

QUENCH DETECTION DIAGNOSTICS ON 3.9 GH XFEL CAVITIES

M. Bertucci*, A. Bosotti, L. Garolfi, P. Michelato, L. Monaco, D. Sertore
INFN Milano - LASA, Segrate (MI), Italy
C. Pagani

Università degli Studi di Milano & INFN, Segrate, Italy

Abstract

This paper presents results of quench localization on 3.9 GHz XFEL prototype cavities tested at LASA vertical test facility. Cavities have been equipped with OST second sound detectors and thermometry sensors. A first guess for quench position has been obtained from modal analysis. Second sound sensors confirmed the quench position resolving also the symmetry degeneracy given by the RF mode pattern analysis. In a subsequent vertical test, second sound and temperature sensors have been installed nearby the suspect quench position. From thermometry mapping, a sudden increase in cavity temperature within a small region is evident, therefore confirming that a local thermal breakdown due to defect heating occurs in the predicted quench point. The quench region deduced with the mentioned techniques is then compared with results of optical inspection.

INTRODUCTION

Several techniques can be employed for quench events detection on superconducting cavities operating below lambda point temperature (2.17 K). One of the most promising methods, introduced at Cornell [1], is based upon second sound waves detection by Oscillating Superleak Transducers (OST), nowadays widely employed in many labs. When dealing with small size superconducting cavities as for the XFEL 3.9 GHz injector section, where the equator-iris distance is only 19.22 mm, the state-of-the-art of second sound method accuracy may not be enough for effective quench localization.

Several error sources can affect a proper quench localization, for instance the uncertainty on sensor positions due to inaccurate placing, extended active sensor surface, or a wrong estimation of time of flight due to the difficult identification of second sound pulse wave front arrival. Furthermore, the dynamics of quench on cavity surface may lead to a transition of the surrounding area into normal conducting region therefore generating an apparently larger quench area on cavity surface [2]. Finally, other phenomena can alter the thermodynamic properties of superfluid helium, locally causing a non-uniform propagation of second sound signals [3].

A full explanation of these effects is still lacking, even if experimental tests on second sound velocity seems to exclude the so-called “too fast” second sound phenomenon as the prime suspect for wrong quench localization [4].

As a consequence, accuracy on second sound

diagnostics is still far from the sought-after value of some mm. Further investigations are needed for a better understanding of physical processes involved during second sound waves production and propagation so to achieve a new degree of method precision.

In the same time, this technique can be combined with other methods in order to cross check the consistency of the results. Such an approach has been already exploited on 1.3 GHz cavities at DESY [5], where Second Sound technique is employed together with temperature mapping, mode analysis and optical inspection.

This paper shows the results obtained with a similar approach on 3.9 GHz XFEL prototype cavities tested at INFN Milano - LASA vertical test facility.

TEST ON A XFEL 3.9 GHZ PROTOTYPE CAVITY

We performed an investigation on the 3HZ02 3.9 GHz cavity, one of the three prototypes expressly manufactured for validation and test purposes in view of the upcoming XFEL 3rd harmonic cavities series production.

This cavity shows a modest Q_0 already at low-field, indicating a poor surface condition, in spite of several BCP treatments [6]. As it is clear from Fig. 1, a sharp Q drop occurs between 12-16 MV/m without any substantial degradation from its initial value until the maximum accelerating field is reached. We have observed no X-ray or electron activity near or at the accelerating field corresponding to the quench.

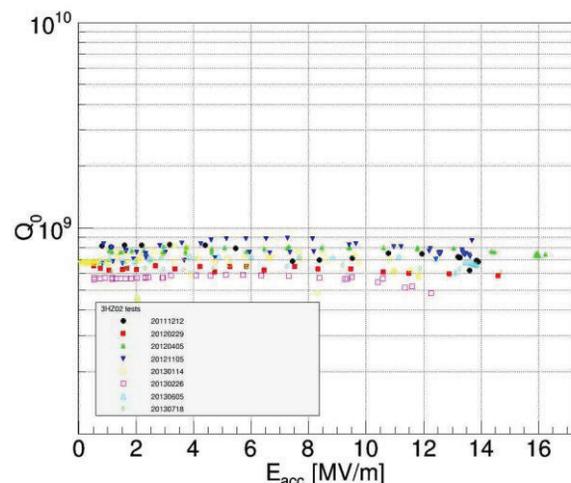


Figure 1: Cavity 3HZ02 Q_0 vs. E_{acc} for several RF tests. A flat low Q_0 and its sharp drop indicate a possible poor surface condition or material inclusion.

This sharp drop of the quality factor can be explained with a cavity thermal instability causing a local or diffuse breakdown of superconductivity.

Our final goal is to identify the occurrence of a local quench event and locate its position on the cavity surface.

Modal Analysis

As a first test, we measured the maximum accelerating field achieved on 9 cavity cells during the power rise in all the 9 fundamental pass band modes. The maximum field value in π mode (in “flat” condition, i.e. with equal fields in each cell) corresponds to the quench field causing thermal breakdown.

Experimental values for maximum fields in each excited mode are shown in Table 1. We recall that cavity eigenvectors are symmetrical with respect to the cavity center so that mode analysis cannot distinguish between any symmetrical couple of cells.

Table 1: Maximum fields in the 9 fundamental pass-band modes. Index 9 corresponds to π mode (“flat” condition). Accelerating fields, also in other mode, compatible with the π mode critical value are underlined in blue.

# Cell	Fundamental cavity pass-band eigenmode index								
	1	2	3	4	5	6	7	8	9
1/9	3.0	5.9	7.2	10.8	16.5	19.2	17.5	16.6	15.3
2/8	8.7	<u>15.0</u>	<u>14.3</u>	<u>14.5</u>	10.8	0.0	9.3	<u>14.6</u>	<u>15.3</u>
3/7	13.4	17.0	7.2	5.7	20.2	19.2	3.2	10.9	15.3
4/6	16.4	11.1	7.2	16.5	3.7	19.2	14.3	5.8	15.3
5	17.4	0.0	14.3	0.0	21.5	0.0	18.6	0.0	15.3
E_{max}	17.4	17.0	14.3	16.5	21.5	19.2	18.6	16.6	15.3

Comparing the field values for the 9 modes, we see that only a quench occurring in 2nd or 8th cell is consistent with the whole modal analysis results. Taking into account the uncertainty in field calculation of about 1 MV/m due to our experimental accuracy, this implies that the same cells may be the cause of thermal breakdown even in the $2\pi/9$, $3\pi/9$, $4\pi/9$ and $8\pi/9$ modes, while for the other modes the quench event occurs in another cells where the maximum field is higher.

Starting from the mode indication, we can focus our attention on this couple of cells as suspect quench sites.

Second Sound

While the modal analysis can yield only an indication about which cells can be a quench site and does not resolve the cell degeneracy, Second Sound Technique can locate it within a 1-2 cm radius zone. For this purpose, it is important a proper choice of OST sensors arrangement around the cavity.

Quench positions have been calculated from experimental OST data employing two different algorithms of trilateration error minimization. The former, developed by LASA, is based on the conjugate subgradient method (CS) and allows a quench-OST line-

of-sight check, excluding from trilateration OST sensors not directly viewed from quench point. The second one, developed by Cornell, uses the Vertex-Pair Calculation Method (VPS) [7], forcing the trilateration algorithm to place the quench on cavity surface.

First of all, we resorted to a configuration with sensors spread all around the cavity, so to crack modal analysis symmetric degeneracy and identify one single cell as quench site. The calculated quench locations are graphically shown in Fig. 2.

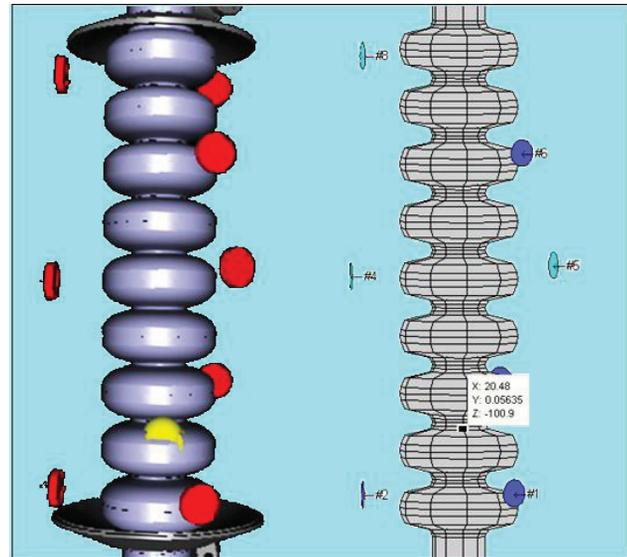


Figure 2: Quench position calculated with CS (left) and VPC (right) algorithms in the “strewn sensors” configuration. The yellow sphere on the left picture represents the uncertainty in quench position calculation.

Clearly, a single cell – consistently with modal analysis predictions – is successfully identified as a quench origin. The two algorithms yield similar results for quench location within few millimeters. Position and accuracies are shown in Table 2 as configuration “1”.

Table 2: Calculated quench positions in both configurations and resorting to both algorithms. All units are in mm. Δ is the distance between the positions calculated with CG and VPC.

	configuration	1	2
Position CG (mm)	x	-19.5	-33.5
	y	-6.7	-19.6
	z	-104.7	-102.8
	quench radius	13.1	3.3
position VPC (mm)	x	-20.5	-32.3
	y	0.1	-23.5
	z	-100.9	-110
Δ (CG-VPC)		7.9	8.3

Once we identified the cell, we arranged a new configuration, with sensors concentrated nearby the supposed quench position, so to be sure that every sensor sees the quench, therefore increasing experimental accuracy. Once again we use the two algorithms to

minimize the error in the trilateration calculation and the results are shown in Fig. 3. We see clearly a more effective determination of quench position when employing CG algorithm. The minimization error, represented by the yellow sphere in the CG algorithm, is clearly reduced. The new calculated locations are reported in Table 2 as configuration “2”.

Second Sound accuracy is better when dealing with configuration 2 due to a larger number of OSTs used for triangulation. A discrepancy still persists between the results obtained with the 2 different algorithms. At any rate, we can refer to this configuration as the more effective for assessing the quench position once its location is roughly determined.

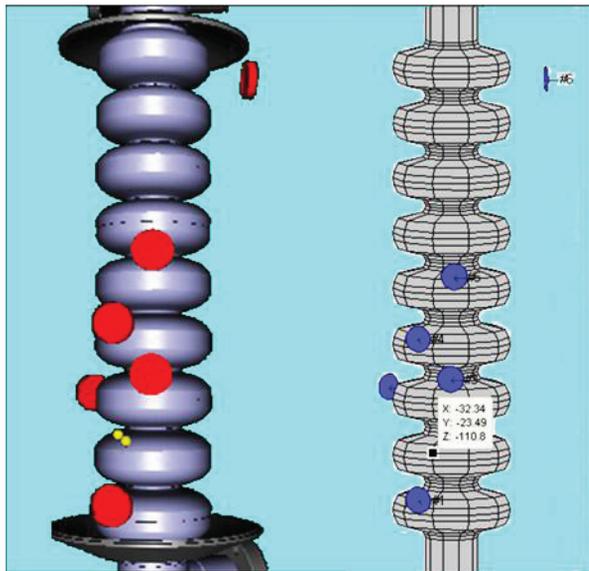


Figure 3: Quench position calculated with CS (left) and VPC (right) algorithms in the “concentrated sensors” configuration.

Fast Thermometry

Taking advantage of second sound indication, we can now focus on a narrow surface zone to have a further validation of quench position by means of temperature mapping technique.

Five thermometry sensors (Cernox[®]) with fast readout electronics are attached to the cavity in the area spotted by the Second Sound detectors. A fast digitizing oscilloscope measures the amplified output from the thermometers signal processing boards. During the cavity test, in correspondence with a quench event, the nearest sensor to the quench position suggested by the OST trilateration shows a consistent temperature rise, confirming the position of the quench. The temperature measured by the other sensors placed around the spot at 10 mm distance does not measure any significant temperature rise. Fig. 4 shows the sensor configuration and the resulting temperature plots. The red curve show the temperature variation when the sensor is far (upper plot) on very near (lower plot) to the quench location. The blue curve shows the transmitted power picked up from

the cavity: after the quench event the cavity does not restore its initial superconducting state within the 500 ms of RF ON pulse. This indicates a strong thermal transition of the cavity caused by the quench.

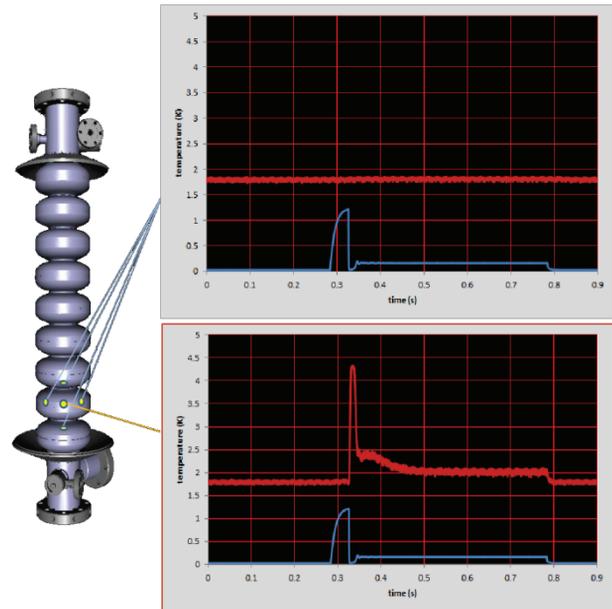


Figure 4: Sensor configuration with corresponding sensor temperature responses (red lines). Blue line is cavity transmitted RF power.

Optical Inspection

Finally, we made an attempt to directly check the presence of a defect on the inner cavity surface as quench origin, nearby the point localized by the previous techniques, resorting to the optical cavity inspection.

The optical inspection of the inner cavity surface is usually performed in the equatorial and iris zone of each cell by means of a rigid boroscope system after cavity welding, bulk BCP etching and 800 °C [8].

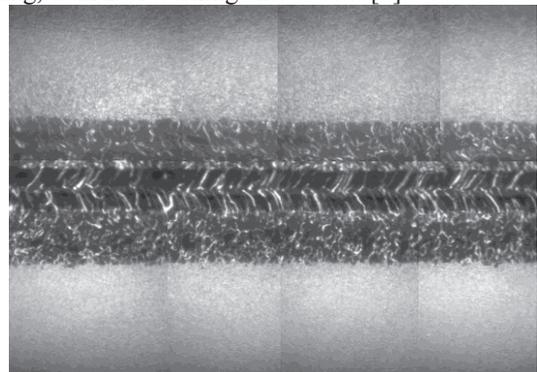


Figure 5: Optical image of cell 2 equatorial region after 800 °C treatment.

Fig. 5 shows the blow-up of the quench zone at equator of cell 2. As it is clear from picture, no “smoking gun” evidence can be obtained from this direct visual inspection. This can be due either to poor optical

resolution (resolution 37 $\mu\text{m}/\text{pixel}$) - failing to detect too small impurities - or to a subsurface defect which obviously cannot be identified with this technique.

CONCLUSIONS

Quench in a 3.9 GHz XFEL prototype cavity has been extensively studied by different methods. We have applied mode analysis to identify cell pairs responsible for quenching the cavity, Second Sound for spotting the quench site and fast thermometry to cross validate the Second Sound results. We have resume also optical inspection images searching for a clear quench site on the cavity inner surface which we could not identify.

Second Sound technique has proven to be reliable in identifying the quench area within 5-10 mm but works has still to be done to reduce even further this uncertainty and allow fast and reliable quench detection on the small 3.9 GHz cavities where the cell distance is 19.2 mm.

ACKNOWLEDGEMENTS

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