Study on the 1.3 GHz low loss shape superconducting cavities at IHEP*

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Abstract As part of the international research program on the superconducting cavity for the International Linear Collider (ILC) R&D on the 1.3 GHz low loss superconducting cavities has been carried out at the Institute of High Energy Physics (IHEP) since 2005. A design of 1.3 GHz low loss cavity shape was proposed and six single-cell cavities of different niobium material were successfully fabricated with standard technology. In this study our priority was on large grain (LG) cavities. The two LG cavities were treated with complete procedures of surface treatments based on chemical polishing (CP) without electro polishing (EP) at IHEP. The two LG cavities and a fine grain cavity were sent to KEK for vertical testing. All the three cavities reached accelerating gradients higher than 35 MV/m and the maximum gradient of 40.27 MV/m was achieved in the LG cavity. This paper presents the process of the vertical RF tests and the comparison of the LG and fine grain cavities's performance.

Key words ILC, superconducting cavity, low loss, large grain niobium

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1 Introduction

The accelerating gradient in the ILC main linac is supplied by over 16000 9-cell superconducting RF cavities grouped into approximately 12.6 m long cryomodules[1]. High gradient cavities (>35 MV/m) are the core components for the ILC. The baseline design of the superconducting cavity is the TESLA design developed at DESY over the past 15 years and the cavity specifications for the vertical test on the accelerating gradient and Q-value are 35 MV/m and 0.8×10^{10} or higher respectively. Although the specific requirements have been demonstrated in recent years at some labs, the reliable achievement remains a major challenge to the 9-cell TESLA cavity[2]. Some parallel R&D programs have been carried out in the superconducting cavity technology community, two of which are the study on the new cavity shapes and the large or single crystal niobium.

The TESLA cavity shape is optimized mainly with respect to $E_{\mathrm{peak}}/E_{\mathrm{acc}}$, which can be reduced to suppress electron field emission (FE) at high gradients[3]. Since that time remarkable progress has been made in surface cleaning and final assembly. Many single-cell and multi-cell cavities were tested at very high gradients of more than 35 MV/m showing no FE from residual particulates on the RF surface wall. The intrinsic RF critical magnetic field and the

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hard physical limit were reached in some tests. To push the gradient elevation further, some new cavity shapes with lower ratios of the peak surface magnetic field to the accelerating electric field ($H_{\rm pk}/E_{\rm acc}$) have recently been proposed by slightly changing the cavity cell wall. Two leading new shapes are the low loss and re-entrant shapes[4]. The new shapes have the advantages of higher gradients and less energy dissipation. In 2006 a low loss shape was designed at IHEP named the IHEPLL shape[5] which is similar to the KEK ICHIRO shape. As insight is often gained through study of single-cell cavities, performance improvement is accompanied. Six single-cell cavities with the IHEPLL shape were fabricated in our study[6].

Fig. 1. Cavities with the IHEPLL shape fabricated at IHEP. (Top three: Tokyo Denki fine grain niobium. Bottom left two: China Ningxia LG Niobium; Bottom right: China Ningxia fine grain niobium).

The LG and single crystal niobium were proposed several years ago as an alternative material to polycrystalline niobium for the superconducting RF cavity. Since LG niobium sheets were available from material vendors, many laboratories developed single-cell or multi-cell cavities made of LG niobium, resulting in encouraging production. The new material showed the potential to simplify the production sequence and consequently reduce the cost, and addressed the present challenges of RF superconductivity. In the framework of the ILC cooperation between IHEP and KEK, we studied the effect of electro polishing (EP) on the single-cell LG cavities with the KEK ICHIRO shape[7]. The maximum accelerating field reached 47.9 MV/m and the features of surface treatments based on EP to the large grain cavity were achieved in our research program. Encouraged by the promising results we continued the single-cell LG cavity research. Two of the six single cell cavities were made of China Ningxia LG niobium. A complete process of surface treatments based on CP (without EP) was carried out on the two LG cavities at IHEP. The LG cavities and one Ningxia fine grain niobium cavity (shown in Fig. 1, named IHEPLG#1 and #2, IHEPFG#3) were sent to KEK for vertical RF tests. In this paper the process and results of the three cavities are presented.

2 Cavity fabrication

The IHEPLL shape was optimized to decrease the $H_{\rm pk}/E_{\rm acc}$ and to achieve ultimate gradients near 50 MV/m. Its $H_{\rm pk}/E_{\rm acc}$ is 35.47 Oe/(MV/m) for the single-cell cavity with beam pipes and its $B_{\rm pk}/E_{\rm acc}$ is 3.55 mT/(MV/m). To fabricate the single-cell cavities standard technology was employed. According to the geometry optimum the dies for deep drawing were manufactured and made of high yield strength aluminium alloy. Two sets of large grain niobium sheets and one set of fine grain niobium sheets were purchased from OTIC, Ningxia, China and three sets of fine grain niobium sheets from Tokyo Denkai, Japan. These sheets were all high purity niobium with RRR of higher than 300. Although the half-cells of the LG cavities were produced by two-step deep drawing, tearing at the iris, strong earring and grain steps at equator region occurred due to the non-uniform grain sizes of the sheets. The fine grain half-cells were free of these flaws as usual.

The half-cells were trimmed to the final size for electron beam welding (EBW) on a lathe. Before EBW the half-cells were thoroughly cleaned by ultrasonic degreasing and light CP (10 μm). Owing to the lack of experience of the technical staff in operating the machine to weld the niobium material, a complete cavity of the Ningxia fine grain niobium was especially arranged to fumble for the parameters of the machine to weld the different parts of the cavity. To penetrate fully the 2.8 mm thick niobium the EBW parameters of the voltage and current were generally 60 kV and 125 mA at a 1200 mm/min. rotating speed. The strategy for the different welding seams was a little adjustment of beam current. Finally the six cavities were welded successfully. By using a defocused electron beam outside weld spatter was negligible and the underbead looked smooth with a CCD (Change Coupled Device). The width of the welding lines was well proportioned and the height was less than 0.25 mm.

3 Surface treatments

In order to propose the surface treatment procedures for the cavities the following aspects were taken into consideration. For the ILC project the fine grain cavity chemically polished has adequately been investigated. LG cavities by electro polishing achieved good results. Our priority would also be given to the large grain cavities. The process of CP would only be applied to the LG cavities in the absence of complex EP. The two LG cavities had both been subjected to surface treatments at IHEP. Brief introductions to these processes follow.

Referring to the machine for centrifugal barrel polishing (CBP) at KEK, a machine was developed as shown in Fig. 2. This machine can accommodate a 1.3 GHz three-cell cavity. The two LG cavities were polished about 150 μm in the machine. The chemical polishing was performed in the vertical and horizontal way to remove 90 μm in total. To relieve the mechanical stress and remove the hydrogen in the niobium the cavities were annealed in a vacuum furnace with the protection of a titanium box. The cavities were heated slowly enough to release the thermal stress and the natural cooling down lasted about 10 hours. After annealing the inner surface of the two LG cavities was compared by CCD. IHEPLG#2 was chosen to prepare for the RF test. The cavity was removed 10 μm by light CP and rinsed for 2 hours by high pressure pure water. In the class 10 clean room of IHEP the cavity was assembled with the input and pick-up antenna sealed by the indium wire. Subsequently baking of 48 hours at 125 ℃ was carried out. The two LG cavities and the Ningxia fine grain cavity were sent to KEK for further testing and processing.

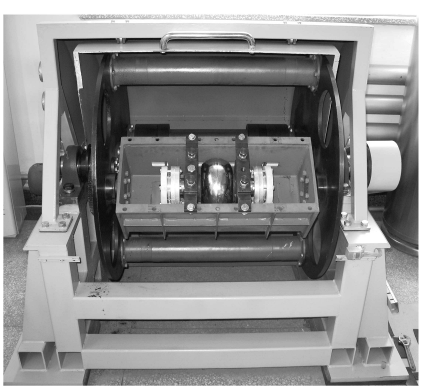

Fig. 2. The machine for centrifugal barrel polishing at IHEP.

4 IHEPLG#2

At IHEP IHEPLG#2 was treated with all the surface treatments and assembled with the couplers. For shipping the inside of the cavity was kept in vacuum. At KEK the cavity was evacuated again and immediately tested. Because the input coupler was loose and the input antenna could perhaps have touched the inner surface during shipping, the first RF test was limited by the strong field emission. The cavity was rinsed by high pressure pure water only for 15 minutes and assembled with KEK couplers (as our couplers mismatched with the KEK flange support of the cryostat). In the second test the maximum accelerating gradient reached 36.5 MV/m before quench happened at the high fields as shown in Fig. 3. Then the field could just stay at 34.72 MV/m with a high quality factor of 1.49×10^{10}. Our technology on the high gradient SRF cavity was confirmed by this test.

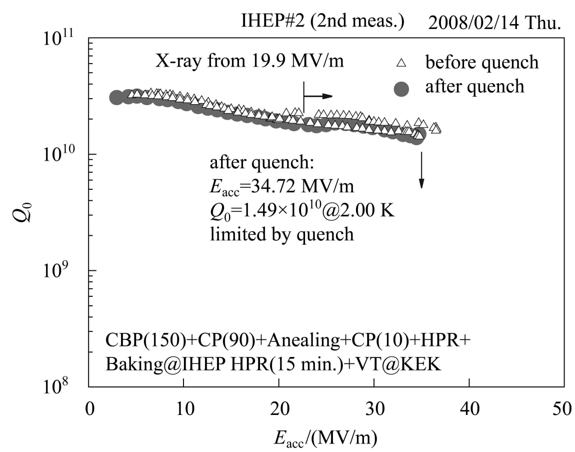

Fig. 3. The performance curves of the 2nd vertical test of IHEPLG#2.

Following the second test the cavity was warmed to about 95 K and naturally stayed at 100±20 K for 39 hours as indicated in Fig. 4. The comparison of the 2nd and 3rd tests is shown in Fig. 5. As quench at high gradients did some harm to the RF surface the maximum field was a little decreased. The quality factor was not reduced, which demonstrated that the performance was not affected by being exposed to the dangerous temperature region. The measured temperature dependence of the surface resistance is indicated in Fig. 6 and in the two tests its surface resistance almost evolved with the same tendency and values. The phenomenon of Q-disease was not seen according to the contrast and our technology was also qualified in the light of avoiding Q-disease.

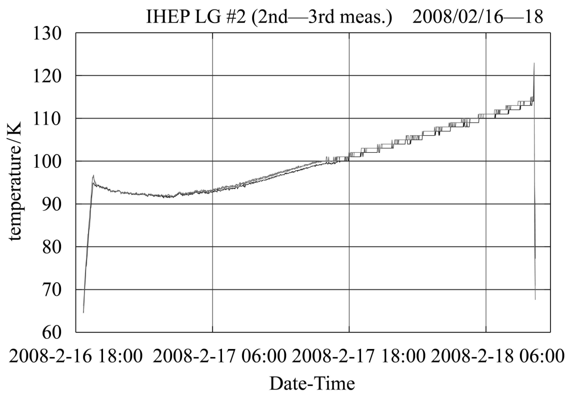

Fig. 4. Temperature of IHEPLG#2 at the dangerous temperature region of 100±20 K.

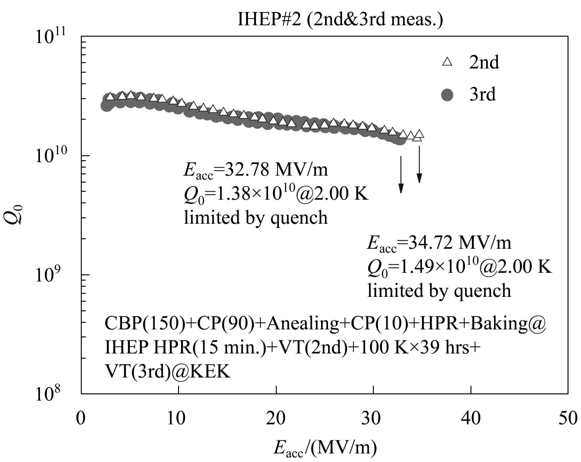

Fig. 5. Comparison of the 2nd and 3rd test of IHEPLG#2.

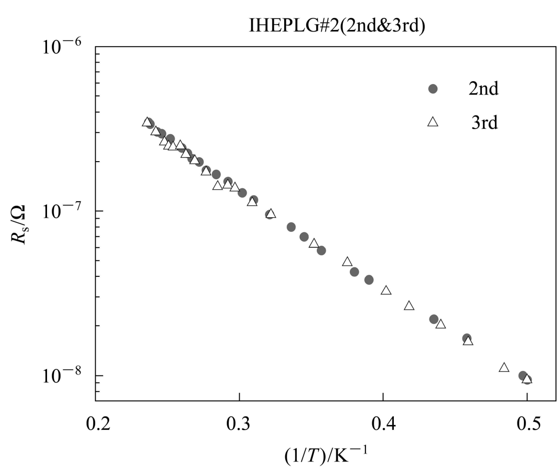

Fig. 6. The temperature dependence of the surface resistance before and after being exposed to the dangerous temperature region.

With our expectation to improve the performance of the cavity the surface was removed 50 μm by additional chemical polishing and baked 48 hours at 125 ℃. In the following RF test, during the first power rise the initial field emission signal was caught at the gradient of 16.22 MV/m. A high power processing (HPP) from 20 MV/m to 25 MV/m overcame some soft barriers of multipacting. The cavity looked to be limited by field emission with a distinct slope. However, at the gradient of 33 MV/m some multipacting barriers were encountered. The barriers caused additional energy consumption and resulted in a low quality factor. Though the barriers were surmounted and the quality factor was improved by the HPP, the residues on the surface produced a light Q-slope. The gradient finally reached 37.23 MV/m and relative to the previous test the quality factor was low due to field emission as indicated in Fig. 7. For further improvement the cavity should be polished again.

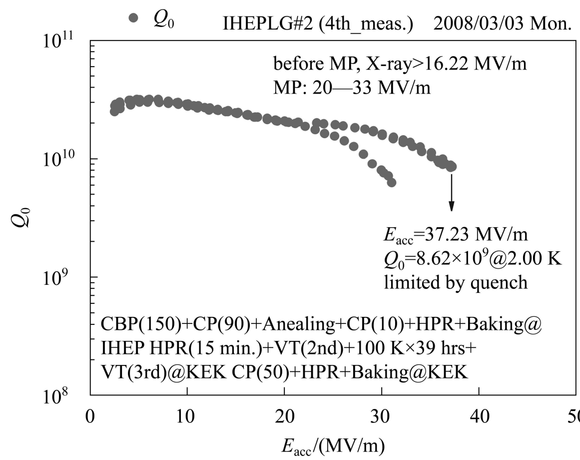

Fig. 7. Excitation curves of the 4th test of IHEPLG#2.

For the 5th RF test the cavity was also removed 50 μm and now the total removal thickness reached 200 μm. The power could smoothly be increased to the gradient of 40.27 MV/m with Q_0 of 1.60×10^{10} without the signal of X-ray and multipacting as shown in Fig. 8.

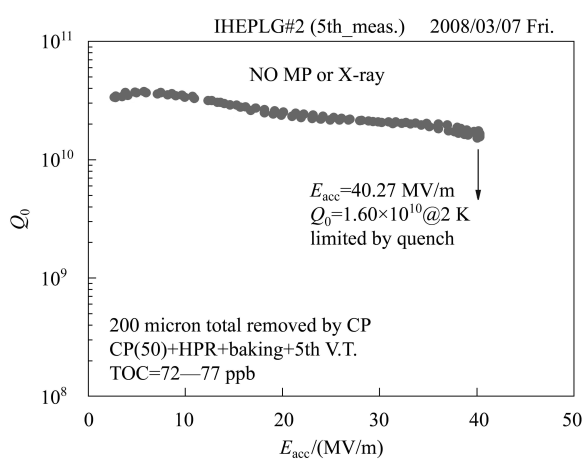

Fig. 8. Excitation curves of the 5th test of IHEPLG#2.

5 IHEPLG#1

At IHEP IHEPLG#1 was processed in parallel with IHEPLG#2 including the procedures of heavy CP of 90 μm and annealing. At KEK the cavity was polished 10 μm by light CP, rinsed for 15 minutes by high pressure pure water and baked as usual. The maximum accelerating gradient was 32.44 MV/m as shown in Fig. 9. Finally the cavity reliably achieved 36.17 MV/m and 1.37×10^{10} after 30 and 70 μm CP as shown in Fig. 10.

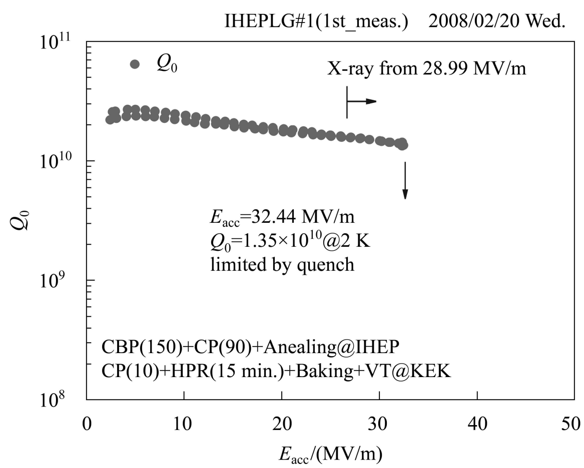

Fig. 9. Excitation curves of the 1st test of IHEPLG#1.

All the tests of IHEPLG#1 and #2 achieved accelerating gradients of more than 32.0 MV/m and were limited by quench. The field levels were continually improved by each CP step as shown in Fig. 11 and the maximum gradient reached 40.27 MV/m with a high quality factor. In all the RF tests the temperature dependence of the surface resistance in the range from 4.2 K to 2.0 K was measured. Curve fitting resulted in parameters to calculate the resistance according to BCS theory. Table 1 lists the resistance values of the cavities at 4.2, 2.0 K and the residual resistance. Compared with the electro polishing cavities, the chemically polished cavities had larger residual resistance because of the rougher surface. However the distinction of the resistance at 2.0 K was not clear.

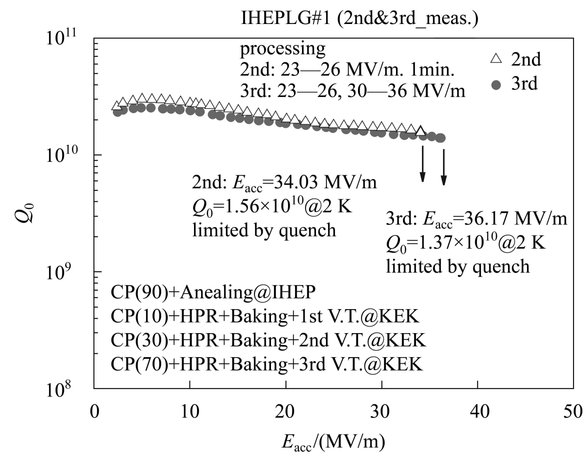

Fig. 10. Excitation curves of the 2nd & 3rd of IHEPLG#1.

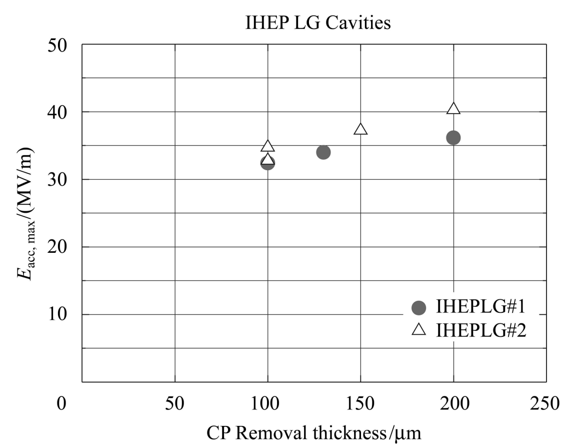

Fig. 11. E_{acc} vs. CP removal thickness on IHEP LG cavities (IHEPLG#1 & IHEPLG #2).

Table 1. The resistance values of the cavities at 4.2, 2.0 K and the residual resistance.

items	IHEPLG#2				IHEPLG#1			IHEPFG#3
	2nd	3rd	4th	5th	1st	2nd	3rd	1st
$R_{BCS,4.2\ K}$	324.994	299.393	322.511	379.363	339.846	329.793	357.136	429.829
$R_{2.0\ K}$	13.9	9.58	11.4	8.99	10.8	9.74	9.10	11.3
R_{res}	9.95	3.08	6.07	4.04	5.76	3.67	3.13	5.91

6 IHEPFG#3

IHEPFG#3 was made of Ningxia fine grain niobium and was arranged to explore the parameters of the EBW machine in the initial plan. From subsequent checking by X-ray the cavity had no defects and was qualified. At KEK the cavity was treated with CBP of removal thickness 175 μm, CP of 150 μm, annealing, light CP and baking as a reference for the IHEP LG cavities. In the RF test the cavity finally achieved 35.70 MV/m with a quality factor of 2.34×10^9 as seen in Fig. 12. The excitation curve exhibited a drop in quality factor at high gradients, which was called Q-slope and often appeared in polycrystalline cavities polished chemically. Field emission of electrons could be excluded as an explanation for the performance degradation since neither X-ray nor secondary electrons were observed. The Q-slope limited the achievable gradients but also would greatly increase the cryogenic load.

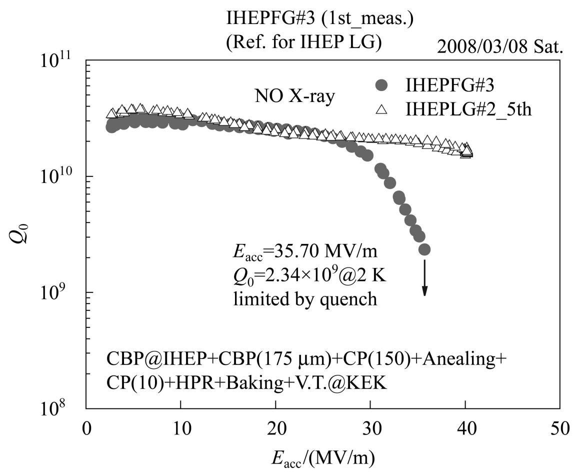

Fig. 12. Comparison of the quality factor behaviors at high gradients between the LG and fine grain cavities treated by CP.

In contrast to the electro polished cavities the remedy to overcome the Q-slope, namely the baking of the cavities at 125 ℃, could not improve the Q-value and gradients of the chemically polished cavities as well[8]. However, Q-slope in the tests of the LG cavities polished by CP was not observed in this paper. The difference reveals the advantages of the LG cavities.

7 Conclusion

In our study on RF superconductivity the 1.3 GHz low loss cavity shape was designed and optimized to allow maximum gradients near 50 MV/m. Six single-cell cavities with the IHEPLL shape were fabricated with standard technology. The two LG cavities were treated with surface treatments based on CP at IHEP. The vertical cryogenic tests were carried out at KEK. All the tests of IHEPLG#1 and #2 achieved accelerating gradients of more than 32.0 MV/m and the maximum gradient reached 40.27 MV/m. The surface treatment procedures based on chemical polishing were concluded for high gradient large grain cavities. The LG cavities, chemically polished, could be compared with the EP performance. In the fine grain cavity test Q-slope was observed in high gradients, with which the advantage of the LG niobium material was concluded.

In the experiments of this paper all the cavities achieved high gradients of more than 35 MV/m, which demonstrated that the technology of RF superconductivity at IHEP had successfully been developed in the last decade. Our technology of the cavity design, fabrication and surface treatments was confirmed from the series of tests. R&D on the 9-cell LG cavity has been started at IHEP.

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