International Competition Drives DESY

Two modifications to its 37-GeV electron-positron accelerator, one in place and one planned, will help the Hamburg laboratory stay ahead

Hamburg. A visitor to the Deutsches Elektronen-Synchrotron (DESY) laboratory on the outskirts of this West German port city spends the night in a guesthouse situated almost directly over the buried tunnel of the first of a new generation of elementary particle accelerators that will carry high energy physics through the 1980's. Through a combination of financial good fortune and foresight, the laboratory easily beat out a rival group in the United States in a race to build such a machine. But the important new physics that is supposed to come with being first has been slow to materialize. Two modifications to the accelerator, one in place and one in the first phases of construction, should help keep DESY ahead.

The accelerator, which the laboratory scientists have named PETRA, is a colliding beam storage ring. Packets of electrons and positrons circulate in opposite directions in a ring-shaped vacuum chamber and collide head on at four points around the circumference of the machine. When PETRA was first turned on almost 3 years ago, it had the highest collision energy of any electron-positron storage ring in the world, almost four times as high as that of the nearest competitor, a smaller storage ring also located at DESY. To exploit their lead over the rival American group that was then building a nearly identical machine at the Stanford Linear Accelerator Center, DESY officials sensibly decided to emphasize exploring the virgin energy territory open to its new accelerator at the expense of optimizing the luminosity. Luminosity is a measure of how often electrons and positrons collide and thereby provide events for experimentalists to analyze. If the luminosity is low, the time needed to gather statistically significant data can become impractically long. Learning how to raise a low luminosity can take one or more years.

But luck has not smiled on the Germans. A family of important elementary particles that theorists hopefully proclaimed would contain a new quark has turned out not to be reachable with PETRA's 37 billion electron volt (GeV) collision energy. This unfortunate happenstance has made "the physics more or less routine," according to one disappointed theoretical physicist. Although experimentalists working at PETRA have uncovered persuasive evidence for another important particle, the gluon, this discovery has failed to set the high energy physics community afire because of its preoccupation with the putative new quark.

At the same time, the luminosity of DESY's new machine has been unexpectedly low. Until recently, the value of this parameter was almost 25 times below the advertised value in the laboratory's 1974 proposal to build PETRA, and members of the five international research teams working there were getting increasingly frustrated by not being able "to do physics" faster. The low luminosity also cast a shadow on the performance prospects of larger colliding beam machines still on the drawing board.

Now things are looking up in Hamburg. Gustav-Adolf Voss, the man who built PETRA, told *Science* that the physicists who run the machine (who are different from the ones who do experiments using particle detectors) this spring successfully installed and tested new sections of the storage ring containing extra magnets that strongly focus the counterrotating beams of electrons and positrons so that they smash into one another more often. These mini-β insertions have already greatly increased the rate of data taking. An excited Harvey Newman from one of the five research teams, the Mark J collaboration headed by Samuel Ting of the Massachusetts Institute of Technology, says, "In 5 weeks of mini-β operation, we have as much data as we got in all of 1980. By the end of the year, we will be able to shrink our error bars by a factor of 2 and we will really see [the effects we are looking for]."

At the same time, DESY is pushing ahead vigorously with a plan to boost PETRA's energy. A prime motivation for the drive to reach higher energy, according to DESY's director of research, Erich Lohrmann, is a desire to find particles containing the so-called top quark, which must have masses larger than can be produced with present PETRA energies. The expansion is a bit of a gamble because it will cost some 20 million Deutschmarks. And it will require an already voracious PETRA to gobble down twice as much electricity as it does now, just as the laboratory is being hit with the same kind of increases in power costs that have been making U.S. high energy physics laboratories curtail their own operations. But there is no guarantee that the top quark even exists, much less that it is reachable with the 45-GeV energy that will be attainable when the project is finished 2 years from now. DESY officials say that the many new particle physics experiments that would be opened up by such a major discovery make the gamble worthwhile. An extra bonus is that Stanford, which has had its machine PEP running for just over 1 year, does not now have the money to match this effort.

Luminosity can be a problem in storage rings because the particle beams are rather diffuse entities, so that collisions are rare. A beam consists of about a trillion particles compressed into one or more packets that are a few centimeters long and have a cross section of 0.04 square millimeter at the collision point. Nonetheless only one pair of particles collide during any one tour around the ring, and only a minute fraction of the collisions results in anything interesting to physicists. Fortunately the beams make over 100,000 revolutions per second and circulate for several hours.

Even so, to get a respectable number of events, accelerator operators have to push their machines to the limit. The beams seem to dance on the edge of instabilities that lurk at every beam intersection point and that threaten to blow the beam apart if the operator tries to put too many particles in a packet. In some ways, the inner workings of storage rings are as mysterious and ill-understood as are those of the particles the rings are built to study. The years-long period for breaking in a new machine can go fast or slow depending on the success of the machine physicist's intuition as to which knobs on the control panel to twiddle and how much to twiddle them.

Obtaining a high luminosity, which roughly corresponds to squeezing a large

0036-8075/81/0626-1488$01.00/0

number of particles into a small packet with a small cross section, has given DESY machine physicists fits, though they prefer not to put it this way. A 1974 version of the proposal to build PETRA advertised a maximum luminosity of 1.2×10^{32} cm^{-2} sec^{-1} and claimed this value would give "acceptable counting rates." Until the successful mini-β magnet experiment, the best luminosity obtained at PETRA was 5×10^{30}. Herwig Schopper, who was director of DESY when PETRA was proposed and built and who has moved on to become Director General of the European Organization for Nuclear Research (CERN) near Geneva, protests mightily when such figures are recited. It turns out, Schopper explained to *Science*, that the luminosity depends on the length of the space left for particle detectors at the beam intersection regions (PETRA has four of these) because there is no room for focusing magnets where the detectors sit. At the insistence of the experimentalists who wanted more space to work in, the space for detectors was later increased by 50 percent, thereby dropping the luminosity by a factor of 3.

So, has PETRA's name been unfairly besmirched by unfounded claims of poor performance? Maybe a little, but a factor of 3 clearly does not explain a luminosity 25 times lower than planned. Although, says Paul Söding, leader of the TASSO collaboration, another of the research teams working at PETRA, "it was actually helpful at first to have a low luminosity so we could learn how to analyze data and so we would have time to debug our detectors carefully, with PEP running nearly as well as PETRA [prior to the mini-β tests] people were clearly getting frustrated." And the Mark J group's Newman was interested enough in the luminosity problem to switch over and temporarily become a machine physicist. In an interview, Newman indicated his concern by spending as much time waving charts of mini-β magnet configurations as discussing physics results.

Mini-β insertions are an extension of the so-called low-β concept that was invented in the 1960's by Voss and the late Kenneth Robinson when both were at the old Cambridge Electron Accelerator at Harvard University. The mathematical expression for the size of a beam in a storage ring contains a function β that characterizes the orbits of the particles in the ring. Low β refers to decreasing this function. Low-β insertions include quadrupole magnets that reduce the cross section of the circulating electron and positron beams, at the point where they collide, to 4 percent of their usual size and thereby enhance the luminosity above that otherwise achievable. At PETRA, the mini-β magnets are placed closer to these interaction regions than the normal magnets (necessitating some modifications to the detectors), which Voss says allowed the beam cross section to be reduced by a further factor of $2^1/_2$. Although this should have increased the luminosity by the same amount, in one of those happy surprises, the luminosity increased by over a factor of 3, to 1.7×10^{31} cm^{-2} sec^{-1} at the most favorable beam energy.

Lead glass modules for JADE detector

PETRA has five international research teams: CELLO, JADE, Mark J, PLUTO, and TASSO. Groups from Japan (JA), West Germany (D), and England (E), constitute the JADE collaboration. A Japanese contribution to JADE consists of 2520 lead glass tapered blocks arrayed in 30 rings of 84 blocks each. The lead glass modules identify photons and electrons among the debris of particle decays and measure their energies. Overall, JADE has the shape of a cylinder whose axis is PETRA's beam pipe. [Source: DESY]

On the U.S. side of the Atlantic, physicists at Stanford have been bedeviled by the same fundamental machine problem that has limited luminosity at PETRA and have had plans for their own version of mini-β insertions for some time. As a result of the DESY success, says Ewan Paterson, an assistant director of the PEP project, the schedule will be advanced. During a summer shutdown, mini-β's will be installed in the West Coast machine. And, adds Maury Tigner of Cornell University, where an intermediate energy storage ring has also been having luminosity problems, "we will be putting in mini-β's this summer come hell or high water."

DESY also has more plans of its own. Voss exclaims, "Small β's are guaranteed to work. The question is how small can we make them before [other effects become important]." In the next year or two it may be possible to try out a new magnet configuration that would reduce β further, but Voss's long-term hope is to develop miniature superconducting magnets that would fit inside the particle detectors without disrupting their work. In this way it may be possible to reduce β to its theoretically minimum value.

The importance of reaching the smallest β possible extends beyond PETRA to future storage rings. A characteristic of the rings called the tune shift is the culprit that determines the luminosity for a given value of β. The tune shift limits how intense the colliding beams can be before certain nonlinear effects that each beam has on the other mutually tear them apart. Up to now, all electron-positron storage rings have been built on the assumption of a certain value of the tune shift that was measured in smaller rings at Stanford and at Frascati, an Italian nuclear physics laboratory near Rome. PETRA, PEP, and the Cornell machine, however, have all exhibited maximum tune shifts of less than one-half the assumed value, much to the great surprise and consternation of all involved.

There is no fundamental understanding of what limits the tune shift and, as one accelerator designer put it, "we have to take the tune shift God gives us." Given this gap in knowledge, the significance of the mini-β experiment, suggests CERN's Schopper, is that clever accelerator physicists can work around such difficulties. CERN is planning an immense electron-positron storage ring (27 kilometers in circumference) that will eventually reach an energy of 260 GeV. Published CERN plans for this ring still use the old tune shift value in calculating the expected luminosity. Since the largest storage rings seem to be the hardest to control, Schopper certainly has to hope his judgment about the mini-β's is correct.

If low luminosities have vexed PETRA, it has performed much better in nearly reaching its design energy of 38 GeV. But, as luck would have it, this energy has not been high enough to satisfy physicists who have been pushing hard for a more energetic machine. A bit of history shows why. Electron-positron storage rings and the so-called "new physics" of quarks and leptons grew up together in the 1970's, when two new quarks to go with the three in the original quark model were discovered and the most fruitful use of these machines was in studying their properties. By the time PETRA was ready to begin physics experiments in the fall of 1978, theorists favored a scheme in which the quarks and leptons came in families of four. Three families were known, each containing two quarks and two leptons—except that the third family had one quark missing; namely, the top quark. Largely on intuitive grounds, theorists expected the top quark to be found in particles with masses that would be producible in PETRA and PEP. But physicists at DESY have seen no sign of any such particle, and at Stanford this negative finding will likely be confirmed.

There is more to the top quark than just filling a blank slot in someone's

DORIS Gets a Facelift

Synchrotron radiation, the intense ultraviolet and x-ray light emitted by electrons in circular accelerators, is more of a curse than a boon to high energy physicists. The light does have a damping effect on the tendency of particle beams to skitter about and thus makes them easier to control. But the energy lost by the circulating beam must be replenished or else the particles would soon run out of steam. As the equations work out, even small, low-energy machines can consume as much electricity as those of much higher beam energy but correspondingly larger size. Such is the case with DORIS, a 10-billion-electron-volt (GeV) electron-positron storage ring at the Deutsches Elektronen-Synchrotron (DESY) laboratory in Hamburg, West Germany, which uses as much electrical power as its 37-GeV cousin PETRA. So, DESY physicists will start this November on a 6-month project to completely rebuild the smaller storage ring. When completed, the machine will reach a slightly higher energy than before (11.2 GeV), generate data at a ten times higher rate, and will nibble electricity only half as fast as it gulps power now.

Revamping DORIS has an important physics goal as well. In 1978, DORIS had its energy increased from 7 to 10 GeV so it could switch from the investigation of the particles consisting of a charm-anticharm quark pair (psi particles) to the probing of upsilon particles consisting of bottom-antibottom quarks (see story). But the more robust DORIS became an electricity-gobbling monster in the process, and the energy was still just a little too low to produce all the upsilon particles and also certain related particles in that family containing only one bottom quark. In the meantime, a new storage ring at Cornell University came into operation and immediately specialized in scrutinizing upsilon particles in detail. Unfortunately for the Americans, the Cornell machine is having trouble producing data at a high rate, thus leaving room for a rebuilt DORIS to steal some of its thunder.

Gustav-Adolf Voss of DESY described to *Science* some of the changes that are in store for DORIS. The machine initially consisted of two separate rings, one for positrons and one for electrons, that intersected at two points where detectors were placed. When DORIS had its energy raised, the accelerator was modified so that both beams circulated in opposite directions in one ring. In the new DORIS there will again be a single ring. Magnets from both the old rings that confined the electrons and positrons to curved paths in the circular vacuum chambers will be rebuilt and placed around the single new beam pipe in such a way that the electric current needed to produce the magnetic field will be greatly reduced and thereby compensate for the synchrotron radiation losses. To raise the rate at which collisions occur and thus decrease the time it takes experimentalists to collect statistically significant data, additional modifications are required. One is the insertion of mini-β magnets (see story) that focus the beam to smaller dimensions in the intersection regions. Another is the construction of a new particle injection system so that beams can be squirted into DORIS at their highest energy. At low energies, beams are unstable and tend to fall apart if too many particles are packed in too quickly.

To analyze the outcomes of electron-positron collisions when the new DORIS reemerges next May, DESY physicists hope to have two new detectors in place. One, named ARGUS, is being prepared now by an international collaboration of physicists. It will be a magnetic detector designed to identify charged particles among the decay products of the collisions. As for the second, unofficial negotiations are under way with the Stanford Linear Accelerator Center over the possibility of moving one of its detectors, the Crystal Ball, to Hamburg. The Crystal Ball specializes in measuring photons emitted in particle decays and would be complementary to ARGUS. If the negotiations fall through, an existing DORIS detector, which is less capable than the Crystal Ball but also is designed for photon measurements, could be upgraded.

Voss characterized the cost of rebuilding DORIS as "peanuts" because the reduced electricity costs would recover the 3.5 million Deutschmarks needed for the job in a single year. Voss adds proudly that the new DORIS will be "the best machine in the world" for studying upsilon particles. A more diplomatic Erich Lohrmann, who is DESY's director of research, suggests that there is enough physics in that energy range for both DORIS and Cornell's storage ring to be occupied for several years. At Cornell, Maury Tigner, who is the architect of the machine there, agrees and adds that the two facilities will have somewhat complementary capabilities.—A.L.R.

favorite classification scheme of elementary particles, emphasizes DESY's research director Lohrmann. A major theoretical effort has gone into finding ways to "unify" the fundamental forces that elementary particles feel: the electromagnetic, weak, and strong nuclear forces. (Eventually, gravity is to be included as well.) At present there is a well-established, unified electro-weak theory, but the most crucial experimental tests await even higher energy accelerators than PETRA. However, a top quark with the requisite properties would be very comforting to adherents of the theory, which among other things has quarks coming in pairs. It is another class of even grander, but experimentally untested, unified theories that try to tie all three forces together that generates the families of four particles. In each case, the absence of the top quark can be incorporated into the theories, but it would be nicer not to have to do this.

A further virtue of top quarks is that they are expected to form a family of toponium particles, which consist of a top quark and an antitop quark. Toponium particles are resonances that are produced copiously when the energy of the storage ring is tuned to match their masses. When they decay, toponium particles produce numerous other particles; they are in essence particle "factories" that physicists can use to study the forces that operate in the world of elementary particles. In 1978, PETRA's lower energy cousin, a storage ring called DORIS (see box), had its energy upgraded from 7 to 10 GeV specifically to study another family of resonances consisting of bottom-antibottom quarks. Together, bottom and top make one quark pair in the unified electro-weak theory.

The top quark is not the only reason for going to higher energy at PETRA. But a second category of experiments also has to do with the unification of the electromagnetic and weak forces. One meaning of unification is that, at higher energies than exist in our day-to-day world, the forces become of comparable strength and indistinguishable. For the electromagnetic and weak forces, this condition is predicted to hold at energies around 100 GeV. But even at PETRA energies, effects called weak-electromagnetic interferences are measurable. For example, the production of two muons from the fireball created by the annihilation of an electron and positron is a purely electromagnetic process at low energies. At PETRA energies it is not; the weak force participates in it, too. And the higher the collision energy, the more pronounced the effect.

DESY officials vehemently deny that all the talk about going to higher energies to look for the top quark means that they are disappointed in the physics results from PETRA so far. They point proudly to the discovery of gluons as a major accomplishment, for example. Björn Wiik, who is a member of the TASSO collaboration, spoke as forcefully as anyone at the laboratory when he told *Science* that the investigations of the gluon events by the PETRA collaborations had all but nailed down quantum chromodynamics as the correct theory of the strong nuclear force that binds quarks together inside elementary particles. Wiik added that, with some exceptions, most future studies will be aimed at quantitatively verifying various details of the theory now that its essential features have been confirmed.

The top quark is like the proverbial carrot dangling from the stick to DESY physicists.

One thing that gluon studies at PETRA definitely did not shed light on, however, was the peculiar nature of the strong nuclear force that apparently prevents quarks from ever being pulled apart, since no free quarks have ever been seen in accelerator experiments. But theorists also have yet to show that quantum chromodynamics has this property, which is called total confinement.

Gluons show up in PETRA by means of an effect in which quarks radiate a gluon just as an electron can radiate a photon when it is accelerated (bremsstrahlung). The radiating quark "exists" only instantaneously as an intermediate state between the time an electron and positron are annihilated in a collision and the energy rematerializes as a collection of elementary particles. With the gradual (because of low luminosity) accumulation of more and more data, most physicists around the world now consider the case for gluons to be very strong. Gluons, somewhat akin to photons in quantum electrodynamics, are massless particles that carry the strong nuclear force between quarks, according to the theory. Since quantum chromodynamics is important in its own right and also as a component of the grand unified theories, gluons eventually have to appear in accelerator experiments if these theories are not to be rejected. Perhaps it is this expectation that gluons *had* to be there that has caused many physicists to assess the gluon discovery as an interesting rather than a major finding.

In any case, construction is under way in the initial phase of a 2-year project aimed at increasing PETRA's energy to 45 GeV. Two previously unoccupied halls, once intended for particle detectors, are being prepared to house eight new klystrons, tubes that convert electricity from the power company into radio-frequency waves to accelerate the electrons and positrons when they pass through special parts of the ring called r-f cavities. The number of these cavities will gradually be doubled, so that by next spring PETRA will be up to 41 GeV and in 2 years up to 45 GeV. When superconducting r-f cavities are developed (several groups are working on them in the United States and Europe), even higher energies are possible, perhaps 60 GeV.

Superconducting cavities would have another considerable advantage; they would save electricity because a certain fraction of the r-f power in conventional cavities is lost. Last year, DESY was hit with a 40 percent increase in the rate charged for electricity. The laboratory had a 20 million Deutschmark power bill, although not all of that was due to PETRA, and it is expected to rise again this year, according to Volker Soergel, who replaced Schopper as DESY director. Together with the rate increase, the laboratory had to suffer through a budget cut of some 12 million Deutschmarks. As a result, DESY physicists were jolted last year with a curtailment in machine running time. With no improvement this year, PETRA will run for only 7 months in 1981, avoiding the coldest winter months when rates are twice as high. Soergel says he hopes to obtain extra money from the German government to cover the increased power consumption of an upgraded PETRA but "in Germany, the budget situation is not brilliant."

In the face of this, the top quark is like the proverbial carrot dangling from the stick to physicists working at DESY. Adding to its tantalizing pull is a recent prediction by Harvard theorist Sheldon Glashow that the toponium particle should be producible with an energy of 38 to 40 GeV, just beyond PETRA's current capability. And what if the energy is not enough? "If the top quark is not there, we have certainly overdesigned our detector," says the TASSO group's Söding.—ARTHUR L. ROBINSON