FROM THE AUGUST 1994 ISSUE

Sweet Little Accelerator

When it comes to particle accelerators, bigger has always meant better. But now a small new machine in Virginia promises to measure up the big guys.

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Last October, when the House of Representatives voted to cut off funding for the 54-mile-round Superconducting Supercollider in Texas, it killed what was to have been the world's largest accelerator--one of those colossal machines designed to examine the behavior of subatomic particles by racing them to near light speed around enormous underground tracks. The attention of the disappointed physics community reverted to the current world champion, the Large Electron Positron collider, or LEP, which occupies a 17-mile tunnel under the Jura Mountains near Geneva, Switzerland.

LEP's name notwithstanding, size is just about the least significant attribute of a particle accelerator.

Depending on the questions accelerators are designed to address, a number of much more relevant criteria give other machines the edge over LEP. In fact, even as the mammoth project in Texas is winding down, accelerator builders in Virginia are putting the finishing touches on a device that is no larger than a horse racetrack. It is known as the Continuous Electron Beam Accelerator Facility, or CEBAF, and it is finally being switched on this summer after 15 years of planning and construction. If all goes well, experiments will begin in the fall. In terms of brute strength, CEBAF is 25 times feebler than LEP, but by another measure it is 1,000 times more potent. It all depends on how you define the prowess of an accelerator.

To compare the values of things, we assign numbers to them: price measures economic worth; grades, academic competence; diameter, the power of telescopes (the bigger the better); and resolution, the effectiveness of microscopes (the smaller the better). Indeed, in our digitally besotted age, the habit of evaluation by numbers has become so ingrained that athletic performance is reduced to a computer ranking, and political clout to an approval rating. But the most egregious oversimplification of this kind, the attempt to capture something as gloriously complex as human intelligence by means of a single number called the IQ, started long before the advent of the computer age.

The rating game breaks down as soon as more than one parameter is used to compute value. Consider the ranking of students. An A in English is obviously better than a B, but how do you compare a student who got an A in English and a B in math with one whose grades are the reverse? Wrangles over who's number one in college football stem from the failure of a simple won-lost record to differentiate between teams in different leagues, and debates about the relative merits of scientific equipment begin as soon as more than one attribute affects the performance of the apparatus.

As long as the value of a thing is represented by a single number, comparisons are straightforward. Any two real numbers can be "well ordered" by the relationship "equal to or greater than." But there is a deep mathematical theorem to the effect that you cannot well order the points in a space of two or more dimensions. There is no way, for example, to label all the points in a square in such a way that they can be listed in a row and assigned a ranking. By the same token, values measured by more than one number cannot be compared.

To get around this problem, people invent figures of merit-- formulas that combine several variables into a single one for purposes of evaluation. A simple example is used by the United Parcel Service, which advises its clients that it cannot handle packages above a maximum size. You are told to add the shortest circumference, called the girth, to the length, and if the result is over 130 inches, the box is unacceptable. By itself, the prescription "girth plus length" makes no more sense than adding your waist size to your height, but it is contrived to combine various measurements in a way that is useful to the UPS people and allows instant classification of odd-shaped boxes. Similarly, our standard measure of brainpower--the IQ--would be much more useful if it combined the straight test score with a creativity quotient, a self-confidence index, and, above all, a degree of perseverance into a figure of merit with far more predictive power.

Nuclear accelerators are usually ranked according to their voltage, which determines the energy of the particles they accelerate. The ratings have crept up like the federal deficit: once they were counted in millions; then they advanced to billions and most recently to trillions. CEBAF, for example, develops 4 billion volts; LEP 100 billion; and the SSC was designed to reach a record 40 trillion.

But energy isn't everything.

Just as a microscope needs more than resolving power, an accelerator needs more than just energy--both must also have intensity. If the illumination in a microscope is too feeble, the image will be too faint, and if an accelerator produces too few interesting collisions, nothing can be learned from it. The intensity of an accelerator is measured by the number of particles it propels per second, or, what amounts to the same thing, the flow of electric charge in its beam. This, in turn, is just the current and is measured in amps. Even as accelerators climbed from millions to trillions of volts, their currents increased by a factor of a thousand, from microamps to milliamps.

Inasmuch as both energy and intensity are useful parameters for comparing accelerators, it is tempting to combine the two by multiplying their numerical values into a single figure of merit. Remarkably, the resulting product not only happens to make sense but equals the energy output per second, or the power, and is measured in watts. (A light bulb that draws half an amp from the wall plug at 120 volts is rated at 60 watts.) Power is what accelerators are all about: power drawn from the electric grid and pumped into a beam of charged particles coursing through a pipe, power carried by the beam into a target (a morsel of solid matter or, in the case of colliders, another beam), and finally, power dumped into a block of cement where it is converted into waste heat. On this scale CEBAF's million-watt output is a hundred times lower than the power developed by LEP.

But power isn't everything, either.

For technological reasons, most accelerators deliver particles not in a steady stream but in short, intense bursts separated by long pauses. This bunched structure of the beam allows the machine time to cool off and get ready for a fresh gulp of energy. The fraction of the time that the beam is on--the duration of a burst divided by the time from the beginning of one burst to the start of the next one--is called the duty factor of the machine. LEP's pulses are a half of a ten-billionth of a second, and the pause in between them a comparatively huge hundred- thousandth of a second (the pulses, which travel at close to the speed of light, are a half-inch in length and are separated by two miles). The result is that the duty factor amounts to a mere five ten-thousandths of a percent. For a certain class of experiments such a low duty cycle, which gives the beam the appearance of a strobe light, is a serious shortcoming and limits the usefulness of the accelerator.

The problems caused by a low duty factor are not associated with the accelerator itself but with the detectors that monitor the experiments for which the machine was designed in the first place. The difficulty is overcrowding: the detectors cannot handle the onslaught of particles jammed into one burst, so they start to miss or to confuse particles from different collisions. Of course, there is an easy cure for this kind of information overload--just turn down the beam current to avoid the traffic jam. But that would be analogous to turning down the light on a sample under a microscope, which would yield a dimmer picture.

A better solution would be to keep the total number of accelerated particles as high as possible while spreading the bunches out to greater length and longer duration--in other words, to increase the duty factor without changing the current. Of course, that would leave the accelerator with no time to cool down between bunches. Yet this is precisely the crux of the CEBAF design, which will achieve a duty factor of 100 percent. As the machine's name implies, its beam will be continuous and will resemble a powerful searchlight rather than a strobe lamp.

The need for a high-energy, high-current, high-duty-factor accelerator has been evident to nuclear physicists for many decades, but nobody was able to build one until Jim McCarthy came along. McCarthy, a physicist at the University of Virginia in Charlottesville, obtained his doctorate at Stanford under the Nobel laureate Robert Hofstadter, who in the 1950s pioneered the art of mapping the structure of nuclei by means of electron beams. Blessed with a cheerful disposition along with a high IQ, a healthy creativity quotient, and a robust self-confidence index, McCarthy possesses a personal figure of mental merit that is raised to an impressive level by his awesome degree of perseverance. In his travels to accelerators all over the world, he was frustrated by the curse of the low duty factor, and 15 years ago he initiated a campaign to build a new machine that would overcome the problem.

On the face of it, his proposal to the powers that must fund the construction of these massive machines--members of the Department of Energy--sounded like a pipe dream. Accelerators were perceived to be big, complex projects undertaken by experts at powerful research universities in the Northeast, West, and Midwest, not by a lone visionary with a couple of graduate students in the South. It wasn't long, though, before McCarthy's determination came to be noticed by the competition. Groups of physicists from MIT, the University of Illinois, the Argonne National Laboratory near Chicago, and the National Bureau of Standards in Washington, each of which had earned its spurs by building accelerators, began lobbying for their own accelerator designs. McCarthy assembled a small team of physicists-- "basically amateurs," he recalls, in a field dominated by professionals-- and strengthened his design by shrewdly harnessing the world's best expert advice, which in the scientific community is traditionally available for the asking. In April 1983 an unbiased panel of 13 prestigious physicists convened in

Washington to assess the five competing proposals for the DOE. To the astonishment of all concerned, they recommended that the plan from Virginia, the dark horse in the race, be approved for construction.

To distinguish his dream machine, which eventually evolved into the present CEBAF, from the great variety of particle accelerators around the world, McCarthy invented a new figure of merit. In energy, current, and power, the machine he envisioned would fall far below existing and planned devices; even a high duty factor by itself had been achieved before, albeit only in the feeblest of accelerators. But if you multiply voltage times current times duty factor (or simply power in watts times duty factor), you get a number that doesn't make any physical sense yet takes proper account of the importance of a high duty factor. It seems as farfetched as the formula UPS uses to discriminate against unwieldy baggage, but it is just as useful. Measured by this clever figure of merit, CEBAF beats LEP, the largest machine in the world, by a factor of a thousand. Now, to be fair, LEP's purpose--like the SSC's--is to create new kinds of matter, a task that requires ultrahigh energies no matter what the cost, and one for which CEBAF is unsuited. Nonetheless, CEBAF's unique combination of strength and intensity with the maximum perseverance confers on it a potency unmatched in the world.

The machine that is going on-line in Newport News is a half- billion-dollar high-tech marvel. The overall scheme is not particularly revolutionary: a stream of electrons, somewhat like the one in a TV tube, circulates in a nearly perfect vacuum in a metal pipe inside a subterranean tunnel that would fit under a seven-eighths-mile racetrack. In each of the two long, straight sections a linear accelerator delivers a forward thrust equivalent to 400 million volts. After five turns and ten boosts, the beam emerges from its pipe with an energy rating of 4 billion volts and is steered to one of three separate experimental halls, or split and shared among them.

The novelty of the design lies in the construction of the linear accelerators. Each consists of a series of hollow cavities made of shiny niobium. These cavities are as big as soccer balls and rather flattened, and they are attached to each other along the tunnel's central axis like a string of pearls. Their walls are pierced along that axis so that the electron beam can thread them one by one. In operation, electric currents surge back and forth in the walls of the cavities, creating strong, oscillating electric fields in the interiors of the cavities. Electrons in the beam are timed to arrive in a cavity just as its field points in the proper direction to accelerate them into the next cavity, a little bit the way marbles might be propelled along a trough by a series of rotating paddle wheels installed above the track. The electrons surf along a wave of electric energy that drives them down the tunnel at ever increasing speed, until they whistle along at a millionth of a percent below their absolute speed limit--light speed.

What makes this accelerator unique is that the cavities are superconducting. In fact, CEBAF will be the world's first major accelerator built entirely with superconducting cavities. The phenomenon of superconductivity has been exploited before in accelerator design. The first S in SSC, for example, refers to the Texas accelerator's intended use of superconducting magnets, but that is an entirely different and unrelated application of the same physical effect. At CEBAF most of the magnets are normal, while the 320 cavities, which constitute the real heart of the machine, are immersed in liquid helium at a temperature of -456 degrees Fahrenheit (just above absolute zero), where niobium offers no resistance to electric currents. This lack of resistance, in turn, prevents the cavities from heating up as they do their job, eliminates the need for pauses to let them cool down, and thus raises the duty factor from a fraction of 1 percent to unity. The perfect match between the problem (low duty factor) and the solution (superconductivity) characterizes CEBAF's design as the kind engineers like to call sweet.

In the early days of accelerator design, the detectors that would actually "see" and make sense of the particle collisions were letter-size photographic plates or bread-box-size Geiger counters, and they were considered mere ancillary gadgets to be developed after the accelerator was finished. In recent decades, however, detectors have evolved into complicated devices in their own right, as big as houses and crammed with electronic equipment. At CEBAF the same criteria that render the accelerator unique according to McCarthy's figure of merit pose new challenges for the detector designers. While LEP and other laboratories have had to grapple with the problems of catching and counting electrons arriving with high energy, or in large numbers, or in a relentless, unbroken stream, no one had to contend with CEBAF's particular combination of these characteristics. In view of the novelty of the experimental equipment, it is not surprising that its cost will reach a significant fraction of the cost of the accelerator itself, and that its construction will take years. Of CEBAF's three main detectors, each housed in its own vaulted hall, only one, a 450-ton steel behemoth painted deep blue, whose imposing bulk hides its exquisite sensitivity and delicacy, is ready now; the others are scheduled for commissioning in 1995 and 1996.

Likewise, only a few of the 800 physicists from all parts of the globe who are lined up to use CEBAF will be lucky enough to start this fall. What they will have at their disposal is, in effect, a cross between a microscope and a pellet gun for probing the atomic nucleus. Quantum mechanics has shown that electrons behave either like waves or like particles, depending on the experimental arrangement, and CEBAF manages to exploit both alternatives at the same time.

Interpreted in terms of waves, an electron beam resembles a light beam, and its ability to resolve fine details increases with energy. In fact, electron accelerators resemble electron microscopes very closely. But whereas the voltages of electron microscopes suffice to make images of viruses and large molecules, the accelerators of the 1950s and 1960s used by Robert Hofstadter were powerful enough to delve 100,000 times deeper, to explore the shapes of nuclei. CEBAF represents another step in this progression and will allow physicists to obtain X-ray-like pictures of the nucleus, revealing its constituent protons and neutrons.

At the same time, however, electrons behave like particles. High- energy accelerators have shot them at individual protons and neutrons, and the unexpectedly violent way in which they bounce off has shown that the targets consist of quarks held together by particles called gluons. But thus far the evidence for quarks has come almost exclusively from these isolated elementary particles, not from nuclei, which are dense clusters of jiggling neutrons and protons. CEBAF is intended to reveal how quarks and gluons behave in the dynamic, complex environment of a nucleus.

By serving as both a microscope and a pellet gun, CEBAF will focus on the meeting ground of two different perceptions of the nucleus-- the older picture of neutrons and protons stacked up like a pile of oranges, and the more recent image of a ball of glue in which quarks float about like seeds in a grape. While these two pictures complement each other in some respects, they conflict in others, and their reconciliation is the principal challenge to nuclear physicists in the foreseeable future.

The theoretical underpinnings of the experiments at CEBAF reflect the dual nature of the nucleus. The theory of protons and neutrons is 60 years old by now, robust, reliable, and extremely useful--but the mathematical foundations are shaky. Its practitioners are like old merchants who run their businesses honestly and profitably by keeping their books on the backs of envelopes and scattered chits of paper, but who haven't an inkling of professional accounting methods and who would fail miserably in a more pressured environment. The theory of quarks and gluons, on the other hand, is mathematically impeccable, though its elegant equations can be solved only in the simplest of cases; applied to entire nuclei they turn out to be almost hopelessly complex. The CEBAF regime is a rugged no-man's-land in which conventional theory ceases to function and the modern theory is all but intractable. For years theorists and experimentalists will be kept busy mapping out this territory, and what all of them hope for most fervently is that they will stumble across something totally new and unexpected. The history of accelerators gives them good reason for optimism.

In the end, the value of CEBAF cannot be measured in terms of its physical parameters but must be expressed in human terms. The intellectual energy that has already gone into its construction, and that will flow through its halls in the future, is impossible to quantify. The power of the ideas it will inspire in the minds of scientists and students cannot be measured. The magnitude of the contributions CEBAF will make to science, as well as to the cultural and economic welfare of society, defies computation. No figure of merit, however cleverly contrived, can predict how it will measure up.