

EXPERIMENTAL RESULTS ON THE FIELD AND FREQUENCY DEPENDENCE OF THE SURFACE RESISTANCE OF NIOBIUM CAVITIES*

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Abstract

We investigate the frequency and field dependence of the surface resistance of single-cell niobium cavities as a function of surface treatment at 1.3 and 2.6 GHz. The surface resistance is broken down into two parts: the temperature-independent residual resistance, R_{res} , and the temperature-dependent Bardeen-Cooper-Schrieffer resistance, R_{BCS} . While R_{BCS} at low fields is known to vary quadratically with frequency, the exact dependence of R_{BCS} and R_{res} on field at higher frequencies are important topics for further investigation. We offer results on a systematic experimental study of R_{BCS} and R_{res} as a function of frequency, f , and peak surface magnetic field, B_{pk} , for clean niobium and high-temperature nitrogen-doped niobium.

INTRODUCTION

Understanding the behavior of the surface resistance of superconducting niobium cavities at frequencies higher than 1.3 GHz is necessary for producing high-gradient, high Q_0 cavities at these frequencies [1]. Higher frequency cavities allow for smaller, more compact accelerators that demand lower cryogenic costs, have reduced cryomodule size, and a lower production cost making them more accessible for commercial, medical, and industrial applications.

We performed RF tests on 1.3 and 2.6 GHz single-cell niobium cavities to see how Q_0 , and therefore, the surface resistance, R_S , depended on f and B_{pk} . In particular, we did baseline tests at both frequencies, then nitrogen-doped the cavities to obtain $R_S(B_{\text{pk}})$ for both surface treatments. This allowed us to decompose R_S into its constituent parts, the temperature-dependent, R_{BCS} , and temperature-independent, R_{res} , to better understand the dependence of these constituents on f and B_{pk} .

SURFACE TREATMENT

Two 1.3 GHz and one 2.6 GHz TESLA-shaped single-cell niobium cavities were used throughout this letter. The surface treatments the cavities received before RF testing are summarized in Table 1. There are slight differences in cavity parameters between the two frequencies so they are highlighted in Table 2.

Each surface treatment began with a vertical electropolish (VEP) to smooth the surface and remove any surface defects or contamination. After this initial VEP, they received an

ultrasonic rinse in de-ionized (DI) water for 30 min with an added detergent and 30 min without detergent. They were then treated with either a de-gas bake in ultra-high vacuum or a nitrogen-dope.

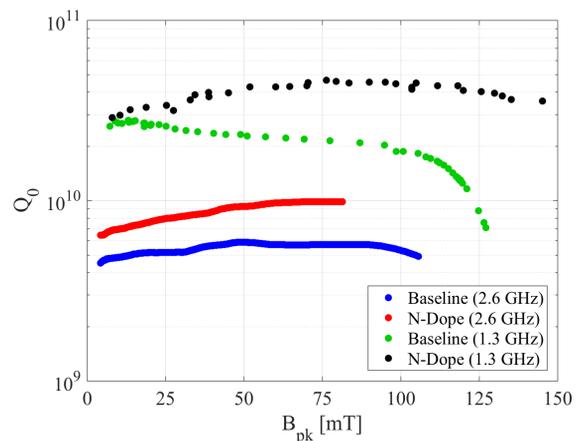


Figure 1: The $Q_0(B_{\text{pk}})$ data at $T = 2.0$ K from the 1.3 and 2.6 GHz cavities with the surface treatments described in Table 1.

The cavity known as LTE1-1 received a 900 °C de-gas bake for 3 hr. After baking it was rinsed with DI water in a high pressure rinsing (HPR) system and was then tested. Cavity LTE1-3 received a typical N-dope [2, 3]. This dope consisted of three steps: (1) an 800 °C de-gas bake in vacuum for 3 hr, (2) an 800 °C N-dope for 20 min with ~40 mTorr of N_2 gas, and (3) an 800 °C anneal in vacuum for 30 min. After doping, it received a 12 μm VEP to remove the lossy nitride layer that grows on the niobium surface during the doping process [3]. It then received a HPR and was tested.

Cavity STE1-1 first received a de-gas bake at 800 °C for 5 hr in vacuum. The de-gas bake was followed by a light 10 μm VEP and a HPR before being tested. Finally, STE1-1 was again de-gassed at 800 °C for 3 hr in vacuum, then N-doped for 2 min in a partial pressure of nitrogen gas of ~40 mTorr, and finally annealed for 6 min in vacuum. After doping, the cavity received a light 6 μm VEP to remove nitrides from the cavity surface and a HPR before being tested.

MATERIAL PROPERTIES

Here we discuss an important material property of all cavities tested with the exception of LTE1-1. The electron mean free path, ℓ , for the de-gassed 2.6 GHz cavity was ~1500 nm, placing it very far into the clean limit. After N-

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Table 1: Cavity Surface Treatments

Cavity	Prep. No.	De-gas Bake	Doping Bake	Anneal	Post-Bake EP
LTE1-1	1	900 °C (3 hr)	–	–	–
LTE1-3	1	800 °C (3 hr)	800 °C (30 min; N ₂)	800 °C (20 min)	12 μm
STE1-1	1	800 °C (5 hr)	–	–	10 μm
STE1-1	2	800 °C (3 hr)	800 °C (2 min; N ₂)	800 °C (6 min)	6 μm

doping, the 2.6 GHz cavity had a mean free path of ~46 nm. For comparison, the 1.3 GHz N-doped cavity had a mean free path of ~35 nm. In this way, both N-doped cavities can be considered to have very similar doping levels. This allowed for a direct comparison in their performance and the behavior of the surface resistance with the only variable being frequency.

RF PERFORMANCE

The quality factor, Q_0 , as a function of B_{pk} for all four cavity tests are shown in Fig. 1. The baseline test of the 1.3 GHz cavity was quite typical. At moderate fields, Q_0 undergoes what is called a ‘medium-field Q -slope’ (i.e. a slight decrease of Q_0 with increasing B_{pk}). Above ~100 mT, the Q_0 experiences a sharp decrease with increasing B_{pk} . This is often referred to as ‘high-field Q -slope’.

The test of the N-doped 1.3 GHz cavity exhibits two important characteristics: higher Q_0 overall and ‘ Q -rise’. The first of these effects is self-explanatory – N-doping increases the overall value of Q_0 compared to a clean niobium cavity by lowering the electron mean free path, ℓ . The ‘ Q -rise’ is simply an increase of Q_0 with increasing field. These two effects due to N-doping were first seen by Grassellino *et al* [2]. Shortly afterwards, Gurevich developed a theory to describe this behavior [4].

The 2.6 GHz baseline test revealed lower overall Q_0 compared to the 1.3 GHz baseline test which is to be expected since, in general, $R_{BCS} \propto f^2$ [5]. However, in this case, ‘ Q -rise’ was already apparent. After receiving the N-dope, the Q_0 increased even further and so did the strength of the ‘ Q -rise’. Note here that neither of the 2.6 GHz tests were taken to quench.

SURFACE RESISTANCE

The quality factor is related to surface resistance, R_S , by the cavity geometry factor, G :

$$R_S = G/Q_0 \quad (1)$$

The geometry factor is a constant that depends only on cavity geometry and is the same for both the 1.3 and 2.6 GHz cavities (see Table 2).

The surface resistance can be decomposed into two parts:

$$R_S = R_{BCS}(T) + R_{res}, \quad (2)$$

where R_{BCS} is temperature-dependent and R_{res} is the temperature-independent component. The field dependence of these two components of the surface resistance are shown

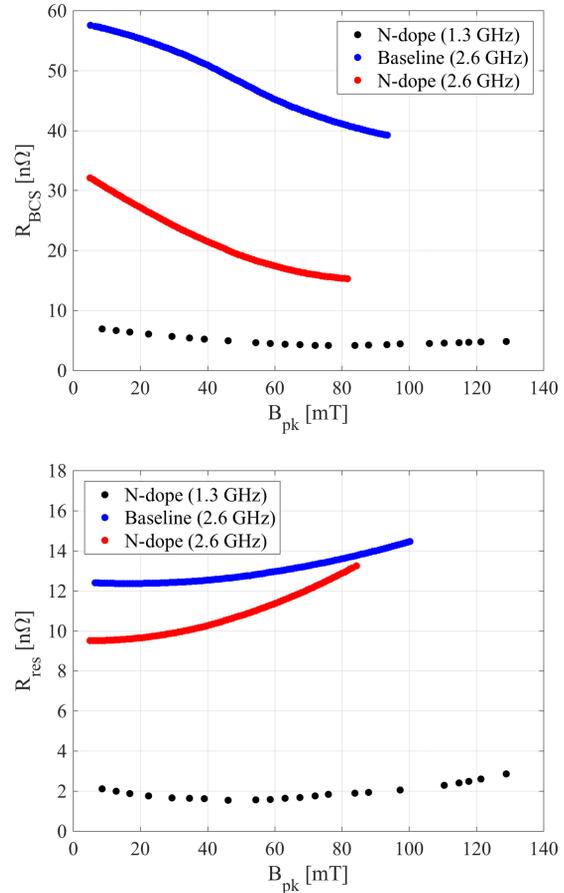


Figure 2: $R_{BCS}(B_{pk})$ at 2.0 K (top) and $R_{res}(B_{pk})$ (bottom) for all cavity data except the 1.3 GHz baseline test.

in Fig. 2. To get a better idea of relative changes in these components, the resistances normalized to their low field value are shown in Fig. 3.

The 1.3 GHz N-doped cavity, had the lowest overall value of R_{BCS} at all fields and had a relative drop inbetween that of the 2.6 GHz baseline and 2.6 GHz N-dope tests. Similarly, the 1.3 GHz N-doped cavity had the lowest overall R_{res} at all fields and was the only one to have a relative drop in R_{res} before it began to increase with field.

The 2.6 GHz baseline test had the highest values of both R_{BCS} and R_{res} compared to the other tests. However, despite not yet being N-doped, it still displayed a relative reduction in R_{BCS} with increasing B_{pk} . The difference in the field dependence in R_{res} between this baseline test and the 1.3 GHz

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Table 2: Cavity Parameters

Cavity	f [GHz]	G [Ω]	$E_{pk}/U^{1/2}$ [$MV \cdot m^{-1}/J^{1/2}$]	E_{pk}/E_{acc}	B_{pk}/E_{acc} [$mT/MV \cdot m^{-1}$]
LTE1-x	1.3 GHz	278	15.1	1.86	4.23
STE1-1	2.6 GHz	278	42.3	1.86	4.25

N-dope test is that R_{res} increases immediately with B_{pk} for the 2.6 GHz cavity.

Finally, the 2.6 GHz N-dope test displayed the strongest ‘Q-rise’ and therefore has the strongest reduction in R_{BCS} with field. The N-dope managed to reduce the magnitude of R_{BCS} by roughly a factor of 2 to 3 over the 2.6 GHz baseline test. It also had the lower R_{res} compared to the 2.6 GHz baseline, but had a stronger relative increase.

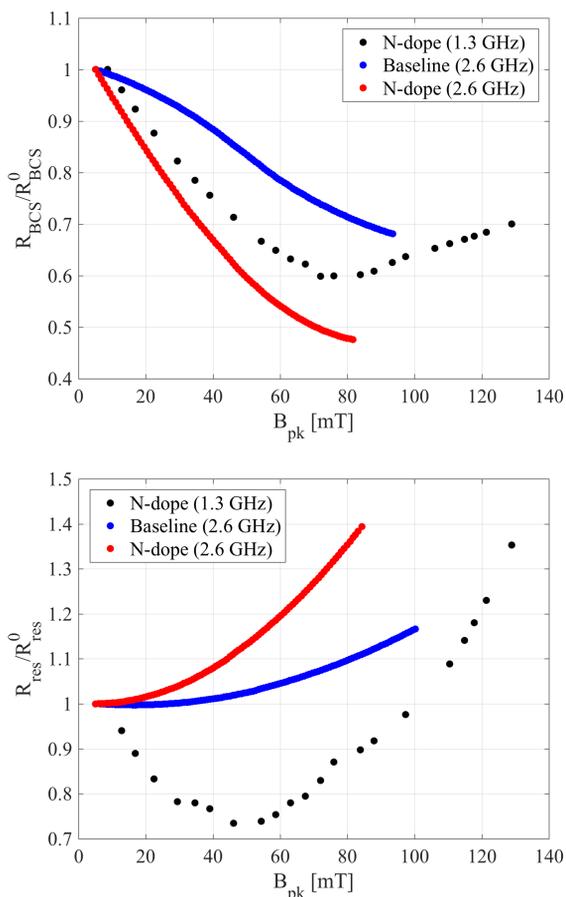


Figure 3: $R_{BCS}(B_{pk})$ at 2.0 K (top) and $R_{res}(B_{pk})$ (bottom) normalized to their values at low field for all cavity data except the 1.3 GHz baseline test.

DISCUSSION

It is not surprising that a drop in R_{BCS} was seen in the N-doped cavities at both 1.3 and 2.6 GHz as they both had similar mean free path. When observing the low field values of R_{BCS} for the 1.3 GHz and 2.6 GHz N-dope tests it should be noted that their values are $\sim 8 n\Omega$ and $\sim 32 n\Omega$, respectively. This indeed follows the BCS prediction that $R_{BCS} \propto f^2$.

What is less clear is why R_{res} also seems to approximately obey an f^2 dependency for the two N-dope tests. Perhaps this was simply a matter of having different amounts of trapped flux due to less efficient flux expulsion at 2.6 GHz or perhaps a higher sensitivity to trapped flux at 2.6 GHz compared to 1.3 GHz.

It is not yet well understood why a clean niobium cavity at 2.6 GHz would also see a reduction in R_{BCS} with field. The Gurevich theory does not have an explicit dependency on frequency. However, his theory is still relatively good for fitting the $R_{BCS}(B_{pk})$ at 2.6 GHz as can be seen in the fits done by Maniscalco [6]. The fact that the fits at 2.6 GHz don’t describe the reduction in R_{BCS} with field as well as they do at 1.3 GHz implies that the theory is incomplete and needs expansion with respect to frequency dependence. Also, it is important to point out that for the 2.6 GHz baseline test, the electron mean free path of the cavity is far in to the clean limit ($\ell \sim 1600$ nm). Note that Gurevich’s theory does not provide good fits for 1.3 GHz cavities in this regime. However, it still can be used fit $R_{BCS}(B_{pk})$ for the 2.6 GHz in the clean limit with an appropriately selected overheating parameter [6]. Further experimental data and extension of the theory to include frequency-dependence of the quasiparticle overheating parameter is needed to better describe the behavior of R_{BCS} and R_{res} in the clean limit and at higher frequencies.

CONCLUSION

We investigated the field and frequency dependence of single-cell TESLA-shaped niobium cavities for both clean and N-doped niobium. It was observed that a clean niobium cavity at 2.6 GHz has a field-dependent reduction of R_{BCS} and increase of R_{res} . It has been suggested that the observed reduction in R_{BCS} with field at higher frequencies is due to a transition to non-equilibrium superconductivity. However, a theory to support this has not yet been developed. It’s possible the reduction is due to a frequency dependence of the overheating parameter, as discussed by Maniscalco [6]. Nitrogen-doping of the 2.6 GHz cavity revealed an improved Q_0 and an even stronger relative reduction in R_{BCS} with field. However, despite R_{res} having a lower magnitude than its clean counterpart, it did increase with field at a faster rate. Further developing a better understanding of the behavior of R_{BCS} and R_{res} at 2.6 GHz and higher frequencies is crucial for optimizing surface treatments so that more compact accelerators with lower cryogenic costs can be produced.

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