OVERVIEW OF CEBAF OPERATIONS AND SRF-RELATED ACTIVITIES AT JEFFERSON LAB*

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Abstract

The Jefferson Lab nuclear physics accelerator, CEBAF, continues to reliably deliver polarized CW electron beams with energy in the range of 1 - 5.5 GeV. The 330 installed 1500 MHz SRF cavity systems perform solidly, contributing a small fraction of the machine downtime. The 5-pass energy capability has been pushed to near 6 GeV by application of *in situ* helium processing to almost all of the cavities. New operational tools have been developed and deployed which allow the operators to quickly reconfigure the linacs for optimal performance under various energy and beamloading conditions. Plans are being developed for upgrading CEBAF to 12 GeV. This requires a new cryomodule design and use of 5.5 recirculations for the top energy. Subsystem development is underway on a 7-cell cavity, new zero-backlash tuner, improved magnetic shielding, and an arc-free waveguide rf feed, as well as a new cryomodule mechanical system. Significant facility changes have been made in preparation for this work. A new rf control system will also be required.

In addition to the successful nuclear physics program, the JLab FEL produced a world-record 1.7 kW CW in the infrared. An upgrade program is ready to begin. Significant efforts have also been directed in support of APT and RIA, as well as collaborations related to cavity fabrication and processing techniques.

1 CEBAF OPERATING EXPERIENCE

1.1 Operations

During fiscal year 1999, CEBAF provided 5360 physics beam hours with an average active-use multiplicity of 2.6. This included delivery of beams throughout the 0.8–5.5 GeV range. Use of polarized electrons has now become standard. No separate commissioning period was allocated as the energy of the machine was increased. There were 4- and 6-week downs in January and June for equipment installation and maintenance.

The sources of unscheduled down time during this year were well distributed among the different systems.[1] Other than the arc trips, addressed below, the SRF system directly contributed 48 minutes (less than 0.1%) of the 1620 hours of unscheduled downtime. (See Figure 1.)

While numerous improvements have been implemented in many systems, only minor changes have been made to the SRF systems. During the January 1999 maintenance

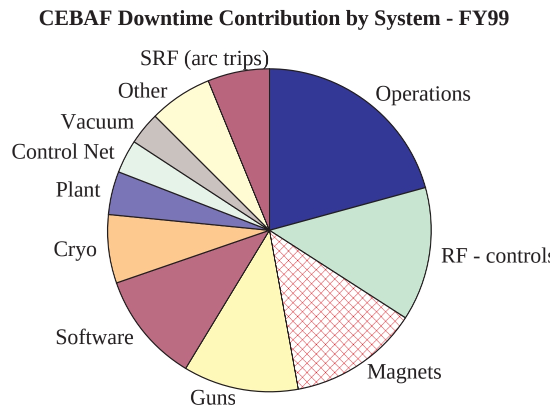

Figure 1. Distribution of downtime sources.

down an additional eight cryomodules received *in situ* helium processing, yielding an additional 52 MV. Almost all of the installed cryomodules have now received this treatment.[2] The processing reduced field emission in many cavities, such that routine operations approaching 6 GeV are being contemplated. Operationally, the most apparent limitation as cavity gradients are increased remains the frequency of arc detector trips of a cavity. The phenomenon is now believed well understood and routines have been developed to systematically manage it.

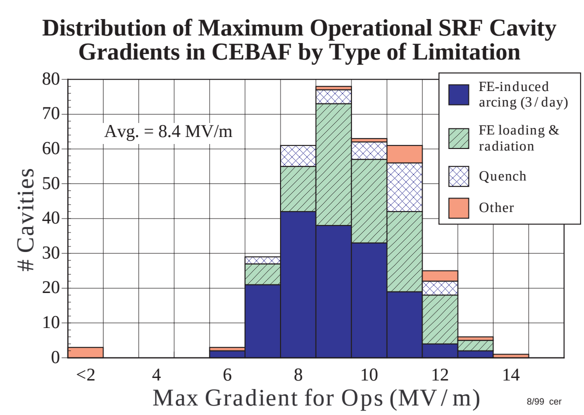

Figure 2. Gradient limitations for CEBAF cavities.

The cryomodules were assembled and commissioned 1991-1993. The most common performance limitation is field emission inside the cavities between 5 and 11 MV/m. (See Figure 2.) As the cold ceramic window on the input rf waveguide (~7 cm off the beamline) is exposed to the resultant electron and x-ray flux, it tends to accumulate a static charge until flash-over occurs, producing the rf trip.[3] The frequency of such trips is a function of cavity gradient and is observed to vary smoothly up to > 1 per hour for many cavities.

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Thus, while there may be cryogenic capacity to absorb the degradation in Q, this arcing phenomenon has become our practical limit. Figure 2 shows the distribution of gradients that yield an arc rate of 3/day for each cavity.

As the CEBAF energy has been increased, so has the sophistication of the tools used to set up and run the machine. Since each of the 330 cavities in CEBAF is individually powered and controlled, we have a large number of degrees of freedom. To get the best performance from the overall system, we have developed a new optimization tool for use by the operators. This software tool (called LEM++) manages the arcing-related trip rate, total cryogenic load, and rf control margin subject to the program-defined constraints of required linac voltage and total beamloading current.[4] As the accumulated knowledge of the individual cavity performance improves, one may translate this into more optimal operation of the machine. In this way the number of arc trips per day during 5.5 GeV operation decreased from ~220 to ~60 between March and July 1999. LEM++ also automatically allocates the available 2 K load according to the rf setup actually used and historical Q_0 values for each cavity.

The operational capability of the CEBAF cryomodules is depicted in Figure 3. The approach to the operational limits of CEBAF is represented in Figure 4.

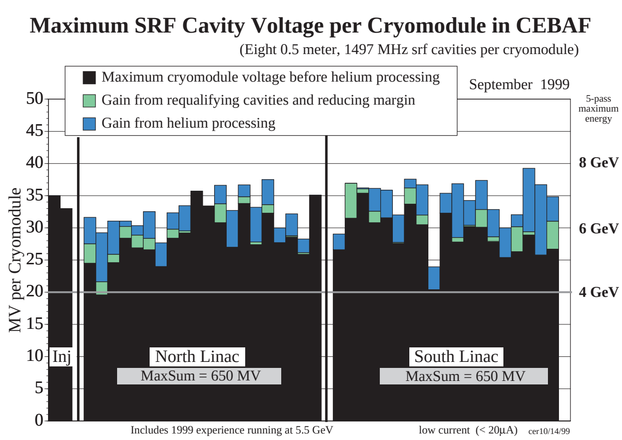

Figure 3. Peak capability of the CEBAF cryomodules.

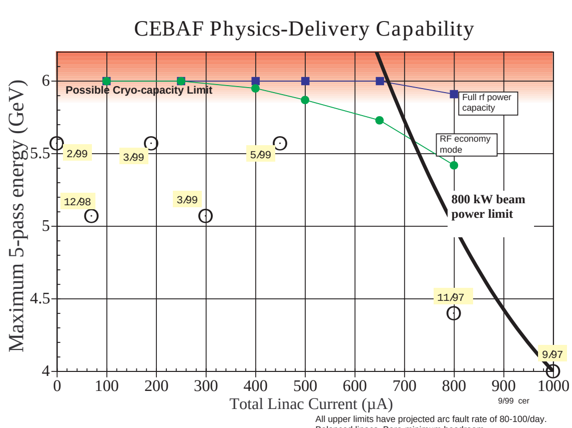

Figure 4. Approaching the limits of CEBAF.

2 PREPARATIONS FOR UPGRADE

Although designed to deliver 4 GeV, the robustness of the installed SRF cavities has permitted convenient increases in energy. CEBAF was first run at 5 GeV in December 1998, then increased to 5.5 GeV in March 1999. CEBAF ran at 5.5 GeV for about 3 months in 1999. The first attempt to deliver 6.0 GeV beam to an experimental area is scheduled for August 2000. This appears to be the limit of what the present CEBAF installation can provide. Design concepts have been explored which lead to CEBAF beam energies of 12 and 24 GeV. [5] See Figure 5.

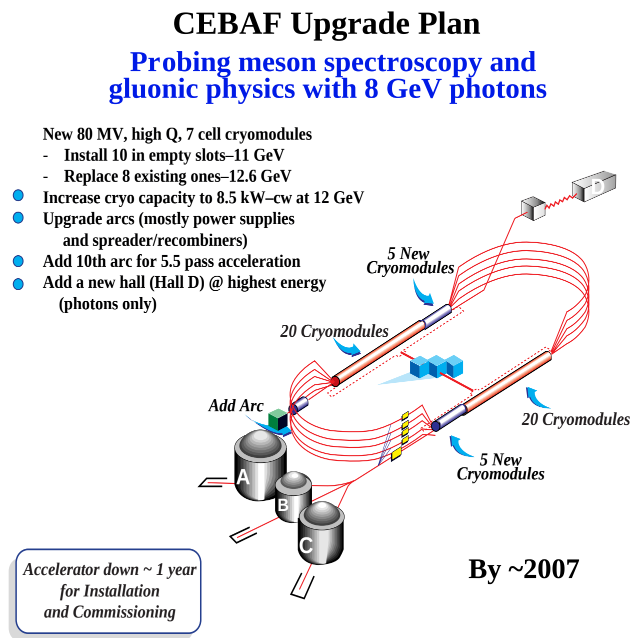

Figure 5. CEBAF upgrade to 12 GeV.

2.1 New cryomodule design

For all upgrade schemes, a new generation of cryomodules is required. The cavities for the upgrade will be 7-cell 1497 MHz structures very similar to the original 5-cell design. Adding the two additional cells permits a 40% increase in voltage for the same level of cavity performance. The rf couplings are being changed. [6] The waveguide HOM couplers are being replaced by two coaxial ports. The fundamental power coupler has been significantly redesigned. The total cryomodule length increases by ~50 cm. Titanium helium vessels will be built around and integral with each cavity. This eliminates all helium-to-beam-vacuum flanges and reduces the required liquid helium inventory.

The upgrade design calls for reduced total beam current (maximum of 400 μA). This, together with the design gradient of 12.5 MV/m and a detuning allowance, including microphonics, of 25 Hz, pushes the optimum external Q of the input coupler to 2.1×10^7.

2.2 New input coupler

The input waveguide coupler has been redesigned to obtain this value while also dramatically reducing field asymmetries on the beamline which produced a transverse kick in the original design.[7] This redesign has also significantly reduced dimensional sensitivity of the coupler geometry. As a consequence, the new cryomodule design does not require interior bellows on the beamline.

To eliminate the susceptibility to arcing at the cold ceramic window, the new design has none. The input waveguide is retained, but the ceramic window is moved out to room temperature, and the option for eliminating its line-of-sight from the cavity incorporated into the waveguide.

2.3 Tuner and rf controls

For the upgrade cryomodule, the bandwidth (~75 Hz) will be significantly less than the Lorentz detuning (~500 Hz at 12.5 MV/m). In addition, to minimize rf power requirements, we want to keep each cavity accurately tuned (~2 Hz). Present designs call for a new tuning system with two parts: a coarse tuner with a range of ±200 kHz and resolution of 100 Hz, and a fine tuner with a range of ±1 kHz and resolution of 1 Hz. [8]

A new rf control system will be needed to deal with these more demanding control requirements. Operational efficiency makes the use of a self-excited loop for each cavity appear very attractive.

2.4 Process modifications

The price to be paid to increase the active length filling fraction by changing from five to seven cells per cavity is the relinquishment of the "hermetic cavity pair" concept used in the original CEBAF design.[9] We are thus preparing to assemble an eight-cavity string for each module as a single clean operation.

Consistent performance of the upgrade cavities will be very important. A series of process-development tests has begun, from which we expect to establish improved procedures for cavity preparation and assembly.[10] These tests are addressing the various chemical processing, cleaning, storage, evacuation, rinsing, and assembly processes.

To provide improved process control for cavity processing, we have recently installed three custom cavity processing stations within our cleanroom. One station provides fully automated flow-through chemical processing. It has been integrated into our acid transfer system and ultrapure water system. Another station is a high pressure rinse cabinet. The third is a final rinse/cavity storage station. All are sized to handle a 7-cell upgrade cavity as well as 5-cell 700 MHz cavities.

2.5 Magnetic shielding

To keep the cryoplant requirements manageable, consistently high Q_0 values will be required of the upgrade cavities. For the new cryomodules, additional magnetic shielding is thus required to reduce the existing ambient fields in the CEBAF tunnel, which in some locations are as high as 4 gauss.

2.6 Residual gas dynamics

Experience with CEBAF has demonstrated that the adsorbed gas in the thermal transition region of the input rf waveguide can be unstable. Although one end of the waveguide provides an excellent 2 K cryopump, for several cavity systems, rapid changes of rf conditions stimulates an observed pressure burst (>1×10^{-7} torr). Because it is most mobile, excessive hydrogen is considered to be the culprit, either directly, or as a catalyst for transient desorption of other species.

An examination of the gas dynamics and appropriate gas source controls has begun, so that we can assure stable performance of the upgrade cryomodules operating at still higher gradients.

3 FREE ELECTRON LASER

3.1 Operations

The Jefferson Lab IRFEL is the world's most powerful tunable source of coherent CW photons. In July 1999, the FEL produced 1.7 kW CW at 3.1 microns. This was accomplished using one each of modified versions of the CEBAF quarter and full cryomodules, and employing energy recovery by returning the spent electron beam through the SRF cavities.

The FEL is intended to serve as a demonstration test bed for industrial processes using intense, tunable photons using technology which is scalable to much higher average powers.

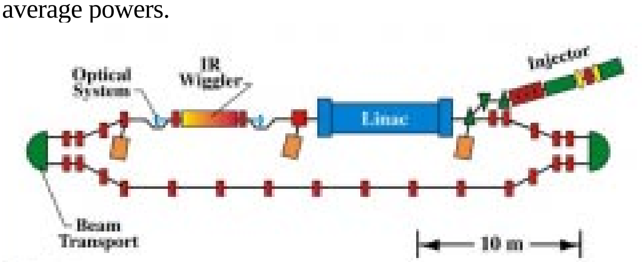

Figure 6. Schematic layout of the JLab IR FEL.

Up to 4.4 mA is routinely and reliably being recirculated with energy-recovery in the FEL's SRF linac, with no signature of longitudinal or transverse instabilities.

In order to address scalability issues, experiments are underway to observe the multipass beam breakup threshold current of the present configuration in order to test the accuracy of existing models. Additional experimental and theoretical studies are in progress to model possible energy instabilities that can arise as fluctuations of the cavities' fields couple to the momentum compaction of the recirculator, energy aperture, and the FEL.

The short (~ps) bunches and high peak current generate a significant amount of high-frequency higher-order-mode power.[11] One particular symptom encountered was anomalous indications from the thermopile IR detectors which are used to provide an interlock for overheating of the warm rf window in CEBAF cryomodules. The detector sits in a tube set into the waveguide sidewall. The tube is well beyond cutoff for the fundamental, but not for the HOM's above 11 GHz, which are readily produced by the FEL bunch train. Installation of copper screens appears to have solved the problem.

3.2 IR FEL upgrade

While we are continuing to support initial user tests and beam dynamics studies, plans have been prepared to upgrade the IR FEL to use a 10 mA, 160 MeV beam. This will require three high-performance cryomodules and additional power for the two injector cavities. We expect to proceed with this upgrade over the next three years.

4 OTHER ACTIVITIES

4.1 Cavity R&D

A series of experiments on single-cell cavities has examined the benefits of an *in situ* bake at ~145°C for up to 50 hours. A surprising increase in Q_0 has been observed which indicates a reduction of BCS surface resistance by nearly a factor of two for high-purity niobium. Further tests are exploring the mechanism that produces this effect. [12]

4.2 Energetic condensation of niobium

Aiming to develop improved methods for producing niobium films, a study is underway which examines the interdependence of niobium ion energy, film structure, and SCRF surface impedance in the formation of niobium films.

4.3 Field emission scanning system

A new system has been developed with which to perform systematic studies of DC field emission from niobium surfaces. The system provides scanning field emission microscopy integrated in common vacuum chamber with SEM/EDX, optical microscopy, and high-temperature (~1400°C) heating. Commissioning of the system has just begun. We expect to use the system both for basic characterization studies and as a diagnostic tool monitoring cavity treatment processes.

4.4 Electron beam weld development

A modest on-going effort continues to develop electron beam weld parameters for niobium which are featureless, quench-free, and do not require costly weld joint preparation.[13]

4.5 Alternatives to wet chemistry

Small efforts are also directed at finding suitable alternatives to the wet chemistry used for niobium cavity surface preparation. We are examining the use of thermal and plasma etching, as well as rapid surface remelting by a global e-beam treatment of an entire cavity surface.

4.6 RIA & APT work

JLab has been collaborating with staff from several other institutions in support of a new accelerator facility for the production of rare isotopes (presently known as "RIA"). In particular, JLab has contributed to design and fabrication of a new superconducting low-beta structure and low-level control systems.[14] Several staff members also contributed to conceptual planning for such a facility.

JLab has provided assistance to the APT project by testing components and modifying facilities in order to process and test some APT cavities in the coming year.

5 ACKNOWLEDGEMENTS

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