THE CONTINUOUS ELECTRON BEAM ACCELERATOR FACILITY*

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Abstract

On February 13, 1987, construction started on the Continuous Electron Beam Accelerator Facility—a 4-GeV, 200-μA, continuous beam, electron accelerator facility designed for nuclear physics research. The machine has a racetrack configuration with two antiparallel, 500-MeV, superconducting linac segments connected by beam lines to allow four passes of recirculation. The accelerating structure consists of 1500-MHz, five-cell niobium cavities developed at Cornell University. A liquid helium cryogenic system cools the cavities to an operating temperature of 2 K. Beam extraction after any three of the four passes allows simultaneous delivery of up to three beams of independently variable currents and different, but correlated, energies to the three experimental areas. Beam breakup thresholds exceed the design current by nearly two orders of magnitude. Project completion and the start of physics operations are scheduled for 1993. The total estimated cost is $255 million.

Introduction

The Continuous Electron Beam Accelerator Facility (CEBAF) will be a 4-GeV, 200-μA, continuous beam, electron accelerator facility for nuclear physics research. The Vogt Subcommittee of the Nuclear Science Advisory Committee has stated succinctly the physics objective of this new accelerator:

> *The search for new nuclear degrees of freedom and the relationship of nucleon-meson degrees of freedom to quark-gluon degrees of freedom in nuclei is one of the most challenging and fundamental questions of physics.*[1]

Consistent with this objective, CEBAF's purpose is to study the structure of the nuclear many-body system, its quark substructure, and the strong and electroweak interactions governing the behavior of nuclear matter.

To accomplish this objective, CEBAF must provide electron beams of sufficient

- energy to provide the kinematic flexibility required to study the transition region;[1]
- intensity (current) to allow precise measurement of relatively small electromagnetic cross sections;
- duty factor to allow the detection of hadronic components emitted from the nucleus in coincidence with the scattered electron;
- beam quality and resolution to allow detailed probing of the multifaceted elements of nuclear structure.

It is this combination of characteristics—high energy $\otimes$ high current $\otimes$ high duty factor $\otimes$ beam quality—which will make CEBAF the world's most powerful microscope for studying the nucleus.

Such an accelerator was called for in 1976 by the National Academy of Science panel (G. Friedlander, Chairman) convened to delineate the future opportunities and objectives of nuclear science.[2] Subsequent panels[3,4,5,6] reaffirmed the need for a high-energy cw electron accelerator, refined its requirements, and established its priority. In 1980, Professor James McCarthy of the University of Virginia submitted a proposal to the Department of Energy (DOE) under the auspices of the newly incorporated Southeastern Universities Research Association (SURA). The submission of the SURA proposal triggered activity within the electromagnetic nuclear physics community to prepare a formal scientific justification and to develop alternative designs. By 1982, five proposals were in hand, including a revised proposal from SURA. During the winter of 1982/83, the NSAC Panel on Electron Accelerator Facilities (D. A. Bromley, Chairman) reviewed and evaluated the proposals at the request of NSF and DOE.[7] NSAC endorsed the panel's recommendation to accept the SURA proposal, and DOE accepted the recommendation.

Originally proposed as a 2-GeV, SLAC-type linac with two-pass, head-to-tail recirculation and pulse stretcher ring, CEBAF was converted to a cw, superconducting, four-pass recirculating linac after a technology review in the summer and fall of 1985.[8,9,10,11] DOE directed CEBAF to proceed with the superconducting linac design, and proposed the project to Congress for construction start in FY 1987. The superconducting accelerating structure adopted had been developed and tested by Cornell University's Newman Laboratory of Nuclear Studies, and had proven its capability to meet CEBAF's requirements.[12]

Basic Choices: Concept and Technology

The beam performance design objectives are:

Energy, E	$0.5\ \text{GeV} \leq E \leq 4.0\ \text{GeV}$
Duty factor	100%
Average current	$\leq 200\ \mu$A
Emittance ($4\sigma^2 = \epsilon\beta$)	$\leq 2 \cdot 10^{-9}$ m-radian
Momentum spread $4\sigma_E/E$	10^{-4}
User multiplicity	3 beams, 3 energies

An intrinsically cw device is the approach of choice to meet these objectives. RF superconductivity is the preferred technology, because it allows higher gradients in cw operation and lower power consumption than room-temperature technology. Even so, beam recirculation is necessary for a cost-effective solution.

The Recirculating Linac Concept

Figure 1 illustrates schematically the solution adopted by CEBAF. Four-pass recirculation, close to the cost minimum, was chosen. The accelerating structure is arranged in two separate linac segments located in the straight sections of the racetrack-shaped configuration, thus minimizing the total accelerator circumference. Each segment is made of 25 cryomodules containing eight cavities apiece, with each cryomodule separated from its neighbors by a warm section containing vacuum equipment, beam diagnostics, and quadrupole and steering dipole magnets. The beam transport system connecting the two linac segments is designed to be strongly focusing, with beam lines of moderately large radii of curvature to minimize quantum excitation effects. Beam transport from linac to linac is achromatic, isochronous, and provides the required match in transverse phase space.

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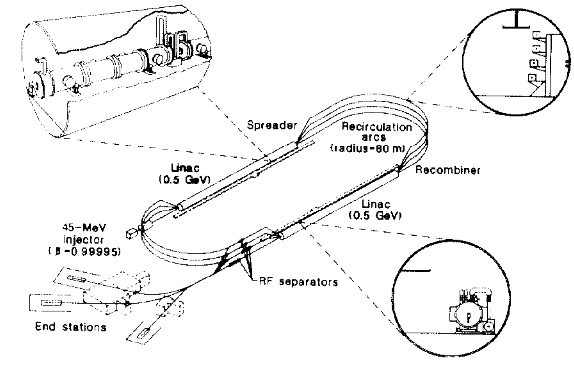

Figure 1. Schematic representation of four-pass recirculating linac concept.

Nominal injection energy is 45 MeV, sufficiently relativistic for the electrons to experience less than 2° of phase slip throughout the entire four-pass acceleration cycle, most of it in the first half of the first linac segment. The injector creates three interspersed 499-MHz bunch trains ($\{1,4,7..\},\{2,5,8,..\}$, $\{3,6,9,..\}$) with individually adjustable current levels. Extraction at fractional energies, i.e., on the 1st, 2nd, or 3rd pass, is accomplished by deflecting bunches to a septum magnet by rf separators operating at 2495-MHz (i.e., 5/3 of the fundamental frequency). This choice of frequency allows the selective extraction of one (or two) of the 499-MHz bunch trains, leaving the remaining ones for further acceleration. Similarly, if all trains are accelerated to the maximum energy, an rf separator allows distribution among three channels. Thus, the recirculation, the differential bunch loading at the injector, and the extraction (or distribution) by rf separators achieve the goal of serving three users with beams of individually adjusted current and up to three different, although correlated, energies.

Status of RF Superconductivity

Since 1979, rf superconductivity has made significant strides forward in structures designed for accelerating speed-of-light particles. In 1979, it was fortuitously found at the University of Genoa[13] that cavities with continuously curving outer walls do not multipactor. Multipacting had long blocked progress to higher gradients in superconducting rf accelerating cavities. Building upon the work of Lyneis *et al.*,[14] who showed that cylindrical cavities exhibit one-point multipacting at their outer walls, Klein and Proch[15] verified by simulation that spherical outer walls do not exhibit this multipacting.

Other important developments have followed. Development of the rastered[16] or defocused electron beam weld has eliminated vacuum voids that cause breakdown by interfering with heat transport. Input couplers and heavily coupled higher-order-mode (HOM) couplers are both mounted on the beam pipes to suppress beam instabilities, avoid local field enhancement, and minimize multipacting.[17] High thermal conductivity niobium, as supplied by manufacturers or as improved by yttrium[18] or titanium[19] gettering, stabilizes the temperature of the niobium surrounding rf-heated hot spots and suppresses breakdown.

A niobium cavity having all of the above improvements was beam-tested in the Cornell CESR storage ring at a gradient of 6.5 MV/m and Q_{res} of 5×10^9. Cavities of somewhat different designs, but incorporating all of the above improvements and operating in accelerators at gradients ≥ 5 MV/m and Q_{res} values $\geq 3 \times 10^9$, are planned in the near future at CERN, DESY, and KEK. KEK plans to use superconducting cavities in Tristan to boost the energy. DESY plans to use them to increase the energy gain per turn in the HERA electron ring. CERN plans to use them to upgrade LEP to LEP II. Darmstadt is building a recirculating superconducting linear accelerator. Saclay, Frascati, Stanford, TRW, and LANL are at various stages of planning accelerators using superconducting cavities.

Beam Breakup

Recirculating a beam through a linac can lead to a transverse instability in which transverse displacement on successive recirculations can excite modes which further deflect the beam. The recirculated beam and cavities form a feedback loop which can be driven unstable at sufficiently high currents. This multipass beam breakup can severely limit current in a superconducting linear accelerator, due to the inherently high Q of transverse deflecting modes of the rf cavities.

Beam breakup at CEBAF has been investigated both with bunch-by-bunch simulations and analytic modeling. This work indicates that the HOM damping designed into CEBAF cavities successfully suppresses HOMs. Threshold currents are nearly two orders of magnitude above the CEBAF design current of 200 μA.[20]

The dominant mechanism for multipass beam breakup can be modeled in an impulse approximation. This is also the regime appropriate to single-pass cumulative beam breakup as observed in SLAC, where extensive computer modeling has been successful. A CRAY computer code has been developed, which models beam behavior with multiple, transverse modes distributed along the linac.[21] Diagnostics to determine threshold currents for instablity and to estimate any steady-state emittance degradation due to the differential bunch loading have been included. In parallel with this effort, an analytic model has been developed. For N passes and M cavities, the solution reduces to finding M zeros of a $2(N\text{-}1)$ dimensional determinant, or equivalently the M eigenvalues of an M-dimensional matrix.[22] Excellent agreement is found between the two techniques.[21]

Stability of the CEBAF linac has been evaluated for the full 400-cavity array distributed along the linac with a FODO lattice. The four strongest HOMs of the cavity were included. The threshold current was found to be 19 mA at 4 GeV and 11 mA at 2 GeV after four passes through the linac (Figure 2). Furthermore, simulation of subthreshold excitation of HOMs, e.g. by differential bunch loading and injection offset, shows no significant emittance increase.

The CEBAF Design

Table I summarizes the CEBAF accelerator parameters.

Table I
Design Parameter List
CEBAF Superconducting Radio-Frequency CW Linac

Beam characteristics	
Electron energy E [GeV]	$0.5 \leq E \leq 4.0$
Average current [μA]	200
Transverse emittance (95%, 1 GeV) [m]	2×10^{-9}
Energy spread (95%)	1×10^{-4}
Duty factor	100%
Simultaneous beams	3
Simultaneous energies	≤ 3

(Continued on next page)

Table I, *continued*

Linac parameters	
Concept	Superconducting cw recirculating linac
Number of passes	4
Number of linac segments	2
Segment length [m]	235
Maximum energy gain per pass [GeV]	1.0
Recirculation time per pass [μs]	4.2
Focusing	FODO
Phase advance per cell (pass 1)	120°
Half-cell length [m]	9.4
Number of cavities per half-cell	8
Number of half-cells per segment	25
Vacuum (before cooldown) [torr]	10^{-9}
Cavity parameters	
Type	Superconducting
Frequency [MHz]	1497
Electric length [m]	0.5
Shunt impedance (r/Q) [ohm/m]	960.0
Design gradient [MV/m]	5.0
Design Q_0 at 2 K, 5 MV/m	2.4×10^9
Typical HOM Q_{external}	10^3 to 10^5
Clear aperture [mm]	70
Transverse HOM Z''/Q [ohms/m^3]	$\leq 16.4 \times 10^4$
Loaded Q (fundamental mode)	6.6×10^6
RF system	
Number of klystrons	418
Klystron power rating [kW]	5.0
Phase control	$< 1°$
Gradient regulation	$< 10^{-4}$
Injector parameters	
Gun energy [MeV]	0.10
Injection energy [MeV]	45
Average current [μA]	200
Transverse emittance (at 0.1 MeV) [mm-mr]	1
Longitudinal emittance [keV-degrees]	$< 15\pi$
Bunch length [degrees]	< 1.0
Pulse capability [μs]	0.05 to 10
Recirculation arc beam lines	
Number	7
Magnetic radii [m]	11.5 to 28.6
Phase advance per period	$2\pi(5/4)$
Periods per arc	4
Cryogenic system	
Total rf load (2.0 K) [W]	2510
Total heat load (2.0 K) [W]	3310
Total heat load (45 K) [W]	8000
System capacity (2.0 K) [W]	4800

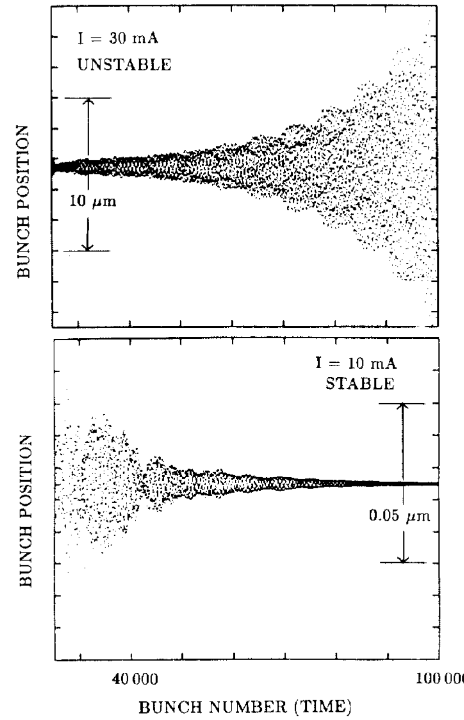

Figure 2. Simulation results clearly show instability for an average current of 30 mA and stability for 10 mA. Bunches are injected off-axis, thereby exciting deflecting modes. Shown is their centroid transverse position leaving the linac after four passes, plotted vs. bunch number, i.e., time.

Injector

The injector provides a high-quality electron beam that is sufficiently relativistic (nominal 45 MeV) to stay in phase with the rf and the recirculating electron beams in the first half of the linac. The bunching, capture, and initial acceleration (up to about 1 MeV) regions are modeled after proven injector designs.[23,24] This beam is then further bunched and accelerated to just over 5 MeV in two five-cell superconducting cavities in a short cryostat, and then accelerated in two full-sized cryomodules to the required 45 MeV before injection into the linac. The entire injector has been modeled with PARMELA, a two-dimensional particle simulation code that calculates phase and radial properties, including space charge effects, for an electron beam. Calculations indicate that a bunch of less than 1° phase angle and 20-keV full width should be obtained at the exit of the injector.[25] The injector enclosure has been designed to accommodate two electron guns to provide both polarized and unpolarized beams.

Acceleration Systems: Cavities, Cryogenic System, and RF System

The accelerating cavities are five-cell, 1497-MHz, elliptical cavities developed at Cornell University (Figure 3). The cavities operate in the π mode, and have a fundamental coupler on the beam line at one end and an HOM coupler on the beam line at the other. The elliptical cavity shape yields low peak surface electric fields, a good chemical rinsing geometry, and good mechanical rigidity. The HOM coupler has two wave guides for extraction of HOMs. HOM Q's are typically in the range of $500 \lesssim Q_{\mathrm{HOM}} \lesssim 170{,}000$, which represents five orders of magnitude of damping.

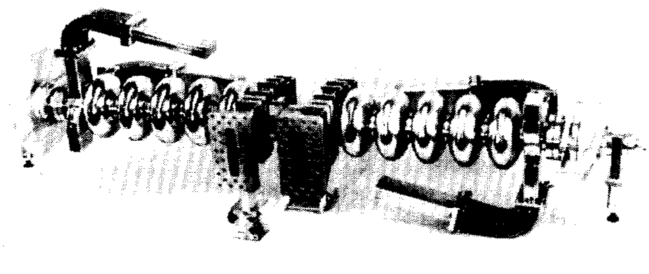

Figure 3. An assembled pair of CEBAF-Cornell superconducting five-cell cavities.

The Cornell cavity was adopted for CEBAF for four important reasons: suitable frequency, gradients in excess of 5 MV/m in laboratory and beam tests, damping of HOMs, and technical maturity, i.e., readiness for industrial prototyping.

Frequency optimization is based on minimizing transverse impedance, which scales as f^3, and delivering a pulse train with a high enough frequency that it appears effectively continuous to the detectors. Since 500 MHz appears continuous to the physics instrumentation, 1500 MHz allows simultaneous service to three users.

CEBAF is engaged in a cavity prototyping program in collaboration with Cornell and five industrial vendors—two European and three American firms. The design specifications are a cw accelerating gradient of at least 5 MV/m, and a Q_0 of at least 2.4×10^9 at 2.0 K and 5 MV/m. Ten tests on four prototypes at Cornell have yielded an average gradient of 8.2 MV/m, and an average Q_0 of 3.1×10^9. In acceptance tests, the first six prototypes produced by industry for CEBAF have achieved an average gradient of 7.1 MV/m. Each test exceeded the gradient and Q_0 specifications. In subsequent tests, the industrial prototypes have achieved gradients as high as 12.0 MV/m. Q_0 values of CEBAF prototypes average 6.5×10^9. Figure 4 shows CEBAF's test results.

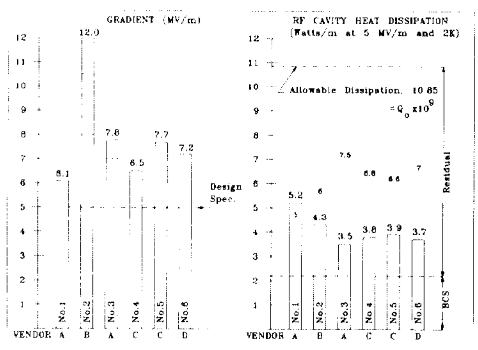

Figure 4. Summary of CEBAF industrial cavity prototyping results. Gradients and Q values exceed minimum requirements significantly.

The operating temperature was selected on the basis of a cost optimization study. Liquid helium refrigeration systems become more expensive (capital and operating costs) as their design temperature decreases. Yet rf heat losses in the cavities increase exponentially with temperature. For CEBAF the optimum is around 2.0 K.

The cryogenic system for CEBAF consists of a 5-kW central helium refrigerator and a transfer line system to supply 2.2-K, 2.8-atm helium to the cavity cryostats, 45-K helium at 4.0 atm to the radiation shields, and 4.5-K helium at 2.8 atm to the superconducting magnetic spectrometers in the experimental halls. Both the 2.2-K and the 4.5-K helium are expanded by Joule-Thompson (JT) valves in the cryostats, yielding 2.0 K at 0.031 atm and 4.4 K at 1.2 atm, respectively. The central helium refrigerator is located in the center of the CEBAF racetrack with the transfer lines located in the linac tunnels. The system capacity as a function of operating temperature is illustrated in Figure 5.

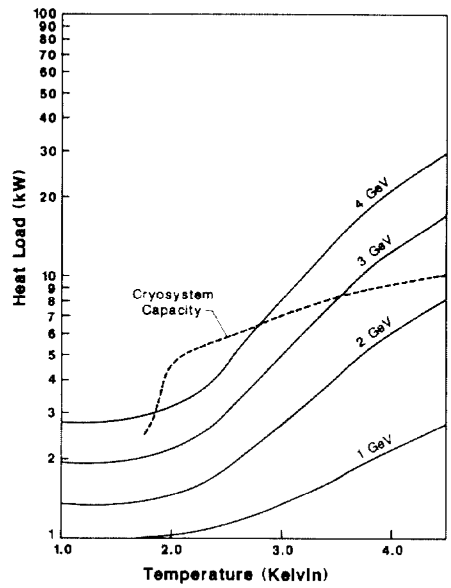

Figure 5. CEBAF cryogenic system capacity and cooling requirements for 1, 2, 3, and 4 GeV at minimum acceptable cavity quality factors Q.

The CEBAF rf system consists of 418 individual rf amplifier chains. Each superconducting cavity is phase-locked to the master drive reference line to within 1°, and the cavity field gradient is regulated to within 1 part in 10^4 by an rf control module. Continuously adjustable, modulo-360° phase shifters are used to generate the individual phase references, and a compensated rf detector is used for level feedback. The close-coupled digital system enhances system accuracy, provides self-calibration, and continuously checks the system for malfunction. Calibration curves, the operating program, and system history are stored in an on-board electrically erasable programmable read only memory (E^2PROM). The rf power is generated by a 5-kW, water-cooled, permanent-magnet-focused klystron. The klystrons are clustered in groups of eight and powered from a common supply.

Losses in the superconducting cavity are completely negligible from an rf point of view. Therefore all the power not used to accelerate the beam is reflected. Since CEBAF must cover operating conditions ranging from virtually no current to 800 μA in the cavities, a wide range of load conditions must be accommodated. The choice of the proper strength of cavity coupling, i.e., the loaded quality factor ($Q_L = 6.6 \times 10^6$), is based on the goal of achieving accelerating gradients up to 10 MV/m at full design current and with incident power $P_{\rm in} \lesssim 5$ kW. Figure 6 shows the accessible gradient and current range.

Optics and Beam Transport System

The beam transport system, consisting of main dipoles, quadrupoles, sextupoles and small steering dipoles, serves to guide and confine the beam through up to four passes through

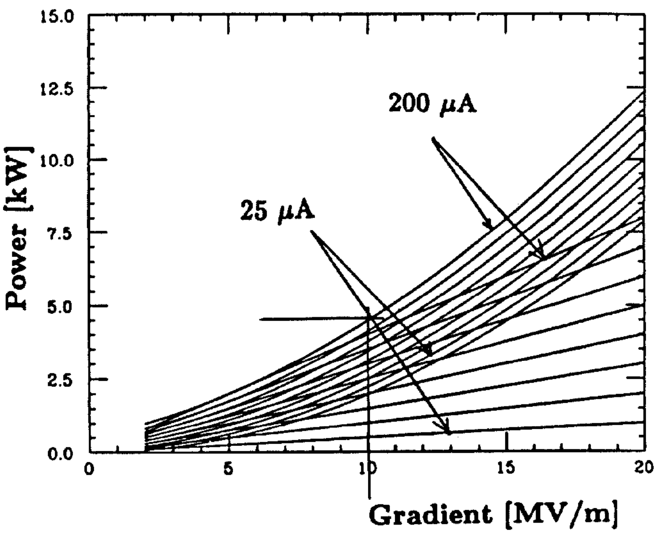

Figure 6. Power requirements versus cavity gradient for linac output current from 0 to 200 μA. Design Q_L is $6.6 \cdot 10^6$ and power available from planned klystron is 5 kW. Straight lines represent power into the beam, curved lines the required incident power.

the accelerator, and to distribute it to the three experimental end stations. Within the accelerator, the three major areas are the two linac segments, the recirculation arcs (seven beam lines bending by 180°), and the sections connecting the linacs to the arcs. Key requirements for the optics are achromaticity, isochronicity, control of beam envelope (β,η functions) and of overall phase advance, and proper matching from linac to linac in transverse phase space. Another important concern is the minimization of synchrotron radiation effects. The design of the optics and beam transport system follows a modular philosophy, attempting as much as possible a one-to-one correspondence between a particular optical function and a subset of magnets.[26]

The linac optics for the first pass are simple FODO arrays with a phase advance per cell of 120° on the beam's first pass. The quadrupole spacing is 9.4 m, set by the pitch of the 8.4-m cryomodule accelerating units separated by 1-m regions for focusing and beam diagnostics. On subsequent passes the beams are acceptably matched to the optics by creating an increasingly larger β function for each pass as the beam enters the first linac.

The linac segments are connected to the arcs by spreaders and long matching sections, while the connection from arcs back to the linac segments is accomplished by recombiners and short matching sections. The long matching sections in the spreader regions provide space for extraction elements.

Spreaders and recombiners are vertical, achromatic bends consisting of a dipole common to all beams bending by an angle (α) inversely proportional to the beam energy, followed by magnets bending by $-\alpha$, now acting separately on each beam. To achieve achromaticity in this arrangement, strong focusing to create 2π phase advance from dipole to dipole is required. The matching sections following the spreaders (or preceding the recombiners) match the beam from linac to arcs, or vice versa, with regard to vertical and horizontal beam ellipse parameters.[26]

The recirculation arc regions are achromatic and isochronous, based upon the second-order achromat principle. In addition, the lattice minimizes the six-dimensional beam-quality degradation due to synchrotron radiation by incorporating sufficiently large bending radii (~30 m magnetic radius for the high-energy beam lines) and strong focusing.

The extraction system, which provides the ability to deliver multiple simultaneous beams of correlated energy, is based upon the use of an "optical amplifier," an rf separator operating at 2495 MHz, and a magnetic septum to complete the separation between recirculated and extracted current. The "optical amplifier" is used to reduce the transverse kick required from the rf separator. The choice of rf separator frequency meets the criterion of $f_s = mf/3$ where f is the accelerator fundamental frequency (1497 MHz) and where m is an integer, but not a multiple of 3. With this choice, every third bunch receives the same kick, while the separator rf phase determines the relative strength of the kick that each bunch of the three-bunch train receives. The rf phase can be set to accomplish a two-beam split (extracted and recirculated) in the three low-energy beam lines, or a three-beam split in the highest-energy beam line. Thus, the system provides three extracted beams, which may consist of any one of the three lower energies together with two beams of the highest energy, or any two of the three lower energies together with one beam of the highest energy, or three beams of the highest energy.[26]

Instrumentation and Control

The central elements of beam instrumentation are several hundred beam current and position monitors that are based on cavities with loaded Q-values around 1000 and operating at 2994 MHz. Profile monitors at the low-energy end in the injector area will be wire scanners, while several beam parameters, such as profile and bunch length, will be measured in the arcs with synchrotron radiation monitors.

The control system's key feature is a two-level computer structure using extensively distributed intelligence and high-power, local capabilities. It provides sufficient capability in the control room to implement such tools as automated tune-up procedures, on-line machine modeling, and simulation.[27]

Experimental Equipment

As electrons and photons are known to be precise and quantitative probes, the physics program at CEBAF will rely heavily upon high-precision detection systems. To perform coincidence experiments, sets of two or three large angular and momentum acceptance spectrometers around the same pivot, or 4π detectors with magnetic analysis, will be used.

The CEBAF facility includes three experimental halls—A, B, and C—fed simultaneously by continuous beams of different (correlated) energies and independently controlled intensities.

Hall A, designed for high-resolution experiments (1.0 to 0.1 MeV) will house two high-resolution (10^{-4} or better) spectrometers with large solid angle (10 msr) and momentum acceptance (10–15%). The 4-GeV/c (expandable to 6-GeV/c) electron and 3-GeV/c hadron spectrometers are made of several homogeneous-field, iron-dominated superconducting dipoles and high-gradient, large-aperture, superconducting cos 2θ quadrupoles, with higher-order correcting coils. The spectrometer arrangement will allow operation with long gas targets, use of polarized beam and/or target, and measurements involving non-coplanar kinematics.

The large acceptance spectrometer in hall B has been designed for photonuclear and low-luminosity ($\leq 10^{33}$ cm^{-2} sec^{-1}) electronuclear studies. It consists of eight superconducting coils generating a toroidal field in eight nearly independent sectors. Fully instrumented, it will allow multiparticle detection and identification within ~80% of 4π and 0.1 to 3 GeV/c in momentum.

Hall C will be devoted to double- or triple-arm experiments with moderate (~10 MeV) resolution. Initial plans include a large momentum acceptance (30%) electron spectrometer and two non-focusing hadron spectrometers with very large acceptances, associated with neutron time-of-flight detectors.

Cost and Schedule

Congress authorized CEBAF's construction in FY 1987 with a first-year budget of $16.2 million. On February 13, 1987—the same day the Program Advisory Committee held its first meeting to discuss and recommend priorities for the scientific program—CEBAF signed its first construction contract, and site clearing began.

The president's budget for FY 1988 requests $33.5 million for construction. The proposed funding profile projects $65 million in FY 1989 and FY 1990, $55 million in FY 1991, and $20.3 million in FY 1992, for a total estimated cost of $255 million. Project completion and the start of physics operations are scheduled for FY 1993.

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