PERFORMANCE OF 3-CELL SEAMLESS NIOBIUM CAVITIES[*]

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Abstract

In the last several months we have surface treated and cryogenically tested three TESLA-type 3-cell cavities, which had been manufactured at DESY as seamless assemblies by hydroforming. The cavities were completed at JLab with beam tube/flange assemblies.

All three cavities performed very well after they had been post-purified with titanium at 1250C for 3 hrs. The cavities, two of which consisted of an end cell and 2 center cells and one was a center cell assembly, achieved gradients of Eacc = 32 MV/m, 34 MV/m and 35 MV/m without quenches. The performance was limited by the appearance of the "Q-drop" in the absence of field emission.

INTRODUCTION

The technology of fabricating seamless multi-cell TESLA- type cavities has been perfected at DESY over the last several years in the context of the CARE program ("Coordinated Accelerator Research in Europe") and it has been reported in several papers [1-3]. Cavities fabricated within this program were available for evaluation; however, testing had to be deferred at DESY because of limited man power. Therefore, JLab offered to evaluate the performance of several of these cavities – not necessarily very unselfishly, because Jlab's interest was also in learning about performance limitations for the seamless forming technology.

A short summary of the forming technology follows:

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.
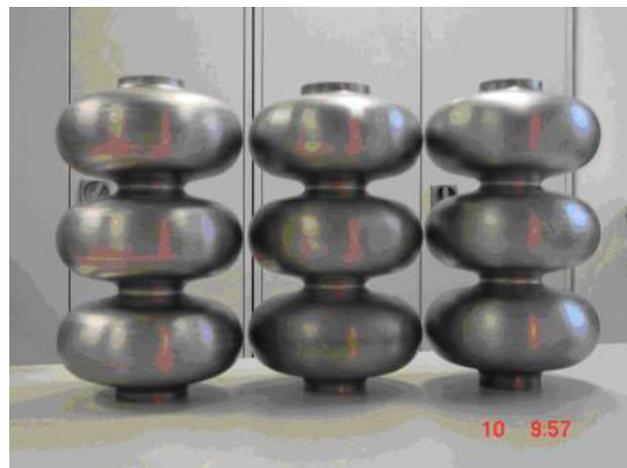

Figure 1: Hydroformed 3-cell niobium cavities.

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EXPERIMENTAL TEST PROCEDURES

Preparation for Testing

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 of material and subsequently sent to JLab for completion with beam pipes and for evaluation. One unit (cavity #1) consisted only of center cells and the two other units (cavity #2 and #3) were an end-cell with two center cells of a TESLA/ILC 9-cell cavity shape.

Beam pipes were welded on at the outside irises; subsequently it was attempted to tune the cavities to a flat field profile, neglecting to achieve a certain target frequency. The tuning turned out to be rather 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. However, during the tuning attempts on cavity #1 , which had not been stress relieved, the center cell of that unit was deformed more than intended. No attempt was made to re-shape this cell.

Before describing in detail the various tests conducted with each cavity, Fig. 2 summarizes the cavity performances after a post-purification heat treatment at 1250C for 3 hrs in a Ti box had been applied to all 3 cavities. None of the cavities was limited by a "quench", but rather by a degradation of the Q-value ("Q-drop") in the absence of field emission at accelerating gradients of E_{acc} = 32 MV/m, 34 MV/m and 35 MV/m for cavities #1, #2 and #3, respectively.

3-cell seamless cavities

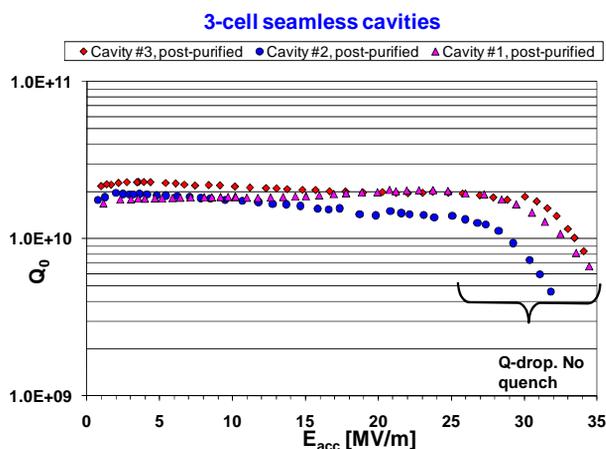◆ Cavity #3, post-purified ● Cavity #2, post-purified ▲ Cavity #1, post-purified

Figure 2: Performance of all 3-cell seamless cavities after post-purification at 1250C for 3 hrs.

These performances are very astonishing and encouraging since they were achieved without electropolishing and the surface finish of the cavity interior is quite rough and

irregular as can be seen in Fig. 3. The idea that excellent performances in cavities made from fine grain niobium can only be achieved with a very smooth/electropolished surface is certainly contradicted by these results.

Figure 3: Examples of interior cavity surfaces.

Details about the Cavity Tests

Prior to initial testing, the cavities were subjected to a final BCP treatment after the before mentioned annealing at 600C for 10 hrs, removing app. 50 µm of material from the interior surfaces, followed by high pressure ultrapure water rinsing (HPR),drying in a class 10 clean room and assembly of input beam line coupler/pumpout port and transmission probe. Because the units had no stiffeners between the cells, the cavities were assembled with external Ti-rods to avoid collapse under the vacuum load; Fig. 4 shows the assembly.

Except for cavity #3 the other two cavities went through several testing cycles prior to the post- purification heat treatments. Common to these tests were several observations:

- High Q-values (low residual resistances < 5 nOhm) at 2K

- Material parameters as derived from the measurement of the temperature dependence of the surface resistance between 4.2K and 2K showed the typical values for the energy gap and the mean free path.

- Difficulties to obtain clean (field emission-free) surfaces, which triggered additional high pressure rinses

- Once field emission was absent, the cavities showed the typical Q-drop around Eacc~16 MV/m, corresponding to Hpeak ~ 70 mT, an unusually low value

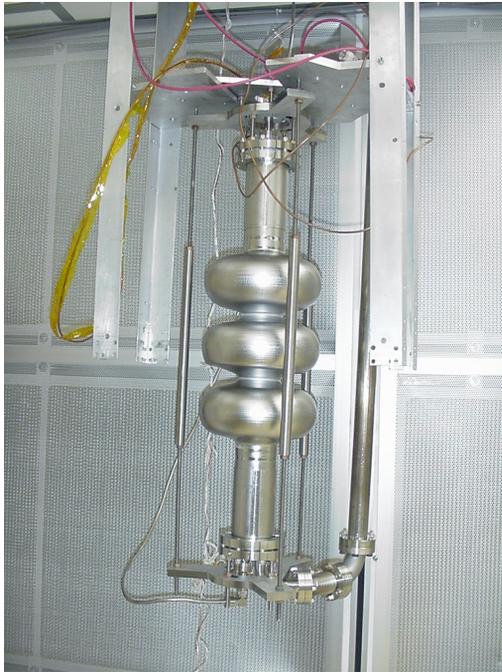- As mentioned above, none of the cavities was limited by "Quench"

Figure 4: 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.

As an example (not a-typical to this investigation, showing the experimental difficulties), the test series for cavity #2 is listed below:

- Test #1: Low Q due to poor magnetic shielding in dewar, vacuum leak due to crack in flange

- Test #2: Improved magnetic shielding, additional material removal, leak in superfluid helium, test at $T > T_{\lambda}$

- Test #3: Cavity repaired by replacing cracked flange, add. BCP, vacuum leak

- Test #4: New HPR after disassembly, vacuum pump failure on test stand, exposure of cavity to air, pump replacement, test aborted

- Test #5: New HPR after disassembly, field emission starting at Eacc ~ 12 MV/m, stopped test

- Test #6: New HPR after disassembly, some FE, but processed well

- Test #7: Post-Purification at 1250 C for 3 hrs, additional BCP removing app. 50 µm

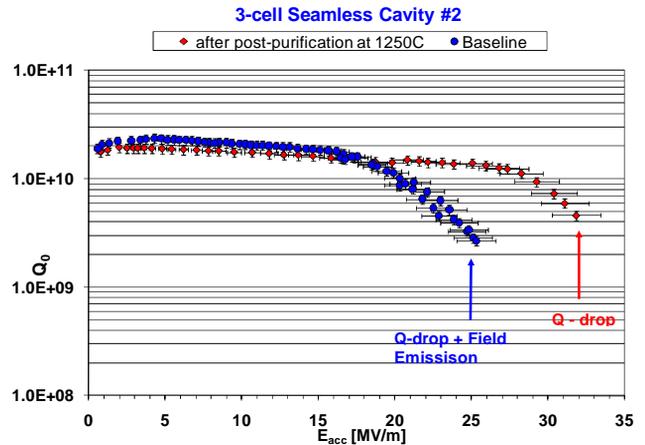The two successful tests (#6 and # 7) are shown in Fig. 5:

Figure 5: Baseline test and post-purification test of cavity #2.

Discussion of Results

Whereas cavity #1 and cavity #2 experienced several testing cycles, for cavity #3 we just applied the "optimum" treatment developed for the other two cavities, namely post-purification and appropriate material removal, yielding the result shown in Fig. 2. In cavity #1 and #2 significant improvements in E_{acc} and especially the onset of the Q-drop were realized. No attempt was made to reduce the Q-drop by "in situ" baking since earlier experiences throughout the community had indicated that fine grain niobium , treated by BCP, does not respond well to baking at 120C. Improvements have been seen only on either large grain niobium surfaces after bcp (quite smooth) and electropolished poly-crystalline surfaces (quite smooth).

The post-purification heat treatment causes two modifications in the material, namely grain growth associated with reduction of stresses and improvement of the thermal conductivity. It has been argued and initial experimental data seem to show, that reduction of stresses in the material can reduce the trapping of magnetic flux lines, which in turn are being responsible for the " hot spots" in the material, causing the "Q-drop" [4,5]. Additionally, the improved thermal conductivity might have prevented a "quenching" of the cavities at the achieved gradients.

As a result of this investigation one can conclude that the seamless fabrication technology developed at DESY over several years is sound and mass production of cavity sub-units (3-cell units) is quite feasible. In connection with a coaxial coupling scheme developed at Jlab/DESY [6] the

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seamless cavity avenue might be a possibility to reduce the costs of a large installation such as the ILC by combining three 3-cell units to a 9-cell cavity. Such an assembly has been successfully fabricated [7] in the past. However, obviously more work for "confidence-building" is needed.

Future Plans

Because of the excellent cavity performances – none of the three cavities quenched, but all were limited by the "Q-drop" - we wanted to subject the cavities to electropolishing treatments and subsequent "in situ" baking to remove the Q-drop and find the performance limit of the cavities. However, it turned out that neither DESY nor Jlab are presently equipped to electropolish 3-cell cavities; in addition, the hydroformed cavities have no stiffening rings (see Fig. 4 for stiffening during cryogenic testing) and we were afraid of deformations due to the weight of the acid. Therefore, our plan changed to combining the three 3-cell cavities to a fully equipped 9-cell TESLA-type cavity with end groups and stiffening rings to be accomplished at DESY with industrial involvement and re-testing of this unit at Jlab after an electropolishing treatment. The fabrication of this unit might cause some difficulties, because all three cavities are presently at different frequencies and need to be tuned to the same frequencies to achieve a flat field profile.

ACKNOWLEDGEMENTS

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