ANALYSIS OF DEGRADED CAVITIES IN PROTOTYPE MODULES FOR THE EUROPEAN XFEL

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Abstract

In-between the fabrication and the operation in an accelerator the performance of superconducting RF cavities is typically tested several times. Although the assembly is done under very controlled conditions in a clean room, it is observed from time to time that a cavity with good performance in the vertical acceptance test shows deteriorated performance in the accelerator module afterwards. This work presents the analysis of several such cavities that have been disassembled from modules of the prototype phase for the European XFEL for detailed investigation like optical inspection and replica.

INTRODUCTION

The assembly of superconducting RF cavities to the string for an accelerating module follows established procedures and is done under controlled conditions in high class clean rooms. This effort routinely demonstrates very good results. At times the good performance of a cavity is not preserved and when operated in the module its maximum achievable gradient is lower, it shows field emission or its losses are higher than expected. Diagnostic methods for a cavity in a module are very limited and if the module is assembled to an accelerator the origins of the deterioration remain unclear. Several modules from the preparatory and prototyping phase for the European XFEL [1] and the S1-global module [2] provided the unique advantage that they were disassembled after the test on the module test bench. This offered the opportunity to study such deteriorated cavities in detail.

Z108 AND Z109

The cavities Z108 and Z109 already have a pretty long history and have been assembled to an accelerating module twice. Both have been part of Module 8 and the S1-global module.

A part of the RF test history of Z108 is shown in Table 1. Prior to string assembly for Module 8 it reached 33.0 MV/m in vertical test number 3. In the module it deteriorated to 25.7 MV/m with field emission. The second test in the same module (test number 5) was done after a transport test of the whole module without any modification to the string. Z108 reached a slightly higher gradient while still exhibiting field emission. After being disassembled from the module string, Z108 was high pressure rinsed and vertically tested again. The performance in test number 6 improved to 31.3 MV/m with no more detectable field emission.

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When tested in the string of the S1-global module, Z108 once again showed decreased performance. The accelerating gradient was limited at 19.5 MV/m with some field emission and high cryogenic losses. Disassembly from the string was again followed by high pressure rinsing and additional vertical tests. While test number 7 was not successful due to a vacuum leak, test number 8 demonstrated restored performance, reaching an accelerating gradient of 32.6 MV/m without field emission.

Table 1: Part of the RF Test History of Z108

Test No.	Date	Type	E [MV/m]	FE
3	11.07.2007	Vertical	33.0	no
4	02.07.2008	Module	25.7	yes
5	08.12.2008	Module	28.0	yes
6	25.06.2009	Vertical	31.3	no
S1-G	30.09.2010	Module	19.5	yes
7	16.08.2012	Vertical	vacuum leak	
8	29.08.2012	Vertical	32.6	no

Table 2: Part of the RF Test History of Z109

Test No.	Date	Type	E [MV/m]	FE
5	22.05.2007	Vertical	30.1	no
6	02.07.2008	Module	21.8	no
7	08.12.2008	Module	21.8	no
8	03.08.2009	Vertical	30.7	no
S1-G	01.10.2010	Module	29.5	yes
9	23.08.2012	Vertical	31.7	yes

Vertical test number 5 of cavity Z109 was limited at an accelerating gradient of 30.1 MV/m without field emission (see Table 2). After assembly to the string the performance in Module 8 was decreased to 21.8 MV/m with field emission being comparable to the zero level (test number 7 and 8). The second module test is after the transport test as in the case of Z109 and the performance remains unchanged. High pressure rinsing recovered the gradient to 30.7 MV/m in test number 8, following the removal from the string.

In the S1-global module Z109 did not suffer from significant performance deterioration (29.5 MV/m), although some field emission was detected.

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DETAILED INVESTIGATION OF AC127

AC127 is the cavity with the most detailed investigation of the degradation in this analysis. Early steps of the investigation are already covered in [3, 4] and partially recapitulated here for completeness.

Test History

Table 3: RF Test History of AC127

Test No.	Date	Type	E [MV/m]	FE
1	13.02.2009	Vertical	31.3	yes
2	11.06.2009	Vertical	27.9	no
3	10.09.2010	Module	19.2	no
4	03.02.2011	Chechia	20.5	yes
5	15.06.2011	Vertical	vacuum leak	
6	17.06.2011	Vertical	19.2	yes
7	18.07.2011	Vertical	17.6	yes
8	02.02.2012	Vertical	15.4	yes

The initial performance of AC127 in the vertical test number 2 before string assembly for the module PXFEL3 was 27.9 MV/m (see Table 3). In the module the maximum achievable accelerating gradient was 19.2 MV/m. During the test in the module no indication for field emission from AC127 was detected but the cavity showed high dynamic cryogenic losses.

After the disassembly from the module a series of RF tests in different configurations (horizontal and vertical) was done. To keep the surface condition as close to the original as possible no high pressure rinses were done after needed (dis)assembly steps for those tests in the clean room.

The first test after the disassembly from the module was done in the horizontal cryostat (CHECHIA, [5]) with pulsed power from a klystron. The maximum gradient was comparably high with 20.5 MV/m and some field emission was detected from an onset field of 19 MV/m. The following vertical tests were done with (number 6) and without (number 7) HOM coupler antennas attached, in order to rule them out as the limiting factor. After test number 7 it was decided to cut the cavity from its Helium vessel in order to do another vertical test with instrumentation that allows the identification of the quench location.

Second Sound Measurement

In the vertical test number 8 the Second Sound set-up at DESY was used to locate the quench spot [6]. For the π-mode the quench location was found in the second cell close to the equator at 269 degrees (details about the coordinate system can be found in [7]). This is consistent with the mode measurement in previous vertical tests that pointed to cells 2 or 8 as the limiting ones.

Optical Inspection

After the last vertical test optical inspection of the inner surface of the cavity was done [8]. A picture of the equator welding seam area close to the determined quench location is shown in Figure 1. On the edge of the equatorial welding seam a dark spot with a concentric ring pattern and a total diameter of about 700 μm is visible. In addition two small dark spots can be seen on the middle of the welding seam. The cavity had been optically inspected during its initial surface preparation cycle. It is worth noting that nothing special was visible at the respective location back then.

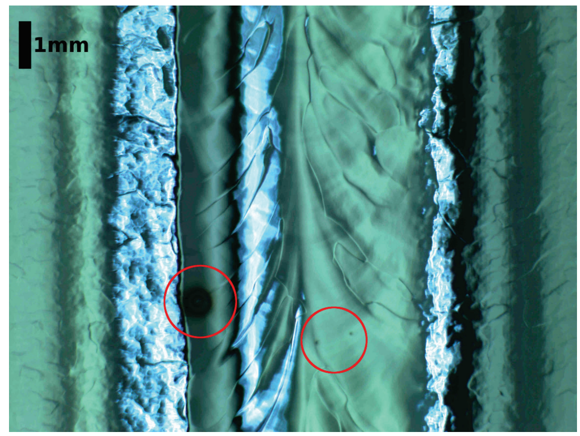

Figure 1: Optical inspection picture of AC127, taken at equator 2, 260 degrees. A big stain is visible on the edge of the equator and two mores spots in the middle of the welding seam.

Replica and Microscopy

In order to investigate details of the defect with higher resolution and gather information about the surface topology a replica of the respective area was taken [9]. An overview over the defects found by examination of the replica is shown in Figure 2. A total of four individual defects is visible. One in the center of the big circular stain (labelled A), one that is not easily visible in the optical inspection picture (labelled B) and the two small black spots (labelled C and D).

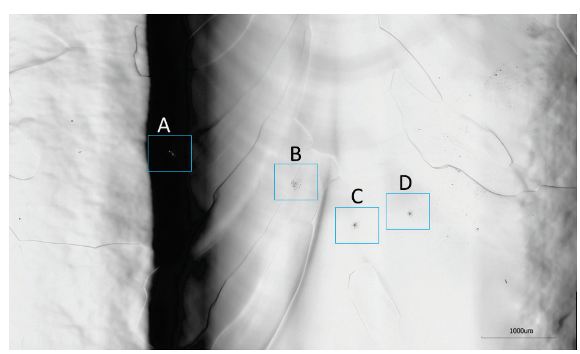

Figure 2: Overview over the defects found by examination of the replica of AC127. The defect in the center of the big stain is labelled A, the two small dark spots C and D. An additional defect that is not easily visible in the optical inspection picture is labelled B.

Figure 3 shows a closer look of defect A. It's size is about 100 μm x 70 μm. The structure resembles material that is

molten in and onto the surface. This assumption is backed by the surface profile in Figure 4. Some areas stick out of the surface, some are slightly recessed. The overall difference in height is only few micrometers.
An image of defect B is shown in Figure 5. This is a group of dozens of small molten craters. Pictures of defects C and D are not shown but look very similar.

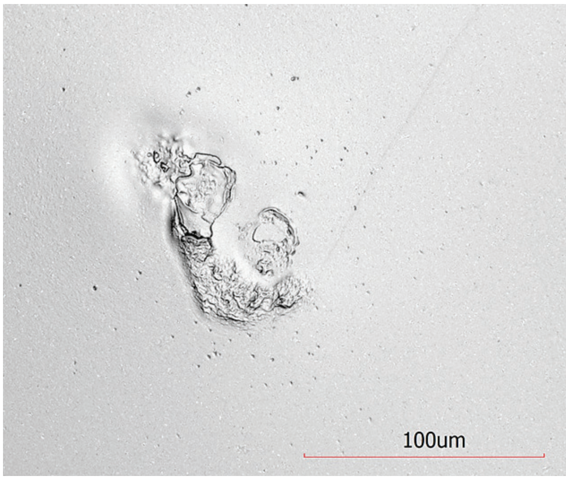

Figure 3: Optical microscope image obtained from the replica of the structure in the center of the big circular stain in AC127 (defect A). It resembles molten material on the surface.

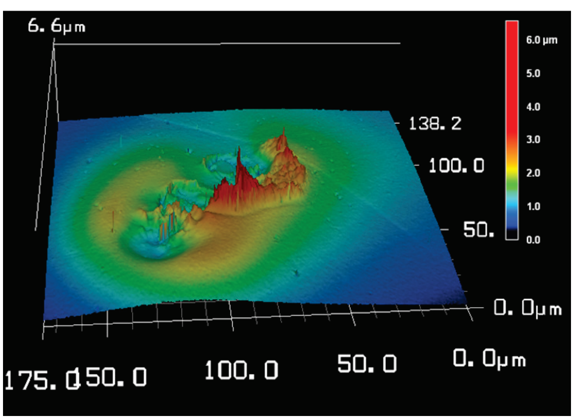

Figure 4: Surface profile obtained from the replica of the structure in the center of the big circular stain in AC127 (defect A).

Interpretation

Mode measurement, second sound measurement and optical inspection consistently identify the defect in cell 2 at 260 degrees as the limiting location. The high resolution pictures obtained from the examination of the replica reveal structures that look like molten material on the surface. A likely hypothesis is that a particle (presumably metallic) was introduced into the cavity during string assembly. The location is compatible with that assumption. Cell 2 is still close to the end of the cavity and the angular position is at 260 degrees. 270 degrees corresponds to the lowest point of the cavity when it is in the orientation in the string with the main power coupler facing sideways. Hence a particle that is blown into the cavity would be expected to settle there.

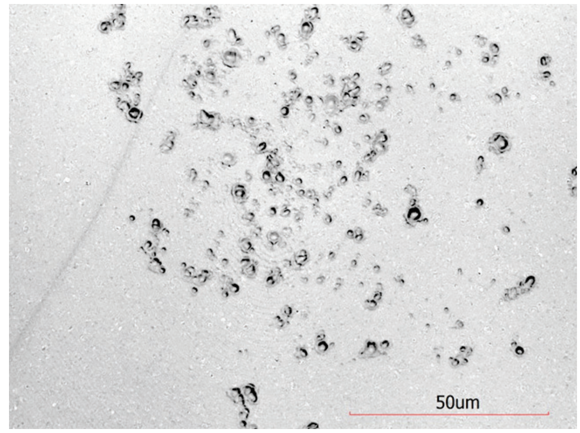

Figure 5: Optical microscope image obtained from the replica of defect B in cavity AC127. Many small molten craters are visible.

Once RF power is applied the metal would melt (defect A) and spatters form the other defects (B, C and D). Non-superconducting material on the inner surface of the cavity would also explain the high dynamic cryogenic losses that were observed during the module test.

AC158 AND CAV00612

Strictly speaking AC158 and CAV00612 did not show degradation in a module. Both cavities have been inadvertently vented before or during string assembly. They were thereupon not assembled to the string but underwent additional vertical tests and high pressure rinses.

Table 4: Part of the RF Test History of AC158

Test No.	Date	Type	E [MV/m]	FE
9	01.06.2012	Vertical	38.8	no
10	11.10.2012	Vertical	9.6	yes
11	01.11.2012	Vertical	34.0	no

Parts of the RF test history of AC158 are shown in Table 4. In test number 9 the cavity reached an accelerating gradient of 38.8 MV/m without detectable field emission. After the accidental venting it was decided to perform a vertical test without an additional high pressure rinse in order to document the deterioration. As expected the cavity only reached 9.6 MV/m with high radiation in test number 10. After this test a high pressure rinse was done and the performance could almost be recovered with an accelerating gradient of 34.0 MV/m and no detectable field emission.

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Table 5: RF Test History of CAV00612

Test No.	Date	Type	E [MV/m]	FE
1	07.04.2014	Vertical	36.2	no
2	09.12.2014	Vertical	19.6	no
3	25.02.2015	Vertical	34.5	no

For CAV00612 the sequence was similar. The RF test history is shown in Table 5. The accelerating gradient in the vertical test number 1 was 36.2 MV/m. After accidental venting during string assembly the cavity was high pressure rinsed and tested again. This time high pressure rinsing apparently was not able to fully remove the supposed contamination. Only an accelerating gradient of 19.6 MV/m was reached in test number 2. In this test no indication for field emission was found. This might also be due to the fact, that the cryostat where it was tested is only equipped with one radiation sensor on the top so that radiation going downwards can remain unnoticed. After this test the cavity was high pressure rinsed again. This time the supposed contamination seems to have been removed. The accelerating gradient in the vertical test number 3 recovered to 34.5 MV/m, close to the original maximum.

SUMMARY

This analysis comprises several cavities with test results before string assembly for a module, while in a module and after being disassembled from a module. All selected cavities have suffered from degradation while being tested in a module compared to the vertical test before. A decrease in the maximum achievable accelerating gradient was accompanied by field emission in the case of Z108 and AC158 and without detectable radiation for Z109, AC127 and CAV00612. In all cases but AC127 the performance could be recovered by additional (in one case repeated) high pressure water rinsing.

The detailed investigation of AC127 revealed a defect on the quench location. It looks like molten material that might have been introduced during string assembly.

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