THE CONTINUOUS ELECTRON BEAM ACCELERATOR FACILITY

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Abstract

Tunnel construction and accelerator component development, assembly, and testing are under way at the Continuous Electron Beam Accelerator Facility. 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. Prototype accelerating cavities, assembled in cryostats and tested on site, continue to exceed performance specifications. An on-site liquid helium capability supports cryostat development and cavity testing. Major elements of the accelerator instrumentation and control hardware and software are in use in cryogenics, rf, and injector tests. Prototype rf systems have been operated and prototype klystrons have been ordered. The initial, 100-keV, room-temperature region of the 45-MeV injector is operational and meets specifications. CEBAF's end stations have been conceptually designed; experimental equipment conceptual designs will be completed in 1989.

Introduction

In February 1987, construction began on the Continuous Electron Beam Accelerator Facility (CEBAF) in Newport News, Virginia.[1] CEBAF will be an electron accelerator facility for nuclear physics research providing continuous 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 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,
- 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.

Performance objectives are:

Energy E	$0.5 \leq E \leq 4.0$ GeV
Beam current	$I \leq 200\ \mu$A
Duty factor	100%
Emittance	$\epsilon \simeq 2 \cdot 10^{-9}$ 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. 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 $\epsilon = 2 \cdot 10^{-9}$ 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 the normalized emittance is not quoted; $\epsilon < 2 \cdot 10^{-9}$ m rad at $E >$ 1 GeV is neither precluded nor guaranteed.

Design Rationale, Performance Objectives, Concept, and Fundamental Choices

A true cw device is the approach of choice to produce a high-quality continuous beam. 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. The conceptually simplest approach would be a straight linac, and the most mature technology that of room temperature rf structures operating in the range of 1500 to 3000 MHz. This approach, however, leads to excessive power consumption (~100 MW for GeV-range beams) and high capital cost. 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 more realistic realm, but even then a straightforward superconducting linac of 4 GeV would not be the most effective approach in terms of either operating costs or initial capital expense. A last optimizing step is accomplished through recirculation, i.e., the repeated passing of the beam through the same accelerating section.

<u>The CEBAF Recirculating Linac Concept</u> Figure 1 illustrates schematically the CEBAF recirculating linac concept. Four-pass recirculation was originally chosen in 1985 as being close to the cost minimum and of acceptable complexity. In spring 1988, however, reevaluation of the cost and complexity issues resulted in a change to five-pass recirculation. Total accelerator circumference is minimized by splitting the acceleration structure into two equal segments located in the straight sections of the racetrack configuration.

*This work was supported by the U.S. Department of Energy under contract DE-AC05-84ER40150. The author acknowledges the technical contributions of CEBAF staff members.

Cryogenic system

Total rf load (2.0 K)	2050 W
Total heat load (2.0 K)	2700 W
System capacity (2.0 K)	4800 W
Total heat load (45 K)	8000 W

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 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.

The entire injector up to 5 MeV 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 at 1.5 GHz and 20 keV full width should be obtained at the exit of the injector. The injector enclosure has been designed to accommodate two electron guns so that in the future both polarized and unpolarized beams can be provided.

Acceleration Systems: Cavities, Cryogenic System, and RF System The five-cell, 1497-MHz, elliptical cavities (Figure 2) 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. Eight cavities are combined in each cryomodule, each of which 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.

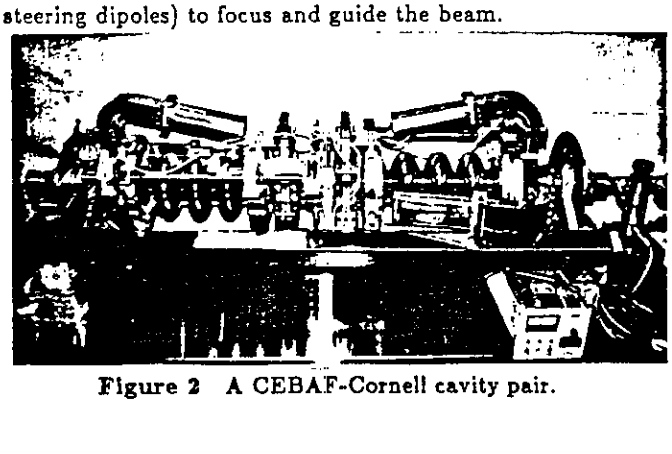

Figure 2 A CEBAF-Cornell cavity pair.

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 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 338 individual rf amplifier chains (Figure 3). 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.

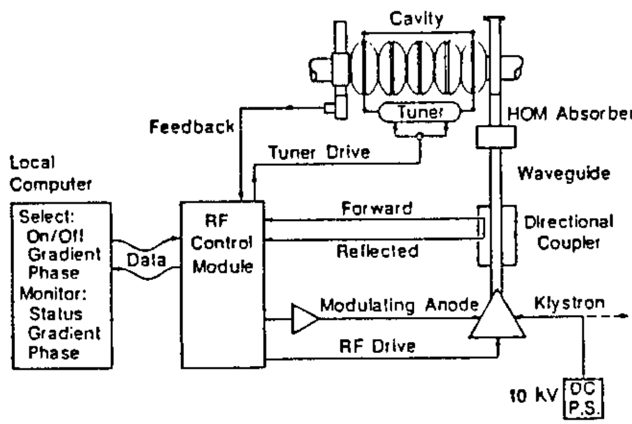

Figure 3 Schematic of rf system.

Energy spread and deviation of central energy from nominal operating value depend on control of bunch length from the injector, as well as of phase and amplitude of the accelerating field. With 320 cavities in the linacs, careful distinction between correlated and uncorrelated errors is necessary. It was found that some tolerances for the individual control modules can be reduced if a feedback loop for overall amplitude, based on beam measurements in a high-dispersion section of the lattice, is used. Requirements still remain stringent with maximum uncorrelated rms errors of a few 10^{-4} in voltage and at most a few degrees in phase. Correlated rms errors must be kept to below $2.2 \cdot 10^{-5}$ in amplitude and 0.24° in phase.

test lab is being prepared to serve advanced R&D, to support machine operation and maintenance, and, most importantly, to support construction by providing processing, testing, assembly, and troubleshooting capability, as well as some level of fabrication capability. Third, CEBAF has pursued an aggressive industrial prototyping program for cavities and cryostats.

Test results for single cavities as well as cavity pairs (Figure 5) show that specifications can be met reliably with respect to both gradient and Q values. However, in some cases low Q values have resulted from identifiable vacuum accidents and from inappropriate chemical processing. A first cryounit has undergone initial rf and cryogenic tests at CEBAF, and tests of a four-cavity subcryomodule were completed in May 1988. In the course of this program a number of needed changes in cryostat design were identified, including increased clearances and other improvements for cavity insertion, improved cavity-support and He vessel-alignment structures, and welded bridging components in the outer vacuum wall. The diameter of the beam pipe connecting two cavities within a pair was reduced to lower field coupling. A full first cryounit of the new design is being tested in stages, and plans are to test a full cryomodule containing eight cavities by summer 1989. The procurement plan for the cavities and cryostat components is coordinated with the R&D schedule. Cavities are to be ordered in spring 1989, and different cryostat components are to be ordered following their thorough testing as prototypes.

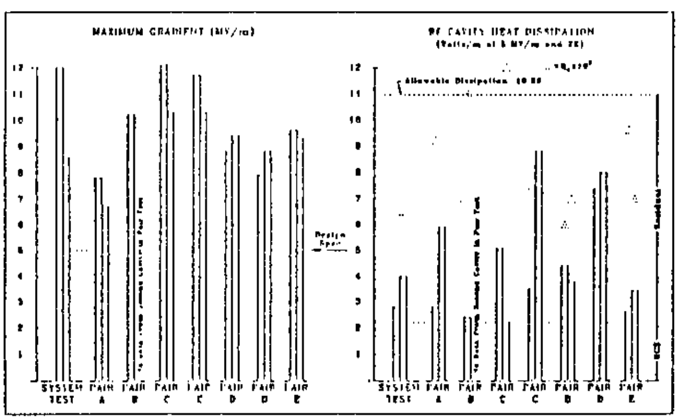

Figure 5 Prototype cavity pair test results.

Beam dynamics feasibility means primarily beam stability but also the capability to maintain beam quality under the action of a number of potentially quality-degrading mechanisms. The most important of these phenomena is the electromagnetic interaction between the beam and the "wall," i.e., the conducting boundary formed by cavities, beam position monitors, and the vacuum pipe. We can distinguish multi-bunch and single-bunch phenomena, and furthermore categorize into single and multipass phenomena. Typically the distinction between single pass and multipass is blurred or disappears for phenomena of interest in the case of intense, widely spaced bunches. For CEBAF the critically important phenomenon is multi-bunch, multipass BBU.

Two codes have been developed to analyze collective beam behavior, a 2D simulation code and a 1D "analytical" code based on matrix techniques. Both codes allow the use of realistic lattices as well as HOM frequency distributions and yield excellent agreement between them with regard to prediction of beam breakup threshold current. Threshold current was found to exceed design current by two orders of magnitude. The 2D simulation also allows study of subthreshold emittance degradation, an effect found unimportant at the few hundred μA level.

An apparent emittance degradation can occur through coupling between longitudinal and transverse phase planes, i.e., differential steering from bunch head to bunch tail. This occurs at the power couplers in the accelerating cavities where the accelerating field varies across the aperture. A "right-left-left-right" arrangement of cavity power couplers was adopted to reduce this effect and meet design specifications.

The increases in momentum spread and emittance have been mentioned previously. Synchrotron radiation introduces a momentum spread, $\sigma_E^2 \propto \gamma^7/\rho^2$, and an emittance increase, $\Delta\epsilon \propto \gamma^5\langle\mathcal{H}\rangle/\rho^2$. Here, γ has its usual relativistic meaning, ρ is the magnetic bend radius, and $\langle\mathcal{H}\rangle$ is a measure of relevant lattice properties. Generous bend radii and strong focusing (i.e. small $\langle\mathcal{H}\rangle$) control σ_E and $\Delta\epsilon$.

Operability is an area deserving early attention because CEBAF is a relatively complex device. It contains nearly 2300 magnets, nearly 2000 of which are on individual circuits; the quadrupoles, steering dipoles, and beam position monitors number over 600 each, and the total beam path length is ~6.5 km with a total phase advance of ~150 π in betatron space. Combined with a severely beam-loaded rf system requiring very precise control, this calls for early attention to operational aspects, issues, and procedures. Early commissioning (e.g., front end test of 25 to 45 MeV in 1990) and extensive computer modeling are key ingredients in our approach. Elements in facilitating commissioning and operations are a very powerful computer control system and a deliberate design philosophy of "functional modularity," i.e., an attempt to maximize one-to-one correspondence between certain components and particular actions on the beam as exemplified in the arc design.

<u>Recent Accomplishments</u> Cavity and cryostat 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 areas such as 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, and acceleration to 500 keV is scheduled for summer 1989. A beam position monitor has been bench tested, and the initial rf separator 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.