

A photograph of two men standing on a balcony of a brick building. The man on the left is wearing a green polo shirt and dark pants, with glasses hanging from his shirt. The man on the right is wearing a blue button-down shirt and jeans, with glasses. They are standing behind a dark metal railing. The building behind them has large, curved brick columns. The text is overlaid in white, bold, uppercase letters at the bottom of the image.

**CORNELL BECAME ONE OF THE LEADING CENTERS FOR THE DEVELOPMENT OF ACCELERATOR TECHNOLOGY AND THE TRAINING OF ACCELERATOR PHYSICS STUDENTS. AND NOW WITH CLASSE (CORNELL LABORATORY OF ACCELERATOR-BASED SCIENCES AND EDUCATION), CORNELL PLANS TO CONTINUE ITS LEADING EDGE.**

(l.) Maury Tigner and (r.) Sol Gruner

## CORNELL'S ACCELERATOR-BASED SCIENCES



### From the Beginning

At the end of the nineteenth century scientists complacently believed that most of the fundamental physical laws governing the universe were known. Newton's laws successfully described forces

ranging from the action of mechanical machines to the motions of the planets. Throughout the preceding 75 years a succession of physicists, starting with Sadi Carnot in France and culminating with Josiah Willard Gibbs in America, had determined laws governing heat engines. In England, James Clerk Maxwell had completely described the basis of electricity. The consequences of this understanding, in the hands of people like Thomas Edison, were rapidly changing the world in innumerable ways. With the coming of scientific understanding, civilization shook off its dependency on animal muscle power and flame illumination, with consequent rapid and profound changes in industry, transportation, and home life.

The view that all was fundamentally understood was shattered in a half year at the end of 1895. On November 8, 1895, Wilhelm Roentgen noticed a green glow emanating from a phosphor screen near an experimental electrical apparatus enclosed in black paper in his Würzburg, Germany, laboratory. An invisible ray produced by his Crookes tube apparatus could penetrate the paper and excite the phosphor. Roentgen had discovered x-rays. In March 1896, Henri Becquerel, who was studying phosphorescence initiated by sunlight, wrapped his photographic plates in black paper and stored them in a drawer until the overcast skies above his Paris laboratory cleared. Much to his surprise, he found that the plates had become exposed anyway, a phenomenon he traced to emanations from some uranium minerals that happened to be in the same drawer. Becquerel had discovered natural radioactivity.

The discoveries by Roentgen and Becquerel rocked the world because they could not be fit into the existing scientific framework of the time. Both discoveries incited an ever-accelerating proliferation of experiments by investigators around the world

and, within just a half century, led to the discovery of the atom and nuclear energy and the development of quantum mechanics. The discoveries indelibly shaped a world that, by the end of World War II, would have been unimaginable in the 1890s. They revealed that the universe is composed of many types of subatomic particles that interact according to rules that were only partly understood. By the end of World War II, it was abundantly clear that serendipitous discoveries in seemingly arcane areas of science sometimes lead to an understanding of nature that results, over the course of decades, in huge consequences for society.

### The Physics of Subatomic Particles at Cornell

A number of Cornell physicists were asked to serve on the Manhattan Project during World War II. After the war, Hans A. Bethe, the physicist who headed the theory division at Los Alamos, returned to the Cornell and persuaded Cornell president Edmund Ezra Day to found the Laboratory of Nuclear Studies (recently renamed the Laboratory of Elementary-Particle Physics, or LEPP) and to build Newman Laboratory to house the activity. LEPP quickly developed into one of the world's leading centers of research in the physics of subatomic particles. The fundamental experimental tools of the trade were particle accelerator machines, so-called atom smashers. Cornell became one of the leading centers for the development of accelerator technology and the training of accelerator physics students. A succession of larger and more powerful electron accelerators were built. The first of these were housed in the basement of Newman Lab. By the 1960s the Newman Lab site was too small for the next generation of accelerators. A new accelerator complex was constructed in a half-mile-circumference tunnel underneath Alumni Fields, and a new building, now called the Robert R. Wilson Synchrotron Laboratory (Wilson Lab), was built at the south end of the tunnel to house the experiments.

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**LEPP QUICKLY DEVELOPED INTO ONE OF THE WORLD'S LEADING CENTERS OF RESEARCH IN THE PHYSICS OF SUBATOMIC PARTICLES. THE FUNDAMENTAL EXPERIMENTAL TOOLS-OF-THE-TRADE WERE PARTICLE ACCELERATOR MACHINES, SO-CALLED ATOM-SMASHERS.**

## The Science of Synchrotron Radiation at Cornell

In 1947 workers at the General Electric (GE) laboratory in Schenectady, New York, chanced upon visible light emanating from a room-sized betatron, as the accelerator was called. Julian Schwinger (who later won a Nobel Prize for work on quantum electrodynamics) published in 1949 a theoretical explanation for the light that the GE workers saw, known as synchrotron radiation (SR). Cornell's physics department was at the time constructing an electron accelerator in the basement of Newman Lab. Faculty members decided to build the world's first synchrotron radiation beamline on this machine to study the new phenomenon. Physics professors Paul Hartman, Diran Tomboulian, and Dale Corson (later a president of Cornell) published their first investigations of synchrotron radiation in 1952. The work completed on the electron accelerator soon established the essential characteristics of synchrotron radiation and ushered in a new era of radiation science. Over the ensuing years, synchrotron radiation proved to be one of science's most important tools.

## A Cornell Accelerator Complex Emerges

From the mid-1960s to the mid-1970s, the huge synchrotron under Alumni Fields was busy accelerating electrons up to 10 GeV energies and then smashing them into a target. The resulting subatomic debris was then analyzed. Researchers learned much about the properties of subatomic particles, but by the mid-1970s, they saw that it would be far more effective to collide electrons and positrons, the antimatter complements to electrons, at very high energies. A second accelerator was added to the synchrotron tunnel in 1979 to store countercirculating

electrons and positrons for collisions in a huge particle detector. This machine, the Cornell Electron Storage Ring (CESR), not only served the particle physics experiment but also produced some of the world's most powerful synchrotron radiation x-ray beams. The National Science Foundation (NSF) funded a new national facility, the Cornell High Energy Synchrotron Source (CHESS) to make x-ray beams available for investigating the structure of materials.

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## What Happens at the Accelerator Complex?

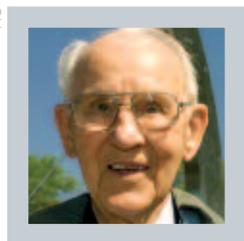
The accelerator complex at Wilson Lab includes CESR to store counter-rotating electrons and positrons and the CHESS facility to utilize the resulting x-ray beams. The electrons and positrons—grouped into clusters of particles, called bunches—collide in the middle of the CLEO detector. The distances between the particles in a bunch are large compared to the size of the particles, so colliding bunches actually pass through one another with only occasional collisions of the constituent

particles. These occasional collisions result in a spray of subatomic particles that the CLEO detector detects and analyzes. Since 1979, elementary-particle physics and x-ray experiments occurred simultaneously, using the very same electron and positron beams.

## Mind-Boggling Scales of Science and Technology

X-ray beams are generated by assemblies of powerful permanent magnets surrounding the CESR vacuum pipe. Heavy steel frames are needed to restrain the 30 tons of attractive force between the magnet arrays on the opposite sides of the pipe. The magnetic fields cause the particles, passing through the pipe at 99.999995 percent the speed of light, to radiate narrow beams of tens of kilowatts of x-ray power. For comparison, the useful x-ray power coming out of a big hospital x-ray machine is barely a watt. The x-ray beams coming out of the CHESS wigglers have power per unit area greater than that encountered at the tip of an electric arc welding rod, can melt through any material in seconds. Yet, by meticulous engineering—after these x-ray beams are collected by x-ray mirrors consisting of a single crystal of silicon a yard long and polished to an average surface roughness of less than the diameter of two atoms—they can focus on samples that are smaller than a red blood cell. It is astonishing to think that a machine that requires an operating staff of almost 200 people can be focused on samples microscopic in size or used to create and study particles that last for a thousandth of a billionth of a billionth of a second.

The Wilson Lab complex has had worldwide impact on many areas of science and technology. Although bigger accelerators exist in the Department of Energy (DOE) national labs, the Wilson Lab is the largest such complex located in the heart of a major research university campus. In great measure, the DOE machines owe their existence to Cornell: many of the significance developments in the field occurred at Cornell and more of the scientists who built and operate the DOE facilities have been trained at Cornell than at any other institution. When the United States decided to build the world's highest-energy particle accelerator (Fermilab in Illinois), DOE persuaded Cornell's Robert R. Wilson to direct the design.



Dale Corson, President Emeritus, Cornell University

**Physics professors Paul Hartman, Diran Tomboulian, and Dale Corson (later a president of Cornell) published their first investigations of synchrotron radiation in 1952.**

The activity at Wilson Lab has produced distinguished results. During the decade of the 1990s one out of seven papers published in *Physical Review D*, the world's major scientific journal of elementary-particle physics, involved data from Wilson Lab. At the same time, one out of five of the most important protein and virus structures—those published in top journals, such as *Nature*, *Science*, and *Cell*—involved data acquired at CHESS. The scientific awards resulting from Wilson Lab data are many, including the 2003 Nobel Prize in Chemistry to Rod MacKinnon (Rockefeller University).

**IT IS ASTONISHING TO THINK THAT A MACHINE THAT REQUIRES AN OPERATING STAFF OF ALMOST 200 PEOPLE CAN BE FOCUSED ON SAMPLES MICROSCOPIC IN SIZE OR USED TO CREATE AND STUDY PARTICLES THAT LAST FOR A THOUSANDTH OF A BILLIONTH OF A BILLIONTH OF A SECOND.**

## Accelerators Keep Pace with Science

Science evolves quickly and, in consequence, the activities at Wilson Lab are in a state of constant change. Elementary-particle physics and x-ray science require more highly specialized machines than in the past, and the fields will evolve in distinct but related directions. Although the questions posed by modern high energy physics require much larger accelerators than can be built at the Cornell site, Cornell faculty and students will be heavily involved in the development of new facilities. The CLEO high energy physics experiment at Wilson Lab is slated for completion in 2008. Cornell's elementary-particle physics faculty will then shift to experiments at the Large Hadron Collider (LHC), a huge machine 27 kilometers in circumference, which is under construction at the CERN laboratory located outside of Geneva, Switzerland. Data from this machine will be analyzed by faculty groups around the world via the worldwide GRID network, an advanced form of the internet, which includes a node at Cornell.

Cornell accelerator physicists expect to work simultaneously on the International Linear Collider (ILC), the next-generation accelerator, which the world's elementary-particle physics community hopes to build. The ILC will consist of two linear colliders, directly evolved from designs originating at Cornell, which will span 40 kilometers. Because of its enormous size and expense, only one such machine will be built, possibly in the central United States. It will be an international collaboration, involving almost every major elementary-particle physics group from around the world. The ILC may one day answer some of the most vexing and fundamental questions about the particles that make up our universe.

## Wilson Lab Evolves

The focus of experiments at the Wilson Lab site will shift to advanced x-ray science. Synchrotron radiation is an essential tool today for determining the atomic structure of molecules and the composition of materials. Synchrotron radiation is

**IT IS FITTING THAT THE FACILITY USED TO DESIGN AND TEST THE SUPERCONDUCTING CAVITIES THAT WILL BE USED FOR THE ERL AND THE ILC IS THE REFURBISHED AREA IN THE BASEMENT OF NEWMAN LAB WHERE THE WORLD'S FIRST SR BEAM LINE WAS MADE IN 1952.**

heavily used by tens of thousands of physicists, biologists, chemists, geologists, materials scientists, engineers, and even artists, archaeologists, and paleontologists. The rapidly growing importance of synchrotron radiation to so many areas of study has resulted in a proliferation of synchrotron radiation-producing machines throughout the Americas, Europe, and Asia—almost 70 at the last count!

### Storage Ring Technology Reaches Its Limit

Practically all of the world's x-ray synchrotron machines are based on technology quite similar to that of the first synchrotron radiation machines in the basement of Newman Lab. This storage ring technology injects electrons into a donut-shaped vacuum chamber surrounded by magnets that confine the electron trajectory to a closed orbit. One or more short accelerating cavities in the ring accelerate the electrons so they get a little boost in energy every time they come around. In this way researchers can store electrons orbiting at nearly the speed of light for hours. At various places along the ring, magnets bend the paths of the electrons, causing the emission of beams of x-rays tangential to the ring.

These beams exit the vacuum chamber by passing through thin metal windows, where they are used by experiments positioned around the ring. Since the 1980s, storage rings have grown larger and produce brighter x-ray beams. The fundamental limits of storage ring technology are well understood, however, and have nearly been reached by a huge machine in Japan. This machine, called SPring-8, is built around the top of a small mountain. It is so large in circumference (about 1.5 kilometers) that the mountain peak sticks out through the middle of the donut-shaped building! Further advances in the quality of SR x-ray beams will require a totally different approach to generating SR.

### Linear Accelerators: a Different Approach

Back in 1965 Maury Tigner, director of CLASSE, proposed that superconducting linear accelerators could be used to accelerate particles and then, by appropriate adjustments, decelerate them. A linear accelerator is a specially constructed long, straight tube, into which both microwaves and electrons are injected. In the accelerating mode, the electrons gain energy from the microwaves. In the decelerating mode, precisely the reverse happens: the very energetic electrons give their energy back to the microwave field. Tigner pointed out that, if the linear accelerator were made of superconducting metal, almost all the energy could be recovered.

Although in 1965 the technology to produce superconducting linear accelerators was in its infancy, there has been steady progress on improving this technology, especially at Cornell, which is a world leader in developing these kinds of accelerators. A few years ago, scientists realized that the technology is now sufficiently advanced to allow an entirely new kind of SR-producing machine that circumvents the limitations of storage rings. Two accelerators built at the Thomas Jefferson National Accelerator Facility in Newport News, Virginia, using superconducting cavity designs and personnel from Cornell, helped convince the scientific community that the technology for superconducting acceleration and energy recovery is finally ripe for combining into an advanced x-ray source based on Energy Recovery Linac (ERL) technology.

### Superconducting Acceleration + Energy Recovery = Energy Recovery Linac

Cornell, the acknowledged world leader in x-ray ERL technology, is proposing to convert the Wilson Lab machine into the world's first ERL x-ray synchrotron source. The development is proceeding in two stages. The first stage, now funded by an award of \$18 million from the NSF, is to perform research and development on prototype technology essential for an advanced x-ray ERL. In two to three years, Cornell expects to submit a proposal to NSF for a full-scale ERL upgrade to the Wilson Lab facility. The proposed ERL machine, costing about \$400 million, will

#### eV/GeV: Measuring Energy

The energy of a particle or electromagnetic photon is measured in units of electron volts, eV. A visible light photon has an energy of a few eV, while an x-ray has an energy of thousands of eV. In order to produce x-ray synchrotron radiation, it is necessary to have a machine capable of accelerating electrons to millions or billions of eV. The 1952 synchrotron was capable of accelerating electrons to 300 million eV (300 MeV). The synchrotron under Alumni Fields could accelerate electrons to almost 10 billion, or giga, eV (10 GeV).



Frank Dimec

# WILSON LAB COMPLEX FACTS

provide beams with capabilities available nowhere else in the world. The ERL will continue Cornell's historic leadership and training role in accelerator physics and x-ray science. Cutting-edge SR x-ray sources have invariably attracted communities of the best scientists working in areas ranging from biology to medicine, from materials science to applied x-ray technology. The novel features and challenges of the ERL are already proving attractive to students with an interest in accelerator physics from around the world.

## Why Are People Excited about an ERL?

ERLs circumvent the limitations imposed by storage rings. An ERL can produce beams many times brighter than any existing storage ring. The beams from storage rings are very different in the vertical and horizontal directions, which limits the ultimate size of x-ray probes. The combination of the brilliance possible with an ERL and round beams allows x-ray probes small enough to perform unprecedented studies of nanomaterials and the microstructure of many kinds of specimens. ERL beams also have the laser-like quality of transverse coherence. This enables entirely new kinds of x-ray microscopies and imaging methods. Yet another distinction is that ERLs allow the production of x-ray pulses that are incredibly short in duration: less than 100 femtoseconds. (To appreciate just how short a time this is, a femtosecond—10<sup>-15</sup> seconds—is to a second as one second is to 32 million years.) Scientists have long dreamed of studying structural changes in physical systems in the 1–1,000 femtosecond timescale: the scale of electronic transition states in enzymes and catalysis, of thermal relaxation of excited electrons in metals and semiconductors, and of many other physical processes of fundamental importance. The ERL offers a way to study these systems.

## Leading the Way

George Moler of Cornell's physics department was taking x-ray photographs within weeks of Wilhelm Roentgen's galvanizing discovery. By 1934 the Cornell cyclotron was launched. The work of many faculty throughout the twentieth century made Cornell a world-renowned center for elementary-particle, accelerator, and x-ray physics. It is fitting that the facility used to design and test superconducting cavities for the ERL and ILC is the refurbished basement of Newman Lab, where the world's first SR beam line was made in 1952. It is also fitting that Cornell merges two major research organizations into a class of their own to reflect the interdisciplinary nature of Cornell's particle physics and x-ray science, called the Cornell Laboratory for Accelerator-Based Sciences and Education, CLASSE. With Maury Tigner as director of CLASSE, James P. Alexander as director of LEPP and particle physics, and Sol Gruner as director of CHESS and x-ray science, along with support and perseverance, Cornell will continue to lead the way in x-ray and elementary-particle science for many years to come.

*Maury Tigner, Director of CLASSE, Physics*  
*Sol M. Gruner, Director of CHESS and X-ray Science, Physics*

Frank DiMeo



(l. to r.) Maury Tigner, Director of CLASSE  
James Alexander, Director of LEPP and Particle Physics  
Sol Gruner, Director of CHESS and X-ray Science

- CESR is almost a half mile in circumference.
- The CLEO detector is 1,000 tons of iron and electronics, 20 feet on a side, consisting of a nested set of 150,000 channels of output electronics; it costs \$60 million to build.
- The core of CLEO is a superconducting magnet, cooled to nearly absolute zero temperature and big enough to drive a car through.
- CESR is powered by four superconducting microwave resonators operating at -452° F.
- The microwaves are generated by vacuum tubes 10 feet tall.
- The microwaves are piped in waveguides two feet wide to the resonators, each of which transfers a quarter million watts of power to the particle beams.
- During operation, billions of watts of electron and positron beam power are circulating in CESR and the microwave resonators, yet the resonators are so efficient that only 60 watts of power are lost.
- It takes a staff of 200 people and about \$25 million per year to operate the complex.
- During its busiest times, the CLEO experiment collaboration involves 25 universities and many national laboratories. At the same time, the CHESS national x-ray facility logs roughly 1,000 visits per year by users from around the globe. Students are an integral part of the activity.
- More than 625 Ph.D. theses have been written based on data collected at Wilson Lab.
- Each year, Wilson Lab hosts 1,000 to 2,000 visitors from elementary and high schools and the general public.
- Now, CLASSE will develop an extension to CESR—the ERL, a linear accelerator—to provide brighter x-rays that can be focused into beams as narrow as one nanometer and fired in pulses as short as tens of femtoseconds.

**“Cornell's Accelerator-Based Sciences: A Timeline” appears on page 115.**