RESULTS ON LARGE GRAIN NINE-CELL CAVITIES AT DESY: GRADIENTS UP TO 45 MV/M AFTER ELECTROPOLISHING

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Abstract

Since 2009 a series of eight nine-cell cavities (AC151 – AC158) of TESLA shape fabricated of large grain (LG) niobium material [1] is under preparation and test at DESY. In a first step all cavities were tested after a BCP treatment. In a second step additional electropolishing is applied to all cavities. In this paper the treatment will be discussed and present results will be reported.

MATERIAL AND FABRICATION

Development of LG disc production was done within the framework of the European XFEL driven R&D program of DESY [2] and the company W. C. Heraeus. One of the particularities was the presence of a single crystal with a diameter larger than 150 mm in the disc's central area. This was essential for avoiding necking and tearing at the iris areas during deep drawing.

The developed multi-wire slicing procedure allows keeping the high residual resistance ratio (RRR) of the melted ingot in the discs. The surface of the sliced discs has a high quality; the roughness was small compared to conventional fine grain sheets.

Three cavities (AC151 – AC153) have been fabricated from material with RRR of about 420. For five cavities (AC154 – AC158) the RRR of the material was about 350. More details about the material are presented in [3].

For the cavities AC155 and AC156 the steps at the grain boundaries, which appeared after deep-drawing, were smoothened by grinding the RF surface of the half-cells.

The complete fabrication was done by Research Instruments GmbH (RI).

CAVITY SURFACE PREPARATION

For all cavities the preparation at DESY started with a mechanical and electrical entrance check. The inner surface of the cavities was visually inspected with a camera system developed at KEK/Kyoto University [4].

BCP Treatment (Figure 1)

The main inside surface removal of about (100 – 110) μm as well as the outside removal of about 10 μm was done by BCP (volume HNO_3 : HF : H_3PO_4 1:1:2) at RI. Inside BCP took place in the RI closed loop system, while outside BCP was done by dipping with protected NbTi-flange surfaces. The subsequent final treatment at DESY started with the standard 800°C firing for 2 h at a pressure < 10^{-5} mbar. After tuning to a field flatness of better than 95 % the final inside BCP of (20 – 30) μm (volume HNO_3 : HF : H_3PO_4 1:1:2) followed in the closed loop DESY system including ultrapure water rinse and first High Pressure Water Rinse (HPR). Flange and pickup assembly followed by final six HPR cycles (2 h each) [5] and helium leak check were done in the cleanroom of class ISO 4. The low temperature heating ("baking") of the evacuated cavity took place at a temperature of 125°C - 130°C for about 48 h in a heating stand outside of the cleanroom.

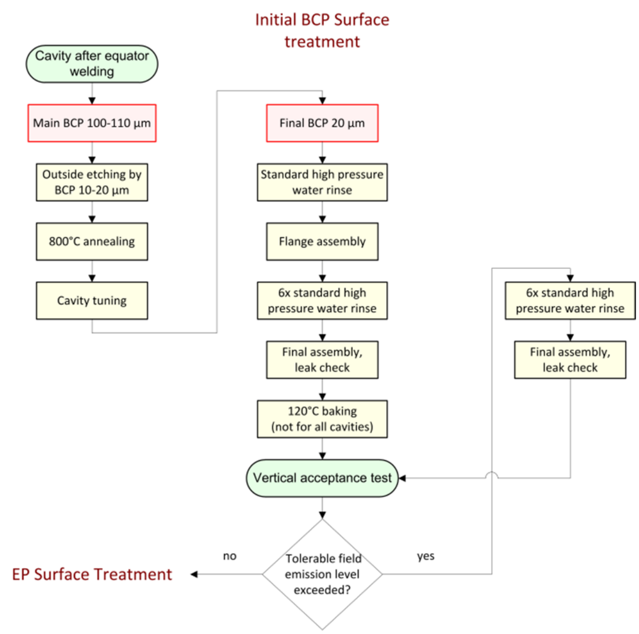

Figure 1: Flow scheme of BCP treatment.

EP Treatment (Figure 2)

After the first vertical acceptance tests (described below) the possible removal with respect to frequency and tolerable length was calculated. Therefore two different procedures were applied:

- For six cavities a main EP at DESY [6] of about (60 – 70) μm was done, followed by an ethanol rinse and an additional standard 800°C firing for 2 h at a pressure < 10^{-5} mbar for hydrogen degassing. Before final EP, the field flatness was checked again and, if necessary, tuned to better than 95 %. The final EP removal was about 48 μm. Ethanol rinse [7], flange assembly, final six HPR cycles and helium leak check took place in the cleanroom of class ISO 4.
- For two cavities (AC151, AC155) the main EP was not possible. Their tolerable length in the cryo-module at the operating frequency would be exceeded due to the additional removal. Therefore, after tuning only the final EP followed by the above

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described steps was applied (except of AC155 with no ethanol rinse after final EP).

The parameter set of the “baking” procedure after EP treatment was identical to the parameters after BCP treatment (except of AC151 with a heating time of 26 h).

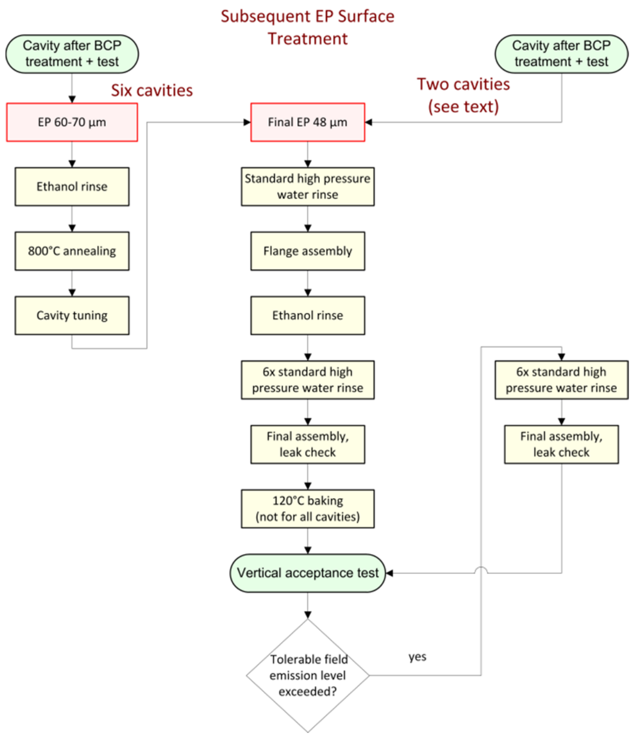

Figure 2: Flow scheme of subsequent EP treatment.

Additional HPR Treatment

In case of strong x-ray radiation in a previous RF test an additional HPR treatment was applied for several cavities. This included four to six HPR cycles of about 2 h each. Usually only the lower beam tube flange was opened but in some cases the HOM feedthroughs were exchanged by blank flanges (see next chapter).

After only HPR treatment no additional “baking” procedure was applied.

VERTICAL ACCEPTANCE TEST

General

For the vertical acceptance test the cavities are either equipped with HOM feedthroughs and a fixed High Q-antenna on the main coupler port or with blank flanges on the HOM ports and a variable High Q-antenna. The former requires the so-called “long pulse” scheme during the cryogenic RF test [8] and does not allow measurement of the $Q_0(E_{acc})$ performance in all fundamental pass band modes. The latter allows cw operation and full measurement of all fundamental pass band modes.

In order to check for a hydrogen contamination of the niobium and the well-known resulting “Q-disease” during cool down a “parking” at about 100 K for several hours is part of the standard vertical test procedure.

The $Q_0(E_{acc})$ performance was determined at 2 K and 1.8 K for comparison.

The Second Sound set-up for localisation of the breakdown area (“quench”) is now available for all test inserts and applied routinely [9, 10]. For the first RF tests reported here the system was still under commissioning and not in use on a regular basis.

Information about the treatment and RF test results can be found in the DESY/TESLA Cavity Data base [11].

$Q_0(E_{ACC})$-PERFORMANCE AFTER BCP SURFACE TREATMENT

After the initial BCP treatment all cavities achieved a gradient of 24.5 MV/m – 28.5 MV/m at 2 K. No difference in the maximum gradient between 1.8 K and 2 K was detected. No evidence of Q-disease was observed. Figure 3 gives the $Q_0(E_{acc})$ performance at 2 K of all eight cavities in their final state before the EP treatment is applied.

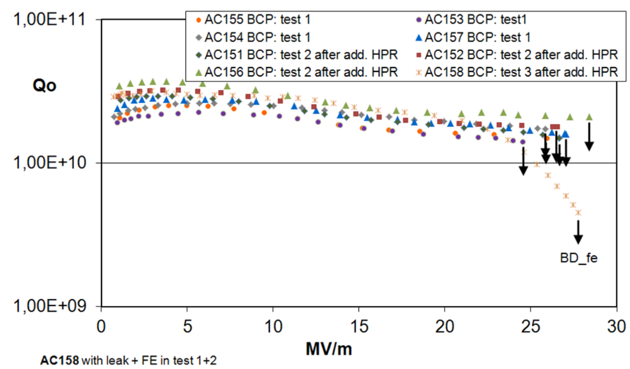

Figure 3: Final $Q_0(E_{acc})$ performance at 2 K after BCP treatment. All cavities are limited by thermal breakdown; AC158 shows breakdown with strong x-rays (BD_fe).

Four out of eight cavities showed no or only low (< 10^{-2} mGy/min) x-ray radiation already in the first RF test. This included the cavity AC155 with 26 MV/m and no x-rays in the π-mode. In the other fundamental pass band modes 26 MV/m – 29 MV/m limited by thermal breakdown without x-rays were achieved. Due to x-rays > 10^{-2} mGy/min in the first RF test three cavities required an additional HPR treatment. In the subsequent RF test no or only low x-rays were detected. These seven cavities were limited by thermal breakdown (BD) at Q_0 values of $(1.4 – 2.1) \cdot 10^{10}$.

One cavity (AC158) showed a vacuum leak at cryogenic temperatures in test 1 and 2. In test 3 after additional HPR treatment and re-assembly the cavity was leak tight, but still strong x-ray radiation was measured. AC158 was limited by breakdown with strong x-rays (BD_fe) at $Q_0 = 4.5 \cdot 10^9$.

Figure 4 gives the yield of maximum and usable gradient of the described cavities AC151 – AC158 and in addition of the earlier LG cavities AC112 – AC114 with similar preparation [12]. The usable gradient [13] 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.

These cavity performances are in full agreement with earlier results on large grain single- and nine-cell cavities at DESY [12, 14].

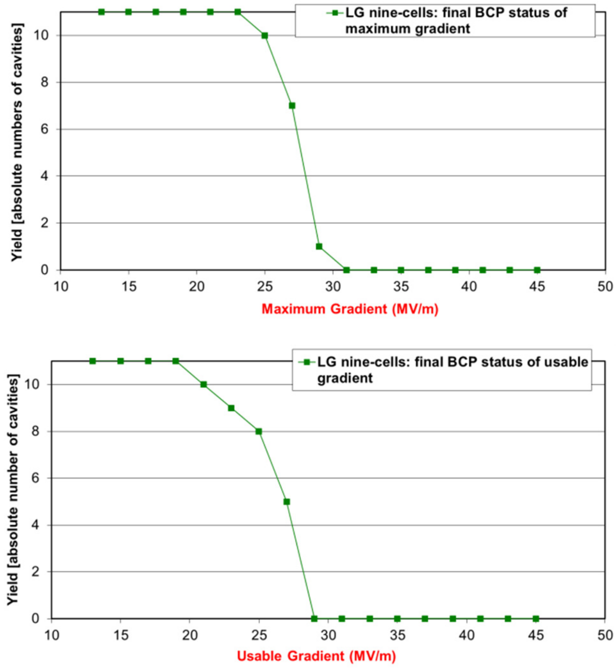

Figure 4: Yield of maximum and usable gradient in the final state after BCP treatment in absolute numbers of cavities.
Note: Results of 3 earlier LG nine-cell cavities included (AC112 – AC114).

$Q_0(E_{acc})$-PERFORMANCE AFTER EP SURFACE TREATMENT

After EP treatment the acceptance test of five out of eight cavities is completed with gradients (31 – 45.5) MV/m at Q_0-values above $1.2 \cdot 10^{10}$ limited by breakdown. No difference in maximum gradient between 1.8 K and 2 K was detected. No evidence of Q-disease was observed. Figure 5 gives the $Q_0(E_{acc})$ performance at 2 K of these five cavities.

For three of the five cavities tested so far no or only low x-rays were detected. Especially cavity AC158 showed no x-ray radiation at all up to its gradient limit of 45 MV/m. The radiation of the cavities AC154 and AC155 exceeded the x-ray level of 10^{-2} mGy/min at 31 MV/m and 40 MV/m, respectively. Except of AC154 the first test after the EP treatment was successful; AC154 required an additional HPR due to strong x-rays and low gradient in a first test (not shown).

The cavities AC155 and AC156 with grinded grain boundaries had gradients of 45.5 MV/m and 31 MV/m, respectively. Within the statistics so far no clear positive effect of this treatment is obvious.

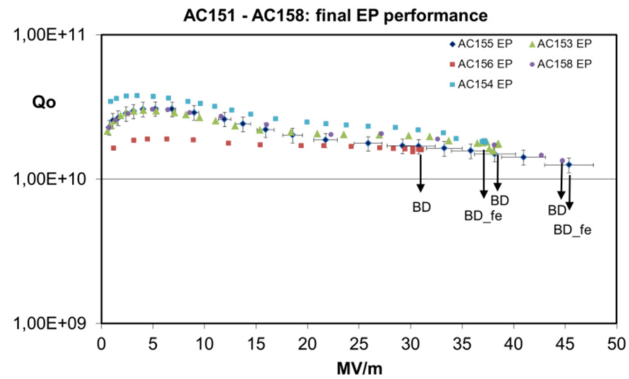

Figure 5: Final $Q_0(E_{acc})$ performance at 2 K after EP treatment.

Figure 6 gives the yield of maximum and usable gradient of the described five out of eight cavities and in addition of the earlier LG cavities AC112 – AC114 with similar preparation [12]. The low gradient result of cavity AC114 is discussed in [12]. Compared to the results after BCP treatment significant higher gradients were achieved.

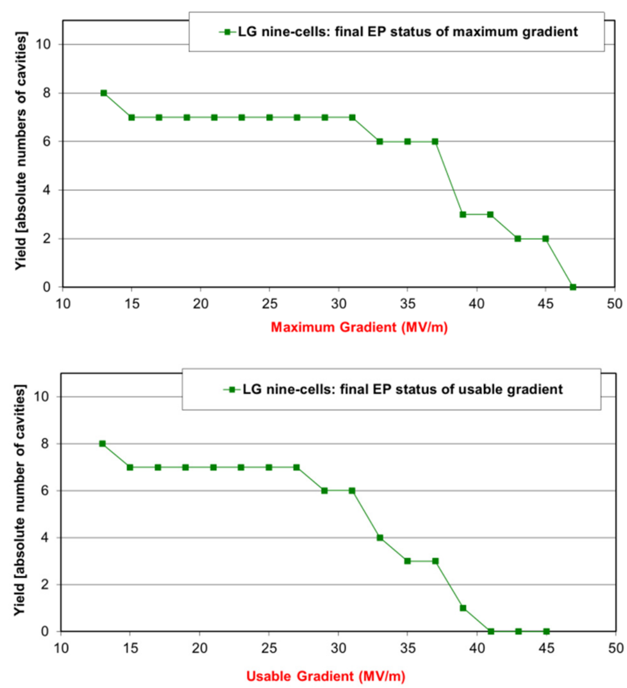

Figure 6: Yield of maximum and usable gradient in the final state after EP treatment in absolute numbers of cavities.
Note: Results of 3 earlier LG nine-cell cavities included (AC112 – AC114).

The interesting and extraordinary test sequence of cavity AC155 is looked at in more detail. Figure 7 shows the initial and final $Q_0(E_{acc})$ performance at 2 K of AC155.

In the initial $Q_0(E_{acc})$ measurement after EP (test no. 2) AC155 was limited at 35 MV/m by breakdown with strong x-rays of at most 0.5 mGy/min. Some decreasing of x-rays (processing) was observed and reduced the radiation to 0.15 mGy/min finally. The x-ray level of 10^{-2} mGy/min was exceeded at 29 MV/m. During this measurement done in cw operation continuing Q-switches occurred above 28 MV/m down to 18 MV/m – 24 MV/m at a Q_0 value well below 10^{10} (see Fig. 7, red squares). In cw operation at constant forward RF power and manually switching off and on the RF power the gradient could be increased successively up to the breakdown field.

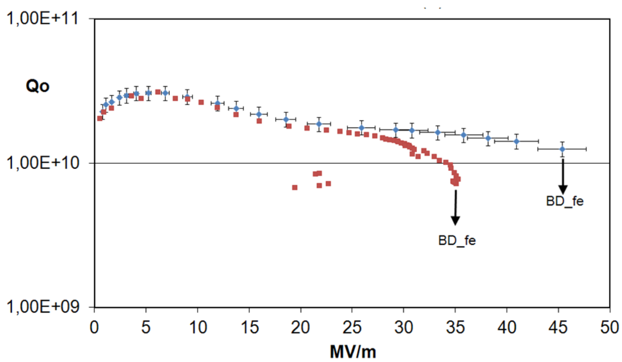

Figure 7: First and final $Q_0(E_{acc})$ performance of nine-cell cavity AC155 at 2 K after EP treatment. Notice the Q-switches at around 30 MV/m down to (18 – 24) MV/m at Q_0 below 10^{10}.

In all subsequent $Q_0(E_{acc})$ measurements (not shown) of the π-mode these Q-switches still appeared above ~ 35 MV/m, while in the pass band mode measurement except of 3/9 π and 1/9 π-mode no Q-switches were observed. Without giving exact numbers there was a clear tendency for shorter "processing" time and less occurrence of the Q-switches with progressing test.

In the final $Q_0(E_{acc})$ measurement of this test no. 2 an excellent gradient of 44.5 MV/m at a Q_0 value of about $1 \cdot 10^{10}$ limited by thermal breakdown was measured.

No difference in maximum gradient between 1.8 K and 2 K was observed. The x-rays were significantly reduced to 0.3 mGy/min at maximum gradient and exceeded the x-ray level of 10^{-2} mGy/min at 34 MV/m. The parasitic excitation of the 7/9 π-mode [15] was observed for most π-mode measurements at gradients > 30 MV/m. The mode measurements showed consistent fields limits within the measurement error in all cells with 46 MV/m in cells 1 & 9, 45 MV/m in cells 2 & 8, 3 & 7, 49 MV/m in cell 5 and 50 MV/m in cells 4 & 6.

The analysis of the quench locations detected by the Second Sound method is in excellent agreement with the mode measurements [10] taking into account the error of the RF measurement, the presence of x-rays in some modes indicating dark current and the surface field close to the fundamental limit.

In order to verify this outstanding result the cavity was warmed up to room temperature and cooled down again (test no. 3). The characteristic RF parameters of the test stand like attenuation of cables and directional couplers were cross checked.

The previous excellent results could be fully confirmed: The final $Q_0(E_{acc})$ measurement (see Fig. 7, blue circles) was limited at 45.4 MV/m at $Q_0 = 1.3 \cdot 10^{10}$ by breakdown. Already in the first $Q_0(E_{acc})$ measurement after the warm-up cycle the x-rays were reduced compared to test no. 2 to now $4 \cdot 10^{-2}$ mGy/min at maximum gradient and exceeded the x-ray level of 10^{-2} mGy/min at 40 MV/m. It is not clear why the x-rays are finally reduced by one order of magnitude, but the removal of the residual gases on the surface by warm-up might play a role.

The parasitic mode excitation of the 7/9 π-mode was observed for the first π-mode measurement. The above described Q-switches occurred less during the $Q_0(E_{acc})$ measurements of the π-mode. The fundamental pass band measurements showed slightly higher fields than in test no.2, which are within the measurement errors.

The achieved gradients of 45 MV/m in two nine-cell cavities at 1.8 K and 2 K are equivalent to magnetic surface fields of 192 mT. Remind the B_{peak}/E_{acc} of 4.26 mT/(MV/m) for the TESLA cell shape [16]. The pass band mode measurements give up to 213 mT for individual cells. This is in agreement with the highest magnetic surface fields measured in other labs [17]. These gradients and surface fields are among the highest fields ever measured in a multi-cell cavity.

SUMMARY

Two large grain cavities AC155 and AC158 achieved a gradient of 45 MV/m corresponding to a magnetic surface field of 192 mT limited by breakdown after EP surface treatment. They are among the best Nb cavities ever tested. The cavity AC155 will be re-tested with T-Mapping and Second Sound for further analysis of this excellent result and the Q-switch phenomenon.

After initial BCP treatment all eight analysed large grain cavities were limited at gradients of 24.5 MV/m – 28.5 MV/m by breakdown. Seven cavities showed no or low x-rays.

The vertical acceptance tests of the remaining cavities are under preparation.

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