1.8 m long sections and a number of new instruments. The beam dynamics experiments include multibunch beam loading compensation, multibunch transverse emittance growth, transverse RF field effects, and field emission which can result in so-called dark current.

The NLCTA is planned to be completed in 1996. Between it and the KEK ATF, a large number of outstanding design questions of the NLC and JLC machines will be studied and elucidated.

TABLE 1

US/JAPAN Collaboration on High Energy Physics

Chronology of Entire SLAC-KEK Program on Accelerator R & D

Program Started in November 1979

Phase I : The Early Years, 1979 - 1985

- RF Superconductivity
- 150 MW Klystron Prototype Program
SLAC/KEK/Mitsubishi/Toshiba Collaboration
- Surface Physics, RF Sources, Klystron Ceramic
Windows, etc.

Phase II : 1986 - Present

- Linear Collider R & D
- June 1990: Sugawara/Richter et al. Meeting at KEK to Focus on 0.5 TeV
center of mass Machine and Speed up Exchanges Between KEK and
SLAC

TABLE 2

US-JAPAN Collaboration Meetings and Workshops

US-JAPAN	Annual Committee on HEP Meetings, alternating between US and JAPAN (and exceptionally in Hawaii in 1992)
KEK-SLAC (since 1987)	Annual Collaboration Workshops alternating between KEK and SLAC
SLAC, KEK et al.	FFTB Workshop at SLAC February 26 - 28, 1992
SLAC, KEK et al.	Final Focus and IR Workshop at SLAC March 2 - 6, 1992
KEK-SLAC	ATF Injector and Damping Ring Workshop at KEK, June 8 - 10, 1992
KEK, SLAC et al.	Emittance Workshop at KEK April 19 - 23, 1993

Typical Number of Scientists Exchanged per Year: 30 → 60

TABLE 3

International Linear Collider Workshops

LC88	SLAC	November 28 - December 9, 1988
LC90	KEK	March 28 - April 5, 1990
LC91	INP, Protvino	September 17 - 27, 1991
LC92	Garmisch	July 25 - August 2, 1992
LC93	SLAC	October 13 - 21, 1993
LC95	KEK	March 1995 (Planned)

Physics with Linear Collider Workshops

1991	Saariselkä,	September 9 - 14, 1991 Finland
1993	Kona,	April 26 - 30, 1993 Hawaii

TABLE 4a

SLAC/KEK LINEAR COLLIDER WORKSHOP

March 1-4, 1988

List of Participants

KEK		SLAC
Y. Kimura, Co-chairman		G. Loew, Co-chairman
T. Nishikawa	S. Ozaki	
S. Iwata	K. Takata	R. Stiening
S. Kamada	S. Kurokawa	E. Paterson
H. Mizuno	S. Takeda	M. Allen
K. Yokoya	M. Yoshioka	R. Ruth
S. Kawabata	K. Hagiwara	J. Sheppard
N. Sasao	K. Oide	R. Palmer
T. Shintake	H. Matsumoto	P. Bambade
T. Shidara	J. Urakawa	N. Toge
M. Akemoto	H. Hayano	
N. Yamamoto	K. Akai	
Y. Takeuchi	H. Fukuma	
S. Hiramatsu	A. Ando	

TABLE 4b

1988 SLAC/KEK LINEAR COLLIDER WORKSHOP PROGRAM

	March 1 (Tue)	March 2 (Wed)	March 3 (Thu)	March 4 (Fri)
09:30	<ul style="list-style-type: none"> - Opening address (T. Nishikawa) - General goals of the workshop (G. Loew) - Linear collider project at SLAC and KEK (J. Paterson & Y. Kimura) - Physics perspectives of next linear collider (K. Hagiwara) - Linear collider design parameter interdependence (R. Palmer) 	<ul style="list-style-type: none"> - Organization of subgroups <p>Subgroup:</p> <ul style="list-style-type: none"> a) linac structures and RF sources b) beam dynamics, wake-fields and tolerances c) final focus, beam-beam effect, alignment,.... d) measurement, instrumentation and control <ul style="list-style-type: none"> - Discussion of the respective programs within each subgroup 	<ul style="list-style-type: none"> - Discussion of the respective R&D programs within each subgroup (continued) - The following topical talks will be given in the subgroup meetings: <ul style="list-style-type: none"> a) General RF breakdown results in structures (G. Loew) c) Test linac facility (S. Takeda) d) FEL studies at KEK (S. Hiramatsu) 	<ul style="list-style-type: none"> - Recommendations for common R&D work from each subgroup - Closing addresses (G. Loew & S. Ozaki)
12:30				
14:00	<ul style="list-style-type: none"> - Status Report <ul style="list-style-type: none"> a) SLC (R. Stiening, et al.) b) R&D at SLAC (R. Ruth & R. Palmer) c) R&D at KEK (T. Takata) d) Theoretical works (K. Yokoya) 	<ul style="list-style-type: none"> - Discussion of the respective R&D programs within each subgroup (continued) 	<ul style="list-style-type: none"> - Discussion of the respective R&D programs within each subgroup (continued) 	
17:00		Tour of KEK accelerator facilities		
	Reception		Banquet

2 of 2

TABLE 5

KEK/SLAC COLLABORATIVE MEETING

JUNE 1, 1989

SSRL Conference Room
Room 322, Building 137

PROGRAM

9:00 - 12:30

WELCOME AND INTRODUCTION

Burton Richter/
Gregory Loew

KEK Activities on Linear Collider R&D

Yoshitaka Kimura

Construction of the KEK Test Accelerator Facility

Seishi Takeda

R&D on High Power Sources and Accelerating Structures

Koji Takata

Final Focus Test Beam

James Paterson/
Katsunobu Oide

2:00 - 6:00

RF Sources Overview

Matthew Allen

Relativistic Klystron Program

Arnold Vlieks

Crossed-Field Amplifiers and Klystrons

Terry Lee

Magnetic Pulse Compression

Gordon Bowden

Cluster Klystrons

Wm. Herrmannsfeldt

RF Pulse Compression

George Spalek

High Gradient Breakdown

Theodore Lavine/
Juwen Wang

TABLE 6
**KEK/SLAC LINEAR COLLIDER
 MINI-WORKSHOP PROGRAM
 May 17, 1991
 SLAC Green Room**

Morning: 9:00 A.M. - 12:30 P.M.

Ron Ruth	(30 min.)	Overview of NLC Program
David Burke	(20 min.)	FFTB Status
Koji Takata	(30 min.)	JLC RF Sources and Accelerating Structures
Seishi Takeda	(30 min.)	ATF Project and JLC R&D Status
George Caryotakis, et al	(30 min.)	SLAC RF Source Program

Afternoon: 2:00 P.M. - 6:00 P.M.

Kaoru Yokoya	(30 min.)	JLC Parameters
Ted Lavine	(20 min.)	RF Pulse Compression Program
Tetsuo Shidara	(20 min.)	Magnetic Compression-Type X-Band Klystron Modulator
Mitsuo Akemoto	(20 min.)	PFN-Type X-Band Klystron Modulator
Kathy Thompson	(15 min.)	Damped and Detuned Structures
Juwen Wang	(15 min.)	Structure Experiments
Harry Hoag	(10 min.)	Structure Design
Ken-ichi Kanazawa	(20 min.)	Emittance Growth due to Residual Gas
Hitoshi Hayano	(20 min.)	BPM Electronics for FFTB

TABLE 7

KEK/SLAC COLLABORATION MEETING
March 8, 1993

PROGRAM

MORNING:	9:00 A.M.	
K. Takata	Overview	(20 min)
S. Takeda	Design and Construction of ATF Linac	(30 min)
H. Matsumoto	S-Band High Power Components	(30 min)
BREAK		(30 min)
S. Kuroda	Damping Ring RF	(30 min)
H. Mizuno	RF Source R&D	(30 min)
T. Higo	Structures R&D	(30 min)
 LUNCH IN ORANGE ROOM:	 12:30 P.M.	
 AFTERNOON:	 1:30 P.M.	
R. Ruth	Overview and NLCTA	(40 min)
R. Phillips	Klystrons	(30 min)
R. Cassel	Modulators	(20 min)
BREAK		(30 min)
T. Lavine	SLED II	(20 min)
A. Vlieks	ASTA	(20 min)
K. Thompson	Multibunch Effects	(30 min)
J. Wang	Accelerator Structures	(30 min)

TABLE 8

JLC and NLC Linear Colliders

Overall and Final Focus Parameters Available at the End of LC 93

	<u>JLC-I(S)</u>	<u>JLC-I(C)</u>	<u>JLC-I(X)</u>	<u>NLC</u>
Initial energy (c. of m.) (GeV)	500	500	500	500
RF frequency of main linac (GHz)	2.8	5.7	11.4	11.4
Nominal luminosity ($10^{33}\text{cm}^{-2}\text{s}^{-1}$) ^a	2.8	4.3	3.7	6
Luminosity w/pinch ($10^{33}\text{cm}^{-2}\text{s}^{-1}$) ^a	4.4	6.5	6.3	8.2
Linac repetition rate (Hz)	50	100	150	180
No. of particles/bunch at IP (10^{10})	1.30	1.0	0.63	.65
No. of bunches/pulse	55	72	90	90
Bunch separation (nsec)	5.6	2.8	1.4	1.4
Beam power/beam (MW)	1.4	2.9	3.4	4.2
Damping ring energy (GeV)	1.98	1.98	1.98	1.8
Total length ($1.1 L_{\text{RF}} + 3\text{km}$)	33.8	21.4	22.5	18.4
$\gamma\epsilon_x/\gamma\epsilon_y$ (m-rad $\times 10^{-5}$)	330/4.5	330/4.5	330/4.5	500/5
β_x^*/β_y^* (mm)	10/0.1	10/0.1	10/0.1	10
σ_x^*/σ_y^* (nm) before pinch	300/3	260/3	260/3	300/3
σ_z^* (μm)	80	80	67	100
Crossing Angle at IP (mrad)	7.3	8	7.2	3
Disruptions D_x/D_y	.13/13	.13/11.7	.07/6	
.08/8.2				
H_D	1.60	1.50	1.72	1.37
Upsilon sub-zero	.24	.21	.16	.095
Upsilon effective	.24	.21	.16	.096
δ_B (%)	10.0	8.1	4.5	3
n_γ (no. of γ per e)	1.62	1.44	.95	.8
$N_{\text{pair}}(p\backslash S(\text{min}, T) = 20\text{MeV}/c, \theta_{\text{min}}=0.15)$	15.8	9.9	2.8	2.4
N_{hadrons}	.44	.25	.07	.04
$N_{\text{jet}} \times 10^{-2} (p\backslash S(\text{min}, T) = 3.2\text{GeV}/c)$	1.68	.90	.22	.1

^a The JLC machines include the luminosity reductions due to the hour glass effect and the crossing angles without crab crossing (0.68, 0.60, 0.70 for S, C and X-Band respectively).

TABLE 9

JLC and NLC Linear Colliders

Main Linacs RF Parameters Available at the End of LC 93

	<u>JLC-I(S)</u>	<u>JLC-I(C)</u>	<u>JLC-I(X)</u>	<u>NLC</u>
Unloaded gradient (MV/m)	22	40	40	50
Beam loaded gradient (MV/m) ^a	18.7	32.5	30.6	37.6
Active two-linac RF length (km)	28	16.7	17.7	14
Section length (m)	3.6	2	1.3	1.8
Two-linac number of sections	7776	8360	13600	7778
Two-linac number of klystrons	1944	4180	3400	1945
Number of sections/klystron	4	2	4	4
Klystron peak power (MW)	85	45	70	94
Klystron pulse length (μ sec)	4.5	3.6	.840	1.5
Pulse length to section (μ sec)	1.2	.6	.210	.250
Pulse compression ratio	3.7	6	4	6
Pulse compression gain	2.4	4.2	3.2	4
a/λ range (input/output cavity)	.13	.160/.120	.236/.138	218/.149
Total two-linac AC power (MW) ^b	106	193	86	141
AC-to-Beam Conversion Efficiency	0.03	0.04	0.09	0.06

^a Before applying further gradient reductions for off-crest running, BNS, etc.

^b This number is based on a combined klystron-modulator efficiency of 45% and a SLED-II pulse compression efficiency of 67%. Power for klystron focusing is not included.

TABLE 10

SLAC - KEK Program

Linear Collider R & D Topics of Collaboration

- Overall Linear Collider Design
- Relativistic Klystrons*
- Lasertron*
- Crossed-Field Amplifier*
- Conventional X-Band Klystrons and Windows
- RF Pulse Compression (Binary Pulse Compression, SLED I and II)
- Magnetic Pulse Compression*
- Modulators
- X-Band Accelerator Structures, Design and Fabrication Problems, High
Voltage RF Breakdown, Field Emission
- Damping Ring Design
- Final Focus Design
- Polarized Electron Sources
- Overall Instrumentation
- Theory, Emittance Growth, Beam-Beam Effects
- Positron Sources, Bunch Compression, etc.

*Program Discontinued

TABLE 11

BREAKDOWN LIMITS IN SEVEN-CAVITY RESONANT DISK-LOADED SECTIONS

FREQUENCY (GHz)	2.856	11.424
PEAK POWER INPUT (MW)	47	14
PULSE LENGTH (μSEC)	2.5	0.800
SURFACE BREAKDOWN FIELD E_s (MV/m)	310	500
MAXIMUM E_{acc} (MV/m)	160	220

$$E_s \sim 222 [f(\text{GHz})]^{1/3} \text{ in MV/m}$$

TABLE 12

FFTB Collaboration
Responsibilities

INP (Novosibirsk)	Magnets
KEK	Instrumentation Final Quad Package Optics Design
LAL (Orsay)	Instrumentation Optics Design
DESY	Alignment
MPI (Munich)	Magnet Movers
SLAC	SLC Beam Power Supplies Alignment Instrumentation Facilities Optics Design

TABLE 13

KEK ATF DAMPING RING

Energy	1.54	GeV
Circumference	138.6	m
Repetition frequency	25	Hz
Number of bunch trains	5	
Number of bunches per train	20	
Inter bunch spacing	2.8	ns
Number of particles per bunch	2×10^{10}	
Maximum average current	0.60	A
Bending field	0.896	T
Number of FOBO cells	36	
Phase advance per cell(hor./ver.)	140/52	degrees
Momentum compaction	0.00197	
Synchrotron radiation per turn	0.173	MeV
Wiggler field strength	1.88	T
Wiggler period	40.0	cm
Total number of wiggler periods	40	
Overall length of wiggler sections	21.1	m
Harmonic number	330	
RF frequency	714	MHz
RF voltage	0.77	MV
Long. threshold impedance	0.22	Ω
Long. damping time	4.88	ms
Bunch length	4.7	mm
Energy spread	0.077	%
Normalized hor. emittance	5×10^{-6}	rad.m
Normalized ver. emittance	5×10^{-8}	rad.m

TABLE 14. NLCTA RF System Parameters

Parameter	NLCTA Design	Energy Upgrade
Linac unloaded energy gain	540 MeV	1080 MeV
Linac active length	10.8 m	10.8 m
Unloaded accelerating gradient	50 MV/m	100 MV/m
Injection energy	90 MeV	90 MeV
RF frequency	11.424 GHz	11.424 GHz
Number of klystrons	3	6
Klystron peak power	50 MW	100 MW
Klystron pulse length	1.5 μ s	1.5 μ s
RF pulse compression power gain	4.0	4.0
Phase advance per cell	$2\pi/3$	$2\pi/3$
HOM suppression technique	Detuning	Detuning

FIGURE 1

Schematic Layout of an NLC

FIGURE 2 Schematic Diagram of JLC-1

Modulator

DSA 602 DIGITIZING SIGNAL ANALYZER

date: 1-NOV-93 time: 15:36:58

FIGURE 4. XL-1 klystron wave shapes. Output power reached 51 MW with an input power of 85 W.

$V_0 = 440 \text{ kV}$
 $I_0 = 332 \text{ A}$
 $f_0 = 11.655 \text{ GHz}$
 $P_{\text{out}} = 51 \text{ MW}$
 $P_{\text{in}} = 85 \text{ W}$

FIGURE 5 CONFIGURATION FOR TESTING TE₀₁ WINDOW IN X BAND TRAVELING WAVE RESONATOR

FIGURE 6. Flower petal transducer.

FIGURE 6. Flower petal transducer.

FIGURE 7

SLED-II Pulse Compression System

3-92
7210A2

DSA 602A DIGITIZING SIGNAL ANALYZER
date: 3-AUG-93 time: 16:16:10

FIGURE 8. SLED-II input and output waves.

FIGURE 9. Toshiba X-Band 80 MW, 100 nsec pulse length klystron.

Released 1/22/92

FIGURE 10 600 KV Klystron Modulator

FIGURE 11

Dipole Transverse Wakefield for 1.8 m Detuned Structure with Gaussian Distribution of f_1 (10%, 4σ)

FIGURE 12. Accelerating electric field E_z along the axis of the 1.8 m long structure, assuming a peak input power of 100 MW.

FIGURE 13. Envelope of the wake function (for the 1.8 m long section) as a function of distance behind the first bunch. At a distance of 10 m, i.e. about 7 bunches spaced 1.4 nsec apart, the wake amplitude exceeds 1%.

1-93

7274A26

FIGURE 14. Envelope of the wake function averaged over four detuned section types having interleaved HEM₁₁ frequency distributions (no frequency errors)

FIGURE 15 75 cm 11.4 GHz Constant-Impedance
Traveling-Wave Structure

FIGURE 16. Cross-section of 1.8 m long structure in normal cell (section B-B) and in pumping cell (section A-A).

DARK CURRENT PRODUCED BY TW ACCELERATOR SECTIONS

FIGURE 17. Field emitted "dark" current as a function of accelerating gradient for 30-cavity and 86-cavity traveling-wave sections. Dates correspond to different RF processing periods.

FIGURE 18. The upper figure shows the output charge vs. incident laser power for the new superlattice photocathode fabricated by the KEK/Nagoya/NEC collaboration. The measurement was done as part of the KEK/SLAC collaboration using the SLC Polarized Gun Test Facility. Achieved here is the 2% quantum efficiency at 757 nm. The limitation on the output is compatible with the space-charge limit of the gun. The bottom figure shows the output pulse shape at various input laser powers labeled in the upper figure. The polarization at 750 nm, measured at Nagoya University, is 71%.

FIGURE 19

Beam Energy	50 GeV
Vertical emittance (ϵ_y)	3×10^{-6} rad-m
Focusing (β_y^*)	100 nm
Beam height (σ_y^*)	60 nm
Aspect ratio (σ_x^*/σ_y^*), adjustable	15
Energy bandwidth ($\delta p/p$)	$\pm 0.3\%$
Bunch population (e^-)	1.0×10^{10}
Pulse rate	10 Hz

0-00

0700A2

Final Focus Test Beam

FIGURE 20
Laser-Compton Spot Size Monitor

しんたけ つもる

T. SHINTAKE KEK: JAPAN

Beam energy	80 MeV
Beam pulse width	2 ns
Number of electrons	4×10^9
Energy spread	$\sim 0.7 \%$
Accelerating gradient	26.7 MV/m
Input power	65 MW (96 MW max. but with no beam acc.)
Structure length	3 m
f_{rep}	50 Hz max

FIGURE 22. ATF S-Band Injector

STANFORD LINEAR ACCELERATOR CENTER	
ENGINEERING SECTION	
LAYOUT #12 OF NLC TA IN END STATION B	
REVISED	BY - MM - 712
DATE	3 - 12 - 88

FIGURE 23. SLAC NLC Test Accelerator

Activities at Brookhaven National Laboratory

The US/Japan Cooperative Program in High Energy Physics has over the past 15 years generated a multitude of excellent physics and technological results. The joint efforts at Brookhaven National Laboratory, although only receiving a small fraction of the total resources of the joint program, have resulted in and are expected to continue to generate some of the most significant results. In the period from 1987 to 1993 the physics focus has been on neutrino interactions, the new discipline of high energy heavy ion physics, the study of rare kaon decays to test the standard model, and the extremely precise measurement of the muon anomalous magnetic moment. In the technological areas the work has included the development of superconducting wire for accelerator magnets, the construction of the worlds largest diameter (15 m) superconducting magnet and the development and construction of the world's first superconducting accelerator inflector magnet. All of these efforts have involved a very close collaborative effort between US and Japanese physicists, engineers, graduate students and technicians.

During this period two programs have been completed:

A Study of Low Energy Neutrino Interactions (E734)
[Hiroshima, INS(Tokyo), KEK, Osaka, BNL, Brown, Pennsylvania,
SUNY-Stony Brook]

Development of Nb₃Sn Wires for Accelerator Magnets
(KEK, BNL)

one program was begun prior to this period and is ongoing:

Relativistic Heavy Ion Collisions at the AGS (E802, E859, E866)
[Hiroshima, INS(Tokyo), Kyushu, Tokyo, Tsukuba, ANL, BNL,
Columbia, MIT, UC Berkeley, UC Riverside];

three programs were begun during this period and are ongoing:

Muon g-2 Experiment at the AGS (E821)
(KEK, Tokyo, Boston, BNL, Cornell, Heidelberg, Illinois, LANL, Yale)

Rare Kaon Decay (E787)
[NS(Tokyo), KEK, BNL, LANL, Princeton, TRIUMF]

Relativistic Heavy Ions at RHIC (PHENIX)
(Japan, USA, Brazil, Canada, China, Germany, India, Korea, Russia,
Sweden).

The following pages are an updated summary of the various cooperative efforts during the 1987 to 1993 time period.

A. A Study of Low Energy Neutrino Interactions at BNL (E734)

The participating groups in this experiment are:

Osaka, KEK, INS(Tokyo), and Hiroshima, BNL, Brown, Pennsylvania,
SUNY-Stony Brook

The original proposal for E734 was to measure elastic scattering of neutrinos on electrons and protons. While this was the primary goal of the experiment significant results have also been obtained from a muon-type to electron-type neutrino oscillation search, from a search for heavy neutrino decays and from a detailed study of quasi-elastic scattering. All of these measurements were made in the wide band neutrino beam ($\langle E \rangle \sim 1.5$ GeV) at BNL. The high repetition rate and good flux of the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory coupled with the low beam energy are advantageous for all of these measurements. Even for the muon neutrino-electron elastic scattering the rate was 1.5 events/ day in the 75 metric ton fiducial volume of the detector. Results were also obtained on a search for oscillations of muon-type neutrinos to electron-type neutrinos using a 3 GeV narrow band beam. The high segmentation and time and pulse height information from the detector yields excellent electron/photon separation and good pion/proton identification which is important for identifying the signals for the various reactions and for reducing and measuring the various backgrounds.

Wide band beam data corresponding to 5.0×10^{19} protons on target (POT) and 4.9×10^{19} POT for neutrino and antineutrino running, respectively, were collected. The data analysis has been completed and all major results from the experiment have been published.

a. Neutrino electron elastic scattering.

Results on both muon neutrino-electron elastic scattering and muon anti-neutrino-electron elastic scattering have been published. A total of 160 muon neutrino-electron elastic scattering events and 97 muon anti-neutrino electron elastic scattering events were used in the analysis. From the cross section ratio of the two

elastic scattering reactions a precise value of the weak mixing angle $\sin^2\theta_W = 0.195 \pm 0.018 \pm 0.013$ was obtained.

b. Neutrino proton elastic scattering

A detailed study of muon neutrino-proton elastic scattering and muon anti-neutrino proton elastic scattering has been published. The data were obtained from separate runs of 0.55×10^{19} POT and 2.5×10^{19} POT for positive (ν_μ) and negative ($\bar{\nu}_\mu$) focused beams, respectively. After all event selection and background subtraction a total of 951 $\nu_{\mu p}$ elastic events and 776 $\bar{\nu}_{\mu p}$ elastic events were obtained. These are almost an order of magnitude larger samples than the best previous experiment. The weak mixing angle determined from the ratio of the cross sections and the differential cross sections was $\sin^2\theta_W = 0.220 \pm 0.016 \pm 0.027$. This is in very good agreement with the value obtained from the purely leptonic neutrino electron elastic scattering process.

c. Search for Heavy Neutrino Decays.

A search has been made for decays of heavy (200-500 MeV) neutrinos. No significant excess of such events has been found and limits can be set on the neutrino mixing matrix elements.

If neutrinos are massive they may, if the mass and flavor eigenstates differ, decay to lighter particles. In this experiment the heavy neutrinos are assumed to come from pion or K decays. The signature for the decay would be a final state with a muon and electron candidate at a common vertex and no excess energy associated with the event. The data used in this analysis come from a single exposure of 0.38×10^{19} POT. To reduce neutral pion background only events with shower energy greater than 1 GeV were used. From the initial data which consisted of 534,000 beam pulses only candidates survived cuts on the electron shower energy (> 1 GeV), the muon length (> 4 collision lengths) and the requirement that there be no additional tracks or disconnected energy in the event. After subtraction the background (determined from the gamma conversion distance distribution), electron neutrino-induced events (2.9 ± 1.1), and charm events (1.3 ± 0.7) the number of candidates remaining was $6.8 \pm 5.8 \pm 3.1$. There is clearly no evidence for heavy neutrino decay. The data can be used to set limits on the neutrino mixing matrix elements, $|U_e H|^2$ and $|U_\mu H|^2$. The limits on $|U_\mu H|^2$ from this experiment are significantly better than earlier results in the mass range $200 \leq m_{\nu H} \text{ (MeV)} \leq 400$ and approach 5×10^{-7} in the region of 350 MeV. The limits on $|U_e H|^2$ are competitive with earlier measurements.

d. Anti-neutrino quasi-elastic scattering.

A detailed study of the anti-neutrino quasi-elastic reaction $\bar{\nu}_{\mu p} \rightarrow \mu^+ n$ in the Q^2 range $\leq 1 \text{ (GeV/c)}^2$ has been published. In the standard model, assuming no second class currents and a dipole form of the axial vector form factor the axial-vector mass m_A can

be determined from the shape of the Q^2 distribution. Alternatively one can search for second class currents using the shape of the Q^2 distribution. This analysis was based on 2.5×10^6 event bursts obtained in an exposure of 2.5×10^{19} protons on target. Candidates for $\bar{\nu}_{\mu p} \rightarrow u^* n$ were defined to be events with a noninteracting track which left the detector after traveling at least 4 collision lengths and an additional short track downstream which was consistent with being a proton recoil from the neutron produced in the primary interaction. A total of 2919 anti-neutrino quasi-elastic candidates survived all the cuts and the background remaining in the sample was estimated to be 11%. The energy and Q^2 for each event were calculated from the measured muon and neutron angle. The best fit value of m_A obtained from the Q^2 distribution was $m_A = 1.09 \pm 0.031 \pm 0.02$ which is very consistent with earlier measurements. Searches for second class currents were performed by looking for nonzero values of the tensor (F_T) or scalar (F_S) form factor, assuming they have a dipole form. No evidence of second class currents was found. The 90% confidence limit (CL) on F_T obtained in this experiment is significantly better than earlier measurements and while the limit on F_S is weaker, it is the first limit on this quantity obtained in a neutrino experiment.

e. Search for $\nu_{\mu} \rightarrow \nu_e$ oscillations using a narrow band beam.

A search for muon neutrino to electron neutrino oscillations using a narrow band beam has been published. No evidence for oscillations was found and the use of a narrow band beam rather than a wide band beam for this type of experiment was evaluated. In principle, a narrow band beam should be superior. It has a well defined peak energy and if there are oscillations then an electron neutrino peak should appear under the muon neutrino peak. In addition there should be less π^0 background as there is no high energy tail in the beam and the primary electron backgrounds do not peak as the muon neutrino spectrum does. However, in the narrow band search discussed here, these advantages were more than offset by the decrease in flux from the narrow band beam compared to the wide band beam. The narrow band intensity is typically a few percent of the wide band and this loss of statistics significantly reduced the sensitivity of the experiment. The analysis was based on 1.26×10^6 bursts corresponding to 9×10^{18} protons on target. A total of $29 \pm 14 \nu_e n \rightarrow e^* p$ events were obtained after all cuts and this was consistent with the number expected from beam contamination. The resulting limits were $\sin^2 2\alpha < 1 \times 10^{-2}$ at 90% CL for large Δm^2 and $\Delta m^2 \leq 2.4 \text{ eV}^2$ at 90% CL for maximal mixing. These are to be compared with the previously obtained limits from the wide band beam run of $\sin^2 2\alpha \leq 3.4 \times 10^{-3}$ and $\Delta m^2 < 0.43$.

B. Development of Nb₃Sn Wires for Accelerator Magnets

The participating groups are:

KEK, BNL

The participating groups in this activity are KEK and BNL. Since Nb₃Sn has a higher critical magnetic field, ($H_{c2} \sim 24$ T), than that for NbTi, Nb₃Sn multifilamentary wires can be operated at high magnetic fields where NbTi magnets cannot be used. For this reason, we have continued to study characteristics, i.e. critical current densities J_c and magnetization, and fabrication methods of alloyed multifilamentary Nb₃Sn wires. In the past, we have shown that magnetization of internal tin processed Nb₃Sn wires was excessively large due to filament coalescence although the values of J_c in these wires were very good ($J_c > 1000$ A/mm² at 10 T). Also, it was shown that magnetization can be reduced by increasing the space between the filaments. However, this resulted in reduction of Nb in the wire thus reduction in J_c . In order to increase J_c in the wires with the separated filaments, a small amount of Ti was introduced into the Sn core. This addition was very effective in increasing J_c (less than 1300 A/mm² at 10 T). This was shown in a small scale fabrication of the wire at Brookhaven National Laboratory (BNL). A similar wire was fabricated by Intermagnetics General Corporation (IGC) on a commercial scale. However, it was found that the production of a Sn-Ti alloy for the core in a large quantity is not as simple as it was envisioned, and the cost of this alloy is significantly higher than it was originally estimated. Furthermore, when the Ti-Sn alloy is casted in a large scale (about 100 kg), Ti-Sn precipitates in the Sn matrix cannot be kept at very small sizes (less than 10 μ m). This resulted in partial rupture of the inner Nb filaments of the internal tin Nb-Sn wires, and in lower critical currents for the wire. Thus, it was decided to reexamine the internal tin Nb₃Sn wires where the Nb filaments were alloyed with Ti and Ta. For this purpose, two types of unreacted subelements were received from IGC. These subelements contained approximately 120 filaments of Ti- and Ta-alloyed Nb. These subelements were rebundled to make two 19-subelement wires, one with the Ti-alloyed and the other with the Ta-alloyed subelements. These wires were drawn to appropriate sizes and heated for a comparison of J_c in Ti- and Ta-alloyed Nb₃Sn wires. In addition, as received subelements were tested for J_c . The results of the measurements are summarized in Table I. In addition to the value of J_c , in order to indicate the width of the transition to the normal state for each wire, the values of "n" were calculated and are listed in the table for $H = 16$ T. Here, n is defined as $\log(V_2/V_1)/\log(I_2/I_1)$ and has been chosen $V_2 = 10$ μ V and $V_1 = 1$ μ V and I_2 and I_1 are the currents to produce V_2 and V_1 at a given value of H.

TABLE I.

Description of Nb₃Sn Multifilamentary Wires

Alloy Type	wt%	Wire Size (mm)	No. of Sub- elem	Fila- ment Size	Heat Treat. ^{a)} °C/h	J _c (A/mm ²) ^{b)}		n ^{c)}
						10 T	16 T	
H	Nb7.5Ta	0.25	1	7	725/48	879	197	18
	Nb1.2Ti	0.25	1	7	725/48	988	347	41
H/B	Nb7.5Ta	0.36	19	2	650/96	907	182	11
	Nb7.5Ta	0.63	19	3.5	725/48	755	189	13.5
	Nb1.2Ti	0.36	19	2	650/96	821	224	20
	Nb1.2Ti	0.63	19	4	725/48	429	128	20
I	Nb7.5Ta	0.35	19	2	725/24	778	245	17
	Nb7.5Ta	0.73	19	5	725/96	774	207	10

^{a)}All of the wires received preheat treatments at 340 and 580° C.

^{b)}J_c is for the area of (Nb₃Sn + CuSn) x 1.05 which included the area of the Ta barrier, and the criterion for I_c was E_c = 0.01 μV/mm.

^{c)}Define as $n = \log(V_2/V_1)/\log(I_2/I_1)$.

As shown in Table I, consistent systematic variations in critical-current densities in the present wires were not observed in regard to variations in the filament size or the type of alloying elements, Ti or Ta, although it shows that J_c at very high field (H > 18 T) is higher for the wires with Ti addition than with Ta. Furthermore, except for the two wires, (H)/Nb1.2 Ti/0.25 mm and (H/B)/Nb1.2 Ti/0.63 mm, there was no significant difference in J_c of the wires regardless of the filament size, heat treating conditions, wire size, nor the alloying elements. The wire of the best critical-current density, (H)/Nb1.2 Ti/0.25 mm, exhibited the sharpest transition at I_c as indicated by the sharpness factor n (n = 41). However, there was no clear correlation between the values of n and J_c for other wires although the n-values varied from 10 to 20 among these wires. This perhaps indicates that it is difficult to evaluate the differences in the values of J_c due to the variation in the filament size or alloying elements unless the

filaments in the wires are uniform enough to have a very sharp transition, i.e. $n > 40$. Furthermore, it is interesting to note that as shown earlier the $\text{Nb}_3\text{Sn} + \text{Ti}$ wire with a very high current density ($J_c = 320 \text{ A/mm}^2$ at 16 T) also exhibited a very sharp transition, $n = 48$ at 16 T. [T. Kuroda, M. Suenaga, C.J. Klamut, and R. Sabatini, IEEE Trans. Mags. MAG-21, 305 (1985).] Thus, it is concluded that in order to achieve very high current densities in these Nb_3Sn wires it is very important to produce wires with very sharp transitions, e.g., $n > 40$ at 16 T. This implies that the uniformity of the filaments along the length of the wires is extremely important for achieving high values of J_c .

C. Relativistic Heavy Ion Collisions at the AGS

Experiment 802

The participating groups in this experiment are:

ANL, BNL, UC Berkeley, UC Riverside, Columbia, Hiroshima, INS (U. Tokyo), Kyushu, MIT, Tokyo, Tsukuba

With the conclusion of the June 1989 silicon beam run, the data-gathering phase of E-802 has been completed. This data has led to more than 13 publications in refereed journals (and many conference reports) by the collaboration. One additional paper on intermittency in the charged particle multiplicity distributions is in the final stages of preparation. A second paper which contains the full accounting of the Si beam inclusive cross sections on targets of Al, Cu, and Au is nearing completion and should be ready in a few months. Figure 1 shows a sample of the data from this paper that was obtained with the silicon beam and an aluminum target, and illustrates the fine quality of the data which will allow detailed comparisons to theoretical calculations. With the completion of these papers the most important results from E-802 will be published and data analysis will slow although the data remain available to members of the collaboration to analyze as they wish.

Fig. 1: Preliminary transverse momentum spectra for p , $7\pi^+$, π^- for central collisions of Si with a Cu target. The spectra are displaced by a decade for each rapidity interval $\Delta y = 0.2$. For the protons the range is $0.5 \leq y \leq 2.1$ and for π^+ , π^- $0.6 \leq y \leq 2.8$.

Experiment 859

The participating groups in this experiment are:

ANL, BNL, UC Berkeley, UC Riverside, Columbia, INS(U.Tokyo), Kyoto, Kyushu, LLNL, MIT, NYU, Tokyo, Tsukuba

Experiment 859 uses the E802 spectrometer with the addition of a second-level trigger to select rare events which include specified particles. This system was commissioned during the 1991 run, and used for production in the 1992 run; the experiment was successfully completed in the 1992 run. The primary physics goals were to obtain high precision spectra of the more rare particles (K^+ , K^- , and antiprotons) produced from collisions of 14.6 A GeV/c Si ions with nuclear targets, and to measure particle source sizes in these reactions from Bose-Einstein correlations between K^+ , π^+ , and π^- pairs. Examples of the correlation measurements are shown in Figure 1, taken from the first E859 publication. After transformation from the particle-pair frames into a single source frame, the K^+ source is marginally smaller than that for π^+ . In addition, data was obtained on ϕ -meson, lambda, and anti-lambda production. The ϕ mass spectrum, constructed from K^+K^- pairs, is shown in Figure 2. The ratio ϕ/K^- was found to be 0.11, comparable to that in pp collisions.

Fig. 1: Correlation functions for 14.6 A GeV/c Si+Au $\rightarrow 2\pi^+ + X$ compared to those for Si+Au $\rightarrow 2K^+ + X$. Note the difference in the relative momentum scale for the two systems. The uncorrected correlation function is shown in (a) and (d), the results of correction for only the two-particle Coulomb repulsion (Gamow correction) are shown in (b) and (e), and the fully corrected data are shown in (c) and (f). The curves are fits to the function $C_2 = N[1 + \lambda \exp(-Q^2 R_Q^2)]$. After transformation into a single source frame the rms radii are 3.22 ± 0.37 fm for K^+ and 3.93 ± 0.28 fm for π^+ .

Fig. 2: Invariant mass distribution of K^+K^- pairs. The solid line is the fit to a function combining a relativistic Breit-Wigner resonance and the background, constructed from mixed events. The inset shows the ϕ -peak with the background subtracted.

Experiment 866 - Gold Beam Experiment

The participating groups in this experiment are:

ANL, BNL, UC Berkeley, UC Riverside, Columbia, INS (U. Tokyo), Kyushu, LLNL, MIT, NYU, Tokyo, Tsukuba

Experiment 866, a continuation of E-802/E-859 using the AGS gold beam, was approved for 2600 hours in January 1991. The scientific goals of E866 are similar to those of E-802/E-859 but the technical difficulties are much larger because of the larger particle multiplicities and multiplicity density. For this reason the collaboration is building a new spectrometer for small angles $6^\circ < \theta < 20^\circ$ and will use the E-802/E-859 spectrometer (Figure 1) for angles greater than 15° . The new spectrometer is to have two magnets with tracking between them and after the second one. Both tracking arrays will be composed of a time projection chamber sandwiched between drift chambers. There were six weeks of Au beam running spanning FY93 and FY94. The forward spectrometer was installed and brought into operation. Part of this time was devoted to testing and evaluating the new components and part to continuing the physics program.

In the spring of FY92, following the Si beam run, there were about two weeks of running with the gold beam. Measurements of the energy deposited in the lead glass array were taken then and are now being analyzed, but preliminary results (Figure 2) show the transverse energy for the Au target is roughly 4.5 times larger than in the Si+Au measurements and different in shape so that it cannot be simply rescaled. The spectra of kaons and pions (Figure 3), also from a Au target, were taken with the E-802/E-859 spectrometer at backwards rapidities. These data are also being analyzed now, but it is clear that the K^+/π^+ ratio has increased to about 25% from about 20% in central Si+Au collisions.

Fig. 1: Upper half: E-802/E-859 spectrometer for use $20^\circ < \theta < 60^\circ$
 Lower half: New forward spectrometer for use $6^\circ < \theta < 20^\circ$.
 FM1, FM2 - Magnets, FDC - Drift Chambers, FTPC - Time Projection Chambers,
 FTOF - Time-of-Flight Wall.

Fig. 2: Preliminary transverse energy spectra taken with the lead glass array for various beam-target combinations.

Fig. 3: Preliminary dN/dy for π^+ , K^+ , K^- for central collisions with the Au beam and a Au target. The measurements are shown as open points; the filled points are the measurements reflected about central rapidity because of the symmetric system. The curves are a model calculation using the code ARC.

D. Muon g-2 Experiment at the AGS (E821)

The participating groups in this experiment are:

KEK, University of Tokyo, Boston University, BNL, Cornell University, University of Heidelberg, University of Illinois, LANL, Yale University

Experiment 821 will measure the anomalous magnetic moment of the muon to a precision of 0.35 parts per million, representing a factor of 20 improvement over the beautiful CERN experiment. The general method is the same as the CERN experiment, involving the storage of muons in a high precision ring at the magic energy of 3.1 GeV. The project involves the construction of a 14-meter diameter superferric muon storage ring which has an ultraprecise magnetic field (homogeneous to 1 part in 10^6 and measured to 1 part in 10^7) and which uses electric quadrupole fields to focus the stored muons. Key improvements over the CERN experiment include the construction of a continuous ring with no ends, using superconducting coils which offer stability and less power supply ripple, and a new magnet shimming technique of introducing a gap between high quality pole steel and the return field iron. The gap allows for long wavelength precision shimming.

The goal of 0.35 parts per million in the moment anomaly would give the experiment a 20 percent measurement of the expected weak contributions from virtual W and Z effects. These would contribute at a 1.7 parts per million level, well below the sensitivity of the CERN experiment. In addition, other effects could contribute at this level, involving new physics - for example, supersymmetric particles. Therefore, a result which agrees with the calculation for the weak contribution would be an important verification of the electroweak theory and would, at the same time, severely constrain unification models. A result different from this would be a strong indication of the presence of new physics or challenge our present understanding of the electroweak theory.

In JFY 1991 the winding of the four superconducting coils was completed. Each coil is a stack of 24 turns of TOPAZ-style conductor, 14 meters in diameter wound onto a 20 cm high aluminum mandrel. This will be the largest diameter superconducting magnet in the world. The inner cryostats were finished in February, 1993. The outer cryostat was finished in October 1993. Machining of the iron yoke (1000 tons) was completed in January 1993. Special low carbon steel poles were fabricated in Japan and are now being machined at Ranor Corp., Westminister, MA with delivery to BNL by February, 1994. KEK and BNL have collaborated in the coil design, and on the specifications for the yoke and pole steel.

The 1.5 Tesla superconducting inflector is being supplied by KEK. This device cancels the magnetic field seen by the beam (pions or muons) as it approaches the storage

region. The 0.5 m model was successfully energized at 2000 A in March 1993. It was tested at 3000 A in April, 1993. Construction of the 1.7 m magnet has commenced.

The beam vacuum sector was designed in JFY 1992. The first beam vacuum sector was built in FY 1993, including a new design for the electrostatic quadrupoles using flat rather than hyperbolic electrodes. A conceptual design and model are complete for a cart which will carry NMR probes in the vacuum to measure the magnetic field periodically (Yale). CERN turned off the field and removed the vacuum tube to map the field. NMR probes for shimming are complete (Heidelberg). Scintillating fiber/lead calorimeter prototypes have been built and tested (Univ. of Illinois). A light guide is being developed. A flash ADC which will digitize the calorimeter signals every 5 nanoseconds is being built (Boston University).

The beam line and target civil construction will be completed in FY 1994. KEK is developing a scintillating fiber profile monitor to track the injected beam parameters.

The g-2 magnet will be assembled in FY 1994 and shimmed to 1 parts per million in FY 1995. The first g-2 run is expected in FY 1996.

E. Rare Kaon Decay (E787)

The participating groups in this experiment are:

INS(Tokyo), KEK, BNL, LANL, Princeton, TRIUMF

E787, a search for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and related decays, was originally approved in 1983 as a collaboration of BNL, Princeton University, and TRIUMF. The limit on $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ then in force, $< 1.4 \times 10^{-7}$, was about three orders of magnitude higher than the Standard Model (SM) expectation. This large window has allowed E787 to be sensitive to a great variety of possible new physics. Any K^+ decay that results in one π^+ and one or more noninteracting particles ($K^+ \rightarrow \pi^+ + \text{"nothing"}$) can be observed. NonSM candidates for the latter are photinos (or other light SUSYons), majorons, nonSM Higgs, axions, familons, hyperphotons, etc. In addition, new physics can enhance (or suppress) the process $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ with respect to the SM prediction. The SM calculation of this decay is very clean (no significant long-distance contributions, small, reliably calculable QCD corrections, etc.) so that in the absence of new physics its measurement can place important constraints on the Kobayashi-Maskawa parameters and the top-quark mass. For example, given a value of m_t , a relatively accurate determination of $|V_{td}|$ can be extracted from the measurement of $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu})$.

After a period of design, construction and testing, the experiment took major data runs in 1989, 90, and 91. At this point, having collected data expected to yield a sensitivity of $\sim 1-2 \times 10^{-9}$, the potential of both the beam and the apparatus was largely exhausted, necessitating major upgrades to both in order to make further progress. The motivation for doing so is very strong. There is still a significant window for new physics in $K^+ \rightarrow \pi^+ + \text{"nothing"}$ and, more important, the Standard Model beckons. $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ offers a virtually unique opportunity in which one-loop electroweak contributions comprise the entire quantity being measured rather than just a tiny correction. It also has become clear that alternative methods of determining $|V_{td}|$ are problematical, focusing attention on this approach. Finally, the experiment has yielded many other interesting measurements, and has the potential for a good deal more if upgraded.

In response to this, an upgrade proposal calling for a new beam and major changes to the apparatus was approved in November of 1989. A new beam, LESB3, was designed. Work also began on apparatus improvements. It was recognized at that point that the scale of the upgrade, combined with the necessity of running and analyzing the experiment throughout much of the upgrade period, would require augmenting the collaboration. Therefore participation was sought among Japanese physicists from KEK and Tokyo/INS. In 1992 physicists from these institutions joined the collaboration. The participation of these groups is essential to the successful continuation of the experiment. One of the major systems of the upgrade is the Csl photon veto. This consists of two endcaps and a cylindrical liner for the present barrel veto. This will increase the rate-taking capability of the apparatus (otherwise limited by random vetoes) as exploitation of the AGS Booster allows the K^+ beam intensity to be raised, and will improve the π^0 vetoing efficiency by a factor 10 or more. The endcaps are particularly critical because they have to cope with extremely high rates. The Japanese groups have taken on the responsibility of designing and building the downstream endcap. Equally important, they are providing a large part of the intellectual input to the photon veto project in general. Their design efforts during JFY 1992 have been critical to both Csl endcaps, they are building calibration systems for the endcaps, and they are playing a large role in R&D for future photon veto upgrades. We also expect them to become major participants in the analysis of the experiment, and broaden as well as deepen its physics output.

In addition to the new beam, which was successfully completed in FY 1992, and the Csl veto system, E787 is upgrading the beam instrumentation, replacing the trigger, data acquisition system, K^+ stopping target and central drift chamber, upgrading the range stack, and augmenting the electronics. An engineering run and data taking is scheduled for FY94.

The figure shows the past history and future projection of the progress of E787.

F. Relativistic Heavy Ions at RHIC - PHENIX

The PHENIX experiment is one of two large-scale detectors approved for running at the start of RHIC operations in 1999. PHENIX was proposed by an international collaboration of more than 300 physicists and engineers from 43 institutions in 10 countries. The collaboration includes "PHENIX-J," a group of 41 physicists from seven institutions in Japan. Table 1 lists all the participating institutions.

The goal of the PHENIX experiment is to discover a new phase of matter called quark-gluon plasma. The physics issues related to this new phase, together with experimental signatures that PHENIX intends to measure, are summarized in Table 2. Our goal is to measure as many potential signatures as possible to determine if this new phase of the QCD vacuum is created in heavy-ion collisions at RHIC.

The PHENIX detector is shown in Figure 1. It is designed to detect lepton pairs, photons, and hadrons produced in heavy-ion collisions at the highest energies and luminosities RHIC is designed to provide.

TABLE 1

Institutional participation in the PHENIX collaboration

PHENIX Collaboration

Brazil:		Russia:	
U. Sao Paolo	3	IHEP-Protvino	28
		INR-Moscow	7
Canada:		ITEP-Moscow	8
McGill U.	8	JINR-Dubna	16
		Kurchatov Inst.	8
China:		PNPI-St. Petersburg	14
CIAE	13	Individual	2
IHEP	8		
Inst. Mod. Phys.	8	Sweden:	
Peking U.	4	Lund U.	9
Germany:		U. S. A.:	
U. Munster	4	U. Alabama	4
Individual	1	BNL	20
		UC-Riverside	5
India:		Columbia U.	13
BARC, Bombay	3	Florida State	2
		Georgia State	3
Japan:		Idaho NEL	4
Hiroshima U.	4	Iowa State/Ames Lab.	8
INS, U. Tokyo	5	LLNL	9
KEK	7	LANL	14
Kyoto U.	2	Louisiana State	4
Nat. Inst. Rad. Sci.	1	MIT	2
U. Tokyo	5	SUNY-Stony Brook	12
U. Tsukuba	16	ORNL	11
Individual	1	U. Tennessee	4
		Vanderbilt U.	3
Korea:		Yale U.	9
Chung-ang U.	1	Individual	2
Korea U.	4		
Seoul Nat. U.	6	Total	326
Soong-Sil U.	1

Fig. 1: A three-dimensional cutaway view of the PHENIX detector, showing the location of the various detector subsystems. The detector subsystems are labeled in the figure.

TABLE 2

Physics Issues Related to Quark-Gluon Plasma

QGP Physics Issues	Probes
<u>Nature of the Phase Transition</u> ● First-order: Entropy Jump $\rightarrow$ Second rise in the p_T $\rightarrow$ spectra of π, K, p ● Second-order Fluctuation $\rightarrow N(\pi^0)/N(\pi^+\pi^-)$, $d^2N/d\eta d\phi$	Hadrons Hadrons, Photons
<u>Debye Screening of QCD Interactions</u> ● $r(\Psi)=0.13 \text{ fm} < r(J/\psi)=0.29 \text{ fm} < r(\psi')=0.56 \text{ fm}$ $J/\psi \rightarrow e^+e^-$ at $y \simeq 0$ $J/\psi \rightarrow \mu^+\mu^-$ at $y \simeq 2$ $\psi', \Psi \rightarrow \mu^+\mu^-$ at $y \simeq 2$	Electrons Muons
<u>Chiral Symmetry Restoration</u> ● Mass, Width, Branching: $\phi \rightarrow e^+e^-, K^+K^-$ $\text{with } \Delta m \leq 5 \text{ MeV}$ ● Baryon Susceptibility: Production of antinuclei ● Narrow σ meson?	Electrons Hadrons
<u>Thermal Radiation of Hot Gas</u> ● Prompt γ , Prompt $\dot{\gamma} \rightarrow e^+e^-$	Photons, Electrons
<u>Strangeness and Charm Production</u> ● Production of K^+, K^-, K_L^0 $\phi \rightarrow e^+e^-, K^+K^-$ at $y \simeq 0$ $\phi \rightarrow \mu^+\mu^-$ at $y \simeq 2$ D meson: $e\mu$ coincidence	Hadrons Electrons Muons
<u>Jet Quenching</u> ● High p_T Jets via Leading Particle Spectra	Hadrons
<u>Space-Time Evolution</u> ● HBT Correlations for $\pi\pi$ and KK	Hadrons

The PHENIX-J group intends to provide significant instrumentation for the detector, including ring-imaging Cerenkov (RICH) counters, a high-precision time-of-flight (TOF) array, beam-beam (BB) counter arrays, and the coils for the central magnet. The design is based on the results of a comprehensive R&D program and on extensive simulations of detector performance. Figure 2, for example, shows the expected dielectron performance for eight days of RHIC running with Au + Au at 100 GeV/A per beam. The vector mesons are clearly seen in the e^+e^- channel prior to final cuts and background (like-sign) subtraction.

In addition, the PHENIX-J group tested a slat design for the high-precision TOF system. They succeeded in obtaining a resolution of better than 100 ps for a thin ($1.2 \times 1.2 \text{ cm}^2$) and long (1 m) scintillation counter. Test for the beam-beam counter also proved successful.

The design concept for PHENIX was worked on throughout FY 1992. This work culminated in the production of a preliminary conceptual design report (pCDR) in June of 1992 and a detailed conceptual design report (CDR) in late January 1993. These documents were reviewed by the RHIC Technical Advisory Committee (TAC) and the BNL High Energy and Nuclear Physics Program Advisory Committee (PAC). Based on the successful reviews of the CDR by the TAC and the PAC in February 1993, PHENIX was approved to begin spending construction funds on the final detector engineering design and on long lead-time procurement items. A final review of the cost, schedule, and management plan for PHENIX is planned to take place in November 1993.

Fig. 2: The full dielectron pair mass region, showing the ω , the ϕ , and the J/ψ at their expected rates.

Activities at Cornell University

This report covers the continuing activities of the Cornell University Laboratory of Nuclear Studies superconducting radio frequency (SRF) program for the period November 1988 to November 1993. During this period supplementary support was received from the US-Japan Agreement in the amount of \$301,796. Principal support of these activities was received from the National Science Foundation. Visiting scientists from DESY, KEK, Los Alamos, Novosibirsk, Orsay and Wuppertal had a strong participation in the work reported.

The mission of the SRF program is to advance the technology of rf superconductivity for use in future accelerators at the luminosity and energy frontiers. Specifically we target the development of SRF towards increasing the current and thereby the luminosity of the Cornell Electron Storage Ring (CESR). We pursue basic research to understand the limitations on the performance of SC cavities and to develop new techniques to reach higher gradients. Besides the benefit to cavities for high current storage rings, this research would also prove beneficial to a future TeV Superconducting Linear Collider (TESLA).

Brief History

Over the last 20 years a number of pioneering initiatives were taken at Cornell, starting in 1974 with the first beam test of an SRF cavity in a high energy accelerator, to the first application of SRF cavities to an e^+e^- storage ring collider in 1985. Cornell SRF cavity technology was adopted as the core technology for CEBAF, a 4 GeV recirculating CW superconducting linac for precision nuclear physics. Over the same period, new techniques were developed to advance cavity performance, such as improving the purity of niobium to provide thermal stability, and high pulsed RF power processing to reduce field emission *in situ*.

SRF for High Luminosity Storage Rings, Accelerating Cavities

The primary focus has been on the goal to develop SRF cavities for improving the luminosity of CESR. High luminosity colliders such as B-factories, tau-charm factories, as well as the LHC stand to gain from the use of SRF. To achieve high luminosities in any of these machines, 1 - 2 amps of current need to be stored in many bunches spaced a few meters apart. To avoid multibunch instabilities, such high currents and tight bunch spacing make it imperative to lower the beam-cavity interaction

(impedance). Short bunches required to squeeze the beam at the interaction point demand high accelerating voltage. By operating with high gradient SC cavities (5-10 MV/m), the number of high impedance accelerating cavities can be reduced over copper cavities which provide 1 - 2 MV/m for existing storage rings. SRF cavities allow the use of large beam holes, which further cuts the impedance. To minimize the power dissipation for a desired accelerating field, copper cavities are forced to have geometries that intensify the harmful beam-cavity interaction. In particular the beam holes must be made small. With low loss superconducting cavities, large beam holes become affordable. As added bonuses, capital and operating cost savings can be realized from the reduced RF installation which no longer needs to provide for rf power dissipation in the SC cavity walls.

To operate with high currents, SRF cavities used in the present generation of storage rings (TRISTAN, HERA and LEP) need to be advanced in several respects, in particular their input and output power handling capabilities, as well as the damping of the beam induced higher order modes (HOMs). We made substantial progress toward meeting these challenges.

Our major thrust is to develop, procure and test components of hardware with a view to assembling a complete superconducting accelerating cavity system for test with a CESR beam in early 1994.

An attractive approach to meet the high power requirements accompanying ampere size beam currents is to reduce the input and output coupler loads by distributing the power to be handled over many single-cell cavities. We have completed the design of a single cell SC cavity with individual input and output couplers. An innovative cell shape makes the impedance of all HOMs very low. Large diameter (24 cm) beam pipes, with flutes on one of the beam pipes, propagate all the HOMs out of the cavity and the cryostat. Outside the cryostat the HOMs are damped in sections of beam pipe that will be lined with ferrite. In comparison to small coaxial HOM couplers now in use for extracting 10-100 watts of power, the 24 cm diameter beam pipe will be more suitable for extracting the 10 kwatts expected for ampere size beam currents. Q's of HOMs are lowered by using 15 cm long ferrite lined beam pipes outside the cryostat. The input coupler is selected to be of the waveguide type so the power densities are low, and only the outside wall needs cooling. This approach should allow substantially higher power than the 100 kwatts capability of present day coaxial input couplers.

A 500 MHz niobium single cell cavity with niobium waveguide input coupler was received from industry and successfully tested. The cavity exceeded 10 MV/m gradient at a Q of 10^9 , so that the established capability is 3 MV total, with 100 watts RF dissipation. For comparison, our 5-cell NC cavities presently operating in CESR achieve 2.4 MV total with an RF dissipation of 150 kwatts.

Two planar waveguide windows were received from industry and tested together to 250 kwatts CW travelling wave power and 125 kwatts reflected power. Instead of the customary alumina ceramic, the window material is beryllium oxide, which has an order of magnitude higher thermal conductivity.

A 500 MHz copper single cell cavity of the same design as the niobium cavity was also received from industry and equipped with low power ferrite HOM loads on the beam pipe. Q values between 20 and 70 were measured for monopole modes and between 20 and 150 for dipoles. With the low impedance cell design and the strong damping achieved, stability calculations show that it will be possible to store 1 - 2 amps of average current in storage rings without a complex bunch to bunch feedback system against longitudinal multibunch instabilities. Without the low impedance solution offered by the SRF cavity approach a high power and high bandwidth feedback system would be essential for corrections. We believe that removing the impedance at the source is a more effective approach against multibunch instabilities than complex correction techniques.

Measurements were carried out on the permittivity and permeability of ferrite over the frequency range 300 kHz to 20 GHz. From these properties we made an assessment of the broad band impedance, both longitudinal and transverse, of ferrite lined HOM loads. Knowledge of the coupling impedance gives us information to assess the interaction of the HOM loads with the beam and to predict beam instabilities. We used various approaches: the LLNL program AMOS, our own analytic procedure, and direct measurement by making the load the outer conductor of a coaxial transmission line. The overall result is that the broadband impedance, both longitudinal and transverse should have no adverse effect on the single bunch currents needed for increasing CESR luminosity.

Engineering studies for the HOM load are under way. These include bonding to a metal shell, vacuum properties up to 100 C, tensile strength, and thermal conductivity measurements. To establish the tolerable power density, small scale and full scale HOM loads are being prepared and tested with high power microwaves. Preparations are underway for a test in CESR of a long section of small diameter beam pipe lined with ferrite.

We have completed the design for the cryostat and mechanical tuner. The design of the cryostat was challenging because of the very large beam pipes, the high input power waveguide coupler and the need to assure a dust free environment to the inside of the cavity during assembly. The cryostat is under fabrication by industry and delivery is expected in November, 1993.

For the upcoming beam test in CESR, auxiliary components such as thermal transitions, sliding joints, gate valves are designed, fabricated and tested. All these auxiliary components have a very large (24 cm) bore, to maintain compatibility with the

large bore, low impedance SC cavity. Instrumentation for interlocks and diagnostics is designed and being assembled.

The objectives for the beam test are to operate the cavity at the maximum possible gradient and store the maximum possible beam current. With CESR it should be possible to access 170 mA. Other objectives are to couple the maximum power to the beam through the input coupler and window, and to extract the maximum possible HOM power. We hope to explore single and multibunch stability issues.

Crab Cavity Development

The close bunch spacing desired in a high luminosity storage ring calls for another important application for superconducting cavities. To permit the largest number of bunches, an attractive method to separate the e^+ and e^- beams before and after collision is to arrange an angle crossing. Harmful coupling between synchrotron and betatron motion can be eliminated with "crab" compensation, wherein the bunches are rotated so as to collide head on at the interaction point, and then straightened out after collision. All B-factory proposals consider "crab crossing" as an upgrade path to higher luminosity. Crabbing is achieved with an RF cavity which deflects the bunches rather than accelerating them. An SRF cavity is the most attractive approach, because the total kick necessary can be provided by a single cell, thus minimizing the added impedances.

Considerable progress was made on the R&D for crab cavities. The cavity is shaped rather like an accelerating cavity, but is operated in the first deflecting mode (the TM₁₁₀ mode) because it has the highest transverse shunt impedance. The cell is slightly flattened at the equator to separate the degenerate frequencies of the horizontal and vertical polarizations of the TM₁₁₀ mode. Q values of unwanted modes need to be damped to < 100 . Since the deflecting mode is not the lowest frequency mode, the lower modes require special attention, in particular the fundamental (TM₀₁₀) mode. To damp these modes, we developed the beam line coaxial coupler. A hollow center conductor, coaxial with the beam line, couples strongly to the unwanted lower frequency modes, but does not couple to the TM₁₁₀ mode by virtue of field symmetries. All other modes couple out of the regular beam pipe on the other side of the cavity. A small vertical asymmetry built into the tip of the coaxial coupler guides out the unwanted (vertical) polarization of the crab mode.

A 1/3 scale copper crab cavity was bench tested with low power ferrite HOM loads, similar to the ones planned for the accelerating cavity. Q values below 100 could be obtained for all dangerous parasitic modes. A 1/3 scale niobium crab cavity with the coaxial beam line coupler was built and cold tested. It reached a surface electric field of 20 MV/m at a Q of 10^9 . A full scale cavity that reaches the same surface fields will provide a kick of 1.8 MV, sufficient to compensate the crossing angles of about 10

mradians contemplated by most machines. The niobium and copper cavities have been sent to KEK where further tests are planned.

TESLA Activities

The idea of TESLA (TeV Superconducting Linear Accelerator) continues to gather momentum. There are many compelling attractions of the SRF approach to linear colliders. Low RF peak power reduces capital cost. A low RF frequency (1.3 GHz) leads to a large beam hole that minimizes the wakefield effects in the linac. A large spacing between bunches provides long times for wakefield damping and clearing the detector. A large final focus spot size relieves the many challenges in generating, preserving and bringing to collision beams of low emittance. The first international workshop on TESLA was held at Cornell in July 1989 to work on a parameter list, and explore ideas on TESLA structures, high gradients and cost reduction. Cornell continued work on these fronts in collaboration with the world TESLA community.

DESY is now putting together a 40 meter long test linac to address gradient, cost and system performance issues. We assisted DESY with the test facility proposal, transfer of high gradient SRF technology and advice on the installation of the necessary facilities.

The major challenges for TESLA are to increase the gradients from today's levels of 5-10 MV/m to 20-30 MV/m and to lower the costs. These have been important objectives of our work on gradient improvement and basic studies.

The most promising techniques for high gradients are high pulsed power RF processing to overcome field emission and high purity, high thermal conductivity niobium to overcome thermal instabilities. Both approaches have been pioneered and intensely pursued at Cornell. Substantial progress has been registered on both fronts. We are pleased to report that by using these approaches, we have provided for the first time an existence proof for the TESLA goals: we reached an accelerating gradient of 25 MV/m at a Q of 2×10^9 in a 5-cell cavity at the TESLA frequency of 1.3 GHz.

Our High Pulsed Power (HPP) RF processing work started with 1-cell, 2-cell and 9-cell cavities at 3 GHz. We used power levels between 5 and 150 kwatts and pulse lengths between 100 and 1000 msecs. In all cases, HPP was found very effective in reducing field emission *in situ*, with improvement factors between 2 - 3. Accelerating fields between 15-20 MV/m were reached with two 9-cell structures in 7 consecutive tests. In each test the surface of the cavity was prepared anew. In each case heavy field emission was successfully processed with HPP to reach the final field levels. The effectiveness of processing depends on the highest surface electric field reached in the pulsed processing stage and not on the peak RF power or the processing time. In

the pulsed conditioning phase the maximum surface fields we reached were: 60 MV/m in 9-cells, 72 MV/m in single cells and 113 MV/m in a special 2-cell (see below). The processing was also proved effective against new field emission when additional contaminants were introduced by deliberate vacuum "accidents".

Encouraged by this progress we launched a program with the help of TESLA collaborators from FNAL and DESY to apply HPP to 1.3 GHz multi-cell structures. Boeing lent us a klystron and modulator which we installed at Cornell and commissioned to provide 1.5 Mwatts power at 150 msec pulse length. First tests with 1-cell and 2-cell cavities confirmed that the HPP technique is equally effective at the new frequency. After learning experiences in proper placement and conditioning of windows in the HPP coupler, we successfully applied HPP to 5-cell cavities. We achieved 18 and 25 MV/m accelerating in two 5-cell structures. Substantial improvements (factors of 2-3) were realized by conditioning away field emission during HPP using up to 1 Mwatt of power. A third 5-cell structure also improved with HPP but is limited by thermal breakdown to $E_{acc} = 14.5$ MV/m. Its thermal conductivity is being improved by the Cornell developed technique of heat treatment at 1400 C in the presence of Titanium foils.

The purity and thermal conductivity of niobium delivered by industry keeps increasing steadily. RRR (residual resistivity ratio) of 250 to 400 is available today from U.S. and European firms. RRR of 500 - 1000 is available from Russia. We routinely acquire material of increasing purity from all these sources to make test cavities. Our own process of improving the RRR of commercial niobium by solid state gettering with yttrium or titanium is still capable of doubling the as-received RRR. This procedure is being applied both to finished cavities as well as cavity parts to ensure the best protection against premature breakdown of superconductivity from thermal instabilities.

Basic SRF Research

The limitation to HPP has been shown by careful thermometry measurements on 1-cell cavities, to arise from thermal breakdown at the high magnetic field region of the cavities. This limits the maximum electric field accessible to the iris regions for processing away emitters. To get around this limit, a 2-cell cavity with a lower ratio of surface magnetic to electric field was constructed. In tests with HPP on this cavity it was possible to surpass all previous electric fields to reach 113 MV/m pulsed and 100 MV/m CW, corresponding to a world record CW accelerating field of 34.5 MV/m.

We made two important breakthroughs in basic understanding of field emission in SRF cavities. In the first we identified the sources of emitters, and in the second we revealed how field emitters process in RF fields.

We developed a new type of superconducting cavity, called the "mushroom" cavity with which it is possible to expose a small region of niobium (called the dimple) to a very high RF electric field, and subsequently to examine this region with surface analytical instruments like: the scanning electron microscope (SEM), energy dispersive X-rays (EDX) for element analysis and Auger electron spectroscopy (AES) for more surface sensitive element detection. In the RF tests we successfully exposed the dimple to fields ranging from 50 to 145 MV/m. Subsequently in the SEM we found 5 -10 μm craters of molten niobium, covered with a thin (100 Angstrom) layer of foreign elements. Frequently we encountered mm size foreign element debris in various stages of melting in the vicinity of the craters. In order of the frequency of occurrence, the impurities found in or near the craters were: Fe, Cr, Si, F, Cu, In, Ni, C and Mn. We believe that particulate "dust" originating from the cavity assembly and test environments is an important source of field emitters. Surrounding the molten craters, we always found 100 μm starburst shaped spots that appear dark in the SEM, but are invisible in the optical microscope.

Similar results were obtained in studies with several 1-cell 3 GHz accelerator cavities, that were dissected after locating and processing field emitters. Before processing, emitters were located by mapping the heating caused by impacting electrons. The emitters pin-pointed by the temperature maps were then processed by application of HPP, and in one case CW RF. After dissection, SEM examination of the suspect areas revealed molten craters, foreign element debris and starbursts, very similar to those found in the mushroom cavity.

The features found in the high electric field region of the mushroom and accelerator cavities suggest the occurrence of a spark (micro-discharge) in the high RF field. We surmise that emitter processing takes place by the explosive mechanism associated with the spark. The plasma of the spark is responsible for the starburst, while the central molten core is the region where most of the energy during the spark is dissipated. Fragments of foreign material, most likely the root cause of the emission are expelled during the crater formation.

Studies were carried out to determine what is the maximum RF surface magnetic field that a niobium surface will support before superconductivity will quench. The upper limit established by previous studies at Cornell and other labs was 1700 Oersted. Using short pulses (200 msec) of 150 kwatts power in a single cell 3 GHz cavity, we reached a surface magnetic field of 2070 Oersted, at a Q near 10^7 . The Q is not higher because of a small growing normal conducting region. But over 95% of the cavity area the surface is still superconducting. This result provides the first experimental verification that niobium cavities are inherently capable of providing accelerating fields as high as 50 MV/m.

Facilities

Comprehensive facilities are available at Cornell for the design, fabrication, preparation and testing of SC cavities as well as for basic research. These facilities have proved critical to our efforts to advance SRF technology for future accelerators. Several upgrades to our facilities have been carried out, including a new ultra-pure water system, a new chemical treatment facility, vertical dewar test set-ups for the high luminosity, TESLA and basic research cavities, and an SEM/EDX system for microscopic examination of niobium surfaces.

PUBLISHED PAPERS

5th Workshop on RF Superconductivity, CEBAF, October 93

(Proceedings to be published)

- 1) Superconducting RF Activities at Cornell University, J. Kirchgessner et al.
- 2) On Reaching 25 MV/m Accelerating Using High Pulsed Power RF Processing, C. Crawford et al.
- 3) A Summary of HPP Studies on 3 GHz Niobium Cavities, J. Graber et al.
- 4) A New Upper Limit to the Maximum RF Critical Field for Niobium, J. Graber et al.
- 5) Microscopic Examination and Elemental Analysis of Field Emission Sites in 5.8 GHz Superconducting Mushroom Cavities, T. Hays et al.
- 6) The Use of Superconducting RF for High Current Applications, J. Kirchgessner.
- 7) Review of Various Approaches and Successes in Raising Gradients and Q's for TESLA, H. Padamsee.

Particle Accelerator Conference, Washington DC., May, 1993

(Proceedings to be published)

- 1) Preparation and Testing of a Superconducting Cavity for CESR-B, D. Moffat et al.
- 2) The Interaction of a Beam with a Beam Line Higher-Order Mode Absorber, W. Hartung et al.
- 3) In Search of Trapped Modes in the Single-Cell Cavity Prototype for CESR- B, W. Hartung et al.
- 4) Development of a Crab Cavity for CESR-B, K. Akai, et al.
- 5) An Update on High Peak Power (HPP) RF Processing of 3-GHz, Nine Cell Niobium Accelerator Cavities, J. Graber et al.
- 6) Microscopic Investigation of RF Surfaces of 3 GHz Niobium Accelerator Cavities Following RF Processing, J. Graber et al.
- 7) A World Record Accelerating Gradient in a Niobium Superconducting Accelerator Cavity, J. Graber et al.
- 8) Status and Outlook for High Power Processing of 1.3 GHz TESLA Multicell Cavities, J. Kirchgessner et al.
- 9) 20 MV/m Accelerating Gradient with Heat Treatment of a Six-Cell, 1.5 GHz Cavity for TESLA, J. Kirchgessner et al.
- 10) Design, Fabrication and Testing of a Cavity Etching System at Cornell, D. Moffat et al.
- 11) Test Results and Design Considerations for a 500-MHz, 500-kW Vacuum Window for CESR-B, D. Metzger et al.
- 12) Cryostat for a Beam Test with the CESR-B Cavity, E. Nordberg et al.
- 13) A Statistical Model for Field Emission in Superconducting Cavities, H. Padamsee et al.

- 14) Thermal Modelling of Cryogenic Accelerating Structures, H. Muller et al.

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- 1) Microscopic examination of field emission areas in superconducting Nb cavities, D. Moffat et al., p. 21.
- 2) Prototype 500 MHz planar RF input window for a B-factory accelerating cavity, J. Kirchgessner et al., p. 678.
- 3) Accelerating cavity development for the Cornell B-factory CESR-B, H. Padamsee, et al., p.783.
- 4) Application of Superconducting RF to linear colliders, H. Padamsee (invited) , p.2042.
- 5) High peak power RF processing studies of 3 GHz Nb cavities, J. Graber et al., p. 2411.
- 6) Increase in RF surface resistance of Nb as a result of acid treatment, D. Moffat et al, p.241.
- 7) Test results on 3 GHz structures for a superconducting linear collider, R. W. Roth et al, p.2417.
- 8) Field emission studies of heat treated and chemically treated superconducting cavities, H. Padamsee, et al, p.2420.
- 9) Crab cavity development for the Cornell B-factory, CESR-B, p.2423.
- 10) Development and test of an accelerating cavity shape for a superconducting linear collider, J. Kirchgessner et al, p.2426.

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- 1) Superconducting RF Activities at Cornell University, J. Kirchgessner et al.
- 2) Design Challenges for High Current Electron Storage Rings, H. Padamsee et al.
- 3) RF-Field Emission: Update on Studies of the Nature of Field Emission Sites., D. Moffat et al.
- 4) Status Report on TESLA Activities, H. Padamsee.

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- 2) New Results on RF and DC Field Emission, H. Padamsee et al.
- 3) The Effects of Exposing Well Processed RF Surfaces of Superconducting Cavities to Various Media, Q. S. Shu et al.
- 4) Superconducting Niobium RF Cavities Designed to Attain High Surface Electric Fields, D. Moffat et al.
- 5) High Peak Power Processing of Superconducting Cavities, J. Graber et al.

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- 1) Superconducting RF Linear Collider, D. L. Rubin et al.
- 2) Higher Order Mode RF Power Extraction from Polarized Cavities with a Single Output Coupler, J. Kirchgessner et al.
- 3) Field Emission Processing of Superconducting RF Cavities with High Peak Power, J. Kirchgessner et al.
- 4) R&D in Progress to Overcome Field Emission in Superconducting Accelerator Cavities, Q. S. Shu et al.

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- 1) Design Challenges for High Current Storage Rings, H. Padamsee et al, Particle Accelerators 1992, Vol 40, p. 17-41 (1992).
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Activities at Lawrence Berkeley Laboratory

LBL Particle Data Group Collaboration with Japan

The U.S.-Japan Collaboration of the Particle Data Group (PDG) has been a critical element in the production of the the Review of Particle Properties (RPP) and other PDG publications since 1986.

The Review summarizes the status of High Energy Physics. It is the definitive arbiter of particle properties and provides many vital reviews of experimental and theoretical physics.

The Review is requested by 14,000 people and the booklet version by 28,000 people. It is cited by 7% of all papers in our field, far more than any other publication.

The Japanese support comes in two forms: a) manpower, and b) funding. Under the guidance of Dr. Kasuke Takahashi and now Dr. Yoshio Oyanagi, both aspects have grown substantially during the last few years. Four Japanese physicists (Drs. Ken-ichi Hikasa and Hitoshi Murayama of Tohoku University and Drs. Kaoru Hagiwara and Setsuya Kawabata of KEK) are intensively involved in the encoding of data and the writing of "mini-reviews" on searches for top quarks, heavy bosons (W , Z , etc.), Higgs bosons, compositeness of quarks and leptons, supersymmetry, axions, and even more exotic particles. They read the experimental papers, encode them, and check the produced "listings." In recognition of the substantial contribution by the Japanese members of our collaboration, we chose to make them the first authors of the 1992 edition of RPP. On numerous occasions these collaborators have visited LBL during the final production phases to help insure the quality of these sections of RPP.

In addition, Dr. Oyanagi has made substantial contributions to the encoding and checking of "A Guide to Experimental Elementary Particle Physics Literature" (LBL-90), and of "Current Experiments in Elementary Particle Physics" (LBL-91) which is now produced by a LBL-KEK-SLAC- CERN-Serpukhov collaboration.

The Japanese collaboration this year is providing 2.5 million yen to cover the production and distribution costs associated with copies of RPP received by Japanese physicists. Additional funding is provided to support travel to the US by our Japanese collaborators. They are also providing one million yen to support the production of LBL-91. In conclusion, the U.S.-Japan Collaboration has evolved into a very successful and essential effort that produces materials used by physicists around the world.

Silicon/Electronics collaboration with LBL

For several years, a very small amount of funding has been provided to U of Tokyo and KEK for collaboration in silicon detectors and electronics with the LBL group.

LBL is a strong center for these technologies, having developed the SVX for the FNAL Tevatron Collider, the silicon tracker for SDC, the wedge detectors for the D0 upgrade and the B factory, and pixel detectors. The collaboration with LBL has been primarily in the form of engineering and design consultations by the Japanese groups. This effort included the design and testing of a series of four custom integrated circuit preamplifiers for large area silicon detectors.

APPENDIX V

ANNUAL BUDGET TABLES U.S./JAPAN PROGRAM FOR COOPERATION IN HIGH ENERGY PHYSICS 1989 - 1993

Budget Plan for JFY 1989

PROJECT	LAB	AMOUNT (M\$)
EXPERIMENTS		
CDF	FNAL	235
Polarization (E704)	FNAL	60
Emulsion (E653)	FNAL	30
Heavy Ion (E802)	BNL	130
SLD	SLAC	135
Bubble Chamber (E745/782)	FNAL	30
g-2 R&D (E821)	BNL	30
ACCELERATOR R&D		
SC Magnet	CDG/KEK	270
Linear Collider	SLAC/KEK	230
SC RF Cavity	Cornell/KEK	20
DETECTOR R&D		
Detector R&D	LBL	18
Detector R&D	CDG/KEK	150
Particle Data	LBL	2
Reserve & Cutdown		72
TOTAL		1412

Budget Plan for JFY 1990

PROJECT	LAB	AMOUNT (M¥)
EXPERIMENTS		
SLD	SLAC	150
CDF	FNAL	259
Heavy Ion	BNL	130
Polarization	FNAL	45
Emulsion	FNAL	5
Bubble Chamber	FNAL	30
ACCELERATOR R&D		
Linear Collider	SLAC/KEK	270
SC Magnet	BNL/FNAL/SSCL/KEK	250
μ Storage Ring	BNL/KEK	20
RF Cavity	Cornell/KEK	20
DETECTOR R&D		
Detector R&D	LBL	7
Detector R&D	BNL/FNAL/SSCL/LBL/KEK	202
Other		3
Reserve & Cutdown		72
TOTAL		1454

Budget Plan for JFY 1991

PROJECT	LAB	AMOUNT (M¥)
EXPERIMENTS		
SLD	SLAC	95
CDF	FNAL	244.5
Polarization	FNAL	20
Heavy Ion	BNL	115
ACCELERATOR R&D		
Linear Collider	SLAC/KEK	310
SC Magnet	SSCL/KEK	100
μ Storage Ring	BNL/KEK	20
RF Cavity	Cornell/KEK	20
DETECTOR R&D		
Detector R&D	SSCL/KEK	395
Detector R&D	LBL	5
Other	PDG	3.5
Reserve & Cutdown		90
TOTAL		1418

Budget Plan for JFY 1992

PROJECT	LAB	AMOUNT (M¥)
EXPERIMENTS		
SLD	SLAC	50
CDF	FNAL	250
Polarization	FNAL	20
Emulsion	FNAL	20
Heavy Ion	BNL	112
ACCELERATOR R&D		
Linear Collider	SLAC/KEK	350
μ Storage Ring	BNL/KEK	20
RF Cavity	Cornell/KEK	20
DETECTOR R&D		
Detector R&D	SSCL/KEK	395
Detector R&D	LBL/KEK	5
Rare K Decay	FNAL/BNL	60
OTHER		
Particle Data	LBL/KEK	3.5
Reserve for Adjustment		35
Reserve/Cut Down		74.5
TOTAL		1418

Budget Plan for JFY 1993

PROJECT	LAB	AMOUNT (M¥)
EXPERIMENTS		
SLD	SLAC	70
CDF	FNAL	177
Polarization	FNAL	5
Emulsion	FNAL	15
Heavy Ion	BNL	160
Kaon Rare Decay	BNL	40
Kaon Rare Decay	FNAL	90
ACCELERATOR R&D		
Linear Collider	SLAC	310
SC Magnet	BNL/FNAL/SSCL	10
Muon Storage Ring	BNL	20
High Luminosity Storage Ring	Cornell/SLAC	30
DETECTOR R&D		
Detector R&D	LBL	5
Detector R&D	BNL/FNAL/SSCL	395
OTHER		
Particle Data	LBL	4
Reserve for Adjustment		15
Reserve/Cut Down		72
TOTAL		1418

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