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STATISTICAL ANALYSIS OF THE 120°C BAKE PROCEDURE OF SUPERCONDUCTING RADIO FREQUENCY CAVITIES

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Abstract

DESY is and was very active in R&D related to SRF cavities. Many single- and nine-cell cavities with different surface treatment histories were tested vertically. Results of these cold tests are accelerating gradient and quality factor of the cavities. Using the large number of available datasets the parameters of the 120°C bake procedure, which is applied to avoid high-field Q-slope, are analysed. The impact of different durations and temperatures on accelerating gradient, quality factor and residual resistance is studied in detail and is compared to results obtained with the recently proposed procedure of modified low temperature bake. For this procedure additional four hours at temperatures around 75°C are implemented before the standard bake at about 120°C. Since the claim is, that cavities treated with such a modified procedure achieve extra-ordinary large accelerating gradients it is a very interesting research field for the European XFEL continuous wave mode upgrade. For this purpose cavities with high quality factors are needed, but in addition large maximal accelerating fields are required to maintain high energies in the pulsed operation mode of the accelerator.

THE 120°C BAKE PROCEDURE

Modern superconducting radio frequency (SRF) cavities are made of Niobium and are used worldwide in a large variety of particle accelerators. The requirements on the surface quality are extremely high in order to enable outstanding performances. One standard surface treatment procedure for SRF cavities (e.g. applied for the European XFEL) contains besides the electrochemical polishing two heat treatments. The first one at 800°C is applied before the final chemical treatment. It releases mechanical stress in the material and gets rid of the hydrogen. The second treatment, normally at 120°, is executed directly before the first vertical performance test of the cavity. This bake procedure is needed to cure the so called high-field Q-slope. A heat treatment at about 120°C for typically 24 h - 48 h under high vacuum conditions inside the cavity prevents this effect.

Several reasons for the Q-slope and methods to overcome it by heat treatments are reviewed in [1]. Nano-hydrides are also discussed [2] as possible reason for the degradation of cavities at high fields.

At DESY, the bake procedure is implemented via a simple setup with heating coils. The systematic temperature uncertainty is described by $\Delta T = 0.5$°C over a single-cell cavity and even about $\Delta T = 5$°C over the height of a nine-cell cavity.

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DATA SAMPLE AND SELECTION CRITERIA

Almost 400 bake procedures at different temperatures are recorded in the DESY cavity database [3] in addition to the 832 European XFEL series cavities. Since the latter all underwent the standard bake procedure at 120°C for 48 hours, they are not part of the here analysed sample. Only standard cavities with completely recorded histories are allowed. Special treatments like baking with Argon or heat treatments conducted not at DESY are excluded as well.

The cavities in the sample vary in the number of cells, their manufacturer, the surface treatment they experienced and the test stands on DESY campus at which the vertical test was performed. The described selection results in 158 vertical tests of 111 individual cavities. 26 single cell cavities, two three cell cavities and 83 nine cell cavities.

The results, which are presented here, are always deduced from vertical performance tests executed at a liquid Helium temperature of 2 K. Since a vertical test will only be ended after two reproducible power rises, only the last power rise of each test is used. In cases where multiple test after a heat treatment exist, the one with the best Q_0 @ 7 MV/m is chosen.

Temperature Distribution

To illustrate the variety of the data sample, in Fig. 1 the distribution of the bake procedures over the baking temperatures are shown.

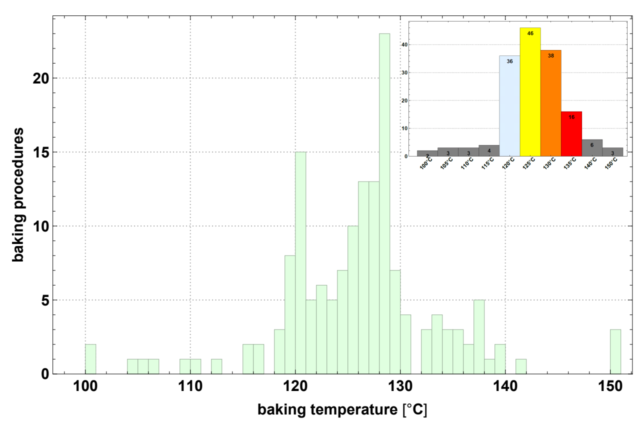

Figure 1: Temperature distribution of all cavity bake procedures. On the upper right, the binning, used in the analysis, is displayed.

This sample allows for 5°C wide bins with sufficient statistic in the three bins from 120°C to 130°C. Even wider binning does not allow for meaningful statements and would require a bin centre correction, which is not applied in this analysis.

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Statistical Limitations

Due to the limited statistics, the temperature and duration of the bake procedure can be studied only. In Fig. 2, the underlying samples for this analysis are shown.

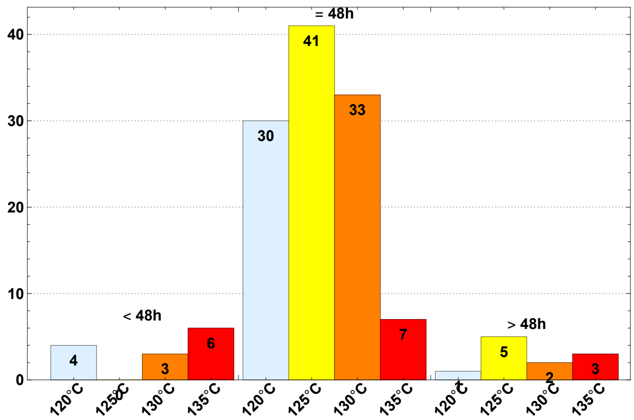

Figure 2: Binned temperature distribution of bake procedures sub-divided for different treatment durations.

Further distinction concerning the material and Niobium vendor or the vertical test limit like breakdown, field emission or power limit are not possible. The same holds true for the surface treatment, which was applied to the cavities and the cavity performance in tests at lower liquid Helium temperatures.

OBSERVATIONS

In the following Figs. 3 - 6 for all the parameters the mean value in each bake temperature bin is given together with $\sigma / \sqrt{N}$. Whether the mean value is a sensible representation or not was analysed in detail, more can be found in [4]. Since no better parameter is available and only in some bins the spread is extremely wide, it is used in the following.

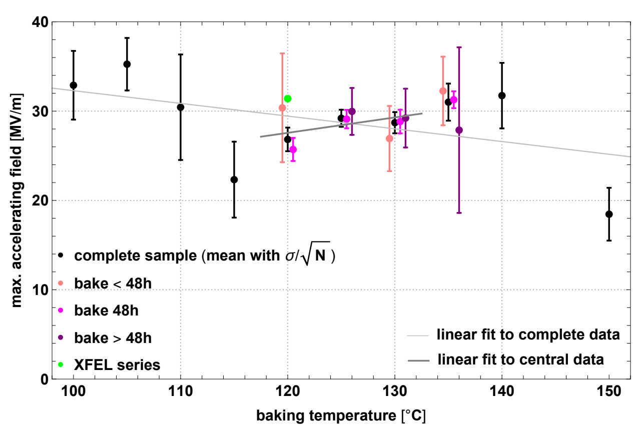

Figure 3: Maximal accelerating gradient displayed over bake temperature.

In all figures, the complete data sample as well as points for samples differentiated by baking durations are shown. But this distinction is only possible in the central bins with statistics above 20 entries per bin. Even there, not in every bin all duration values are available, sometimes data points are missing due to insufficient statistics. For comparison the results of the European XFEL-series cavities –all treated according to the 120°C standard procedure– are displayed as well.

To guide the eye and allow for an easy assessment of the results, linear fits to the data are shown in addition. One for the complete temperature range and one only for the statistically dominating region in the three bins from 120°C to 130°C. Both fits include the data and uncertainties of the complete data sample depicted in the black dots.

A trend to slightly lower maximal accelerating gradients towards larger temperatures for the bake procedure is visible in Fig. 3, but the data points comprise huge uncertainties. Hence, the linear fit of the central region is more sensible and this one indicates a clear improvement with increase of the baking temperature.

The quality factor Q_0 measured at 7 MV/m is chosen as parameter since it exists for all analysed cavities, results are shown in Fig. 4.

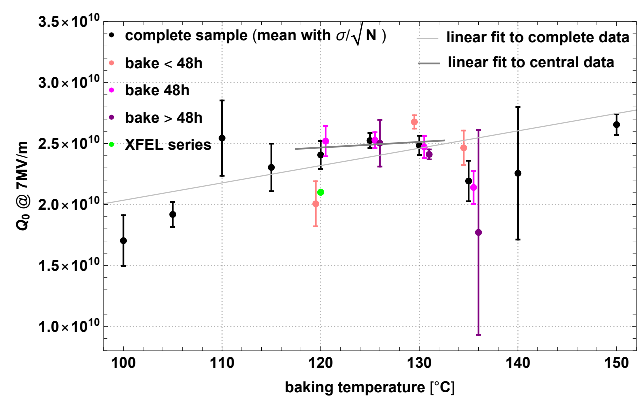

Figure 4: Quality factor measured at an accelerating field of 7 MV/m versus bake temperature.

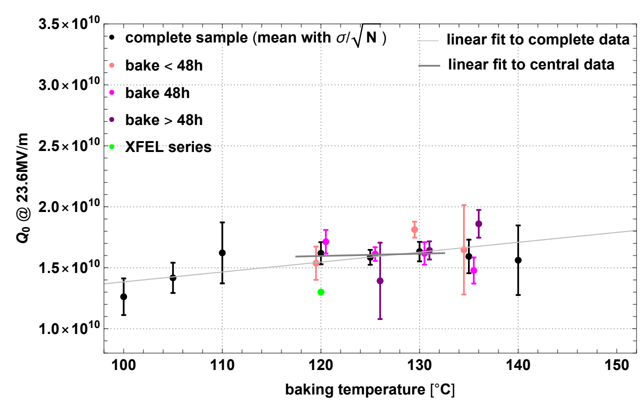

Figure 5: Quality factor measured at an accelerating field of 23.6 MV/m versus bake temperature.

In contradiction, not all cavities reached the European XFEL design value of Q_0 = 23.6 MV/m. Therefore in Fig. 5, the statistics are reduced a little further. In both

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Figs. 4 and 5, a trend to better performances with higher bake procedure temperatures is visible, even though for the central bins almost no development can be seen.

In Fig. 6, values for the residual resistance are shown versus the bake temperature. Since this resistance value is deduced from a fit to Q(T) dependence, which is not measured for all cavities, here the statistics are reduced further again. Judging this figure it should be kept in mind, that lower resistance values are preferable. Both, the overall tendency as well as the fit to the central bins show a light degradation with increasing temperatures.

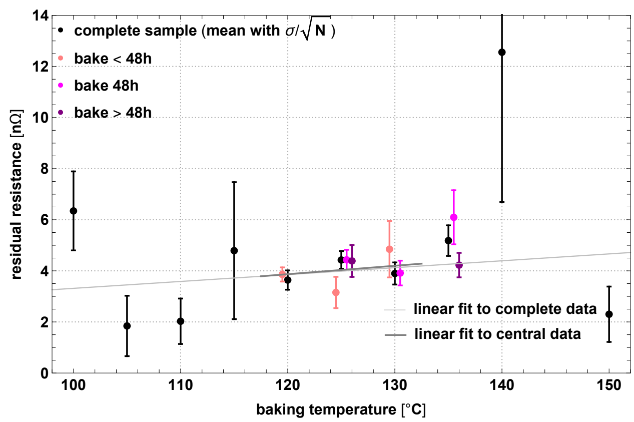

Figure 6: Residual resistance displayed over bake temperature.

A conclusion concerning the baking durations is very difficult. Comparing the results of cavities with longer bake procedures with such of cavities with shorter heat treatments a small but uncertain tendency towards shorter bake procedures can be deduced.

TEMPERATURE OPTIMISATION

In order to get a basis for reliable conclusions and the possibility to identify room for improvements an overview plot was created. In Fig. 7 all parameters are compared and normalised to their value at 120°C and 48 hours, since this is up to now the standard working point.

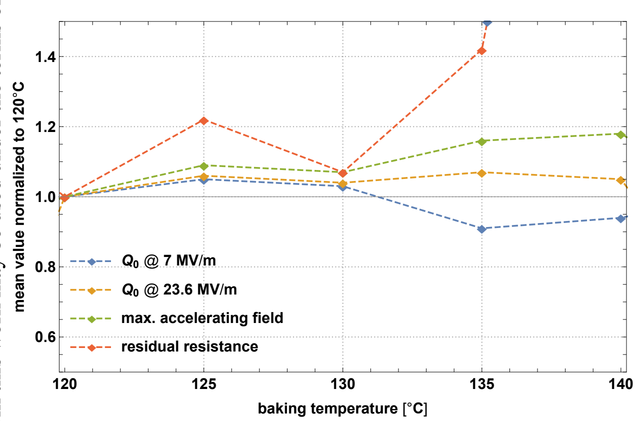

Figure 7: Normalised values of all studied parameters plotted over bake temperature.

At 120°C all studied measures are by definition one. For the quality factors and the accelerating field a moderate rise can be seen up to 130°C. Afterwards the accelerating gradient and the Q_0 @ 23.6 MV/m rise further, while the quality factor at lower field drops. The residual resistance shows an increase in the beginning, declines towards 130°C, before it steeply rises. Again, for the residual resistance the lowest possible value is preferable.

Hence, the apparent choice for an optimised temperature for the bake procedure is 130°C. Here 5%-10% improvement can be reached in three variables without too much losses in the residual resistance.

MODIFIED LOW TEMPERATURE TREATMENT

A year ago an astonishing observation was reported in [5]. Kind of accidentally, cavities were held at about 75°C for four hours before the standard bake procedure was performed with 48 hours at 120°C. The afterwards executed vertical performance tests showed outstandingly good results for accelerating gradients and quality factors of four different single-cell cavities.

In case such a slight and easy-applicable modification of the final treatment is able to improve the cavity performance that much, it could be a very elegant satisfaction of the demand for the next generation SRF cavities. Hence, at DESY investigations in this direction started immediately and three nine-cell cavities were heat treated following this new recipe called modified low temperature bake. Before, they underwent a cycle of bulk electropolishing (EP), annealing at 800°C and final polishing (40 µm EP).

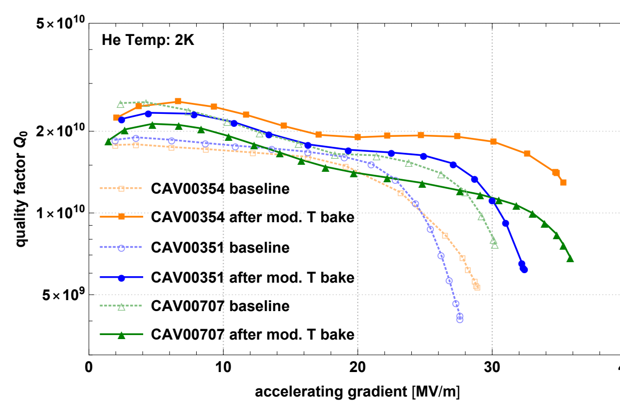

Figure 8: Q_0(E) curves for all cavities baked at DESY applying the modified low temperature procedure.

The performance of those cavities can be seen in Fig. 8 Obviously, all cavities were cured from an early Q_0-slope and reached larger maximal accelerating gradients than before. Two of them show in addition over the complete gradient range larger Q_0 values. But no extraordinary large accelerating gradients, like reported in [5], are reached.

In order to get a better chance to assess the effect of the modified low temperature bake procedure a simple comparison was performed. The two cavities, which showed

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also improvements concerning the quality factor, have been taken out of the XFEL-series production due to some problems while the surface treatments. Afterwards they were re-worked and heat treated like described above. This gives the chance to compare them to their sister cavities, which were produced in the same batch, remained in the standard European XFEL treatment cycle and with it underwent a normal 120°C bake procedure. In Fig. 9, this comparison can be found. The resulting quality factors of the modified low temperature procedure are slightly better but the reached accelerating gradients are of the same order as for the cavities treated according to the standard recipe.

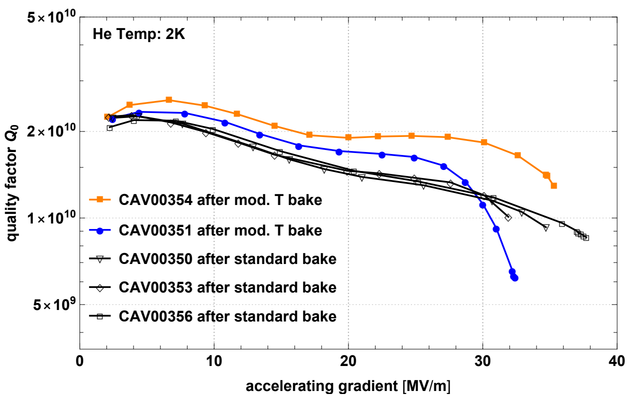

Figure 9: Q_0(E) for cavities which underwent the modified low temperature procedure, compared to their sister cavities which were treated with the standard procedure.

Since a batch of eight DESY single-cell cavities were treated with a bulk EP process recently, the chance to test this step of an additional four hours treatment at 75°C is given. Their results will give more statistics to evaluate the process further.

CONCLUSION

In summary it can be stated that although results of many cavities are collected and documented in the DESY cavity database [3] not all aspects can be answered due to limited statistics for the huge parameter space available for cavity surface treatments.

The analysis of the existing data concerning temperature and duration of the so called 120°C bake procedure shows only little room for improvement. A rise of 10°C will be performed for future procedures at DESY. In addition, the duration will be reduced from 48 to 24 hours to collect also statistics for this case. Shorter bake durations are preferably in order to speed up the preparation for a vertical cavity test. In addition, this reduction of bake duration is also cost reducing.

In case the expectations concerning the modified low temperature bake will be met, a very simple and elegant way to improve SRF cavity performances is found. Up to now, experiments at DESY could not reproduce the outstandingly good results presented in [5].

As a result of the here presented studies, the next bake procedures, which will be applied at DESY, are characterised by the following parameters: Four hours heat treatment at 75°C, followed by 24 hours at 130°C.

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