PRELIMINARY RESULTS FROM MULTI-CELL SEAMLESS NIOBIUM CAVITIES FABRICATED BY HYDROFORMING *

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Abstract

The technology of forming multi-cell seamless niobium cavities has been developed at DESY within the European CARE (Coordinated Accelerator Research in Europe) program. Three-cell units have been manufactured successfully and a 9-cell cavity has recently been completed from three sub-sections and has been successfully tested at DESY.

Additionally, we have equipped two 3-cell units – one center unit of a 9-cell cavity and one end-unit – with niobium beam pipes, have tuned these units and carried out cryogenic radio-frequency (RF) tests after standard BCP surface treatments had been applied to these cavities.

In addition, we have taken temperature maps with JLab's two-cell thermometry system to compare with standard electron-beam welded cavities.

This contribution will report about the preliminary cryogenic test results and the T-mapping – this is an ongoing investigation.

INTRODUCTION

Traditionally, rotational symmetric (elliptical) niobium accelerating cavities are fabricated by deep drawing of half-cells and, after machining to the length dimension, they are completed by electron beam welding (EBW) at the irises and the equators. Improved quality control procedures during the mechanical fabrication and the EBW resulted in cavity performances which, in some cases, came close to the fundamental limits of the high purity niobium. However, more recently improved inspection methods revealed that features in the weld and heat affected zone in a multi-cell cavity can and have contributed to limitations in cavity performance [1]. Therefore, electron beam welds have come again under scrutiny worldwide, mainly because the performance goals for cavities for the International Linear Collider (ILC) are quite close to the fundamental limitations of the material and any fabrication defects override the material properties.

Contrary to this experience, seamless cavities have no equator welds (the high magnetic field region in an "elliptical" cavity) and therefore an improved reliability could be expected. Additionally, cavity fabrication costs could be reduced, especially, if the end-groups of an accelerating cavity (these are the parts of the cavity, which are outside the cell structure and provide input coupling capability and higher order mode damping capability) can be flanged onto the cell structure [2]. Seamless cavity fabrication techniques have been pursued in the last years mainly at INFN Legnaro [3] – the chosen method was spinning – and at DESY (hydroforming) [4]. Both methods have produced single-cell cavities with high performance [5]. This contribution reports about an extension of the single-cell work to multi-cell cavities, 3-cell and 9-cell.

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CAVITY FABRICATION TECHNIQUE

The hydroforming technique, developed at DESY over several years, has been described in details in previous publications [4-6]. Here we will only summarize the essential steps in the process and describe the extension from the single-cell to the multi-cell hydroforming.

For hydroforming, one starts with a seamless tube of a diameter intermediate between iris and equator. During the computer controlled forming, a two-stage process takes place, namely a reduction of the tube diameter in the iris region and an expansion of the tube in the equator area. Considerations of surface roughness at the iris region for too much diameter reduction and work hardening at the equator for too much expansion determined a tube diameter of 130 mm to 150 mm to be the optimum for 1300 MHz TESLA/ILC type cavities.

The tube diameter reduction at the iris was optimized – after research into different methods such as hydraulic necking, electromagnetic strike necking and spinning – by using a specially profiled ring being moved in radial and axial directions. For this purpose a computer controlled hydraulic machine has been built, which is useable for up to 3-cell cavities.

During hydraulic expansion of the equator region an internal pressure is applied to the tube and simultaneously an axial displacement, forming the tube into an external mold. The hydraulic expansion relies on the use of the correct relationship between applied internal pressure and axial displacement under the assumption that the plastic limit of the material is not exceeded, which would result in rupture. Material uniformity of the tubing and the experimentally determined stress-strain characteristics as well as simulation calculations are essential and have led to a successful development of the hydroforming technology. A hydroforming machine was specially built for the tube expansion. Since no tubing with uniform material properties were commercially available, much effort was invested in researching – in collaboration with industrial partners and scientific institutions – several tube forming technologies (spinning, back extrusion, forward extrusion, flow forming and deep drawing). A combination of spinning or deep drawing with flow forming gave the best results. In Fig. 1 a set of hydroformed 3-cell cavities is shown.

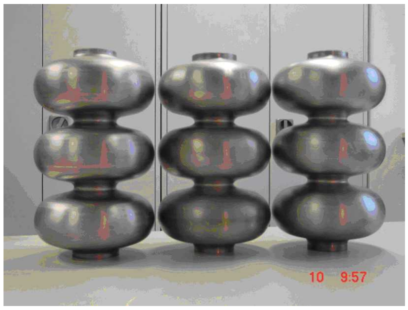

Figure 1: Hydroformed 3-cell niobium cavities.

EXPERIMENTAL TEST PROCEDURES

Single 3-Cell Units

After the hydroforming was completed at DESY, the 3-cell units as shown in Fig. 1 were barrel polished also at DESY removing approximately 100 µm and subsequently sent to JLab for completion with beam pipes and for evaluation. One unit (cavity #1) consisted only of center cells and the second unit (cavity #2) was an end-cell with two center cells.

Beam pipes were welded on at the outside irises and it was attempted to tune the cavities to a flat field profile. This turned out to be quite difficult, the cavities were quite stiff and "springy", most likely from the massive mechanical deformation during the forming process. A stress relieving annealing step at 600 °C for 10 h in high vacuum after app. 100 µm of material removal by BCP (Buffered Chemical Polishing: 1:1:1 ratio of nitric acid, hydrofluoric acid and phosphoric acid), softened the cavities appropriately and tuning could be accomplished.

For the cryogenic testing the cavities received standard BCP removing various amounts of niobium as indicated in the caption of Fig. 4. A high pressure rinsing (HPR) for two passes of 2 h each from the top of the cavity to the bottom followed after the BCP and subsequently the cavities were dried in a class 10 clean room for several hours prior to the attachment of input coupler/pump-out port and transmission probe port. The cavities were evacuated on the cryogenic test stand (Fig. 2) to a vacuum of typically < 10^{-8} mbar prior to cool-down to liquid helium temperature.

The cryogenic testing consisted of measuring in some cases the temperature dependence of the surface resistance, the pressure sensitivity of the cavity, the Q_0 vs. E_{acc} performance in the π-mode and the Lorentz-force detuning.

Because the 3-cell seamless cavities have no stiffening rings between the cells, they were "externally" stiffened by an arrangement of Ti-rods/stainless steel threaded rods as shown in Fig. 2 to avoid a possible collapse under the vacuum load.

Figure 2: 3-cell cavity attached to test stand with external support rods. The cavity is located in the clean room in front of a horizontal laminar flow system.

9-Cell Cavity

A 9-cell cavity was completed at Zanon, Italy, from three 3-cell units by electron beam welding from outside at the irises, then by adding stiffening rings and end-groups as for the conventional cavities.

Prior to tuning the cavity was "softened" by a 800 °C annealing step after removal of 40 µm by BCP. A "traditional" surface treatment of electropolishing (170 µm), ethanol rinsing, 800 °C heat treatment, electropolishing (48µm) and HPR at DESY preceded the cryogenic test.

RESULTS AND DISCUSSION

The performance of the 9-cell cavity is shown in Fig. 3: the cavity reached a maximum gradient of E_{acc} = 30.3 MV/m, limited by the Q-drop without field emission and no Q-disease. From mode measurements it was determined that individual cells had fields between 30 MV/m and 39 MV/m. The next step in the evaluation is an "in-situ" baking at 120 °C with the expectation of eliminating the Q-drop.

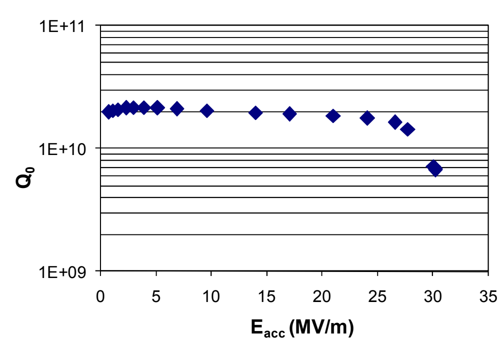

Figure 3: Performance of seamless 9-cell TESLA cavity.

We carried out three tests of the 3-cell units with different amounts of material removal on cavity 1 and two tests on cavity 2. The results are shown in Fig. 4. In addition, cavity 1 was re-tested with a 2-cell temperature mapping system after test 3.

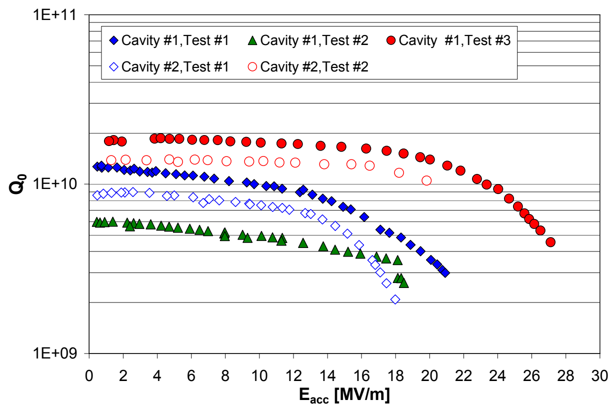

Figure 4: Summary of test results at 2 K from cavity 1 and 2. The total material removal was 150µm (test 1), 200µm (test 2) and 220 µm (test 3) for cavity 1; 200µm (test 1) and 250µm (test 2) for cavity 2.

Except for test 2 in cavity 1 no field emission was encountered. In this test a field emitter turned on at the highest field. Otherwise, the Q-degradations at the highest obtained gradients are caused by the "Q-drop", which starts at rather low gradients. As found earlier, heavy mechanical deformation of the niobium – without sufficient stress relieving – seems to be responsible for the low Q-drop onset [7]. More material removal might shift the onset fields to higher values; however, as is known, the Q-drop cannot be eliminated in poly-crystalline material after buffered chemical surface treatment only.

Test 2 of cavity 1 shows a rather low Q-value. This can be attributed to insufficient shielding of the Earth magnetic field (~ 150mG) in the dewar used for this test, due to a faulty power supply for the compensation coil. The additional resistance caused by the frozen-in flux amounts to ~50 nΩ, which would limit the Q-value at 2K to roughly 5×10^9. The first test of cavity 2 had a similar problem in another dewar, which had residual field of ~ 70 mG. In test 3 of cavity 1 a high Q-value was obtained after the magnetic shielding was improved to 5-7 mG over the cavity volume and an improvement of the onset field for Q-drop because of more removed material. Test 2 of cavity 2 was limited by a discharge due to poor vacuum in the cavity. In this test a "super-leak" was encountered caused by a crack in the cavity beamline flange. A re-test will be carried out after replacement of the defective flange.

The Lorentz-force detuning coefficient of the 3-cell, unstiffened cavity was determined to be k_L=-4.5 Hz/[(MV/m)^2], a factor of ~ 3 higher than for a cavity with stiffening rings. The sensitivity to the helium bath pressure in the configuration as shown in Fig. 2 was 185 Hz/mbar.

The 2-cell T-mapping system was assembled on the top and bottom cells of cavity 1. The sensors cover a region ~ 4 cm on each side of the equator. The T-maps show several "hot spots" in the equator (high magnetic field) region of both cells, although they appear to be more intense in the top cell (Fig. 5). The field dependence of the "hot-spots" temperature is nearly quadratic up to a peak surface magnetic field (B_p) of about 100 mT, when the Q-drop begins, above which the exponent *n* in the power-law dependence $\Delta T \propto B_p^n$ increases to about 6-10. Such dependence has been commonly observed in BCP-treated polycrystalline Nb cavities. More T-mapping measurements are planned, especially when the cavity reaches its quench field.

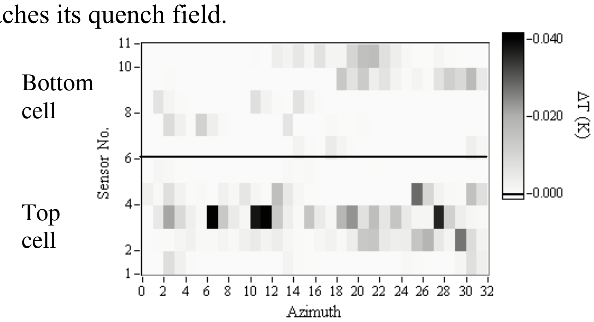

Figure 5: "Unfolded" T-map at the highest field achieved in cavity 1, test 3. The "azimuth" variable covers the cell's circumference, while "sensor no." covers a region ~ 4 cm on each side of the cells' equator (on rows no. 3 and 8). Hot-spots are visible in the equator area of both cells.

SUMMARY

These preliminary results from the seamless 3-cell cavities give an indication of the soundness of the technology developed at DESY. The quench limitations of the cavities have not been reached because of the "Q-drop". Future experiments will incorporate post-purification heat treatments, electropolishing and "in-situ" baking, which most likely will improve the cavity performances. T-maps showed the presence of "hot-spots" with location and field dependence similar to those observed in standard BCP-treated polycrystalline cavities.

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