RECENT EXPERIENCE WITH NINE-CELL CAVITY PERFORMANCE AT DESY

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Abstract

The rf performance of the last nine-cell cavity production for TTF/FLASH[1] is analysed with respect to maximum gradient, usable gradient and field limitation. 30 cavities have been manufactured at one company from high RRR niobium (RRR > 300) by two vendors. All cavities have been treated by a long (>150 µm) horizontal EP (Electropolishing) and 800° C firing. The cavity performance after final short (app. 50 µm) EP with or without subsequent ethanol rinse as well as a short chemical etch (~10 µm BCP) is compared.

INTRODUCTION

The forth production series for TTF/FLASH consists of 30 nine-cell cavities fabricated by E. Zanon Spa. The cavities are made of high RRR niobium with RRR > 300. 15 cavities are made of Wah Chang niobium, 14 cavities of Tokyo Denkai niobium and one cavity (Z111) of mixed material. Three pre-series cavities Z82 - Z84 show irregularities during fabrication and the results are not included in the statistical analysis.

The preparation started for all cavities with an electro-polishing (EP) of about 150 µm, an outside etch using buffered chemical polishing (BCP) and a 800 C annealing under UHV conditions. This was followed by one of the following treatments:

- Final EP of 40-50 µm, HPR, vertical test, 120-125 C bake for 48h ("bake") and add. vertical test. Partially, the vertical test before bake was skipped.
- Final EP of 40-50 µm with subsequent ethanol rinse, HPR, vertical test, bake and add. vertical test. Partially the vertical test before bake was skipped. The additional ethanol rinse was added during the ongoing cavity preparation in order to remove a possible sulphur contamination after EP[2].
- Final BCP of 10 µm, HPR and vertical test for eight cavities. Only five cavities were tested after bake in addition.

Due to insufficient performance during the previous rf test or preparation several cavities were re-processed applying an additional HPR only or an additional final EP + HPR. Partially, the EP treatment was performed with a subsequent ethanol rinse.

Four cavities including all three pre-series cavities have been post-purified by 1400 C titanisation. These results are given separately, but not included in the statistical analysis.

In total approximately 90 tests of 29 cavities were performed and analysed with up to 7 tests per cavity.

METHOD OF ANALYSIS

All tests have been analysed with respect to maximum gradient, usable gradient and gradient limitation (e.g. quench, field emission). For field emission analysis the onset level $E_{acc,onset}$ defined as the gradient where the x-ray radiation exceeds a level of 10^{-2} mGy/min at the test stand. The usable gradient is defined as the lowest value of either quench gradient, gradient where x-ray radiation exceeds 10^{-2} mGy/min or 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 TTF/FLASH rf pulse scheme, which is the cryogenic operational limit.

In general the last Q(E) measurement of each test was 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.

According to the subject of analysis the adequate test following a given preparation process was chosen. For example, the analysis of quench fields makes no sense in tests before bake with the typical Q-slope, while for the analysis of field emission the first test after preparation is a good choice.

RESULTS OF LATEST TEST

The average of maximum $<E_{acc,max}>$ and usable $<E_{acc,usable}>$ gradient of the latest vertical test of 27 cavities is summarized in Table 1. This contains either the gradient of the vertical test before tank welding or the last stable gradient as the status of today. Obviously this may differ from the analysis of the best results.

Table 1: Average of $<E_{acc,max}>$ and $<E_{acc,usable}>$ of latest vertical test

Preparation: Latest Vertical Test	$<E_{acc,max}>$ **[MV/m]**	$<E_{acc,usable}>$ **[MV/m]**
EP without ethanol	30 ± 4	29 ± 3
EP with ethanol rinse (without Z110; see below)	32 ± 6	30 ± 4
Short BCP ("EP+") (without Z111; see below)	30 ± 2	29 ± 2

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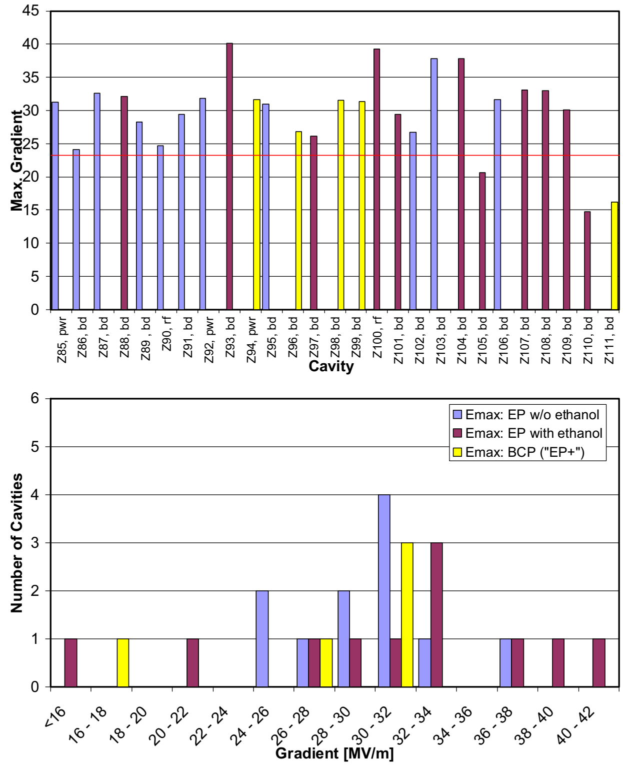

Figure 1: Maximum gradient of 27 cavities (top) and distribution of maximum gradient (bottom) depending on preparation

For all final preparation steps both <$E_{acc,max}$> and <$E_{acc,usable}$> give very similar results. No final preparation is preferable. The usable gradients are close to the maximum gradients. Remarkable is the small standard deviation for the final BCP treatment.

Figure 1 (top) shows the maximum gradient for each cavity depending on the final preparation. Eye catching are the cavities Z110 and Z111 with the lowest gradients of only about 15 MV/m limited by quench. As discussed in detail below, the low gradient is caused by a fabrication problem and these cavities are excluded from the statistical analysis, too.

Figure 1 (bottom) gives the distribution of the maximum gradients depending on the preparation. Final

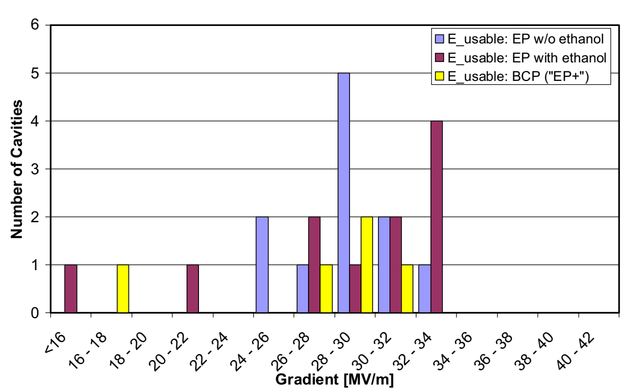

Figure 2: Distribution of **usable** gradient depending on preparation

EP treatment with ethanol results in highest gradients up to 40 MV/m, but shows the broadest scatter of maximum gradients. In addition to the low gradients of Z110 and Z111 the cavity Z105 is noticeable with a gradient of only 21 MV/m. This cavity showed a gradient up 30 MV/m without quench in two previous tests. After each of these tests it degraded due to a vacuum leak and an activation of strong field emission. Figure 2 shows the distribution of the usable gradient. In general the scatter of gradient is less pronounced. In the next chapters, we will try to distinguish between fabrication and preparation dependencies.

CAVITY PERFORMANCE AFTER FIRST PREPARATION

A comparison of the three final preparation steps for the first preparation is not trivial as the 120 C-bake[3], which is indispensable when aiming for the full cavity performance, was not applied to all cavities. Moreover, in contradiction to the usual experience two BCP treated cavities suffered from stronger field emission without an obvious reason after bake. To determine the first preparation cavity performance, generally the test after the 120 C bake is chosen with exception of the above mentioned cavities. An additional High Pressure Rinse (HPR) after a previous is handled as a re-treatment and not taken into account for the first preparation statistics.

Table 2: Average of <$E_{acc,max}$> and <$E_{acc,usable}$> of the test after first preparation

Preparation: **First preparation**	**<$E_{acc,max}$> [MV/m]**	**<$E_{acc,usable}$> [MV/m]**
EP without ethanol	26 ± 4	24 ± 5
EP with ethanol rinse (without Z110; see below)	26 ± 6	23 ± 6
Short BCP (“EP+”) (without Z111; see below)	29 ± 2	27 ± 4

The results of the first preparation – especially for EP with and without ethanol rinse – were far below the expectations (Table 2, Figure 3 top). The usable gradients of 11 of 25 analysed cavities (with Z110 + Z111 in addition) were below 24 MV/m after first preparation (Figure 3 bottom). For most (10) cavities the tolerable x-ray radiation level was exceeded due to strong field emission. Remarkable is the comparably good reproducibility and low standard deviation achieved after BCP final treatment.

A detailed discussion of quench and field emission limitations follows below.

RE-PROCESSING BY EP AND HPR

Additional EP

Due to the insufficient performance after the first preparation, 13 cavities have been re-processed applying an additional EP of typical 40 - 50 µm followed by the standard rinsing and assembly procedures. Due to the introduction of the subsequent ethanol rinse after EP during the ongoing cavity preparation only 10 cavities have been re-treated using EP with ethanol rinse.

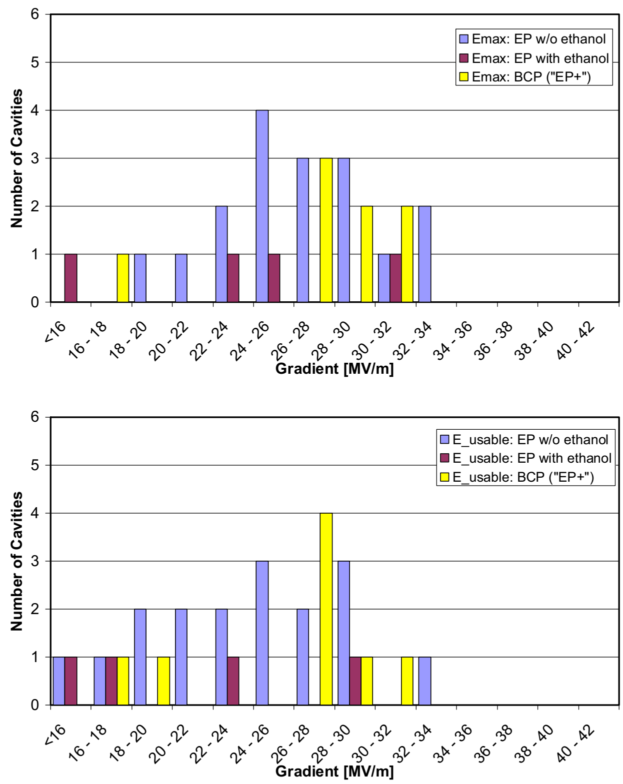

Figure 3 Distribution of maximum (top) and usable (bottom) gradient after first preparation

Before re-processing 10 of 13 cavities showed strong field emission loading, while 3 cavities were limited by quench between (23 – 27) MV/m. Nearly all (12 of 13) cavities improved to wide scattering gradients of (26 – 40) MV/m and an average gain of $E_{acc,max}$ = 6,2 MV/m. In particular the field emission behaviour improved significantly.

Additional HPR

10 cavities were re-rinsed without any chemical treatment following a previous rf test. Four of five cavities showing field emission loading could be improved significantly. One cavity remained unchanged. Remarkably two cavities degraded significantly after the appearance of a vacuum leak in the test stand followed by HPR. Obviously, the contamination of either the vacuum leakage or the additional assembly and handling procedures could not removed with HPR only.

ANALYSIS OF QUENCHES

Main tool for the localisation of a local thermal breakdown is a temperature mapping (T-mapping) system. Together with the interpretation of rf and x-ray signals in most cases it allows to distinguish between quenches caused by local thermal breakdown, field emission or multipacting. Local thermal breakdowns located in the

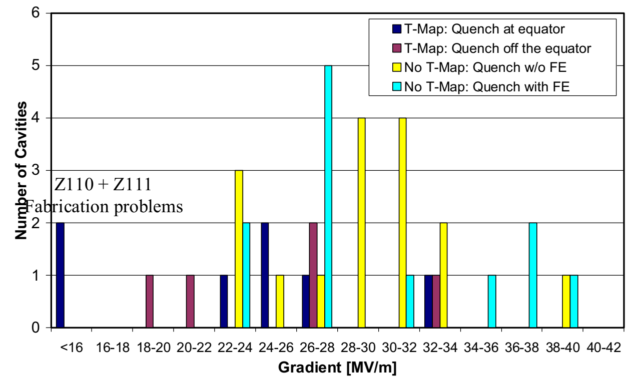

Figure 4: Analysis of quench gradients

weld area strongly indicate a problem during fabrication (i.e. cleanliness during weld preparation). Unfortunately due to lack of time or technical reasons several cavities with quenches below 25 MV/m have not been investigated by T-mapping.

Independent of the cavity preparation all quench limited tests are grouped in four classes. Re-processing results in double appearance of these cavities. Obviously repeated tests without any treatment (e.g. assembly of T-mapping only) are not counted twice.

- Identified quench location by T-map at the equator region.
- Identified quench location by T-map **off** the equator i.e. defect in the niobium material, field emission induced quench
- Quench without field emission not localized by T-mapping
- Quench with field emission not localized by T-mapping

Figure 4 gives the distribution of the quench gradients according to the described classes. The last two cavities (Z110 + Z111) of the last production batch show a quench at about 15 MV/m located in the weld region. Though no deviation from the welding specification has been reported, this clearly indicates a problem during the cavity fabrication. It is remarkable that a 1400 C titanisation with subsequent etching could not improve the performance of Z110 confirming a grave defect. Z105 shows a located quench at 21 MV/m off the equator after field emission processing. Whether the twofold degradation of this cavity, which is also part of the last production batch, can be related to fabrication problems is doubtful, because of strong field emission and vacuum leak problems in the respective tests. While most of the further cavities with gradients below 25 MV/m have been improved after re-treatment, the cavity Z86 with an unlocated, field emission free quench at 24 MV/m was welded into the Helium tank without further T-mapping analysis and attempt for improvement.

As a summary the broad scatter of quench fields between 15 – 40 MV/m without the influence of field emission emphasizes the need of thorough T-mapping analysis of all suspicious cavities with respect to fabrication and material faults. Obviously in the current

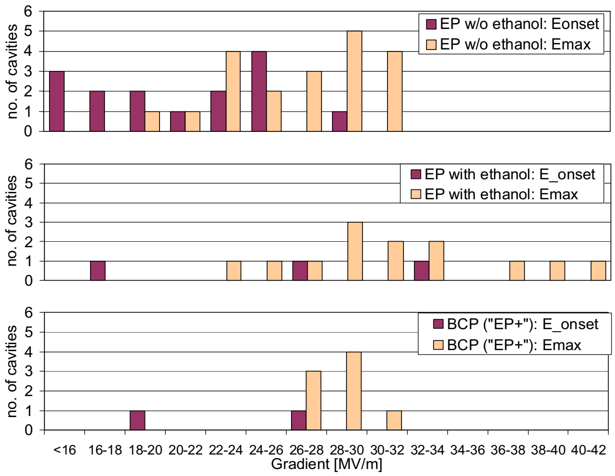

Figure 5: Comparison of $E_{acc,max}$ and $E_{acc,onset}$ for EP without ethanol rinse (top), EP with ethanol rinse (middle) and final short BCP treatment (cavities Z110 + Z111 not included)

production series unexpected fabrication problems seriously affected the cavity performance.

ANALYSIS OF FIELD EMISSION

For the analysis of field emission properties depending on the final preparation process an equal quality of the preparation and assembly environment is assumed. It is obvious that any temporary malfunction of e.g. the HPR system or cleanroom ventilation would result in a systematic misinterpretation of the results.

The analysis of field emission is based on the test immediately following the preparation independent if a 120 C-bake is applied or not. As mentioned above an additional HPR is regarded as a re-processing and not taken into account. Again only the final Q(E)-measurement is analysed neglecting any processing or degradation effects especially during the first Q(E)-run. The available dataset consists of 20 EP treatments without ethanol rinse, 13 EP treatments with ethanol rinse and 9 final short (10 µm) BCP treatments.

In figure 5 a comparison of the three preparations is given. For all tests the maximum gradient $E_{acc,max}$ is plotted, while the onset gradient $E_{acc,onset}$ appears only for field emission loaded cavities. In Table 3 the average gradients are summarized. The average of $E_{acc,onset}$ is given only for "EP without ethanol", where in 15 of 20 analysed tests field emission above the threshold at $E_{acc,onset}$ was detected. For both "EP with ethanol" and "short BCP" field emission above the threshold has been detected at $E_{acc,onset}$ in only 3 (of 12) and 2 (of 8) cavities, respectively. Therefore no average gradient is given (cavities Z110 + Z111 not included) for these batches.

Table 3: Average of $\langle E_{acc,max}\rangle$ and $\langle E_{acc,onset}\rangle$ of the test immediately following the preparation

Field emission analysis preparation	**$\langle E_{acc,max}\rangle$ [MV/m]**	**$\langle E_{acc,onset}\rangle$ [MV/m]**
EP without ethanol	27 ± 4	21 ± 5
EP with ethanol rinse (without Z110)	31 ± 5	- *
Short BCP ("EP+") (without Z111)	28 ± 1	- *

* Remark: For "EP with ethanol" and "short BCP" only 3 (of 13) and 2 (of 9) cavities, respectively, exceeded the field emission threshold at a lower gradient. Therefore no average gradient is given.

As a clear consequence an ethanol rinse is required after electro polishing for a reproducible low field emission loading. Both, "EP with ethanol" and "short BCP" give a comparable performance with respect to field emission. Reproducibly gradients above 25 MV/m are achieved without achieving $E_{acc,onset}$.

HORIZONZAL TEST RESULTS

Though more cavities have been welded into their helium vessel for accelerator use, only 15 cavities underwent a separate fully equipped horizontal ("Chechia") test. The additional cavity Z83 of the pre-series after 1400 C titanisation (see below) is not taken into account, although it gave a good result. 3 cavities with final short BCP treatment were tested horizontally with maximum gradients between 19 – 27 MV/m. Remarkable is the drastic degradation of Z94 from 32 MV/m in vertical test to 19 MV/m and of Z99 from 31 MV/m to 25 MV/m. In both cases the horizontal test was limited by quench with no or low field emission loading. When analysing the rf test data, the most probable cause for the degradation is strong field emission processed at the beginning of the horizontal test for both cavities. In figure 6 Z94 is marked by a red circle. After final EP treatment 12 cavities were tested with gradients between 23 – 39 MV/m. The cavity Z89 degraded from 28 MV/m to 23 MV/m. The reason could not be identified. Due to a lack of time, three cavities have been tested horizontally without 120 C bake. As expected this resulted in low Q-values at high gradients for two cavities.

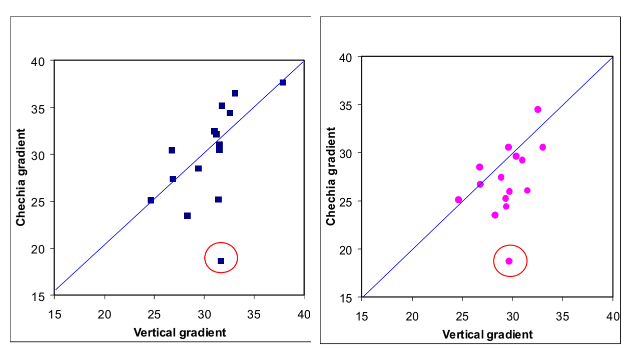

Figure 6: Comparison of horizontal and previous vertical test result for both maximum and usable gradient

Figure 6 gives the direct comparison of horizontal and previous vertical test result for both maximum and usable gradient. All maximum gradients are limited by quench. The usable gradients of 5 cavities are limited by quench. 8 cavities exceed the tolerable cryogenic losses, which is partially close to the quench or field emission limit. 3 cavities are limited by exceeding the x-ray radiation limit as a clear deterioration compared to the previous vertical test.

MORE ANALYSIS

Effect of 120 C bake

In good agreement with the general experience[3] for EP treated cavities a (120 – 125) C bake for 48 h under vacuum conditions cures the typical Q-slope effectively. Though this procedure is well established it is time consuming and labour intensive. A higher temperature and shorter time was tested with good results on single-cell cavities[4, 5], but improves only the duration. A real simplification for the future may give an open bake procedure in the cleanroom under Argon or nitrogen atmosphere [5, 6].

For short BCP treated cavities no final conclusion can be drawn. Only five cavities were baked with two of them degraded due to field emission after bake. One cavity showed field emission before and after bake. The remaining two cavities showed a clear improvement of the Q-value and (nearly) no field emission before and after bake. More tests and comparison to the results of other labs are necessary.

Effect of 1400 C post-purification

In contradiction to the previous cavity productions only four cavities have been 1400 C post-purified by titanisation. As the treatment was applied to the pre-series cavities Z82 – Z84 and the faulty cavity Z110 only, no significant data are available.

SUMMARY

Unexpectedly, both the maximum and usable gradients of the fourth production cavities show a wide scatter in vertical and horizontal tests. Due to un-identified fabrication problems in the last production batch two cavities are limited at 15 MV/m. Several cavities had a quench limitation between 20 MV/m to 25 MV/m after the first preparation, which mostly could be improved by an additional chemical treatment. More than one third of the cavities showed unacceptable field emission loading after the first preparation process, partially due to the application of EP without subsequent ethanol rinse. An ethanol rinse after EP is mandatory for low field emission loading. Highest gradients of up to 40 MV/m were measured after EP with ethanol rinse. Application of a short BCP of 10 µm removal after an initial electro polishing of about 150 µm resulted in maximum gradients between 26 MV/m and 30 MV/m with good field emission performance. Some degradations and unusual behaviour require more statistics for this treatment. Re-processing of field emission loaded cavities with only HPR instead of an additional chemical treatment is effective. Still 3 of 16 cavities degraded significantly in their performance from vertical to horizontal test indicating, that the assembly and cleaning procedures are not optimised. The standard 120 C bake is well established for electro polished cavities, but optimisation of the process is desirable. For BCP treated cavities more tests and investigations on the bake procedure are necessary.

ACKNOWLEDGEMENT

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