FABRICATION AND TEST OF SUPERCONDUCTING RF CAVITIES FOR CEBAF

U. Klein, A. Palussek, M. Peiniger, H. Vogel
Interatom GmbH, Accelator and Magnet Technology, D-5060 Bergisch-Gladbach, FRG
H. Piel
Fachbereich Physik, Bergische Universität-Gesamthochschule Wuppertal, D-5600 Wuppertal, FRG

Abstract

In fall 1985 Interatom started with the fabrication and cryogenic rf measurements of Cornell designed superconducting accelerating structures for CEBAF. Current diagnostic methods like temperature mapping and improvement methods like postpurification of the niobium structures by titanification have been applied. In two cavities assembled to one cavity pair accelerating fields of 12.1 and 10.4 MV/m were achieved at a quality factor of 2.5 and $4 \cdot 10^9$, respectively, significantly exceeding the design values (5 MV/m at $3 \cdot 10^9$). The applied fabrication and preparation steps are described and the rf performance of the cavities is discussed.

Introduction

CEBAF is presently the largest accelerator to be built using superconducting accelerating cavities. Several hundreds of cavities with a total active length of 210 m and corresponding cryostats have to be fabricated, assembled and tested in the next few years.[1]

Interatom is engaged in the CEBAF project since 1985. At first single cavities have been fabricated and cryogenically tested.[4] In a second step Interatom performs the construction of two prototype cavity pairs their assembly in a horizontal cryostat to one accelerating unit for later use in CEBAF. This project which is carried out in very close collaboration with CEBAF includes fabrication (niobium parts), preparation, assembly and cryogenic rf test. Until now the appropriate facilities have been set up and the first cavity pair was assembled and tested successfully.

Cavity Manufacturing and Postpurification

The smallest individual component of this accelerator, the "cryounit" consists of a cryostat with a "pair" of cavities installed.[2] Each cavity pair is formed out of two Cornell designed 1.5 GHz five cell niobium structures[3] hermetically sealed with cryogenic gate valves and Kapton rf windows closing the beam pipes and the fundamental power waveguide couplers, respectively.[2]

Until now four cavities have been fabricated (cavity # 1 and 3) or are in fabrication (# 8, 9) at Interatom on the basis of the fabrication procedure worked out at Cornell University[5]. The cavity consists of three major subassemblies, the five accelerating cells, the higher order mode coupler and the fundamental mode waveguide coupler. The cells are being manufactured out of 3.2 mm niobium sheet material of high purity from W.C. Heraeus (cavities #1 and 3) and Teledyne Wah Chang (cavities #8 and 9) with a residual resistance ratio (RRR) of 120 and 250, respectively. Reactor grade niobium material with RRR ≈ 40 is used for the coupler parts. A few fabricational steps are performed different from the Cornell procedures[5] .
The most important are the following:

- The electron beam welding is carried out with a defocussed beam technique instead of the rhombic raster technique used at Cornell.
- Furthermore no chemical resist was used for the protection of welding areas during the chemical etching in a buffered solution of $HF-HNO_3-H_3PO_4$ (BCP).

To improve the thermal stability of the cavities #1 and 3 postpurification by solid state gettering in a pure titanium atmosphere at 1300°C[6] was carried out with the complete structures after several cryogenic rf tests. Measurements of the thermal conductivity $\lambda(T)$ performed on niobium samples which were cut from the plates before deep drawing and postpurified together with the cavities showed an increase of the RRR from 124 ± 12 before the titanium treatment to 380 ± 40 after it (fig.1). The RRR was determined from the empirical relation RRR = $4 \cdot \lambda(4.2$ K), λ in W/mK. [7]

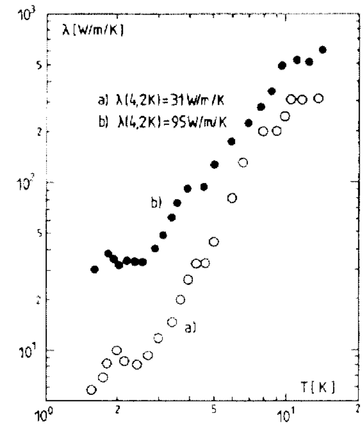

Fig. 1: Thermal conductivity of a niobium sample as a function of temperature before (curve a) and after (curve b) postpurification. (niobium supplied by W.C. Heraeus)

To remove the titanium from the niobium surface in case of cavity #1 a special chemical etching solution was applied at first. This resulted in an excessive penetration of hydrogen into the niobium substrate. Therefore the cavity was subsequently outgased at 1200°C for one hour in an ultra high vacuum furnace. The titanium layer of cavity #3 was dissolved by the conventional BCP so that no further heat treatment was necessary. The fabrication of the cavities #8 and 9 is nearly completed. Because of its high RRR of 250, no postpurification is planned at this moment.

Room Temperature Measurements

Rf-Properties and Cavity Shape

Once the cavities are fabricated the accelerating mode frequency, the field flatness of the five cell structure, the external Q of the fundamental mode coupler (Q_{ext}) and the Q of the rf probe (Q_{probe}) have to be adjusted to its design values. Furthermore these cavities have to fit with high mechanical precision (≤ 0.1 mm) into a helium vessel, after they have been combined to a cavity pair (fig.2) and successfully tested under cryogenic temperatures. To fulfill these requirements, special tuning facilities for the mechanical deformation of the single cells and the fundamental power coupler have been designed and built. Until now, the adjustment of both the rf properties and the mechanical shape of the cavities #1 and 3 (pair 1/3) has been successfully carried out. The rf properties are listed in the tables 1 and 2. The comparably small deviation of the frequency in the as fabricated state from the specified value is due to the "guided" cavity manufacturing by frequency adjustment of the single cells.

Table 1 : rf properties of the first two CEBAF cavities measured at room temperature and atmospheric pressure (x: before last BCP and mounting to a cavity pair)

cavity	frequency [MHz] as fabricated	final^x	field flatness [%] as fabricated	final^x	Q_{ext} final^x
# 1	1494.8	1495.0	± 8	± 2	1.3 E6
# 3	1495.6	1495.0	+5/-6	± 3	1.6 E6
specified		1495.0^x		≤ ± 5	6.6 E6 (only specified for cavities # 8, 9)

Mechanical Stability

The mechanical stability of the cavities #1 and 3 were studied by measuring the shift of the accelerating mode frequency Δf due to the deformation of single cells under the influence of an axial force ΔF in the elastic and inelastic range. Within errors of ± 10 % the results are the same for both cavities. The cavity "spring constant" was determined to $\Delta f/\Delta F$ = 0.1 kHz/N. Inelastic deformation initially starts at axial forces of ΔF_{inel} = 30.000 ± 2.400 N. It reduces drastically to ΔF_{inel} = 3.400 ± 900 N after the titanium treatment. This value is only about twice as high as the forces acting upon the cavity in the evacuated state. Therefore exceptionally careful handling of these cavities is required, especially when mounted to a hermetically sealed cavity pair. Furthermore these results imply not to use niobium material with a thickness less than 3.2 mm if postpurification is foreseen.

Preparation and Clean Room Assembly

After tuning and mechanical adjustment, the cavities undergo a final BCP and a subsequent rinsing with demineralized, filtered water in most cases under supersonic agitation. The mounting is carried out in a class 10 clean room. For the assembly of a cavity pair (fig.2), several subsystems have to be prepared in addition to the cavities.[2] The Kapton windows mounted to the fundamental power waveguide couplers as well as the viton sealed gate valves flanged on both ends of the pair are outgased at temperatures between 120 and 150°C under high vacuum conditions. Indium gaskets are used in all cases. To enable the very delicate mechanical adjustment of the cavity pair, the assembly is done in a stainless steel fixture on a precision table in the clean room (fig.2). Finally the cavities and the waveguides of the sealed pair (separated by the Kapton window) are evacuated and leak checked.

Cyogenic Rf Tests

After being assembled the cavity or the cavity pair is transported to the cryogenic test area at the University of Wuppertal and mounted to a test insert. A special test insert was constructed for the cavity pairs. It is equipped with separately working temperature mapping systems and variable input couplers for both cavities and allows an easy and time saving mounting and dismounting. Separate ultra high vacuum lines are used both for the cavities and the waveguide couplers. [11] Several tests have been carried out with the cavities #1 and 3 in single and paired state. In general the CEBAF design values were exceeded after an initial diagnostic test followed by a "guided" repair which is enabled by using the temperature mapping technique.[8,9] A rotating array of 89 temperature sensors scans each cavity surface for enhanced rf losses. As an example in fig.3 temperature maps of cavity # 3 taken below quench field in the accelerating mode and two other passband modes are shown.

Fig. 2: Clean room assembly of a CEBAF cavity pair

The background temperature profile exhibits the rf losses due to the field distributions of the passband modes. The peaks are generated by microscopic defects. Dependent on the passband mode excited they cause field breakdown at different locations. The localised defects are subsequently ground by an appropriate grinding tool .

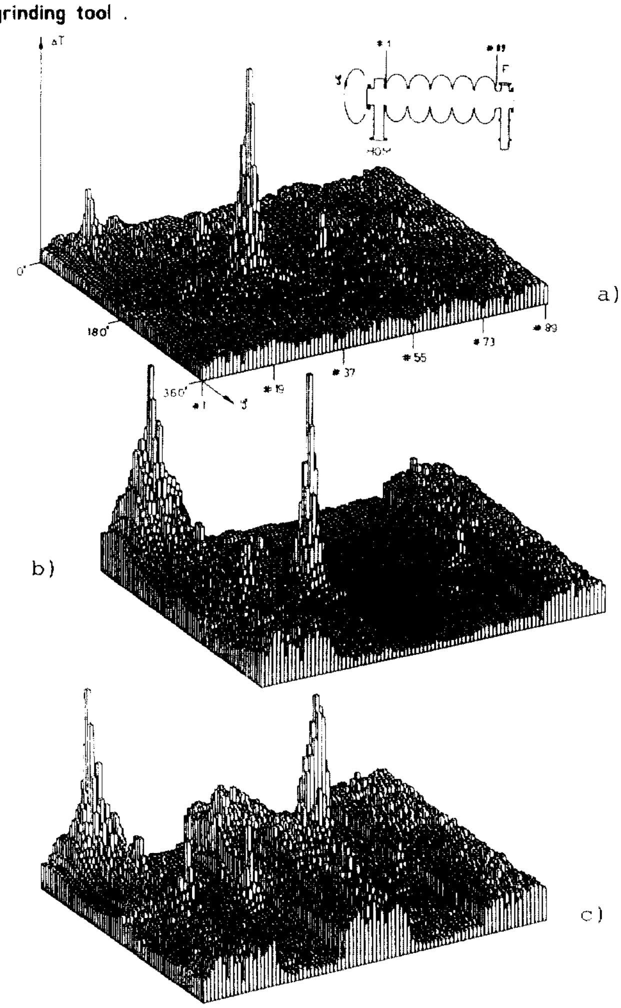

Fig. 3: Temperature maps of cavity # 3 taken in the accelerating (π) (a), 4/5 π (b) and 3/5 π (c) mode

The acceptance test results of the single cavities before the titanium treatment and the cavity pair after the postpurification are presented in table 2. Accelerating fields E_a significantly exceeding the design values have been achieved after postpurification (fig.4). The maximum value of E_a = 12.1 MV/m achieved in cavity * 1 corresponds to a peak magnetic and electric surface field of 560 Oe and 30.7 MV/m, respectively. In these cases no quenching occured and E_a was limited by electron field emission loading[10]. The maximum fields were reached only after a few minutes of rf processing. Helium processing was applied afterwards but did not improve the results.

Table 2: Acceptance test results of the cavities * 1 and 3 (x : notation according to fig.3)

Cavity	T [K]	E_a^{max} [MV/m]	Q_0 at E_a= 5 MV/m [x E9]	Comment/ field limitation
Specified	2.0	≥ 5.0	≥ 2.4	f = 1497.0 ± 0.3 MHz Q_{probe}= 1.3 E11 (goal)
Single cavity tests (before titanium treatment)				
* 1	2.0	6.1	3.3	quench at res. 69/75°
* 3	2.0	7.7	7.5	quench at res. 33/0°
Cavity pair test (after titanium treatment)				
* 1	2.15	12.1	4.8	f = 1497.22 MHz Q_{probe} = 0.98 E11 electron field emission
* 3	2.15	10.4	7.5	f = 1497.08 MHz Q_{probe} = 0.84 E11 electron field emission

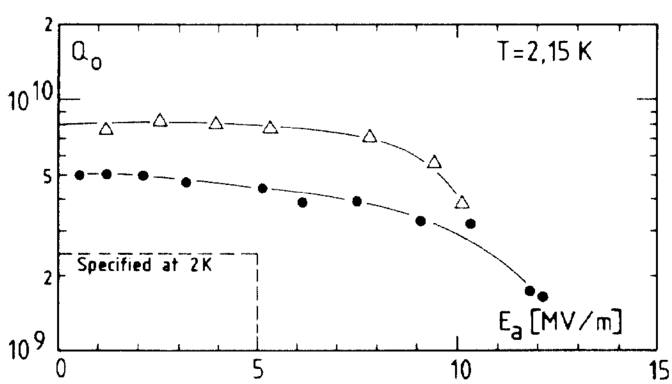

Fig.4: Cavity's Q as a function of accelerating field of the cavities * 1 (●) and 3 (Δ) after the titanium treatment, assembled to a sealed cavity pair

The experimental surface resistance data $R_s(T)$ were fitted to the BCS dependence in the form

$$R_s(T) = \frac{A}{T} \exp\left(- \frac{\Delta}{kT} \right) + R_{res} = R_{Nb}(T) + R_{res}$$

Resulting fit parameters namely the surface resistance of niobium R_{Nb} at 4.2 K, the reduced energy gap Δ/kT_c (T_c set to 9.2 K) and the residual resistance R_{res} are given in table 3.

The increase of R_{Nb} (4.2 K) after the titanium treatment is in agreement both with results obtained at Cornell[6] and (qualitatively) with expectations based on BCS theory [12]. Furthermore the data indicate a change of Δ/kT_c towards higher values with deoxidation of the niobium surface [6,13]. The lower values of R_{Nb} (4.2 K) and Δ/kT_c of cavity * 1 compared to the data of cavity * 3 is intepreted to be due to a reoxidation of the niobium surface of cavity * 1 during the additional heat treatment at 1200°C.[15]

Table 3: rf properties of the cavities * 1 and 3 (x : measured after tit.treatment but before annealing)

Cavity	RRR	R_{Nb}(4.2K) [nΩ]	Δ/kT_c	R_{res} [nΩ]	Comment
	>40	620	1.86	-	ext.BCS theory[14]
* 1	124	660	1.89±0.04	24	before tit.treatm.
* 3	124	670	1.90±0.05	22	before tit.treatm.
* 1	380x	910	1.84±0.07	18	after tit.treatm.and anneal.(1200°C, 1h)
* 3	380x	1070	2.10±0.07	15	after tit.treatm.

Conclusion

Four Cornell designed superconducting accelerating structures have been built for CEBAF. Two of them were postpurified, combined to a hermetically sealed cavity pair and subsequently tested. For this purpose appropriate facilities for preparation, cleanroom assembly and cryogenic rf tests have been set up. In the first cavity pair which was mounted for installation in a horizontal cryostat an energy gradient of 11.3 MeV per meter accelerating length at Q values above 2.5 · 10^9 was achieved.

Acknowledgement

We would like to express our gratitude to all members of CEBAF who helped to make this prototype project possible. The very close and fruitful collaboration with the members of CEBAF's SRF and engineering devisions especially with P. Kneisel, T. Mann and B. Moss is highly appreciated. Special thanks are given to R. Fleck and J. Zander for their support during the rf tests and to M. Hagen who carried out the thermal conductivity measurements. We are very grateful to the Kernforschungszentrum Karlsruhe for permitting the use of the large ultra high vacuum furnace, to H. Baumgärtner for carrying out the heat treatments of the cavities and to J. Halbritter for discussing the heat treatment results.

References

[1] e.g. C.W.Leemann, 1986 Lin.Acc.Conf.Proc., 194, Stanford, Ca., USA, 1986
[2] G.Biallas et al., ibid [1], 73
[3] P.Kneisel et al., IEEE Trans.Mag-21, 1000, 1985
[4] R.Sundelin et al., ibid [1], 444
[5] L.Phillips, SRF-860102-EXA, Cornell University Internal Report, 1986
[6] P.Kneisel, Journ.Less.Com.Met., 139, 1988
[7] H.Padamsee, Proc.2nd Workshop on Rf Superconductivity, 339, CERN, Geneva, 1984
[8] H.Piel and R.Romijn, CERN/EF 80-3, Geneva, 1980
[9] G.Müller, ibid [7], 377
[10] W.Weingarten, "Electron Loading", ibid [7], 551
[11] P.Kneisel, CLNS 87/60, Cornell University, Ithaca, 1987
[12] J.Halbritter, Z.Physik, 238, 466, 1970
[13] W.Schwarz, J.Halbritter, J.Appl.Phys., 48, 4618, 1977
[14] U.Klein, thesis, WUB-DI 81-2, University of Wuppertal, 1981
[15] G.Müller and H.Padamsee, Proc.of the Part.Acc.Conf., Washington DC, 1987