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NITROGEN DOPING STUDIES OF SUPERCONDUCTING CAVITIES AT PEKING UNIVERSITY *

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Abstract

Nitrogen doping studies with 1.3 GHz superconducting cavities were carried out at Peking University in recent years. We have realized 4×10^{10} of high quality factor at 12 MV/m and 2.0 K with large grain single cell cavities by heavy doping. To improve the accelerating gradient of high Q cavities, light doping recipe is adopted. Accelerating gradient is improved to 20 MV/m and the quality factor is larger than 3×10^{10} at 16 MV/m and 2.0 K for light doped cavities. The nitrogen treatment, test and analysis are presented in this paper.

INTRODUCTION

Nitrogen doping on superconducting radio frequency cavity is a common way to increase the intrinsic quality factor Q_0 of superconducting cavities. It was discovered by FNAL in 2013 [1], and developed by FNAL, Jlab and Cornell University in the next few years [2, 3, 4]. Other methods were also put forward to increase the Q_0, such as low temperature nitrogen infusion [5], 75°C baking [6]. Nitrogen doping is proved to realize the highest Q_0 of superconducting cavity. Nitrogen doping studies were carried out at Peking University in recent years with 1.3 GHz single cell cavities. On large grain niobium cavities, heavy doping and light doping researches were both carried out. 4×10^{10} high quality factor was realized at 16 MV/m and 2.0 K.

NITROGEN DOPING AND VERTICAL TEST

Heavy Doping on Large Grain Niobium Cavity

Heavy doping recipe was attempted at Peking University in 2017 [7]. The 1.3 GHz single cell large grain niobium cavity LG1 was used in experiment. The cavity was processed as following: Buffered Chemical Polishing 250 μm to remove surface damage layer, Annealing at 800 °C for 3 hours, nitrogen doping process for 20 minutes and annealing for 30 minutes at 800°C, EP 15 μm, high pressure rinsing and vertical test, EP 8 μm and vertical test again. After all these processing and test, the cavity was etched 50 μm with BCP and tested as baseline.

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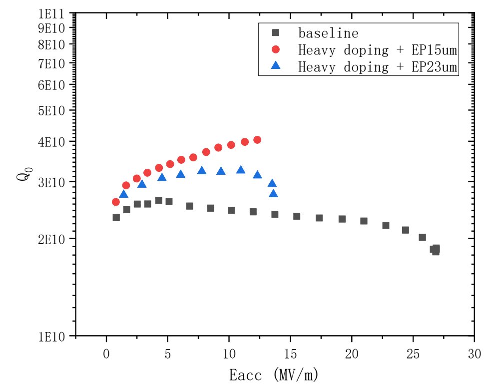

Figure 1: Q_0 vs Eacc for the large grain cavity LG1 after heavy doping.

The results of vertical test are shown in Figure 1. After heavy doping and EP 15 μm, the Q_0 reaches 4.0×10^{10} at 2.0 K when Eacc is around 12 MV/m. The quench field is 12.3 MV/m. After another 8 μm EP (totally 23 μm EP after heavy doping), the quench field increased to 13.6 MV/m. But the Q_0 degraded to 3.2×10^{10} at 2.0 K and 12 MV/m. After heavy doping, the Q_0 is much higher than baseline, which is 2.4×10^{10} at 2.0 K and 12 MV/m. To improve the accelerating gradient of nitrogen-doped cavity, we adopted light doping recipe.

Light Doping Recipe on Large Grain Niobium Cavity

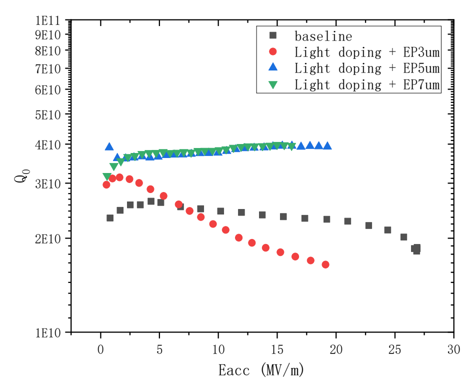

Figure 2: Q_0 vs Eacc for the large grain cavity LG1 after light doping.

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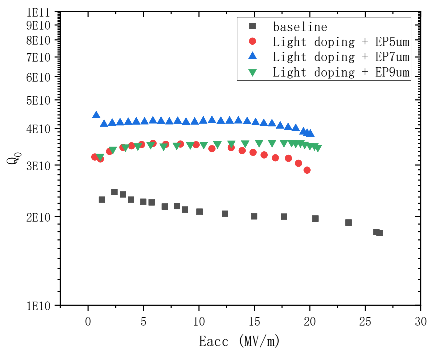


Figure 3: Q_0 vs Eacc for the large grain cavity LG3 after light doping.

The 1.3 GHz single cell large grain niobium cavity LG1 and LG3 were Buffered Chemical Polished 50 µm to reset the inner surface. Then the cavities were annealed in the high temperature furnace at 800°C for 3 hours. After that, nitrogen gas was injected into the chamber for 2 minutes and the cavities were annealed in vacuum at 800°C for another 6 minutes. After light doping, the cavities were electro-polished with different depth to find out the optimal parameter. For cavity LG1, totally EP of 3 µm, 5 µm and 7 µm were performed and vertical test was carried out after each EP. For cavity LG3, EP of 5 µm, 7 µm, 9 µm were adopted after doping. The vertical test results are shown in Figures 2 and 3.

From the results of LG1, we find that EP 3 µm is too small to remove the bad superconducting niobium nitride phase of light doping. Q_0 reaches 3×10^{10} at 2.0 K in low field. But it degrades quickly as Eacc increases, see the red line in Figure 2. Q_0 decrease to less than 2×10^{10}, lower than the baseline. The degradation was solved by another 2 µm EP. Q_0 increases with Eacc from the low field to medium field range, reaches 4.0×10^{10} at 2.0 K and 16 MV/m, and the accelerating gradient is nearly 20 MV/m, see the blue line in Figure 2. The result of totally 7 µm EP after light doping doesn't change much, see the green line in Figure 3.

From the results of LG3, EP 5 µm after light doping displays a rainbow shape of Q_0 vs Eacc. Q_0 is more than 3×10^{10} below 20 MV/m at 2 K temperature. The Q_0 of EP 7 µm is the highest in comparison with EP 5µm and EP 9 µm. The accelerating gradients are all around 20 MV/m.

The vertical test results of LG1 and LG3 show our light doping recipe successfully increases the quality factor and improves the accelerating gradient compared to heavy doping recipe.

Quality Factor vs Temperature Measurement on Nitrogen Doping Large Grain Cavity

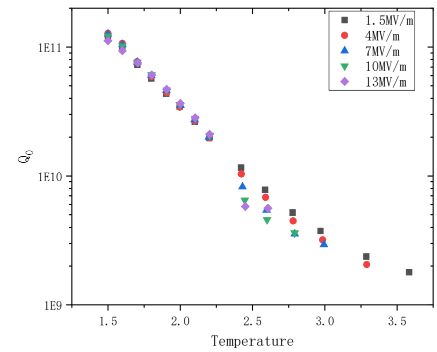


Figure 4: Q_0 vs T of the nitrogen doping large grain cavity LG3.

To study the surface resistance of nitrogen doping cavity, LG3 after light doping and EP 7 µm was analyzed in vertical test. Quality factor vs temperature was measured at different accelerating gradient (1.5 MV/m, 4 MV/m, 7 MV/m, 10 MV/m and 13 MV/m), as shown in Figure 4.

The Q_0 is inversely proportional to surface resistance R_s. The surface resistance R_s consists of two parts, temperature dependent BCS resistance (R_{BCS}) and material dependent residual resistance (R_{res}).

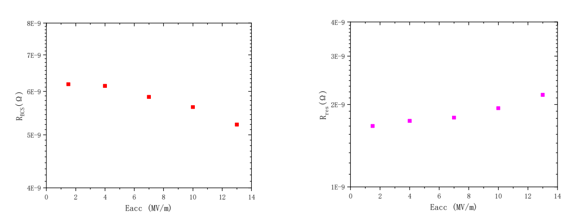
$$Q_0 = G/R_s = G/(R_{BCS} + R_{res})$$

$$R_{BCS} = A\frac{\omega^2}{T}\exp\left(-\frac{\Delta(0)}{kT_C}\frac{T_C}{T}\right)$$

$$A \propto (1+\frac{\xi_0}{l})^{3/2}\frac{l}{\xi_0}$$

Where T is the temperature, k is Boltzmann constant, T_C is the critical temperature, ω is the frequence of cavity, $\Delta(0)$ is the energy gap at 0 K, A is the coefficient related to London penetration depth λ, coherence length ξ_0 and mean free path l.

Parameters of the cavity are obtained by fitting the curve with Equation above and calculating with SRIMP code [8].



(a) (b)

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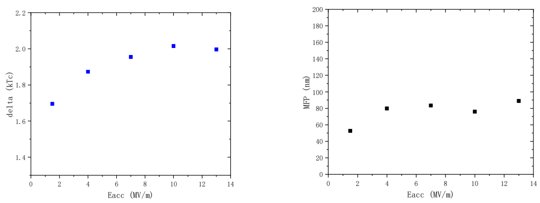

(c) (d)

Figure 5: Parameters of the cavity LG3.

R_{BCS} is 5.0-6.2 nΩ at 2K, and decreases with Eacc (see Figure 5a). That is the main reason of Q_0 improvement and anti-Q-slope on nitrogen doping cavity. R_{res} is 1.6-2.2 nΩ, and increases with Eacc (see Figure 5b). The energy gap $\Delta(0)$ is 1.7-2.0 kT_C, and increases with Eacc (see Figure 5c). Mean free path is 50-90 nm (see Figure 5d), which is in intermediate range. Interstitial nitrogen brings the clean cavity surface to an intermediate mean free path range, which decreases the BCS resistance in comparison to normal treatment cavity.

SUMMARY

Nitrogen doping studies with 1.3 GHz superconducting cavities were carried out at Peking University in recent years. For heavy doping recipe on large grain niobium cavity, the Q_0 improvement and anti-Q-slope are obvious in contrast to baseline. For light doping recipe on large grain niobium cavity, accelerating gradient is improved to 20 MV/m and the quality factor is larger than 3×10^{10} at 16 MV/m and 2.0 K. Especially for EP 7 µm after light doping, which is the optimal EP depth in our experiment, Q_0 reaches 4.0×10^{10} at 16 MV/m and 2.0K for large grain niobium cavities. More researches on large grain and fine grain cavities will be carried out for the next step.

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