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THE CONTINUOUS ELECTRON BEAM ACCELERATOR FACILITY: PROJECT STATUS AND PHYSICS OUTLOOK

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ABSTRACT

Nuclear physics research program planning, accelerator tunnel construction, and accelerator component development, assembly, and testing are under way at the Continuous Electron Beam Accelerator Facility, Newport News, Virginia. CEBAF's 4-GeV, 200-μA superconducting recirculating accelerator will provide cw beam to simultaneous experiments in three end stations for studies of the nuclear many-body system, its quark substructure, and the strong and electroweak interactions governing this form of matter. An experimental program is being defined in collaboration with the user community. The experimental halls have been designed, and preliminary experimental equipment conceptual designs have been prepared. Planned for Hall A are two 4-GeV/c high-resolution ($\delta p/p \leq 10^{-4}$) spectrometers (HRS) with moderate acceptance ($\sim$ 8 msr) for a program of completely exclusive experiments in which the nuclear final state has to be fully specified. A CEBAF large acceptance spectrometer (CLAS) is planned for the program of Hall B, which will include bias-free investigation of hadronic final states in inelastic electron scattering and detection of multiple-particle final states. The CLAS will be a multi-gap device based on a toroidal magnet with six superconducting coils arranged around the beamline to produce an essentially circular magnetic field. Hall C is envisioned as serving a diversity of interests, including form factor measurements, parity violation investigations, form factors of nucleon resonances, and a high-Q^2 baryon resonance program. A moderate-resolution, high-momentum, 6-GeV/c spectrometer (HMS) together with several specialized second arms—in particular, a symmetric toroidal array spectrometer—are being planned to carry out Hall C experimentation.

KEYWORDS

Electromagnetic nuclear physics; electron accelerator; accelerator design; superconducting rf technology; cryomodule; cavity; continuous beam; coincidence experiments; spectrometer; symmetric toroidal array spectrometer.

INTRODUCTION

In February 1987, construction began on the Continuous Electron Beam Accelerator Facility (CEBAF), a laboratory for nuclear physics research in Newport News, Virginia (Fig. 1). The accelerator will provide continuous electron beams with energies between 0.5 and 4 GeV and currents up to 200 μA. CEBAF's purpose is to study the structure of the nuclear many-body system, its quark substructure, and the strong

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and electroweak interactions governing the behavior of nuclear matter. This requires electron beams of sufficient:

- energy to provide the kinematic flexibility required to study the transition region,
- intensity (current) to allow precise measurement of relatively small electromagnetic cross sections,
- duty factor to allow coincidence experiments, and
- beam quality to allow high-resolution experiments.

This combination of characteristics—high energy, high current, high duty factor, high beam quality—makes CEBAF a unique tool for nuclear physics research.

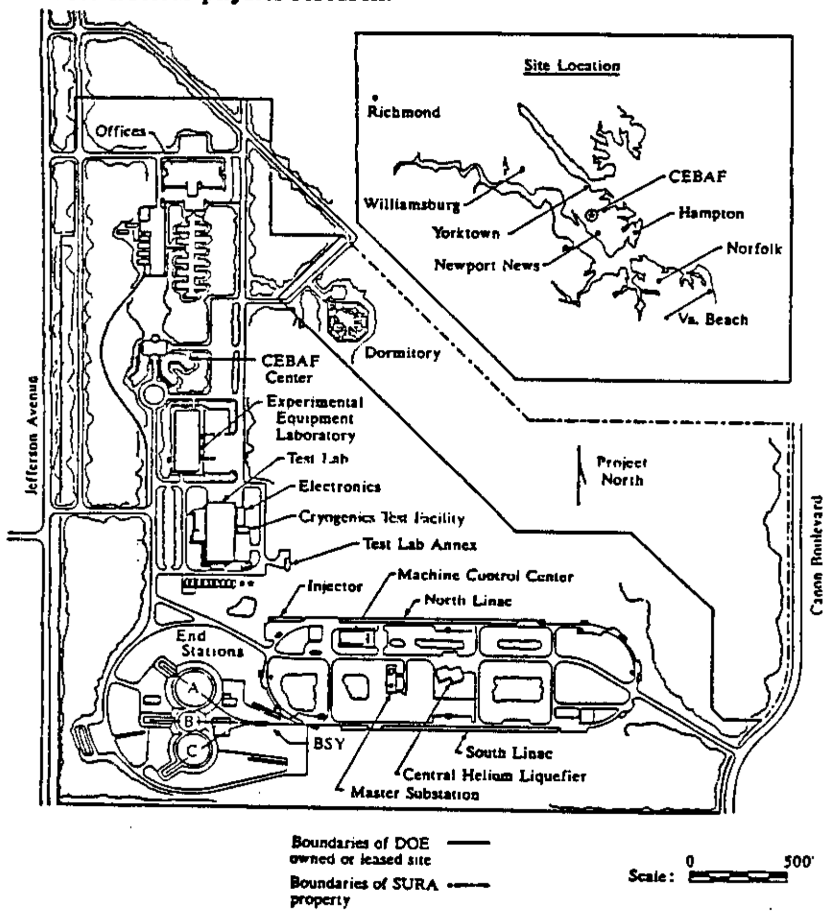

Fig. 1 CEBAF's site plan. The superconducting recirculating accelerator will serve nuclear physics experiments in three end stations. The experimental equipment laboratory will support detector assembly and related work, and the dormitory will accommodate visiting experimenters.

Performance objectives are:

Energy	$0.5 \leq E \leq 4.0$ GeV
Beam current	$I \leq 200\ \mu$A
Duty factor	100%
Emittance (95%)	$\epsilon \simeq 2 \cdot 10^{-9}$ m rad
Momentum spread	$\sigma_E/E = 2.5 \cdot 10^{-5}$
User multiplicity	3 beams

The 200-μA total output current can be distributed in controllable ratios between three end stations (Fig. 2). The emittance is unnormalized and refers to the full beam size, i.e., $\sigma_x^2 = \frac{1}{4}\epsilon_x\beta_x$. The value of $\epsilon = 2\cdot10^{-9}$ m rad at 1 GeV is equivalent to $\epsilon_N \simeq 10^{-6}$ m rad in storage ring terminology (i.e., $\sigma_x^2 = \epsilon_{N,x}\gamma\beta_x$). Due to various emittance-degrading effects we do not quote the normalized emittance; $\epsilon < 2 \cdot 10^{-9}$ m rad at $E >$ 1 GeV is neither precluded nor guaranteed.

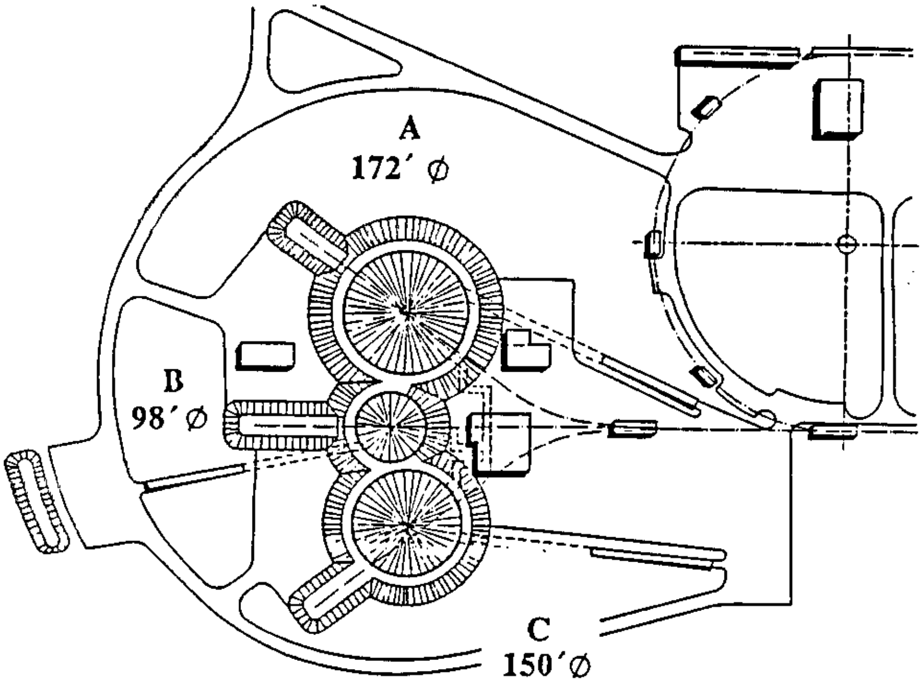

Fig. 2 Plan view of CEBAF's three end stations, showing beamlines from the accelerator and truck ramps for equipment access. Support facilities will include a counting house (center) with one counting room per end station, and parking for users' trailers.

First beam to an experiment is scheduled for 1994. This paper outlines the growth and progress of CEBAF's planned program of nuclear science, and then describes the accelerator and reports its construction status.

NUCLEAR PHYSICS RESEARCH AT CEBAF

CEBAF will be a user facility—a research tool for the nuclear physics community. In parallel with the efforts to design and construct the accelerator, CEBAF has from the beginning collaborated with the national and international user community to plan experiments and the necessary instrumentation to exploit the accelerator's capabilities. The present status of the planning for each end station is summarized below, followed by a description of the scientific program planning process and CEBAF's physics outlook.

End Station A An important part of the CEBAF physics program involves completely exclusive experiments in which the nuclear final state has to be fully specified. The physics program of Hall A will therefore include:

- Measurement of elastic and inelastic form factors.
- $(e,e'N)$ reactions for study of single-nucleon density distributions, momentum distributions at high momenta, and the electromagnetic structure of bound nucleons.
- $(e,e'd)$, $(e,e'\,^3He)$, $(e,e'2N)$ *reactions* to specified final states (multinucleon correlations).
- $(e,e'\pi)$ reactions (nucleon and nuclear pion fields).
- $(e,e'K)$ reactions for preliminary hypernuclear physics investigations.

A pair of 4-GeV/c high-resolution ($\delta p/p \leq 10^{-4}$) spectrometers with moderate acceptance ($\sim$ 8 msr) will be used to carry out this experimental program. Table 1 lists the main optics design characteristics. Figure 3 shows a side view of such a spectrometer.

Table 1. Main Optics Design Characteristics
4-GeV/c QQDQ Spectrometer

Maximum momentum		4 GeV/c	
Total bending angle		45°	
Optical length		23.4 m	
Configuration		vertical	
Momentum acceptance		± 5%	
Momentum dispersion		12.3 m	
Radial magnification		-2.45	
$\|D/M\|$		5.0 cm/%	
Momentum resolution		$\sim 10^{-4}$	
Angular acceptance horiz.		± 30	
(mr) vert.		± 65	
Solid angle (msr)		7.8	
Horizontal angular resolution		~ 0.5 mr	
Transverse length acceptance		±5 cm	
Transverse position resolution		~ 0.15 cm	
Quadrupoles:	Q_1	Q_2	Q_3
Bore radius (m)	0.15	0.26	0.31
Pole tip field (T)	0.84	0.81	0.91

General Arrangement

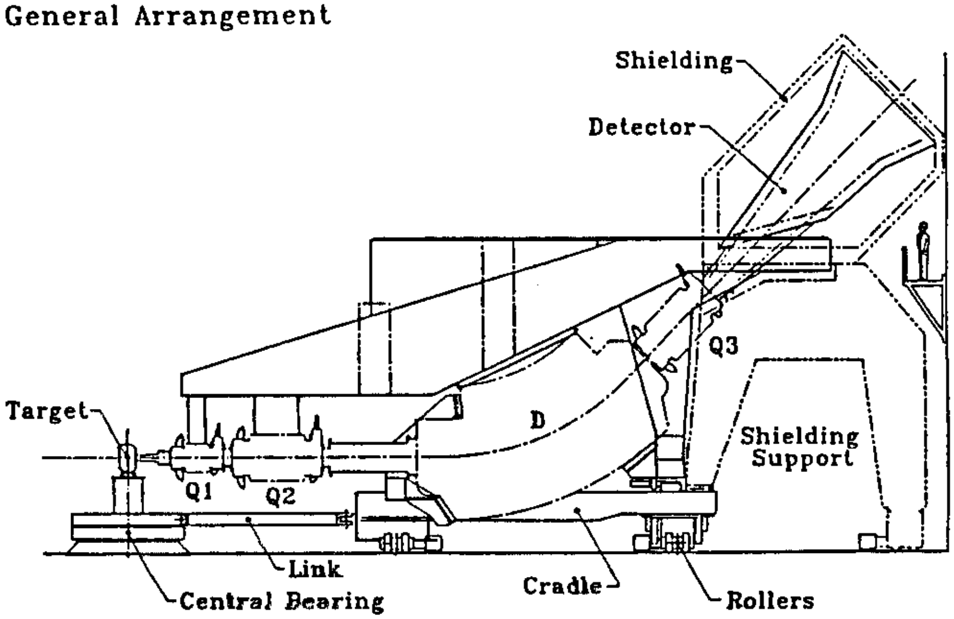

Fig. 3 Side view, 4-GeV/c high-resolution spectrometer.

Hall A (Fig. 4) will have an interior diameter of 172 feet, equipment access via a truck ramp, and a 20-ton overhead crane. The spectrometers will rotate around a common axis on rigid support structures traveling on concentric rails. Co-program managers for Hall A are CEBAF's Jean Mougey (formerly of Saclay, France) and Robert Lourie of the University of Virginia.

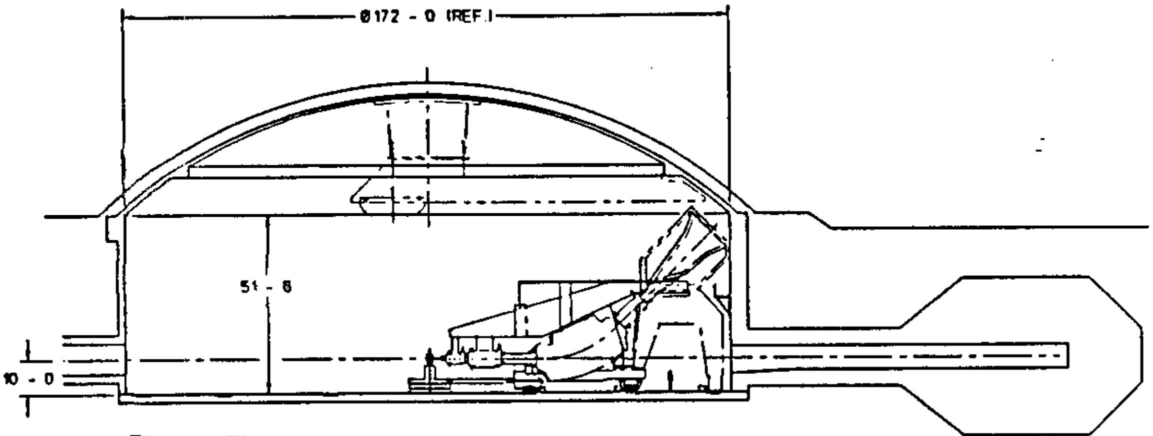

Fig. 4 Elevation view, End Station A.

End Station B

The Hall B program will include:

- Bias-free investigation of hadronic final states X in inelastic electron scattering; i.e., $(e, e'X)$, $X = N, \pi, N + \pi, N + N$.
- Detection of multiple-particle final states; e.g., electromagnetic transition form factors of 3-quark systems, resonance production and propagation in nuclei, and multi-nucleon emission.

The CEBAF large acceptance spectrometer (CLAS) will carry out this program. The multi-gap device will be based on a toroidal magnet (Figs. 5 and 6) with six superconducting coils arranged around the beamline to produce an essentially circular magnetic field. The CLAS will cover a large angular and momentum range for charged particles, photons, and neutrons, and will have moderate momentum and angular resolution and good particle identification capabilities. The particle detection system consists of drift chamber superlayers to determine charged-particle tracks, scintillation counters for the trigger and for time-of-flight measurements, and shower counters to detect electrons and photons. The six segments are individually instrumented to form six independent magnetic spectrometers. The high luminosity and count rate capability of the CLAS will be important for investigation of processes with small cross sections. Use of the CLAS with polarized targets and neutron counters with long flight path will broaden the Hall B program. Table 2 enumerates the key features and performance characteristics of the CLAS.

A tagged bremstrahlung beam is planned for Hall B as an important adjunct to CLAS. Nearly half of the first round of letters of intent to use CLAS involve the use of tagged real photons. An advantage of studying real photoproduction over electrophotoproduction is that only four complex amplitudes need to be considered. Real photoproduction may be experimentally simpler also because backgrounds should be less severe with a real proton beam.

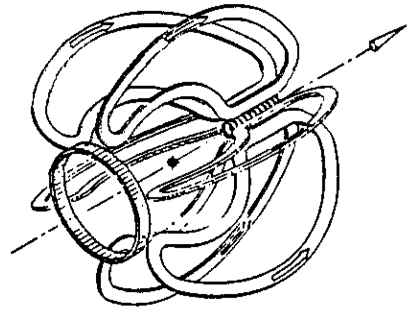

Fig. 5 Six-coil torus configuration.

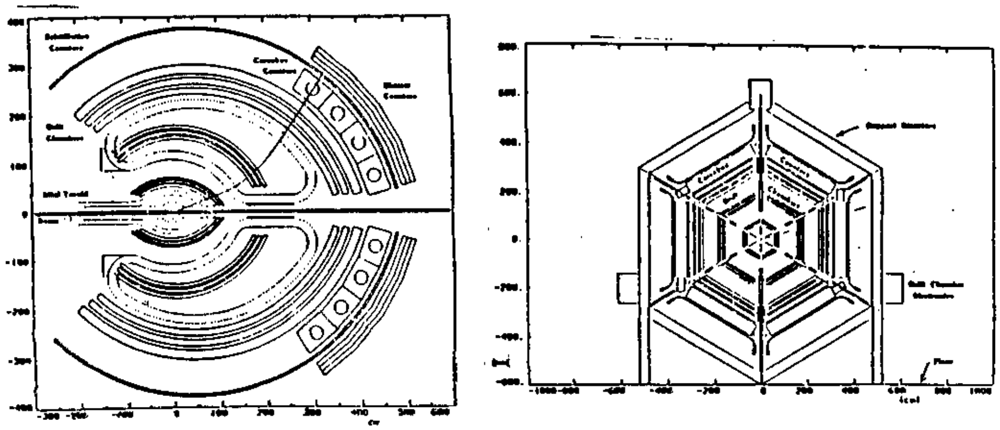

Fig. 6 CEBAF Large Acceptance Spectrometer (CLAS), side and longitudinal views.

Table 2. CEBAF Large Acceptance Spectrometer

Key Features and Performance Characteristics

- Toroidal magnetic field from six superconducting coils
  - $\int$ Bdl — $\sim$ 2.5 Tm at 10° θ; $\sim$ 0.7 Tm at 90° θ; Max field $\sim$ 2.5 T
  - ϕ-Acceptance — 50% at 10° θ; 85% at 90° θ
- Nine superlayers of hexagonal drift cells
- $\sim$ 38,000 active wires
- $L \geq 10^{34}$ cm^{-2}sec^{-1}
- Flexible pre-selection electronics to avoid taping uninteresting events

Figure 7 is an artist's conception of the CLAS in Hall B. The hall is planned to have an inside diameter of 100 feet, equipment access via a truck ramp, and an overhead crane. Space will be provided to move the CLAS aside for smaller scale experiments using the tagged photon beam. Co-program managers for the CLAS are Bernhard Mecking of CEBAF and Robert McKeown of the California Institute of Technology.

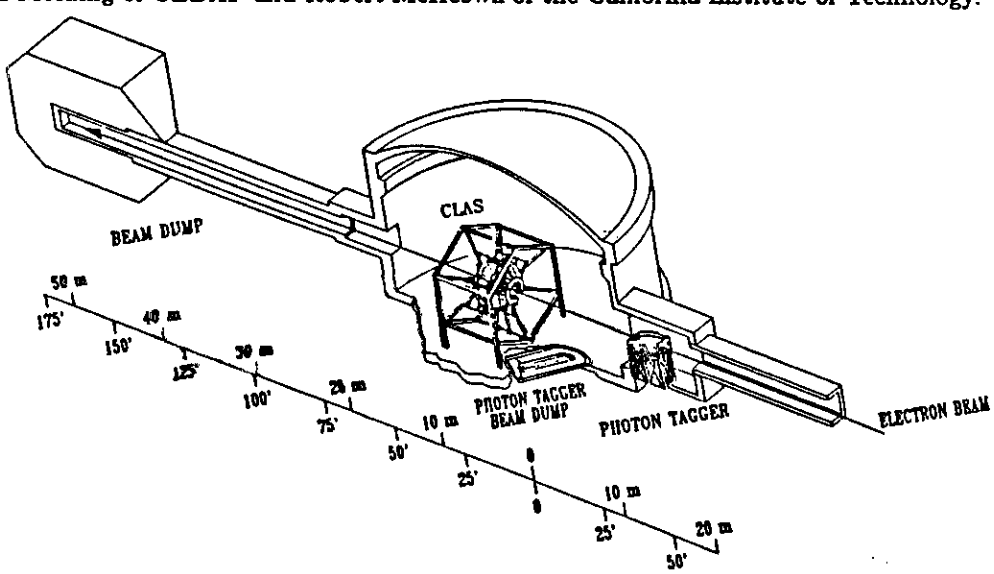

Fig. 7 An artist's conception of the CLAS in End Station B.

End Station C

The scientific program conducted in Hall C is being planned to allow for considerable flexibility in the research possibilities. The following discussion includes research topics which are being considered. Topics will include the physics of high q^2 processes, electroweak interactions, tests of the standard model, longitudinal-transverse interference cross sections, and a variety of particular experiments requiring specialized apparatus. The instrumentation for Hall C will be tailored to specific programs and experiments.

Despite the fact that the instrumentation for Hall C will be driven by user's interests in specific experiments, these instruments need not be single-purpose. One of the principal functions of the steering committee has been to encourage the evolution of user proposed designs into instruments of maximum flexibility and utility. Indeed, there are several different experimental programs that will utilize each of the proposed instruments. The initial complement of instruments planned for Hall C includes a High Momentum Spectrometer (HMS) that will serve as a hadron spectrometer for high-q^2 physics and as an electron spectrometer for a series of coincidence experiments utilizing "second-arm" spectrometers, each of which has been optimized for a different physics program. These "second-arm" spectrometers include: the first-generation Short Orbit/Hypernuclear spectrometer systems and the second-generation Symmetric Toroidal Array (STAR) spectrometer for out-of-plane coincident electron scattering studies of nucleon and nuclear structure. These first-generation second-arm instruments are each summarized briefly below.

In order to convey a feeling for the scale of these instruments, Fig. 8 shows an artists sketch of Hall C with the HMS and SOS/HNSS spectrometers configured for an experiment. The primary entrance to the end station is via a 400 foot 10 degree slope tunnel. Figure 9 shows a plan view of the proposed spectrometers and their relative dimensions, excluding the Hypernuclear Spectrometer System which has a separate pivot. A maximum of two of the "user" arms could be mounted simultaneously around the primary pivot. Other "user" arms would be stored off to one side within the end station.

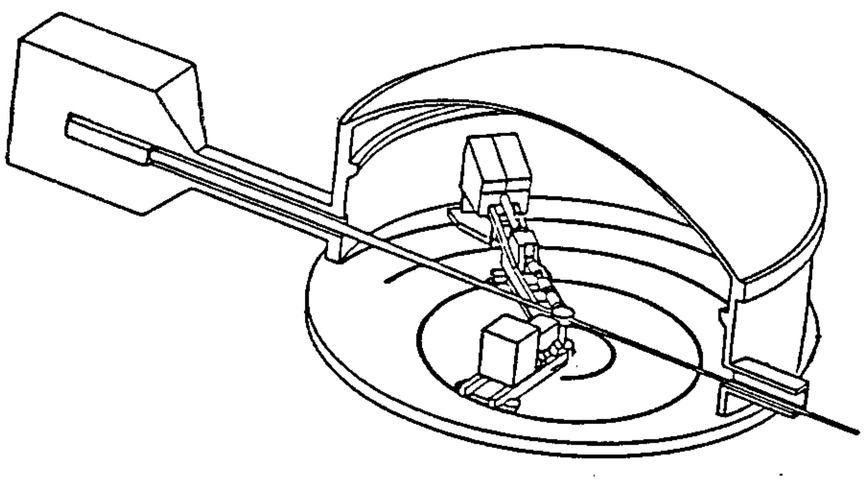

Fig. 8 Artist's conception of Hall C with two spectrometers.

With the relatively small cross sections that are typical of the high q^2 electron scattering studies planned for Hall C, luminosity is one of the critical issues. Several other specific experiments anticipated for Hall C (such as parity violation and hypernuclear spectroscopy) also require large luminosities. To meet the needs of the program, Hall C will be adequately shielded to permit all of these experiments to run with the full CEBAF beam intensity and realistic targets without compromising radiation safety limits.

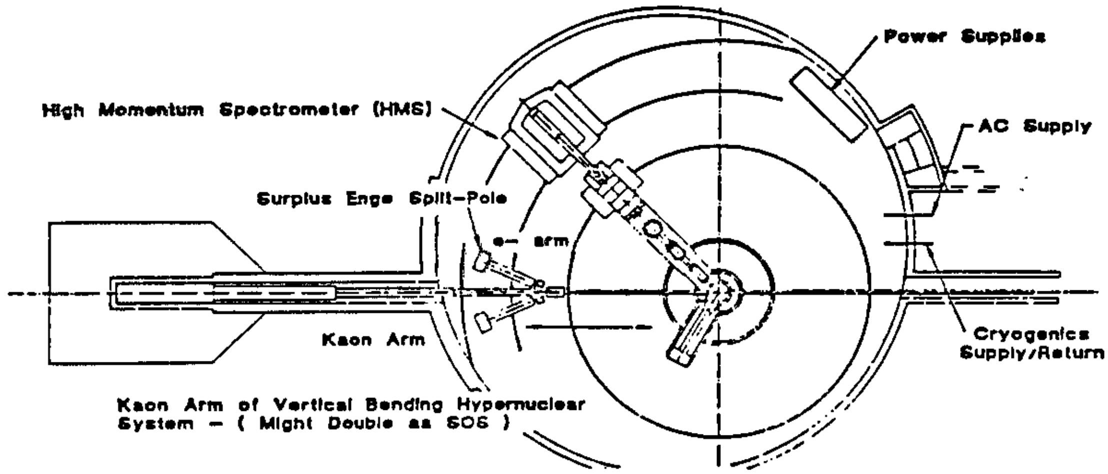

Fig. 9 Plan view of Hall C with proposed spectrometers.

A variety of experiments such as parity violation, out-of-plane spectroscopy, and nucleon form factor measurements will require polarized electron beams, and Hall C will be equipped with a back scattering Laser Polarimeter. A group from the University of Illinois is collaborating with CEBAF in R&D aimed toward the development of a polarized source with the highest possible figure of merit.

A major accomplishment in physics in the last fifteen years has been the success of the electroweak model of Glashow, Weinberg, and Salam in describing the unification of the electromagnetic and weak forces. The CEBAF parity-violation program will constitute a major test of the validity of, and extensions of the standard model of electroweak unification. It is important to state that this program is not simply a precision measurement of $\sin^2\theta_w$ in the electron-quark sector. Parity violation measurements yield unique combinations of coupling constants predicted by the standard model such that, after radiative corrections, $\sin^2\theta_w$ can be extracted if the standard model is rigorously correct. If extensions to the model exist, the quark-electron sector, which is accessible via parity violation measurements, has a combination of coupling constants sufficiently distinct from those measurable in other sectors that a very strong model dependent lower mass limit on a higher mass Z' can be obtained.

The High Momentum Spectrometer (HMS). The High Momentum Spectrometer is unanimously considered by the Hall C steering committee to be the highest priority instrument. The CEBAF Program Advisory Committee, in its initial review of experimental equipment, has supported the HMS as the keystone of Hall C activities. Many of the experiments that users are anxious to perform center on physics at high q^2 and other short-distance phenomena accessible through either $(e, e'N)$ or photodisintegration. Many of these experiments require reasonable resolution detection of protons with momenta well in excess of 4 GeV/c, even though the CEBAF electron beam will be limited to energes of $\leq$ 4 GeV in its initial stages. If future machine upgrades result in higher beam energies, it will become desirable to momentum analyze electrons of energies above 4 GeV. For these reasons, the High Momentum Spectrometer (HMS), which will be capable of analyzing momenta of 6 GeV/c or higher, is the "core" device for Hall C. The HMS will also serve as the "electron" arm for a large program of coincidence experiments that will use a second instrument for coincident detection. These experiments will utilize the 4 GeV beam anticipated at turn-on, and can be extended to higher energy as the accelerator performance is upgraded.

The specifications of the HMS design have been chosen to meet the requirements of most of the proposed experiments. A collaboration between University of Illinois, University of Virginia, Argonne National Laboratory, Caltech, MIT, and CEBAF have studied options to realize this spectrometer. A schematic of the

HMS is shown in Fig. 10. The characteristics of the design that have emerged from these studies are summarized in Table 3.

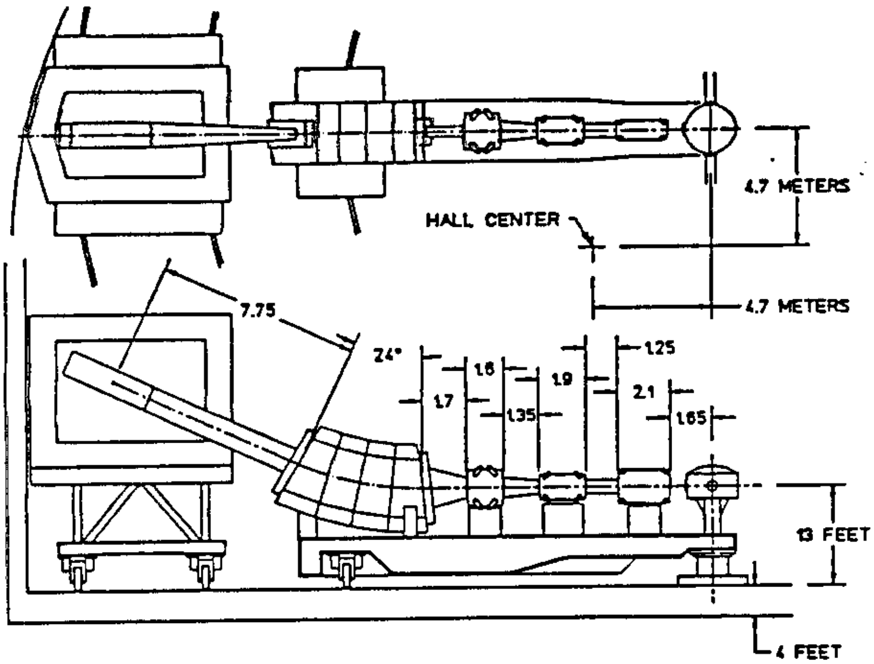

Fig. 10 Schematic of the HMS.

Table 3. QQQD Spectrometer Tuning Modes

Quad mode	Transverse Focusing mode	Target length	Solid Angle	D/M	Vertex Reconstruction 10 deg	Vertex Reconstruction 90 deg	Scatt. Angle Error
XYX	para-pt	10 cm	6.4 msr	1.8	17 mm	3 mm	0.3 mr
XYX	para-pt	10 cm	3.3 msr	1.8	17 mm	3 mm	0.3 mr
XYX	pt-pt	10 cm	6.4 msr	1.8	3.0	0.6	0.9

Note: Resolutions include 0.17 mm detector resolution and 0.25 mr measurement uncertainty in angle at the detector. Eight reconstruction terms are used for momentum and six each for vertex position and in-plane scattering angle.

The Short Orbit Spectrometer (SOS). Electroproduction of low energy pions or kaons from few-nucleon systems provides a wealth of information on their pion and strange quark content. Experiments that study these phenomena must deal with the fact that these ions and kaons are likely to decay before reaching the detector stack. In order to carry out such experiments, a group at Argonne National Laboratory is proposing to build the Short Orbit Spectrometer (SOS), a device with moderate resolution and acceptance but exceptionally short flight paths. The HMS would once again serve as the electron detection arm. Designs are limited to momenta no higher than 1.5-2 GeV/c, and it appears that existing designs and/or magnetic elements may be employed. This spectrometer can be heavily shielded and have good enough resolution to permit it to operate, in coincidence with the HMR, at the highest luminosities allowed at CEBAF. The Argonne group has generated a spectrometer design having the characteristics summarized in Table 4. A schematic of the SOS is shown in Fig. 11.

Table 4. Short Orbit Spectrometer (SOS) Characteristics

Configuration	$QD\bar{D}$
Horizontal opening angle	120 mr
Vertical opening angle	80 mr
Solid angle	9 msr
Momentum at B_{nom}	1.5 GeV
Momentum acceptance	40%
Dispersion	2.7 cm/%
Optical length	7.4 m
Resolving power	2200
Angular range	> 15°
Total weight	110 tons
Distance, target–Q1	1.5 m

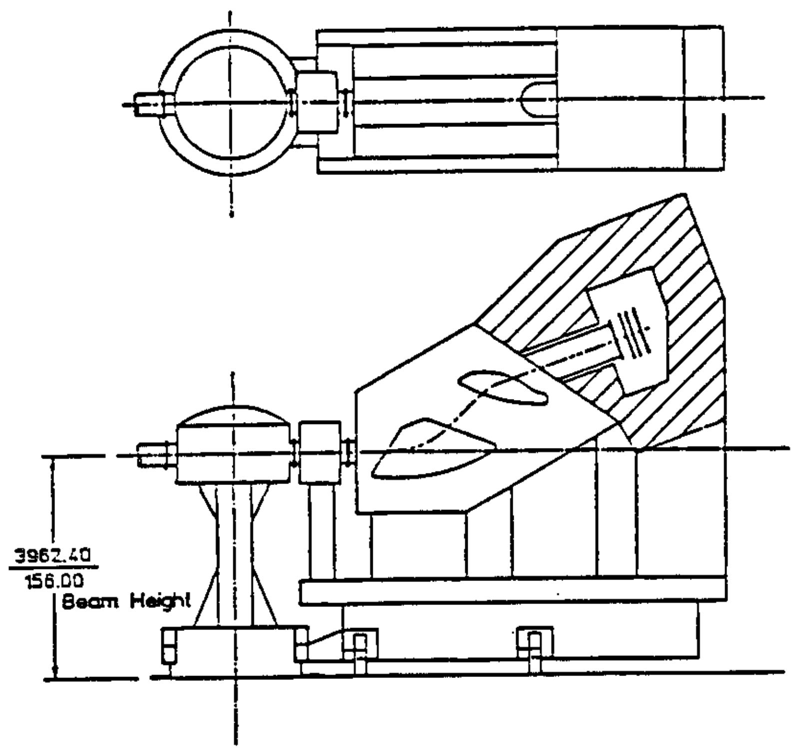

Fig. 11 Schematic of the SOS.

The Hypernuclear Spectrometer System (HNSS). The relatively high energy and exceptional beam quality at CEBAF will make it possible to study the splitting of individual levels in hypernuclei via high resolution $(e, e'K)$ coincidence measurements on complex nuclear targets. Kinematics dictate that the electron and kaon both be detected at very small angles relative to the beam line, although the maximum momentum of both particles is modest. A group from the University of Houston has designed a Hypernuclear Spectrometer System (HNSS) for this program consisting of a pair of high resolution, small angle spectrometers. The high quality of these instruments makes them also useful for other low q^2 electroproduction experiments that require similar kinematics. This instrumentation would take the form of a movable pair of short, high resolution spectrometers. The kaon spectrometer resolution has been estimated to be of the order of 150 keV FWHM. For a 0.03 gm/cm^2 target the net resolution has been estimated and is given in Table 5. This resolution may be improved somewhat by reducing target thickness but keeping the same luminosity. However, the dominant resolution contribution comes from the primary beam and only a dispersed beam can reduce this value significantly.

Table 5. Hypernuclear Spectrometer System (HNSS) Design Goals

Primary Beam	$(\delta p/p \simeq 10^{-4}$ at 1.8 GeV/$c)$	180 keV
Inelastic Electron	$(\delta p/p \simeq 2 \times 10^{-4}$ at 0.3 GeV/$c)$	60 keV
Kaon Spectrometer	$(\delta p/p \simeq$ at 1.2 GeV/$c)$	120 kev
Kaon Energy loss	(1.7 MeV/gm/cm^2)× 30 mg/cm^2	51 keV
Overall Resolution		230 keV

Symmetric Toroidal Array Spectrometer (STAR). The STAR is shown schematically in Fig. 12. Based on an eight-sector toroidal design, it will be a large solid angle, high-luminosity device with a convergent focal area. The STAR will be used for out-of-plane measurements, parity violation measurements, "180°" (e, e'), and $(e, e'2N)$. Its characteristics are as follows:

- Range of opening angles about $\vec{q}$ to span $0° < \theta_p \lesssim 40°$
- Nominal maximum momentum (for all θ_p) $p_{max} \geq 1.5$ GeV/c
- Momenta as high as 4 GeV/c for small θ_p
- Momentum resolution $\leq 10^{-3}$
- θ_p angular resolution $\leq 0.1°$
- ϕ_p angular resolution $\leq 0.1°$
- Large solid angle Ω
- Can accommodate
  - Extended and/or polarized targets
  - Focal plane polarimeter

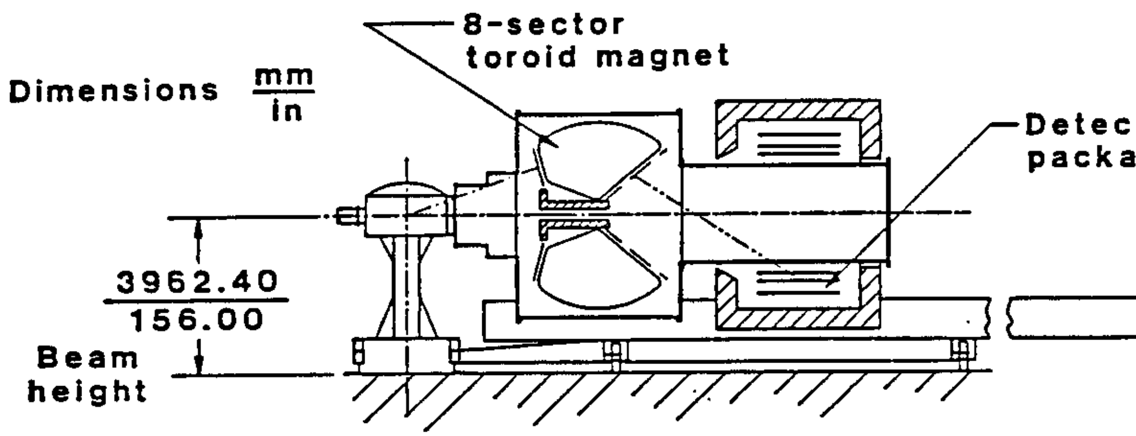

Fig. 12 The symmetric toroidal array spectrometer (STAR) for End Station C.

Hall C will have a diameter of 150 ft, with the beamline passing through the hall off center in order to accommodate the planned combinations of equipment. A truck ramp will provide equipment access. Co-program managers are Roger Carlini of CEBAF and Lawrence Cardman of the University of Illinois.

Scientific Program Planning: Background

The envisioned program of nuclear science has driven the instrumentation design and end station civil construction design. Workshops, summer studies, task forces, and other formal and informal collaborative efforts since early in the 1980s have advanced the interlinked planning for physics experiments and for equipment and facilities. In 1987, the Program Advisory Committee (PAC) was formed to advise CEBAF on the direction and progress of scientific program planning. Table 6 lists the current PAC membership.

Also in 1987, Technical Advisory Panels (TAPs) were formed to provide detailed technical guidance on equipment for specific halls, and a first round of letters of intent (LOI) was received from prospective users.

By late 1988, a year that saw 18 different scientific program planning meetings of CEBAF staff and users, the partnership between CEBAF and the nuclear physics community had produced:

- a second round of letters of intent—90 LOI from 233 physicists at 58 institutions in 7 countries,
- preliminary conceptual designs of experimental equipment to carry out such experiments, and
- a conceptual design report for the civil construction of the end stations, planned as domed buildings (Figure 2) whose circular shapes maximize usable floor space for experimental equipment.

In February 1989, PAC3 (third meeting of the PAC) reviewed the second-round LOI and the experimental equipment preliminary designs, and endorsed the overall planning for the three halls' complementary programs of research. By summer 1989 the CEBAF User Group numbered about 680 individual users from 176 institutions.

Physics Outlook

Thus CEBAF's present scientific program focus is on planning and prioritizing the experiments in detail, finalizing the designs, and building the equipment. This effort will require massive participation by the scientific users. CEBAF has called for collaborations to form and to submit detailed proposals for physics research, to complete experimental equipment conceptual designs, to build detector subsystems at home institutions, to provide scientific program preparation efforts, and to contribute substantially to equipment funding. The Conceptual Design Report (CDR) with scope, cost, schedule, and detailed collaboration arrangements is to be ready December 1989.

CEBAF has also called for physics proposals, which are due by October 30, 1989. PAC4 in December 1989 will meet to review and approve proposals and to recommend CEBAF's initial experiments.

More detailed information, including the Experimental Equipment Preliminary Conceptual Design Reports and the End Station Civil Construction Conceptual Design Report, is available from CEBAF. The collaborations are now forming, and are actively seeking new members to contribute to preparations for, and later to take part in, experiments at CEBAF. International participation is welcomed.

Table 6. CEBAF 4th Program Advisory Committee

J. Schiffer, Chairman (Argonne)	R. Arnold (American University)
R. Eisenstein (Illinois)	S. Fantoni (Pisa)
J. Friar (Los Alamos)	B. Frois (Saclay)
T. W. Donnelly (MIT)	S. Kowalski (MIT)
H. Thiessen (Los Alamos)	N. Isgur (Univ. of Toronto)
J. McCarthy (UVA)	P. Barnes (Carnegie-Mellon)

ACCELERATOR DESIGN

A true cw device is the approach of choice to produce the high-quality continuous beam needed for the program of nuclear science described in the first half of this paper. Low peak current for a given average current lowers emittance, and continuously operating rf systems can be controlled more precisely in both phase and amplitude, thereby leading to smaller energy spread and smaller variations of average energy. At a gradient of 5 MV/m, assuming cavity Q-values in the 10^9 range and cryogenic plant efficiencies of $\sim 10^{-3}$, total power dissipation for a superconducting linac translates into wall plug power of a few kW/m of accelerating structure. This lowers power consumption into a realistic realm. A last optimizing step is accomplished through recirculation, i.e., the repeated passing of the beam through the same accelerating section.

The CEBAF Recirculating Linac Concept

Figure 13 illustrates schematically the CEBAF recirculating linac concept. Total accelerator circumference is minimized by splitting the acceleration structure into two equal segments located in the straight sections of the racetrack configuration.

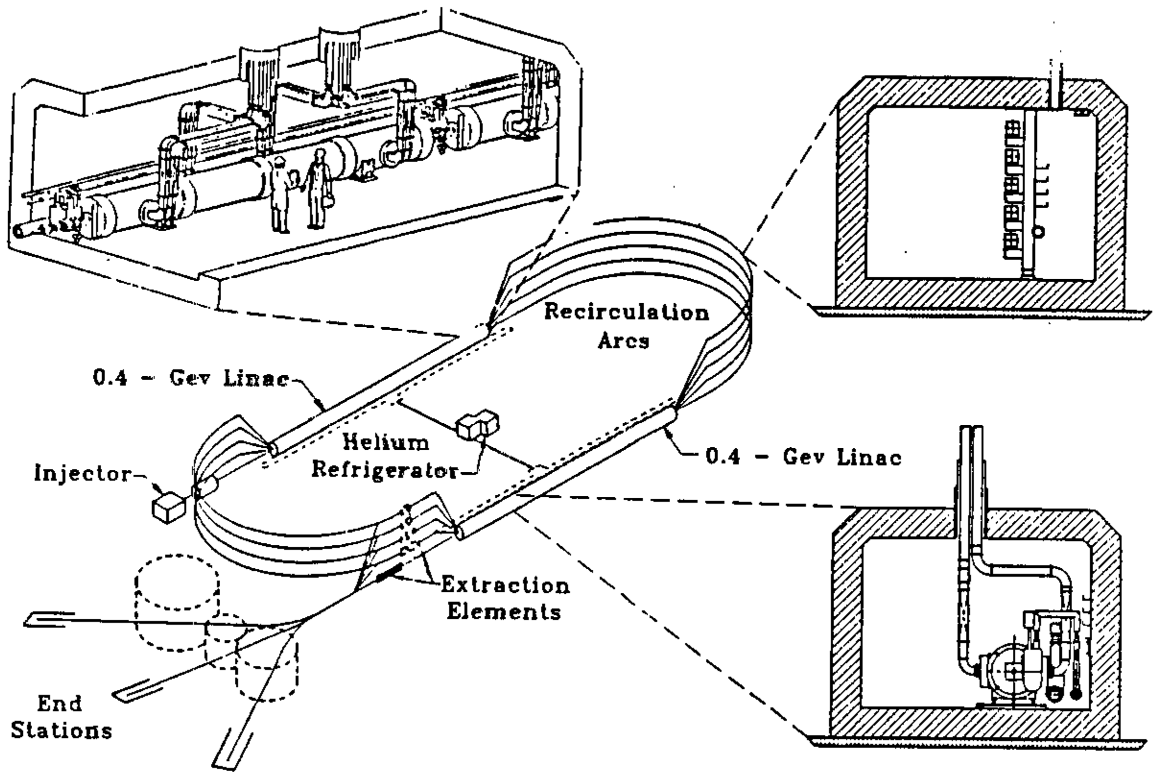

Fig. 13 Schematic diagram of the CEBAF superconducting, five-pass recirculating linac. The cutaway shows $1\frac{1}{4}$ cryomodules in the tunnel. Four cryounits, each containing a cavity pair, comprise each cryomodule. Cryounits are fed rf power alternately in a right-left-left-right pattern.

The beam transport lines connecting the two linac segments are achromatic and isochronous, provide matching in all phase space coordinates, and are designed with adequate bend radii and strong focusing to minimize quantum excitation to preserve the high beam quality.

The entire machine is operated in true electron linac mode, i.e., with the particle bunches "riding the crest" of the sinusoidal rf wave shape without longitudinal focusing, relying on the extreme relativistic motion of the electrons.

The CEBAF Design: Systems Highlights

Table 7 summarizes the CEBAF accelerator parameters.

Table 7. Design Parameter List
CEBAF Superconducting Radio-Frequency CW Linac

Beam characteristics

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

Injector. The injector will provide 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 0.5 MeV) regions utilize room-temperature technology and are modeled after proven injector designs. This beam is 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. At the nominal injection energy of 45 MeV, total phase slip (with respect to a reference particle moving at $\beta \equiv 1$) is less than 2°, through five passes, most of which occurs in the first half of the first pass through the first segment.

Acceleration Systems: Cavities, Cryogenic System, and RF System. The five-cell, 1497-MHz, elliptical cavities (Fig. 14) developed at Cornell University and adopted for CEBAF provide 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 and production. The cavities operate in the π mode, and have a fundamental coupler on the beamline at one end and an HOM (higher order mode) coupler on the beamline at the other. The elliptical shape yields low peak surface electric fields, a good chemical rinsing geometry, and good mechanical rigidity. The HOM coupler has two orthogonal waveguides for extraction of HOMs. HOM Q's are typically in the range of $500 < Q_{HOM} < 170{,}000$, which represents five orders of magnitude of damping. Each linac segment contains 80 m active length in the form of 160 cavities, providing 0.4 GeV energy gain per segment at a gradient of 5 MV/m.

Cavities are paired for operation at 2K within liquid-helium cryostats called cryounits. Every four such cryounits are integrally linked to form the accelerator's basic operating unit, the cryomodule. Each cryomodule is connected to its neighbor by a warm section containing beam vacuum pipe, vacuum equipment, beam monitors, and magnetic elements (quadrupoles and steering dipoles) to focus and guide the beam.

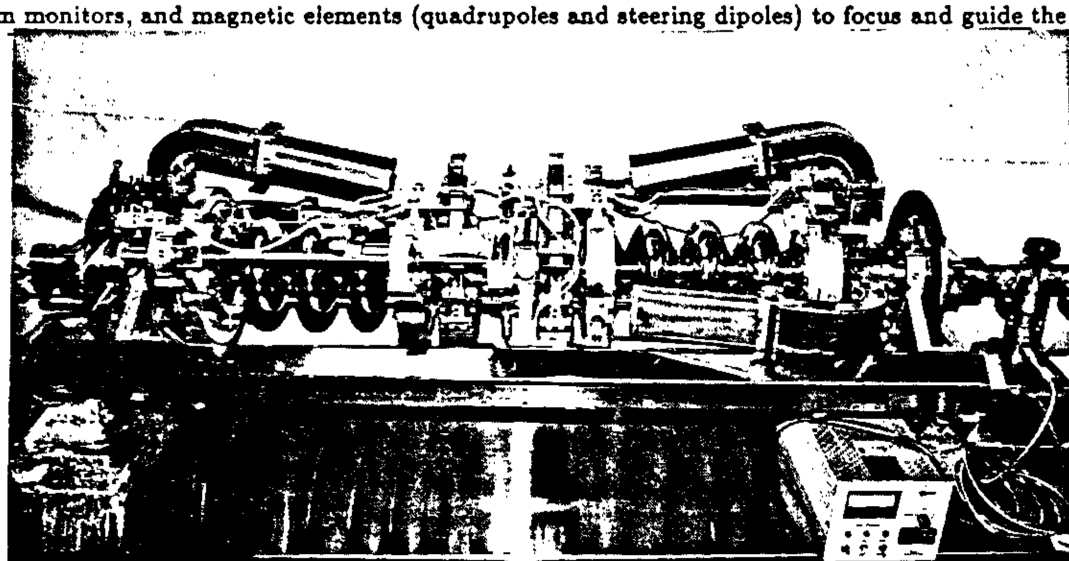

Fig. 14 A CEBAF-Cornell cavity pair.

The cryogenic system for CEBAF consists of a 4.8-kW central helium refrigerator and a transfer line system to supply 2.2-K, 2.8-atm helium to the cavity cryostats, and 38-K helium at 4.0 atm to the radiation shields. The 2.2-K helium is expanded by Joule-Thompson (JT) valves in the cryostats, yielding 2.0 K at 0.031 atm. The central helium refrigerator will be located in the center of the CEBAF racetrack with the transfer lines located in the linac tunnels.

The superconducting structures rf system consists of an individual rf amplifier chain for each cavity. Each superconducting cavity is in turn 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 used for level feedback. 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.

Beam Transport. Beam transport channels can be classified into the beam switchyard (BSY), distributing beam to the end stations, and the accelerator internal transport elements. Looking at the latter, we can distinguish between the linac focusing structure and the nine recirculation half-arcs, five at the accelerator's east end, and four at the west end.

The multi-user beam distribution system has two key elements: the injector and the rf-separator (deflecting cavities) in the extraction line. The injector creates three interspersed bunch trains, $k + 3N, k = 0, 1, 2,$ and $N = 0, 1, 2, 3...$, where bunches with different k can have different bunch charges, i.e., currents. The rf-separator deflects the beam, the optics amplify the initial deflection, and septum magnets extract beam for simultaneous delivery to all three end stations. At an operating frequency of ~1000 MHz for the rf-separator and ~1500 MHz for the rf system, the separator phases are independent of N and amount to ϕ_0, $\phi_0 + 240°, \phi_0 + 120°$ for bunch trains $k = 0,1,2$ respectively. Of particular usefulness are the initial phases $\phi_0 = 0$, leading to 0°, 240°, 120° resulting in a "straight," "left," "right" distribution (e. g., for distributing beams of equal energy to three end stations), and $\phi_0 = 90°$, leading to 90°, 330°, 210° resulting in a "one right," "two left" separation sequence to deliver beam to two end stations.

Instrumentation and Control. The central elements of beam instrumentation are several hundred beam current and position monitors. Profile monitors in 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.

Control system requirements are to implement setpoints, and read, analyze, and display systems values for the injector, rf including cavity parameters, beam transport and diagnostics, cryogenics and vacuum, and personnel and machine safety. The control system must provide efficient human interface for about 20,000 input/output data points. These requirements are met by a hardware-intensive system that has a computer hierarchy of two levels, supervisory and local. The system can be configured with a maximum of 10 supervisory-level computers, each of which can have a subsystem of up to 20 local-level computers. Local area networks (LANs) and computer automated measurement and control (CAMAC) devices enable intelligence to be extensively distributed for automated control capabilities at the local level. This control system allows control algorithms to be put together with great efficiency. Control system applications can be quickly developed without programming, and control databases or run-time displays can be modified without requesting custom software updates.

Recent Accomplishments

Cavity, cryostat, and cryomodule testing is now supported by the on-site liquid helium capability of a cryogenics test facility, while preconstruction R&D is actively going on in magnets, magnet measurement, injector and rf separator development, beam diagnostics, and computer modeling. Major elements of the control system are in use in the test lab for cavity and cryostat testing, cryogenics control, rf tests, and injector tests. The injector gun has been thoroughly tested at 100 keV and meets the beam quality requirements. A chopped and bunched 200-keV beam has been obtained. A beam position monitor has been bench tested, and the initial rf separator (for simultaneous extraction of beams) has been designed and early prototype measurements performed. An initial version of an accelerator computer model is in place, and extensive calculations, numerical and analytical, have established an initial impedance catalog for the full frequency range applicable to CEBAF's short bunches, i.e., over several hundred GHz, far beyond pipe cutoff. A preliminary accelerator commissioning plan has been prepared.

Tunnel civil construction began in summer 1988, and is now 51% complete. The central helium liquefier (CHL) is being fabricated by industry. The building to house the CHL is 99% complete; CHL installation is to begin in October 1989. Preoperations and subsystem commissioning will start in 1989. First beam to an experiment is scheduled for 1994.

Table 8 outlines key project milestones.

Table 8 CEBAF Project Milestones

Start construction	2Q FY 1987 (complete)
Experimental area conceptual design	3Q FY 1988 (complete)
Linac enclosure construction under way	4Q FY 1988 (complete)
First Cryomodule assembled	4Q FY 1989 (complete)
Start front end test (to 25 MeV)	1Q FY 1991
Start linac installation	1Q FY 1991
Start CHL operations	4Q FY 1991
Start arc installation	3Q FY 1991
Start north linac beam commissioning	2Q FY 1992
Construction project complete	3Q FY 1993
First beam to experiment	2Q FY 1994