LOW TEMPERATURE HEAT TREATMENT EFFECT ON HIGH-FIELD EP CAVITIES

J. Hao[*#], D. Reschke, A. Brinkmann, L. Lilje, DESY, D-22603 Hamburg, Germany
*Institute of Heavy Ion Physics, Peking University, Beijing 100871, China

Abstract

It is well known that low temperature (100-150) ºC heat treatment ("bakeout") has positive effects on the performance of high field EP cavities. About 60 test results are analysed based on single-cell cavity experiments of the CEA-CERN-DESY collaboration and nine-cell cavities at DESY. The average gradient Eacc,max increased from 31.9 MV/m to 35.6 MV/m after baking. No dependency of Eacc,max and the gain of Eacc,max on the baking temperature is observed. The Q-value at maximum gradient Q_0(Eacc,max) depends significantly on the bake temperature. The average Q_0(Eacc,max)'s are 5.3×10^9, 9.2×10^9 and 8.0×10^9 at bake temperature (100-110) ºC, (120-130) ºC and (130-140) ºC, respectively. Comparison of BCP and EP cavities shows that at least 60-80 µm EP on a BCP surface is necessary. More than 10-15 µm removal of the surface by BCP will reduce the performance of an EP cavity.

INTRODUCTION

The quality factor of a superconducting cavity will degrade at high field after Buffered Chemical Polishing (BCP, or etching) and Electropolishing (EP). This is the so-called “Q-drop” or “Q-slope”. Recent researches show that low temperature treatment (bakeout) has positive effect on reducing the Q-slope of EP cavities[1,2,3]. The bake temperature is around 100-150 ºC.

In this paper, analyses have been done to reveal the low temperature baking effects on superconducting cavities. All the results are based on the single-cell cavity experiments of the CEA-CERN-DESY collaboration and nine-cell cavities at DESY. About 50 EP and 11 BCP cases are included. The accelerating gradient, Q value, effects of baking temperature and other parameters are analysed before and after bakeout.

ANALYZING PRINCIPLE

All the analysed cavities (tests) are etched or electropolished for a certain depth. After vertical cold test, the cavities are baked at 100-140 ºC under vacuum (“in-situ” baking). The baking time is between 24 to 96 hours and most of the baking duration is 48 hours.

According to the removed depth of cavity surface and removal sequence, the cavities are classified into 4 groups:

- BCP after EP: less than 60µm BCP after EP before the rf-test.
- EP after BCP: less than 60µm EP after BCP before the rf-test.
- Pure EP: more than 60 µm EP before the RF test.
- Pure BCP: more than 60 µm BCP before the RF test.

The baking effects are analysed on EP cavities (including pure EP cavities and no more than 10 µm BCP after EP cavities) and BCP cavities (including pure BCP cavities and EP after BCP cavities). The analysed parameters are as following:

- Eacc,max and Eacc,gain;
- Eacc and Eacc,gain@ $Q_0=1 \times 10^{10}$, gradient at high Q;
- Eacc and Eacc,gain@100W*Ncell/9, where Ncell is the number of cells. This parameter is related to about 1 W cryogenic loss during TESLA pulse operation [4]
- Q(Eacc,max) at different bake temperature, the temperature dependency;
- BCP and bakeout, what’s the tolerant BCP depth for an EP cavity;
- Q(Eacc,max) at different oxygen diffusion length, the affection of oxygen.

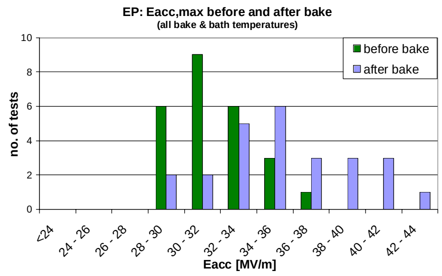
We neglect cavity tests with strong field emission and with repeated baking.

BAKEOUT RESULTS

Eacc,max Before and After Bake for EP Cavities

The accelerating gradient is one of the most important parameters for superconducting cavities. The accelerating gradient Eacc,max and the gain of Eacc,max for EP cavities are shown in Fig. 1. The cavity tests after repeated baking are not included. A gain of 3.7 MV/m on Eacc,max gain is obtained after baking from 31.9 MV/m to 35.6 MV/m. For 3 cavities, the gradients are over 40 MV/m. The maximum is 44.0 MV/m for cavity 1B5. The results show high scatter of Eacc,max (from 29.5 to 44.0 MV/m) and Eacc gain (from –5.0 to 12.4 MV/m).

3 tests after repeated baking show no improvement in gradient.



[#] jiankui.hao@desy.de

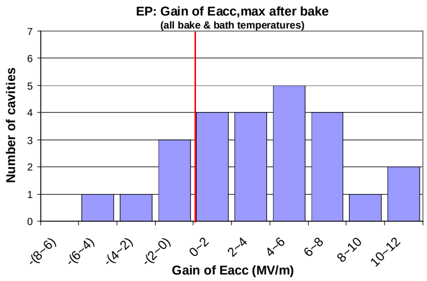
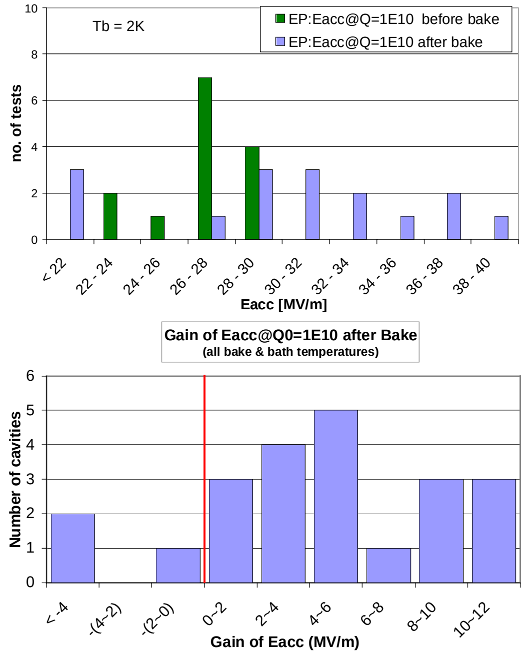

EP: Gain of Eacc,max after bake
(all bake & bath temperatures)

Fig. 1: Eacc,max (top) and Eacc,gain(bottom) after bake

Eacc at $Q=1\times 10^{10}$ Before and after Bake for EP Cavities

The Eacc and the Eacc gain at $Q=1\times 10^{10}$ are shown in Fig. 2. The gradients at $Q=1\times 10^{10}$ are improved after baking under various bath temperature. At bath temperature Tbath=2.0 K, a gain of 3.7 MV/m is obtained (from 27.0 to 30.7 MV/m). For all bath temperature (2.0 K to 1.5 K), the averaged gain is 4.2 MV/m (from 25.7 to 29.9 MV/m).

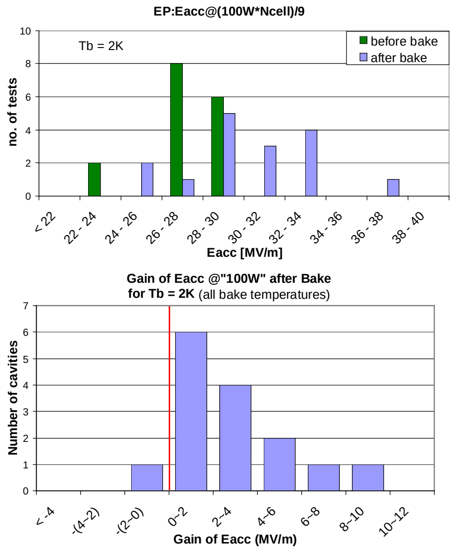


Gain of Eacc@Q0=1E10 after Bake
(all bake & bath temperatures)

Fig. 2: Eacc@$Q=1\times 10^{10}$ (top) and Gain(bottom) after bake

Eacc at 100W*Ncell/9 Before and After Bake for EP Cavities

Eacc@100W is somewhat like Eacc@$Q=1\times10^{10}$, but is more related to the cryogenic loss. The results are shown in Fig. 3. A gain of 3.7 MV/m (from 27.4 to 31.1 MV/m) is obtained at Tbath=2.0 K. At all bath temperature, the gain is 2.8 MV/m (from 27.3 to 30.1 MV/m).


EP:Eacc@(100W*Ncell)/9

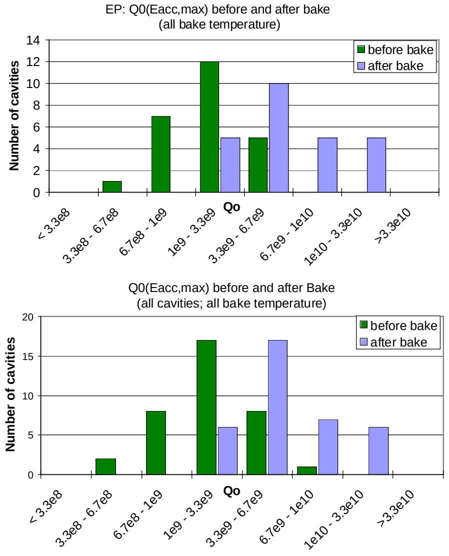
Gain of Eacc @"100W" after Bake
for Tb = 2K (all bake temperatures)

Fig. 3: Eacc@100W(top) and Gain(bottom) after bake

Q_0(Eacc,max) Before and After Bake

The quality factors at highest gradient are shown in Fig. 4. All cavities (EP and BCP) at all bakeout temperature are included. For EP cavities, averaged Q(Eacc,max) is increased from 1.9×10^9 to 6.7×10^9 after baking (all baking temperature). When BCP cavities are included, Q(Eacc,max) reached 6.5×10^9 from 2.3×10^9.

Fig. 5 shows the Q(Eacc,max) at different baking temperature. The exact values are in Table 1 in the following section "bake temperature dependency". The baking temperatures are divided to 3 groups: 100-110 ºC, 120-129 ºC and 130-139 ºC. We have no cavities baked at 110-119 ºC by chance. From Fig. 5 we can see that higher Q(Eacc,max) are obtained at higher baking temperature. One point to mention is that only 4 cavities are baked at temperature 130-139 ºC up to now. More tests are under preparation.


EP: Q0(Eacc,max) before and after bake
(all bake temperature)

Q0(Eacc,max) before and after Bake
(all cavities; all bake temperature)

Fig. 4: Q(Eacc,max) for EP(top) and all cavities(bottom) before and after bake

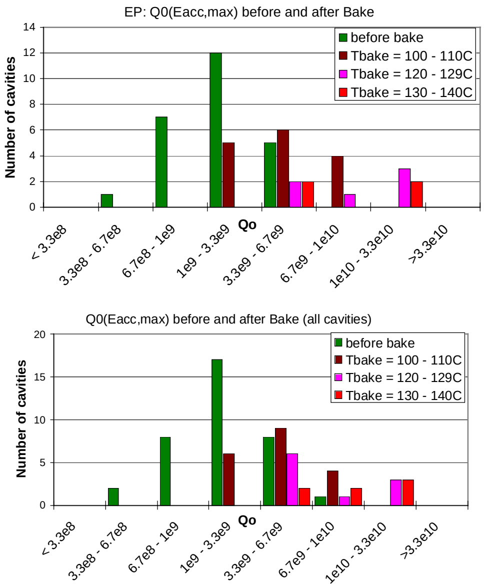


Fig. 5: Q(Eacc,max) for EP(top) and all cavities(bottom) at different bake temperature

Bake Temperature Dependency

The averaged values for Eacc,max, Eacc@Q=1× 10^{10}, Eacc@100W and Q(Eacc,max) at different bake temperature are listed in Table 1. In table 1, Eacc is only for EP cavities and Q is for EP cavities and all cavities (in the brackets). The ratio for Q(Eacc,max) is Q(Eacc,max, before bake)/Q(Eacc,max, after bake). From the table we can see that there is no obvious dependency on baking temperature for Eacc,max after baking.

For Q(Eacc,max) higher bake temperature results in higher Q. One possible interpretion is due to the diffusion of oxygen during baking.

During the baking, the adsorbed oxygen or surface oxides will be diffused into the bulk niobium with the follow diffusion law[5]:

$$\overline{x} = \sqrt{2 \cdot D_0 \cdot \exp(-\tfrac{E_A}{R \cdot T}) \cdot t}\,,$$

where $\overline{x}$ is the averaged diffusion length, D_0=0.015 cm^2/s is the diffusion constant for oxygen in niobium, the activation energy E_A=112890 J/mol, R=8.31 J/(K·mol), T is the temperature, t is the diffusion time. According to the baking parameters, we can get the oxygen diffusion length into the niobium. The Q's in different diffusion length are shown in Fig. 6. The Q at large oxygen diffusion length is higher than at small oxygen diffusion length.

K. Saito and P. Kneisel[2] explained the low gradient behaviour due to oxygen diffusion effect with the two fluid model. Oxygen diffusion from the surface into the bulk shortens the mean free path. Shortened mean free path shortens the coherence length. At smaller mean free path, the R_{BCS} decreases.

For the high gradient behaviour B.Visentin has given an overview for several models trying to describe the improvement of the quality factor at high fields[6].

Table : 1 Bake temperature dependency of Eacc and Q

	bake T(°C)	before bake	after bake	Gain	Ratio
Eacc,max (MV/m)	**all**	**31.9**	**35.6**	**3.7**	
	100-110	**31.9**	**35.9**	**4.0**	
	120-129	**32.6**	**35.8**	**3.2**	
	130-139	**30.8**	**34.4**	**3.6**	
Eacc @Q_0=1× 10^{10} (MV/m)	**All**	**27.0**	**30.7**	**3.7**	
	100-110	**25.9**	**30.5**	**4.7**	
	120-129	**27.9**	**29.4**	**1.5**	
	130-139	**28.2**	**29.6**	**1.5**	
Eacc @100W*Ncell/9 (MV/m)	**All**	**27.4**	**31.1**	**3.6**	
	100-110	**27.7**	**30.5**	**2.8**	
	120-129	**27.7**	**31.0**	**3.3**	
	130-139	**26.5**	**30.5**	**4.0**	
Q_0(Eacc,max) EP(all cavities) (*10^9)	**All**	**1.9(2.3)**	**6.7(6.5)**		**3.5(2.9)**
	100-110	**2.0(2.2)**	**5.3(5.1)**		**2.6(2.3)**
	120-129	**1.8(2.0)**	**9.2(7.7)**		**5.0(3.8)**
	130-139	**1.5(2.7)**	**8.0(8.9)**		**5.4(3.3)**

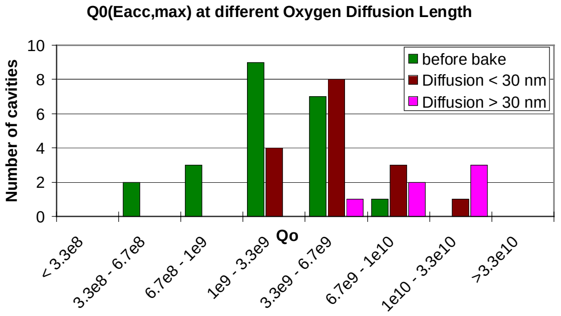


Fig. 6: Q(Eacc,max) distribution at different oxygen diffusion length

BCP & EP Cavities

To comparison of BCP and EP cavities, we can get 4.7 MV/m (from 26.7 to 31.1 MV/m) gain for Eacc@100W and 5.7 MV/m (from 25.0 to 30.7 MV/m) gain for Eacc@Q=1×10^{10}, see Fig. 7.

EP results show broad scattering because multipacting effects often occur at around 20 MV/m.

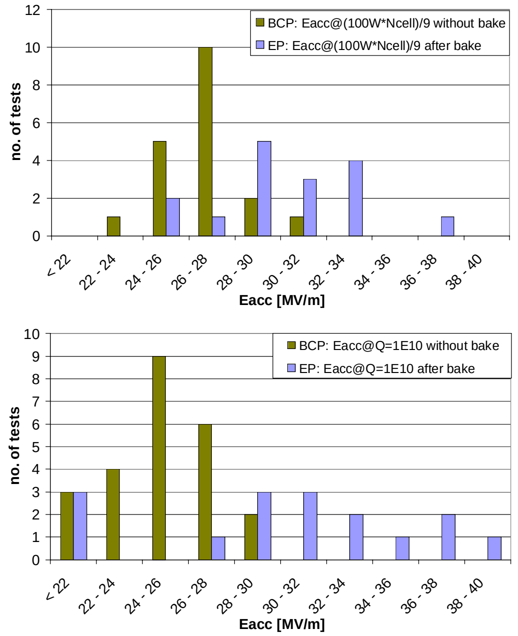


Fig. 7: Comparison of BCP and EP cavities

Emax vs. etched depth of cavity is shown in Fig. 8. The Eacc of originally EP cavities degrade with increasing BCP removal.

A series BCP's are done on cavity 1P6. Each BCP is about 20 µm. After each BCP, the cavity was baked at 100 °C for 48 hours. The Q vs. E curves after bake are shown in Fig. 9, the bath temperature is 2.0 K. We can see clearly that each BCP will degrade the cavity performance. After the third BCP, 60 µm surface was removed by EP and baked at 120 °C for 54 hours, the cavity performance was partially recovered.

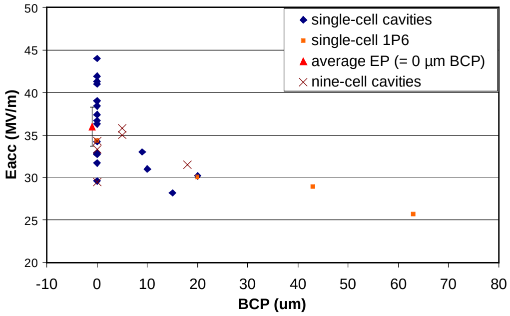


Fig. 8: Performance degradation with BCP thickness

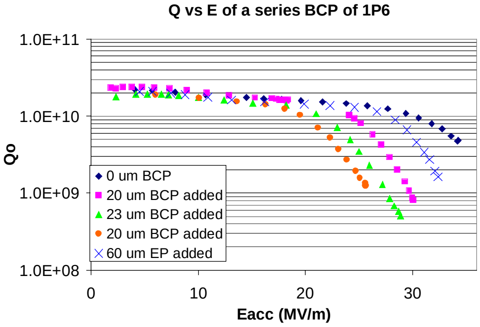


Fig. 9: Q vs. E of a series of BCP on 1P6

CONCLUSIONS

Analyses have been done on low temperature treatment (bake) on EP and BCP cavities. It is obvious that EP + bake is an effective method to improve the performance of superconducting cavities. For EP cavities after EP+bake, the averaged Eacc,max, Eacc@Q=1×10^{10} and Eacc@100W increased by more than 3.5 MV/m. Bake at higher temperature results in higher Q_0(Eacc,max) than at (100 - 110) °C. The performance of a EP cavity will start to degrade if more than 10 µm BCP is done on the EP surface.

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