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RADIAL TUNING DEVICES FOR 1.3 GHz TESLA SHAPE CAVITIES*

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Abstract

Radial tuning devices at DESY can be applied to any TESLA shape 1.3 GHz cavity to reduce its elongation due to excessive additional material removal (>300 µm) or to compensate critical manufacturing uncertainties. Radial deformation of cavity cells can be provided by a special chain or a rolling device with three rollers. The chain distributes the radial forces on the equator area around the cell. The rollers are moving radially in relation to the rotating cavity and provide an equator diameter reduction. Both devices have the contour close to the cell shape at the equator area. The required equator radius deviation depends on the tuning target and usually varies between (0.02...0.60) mm. Different aspects of the tuning procedure and material properties are described using the example of cavity rolling.

INTRODUCTION

Conceptual design of 9-cell 1.3 GHz superconducting niobium cavities for electron-positron collider TESLA [1] was approved in the TESLA Test Facility (TTF) linac at the end of the last century at the Deutsches Elektronen-Synchrotron (DESY). Since that time this type of elliptical cavities is commonly used for large scale superconducting accelerator projects like the European X-Ray Free-Electron Laser (EXFEL) and the Linac Coherent Light Source (LCLS)-II. This is motivating of scientific society to optimize the technological process for TESLA shape cavity manufacturing through the last three decades. The technique of forming seamless (weld-less) cavities by hydroforming [2] was developed at DESY. Some reshaping devices were involved during this work and they allow providing both reduction of equator radius and shape adjustment. They were also used for compensation of cavity elongation during extra chemical treatment [2, 3] and for Higher Order Mode (HOM) suppression improvement of EXFEL cavity [4]. More detailed information about these devices and operating process will follow this chapter.

Usual modern cavity fabrication procedure (which was used for EXFEL and LCLS-II projects) requires only standard (longitudinal) tuning with a cavity tuning machine (CTM) [5], which allows achieving required fundamental mode frequency (F) and field flatness (FF), keeping the eccentricity (ECC) of cells in tolerances [6].

Sensitivity of fundamental mode frequency to deformation of different cavity dimensions (L – length, R_e – average equator radius, Ri – average iris radius) [7]:

$$dF = \frac{\partial F}{\partial L}dL + \frac{\partial F}{\partial R_e}dR_e + \frac{\partial F}{\partial R_i}dR_i \qquad (1)$$

where $\frac{\partial F}{\partial L} = 300\frac{kHz}{mm}$, $\frac{\partial F}{\partial R_e} = -14.6\frac{MHz}{mm}$ and $\frac{\partial F}{\partial R_e} = 4\frac{MHz}{mm}$.

Acceptable deviation of cavity frequency is usually limited by +/- 100 kHz. This value corresponds to length deviations about +/- 0.3 mm. If a cavity is used for R&D investigations, its length is not critical, but before integration into helium tank and usage in the linac, cavity length deviation is usually limited by +/- 3 mm.

Accurate fabrication and usage of special equipment as HAZEMEMA [8] guarantee cavity length accuracy below 1 mm. But sometimes additional material removal during an acid treatment is required. It causes fundamental mode frequency reduction, which usually can be compensated by cavity elongation during standard tuning.

To avoid excessive lengthening over the limit (+3 mm) radial tuning can be applied. The radial tuning deforms cell equator area radially while keeping cell and cavity length constant.

RADIAL TUNING DEVICES

In comparison of radial tuning to conventional tuning it is not reversible and can be applied only in one direction. Cell equator radius can be reduced but not increased. As well precision and predictability of radial tuning is much lower compared to conventional cell length tuning.

At DESY there are two different tooling's for radial tuning available.

Principals of their functionality are described below.

Chain

The chain distributes the radial forces on the equator area around the cell (Fig. 1). The tuning chain consists of eight brass pressing shoes following the outer cell contour in the equator area. They are mounted to the stainless steel made chain itself sliding.

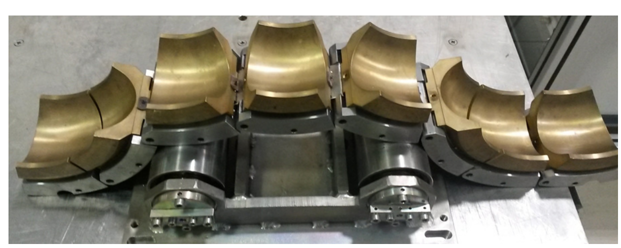

Figure 1: Opened stainless steel tuning chain with eight brass pressing shoes.

The chain can be installed and closed by a screw lock to each of the nine cells of a cavity separately as shown in Figs. 2 and 3.

The tuning or reshaping is performed by further tightening of the screw lock which leads to a reduction of the gaps between the pressing shoes. With this gap

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reduction a plastic deformation of the equator radius is achieved. During closing of tuning chain the frequency change is observed as well as the length of cavity and cell is kept constant.

The blue arrow in Fig. 2 indicates direction of movement while closing the tuning chain. Red arrows display homogenious force distribution by the sliding pressing shoes around the equator.

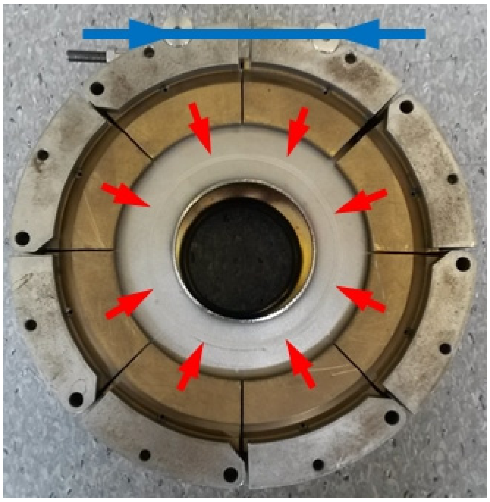

Figure 2: Closed tuning chain with cavity cell.

Unfortunately this procedure of radial tuning is limited on the one hand side by mechanical dimensions of tuning chain itself and on the other hand side by unpredictability of radius reduction.

A further reduction of equator radius neither elastically nor plastically cannot be achieved when all gaps between pressing shoes are completely closed. By tightening of screw lock forces from chain start to deform cell equator radius elastically first. Whenever the flow limit of pure niobium material between elastic and plastic deformation is reached by gap reduction, equator radius is reduced abruptly. Thus the end value of deformation cannot be achieved within a reliable precision.

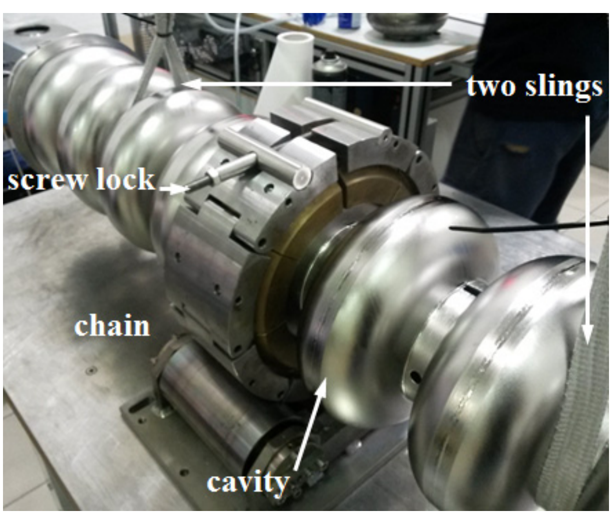

Figure 3: Tuning chain installed to cavity.

Assembling of a tuning chain on cavity is quite challenging (Fig. 3) due to the comparatively high weight for both of them. It was found a solution: chain is fixed on the working desk and cavity is hanged up with two slings by cavity lifter. So the cavity position relative massive chain could be adjusted to prevent unwanted deformations by gravity forces.

For further use this device needs to be improved as well as the material properties of pure niobium to be understood better.

Rolling Device

Second tooling for radial tuning available at DESY is a rolling device.

Main parts of rolling device (Fig. 4 and 5) are two equal form rollers made by stainless-steel. They are kept by two adjustable transmission joints. The form rollers are moving radially in relation to the rotating cavity and provide an equator radius reduction.

Presented in Fig. 4 outer contour of both form rollers is vice versa egg shaped. Its form does not follow theoretical outer shape of cavity cell.

During rolling of cavity an elastic counter roller (see Fig. 4 and 5) made by NBR – Nitrile Butadiene Rubber-deforms the equator area of the cell elastically.

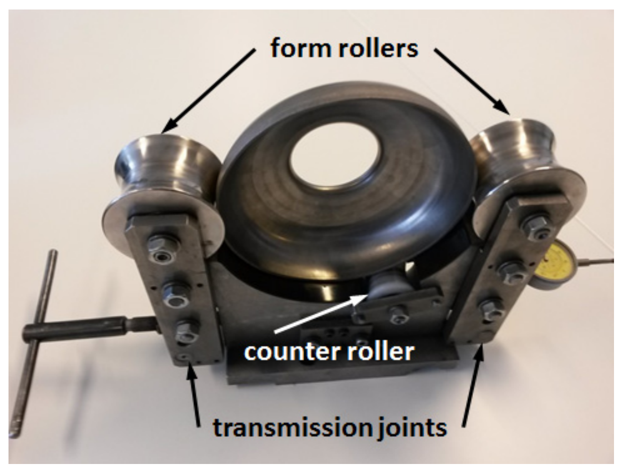

Figure 4: Rolling device with cavity half-cell.

The red arrows (Fig. 5) indicate the force distribution on cavity cell while the green arrows show principle of rotating cavity cell and rollers.

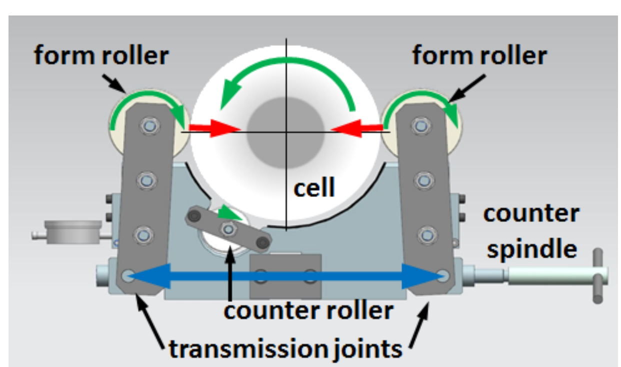

Figure 5: Principle of rolling device.

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Rollers and transmission joints are manually driven by a counter spindle integrated to heavy central carrier unit (blue arrow).

TUNING PROCEDURE

Due to fact that presented tuning chain (Fig. 1-3) still needs to be improved only the procedure for rolling device is presented in detail. Nevertheless general procedure for both devices is comparable.

To provide an accurate control under cavity deformation, frequency measurements are used. They usually are more accurate in comparison with mechanical measurements.

The tuning plan is calculated to guarantee homogeneous radius reductions for all 9 cells. But field flatness (2) on fundamental mode has to be adjusted (FF > 97%) prior to radial deformations.

$$FF = \frac{min|E(i)|}{max|E(i)|}\,100\%, \tag{2}$$

where $E(i)$ is an amplitude of electric field in cell i = 1..9.

If HOM suppression improvement is required for TM011 mode the first cell can be compressed to achieve the required field distribution (see [4] for details).

Fundamental mode frequency during FF adjustment has to be corrected according Eq. (1), where $dR_e = dR_i = 0$ and dL is a value of necessary length reduction.

Deviations of fundamental mode frequency during cells deformation (tuning plan) are calculated by the well-known method [9]. It based on the measurements of fundamental mode (TM010) spectra (9 frequencies) and the amplitudes of electric field in the centers of all cells on each mode (81 amplitudes).

We always have to follow a tuning plan, starting with deformation of the first cell, continuing with the next, when the target pi-mode frequency is achieve with accuracy +/- 20 kHz.

Either after a rolling of all cells or in case of a strong mistake (value depends on cavity, target frequency and cell number) of any cell these measurements and new tuning plan calculation have to be repeated.

After the cavity is installed on the base (Fig. 6) between the rotating flanges, rolling tool is connected with a cavity cell, measurement devices (NWA, RF amplifier) have to be connected to cavities antennas with two long RF cables.

Cell is pressed strongly between the form rollers.

With start of rolling process a very high pre-stress by the form rollers is adjusted first. The adjusted level of pre-stress depends on deformation value for effected cell and material properties (e.g. elasticity of a cell).

The offset of elastic counter roller (Fig. 5) is adjusted on a level where it is ensured deformations brought to cavity cell are mostly elastically. The cell is squashed in the contact area of counter roller and simultaneously stretched on the opposite side of cell due to fact the cavity ends are kept on axis.

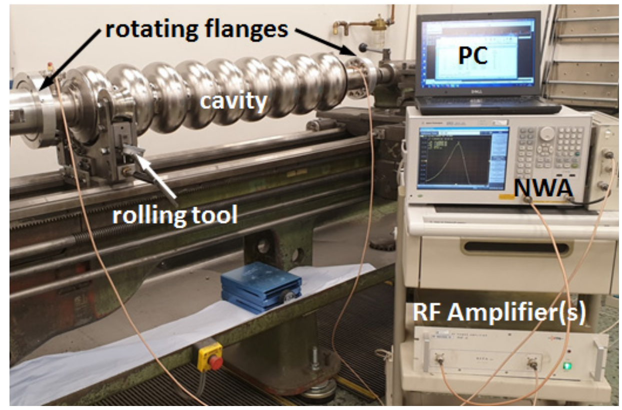

Figure 6: Radial tuning with rolling device and frequency control measurements.

Depending on different treatments cavity elasticity is mostly related to thermal treatment and recrystallization level. The center axis of counter roller is shifted among the cavity axis by 0.2 mm (for end cells) to 0.5 mm (in the middle).

Reaching flow limit during rolling relatively early in combination with a fast frequency drift is well known for weak or high temperature treated cavities. This is due to low hardness and high elasticity of material.

By ongoing rolling and simultaneous reduction of pre-stress the equator diameter decreases further until there is no more stress or contact between form rollers and cells.

The tuning or deformation value can be achieved more precise and predictable when starting with high pre-stress and fast reduction of pre-stress within reaching flow limit and start of frequency drift versus rotations. The velocity of reducing pre-stress from form rollers versus rotations is given by experience.

This allows reliable and predictable results.

After deformation value is reached the cell is hardened again by smooth deformation from elastic counter roller.

Material properties of Niobium are as well specific as surprising- giving a good answer why the rolling procedure is none awaited to be performed.

EXAMPLE

One of the R&D cavities (Z84) for TTF project at DESY was used for testing of a surface treatment infrastructure. It had been polished several times by centrifugal barrel polishing (CBP) and electropolishing (EP), before its weight reduces from 26 kg to 20 kg. It corresponds to about 600 µm of wall thickness reduction. Cavity characteristics had significant deviations relative nominal frequency (1297.37 MHz) and length (1059.0 mm) and marked with "*" in Table 1 (before rolling). So it was decided to make a radial tuning. This operation was divided in 4 steps: 1 – frequency correction of 1 MHz (about 60 µm deformation of equator radius), 2 – 2 MHz, 3 – 2 MHz and 4 – 1 MHz.

During prior tuning FF value achieved 98 %, but cells eccentricity increased. Usually a cavity becomes straighter during rolling, thus we left ECC = 0.63 mm.

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Table 1: Cavity Characteristics During Rolling

	F, MHz	dF, MHz	FF, %	L, mm	dL, mm	ECC, mm
Before rolling	1292.17	5.20*	98	1062.8	3.8*	0.63
After rolling 1	1293.21	1.04	86	1062.6	-0.2	0.34
After rolling 2	1295.24	2.03	87	1062.3	-0.3	0.29
After rolling 3	1297.31	2.07	87	1059.9	-2.4	0.28
	dF SUM	**5.14**		**+ dL SUM**	**-2.9**	
After tuning	1297.23	0.14*	98	1059.9	0.9*	0.37

Cavity characteristics after each iteration of rolling are presented in table 1. Cells eccentricity during radial tuning gradually decreases up to 0.28 mm. Fundamental mode frequency increases according the tuning plan, but FF was reduced because of inaccuracies of radial deformations in different cells.

Irregularity of these deformations is also confirmed by inequality of eigenfrequencies in different cells (Fig. 7). The highest deviation was observed after the third rolling. It can be explained by strong cavity length reduction, which indicates that both longitudinal and radial deformations were taking place simultaneously. So deviation of both parameters R_e and L in Eq. (1) caused additional frequency control uncertainty.

Total length reduction (dL SUM in Table 1) after rolling 3 was -2.9 mm. It corresponds to fundamental mode frequency deviation of about 1 MHz and it was no necessity in rolling 4. This step was skipped.

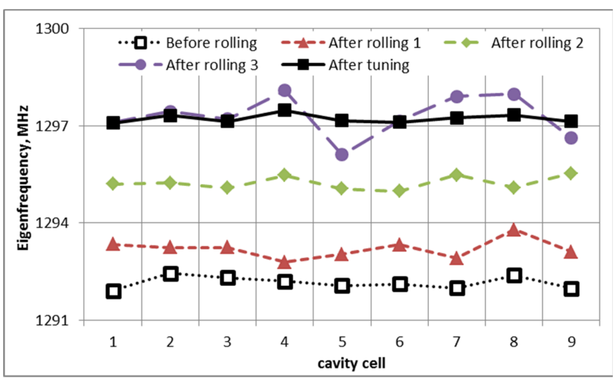

Figure 7: Cavity cells eigenfrequencies before and after each of 3 rolling.

Standard longitudinal tuning was applied after final radial tuning. One can observe significant reduction of cavity characteristics deviations (dF and dL). They marked with "*" in the last raw of Table 1.

Field distribution for the second monopole mode (Fig. 8) shows some asymmetry reduction and increase of field amplitudes (maximal in cell #4). But it should not play significant role for efficiency of HOM suppression [4], because we could keep the maximal field amplitude in cell #1.

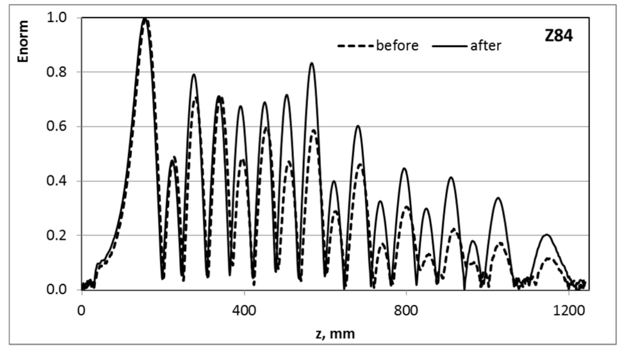

Figure 8: Normalized field distribution |E(r=0,z)| on cavity axis for second monopole mode TM011 – before rolling (dash line) and after final standard tuning (solid line).

SUMMARY

Radial tuning comparatively to conventional one is not reversible and can be applied only in one direction. Cell equator radius can only be reduced. So precision and predictability of radial tuning is more important than for conventional cell length tuning. We can propose two ways of improvement of rolling accuracy:

1. Length fixation is only in one direction (preventing elongation). It is useful only for hard cavities. So length reduction has to be prevented either for soft cavities or for strong deformations (> 200 µm).
2. Divide the planned deformation in several iterations. Small deformation could be done with higher predictability and possible inaccuracies can be compensated by the next iteration.

Reduction of cells equator radii was successfully approved for TESLA shape cavities of TTF [2], EXFEL [4] and LCLS-II [3] projects.

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