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Nitrogen doping/infusion of 650 MHz cavities for CEPC

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Abstract The nitrogen doping/infusion of 650 MHz cavities for the circular electron positron collider (CEPC) is investigated in this study. Two 650 MHz 1-cell cavities are first treated via buffered chemical polishing (BCP), followed by nitrogen doping. A “2/6” condition is adopted, similar to that for 1.3 GHz cavities of Linear Coherent Light Source II. The quality factor of both cavities improved to 7×10^{10} in low fields, i.e., higher than that obtained from the baseline test. One 650 MHz two-cell cavity is nitrogen infused at 165 °C for 48 h with a BCP surface base. The intrinsic quality factor (Q_0) reached 6×10^{10} at 22 MV/m in the vertical test, and the maximum gradient is 25 MV/m, which exceeds the specification of the CEPC (4×10^{10} at 22 MV/m).

Keywords Superconducting radio frequency cavity · Nitrogen doping · Nitrogen infusion · Quality factor · Accelerating gradient

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1 Introduction

Currently, superconducting radio frequency (SRF) cavities with a high quality factor (Q) are adopted in large accelerators worldwide [1, 2]. The Linear Coherent Light Source II (LCLS-II) in America uses a specific condition for nitrogen doping to increase Q_0 of 1.3 GHz 9-cell cavities. The average Q_0 of 280 nitrogen-doped 9-cell cavities reached 3.1×10^{10} at 16 MV/m, which exceeded the specification of 2.7×10^{10}. Owing to the excellent results of nitrogen doping, the LCLS-II High Energy program has continued to adopt nitrogen-doped cavities [3], which can be operated at 20.8 MV/m with Q_0 of 2.7×10^{10}. In China, the construction of the Shanghai high repetition rate XFEL and extreme light facility (SHINE) began in April 2018, for which six hundred 1.3-GHz 9-cell cavities were required to obtain an 8 GeV electron beam. Moreover, the nitrogen doping of 1.3 GHz cavities was conducted in several institutes including the Peking University in China [4–6], and preliminary improvement was observed.

The circular electron positron collider (CEPC) is a high-energy collider at the Higgs factory that can operate in the W and Z modes [7]. The SRF system of the CEPC is extremely challenging because of the associated wide beam energy and current [8]. Two hundred and forty 650 MHz two-cell cavities exist in the collider, and ninety-six 1.3

GHz nine-cell cavities exist in the booster of the CEPC tunnel, which is located 100 m underground. The 650 MHz two-cell cavity will be operated in continuous wave mode with high Q, rendering the cryogenics system economical. The Q_0 was 4×10^{10} at an accelerating gradient (E_{acc}) of 22 MV/m for the vertical acceptance test, and 1.5×10^{10} at 19.7 MV/m for the operation [9]. This specification is critical for the SRF cavity of a circular collider, which has a more constrained environment than linacs (such as LCLS-II and SHINE).

Compared with the nitrogen doping/infusion of 1.3 GHz cavities, that of 650 MHz cavities are investigated less. Nitrogen doping of 650 MHz cavities was conducted at Fermi National Accelerator Laboratory (FNAL) [10]; it reached $\sim 7 \times 10^{10}$ at 22 MV/m and recorded the highest Q worldwide. Nitrogen doping/infusion of 650 MHz cavities for the CEPC was conducted in collaboration with the Institute of High Energy Physics and Peking University. Nitrogen doping/infusion studies worldwide are primarily based on electro-polishing (EP), which can achieve a higher E_{acc} than BCP. However, EP facilities are complicated and expensive, and EP conditions for 650 MHz cavities does not exist China. By contrast, BCP is considerably simpler and more convenient process than EP. Therefore, nitrogen doping/infusion based on BCP has been adopted and proven to be effective. Two 650 MHz one-cell cavities received nitrogen doping, and one 650 MHz two-cell cavity received nitrogen infusion. The nitrogen doping/infusion treatment and vertical test of 650 MHz superconducting cavities are presented herein.

2 Nitrogen doping of 650 MHz 1-cell cavities

In this study, nitrogen doping was conducted on two 650 MHz 1-cell cavities (650S1, 650S2) made of fine-grain Nb. The primary parameters of the Nb used are listed in Table 1.

BCP was performed prior to nitrogen doping/infusion. The polishing was performed at the vertical BCP facility of Ningxia Orient Superconductor Technology Co., Ltd.

Table 1 Primary parameters of fine-grain niobium

Parameter	Value
RRR	350–400
ASTM size	6.0–5.5
HV10	~ 47.8
Yield strength (MPa)	~ 64
Tensile ultimate strength (MPa)	~ 170

(OSTEC), as shown in Fig. 1, which has been used for all types of SRF cavities. Both cavities received bulk BCP (150 μm), annealing at 750 °C for 3 h, and light BCP (30 μm). Subsequently, they were assembled in a clean room and subjected to low-temperature baking (120 °C for 48 h). The vertical test results (baseline) of the two cavities are shown in Fig. 2. The maximum gradients of 650S1 and 650S2 reached 19.3 and 24.7 MV/m, respectively. Field emission, which might have resulted from contamination during the process, was observed at low fields in both cavities.

After performing the vertical test on the BCP baseline, both cavities received another light BCP (30 μm) to eliminate contamination on the inner surface. The two cavities were nitrogen doped based on a "2/6" recipe, similar to that for the 1.3 GHz cavity of LCLS-II. First, the furnace was pumped until the pressure was less than 2×10^{-4} Pa. Second, the furnace was heated by ramping its temperature to 800 °C for 3 h. Third, the furnace was maintained at 800 °C for 3 h for annealing. Finally,

Fig. 1 (Color online) Setup for BCP of 650 MHz 1-cell cavity

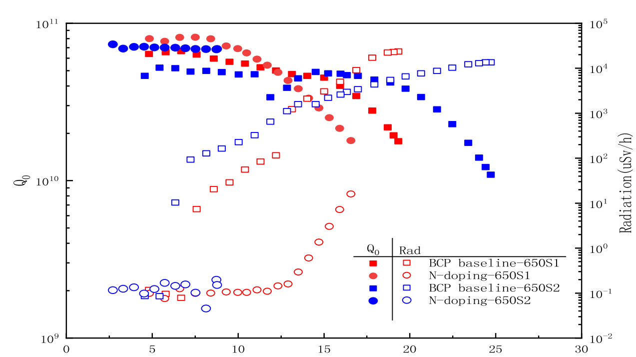


Fig. 2 (Color online) Vertical test results of 650S1 and 650S2 (at 2.0 K)

Table 2 Primary parameters of 650 MHz 2-cell cavity

Parameter	Value
Beam aperture (mm)	156
B_{peak}/E_{acc} (mT/(MV/m))	4.2
E_{peak}/E_{acc}	2.4
R/Q (Ω)	213
G (Ω)	284
K	2.86%

nitrogen gas was injected into the furnace for 2 min at ~ 3.5 Pa, followed by annealing at 800 °C for 6 min. Finally, the furnace was cooled to ~ 50 °C under vacuum.

Because it is extremely difficult to achieve uniform removal via BCP, neither cavity underwent etching after nitrogen doping. The vertical test results at 2.0 K are shown in Fig. 2. The Q_0 of both cavities exceeded 7×10^{10} at low fields, which was higher than that obtained via the BCP baseline test. The Q-slope of 650S1 was evident above 10 MV/m; cavities 650S1 and 650S2 quenched at 16.6 and 8.8 MV/m, respectively. To remove the niobium nitride phase layer, the inner surface of the cavity after nitrogen doping must be removed lightly, and this is generally achieved via EP. Because no EP device exists, it is more suitable to improve the Q and E_{acc} of 650 MHz cavities via nitrogen infusion, which requires no EP of the inner surface after infusion [11].

3 Design of 650 MHz 2-cell cavity

Nitrogen infusion was performed on a 650 MHz 2-cell cavity. One 650 MHz 2-cell cavity was designed, manufactured, post-processed, nitrogen-infused, and tested.

The radio frequency (RF) design of a 650 MHz 2-cell cavity (650D1) was optimized to minimize B_{peak}/E_{acc} and E_{peak}/E_{acc}. Meanwhile, the R/Q and cell coupling (k) should be maximized. The final RF parameters are presented in Table 2 [8].

The two important mechanical parameters of the 650 MHz 2-cell cavity were the Lorentz force detuning coefficient (K_L) and frequency sensitivity to pressure (df/dp). The geometry and dimensions of the cavity are shown in Fig. 3. Two cavity wall thicknesses (3 and 4 mm) were compared, as summarized in Table 3. Finally, the 4 mm thickness was adopted because of the lower K_L and df/dp.

4 BCP baseline test of 650 MHz 2-cell cavity

The 650 MHz two-cell cavity (650D1) was manufactured with fine-grain Nb, same as the 650 MHz one-cell cavity. Before nitrogen infusion, the cavity received bulk BCP (200 μm), annealing at 800 °C for 3 h, and light BCP (30 μm); subsequently, it was assembled in a clean room. A vertical test was performed after these treatments, as shown in Fig. 4. The vertical test system comprised double magnetic shields, and the residual magnetic field around the cavity was less than 5 mGs. No compensation coils were used during the vertical test. Fast cooling was performed at a speed of ~ 5 K/min. The vertical test results of the BCP baseline at 2.0 K are shown in Fig. 5. The Q_0 of 650D1 reached 3.3×10^{10} at 22 MV/m. Finally, the cavity quenched at 26.5 MV/m with a Q_0 of 1.4×10^{10}. Strong multipacting occurred when the gradient was 11–18 MV/m; however, it can be avoided by increasing the input power. The simulation shows that multipacting can occur between 8 and 20 MV/m, which is consistent with the vertical test [9]. The radiation resulting from field emission began to increase at 18.8 MV/m, indicating contamination on the inner surface of the cavity.

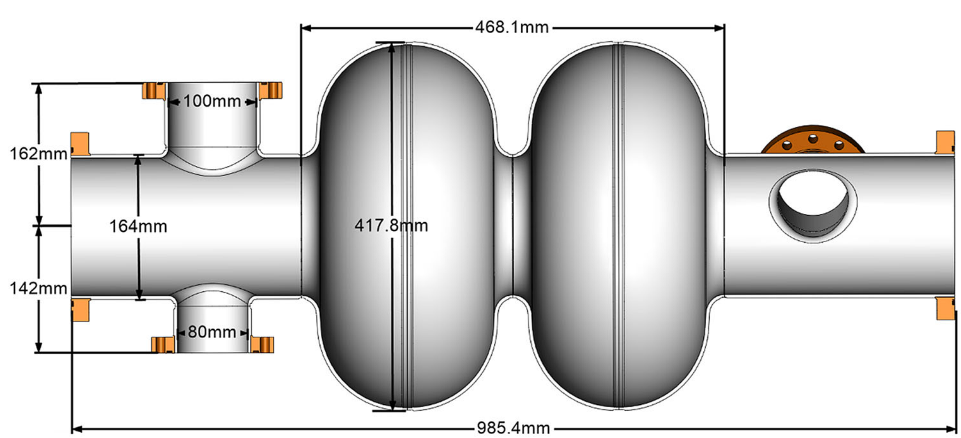


Fig. 3 (Color online) Geometry and dimensions of 650 MHz 2-cell cavity

Table 3 Mechanical parameters of 650 MHz 2-cell cavity

Parameter	Condition	Units	3 mm	4 mm
Max stress (under 2 atm)	Beam ports fixed	MPa	24.7	20
d*f*/d*p*	Beam ports free	Hz/mbar	256	185
	Beam ports fixed	Hz/mbar	6.4	0.95
Tuning sensitivity	–	kHz/mm	558	313
Tuning stiffness	–	kN/mm	3.7	6.4
Tuning range (293 K)	–	kHz	705	353
K_L	Beam ports free	Hz/(MV/m)^2	8.2	7.4
	Beam ports fixed	Hz/(MV/m)^2	0.88	0.6

5 Nitrogen infusion of 650 MHz 2-cell cavity

The 650 MHz two-cell cavity (650D1) received another light BCP (30 µm) and high-pressure rinsing (HPR) to remove possible contamination and reset the inner surface after the BCP baseline test. Subsequently, the cavity was transferred to a furnace for nitrogen infusion [12]. All six flanges were covered with clean Nb foil to avoid contamination and dust during nitrogen infusion, as shown in Fig. 6.

The "165 °C 48 h" condition, which may achieve a higher Q than the "120 °C 48 h" condition, was adopted in nitrogen infusion [11]. The pressure and temperature during nitrogen infusion are shown in Fig. 7. First, the furnace was heated by ramping the temperature to 800 °C and maintaining it at that temperature for 3 h for annealing. Second, the furnace was cooled to 165 °C and maintained for half a minute. Third, nitrogen gas was injected into the furnace for 48 h at ~ 3.5 Pa. Finally, the furnace was cooled to ~ 50 °C under vacuum.

The inner surface of the nitrogen-infused 650D1 was analyzed using a new inspection camera. A typical image of the equator is shown in Fig. 8a; it is considerably rougher compared with that observed after EP, as shown in Fig. 8b. No defects were observed on the entire inner surface of the 650D1.

After nitrogen infusion, 650D1 underwent HPR and was assembled in a clean room for vertical testing. The vertical test results of 650D1 at 2.0 K are shown in Fig. 9. In the first vertical test, Q_0 reached 7.2 × 10^{10} at 9 MV/m, which was 40% higher than the BCP baseline. However, Q_0 decreased rapidly above 9 MV/m because of strong field emissions induced by contamination during clean room assembly and transfer. Finally, the gradient reached 13.6 MV/m with a Q_0 of 5.2 × 10^9. To eliminate the field emission, 650D1 was subjected to HPR and re-assembled, followed by a second vertical test. At this time, the cavity achieved a higher Q_0 than the BCP baseline over the entire range of gradient. The Q_0 was 6 × 10^{10} at 22 MV/m, which exceeded the vertical test specification (4 × 10^{10} at 22 MV/m) for the CEPC. This result is similar to that recorded by FNAL (7 × 10^{10} at 22 MV/m), which was based on EP. Therefore, nitrogen infusion based on BCP is applicable in medium fields (~ 20 MV/m). No field emission was observed until the quench gradient reached 25 MV/m with a Q_0 of 3.3 × 10^{10}. Multipacting was avoided by increasing the input power. To eliminate the multipacting effect, a new 650 MHz 2-cell cavity has been designed and proven to be effective [13].

Fig. 4 (Color online) Vertical test of 650 MHz 2-cell cavity

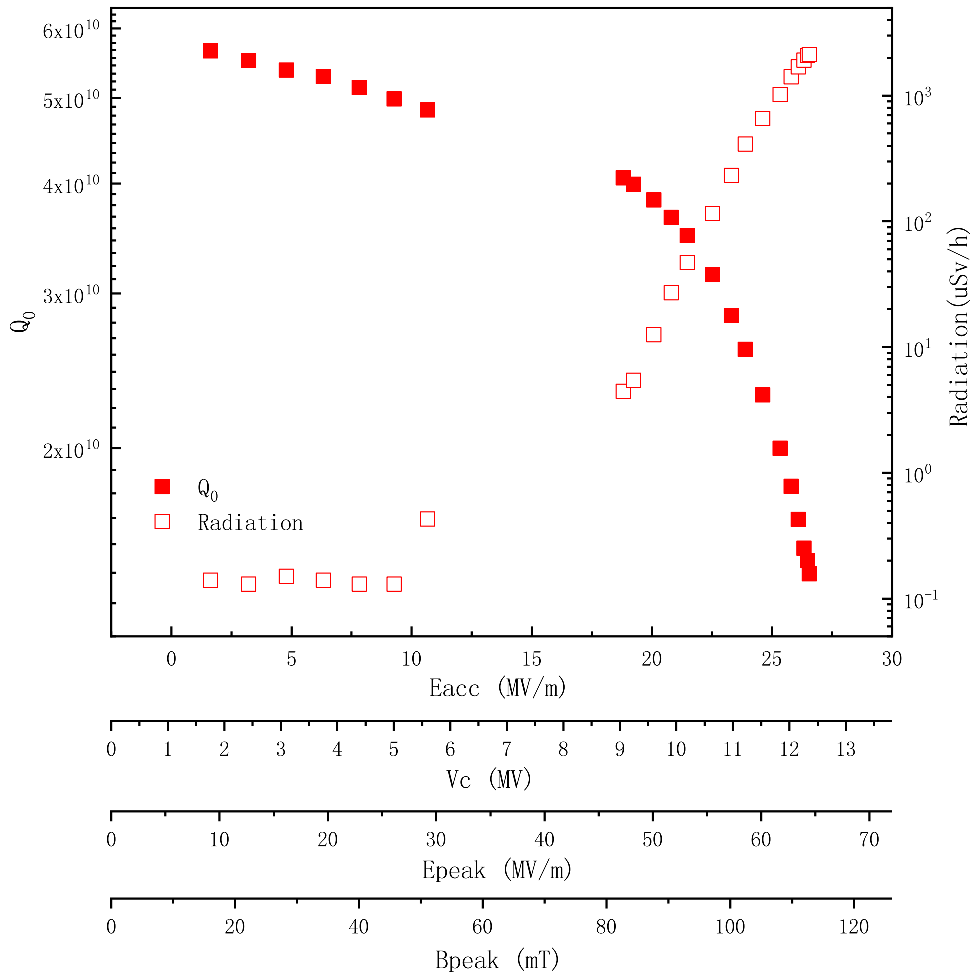


Fig. 5 (Color online) Vertical test results of BCP baseline (at 2.0 K)

Fig. 6 (Color online) Nitrogen infusion of 650 MHz 2-cell cavity

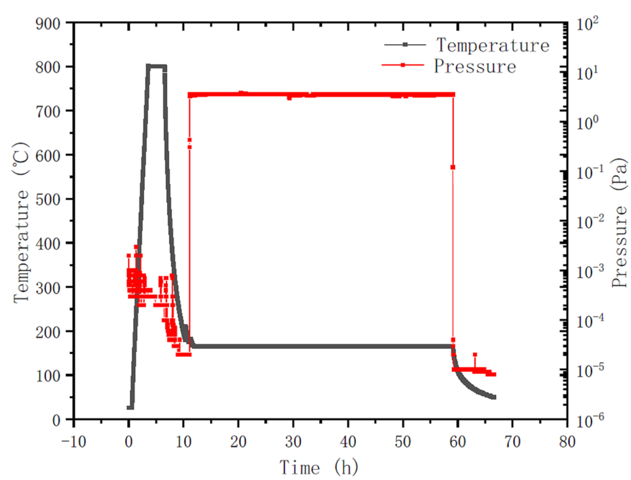
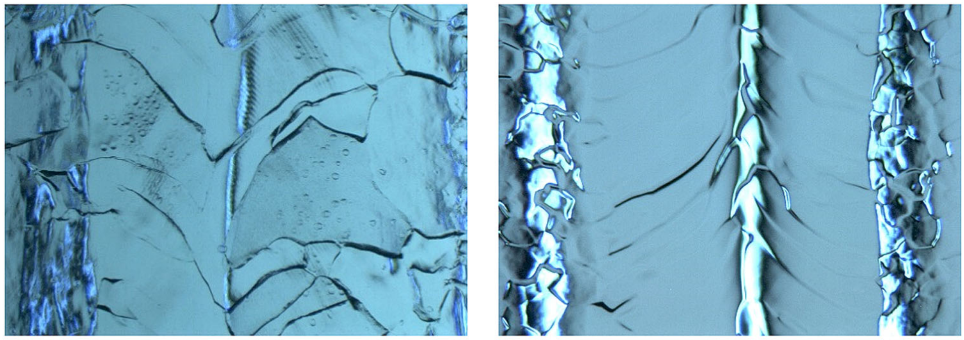


Fig. 7 (Color online) Temperature and pressure during nitrogen infusion



(a) (b)

Fig. 8 (Color online) Inspection of cavity equator. (a) 650D1 (nitrogen infused); (b) 1.3 GHz cavity (after EP)

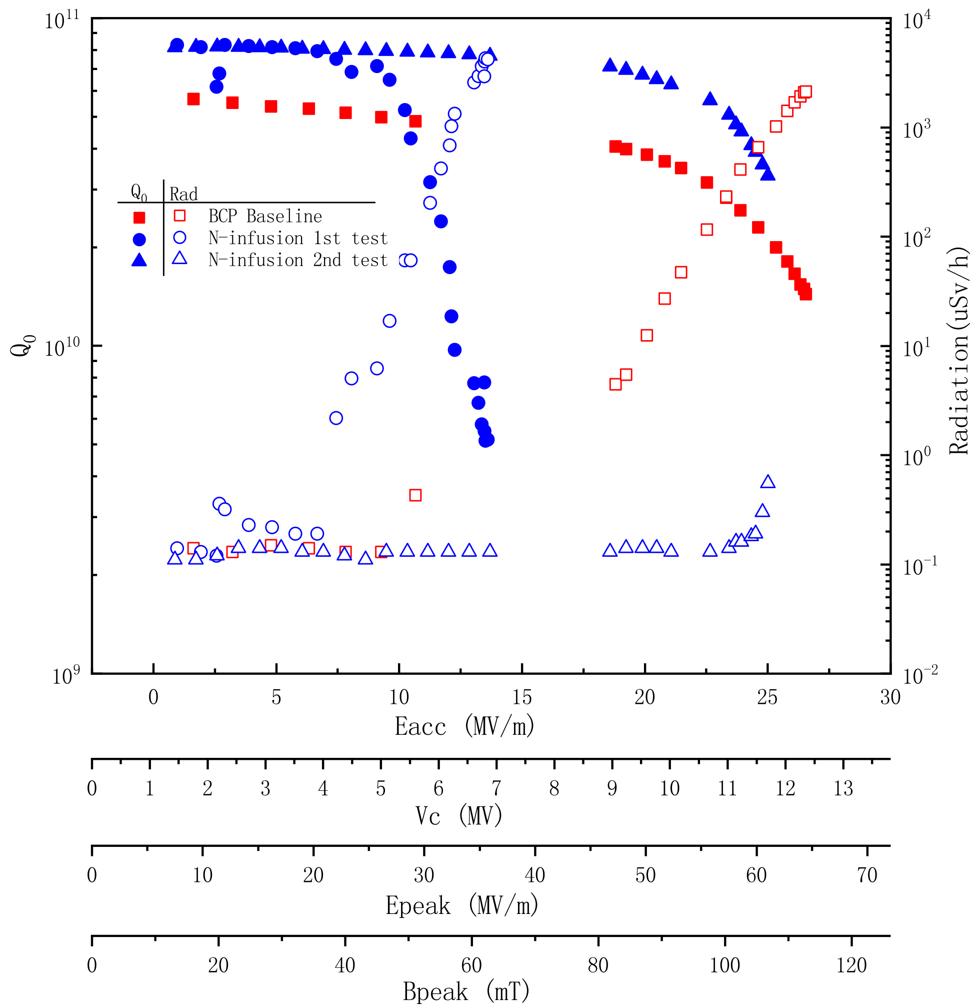


Fig. 9 (Color online) Vertical test results of 650 D1 (at 2.0 K)

6 Conclusion

Nitrogen doping and infusion studies were conducted on 650 MHz superconducting cavities for CEPC. Owing to the lack of EP conditions for the 650 MHz cavity and to identify other possible methods, a BCP surface baseline was adopted, and no BCP or EP was conducted after nitrogen doping/infusion.

Owing to nitrogen doping, the Q_0 of the 650 MHz 1-cell cavity exceeded 7×10^{10} at low fields, which was higher than the 5–6 $\times$ 10^{10} obtained via the BCP baseline test. The 650 MHz 2-cell cavity attained a Q_0 of 6×10^{10} at 22 MV/m after nitrogen infusion based on the "165 °C 48 h" condition. It was evident that nitrogen infusion increased Q_0. Both Q_0 and E_{acc} exceeded the specifications of the CEPC.

Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Peng Sha, Jian-Kui Hao and Ji-Yuan Zhai. The first draft of the manuscript was written by Peng Sha and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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