SUPERCONDUCTING PERFORMANCE OF CEBAF/CORNELL PROTOTYPE CAVITIES FABRICATED BY BABCOCK & WILCOX

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Abstract

Babcock & Wilcox (B&W) is participating in the development of an industrial production capability for CEBAF superconducting rf accelerator cavities. Five-cell elliptical cavities of the Cornell design (operating frequency 1500 Mhz) have been fabricated at B&W and tested at the Cornell Laboratory of Nuclear Studies (LNS). Performance specifications (accelerating field of 5 MeV/m at a residual quality factor of 3 x 10^9) have been exceeded by comfortable margins in the first two prototypes. A comparison between the performance of cavities fabricated from niobium of different purities is presented.

Introduction

CEBAF is the largest accelerator to be built in the U.S. using superconducting rf cavities. For timely production of 220 meters of cavities required, it is important to qualify industry at the earliest possible stage so that problem areas can be identified and people trained to develop the appropriate sensitivities. Industrialization of this advanced technology could also prove valuable for accelerators beyond CEBAF. To ensure a successful transfer of technology, a partner relationship between Cornell LNS and B&W was established and found essential to the final success of the prototypes built. The Cornell cavity has been chosen by CEBAF because of the advanced state of the design,[1] because of successful tests results already achieved by Cornell on prototypes built by Cornell, and because of successful tests in the Cornell Electron Storage Ring (CESR).[2]

Three cavities were fabricated by B&W, the major differences among them was the RRR of the Nb used: the first one from RRR = 100 Nb as received from the supplier, the second from RRR = 380 Nb, achieved by yttrification[3] of 200 RRR material, and the last one to complete the cavity started by TRW.[4] The third cavity, which has yet to undergo final testing also had a RRR of 380 achieved by yttrification at TRW of RRR = 200 material.

Structure

Figure 1 shows an exploded view of the cavity for identifying manufacturing components. The structure can be divided into three major subassemblies: the fundamental power waveguide coupler assembly (FPC), the higher order mode waveguide coupler assembly (HOM) and the center cell assembly. The center cell assembly is made completely from high RRR Nb, and each of the coupler subassemblies also includes a high RRR half-cell. For the most part, the B&W strategy was to adopt the Cornell fabrication technology as closely as possible considering the facilities available at B&W. Final tuning, chemistry and cold tests were carried out at Cornell LNS. Cornell has also made available, dies for all the deep drawing work, drawings, computer numerically controlled milling machine information and a fabrication procedures document.[5]

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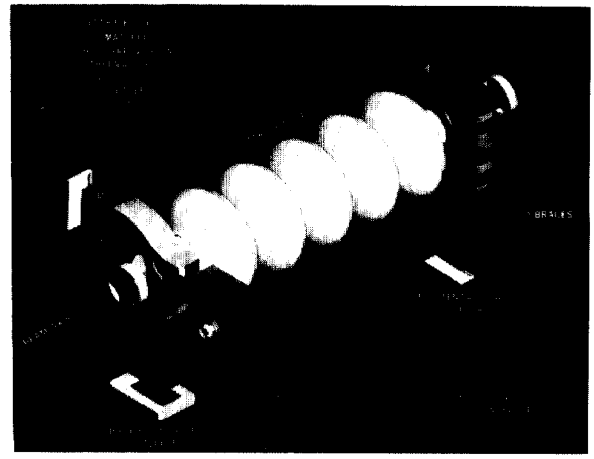

Figure 1. Exploded view of Cornell/CEBAF 5-cell elliptical cavity.

Fabrication Notes

Material Properties

Niobium used for the cells of the first cavity was borrowed from the Cornell supply of W. C. Heraeus high RRR Nb. The RRR reported by the supplier was 95. RRR measurements were made on five samples from the plate before shipping to B&W as well as from each of the disks cut from the cups after stamping. RRR's were also measured from samples cut from the disks of the 2nd or 3rd cavity. Results from the RRR surveys are given in Table 1 below.

Table 1

Cavity #	1	2	3
RRR	118±24	385±85	380±18

Reactor grade Nb from Teledyne Wah Chang and Cabot was used in all other regions of the cavity.

Cavity Fabrication

The first two cavities were ordered in January 1986. B&W personnel visited Cornell on several occasions to acquaint themselves with various operations involved in cavity fabrication. Frequent visits to B&W were made by Cornell personnel to help develop a cavity manufacturing capability as well as to monitor the results at appropriate stages.

Procedures described in the cavity fabrication manual prepared by Cornell were followed by B&W with some exceptions which are noted in the discussion below.

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Electron Beam Welding

Welding was carried out in a Sciaky machine which can be computer numerically controlled. All weld joints were extensively simulated using flat pieces with machined weld preparation joints as well as using spare cups and spare coupler parts. The rhombic raster technique[5] was not adopted and was replaced by a defocussed beam technique perfected by B&W. Welding high RRR material in a poor vacuum could be detrimental to the thermal conductivity of Nb if gaseous impurities are dissolved at high temperatures. The nominal weld pressure in the B&W weld chamber is 1×10^{-4} torr, although by the time the welds are actually performed the pressure can drop further to 5×10^{-5} torr. In the welded zone the RRR measured 281. In a parallel study, we welded similar high RRR material using the Cornell rhombic raster[5] weld parameters. After pumping for the usual time interval for welding 5-cell cavity equators, the RRR in the weld zone measured 310. From these studies we concluded that the base pressure in the B&W weld chamber after the standard pump down time was adequate in comparison to the Cornell welds which perform satisfactorily.

Using flat plates with machined weld steps as well as a full equator mock-up, it was determined that after 5 minutes of BCP chemical etching in a buffered solution of HF, HNO_3 and H_3PO_4, the equator weld could be carried out successfully without changing the weld parameter. Even after a 20 minute etch, when the total weld step was thinner by .010" to .015", the same equator weld parameter was found successful. Based on these studies, it was decided to omit the chemical resist application used at Cornell for the purpose of protecting the equator weld step during the heavy etch stage. This improved the possibility of keeping the weld area clean and saved several operations.

The finished HOM and FPC assemblies were leak tested and all the welds were examined closely from the inside with a borescope. The fabrication of the first cavity was completed in early May, the second cavity by the middle of July 1986 and the third by the middle of January 1987. For the first cavity, a 1/16" lump in the vicinity of a repair region in one of the equator welds was ground smooth at Cornell LNS, using a computer directed grinding machine. In addition, one of the other two equator hole repairs as well as a discoloration spot in the cell adjacent to the FPC were also ground. The second cavity had no equator weld repairs.

Room Temperature Bench Measurements of RF Properties

Frequency and Field Profile

For the first two cavities, the accelerating mode frequencies in the as-received condition are listed in Table 2. These should be compared with the target room temperature value of 1494.5 Mhz. For each cavity several iterations of tuning by expanding individual cells was necessary to achieve a flat field profile. The yttrified cavities were substantially easier to deform due to the lowered yield strength of the higher purity, larger grain size material. During this tuning stage the fundamental mode frequency was simultaneously brought to 1494.5 Mhz. Table 2 also lists the fundamental power coupler external Q, and the overall cavity length after tuning to the desired frequency. The FPC coupler body was compressed to increase the Q_{ext} closer to the desired value of several 10^6.

Table 2

Cavity #	1	2
Bench Frequency (Mhz) as-received	1495.06	1487.34
------After Tuning to 1494.5------		
Field Flatness	±0.2%	±0.8%
Cavity Length (cm) (Drawing: 65.74)	65.63	64.5
Q_{ext}	1.5×10^5	5.1×10^5
Final Q_{ext}	5.7×10^6	1.7×10^6

Preparation for Cold Tests

The cavities were cleaned and chemically etched by the usual procedure for Cornell 5-cell elliptical cavities and assembled in a Class 10 clean room. After evacuation and pumping for 2 days with an ion pump, vacuum levels of 1×10^{-7} torr were reached.

Cold Test Results

Table 3 details the accelerating mode frequency and the performance of the first two cavities near 2 K. The residual resistance R_0 was determined by fitting the temperature dependent Q data between 4.2 and 2 K. Using a geometry factor G = QRs = 275 Ohms, the data can be used to determine R_0, and to make a rough estimate of the RRR of the Nb at the rf surface.[6] The data is fit to the function:

$$R_s = A/T \times \exp(-17.67/T) + R_0$$

to determine A and therefore the RRR. For the first cavity, the enhancement in the BCS losses due to higher RRR is 17%, somewhat lower than expected enhancement from the bulk RRR values of 110; for the second cavity the enhancement is approximately 60%, in better agreement with the bulk RRR of 385±85.

Table 3

Frequency (Mhz) Desired 1497.0±0.1 Mhz	1496.63	1497.0
Low Field Residual Resistance (nΩ)	16	39
Q_{res} (lowfield)	1.7×10^{10}	7×10^9
A/A_{BCS}	17%	63%
E_{acc} (max) (MeV/m) Desired: 5 MeV/m	6.5	7.7
Q_{Res} at 5 MeV/m	1.2×10^{10}	7×10^9
Q_{total} at 5 MeV/m Desired: 2.4×10^9	7×10^9	3.5×10^9
Field Limitation	Thermal Breakdown	Field Emission

Accelerating Fields and Qs Achieved

The high field performance for the first two cavities is compared in Fig. 2. For the first cavity the residual Q at low field was 1.7×10^{10} and remained essentially unchanged to the maximum field of 6.5 Mev/m when it was 1.2×10^{10}. The limitation was due to thermal breakdown. The Q_{res} exceeds CEBAF specifications by a factor of 4, and the highest

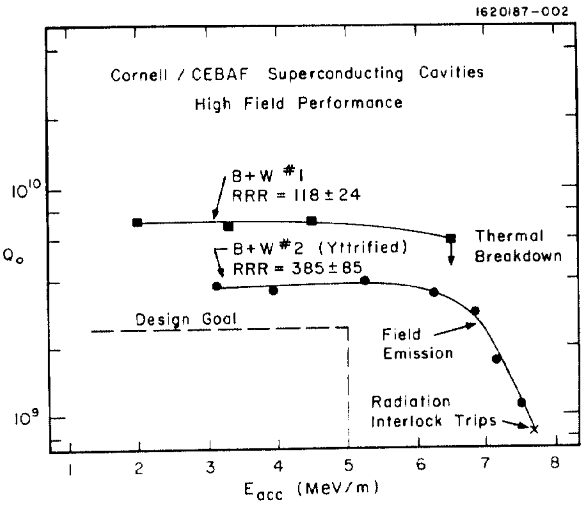

Figure 2. High field performance.

accelerating gradient reached exceeds goals by 30%. There were no discernible signs of field emission loading.

At low fields, the residual Q determined for the second cavity was 7 x 10^9. During the second cavity test, first signs of electron loading appeared at a low field of 2.5 Mev/m, but the field and Q improved discontinously at this level, presumably due to rf processing of the dominant emitter(s). Up to a field of 6.3 Mev/m, the Q remained between 3.4 and 3.9 x 10^9. Above this level, heavy field emission dropped the Q to ~1 x 10^9 at 7.7 MeV/m when the radiation interlocks tripped. No thermal breakdown was seen and the maximum field was determined by frequent radiation interlock trips. The residual Q at 5 Mev/m of the second cavity exceeds the CEBAF goals by a factor of 2 and the highest gradient reached was over 50% of the goals. Figure 3 shows the two cavities fabricated.

On warming each cavity to room temperature, the field profile was remeasured and found unchanged.

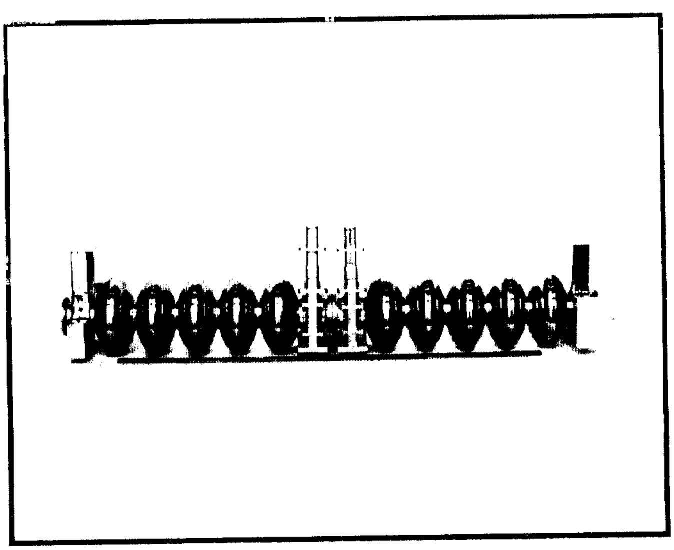

Figure 3. Prototype cavities fabricated by Babcock & Wilcox.

Conclusions

Successful application of superconducting rf technology on a large scale depends on early and effective technology transfer to industry. Close interaction between Babcock & Wilcox and Cornell LNS was crucial to the process.

The first Babcock & Wilcox prototype cavities exceeded CEBAF performance goals with respect to residual Q and accelerating field without the need for any guided repair cycles. The maximum fields reached were 6.5 Mev/m and 7.7 Mev/m. Since each cavity in CEBAF will be powered independently, the higher gradient capability can be used to full advantage.

Babcock & Wilcox is the first American firm to acquire the technology of manufacturing niobium microwave superconducting cavities.

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