RF MEASUREMENTS FOR QUALITY ASSURANCE DURING SC CAVITY MASS PRODUCTION

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Abstract

The publication will describe the comprehensive program and results of RF measurements taken during the mass production of superconducting cavities for the European XFEL.

INTRODUCTION

The demanding performance requirements coupled with the ability to provide quick and accurate quality control of more than 800 cavities during mass production for the European XFEL gave us an impulse to organize an automatic quality assurance (QA) procedure basing on RF measurements [1].

Mass Production

Cavity life cycle can be divided in three major phases:

1. Pre-production: niobium sheet mechanical and material purity controls [2].
2. Production: mechanical cavity fabrication.
3. Post-production: cavity RF tests and operation.

Many critical RF measurements are necessary from niobium sheet control up to the accelerating module being ready for the linac installation. During the mechanical fabrication the cavity half-cells, dumb-bells and end-groups (Fig. 1) are measured and sorted. The cavity spectrum and field profiles are measured and tuned. The Higher Order Modes (HOM) couplers filter tuning, vertical cavity RF tests, cavity checks during the string assembly and final cavity performance measurements in the module as well as the fundamental mode and HOM RF spectra measurements complete the sequence.

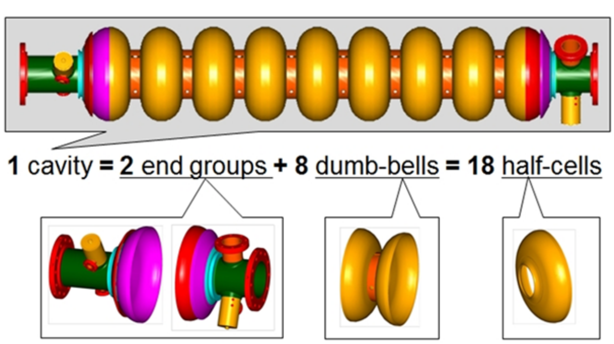


Figure 1: European XFEL cavities subcomponents.

This article will be concentrated on quality assurance during cavity production. Some aspects of post-production control will be mentioned only in case of their importance for mass production.

Purpose of Quality Assurance

The main purpose of the QA, based on RF measurements, is achieving both the RF and the mechanical specifications:

a) fundamental mode frequency at 2 K before adjustment to 1.3 GHz:
   F(TM010,pi) = (1299.7 ± 0.1) MHz;
b) flatness of field distribution: FF > 90 %;
c) cavity straightness:
   cell and flange eccentricity ECC < 0.4 mm;
d) final cavity length: L = (1059 ± 3) mm;
e) cells shape (inner cavity surface fluctuation):
   accuracy = ± 0.2 mm.

Different processes (Final EP and Flash BCP) and infrastructure parameters have to be taken into account during cavity production.

For example, it was noticed that a field amplitude degradation of about 3 % occurred at one end of the cavity after final BCP. This fact is now taken into account during the cavity tuning for this procedure.

The field flatness (FF), eccentricity (ECC) and pi-mode frequency can usually be achieved without any difficulties during cavity tuning [3, 4]. Reducing the time of this operation to 4 hours was very important before starting mass production.

Cell shape is generally checked during subcomponent control with quick RF measurements on HAZEMEMA [5] and precise mechanical 3D inner cavity surface measurements when needed.

Final cavity length depends on the accuracy of sub-component trimming and can be predicted before cavity equator welding with a mean accuracy ±0.4 mm.

RF Measurement Choice

Rf measurements for QA were chosen:

1. to measure and calculate RF characteristics (frequency, field, quality-factors);
2. because they are more flexible than mechanical one and do not require mechanical contact with inner cavity surface;
3. due to very high sensitivity to mechanical deviations.

Accuracy of transverse deviations determination for cavity geometry (cell's diameters) is about 0.1 μm/kHz. This was demonstrated on example of small geometry deviations estimations for TESLA shape cavities arising from inner surface polishing [6].

Sensitivity of the fundamental-mode frequency to longitudinal cavity deformations is 300 kHz/mm, which allows tracking of about 3 μm/kHz.

ISBN 978-3-95450-178-6

Estimating the equator welding stability for the European XFEL cavities [7], we were able to determine longitudinal deviations about 60 µm. It is about 10 – 20 % of the cell length reduction during equator welding.

REALIZATION

Both cavities manufacturers (RI Research Instruments GmbH (RI) and Ettore Zanon S.p.A. (EZ)) were provided with documentation and special machines to perform accurate RF measurements, quick and precise cavity tuning and data transfer to DESY. Some of the most important aspects are data collection, automatic analysis and a quality information feedback between DESY and cavities manufacturers.

Documents & New Technique

Before the mass production started in 2013, DESY had prepared the European XFEL specification, which describes all important steps of QA, nominal values and their tolerances for all controlled parameters:

- XFEL/003 – quality assurance and quality control;
- XFEL/014 – frequency measurements on dumb-bell, half-cell, end group and cavity;
- XFEL/014 – technical specification for welding in the helium tank;
- XFEL A-D – series surface and acceptance test preparation,
- manual for Half-Cell Measurement Machine (HAZEMEMA),
- manual for the Cavity Tuning Machine (CTM).

EZ and RI personnel were trained to operate the new machines (HAZEMEMA and CTM) and regular maintenance work and remote support were provided by DESY experts during the entire period of cavity mass production [8].

Based on the European XFEL specifications and the manuals for the new techniques, both cavity manufacturers prepared their own instructions.

Acceptance Levels

There are three Acceptance Levels (AL) during cavity manufacturing, where DESY has to accept all previous steps before production can be continued to the next phase.

At AL1 we control characteristics of all subcomponents (half cells, dumb-bells and end-groups), equator welding characteristics and estimate final cavity length.

At AL2 we check the cavity characteristics after:

- main cavity surface treatment,
- cavity tuning,
- integration into helium tank (HT),
- pressure test (PT).

After the final cavity surface treatment and assembling of all antennas we check the fundamental mode frequency and estimate the cavity deformation at AL3 before the cavity is finally sent to DESY.

The cavity is formally accepted if it has successfully passed AL3 (albeit without a performance guarantee from the vendor). In some cases, where there are non-conformities, we can propose a “limited acceptance” (acceptance pending RF cryo tests) or require some rework actions.

Database Analysis

The check of cavity parts implies the measurements of the length and the frequencies for half-cells, dumb-bells and end groups. They have to be corrected by reshaping or reducing their length and then measured again.

After all dumb-bells have been produced and corrected they should be sorted to provide the required asymmetrical HOMs amplitudes distribution after field flatness tuning on fundamental mode.

At this level we analyse mechanical and RF characteristics such as frequencies, lengths, shape stability and trimming accuracy for cavity subcomponents, as well as dumb-bell symmetry and their composition according to the European XFEL specifications.

Based on frequency and length measurements after equator welding, we can calculate the final welding parameters (average shrinkage and transverse deformations) and estimate the cavity length deviation, which has to be in range of ± 3 mm.

The results of final measurements for all subcomponents and cavities after welding are presented in the XFEL cavity database (DB) for AL1 (Fig. 2). In case that any parameter is out of tolerance, the measured or calculated value will be marked with a red background, along with the cavity status (name) on the main software panel of graphical user interface (GUI).

All cavities have to be tuned and measured several times before they can be welded into the helium vessel. The goal of cavity tuning is to simultaneously achieve the nominal RF (Fig. 3 a – fundamental mode spectrum and field flatness) and geometry (Fig. 3 b – length and eccentricity) characteristics. The mechanical and RF measurements are needed to calculate an effective tuning plan (model).

At this stage up to three tunings may be needed. Cavity conditions differ and depend on the value of the remaining planed chemical surface removal, on the existence of the field measurement system, and on the welded rings and bellow for the helium vessel.

The longitudinal cavity axis is used for calculating the cell displacement (centre offset). These values are subsequently used for optimization of the cavity position relative to the beam line.

One of the main RF characteristics after the final tuning is a cavity fundamental mode spectrum, which correlates with the field distribution. After the next step the cavity is normally in a closed condition (under vacuum) with all flanges assembled. Therefore, only the cavity fundamental mode spectrum can be used to trace possible deformations and field distribution changes.

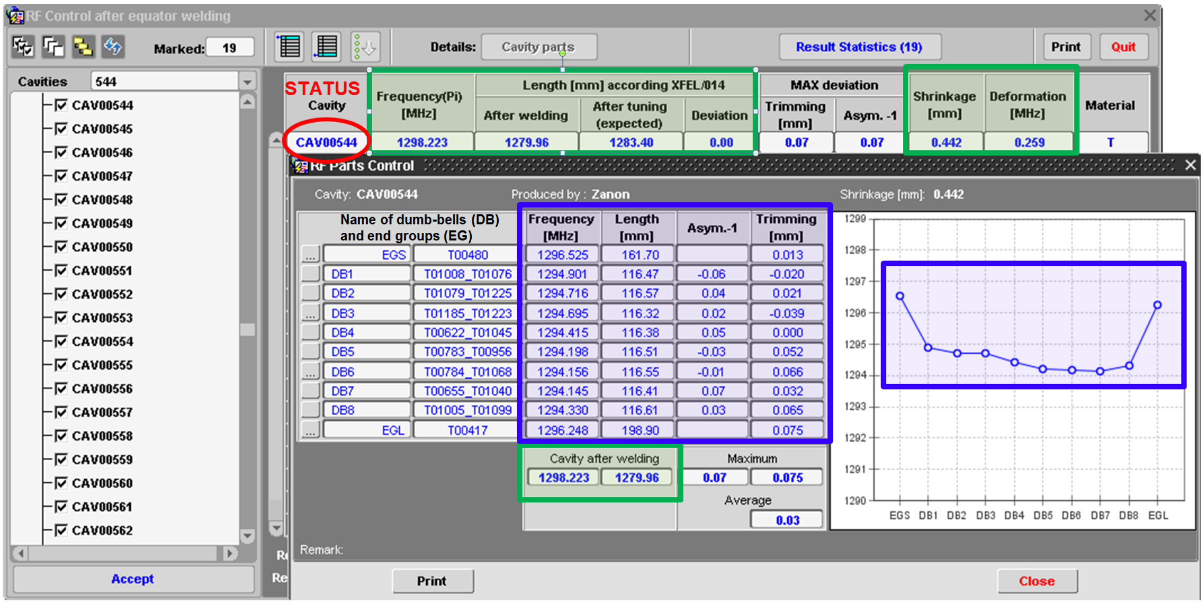
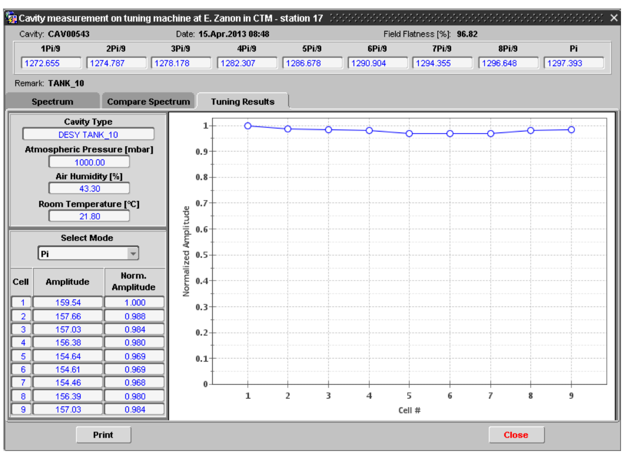
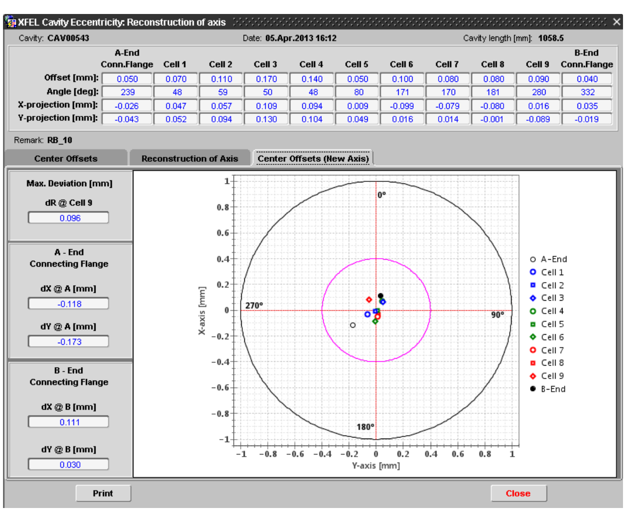


Figure 2: XFEL cavity DB data for AL1: in blue boxes – before cavity welding, in green boxes – after welding.



a)



b)

Figure 3: XFEL cavity DB data (details) for AL2: a) RF characteristics; b) mechanical measurements results.

The mean spectrum deviation (MSE) can be calculated using the following algorithm:

1. Two spectra are required (SP1 = $\{f_i\}$, SP2 = $\{F_i\}$) where i = 1…N, SP1 is measured spectrum, SP2 is the reference spectrum with known field distribution, N = 9 is the number of cavity cells.
2. The relative spectrum is calculated as:
   RS = $\{R_i\} = \{F_i/f_i - F_N/f_N\}$.
3. A linear fit is calculated for the relative spectrum:
   L = $\{L_i\}$ = linear_fit$\{R_i\}$.
4. The mean squared error is then calculated as:
   $$mse = \sum_{i=1}^{N} (R_i - L_i)^2 \Big/ N$$
5. The mean spectrum deviation is calculated as:
   $$MSE\,[kHz] = \sqrt{mse} \times f_\pi^{op}, f_\pi^{op} = 1.3GHz$$

The European XFEL specification limit is MSE < 10 kHz, which corresponds to a 10 % change in the fundamental mode field amplitude.

The presentation of AL3 GUI in the XFEL cavity DB (Fig. 4) is very similar to AL2 GUI, but contains new values (in blue bars):

- transmission between high-Q and probe antennas;
- pi-mode frequency for cavity with vacuum;
- fundamental mode spectrum deviation (MSE).

There are 39 inspection sheets for each cavity, which have to be transferred via the Engineering Data Management System [9] to the XFEL cavity DB. More than 700 measured and calculated values from the DB are analysed to generate the three status results – one for each AL for the QA procedure, as described above. The system allows rapid quality control and feedback to the cavity manufacturers.

Only in the case of a negative status, when cavity name is marked red in corresponding AL GUI of XFEL cavity DB, are the RF experts required to analyse the production details and determine the next steps.

ISBN 978-3-95450-178-6

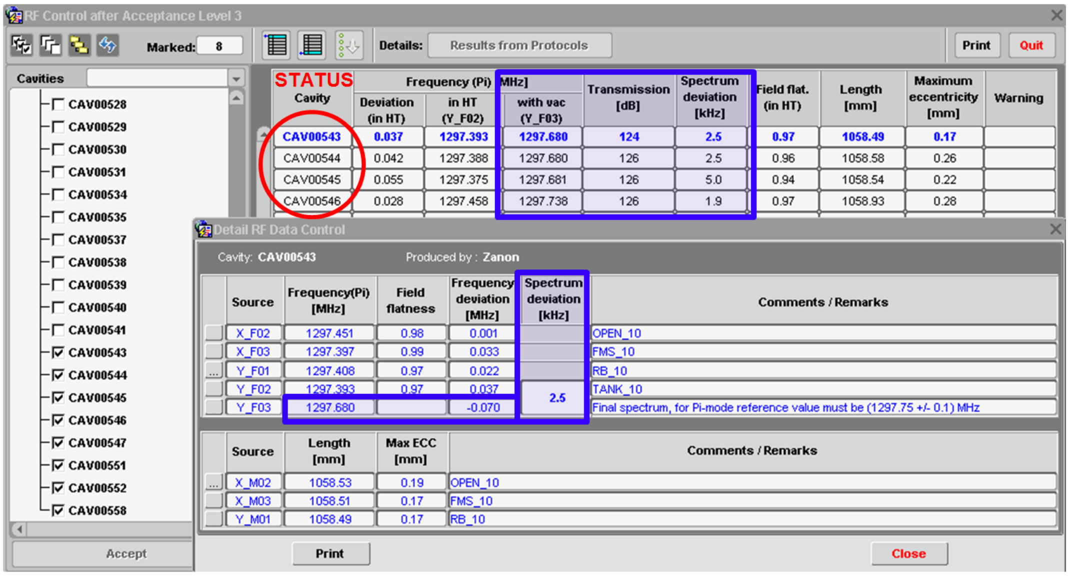


Figure 4: XFEL cavity DB data for AL3.

STATISTICS

Statistical data in series production are very important and have to be observed in order to detect trends during cavity mass production.

In contrast to the cavity length and fundamental mode spectra at room temperature, which can be measured during mass-production, final pi-mode frequency at 2 K is only measured during cold cavity tests at post-production phase.

Thus analysis of the statistics of the cryo-test results has to be taken into account during quality assurance procedures.

Adjustment of Main Parameters

Comparison of the fundamental mode frequencies at room temperature and at 2 K for the first 104 European XFEL cavities is shown in Fig. 5. The specification requirements (XFEL/A-D, Table TC13) are also indicated.

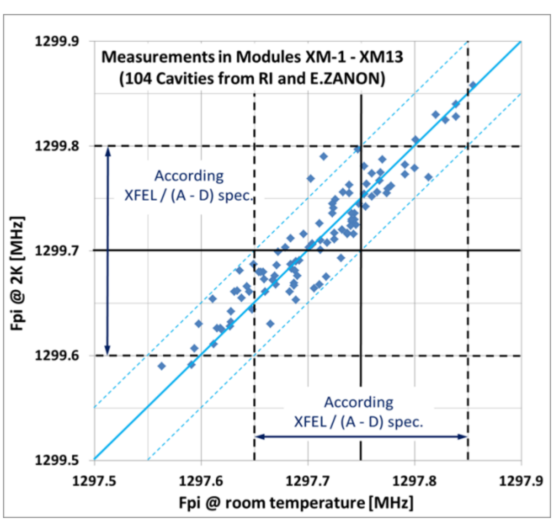


Figure 5: Comparison of the pi-mode frequencies (Fpi) at room temperature and 2 K.

Despite the fact that at the beginning of mass production some cavities' frequencies at room temperature were out of European XFEL tolerance, most of them were satisfied the criterion at 2 K. It can be explained by discrepancy of planned and real frequency changes during cool down to 2 K.

The average real frequency changes during cool down is 2.00 MHz, and the fluctuation of about ± 0.05 MHz can be explained by seasonal changes of room temperature in the range ± 5 °C. The planned value of frequency change during cool down (according XFEL/A-D) is 1.95 MHz. Thus the CTMs were subsequently adjusted to tune the cavity closer to the nominal frequency value at room temperature, and now the frequency does not exceed the value of 1297.80 MHz.

Figure 6 gives the frequency at 2 K for RI cavities, showing that the demanding European XFEL tolerance F(TM010,pi) = (1299.7 ± 0.1) MHz is achieved. The statistics for E. Zanon and RI cavities are very similar.

Due to the use of automatic cavity tuning machines, cavity eccentricity and field flatness within the European XFEL specification are always achieved.

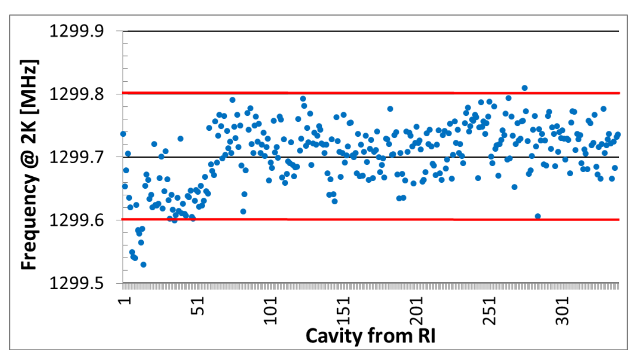


Figure 6: Fundamental mode frequency at 2 K during mass production.

The very high accuracy of cavity length (Fig. 7) is a result of accurate subcomponent trimming, efficient dumb-bells composition and stable infrastructure parameters for electro-polishing and welding machine. It allows the reduction of average length value during mass production to 1058 mm (requested by DESY to optimize the cavity positioning in accelerating modules).

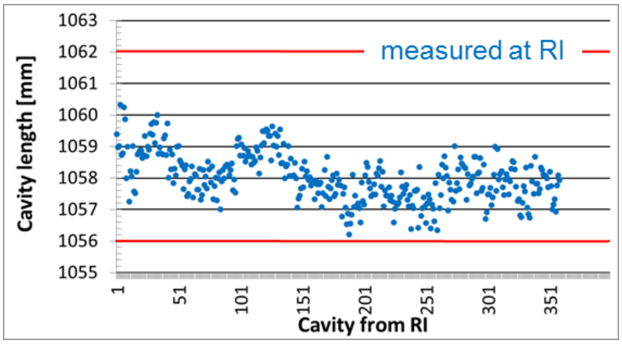


Figure 7: Final cavity length during mass production.

The distribution of the spectrum deviation (Fig. 8) shows that all cavities have MSE < 10 kHz.

The accuracy of the frequency measurement is about 1 kHz, so the mean spectrum deviation values below ~2 kHz are negligible.

Taking into account that the field distribution changes about 3 % during flash BCP, which can change the spectrum by about 3 kHz, MSE ≤ 5kHz is still acceptable.

HOM Suppression for TM011

The first two dipole modes, TE111 and TM110, are well-coupled to the HOM couplers, because they have maximum field in the cavity end cells.

The second monopole mode TM011 requires additional asymmetry of the cavity geometry, and its field distribution is very sensitive to inaccuracy in the cavity shape [10].

Unfortunately the original European XFEL tolerance for the cavity inner shape was not satisfied for many cavity parts. Up to 10 % of surface could have shape deviation between ± (0.2…0.3) mm.

Based on the high sensitivity of the TM011 field distribution to the cavity shape accuracy, we have determined the impact of mechanical form deviations on HOM suppression efficiency (Fig. 9).

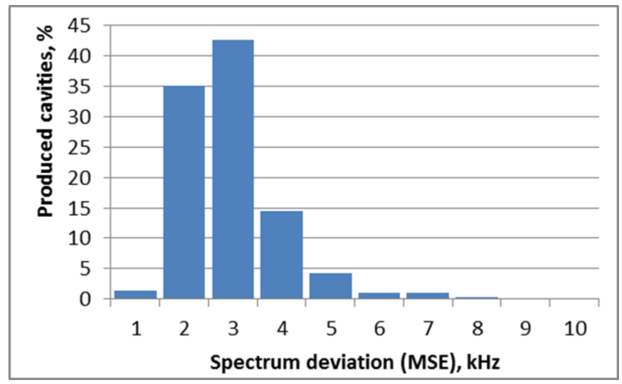


Figure 8: Spectrum deviation distribution for the European XFEL cavities.

We have been working on HOM suppression improvement in close collaboration with RI and EZ. The results of increasing the damping efficiency for the TM011 mode for EZ cavity are presented in [11]. Publication of the practical aspects of HOM suppression improvement during serial production at RI is in preparation.

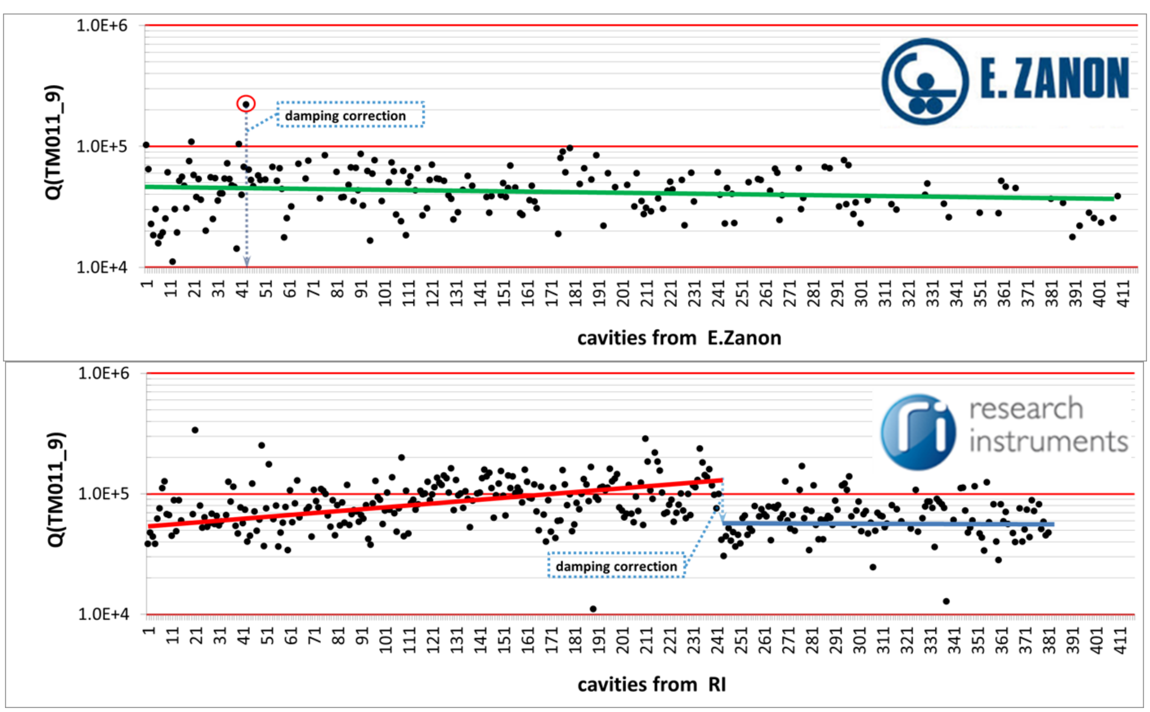


Figure 9: TM011 results during mass production.

ISBN 978-3-95450-178-6

SUMMARY

Motivations for automation of QA during cavity production were:

- large scale project - more than 800 cavities,
- limited time period - about 100 weeks,
- strict requirements to controlled parameters,
- necessity to control a huge amount of data –more than 700 values per cavity.

The main aspects of quality assurance during SC cavity mass production for the European XFEL project are:

1. Automation of RF measurements. The new machines (HAZEMEMA and CTM) speed up the tuning and RF measurements by about 80 %.
2. Preparation of new tools and GUI in the XFEL cavity DB for automatic data collection, presentation and analysis. This facilitates simplified control of the 3 acceptance levels during cavity fabrication, instead of manual analysis of 39 documents for each cavity.
3. Fast quality information feedback between DESY and cavity manufacturers (RI and EZ). When needed the cavity characteristics can be corrected and controlled during mass production.

Analysis of HOM suppression results required additional RF measurements during mass production and replacement of the sequences described in the European XFEL procedure:

- full RF measurements after equator welding;
- analysis of welding stability;
- analysis of surface treatment influence;
- estimation of HOM suppression during the cavity vertical test, before integration into accelerating module.

ACKNOWLEDGMENT

I would like to thank:

- all colleagues from Ettore Zanon S.p.A., RI Research Instruments GmbH and Institute of Nuclear Physics Polish Academy of Science (IFJ PAN) for their important contributions to the measurements, as an integral part of cavity production and quality control;
- DESY colleagues from the European XFEL cavity production team and IPP group for supporting and development of the EDMS, and personally participants of DESY Cavity Database Team (Vladimir Gubarev, Sibel Yasar and Paul-Dieter Gall) for supporting the data storage, analysis and representation for the European XFEL cavities [12].

My particular thanks go to:

- Wolf-Dietrich Moeller and Guennadi Kreps, who helped me a lot in my work and made this publication possible,
- Katrin Lando for her patient assistance with my publications, so I can concentrate on quality assurance during superconducting cavity mass production.

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