JEFFERSON LAB, A STATUS REPORT*

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Abstract

Thomas Jefferson National Accelerator Facility (Jefferson Lab; formerly known as CEBAF), operates a 4 GeV, 200 μA continuous wave (CW) electron accelerator that re-circulates the beam five times through two superconducting 400 MeV linacs. Electrons can be extracted from any of the five recirculation passes and beam can be simultaneously delivered to the three experimental halls.

As the commissioning stage nears completion, the accelerator is becoming a fully operational machine. Experiments in Hall C have been underway since November 1995 with beam powers of over 300 kW at various energies. Hall A has received beam for spectrometer commissioning, while Hall B is expected to receive its first beam in the fall of 1996. Accelerator availability of greater than 70% during physics runs and excellent beam quality have contributed to making Jefferson Lab a world class laboratory for accelerator-based electromagnetic nuclear physics. With the high performance of the superconducting RF cavities, machine upgrades to 6 GeV, and eventually 8 to 10 GeV are now in the planning stages. Operational and commissioning details concerning all aspects of the machine will be discussed.

Introduction

As the commissioning process at the Jefferson Lab comes to an end, the emphasis is shifting from just making the machine work to making it work reliably and reproducibly. The physics experiments scheduled at the three end stations demand that the accelerator have the flexibility to provide a wide range of beam parameters and to do so with high precision and a minimum of downtime. These parameters range from currents as low as a few nanoamps to Hall B to over 100 μA to Halls A and C; beam energies from 0.5 to 4.0 GeV; small energy spread; tight control over beam stability; and all of the halls want highly polarized beam for many of the planned experiments. The accelerator must be able to provide beam to all three halls simultaneously as well as be able to switch to performing accelerator development tasks whenever the beam is not needed and then to return the beam on target as soon possible. The accelerator has been designed, built, and commissioned with these demands in mind.

The accelerator is a CW machine consisting of a 45 MeV injector capable of producing three beams, two 400 MeV superconducting linacs, nine recirculation arcs, a beam switchyard, and three experimental halls. The three beams have independently controllable current at 499 MHz that fills alternating buckets in the 1497 MHz accelerating field of the superconducting cavities. The beams are split by 499 MHz room temperature RF separator cavities which deflect bunches from any recirculation pass either to the beam switchyard or for further recirculation around the accelerator.

Important components of the accelerator are individual klystrons and control modules for each superconducting cavity, multiple beam capability, polarized beam capability, the EPICS (Experimental Physics and Industrial Control System) control system, and a highly reliable central helium refrigerator. The individual rf systems allow each cavity to be run at its optimal level and provide precise control over phase and gradient. The multiple and polarized beam capabilities are important for performing experiments simultaneously in the three end stations. The use of EPICS has proven to be a good choice in terms of reliability and flexibility for machine control. The high availability of the accelerator so far would not have been possible without the excellent performance of the central helium refrigerator.

Many details of the accelerator design have been discussed in previous conferences [1,2]. Here, the status of various subsystems will be reviewed, including the most recent progress. Since the accelerator at the Jefferson Lab is now a production machine for the nuclear physics community, the efforts, both present and planned, to make it highly reliable and flexible will be covered.

System Status

The accelerator consists of two superconducting linacs with a nominal energy gain of 400 MeV per pass and nine recirculation arcs. With up to five passes, the accelerator can deliver beams with energies in discrete steps between 845 and 4045 MeV. The magnet system and beam optics have not changed substantially since the last conference [2].

The injector is a unique system that must deliver three interleaved 499 MHz beams with each beam having individually adjustable current to match the requirements of the three experimental halls. The injector has been thoroughly modeled with PARMELA with excellent agreement. Several special diagnostics unique to the injector will be discussed later. The three beams can be extracted to separate experimental halls using normal conducting, highly efficient 499 MHz rf separator cavities [3,4]. The kick generated by the cavities is amplified by quadrupoles and septum magnets to either deflect the beam to an experimental hall or to recirculate. The geometry dictates that only one beam per

* Work supported by U.S. DOE contract DE-AC05-84ER40150

pass can be extracted to an end station, except for the highest energy pass, where all three beams can be sent to the halls simultaneously.

Since more than half of the planned experiments require the use of polarized electrons, the polarized electron source is becoming the focus for much attention. The polarized photocathode electron source, developed at the University of Illinois, has been installed in the injector region of the tunnel and integrated into the control system. A highly stable diode laser [5] locked to the master oscillator at 499 MHz drives the photocathode and produces a pre-chopped, polarized beam. A precision spin manipulator using electrostatic deflectors [6] allows the spin to be set to an arbitrary angle which can be varied to give the maximum polarization at the target. Another important feature under development is a 5 MeV Mott polarimeter for precisely measuring the polarization. With the first experiment using polarized beam planned for February 1997, much work remains to be done.

The superconducting RF system consists of 338 cavities in 42 full cryomodules and a quarter-cryomodule in the injector. This presently represents the largest installation of superconducting cavities in the world. A klystron drives each individual cavity, and each has its own low level RF controller. Having individual controls allows each to be run at its optimal level with precise control over the phase and gradient. The cavity performance has considerably exceeded the design goal of 5 MeV/m [7]. The entire RF system can be controlled and monitored from a single control system screen [8] that provides the operators with the ability to quickly locate problems. During commissioning, the klystrons have been operated at a voltage of 7 kV instead of their nominal 11.6 kV setting to save on the power bill. This has limited the total linac beam current to less than 400 μA versus the design value of 1 mA. As higher beam currents are sent to the end stations, the high voltage of selected klystrons is increased to support increased beam loading.

The central helium refrigerator continues to provide 2.08 K helium to the cavities with outstanding performance, achieving over 95% availability during the scheduled accelerator running period. The system, which can support 4800 W, presently operates with a constant heat load of about 3100 W, of which 1500 W is the actual RF heat load.

EPICS performs the difficult task of controlling and monitoring the numerous systems on the accelerator [9]. With over 40,000 control points and 120,000 database records, the accelerator has one of the largest installations in the world. EPICS is supported by an international effort and sharing between these groups reduces redundant software development. The open system architecture makes it possible to access the control system using more familiar programs such as Mathematica, Tcl/Tk, UNIX, and C. Thus much of the high-level application programming development can be done by accelerator scientists, leaving the controls group to focus on the difficult low-level work. As commissioning of the accelerator and the control system nears completion, the controls group can now concentrate on making the high-level applications more robust and reliable.

The very high average beam powers make machine protection an important issue. An initial system based on photomultiplier tubes proved to be cumbersome to set up and not always reliable. A new system, the beam loss accounting system [10] uses the "what goes in must come out" principle to measure beam loss in the accelerator. Stainless steel pillbox cavities at 1497 MHz pick up the beam current at the end of the injector and immediately before all of the experimental halls and beam dumps. The cavities are cross calibrated and will trip the beam off if the beam loss is greater than preset limits. These limits are presently an integrated beam loss of over 2.5 μA, or an instantaneous loss of 2500 μA-μs beyond a 2.5 μA threshold. This new beam loss accounting system is a major improvement in the setup and operation of the machine in a safe manner.

Machine Reliability and Reproducibility

To maintain our present goal of over 70% (and ultimately higher) uptime during physics runs, machine reliability and reproducibility are very important issues. Improving reliability and reproducibility covers a broad scope of topics, some of which are described here.

With over 2000 magnets, over 300 RF cavities, and 120,000 database records, keeping track of all of the operationally important settings is a difficult task. An operator-friendly interface that allows machine settings to be saved, restored, or compared [11] performs this task. Particularly useful is the ability to compare the present machine state to previous settings to find values that have gone off nominal.

In the early days, rebooting the IOC's (Input-Output Controllers) that run the EPICS control system caused great consternation in the control room as the beam would never come back exactly as before. To alleviate this problem, a system for saving before and restoring after a reboot was implemented. All of the volatile signals on each IOC have been determined and are saved and then restored in the appropriate order. One particularly pernicious problem was magnet irreproducibility. The only way to return the machine to its pre-reboot state was to cycle each magnet on that IOC through its hysteresis loop. A multidisciplinary group was dispatched to solve the problem and discovered that zero current was being sent to the magnets briefly during the reboot, thus causing them to fall off their hysteresis loop temporarily without informing the alarm handler. The problem was fixed and the machine reproducibility greatly improved.

As was mentioned earlier, the high average beam powers require a tight control over the beam to limit accidental beam strikes. One way to do this is to provide a security system to keep unauthorized persons from changing any control system parameters. Such a system has been implemented in EPICS and presently gives access only to the accelerator operations staff. Others may be granted access for testing or other purposes by request to the control room. While the security system cannot stop malicious damage, most unintentional

changes will be caught. In addition to machine protection, the security system provides another way to increase machine reliability during physics runs.

The EPICS alarm handler provides an efficient way to monitor systems to ensure that they stay within prescribed limits. A good example is the alarm handler for the magnet system. Numerous problems are monitored, with the mismatch condition and the off-loop condition being the most important. A magnet mismatch alarm occurs whenever the desired setpoint differs from the readback by a specific amount implying a hardware problem, while the off-loop alarm occurs whenever the software determines that the magnet has gone off its predetermined hysteresis loop. A new application of the alarm handler is its use in configuration control. Configuration control refers to a particular machine setup that is considered fixed and should not be changed by the operations staff. For example, a configuration alarm system has been implemented in the injector that includes settings for magnets, RF gradients and phases, and beam position monitor calibration factors. If any of these settings stray from their fixed values for whatever reason (operator error, computer error, etc.) an alarm will inform the operators.

Setting up the machine in a reproducible fashion can be hampered when different people do the work in slightly different ways, even when following the same written procedure. To improve stability, an "auto turn-on" sequence is being developed that will guide the operator through the task of turning on the machine, and automate the procedure as much as possible. For some systems which are not fully incorporated into the control system, automation is not yet possible and the program will present a list of tasks to perform. Eventually, the "auto turn-on" will become a "one button turn-on", thus reducing the person-to-person variability in machine setup.

A final topic for improving machine reliability is hardware tracking. Tracking hardware problems can show trends and identify common problems that need attention. A simple interface [8] allows operators and technicians to note hardware problems for RF cavities and control modules, beam position monitors, or magnets. A log of the problems for each item is kept and can easily be examined and compared to others. Another tracking system is the downtime logger. Whenever the beam is off for an extended time, the downtime logger is invoked and an operator enters the reason for the downtime. The operator then notifies the logger when the problem is resolved and the beam has been returned to its target. This system makes it easy to find the total up time, down time and tune time for the accelerator, as well as providing a simple mechanism for finding recurring faults that are limiting uptime.

Operational Issues

The setup and operation of an accelerator with such a large number of individual elements requires careful attention to written procedures that make use of quick, effective diagnostic methods. During commissioning, these procedures were developed by accelerator physicists and carried out by the operations staff. As mistakes were found and methods improved, the procedures were updated to reflect the improvements. All of the knowledge gained during the debugging of the machine setup was not forgotten, but turned into a trouble-shooting guide. The trouble-shooting guides are on-line information that guide the operators through a sequence of symptoms and solutions. The accelerator experts are thus relieved of having to respond to every crisis that occurs, leaving them more time to work on machine improvement and development.

To facilitate machine setup and to verify that the accelerator meets the necessary specifications, a number of useful diagnostic tools have been developed, some of which are described below.

One of the more important machine parameters is energy spread (specified to be $< 10^{-4}$, 1σ). The beam emittance (specified to be $\varepsilon_{rms} < 2\times10^{-9}$ m at 1 GeV) is typically lower than what is required by the end stations and is not an issue, except for betatron matching between accelerator sections. The origin of the energy spread is in the injector. If all of the cavities in the accelerator are perfectly crested, the injector must provide a bunch length of less than 2° (3.6 ps). The nominal bunch length for the injector (1°) is lower than this. The bunch length is measured and monitored using several different methods (see D.X. Wang, this conference, for more details).

The first method uses a 6 GHz pickup cavity to measure the time of flight for small slices of the bunch as it is swept across a slit in the beam chopper[12]. A plot of the input phase versus the output phase at the pickup cavity yields the bunch length. An operator interface can carry out the measurement in about 10 seconds, and after a few iterations, the phases of the injector RF components can be set to within 0.1° by matching the measured phase space to the optimum configuration as determined by PARMELA simulations. By doing a harmonic analysis of the data, the amount of phase change necessary to bring the phase space to its ideal configuration can be calculated and the whole process automated [13]. The disadvantage of this phase transfer method is that it cannot be carried out during normal beam operations, and that is it sensitive to space charge effects.

A new method based on coherent synchrotron radiation (CSR) has recently been developed [14]. A magnetic chicane separates the injector from the linac, and a special diode sensitive to a wavelength corresponding to the nominal bunch length is positioned after the first dipole in the chicane to pick up the coherent synchrotron radiation. The radiated power at constant beam current is inversely proportional to the bunch length and can be calibrated against a backphasing measurement. The CSR method provides a non-destructive measure of the bunch length and can operate in pulsed or CW mode. The CSR signal is presently being incorporated into the control system.

Two other important parameters affecting the energy spread are the path length and the M_{56}, or the change in path

length with energy change. Both of these parameters are measured using sensitive phase detection methods. For the first pass in the accelerator, the maximum energy is set by phasing the rf cavities in each linac. For the upper passes, the phasing cannot be altered, and the path length through each arc is set by using "dogleg" magnets [15]. The path length from pass to pass is measured by detecting the phase difference in a 1497 MHz cavity in the line common to all of the passes. The signal from the first pass is used as a reference, and the phase error signal between the first pass and other passes gives a measure of the path length difference with an accuracy of 0.05°. The dogleg magnets can then be adjusted to zero the phase error. The whole measurement process has been incorporated into the control system and an operator can measure and correct the path length for all passes in less than ten minutes.

The recirculation arcs are designed to be achromatic and isochronous, implying that the M_{56} matrix element should be zero. With a non-zero M_{56} the energy spread across the bunch will cause it to debunch through the arc, thus increasing the energy spread for the next arc. The same cavities used for measuring the path length are also used to measure M_{56}. By modulating the beam energy before entering an arc, and picking up the phase error signal after the arc, the M_{56} can be measured to within an accuracy of 10 cm in 2 minutes. The M_{56} can then be set to zero by measuring it as a function of quadrupole scaling for a family of quadrupoles in the arc proper and choosing the scale factor that minimizes M_{56}.

All of the above measurements are difficult to perform unless all of the accelerating cavities are operating near their crest in phase. In the early stages of commissioning, this was a time consuming task requiring the operators to phase each cavity manually. Such methods are clearly not acceptable for an operational machine where machine time is at a premium. The energy of the beam can be calculated to 2×10^{-5} by fitting the beam orbit through an arc to the machine model. Each cavity can then be automatically set by a program [16] which varies the phase of the cavity by ±30° and measures the fitted energy at several phase points. By fitting the results to a sinusoidal curve, the phase providing the maximum energy can be found. Each cavity requires 1 to 2 minutes to set with a resolution of 1-2°.

Results

The accelerator provided beam for its first nuclear physics experiment in November of 1995, culminating over 10 years of design, construction, and commissioning. Highlights of the accelerator operation include:

- the completion of 3 experimental programs in Hall C
- delivering 25 μA, CW beam at five discrete energies in an 8 hour period
- delivering beam from the polarized source to an end station
- delivering CW beam to Hall A (5 μA) and Hall C (60 μA) simultaneously
- running at greater than 1 GeV for one pass
- maintaining an average accelerator availability of over 70% during physics runs [17], and
- delivering beam with a maximum power of over 300 kW.

The maximum delivered single beam current (see Table 1) for various energies are listed below.

Table 1 Beam current results

Energy (MeV)	Max Current (μA)
45	200
845	135
1645	90
2445	55
3245	62
4045	80

Long Term Plans

In response to the needs of the nuclear physics community, several longer term programs are under way to provide the wide range of beam parameters necessary for all of the planned experiments. These programs cover multiple guns, the ability to easily run the accelerator at any allowable energy, and future energy upgrades.

The present injector has the capability of delivering three unpolarized beams with currents covering a dynamic range of about 1:2,000. It can also deliver one polarized beam (not at the same time as unpolarized). While this situation has been adequate for commissioning, it will not fulfill all of the upcoming experimental requirements. Hall B will require a few nanoamps when it comes on line and Halls A and C often need over 100 μA. All of the halls want polarized beam, and beams with the maximum polarization cannot be delivered to all three halls simultaneously for an arbitrary energy from one gun [18]. All of these requirements point to the need for multiple guns and an injector to merge the beams into alternating rf buckets. Work is under way to design an injector that will cover the whole range of current, polarization, and pulse structure needed for the planned physics program.

During commissioning, the energy of the injector has been set to an energy of 45 MeV, and the linacs to 400 MeV, giving deliverable energies from 845 MeV to 4.045 GeV, and the beam optics have been optimized for this setup. Work on a momentum management system has begun which will set both the distribution of rf gradients based on the total desired energy and current and the optical lattice. Preliminary tests of this system were performed in a 1 GeV, single pass test, but much work remains to be done. For example, it is not yet known if simply scaling the magnet settings with the momentum change will work, or if a model based system will provide better results

The last major aspect of the long range planning is an upgrade to push the maximum available energy above 4 GeV. The outstanding operation of the superconducting cavities makes running at energies approaching 6 GeV a possibility in the near future, requiring only upgraded dipole magnet power supplies. Ways to push to energies beyond this are also being studied, but will require considerably more time and money.

Conclusion

As the commissioning stage nears completion, the accelerator at the Jefferson Lab is becoming a fully operational machine. Experiments in Hall C have been underway since November 1995 with beam powers over 300 kW at various energies. Hall A has received beam for spectrometer commissioning, and beam to Hall B is expected in the fall of 1996. Accelerator availability of greater than 70% during physics runs and excellent beam quality have contributed to making Jefferson Lab a world class laboratory for accelerator-based electromagnetic nuclear physics.

Considerable effort has gone into improving the reliability and reproducibility of the machine by concentrating on the many subsystems that make up the accelerator. This includes topics such as automation, trouble-shooting guides, useful alarm handlers, fast and efficient diagnostics, tight control over computer reboots, hardware tracking, and control system security. All of these topics not only improve the operability of the machine, but also give the operations staff the ability to efficiently run the machine without continual input from the accelerator scientists.

Operational highlights include: delivering 25 μA CW beam at five discrete energies in an eight hour period; delivering beam from the polarized source to an experimental hall; running at greater than 1 GeV for a single pass; delivering 4.0 GeV, 80 μA CW beam to an experimental hall; delivering rf separated beam to Hall A and Hall C simultaneously; and sending three separate 60 μA CW beams to a dump.

Plans for the future include a number of topics of interest to the users. To provide the widely varying beam requirements of the three experimental halls, the injector will be expanded to have multiple guns that can operate simultaneously. Improvements of the accelerator as a whole to further increase machine reliability are a must. Finally, a plan is being developed to upgrade the maximum beam energy to 5-6 GeV, and eventually to 8-10 GeV as feasible.

References

[1] G.A. Krafft, "Status of the Continuous Electron Beam Accelerator Facility", Proc 1994 Linear Accel. Conf., 9 (1994)

[2] R. Legg, "Operating Experience at CEBAF", Proc. 1995 Eur. Part. Accel. Conf., in publication.

[3] C. Leemann and C. G. Yao, "A Highly Effective Deflecting Structure", Proc. 1990 Linear Accel. Conf., 232 (1990).

[4] R. Kazimi, J. Fugitt, A. Krycuk, C.K. Sinclair, and L. Turlington, "CEBAF's New RF Separator Structure Test Results", Proc. 1995 Part. Accel. Conf, 1109 (1995).

[5] M. Poelker, "High Power Gain-switched Diode Laser Master Oscillator and Amplifier", Appl. Phys. Lett. **67**, 762 (1995).

[6] D. Engwall., B. Dunham, L.S. Cardman, D.P. Heddle and C.K. Sinclair, "A Spin Manipulator for Electron Accelerators", Nucl. Instr. Methods **A324**, 409 (1993).

[7] C. Reece, M. Drury, C. Hovater, J. Mammosser, T. Powers and J. Preble, "Performance Experience with the CEBAF SRF Cavities", Proc. 1995 Part. Accel. Conf, 1512 (1995).

[8] J. Karn, B. Dunham, and M.G. Tiefenback, "Operational Monitoring of the CEBAF RF System", Proc. of 1995 Part. Accel. Conf., 2271 (1995).

[9] K. White and D. Kehne, "Operational Experience with the CEBAF Control System", Proc. of ICALEPCS 1995, in publication.

[10] R. Ursic, K. Mahoney, C. Hovater, A. Hutton, K. Jordan, J. Mammosser, and C.K. Sinclair, "CEBAF Beam Loss Accounting", Proc. 1995 Part. Accel. Conf., 2652 (1995).

[11] B. Dunham, "Control System Data Management from an Operational Point of View", Proc. of ICALEPCS 1995, in publication.

[12] C.G. Yao, "A New Scheme for Measuring the Length of Very Short Bunches at CEBAF", Proc. of the 1990 Beam Instr. Workshop, 254 (1990).

[13] G.A. Krafft, "Correcting M56 and T566 to Obtain Very Short Bunches at CEBAF", Microbunch Workshop, 46 (1995).

[14] D.X. Wang, G.A. Krafft, E.J. Price, T. Crowe, D. Porterfield, and P. Wood, "Fast Coherent Synchrotron Radiation Monitor for the Bunchlength of the Short CEBAF Bunch", Microbunch Workshop, 502 (1995).

[15] G.A. Krafft, M. Crofford, C. Curtis, D.R. Douglas, S.L. Harwood, *et al.*, "Measurement and Adjustment of the Path Length at CEBAF", Proc. 1995 Part. Accel. Conf., 2429 (1995).

[16] M. Tiefenback and K. Brown, "Automated RF Phase Cresting in the CEBAF Linacs", CEBAF Tech Note TN-96020.

[17] S. Suhring, private communication

[18] C.K. Sinclair, "Accelerator Setups Which Provide Longitudinal Beam Polarization to More than one Experimental Hall Simultaneously", CEBAF Tech Note TN-96032