STATUS OF THE CONTINUOUS ELECTRON BEAM ACCELERATOR FACILITY*

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Abstract

The Continuous Electron Beam Accelerator Facility (CEBAF) is a high-intensity, continuous wave (CW) electron accelerator to be used for high energy nuclear physics research. During the past eight years, an electron accelerator based on superconducting radio frequency (SRF) technology has been designed, built, and operated single-pass, producing an electron beam of outstanding quality. Initial beam delivery to a nuclear physics experiment occurred in late July of 1994.

Following a brief review of the CEBAF design, these topics will be discussed: the installation status, the commissioning and operations experience on the accelerator since the last conference including CEBAF experience with SRF technology, the CEBAF accelerator physics and beam properties measurements to date, and the performance goals for the extended nuclear physics run starting at the end of 1994.

Introduction

The CEBAF accelerator, shown schematically in Fig. 1, consists of a 45 MeV injector, two side-by-side 400 MeV superconducting linacs, 9 recirculation arcs that shuttle the beam through the linacs up to 5 times for 4 GeV total energy, and three experimental halls. Cooling for the superconducting linac cavities is provided by a 4800 W, 2 K helium refrigeration plant, the Central Helium Liquefier. RF power for the cavities is provided by 5 kW klystrons, one for each cavity, located in service buildings above the linacs.

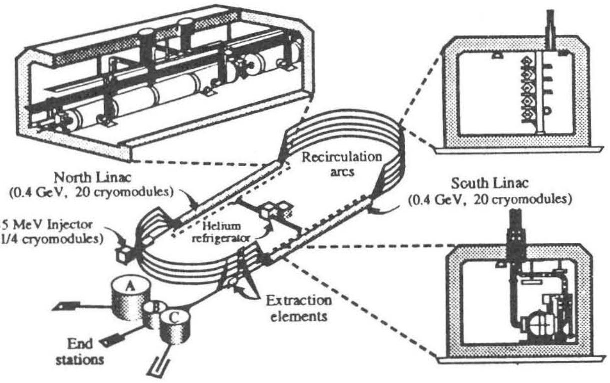

Fig. 1 Schematic View of the CEBAF Accelerator

Construction of the accelerator began in 1987. Since then the superconducting linacs, the RF and cryogenic systems for the linacs, the first pass recirculation arcs, and one experimental hall, Hall C in Fig. 1, have been operated with beam. With both linacs running single pass, a beam of 808 MeV energy has been achieved. Initial physics experiments have been performed in Hall C at 600 MeV beam energy.

Many details of the CEBAF design were summarized in the conference proceedings of the last linac conference [1]. Here, the subsystem developments since then will be summarized, following the order of topics covered in that publication. The bulk of the report will concentrate on beam dynamics studies that have been accomplished in the last two years. The remainder of the report details the operational results of the most recent run of the accelerator.

Accelerator Status

Accelerating Structures: Each linac contains one hundred sixty 0.5 m active length 5-cell superconducting niobium cavities, tuned to 1497 MHz. In the past two years there have been no significant changes to the cavities or to the cryomodules that contain the cavities. Continued refinement of cavity processing and handling technique yielded performance improvements during the second half of production [2]. A summary of the performance of a large sample of CEBAF cavities in vertical tests is given in Fig. 2, where the usable accelerating gradient and Q of the cavities in the sample are plotted. The mean values of the distributions exceed CEBAF specifications in both gradient (5 MV/m) and Q (2.4×10^9) by a factor of two.

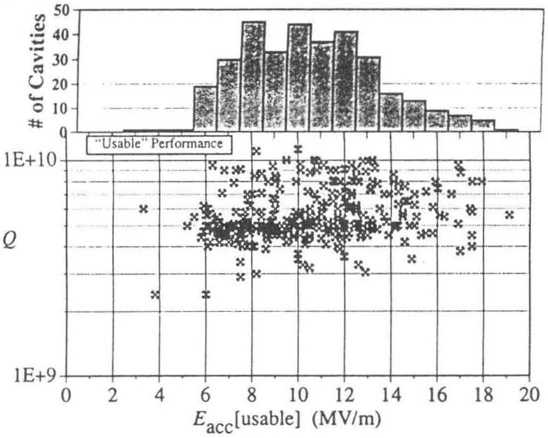

Fig. 2 Performance of the Superconducting Cavities in Vertical Tests

The usable gradient for a cavity is the minimum of the gradient where the unloaded Q passes 2.4×10^9, of the

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gradient where 1 W of field emission occurs, and of the quench gradient minus 1 MV/m for that cavity. As such, it provides a measure of the maximum gradient the cavity should be operated at. In practice, usable gradient is lost going from vertical tests to the accelerator tunnel. Also, the RF power to drive the cavities is limited once there.

Each CEBAF linac has twenty cryomodules containing eight superconducting cavities apiece. At present, forty-two cryomodules have been constructed and installed in the injector and linacs. Ninety-six percent of the installed cavities meet full operational specifications.

RF System: The RF system for each module consists of a power supply, eight klystrons for the eight cavities in a module, and eight RF control modules. In the north linac nineteen complete systems are available; the twentieth will be complete with the addition of some klystrons. In the south linac seventeen modules are complete, two additional modules lack klystrons, and one module's parts have served as a "spares inventory" for the rest of the accelerator. The klystron failure rate has been close to expectations; replacement klystrons and spares will be purchased in the coming year.

In the past two years, an improved calibration algorithm has been installed in the RF control modules throughout the machine. Such calibration has insured interchangeability of control modules. The noise performance of the controls has not changed substantially from the last conference, and is summarized in another invited talk at this conference [3].

Other substantial improvements have been made to the RF controls to enhance the operability of the RF systems. An example is an automatic cavity tuning mode, which serves first to coarsely tune, then finely tune, and finally to place the cavity controls in an automatic tune tracking mode. This system has completely eliminated the need for network analyzer tuning of cavities in the service building. An on/off/trouble status screen allows quick recovery from RF fault conditions and an RF system monitor summary screen allows one to quickly find cavities in out of tolerance conditions. The latter has been useful in associating instances of beam jitter with problems in particular cavities in the linacs.

Beam Transport: The beam transport system consists of 2200 magnets, 1800 magnet power supplies, 100 shunt current supplies, and approximately 4.5 km of vacuum beam pipe. At this time, all magnets are installed and operational, except for the path length adjustment magnets in passes four and five, and septum magnets throughout those same passes. As determined by beam optics studies, the first pass magnets are operating properly.

Except for the regions near the fourth and fifth pass septa, all of the vacuum tubing and ion vacuum pumps are installed. Outside of the superconducting linacs, where the pressure is much lower, the vacuum system consistently achieves pressures below 10^{-7} T with the low duty factor beam currently being produced. It is expected the pressure in the arcs will rise somewhat when higher current CW operation starts, due to synchrotron radiation desorption of gas from the vacuum chamber.

Cryogenic Systems: During the 1993 north linac test, the beam energy achieved was limited to 250 MeV by cryogenic capacity, and operation was frequently hindered by inadequate system stability. However, due to recent changes in hardware and operating procedures, the Central Helium Liquefier (CHL) has been operating reliably and the cryomodules now run at the 2 K design value. The cryogenic system was remarkably quiet during the final two months of the recent run at close to full load. The CHL, the world's largest 2 K helium refrigerator, is fully operational.

Injector: The injector has undergone substantial development since the last conference. One change was to place the existing thermionic gun at 90° to the main beam line. With the addition of a separate photocathode polarized electron source, such an arrangement allows one to easily switch from polarized to unpolarized beam by changing the magnetic field of a switching dipole. A chicane at the end of the injector was completed. It allows the relatively low energy injector beam to be injected onto the north linac beam axis along with the higher pass beams. This chicane has been useful for energy spread monitoring.

An additional requirement of the injector is that each of the experimental halls be able to receive independently variable current. To support this requirement, a 499 MHz third subharmonic chopper system has been assembled and installed. Its main elements are two 499 MHz square pillbox cavities driven in transverse deflecting modes and a three slit chopping chamber, where the three slits are independently controllable and separated by 120° on the chopping circle. The stability of the chopping system has been increased by placing independent control on each of the four RF channels of the choppers, and by installing extra headroom in chopper power.

The superconducting cavities in the injector were replaced with newer, higher gradient cavities. This upgrade allows the injector to be operated at 68 MeV, consistent with accelerating to 6 GeV in the main linacs. The details of all the injector work are outlined in a contributed paper to this conference [4], including the results of measurements which demonstrate that the injector specifications have been achieved.

Polarized Beam: A polarized photocathode electron gun, developed at the University of Illinois, has been moved to CEBAF. It is being reassembled and moved into the tunnel in stages during beam down times. The gun is scheduled to operate early in 1995. Nuclear physics experiments involving polarized beam could begin soon thereafter.

Controls: Toward the end of the 1993 north linac test, it became clear that the previous TACL controls were not developing quickly enough to run the whole accelerator. Based partly on the relative modernness of the system, partly on the fact that CEBAF could adapt software developed by sister DOE laboratories, and partly on the "ease" of migrating from TACL, a control system based on the Experimental Physics and Industrial Control System (EPICS) was chosen for the CEBAF controls. The CEBAF controls have been migrating to EPICS throughout 1994 starting with the RF controls, then the diagnostic and magnet controls, and finally the high level controls. With the exceptions of the CHL controls and the injector controls, the whole accelerator now uses EPICS. CEBAF is currently the largest EPICS installation, with over 100,000 EPICS records controlling the accelerator. Changing the controls in such a short time presented a significant challenge.

Beam Dynamics

In this section, several beam dynamics measurements are discussed: the bunch length in the injector by measurements of the phase transfer characteristics of the injector, the arc momentum compaction, and the first pass recirculation path length. Also the performance of the slow feedback systems presently in place at CEBAF is addressed. For the first three topics, precision phase detectors are utilized to obtain relative time of flight information about the electron beam bunches. The phase of a beam derived signal is compared with an RF signal derived from the master phase reference system through a mixer. A variable phase shifter is used to calibrate the measurement.

In order to achieve small energy spread in the CEBAF beam ($\sigma_E/E \approx 2.5 \times 10^{-5}$), it is necessary that the length of the beam bunches be under 1° of RF phase. The bunch length is largely determined by longitudinal beam dynamics effects in the front end of the CEBAF accelerator. The setup procedure for the bunching in the front end, especially the amplitude and phases of the normal conducting RF cavities in the injector, was previously computed with PARMELA. The results of the calculations, at 5 MeV right upstream of the first full cryomodule of the injector, are shown in Fig. 3 [5]. Two things about the phase space should be noted. The full width phase extent of the bunch is 0.4° and the characteristic double folding of the phase space yields an ϵ shape. In addition, the full width energy spread of 20 keV is negligible on the scale of the full accelerator energy.

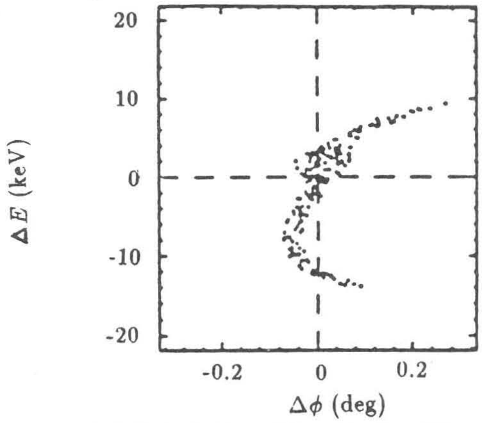

Fig. 3 PARMELA Calculation of Longitudinal Phase Space at First Cryomodule in Injector

In 1990, C. G. Yao proposed a method to determine bunch length by making RF phase measurements [6]. The method yields a phase transfer function and allows the bunch length of the CEBAF beam to be minimized during routine operation. Hardware and software have been developed to measure the transfer function in a few seconds. The installed hardware consists of several 6 GHz pickup cavities at strategic locations on the beam line; a 70 MHz phase modulator that modulates the 499 MHz phase of all the chopper RF fields, leaving the RF fields in the rest of the injector unchanged; a 6 GHz phase detector; and a transient recorder for data aquisition. Triangle wave phase modulation of ±30° of 1497 MHz phase is digitized and applied to beam passing through a narrow 10° slit. The modulation covers the 60° phase extent of the beam passing the chopping slit at full current. The time of arrival at the 6 GHz cavities is measured with the output of a phase detector, which is digitized and displayed as in Fig. 4. In the diagnostic display, the phase detector output is displayed horizontally and the modulation phase is displayed vertically. The ϵ shape of the phase space plot and the correct bunch length are clearly reproduced.

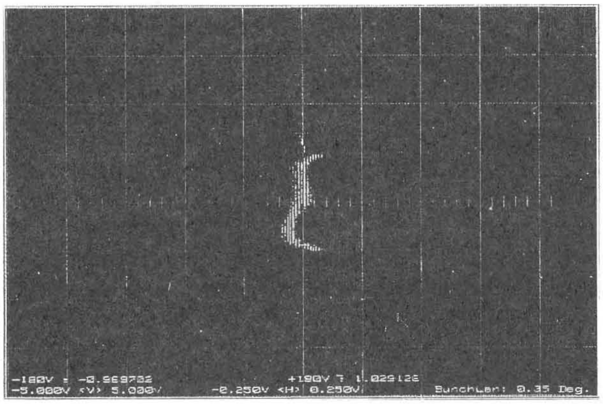

Fig. 4 Phase Transfer Function Acquired for Nominal Injector Conditions

The bunch length measurement system provides a quick determination of whether the injector RF cavities are adjusted properly and a quick diagnostic for bunch length optimization. The noise in the technique currently allows relative time measurements to about 200 fsec. Comparisons with the zero-phasing method of determining the bunch length yield agreement to 20% over the range of 1° to 4°. The method has allowed routine minimization of the bunch length to under 1°.

In the CEBAF arcs, the momentum compaction is adjustable over a broad range by varying pairs of quadrupoles in each arc, a betatron half-wavelength apart. The measurement of the momentum compaction uses precision phase detectors to track the time of arrival of an energy modulated beam. The measurement of the M_{56} linear transfer matrix element from the front end of the east arc spreader to the 90° point provided a nice test of design and modeling against observation [7], as well as verifying the isochronicity and tunability of the transport system.

Two optics sets were calculated using DIMAD. The first was the nominal isochronous arc tuning, with a nominal M_{56} of 0 m. The second was a special tuning with a nominal M_{56} of -1 m. The special tuning was measured to have an M_{56} of absolute magnitude of 1.4 m; the deviation from design is equivalent to a quadrupole excitation error of 6% in the family used to control momentum compaction. The nominal tuning was measured to have an M_{56} of 18.5 cm. Small corrections of 1–2% were iteratively applied to the compaction control quadrupoles while M_{56} was repeatedly measured. After these quads were shifted by an average of 3%, the M_{56} was measured to be 1.8 cm.

The path lengths of the arcs may also be determined using precision phase detectors. By making relative measurements of the amplitude and phase of beam generated signals when only first pass beam is present, when first and second pass beams are present, and when only second pass beam is present, it is possible to infer the phase difference between the first and second pass beam signals. Such a measurement was done with 600 MeV beam recirculated back to the front end of the north linac. The measurement, good to one degree of 1497 MHz phase, showed that the once around path length is at the design value ±0.6 mm. The electronic noise of the measurement allows a precision of 50 μm if the phase detector is better characterized. The path length was changed using an installed magnetic path length adjustment chicane. The indicated path length change was 9.2° of 1497 MHz phase for a computed change of 10°.

The CEBAF optics has been measured at various locations throughout the accelerator. The procedures based on these optics have been worked through and successfully applied to commission the accelerator. The emittance of the CEBAF beam has been measured and upper limits on the energy spread have been derived based on measured beam spots and known dispersion values. The accuracy of the measurements will be improved by a factor of six when it is possible to study the beam with a high dispersion arc lattice, after the energy spread is systematically determined by measuring the spot size as a function of dispersion at a given location.

In order to enhance the stability and reproducibility of the CEBAF beam, orbit and energy locking software has been developed to correct slow drifts. This effort has been successful at holding the beam position in groups of BPMs to less than 100 μm with an update rate of about 10 second [8]. Using a BPM at a dispersed location and the cavity gradient set values as a controlled variable, it was possible to stabilize the slow relative momentum drift to less than 1×10^{-4}.

Operational Experience

In the past two years there have been two extended periods of running. The first period extended from August 1992 until April 1993 and the second period extended from November of 1993 until the end of July 1994.

During the first period of running, three quarters of the north linac cavities and three quarters of the lowest energy beam line in the east arc were completely installed. Also a high power dump was installed at the end of the linac.

The major accomplishments of the run were: maximum beam energy of 250 MeV, usual beam energy of 150 MeV, 100 μA CW beam current to the high power dump, and 6×10^{-3} duty factor pulsed beam to the three-quarters point of the east arc. More important, early experience was gained in operating the north linac. The main problems encountered here were addressed over the subsequent shutdown, allowing commissioning to proceed more expeditiously. For example, the need for automatic tuning of the cavities was particularly apparent during the early run.

Several notable technical achievements happened during this time. Linac and arc optics were verified and setup procedures were successfully tested. The bunch length measurement system and the bunching setup procedure were used to obtain short bunches reproducibly. Initial versions of orbit locking, energy locking, automatic cavity phasing (spectrometer based), and linac cresting software were tested. The performance of the cavity controls under high beam loading was tested using a special cavity with a large external Q. The method for measuring the M_{56} of the arc was tested, and a method for quick dispersion suppression was developed.

During the shutdown from April 1993 to October 1993 a substantial amount of work was completed. The injector was upgraded, both north and south linacs were completed, most of the magnet installation in the west arc and much of the magnet installation to the halls was completed. In addition, planning and initial work on the EPICS conversion occurred at this time.

The just-completed commissioning run began in November of 1994, with several periods of installation activity scheduled during the run. The goal through March of 1994 was to get the injector commissioned. April was devoted to recommissioning the north linac (necessitated by the software change), May was devoted to installation activity, and June and July were devoted to beam to Hall C, with some installation occurring in August and September.

The major accomplishments of the run were: 808 MeV beam energy in one pass, 600 MeV beam delivered to nuclear physics experimenters over a few day period, recirculated beam back to the north linac, and the overall path length verified. Pulsed beam was used, except for sporadic high current CW running in the injector. Throughout the running, the performance of the EPICS controls was scrutinized, especially as larger portions of the machine came on line. The controls have largely met expectations.

The main technical accomplishments during the run were: completion of injector commissioning and injector characterization, debugging of the automatic cavity tuning systems, continuous operation of all four stages of cold compression in the helium cooling plant, conversion of low-level controls to EPICs; operation of several high level applications which provided feedback control against slow drifts in the systems, and completion of optics studies that verified basic machine performance.

This section is concluded with a more detailed summary of the experience during the beam delivery to Hall C. The beam energy was 600 MeV, the macropulse beam current was 12 μA, the duty factor was 1.8×10^{-2}, and the beam spot as measured with a phosphor screen near the target was about 1 mm. The relative energy spread was not measured, but based on previous experience was probably under 10^{-4}. One hundred fifty-five of the 162 cavities available in the injector and north linac were up, producing an average gradient of 3.87 MV/m, and 132 of one 136 cavities available in the south linac were up producing an average gradient of 4.55 MV/m. During operations, the trip rate was approximately 20 per 8 hr shift, with a low of 7 during one shift. It takes about half a minute to recover from these trips. During the scheduled time, beam was on 69% of the time. Of the off time, most was spent in recovering from computer reboots and in providing the experimenters access to Hall C.

At the end of the run, time was devoted to operating the accelerator at a single pass beam energy of 808 MeV. This was achieved by raising the gradient set points in the RF controls of on-line cavities and by reloading the optics based on the higher beam energy. During the test 154 of the cavities available in the injector and north linac produced an average gradient of 5.19 MV/m, and 132 cavities available in the south linac produced an average gradient of 6.18 MV/m. The trip rate ($\approx$12/hr) was noticeably higher at the higher gradient; however, it is likely that finding a better orbit through the accelerator will solve this problem.

Future Plans

CEBAF will be down until mid-September 1994. Some installation activity, principally associated with beam diagnostics upgrades, will be completed. In the coming run period, two main goals will be paramount. Starting in the beginning of October, data taking with CW beam will begin in Hall C. Until then, and in various scheduled weeks after the first week of October, the main accelerator physics issue is multipass recirculation. The current plan is to have two-pass beam at 1.4 GeV in September and three-pass beam at 2.1 GeV at the end of November. A shutdown early in 1995 will allow component installation in passes four and five to be completed, followed by full 5-pass recirculation to 4 GeV in the second quarter of calender year 1995. Sometime around the next linac conference, CEBAF hopes to provide 6 GeV beam to experimenters.

In the rest of the calendar year, CEBAF hopes to provide experimenters with 500 hours of beam time, 1200 hours scheduled with an availability of 40%. The plan is to run 22 weeks of beam for nuclear physics experiments in 1995, 30 weeks of beam in 1996, and 33 weeks of beam in 1997, with at least 50% availability by the second quarter of 1995, 65% availability by the first quarter of 1996, 70% availability by the third quarter of 1996, and 80% availability by the third quarter of 1997. Hall A is to come on line at the end of 1995 and Hall B is to come on line about one year later.

The duty factor of the beam will be raised to 100% sometime later this calendar year, with a goal of 25 μA beam current. In the middle of 1995 the goal in current is 100 μA and the final design goal of 200 μA beam current is planned for second quarter 1996. The polarized gun is being installed this month and should be ready for initial beam tests early in 1995. It is expected that high polarization will be available by the first quarter of 1996, delivering moderate average current beams.

Conclusions

An accelerator based on SRF technology is nearing completion at CEBAF. The accelerating cavities are performing beyond specifications. Nuclear physics experimentation has begun with delivery of the first beam to Hall C. The beam dynamics of the accelerator is as predicted. Beam has been transported with good transmission through one pass of the accelerator. Simulations of the bunching process have been verified to high precision. The emphasis of beam studies is shifting toward establishing efficient operations, through better software, controls, and procedures.

Acknowledgements

The hard work of every CEBAF employee was needed to push the accelerator to its present state. The payoff will start accumulating with physics results in the coming years.

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