

A CROSS-LAB QUALIFICATION OF MODIFIED 120°C BAKED CAVITIES

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Abstract

Within a cross-laboratory effort to understand and standardize the nitrogen-infusion and the low T bake procedure, one large grain and two fine grain single-cell cavities were treated and tested at FNAL. Subsequently they were sent to JLab and/or DESY for a cross-laboratory comparison of the RF performance and its dependence on test conditions like cooldown and the magnetic environment of the cryostat.

MOTIVATION

Nitrogen infusion [1] and the most recent low temperature (low T) bake [2] brought up the necessity to re-investigate the fundamental processes assuming to happen at the inner surface of cavities during their fabrication and treatments. The treatments are still not fully reproducible surface treatment processes in the different labs. In order to separate the influence of the different parameters of treatment and testing on the cavity performance, cavities were sent to test the same cavities under the same conditions (fully assembled, no further treatments prior to testing).

CAVITY HISTORY

Currently, three single-cell cavities were used for this study. Two fine-grain(FG) cavities and one large-grain(LG) cavity, where two were infused and one was low T baked. The details for each cavity are given below.

IDE3 Cavity IDE3 is a DESY fine-grain cavity made out of Heraeus RRR300 material. It was last tested after electropolishing and baking in 2008 and was stored on shelf at DESY since then. Before sending it to FNAL, it received a HPR and was tested at DESY (Test 1). FNAL did a first nitrogen infusion run but identified an unfortunate air-leak in the nitrogen injection valve after the treatment. Therefore a 60 μm electropolishing (EP) was performed in order to "reset" the cavity performance. During the standard 120° C bake, a faulty thermal-sensor caused a halt at 75° C for 4 hours before achieving the 120° C for 48 h [2]. This process is now called low T bake. The decision was to move on with nitrogen infusion at 120° C and then test it at FNAL (Test 2). Afterward, the cavity was sent vented and with transport flanges to DESY. After arrival, it received a HPR and was then tested several times (Tests 3 and 4).

IDE20 The DESY cavity IDE20 was sent to FNAL in 2011 for tumbling and coating studies [3]. It is a large-grain cavity made out of Heraeus RRR505 material. The cavity surface was electropolished with a total removal of 60 μm and a subsequent low T bake was applied. Again, the next step was to infuse the cavity at 120° C and test it at FNAL (Test 1). Afterward, the cavity was sent vented and with transport flanges to DESY, received a HPR after arrival and was tested several times (Tests 2-4).

AES022 This FNAL cavity made from Tokyo Denkai material was used to study the low T bake procedure. It was one of the cavities at which FNAL observed a 'bifurcation' of the measured Q_0 vs. E_{acc} curve. Depending on the temperature of the cryostat prior to the cooldown, either a lower or upper quality factor curve was observed. Once the upper branch was measured, meaning the cavity was cooled down after a higher starting temperature of the cryostat, the lower branch couldn't be reproduced (Test 1) [4,5]. To check this observation, the cavity was sent to JLab and tested (Test 2). The two branches were observed testing the cavity in two different cryostats and an alternative explanation of the origin of the bifurcation was discussed [6]. The cavity was then sent back to FNAL, retested (Test 3) and then finally sent to DESY (Test 4). At DESY, several cooldown scenarios were tested (starting temperature, cooldown gradient and spatial temperature gradient). After the tests, the cavity is now sent to KEK for further measurement. During all these tests across the labs the cavity was always fully assembled and was never vented to prevent any falsification from possible pollutions or assembly or treatments.

RESULTS

IDE3

In test 1 at DESY before sending the cavity, the quench field was 39 MV/m - all tests depicted in Fig. 1.

The cavity was tested at FNAL after the infusion and achieved 46 MV/m, and was quench limited as well (test 2). After arrival at DESY, in test 3, the cavity showed a strong FE event during first power rise above 10 MV/m which can be explained from the fact that the cavity underwent another assembly at DESY. The quality factor at gradients below the FE event were comparable to FNAL. After processing in test 3, the quality factor was significantly lower and the cavity

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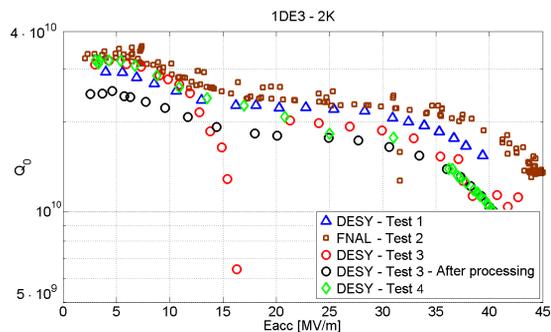


Figure 1: Q_0 vs. E_{acc} at 2 K of 1DE3 for different steps. At low fields below ≈ 15 MV/m, the cavity performance is identical (within errors) between the labs. After infusion an increased Q_0 at gradients above 30 MV/m is observed. After the HPR subsequent to the FE event the Q_0 -value at fields is significantly lower.

quenched at 41 MV/m. The cavity underwent an additional HPR and was retested (test 4) with no FE observable. The values of the quality factor below 10 MV/m were still comparable to the FNAL test results but decreased significantly above compared to FNAL and the quench field remained at 41 MV/m. In test 4, two different cooldowns were applied and the cavity measured. The temperature data taken with CERNOX sensors attached to the cavity equator is shown in Fig. 2 and values of key parameters are given in Table 1.

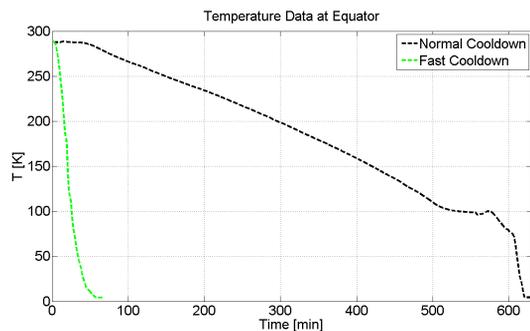


Figure 2: Temperature profile measured at the equator of 1DE3 for the normal and fast cooldown. Details given in Table 1.

The normal cooldown procedure is PLC controlled and shows highly reproducible values for the key parameters of the cooldown. The fast cooldown is operated manually and can be steered individually if needed.

Figure 3 shows the 1.8 K measurements of 1DE3 for different tests and cooldowns. The Q_0 vs. E_{acc} curves obtained after normal cooldown of test 1 and 4 are identical within errors. The fast cooldown applied after the normal cooldown of test 4 showed a significant increase in the quality factor. The relative increase is depicted in Fig. 4.

1DE20

The cavity was sent 2011 to FNAL which used this large grain cavity for different research projects. After resetting

Table 1: Cooldown Parameters For The Normal And Fast Cooldown Of 1DE3

Cooldown	Normal	Fast
T_{start}	288 K	288 K
$dT/dt@T_c$	6.4 K/min	1.8 K/min
dT/dt_{100K}^{288K}	0.5 K/min	13.4 K/min
$dT/dx_{Bottom@T_c}^{Eq}$	8.7 K	7.5 K

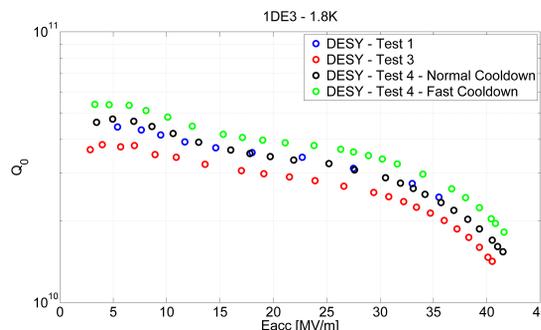


Figure 3: Q_0 vs. E_{acc} at 1.8 K of 1DE3. The performance before infusion (Test 1 - blue) and after additional HPR after the FE event (Test 4 - black) are identical. Field emissions in the test after the infusion (Test 3 - red) are the cause for the lower Q_0 . The subsequent fast cooldown (Test 4 - green) shows a significantly higher quality factor to the normal cooldown (Test 4 - black) of the retest - see Fig. 4.

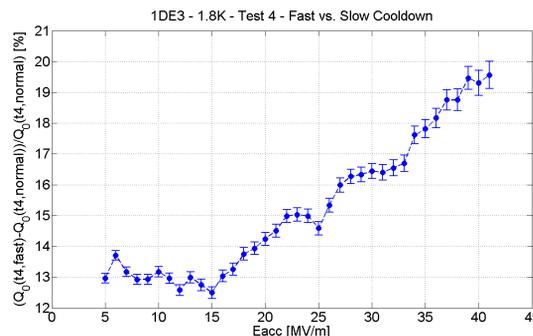


Figure 4: Relative increase of ΔQ_0 vs. E_{acc} at 1.8K comparing fast and normal cooldown of Test 4. A significant difference of more than 10% is seen.

the surface, the cavity was tested (not shown here) and then infused at 120° C. Test 1 at FNAL was after the infusion process and showed a high quality factor and a quench field of 38 MV/m, see Fig. 5. The cavity was sent to DESY vented with transportation caps and the first test showed a significant lower quality factor and quench field of 33 MV/m (test 2). For this test, RRR coils were attached to the cavity. The cavity was then installed immediately into another insert without any surface treatment or assembly and tested in the same cryostat (test 3) after a normal cooldown and a fast cooldown.

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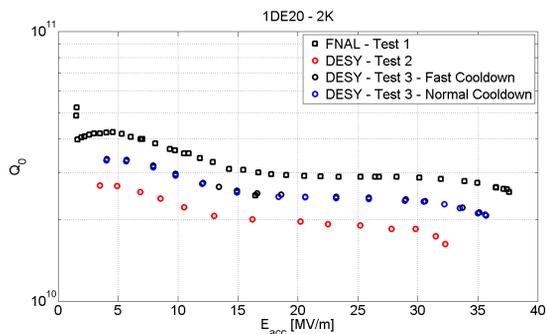


Figure 5: Q_0 vs. E_{acc} at 2 K for 1DE20. After infusion (red) test was with RRR coils equipped. Difference between retest (black/blue) and after infusion (red) and FNAL (black squares) not understood.

No influence of the cooldown process was observed but a drastic increase of the quality factor between test 2 and 3 at DESY, see Table 2.

Table 2: Comparison Of RF Results Between Test 2 And Test 3 At DESY

Test	$Q_{0,max}(2\text{ K})$	$Q_{0,max}(1.8\text{ K})$	$R_{res}[n\Omega]$
2	$2.7 \cdot 10^{10}$ (10 nΩ)	$4.5 \cdot 10^{10}$ (6 nΩ)	3 nΩ
3	$3.4 \cdot 10^{10}$ (8 nΩ)	$5.9 \cdot 10^{10}$ (4.6 nΩ)	2.1 nΩ
Δ	+26%	+31%	-0.9 nΩ

The R_{res} was obtained by measuring the $Q_0(T)$ curves. An important point is, that decrease of the residual resistance R_{res} is not sufficient to explain all of the increase of the quality factor between the tests. The difference of the residual resistance R_{res} could be traced back to the attached RRR coils, which were operated during cooldown. The current in the coils while crossing T_c created trapped flux contributing to R_{res} . This has been confirmed by analyzing the R_{res} data of cavities measured with and without RRR coils attached to them, where on average a 1 nΩ difference was observed.

To further study the possibility of other flux trapping contributions, the cavity was retested with an active shielding. The magnetic field sensors showed a reduction of a factor 2-5 when the shielding was attached to the cavity and the results are shown in Fig. 6.

To deconvolve the surface resistance into its contributions R_{res} and R_{BCS} , the cavity was tested at 1.6 K. Although there is still a contribution to the surface resistance from R_{BCS} at 1.6 K, the low field value for the R_{res} is in agreement with the value obtained from the $Q_0(T)$ measurement. In Figures 7 and 8, the results for 1DE20 are overlayed with measurements from FNAL on other nitrogen infused cavities. While the R_{BCS} shows the same dependence on the field/gradient, the comparison of R_{res} is of limited significance as the measurements are taken at different temperatures.

Until now, no influence from the cryostat, insert or cooldown has been found which further explains the difference in the observed quality factors at FNAL and DESY

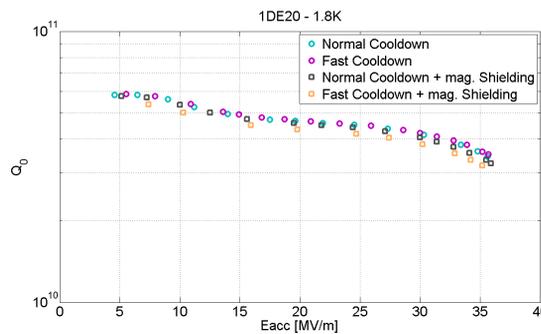


Figure 6: Q_0 vs. E_{acc} tests at 1.8 K of 1DE20 for various combinations on cooldown and magnetic shielding installed and are all performed at DESY. No influence from the cooldown procedure or the shielding was observed.

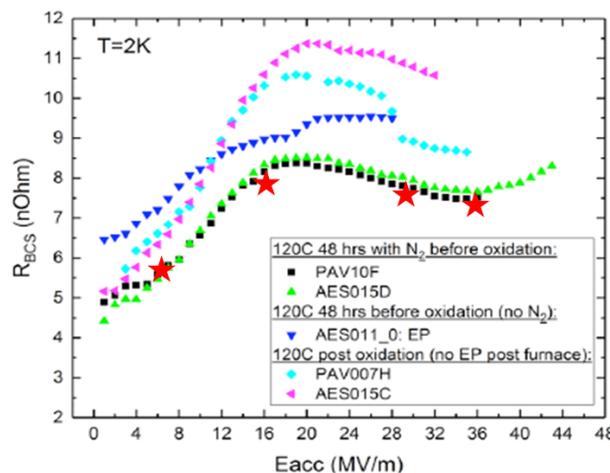


Figure 7: Deconvolution of the surface resistance R_S into R_{BCS} of typical nitrogen infused cavities at FNAL. Plot taken from [1]. The DESY measurement (red stars) was taken at 1.6 K. R_{BCS} 'behaves' infused.

besides the contribution from the RRR coils. The difference arises from the R_{res} of the cavity, as shown in the deconvolution.

AES022

The cavity underwent extensive studies regarding the low T bake procedure at FNAL (test 1) [2], [4] and was sent to JLab for the confirmation of the measurements (test 2) [6]. It was then tested again at FNAL (test 3) and sent to DESY for the cross-lab qualification (test 4). The cavity was tested "as received" with no further vacuum connection done. It was installed in the insert where it was only mechanically fixed at the top of the cavity during the first cooldown series. Both Q -values Q_t , Q_{ext} for the antennas of the cavity jumped between two values for subsequent power rises and a frequency change accumulated for every cooldown applied. These issues were solved by fixing the cavity at the bottom flange at the insert in addition for the following tests. The DESY tests shown here are after the additional fixation of

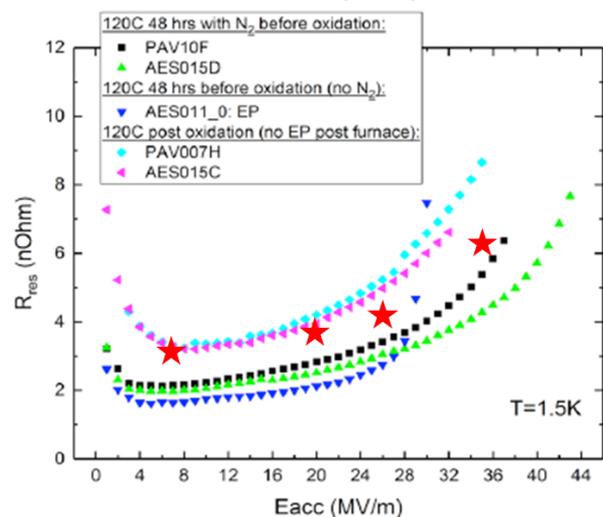


Figure 8: Deconvolution of the surface resistance R_S into R_{res} of typical nitrogen infused cavities at Fermilab. Plot taken from [1]. The DESY measurement (red stars) was taken at 1.6 K.

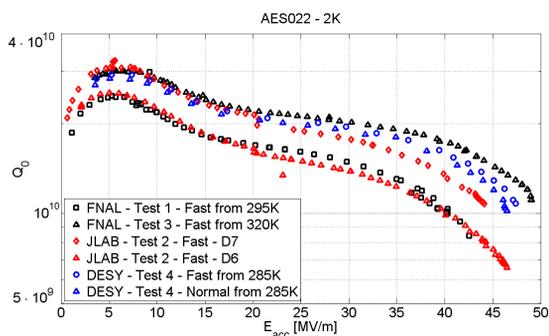


Figure 9: Q_0 vs. E_{acc} at 2 K for AES022.

the cavity. In Fig. 9 the cross-lab comparison for the 2 K measurements is shown.

Two groups of curves are seen ('bifurcation'). While FNAL cooled down with different starting temperature, JLAB used two different test cryostats (D6 / D7). In both cases the $Q_0(E)$ shifted to the upper or lower branch. DESY applied the standard and the fast cooldown and several different starting temperatures of the cryostat prior to the cooldown but all results are identical within errors. The upper branch of the $Q_0(E)$ curves includes results from all three labs, the lower couldn't be reproduced at DESY. This is in agreement with the statement from FNAL, which observes a dependency on the cryostat temperature before the cooldown but once the upper branch is measured, the lower cannot be reproduced. On the other hand, this contradicts the results obtained from JLab which saw both branches and gives a different hypothesis for explanation based on additional losses caused by different magnetic environments in two different cryostats. DESY only measures the upper branch and does not observe any dependency on cooldown parameters and no different cryostat or magnetic environment was used.

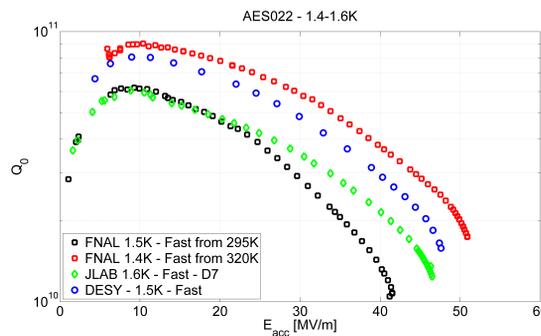


Figure 10: Q_0 vs. E_{acc} curves at different low temperatures across the labs.

JLab and DESY observed Multipacting during AES022 tests. JLab pumped the cavity during testing, possibly allowing a small amount of water to reenter the cavity through cryo-pumping. DESY observed Multipacting only for some cooldowns (two out of four) and - unusually - only in the second power rise if the cavity quenched in the first power rise. A possible explanation for this behavior is trapped water which freeze out at different regions during different cooldowns, depending on the spatial temperature gradient while cooling down. During Multipacting, the magnetic field sensors observed a reduction of 6-8 mG when the cavity quenched and subsequently, the quality factor reduced from $2.8 \cdot 10^{10}$ to $2.6 \cdot 10^{10}$. Assuming that all of the flux was trapped and increased the surface resistance, a sensitivity S of $\approx 0.1 \text{ n}\Omega/\text{mG}$ can be derived.

A comparison of various lower temperature measurements is shown in Fig. 10.

The FNAL curves show different quality factors for the two different starting temperatures which is expected for the different temperature of the measurement (1.4 K vs. 1.5 K). The DESY 1.5 K measurement is above the FNAL 1.5 K measurement, which is not understood yet. The JLab 1.6 K curve is quite well in agreement with the lower part of the FNAL 1.5 K curve but lies between the FNAL 1.5 K and the DESY 1.5 K curve at higher fields.

CONCLUSIONS

The main conclusion is that the rf measurements across the labs are in agreement with each other and observed differences originate from individual effects as shown here. The Q_0 vs. E_{acc} curve for 1DE3 at low fields is in agreement but a strong FE even in test 3 prevented further comparison. The R_{BCS} part of the 1DE20 measurement is in agreement with the expected curves from other FNAL measurements but unidentified contribution to R_{res} exist. This study further identified the operation of the RRR coils while cooling down as a source for an additional R_{res} contribution. The measurement of AES022 showed a strong agreement between FNAL, JLab and DESY since all measurements in the upper branch agree with each other, taking the Multipacting into account. The lower branch couldn't be reproduced at DESY and the origin of branching is not unambiguously identified.

An influence of cooldown parameters on the performance was not observed at DESY.

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