SUPERCONDUCTING CAVITY DEVELOPMENT FOR THE CEBAF UPGRADE*

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Abstract

Long-term plans for CEBAF at Jefferson Lab call for achieving 12 GeV in the middle of the next decade and 24 GeV after 2010. In support of these plans, an Upgrade Cryomodule, capable of providing more than twice the operating voltage of the existing CEBAF modules within the same length, is being developed. In particular, this requires the development of superconducting cavities capable of consistently operating at gradients above 12 MV/m and $Q \sim 10^{10}$. We have engaged in a complete review of all the processes and procedures involved in the fabrication and assembly of cavities, and are modifying our chemical processing, cleaning, and assembly facilities. While we have retained the cell shape of existing CEBAF cavities, the new superconducting structure will be substantially different in several respects, such as the higher-order-modes damping and the fundamental power coupling systems. Design features and experimental results will be presented.

1 INTRODUCTION

CEBAF's long-term institutional plan calls for an energy upgrade to 12 GeV in the middle of the next decade, and to 24 GeV after 2010. While the details of the upgrade path are still being developed, a top-level parameter list has been generated which guides the selection between the various options [1]. The Upgrade Cryomodule is the key component of the upgrade of the acceleration system. Its design is also somewhat insensitive to the details of the upgrade option that is ultimately chosen, once the top-level parameters have been defined, and it can be viewed as a building block that can be applied to a large number of upgrade paths. For these reasons, most of the development efforts in support of the upgrade are directed toward the development and demonstration of prototype Upgrade Cryomodules.

In order to increase the voltage that is provided by a cryomodule within a given length, one can either increase the gradient at which the cavities are operating, or increase the effective accelerating length, or both. While it may be argued that maximizing the accelerating length is the approach that presents the least technological risk, for cw accelerators such as CEBAF, maximizing the length instead of the gradient has the added advantage of lowering the dynamic load on the refrigeration system.

For this reason, it was decided early that the Upgrade Cryomodule would still include 8 cavities, but that these would be 7-cell cavities (70 cm) instead of the present 5-cell (50 cm). The baseline option calls for these cavities to provide a minimum voltage of 8.75 MV with a maximum power dissipation of 17.5 W at 2K, *i.e.* their Q must be at least 6.5×10^9 at 12.5 MV/m. Thus the greatest challenge is not so much in achieving a high gradient but in maintaining a high Q at high gradient. Given the constraint imposed by the available refrigeration (17.5W per cavity), cw operation at 15 MV/m would be practical only if the Q at that field were at least 10^{10}.

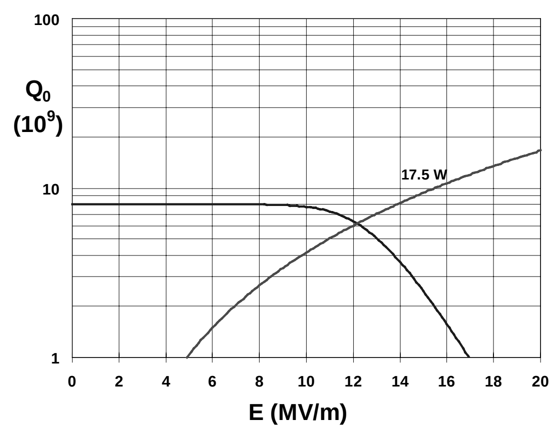

Figure 1: Design Q-curve for the Upgrade 7-cell cavity, with line of constant 17.5 W power dissipation

2 CAVITY DESIGN

2.1 Cell Geometry

While the CEBAF cavity cell design could be improved, the potential benefits do not seem critically important, and the first 7-cell cavity prototype has been built using the existing cell geometry.

The existing cell shape is characterized by ratios E_p/E_{acc} of 2.6 and H_p/E_{acc} of 47 Oe/(MV/m). Designs with lower ratios exist; however, as was mentioned before, the greatest challenge is not so much high gradient as low power dissipation. In that respect, the shunt impedance of the existing design compares well with that of others. Another attractive feature of the existing cell design is the

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relatively high cell-to-cell coupling coefficient (3.3%), which reduces the sensitivity of the field profile to the lack of dimensional uniformity and mechanical stability as the number of cells is increased. A redesign of the cells is still an option, although a low priority one.

2.2 Intercavity Beamline

The topology of the Energy Upgrade cryomodule places a full complement of couplers between each pair of adjacent cavities. The mechanical design of this region has proved a challenge. The required functionality includes: a Fundamental Power Coupler (FPC), 2 Coaxial Higher-Order-Mode (HOM) dampers, a field probe, tuner, connections to the LHe vessel, and a demountable joint.

One of the concerns raised in the desire for longer accelerating length within the same overall footprint of the module (increasing fill factor) is that the separation between cavities is small enough to lead to undesirable amounts of crosstalk. This was explored at some length [2] and found not to be a problem. For very short separations, half-integral wavelength separations ($\lambda/2$, or λ) are needed to keep the real power flow small. $\lambda/2$ spacing is much too short to place couplers in the intercavity space and places severe demands on the demountable joint. λ spacing has some attractive features, and some attempts were made to design the needed functionality into this space. No solutions were found that appeared practical to assemble.

For separations larger than λ, the crosstalk between adjacent cavities is small enough not to require a "magic" choice of distance. At the current design value of 30 cm (1.5 λ), the power flow between cavities under nominal conditions is negligible.

2.3 Fundamental Power Coupler

Experience with waveguide couplers in the CEBAF design was generally positive. Waveguide couplers can be made relatively flexible and forgiving of displacements along the beamline. Heat loads are easily controlled, and there are no tight manufacturing tolerances.

One unpleasant feature of the original waveguide coupler was a large transverse beam kick. This characteristic originated from its synchrotron heritage, where the damping of the $4\pi/5$ TM_{010} mode was important for beam stability. In the present (relatively) low-current linac application, this is not an issue, and the coupler itself could be adjusted for near zero transverse kick [3].

The remaining displeasure with our existing coupler system centered on the windows, in particular the location of the cold window close to the beamline. We have settled on a revised topology [4] that has a single warm ceramic window (shielded from line-of-sight interaction with the cold cavity) that is not required to pass HOMs. This does place more stringent demands on the waveguide thermal transition. It must be installed nearly free of particulates, and with low outgassing characteristics.

2.4 Higher-Order-Mode Couplers

Among the modifications implemented in the cavities for the CEBAF Energy Upgrade is the HOM damping scheme. In the original CEBAF design a healthy safety factor against multipass beam breakup was included. The Q's of the relevant dipole modes were maintained at the 10^3-10^4 level in order to guarantee two orders of magnitude margin in the threshold current for instability.

To re-evaluate the requirements for HOM damping in CEBAF, a program of measurements, simulations and experiments is being implemented. Measurements of HOMs in the accelerator and FEL have shown that self-polarization of the coupler can enhance the Q of some modes to levels as high as 5×10^7. Even with these high Q's the machine is stable against BBU for the nominal current. Therefore we expect that, for the Energy Upgrade, even higher Q_{ext} would be acceptable because the average current in the accelerator will be lower, and the injection energy and the overall energy of CEBAF will be higher. We estimate that the requirements on the Q_{ext} of dipole modes could be relaxed by about two orders of magnitude, up to 10^5-10^6 from 10^3-10^4.

At present, the baseline design includes a tuned filter HOM damping scheme following the TESLA-Saclay design [5], which is compatible with the integrated helium vessel used for the Upgrade cavities.

The possibility of eliminating entirely specialized HOM absorbers is also under investigation. A program of studies of HOMs is being implemented, which will help in clarifying the true HOM limitations at CEBAF and in the FEL.

3 FACILITIES AND PROCEDURES

In order to meet the design specification of high gradients and low losses with tighter distribution in performance, and mechanical changes to the cavity and cryostat design, we concluded that an upgrade of the facilities and the assembly procedures used for the fabrication of CEBAF cryomodules was needed. The goal was to increase the control over process and assembly variables. The production run of CEBAF cryomodules (1990-1994) generated a broad distribution of acceptable operating gradients between 4 and 14 MV/m. The most predominant limitation in individual cavity performance is field emission and field-emission-related RF window arcing, mainly due to surface contamination from process and hardware particulates. Our review has led to an assembly procedure that will pre-qualify the 7-cell cavities by vertical testing of the 7-cell assembly prior to addition of beam tube couplers. After qualification, the couplers and helium vessel will be added and the cavity will be prepared for final assembly of an 8-cavity string. The final string assembly will then be completed in the Class 100 production cleanroom. To reduce particulates and to narrow the individual cavity performances in the final string, production semiconductor-style chemistry and high-pressure rinsing (HPR) cabinets have been installed in the cleanroom. The chemistry and the HPR cabinets are self-contained, PLC-controlled and menu-driven. In addition to these cabinets, a part-cleaning cabinet and a final ozone-rinsing cabinet are currently being designed as part of the final string assembly procedures. During the commissioning of these new facilities, procedures will be adjusted as necessary to reduce exposure of internal cavity surfaces to particulates generated by assembly in order to meet the new module performance specifications.

4 PROTOTYPE 7-CELL CAVITY

A 7-cell cavity was built from existing half-cells and dumbbells remaining from the CEBAF cavity production phase. Particular care was taken in the preparation of the dumbbells prior to joining them by electron beam welding: each dumbbell was carefully inspected and mechanically ground, removing all visible surface imperfections such as indentations or scratches. Subsequently, the dumbbells were degreased and chemically polished for 1 - 2 min, partially removing the surface damage layer. The equatorial welds were done from the outside with standard welding parameters, but only one dumbbell was added at a time starting from one end half-cell and each weld was thoroughly inspected. If necessary, some mechanical grinding of the welds was done with subsequent degreasing and slight chemical polishing. Prior to completing the equatorial welds, beam pipe assemblies were welded to the end half-cells.

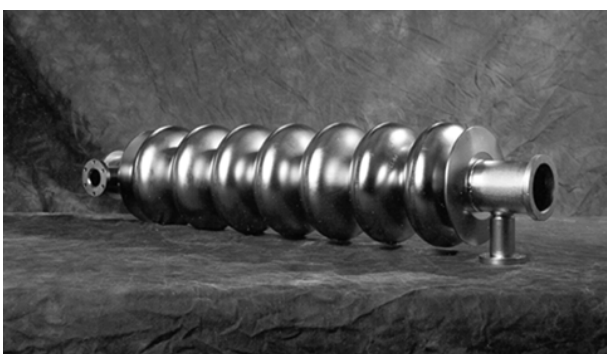

Figure 2: Prototype 7-cell cavity

The cavity had a π-mode frequency of 1494.45 MHz with a field-nonuniformity of 16 % (in E^2). After pretuning the π-mode to 1494.6 MHz and a field flatness of 5%, the cavity was chemically prepolished 3 times for 2.5 min; the acid temperature did not rise above 25 ^{o}C. The total frequency shift was about -500 kHz, corresponding to a material removal of approximately 90 µm, assuming a uniform material removal over the entire cavity surface.

For the final surface preparation, the cavity was degreased for 1 hour in a caustic solution with ultrasonic agitation. After pure water rinsing, buffered chemical polishing was done, removing an additional 75 µm. Thorough rinsing was followed by high-pressure ultrapure water rinsing for more than 90 min.

In the clean room the cavity was rinsed twice with reagent grade methanol. Immediately after assembly, the cavity was attached to the vertical test stand and evacuated by a turbo pump for typically 15 min. When a pressure of less than 5 x 10^{-6} torr was reached at the turbo pump, the cavity vacuum system was transferred to the ion pump on the test stand. Fast cooldown of the cavity to 4.2K took place in approximately 1 hour; during pump-down to 2K the temperature dependence of the surface resistance was measured. A residual surface resistance of 7.8 nΩ corresponding to a Q_{res} of $3.5x10^{11}$ was measured.

At 2K the cavity gradient was initially limited to 16.3 MV/m by a breakdown, which seemed to be initiated by field emission. After He-processing the quench limit improved to 17.5 MV/m at a Q-value of $6.2x10^{9}$. During the pump-down of the helium bath from 4.2K to 2K a pressure sensitivity of 99 Hz/torr was measured.

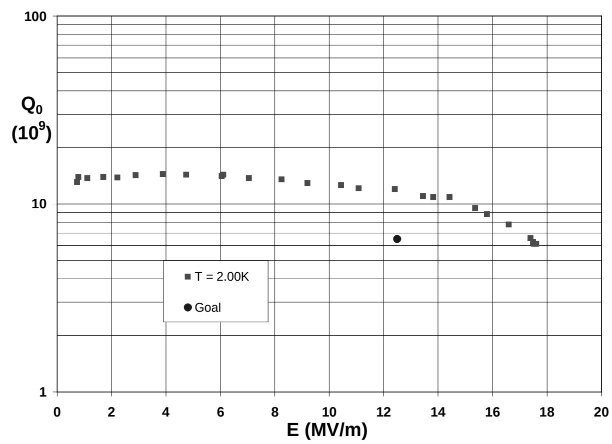

Figure 3: Results of the test of the first 7-cell prototype.

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