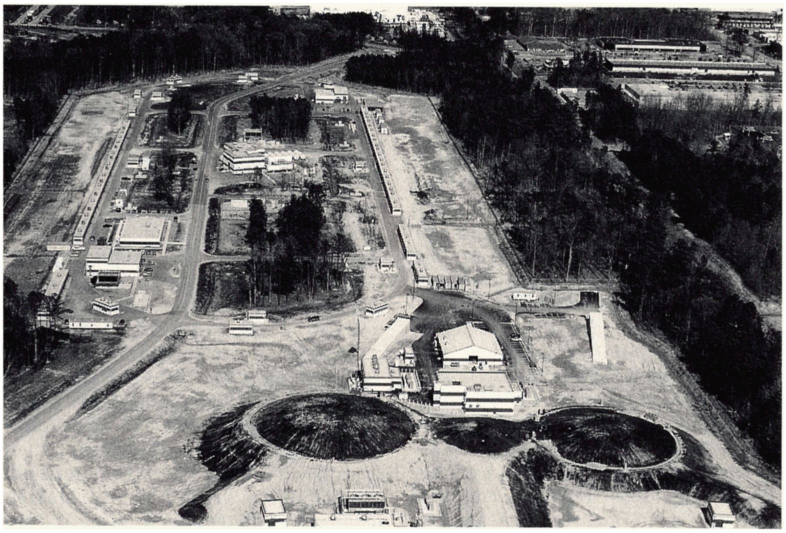
CEBAF READIES ITS ELECTRON BEAM FOR STUDIES OF NUCLEONS AND NUCLEI

In April 1983 the Southeastern Universities Research Association won an intense competition for construction and operation of a continuous-wave electron accelerator in the energy range 0.5–4.0 GeV designed for studies in high-energy nuclear physics. Four years later Hermann Grunder, director of SURA's proposed Continuous Electron Beam Accelerator Facility at Newport News, Virginia, initiated a radical change in the design of the accelerator from one that would stretch a pulsed beam to one that used superconducting cavity technology, just then becoming viable for large-scale applications, to create an intrinsically continuous beam. (See PHYSICS TODAY, July 1983, page 57; February 1986, page 18; and April 1992, page 19.) Construction of CEBAF began in 1987 and is now nearing completion.

This June, in addition to reviewing 43 proposals for experiments at the accelerator, CEBAF's Physics Advisory Committee reviewed letters of intent for experiments that would require a 6-GeV electron beam. It thus confirmed a long-standing expectation that the 4-GeV maximum energy that was the stated CEBAF goal for over a decade would be exceeded. In fact the superconducting rf cavities that accelerate the electron beam and that are responsible for the enhanced energy are better than specifications, having on the average a gradient of 9.6 megavolts per meter and a quality factor Q of 7.1×10^9 as opposed to the targeted 5 MV/m and 2.4×10^9.

CEBAF is a pair of recirculating rf linacs that will accelerate a continuous beam of electrons for coincidence studies of nuclei and nucleons. The construction is funded by DOE and is due to be completed by early 1995, at a total project cost of $515 million; that sum includes the detectors for one of the experimental halls and part of the detectors for another. The remaining detectors will take an additional 18 months and $39 million. The beam will become available for experiments in one of the halls in the spring of 1994 at an initial energy of 800 MeV, with the 4-GeV goal being reached by December of 1994.



Aerial view of the CEBAF accelerator site. North is to the top left. The three circular features in the foreground mark the three underground experimental halls A, B and C (from left to right). One can trace the accelerator path by starting to the left of the picture and following the aboveground buildings around the "racetrack." The injector building is partially obscured by the trees to the left and is in line with the long thin building over the north linac. In the middle is the central helium liquefier building.

The enhanced energy, coupled with a continuous beam at 200 microamps, has experimenters excited. At 4 GeV, the virtual photon from a scattered electron has a wavelength of tenths of a fermi (that is, on the order of 10^{-16} m) and is already looking inside a nucleon. A higher energy offers a deeper glimpse into how quantum chromodynamics, the theory of strong interactions, behaves in the regime where quarks and gluons form mesons and baryons and ultimately, nuclei.

Superconducting cavities

The superconducting rf cavities that accelerate the beam were designed at Cornell University, fabricated by Siemens in Bergisch Gladbach near Cologne, Germany, and chemically processed, tested and assembled at CEBAF. (See the cover of this issue.) The five-cell niobium cavities are about half a meter long and are designed to operate at 1.5 GHz at a temperature of 2 K. The enhanced performance is credited to very careful handling through all the manufacturing stages. After acid etching and rinsing, the cavities are paired, hermetically sealed (obviating the need for routine maintenance), evacuated, tested and grouped into cryogenic modules, with eight cavities to each module.

Each of the two 250-meter-long linear arms of the CEBAF accelerator comprises twenty of these cryogenic modules. The arms are connected by arcs, forming an overall shape rather like that of a racetrack. (See the figures on pages 17 and 19.) The beam will circulate up to five times through the racetrack, so that any given cross section may have electrons at five different energies. Since the electrons will all be moving at essentially the speed of light, the different-energy components of the beam will stay in phase in the linear arms.

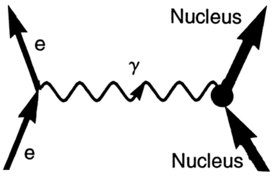
The main barrier to increasing the beam energy beyond 4 GeV comes from the arcs: A few of the magnets that bend the beam, and many of their power supplies, are at present designed for a maximum of 4 GeV. It is anticipated that upgrading the beam from 4 to 6 GeV will take a year; the roughly $1 million needed may come from the accelerator improvement budget. Further upgrades will also require supplementing the refrigeration system and some of the detectors. An energy of 8 GeV is foreseen five or so years down the road. "How fast the upgrades proceed will be driven by the physics motivation for getting to higher energies and depends on Federal approval and funding," says Beverly Hartline, the project manager.

That the beam energy will be 4 GeV after five circulations means that at each pass through a linac the energy will increase by 400 MeV. Earlier this year the north linac was tested at 245 MeV and 110 microamps, and cryogenic modules continue to be installed in the north and south linacs. At the current rate all the cryomodules will be installed by December of this year. Problems with the refrigeration system (the component that cools to 2 K failed last year) are believed to have been solved as of July. Experiments will start in hall C in spring of 1994 and by fall should be yielding meaningful data.

As a spinoff of CEBAF's physics program, its operators hope to apply the expertise acquired in making its superconducting cavities to building two free-electron lasers.

Electron scattering

CEBAF offers several features that are appealing to experimenters. Electron scattering is clean: There are few reaction products. The electron interacts with the nucleus via a virtual photon, as shown below:



The e–γ–e vertex is purely electrodynamic and therefore calculable. Interpreting an event is much easier than, say, for a $p\bar{p}$ collision: "With a point-like probe, you know what you're doing," remarks Larry Cardman of the physics division. The continuous beam (duty factor of 1) and high current (200 microamps) will allow high statistics. The beam consists of bursts of electrons separated by roughly a nanosecond; such a microstructure is intrinsic to rf linacs. "Continuous" in this context means that this "string of pearls" (as Christoph Leemann, head of the accelerator division, describes it) is unending—the beam is on all the time. By contrast, at the higher-energy SLAC linac (duty factor of 10^{-4}), the strings are broken into sections roughly 2 microseconds long and are separated by 8 milliseconds: The beam is on only 1/5000 of the time. At comparable currents, each "pearl" at SLAC must have 10^4 more electrons than at CEBAF; as a result, when it hits a target there are multiple interactions within the resolution time of the detectors, making it very difficult to measure fragments of the target along with the scattered electron. At CEBAF, it is much easier to do such coincidence experiments.

Experimenters have long used electron scattering to map out, for example, the electromagnetic response of the nucleus or nucleon by measuring the energy and momentum of only the scattered electron. Observing the reaction products as well, in coincidence with the scattered electron, can now reveal—to better precision than ever before at such high energies—how the nucleon or nucleus reacts when it is hit by a probe.

Because the CEBAF beam has a small cross section and angular divergence (emittance of 2×10^{-9} m-radian) and an energy spread of 10^{-4}, it allows high-precision measurements. It can be polarized from 50% to 90%, depending on the intensity required. A polarized beam is essential for several experiments, such as those approved for measuring parity violation or spins of excited states. Up to a quarter of the experiments also will use the tagged photon beam available in one of the experimental halls. In this technique, the electron beam is directed onto a thin target and emits photons by bremsstrahlung. The energy of an electron after it has emitted a photon is measured and the energy of the coincident (real) photon is therefore known. About 10^9 such "tagged" photons can be made per second. These photons provide a complementary probe to the virtual photons of electron scattering experiments.

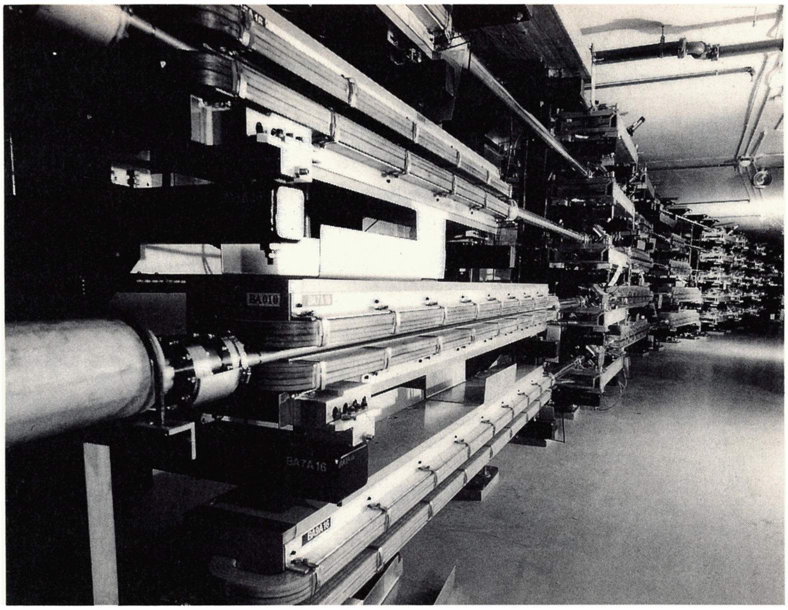
Experimental halls

The three experimental halls can be supplied simultaneously with beams at tailored intensities and at any of the five energies. If the operating budget stabilizes at about $60 million per year, CEBAF should ultimately be able to supply lots of beam time—about 35 weeks per year in each hall.

The halls, designated A, B and C, are equipped with different detectors suited to different styles of operation. Hall A has two 30-meter-long high-momentum superconducting spectrometers that can detect particles having momenta up to 4 GeV/c with a momentum resolution of 10^{-4}. They will typically detect the scattered electron and one other emitted particle in coincidence. Originally envisaged for high-momentum nuclear structure studies, these detectors are now also lined up for experiments that range from measuring quark momentum distributions to studying the pion field in the nucleus.

Hall B has the CEBAF Large-Acceptance Spectrometer. Built to produce a toroidal magnetic field encircling the beam direction, CLAS will detect most of the particles emitted in an event. It embodies a mode of experimentation akin to particle physics, involving a high rate of data collection (a terabyte per day) and larger collaborations. While the angles and energies of the emitted particles will be measured with a precision of 1%, far less than in Hall A, this detector will be very useful for obtaining full angular distributions of product particles and for studying reactions that emit three or more particles. For example, all the pions or kaons emitted from a nucleonic resonance can be collected and used to reconstruct the spin and isospin of the excited hadron. The tagged photon beam is available in hall B. One of its planned uses is to probe QCD sum rules that indicate the strange-quark content of the proton and neutron.

Hall C has one short spectrometer for short-lived particles such as kaons and a large, high-energy one for the electron; most of it is still empty floor space. The complement of detectors is being made by the users, who will tailor them to their individual needs. By prescience rather than providence, the high-momentum spectrometer has a maximum energy range of 6 GeV (stretchable to 7.5 GeV). Both detectors can measure momenta to better than one part in 10^3. Experiments planned for this hall range from measuring neutron electric form factors at high momentum transfer to creating strange nuclei. As mentioned earlier, hall C will come on first, in 1994. Hall A will start up in the fall of 1995, and hall B in the fall of 1996.



The east recirculation arc at CEBAF, showing some of the 1100 magnets used to focus the beam and to steer it to the south linac after acceleration in the north linac. The five beam lines are stacked vertically; those carrying less energetic electrons are higher. The long coils in front belong to the bending magnets.

QCD and nuclear physics

QCD has been tested in higher energy regimes where quarks are asymptotically free and perturbative calculations are feasible. CEBAF will concentrate on the murky realm where quark–gluon physics meets meson–baryon physics. Bare quarks having masses of only a few MeV are dressed with glue to create the much heavier (roughly 300 MeV) constituent quarks that make up protons and neutrons; the latter interact via mesons, themselves composed of bare quarks and gluons, and in turn form nuclei. Nathan Isgur, head of the theory group at CEBAF, stresses that the gluons add so much mass to the quarks that "one can think of the world as being made primarily of glue."

The two steps in the gluing of matter—quarks into nucleons, and nucleons into nuclei—remain mysterious, and both will be investigated at CEBAF. A series of experiments on hadronic excitations will probe the constituent quark model; others will look for gluonic states or for strange quarks inside the proton or neutron. The interaction of a high-momentum proton with the quark–gluon nuclear medium will be studied, for example, in the experiments on "color transparency," and high-energy gammas will knock out simultaneous baryons to probe how two protons break up when they get close enough to become a six-quark system. Some studies will measure elastic and inelastic responses of few-nucleon systems or correlations in the nuclear medium at high momentum transfers; other experiments will test nuclei for what they do when a proton in a nuclear orbital has a kaon knocked out of it, leaving a strange nucleus known as a hypernucleus. These are only a few of the 55 experiments that have been approved for the first three years. (Eleven more are conditionally approved.) "Probably the most exciting physics we will see is stuff we haven't even thought of yet," says Brad Filippone of Caltech.

One caveat is that the QCD Lagrangian is not amenable to calculation in the nonperturbative regime, and hence to direct comparison with experiments at GeV energies. Theorists content themselves with models that combine quark or hadronic degrees of freedom with phenomenological interactions. "Everyone would love to calculate CEBAF observables directly from QCD, but the prospects of actually doing this in the near future are rather dismal," says Tom Cohen of the University of Maryland. "The current challenge is to combine hadronic and quark-based descriptions in a consistent way."

That CEBAF observables will receive intense scrutiny is assured by the large number of job openings related to the facility—quite an anomaly at this time of shrinking job prospects in physics. The initial proposal for CEBAF contained a promise by presidents of the nearly 30 universities comprised by SURA at that time to create 30 new faculty positions. A rough head count shows that the equivalent of 72 new positions in nuclear physics—over 50 of them in CEBAF-related physics—have been added in southeastern states since 1982. (This number does not include the equivalent of 83 full-time positions with CEBAF.) One instance is Old Dominion University. While suffering a 20% budget cut like all Virginia state universities, it still managed to create 11 new full- or half-time CEBAF-related positions in the last two years. "We saw a unique opportunity to create an internationally prominent group," says James Cox, the department chair. "With the help of our president, James Koch, we made it a reality." Hampton University's physics department has added five nuclear physicists to its original two and last year became accredited with a PhD program.

As the spring of 1994 nears, both the pace of work and the excitement are building up. Cavities are being installed. The last water leaks (the racetrack and halls are under the water table) are being sealed. Users are busy putting together their targets and detectors and trying to earn an early place in the queue. Simpler experiments will tend to go first; they will bear the brunt of the startup and calibration hitches. Many experiments need a spectrum of energies and will interleave their runs as the beam is upgraded to higher energies. "I was involved when the equipment for the halls were first being discussed," said Filippone. "It didn't seem real. It's good to see that it's actually happening."

—MADHUSREE MUKERJEE ■