N-DOPING STUDIES WITH SINGLE-CELL CAVITIES FOR THE SHINE PROJECT*

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Abstract

The SHINE SRF accelerator is designed to operate in CW mode with more than six hundred superconducting cavities. In order to reduce the high cost of construction and operation of the cryogenic system, high-Q cavities with nitrogen-doping technology together with traditionally treated large-grain cavities have been considered as two possible options. In this paper, we present N-doping studies on single-cell cavities fabricated with fine-grain and large-grain niobium.

INTRODUCTION

The Shanghai HIgh repetition rate XFEL aNd Extreme light facility (SHINE), updated from the previous name SCLF, is under construction in Shanghai. The SHINE accelerator is designed to deliver an electron beam till 8 GeV based on a CW superconducting (SC) RF Linac [1], applying six hundred 1.3 GHz cavities and sixteen 3.9 GHz cavities.

The main challenge is the 1.3 GHz cavities with specification of Q_0=2~3×10^{10} at E_{acc} = 14~18 MV/m. The fine-grain (FG) cavities with traditional surface treatments, such as BCP, EP together with 120 °C mild baking cannot meet the SHINE high-Q requirements. In recent years, the newly developed technologies, including N-doping, N-infusion and low temperature baking offers the possibility [2, 3, 4]. Especially, the high-temperature N-doping technology discovered by FNAL, further developed by a triparty composed by FNAL, JLAB and Cornell, has been applied on the series production of LCLS-II cavities and is expected to witness beam operation in the following years. In addition, a cavity fabricated with large-grain (LG) niobium is usually expected to have higher Q_0 comparing to a fine-grain one under similarly traditional surface treatment, offering another possibility to achieve Q_0>2×10^{10} at E_{acc} = 14~18 MV/m [5,6].

Aiming to reach the SHINE high-Q requirements, three laboratories in China, including Institute of High Energy Physics of the Chinese Academy of Sciences (IHEP), Peking University (PKU), and our lab in Shanghai, have been carrying out the relative studies on N-doping technology as well as on large-grain cavities.

We have fabricated eight 1.3 GHz single-cell cavities, among them half in FG and the other half in LG niobium. Different surface treatments, including various N-doping recipes and no-nitrogen baseline one, have been applied on these cavities. These 1.3 GHz cavities are fabricated at Ningxia and tested at PKU.

Besides, another eight 3.9 GHz single-cell cavities made in FG and LG niobium from Ningxia have also been fabricated not only to study the N-doping technology on higher frequency cavities but also to pre-prepare some relative devices and skills for the project. Some of them have been tested at IHEP, with a baseline test at INFN-LASA. Due to less priority, 3.9 GHz cavities will be not be reported in detail here.

In this paper, we present the design, fabrication, surface treatment and vertical test results of the single-cell cavities that are dedicated to N-doping studies.

CAVITY DESIGN AND FABRICATION

A design of a single-cell cavity can be divided into three parts: the shape of the cell, the length of the tubes, and the size of the flanges.

Firstly, in order to present a RF performance similar to the 9-cell cavity, we designed a single-cell cavity with closer peak-field ratio to the 9-cell one. Therefore, we chose the longer end half-cell of TESLA cavity to form the 1.3 GHz single-cell cavity [7], and chose the inner-cell of the E-XFEL third-harmonic cavity for the 3.9 GHz single-cell cavity [8]. The design parameters for the 1.3 GHz and 3.9 GHz single-cell cavities are shown in Table 1.

Table 1: Single-Cell Cavity Design Parameters

Cavity type	1.3 GHz	3.9 GHz
Design freq. (MHz)	1299.8	3814.5
G (Ω)	278	271
R/Q (Ω)	105.0	91.9
L_{eff} (mm)	115.4	38.4
E_p/E_{acc}	1.88	1.85
B_p/E_{acc}(mT/(MV/m))	4.28	4.60
Φ_{tube} (mm)	78	30
L_{tube} (mm)	155	70

Secondly, for the tube length, we balanced the influence of Q measurement with stainless-steel flanges and the cost of tube material, and chose a proper length for both cavity types. Finally, to choose the flanges, we mainly consider the compatibility issues, including the existing sealing flanges, interfaces, and the existing equipment such as simple EP device, HPR etc. Therefore, we chose the standard TESLA-cavity flange for the 1.3 GHz single-cell cavity, and designed a large flange for the 3.9 GHz single-cell cavity, suitable to the future 3.9 GHz 9-cell cavity as well.

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In order to speed up the surface treatment research and to achieve a repeatable result, a total of 16 single-cell cavities have been fabricated, as shown in Figure 1.

Figure 1: 16 single-cell cavities made in FG and LG Nb.

Due to the tricky mechanical property of LG niobium and a relatively higher deformation rate to form a 3.9 GHz half-cell, the wall thickness was not uniform at the trial stage. Many efforts were made to improve the cell-shape and wall-thickness uniformity. Except two half-cells were not measured, the wall thickness of the other 6 LG half-cells used on the single-cell cavities is shown in Figure 2. The equator, position 1 is cut thinner to ensure full penetration of EB welding.

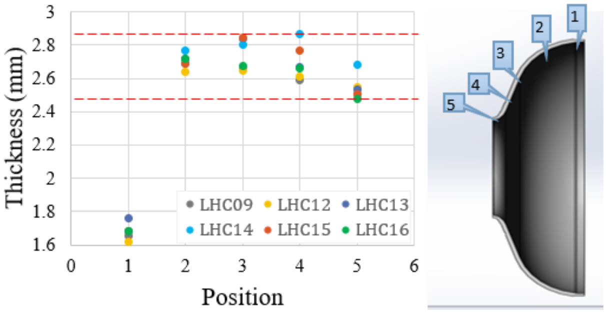

Figure 2: Wall thickness at different positions of the fabricated LG 3.9 GHz half-cells.

SURFACE TREATMENTS

After fabrication, the single-cell cavities are surface treated for N-doping studies or baseline measurements. For the 1.3 GHz cavities, all the N-doped ones experienced heavy polishing with a combination of BCP and EP, followed by a high-temperature heat treatment and a N-doping at 800℃, and finished with light polishing by EP.

The surface damaged layer is etched by not only EP but a combination with BCP to increase the average etching rate due to time limit at the company. Concerning to the baseline cavities in the first batch, all of them are etched by only BCP at both heavy and light polishing steps, in order to exclude an uncertain influence by the simple EP. In order to preclude a possible Q-decrease caused by flux trapping in the damaged layer, according to PKU's studies on Ningxia OTIC niobium [9], the heavy-polishing thickness has been increased to 250 μm for all the eight 1.3 GHz single-cell cavities. In future, more studies are required to evaluate this proper thickness removal for 9-cell cavities.

Previous studies by FNAL showed that for a cavity made in Ningxia's FG niobium, the annealing temperature needs to be increased to 950/975 °C to benefit enough high Q_0 from N-doping treatment [10].

Due to the possibly nonuniform removal by the simple EP device, we started the studies from the heavy-doping recipes, developed by JLab and Cornell University [11], to bear larger thickness error in the light polishing after doping. Meanwhile, we have also studied the 2/6-recipe developed by FNAL. More recipes are also in trial or under development, including the recent 3/60-recipe developed by JLab that is able to bring the maximum accelerating gradient higher than 30 MV/m [12].

After high-temperature N-doping, the poor SC nitride layer has to be removed by chemical polishing. For 2/6 recipe, FNAL studies show that the optimum thickness removal is 5 - 7 μm; and for 20/30 recipe, JLAB studies show that the optimum removal range is 10-25 μm [13]. For 2/6 recipe, we adopt 5 μm for the 1300-L03 cavity. And for 20/30 recipe, we adopted 15 μm for 1.3 GHz LG cavities, and 20 μm for 1.3 GHz FG ones. The recipes applied on the 1.3 GHz single-cell cavities are shown in Table 2. Among them, the cavity 1300-S02 suffered an accident of acid residue after 1st EP light polishing, removed by 5 μm EP etching as solution, but then suffered an HPR rod stop that created 3 burning circles in the tube. Due to this reason, 1300-S02 was re-treated for N-doping and vertical test.

Table 2: Surface Treatment Recipes for The Eight 1.3 GHz Single-Cell Cavities

Cavity N°	**Heavy polishing [um]**	**HT for 3h**	**N-doping @ 800C ~3.3 Pa**	**Light polishing**
1300-S01	BCP170+EP80	975℃	20/30	EP20
1300-S02 (1st treat.)	BCP170+EP80	975℃	20/30	EP20+EP5
2nd treat.#	EP20	800℃	20/30	EP20
1300-S03, S04	BCP250	800℃	-	BCP20
1300-L01, L02	BCP170+EP80	800℃	20/30	EP15
1300-L03	BCP170+EP80	800℃	2/6	EP5
1300-L04	BCP250	800℃	-	BCP20

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VERTICAL TEST

Clean Assembly

After surface treatment at company, the cavities are sent to SRF lab for vertical test preparation, including ultrasonic cleaning, high pressure water rinsing (HPR), clean assembly, leak check and so on. In order to reduce surrounding residual magnets, the flanges, bolts and screws are made in 316L stainless steel, and annealed in high temperature furnace. Before mounting to the cavities, each bolt and screw is checked with residual magnet measurement device. Figure 3 shows the single-cell cavities cleanly assembled on the insert for vertical test at PKU.

Figure 3: Single-cell cavities cleanly assembled on the insert for vertical test.

Test Results

Figure 4 shows the vertical test results of 1.3 GHz LG cavities. All the three N-doped LG cavities achieve high Q_0 at 2K with maximum accelerating gradient (E_{acc}) higher than 18.5 MV/m. Among them, the maximum E_{acc} of lightly N-doped cavity L03 reaches 22.5 MV/m. And the two heavily N-doped cavities, L01 and L02, show similar RF performances. The RF performance of all these three cavities exceeds the SHINE specifications. Compared with the BCP baseline cavity L04, Q_0 is obviously improved, and the anti-Q-slope phenomenon, a typical characteristic of N-doping, is also observed. These test results show that a repeatable N-doping technology has been realized on LG single-cell cavities.

Concerning to the baseline cavity, L04 reaches 2.3x10^{10} at around 5 MV/m, which is a normal level, but Q_0 decreases rapidly after 6 MV/m, and the maximum E_{acc} only reaches to 9.5 MV/m, accompanied by a strong X-ray radiation. The strong field emission is very likely due to a contamination by changing the CF35 copper gaskets, in order to seal the leakages found at the valve flanges that are near to the open tube of cavity. During the re-assembly, the other cavity L01 was mounted on the same insert with valve closed, hence suffered less contamination. The other two LG cavities, L02 and L03 that were tested at another cooldowns, without appreciable field emission.

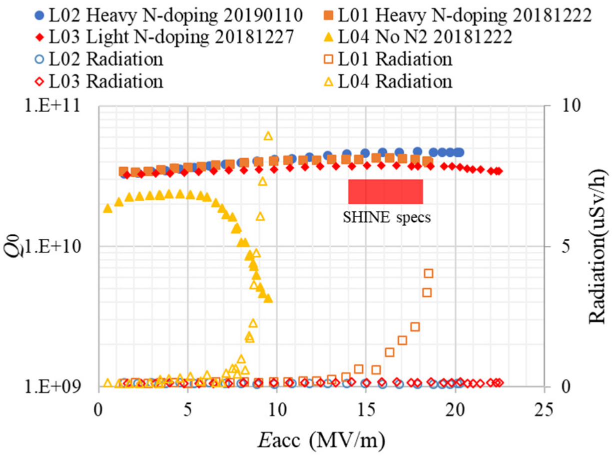

Figure 4: Test results of 1.3 GHz LG cavities at 2K.

During the tests of 1300-L03 cavity, we found that Q_0 decreased about 10% after each quench. As shown in Figure 5, the first quench appeared at 18 MV/m (T1), the second at 17.5 MV/m (T2, power decreased from maximum), and the maximum Q_0 droped to 3.6x10^{10} (about 20% lower than T1); the third quench appeared at 1.6 K with a maximum E_{acc} reached to 22.5 MV/m. The fourth quench happened at 2 K test (T3) after rising temperature from 1.6K. After 4 quenches, the Q_0 at 2K was only 3.4x10^{10}, but the maximum E_{acc}=22.5 MV/m was maintained. The Q_0 drop is likely due to the trapped flux during each quench.

To verify this assumption, we raised the temperature to 15 K and re-cooled down to 2 K. In the 4th test (T4), the Q_0 increased to 3.7x10^{10} and the maximum E_{acc} reached again to 22.5 MV/m, as shown in Figure 5. This result partially verifies the above assumption, but Q_0 still does not return to the level in T1, which maybe explained that the temperature up to 15 K is still too low to create an enough vertical temperature gradient to effectively expulse flux [14].

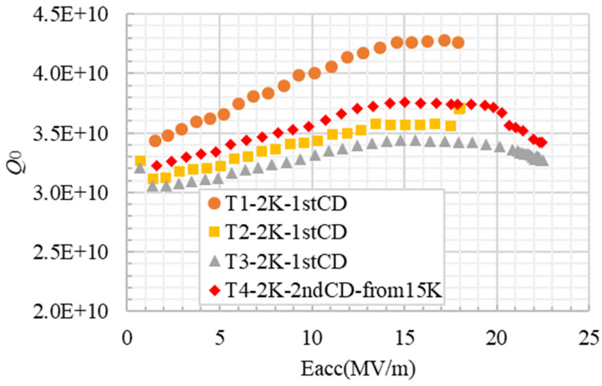

Figure 5: N-doped cavity, 1300-L03 Q-E curves at 2K after different number of quenches.

In the first batch of surface treatment, the N-doping results on 1.3 GHz FG cavities are not as good as the

LG ones. Figure 6 shows the test results of the two FG cavities, including the heavily N-doped S01 and baseline S04. Compared with the baseline cavity, the Q_0 of S01 has a significant increase at low E_{acc} region but decreases gradually from 5 MV/m and quenches at 18 MV/m without appreciable field emission. Similarly, even the baseline cavity quenches at a low accelerating gradient. More studies are undergoing to find the reason and to improve the surface treatments.

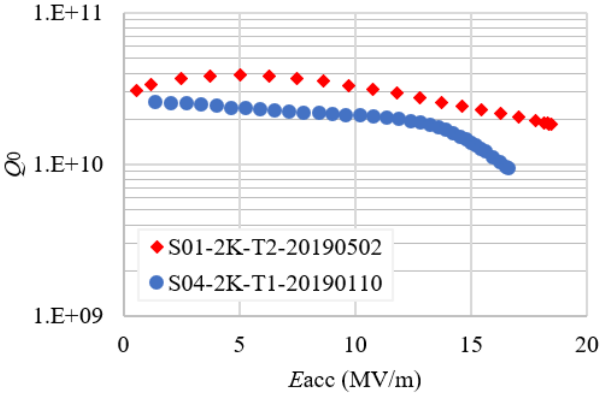

Figure 6: Vertical test results of 1.3 GHz FG single-cell cavities (S01 N-doped, S04 baseline).

SUMMARY

In total, 16 single-cell cavities have been fabricated to study N-doping technology for SHINE project. Up to now, we have realized the 20/30 and 2/6 N-doping recipes on the 1.3 GHz LG single-cell cavities, and have achieved repeatable results. For the 20/30 recipe, Q_0 reaches $4.7\mathrm{x}10^{10}$@E_{acc}=16 MV/m, with a maximum E_{acc}=20.3 MV/m; and for the 2/6 one, Q_0= $3.7\mathrm{x}10^{10}$@16 MV/m with a maximum E_{acc}=22.5 MV/m. Both exceeds the SHINE specification. Q-enhancement by N-doping on FG cavities has been observed but not fully meet SHIEN specification yet. More studies are undergoing to improve the surface treatment technology, including various N-doping recipes.

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