HALF-CELL AND DUMB-BELL FREQUENCY TESTING FOR THE CORRECTION OF THE TESLA CAVITY LENGTH

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Abstract

The first TTF 9-cell cavities had a length exceeding considerably the specified tolerance of ± 3 mm. Therefore a control of the frequency and of the length of cups and dumb-bells for the second production of 29 cavities was performed. We have analyzed errors in shape and weld shrinkage of cups and dumb-bells made by four different companies. A tuning algorithm was applied to compensate for the scattered and systemic offset from the ideal shape. This effort resulted in a length accuracy of the completed cavity of ± 2 mm.

1. INTRODUCTION

Eight TESLA 9-cell cavities are contained in one 12 m long cryostat. Interconnecting bellows are used to compensate small deviations of the length of each cavity. Handling tools for chemistry, furnace treatment and assembly rely on a fixed length of the resonators. Therefore a tolerance of ± 3 mm of the total length of 1283 mm is specified for the cavity production. Unfortunately the length of the beam pipe cannot be trimmed for the compensation of the error of the cavity body because welding the end groups must be finished before completion of the cells. In Fig. 1 the length tolerance of the first 28 cavities from three different companies is displayed. As can be seen, the deviation of the length was quite unacceptable. Therefore the cavity fabrication was analyzed in more details and "in situ" frequency measurements were developed to control the length and resonance frequency of the cells, dumb-bell and 9-cell structure.

2. MECHANICAL TOLERANCES

The cavity contour was calculated by FEM to adjust the right frequency and length at the operating temperature of 1.8 K. The room temperature frequency is extrapolated from these data, including vacuum/air and cool-down effects in the resonance frequency. Tuning of the cavity in respect to a flat field profile at the right frequency is done by lengthening or shortening the iris to iris distance of each individual cell (see tuning machine in Fig. 2). A total length change of 3 mm (i.e. each cell is changed by 3/9 mm = 1/3 mm) results in a frequency change of 1 MHz. This means that a length tolerance of 3 mm of the total cavity limits the allowed error in the contour change of each cell to such an amount which changes the resonance frequency to not more than 1 MHz. With the cavity frequency of 1.3 GHz and a diameter of 210 mm, the tolerable contour deviation is (to the first order):

$$(1 \text{ MHz} / 1300 \text{ MHz})^* \, 210 \text{ mm} = 0.16 \text{ mm}$$

The cavity is welded from cups by electron beam heating at the equator and at the iris. The welding shrinkage changes the resonance frequency by 2.7 MHz/mm at the equator and -0.8 MHz/mm at the iris (assuming equal welding shrinkage at the 9 equator welds and the 10 iris welds). The weld shrinkage can be calibrated, but the scatter in shrinkage must be kept below 0.04 mm at the equator and 0.14 mm at the iris.

3. LENGTH AND FREQUENCY CONTROL DURING SECOND PRODUCTION

During the second cavity production the following quality control steps were applied:

(a) Frequency measurement of all cells,
(b) Contour measurements of some cells,
(c) Frequency measurements of some cells after welding at the iris (dumb-bells),
(d) Frequency measurement of all dumb-bells after welding the stiffening ring.

Step (a) and (d) were carried out for all cups to control the reproducibility of the forming and the welding. Step (b) was used to correlate a resonant frequency change with the contour deviation. Measurement (c) was used to calibrate the contour deformation and the welding shrinkage by the iris weld.

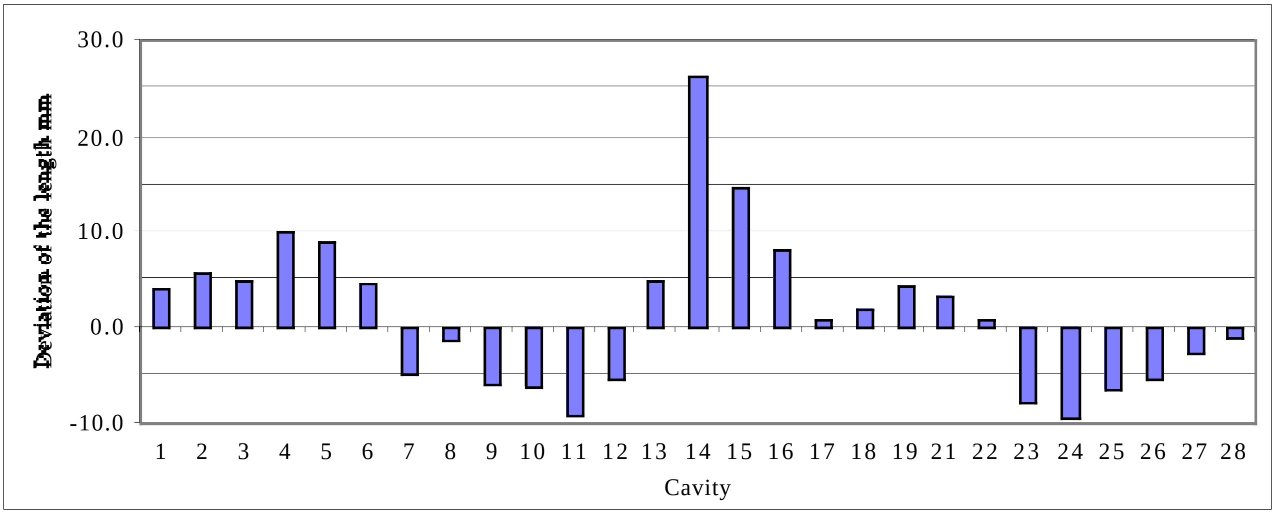


Figure 1: Length deviations of first TTF cavities tuned at the operating frequency
(28 cavities were fabricated by 3 different companies)

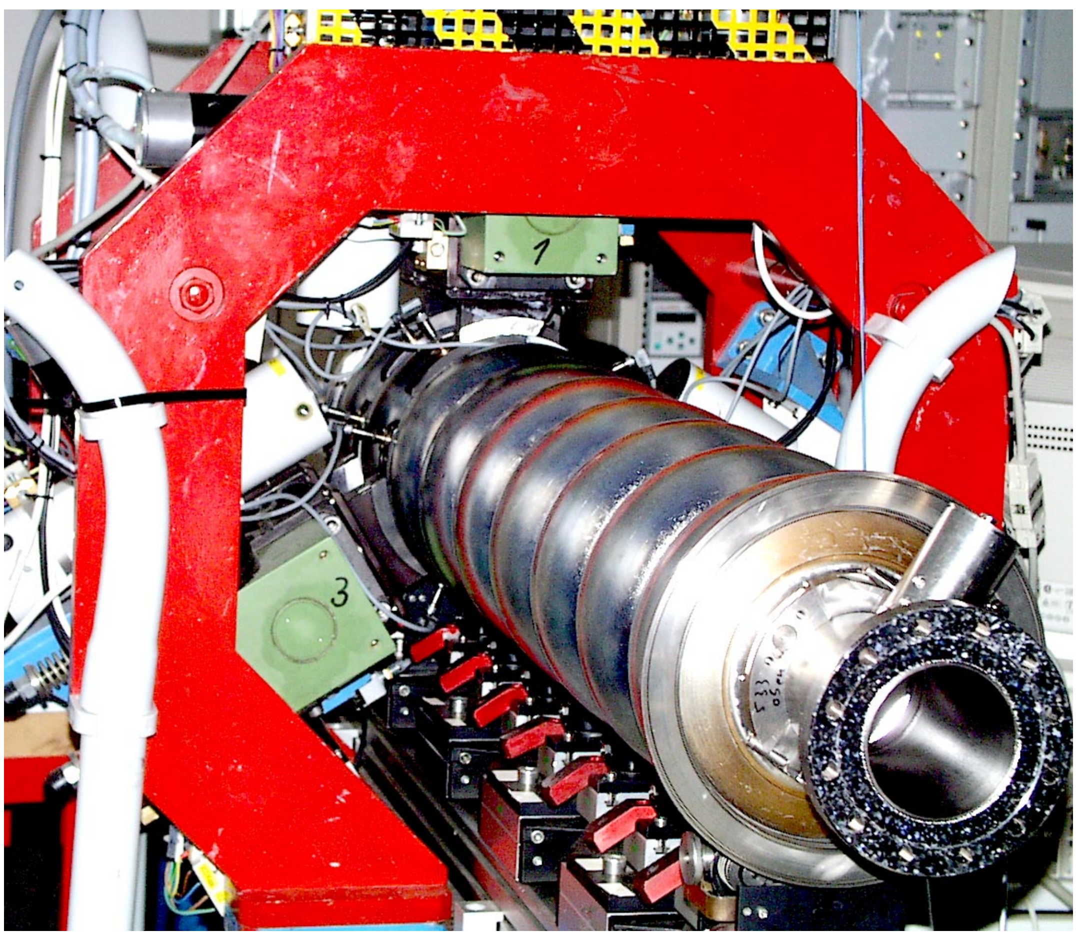


Figure 2: Photo of the computerized tuning machine

3.1. The frequency and the length adjustment method.

The shape error of cups should be corrected before the EB welding. The correction must be performed in such a way that finally the whole 9-cell cavity arrives both, at the right frequency and the right length. The procedure we choose makes use of the opposite change of the frequency due to the volume change in the magnetic field region and in the electric field region. An extension near to the equator (ΔLe, done at the stage of cups) makes the frequency lower while an elongation of a cell (ΔLz, done when tuning the finished cavity) makes the frequency higher (Fig. 3). The frequency sensitivity factors are listed in Table 1.

Table 1: Sensitivity factors

	Equator ΔLe	Length ΔLz
δf [MHz/mm]	- 5.3	5.4

Consider an example where the frequency of the cup is right but the cup is too long by some amount of ΔL. To correct this error one should shorten the equator by ΔL/2 and should squeeze the cell by ΔL/2. This would result in almost no change in the frequency but will reduce the length of the cup by the required amount of ΔL. A similar case is when the length is right but the frequency is too low by -Δf. After the equator is shortened by -0.5*Δf/δf and the length of the cell is increased by pulling by the same amount, we arrive at the right frequency and the length stays almost unchanged . Practically, most of the cups were trimmed before the EB welding in dumb-bells while the plastic deformation ΔLz is always done, with the help of a tuning machine, at the end of cavity preparation after the main BCP treatment.

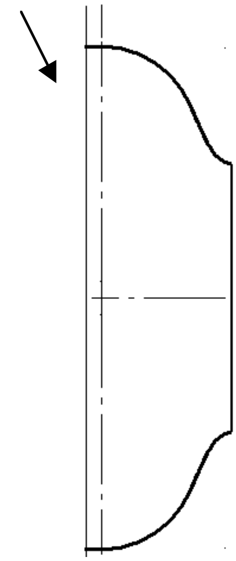
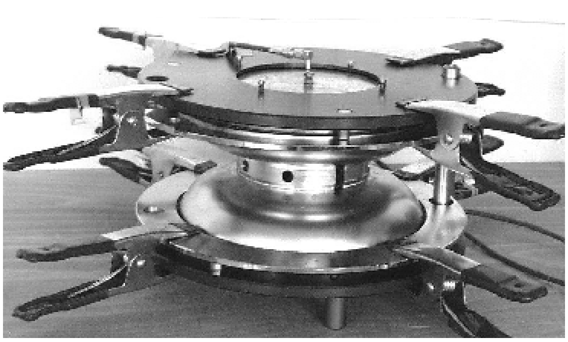


Figure 3: Trimming of the equator to adjust the elongation at the equator

4. THE FREQUENCY MEASUREMENT

4.1 Test set-up.

The cup (dumb-bell) is placed between two plates (Fig. 4). The cup frequency in the test setup is equal to 0-mode frequency because of the electric sheet at the iris. The dumb-bell has two resonant frequencies of 0-mode and π–mode. The plates are made from niobium to avoid a pollution of cups before welding. The resonant frequency of the cup in the test machine is equal to the frequency of cell with electrical boundaries at the equator and the iris. A good RF contact, especially at the equator, is crucial for the frequency measurement. Therefore spring loaded clamps are used to press the equator against the contact plate (see fig. 4, left picture).



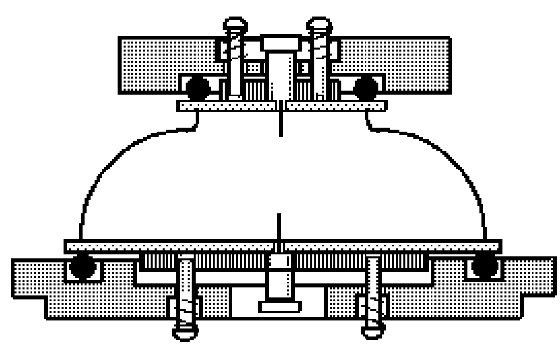


Figure 4: Photo and schematic cross-section drawing of the test device for the frequency measurements of dumb-bells (left) and cups (right)

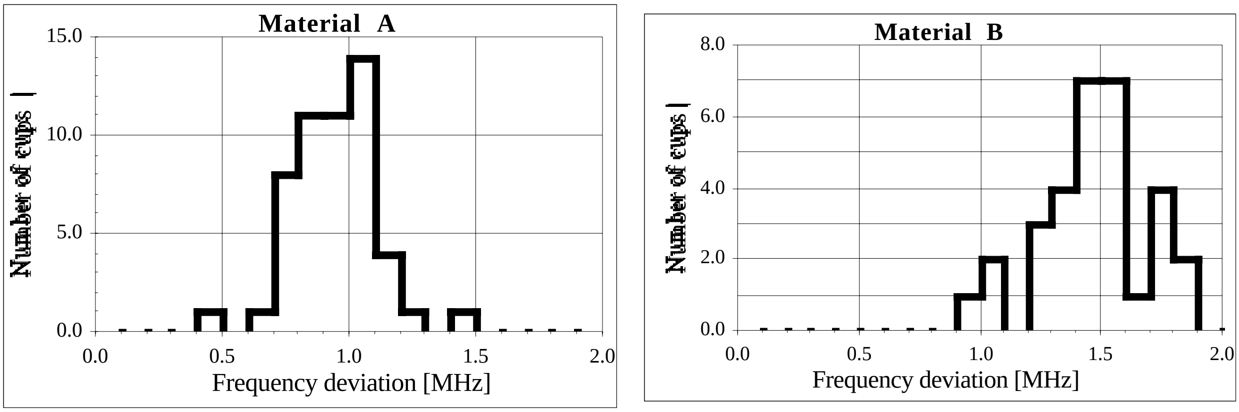


Figure 5: The frequency statistics of 90 (left) and 29 (right) cups from two different materials. Deep-drawing was done with an inner and outer metal tool.

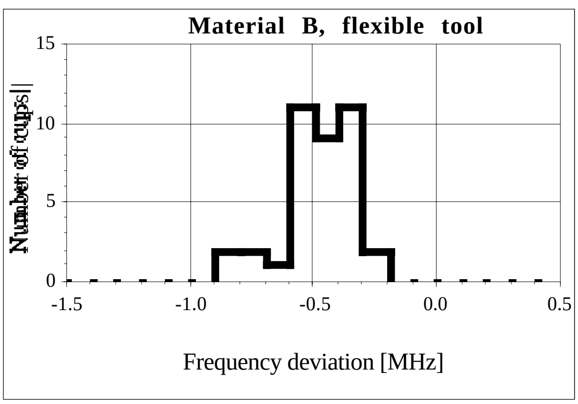


Figure 6: The frequency statistics of cups fabricated by pressing the sheet with a resilient cushion over an inner metal tool.

To perform the measurements two short electrical antennas are placed in the center of contact plates and connected to the Network Analyzer.

4.2. Influence of tooling.

Three different companies were involved in manufacturing of Nb cavities for TTF. The cups were formed from Nb discs in two steps:

- deep drawing step,
- second forming step which corrects deviations at the iris region (small bending radius).

There are two different tools for deep drawing:

1. The sheet is "pressed" between an inner and outer metal tool. This method is sensitive to change in sheet thickness. Furthermore, there is no control that the later "inner" surface of the cups follows the specified contour.
2. The sheet is "pressed" over an inner tool by a resilient cushion or an equivalent hydrolic medium. Hereby the thickness of the sheet is not critical and the "inner" contour of the cup is formed precisely.

160 cups were formed from the same batch of Nb sheets with the two different deep drawing tools. The result is displayed in Fig. 5, right graph, and Fig. 6. It can be seen that the scatter for the resonance frequency is smaller for the second deep drawing method. The standard deviation is 0.2 MHz for method 1 and 0.1 MHz for method 2.

4.3. Influence of Nb material.

The Nb material is specified in respect to

- Degree of re-crystallization,
- Hardness,
- Yield strength,
- Thickness of sheet,
- Electrical properties.

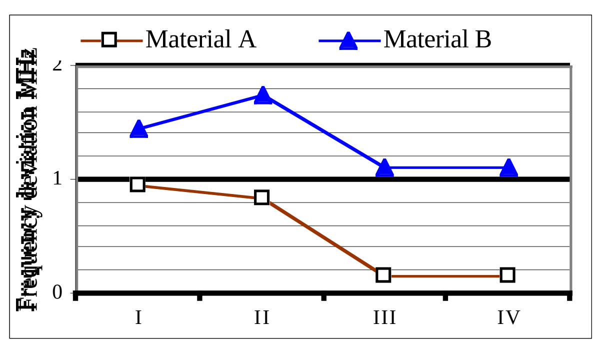
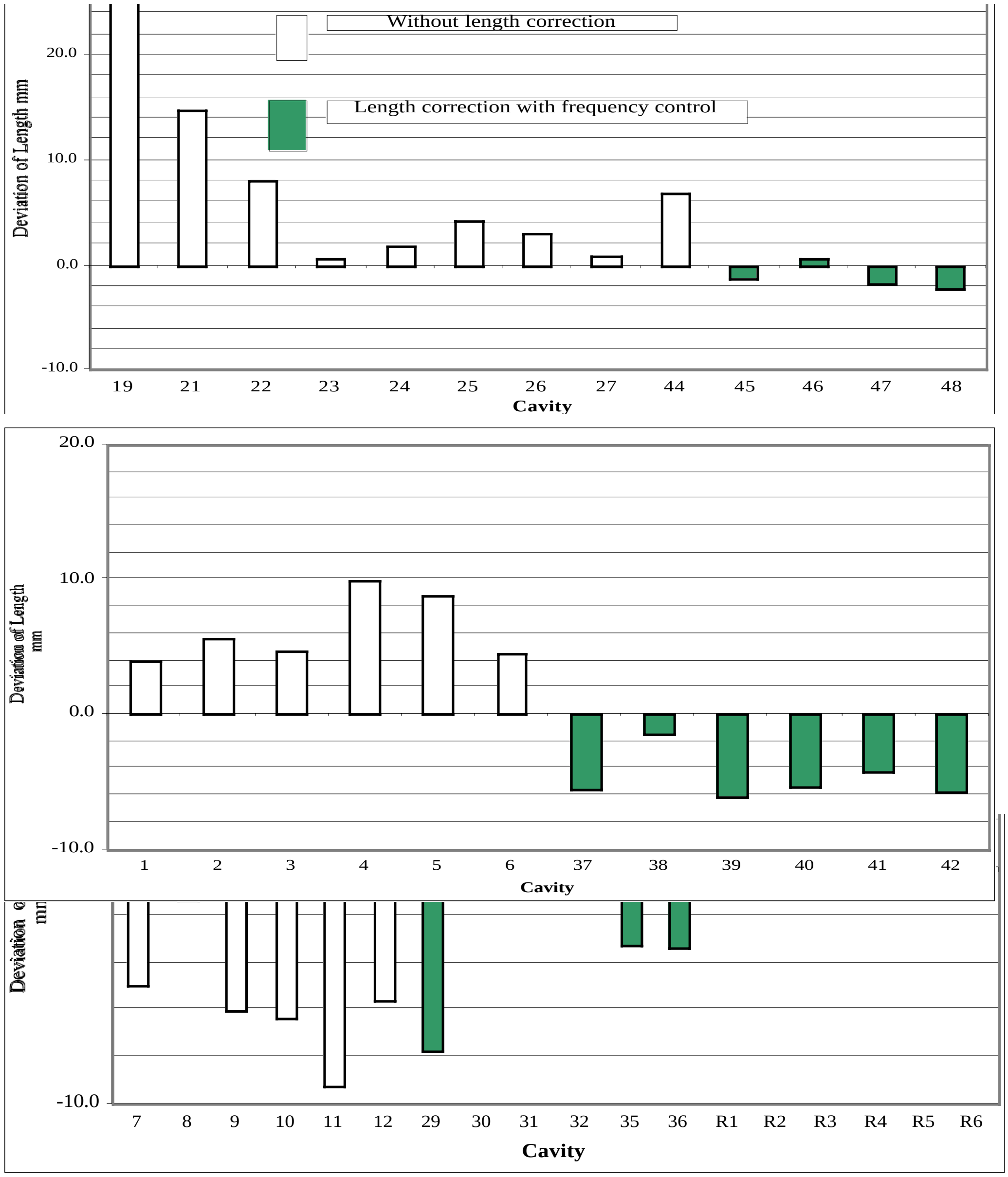


Figure 7: Frequency deviations measured at the different fabrication steps. I - Half cells; II - Dumb-bells after weld of iris; III - Dumb-bells after weld of the stiffening ring; IV - Cells in the cavity.

As a matter of experience, different Nb batches from different companies show different behavior during forming. For example, in Fig. 5 the frequency measurement of 90 and 29 cups from different Nb suppliers after forming with the same tool at the same



company is shown. There is a difference in the frequency off set of 0.6 MHz, but the standard deviation of 0.2 MHz remains constant. It means, that at least the tools for the second forming process might need a fine trimming after some sample forming with the new material. This different behavior of Nb batches is not equally severe for all Nb suppliers. The most likely reason for the non-uniformity is a non-constant degree of re-crystallization of the sheet.

Fig. 8: Comparison of the length deviation of the finished cavities with (shaded bars) and without (light bars) corrections after frequency measurements of the cups.

The degree of re-crystallization is determined by the microscopic examination of the grain structure of only a few cuts from the Nb sheets. Therefore this method cannot exclude variations of the degree of re-crystallization within the sheets or between the sheets.
A simpler check is to measure the hardness HV10 on each sheet of niobium. The hardness HV10 was measured at the corner of all sheets and values above 60 were not accepted.

4.4. Influence of iris and stiffening ring welding

The welding shrinkage at the iris changes the resonant frequency of the cups and this turned out to be reproducible once the welding parameters were fixed. The weld of a stiffening ring from the outside deforms the inner contour of the cups and thus changes the resonance frequency. Since the weld of a stiffening ring is more complicated as is the case of the "plane"
iris or equator weld, the welding conditions at the EB installation at different companies resulted in quite

different contour distortion. Nevertheless, the reproducibility of this distortion is good enough to be compensated. Fig. 7 shows the change of frequency of three production steps at one company from cups to finished cavities.

4.5. Results of finished cavities

21 cavities were fabricated with the control of frequency and trimming the height of cups as described above. Fig. 8 compares the length deviation of the finished cavities with (shaded bars) and without (light bars) corrections after frequency measurements of the cups. Cavities 37, 39, 40, 41 and 42 suffered from a mechanical error of -0.1 mm when cutting the equator. For cavity 29 a wrong prediction of the iris welding shrinkage was applied. All other cavities were delivered within the length tolerance of ± 3 mm. In the future the trimming of length will be carried out at the stage of dumb-bell rather than cups. The advantage is, that

- Possible change of the iris welding can be compensated,
- Change in the stiffening welding can be compensated,
- The planarity of both equatorial planes of a dumb-bell is assured.

5. CONCLUSION AND OUTLOOK

The solution for a mass production must be to assure reproducibility of Nb material parameters, forming and welding properties to such a degree, that the complex frequency measurement is needed only for quality control on a few samples. Based on our experience, reproducibility of welding is not critical. More investigation is needed to reduce the change of forming properties of the Nb sheets from different fabrication lots. In addition the functionality of the forming tools must be optimized to assure the correct inner contour regardless some changes of sheet thickness and material properties.

6. ACKNOWLEDGEMENT

Open discussion and exchange of experience with Nb producers and cavity fabrication companies is greatly acknowledged.