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CEBAF CRYOMODULES: TEST RESULTS AND STATUS *

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Abstract

The Continuous Electron Beam Accelerator Facility, (CEBAF) is undergoing construction in Newport News, Virginia. When completed in 1994, the accelerator will be the largest installation of radio frequency superconductivity. Production of cryomodules, the fundamental cryogenic building block of the machine, has started. They consist of four sets of a pair of 1497 MHz, 5-cell cavities contained in separate helium vessels and mounted in a cryostat with appropriate end caps for helium supply and return. RF, heat load, and mechanical performance of the first unit tested and status of the project will be discussed.

Introduction

The Continuous Electron Beam Accelerator Facility (CEBAF) will provide a low-emittance, 200 μA electron beam with energies up to 4 GeV for fundamental experimental studies in Nuclear Physics to be carried out simultaneously in spectrometers and detectors located in three separate halls.

The beam acquires its energy by recirculating up to five times through two antiparallel linear accelerators (Fig. 1). At CEBAF, the objective of achieving a continuous beam of electrons is reached through the use of superconducting microwave cavities which are operated in a truly continuous wave (CW) mode.

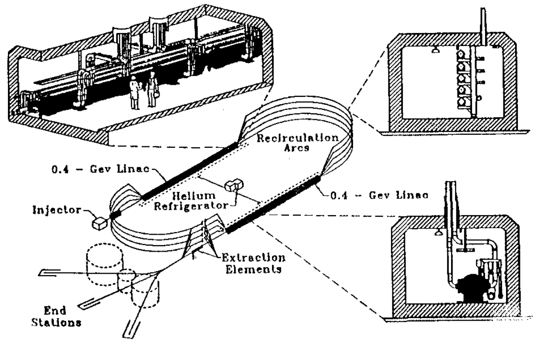

Figure 1. The general structure of CEBAF's recirculating superconducting linacs.

The accelerator will consist of 338 superconducting niobium cavities (160 in each linac and 18 in the injector) originally developed at Cornell University. The 5-cell cavities are excited in the π-mode at a frequency of 1497.000 MHz and at an accelerating gradient of 5 MV/m and will be kept at 2 K by a 4800 W refrigerator, the largest such system operating at this temperature.

Cavities are assembled in pairs (the smallest, independently testable vacuum unit); in turn, these are assembled into a single vessel, thus forming a cryounit. Four such units are joined into a cryomodule: this constitutes the smallest set of cavities which can be independently cooled and installed in or removed from the accelerator system. Overall, a cryomodule must be capable of delivering 20 MeV to the beam while contributing approximately 57 W to the 2 K heat load.

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This paper describes the structure and properties of a cryomodule, the prototype of which has been tested and is being installed in the CEBAF injector for tests with beam energies of 25 and 45 MeV (Front End Test). The results of the extensive measurements performed on the first cryomodule are given.

The Cryomodule

The superconducting cavities used for CEBAF are fabricated out of niobium with high thermal conductivity: this guarantees that the cavities can attain high accelerating gradients even in the presence of losses, without a complete thermal transition to the normal state.

Table I. Superconducting Cavity Design Parameters

f_o (2 K, TM_{010} -π)	1497.0000 MHz
E_{acc}	≥ 5 MV/m
Q_o (2 K, 5 MV/m)	$\geq 2 \cdot 4 \times 10^9$ (5.4 W)
Q_{ext} (FPC)	$6.6 \times 10^6 \pm 20\%$

The cavities are electron beam welded starting from ten drawn elliptical half-cells and from drawn or machined auxiliary parts (fundamental power coupler, Higher-Order-Mode (HOM) coupler, HOM waveguide elbows, beam tubes, etc.). They are tuned for field flatness and frequency of the TM_{010} π-mode so that at 2 K the frequency will be as close as possible to 1497.000 MHz. Typically, the low temperature frequency falls within 100 kHz of the nominal one. Tuners are used to achieve and maintain the final nominal frequency.

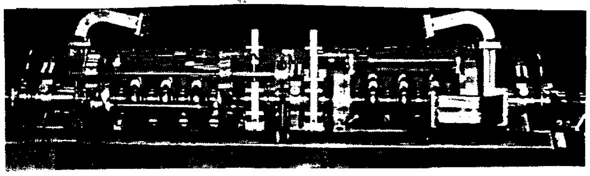

Figure 2. Cavity pair assembly ready for insertion into Helium vessel. Visible are the tuner assemblies, HOM elbows, gate valves, cold windows.

The cavities are then chemically treated to remove surface impurities and assembled in pairs in a class 100 cleanroom. The cavity pairs have cryogenic gate valves in the beam tube and are kept constantly under a vacuum better than 10^{-9} Torr. The gate valves also allow any pair of cavities to be removed for servicing without disturbing the vacuum in adjacent cavity pairs. The gate valves have a 3.8 cm clear aperture, and use all metal construction except for their valve seals, which are made out of Viton. Warm sealing is required, but cold sealing is not. The valves have manual actuation mechanisms and are equipped with locks to prevent unintentional actuation. Each cavity is fitted with a cryogenic alumina or sapphire window on the waveguide of the fundamental power coupler (FPC) and with HOM waveguide elbows and loads.

The HOM waveguide elbows allow modes, generated by the beam at frequencies above 1900 MHz (the HOM waveguide's cutoff frequency), to propagate toward the HOM loads and be

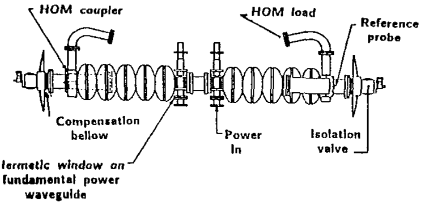

Figure 3. Schematic drawing of cavity pair assembly.

absorbed by them. Modes with frequencies below 1900 MHz must propagate out through the FPC in order for the power to be removed from the cavity. The HOM loads are located at a suitable distance in the HOM waveguide so that the fundamental TM_{010} π-mode is not appreciably damped by them.

Without the HOM loads, the transverse modes excited by the beam could make the beam unstable for beam currents close to the nominal current of 200 μA. With proper mode damping, the instability current is pushed to at least 20 mA.

The CEBAF cavities are the only superconducting structures of any accelerator for which the HOM power is dissipated at the cryogenic temperatures. This feature has the advantage of not adding windows or penetrations to the assembly and also improving the HOM power extraction efficiency. On the other hand, the few hundred milliwatts of HOM power dissipated per cavity during normal operation constitute an additional heat load on the cryogenic system. Other modes of operation of the beam which would increase substantially the HOM power must be excluded unless more refrigerator power will become available.

The present cryomodule contains three different types of loads, which have been evaluated as prototypes. The first two types contain one or two alumina cards coated with a lossy nichrome pattern and placed inside a stainless steel can with the same cross section as the HOM waveguide. The cards are positioned at appropriate locations for efficient absorption of various modes. The third model, which has been adopted for production, uses a zero-porosity, lossy ceramic which is compatible with the ultra-high vacuum of the accelerator and which is thermally grounded to the helium bath via a copper flange.

Because of the unpredictable behavior of the cavity frequency during cooldown and due to the pressure fluctuations in the helium bath, the final frequency of each cavity at 2 K is reached by means of an active tuning system. Mechanical screw tuners are used which operate inside the liquid helium without any lubrication. Yokes installed on the first and fifth cells of the cavity are operated either in expansion or compression via a gear reduction, ball-screw mechanism. Rotary feedthroughs transfer the motion from room temperature stepping motors to the cold tuner assembly. Limit switches prevent excessive tuner travel which could damage the cavities.

Each cavity is equipped with a field probe located in one of the arms of the HOM couplers. Once calibrated (the nominal external Q is 1.3×10^{11}), the probe is used to determine the field level in each cavity and the power extracted is used by the RF control systems which regulate phase and amplitude of the fields in each cavity for energy stability. Two .141" diameter semirigid coaxial cables carry the signal to a helium vessel feedthrough and then to the room temperature vacuum vessel feedthrough.

A rectangular stainless steel, copper-plated waveguide of reduced-height WR650 size bridges the gap between the cold window and room temperature. The waveguide incorporates two sets of bellows for mechanical adjustment and is kept under a vacuum guarded by a room temperature teflon window on one side and the cold window on the other. The vacuum level in this assembly, maintained by a 20 l/s ion pump, is typically 10^{-7} Torr.

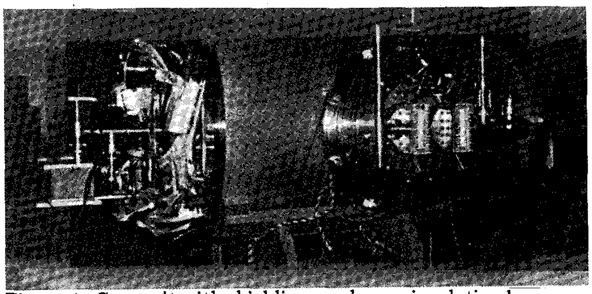

Figure 4. Cryounit with shieldings and superinsulation layers and ready to be connected to the rest of the cryomodule.

Insulation vacuum is established between the inner helium vessel and the outer vessel at room temperature. Layers of superinsulation, the magnetic shielding and the secondary heat shielding at 45 K are found in this space. Inside the helium vessel, heaters are located which facilitate the thermal stabilization of the systems heat load.

The L-shaped end can pair completes the cryomodule vacuum jacket and passes the beam pipe from the helium vessel and cavities to the warm beam pipe region. The L-shape provides room for the steering magnets and vacuum systems needed between each cryomodule. Two female bayonet on each end can accept U-tubes that couple the cryomodule to the helium transfer lines from the central refrigerator and complete two cryogenic circuits. The primary circuit begins in the supply end can where 2.2 K helium gas at 2.8 atm is throttled through a Joule-Thomson valve to 0.031 atm creating 2 K superfluid helium which then passes to the helium vessels. The helium vessels are kept at 0.031 atm by pumping on the 2" return bayonet in the return end can through which the boil-off gas is recycled to the refrigeration system. The secondary circuit passes 45 K helium gas at 3.6 atm through the supply end can, into the cryomodule thermal shielding and back through the return end can to the refrigeration system. Temperature diodes and pressure taps on each end can are used to monitor and control the operating conditions in each cryomodule. To protect the cavities from over pressurization, a safety relief valve and a pressure relief device is provided on the return can. A relief valve is provided on the supply end can to protect the shield circuit. A parallel lift plate is located on each end can to vent pressure in the insulating vacuum space.

The module is equipped with interlocks that monitor the vacuum levels in the window assemblies and in the cavity vacuum. A thermopile infrared detector is placed in each window assembly to observe temperature rises in that region. A photomultiplier tube detects arcing in the same assembly and the related interlock shuts off the RF power in that event. Other interlocks control helium bath pressure, helium level, and tuner's travel.

Production and Test Facilities

The production and testing facilities for superconducting cavities and cryomodules are located inside the Test Lab. Here the tested cavity pairs can be processed into cryounits in four

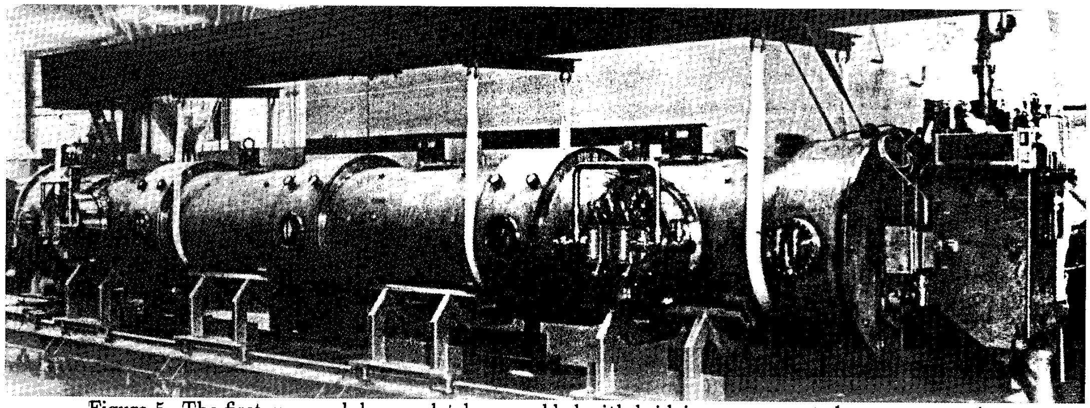

Figure 5. The first cryomodule completely assembled with bridging components between cryounits and end can for primary (2 K) and secondary (45 K) circuits inlet and outlet.

parallel stalls where tuners, thermometers, liquid helium level sensors, waveguide window assemblies, helium vessel, superinsulation layers, thermal and magnetic shielding, vacuum vessel, controls and interlocks hardware are fitted around the cavities. The four parallel lines merge into the cryomodule assembly area, where alignment is done, the gate valves between cavity pairs are opened, bridging components for liquid helium distribution installed between cryounits and the end cans with supply and return lines for both 2 K and 45 K circuits and the Joule-Thomson inlet valve, are placed at both ends of the module. Each cryomodule is then tested in a totally enclosed, radiation shielded area to establish its thermal, mechanical, vacuum and RF performance before its installation in the accelerator tunnel.

A 100 W, 2 K refrigeration system is used for the test areas. The shield circuit is capable of handling up to 500 W, while operating between 28 and 45 K. Using these systems, first the static heat load of each module is measured by determining the additional mass flow when the cryomodule is in the refrigeration circuit.

Two identical systems which use 2 kW CW klystrons have been set up for RF testing. They make use of Voltage-Controlled Oscillators (VCO's) which are phase-locked to the cavity under study using phase-locked loops. Several quantities are measured: the external Q of the fundamental power coupler (FPC), the maximum attainable electric field gradient, the unloaded Q_o of the cavities by calorimetry, at various field levels, the external Q of the field probe. The klystrons are protected by high-power, WR650 waveguide circulators and waveguide switches are used to distribute the power to the appropriate cavity. Because the cavities are strongly overcoupled during these measurements (the nominal external Q of the FPC is 6.6×10^6 which would provide close to a matched condition with a full beam (5 beamlets) of 1 mA), large standing waves occur in the waveguide. To minimize the uncertainties in power measurements induced by the large reflections, several diagnostic ports are available to sample forward and reverse power. Comparison of redundant readings and a careful characterization of the microwave network usually lead to agreement between power readings at the 10% level or better. When the field level in the cavity has been established with good confidence by these power readings, this is used to recalibrate the field probe: it has occasionally been observed that the losses of the cryogenic cable from the field probe to room temperature are subject to unpredictable changes during thermal cycling and in this case only other independent measurements of power can be used to determine the field level in the cavity.

Measurements of the unloaded Q_o as a function of the accelerating gradient E_a are done by determining the amount of power to be removed from a control heater in order to maintain pressure and helium mass flow through the system. This method can provide only a 20% accuracy, but it is sensitive enough to establish whether or not a substantial degradation of the cavity's performance has occurred since it was initially tested and before incorporation into the cryomodule.

During the RF tests, the frequencies and external Q's of all the resonances of the TM_{010} passband are checked, as well as of those higher-order modes which are critical for the operation of the machine.

Eight Geiger-Muller counters are placed around the cryomodule at all times to monitor intensity and space distribution of the radiation produced by field-emitted electrons. Radiation readings are used to correlate the onset of the field emission with increased losses and the final breakdown of the cavities.

The tuner of each cavity is operated, usually to move the π-mode resonance by ±100 kHz about the 1497.000 MHz value. These measurements produce hysteretic calibration curves which are later used in the operation of the accelerator.

The assembly and installation lines and the testing apparatus and procedures have been designed to accommodate the projected production rates of cavities for the CEBAF accelerator over the next three years. A typical production rate of one cryomodule every three weeks has been planned for, with the possibility of speeding up the process (especially those parts connected with cooling and warming up cycles for testing) to produce up to two cryomodules a month.

Results of the Tests on the First Cryomodule

The first cryomodule produced at CEBAF underwent several tests over the last year. Many of the tests were repeated during five different cooldowns, both to evaluate the repeatability of the measurements and to determine whether component and cavity performances might degrade either with time or with repeated thermal cycling. The cryomodule was also transported to the accelerator tunnel and back to the Test Lab to determine whether any aspect of the trip (vibrations, temporary loss of active pumping on some sections, etc.) would adversely affect the properties of the system.

A total of ten cavities were tested, since two of the original ones were replaced when a cold leak developed in a beam pipe indium seal. Other temporary leaks were occasionally observed in other parts of the system. A summary of the results of the tests are given in Table II. Although the module was tested several times, reported here are the results of the latest series of tests. Some of the parameters did change somewhat from test to test as a result of known events (e.g. small leaks, thermal cycling of transmission probe cable, etc.)

Deviations of the values of the external Q of the fundamental value of $6.6 \times 10^6 \pm 20\%$ are generally due to resonances in the input waveguides. Only cavity 1 has a permanently low value which is the consequence of a deformation of the coupler waveguide.

Table II. Results of the Tests on the First Cryomodule

Cavity #	$Q_e(\times 10^6)$	E_{amax} (MV/m)	Q_o (E_a) (10^9)
1	1.6	> 6.4	2.5 (5)
2	4.1	9.4	2.5 (4.5)
3	5.7	7.3	1.7 (5)
4	5.3	8.2	1.3 (3)
5	4.5	8.5	1.6 (5)
6	6.8	7.5	.2 (3)
7	7.4	7.5	1.0 (5)
8	6.0	6.4	1.7 (5)

In most cavities, the maximum attained electric field was at the threshold for field emission induced breakdown: at those fields, the radiation level increased to several hundred mR/hr.

In other cavities, the maximum field represents the highest field reached with the maximum klystron output and a clear breakdown limit could not be established.

One cavity exhibited a Q_o significantly lower than any of the others. In spite of the high losses, a significantly high field could be reached in the cavity before breakdown occurred. It is believed that the losses may not be associated directly with the cavity cells, but that they may occur mainly in some of the other niobium cavity components.

The variations in the external Q of the field probes are mostly due to reflections in the feedthroughs at which the coaxial cables are connected at the helium vessel. Erratic behavior of the transmission losses in those cables has been observed during cooldown and repairs have been affected. The field probe power has been and will be in any case recalibrated at each cooldown to provide the RF control system with an up-to-date and accurate data base.

The cross-talk between the two members of cavity pairs was measured for two of the pairs and it was found that the beam tube between the cavities provides isolation for the fundamental mode of the order of 65-70 dB.

Two of the cavities were operated continuously for close to 24 hours to evaluate their performance over an extended period of time. No major operational problem was encountered, only occasional interlock trips from moderate window heating and arcing in one of the cavities was observed.

All the tuners were exercised and their tuning curves determined. One of them could not be operated during the first three cooldowns, probably because of some remnant lubricant on some mechanical moving parts. That problem was circumvented by continually operating the tuner during cooldown, thus preventing freezing. After the nominal frequency was set by the tuners, drifts were observed between tens of Hertz and hundreds of Hertz per day, depending on the stresses which the tuner-cavity system was subjected to.

Selected higher order modes were observed and their external Q measured against those of an undamped cavity. Typically, most modes were damped from Q's of 10^6 - 10^7 to Q's of 10^3 to 10^4.

The static heat load measured for the cryomodule was about 15 W (the design value is 13 W).

The total heat load produced by the cavity losses is slightly above the design value (each cavity should dissipate 5.4 W or less when operated at the nominal field value of 5 MV/m). Some of the cavities had excessive losses, but these could be operated at lower field levels in order to maintain the overall heat budget under control.

Given the results of the test, a possible operating condition which would provide 20 MeV is given by the following set of accelerating gradients and corresponding dissipations:

Cavity	1	2	3	4	5	6	7	8	Total
E_a (MV/m)	6.5	6.5	6	3	6	2.0	5	5	20 MV
P_d (W)	11	11	12.5	3.6	12.5	4.2	13	7.7	75.5 W

Conclusion

During the past year, a wealth of data, experience and information about the behavior of a cryomodule and its components has been gathered.

The first cryomodule produced at CEBAF has now been successfully assembled, tested and moved to the accelerator. Some of the individual components in this prototype performed below, but close to, the specification. As a whole, the cryomodule performs in a more than acceptable way for operation in the injector which will start in the fall. It will provide 20 MeV to the electron beam with a tolerable dissipation of about 75 W at 2 K. A new cryomodule with full production components will replace this prototype in the near future.

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