

# ANALYSIS OF RF RESULTS OF RECENT NINE-CELL CAVITIES AT DESY

D. Reschke<sup>#</sup>, L. Lilje, H. Weise, DESY, 22603 Hamburg, Germany

## Abstract

About 50 nine-cell cavities of the recent fine-grain niobium cavity productions have been analysed with respect to maximum and usable gradient in the first and last vertical RF acceptance test, respectively. Parameters of the analysis were the manufacturer of the cavities, the location of the Main EP ( $\Rightarrow$  industry or in-house), the final surface treatment ( $\Rightarrow$  final 40  $\mu\text{m}$  EP or short 10  $\mu\text{m}$  “Flash BCP”) and the cavity preparation strategy ( $\Rightarrow$  vertical acceptance test with or without He-tank welded). Moreover, the effect of a re-processing of field emission loaded cavities by an additional ultra pure high pressure water rinsing (HPR) has been investigated.

## CAVITIES AND SURFACE TREATMENT

The fourth production series for TTF/FLASH [1] consists of 30 nine-cell cavities fabricated by E. Zanon Spa. First results have been presented in [2]. The sixth production series consists of additional 15 cavities fabricated by E. Zanon Spa and 20 cavities fabricated by Accel Instruments, respectively. All cavities are made of high RRR fine grain niobium with  $\text{RRR} > 300$ . The preparation started for all cavities with an electro-polishing (EP) of about (110-140)  $\mu\text{m}$ , followed by an ethanol rinse, an outside etch using buffered chemical polishing (BCP) and a 800 C annealing under UHV conditions. The final standard treatments differ. Either one of the following was carried out:

- Final EP of 40-50  $\mu\text{m}$  with subsequent ethanol rinse, ultra pure high pressure water rinsing (HPR), 120C bake and vertical acceptance test.
- Final “Flash BCP” of 10  $\mu\text{m}$ , HPR, 120C bake and vertical acceptance test.

It is emphasized that only final EP treatments with subsequent ethanol rinse are included in this analysis. Partially, the 120C bake was skipped or a vertical test before 120C bake added.

In the standard preparation strategy the welding of the Helium (He) tank takes place **after** the successful vertical RF acceptance test (vertical RF test without He-tank).

For the large scale cavity production of the European XFEL [3, 4] an optimized preparation strategy was proposed [5, 6] (see Fig. 1) with the Helium tank welding **before** the vertical RF acceptance test (vertical RF test with He-tank).

## METHOD OF ANALYSIS

About 50 cavities, which got one or more surface preparations according to the above described state-of-the-art preparation strategies, have been RF tested and analysed. For each cavity the first and the last vertical RF acceptance tests have been analysed with respect to

maximum gradient, usable gradient and gradient limitation (e.g. quench, field emission). Explicitly excluded are RF tests, which were not limited by the cavity, but by cryogenic, RF (e.g. Z144) or vacuum problems, and RF tests after an incorrect preparation of the cavity (e.g. AC120). For about 10 cavities only one RF test was done so far, i.e. the used data for first and last test are identical.

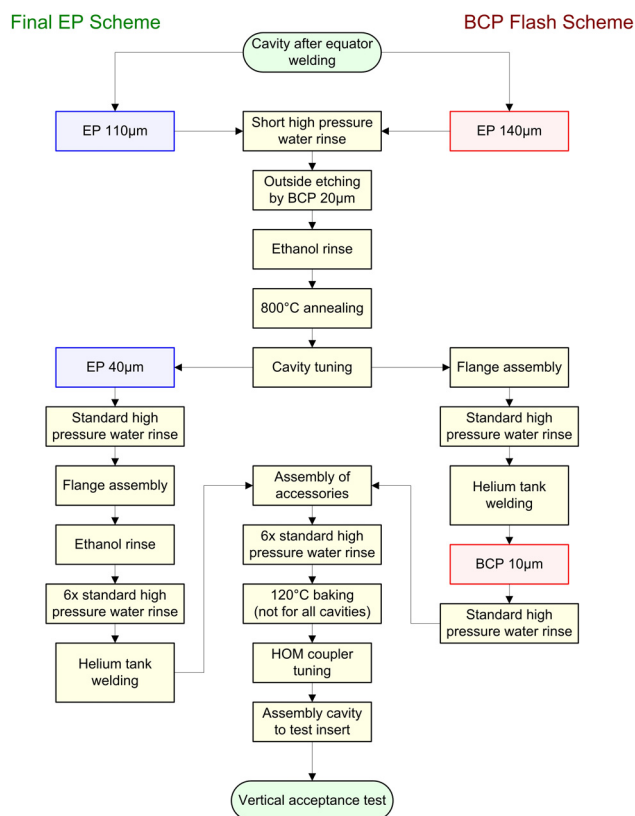


Figure 1: Work flow diagram of the optimized preparation strategy for vertical acceptance test with He-tank welded.

The usable gradient of the vertical acceptance test is defined as the lowest value of either quench gradient, gradient where x-ray radiation exceeds  $10^{-2}$  mGy/min at the DESY’s vertical test stand (on-axis and above the top plate of the cryostat), or where the RF losses in CW operation exceed 100W. The limit for x-ray radiation results from experience with vertical and horizontal tests. Obviously this definition is strongly site dependent and cannot directly be compared to results at other labs. It is highly probable that a cavity with high radiation corresponding to strong field emission will show strong dark current activity during accelerator operation. RF losses exceeding 100 W in CW operation correspond to losses of approximately 1 W per cavity for the

<sup>#</sup>detlef.reschke@desy.de

TTF/FLASH RF pulse scheme, which is the cryogenic operational limit.

In general, the last Q(E) measurement of each test is used for analysis. This choice gives the final (stable) RF performance of the cavity comparable to the subsequent horizontal test or performance in accelerator module operation.

### TYPICAL Q(E) PERFORMANCES

Two characteristic sets of Q(E)-curves of cavities of the 6<sup>th</sup> production series after surface preparation with final EP and final Flash BCP are given in Figures 2a and 2b, respectively. Following the criteria described above, the results for AC120 and Z144 are not included. In addition three Zanon cavities limited by early quench (see below) are excluded as well.

All Q(E) curves are measured at 2 K, which results in a typical Q-value at low gradients of  $(2 - 3) \cdot 10^{10}$ .

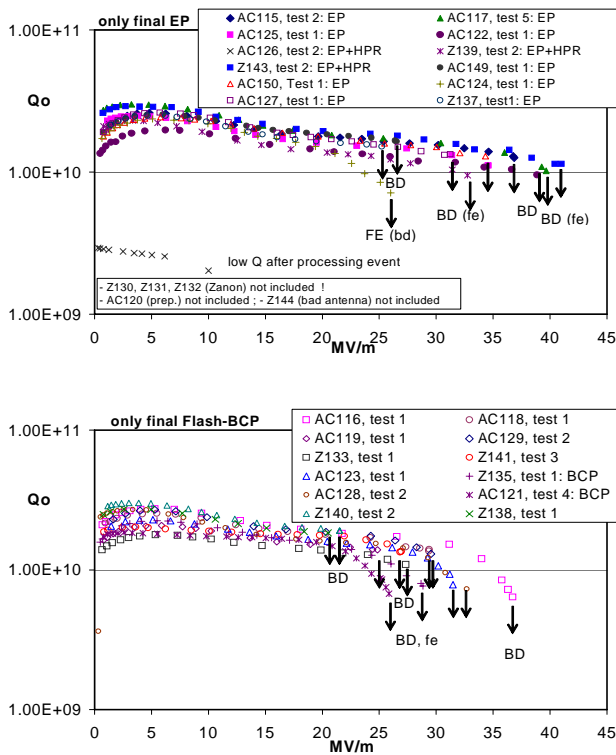


Figure 2a + b: Characteristic Q(E) performances after final EP (top) and final Flash BCP (bottom).

Eye-catching in Fig. 2a is the low Q / low gradient final Q(E)-curve of AC126, test 2, which is the result of a processing event after strong field emission in the previous Q(E) run. Several cavities of the final EP data set show a “flat” Q(E)-performance up to gradients of about 40 MV/m, which indicates a “Q-slope” fully cured by 120C-bake [7]. By contrast several RF tests after final Flash BCP (Fig. 2b) show – though after 120C-bake – a remaining Q-slope at high gradients. Typically, after Flash BCP the quench limitation occurs between (25 – 32) MV/m.

### 05 Cavity performance limiting mechanisms

### MAXIMUM GRADIENT OF CAVITY VENDORS

In Figure 3 the histogram of the maximum gradients of the last RF test depending on the two cavity vendors E. Zanon Spa and Accel Instruments (now Research Instruments) is shown. All last tests (except of AC120, Z144 as described above and Z140 limited by HOM feed-through)) are taken into account independent of the cavity limitation, i.e. field emission limited cavities are included. The low gradient cavities are AC126, test 2 after field emission processing, and seven Zanon cavities limited by quench. The origin of the unexpected quench limitation is still open and under investigation in close contact with the vendor.

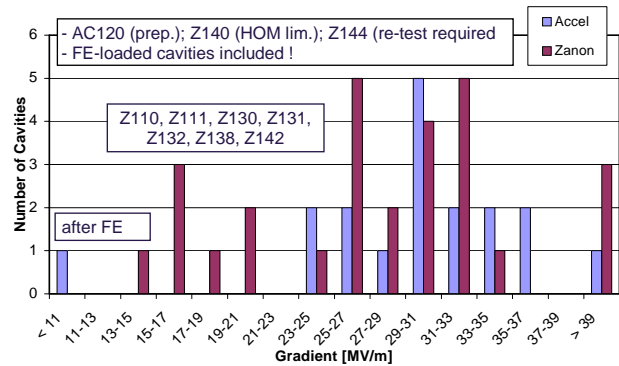


Figure 3: Histogram of maximum gradients of last vertical RF acceptance test depending on cavity vendor.

### MAXIMUM GRADIENT DEPENDING ON MAIN EP LOCATION

Initially, the main EP of about (110-140) μm was done at DESY in-house. In order to prepare the large scale preparation of cavities for the European XFEL, facilities for the main EP treatment have been installed and commissioned at Accel Instruments and Henkel Lohnpoliertechnik. A set of 15 cavities was treated at each company, but not completely RF tested, yet.

In Figure 4 the histogram of maximum gradients of the last RF test depending on the main EP location is shown. The dataset of cavities is identical to the previous chapter. Obviously, no correlation to the main EP location is visible. At both companies the main EP process is industrialized successfully, which is a big step towards the industrial cavity preparation for the European XFEL.

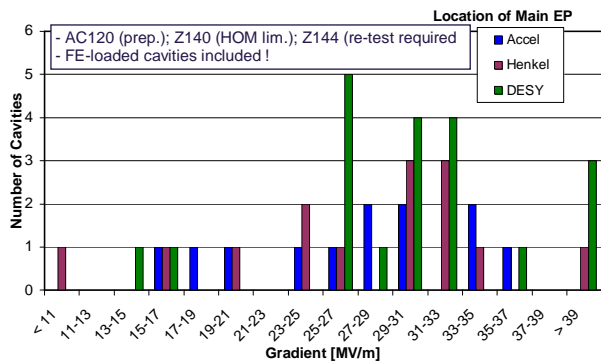


Figure 4: Histogram of maximum gradients of last vertical RF acceptance test depending on main EP location at Accel Instruments, Henkel Lohnpoliertechnik and DESY.

## MAXIMUM AND USABLE GRADIENT DEPENDING ON FINAL TREATMENT

All first and last vertical RF acceptance tests have been analyzed with respect to maximum and usable gradient. The analysis of the last RF test before the assembly of a cavity to a module gives the performance after possible re-treatments due to insufficient results in previous tests. This is typical for a prototype style of cavity and module preparation like applied for TTF/FLASH. The first RF test reflects directly the quality and reproducibility of the surface preparation and handling procedures. For the European XFEL's large scale cavity production and preparation, the first RF test is the relevant figure of merit. As a reminder, for about 10 cavities only one RF test is done so far, i.e. the used data for first and last test are identical.

Two types of final surface treatment have been applied: Final EP of (40 – 50)  $\mu\text{m}$  and final Flash BCP of 10  $\mu\text{m}$ . Few cavities got an additional (5 – 10)  $\mu\text{m}$  after the initial Flash BCP and are handled as Flash BCP treated.

For each final treatment and the comparison of first and final RF test, a dataset of 18 to 25 tests is available. It should be noticed that thus one single RF test represents a 4 % - 5 % step of the yield in each plot.

### Last Vertical RF Acceptance Test

In Figure 5a and 5b the maximum and usable gradient of the last vertical RF acceptance test is compared.

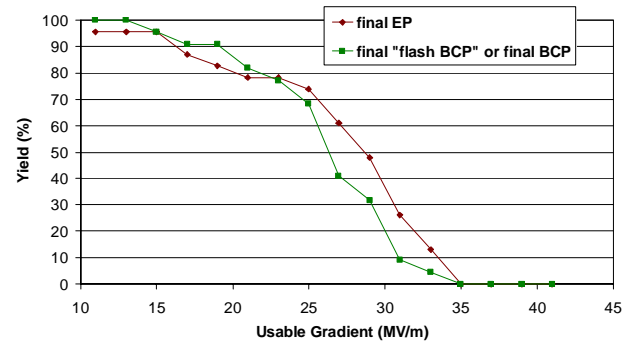
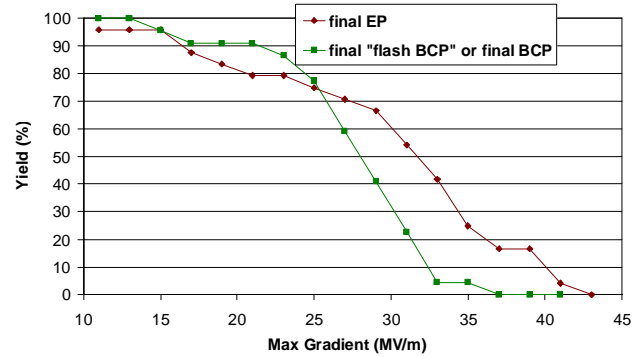


Figure 5a + b: Yield plot of maximum gradient (top) and usable gradient (bottom) depending on final surface treatment for the **last** vertical RF acceptance test.

The yield at 23,6 MV/m - design gradient for the European XFEL - is about 70% – 80%. It is limited by the low gradient Zanon cavities and – for the usable gradient – by few field emission loaded cavities. As more low gradient Zanon cavities got a final EP treatment, this is responsible for the lower yield of final EP compared to final Flash-BCP around 18 MV/m. For > (25 – 30) MV/m the maximum gradient after final EP shows a significantly better yield, which was already indicated by the Q(E)-performances. As field emission is limiting several of the high gradient “final EP-cavities”, this levels the yield of the usable gradient between final EP and final Flash BCP for high gradients. The Q-slope of the “final Flash BCP cavities” (Fig. 2b) does not affect strongly the yield of the usable gradient, because the Q-value is close to  $10^{10}$  up to the maximum gradient and hence the RF losses are well below the 100 W limit. As a final remark, the yield of only 96% for < 11 MV/m is caused by AC126, test 2, again.

### First Vertical RF Acceptance Test

In Figure 6a and 6b the maximum and usable gradient of the first vertical RF acceptance test are compared.

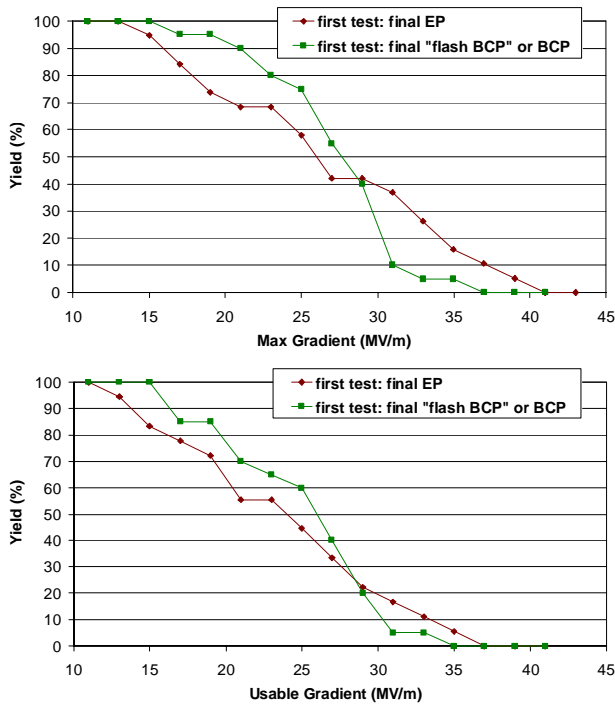


Figure 6a + b: Yield plot of maximum gradient (top) and usable gradient (bottom) depending on final surface treatment for the **first** vertical RF acceptance test

The yield at 23,6 MV/m shows a comparably wide spread with about 50% (usable gradient) / 65% (max gradient) after final EP, and about 60% (usable gradient) / 80% (max gradient) after final Flash BCP with an advantage towards final Flash BCP. Again, the lower yield of final EP compared to final Flash BCP is caused by the fact, that more low gradient Zanon cavities got a final EP treatment for the first RF test. No systematic reason for this behaviour is identified up to now. Until now, only one low gradient Zanon cavity (Z110) is re-processed by 1400C firing and subsequent heavy BCP, but it has not improved its performance [2]. Re-processing by BCP of some of the further cavities is planned for the near future.

For both final treatments about 25% of the cavities (4 out of 19 tests for final EP; 5 out of 20 tests for final Flash BCP) are limited by field emission below the design gradient.

*Comparison of First and Last Vertical RF Acceptance Test*

As described above, the yield for the usable gradient increases from about 50% - 60% for the first RF test to 70% - 75% for the last test referred to the design gradient of 23.6 MV/m. Unfortunately, no simple reason for this improvement can be given, because no standard procedure for the re-treatment of cavities was applied and some cavities show a complex history with several treatments and tests. This is on the one hand due to the need of sufficient cavities for TTF/FLASH accelerator modules including the disassembly of FLASH modules

[4] and the re-treatment and re-test of these cavities. On the other hand, the preparation processes developed continuously in the last years and refined processes have been tested and applied.

Analysis of re-treatments independent of the achieved gradient:

- In case of a low gradient field emission limitation, often a re-processing by HPR only is successful in order to increase the performance with a success rate of 80% - 90% [2], (see below).
- Typically, an additional surface removal by BCP or EP (with subsequent ethanol rinse) followed by HPR improves the performance. This needs to be verified for the low gradient Zanon cavities (see above).
- If the cavities are RF tested before and after 120 C bake, the test before bake is often limited by Q-slope, which results in RF losses exceeding 100 W. As well known, 120 C bake cures this phenomenon.
- Two accelerator modules have been disassembled due to an insufficient performance, and partially the cavities are re-treated and re-tested with good success, but difficult comparison to the first RF test.
- Finally, for some cavities only the first or the last test can be included in the analysis and no direct comparison is possible.

**COMPARISON OF PREPARATION STRATEGIES “WITH HE-TANK” AND “WITHOUT HE-TANK”**

As described above, an optimized preparation strategy (Fig. 1) was proposed and applied with the Helium tank welding **before** the vertical RF acceptance test (“vertical

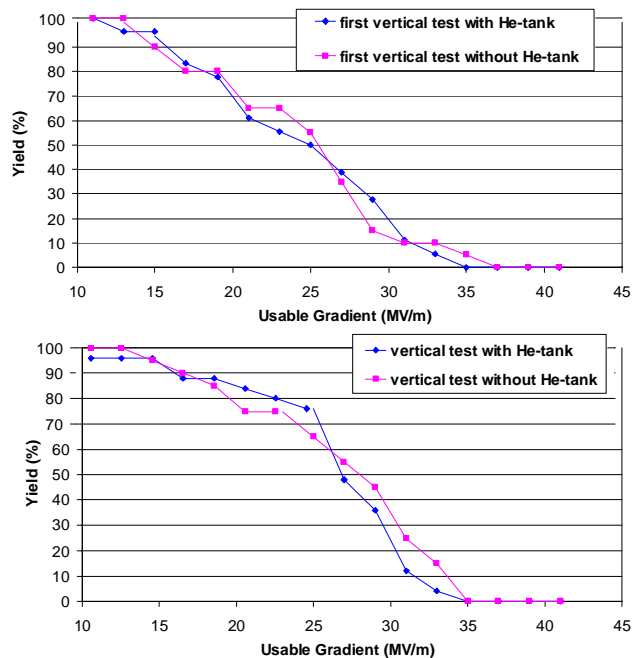


Figure 7a + b: Yield plot of usable gradient for first (top) and last (bottom) vertical RF acceptance test depending on preparation strategy “vertical RF test with He-tank” and “vertical RF test without He-tank”.

RF test with He-tank”) [5, 6]. In Figure 7a + b the usable gradient for the first and last RF test of this new scheme is compared to the established procedure welding the He-tank to the cavity **after** the successful RF test (“vertical RF test without He-tank”).

It is obvious, that the results are absolute comparable, and the new optimized scheme can be applied without any degradation in the cavity performance in the vertical RF acceptance test.

## RE-PROCESSING OF FIELD EMISSION LOADED CAVITIES BY HPR

In the last years more than 10 field emission loaded cavities have been re-processed by HPR only. First results have been published in [2]. Recent results shown in Figure 8 confirm a success rate of about 80% for an improvement in the cavity performance. Only one of seven cavities degraded significantly.

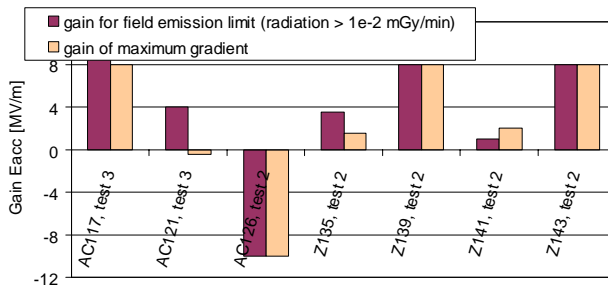


Figure 8: Gain of maximum gradient and field emission limit after HPR only.

## SUMMARY AND CONCLUSION

The analysis of the first and last vertical RF acceptance test of 50 nine-cell cavities of the recent DESY cavity fabrications showed a broad scatter of the usable and maximum gradient. About 25% of the first tests are limited by field emission below the design gradient of the European XFEL of 23.6 MV/m independent of the final surface treatment “final EP” or “final Flash BCP”. In most cases the field emission limitation can be cured sufficiently by a re-processing applying HPR only. It is still open and under investigation, why several cavities of one vendor show a limitation by quench at gradients below the design gradient. No systematic reason for this

behaviour is identified. Both effects – field emission and early quenches – limit the yield to 50% - 80%.

A final surface treatment by EP shows its capability for maximum gradients of > 30 MV/m on numerous cavities. Again, as field emission is limiting several of the high gradient “final EP-cavities”, this levels the yield of the usable gradient between final EP and final Flash BCP for high gradients.

In preparation of the large scale cavity fabrication for the European XFEL:

- The industrialization of the main EP treatment is successful at two companies.
- A new optimized preparation strategy - welding the He-tank to the cavity before the vertical RF acceptance test - was applied successfully.

Based on the presented data the European XFEL cavity first test yield can be about 70% to 80% for the design gradient, assuming firstly, that the yield of field emission limited cavities can be transferred to the industrial cavity preparation and secondly, that the reason for the low gradient quenches of one vendor can be identified and avoided. With an additional HPR and re-test the yield will be well above 90%.

## ACKNOWLEDGEMENT

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