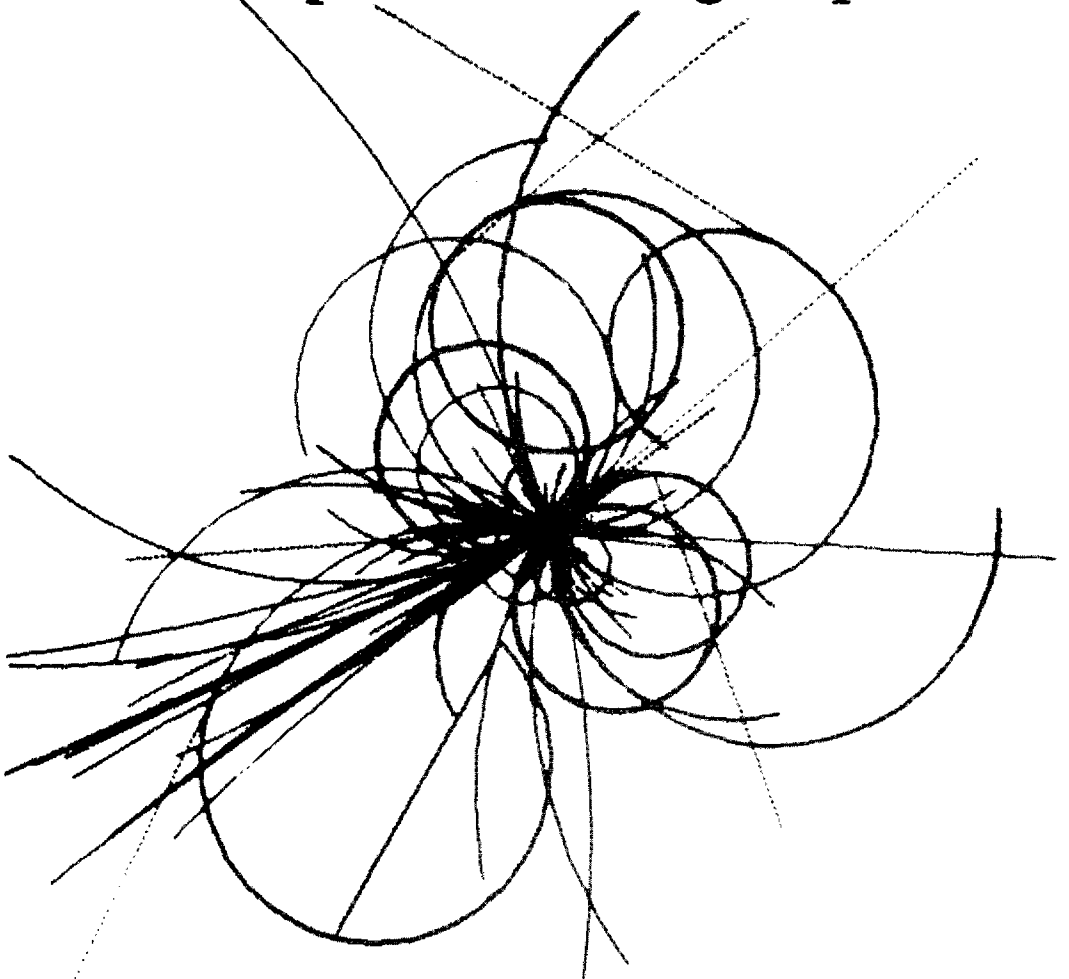
SSC-192

The Superconducting Super Collider



Supercollider!

Chris Quigg

SSC Central Design Group

October 1988

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CHRIS QUIGG

SSC Central Design Group†
Lawrence Berkeley Laboratory, Berkeley, California 94720 USA

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*Lecture given November 18, 1987, at Ecole Polytechnique, Palaiseau as "La Physique des Particules: découvertes, éclaircissements, outils" in the 1987 Bernard Gregory Lecture Series.

†Operated by Universities Research Association, Inc., for the United States Department of Energy.

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My subject tonight is a scientific adventure that I hope will engage the imaginations of all of you over the next decade: the construction of a large scientific instrument to pursue our study of the basic constituents of matter.

Since the earliest times astronomy, or what was at first merely star-gazing, has been a source of modern science. It is natural for us to look around the world we live in and to ask questions about it. When you look up at the stars, you may begin to pose questions to yourself: What are they? What holds them up? How do they move? What is the source of starlight? Then you get to deeper and more remote questions: How were the stars formed? How did the universe begin? What might be its eventual fate?

At every stage in this sort of inquiry, there are a number of things that we understand and some that remain beyond our ken. Isaac Newton, a great hero of rational thought and a founder of modern science, who explained for us how the planets and stars move, was keenly aware of the limitations of his achievement. In his *Principia* he writes,

> The planets and comets will constantly pursue their revolutions and orbits given in kind and position according to the laws above explained; but though these bodies may, indeed, continue in their orbits by the mere laws of gravity, yet they could by no means have at first derived the regular positions of their orbits themselves from those laws.[1]

The law of gravity explains why the heavenly bodies move in regular orbits, but it is insufficient, by itself, to tell us how they got there or what formed them. Newton's response, in tune with the temper of his times, was to attribute the clockwork motions of the stars and planets to God's plan, to the handiwork of a Supreme Watchmaker. He continues,

> This most beautiful system of the sun, planets, and comets could only proceed from the counsel and dominion of an intelligent and powerful Being.[2]

In earlier times, when belief in magic was widespread, people invoked mysterious causes or the continuous and miraculous action of the gods for what lay beyond human understanding. In the late twentieth century, our ideal of explanation for what we have not understood is to formulate hypotheses to be tested, and to use these to guide our search for further truth.

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* Operated by Universities Research Association, Inc., for the U.S. Department of Energy.

[1] I. Newton, *Principia Mathematica*, Book III: The System of the World, General Scholium, pp. 2-3, 1687.
[2] Ibid.

A Comprehensible Universe

Remarkable as Newton's discovery of the law of gravity was, Newton achieved something even more remarkable. He recognized the *universality* of the law of gravity. His recognition that the force responsible for objects falling to Earth is the same force responsible for the motions of the stars and planets was perhaps more important than the determination of the form of the force law itself. First, it illustrates the idea that the same laws of Nature hold at all times and in all places. This is the basis for our conception of the universe as an orderly, rather than a capricious, place—a universe we may hope to comprehend. Second, the realization that in terrestrial laboratories we can learn the physical laws that govern the structure of the universe has profoundly affected our civilization. In the same way, what we learn by studying the heavens can be applied here on Earth.

From the simple act of looking up at the stars to asking about the origin of starlight and the formation of the universe, we retreat from common experience. We ask questions about things we never encounter in everyday life. We haven't, any of us, lived through the beginning of the universe, and yet we can try to understand how it might have been. Having found in earthbound experiments that light propagates at the same finite speed under all circumstances, we can use astronomical observations to look back in time. Nor are we restricted to looking up at the sky with an unaided eye. We have learned to build instruments to enhance our perceptions: to record light, and heat, and x rays, and radio emissions. The largest of these instruments is in the American Southwest. It is an array of twenty-seven dish antennas, each eighty-two feet (twenty-five meters) in diameter, arranged along some thirty miles (fifty kilometers) of railroad track in the form of three triangular spokes. These dishes, interconnected by electronics and computers, make a single radio telescope that listens to radio jets of galaxies and quasars far away from us. In addition to extending our senses, we have also learned to go beyond passive observation, by replicating in the laboratory conditions similar to those that prevailed in the early universe.

The Role of Elementary-Particle Physics

Elementary-particle physics, the field that the Supercollider is designed to illuminate, is the science of the ultimate constituents of matter and the interactions among them. It tries to answer a couple of very simple questions: What is the world made of? and How does the world work? In common with other scientists, we hope that by exploring the basic laws of Nature, by finding laws that have a wide scope of applicability, we will better understand our universe and eventually have the possibility of putting that understanding to humane and productive use.

It is convenient to organize our knowledge in response to these two basic questions. We can analyze all phenomena in the natural world in terms of the fundamental, basic constituents—the smallest, simplest things that make up everything around us—and the forces by which they interact with each other. Now, no one one tells you—there is no way of proving before you start—that this is the one true way to organize what we know. All we can say is that historically this has been a fruitful intellectual framework.

Indeed, long ago, our scientific ancestors organized their understanding of the universe by saying that the fundamental constituents were *earth, air, fire,* and *water*. These were supposed to interact by means of *love* and *strife*, the two fundamental forces that govern the universe. Over time, the identity of these fundamental constituents and of the basic forces has changed as we have learned more, but throughout scientific history the framework of constituents and forces has been convenient and suggestive.

The original idea that there might be fundamental constituents goes back to the Greek natural philosophers of the fifth century B.C. It was first rendered into Latin hexameters in an epic poem about the nature of the universe by Titus Lucretius Carus. During the first half of the first century B.C., Lucretius wrote,

> ... many things have elements in common,
> But differently combined...
> ... It is most important
> Both with what other elements they are joined,
> In what positions they are held together,
> And their reciprocal movement. The same atoms
> Constitute ocean, sky, lands, rivers, sun,
> Crops, bushes, animals; these atoms mingle
> And move in different ways and combinations.
> Look—in my lines here you can see the letters
> Common to many of the words, but you know
> Perfectly well that resonance and meaning,
> Sense, sound, are changed by changing the arrangement.
> How much more true of atoms than of letters![3]

To explain what we have made of the idea of basic constituents and fundamental forces in the 1980s, I will begin by telling you a little bit about what we know. What particle physicists call the Standard Model is a conceptual picture that summarizes our current understanding of the smallest bits of matter and how they go together. Because the principal subject of this article is a new scientific instrument, I want to pay some attention to how we know these things, to the process of experimentation and making discoveries. Then I will come to the open questions that face us, questions raised by the knowledge we have accumulated. Finally I will introduce the Supercollider, the instrument of choice to deepen our knowledge of the laws that govern the universe.

What We Know

Ours is hardly the first time in history that physicists have believed themselves close to an enduring understanding of the laws of Nature. What, then, are the grounds for believing that, whether or not a grand synthesis of natural law is near at hand, important progress is under way? Over the past two decades, the age-old struggle to describe and comprehend the nature of matter has been rewarded by a radically new and simple picture of Nature on the most basic level. A host of new experimental results, made accessible by a new generation of particle accelerators, and the accompanying rapid convergence of theoretical ideas have brought to the subject a new coherence and have raised new aspirations. The new insights embodied in the Standard Model not only provide a framework for describing and understanding the world around us, but also elucidate the first instants after the creation of the universe. In the same tradition as earlier interpretations, the Standard Model has two elements: a set of fundamental constituents, at least for our generation of scientists, and a small number of fundamental interactions. The fundamental constituents are called *leptons* and *quarks*. A class of mathematical theories called *gauge theories* provides a common framework for discussing all the fundamental interactions and therefore gives us the hope of seeing connections between these interactions.

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[3] *De Rerum Natura*, I. 815–29, ca. 50 B.C. For a discussion of some similarities and differences between ancient and modern conceptions of the fundamental constituents, see Julia H. Gaisser and T. K. Gaisser, *American Journal of Physics* **45**, 439 (1977).

Discoveries, Insights, and Tools

Before entering into the details of the Standard Model, let me say a few words about method. In summarizing what we know, it is easy to fall into the trap of overemphasizing the role of theory and cogitation and therefore underplaying the essential role of experiment. Instead, let us underline the connection between these two activities. Theory, taking facts that we observe in the universe around us and trying to make a logical framework of them, can be characterized by other names such as insight or abstraction. For experiment, we can substitute the word discovery, for learning things about our environment. The great glory of modern science, our essential progress since Aristotle invented logic, is its reliance on empirical studies. The creation and interpretation of new experience is at the heart of what is called the scientific method.

Having noted the important interplay of theory and experiment, we must not forget the third essential component of scientific progress: technology. The availability of new tools makes it possible to conceive and carry out new experiments, to test new hypotheses, and to make new discoveries. In elementary-particle physics, the history of accelerator and detector technology precisely parallels and, if you wish, leads the development of our understanding of Nature. Whenever we can measure things more precisely or look where no one has been able to look before, we have the potential for new discovery. From those new discoveries often flow insights. Having made those discoveries we can use them for calibrations or to invent new tools.

Abstract descriptions of the scientific method refer only in passing, if at all, to the means of experimentation, or to the means of theoretical calculation. Therefore, it is not surprising that when I look at my children's school science textbooks, I find that the last person in recorded history who made a new scientific instrument and then used it to make a scientific discovery was Mr. Leeuwenhoek, who in the seventeenth century combined two magnifying glasses into a microscope and used his new instrument to learn what was inside an onion cell. After that, perhaps the technology became too complicated to be explained in school books, but it is not true that (as you might conclude from some textbooks) the way science happens today is that Mr. X or Ms. Y had this or that idea and tried it out and it worked and that was that.

There are examples of the importance of new tools, not just in elementary-particle physics, but all over the map of science. Think, for example, of molecular biology and genetic engineering. That whole enterprise emanates from the discovery that certain enzymes, little chemicals, like to take a bite out of DNA molecules at a certain point. That is a discovery. It is waiting there for the prepared mind; the prepared mind can then think about it and say, "Perhaps there are other chemicals that like to take bites out of DNA at other points." Follow that idea and then, by random selection or by informed choice, try to create a catalog of what those chemicals are and where they take little nibbles out of DNA molecules. Having done that, you find yourself with a new tool to pursue the fundamental aspects of molecular biology. You can take apart and put back together the molecules that carry the blueprint of life. You can try to snip out a little segment of DNA and replace it with another little segment you have found in another place. Observation of the consequences feeds back into our understanding of how the code of life finds expression in the structure and function of organisms, giving us whole new lines of experimental investigation to undertake. This interplay between discoveries, insights, and tools has already begun to improve our quality of life through the development of insulin-producing microbes and other new life forms and has contributed as well to the life of the stock market.

The synergy between instruments and experiments and theory needs to be understood and emphasized. It is myopic when academics, convinced of the purity of their research, argue that technology is the laggard stepchild of fundamental discovery. It is equally myopic when technologists, persuaded that fundamental discovery is merely a spin-off of technological innovation, inveigh against basic researchers as ne'er-do-wells wasting their own time and the taxpayers' money. In truth, basic research and new technology nourish one another, and both are essential to the scientific enterprise.

The Standard Model of Elementary-Particle Physics

As I have already remarked, one of our jobs as scientists is to try to find general laws. One of the contributions that physics has made toward understanding the universe in terms of a few laws is to recognize that all the forces that we experience around us—friction, the force of the wind, lift and drag in an airplane, the sideways push that you feel when rounding a curve in a car, the integrity of solid matter, which makes it difficult to penetrate with blunt instruments—all of these can be explained in terms of a small number of more basic forces. Two of these, the strong interaction, responsible for holding protons and neutrons together in nuclei, and the weak interaction, responsible for radioactivity, were discovered in the 1930s. Electromagnetism has been known in the form familiar to us since about the middle of the nineteenth century. Then it was realized that electricity, represented by a lightning bolt, and magnetism, seen in the gentle sweep of a compass needle, were really two aspects of the same force. Those three forces, plus gravitation, account for every phenomenon that we have ever seen in the laboratory or in everyday experience. That is a great simplification, having a list of only a few forces, rather than having to invent a new explanation for everything that takes place.

When the four forces were recognized in the thirties, three or four elementary particles were known: the *proton* and *neutron*, which make up the nucleus; the *electron*, a light, charged particle that flies around the nucleus and is responsible for the structure of atoms and crystals; and the *neutrino*, hypothesized but not then directly observed, which was necessary to understand some aspects of radioactivity.

Though we may speculate about additional forces, this list of the fundamental forces is still serviceable today. On the other hand, by looking more and more closely at the proton and neutron, it was found that those were not elementary particles. They could be divided up, they had—figuratively speaking—gears and wheels inside. By a long series of experiments that I will describe to you only very schematically, we recognized, about ten or fifteen years ago, a new set of fundamental constituents. The proton and neutron are put together of a number of little objects that are fancifully named *quarks*. We know of six different kinds of quarks, which we call *up* and *down*, *charm* and *strange*, *top* and *bottom*. (If *love* and *strife* were good enough for the ancients, we can be permitted this display of frivolity.) The top quark is hypothesized, to complete the pattern, but it has not yet been observed.

The electron, as far as we know, really is an elementary particle. We haven't found any gears or wheels inside it. We have observed the electron's partner, the neutrino, and found some friends of the electron that behave in many respects like it and are paired with their own neutrinos. The list of fundamental constituents displayed in Figure 1 is the set of things that, so far, we can't see inside.

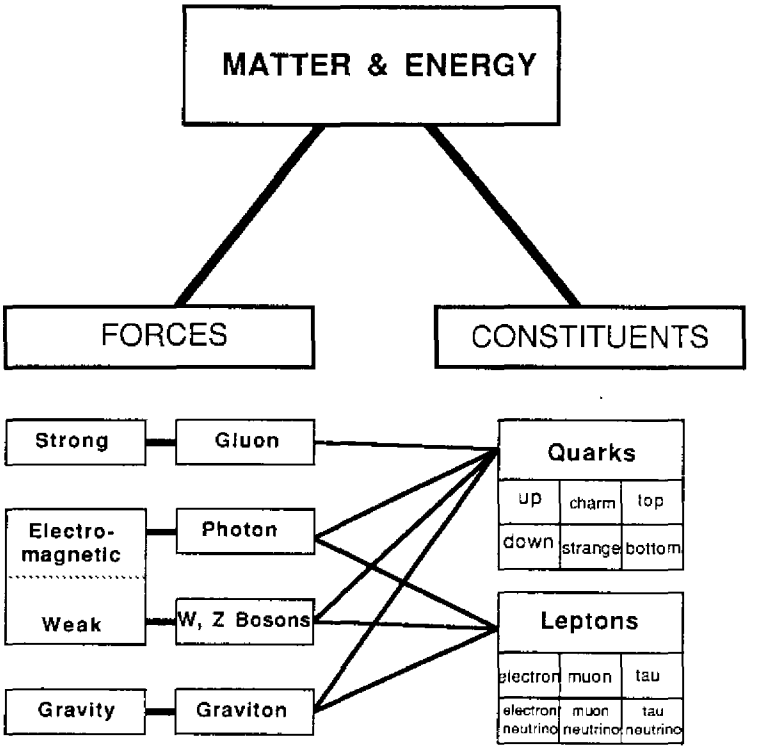


Figure 1: The Standard Model of Elementary-Particle Physics.

Although we haven't discovered any new forces, we have learned to do more than simply describe what form the forces take. We have begun to see the possibility of connections between the four forces. Just as electricity and magnetism have a deep connection with one another, so it seems that the radioactivity interaction, the weak interaction, is intimately connected with the electromagnetic interaction in a way that we *almost* have mastered, but not quite. Part of the scientific motivation for the Supercollider is to master the details of that connection and thus to remove that little dashed line that separates the weak and electromagnetic interactions in Figure 1.

We have also learned that descriptions of the interactions that make sense on the very small scale—which means the scale of very high energies where the effects of relativity come into play—must be quantum theories that require each of the interactions to have a messenger or carrier particle. We call the carrier of the strong force the *gluon* because it glues quarks together. The carrier of electromagnetism is called the *photon*. The weak interaction is carried by *W* and *Z bosons*, and we expect gravity to be carried by the *graviton*.

The Periodic Table of the Elements

The development of the Standard Model is not the first time in history that scientists have discerned suggestive patterns. The progress we have made from the thirties to the present can be likened to the progress made in chemistry about a century ago. In the middle of the last century it was finally understood that the basic constituents of that day were about twenty elements, and that out of those elements you could build up all the substances that were found in the rocks and soil. John Dalton was the person who understood that each sulphur atom weighed this much and each oxygen that much, and so on, and that combined together the elements could

make the compounds that we see. (The invention of precision balances made it possible to do very accurate chemistry experiments, building on that insight.) Chemists built up a greater and greater body of quantitative knowledge leading, just over a hundred years ago, to the invention by Dmitri Mendeleev of the *periodic table*. The periodic table organized the elements in a neat pattern of rows and columns and related the position of an element to its properties. Gaps in the table correspond to undiscovered elements and characterize the properties of those missing elements. Since Mendeleev's time, many more elements have been discovered. They all fit a pattern that is a simple generalization of his. This way of organizing all the elements is one of the bases of modern chemistry and, hence, of the life we live.

The development of what has become a second great influence upon modern technological society was stimulated by the desire to understand Mendeleev's pattern. Why is it that an element in a certain column of the periodic table has the properties that it does? Such questioning, buttressed by quantitative information, gave rise in the second decade of this century to the invention of *quantum mechanics*, a new picture of how the world works. Quantum mechanics and the periodic table are the intellectual tools that enable us to understand the chemistry of our industrial society, the functioning of life at the subcellular level, lasers, solid-state electronics, and superconductivity.

Seen in the context of the evolution of chemistry, we find ourselves today in elementary-particle physics at an intermediate stage. In common with Mendeleev's periodic table, our Standard Model has gaps that correspond to undiscovered particles and forces. We know, for example, that the top quark will be found because our "periodic table" requires it. However, we are a little bit beyond having simply recognized the patterns of quarks and leptons, because we understand a good deal about the forces by which the constituents interact. Yet we haven't explained everything that lies behind the patterns. We haven't quite made the complete penetration of understanding that came for chemistry in the beginning of this century with the invention of quantum mechanics. That is our unfinished business; that is what we would like to do.

The way we advance our understanding is to probe the structure of matter on ever finer scales. Our brief as high-energy physicists is to find the most fundamental constituents and the interactions among them. To do this, we build experimental instruments that are combinations of particle accelerators and detectors. Those together make up our microscopes, the tools that we use to look within matter and see what is there. In order to seek out deeper levels of matter within the nucleus or within the quarks, we require higher and higher energy beams that can penetrate further within, shake up what is there, and help us to find the secrets locked within the realm of fundamental particles. In order to see finer details, we must use probes of higher energy.

Experiments in Elementary-Particle Physics

Now let me tell you everything you need to know about experimental elementary-particle physics. There is a lot of hoopla in this field, but my colleagues actually only do one experiment—the one shown in Figure 2. The experiment begins with something called a beam. At the largest laboratories, the Fermi National Accelerator Laboratory in Illinois and CERN, the European Laboratory for Particle Physics in Geneva, the beam often consists of many millions of protons—hydrogen nuclei—accelerated to very high energy, moving at almost the speed of light. The second element of an experiment is a prepared target, which might be a bottle of liquid hydrogen or a thin foil of some metal. The beam hits the target, and an experimental physicist stands off to the side with a tin cup in hand and catches whatever comes out.

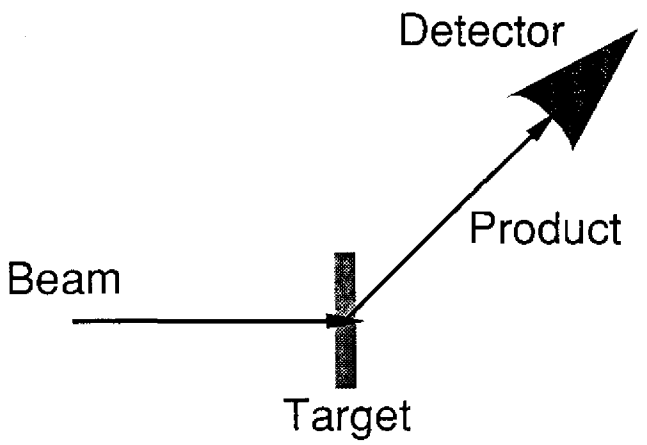


Figure 2: The experiment.

The experiments done today are not quite so simple as this. There are actually fifty to a hundred particles coming out of each collision. If you examine the list of authors of some recent experimental reports, you find that what is really going on is that there are fifty to a hundred guys standing around with tin cups catching things. Now, you could have just one big bucket that permits you to say that something happened: something fell into my bucket after the beam hit the target. But it is much more interesting to have lots of little tin cups so you can say that one came over here, and one came over there. This is how we try to build our detectors. You can even do better: you can build fancy tin cups that say the one that landed in here was a pion and the one that landed there was an electron. In other words, you try to characterize as best you can everything that went on, to understand what matter was created out of the energy of the collision between beam and target. That is what experimental physicists do.

I have to reveal that some people in this field are incredibly lazy. There are people who do away with the beam entirely and have only a target. The largest experiment of this kind is a big steel tank about 50 feet (16 meters) in diameter and 50 feet (16 meters) high, which holds about 750,000 gallons (2.9 million liters) of pure water. The tank lies some 3300 feet (1000 meters) underground in the Kamioka mine in Japan, about 200 miles (300 km) west of Tokyo. Those people are looking at their big vat of water, their target, waiting for a proton to decay and wink at them. They have been waiting about five years so far, and it hasn't winked yet, but when it does they will be ready.[4] Other lazy physicists have a beam but leave out the target and merely wait for the beam to decay. They just stand there watching the beam go by with their tin cups held out. Finally, some physicists leave out both the beam and the target; they are called theorists.

A Simple Experiment

You might be asking yourself what it means to inspect targets with a variety of beams. This question can best be answered with a demonstration. Here is an ordinary glass that contains some innocent-looking fluid, and here is a second glass containing another innocent-looking fluid.

[4]This tells us that the lifetime of the proton is in excess of 10^{31} years. While waiting for a proton to decay, these experimenters have observed other things, such as the burst of neutrinos emitted by Supernova 1987a.

Finally, here is a bag of white powder. These are my targets. To see what it is like to do a high-energy physics experiment, we use our eyes as detectors. If we shine light—our beam—on them, they don't look very exceptional. One liquid is red, the other is blue, and the powder is white.

By turning off the lights, we can see what it is like for those intrepid experimenters who don't have a beam at all. Now if I change my beam to a higher-energy beam of ultraviolet rather than visible light, marvelous things happen. First of all, the blue liquid begins to emit an eerie glow. The red liquid also emits an eerie glow, very bright; you see it looks like shiny white paint. My white powder also glows, and so, for that matter, does my shirt.

Now, what has happened? I changed my beam, I looked at the world in a new way, and I found something different. Instead of simply reflecting the ultraviolet light (which our eyes are ill-equipped to detect), the targets absorbed the incident beam and re-emitted visible light. All these mysterious substances that glow with an otherworldly glow, by the way, are laundry detergents. This is one of the great by-products of modern science. People driven by curiosity in the laboratory sixty or seventy years ago noticed that weird things happened when they exposed targets to a new beam. In modern Western civilization we use the fruits of their inventions to lace laundry detergent with brighteners so that our shirts will stand out and look clean even when they are not. The lesson of our little experiment is this: if you want to know what the Supercollider is going to do to change your life, we're going to give you cleaner shirts.

Fixed-Target Experiments

I have told you schematically about my friends the experimenters and their tin cups. Let us now be a little more explicit. The basic idea is that, if we learned something by shining a light on a target, or by shining the more energetic ultraviolet lamp on it, then we may be able to learn still more by hitting the target as hard as we can and seeing what comes out. One style of experiment is called a fixed-target experiment. The target is sitting still, and we blast it with a beam. The beam is prepared in the accelerator, and the way an accelerator works at Fermilab or CERN is shown in Figure 3. It begins with an ion source—a bottle of hydrogen gas—connected to a little pre-accelerator, similar to the electrostatic device that propels electrons toward the screen of a television picture tube. Once the protons have been set in motion, they are boosted to higher energy in a linear accelerator, riding electromagnetic waves the way surfers ride ocean waves. Next, the protons are directed into a big ring several miles around, which consists of a series of magnets to bend the path of the beam and confine it to a circular orbit. Within the ring are many magnetic lenses to focus the beam so it is concentrated and can be controlled well. Every time the beam passes a certain spot in the ring, it encounters some accelerating structures connected to a radio generator, which is ultimately plugged into the power line. Each time a particle comes around it gets a little kick from the accelerating structures, so that it goes faster and faster. Once it has reached the desired energy, we extract the beam and use it for experiments.

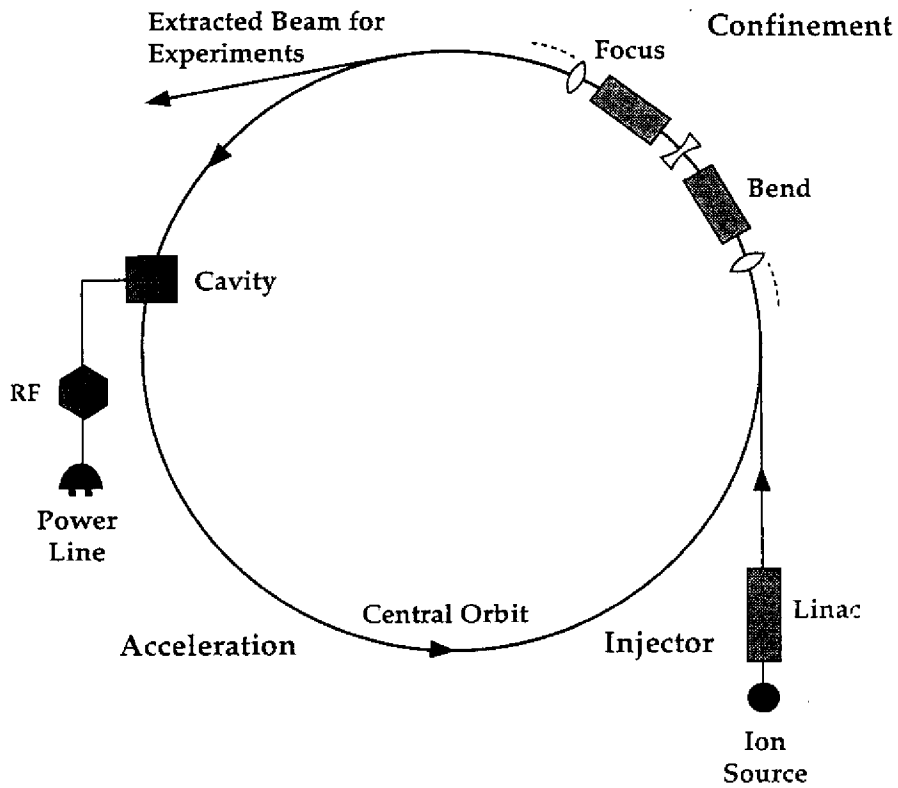


Figure 3: Schematic diagram of an a circular accelerator.

It is really true that detector systems are like tin cups, but they are a little more complicated. Figure 4 shows a piece of one of the detectors at Fermilab—all told this apparatus is about seventy or eighty feet long. It has a number of different components to it. The crane is used by riggers who perform marvelous feats: positioning hundred-ton objects to within a couple of millimeters—great artists. Various components measure the position of particles as they come out—they serve as the tin cups. Magnets bend the paths of charged particles so we can determine how energetic they are. The tracks of low-energy particles are tight spirals; very energetic particles are hardly deflected at all. This particular experiment is an Italian–American collaboration. One of the Italian contributions to this big monster of a detector—eighty feet long—is a tiny device called a silicon microstrip detector, which is a thing of beauty. It is only a few inches across. It sits right by the target, inside a copper-lined room that looks like the treasure room at the Vatican museum. The job of the silicon microstrip detector is to measure the positions of outgoing particles with very high resolution. You see that while building these enormous pieces of apparatus to try to track all the particles and find out what they are and where they are going, we need not only the skills of heavy metal working and mechanical engineering, but also the finest and most advanced microelectronics that people can build.

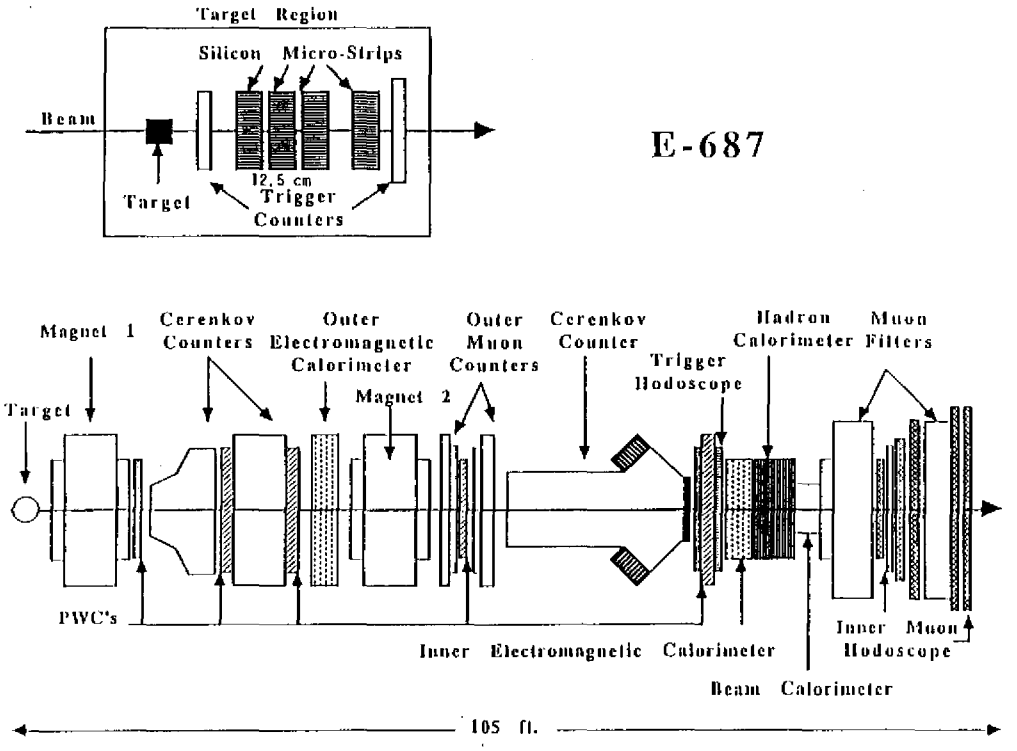


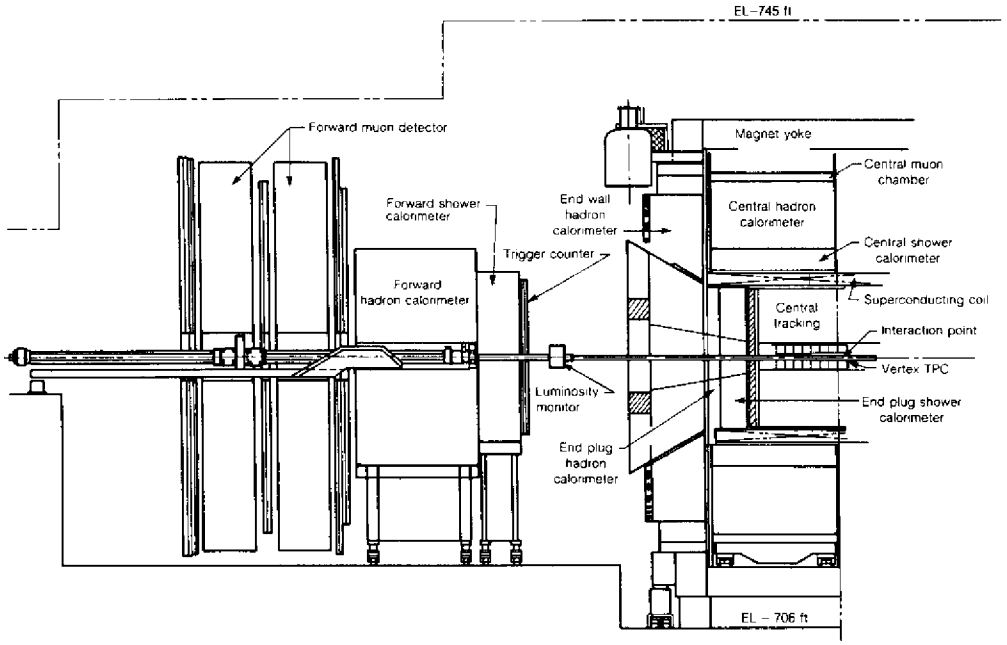
Figure 4: A typical fixed-target experiment (Fermilab E-687), used to study the interactions of high-energy photons with various targets.

Colliding-Beam Experiments

We can easily imagine another style of experiment. If it was a good thing to blast one particle as hard as you can, the next step is to line two accelerators up and blast the beams at each other, because then really interesting things ought to happen. One experiment of this kind is installed at the Fermilab proton-antiproton collider. It is an Italian-Japanese-American collaboration in which important elements of the detector have been brought by people from various American universities and from institutions abroad. Figure 5 shows the body of the detector, which incorporates a very large cylindrical magnet to analyze the products of the collision. The collision point is surrounded by a series of detection devices whose collective task is to say that a particle came over here and it was probably this kind of particle.

What Has Astronomy Taught Us?

Let us return for a moment to astronomy. What have we learned since those early years of gazing up at the stars and wondering about them, since we have been able to make organized observations and make surveys in a coherent way? First, we have learned that the universe is very old. We are not quite sure how old it is; it might be ten billion years old, it might be twenty billion years old. But on the human scale, that is a very long time! Second, all the stars around us—all the stars that we can see—are moving away from us, and the most distant stars seem to be moving away from us faster than those that are close to us. Third, as far as we can tell by looking around at different directions in the sky, there is nothing very notable about our location, other than the fact that we are here to notice that there is nothing notable about it. If you look around, the density and character of stars is about the same in all directions, at least on some very large scale.



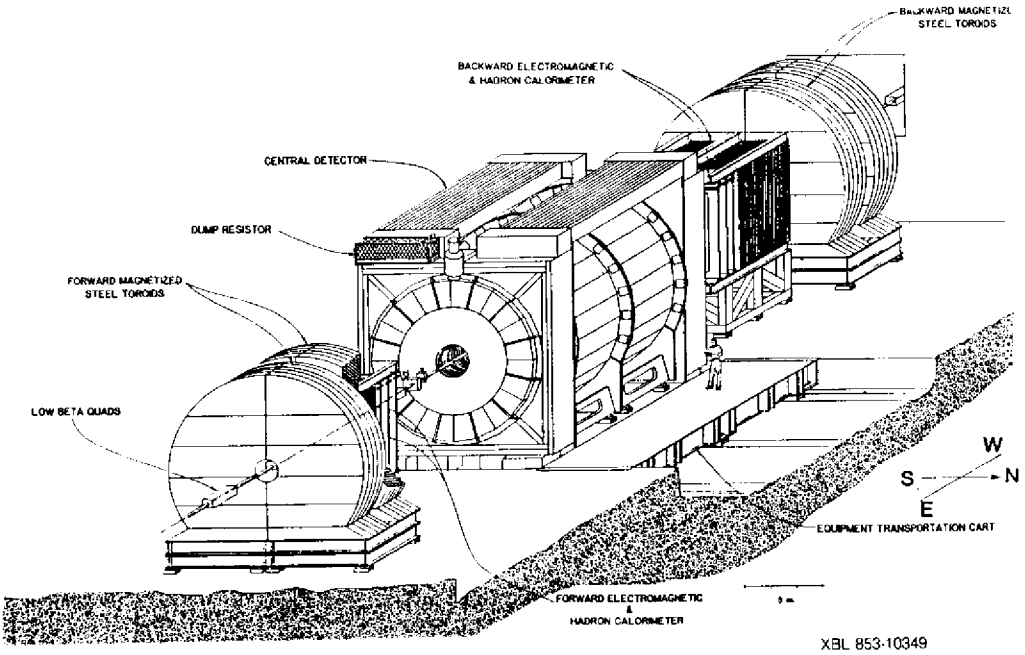


Figure 5: The Collider Detector at Fermilab, used to study collisions of 0.9-TeV protons and antiprotons.

If we take these observations, and if the universe is not capricious—if there are laws of Nature that apply, not only here and now, but throughout the universe, in the past, present, and future—then we can try to extrapolate back in time to what the beginning must have been like.[5] Running the film of the universe's life story backwards, we find that the universe once had to be very small and hot and dense. People give different poetic names to that original occurrence—"the original singularity," for the mathematically inclined; "the primeval fireball"; "the big bang"; or, as my favorite French newspaper likes to call it, *"le grand boum."*

Very well, one of the first things you have to do when you make a scientific theory is to try to find consequences of that theory. There are a few consequences that we can derive from the big bang theory. The first is that the universe we see around us, the place we are living here and now, should be bathed in the glow of the original explosion. By virtue of the fact that the universe has expanded, all the primordial energy has been dispersed. That means that it is much colder here and now than it was there at the beginning. The average temperature of the universe is about three degrees above absolute zero, about the same temperature as the superconducting magnets we plan to use in the Supercollider, so very cold indeed. In fact, a series of measurements starting in the middle 1960s have found that glow—the cosmic microwave background radiation—which is a remnant of the original glow from the explosion.

Light elements are both the raw materials and the fuel burned in stars to make the more complex heavy elements. Consequently, the light elements we see around us in the universe, such as helium and deuterium, should be the relics of what was produced in the original explosion. We can measure the abundance of those substances today, and we can calculate what the abundance should be if the universe was as we think it was. The agreement is excellent.

Finally, let us remember that light takes a certain amount of time to go from one place to another. From the sun to Earth it takes about eight minutes; longer distances take proportionately longer times. This means that by looking back to the distant stars we see the light that was emitted from them a long time ago. Looking at the distant stars shows us the way the expanding, evolving universe used to be.

The great lesson that astronomy has taught us is that we don't have to simply look up at the sky and wonder, but that we can try to find explanations. When a new star appears, as one did in early 1987, in the patch of sky known as the Large Magellanic Cloud, we don't have to worry that it signals the end of the world. We can instead understand, at least roughly speaking, what is happening: it is the explosion—a supernova—of an old and not very bright star. We can try to learn something from that event by measuring the signals coming to us from that explosion. Such cataclysms dispersed the heavy elements, the ones we are made of, throughout the universe.

What We Know We Don't Know

The construction of the Standard Model is a great achievement, on a par with the discovery of the periodic table and the beginnings of the invention of quantum mechanics. It shows the way toward a simple, organized explanation and understanding of everything that goes on in the universe at the most elementary level. At the same time, as our conception of

[5]The assertion that natural laws are uniform in time and space is not derived from experiment, but it is an assumption without which we cannot hope to make sense of history. If Nature is fickle, if the gods intervene at their whim, of what use is Reason?

matter based on quarks and leptons has become better established, we have become increasingly aware of its shortcomings. Having arrived at a new level of understanding, we can look critically at our collective achievement and try to ask what we haven't succeeded in doing. What are the questions raised by the Standard Model that it cannot answer? A few arise immediately. Why does it work? Look into the inner mathematical workings of it and ask whether everything is in good order or whether any dirty little secrets are swept under the rug. Must we invoke a minor miracle here or there? You can ask whether the Standard Model can be complete, whether in order for it to make sense there might not have to be some other elements that were missing until now. If you are convinced that you don't have the whole story, you can try to understand where the Standard Model will fail.

Such questions are of interest, of course, only if you have at least a partial understanding. If you have a theory that doesn't explain anything, it is not interesting to ask why it works. In the Standard Model, we do have a credible theory to which we can look for guidance. By doing so, we can define a frontier where things cease to make sense. It is the scale of energies of about *one trillion electron volts* for the collisions between quarks and leptons and the force carriers. Or, if you like, it is on a very small scale: less than a billionth of a billionth of a meter. This is the place where our current understanding doesn't quite make sense, where there must be something new and interesting going on.

This is one of the arguments that we make to ourselves when we try to decide what the next step should be: we look into our current understanding and try to determine where it breaks down and where there will be new clues. The response sets the scale of the Supercollider. In addition, of course, whenever we explore new territory in particle physics we share the excitement of the unknown with other adventurers. When we build a new instrument, we are like astronomers looking out to a greater distance with new telescopes, like low-temperature physicists building new refrigerators that can get them a little bit closer to absolute zero, like medical researchers looking within the body in new ways. There are always new phenomena to discover when you look where no one has been able to look before. It is our confident expectation that, in addition to the questions that we know we wish to answer, there will be new questions and new answers.

Now let us review in general terms some of the questions about Nature that are raised, but not answered by the Standard Model. This will indicate the kind of initial exploration that we want to conduct with the Supercollider. In the same way that, once having constructed the periodic table, our scientific ancestors asked themselves what made the elements behave according to certain patterns, we now want to know what determines the properties of the quarks and leptons. It is very nice to be able to put them in the little boxes we saw back in Figure 1 and notice the relations between them, but how much more satisfying it would be if we could tell how much a quark or lepton will weigh and how it will behave under particular circumstances.

We have evidence for six quarks and six leptons, but we don't have any reason why there should only be six of each, or that there should indeed be six of each. How many of them are there? From a self-centered perspective, just having up and down quarks and electrons would seem to be fine: that is the stuff we are made of. What role do the other quarks and leptons play in shaping the world around us?

There are many close similarities among the quarks and leptons. Indeed, mathematical consistency of the theory that brings radioactivity and electromagnetism together requires that there be a connection between quarks and leptons. For each set of quarks there has to be a set of leptons. How are the properties of the quarks and the leptons related?

We have no direct experimental evidence that the quarks and leptons are not fundamental. We haven't seen anything inside them, but we recall that atoms, nuclei, and protons all looked fundamental in their turn. Yet, when they were scrutinized more closely, there was something inside, there were simpler constituents to be found. Are there even simpler and more fundamental things to be found inside the quarks and leptons? The observation of constituents within the quarks and leptons would give us a better understanding of the properties of today's fundamental constituents and the ability to construct a more complete picture of Nature.

We may ask whether there are other kinds of matter, not made of quarks and leptons, that we haven't yet seen.

In addition to those questions that pertain to the constituents, there are some questions that have to do with the forces. I hinted to you that we have found a nearly complete connection between the weak interaction and electromagnetism. However, there is a fundamental difference between the interactions that we observe. Electromagnetism acts over very large—astronomical—distances. We can check the laws of electromagnetism out to interplanetary separations, and the influence of electromagnetism is felt at those vast distances. The weak interaction, which I have tried to tell you is friend and partner to electromagnetism, acts only over a range which is small even compared with the size of an atomic nucleus. What makes radioactivity and electromagnetism different and yet at the same time so similar?

Having seen the complete unification of electricity and magnetism in electromagnetism, and the partial unification of the weak and electromagnetic interactions, we may ask whether there is in fact an underlying unity among all the fundamental forces.

Finally, as with the fundamental constituents, we may inquire whether there are new fundamental forces that we haven't seen before.

New Tools

Both these specific questions and more general arguments set a scale of energy or size that we need to explore, the domain of energies of about a million million electron volts, of distances smaller than a billionth of a billionth of a meter. Physicists do not believe that within the energy range now available there are or will be enough clues for us to piece together a theory of the nature of matter. This conviction—together with our awareness of the value of exploration, our appreciation of the countless instances when unexpected, puzzling, and ultimately illuminating new observations have come out of accelerator experiments—is what motivates the quest for higher energies, for a microscope of higher magnification.

We can only accelerate electrically charged, stable particles. Nature provides us with protons and electrons and their antiparticles. Therefore, we can imagine exploring the new domain in one of three ways. We might take electrons and anti-electrons, fundamental particles, and collide them together with one or two or three trillion electron volts (TeV) per beam and watch what happens. Alternatively, we could collide a pair of protons, each of which is a collection of quarks and gluons, in which the energy of the protons is about ten or twenty TeV per beam. In this case, the energy carried by an individual quark will be a few TeV. Finally, we could arrange collisions between an electron of a few TeV and a proton of a few tens of TeV. These are the three choices in principle. An electron–anti-electron or electron-proton collider at these energies is well beyond our current technical means. The instrument of choice is a superconducting proton-proton collider, for which the essential technology is firmly in hand: the Superconducting Super Collider, or SSC.

The SSC will be a chain of accelerators, linked to boost barely moving protons to nearly the speed of light. The particles reach increasingly high energies in a cascade of four accelerators that make up the injector, from which they are fed into the collider ring.

The collider ring is the heart of the SSC. In this underground oval tunnel, ten feet in diameter and fifty-three miles in circumference, two beams of protons are accelerated in opposite directions. Superconducting electromagnets in the collider ring guide each proton beam through a stainless steel pipe about one and a quarter inches in diameter. Magnets curve the paths of the beams, making it possible to build the accelerator in a loop, rather than a straight line, and thus realize substantial economies by repeatedly using the same components to accelerate and manipulate the beam. The protons travel in compact bunches, with some eight billion protons in each bunch. Each second, the fifteen thousand bunches that fill each beam pipe make three thousand laps around the ring. On every lap, a pulse of radio waves boosts the energy of each bunch, until the protons reach their final energy—twenty trillion electron volts. The circulating beams are maintained at that energy and focused into head-on collisions where detectors can record particles produced from the energy of the collision.

Superconducting magnets are used because they make possible substantial savings. At low temperatures, certain materials become superconductors, in which electricity is able to flow without resistance. A superconducting material dissipates no energy in heat—it just carries the current you put into it *without electrical resistance*. Such a material, an alloy of niobium and titanium, will be used to fabricate the coils for the SSC magnets. The conductor is made of twenty-three copper wires, inside of which are embedded thousands of fine fibers of niobium-titanium alloy, each about one-sixth the diameter of a human hair. It is those niobium-titanium fibers that carry the current. When cooled to the temperature of liquid helium, about four degrees above absolute zero, each one of the strands carries about five hundred amperes. That is twenty or thirty times what a slightly bigger wire carries in your house before the fuse blows. Once the SSC magnets are turned on, electric power is only required to drive the refrigerators that keep them cold, not to replenish the current in the magnet coils. A Nonsuperconducting Super Collider with conventional magnets would require four gigawatts of electrical power, costing about $2 billion per year. The SSC's average power requirements are about forty times smaller. In addition, superconducting magnets can create magnetic fields several times stronger than conventional magnets, thus confining the protons to a tighter orbit and reducing the ring's perimeter.

At the interaction regions the two beams are steered into head-on collision. Experimental apparatus at these points is designed to provide two kinds of information: to identify the particles produced in the collisions by measuring their properties and to determine as precisely as possible the path each particle followed. Although similar in concept to existing detectors, SSC detectors will be physically larger and more complex. Using a vast array of state-of-the-art components, international teams of physicists and engineers will design, construct, install, and operate the experimental apparatus at the SSC.

Although we profit from the increased magnetic fields made possible by superconductivity, the Supercollider is still an instrument of imposing size. The circumference of a collider is about thirteen miles times the energy measured in trillions of electron volts divided by the magnetic field measured in teslas. For a collider that has twenty-trillion-electron-volt beams confined by 6.5-tesla magnets, the curved parts of the machine will be about forty miles around. If we remember that the point of building this instrument is not just to make protons run around and around, but actually to do experiments with them, we must provide space unencumbered by

the bending magnets to put in the experimental detectors, the focusing magnets, and the acceleration gear. In our design for the Supercollider, the circumference is about fifty-three miles (eighty-four kilometers). Fifty-three miles around is big. In Figure 6, I show you the size of the Supercollider superimposed on Washington, D.C. The machine is about the size of Interstate Highway 495, the Washington Beltway.

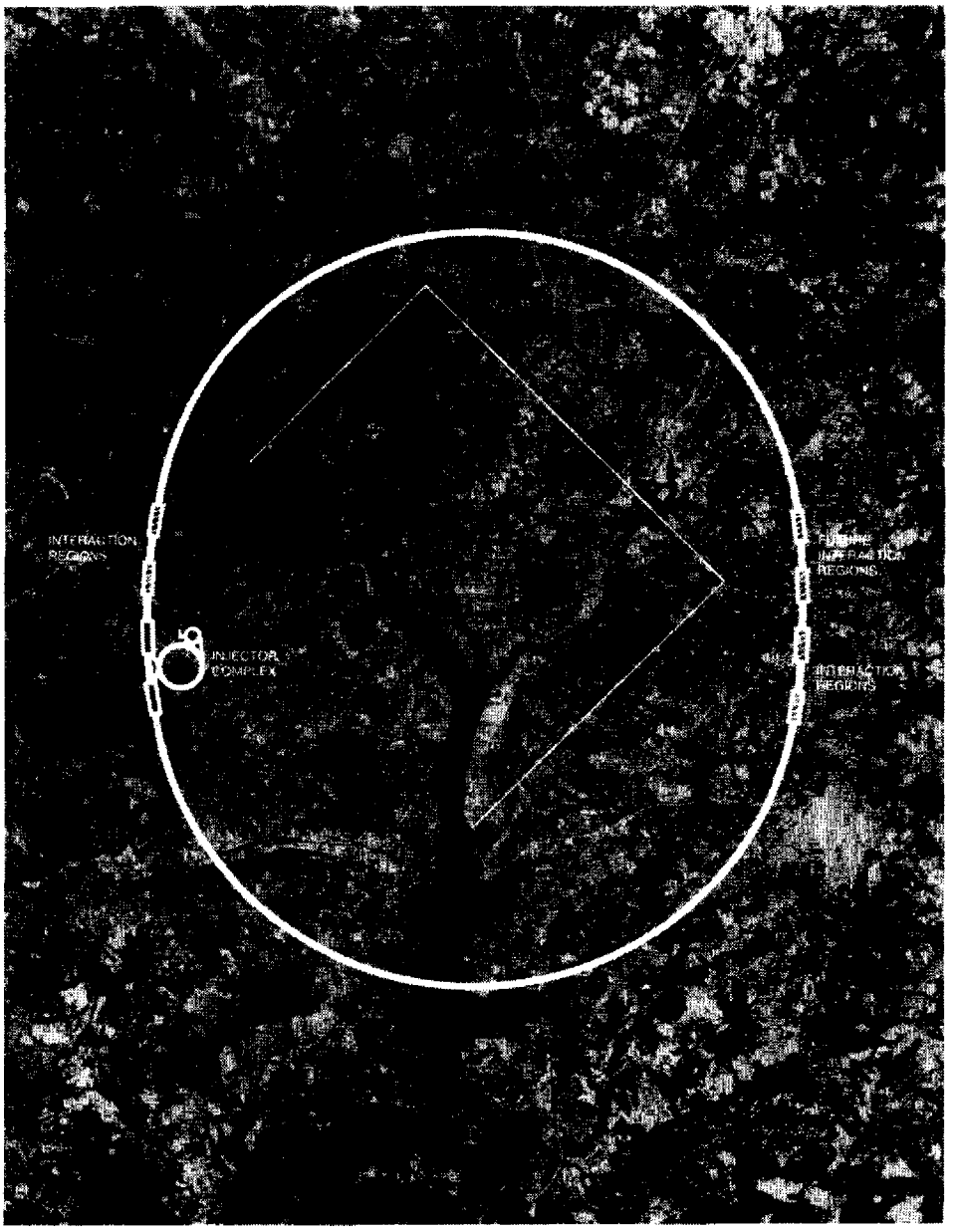


Figure 6: Outline of the Supercollider superimposed on the Washington, D.C., area.

It is reassuring that the Supercollider is the size of previous human structures. Nevertheless, it is large and complicated and costly, and so it must be designed with care. Within the tunnel (shown in Figure 7), the two counter-rotating beams of protons are confined in magnets. The beam pipes must be maintained under an exquisite vacuum, about one hundred-billionth of normal atmospheric pressure, so the proton beams can be circulated for at least a day. If the protons bumped into air molecules as they traveled around the ring, they would lose energy and be deflected from their proper orbit. The same cryogenic system that keeps the magnet coils cold and superconducting helps maintain the necessary vacuum by chilling the beam tube. Any stray molecules inside the pipe tend to adhere on the cold inside walls of the beam pipe, out of the protons' way, just as a damp finger sticks to an ice cube. Eight straight sections are planned in which to do experiments and the business of acceleration.

The tunnel will be at least thirty feet below the ground, for radiation protection. The particle beam is the source of radiation, just as in an ordinary television set. Present only when the accelerator is operating, the proton beam can be steered by electric or magnetic fields. When the accelerator is switched off there is no beam, and no radiation is being produced. The substantial amount of earth covering ensures that even if the beam is lost from its orbit, persons are protected from harm.

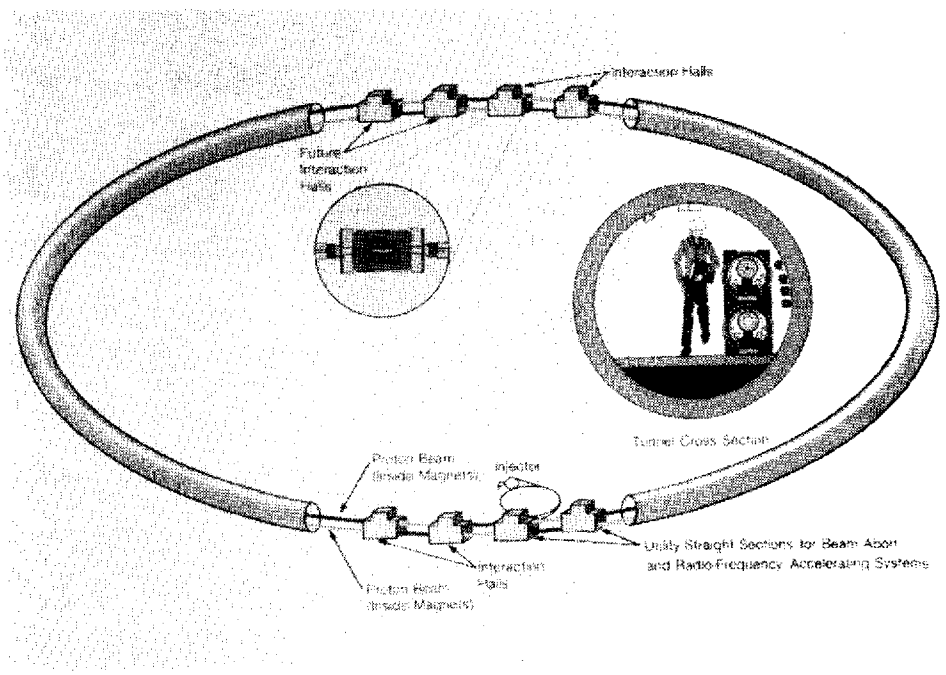


Figure 7: Proposed layout for the SSC. Interaction halls cluster on the two gently curved sides of the collider ring. In this perspective the near cluster incorporates the injector complex, the radio-frequency accelerating system, beam absorbers, and two of the six interaction halls where stored proton beams will collide head-on. The far cluster adds four more interaction halls, two of which are reserved for development after research begins. The schematic enlargement of an interaction hall shows a detector surrounding the point at which two beams collide; the cross section to the right shows the position of the two superconducting magnet rings in the tunnel.

Toward the SSC

Although the scientific need for a step to much higher energies was already apparent, in broad terms, a decade ago, it was necessary to develop the technical means to take that step. Formal studies of the feasibility of a multi-TeV accelerator began with workshops sponsored by the International Committee on Future Accelerators at Fermilab in 1978 and at CERN in 1979. Various possibilities for very high-energy accelerators, including proton-proton colliders at tens of TeV per beam, were examined. The idea of the SSC itself began to take shape at the 1982 Summer Study on Elementary Particle Physics and Future Facilities organized in Snowmass, Colorado, by the Division of Particles and Fields of the American Physical Society. The SSC initiative was followed up with workshops on accelerator and detector issues held during 1983 at Cornell University and at the Lawrence Berkeley Laboratory.

Encouraged by the successful operation of Fermilab's superconducting Tevatron, which has boosted protons to energies of nearly one trillion electron volts, a High Energy Physics Advisory Panel (HEPAP) Subpanel on Future Facilities recommended "the immediate initiation of a multi-TeV high-luminosity [high collision-rate] proton-proton collider project with the goal of physics at the earliest possible date." This recommendation was unanimously endorsed by HEPAP in July of 1983. The Department of Energy responded by allocating funds for preliminary SSC R&D in the fall of 1983.

In December 1983, the Department of Energy and the directors of the U.S. high-energy physics laboratories chartered a Reference Designs Study to produce example designs of a proton-proton collider with energy of 20 TeV per beam that would yield about 100 million collisions per second. Three different approaches were investigated; it was found that any of them could form the basis of a technically feasible SSC, costing approximately three billion (FY84) dollars.

Early in 1984, the Department of Energy contracted with Universities Research Association, a consortium of sixty-six leading research universities, to direct and coordinate the SSC research and development program. For this purpose the SSC Central Design Group was established, accepted the hospitality of the Lawrence Berkeley Laboratory, and began work on a non-site-specific conceptual design. Participants included Brookhaven National Laboratory, the Fermi National Accelerator Laboratory (Fermilab), Lawrence Berkeley Laboratory, the Texas Accelerator Center, and experts from many laboratories and universities in Canada, Western Europe, Japan, and the United States. American industrial firms also played an important role.

By March of 1986 this team had prepared a Conceptual Design for the SSC. Every major system had been thought through, and a detailed cost estimate had been made. The Conceptual Design was not planned for any specific site, since we don't yet know where the laboratory will be built. During the summer of 1986, the Department of Energy and independent experts reviewed the cost and technical feasibility of the machine described in the Conceptual Design Report. President Reagan endorsed the SSC as a national goal in January 1987. In April of that year, the Department of Energy began a site search; forty-three sites were proposed.

Twenty-one wise persons assembled by the National Academies of Sciences and Engineering reviewed the proposals and, on December 24, 1987, presented to the Department of Energy a short list of eight "Best Qualified Sites." One site was subsequently withdrawn, leaving the seven candidates shown in Figure 8. The Department of Energy plans to designate a preferred site in November of 1988. From the time the site is available, sometime in 1989, it will take about seven and a half years to build the machine. We hope to be doing science with the SSC by 1996.

Figure 8: Proposed SSC laboratory sites under consideration by the Department of Energy.

It is an imposing challenge to try to build an instrument this large, to answer questions that are of such profound importance. It is an expensive proposition. Including detectors, computers, the accelerator itself, and a large allowance of funds for contingency, the price tag over ten years comes to $4.4 billion, a significant investment. Many of us have now committed a part of our lives to seeing that this bold and innovative project is brought to reality. We believe—with our colleagues around the world—that it is the kind of instrument that is essential for the progress of our field. I hope that in ten years I can come back and tell you what we have found on the voyages of discovery into uncharted reaches of inner space on which the Supercollider will carry us.

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