RESULTS ON QUALITY FACTORS OF 1.3 GHz NINE-CELL CAVITIES AT DESY

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Abstract

Superconducting cavities made of niobium are the basis of many particle accelerators around the world. Besides the quest for high accelerating fields for projects like European XFEL [1] and the International Linear Collider [2], the quality factor, a measure for the resistance and hence the ohmic losses, is of importance, because it eventually determines the cryoplant size and its costs of operation. Especially for current and future accelerators operating in continuous wave (CW) mode (e.g. [3]), the dynamic heat load generated by cavity operation exceeds the static heat load by far and thus requires minimisation. To investigate the current quality factor performance at various fields of 1.3 GHz cavities at DESY, the test results of some 50 recent cavities with state-of-the-art treatment have been examined regarding surface treatment and material [4].

INTRODUCTION

The minimisation of the ohmic losses in superconducting cavities during operation is of importance, because the operating temperature of $T = 2\,\mathrm{K}$ or less is demanding in terms of providing a fair amount of liquid helium as coolant. A measure for the surface resistance R_s is the (unloaded) quality factor Q_0, which is determined during vertical RF tests. The dissipated power for continuous wave operation is then calculated via

$$P_{\mathrm{diss}} = \frac{E_{\mathrm{acc}}^2 l^2}{(R/Q)\,Q_0} \qquad (1)$$

with E_{acc} as accelerating field, $l = 1.038\,\mathrm{m}$ as active length and $R/Q = 1030\,\Omega$ as geometric factor for a TESLA 9-cell cavity.

To analyse latest test results, only quality factor vs. accelerating field (Q vs. E_{acc}) cavity test data [5] from recent standard cavity production series, starting from cavity AC112 are taken into account. In addition, results of the four reference cavities of each cavity vendor providing cavities for the European XFEL have been examined. The cavities AC112-AC114 and AC151-AC158 are made of large grain (lg) niobium [6], while the rest are made of fine grain (fg) material. All cavities have been heated in a vacuum furnace and received (electro-)chemical surface treatments which are referred to as follows [7]:

- EP: electropolishing
- BCP: buffered chemical polishing
- EP+: BCP Flash (up to 20 μm BCP on an EP surface)

All measurements have been carried out at a helium bath temperature of $T = 2\,\mathrm{K}$. Data recorded with radiation exceeding $10^{-4}\,\mathrm{mGy/min}$ (resolution limitation) on the cryostat lid has not been taken into account. This results in a set of 71 cavity tests of more than 50 cavities. The quality factors of each dataset have been averaged and the uncertainties shown in the figures are given by using the standard deviation of the data. Towards higher accelerating fields, some cavities suffer from field emission or thermal breakdown, thus the averaged value is created of fewer data (for more details see [4]). Further detailed examination of current quality factor data is also given in [8].

The next section shows quality factors achieved for the different surface treatments, followed by a comparison of the quality factors for cavities made of large and fine grain niobium. In the subsequent section the residual resistivity ratio (RRR) of the niobium sheets used for cavity production is assigned to the quality factors obtained in the vertical cavity tests, followed by a summary of the results.

SURFACE TREATMENTS

A direct comparative quality factor analysis for all surface treatments applied at DESY is possible for the cavities fabricated of large grain material, since the sequence of surface treatments and corresponding tests have been chosen for that reason.

All eleven cavities had a BCP surface treatment with subsequent vertical test. To compare between BCP and EP surface, all cavities got an additional EP treatment to obtain a ’new’ EP surface, followed by another vertical test. Due to disassembly, tank welding and reassembly of flanges and antennas, four cavities received an EP+ treatment.

As shown in Fig. 1, the difference of cavity quality factors for BCP and EP surface is almost negligible. The slope in Q_0 is almost the same up to $E_{\mathrm{acc}} \leq 15\,\mathrm{MV/m}$, but a small offset of $\Delta Q_0 \leq 10^9$ applies, which is within uncertainty but may account for the different surface properties, as EP leaves a smoother surface (see [9]). In addition, it is visible that BCP treated cavities do not reach fields higher than 30 MV/m.

The EP+ data yields a higher quality factor which has to be attributed to one out of the four cavity tests. Cavity AC157 showed a much higher Q_0 than expected, which has been explained with a high coupling factor $\beta > 10$ during test yielding a lower external quality factor and an overestimation of Q_0. If this dataset is subtracted, the EP+ values are also in very good agreement with the BCP and EP data.

The range from 20-25 MV/m shows no significant change for BCP and EP cavities, the small offset in Q_0

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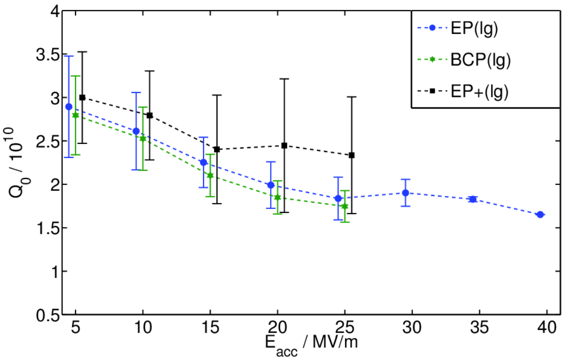

Figure 1: Averaged quality factors for different accelerating fields of eleven large grain cavities with different surface treatments. All treatments yield similar quality factors, for EP+ only four cavities were available and one cavity measurement yields a very high $Q_0 > 3 \times 10^{10}$ up to 20 MV/m.

persists, for EP+ only two cavities are included, which explains the increasing offset. Overall, if the cavities do not suffer from field emission, Q_0 is always above 1.6×10^{10}, which is a promising result for further cavities being assembled from large grain material and receiving state-of-the-art treatment.

For cavities made of fine grain material, only electropolished and EP+ cavity tests are available in a sufficient number: 19 EP surfaces and 18 EP+ surfaces. In contrast to the large grain cavities, where the cavity sample is the same for all treatments, only six fine grain cavities were tested with both surface treatments. Thus the comparison in Fig. 2 only allows statements related to the surface treatments, since only few cavities are contained in both datasets.

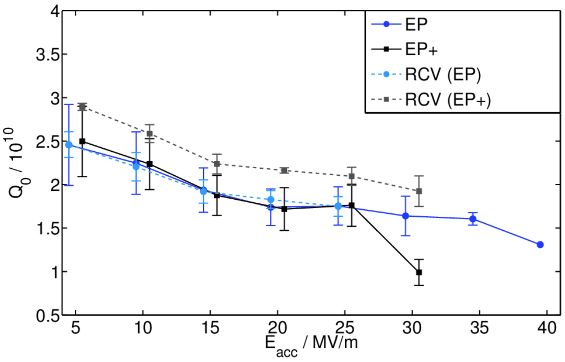

Figure 2: Averaged quality factors for different accelerating fields for fine grain cavities sorted by surface treatment. Although the data samples do not include all the same cavities, it is obvious that EP+ does not affect the quality factor negatively. The dashed lines show the reference cavities (RCV) of the industrial cavity production for the European XFEL, which meet the quality factors of the earlier cavities within uncertainties.

There is almost no difference in Q_0 for the surface treatments up to $E_{\mathrm{acc}} = 25\,\mathrm{MV/m}$, although the tests available at this accelerating field reduce to 5 or 4 cavities respectively (EP/EP+) due to field emission. The drop of the quality factor at 30 MV/m for the EP+ cavities can be accounted to the only two cavities remaining at this field: AC128 and AC129 got the full treatment, including 800°C annealing and 120°C baking. They show no field emission and yet exhibit a strong reduction in the quality factor, which lacks of an explanation.

The first pre-series cavities, so-called reference cavities (RCVs), assembled by the cavity vendors for the European XFEL series production have been treated at DESY according to the treatments planned at the vendors' facilities. At a first glance, a slightly higher quality factor for cavities for EP+ is seen, but nevertheless, statistics is limited and measurement errors itself have not been taken into account. The values obtained are within uncertainty of the previously discussed EP+ cavity sample. The EP RCVs match the curve for EP treated cavities perfectly. One of the EP+ RCVs exhibits some field emission above 15 MV/m, but the overall conclusion for the RCVs is, that the cavities exceed the specified quality factor of $Q_0(23.6\,\mathrm{MV/m}) > 10^{10}$ given in the technical design report for the European XFEL easily.

LARGE- AND FINE GRAIN MATERIAL

Large grain cavities have several advantages regarding the quality factor and heat dissipation: The surface is much smoother after surface treatment and less grain boundaries contribute to the surface resistance [10]. For easier comparison, the EP data of the previous figures for large and fine grain material is combined in Fig. 3.

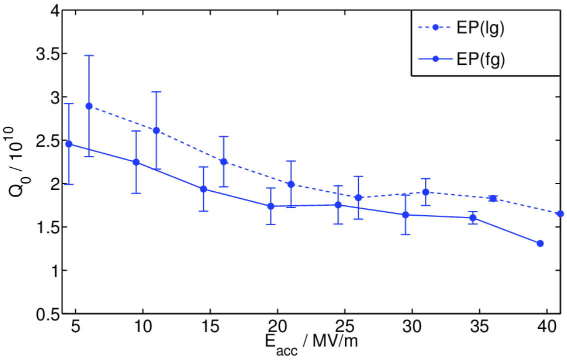

Figure 3: Quality factors of cavities made of large grain material compared to fine grain material.

It is obvious, that the cavities made of large grain material yield higher quality factors than fine grain cavities. The difference in surface resistance is about $2\,\mathrm{n}\Omega$ ($\approx 20\%$), which results in a reduction of dissipated heat of about 1/6 for the large grain cavities, due to a reduced overall length of grain boundaries. The cavities for large scale productions are still made of fine grain material since the niobium vendors cannot produce a sufficient amount of large grain material up to now, and the assembly of those cavities is difficult [11].

INFLUENCE OF RRR

A comparison of different niobium ingots is possible by using the eleven large grain cavities, as these were fabricated of three different ingots with different RRR:

- RRR(AC112-114)=505
- RRR(AC151-153)=406-438
- RRR(AC154-158)=340-355

Note that the RRR specified was measured for the single niobium sheets, so changes of RRR due to forming, welding and treatment are not taken into account. The quality factors of the cavities, separated by ingots and surface treatment are given in Fig. 4. The cavities made from lower RRR material yield higher quality factors due to lower R_{BCS}, which complies with calculations and previous measurements [12]. Although a complete change of the surface (from BCP surface to clean EP surface) took place, the sequence of the quality factors compared to the sheet RRR remains the same up to 20 MV/m, there is no major variation of RRR due to the surface treatments. Above this threshold, other loss mechanisms are dominant (e.g. [13]).

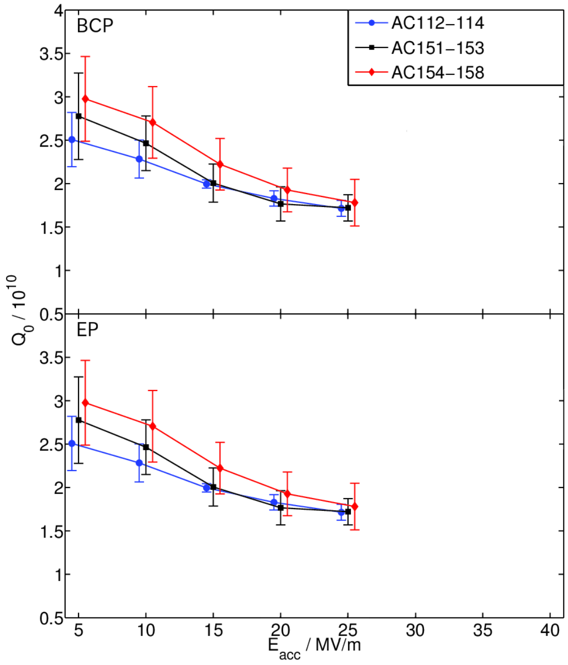

Figure 4: Comparison of quality factors for cavities made of different niobium ingots with varying RRR.

SUMMARY

Quality factors of about 70 tests of superconducting 1.3 GHz 9-cell cavities at DESY have been examined. While there is no significant difference of Q_0 for different surface treatments, large grain cavities feature 10-20% higher quality factors than those made out of fine grain niobium, which coincides with observations made at other laboratories. Cavities made of niobium with higher RRR show a slightly lower quality factor, which is also consistent with other observations.

In summary, the cavities show promising results regarding the specifications of current large scale accelerator projects, which require quality factors $Q_0 > 10^{10}$. Most of the cavities also meet the requirements ($Q_0 > 2\times10^{10}$) for CW accelerators at accelerating fields $E_{\mathrm{acc}} < 20\,\mathrm{MV/m}$.

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