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IMPROVEMENT OF CAVITY PERFORMANCE BY NITROGEN DOPING AT KEK

T. Okada*[1], Y. Hori[1, 2], E. Kako[1, 2], T. Konomi[1, 2], H. Sakai[1, 2], T. Saeki[1, 2], K. Umemori[1, 2], Y. Yamamoto[1, 2], T. Dohmae[2], M. Egi[2] J. Kamiya[3], S. Kurosawa[3], K. Takaishi[3],
[1]SOKENDAI, Oho, Tsukuba, Ibarkai, 305-0801, Japan
[2]KEK, Oho, Tsukuba, 305-0801, Japan, [3]JAEA, Tokai, naka, Ibaraki, 319-1195, Japan

Abstract

Reducing loss at the surface of a superconducting cavity is important for reducing the cost of accelerator operation. Nitrogen doping is an effective breakthrough for direct applicaton in High-Q superconducting cavities. At KEK, the nitrogen doping technique is applied to single and three-cell niobium TESLA-like cavities. A J-PARC furnace has a cryopump and three turbopumps, in addition to scroll-pumps, to achieve an oil-free environment. The quality factor of nitrogen doped cavities was improved in comparison with the standard treatment. The temperature dependent resistance decreased with an increase of the accelerating gradients. The nitrogen doping recipe was applied to the single-cell and three-cell cavities applied, and the results of the vertical test are described.

INTRODUCTION

Nitrogen doping is an effective breakthrough in the field of High-Q superconducting cavities [1]. The quality factor Q_0 is represented by $Q = G/R_s$ without field emission. The geometrical factor G is defined by only the shape of the cavity, while R_s represents its surface resistance. The geometrical factor of the TESLA-like cavity is approximately about 280 Ω. The nitrogen doping technique had been investigated at KEK using the large and small furnaces in the mechanical engineering center at KEK. However, this has resulted in the deterioration in the quality factor of the treated cavities [2]. The likely cause of the unsatisfactory results is related to the vacuum system of the furnace. Nitrogen doping and nitrogen infusion were successfully tested using the other furnace at J-PARC which has an oil-free pump system [3].

DOPING PROCEDURE

The oil-free furnace at J-PARC annealed vacuum components as usual. The cryopump was operated at 10000 L/sec. The three turbopumps and scrollpumps have pumping speeds of 3000 L/sec ×3, 500 L/min ×3, respectively. During the introducing of high purity nitrogen gas, the pumps were stopped and the portable pump was used for a deep doping recipe in the single-cell cavity. Durring this process for a light doping, the pumping speed of the turbpumps and scrollpumps were decreased by 50 %. Both the heavy doped and light doped nitrogen doping recipes were applied to the two cavities as shown in Table 1.

* okadat@post.kek.jp

Table 1: Nitrogen Doping Applied to the Two Cavities

Cavity	**Recipe**
Single-cell	800 °C 3 hour + 800 °C for 20 min 2.7 Pa nitrogen + 800 °C for 30 min w/o nitrogen + EP 15 *m*
Three-cell	800 °C 3 hour + 800 °C, 2 min w/3.0 Pa nitrogen, + 800 °C, 6 min w/o nitrogen + EP 5 *m*

The single cavity is the TESLA-like shape and is made of fine grain niobium from Tokyo Denki, with an RRR is approximately about 300. The three-cell cavity is also a TESLA-like shape and is made of fine grain high tantalum niobium from CBMM that was melted twice to yeild an RRR of less than 300 [4]. Figure 1 shows the set-up of the nitrogen dope treatment at J-PARC furnace. Both recipes begin with 3 hours of annealing at 800 degrees after high-pressure rinsing and packing. Figure 2 shows the temperature and pressure data for the nitrogen dope treatment. The pressure was 4.8 Pa during the period when the nitrogen was introduced to the three-cell, and was steadied 3 Pa state then. After treatment, the cavity was packed into a plastic bag and transported to KEK.

Figure 1: The set-up of nitrogen doping using oil-free furnace at J-PARC.

EXPERIMENTAL SET-UP

The cavities were measured at the vertical test stand in KEK [5]. The ambient magnetic field was maintained to less than a few mG using the solenoid coil for the single-cell

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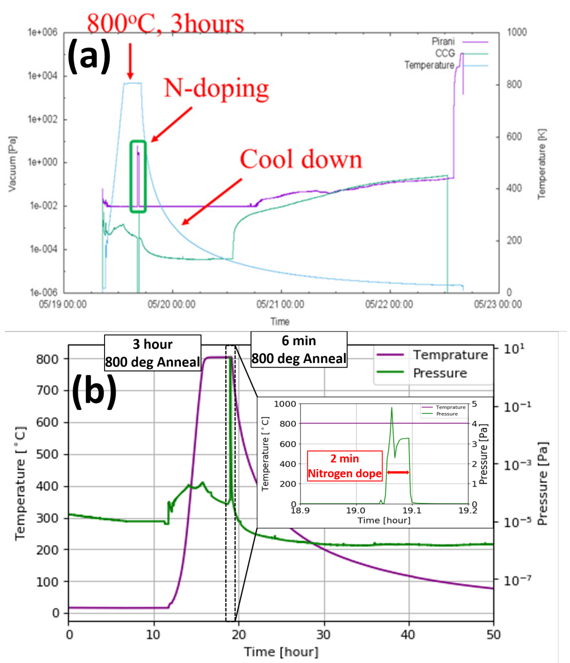

Figure 2: The temperature and pressure data in the nitrogen doping for a) single-cell applied heavy dope [3] and b) three-cell applied light dope.

cavity. The solenoid jig did not fit in the case of the three-cell cavity. The ambient magnetic field is about 6 mG. Figure 3 shows the set-up of the vertical test for the superconducting cavity with fluxgate sensors and silicon thermometers at the equator of cavities. To identify the location of a quench region, the mapping system consists of carbon resisters every 15 degrees, and silicon PIN photodiodes were mounted to each iris area. A heater was used to achieve an temperature gradient [3].

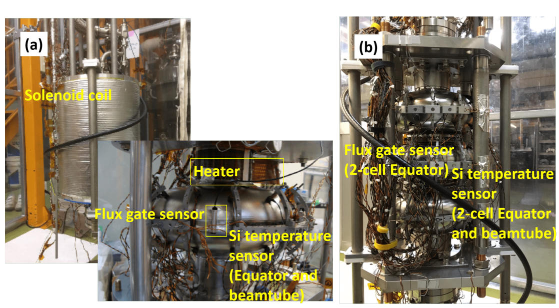

Figure 3: The picture of the set-up for vertical test. a) Solenoid coil, Si sensers and flux gate senser for single-cell cavity applied heavy dope. Using solemoid coil for cancel ambient magnetic field. b) For three-cell cavity applied light dope without solenoid coil.

EXPERIMENTAL RESULTS AND ANALYSIS

The surface resistance is expressed by

$$R_s(T) = R_{BCS}(T) + R_{res}, \tag{1}$$

where $R_{BCS}(T)$ is a temperature depended term and R_{res} is a temperature independent term. Using an approximation, the surface resistance is fitted by as follows:

$$R_s(T) = \frac{A}{T}\exp^{\frac{-\Delta}{k_B T}} + const, \tag{2}$$

the $R_{BCS}(T) = \frac{A}{T}\exp^{\frac{-\Delta}{k_B T}}$ is defined and R_{res} is defined as a constant term. The fitting constant A, exponent related to Δ, and the constant term is determined by a least-squares method in this study.

Single-cell Cavity

The quality factor of the cavity was measured at temperature of 2.0 K, 1.8 K, 1.6 K, and 1.5 K. The upper left of Figure 4 shows the relationship between the quality factor and the accelerating gradient. The reference is the result of the standard recipe that 800 °C annealing and a few EP and 120 °C baking, applied the same cavity. The quench field decrease from 40 MV/m to 14 MV/m and the quench location was changed. The quality factor increased to 3.1×10^{10} from 1.9×10^{10} at 14 MV/m and a temperature of 2.0 K.

The measurement was stoped at 10 MV/m for value of 1.8K, 1.6K, and 1.5K. The surface resistance is separated into the BCS resistance and the residual resistance from the fitting method using data at each temperature. The upper center nad right of Figure 4 shows the result of the BCS and residual resistance as a function of the accelerating gradient. The nitrogen doped cavities exhibitted a distinct anti-Q slope with an increase of accelerating gradient. This result of the BCS resistance exhibits anti-Q slope. The residual resistance decreased to under 2 nΩ. These results show that the nitrogen dope study was successful using the J-PARC furnace.

Three-cell Cavity

Other nitrogen doping recipes light dope was applied to the three-cell cavity. The cavity was measured in the π mode.

The lowerr left of Figure 4 shows the result for measurement of the quality factor as a function of the accelerating gradient at each temperature. The quench field decrease from 35 MV/m to 20 MV/m after nitrogen light doping. The quality factor increase from 1.1×10^{10} to 1.6×10^{10} at 2.0 K. However, at other temperature, the quality factor did not change. Figure 4 lower center and right shows the result of analyzing the surface resistance. The result of the BCS resistance is obtained by fitting of 2 MV/m to 10 MV/m. The BCS resistance decrease with increase accelerating gradient for nitrogen light doped cavity. The analysis of the result includes the quality factor measurement at 4.2 K. The light doping method for three-cell cavity succeeded by anti-Q slope achievement. The residual resistance not changed.

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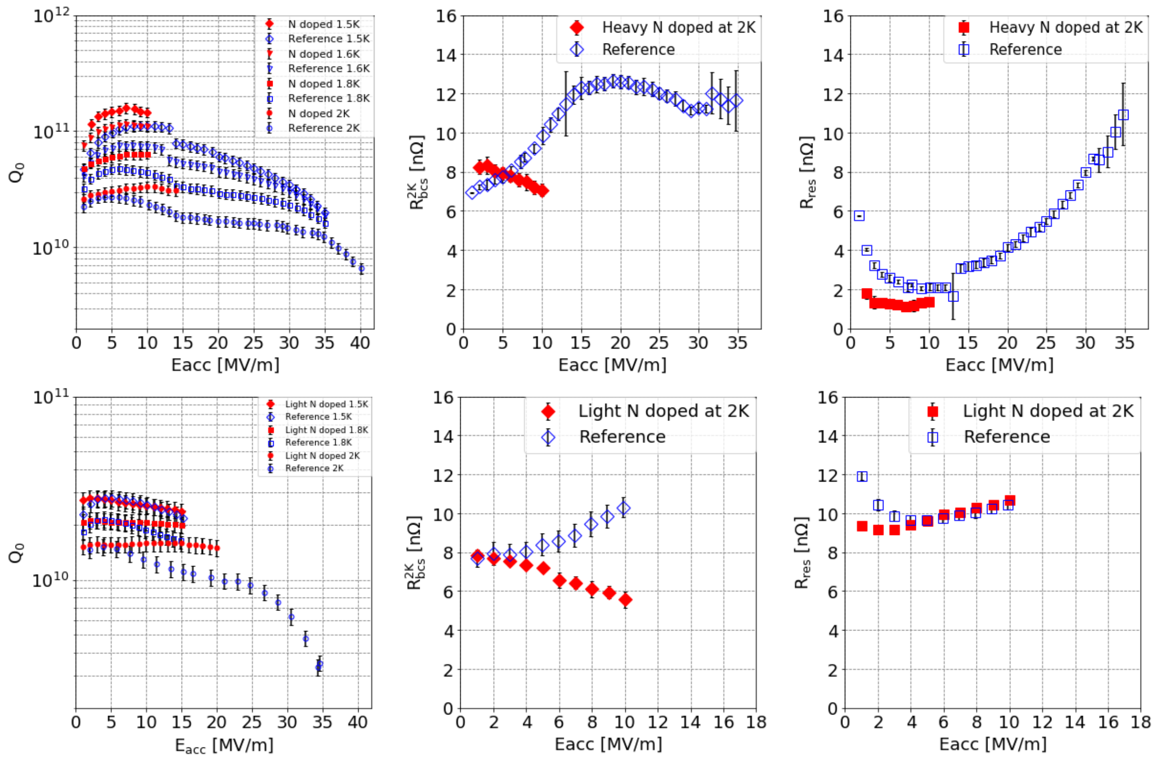

Figure 4: Upper figure shows the result of the heavy doped single-cell cavity. Lower figure shows the result of the light doped three-cell cavity.

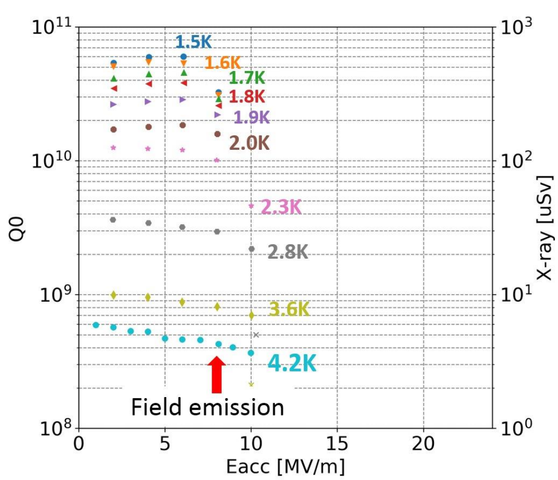

Figure 5: The quality factor measurement retried at each temperature from 1.5 K to 4.2 K.

The test of the three-cell cavity in order to measure the temperature dependence of the nitrogen dope effect was tested. Figure 5 shows the result of measurement at each temperature.

Unfortunately, this measurement occurs the field emission at low gradient about 8 MV/m. Increasing Q starts from about 2.3 K. The re-measurement of the quality factor without field emission is planed.

SUMMARY AND DISCUSSION

Two nitrogen doping recipes were applied in the single-cell cavity and three-cell cavity, respectively. The quality factor at 2.0 K has increased. The BCS resistance exhibit an anti-Q slope in both experiments. The study of nitrogen doping using J-PARC furnace was succeeded. Because the result of the light doped the three cell cavity is not measured with magnetic field cancellation, it is necessary to use the solenoid coil to improve the ambient magnetic field. It is anticipated that the temperature independent term is decreased, result in the quality factor increase. However, the nitrogen doping effect of three-cell over 2.0K temperatures was not outstanding. In particular, an anti-Q slope has not exhibited at 4.2 K.

Overall, the nitrogen doping was successful and the study of nitrogen doping and nitrogen infusion has been initiated at KEK [6, 7].

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