TEST RESULTS ON A CEBAF/CORNELL PROTOTYPE SUPERCONDUCTING CAVITY FABRICATED BY TRW

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Abstract

Large scale application of superconducting rf cavities to accelerators requires an industrial fabrication capability. Both development of sound fabrication techniques as well as particular sensitivities critical to the performance of superconducting cavities are necessary for successful technology transfer. Good results with the first cavity built with these goals in mind prove that the technology issues related to acceptable performance are understood and controllable.

Introduction

From January to September 1986 TRW's Electronics and Defense Sector was under contract to the Southeastern Universities Research Association (SURA) to fabricate for the Continuous Beam Accelerator Facility (CEBAF) 1500 Mhz, 5-cell superconducting linear accelerator cavities of the design developed at the Newman Laboratory of Nuclear Studies at Cornell University. Cornell has already built and tested 4 successful prototypes for storage ring application[1]. The objective of this project was to transfer the fabrication technology developed at Cornell to an industrial firm demonstrating that a successful cavity could be built outside the development laboratory. It is hoped that experiences gained by this activity and the lessons learned will be of assistance to CEBAF in qualifying vendors for large scale production in the near future. To compress the timing we took advantage of the expertise and facilities that exist at Cornell LNS for tuning, final chemistry and cold testing.

Manufacturing Notes

TRW followed Cornell procedures as closely as possible in almost all areas. Beginning in November 1985, the TRW project team sent key team members representing project management, sheet metal forming, machining, cleaning, and welding operations to Cornell to learn procedures from the staff at Newman Lab. Draft procedure documents were obtained from Cornell[2] along with leads on sources of equipment and consumables necessary for the project. Frequent contact was maintained for the duration of the project between TRW and Cornell Staff. At the same time, laboratories were set up in the TRW plant for performing chemical processing, a 100 ton hydraulic press was acquired for forming cell and coupler parts and an electron-beam welding vendor (EBTECH) was brought on board to develop welding parameters.

The philosophy was to minimize the risks in transferring the technology to industry by replicating Cornell procedures and making maximum use of their experience by staying in close contact with Cornell during all phases of fabrication. However, because of the differences in existing equipment and experience of the two staffs, it was necessary to modify some of the processes after consultation with Cornell. These resulted in significant benefits in terms of time, cost and convenience. These modifications included:

Use of a water soluble drawing lubricant for forming sheet metal parts (Withrow X-52) which has eliminated occasional scraping problems encountered at Cornell.

Use of water-soluble plastic spray (Spraycat W-2247-2 Blue from Spraycat Corp., Los Angeles, CA) rather than tape to protect niobium surfaces during machining.

Use of a lathe rather than a vertical mill to machine the iris and equator edges of the half-cells.

Development of fixtures that allowed the equators of the half-cells to be final machined after completion of iris welding and heavy chemical etch stages. This eliminated the cumbersome need for photoresist protection of the equator during chemistry.

The last two modifications were particularly helpful as the cylindrical geometry of the half-cells lends itself naturally to the use of a lathe. Eliminating the steps associated with applying and removing the resist saved one to two days per cell-pair and removed the risk of trace contamination due to incomplete photoresist cleaning.

Interfacing Production Sequences

A major difficulty encountered was having our several processing areas - chemical, machining, welding and forming - located in multiple buildings at TRW, some separated by miles from others, and the welding facility separated by a 1 hour drive. Colocation of facilities would greatly improve the flow of parts through the various processing sequences and allow a considerable decrease in assembly time.

Material

Some schedule delay resulted from the difficulty in readily obtaining Nb, especially adequate quantities of high RRR material. Most of the material for the first cavity was loaned to TRW by Cornell because of the long lead time from commercial suppliers. W. C. Heraeus high purity Nb with RRR ~95 was used for the first cavity cells and TWCA Nb with RRR = 200 for the second cavity cells. One out of 11 plates from TWCA for the second cavity delaminated near an edge during the half-cell forming operation, indicating that the supplier had not sheared off sufficient quantity of material from the rolled plate edges. Considerable effort must be expended in the future to work with Nb suppliers to improve delivery schedules and to insure that material is of adequate quality.

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Welding

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. To verify the cleanliness and vacuum quality of the two e-beam welders used, test weld beads were performed on several samples of high purity Nb (RRR = 420). After some initial discouraging results due to improper fixturing and inadequate cleaning, welds could be performed without deteriorating the RRR value below ~300, providing the chamber was pumped for a least 20 minutes with the diffusion pump. In a parallel study, we welded similar material in the Cornell weld chamber using standard rhombic raster equator weld parameters.[2] 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 Ebtech weld chambers would be satisfactory.

Substantial development work had to be invested in achieving acceptable welds. We concluded that accurate modelling of each weld using duplicate part configurations is vital to ascertaining final weld parameters. The use of flat samples provides only an approximate parameter range and is insufficient for basing actual weld data. Considerable difficulties were encountered during welding coupler parts when parameters derived from plate studies were used, and resulted in a large amount of corrective machining and sheet metal straightening work to remove excessive warpage or to repair holing. For the cells of the first cavity, the first three equator welds did not achieve adequate penetration with the planned outside weld pass, but could fortunately be repaired with a cosmetic inside pass.

In implementing the Cornell "rhombic raster"[2] welding method we had to devote considerable attention to the raster drive electronics to ensure that the beam was faithfully following the raster pattern imposed, and that there were no hot spots within the rhombus caused by dwelling of the beam during the scan. After the raster was successfully implemented, substantial gains were registered in the reproducibility of the welds and parameter ranges for a given weld geometry were significantly widened.

All welds were carefully inspected with a borescope. One incomplete penetration area detected in the fundamental coupler body was repaired.

Yttrification[3]

To check the vacuum quality and appropriateness of TRW's vacuum furnace, several samples of multiple e-beam melted high purity Nb with a RRR value of 140 were yttrified. The resulting RRR values ranged from 270 to 350 indicating the acceptability of the furnace. Half cells from RRR = 200 material for the second cavity were yttrified following the Cornell method and measurements made on 20 samples cut from the half cells showed RRR = 380 ± 18.

Room Temperature Bench Measurements of RF Properties

Frequency and Field Profile

The accelerating mode frequency of the cavity as received was 1487.8 Mhz, compared with the target frequency of 1494.5 Mhz.

The field profile (E^2 vs position) in the accelerating mode was not flat, with an rms devision in the axial field at the center of the cells of 23%. After a few iterations of tuning by expanding individual cells, a flat field profile was achieved (rms deviation of 2% in E) while the fundamental mode frequency was simultaneously brought to 1494.5 Mhz. The frequencies of all modes of the accelerating pass-band before and after tuning are given in Table 1. The cell-to-cell coupling coefficient is determined to be .036 compared to .033 for Cornell built prototypes. The overall length of the cavity was 0.63 cm longer than drawing specifications (actual length = 66.37 cm).

Fundamental Power Coupling

Table 1 lists the Q ext values of each of the modes of the accelerating pass band after completion of tuning. the fundamental mode coupling could not be determined as precisely as desired due to VSWR of the measuring system. Of the 4 CEBAF prototypes tested at Cornell this cavity came closest to the desired external Q of 2.2×10^6 without mechanical tuning of the FPC body. A more precise determination will be performed after a specially designed low VSWR waveguide to coax adaptor is received.

The cavity was degreased and chemically etched for 4 minutes using standard chemical procedures at Cornell. After chemistry, the cavity was rinsed with high purity water and high purity methanol, assembled in a Class 10 clean room in the customary manner. After evacuation and pumping overnight with an ion pump, the cavity vacuum reached 4×10^{-7} torr and improved to 8×10^{-8} torr in two days.

Mode	Frequency As Received Mhz	After Tuning Mhz	Coupling (Q ext)
π	1487.6	1494.5	$>6.3\times10^5$
$4\pi/5$	1480.6	1489.2	5.1×10^5
$3\pi/5$	1466.6	1476.1	1.4×10^5
$2\pi/5$	1450.6	1460.9	5.9×10^4
$\pi/5$	1436.6	1447.0	7.6×10^4

Table 1. Frequencies and external Q for fundamental mode pass band at room temperature.

Cold Test Results

The cavity was tested in a vertical cryostat. Unfortunately, the customary cryostat for testing 5-cell cavities was under repair at the time so that the lowest temperature we were able to reach with the available pumps and the spare short cryostat was 2.1 K instead of the desired 2.0 K.

Cold Frequency

The frequency of the accelerating mode was 1496.964 Mhz at 2.2 K which is 36 Khz lower than the CEBAF specification of 1497.0 Mhz. The pressure sensitivity of the frequency was found to be -72 Hz/torr, within the expected range.

Temperature dependence of Q_0

The best Q_0 during the test at low field was 8.1×10^9. The temperature dependent Q data between 4.2 and 2.2 K was used to make a determination of the residual Q and a rough estimate of the RRR of the Nb at the rf surface. The data is fit to the function:

$$Rs = A/T \times \exp(-B/T) + R_0$$

to determine A and R_0. Here the prefactor A depends on the electron mean free path and therefore the RRR, and R_0 is the residual resistance. From the best fit we obtained R_0 = 9 nano - Ohms, corresponding to a residual Q of 3.06×10^{10} at low field and $A = 2.21 \times 10^{-4}$. When compared with the BCS value of $A = 1.95 \times 10^{-4}$ for a RRR = 25[4], the enhancement of the BCS losses due to higher RRR is 13% corresponding to a RRR 60 near the surface. This is lower than the bulk value of 100. In agreement with reported results, we conclude that the RRR of as manufactured sheet is lower than the bulk for the first few 100 microns near the surface.[5]

High Field Performance

The Q_0 remained essentially independent of field level and between 6.5 to 7.5×10^9 until thermal breakdown was reached at 7.2 Mv/m. At the CEBAF design gradient of 5 Mv/m, the Q_0 was 6.9×10^9 at 2.1 K, and the Qres was 1.7×10^{10} after subtracting the BCS losses of 16.5 nano-ohms. The Qres exceeds CEBAF design goals by a factor of 4, and the highest accelerating gradient reached exceeds design goals by 44%. Thermal breakdown was the field limiting mechanism (maximum surface magnetic field reached was 338 Gauss), and there were no discernible signs of field emission loading (maximum peak surface electric field reached was 18 Mv/m).

This cavity exceeded CEBAF performance goals with respect to Q and accelerating field without the need for any guided repair cycles.

Conclusions

The first TRW cavity successfully met all of the performance goals set for it and is ready for inclusion in the first CEBAF cryostats. Parts for the second cavity have been shipped to Babcock & Wilcox for completion of the cavity.

The partner relationship between Cornell LNS and TRW was essential to the final success of the prototype.

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