Commissioning of CEBAF*

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Abstract

Construction of the CEBAF accelerator, a 4 GeV CW recirculating linac, is virtually complete. The 338 power sources and superconducting RF cavities, which have all run above nominal operating gradient in vertical tests (average 10.7 MeV/m), are installed. All the major components of the nine recirculation arcs are installed and aligned. Pre-commissioning was performed in parallel with construction. Ninety-nine superconducting cavities were operated simultaneously at the nominal gradient of 5 MeV/m. A maximum beam current of 110 μA CW (200 μA design) was reached. A cryomodule with eight cavities has operated at 8 MeV/m. Commissioning of the entire machine began in May 94. Results obtained during commissioning of the two linacs and the first arc are presented. 600 MeV beam is ready to be brought to the first experimental hall meeting a DOE milestone established in 1988.

I. INTRODUCTION

CEBAF is a $600M accelerator facility under construction in Newport News, Virginia, funded by federal (DOE), state, local, and foreign contributions. Currently the project is 94% complete, and is on cost and schedule. Most of the remaining work is the completion of the second and third experiments, the accelerator itself being virtually complete as is the first experiment in Hall C. The present laboratory staffing level is 476 people, of whom 255 are in the Accelerator Division. The nuclear physics user community is extremely active with 850 members, 400 with approved experiments coming from 103 institutes. Three years of experiments are currently approved and an equal number of proposals are awaiting approval.

CEBAF is a 4 GeV, 200 μA CW accelerator with five passes through two 400 MeV superconducting linacs. The superconducting linacs use 1497 MHz five-cell niobium cavities operated at 2 K with a nominal gradient of 5 MeV/m and a Q_0 of 2.4×10^9. Three 499 MHz CW beams can be delivered simultaneously to three separate experimental halls, with independent current control. Beam from any recirculation pass can be delivered to any of the three experimental halls using RF separators.

Exceptional beam quality is required for the physics program: 4σ emittance less than 2×10^{-9} m-rad above 1 GeV and 4σ energy spread less than 10^{-4}.

The original design called for the linacs to be superconducting for efficiency, high beam quality and CW operation. Cost optimization led to a concept of multipass beam recirculation and this also provides the multi-energy operation. Some key design features are: a separate RF system per cavity for control of microphonics and operational flexibility; operation at 2 K for cost optimization (this means that the liquid helium is superfluid, giving increased cooling), and isochronous, achromatic beam recirculation arcs.

II. CRYOGENIC SYSTEM

The Central Helium Liquifier (CHL) is designed for 4800 W @ 2.0 K, the seventh largest helium refrigerator system in the world[1]. It has more sub-lambda capacity than all the other sub-lambda systems in the world combined. In addition, there are 2 km of shielded liquid helium transfer lines and two additional small refrigerators, one for the cryomodule test facility (CTF) and one to service the cryogenic experimental magnets. The system is currently fully operational and is supporting full gradient operation of the linacs. The commissioning schedule to reach this point has been tight (see Table 1), particularly when it has been interleaved with periods when operation to support commissioning of the accelerator was required.

Table 1. Cold Compressor Commissioning	
4/93	3.3 K test
6/93	2.9 K test
9/93	CEBAF assumes responsibility, tested new control algorithm, 2.2 K test
10-12/93	Modified 4.5 K refrigerator
1/94	2.1 K test
2-4/94	Accelerator commissioning using vacuum pumps
5/94	Accelerator commissioning using cold box @ 2.3 K
6/94	Fully operational 2.0 K, 4800 W; currently supporting accelerator operation at 2.1 K

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III. SUPERCONDUCTING CAVITIES

The superconducting RF acceleration system consists of 338 five-cell cavities in $42^{1}/_{4}$ cryomodules. All are installed and functional; for schedule reasons, two cryomodules have not yet been fully commissioned in the tunnel. Every cavity exceeds the specification for gradient and quality factor, the average being twice the specification (see Figure 1)[2].

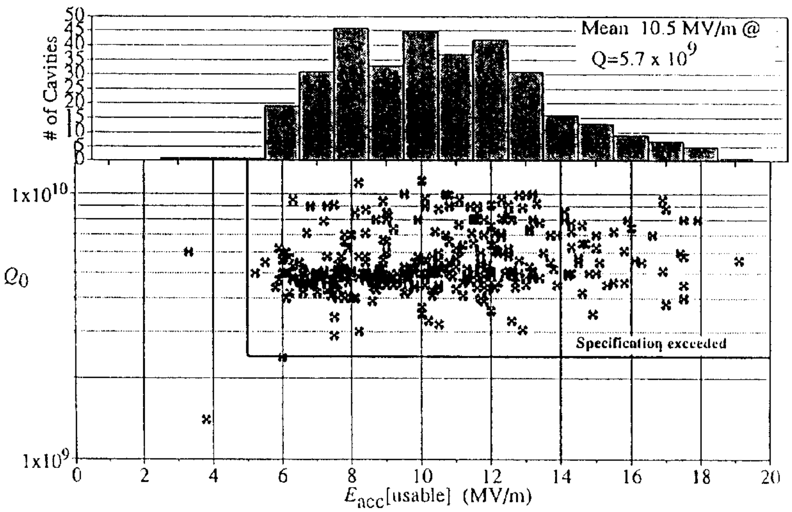

Figure 1. Gradient versus Q for cryomodules

Cavities in the injector and north linac have operated with beam for a total of 7200 hours (3800 hours with the injector only) and a large body of operating experience has been accumulated. In 1993, 99 superconducting cavities (93% of those available at the time) were operated at the design gradient (5 MV/m), and 245 MeV was attained briefly, limited by the cryogenics capacity at the time. A complete cryomodule operated with beam at an average accelerating gradient of 8 MeV/m, 60% above design. The gradient was limited for several different reasons: field emission limit of 1 W/cm^2, quench limits 1 MeV/m below that seen in vertical tests, waveguide vacuum trips, and waveguide arc trips (some probably spurious)[3].

Beam-induced microphonics were observed when the 60 pps pulsed beam was mis-steered into the cavities, taking the cavity out of phase lock. Varying the beam repetition rate redistributed the problem among the cavities, since not all cavities have the same resonant frequency. The mechanism postulated was bubble formation in the liquid helium. This effect caused some operational difficulty in steering the beam but was much improved by operating with superfluid helium. Helium temperature changes during CHL commissioning affect the cavity tuning; keeping all of the cavities in tune was hard prior to the availability of the autotrack software package (see below).

IV. RF SYSTEM

The RF system consists of one klystron per cavity and one high power amplifier (HPA) per cryomodule[4]. In all there are 340 klystrons in 43 HPAs and 344 low-level control modules. This includes amplifiers for the "warm" injector cavities. In addition there is a master oscillator and phase distribution system. The control modules have an embedded 186 computer and have fairly sophisticated control algorithms.

Operationally, these low-level control loops functioned well but are still being tuned for optimum stability under commissioning conditions. The high-level control software also functioned well with the same caveat. The modules were measured at three different temperatures and the compensation corrections calculated. These temperature compensations have not yet been activated so operation in the hot summer weather has been difficult. These advanced features will be commissioned in July.

V. BEAM TRANSPORT SYSTEM

The beam lines in the two linacs, nine recirculation arcs and the beam switchyard contain 2241 magnets and stands, 4.5 km of vacuum line, three 1 MW beam dumps, two 150 kW beam dumps, all surveyed and aligned to 200 µm. It is worth noting that the first beam transited the east arc without requiring a single corrector — evidence of excellent construction and alignment.

The DC power system consists of 1831 trim supplies (10^{-4}), 21 dipole supplies (10^{-5}), 11 septum power supplies (10^{-5}), and 84 shunts (10^{-4}).

VI. CONTROL SYSTEM

CEBAF originally developed the TACL control system[5] and has many years of successful experience with it. However, operational experience with the accelerator indicated that there were major problems in scaling to a large system (100,000 control points). Several options were studied: further upgrading TACL; importing ACNET from Fermilab; and joining the EPICS[6] collaboration. EPICS was selected because migration from TACL to EPICS could be staged, as EPICS is compatible with TACL (both are name-based) and with existing CEBAF computer hardware. Assistance was also available from the other EPICS collaborators to jump start the conversion. Despite this decision to convert the accelerator control system, the cryogenic plant will continue to run under TACL until at least 1995. It has an excellent reliability record: ~49,000 hours in the CTF and 29,000 hours in the CHL.

The existing TACL applications are being migrated to EPICS in stages, consistent with the commissioning schedule; this control conversion schedule is primarily software driven as the hardware upgrade is virtually complete. The RF, magnets, and diagnostics have already been successfully converted to EPICS, and all the basic tasks will be completed by September. Future developments will be primarily in high-level software, particularly in application software and providing an integrated database. At this time, the CHL and the injector are being controlled by TACL while the rest of the accelerator is controlled by EPICS. The control systems are operated side-by-side in the control room with little complaint from the operators.

VII. Commissioning Teams

Commissioning is being planned and executed by inter-disciplinary teams. The teams are:

Planning Team
Hardware Team
Injector Team
Linac Team
Optics Team
Hall C Team
Extraction Team

A global commissioning strategy was developed by the Planning Team which identified the major steps of the commissioning, the goal of each step and the pre-requisites for initiating the step. Each team studied the global strategy and decided which steps were their responsibility. Each step was then broken down into sub-steps, identifying the goals and pre-requisites. Each sub-step was worked on by one or more members of the team to produce a detailed procedure that is used in the control room. All of these documents are available on-line on a computer, inter-linked using FrameMaker. The steps and sub-steps are also on a scheduling program (MacProject) which enables us to plan the preparation and commissioning.

VIII. Injector

A major upgrade of the injector was undertaken in the latter half of 1993, and the injector was re-commissioned in 1994[7]. Third-subharmonic chopper cavities were installed and tested to give three-beam capability. The SRF cavities in the injector were upgraded to late-production cavities to provide more headroom. By detailed study of the lowest energy region, 60 Hz beam motion was virtually eliminated.

Studies of the electron bunch formation agree with simulations to about 50 fsec (see Figure 2)[8]. The electron bunch is stable to 50 fsec over a few minutes, and stable to 400 fsec over hours in winter. In summer, there are still diurnal thermal drifts which are being actively pursued. Start up from cold state can be achieved in less than 25 minutes, including making standardized measurements of beam parameters.

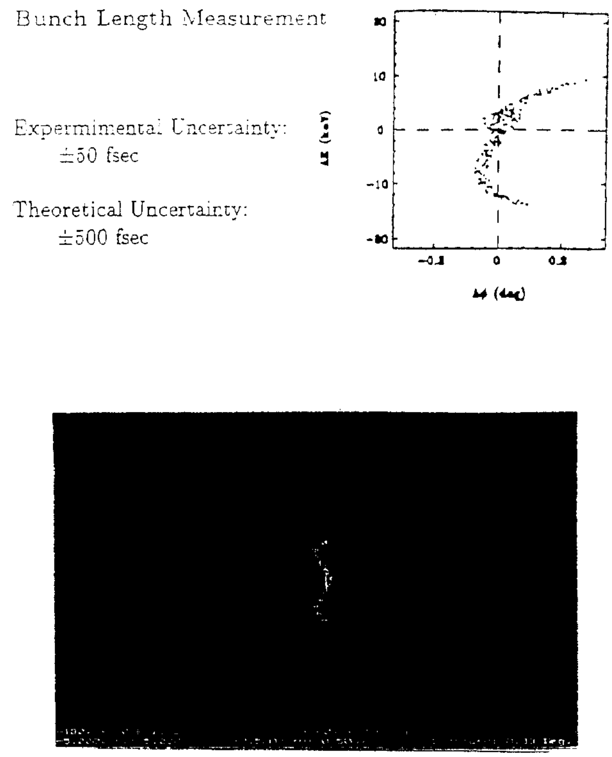

Figure 2 Injector Modeling and Measurements

200 μA CW beam was transported to the 45 MeV beam dump in the injector, showing that there is no operational limitation to the current. The maximum current reached in the linac so far was 110 μA CW (specification 200 μA CW), limited by the time devoted to tuning up the machine protection system.

IX. Linac RF Operation

Operation of the linacs requires sophisticated high-level software and tuning techniques which have been brought on-line in the past few weeks.

Autotune provides an automated measurement of the cavity resonance frequency, tunes the cavities to the operating frequency, and maintains them at the correct frequency during temperature shifts and beam loading changes.

The cavity tuning procedure is accomplished in three steps. Rough tuning is done in burst mode. The cavity resonance frequency *fo* is measured by driving the cavity with a noise spectrum. The phase of the incident signal is modulated with a bandwidth limited (±5 kHz) pseudo-random signal. The resonant frequency can be determined to within ±50 Hz from the response signal of the field probe, which has a narrow frequency spectrum ($Q_L = 6.6 \times 10^6$). Stepper motors bring the cavity to tune within 100 Hz.

Sweep mode provides more exact tuning. Single sideband modulation is applied to the carrier while sweeping the modulation frequency over a range of ±200 in steps of 5 Hz. The modulating frequency is compared to the predicted curve to determine the resonance frequency as well as the phase offset.

Autotrack locks the cavity on frequency, using the phase offset determined in sweep mode to keep the cavity tuned to the operating frequency

The autotune package has been used exclusively to tune and maintain cavities since April. It has been vital to our ability to maintain almost three hundred RF cavities operational at any time.

The initial phase of the cavities is set using transient phasing[9]. This procedure sets the cavity phases to within 5° of crest using beam-induced transients. Pulsed beam (250 μA peak, 20 μsec bursts) is used to induce transients in the gradient signal which are observed remotely in the control room. The minimum corresponds to setting the cavity at zero crossing. The phase is increased by 90° on the accelerating side to set the cavity on the accelerating crest (see Figure 3).

More precise cavity phasing is achieved by maximizing the linac energy[9]. The spreader region at the end of the linac is set up in spectrometer mode (high dispersion) and one or more BPMs are used to measure energy changes. The phase of an individual cavity is changed by ±30°. The initial beam position and beam position changes are recorded, and the crest phase is found by curve fitting. The reproducibility is better than 1°, and the phasing time is about 2 minutes per cavity.

Similarly, the cavity gradients are calibrated with beam to better than 2%. The initial probe calibration which is obtained from the external Q is then updated in the database.

The Linac Energy Management program (LEM)[10] is based on a SLAC program. Given the available cavities and the required energy at the end of the north or south linac, the program optimizes the cavity gradient distribution using individual cavity characteristics. In 1993, the criterion was to reduce the total heat-load on the CHL. This year, the emphasis has been on maximizing the headroom against loss of phase lock. The program then calculates the energy profile along the linacs, calculates the linac quad values consistent with the calculated energy profile for different FODO cells (60°, 90°, 120°), and loads and sets the RF and quads (including hysteresis). This program enables the operators to rapidly compensate for changes in the cavity complement.

Orbit lock[10] is used to calculate corrector strengths and cavity voltages to maintain a

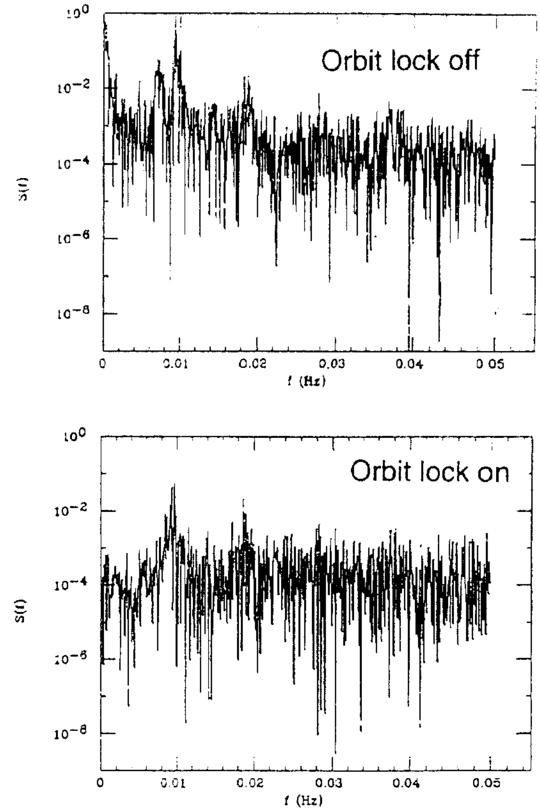

Figure 4 Position Feedback Data

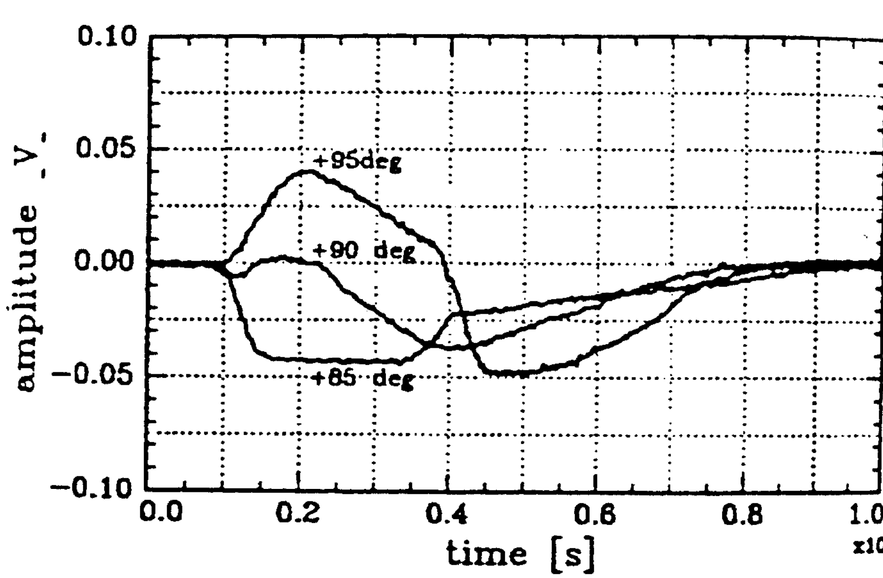

Figure 3 Transient Phasing Results

golden orbit. The calculations are based on a DIMAD model and the user may select any number of available BPMs and correctors. Single-value decomposition yields optimum results for any combination of BPMs and correctors. The orbit lock keeps beam stable to within 200 μm and has just become operational. It is the first step to providing fast feedback. The noise spectrum is being evaluated to derive the specifications for a fast feedback system to be implemented in the next few months (see Figure 4).

X. MEASUREMENTS WITH BEAM

The beam emittance has been measured at 5 MeV and 45 MeV with low-power beam (~20 μA peak current, 100 μsec pulse width). The results in Table 2 show that the emittance is smaller than specification and consistent with adiabatic damping. The energy spread was measured at 45 MeV and is consistent with the specification.

Table 2. Measurement of Beam Properties

	5 MeV	45 MeV	
Emittance			
Measured ε_x	40×10^{-9}	5×10^{-9}	m-rad
Measured ε_y	30×10^{-9}	2.6×10^{-9}	m-rad
Nominal $\varepsilon_{x,y}$	100×10^{-9}	11×10^{-9}	m-rad
Energy Spread			
Measured $^{\delta p}/_{p}$		$\leq 6.7 \times 10^{-5}$	
Nominal $^{\delta p}/_{p}$		2.5×10^{-5}	@1 GeV

The isochronicity of the east arc was measured by modulating the linac energy with a square wave driving one superconducting RF cavity[11]. A 1500 MHz precision phase detector measured the phase difference between a reference signal from a linac RF control module and a beam signal from a BPM at the 90° point of the arc. Two optics sets were calculated by DIMAD to give different values of M_{56} (change of path length with energy) and were measured using this technique:

nominal M_{56} 100 cm measured 1400 cm
nominal M_{56} 0 cm measured 18.5 cm

Small tweaks to the optics corrected the M_{56} of the latter case to:

measured 1.8 cm specification ≤ 10 cm

The accuracy of this technique is better than 3 mm.

XI. PRESENT STATUS

At this time, the injector is operating at 45 MeV (spec 45 MeV), the north linac is accelerating by 255 MeV (spec 400 MeV), the east arc is operating at 300 MeV (spec 445 MeV), the south linac is accelerating by 300 MeV (spec 400 MeV) and the beam switchyard and Hall C lines are operating at 600 MeV (spec 845 MeV). The goal for the present accelerator run was set in 1988 — deliver beam to Hall C by June 30, 1994. At present we are on track to meet this deadline (if the weather cooperates).

XII. THE LONG-TERM OUTLOOK

Accelerator operation is liable to be budget driven at 40 weeks per year. Specific accelerator goals are:

- Achieve three-hall operations by late 1996.
- Upgrade CEBAF energy to 6 GeV — upgrade to 8 GeV by the end of the decade.
- Improve source and beam versatility: bunch time structure, polarization, current dynamic range.
- Achieve 80% availability by FY '98.
- Develop concepts and plans for further upgrades as science needs dictate.

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