IN-DEPTH ANALYSIS OF THE VERTICAL TEST RESULTS OF THE THIRD-HARMONIC CAVITIES FOR THE E-XFEL INJECTOR

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Abstract

The results of the vertical tests performed at LASA on the 3.9 GHz third-harmonic cavities for the E-XFEL injector are here discussed. Analysis of experimental data allows to confirm that such high frequency cavity, prepared with standard BCP treatment and 800°C annealing treatment, suffers an intrinsic performance limitation at around 22 MV/m (@ 2 K) due to a global thermal dissipation mechanism. A quantitative interpretation of the high field Q slope is also presented according to the latest theoretical models of field-dependent surface resistance.

INTRODUCTION

In the frame of the joint INFN and DESY in-kind contribution to the European XFEL (EXFEL), 20 third-harmonic 3.9 GHz superconducting cavities has been fabricated and tested by LASA. These cavities have been employed for the construction of two third-harmonic modules – one currently operating in the injector section of the XFEL, the other one providing a spare component to the facility – allowing to compensate nonlinear distortion of the longitudinal phase space produced by the first acceleration stage.

Beyond the series production, 3 prototype cavities - employed for production and processing optimization - and one large grain cavity - intended for a non-in kind R&D activity on ingot niobium - complete the picture of INFN activity on third harmonic resonators, with a total amount of 24 cavities, produced and treated by the qualified industrial vendor (Ettore Zanon SpA) and vertically tested at the LASA experimental facility.

The production stage concluded with a full achievement of project specifications (E_{acc}=15 MV/m and $Q_0=10^9$) [1], the remarkable amount of experimental data so far collected is here analysed from a scientific point of view in order to put into light the peculiar features of high frequency RF superconductivity. The high number of measured cavities with same treatment history offers for the first time the benefit of a great statistical significance, eventually consolidating the results and the conclusions obtained thanks to the previous experience of DESY and FNAL in the development of FLASH third harmonic system [2].

VERTICAL TESTS AT LASA

Being the fabrication and vertical test experience for the EXFEL 3.9 GHz cavity series production already discussed in detail in [1], we report in table 1 only the main treatment steps which are expected to have an influence on the cavity performances and on Nb material characteristics. The material employed is Tokio Denkai with RRR=300.

Table 1: Treatment Steps for 3.9GHz Series Production

Step	Description
1	Bulk BCP (1:1:2) approx. 120 µm removal
2	External surface BCP (1:1:2) for 20 µm removal
3	Heat treatment at 800°C for 2h
4	Final BCP (1:1:2) approx. 35 µm removal
5	12h high pressure Rinse

Surface Resistance vs. T

The cavity surface resistance is measured during the cooldown process, starting from about 4.2K up to 1.8K or below. Figure 1 shows the Rs vs T curve together with the result of fit for 3 different cavities. The data are here fitted with SUPERFIT 2.0 [3], which employs the Halbritter quasi-exponential formula for fitting the temperature dependent surface resistance. Together with band gap Δ and residual resistance R_0, the electron mean free path l_e is here also considered as a free parameter, given its great importance in determining the RF performances of Nb surface. $T_c = 9.25$ K, $\lambda_l = 32$ nm, $\xi_0 = 39$ nm are assumed as fixed values for critical temperature, London penetration depth and coherence length, respectively [4].

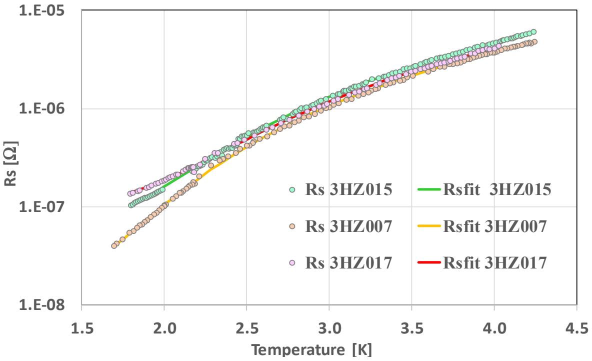

Figure 1: Experimental and fitted Rs vs T curves for cavities 3HZ007, 3HZ015 and 3HZ017.

The result of fit for the series production cavities and the large grain cavity 3HZ0LG are pointed out in table 2. As already discussed in [1], there is a great scatter in the values of residual resistance. Moreover, the values of mean free path ranges from 34 nm (nearly the “dirty” limit) up to 290 nm (towards “clean” limit). Cavity 3HZ022 is omitted due to some anomalies in data acquisition.

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Table 2: Results of Fit on Surface Resistance

cavity	Δ/kT_c	l_e (nm)	R_0 (nΩ)
3HZ004	1.76	49	48.5
3HZ005	1.79	103	34.9
3HZ006	1.82	96	44.8
3HZ007	1.81	164	14.4
3HZ008	1.85	118	51.8
3HZ009	1.83	236	63.1
3HZ010	1.81	182	85.3
3HZ011	1.77	34	25.9
3HZ012	1.90	102	54.7
3HZ013	1.83	102	12.4
3HZ014	1.82	95	24.0
3HZ015	1.83	289	64.4
3HZ016	1.78	77	14.0
3HZ017	1.85	184	108
3HZ018	1.79	84	27.9
3HZ019	1.80	108	24.9
3HZ020	1.80	87	20.6
3HZ021	1.79	63	18.4
3HZ023	1.81	84	33.1
3HZ0LG	1.78	63	66.8

Cavity Vertical Tests

Figure 2 offers in a glance the whole results for the series production cavities tested at 2K.

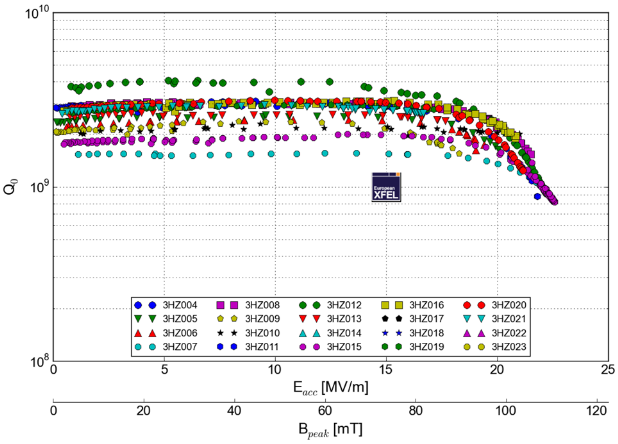

Figure 2: Summary plot of all power rises at 2K for the series production 3.9 GHz XFEL cavities. The qualification value is also shown.

At first sight, there is a big scatter in the Q_0 at low field, due to the related differences in residual resistance. The maximum accelerating field ranges from 15 MV/m for cavity 3HZ014 to 22.3 for cavity 3HZ015. Most of the cavities (12 out of 20) are quenching in the 20-22 MV/m interval, with a noticeable reduction of Q_0, starting at about 17 MV/m, and then reaching even less than the half of its low-field value at the quench field. Figure 3 shows the $R_{BCS}/R_{BCS,0}$ ratio as function of accelerating field, where $R_{BCS,0}$ is low field temperature-dependent surface resistance, calculated as $R_{BCS} = G/Q_0 - R_0$, with $G = 280\ \Omega$, assuming a field-independent residual resistance. The trend is similar for most of the cavities, while 3HZ004, 3HZ009 and 3HZ014, which all quench below 20 MV/m, show a more rapid increase of surface resistance.

As already noticed by other labs [5], in the 5-15 MV/m zone a slight but evident reduction of surface resistance occurs. The minimum is at 12 MV/m, with a 15% reduction of R_{BCS}, except for cavity 3HZ009 where the minimum occurs at lower fields with a remarkable reduction of 22%.

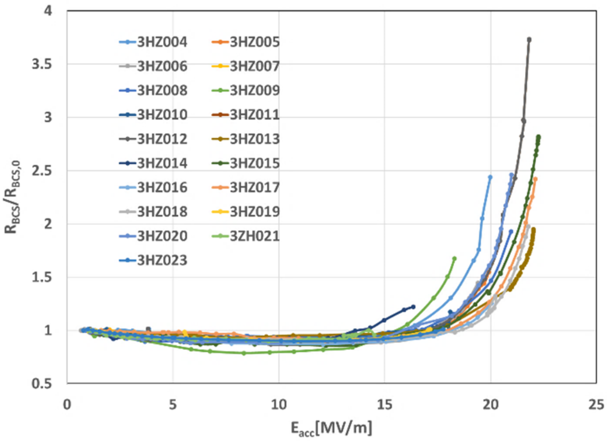

Figure 3: $R_s/R_{s,0}$ as function of accelerating field for series production 3.9 GHz XFEL cavities at 2K.

For each cavity test, second sound signals have been acquired at the quench field, but only in few cases the reconstruction algorithm [6] has been able to give a sharp indication of a single hot spot, namely only for cavities quenching below 20 MV/m. For the other ones, although second sound signals are unequivocally detected, no clear indication of a quench spot can be obtained. This, together with the narrow range of breakdown fields and the significant high field Q-slope, lead to invoke an innate global mechanism of thermal dissipation as the ultimate cause of cavity thermal breakdown.

DISCUSSION

Starting with the previous considerations, a more in-depth analysis of which kind of mechanism could trigger a global thermal runaway is here presented. 3.9 GHz cavities produce a great dissipation due to high surface resistance so as first attempt the simple thermal feedback model is exploited. Surface resistance is calculated as function of field by solving the heat balance equation:

$$\frac{1}{2}R_s(H,T)H^2 = \frac{(T-T_0)}{R_B} \qquad (1)$$

where the thermal resistance is defined as $R_B = \frac{d}{k} + \frac{1}{h}$. d is wall thickness, k is thermal conductivity, h the Nb-He heat transfer coefficient. The field dependence of surface resistance for the time being is neglected. B_{peak}/E_{acc} is 4.9 mT/(MV/m), Wall thickness is d=2.3 mm and conductivity is assumed $k = 50 W/mK$. Cavity 3HZ007, which quenches below 20 MV/m (point-like quench), has been tested at 2.2K and 2K, namely in 2 different thermal regimes for Nb-He heat transfer [7]. At 2.2K, heat exchange between Nb and He I (normal fluid) is limited to values around $100-1000\ W/m^2K$ while below the lambda point (superfluid) typical values in the range of $5\cdot10^3-10^4 W/m^2K$ can be assumed for Kapitza boundary conductance. Figure 4 shows the experimental data together with the fitting results obtained by applying eq.1 with the 2 above mentioned different thermal regimes. In the 2.2K case, the fit result matches very well the experimental data assuming $h = 250\ W/m^2K$ (normal convection regime) while for 2K the closest match, obtained with $h_K = 10^4\ W/m^2K$, is shown.

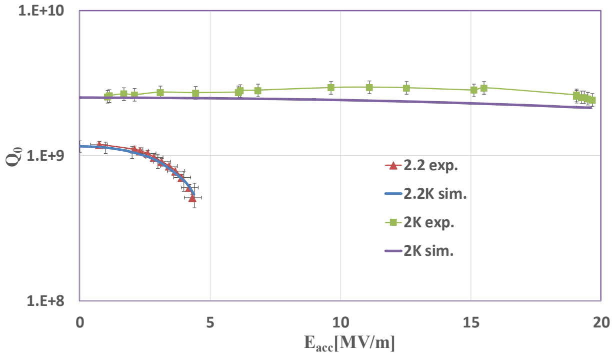

Figure 4: Experimental and simulated Q vs E_{acc} curves for cavity 3HZ007 at 2K.

It is evident that in the medium field zone (5-15MV/m) the thermal feedback model underestimates the Q-value because of the slight anti-slope starting at low field. It is nevertheless worth to notice that, assuming a resistive defect as cause of thermal breakdown, one should expect the breakdown field scaling as [8]:

$$H_{bd} \div \sqrt{\frac{(T_C-T)}{R_B}} \qquad (2)$$

So that, employing the previously mentioned references for h and k at 2K and 2.2K, one obtains that $H_{bd}(2K)/H_{bd}(2.2K)\sim5$, which is very close to the ratio of measured maximum accelerating fields.

Given that the simple thermal feedback alone does not allow to reconstruct both the medium-field anti-Q slope and the high field Q behaviour, we resort to the field dependent BCS resistance model developed by A. Gurevich [9]. Such a formalism applies mainly to dirty superconductors which is not truly our case, but we can assume to be nearer to dirty limit ($l_e < \xi_0$) than to clean limit ($l_e \gg \xi_0$) since, as reported in table 2, $l_e \sim \xi_0$ for most of the cavities.

This model assumes a non-equilibrium density of states for quasi-particles generated by interaction of RF field with Cooper pairs. As a consequence of non-equilibrium, the field induced broadening of density of states reduces the temperature dependent surface resistance at medium fields, then producing the characteristic anti-Q slope behaviour. From the other side, the quasiparticles are no more in thermodynamic equilibrium with the Nb lattice so producing a significant overheating of RF surface. The magnitude of such a temperature mismatch between Nb-RF surface and bulk depends upon the kinetic balance between RF period ($2.5\cdot10^{-10}s$ for 3.9 GHz frequency), quasiparticle recombination time and quasiparticle-phonon scattering time, which are respectively $1.7\cdot10^{-8}s$ and $0.4\cdot10^{-6}s$. In case of 3.9 GHz cavities, both values are much higher than the RF period so the mechanism of non-equilibrium is expected to be favoured. According to these considerations, the thermal feedback in eq. 1 is extended considering a field-dependent surface resistance, (whose complete theoretical treatment can be found in [9]) and adding an additional quasiparticle-phonon heat transfer coefficient (Y) to the overall thermal resistance:

$$\alpha = \frac{1}{Y} + \frac{1}{h_K} + \frac{d}{k} \qquad (3)$$

Since no simple analytical expression is available for Y, the overheating parameter α is treated as a free parameter.

Figure 5 shows the results of field-dependent resistance fit for cavity 3HZ015 at 2K, compared with the results obtained with simple thermal feedback model.

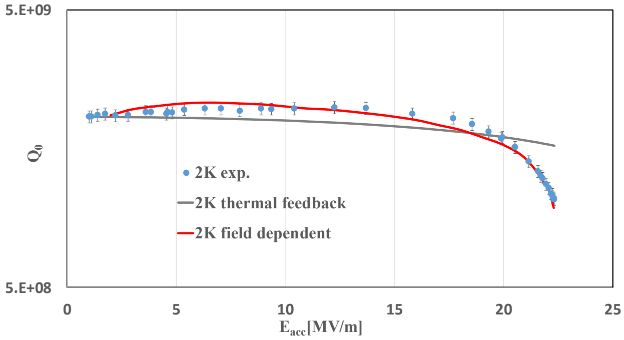

Figure 5: Experimental and simulated Q vs E_{acc} curves for cavity 3HZ015 at 2K.

The best fit is obtained with $\alpha = 0.55\cdot10^{-3}\ W/m^2K$. Assuming the previously mentioned references for h_K and k, this corresponds to $1/Y\sim0.4\cdot10^{-3} W/m^2K$, that is about the 70% of total overheating.

CONCLUSIONS

A preliminary analysis of the experimental results of the 3.9 GHz third-harmonic cavities for the E-XFEL injector has been presented. These observations allow us to conclude that, apart for few cavities quenching below 20 MV/m due to local defect heating, a global thermal dissipation mechanism arising at high field is likely to be responsible for cavity limitation at around 22 MV/m. Such mechanism, triggered by quasiparticle overheating, is the other side of the coin of the slight anti Q slope occurring in the medium field zone. According to this frame, the breakdown field is defined as the lowest value for which eq. 1 does not admit any solution. Thus, no heat balance is possible and the system undergoes a thermal instability leading the cavity to breakdown.

In a future work, this point will be examined in depth even from a theoretical point of view, and a more systematic description of experimental results and performance analyses will be presented, so to give more consistency to the considerations herein introduced.

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