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EXPERIENCE OF LCLS-II CAVITIES* RADIAL TUNING AT DESY

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Abstract

Radial tuning (rolling) was applied to three LCLS-II cavities to prevent that their lengths exceed the technical limits. The cavities have a reduced frequency due to additional material removal during cavity treatment well beyond the baseline recipe. The mechanical condition of the cavities was relatively soft because of the thermal history and the niobium manufacture requirement of an optimal flux expulsion. The niobium was highly recrystallized by 3 hours annealing at 900°C and 975°C respectively. Each cavity received an inner surface treatment of 200 µm electro-polishing (EP) and an external 30 µm buffered chemical polishing (BCP) as part of the baseline recipe. Each cavity received an addition ~100 µm of chemical removal along with a second annealing treatment before the radial tuning process. Detailed information about the accuracy and homogeneity of LCLS-II cavities rolling is presented as well as results of field distribution analysis for TM011 zero-mode with a comparison to standard cavities.

INTRODUCTION

More than 370 superconducting radio frequency (SRF) TESLA-type 1.3 GHz cavities for Linac Coherent Light Source (LCLS)-II project [1, 2] were manufactured by two European vendors: Ettore Zanon S.p.A. (EZ) and RI Research Instruments GmbH (RI). LCLS-II used "build-to-print" SRF cavity production strategy, developed at the Deutsches Elektronen-Synchrotron (DESY) for the European X-FEL (EXFEL) project [3].

The cavities used for the LCLS-II production are all treated using high temperature nitrogen doping to enhance the mid-field Q0, reducing the cryogenic load of the Linac. Unfortunately this technology requires a complete surface removal and re-heat treatment in case of cavity rework, unlike EXFEL which only required a light flash BCP [3]. Prior to re-doping, depending on the rework requirements, 30 to 100 µm of chemistry is needed to remove the initial doping – adding length to the cavity to stay within the frequency tolerance.

All cavities comply with the tight LCLS-II specification requirements (see Table 1) after standard tuning under room temperature conditions. Cavity length at this manufacturing step is measured between the connecting flanges (see Fig. 1) and frequency corresponds to operating pi-mode of TM010 at room temperature and air pressure.

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Table 1: Target Cavity Characteristics After a Standard Tuning

Parameter	Value
Length (L_T), mm	1061 ± 3
Frequency (F_T), MHz	1297.96 ± 0.05

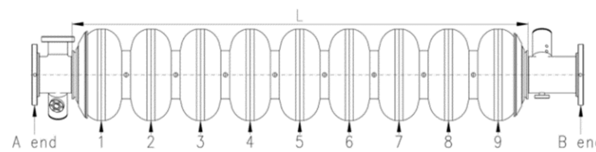

Figure 1: 9 cell cavity length (L).

Effective elongation (ΔL) indicates the length deviation relative target value after the standard (longitudinal) tuning exactly to target frequency. Maximal value of additional EP treatment (ΔR) in case the length is within the limit ($\Delta L_T = 3$ mm). These parameters can be calculated:

$$\Delta L = (L - L_T) - \frac{F - F_T}{\partial F / \partial L}, \quad (1)$$

$$\Delta R = (\Delta L - \Delta L_T) \frac{\partial F / \partial L}{(\partial F / \partial R)_{EP}}, \quad (2)$$

where sensitivity of pi-mode frequency (F) to deviations of cavity length (during standard tuning) and inner contour radii (during electropolishing process):

$$\frac{\partial F}{\partial L} = 300 \frac{kHz}{mm}, \quad \left(\frac{\partial F}{\partial R}\right)_{EP} = -6 \frac{kHz}{\mu m}.$$

Some LCLS-II cavities required extra treatment of about 100 µm chemical removal. But it was not possible to provide it for three of them, because their effective elongation almost achieved the limit ΔL_T (see Table 2).

Table 2: Cavity Characteristics Before Rolling

Cavity	L, mm	F, MHz	ΔL, mm	ΔR, µm
EZ-1	1063.7	1297.90	2.9	5
RI-1	1063.6	1297.89	2.8	8
RI-2	1064.0	1297.96	3.0	0

Another important cavity characteristic is field flatness (FF) on operating mode. It equals a ratio between minimal and maximal E-field amplitudes on cavity axis in the middle of different cells:

$$FF = \frac{min|E(i)|}{max|E(i)|} 100\%, \quad (3)$$

where i = 1..9 – cavity cell.

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Radial tuning procedure [4], which was used at DESY originally for hydroformed elliptical cavities [5], provides reduction of effective elongation by decrease of equator radius for all 9 cells (see Fig. 1).

RADIAL TUNING

Prior to the rolling all three cavities were tuned by cavity supplier EZ (one cavity) and RI (two cavities) to achieve a flat field distribution on operating mode with FF = 98 % (standard tuning of cells length). It was required for calculating of the radial tuning plan (Table 3) for homogeneous deformation of all cells. Different frequency deviation dF(i) corresponds to equal deformation of cell (i = 1..9). This fact can be explained by sensitivity changes (dF/dR)RT due to perturbation of field distribution for fundamental mode.

Table 3: Frequency Deviation After Cell Deformation (kHz)

Cell #	EZ-1	RI-1	RI-2
1	87	145	152
2	117	191	204
3	101	153	193
4	93	96	123
5	48	84	87
6	55	66	62
7	42	57	52
8	50	47	49
9	56	69	77
SUM	**649**	**908**	**999**
ΔL, mm	0.4	-0.6	-0.7
ΔR, µm	132	178	185

Final frequency deviation (SUM, in Table 3) after radial tuning of all 9 cells provides reduction of effective elongation (about 2 mm for EZ-1 and over 3 mm for RI cavities 1 and 2) and increases maximal possible value of additional EP treatment over 100 µm (Tables 2 and 3). These values correspond to equator radius reduction about (40-70) µm [6]. So the mechanical control on this deformation level becomes challenging taking into account relatively high fluctuations of outer geometry shape in equator area. It explains the choice of frequency control plan.

One can observe the relatively flat distribution of cells eigenfrequencies before rolling (see Fig. 2).

Different material properties (e.g. Nb hardness) of the cavities and limited accuracy of rolling procedure did not allow making the homogeneous deformation of 9 cells according to prepared plan (Table 3) for all cavities.

Maximal radial tuning inaccuracy for EZ cavity is 18 kHz in cell #9. It corresponds to about 10 µm additional reduction of equator radius there. Nevertheless we could keep FF on the level of 93 % and pretty smooth eigenfrequencies distribution (Fig. 2) after rolling.
Maximal radial tuning inaccuracy for RI-1 cavity is 121 kHz in cell #9, but the first significant error were done already for the cell #1. We have over pressed it on 95 kHz (about 40 µm). Further tuning plan (Table 3 for RI-1) became useless. Nevertheless we decided to proceed, trying making the equal deformation in all cells by the tactile feeling of applied forces and control of the imprints on cavity cells from the tuning tool (rollers). Field flatness was reduces till 66 % and eigenfrequencies of RI-1 cavity (Fig. 2) after rolling indicate small deformation of cells #4 and #5 and strong deformation of cell #8. Further correction was possible only for cells #4 and #5, but it was decided to keep it as it is.

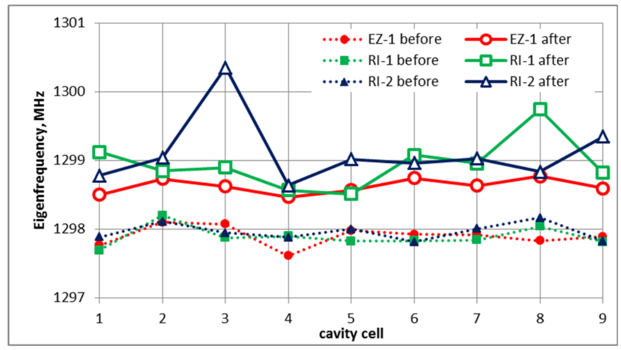

Figure 2: Eigenfrequencies of cavity cells before and after radial tuning.

Maximal radial tuning inaccuracy for RI-2 cavity is 230 kHz in cell #3. But we proceed similar to cavity RI-1, trying making the equal deformation in all cells. Correction of such errors by radial tuning is not possible. An increase of the cell #3 radius can be provided by e.g. local material removal from the inner surface. So it was decided to keep it as it is before conclusion about the efficiency of Higher Order Modes (HOM) analysis.

Results of the measurements of cavities frequency and length after radial tuning are collected in Table 4. One can see that in addition to planned pi-mode frequency raise due to radial compression, cavities have also longitudinal deformation. EZ-1 elongation of 0.3 mm accompanied with additional increase of pi-mode frequency. It is normal behaviour for a pretty hard cavity, when stresses in the material collected during radial deformations are coming out after cavity disassembly (cavity is fixed against elongation during radial tuning) from rolling device. RI cavities show opposite behaviour. Cavity length reduction (0.4 – 0.8) mm indicates on very soft material.

In spite of different individual results for each LCLS-II cavity, all of them reduced effective elongation parameter and additional EP treatment up to 100 µm can be provided for them without a risk that their lengths exceed the technical limits.

Table 4: Cavity Characteristics After Rolling

cavity	L, mm	F, MHz	ΔL, mm	ΔR, µm
EZ-1	1064.0	1298.63	0.8	112
RI-1	1063.0	1298.98	-1.4	220
RI-2	1063.2	1299.14	-1.7	237

All three cavities were tuned again (standard tuning of cells length) by cavity supplier EZ and RI to achieve a flat

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field distribution on operating mode with FF = 98 %. Then field distribution for second monopole TM011 zero-mode was measured on cavity axis (Fig. 3). Dash lines present standard LCLS-II cavity condition before rolling.

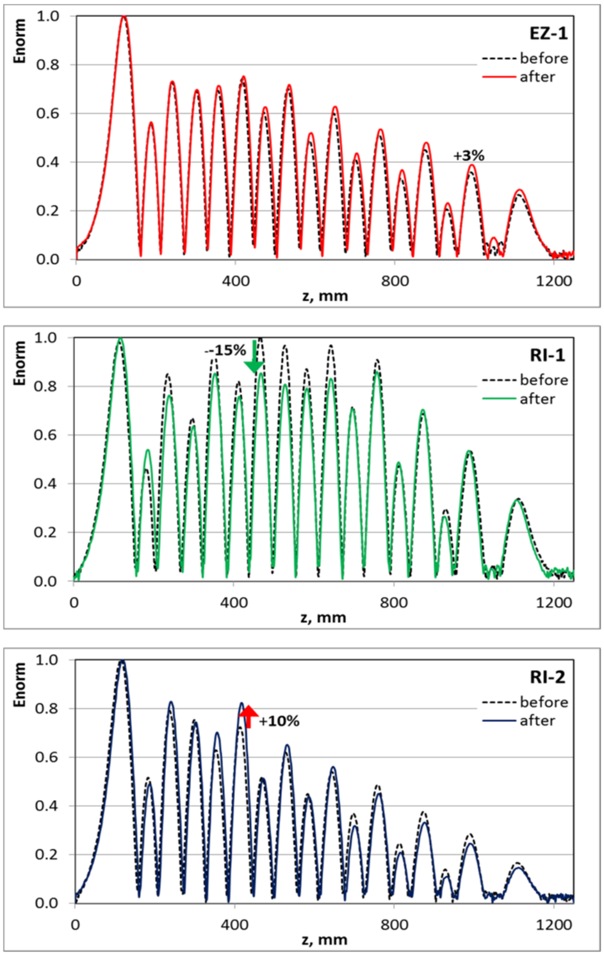

Figure 3: Normalized field distribution |E(r=0,z)| on cavity axis for second monopole mode TM011.

Very low deviation (3 %) for EZ-1 clearly indicates homogeneous radial deformation for all cells. Field reduction (- 15 %) in the middle cells of cavity RI-1 should not play significant role for efficiency of HOM suppression [7], because we could keep the maximal field amplitude in cell #1. The same conclusion can be taken for cavity RI-2.

SUMMARY

Based on our experience with LCLS-II cavities, we can come to the following conclusions:

- radial tuning at DESY allowed to decrease the cavities lengths about 2 mm for EZ-1 and over 3 mm for RI-1,2 or/and provide possibility of an additional chemical treatment (over 100 µm EP);
- the most accurate (homogeneous) deformations of all 9 cells were provided for cavity EZ-1 (see Fig. 2). The reasons of deviations in some cells for RI-1, 2 can be explained by different hardness of cavity material and limited accuracy of radial deformations process [4];
- deviation of field distribution for TM011 zero-mode relative to standard cavities is less then between the cavities before rolling. So the radial tuning inaccuracy brings no significant impact to HOM suppression efficiency.

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