Operating Experience at CEBAF*

Robert Legg, CEBAF, Newport News, USA

Abstract

CEBAF, the Continuous Electron Beam Accelerator Facility, is a five-pass, recirculating, superconducting rf linac designed to provide exceptional beam quality at 4 GeV up to 200 microamperes CW. It is made up of an injector, two 400 MeV linacs and nine recirculation arcs having a total beamline length of more than 4.5 kilometers. On November 5, 1995 CEBAF delivered a 4 GeV, 25 microampere CW electron beam to the first of three experimental halls and the experimental physics program was started 10 days later. Accelerator availability during the first month of the experimental run exceeded 75%. Beam properties measured in the experimental hall to date are a one sigma momentum spread of 5×10^{-5} and an RMS emittance of 0.2 nanometer-radians, better than the design specification for CEBAF. CW beam has been provided from all five passes at 800 MeV intervals. Outstanding performance of the superconducting linacs suggests a machine energy upgrade to 6 GeV in the near term with eventual machine operation at 8 - 10 GeV. Results from the commissioning and operations experience since the last conference will be presented.

1 INTRODUCTION

The baseline specifications for CEBAF require the delivery of three separate beams of 0.5 to 4 GeV energy to three independent experimental halls simultaneously.

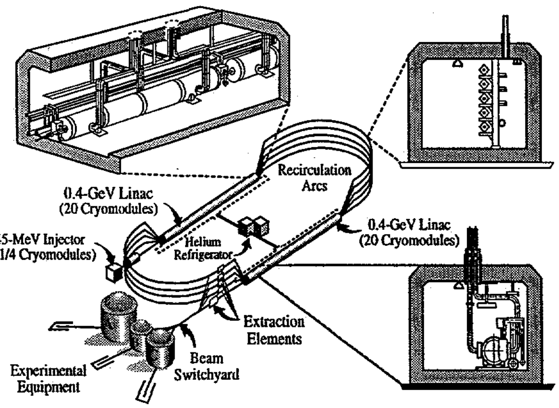

Figure1

The beams must be CW at 499 MHz and have independently controlled currents up to 100 microamperes each. The beams themselves must have 4σ emittances better than 10^{-8} m-rad and full width half max energy spreads of less than 2×10^{-4}.

*Work supported by USA DOE#DE-AC05-84ER40150

The design concept to meet these specifications is a recirculating, cw, superconducting linac, see Figure 1. Superconducting rf cavities were chosen because of their high efficiency at converting rf power to accelerating gradient in CW mode, particularly at the low average currents used in the coincidence experiments CEBAF is designed to perform. This reduced the rf power requirements for the system, but required a large reliable helium refrigerator. The recirculating linac concept optimized the total cost of the facility by trading off additional accelerating cavities against additional recirculation beam transport. The recirculating linac concept also has the advantage that multiple beam energies can be provided easily if individual beams can be extracted from each separate recirculation pass.

Key design features of the CEBAF accelerator are individual klystron and rf controls for each srf cavity, a three beam injector, and an rf separation system. The individual rf systems allow the rf drive to be optimized for each srf cavity to give maximum gradient. The injector produces three interleaved 499 MHz beams. The rf separators are room temperature 499 MHz cavities which provide transverse kicks to steer the three 499 MHz beams generated in the injector to the beam switchyard or the recirculation path.

The commissioning philosophy was dictated by an aggressive schedule and the overall size and complexity of the machine. Systems were commissioned without beam as soon as they became available. When systems were commissioned with beam written test plans were used to record the purpose of the test and the results which were expected. Commissioning of the machine setup started with a set of nominal magnet settings extracted from the design model and put in a restorable file for the control system. These gave a reproducible starting point for all commissioning procedures. Machine setup proceeded from that starting point with written test procedures which stated a specific purpose for the procedure; e.g. Setup of Arc 1. The results, a set of corrector, quadrupole and dipole magnet values and beam position monitor readings, were saved for analysis offline using the modeling codes and as restorable starting points for later setup procedures. The written procedures themselves were changed where they were wrong or as better methods were discovered. Progress was made systematically in setting up the machine.

The last step in commissioning was to understand the properties of the machine using data files generated with beam in the machine. Analysis of the data led to an understanding of the specific and systematic errors in the model of the machine. This improved the model and will eventually allow machine configuration files to be built from the model which will not require manual operator intervention for operation.

2 SYSTEM OVERVIEW

The accelerator is made up of two antiparallel superconducting linacs operating at 1497 MHz. The beam is accelerated 400 MeV per pass through each linac. The linacs are connected by 180 degree isochronous, achromatic arcs. The beam is recirculated five times through each linac for a final energy of 4.045 GeV. The injector must deliver three interleaved 499 MHz beams of up to 100 microamperes current each. The energy of the beam delivered from the injector scales from 25 to 67.5 Mev as the linac energy is varied. CEBAF has already operated the linacs at up to 1000 MeV per pass with the presently installed cryomodules and anticipates operation at up to 1200 MeV per pass as a near term upgrade.

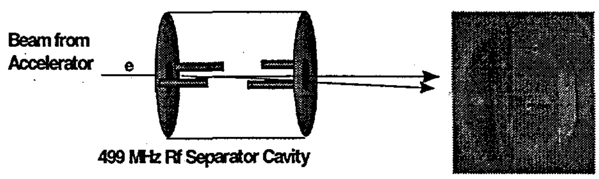

Figure 2

The beam is extracted to separate experimental halls through the use of warm 499 MHz rf cavities[1], see Figure 2. They provide transverse kicks to the beam which are then amplified by a carefully designed quadrupole system. These kicks move one 499 MHz pulse train far enough off the machine axis for septum magnets to steer it out into the beam switchyard. The beams to be recirculated are also given smaller kicks of opposite sign which steer them past the septum magnets and into the arc for transport to the next linac. This geometry dictates that only one beam of a given energy can be extracted for transport to an experimental hall. Our implementation does allow extraction of three full energy beams to the halls simultaneously.

The superconducting rf system is made up of 338 cavities in 42 and 1/4 cryomodules. This presently represents the largest installation of superconducting rf cavities in the world. Each cavity is powered by its own klystron with a separate low level rf controller. Each of these low level rf controllers is interfaced to the control system. The superconducting cavities have greatly exceeded the original design goals of 20 MV of accelerating gradient per cryomodule[2], see Figure 3, and can presently support operations in excess of 5.2 GeV. The limitation for the system presently is rf drive power from the klystrons. The limit is caused by a temporary reduction of the klystron beam voltage performed to lower site energy costs during the commissioning effort. The 2K refrigerator which cools the cavities can support 4800 W at 2 K and has had a > 95% availability during the scheduled accelerator runs. The system presently runs with a constant heatload of about 3100 W, of which 1500W is actual rf heatload.

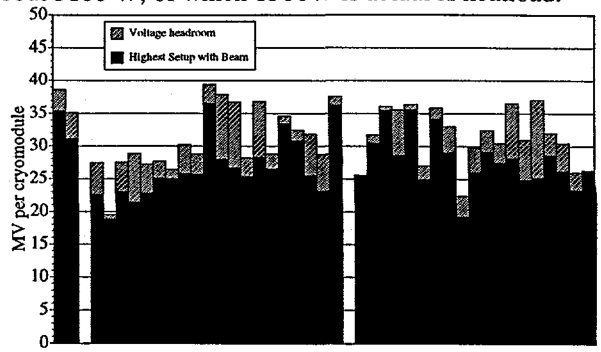

Figure 3

In 1993 CEBAF replaced its in-house developed control system with EPICS (Experimental Physics and Industrial Control System), the product of a multi laboratory collaboration. The use of EPICS has given us an open system architecture which is accessible from MATLAB, tcl/tk, UNIX, C, etc. The CEBAF operations and accelerator physics staff generated many of the high level applications necessary for commissioning in these more familiar formats. The CEBAF controls group provided the low level controls which made integrating the applications possible, in the process acting as system administrators and arbitraters between the commissioning teams and the hardware designers. This integration effort allowed CEBAF to become one of the largest installations of EPICS while simultaneously commissioning the accelerator over a two year period[3]. There are presently over 40,000 control points and more than 120,000 database records in the control system.

The beam transport system contains more than 2200 DC magnets which were individually field mapped before installation. Each magnet is tracked through a hysteresis loop to make the setting used more reproducible. To carry that reproducibility from the setpoint to the actual field, the power supplies used have relative accuracies ranging from 10^{-3} for correctors to 10^{-5} for dipoles. This reproducibility is necessary to allow beam to be restored to a desired orbit using a previously saved magnet configuration.

The average current in the beam at CEBAF can be up to 200 micoamps. This high average current, combined with a small spot size (<100 microns) may melt through the vacuum containment after a calculated integrated beam loss as low as 25,000 μA-μsec. The threshold for beam loss at which beam operation is terminated has been set to 20% of this value, 5000 μA-μsec, with a 2 μA minimum current. To measure this integrated loss, a system based on beam current accounting[4], as opposed to loss monitoring, was instituted. The system uses cavity monitors in the beamlines to measure the beam current at the exit of the injector and the entrances to the experimental halls and other beam dumps; e.g beam switchyard dump. The signals from the cavity monitors at the entrance and exits of the accelerator are compared and the difference is the beam loss in the accelerator. If the beam loss signal is above a threshold level it is integrated. If the integrator output reaches a threshold it shuts off the beam. The system also gives a realtime beam loss signal to the operations crew controlling the accelerator by which the presence of beam loss can be judged quantitatively.

3 COMMISSIONING

The challenge of commissioning is to establish the means to meet the baseline specifications reliably. $\Delta p/p$ has multiple sources all related to rf/beam misalignment, which must be budgeted. This error budget is divided between rf cavities operating off crest with respect to the beam, pathlength errors from pass to pass and M_{56} across the arcs. The size of the error budget is strongly dependent on the bunchlength since the error terms contribute momentum spread because of the difference in accelerating gradients in the rf cavities at the front and rear of the bunch. If everything else is perfect, it is still necessary to maintain a bunchlength of less than 2 degrees (3.6 psec) to meet the specification. If the bunchlength is kept to 1 degree, 1.8 psec, the allowable RMS error budget is 2 degrees of rf phase. The budget for the rf phase in the cavities is +/- 1 degrees with respect to the electron beam. This includes the low level controls and the master oscillator system. The pathlength must be measured, set and regulated to +/- 0.5 degrees. The error budget for M_{56} across each arc is much less than 0.5 m. To commission the machine it is necessary to measure and set the quantities of bunchlength, pathlength, M_{56}, and cavity phasing with respect to the beam.

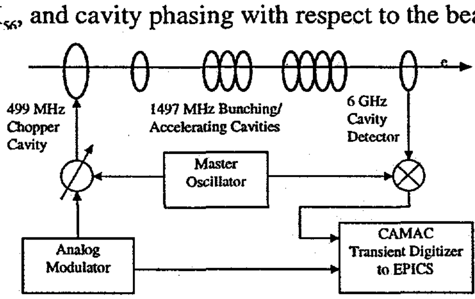

Figure 4

To measure the bunchlength at the end of the injector a phase transfer, M_{55}, measurement is done between the rf choppers and a cavity detector in the 5 MeV/c region[5]. This measurement is done by inserting a 10 degree bunch at the rf choppers rather than the normal 60 degree bunch. The rf phase of the choppers is then wobbled by +/-30 degrees to sweep the original bunchlength. The signal from the detector cavity is mixed with a reference from the master oscillator to produce a relative phase signal. This phase signal is proportional to the arrival time of the bunch at the cavity. By digitizing this phase signal and the phase of the choppers simultaneously and then plotting them against each other a plot of phase compression is generated in real time using control system software, see Figure 4[6]. This gives the shape of the bunch in phase space and a value for the bunchlength which was cross-calibrated against a backphasing technique. Using this tool a sensitivity study of bunch length versus bunching, capture and initial accelerator cavity amplitudes and phases was done for cross calibrating the PARMELA models of the injector. This system now allows operators to routinely measure the bunchlength as part of normal injector setup with a resolution of <0.1 degrees in less than 10 minutes. This system though has two significant drawbacks, it is destructive of the beam and is sensitive to space charge effects. To overcome those problems, a system using Coherent Synchrotron Radiation to measure the bunchlength[7] is being commissioned. The radiation is produced in the magnetic chicane where the injector is merged with the main machine and is detected in a room temperature diode. The radiated power at constant current is proportional to the bunchlength and has been calibrated against a backphasing technique. This system has a resolution better than 20 femtoseconds. It also is a non-intrusive, continuous measurement well suited to the CEBAF experimental program.

Once the injector bunchlength is set properly, the cavities must be set and maintained in phase with the beam. To do this, the beam orbit through the recirculation arc is fit against the machine model and an energy for the actual beam is calculated from the fit. The resolution of this measurement is about $2x10^{-5}$. To crest a cavity, the phase of the cavity is adjusted by +/-30 degrees and the energy re-measured. The plot of the measured energies versus phase offsets is fit to a cosine curve. From the fit a phase at which the energy is maximized is calculated. This is the zero degree "crest". Resolution with this technique is 1-2 degrees with each cavity requiring 1-2 minutes to set. This routine is automated and can be run during the machine development periods to keep the cavities on crest.[8]

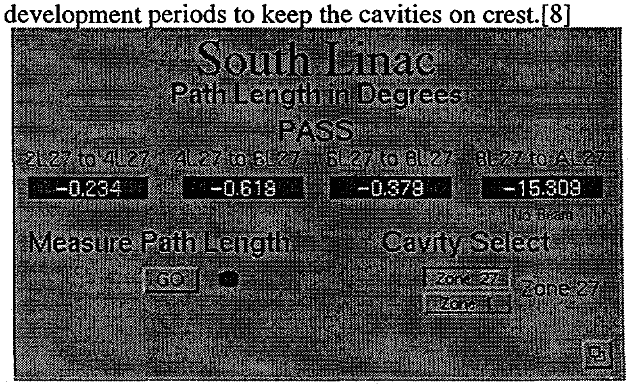

Figure 5

The pathlength from pass to pass is measured by a 1497 MHz cavity in the common beamline. The signal produced by the first pass beam through the cavity is mixed with the master oscillator to produce a phase error signal. The phase of the master oscillator is then adjusted to zero the phase error signal. The second pass beam is then put through the cavity and the difference in longitudinal position in the cavity between the first pass beam and the second pass beam shows up as a voltage on the phase error signal. If the rf phases are set to crest on the first pass as described above, all phase errors are due to pathlength errors during recirculation. By calibrating the detector using known phase changes in the reference, the relative pathlength errors of each recirculated beam with respect to the first pass beam can be measured in rf degrees[9]. The signals are then digitized for the control system. By putting the signals into EPICS it allows the pathlength measurement to be automated, see Figure 5, and digital signal processing techniques applied. The resolution of the measurement using those techniques is ~0.05 degrees. Correction of errors is accomplished by adjusting a three magnet chicane in the previous arc using a table of pathlength change versus integrated field settings for the magnets. Using this technique operators measure and correct pathlength in less than ten minutes.

The M_{56} across each arc must be budgeted as part of the momentum spread. If the $\Delta p/p$ is $2x10^{-4}$ in the machine, the bunchlength will grow 0.36 degrees/m of M_{56} with subsequent increase in $\Delta p/p$ proportional to the cosine of the bunchlength. To measure M_{56} across an arc the cavity monitors used for pathlength measurements are used. These cavities already provide a phase error signal proportional to the beam arrival time as outlined above.

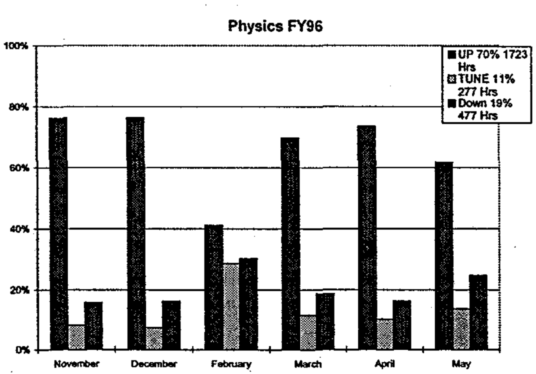

Figure 6

By modulating the momentum of the beam upstream of the cavity while monitoring the output of the phase detector a signal proportional to M_{56} is produced. With the known calibration constants for cavity phase versus detector output, a measurement of the M_{56} across an arc can be made with a resolution of better than 10 cm in 2 minutes. This system also acts as a separate check of the arc optics as an isochronous, achromatic bend. To adjust the M_{56} of the arcs, a set of quadrupoles in the four superperiods of the arc are scaled four times and the M_{56} across the arc is measured. A linear fit of the quadrupole scaling to the M_{56} measurements can be extrapolated to give a set value for the quad scaling at the point at which M_{56} is zero.

A new system which is being commissioned presently is a 30 Hz modulator system[10] which exploits the fact that the BPM systems take samples at 60 Hz. By putting alternating BPM measurements in two averaging buffers and synchronously modulating the beam with transverse kicks or momentum changes at 30 Hz, a plot of the two BPM buffers provides a difference orbit or a dispersion measurement updated at 30 Hz. The data from these kicks is also used to calculate the Courant-Snyder invariant to pinpoint the locations of lattice errors.

4 RESULTS

CEBAF delivered first beam to an experimental hall in July 1994. It was low duty factor at 845 MeV. In the 16 months that followed, construction of the accelerator and experimental hall was completed. Commissioning of hardware, including the spectrometers in the hall and the diagnostics described above, was completed. This effort culminated in a 4 GeV, 25 microampere, CW beam to the first of three experimental halls on November 5, 1995. The first nuclear physics experiment started 10 days later. Since then we have completed two experimental programs in Hall C, delivered CW beam at five discrete energies in a single eight hour period, delivered beams to a beam dump and an experimental hall simultaneously, generated a 45 MeV rf modulated beam from a GaAs photocathode, put beam into a second experimental hall and boosted the delivered current to 50-60 microamperes routinely. This was all done while maintaining an average accelerator availability of 70% during the scheduled experimental periods, see Figure 6[11].

The beam properties have been measured at several different energies, with results tabulated below:

Energy, MeV/c	x ε, nm-r	y ε, nm-r	Δp/p
45	3.0	2.7	1E-3
845	0.6	0.5	1E-4
2445	0.8	0.2	5E-5

The parameters are better than the baseline specifications for CEBAF. The improvements in the $\Delta p/p$ demonstrate the continuing efforts in improving the setup using the diagnostic systems described above.

The maximum beam currents achieved for the 5 passes are:

Energy, GeV/c	Current Achieved, μA	Rf Limit,μA
0.045	180	-
0.845	135	180
1.645	90	180
2.445	55	140
3.245	62	105
4.045	35	84

The rf limits on beam loading are lower presently than for normal operation because of the temporary rf power limitation described above.

5 LONG TERM OPPORTUNITIES

CEBAF has had great initial success, but must continue to run its presently approved experimental program reliably in the future. Half of the presently approved experiments plan to use polarized beam making operation of the polarized photocathode source essential. First beam has already been delivered to experimental Hall A and production beam delivery for commissioning the experimental equipment is scheduled to begin in July. Hall B is scheduled to receive first beam in October with commissioning to follow. The operation of multiple experimental halls will require that the setup of simultaneous CW beams to experimental halls be a routine occurrence. In the fall of 1996 small changes in the machine accelerating gradients will be made to allow smoothly variable energies to be provided to the experimental halls. This change will require the ability to accurately scale the machine model and obtain lattice elements from a realtime model server. Preliminary tests of this system were performed in the 1 GeV/c single pass experiment referenced above, but much work remains. The outstanding operation of the SRF systems makes 6 GeV operation a near term goal, primarily requiring some new power supplies in the recirculation arcs. A user-driven workshop has recommended an upgrade in energy to 8 to 10 GeV. This is being studied and is considered possible through the rework of installed cavities and an upgrade of the major dipole power supplies. These changes can be done during the regularly scheduled maintenance periods. The machine will be upgraded in a systematic fashion without impact on the scheduled experimental program.

6 SUMMARY

CEBAF has successfully started its experimental physics program. The commissioning philosophy based on written test procedures has productively used accelerator beam time. Procedures were updated as necessary and integrated into the operator interface. Several new diagnostics have been commissioned to allow fast routine measurements of bunchlength, pathlength, M_{56}, dispersion, beam loss, Courant-Snyder invariant and cavity phasing as part of normal machine setup and operation. These diagnostics have been incorporated into the EPICS control system as part of the standard operator interface. They allow the operations crews to setup the machine according to a procedure and meet the stringent baseline specifications of CEBAF.

The accelerator has delivered 3.2 GeV, 60 microampere, CW beam to an experimental hall; delivered three separate 60 microampere CW beams to a single dump simultaneously; delivered beam at > 1 GeV on a single pass; delivered rf separated beam to an experimental hall and a dump simultaneously; and delivered 25 microampere CW beam at five discrete energies in an eight hour period. The beam properties that have been measured so far meet or exceed the baseline specification. At the same time the machine has had a beam availability to the experimental hall of 70%.

A plan has been developed to upgrade the machine energy to 6 GeV in the near term with a long term goal of 8 to 10 GeV. This plan will be carried out during the normal scheduled maintenance periods.

7 REFERENCES

[1] C Leemann and C G Yao, "A Highly Effective Deflecting Structure", Proceedings of the 1990 Linear Accelerator Conference, p. 232

[2] C Reece, M Drury, C Hovater, J Mammosser, T Powers, J Preble, 'Performance Experience with the CEBAF SRF Cavities', Proceedings of 1995 Particle Accelerator Conference, p. 1512

[3] K. White, D. Kehne, "Operational Experience with the CEBAF Control System",Proceeding of ICALEPS 1995, publication pending

[4] R Ursic, K Mahoney, C Hovater, A Hutton, K Jordan, J Mammosser, C Sinclair, "CEBAF Beam Loss Accounting", Proceedings of 1995 Particle Accelerator Conference, p. 2652

[5] C G Yao, "A New Scheme for Measuring the Length of Very Short Bunches at CEBAF", Proc. Of the 1990 Beam Instrumentation Workshop, AIP Conference No. 229, p. 254-259

[6] G A Krafft, "Correcting M5,6 and T5,6,6 to Obtain Very Short Bunches at CEBAF", Micro-Bunch Workshop, AIP Conference Proceedings 367, p.46-55, 1995

[7] D X Wang, G A Krafft, E J Price, T Crowe, D Porterfield, P Wood, "Fast Coherent Synchrotron Radiation Monitor for the Bunchlength of the Short CEBAF Bunch", Micro Bunch Workshop, AIP Proceedings 367, p.502, 1995

[8] M Tiefenback, K Brown, "Automated Rf Phase Cresting in the CEBAF Linacs", CEBAF TN-96020

[9] G A Krafft, M Crofford, C Curtis, D R Douglas, S L Harwood, R Kazimi, R Legg, W Oren, K Tremblay, D Wang, "Measurement and Adjustment of the Path Length at CEBAF", Proceedings of 1995 Particle Accelerator Conference, p. 2429

[10] V. Lebedev, private communication

[11] S. Suhring, private communication

DISCLAIMER