6th International Particle Accelerator Conference IPAC2015, Richmond, VA, USA JACoW Publishing
ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-WEPTY034

T-MAP STUDIES ON GRADIENT-LIMITING MECHANISM IN NITROGEN DOPED CAVITIES*

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Abstract

Nitrogen doping results in ultra-high quality factors in SRF niobium cavities but currently achievable gradients in doped cavities are, on average, somewhat lower than in EP/120 °C baked cavities. The origin of this difference is explored in the reported work by detailed temperature mapping studies on several single cell nitrogen doped cavities.

INTRODUCTION

Superconducting accelerating cavities have recently received a large improvement in terms of quality factor, thanks to the discovery of nitrogen doping treatment. Before this beneficial treatment was discovered, the performance of niobium cavities were limited, in terms of Q-factor, to $2 \cdot 10^{10}$ at 16 MV/m (at 2 K, for 1.3 GHz cavities). Nitrogen doped (N doped) cavities can instead reach quality factors of $4 \cdot 10^{10}$ at 16 MV/m [1]. On the other hand, the performance achieved in terms of accelerating field is nowadays lower for N doped cavities, that is in the range of $20 - 30$ MV/m, compared with EP/120 °C baked cavities which reach even 40 MV/m.

In this paper the quench mechanism is analyzed using temperature maps [2] captured before and during the quench of nitrogen doped cavities, allowing the localization of the quench spot. The study is done taking into account cavities with different doping treatment, in order to see if any differences appear between them, or if something systematically occurs before or during their quenches.

EXPERIMENTAL SET-UP

For the doping treatment, niobium cavities are typically treated with 800 °C degassing in HV for 2-3 hours, followed by injection of niotrogen (N_2) at high temperature. The N_2 flow is set to a specific partial pressure for a certain amount of time. During this step nitrogen reacts with the niobium at the surface and diffuses inside. After that, it is possible to perform a second, optional, step in which the cavity is maintained at high temperature, without nitrogen, in order to promote the diffusion of the nitrogen atoms inside the bulk, smoothing the concentration profile. Then, the heating is shut off and the cavity is let cooling till room temperature.

In Table 1 the nitrogen doping treatment of the analyzed cavities is listed. Only the cavity TE1AES011 is doped including the second step which promote the nitrogen diffusion. Depending on the doping treatment the cavity can be under-doped, for example increasing the time of the second step, or over-doped, for example increasing the time of the first step [3].

Table 1: Doping Treatment of the Analyzed Cavities

Cavity	Doping Treatment
TE1AES003	28 mTorr of N_2 for 10 min at 1000 °C
TE1NR005	25 mTorr of N_2 for 10 min at 800 °C
TE1AES011	25 mTorr of N_2 for 2 min at 800 °C plus 6 min without N_2 at 800 °C
TE1ACC002	25 mTorr of N_2 for 20 min at 800 °C

After the doping treatment the cavities are electropolished with a total removal of about $5 \mu m$ for all the cavity analyzed except for TE1AES003 in which the removal is about $60 \mu m$.

The temperature map system was used to capture the cavity temperature before and during the quench, in order to understand the mechanism responsible to the quench. The T-map system used in this experiment is shown in Fig. 1. It consists on 36 board placed around the cavity every 10°, and 16 thermometers are placed on each board, for a total of 576 thermal sensors all around the cavity.

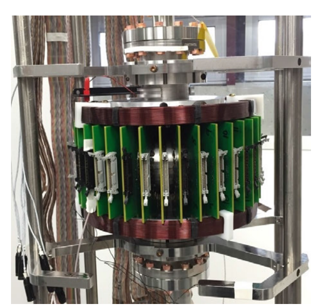

Figure 1: Picture of the T-map system.

RESULTS AND DISCUSSION

The Q-factor versus accelerating field of the nitrogen doped cavities for the T-map runs analyzed in this paper is shown in Fig. 2. The RF test of one EP and one EP/120 °C cavities are also shown as reference. It is important to notice that some of the N doped cavities do not show very high Q performance during these T-map runs because these tests were done with some imposed magnetic field and under not full flux expulsion cooling regimes. In particular the TE1ACC002 cavity had showed significant flux trapped under 10 mGauss field applied via Helmholtz coils.

Comparing TE1AES011 with the EP cavity, they reached almost the same accelerating field, but it is possible to notice that TE1AES011 is not affect by high-field Q-slope

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Table 2: Summary of the Quench Fields of the Nitrogen Doped Analyzed Cavities

Cavity	Doping	Quench field
TE1AES003	10min 1000 °C	21.5 MV/m
TE1NR005	10min 800 °C	21.7 MV/m
TE1AES011	2/6min 800 °C	30.5 MV/m
TE1ACC002	20min 800 °C	17.5 MV/m

(HFQS), which is instead peculiar of EP cavities. High-field Q-slope of EP cavities can be cured by baking the cavity at 120 °C [4], as it can be seen also from the graph. The fact that TE1AES011 does not exhibit any high field Q-slope is therefore very important, as it is the first alternative treatment to the 120 °C bake capable of eliminating the HFQS, pinpointing to a role of "surface doping" in the elimination of high field Q-slope losses mechanism.

The quench fields of doped cavities are listed in Table 2. It has been shown [3] that quench fields in N doped cavities are more and more severely degraded with heavier doping levels, and that the best accelerating gradients are obtained with lighter doping recipes. This is consistent with what shown by the values in Table 2. In particular, highly doped cavities, as TE1ACC002, show lower quench field than lower doped cavities, as TE1AES011 which is the only one that reaches 30 MV/m.

The t-maps taken just before the cavity quench are shown in Fig. 3. In these images the cavity equator corresponds to thermometer number 8, while thermometer numbers 1 and 16 shows the temperature at the two iris. The quench spot location is indicated in these images with the red circle, and the actual location can be clearly seen from the t-map taken exactly during the quench. In Fig. 4 the t-map acquired during the quench of TE1AEA011 (b) and TE1ACC002 (c) are shown.

The first important thing to notice is that no one of the cavities analyzed show pre-heating at the quench spot, i.e. a particular spot which heats up as a function of the accelerating field and which eventually lead to quench. Indeed, all the T-maps taken before the quench show very small not localized heating, on the order of magnitude of some millikelvin, which can not be attributed to quench pre-heating, but rather to other dissipative effects, as for example trapped flux.

In Fig. 5 the temperatures of the quench spots are plotted as a function of the accelerating field for all the nitrogen doped analyzed cavities, and for an EP undoped cavity. This graph further underline that the temperature at the quench spot does not show any dependence with the accelerating field in the case of N doped cavities, and no quench pre-heating. The behavior appears then completely different than the undoped EP cavity in which the temperature exponentially increases as a function of the accelerating field. This comparison in Fig 5 clearly shows the absence of HFQS heating in doped versus undoped cavities.

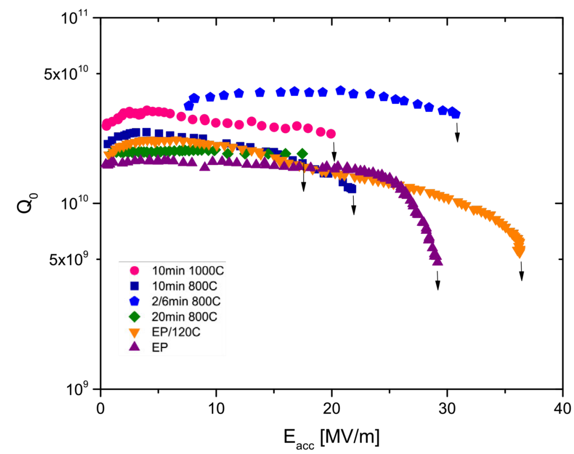

Figure 2: Q-factor versus accelerating field curves at 2 K of nitrogen doped, EP and EP/120 °C cavities.

The absence of pre-heating allows to exclude also the thermal-breakdown as possible mechanism of quench of nitrogen doped cavities. Indeed, thermal-breakdown is due to a normal-conducting defect which heats up as a function of the accelerating field, and when the critical temperature is locally overtaken the dissipations drastically increases in that region causing quench [5].

The images of Fig. 3 allow also to rule out multipacting (MP) as a mechanism of early quench in N doped cavities, since the typical (two point) MP signature would appear as a line of heating which crosses the equator, in correspondence of the two points of the cavity from which the electrons are ejected [4]. This is an important conclusion, as multipacting has been one of the main suspected culprits of the premature quenches in N doped cavities, since the quench field levels always appears close to MP barriers.

The T-map of Fig. 3 (d), shows a tiny heating effect, of some millikelvin, along the cavity equator. This heating seems to be related at the trapped flux, due to a non perfect magnetic field expulsion during the superconducting (SC) transition of the cavity. This trapped flux particularly depends on the SC transition dynamics for nitrogen doped cavities. In any case, this heating can not be related to quench because for different amount of trapped flux the quench field does not show significant variation [6].

Looking at the quench spot location, Fig. 4 b) and c), and comparing it with the profile of the magnetic field inside the cavity, Fig. 4 a), the quench spot always appear in the high RF field region. These facts suggest that the cavity does not quench because of a normal-conducting defect at the surface, as it happens for thermal-breakdown, but rather the quench seems to have a magnetic nature.

Different concentration of interstitial nitrogen atoms can cause the variation of the lower critical magnetic field $Hc1$. Indeed, previous studies [7, 8] show that the presence of interstitial atoms in the niobium can lower Hc_1 and, depending on the nitrogen concentration, this effect can be more or less severe.

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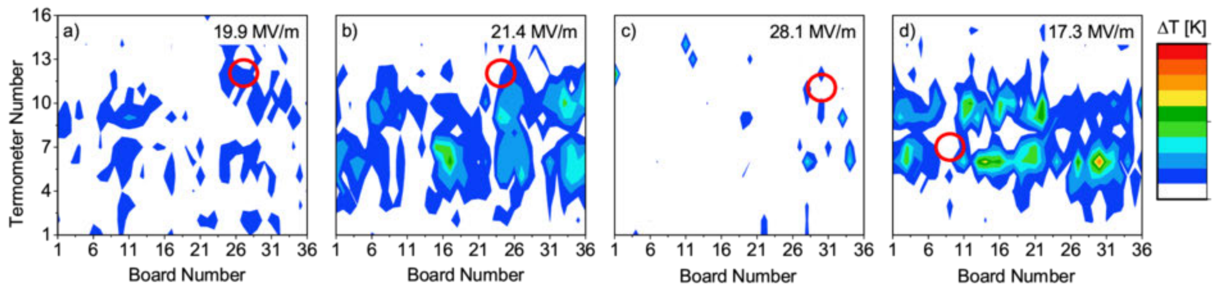

Figure 3: T-map captured just before the quench of four different nitrogen doped cavities: a) TE1AES003, b) TE1NR005, c) TE1AES011, d) TE1ACC002.

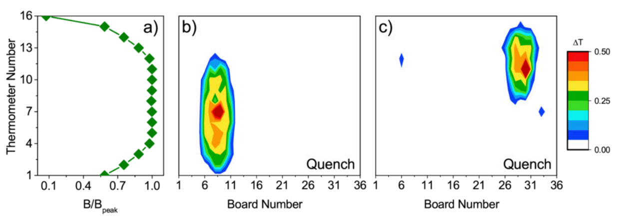

Figure 4: a) Thermometer number as function of the magnetic field inside the cavity. T-map during quench of doped cavities: b) TE1ACC002, c) TE1AES011.

Taking into account these differences in terms of lower critical field, a possible explanation of quench in nitrogen doped cavities might be the overcoming of the critical field. Indeed, where bumps or grain boundaries are present in a high field region, the magnetic field is locally enhanced as a consequence of the Meissner effect. Because of that, the magnetic field will result higher close to feature with high aspect ratio [9].

Adding together the two effects, the lower H_{c1} in case of heavily doped cavities and the local enhancement of the magnetic field, it follows that the probability of premature

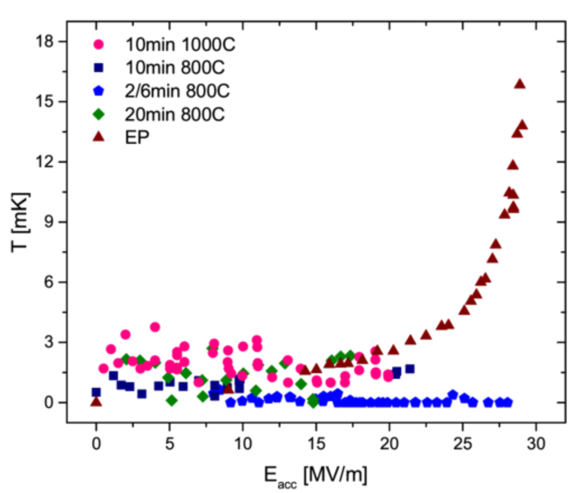

Figure 5: Temperature at the quench location as a function of the accelerating field.

quench is higher for over-doped cavities, for the same micro-roughness.

Another possible explanation could be that different nitrogen doped treatments promote the formation of nanometric normal-conducting defects, with different size depending on the doping treatment. These defects can be for example non-stechiometric NbN phases which precipitates at the grain boundaries. Thanks to the proximity effect these defects may behave as superconductors, without showing any heating effect as a function of the accelerating field. The break-down field of these defects depends on their size, and is lower than the surrounding superconductor [10]. In particular, the smaller the defect and the higher is its critical field. In this scenario doping treatments which promotes formation of smaller defects will have higher quench field than doping treatment which promotes formation of larger defects.

CONCLUSIONS

The quench mechanism of nitrogen doped cavities has been studied with T-map and reveals that the premature quench in N doped cavity is sudden and never shows any pre-heating. The quench spot seems to appear always in the high magnetic field region of the cavities, so, combining these two evidences it appears that the mechanism of quench should have a magnetic nature.

One possible mechanism could be the overcoming of the lower critical field, which might be lowered after the nitrogen treatment. Another possible mechanism could be the overcoming of the break-down field of nanometric defects which behave as superconductors because of the proximity effect.

T-maps also clearly show the absence of HFQS losses in higher gradient N doped cavities, showing for the first time that there is an alternative treatment to the 120 °C bake which eliminates the HFQS.

REFERENCES

[1] A. Grassellino et al., Supercond. Sci. Technol. 26 102001 (2013)

[2] J. Knobloch, H. Muller, H. Padamsee, Rev. Sci. Instrum. 65, 3521 (1994)

ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-WEPTY034

[3] A. Grassellino, “High Q_0 Development”, these proceedings, MOYGB2, IPAC ’15, Richmond, USA (2015)

[4] H. Padamsee, J. Knobloch, T. Hays, *RF Superconductivity for Accelerators*, (Wiley-VCH Verlag GmbH and Co. KGaA, Weinheim, 2008), 199

[5] H. Padamsee *RF Superconductivity: Science, Technology and Applications*, (Wiley-VCH Verlag GmbH and Co. KGaA, Weinheim, 2009), 129

[6] A. Romanenko et al., J. Appl. Phys. 115, 184903 (2014)

[7] W. DeSorbo, Phys. Rev. 132, 107 (1963)

[8] A. Vostrikov et al. “Modifications of Superconducting Properties of Niobium Caused by Nitrogen Doping Recipes for High Q Cavities ”, these proceedings, WEPTY022, IPAC ’15, Richmond, USA (2015)

[9] J. Knobloch, et al. "High-Field Q-Slope in Superconducting Cavities Due to Magnetic Field Enhancement at Grain Boundaries", in Proc. of SRF 1999, Santa Fe, USA (1988)

[10] A. Romanenko et al., Supercond. Sci. Technol. 26 035003 (2013)