IMPURITY DOPING OF SUPERCONDUCTING RF CAVITIES *

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Abstract

Impurity doping of bulk-niobium superconducting radio frequency (SRF) cavities is a relatively new field of study and the underlying physics is not yet fully understood. Previous studies [1–3] have shown both a decrease in the temperature dependent component of the surface resistance, R_{BCS}, at low fields and a decrease in R_{BCS} with increasing accelerating gradient, E_{acc}; these correspond to a higher intrinsic quality factor, Q_0, at low fields and the presence of the so-called 'anti-Q-slope' at higher fields. Here we present results on initial investigations on the effects of alternative inert dopants on the Q_0 of SRF cavities in pursuit of the optimal dopant and doping level.

INTRODUCTION

Nitrogen doping of SRF cavities has consistently been shown to improve RF performance (i.e. increase the low-field intrinsic quality factor, Q_0) and cause an 'anti-Q-slope' [1, 4, 5] (i.e. an increase of Q_0 with increasing accelerating field E_{acc}). However, nitrogen is the only dopant that has been studied with any depth so far. It is not yet known whether there are other dopants that can match or exceed the performance increases seen in nitrogen doped cavities. Here we discuss two alternative inert dopants, helium and argon, and their effects on cavity performance.

EXPERIMENTAL PROCEDURE

A single-cell ILC-shaped 1.3 GHz niobium cavity, LT1-1, was tested using various preparation methods and dopants. The cavity first underwent a hard reset via a 145 μm buffer chemical polish (BCP) of the outside of the cavity and a 20 μm electropolish (EP) of the inside surface to rid the cavity of a prior nitrogen dope followed by high-temperature vacuum treatment to degas the cavity of hydrogen introduced by the etching. It was then RF tested in a vertical test dewar. The test produced poor results prompting further etching and vacuum heat treatment which is referred to as a 'standard treatment'. Following the RF test of the standard EP treatment, the cavity was then doped with argon and retested. Finally, the cavity underwent a helium dope and was again retested. Cavity preparation protocols are summarized in Table 1. We present the results of the these two doping treatments compared to the standardly prepared niobium cavity and a typical nitrogen doped cavity.

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INERT GAS DOPING

Baseline Test

After performing the hard reset of LT1-1, described above, an additional standard treatment was applied. This standard treatment consisted of a 5 μm electropolish of the inside surface of the cavity followed by a 900 °C bake in the ultra-high vacuum (UHV) furnace for 3 hours.

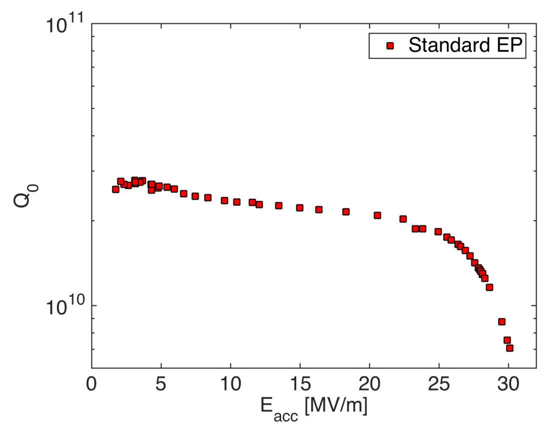

Figure 1: Quality factor, Q_0, vs. accelerating gradient, E_{acc} at T = 2.0 K for the standard treatment of LT1-1. Note the presence of both the medium-field and high-field Q-slope typical of standardly prepared niobium cavities.

The standard EP treatment has all the typical characteristics of a standard bulk-niobium cavity (see Fig. 1). In particular, the characteristics it displays are a medium-field Q-slope in the range from 5 MV/m to 25 MV/m and a high-field Q-slope above 25 MV/m [6].

Argon Dope and RF Performance

The argon doping procedure of LT1-1 is summarized in Table 1. It was first degassed in the UHV furnace at 800 °C for 1 hour followed immediately by a bake at 990 °C in a 45 mTorr Ar environment. Figure 2). shows the temperature of the furnace and the partial pressure of the argon environment as a function of time.

Figure 3 shows the results of Q_0 vs. E_{acc} measurements for the argon-doped cavity compared to the results of the baseline test. The argon dope had no noticeable effect on cavity performance except for a reduction of quench field. The quench itself was detected by observation of a sudden drop in the transmitted power to the cavity followed by a steady rise until the cavity quenched again. This is indicative of an ordinary thermal quench caused by a defect introduced during assembly of the cavity onto the test stand. Like the standard treatment, the argon dope also possesses the characteristic medium-field Q-slope. With these facts considered,

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Table 1: Cavity Preparation Protocols for LT1-1. Electropolishing (EP) is used to reset the inner surface of the cavity.

Treatment	EP (μm)	Vacuum Bake	Dope Temperature
Standard	5	900 °C (3 hr)	-
Argon Dope	-	800 °C (1 hr)	1000 °C (1 hr)
Helium Dope	-	800 °C (20 min)	900 °C (5 min) → 1000 °C (5 min)

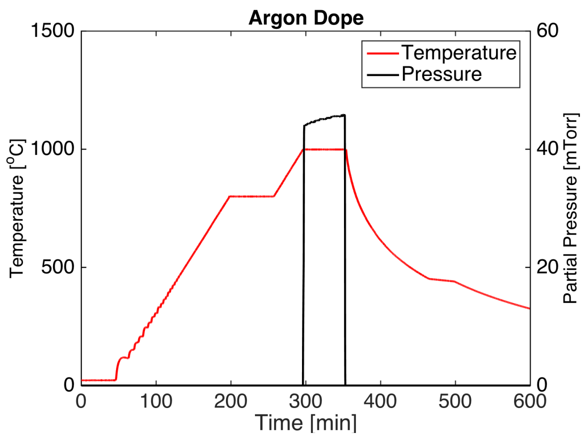

Figure 2: Bake trend of the Ar dope of LT1-1. The temperature of the furnace is shown in red and the partial pressure of Ar in black. The dope was done at 990 °C for 1 hour. Notice the slight increase in pressure over the doping period. This is due to some outgassing of other impurities, such as hydrogen and oxygen, from the cavity walls.

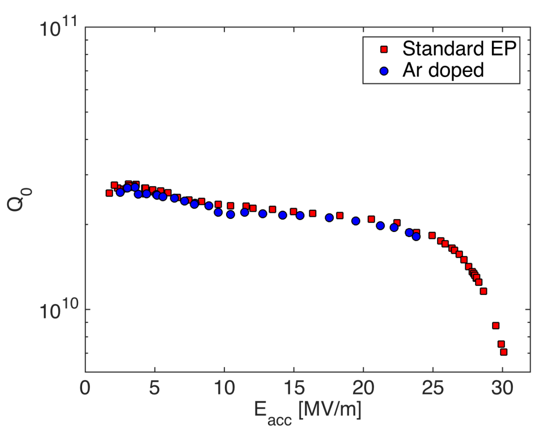

Figure 3: Q_0 vs. E_{acc} performance at T = 2.0 K of LT1-1 before and after the argon dope. Both show identical performance except for the absence of high-field Q-slope after the Ar dope. The quench was likely due to a defect introduced by cavity test stand assembly and not caused by the dope.

It is likely that little to no argon diffused into the niobium during the doping process. If argon has diffused into the niobium, the mean free path of quasiparticles in the RF layer would decrease leading to a decrease of the surface resistance at low fields as is seen in nitrogen doped cavities.

Helium Dope and RF Performance

No chemical reset was performed between the test of the argon dope treatment and the helium dope since the argon dope, by itself, had no effect on cavity performance. LT1-1 was then doped with helium according to the following procedure: The cavity first underwent 20 min of degassing at 800 °C in UHV, followed by a dope at 900 °C for 5 min in a 35 mTorr helium atmosphere. The furnace temperature was then raised to 990 °C in the presence of the helium atmosphere and held for an additional 5 min. The temperature of the furnace and partial pressure of helium during the heat treatment is shown in Fig. 4. Interestingly, the temperature increase from 900 °C to 990 °C should have resulted in an approximately 10% increase in the partial pressure of the helium atmosphere if it we treat the helium, to a good approximation, as an ideal gas. However, the pressure increased only by about 3%. It is possible that the pressure did not decrease as dramatically as a nitrogen dope since helium does not chemically react with the niobium. Thus, helium diffusion into the niobium would not create such a dramatic pressure drop compared to nitrogen. This was the first indication that helium uptake and diffusion into the niobium may have occurred.

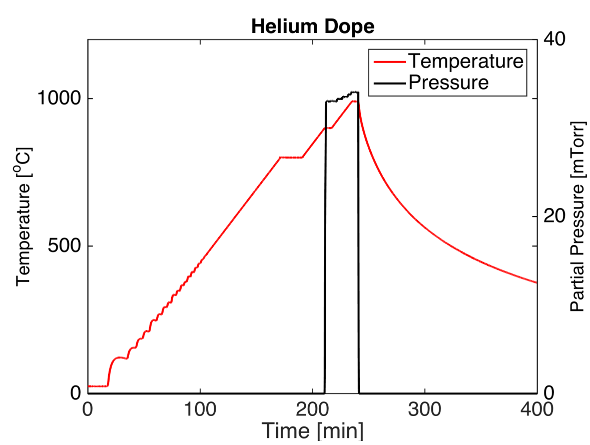

Figure 4: Bake trend of the He dope of LT1-1. The temperature of the furnace is shown in red and the partial pressure of He in black. The pressure of the He atmosphere should have increased by about 10% during the increase from 900 to 1000 °C. However, the pressure only increased by roughly 3%, which is indicative of helium uptake.

The helium dope had noticeable and exciting effects on cavity performance. The medium-field Q-slope is no longer present, the low-field Q_0 has increased and a slight anti-Q-slope is apparent. This can be seen in the Q_0 vs. E_{acc} data of the helium doped cavity taken at T = 2.0 K as shown in Fig. 5 compared to the standard treatment and a typical nitrogen-doped cavity. These characteristics are common to nitrogen-doped cavities [1, 4, 5]. Furthermore, the cavity was limited by a quench at low field (i.e. E_{acc} = 16 MV/m).

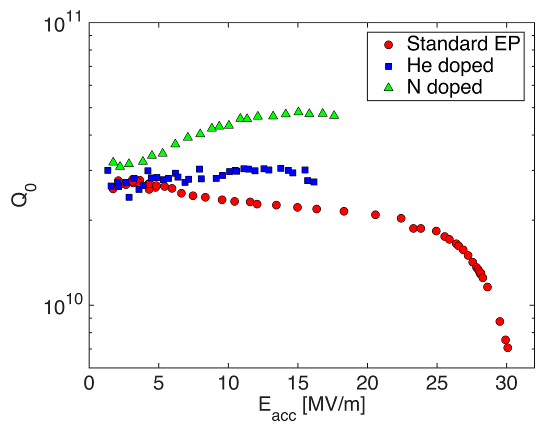

Figure 5: Q_0 vs. E_{acc} performance at T = 2.0 K of LT1-1 before and after the He dope and compared to a nitrogen doped cavity. Both doped cavities show an anti-Q-slope and low quench field.

DISCUSSION AND OUTLOOK

The argon dope of LT1-1 proved to be unfruitful; no change in performance occurred over the standard treatment. The lower quench field of the argon treatment appeared to be casued by an ordinary defect introduced during cavity assembly. The results of the helium dope has shown to be much more interesting: it resulted in a slight anti-Q-slope and increased low field Q_0. These are also characteristics of typical nitrogen doped cavities and are indicative of successful helium diffusion into the niobium. Further helium doping treatments need to be done in the future to maximize this increase in Q_0 and anti-Q-slope behavior.

In the future, surface analysis will be performed via secondary ion mass spectroscopy to measure helium concentration as a function of depth into the niobium to measure mean free path in the RF layer of the cavity. Furthermore, additional dopes using helium at 990 °C will be performed for longer periods of time to increase doping level before more RF tests are done. Finally, studies with the other inert gases not tested here will be used in future doping procedures.

REFERENCES

[1] A.Grassellino *et al.*, "Nitrogen and argon doping of niobium for superconducting radio frequency cavities: a pathway to highly efficient accelerating structures", in *Superconductor Science and Technology*, vol. 26, no. 10, p. 102001, 2013.

[2] J. T. Maniscalco *et al.*, "Studies on the field dependence of the BCS surface resistance", in *Proc. IPAC'16*, Busan, South Korea, 2016, paper WEPMR028, this conference.

[3] D. Gonnella *et al.*, "Dependence of surface resistance on N-doping level" in *Proc. IPAC'16*, Busan, South Korea, 2016, paper WEPMR027, this conference.

[4] D. Gonnella *et al.*, "Update on nitrogen-doping: Quench studies and sample analysis", in *Proc. IPAC'15*, paper WEPTY073, p. 3450.

[5] D. Gonnella *et al.*, "Nitrogen treated cavity testing at Cornell" D. Gonnella, M. Ge, F. Furuta, and M. Liepe, "Nitrogen treated cavity testing at Cornell" in *Proc. LINAC'14*, paper THPP016, p. 866.

[6] H. Padamsee, J. Knobloch, and T. Hayes, *RF Superconductivity for Accelerators*, Wiley-VCH, 2nd edition, 2008.

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