1. Introduction

A 2-cell cavity was designed by J. Sekutowicz to investigate the influence of electric and magnetic fields on the surface resistance of niobium at high rf fields ($B_p \approx 100$ mT, $E_p \approx 50$ MV/m) [1]. The cavity is tested in the $TM_{010}$-0 (at 1382 MHz) and $TM_{010}\pi$ (at 1495 MHz) modes. In the $\pi$-mode, the surface electric field is about a factor of 3.7 higher in a small region near the iris between the two cells than anywhere else on the surface in both 0- and $\pi$-modes. In the 0-mode, the magnetic field is close to the maximum value both at the cells’ equator and at the iris between the two cells, while in the $\pi$-mode it is maximum only in the equator regions. Details about the cavity shape, field distributions and electromagnetic parameters are given in Ref. [1].

A niobium version of this 2-cell cavity has been built and tested up to $B_p \sim 170$ mT ($E_p \sim 77$ MV/m) and 150 mT ($E_p \sim 19$ MV/m) in the $\pi$- and 0-mode respectively [1], in the absence of field emission. The $Q_0$ vs. $B_p$ curve is characterized by a sharp drop of the quality factor starting at about 140 mT. Since the peak surface fields occur in regions where electron beam welds between cavity parts are present, we proposed to fabricate a “seamless” cavity with this geometry, to investigate whether the welds are responsible for the Q-drop.

2. Cavity fabrication

The cavity was made at DESY by hydroforming a Nb-Cu tube. The 1 mm thick Nb tube was explosively bonded inside a 3 mm thick Cu tube [2]. This seamless Nb-Cu technology was successfully applied on TESLA 1.3 GHz single-cell cavities. The presence of Cu should improve the thermal conduction of the rf power dissipated on the niobium surface. Niobium beam tubes needed to be electron beam welded to the cavity at Jefferson Lab. A first attempt was not successful due to the copper contamination in the weld region. A leak-tight weld was obtained by removing the copper outer layer up to about 0.5’ away from the weld region, then welding the Nb beam tube from the inside to the thin Nb layer of the clad material and adding an outside interpenetrating weld for rigidity.

The cavity flanges were made of Nb55Ti sealed with AlMg3 gaskets. A picture of the completed cavity is shown in Fig. 1.
3. Multipacting simulations

During the rf tests of the niobium cavity multipacting was found in both modes in 90% of the tests. The multipacting was overcome by about 1h of rf processing. Simulations with the code FishPact [3] were done to investigate the location of the multipacting. Several trajectories with electron final energies between 33 and 540 eV were found at field levels within the range experimentally measured in both modes. In the \( \pi \)-mode it was found between \( E_p = 3.5-15 \) MV/m and between \( E_p = 1.5-4.9 \) MV/m in the 0-mode. The following figures (Figs. 2-5) show multipacting trajectories calculated with FishPact. Both initial and secondary electron energy was set to 2 eV. The “steps” in the geometry of the beam pipes are due to the presence of two adapting rings with slightly different diameters. As can be seen in the figures, multipacting mainly occurs in the beam pipe transition.

Fig. 1. Seamless 2-cell cavity made of hydroformed Nb-Cu.

Fig. 2. Multipacting trajectories in the \( \pi \)-mode for \( E_p = 3.9 \) MV/m, \( \phi = 230^\circ \) (left) and for \( E_p = 11.6 \) MV/m, \( \phi = 270^\circ \) (right).
Final energy after 10 impacts: 77.6 eV

Fig. 3. Multipacting trajectories in the π-mode for $E_p = 7.8$ MV/m, $\phi = 270^\circ$ (left) and for $E_p = 7.8$ MV/m, $\phi = 240^\circ$ (right).

Final energy after 10 impacts: 33.1 eV

Final energy after 10 impacts: 53.3 eV

Fig. 4. Multipacting trajectories in the π-mode for $E_p = 15.5$ MV/m, $\phi = 260^\circ$. 
4. Cavity treatments and test results

The preparation for the first rf test consisted of degreasing the cavity with soap and water under ultrasonic agitation, 2×50 µm BCP 1:1:2 followed by 3 h HPR. The cavity was dried overnight in the class 10 clean room, assembled and evacuated to about 10⁻⁸ mbar. The high power rf test at 2 K showed multipacting at low field and a decrease of the quality factor for increasing rf field up to 47 mT, in absence of field emission. Similar performance had been observed during rf tests of seamless cavities in the past [4] and it improved by additional chemical etching, which should give a progressively smoother surface.

The cavity was processed again with BCP 1:1:2 to remove about 50 µm, after degreasing, followed by 2 h HPR. The cavity was dried overnight in the class 10 clean room, assembled and evacuated to about 10⁻⁸ mbar. The high power rf test at 2 K showed again multipacting at low field which processed up to 60 mT and a similar Q vs. Bₚ behavior as in the first test, with a strong “Q-slope” without field emission. In the second test the low-field Q was lower than measured previously.

We suspected hydrogen to be responsible for the strong “Q-slope” and the cavity was degassed in a vacuum furnace at 600 °C for 10 h. Then it was degreased, 50 µm were removed in two steps by BCP 1:1:2, followed by 2 h HPR. The cavity was dried overnight in the class 10 clean room, the top flange was assembled and the cavity was rinsed again for 2 h and dried overnight. The bottom flange with pumping port was assembled and the cavity was evacuated to about 10⁻⁷ mbar. The low-field Q at 2 K was only about 10⁻⁸ for the π-mode and 3×10⁻⁸ for the 0-mode. It was suspected that the cool-down across the critical temperature of niobium was not uniform, causing thermoelectric currents at the Nb-Cu interface which generate magnetic flux trapped in the niobium, as was previously observed on tests on TESLA single-cell cavities [5]. The cavity was warmed up to 15 K, then cooled-down very carefully below 9.3 K. The temperature gradient between the bottom and the middle of the cryostat, where the cavity is located, was lower than 300 mK. Nevertheless, the low field Q at 2 K did not improve.
mode the Q increased with increasing rf power, as could have been caused by a multipacting barrier.

The cavity went through a new surface preparation consisting of degreasing, 10 µm BCP 1:1:2, 2 h HPR. The cavity was dried overnight in the class 10 clean room, the top flange was assembled and the cavity was rinsed again for 2 h and dried overnight. The bottom flange with pumping port was assembled and the cavity was evacuated to about 10^{-7} mbar. The residual gas was mostly H₂O, so we decided to bake the cavity at 120 °C for 12 h. The pressure improved to about 5×10^{-9} mbar at room temperature after baking.

The cavity was carefully cooled down to 2 K but the low-field Q was more than two orders of magnitude lower than expected: 2.5×10⁷ and about 1.5×10⁸ in the π- and 0-mode respectively. There was no indication of processing from multipacting as the quality factor kept decreasing with higher rf power. A plot of Q vs. Bₚ for the four rf tests at 2 K of the Nb-Cu 2-cell cavity is shown in Fig. 6.

![Fig. 6. Summary of the rf test results at 2 K of the Nb-Cu 2-cell cavity.](image)

We suspected that some of the copper might have been exposed due to the chemical treatments and possibly non-uniform Nb thickness, causing additional losses in the rf fields. Therefore, the cavity was cut lengthwise by wire EDM to visually inspect its interior. The niobium layer looked very uniform but it was quite rough, especially in the region of higher stresses during forming (equator). We noticed a gap between the first adapting niobium ring and the cavity iris, indicating that the weld was not fully inter-penetrated. Since significant rf field is present in this region, this might have contributed to additional losses. Figure 7 shows a picture of the cavity halves.
5. Conclusions

A seamless Nb-Cu 2-cell cavity was built to investigate the role of the electron beam welds on the high field losses in superconducting niobium cavities. Unfortunately, these tests did not meet the anticipated objectives: the maximum peak surface magnetic field achieved with the cavity at 2 K was about 60 mT, more than 50% lower than the field achieved in the 3 mm thick niobium version of the cavity. Several problems were encountered:

- Multipacting at low field was harder than in the full-niobium version and baking of the cavity to reduce the H$_2$O and lower the secondary emission yield was not successful
- It was difficult to maintain a temperature gradient lower than 0.5 K over one meter in the vertical cryostat during cool-down across 9.25 K and this might have contributed to higher residual losses due to thermo-currents and trapped magnetic flux. This could be a drawback of the Nb-Cu technology applied to long multi-cell cavities.
- The niobium surface was significantly rough after removing about 200 µm by BCP, especially in the highly deformed areas of the cavity. This could have been the cause for the strong Q-degradation at moderate field.
- The electron beam welds at the cavity/beam pipe transitions were not fully penetrated, leaving a gap between the two parts. This might have cause additional losses due to the poor thermal contact in the weld region.

6. References

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