Influence of tests results on serial production of EXFEL superconducting cavities

D V Kostin and A A Sulimov
Deutsches Elektronen-Synchrotron, DESY, Notkestrasse 85, 22607 Hamburg, Germany
E-mail: Alexey.Sulimov@DESY.DE

Abstract. The European XFEL (EXFEL) 1.3 GHz cavities were produced without any final cold RF performance guarantee for characteristics like accelerating gradient, quality factor or field emission. In the case of low-performance, DESY provided all re-treatment procedures in order to improve these characteristics getting closer to specification levels. But EXFEL cavities have very tight tolerances for the parameters like cavity length, cells eccentricity, fundamental mode frequency and field distribution on the operational mode. Usage of modern infrastructure, analytical methods and powerful tools of the database analysis allows us not only keeping these characteristics in specified ranges, but also investigate the cavity shape uncertainties and improve the damping of the higher order modes.

1. Introduction
European x-ray free electron laser [1] is an international project with 11 participating countries (Denmark, France, Germany, Hungary, Italy, Poland, Russia, Slovakia, Spain, Sweden and Switzerland). It is located in Germany between injector hall in DESY (Hamburg) [2] and experimental hall in Schenefeld (Schleswig-Holstein). The X-ray research laser facility is scheduled to start user operation with 1 beamline and 2 experiment stations in 2017 [3]. Electrons will be accelerated to planned energy of 17.5 GeV in superconducting radiofrequency (RF) resonators of 2 km long linear accelerator [4]. TESLA-shape 1.3 GHz Niobium cavities have 9-cells, 2 higher order mode (HOM) couplers and are operated at 2 K. But commissioning of more than 800 of those cavities requires detail tests of each accelerating element with strict requirements to its individual characteristics.

2. Cavity characteristics
The most important individual characteristics of main accelerator component can be separated into two classes: cryogenic parameters, which are controlled at operational temperature, and parameters at room temperature, which are measured by normal conditions.

2.1. Cryogenic parameters
This set of characteristics is usually satisfying the planned values if cavities were produced according to the original recipe, which is completely described in the specification for cavity manufacturers.

2.1.1. Unloaded quality factor \((Q_0)\). It is characterized by the power loss in cavity walls under superconducting condition. Planned value is over 1.0E+10.
2.1.2. **Field emission (x-ray)**. It is characterizing the cavity dark current and identified by the appearance of radiation outside the cavity in the cryostat. Planned value is below 1.0E-2 mGy/min.

2.1.3. **Accelerating Gradient (Eacc)**. It is an integral of accelerating field affected on an electron at 1 m of the cavity. There are two kinds of gradient: maximal and usable. The usable gradient is limited by criteria for previous two parameters (2.1.1. and 2.1.2) and its planned value is over 23.6 MV/m.

2.1.4. **Fundamental mode frequency (Fpi @ 2K)**. It is a frequency of mechanically relaxed cavity before tuning to the exact value of 1.3 GHz. Planned value for cavity under this condition is (1299.700 ± 0.100) MHz.

2.1.5. **HOM spectra (HOM SP)**. This is a set of frequencies and loaded quality factors for each mode and polarization in three passbands TE111, TM110 and TM011. Some of them require a special attention [5, 6].

### 2.2. Parameters at room temperature

The EXFEL cavities have very tight tolerances for the parameters, which are describing the cavity condition before a cryogenic test.

2.2.1. **Field flatness (FF)**. It is a ratio between the minimal and maximal amplitude of longitudinal E-field on cavity axis in the middle of cells for the fundamental mode. Planned value after cavity integration in helium vessel and the pressure test is over 90 %.

2.2.2. **Fundamental mode spectrum (FM SP)**. It is nine frequencies of the TM010 mode. Stability of this parameter indicates the level of non-uniform deformations and risk of FF changes. Planned value of the highest frequency of FM SP (Fpi) for cavity under vacuum is (1297.750 ± 0.100) MHz.

2.2.3. **Cavity eccentricity (ECC)**. It is a maximal value of cells and flanges centers displacement relative to axis crossing the middles of reference rings [7]. Planned value before cavity integration in a helium vessel is below 0.4 mm.

2.2.4. **Length (L)**. It is a longitudinal dimension, which is critical for cavity integration in accelerating module. This parameter is measured (or calculated) either between the end flanges or between reference rings [8]. Planned value of cavity length between reference rings is (1059 ± 3) mm.

2.2.5. **Shape deviation of the inner surface**. This parameter allows us to keep the TESLA shape geometry close to drawings and simulated cavity shape. Planned value for cavities components in original specification is ±0.20 mm. It was an agreement between DESY and cavity manufacturers that deviation up to ±0.30 mm can be accepted only for 10 % of cells surface.

### 3. Cavity tests and influence of their results

Cavity tests – it is a set of measurements under cryogenic and room temperatures. Cryogenic tests are expensive and time-consuming. Their amount has to be reduced for serial production of more than 800 cavities. This problem was solved by the founding of the exact procedure of cavity manufacturing, including all details of chemical surface treatment, and its implementation in an industrial process. The quality assurance procedure at room temperature provides us with a possibility of supervising the complete production sequence.

The Engineering Data Management System [9] and EXFEL cavity database [10, 11] automatize the documentation flow, collecting the data and results control during the cavities manufacturing and both types of tests.
3.1. Cryogenic tests

Cavity performance measurements at 2K are done for the separate cavities in a vertical cryostat for 4 cavities in CW mode and in accelerating module in the module test stand after the tuning to the operating frequency [12-18]. In the module test, each of 8 cavities is tested first separately by tuning it to the operating frequency of 1.3 GHz up to a breakdown (quench) or RF power limit. Operating gradient limit is given by described tolerances from a breakdown and gamma radiation (field emission – dark current). A general RF power limit is set by 31MV/m for a cavity. After a single cavities tests, all 8 cavities are tested together in the module to get a cryogenic performance as well as combined field emission properties. Obtained operating gradients are realized as a fixed tailored RF waveguides power distribution to maximize a module acceleration with given limitations.

Unloaded quality factor, field emission and accelerating gradient are generally satisfying the EXFEL specification requirements. The test results of these parameters have no impact on serial production. In the case of necessity, these characteristics can be improved by re-treatment with an individual plan for each cavity. Average value of the accelerating gradient for all EXFEL cavities is 27 MV/m and estimated final energy of the accelerated beam is over the planned value [19, 20].

Fundamental mode frequency at 2K is well correlated with room temperature measurements. The planned difference in EXFEL specification is 1.95 MHz, but statistical analysis of first twelve modules detected a systematic error and real frequency changes during cooling down is (2.00 ± 0.05) MHz.

During cavity vertical test it was observed that the damping of the second monopole mode (TM011) showed the largest variation and sometimes up to 2-3 times lower than the originally allowed limit. It was concluded that this TM011-damping degradation was caused by cavity geometry deviation within the specified mechanical tolerances [6].

Solving the problem with HOM SP and adjusting of Fpi @ 2K had the most influence on cavity serial production. These aspects were integrated into quality assurance procedure at room temperature.

3.2. Quality assurance at room temperature

Control of cavity parameters under the normal conditions [7] begins by the cavity manufacturers RI Research Instruments GmbH (RI) and Ettore Zanon S.p.A. (EZ) under the supervision of DESY (Hamburg) and INFN (Milano) [21].

The Cavity Tuning Machine (CTM) and Half-Cell Measurement Machine (HAZEMEMA) [22] were used for room temperature measurements and adjustment of corresponding cavity characteristics. The routine tuning on the CTM allowed us to keep cavity eccentricity and field flatness inside the tolerances. The final statistic shows that more than 70 % cavities have FF over 95 % and ECC for 75 % cavities is below 0.3 mm.

More efforts were required to adjust the CTM for correcting of the pi-mode frequency of FM SP. This characteristic depends on production step, cavity filling (air, argon or vacuum), and the presence of field measurement system (FMS). Fluctuation of all parameters of the chemical treatment procedure, which are individual for RI and EZ, change Fpi value. It was determined at the beginning of production that Fpi for full equipped cavity under vacuum is below planned value. After collecting and analysis of some statistics, the reasons of Fpi deviations were identified and the corresponding correction for the CTM parameters was done. The same algorithm was used, when EZ installed their own infrastructure for main electropolishing process and the ratio of removed material from equator and iris areas [23] caused an increase of Fpi value.

Measurements of cavity components on the HAZEMEMA [24] allow predicting of final cavity length before equator welding [25]. The accuracy of this prediction is 0.4 mm [8]. This is several times lower than tolerance for this characteristic. It provides us with a possibility to variate the cavity length during production being always inside the specified tolerances. In the middle of serial production, some limitation of usage the cavities on the first position in an accelerating module were determined. This problem was solved by reduction an average value of L till 1058 mm.

Quality assurance of cavity production is finalizing by comparison of incoming inspection results [26] with full documentation from cavity manufacturer. Non-uniform cavity deformation and risk of
FF changes are estimated by FM SP deviations. In case this value overcomes a specific limit the cavity had to be sent back to the manufacturer to repeat some reference measurements and repair the cavity if it was necessary.

The impact of cells shape uncertainties on the degradation of HOM damping efficiency was analyzed [27, 28]. Additional RF measurements and calculations of cells’ eigenfrequencies were integrated into serial production procedure. They were used to identify equator welding instabilities and influence of electropolishing processes on cavity FM SP [23, 25]. Finally, the cells shape uncertainties were compensated by asymmetrical field (length) correction of cavity end cells.

4. Conclusion
Finally, we can select the cavity characteristics which needed the most concentration during EXFEL serial cavity production.

Target values for fundamental mode frequency and cavity length have to be changed several times. So the statistics of test results for already produced cavities was used for adjusting of manufacturing parameters on the CTM and HAZEMEMA.

The most challenging problem was increasing of HOM damping efficiency. It requires a special attention on data analysis of inner surface shape deviations, preparation of additional measurements and calculations before implementation of necessary corrections in the process of serial production.

Collaborations between participants of the EXFEL project, elaborately prepared specification for cavity manufacturing and taking into consideration of the tests results guaranteed the success of EXFEL cavity mass production.

References
[1] H. Weise, ‘The TESLA X-FEL Project’, in Proceedings of EPAC 2004, Lucerne, Switzerland.
[2] www.xfel.desy.de
[3] www.xfel.eu
[4] “XFEL: The European X-Ray Free-Electron Laser - Technical Design Report”, DESY, Hamburg, Germany, DESY_06-097, 2006, doi:10.3204/DESY_06-097
[5] J. Sekutowicz, “HOM Damping and Power Extraction from Superconducting Cavities”, in Proceedings of LINAC 2006, August 21-25, 2006, Knoxville, Tennessee USA, pp.507-510.
[6] A. Sulimov et al., “Efficiency of High Order Modes Extraction in the European XFEL Linac”, in Proceedings of LINAC 2014, Geneva, Switzerland, 2014, pp. 883-885.
[7] A. Sulimov, “RF Measurements for Quality Assurance During Cavity Mass Production”, in Proceedings of SRF2015, Whistler, BC, Canada, 2015, pp. 955-960.
[8] A. Sulimov et al., “The Statistics of Industrial XFEL Cavities Fabrication at Research Instruments”, in Proceedings of SRF 2013, Paris, France, 2013, pp. 234-236.
[9] J. Iversen et al., “Using an Engineering Data Management System for Series Cavity Production for The European XFEL”, in Proceedings of SRF 2013, Paris, France, 2013, pp. 183-185.
[10] P.D. Gall et al., “XFEL Database Structure & Loading System”, in Proceedings of SRF2015, Whistler, Canada, 2015, pp. 1166-1167.
[11] P.D. Gall et al., “XFEL Database User Interface”, in Proceedings of SRF2015, Whistler, Canada, 2015, pp. 1168-1170.
[12] D. Kostin et al., “Update on Module Measurements for the XFEL Prototype Modules”, in Proceedings of SRF2011, Chicago, IL USA, 2011. pp. 65-68.
[13] D. Reschke, for the European XFEL Accelerator Consortium, “Performance Of Superconducting Cavities for the European XFEL”, in Proceedings of IPAC2016, Busan, Korea, 2016, pp. 3186-3191.
[14] J. Swierblewski, “Large Scale Testing of SRF Cavities and Modules”, in Proceedings of LINAC 2014, Geneva, Switzerland, 2014, pp. 426-430.
[15] M. Wiencek et al., “Improvements of the RF test procedure for European XFEL cryomodules”, in Proceedings of SRF2015, Whistler, Canada, 2015, pp. 914-918.
[16] D. Reschke, “Infrastructure, Methods and Test Results for the Testing of 800 Series Cavities for the European XFEL”, in Proceedings of SRF2013, Paris, France, 2013, pp. 812-815.
[17] M. Wiencek et al., “Update and status of the test results of the XFEL series accelerator modules”, in Proceedings of SRF2015, Whistler, Canada, 2015, pp. 319-323.
[18] O. Napoly, “Module performance in XFEL cryomodule mass production”, in Proceedings of SRF2015, Whistler, Canada, 2015, FRAA02.
[19] H. Weise, “Status of the European XFEL”, in Proceedings of LINAC2016, East Lansing, MI, USA, 2016, MO1A02
[20] N. Walker et al., “Performance Analysis of the European XFEL SRF Cavities, from Vertical Test to Operation in Modules”, in Proceedings of LINAC2016, East Lansing, MI, USA, 2016, WE1A04
[21] W. Singer et al., “Production of superconducting 1.3-GHz cavities for the European X-ray Free Electron Laser”, Phys. Rev. Accel. Beams 19, 092001 – Published 9 September 2016
[22] J.-H. Thie et al., “Operation Experience with Half Cell Measurement Machine & Cavity Tuning Machine in 3 Years of the European XFEL Cavity Series Production”, in Proceedings of SRF2015, Whistler, Canada, 2015, pp. 1149-1153.
[23] A. Sulimov et al., “RF Analysis of Electropolishing for EXFEL Cavities Production at Ettore Zanon Spa”, presented at LINAC 16, East Lansing, MI, USA, 2016, paper TUPL035.
[24] A. Sulimov et al., “Description and First Experience with the RF Measurement Procedure for the European XFEL SC Cavity Production”, in Proceedings of IPAC’11, San Sebastian, Spain, 2011, pp. 277-279.
[25] A. Sulimov, “RF Analysis of Equator Welding Stability for the European XFEL Cavities”, in Proceedings of SRF2015, Whistler, BC, Canada, 2015, p. 1272-1273.
[26] K. Krzysik et al., “Tests of the 1.3 GHz Superconducting Cavities for the European X-Ray Free Electron Laser”, in Proceedings of SRF2013, Paris, France, 2013, pp. 191-193.
[27] A. Sulimov et al., “HOM Suppression Improvement for Mass Production of EXFEL Cavities at RI”, in Proceedings of LINAC2016, East Lansing, MI, USA, 2015, THPLR018
[28] A. Sulimov et al., “Practical Aspects of HOM Suppression Improvement for TM011”, in Proceedings of SRF2015, Whistler, BC, Canada, 2015, pp. 1277-1278.