from New York to Los Angeles, for instance. "Ten years ago I had a lot of problems with jet lag," he says, but with his bright light treatments, he adjusts easily to new time zones.

Czeisler notes his data also imply that the result of 3 days of exposure to light was not simply three times the result of 1 day's exposure. The first pulse of light, Czeisler says, made the circadian cycles irregular and suppressed their magnitude—that is, the changes in the body temperature throughout the day were smaller than normal. "Two cycles of exposure crushed the amplitude," he says, and the third exposure reset the pacemakers to new phases.

For theoreticians such as Winfree, the Czeisler data have important implications for the correct mathematical description of how the human circadian clock responds to light. Weak resetting is analogous to moving the hands on a clock ahead or behind by a hour or two. But in the strong response elicited by Czeisler, the clock is shifted by 10 or 12 hours without moving the hands through the intermediate positions—there is, in some sense, a discontinuous jump. Mathematically, these are two fundamentally different types of responses, called Type 1 and Type 0. (The 1 and 0 refer to a concept from algebraic topology—the winding number of the response curve.)

The fact that humans exhibit Type 0 resetting has an intriguing consequence, proved by Winfree: The right amount of light applied at the right time can bring the inner clock to a stop, so that there is no longer a strong circadian rhythm. Czeisler's claim that he crushed the amplitude of the circadian rhythm in some subjects seems to verify Winfree's theoretical prediction.

Kronauer brings all this down to earth with a simple example based on the predictions of his model, which he says agree with the data from Czeisler's trials. Suppose you fly to Sydney, Australia, 14 hours ahead of Eastern Standard Time. If you immediately go to work, so that you are exposed only to interior lighting, your clock will be reset only by about 1 hour each day. It will take 10 days to fully adapt.

But if you spend the first day outside, 6 to 8 hours of bright sunshine (about 100,000 lux) should do the work of the first two exposures in Czeisler's experiment: It will crush the amplitude of your internal circadian pacemaker and prepare it to be reset to the proper time with light exposure on the following day. Another day outside should lock your clock into Australian time.

So if you're flying to Australia, be sure to get there a couple of days early—go to the beach, catch some rays. Tell your boss it's doctor's orders. ■ ROBERT POOL

New Machine Sparks Rivalries at CERN

An intense 10-year effort by physicists and engineers at CERN is soon to bear fruit, when LEP, the world's largest particle accelerator, comes on-line next month

Geneva

LIKE SPRINTERS PREPARING for the big race, international teams of physicists at the European Laboratory for Particle Physics (CERN), Geneva, are operating in an atmosphere of rising tension and excitement as they make their final preparations for the "big event."

If all goes according to plan, the first week in August will see the maiden run of colliding beams of electrons and positrons in what will, for several years to come, be the world's largest particle accelerator, the 200-GeV Large Electron-Proton Collider (LEP).

The sense of anticipation in Geneva is intense. Four separate detectors, each a complete piece of experimental apparatus manned by its own team of several hundred physicists from around the world, are located at four different points around the LEP ring. And each has a chance to come up with the first anticipated result of major importance to physicists: a description of the chargeless Z particle that is sufficiently detailed to answer key questions about the fundamental building blocks of matter.

Later on, when the accelerator has been brought up to its full operating energy, the same groups will have an even bigger prize in their sights, namely proof of the existence of the two particles next on the "to be discovered" list. These are the top quark and the elusive Higgs boson, widely postulated as the source of the mass of the W and Z particles (both of which were first seen at CERN in the early 1980s).

With such attractive quarries looming, it is perhaps not suprising that scientists at CERN are working overtime to improve the chances of their team being the one that grabs the headlines. The one big surprise is that the CERN physicists are moving toward their prized goal virtually without competition from a key research facility in the United States, once seen as a big threat.

Carlo Rubbia: *His drive has brought LEP on-line at a rapid clip. He'll be looking for dramatic results.*

Late last year CERN physicists had watched anxiously as the European laboratory's main rival, the newly commissioned Stanford Linear Collider, seemed all set to crank out Z particles, precisely what LEP is designed to do. It looked as if CERN would not only be the loser in the race, but also would have lost to a more modest machine. The brainchild of Burton Richter, director of the Stanford Linear Accelerator Center (SLAC), the linear collider was seen in Europe as something of a spoiler—a deliberate attempt, fueled by appeals to U.S. chauvinism and the vaunted merits of "Yankee ingenuity," to cream off the most exciting discoveries in a cut-

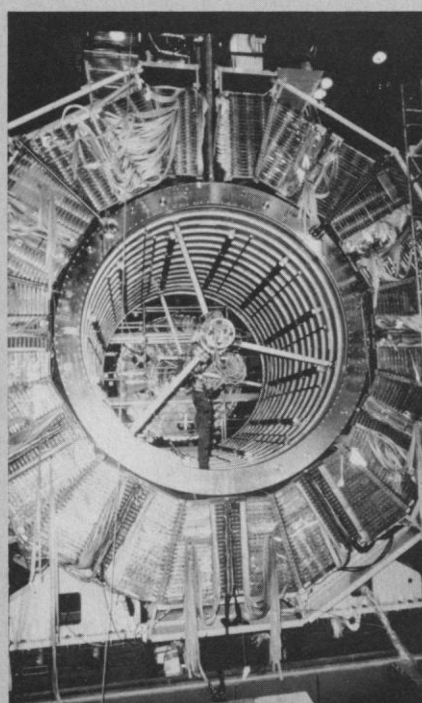
Acronyms in Search of Particles

The largest of the four LEP experiments, each of which receives most of its funding from outside CERN, is known somewhat prosaically as L3. More than 400 physicists from the United States, Europe, the Soviet Union and the People's Republic of China will collaborate on L3, an unprecedented joint effort. The team has been put together by Nobel Laureate Samuel Ting of the Massachusetts Institute of Technology.

The detector itself is as tall as a four-story house. It is distinguished from the other three in that the coil which produced its magnetic field is at the perimeter of the detector, rather than close to its heart. Achieving this has meant using 8500 tons of steel for the magnets that produce the field—more than the Eiffel tower in Paris—but it also provided unprecedented precision for tracking muons. These have long been Ting's specialty, and, he hopes, will prove the key to finding the Higgs boson.

The next detector down in size is known as DELPHI. Incorporating the biggest superconducting magnet in particle physics—its cryostat has an internal diameter of 5.2 meters—DELPHI will specialize in precise three-dimensional measurements of the physical characteristics of the leptons and photons produced in the LEP electron/positron collisions.

More 400 scientists, coming from 40 separate research institutes, are involved in the DELPHI experiments alone, and the detector contains much state-of-the-art technology, including Ring Imaging Cherenkov counters that will be used to identify hadrons. "DELPHI is probably the most sophisticated of the four detectors, and we hope that it will produce the richest physics," says Peter Renton of the University of Oxford.



LEP detector: *Looking into the barrel of ALEPH.*

The most conventional machine is known as OPAL. Based on well-established detector techniques, including the use of lead-glass blocks for its electromagnetic detector and streamer tubes for detecting hadron showers, OPAL will be able to provide highly accurate identification of electron and photon energies.

The fourth detector, like OPAL, is a general purpose detector, ALEPH. Perhaps the simplest of the four, its particular skill will be in tracking and identifying all types of charged particles. To do this with unprecedented accuracy, it will use a powerful Time Projection Chamber developed at the University of California, Berkeley to provide highly detailed information about particle positions.

The different capabilities of the four experiments will be most strongly felt when the accelerator comes up to its full power sometime next year. Operating at beam energies above 80 GeV that will be achieved once superconducting radio frequency accelerating cavities are introduced, this will in particular make it possible to study the production of W+W- pairs.

It is at the higher energy levels, for example, that the first evidence for the existence of the top quark is likely to appear (although, given the right circumstances and and slice of luck, there is a small chance that it could before). And it will also be when the greater luminosity means that LEP is producing Z particles by the tens of thousands that the Higgs particle will finally emerge.

"We really have no precise clues as to where to look for it; it will be like looking for a needle in the proverbial haystack," says Renton of DELPHI. "The hope is to study about 10 million collisions over the next 3 or 4 years, and among these, we may be looking for signals of about 10 events." With that kind of signal to noise ratio, you need the right machines and the right teams working them. ■ D.D.

rate operation that would leave to Europe the less glamorous tasks of filling in the gaps.

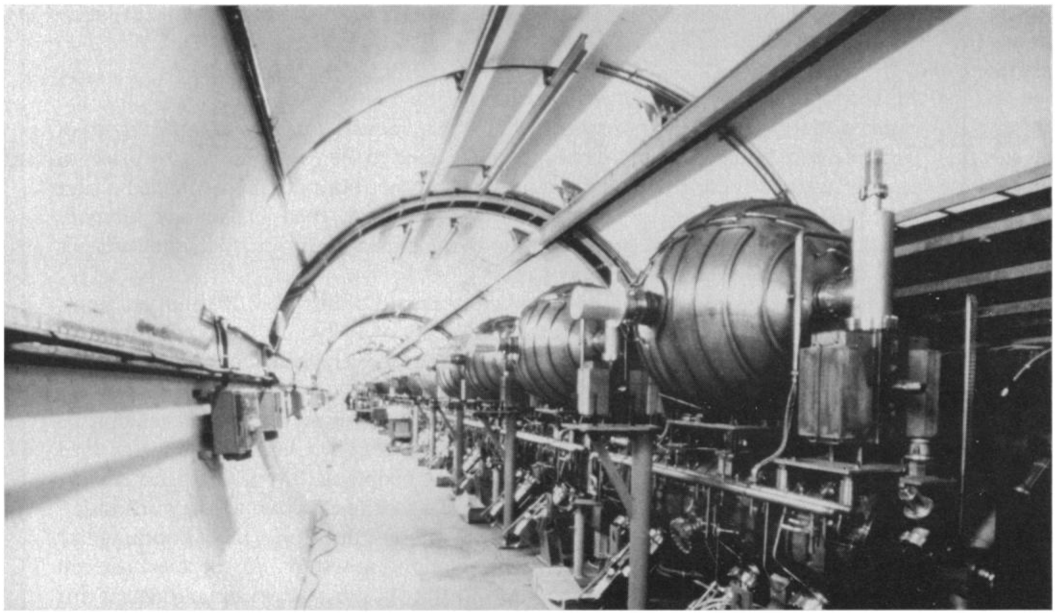
But as physicists at CERN involved in LEP (about 200 of whom are U.S. citizens, out of a total of 1200) tell it, these fears have largely evaporated. Delays in the completion of the Stanford machine have diminished the chances that it will prove to be a serious challenger, either scientifically or politically, they say. It's true that the California physicists greeted the first Z particle with much hoopla in April; but the machine is still producing Zs at the rate of only a few a day. Several thousand per day, however, are going to be needed before any significant conclusions can be reached about the precise characteristics of the particle, and—if everything goes according to plan—LEP will be able to produce these in only a few days of operation.

"From our point of view, what has happened with the SLC has been too perfect for words," says CERN physicist Alasdair Smith. "The machine has not failed to work, which would have made things difficult for everyone in high energy physics; but neither have they come up with thousands of Z particles before we have even started, which had been their original plan. It leaves the real crunch to us."

And Smith and his CERN colleagues are experiencing the unique features of that crunch. "In the past . . . the main competition has tended to be between different accelerators," says former CERN director-general Herwig Schopper, who has since joined one of the experimental teams. "Competition in the future will be between different groups working around the same accelerator."

This translates into a second unique aspect of CERN's research environment: "There has always been competition," Smith points out, "but it has never been as intense as it will be now, because people have never been doing virtually identical experiments." From this, Smith concludes that: "If one group feels it has found something significant, they know another group will have more or less equivalent data, and perhaps they will do a better job at analyzing it."

As Schopper proudly points out, LEP has been built on time and at a total cost of about $660 million, all of which was achieved within CERN's constant operating budget. This has been achieved through imposing draconian restrictions on spending, a new experience for a laboratory which has, in the past, been accused by its detractors of "gold-plating" its equipment in comparison to that in U.S. accelerators. In a series of moves that have at times caused considerable ill-feeling and discontent



LEP: *A 27-kilometer underground ring that looks to the future.*

tries, sets itself apart from the other experiments, not only because it has the largest and most expensive equipment (one-third of which is paid for by U.S. sources, primarily the Department of Energy) but also by the autocratic single-mindedness with which it is run by MIT's Samuel Ting.

Other teams have adopted a different, less autocratic approach. "There are two ways of doing it," says Alasdair Smith of OPAL, the smallest team with about 250 scientists. "You can have the L3 type of operation; or you can do something which is more democratic. We have been lucky in that we have not had any really strong personalities and relatively few prickly characters; the more democratic type of organization can be disastrous if people do not get on."

among both scientific and technical staff, some experimental apparatus—even that with life left in it—has been closed down, staff numbers have been cut, and administrative services have been pared to the bone.

The construction of the accelerator, too, which is buried underground at depths ranging from 50 to 170 meters, and extends from the plain next to Lake Geneva right up to the edge of the Jura mountains, has had its headaches. To meet opposition from local residents, all the electric cabling had to be buried in trenches. And digging was halted for several months in late 1986 after construction crews unexpectedly came across an underground river.

Then there are the bizarre problems of LEP's location. Although the main CERN buildings are situated in Switzerland, three quarters of the LEP tunnel—as well as all four experimental areas—are in French territory. Passing from one to the other requires continual customs checks: "It's not easy to get used to having to show your passport the whole time," says University of Wisconsin physicist Bruce Leclair, one of the U.S. scientists participating in LEP experiments.

But the problems and difficulties are being forgotten as 15 July approaches: the first bunch of electrons, accelerated by CERN's impressive hardware, will bolt entirely round the LEP's ring. Originally, the plan had been to allow a couple of months for fine-tuning the ring's 5000 magnets and checking out the complex vacuum system through which the electrons and the positrons will pass. But Carlo Rubbia, the charismatic boss of CERN, is not a patient man, and he insisted that this be reduced to 21 days—a time scale that will allow a first run with colliding beams early in August. It also implies, perhaps over-optimistically, that all the equipment will work as it should the first time the switch is thrown.

If it does, life at CERN will move rapidly into overdrive. All four experiments will be able to have a first crack at sizing up the Z particle when collisions start in August. The current plan is for an initial pilot run of up to a week with an energy of 45 GeV in each of the two beams, gradually focusing down until the precise energy mass of the Z can be ascertained. Even at an initial luminosity that will be an order of magnitude less than the final design figure, each experiment will be able to intercept a few thousand Zs a day.

This is already much higher than the rate expected at SLAC. "They have not nipped us in the initial steps, as we had feared they might," says Peter Renton of Oxford University. "If they had had 10,000 Z particles by this stage, it would have taken us about a year to get into a competitive position as far as producing new physics. But that does not appear to be the case."

But with the California physicists keeping up the pressure, no one is being allowed to slip. "It's going to be frantic," says Leclair of Wisconsin. "And there is already tremendous pressure to have things frozen by the time we start taking data and are ready to go."

Each of the four detectors has been set up as a multinational research project in its own right. Each has been designed to emphasize particular aspects of particle detection (see box). And each has developed a slightly different management style.

L3, which involves over 400 scientists from 37 different institutions in 13 coun-

Indeed, there has at times been friction between the teams, for example, over access to CERN's limited resources or over the acknowledgment of technical ideas exchanged between team members. "Relations between us and OPAL have been reasonably good," says Imperial College's Peter Dornan of the ALEPH team. But he admits that "there have been a few slightly acrimonious moments with DELPHI." And as for L3, "Ting has his own way of running things."

Given that, in the initial stages at least, each of the four teams will be trying to be the first to come up with the characteristics of the Z particle, everyone expects the atmosphere to remain tense for the first few months. "There's no doubt that it will be a race; there are no two ways about it," says Dornan, a member of the team which has been designing experiments for one of the four detectors, ALEPH. "This means you have to be fast, but you also have to be right. You do not want to get a reputation for publishing preliminary junk; but neither do you want to be a couple of months behind everyone else."

For some, the result is a less-than-welcome change from the early days at CERN, when the considerable differences between experiments being carried out on different accelerators meant that there was wide discussion of even very preliminary results. "With electron machines, most people's experience is that some groups get very paranoid," says Smith of the OPAL detector.

Not everyone, however, sees such competition as necessarily a bad thing. Indeed, scientists involved in the L3 experiments have been organized by Ting in a way that deliberately encourages close rivalry, for example, by requiring that all potentially interesting data be analyzed by two separate teams completely independently.

"If both teams come up with the same results, we can already be much more sure that there is not a mistake," says Mannfred Steuer, a physicist from the Massachusetts Institute of Technology who works with Ting on the L3 detector. "Competition [between the different experiments] is a good thing, because it will ensure that one gets the results very fast, and also that they are unbiased."

The results obtained in the first few months of operation will be important for more than their scientific significance. They will also be used by CERN director Rubbia to decide what type of upgrading of LEP in the mid-1990s he should try to persuade the member states to back. This will be high on the agenda when research ministers meet to discuss CERN's future early next year.

There are two main possibilities in the medium term. One is to increase the energy levels in the LEP ring (a move that would require applying for new planning permission from local authorities). The other is to introduce polarized beams, a step already being planned at Stanford.

Looking further into the future, the 14 member states will also have to decide what type of support to give to Rubbia's proposal for a second, superconducting ring in the LEP tunnel. This would turn LEP into a Large Hadron Collider capable of producing collisions at around 10 TeV; this energy range approaches that of the proposed Superconducting Super Collider in the United States—but, according to LEP officials, at about one-fifth the cost of that mega-machine.

It will be no easy task to squeeze the money for LHC out of governments for whom high energy physics no longer has the same glamour it once did. But Rubbia seems determined to put some of this glamour back; despite the cuts, for example, the advertising firm Saatchi and Saatchi has already been brought in to advise on how best to stage the official opening of LEP later this year, with guests ranging from the King of Norway to British Prime Minister Margaret Thatcher.

For most CERN physicists, however, the pomp and glamor of such a ceremony will be a side-show to the real action. After 10 years of design work and construction all eyes are on the performance of LEP as it slips into action in the next few weeks. Whatever happens, there is certain to be a great deal of work to do and hundreds of pairs of hands put to the task.

■ DAVID DICKSON

Another Piece of 3.14159 . . . ?

In 1666, Isaac Newton turned some knobs on his newly invented calculus and cranked out a decimal approximation to the ancient number pi—the ratio of circumference to diameter of a circle. "I am ashamed to tell you to how many places of figures I carried these computations, having no other business at the time," he later wrote. The figure was 16. If Newton was ashamed, then David and Gregory Chudnovsky might well be mortified: the two Columbia University mathematicians have computed 480 million digits of pi.

The Chudnovskys' feat eclipses the previous record of just over 201 million digits, set last year by Yasumasa Kanada of the University of Tokyo. If *Science* tried printing their result, the digits would fill up every page of every issue for the rest of the century. So you might ask: Why would they do this?

One reason for computing digits of pi is pure competitiveness and what can only be called the Mount Everest syndrome: because it's there. The Chudnovskys maintained silence during the calculation, not even telling the people at IBM or Cray exactly what they were doing, lest the competition dedicate a machine or two to the same task.

But there's a practical use for their work, as well. For one thing, there's nothing like a good run of pi digits to shake down a new computing system. For another, you can investigate a variety of number-theoretic and statistical hypotheses regarding pi this way: for instance, the relative frequency of various digit strings. The Chudnovskys' result allowed them to improve an analytic theorem regarding rational approximations to pi.

So if you accept the importance of this work, you may come to the question: how in the world did they do it? Part of the how, of course, is computers. The Chudnovskys carried out their calculations on a CRAY 2 at the Minnesota Supercomputer Center in Minneapolis and on an IBM 3090-VF at the IBM Yorktown Heights Research Center in New York. The rest of the how is pure mathematics. "In order to compute a number well, you have to know it intimately," says David Chudnovsky. Their calculation is based on a formula which the Chudnovskys discovered in 1984, relating pi to an infinite sum of rational numbers. The new formula was inspired by one discovered earlier this century by the Indian mathematician Srinivasa Ramanujan. William Gosper of the Symbolics Inc. in Palo Alto, California, used the Ramanujan formula in 1985 to obtain a short-lived record 17 million digits of pi. Both formulas stem from deep relationships in number theory and algebraic geometry.

But what if a cosmic ray or a power surge or a speck of dust on a disk messed something up in the calculation—how would you ever know? "We have an absolutely sure-fire way of validation and verification of the calculations," David Chudnovsky says. The verification is based on deep number-theoretic properties of the infinite sum, which they proved only last year. It can be thought of as a sophisticated version of the old accountants' trick of checking calculations by casting out nines; for the Chudnovskys a large set of prime numbers do essentially the same thing.

The Chudnovskys were extremely careful in handling the data. "We deposited on every media—disk or tape or anything else—the data together with a complete set of keys. . . . This means that every time we wrote in and every time we wrote out, we were checking whether we were correctly writing in and correctly writing out," David Chudnovsky says. "Out of all the computational time, over 90% of it went on verification, and the real run was under 10% of CPU time—which shows that our algorithm was pretty good."

Finally, there's the question, Where do we go from here? The answer to that one is that inherent in the Chudnovsky victory is the seed of its eventual defeat. A key new feature of their approach, the Chudnovskys say, is that it is expandable: more digits can be added on demand. By that they mean that you don't have to start from scratch to beat them, you can use their own method to pick up from where they left off or at any point in the chain of digits. So the procedure can actually be farmed out, with independent computers contributing to the calculation. That possibility evokes perhaps the grandest aspect of the Chudnovsky vision: a "pi chain letter" leading to a multibillion-digit decimal expansion of pi. The burghers of Oklahoma, who once tried to eliminate by legislation all the decimal places from pi because it was too complicated, will not be pleased.

■ BARRY A. CIPRA

Barry Cipra is a mathematician and writer based in Northfield, Minnesota.