

# Gradient Yield Improvement Efforts for Single and Multi-Cells And Progress for Very High Gradient Cavities \*

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**Abstract**

ILC cavity specification was fixed at the ILC Snowmass workshop 2005. However, after the workshop DESY developed a low production yield problem on the TTF cavities. GDE R&D board has built a task force to solve the problem. This task force proposed S0/S1 studies and accepted by GDE. DESY has nearly demonstrated the 35MV/m high gradient module, even the gradient yield is still low. The other major laboratories, FNAL, JLAB and KEK also started the R&D. S0 study has started in JLAB. STF activity has started in KEK. In these activities, 9-cell cavity result is accumulated. S0 single cell program has been started and very promising recipe has been developed. We have a remarkable improvement with high gradient in these two years. High gradient shapes: Low loss or Re-entrant has brought a breakthrough. Now the world record is 60MV/m. In this paper these worldwide activities are presented.

## INTRODUCTION

### ILC Cavity Specification

ILC cavity specification was fixed by the following discussion during the Snowmass ILC workshop in 2005[1]. To date the experimental gradient limitation of niobium SRF cavity has become close to the fundamental limitation, which could be determined by RF magnetic property. An estimated RF magnetic critical field is around 1750Oe [2]. Taking this number for the TESLA shape, which has  $H_p/E_{acc}=42.6$  Oe/(MV/m), the gradient limitation is 41MV/m. By an analysis of DESY-TTF electropolished best cavities, the gradient could lower by ~10% from the fundamental limitation and spreads in industrial production into a Gauss distribution with 5% scatter. As the result, ILC cavity would distribute as to have the centre at 37MV/m and 5% scatter as seen in Fig.1 (blue Gauss distribution). The accept gradient should be 35MV/m in order to have 85% yield. For the operation, the gradient must have a 10% more margin. Thus the operation gradient was fixed as 31.5MV/m. The same discussion was applied for ACD cavity shapes. In this case, the critical gradient would be 47MV/m in those days. Table 1 summarizes the ILC cavity specification for both BCD and ACD. In this discussion, several people were against such a high gradient specification but finally we chose these numbers.

Table 1: ILC cavity specification

	TESLA Shape	LL/Reentrant Shape
Acceptance	Eacc = 35MV/m Qo = 0.8E10	Eacc = 40MV/m Qo = 0.8E10
Operation	Eacc = 31.5MV/m Qo = 1E10	Eacc = 36MV/m Qo = 1E10

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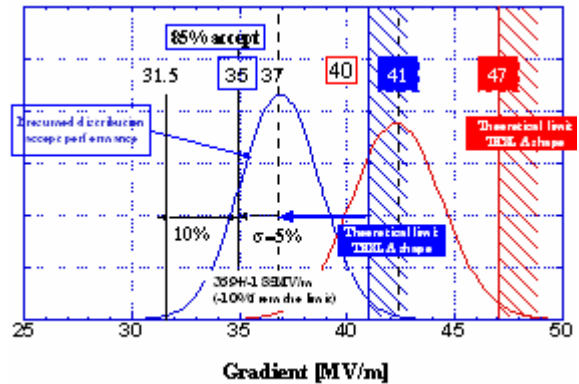


Fig.1: The determined process for ILC cavity specification

### Gradient Low Yield Issue

After the Snowmass workshop, DESY people showed the all data on the TTF cavities [3]. It is presented in Fig.2. The blue marks are the results on cavities treated by buffered chemical polishing (BCP) and red ones are by electropolishing (EP). Since 2001 DESY has started to use EP, then they have completely switched to EP from BCP in 2003. Fig.2 includes all results: hydrogen Q-disease (yellow elliptical area) and none baked cavity results (black elliptical area). These data can be eliminated because we have cures. Even ignoring these data, the gradient yield is scattered between 22MV/m and 35MV/m (23% scatter). We have to settle this large gradient scatter problem. What gradient is still lower than the ILC specification is another issue. We have to resolve these issues in these one or two years.

### GDE S0/S1 Task Force

After developed this situation, ILC-GDE R&D Board has built two task forces on cavity in 2006: so called S0 and S1 [4]. S0 task is to understand the gradient scattering issue. Methodology of S0 is to take statistics first applying

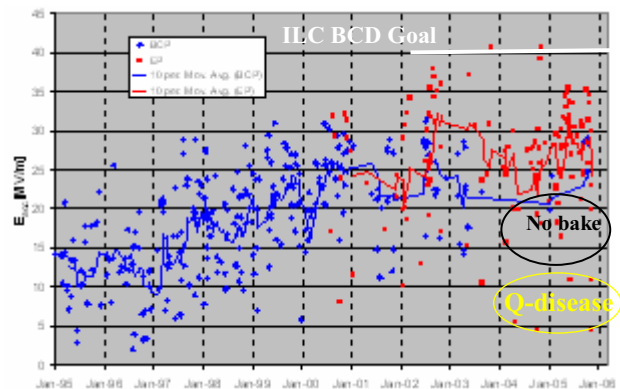


Fig.2: Scatter in the gradient on DESY TTF cavities. Courtesy of DESY.

the recipe taken place in a lab to several cavities; so called S0 tight-loop. After this, these cavities should send other labs for the cross check. If one finds a better recipe in this first tight-loop, other lab will try it for other cavities and confirm the performance (second tight-loop). S1 task is to make the proof of principle of the ILC cavity specification with 90% yield by production-like cavities: process and test of 10's cavities. The time scale of these tasks should be commensurate with completion of the EDR: mid of 2009. This tight loop study has been started in the major labs.

**MULTI-CELL STUDIES IN LABS**

**DESY Activity**

So far DESY is only the place where 1.3GHz 9-cell SRF cavity is massively produced for the FLASH/Euro XFEL. Fig.3 shows the cavity average gradient (usable) between vertical test and real module operation in the FLASH [5]. The gradient in the vertical test is gradually improved and is getting close to the ILC operation gradient. However, it is still lower by 5MV/m from the ILC accept gradient. The operation gradient reduce by 10±6% from the vertical tested result. This reduction is close to the assumption of the ILC specification but still the scatter is too much.

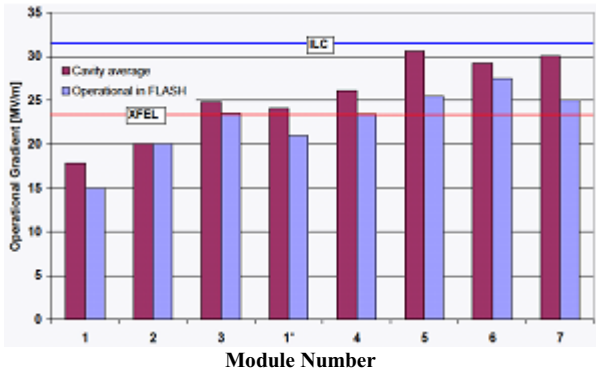


Fig.3: DESY FLASH cavity performance. Courtesy of DESY [5].

**Ethanol Rinsing @ DESY**

Recently DESY has investigated ethanol rinsing after EP to improve the gradient yield [6]. Fig.4 shows the result. Ethanol rinsing pushes up the on-set of the field emission (FE). Taking ethanol rinsing, FE on-set becomes very close to the hard quench field (Eacc,max). It should be emphasized that ethanol rinsing can remarkably reduce

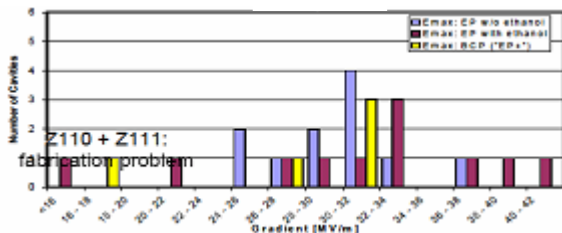


Fig. 4 Ethanol rinsing effect on multi-cell cavity. Courtesy of DESY [6].

FE. Fig. 4 includes the lower quench field around 16 MV/m. DESY suspects these to be a fabrication error. ZANON, which is a well-qualified vendor, fabricated these cavities but they might have still fabrication error, especially electron beam welding (EBW) at equator [7]. EBW could be another issue for the high gradient yield.

**JLAB S0 Tight Loop Study**

A real S0 tight loop study has been started at JLAB/FNAL [8]. FNAL sent two 9-cell cavities to JLAB, which were fabricated by a well-qualified vendor (ACCEL). After the material removal of ~150µm by EP @ JLAB, they applied the following JLAB's recipe:

- 1) Degreasing, 2) EP 20µm, 3) Degreasing,
- 4) First HPR+Drying, 5) First clean-room assembly,
- 6) Second HPR + Drying, 7) Final Cleanroom assembly,
- 7) Evacuation and Leak check, 8) Baking (110°C),
- 9) Cold test.

They repeated 4 times this procedure. The test results are shown in Fig.5. It should be emphasized that degreasing process by MICRO-90 after EP is their special [9]. A trend can be seen that the ILC specification cannot be satisfied in the first test but can do after a few more tests. Occurrence of FE looks to be small (the probability 13%). We have to remind that the detergent MICRO-90 can resolve sulphur [10]. This suppression of FE might relate to the removal of sulphur contamination in EP.

Fig.6 shows the best gradient with production-like cavities. Result of DESY-TTF cavities and JLAB tight

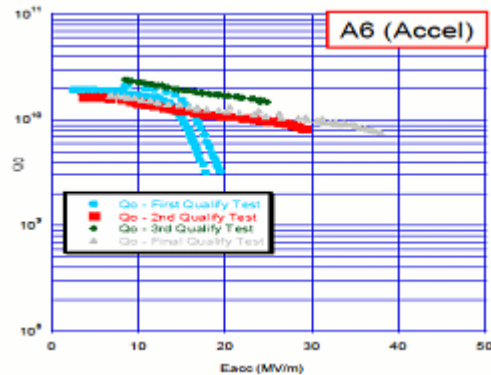
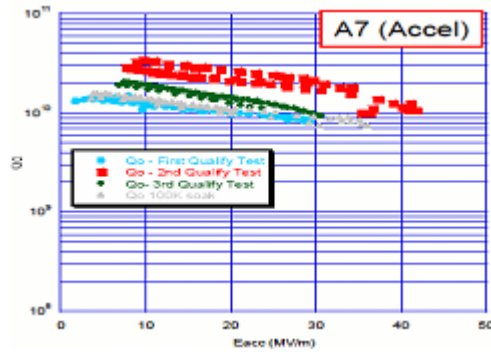


Fig.5: S0 tight loop study results in JLAB on well-qualified vendor, Top for A7 cavity and Bottom for A6 cavity. Courtesy of JLAB.

loop result are combined. It should be emphasized that the best gradient is getting the ILC accept specification.

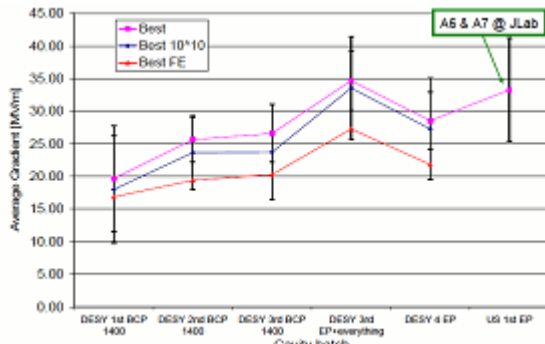


Fig.6: Improvement of best gradient in production-like. Courtesy of FNAL

**New Vendor Cavities in USA**

The similar light loop study was done for four cavities from new US vendor (AES) in JLAB. The results are shown in Fig.7. The best result was 28MV/m by 4th cavity but other three cavities were limited by hard quench between 15MV/m and 20MV/m. One cavity was investigated by local T-mapping around equators and they found local heating at a location [11]. The equator EBW is suspected as the cause of the low limitation.

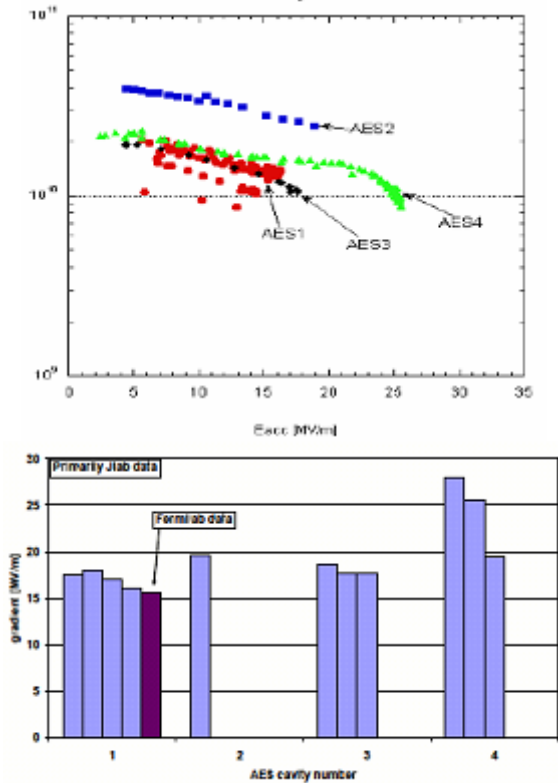


Fig.7: So tight loop study on unqualified vendor cavity in USA. Courtesy of JLAB.

**KEK STF Baseline Cavities**

So far two groups are developing ILC cavity in KEK.

The first one, so called STF baseline cavity group, is developing TESLA-like cavity modified a little bit end cell shape to suppress Lorentz detuning [12]. Their cavity goal is the same as the ILC specification. They fabricated four cavities by Japanese vendor (MHI) and evaluated the cavity performance. Their cavity preparation recipe is in principle same as the TRISTAN cavity recipe [13]. However, small modifications are there. The mechanical grinding process is changed from buffing to centrifugal barrel polishing (CBP) [14]. Hydro-peroxide ( $H_2O_2$ ) rinsing was eliminated after the final EP rinsing. The results are presented in Fig.8. Qo-Eacc curve in Fig.8 top is the result after repeated twice the recipe. The cavity #2 took place  $H_2O_2$  rinsing before 5th test and reached 29MV/m. Other three cavities without  $H_2O_2$  rinsing were limited around 20MV/m. They put locally temperature sensors on the equator of suspected cell by pass-band mode measurement and found local heating. They suspect the equator EWB on the 20MV/m limitation [15].

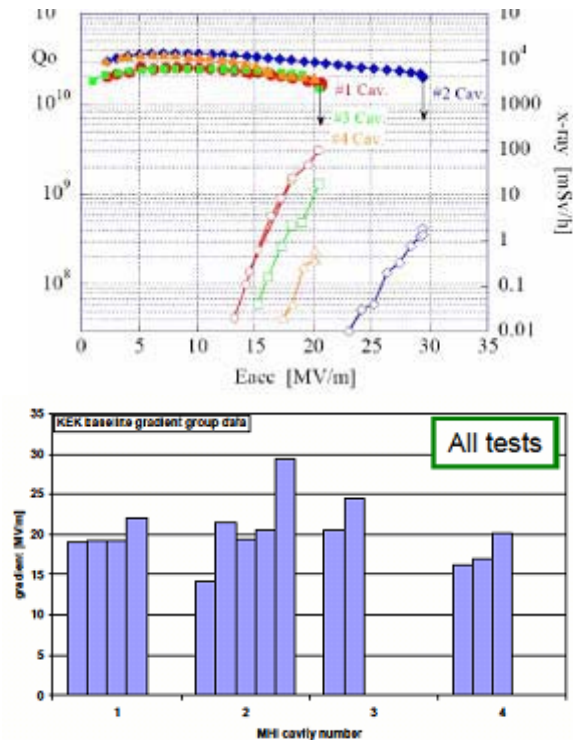


Fig.8: Cavity performance of the STF Baseline cavities.

**LL Cavities**

The other group in KEK, so called WG5-Asia, is developing the ILC ACD cavity, especially LL (Ichiro) cavity to push the gradient higher than 40MV/m. The first design involved the superstructure concept, which needs a space more for HOM couplers on the beam tube between cavities. They designed to have a larger beam tube ( $108\phi$ ) on one side. They fabricated four LL 9-cell cavities [16]. The first cavity has straight beam pipes and other three have full end group: HOM ports, input coupler port, pick up coupler port and He vessel end plate (see Fig.11 right cavity picture). These cavities were prepared by the

following process: 1) Centrifugal barrel polishing (CBP), 2) Light BCP (10 $\mu$ m), 3) Annealing (750 $^{\circ}$ C, 3hr), 4) Pre-tuning (field flatness 96%), 5) EP (80 $\mu$ m), 6) HPR (60kg/cm $^2$ , 6hr), 7) Bake (120 $^{\circ}$ C, 48hr), and 8) cold test. In addition, the process: EP (20 $\mu$ m)+HPR+Bake was repeated for further tests. The first cavity reached 29.3MV/m and was limited by hard quench after a few tests. SLAC multipacting (MP) simulation suggested a barrier at 30MV/m, which occurred at the taper of 108 $\phi$  - 80 $\phi$  beam pipe [17]. Y.Morozumi in the WG5-Asia group made MP simulation and obtained similar result [18]. SLAC/KEK MP simulations both pointed other barriers at 16MV/m by two point MP at the END cell equator and 22MV/m two point MP at the centre cell equator. The single cell study result is shown in Fig.9 to compare with the 9-cell simulations. Both simulations well fit the experimental results. The other cavities with full END groups were limited between 15 MV/m and 20MV/m due to field emission. The MP simulation developed MPs in the HOM cylinder also as seen in Fig.9.

Between mid of 2006 and early of 2007, both groups used the EP facility very hard. They found contamination from their HPR pump on the early 2007. Grained contaminants were observed on the final filter in the HPR system. This contamination accumulated every the long-term operation of the pump. Silicon was detected by the element analysis of the contaminant. They use plunger pump. This pump uses silicon oil at the plunger sealing. They changed the final filter and could overcome this problem. The reason why the baseline cavities were not suffered so much by this problem might be having their preparation just after replacing the filter. LL 9-cell cavity often followed the baseline cavity preparation. This might

contaminate their cavities. The field emission could be related to the HPR pump contamination. Finally their HPR system was stopped for a half of year to replace the pump. They replaced it diaphragm pump on end of September 2007. WG5-Asia group is testing this pump by single cell cavities. MP has disappeared in these tests, which has been almost always observed before. S0 study on 9-cell cavity will start soon in KEK.

The LL cavities had other problem: low Q problem. RF simulation suggested that RF heating happens at vacuum sealing gap due to the strong RF magnetic field leaking though the 108 $\phi$  large beam pipe. They modified the sealing structure to have no gap, and this problem was fixed. As the current LL design looks to have various problems, finally they have redesigned cavity shape, which has 80 $\phi$  beam pipe on both cavity side (new shape) but no changed the centre cells. One cavity of old shape will be tested in STF. Other three cavities will be used for S0 tight loop study.

**PAL/KEK/JLAB Collaboration**

WG5-Asia group had two steps on this re-designed cavity R&D: demonstrate the high gradient performance first separating the END group issue, then investigate the cavity with full END group. As the first step, they have fabricated two re-designed 9-cell cavities having straight beam pipes. One was fabricated by KEK. The other is by PAL. PAL brought 6 dumbbells with stiffener EBW welded and end cups. KEK prepared the end caps and straight beam pipes. They made EBW assembly by these parts using Japanese EBW company. This PAL cavity (Ichiro#6) is now under preparation for S0 light loop study in KEK.

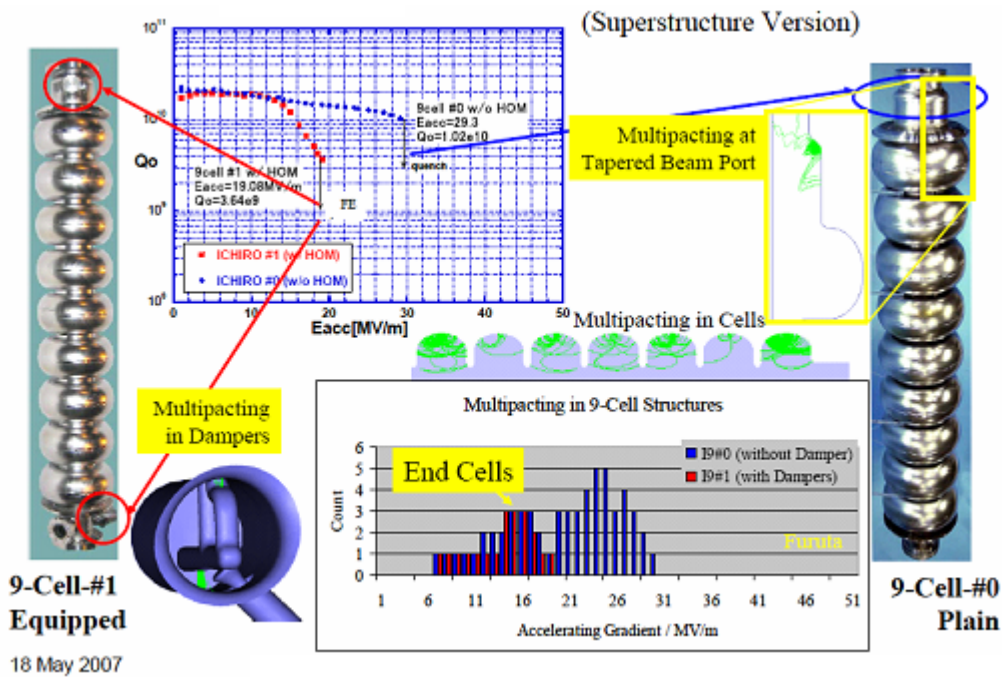


Fig.9: Result of LL 9-cell cavities in WG5-Asia Group

The other cavity (Ichiro#5) fabricated by KEK was tested using the WG5-Asia best recipe: +EP (20 $\mu$ m)+EP (3 $\mu$ m, fresh acid)+ Degreasing (MICRO-90, 2%)+HPR+Baking (120 $^{\circ}$ C, 48hr), however, the cavity gradient was limited 22MV/m by quench during RF processing. After the quench, field emission was initiated and Q dropped. They judged the HPR system (not yet replaced the pump) mentioned above might be a problem. They decided to send it JLAB and make S0 tight loop study. After pre-tuning the field flatness up to 96% and it was sent JLAB filling clean air. At JLAB, they found the field flatness was destroyed to 76% by one cell deformation. They don't know what happened during the shipping. JLAB pre-tuned and recovered the field flatness up to 93%. They made acceptance test after degreasing and HPR. In this workshop, I have reported a preliminary test result on the Ichiro#5 with Eacc,max=41MV/m and Qo=2E10 but this result might be wrong. The calibration of Eacc might be wrong. They are correcting the data now. Anyway, they started the S0 tight loop for Ichiro#5, and they will have some results soon.

### SINGLE-CELL STUDY

#### TTC WG1 Recommendation

WG5-Asia group has developed high gradient single cell cavities by LL shape. Fig.10 shows the statistics in the all single-cell tests (totally 112 tests) on the their maximum gradient. One can see two Gaussian distributions: one (blue) related to FE, other one (red) related to hard quench. The FE problem was due to their facility problem slept before re-starting the activity or

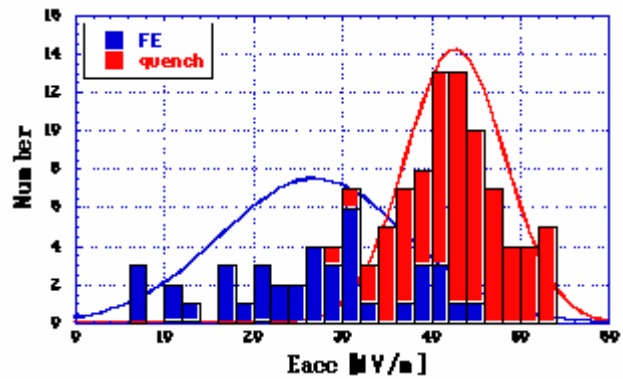


Fig.10: Gradient Scatter in single cell cavity study (KEK)

experience of newcomers who have joined in ILC activity. However, this problem was almost fixed. The issue to be concerned is the second one. In the TESLA Technical Collaboration (TTC) meeting at Frascati on September 2006, WG1 group discussed hard contamination issue on the low yield seen in DESY-TTF cavities. They recommended a prioritised R&D plan [19]. In this recommendation, revisiting the rinsing method was emphasized. Especially sulphur contamination happened during EP should be more concerned because it is well known as a good field emitter.

#### WG5-Asia Single Cell R&D Plan

After this meeting, WG5-Asia group has made a single cell R&D plan. It is summarized in Table 2. The R&D issues were scored to prioritise from past their experiences on safety issue, presumed cost increase, and expected performance. They have started the study from the ILC BCD preparation (Top line in Table 2). In this

Table 2: Prioritised single cell study items in KEK

	Expected yield rate	Disadvantage	Comment	Simplicity & Safety	Cost increase	Score	Priority
EP(20) + HPR+Bake	0.7		ILC BCD	1.0	1.0	1.0	Reference
EP(20)+H <sub>2</sub> O <sub>2</sub> +HPR+Bake	0.9	Cost increase	TRISTAN Recipe	1.1	1.1	1.17	1
EP(20)+Degreasing+HPR+Bake	0.9	Cost increase	29MV/m with TESLA 9-cell cavity @ Jlab	1.1	1.1	1.17	1
EP(20)+Alcohol +HPR+Bake	0.85	Cost increase Cure against burst	Stopped @ KEK Desy trying	1.15	1.15	1.06	2
EP(20)+HF rinsing+HPR+Bake	0.8	Cost increase Hazardous	Not so big potential but low FE @ KEK	1.1	1.15	0.99	3
EP(20)+Boling W +HPR+Bake	0.8	Cost increase complex	Hydrogen doping	1.1	1.15	0.99	3
EP(20)+EP(3 with fresh)+HPR+Bake	1.0	Cost increase	45MV/m with LL shape @ KEK	1.1	1.2	1.19	1
EP(20)+Oxipolishing +HPR+Bake	0.9	Additional process	Stopped @ KEK	1.5	1.3	0.99	3

single cell program, they fabricated 6 cavities and used these repeatedly for each items. They took statistics by these 6 cavities and investigated the average gradient and the scatter. A detail report is presented on this single cell study by F.Furuta et al. in this workshop [20].

**ILC Baseline Preparation**

So far the ILC BCD cavity preparation is the recipe: final EP (~20µm) + HPR+Bake after a heavy material removal (> 100µm). Fig.11 shows Q-Eacc curves on this preparation. Fig.12 shows the scatter of the maximum gradient on ILC BCD recipe. The blue Gaussian distribution is one of the ILC accept specification. The red one is the fitted Gaussian distribution on the experiment result of WG5-Asia’s LL single cell cavities. The average gradient is 46.5±8.0MV/m and the scatter is 17%. The accept rate of ILC ACD performance is 83%. The scatter is large as same as the 9-cell cavity case in DESY-TTF. WG5-Asia group has confirmed the large scatter in single-cell cavities also.

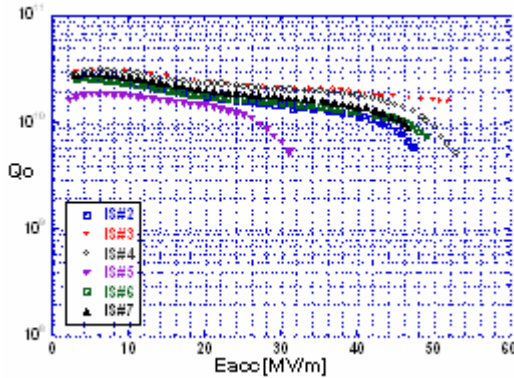


Fig. 11: Gradient performance on ILC BCD preparation

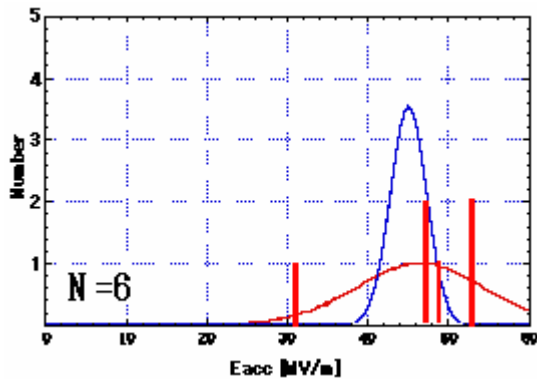


Fig.12: Gradient scatter on the ILC baseline preparation. Average gradient is 46.5±8.0MV/m (17%), Accept rate is 83%.

**Strengthened Rinsing Methods**

In order to understand this scatter, the next step could be to try strengthened rinsing method as discussed in the Frascati TTC meeting. If one concerns sulphur as the cause of the scatter, H<sub>2</sub>O<sub>2</sub> rinsing or alcohol rinsing would

be candidates because it is well known these can dissolve sulphur. H<sub>2</sub>O<sub>2</sub> rinsing has been used in the TRISTAN cavity preparation [13]. However, it was stopped in the later TESLA activity in KEK because their 1.3 GHz single cell cavities could produce 40MV/m high gradient by the recipe without H<sub>2</sub>O<sub>2</sub> rinsing [21]. On the other hand, alcohol rinsing also has been used in the TRISTAN cavity R&D but was stopped in the TRISTAN recipe because FE was no problem at least up to 10MV/m in those days. Alcohol rinsing would have a problem of deflagration. In addition, DESY proposed to revisit alcohol rinsing in the Frascati TTC meeting 2006. From these reasons, WG5-Asia group put a lower priority for alcohol rinsing in Table 2. Recently degreasing method after EP has been developed in JLAB [9]. As seen in Fig.5, they have reached 40MV/m on an ILC 9-cell cavity by this method. They use the detergent MICRO-90 and it can dissolve sulphur. KEK has investigated the sulphur solubility of the MICRO-90. When they made cleaning their EP tank, they picked up sulphur grains. They put these grains in the 2% MICRO-90 and kept one night. This detergent contains sulphur component itself but an increase of the sulphur concentration was observed from 350ppm to 500ppm. Degreasing method is easy. WG5-Asia group put a high priority in Table 2. WG5-Asia group has tested H<sub>2</sub>O<sub>2</sub> rinsing and degreasing in their single cell program.

**H<sub>2</sub>O<sub>2</sub> Rinsing**

Fig.13 shows the result on H<sub>2</sub>O<sub>2</sub> rinsing. In this test, cavities were treated by the recipe: EP (20µm)+H<sub>2</sub>O<sub>2</sub> (10%, V/V) rinsing + HPR (70kg/cm<sup>2</sup>,1hr)+Bake (120°C,48hr).

Four test results were collected so far. Study is still under way. FE limited the gradient in one case. Hard quench limited the gradient in the range 35-45MV/m in two cases. A trend of high Q at Eacc > 40MV/m is observed. Average gradient was 42.6±7.6MV/m and reduced by 10% from the ILC baseline preparation. The gradient scatter is still 18% and is same or even worth compared to the ILC baseline recipe (17%). Multipacting rather

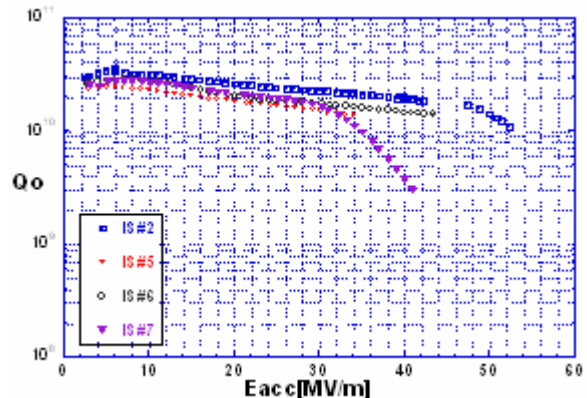


Fig.13: Gradient scatter on H<sub>2</sub>O<sub>2</sub> rinsing after final EP. Average gradient is 42.6±7.6MV/m (18%), Accept rate is 50%.

reduced by this recipe as discussed later. One result has no multipacting. These experimental facts suggest that  $H_2O_2$  rinsing removes rather the contamination caused MP but cannot take away the origin of gradient scatter.

### Degreasing with MICRO-90

Fig.14 shows the result on degreasing effect on MICRO-90. In this study, preparation recipe is: EP (20 $\mu$ m)+ Degreasing with 0.2% MICRO-90 detergent +Hot bath rinsing (50 $^{\circ}$ C, 1hr)+HPR (70kg/cm $^2$ ,1hr)+ Bake (120 $^{\circ}$ C,48hr). The 0.2% dilution of the detergent is used in JLAB so far. Five tests have been finished so far and one more test will be done soon. Two results reached 50MV/m. Hard quench limited around 40MV/m in two cases. FE limited at 40MV/m in one case. Average gradient is 44.2 $\pm$ 6.0MV/m and decreased by 6% from the ILC baseline recipe. The gradient scatter is 14.5% and still large. Comparing Fig.13 and Fig.14, one can find out a trend that this degreasing method suppresses FE at high gradient. Multipacting also reduced remarkably as discussed later. These experimental results suggest that degreasing removes the contamination caused FE or multipacting but cannot take away the origin of the gradient scatter.

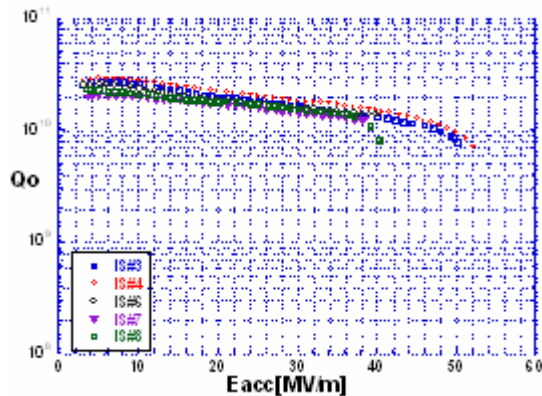


Fig.14: Gradient scatter on Degreasing after final EP. Average gradient is 44.2 $\pm$ 6.0MV/m (14.5%), Accept rate is 60%.

### Flash EP

Above two experiments conclude that only the strengthened rinsing method cannot make narrow the gradient scatter. This tells us that origin of the gradient scatter is a different mechanism from such a contamination caused FE or MP. Some residue combined to niobium might remain on the SRF niobium surface even taking these strengthened rinsing. A flash EP might remove the residue. WG5-Asia group tried an additional 3 $\mu$ m EP with fresh EP acid after water rinsing of the final EP (20 $\mu$ m). In the flash EP procedure, the acid is not circulated in the horizontal EP system. The EP acid is closed in the cavity. So EP acid temperature is increased easily during EP process due to no heat exchange. The EP process is several times stopped and water-cooled on the way to the 3 $\mu$ m material removal in order to decrease acid temperature. Fig.15 shows the result on the flash EP. The

recipe of this test is: EP(20 $\mu$ m)+EP(3 $\mu$ m, fresh acid) + HPR(70kg/cm $^2$ ,1hr)+Bake(120 $^{\circ}$ C,48hr). This recipe brought excellent results. Fig.15 shows the Q-Eacc curves on six cavities. Fig.16 shows the statistics. Average gradient is 46.7 $\pm$ 1.9MV/m. Gradient scatter. It is only 4%. The ILC ACD accepted ratio is 100%. Multipacting

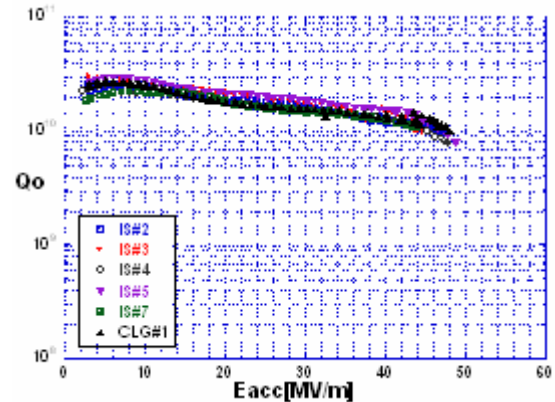


Fig.15: Q-Eacc curves on flash EP. Average gradient is 46.7 $\pm$ 1.9MV/m (4%), Accept rate is 100%.

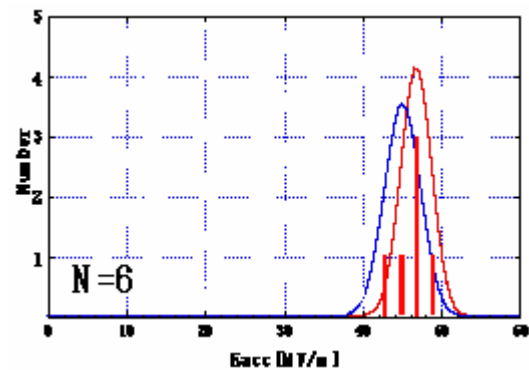


Fig.16: Eacc,max gradient distribution on the flash EP.

appeared in all tests but it was processed out in 20min and after this processing X-ray was not observed above 35MV/m.

### Multipacting on Various Recipes

In these single cavity studies, any T-mapping system was not used. They judged MP by X-ray appearance, which suddenly happened at the presumed gradient by MP simulation. MP simulation suggests the two points first order MP over 18MV/m on LL single cell cavity [18]. Fig.17 shows the probability of X-ray appearance on various preparation recipes. X-ray could be happened by MP electron bombardment on the cavity wall. Therefore the X-ray probability can be considered as that of MP occurrence. In Fig.17, the notations mean

EP (80 $\mu$ m): EP (80 $\mu$ m)+HPR (70kg/cm $^2$ ,1hr)  
+Bake (120 $^{\circ}$ C,48hr),

EP (80+3 $\mu$ m): EP (80 $\mu$ m)+EP (3 $\mu$ m,fresh acid) +  
HPR (70kg/cm $^2$ ,1hr)+Bake (120 $^{\circ}$ C,48hr),

EP (20 $\mu$ m): EP (20 $\mu$ m)+HPR (70kg/cm $^2$ ,1hr)+  
Bake (120 $^{\circ}$ C,48hr),

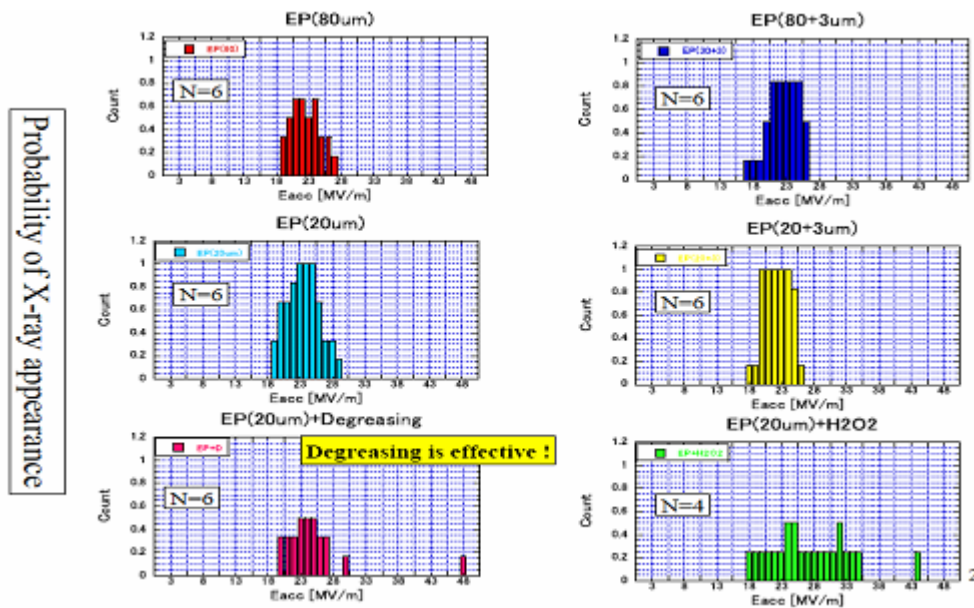


Fig.17: Strengthened rinsing effect on multipacting

EP (20+3 $\mu$ m): EP (20 $\mu$ m)+EP (3 $\mu$ m,fresh acid) + HPR (70kg/cm<sup>2</sup>,1hr)+Bake (120<sup>o</sup>C,48hr),  
 EP (20 $\mu$ m)+Degreasing: Degreasing recipe mentioned above,  
 EP (20 $\mu$ m)+H<sub>2</sub>O<sub>2</sub>: H<sub>2</sub>O<sub>2</sub> rinsing recipe mentioned above.

Multipacting reduces about half by the degreasing or H<sub>2</sub>O<sub>2</sub> rinsing. It should be emphasized that every multipacting in Fig.17 can be RF processed out in 20min and it does not appear any more in the other high gradient measurement, if the cavity is kept cool. When the cavity is once warmed up to ~200K and re-cooled again, this multipacting appears again. MP processed effect has a memory up to ~200K [22]. This fact suggests us the contamination caused MP might be a gaseous sulfide.

**A Possible Explanation for The Gradient Scatter**

Recently Cornell University took nice picture on sulphur contamination by EP as seen Fig.18. They have confirmed this sulphur contamination dissolve in alcohol rinsing but leave an imprint on the niobium surface as seen in Fig.19. They did not yet analyze the chemical composition of the imprint but it could be niobium-sulfide.

Fig.18 shows a summary of single cell studies on gradient scatter done by WG5-Asia. Gradient scatter depends on the amount of EP material removal. The heavier EP has the larger scatter. The flash EP always reduces the scatter and the effect is the larger in the lighter EP.

**Niobium-Sulfide**

Here, an idea can be given on the mechanisms of the gradient scatter and FE or MP. There could be two S-particle contamination processes as presented in Fig.20: large S-particles and fine S-particles. During the EP process, the probability is large for sulphur particles to stick the SRF surface because EP acid includes a lot of S-

particles. Once S-particle stuck on the SRF niobium surface, niobium-sulfide generates at the particle-niobium contact. The sulphur of the niobium-sulfide would diffuse into niobium bulk in a several hours. If the diffusion depth is deep enough, S still remains even after flash EP 3 $\mu$ m or HPR, and stay on the SRF surface as a cause of

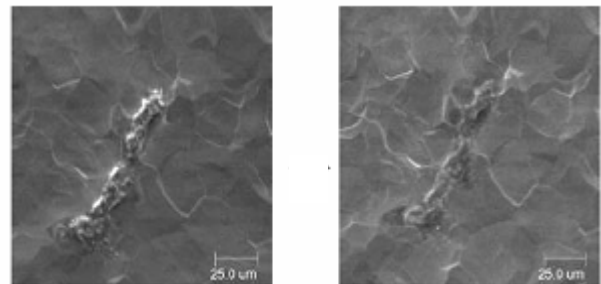


Fig.18: Sulphur particle contamination during EP Left: the contamination, Right: After rinsing with ethanol, Courtesy of Cornell University

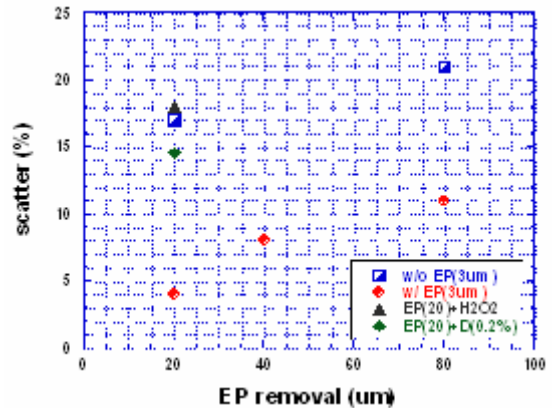


Fig.19: Material removal dependence of the gradient scatter.



the hard quench. If one takes a light EP maybe 20µm (1.5 hr), the diffusion depth might be less than 3µm, thus the flash EP could remove the niobium-sulfide. This model can explain why the flash EP is not enough on heavy EP (80µm) to reduce the scatter. In this case, EP duration is longer than 4 hours and the diffusion depth could be deeper than 3µm.

Light BCP might be usable instead of the flash EP but not easy. One should remind the Q-slope in the BCP'd polycrystalline cavity. The material removal of 10µm by BCP after EP already brings the Q-slope and it cannot be eliminated perfectly by even baking. Material removal should be small in the BCP case. However, material removal control is very difficult in light BCP due to the run-away reaction.

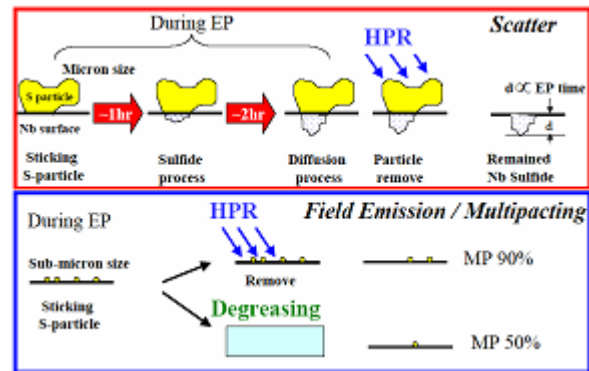


Fig.20: Two contamination processes of the sulphur particles.

**Fine S-Particle Contamination**

The other is by the sticky fine S-particle contamination. In this case, particle-niobium contact could be not so serious because the contact area is very small. However, the fine particles would be difficult to remove even by HPR because HPR has sometimes off-shooting these particles. The remained fine particles would happen MP or FE. For this fine S-particle contamination case, H<sub>2</sub>O<sub>2</sub> rinsing, alcohol rinsing and degreasing is effective because these can dissolve the S-contaminations and flush away.

**End Single-Cell Study**

As described above, WG5-Asia group has nice results on single cell cavities but their 9-cell cavity result is still not so excellent as seen in Fig.9. A cause for this might be the contamination from their HPR pump. However, other possibility might be problem in the END group of the 9-cell cavities, which has very complicate structure having HOM ports, input port pick up antenna port. They have

started to study the influence. They have fabricated several END single-cell cavities as seen Fig.21. ISE#1 has the same END cell shape as the old Ichiro 9-cell cavity but has straight beam pipes. This cavity will be tested on RF heating at the end vacuum sealing by magnetic field leaking through the 108φ large beam pipe. ISE#2 is also same shape as the old Ichiro end cell and has a tapered 108φ beam pipe on one side. This will be tested MP at this tapered beam pipe. ISE#3 is the same end shape as the re-designed new Ichiro 9-cell cavity but has straight beam tubes. ISE#4 is same as ISE#3 but has a HOM cylinder and input coupler port. ISE#5 is the full end single cell cavity of the new Ichiro 9-cell cavity. ISE#3 - #5 cavities will be study on the rinsing effect.

The bottom line in the table of Fig.21 shows the results so far reached. ISE#2 and #3 having straight beam pipes have reached the critical field without field emission. MP at the tapered beam pipe was concerned with IS#2 but it was processed out and reached the theoretical limitation. So the MP at the tapered beam tube is not the critical



Cavity	ISE#1	ISE#2	ISE#3	ISE#4	ISE#5
Ep/Eacc	2.49	2.49	2.25	2.25	2.25
Hp/Eacc [Oe/(MV/m)]	43.4	43.4	38.8	38.8	38.8
Theoretical Eacc,max[MV/m]	40	40	45	45	45
Eacc,max [MV/m], So far reached	26	41	50	51	33

Fig.21: End Single cell cavities fabricated in KEK

field limitation. The cavities with ports were treated using WG5-Asia best recipe but were limited around 33MV/m by field emission. This suggests they need more careful rinsing around beam ports or additional more strengthened rinsing method like ethanol rinsing.

### PROGRESS FOR VERY HIGH GRADIENT CAVITIES

Very high gradient cavity R&D is our endless challenging issue. Especially, for the ILC high gradient cavity is very important for energy reach in physics. From machine operation point of view, we need a big margin in such a large machine. In the 1st ILC workshop in KEK on Nov. 2004, WG5-Asia group has proposed to developed high gradient cavity scooping 50MV/m. The history of high gradient improvement suggests that current limitation around 40MV/m on TESLA shape cavity could be by the fundamental RF magnetic field. The fundamental magnetic field could be ~1750 Oe. TESLA shape was optimised on Ep/Eacc to suppress field emission. TESLA R&D started around 1990. In those days, FE was most concerned issue. This problem was much more suppressed by HPR since 1995. Afterwards, the gradient has reached 40MV/m. Even the critical field limits TELA cavity at 40MV/m, still 50MV/m is possible if one choose the cavity shape with a lower Hp/Eacc ~35 Oe/(MV/m). Here Hp is the surface peak magnetic field. This kind of claim has been started from 2001 in the 10th SRF workshop in KEK [23]. Currently we have two candidates for high gradient shape as shown in Fig.22: Low loss shape (LL) and Re-entrant shape (RE). The first one was designed by J.Sekutowicz in DESY [24] and the second one was by V.Shemelin et al. in Cornell University [25]. After the ILC first workshop, KEK and Cornell University have started the high gradient R&D for ILC.

#### Principal Proof of 50MV/m

In the last SRF workshop in Cornell University, the demonstration of high gradient has been already started [26]. Cornell reported 46MV/m on RE cavity by their vertical EP [27]. Just after the workshop, end of August 2005 WG5-Asia group reached 47MV/m on RE cavity, which was fabricated in Cornell and made surface preparation in KEK. Successively this result, end of 2005 to mid 2006, they have reached 52.3MV/m on RE cavity, and 53.5 MV/m on LL (IS) cavity. They have successfully made principal prove 50MV/m on the high gradient shapes on SRF niobium cavity [28,29].

#### World Record of High Gradient

Thus, RF magnetic field limits the gradient is well recognized in this field. Cornell University has re-designed their RE cavity shape to lower Hp/Eacc reducing the diameter of bore from 68 to 60 mm. They built two new RE single cell cavities. They sent both KEK to make centrifugal barrel polishing because their equator EBW seam was not great. After CBP, KEK sent back one

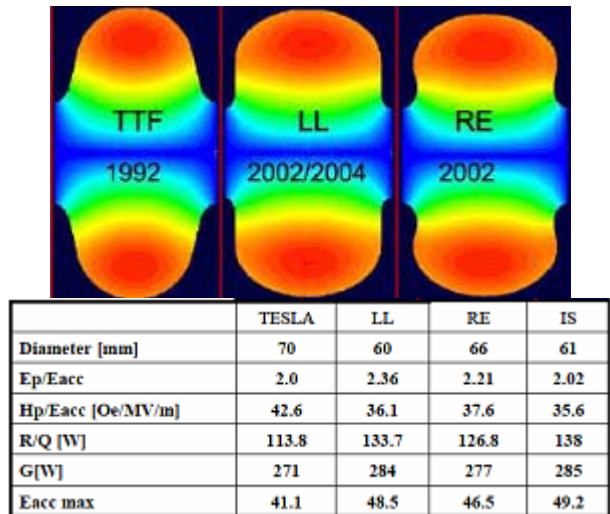


Fig.22: High Gradient shapes and RF parameters

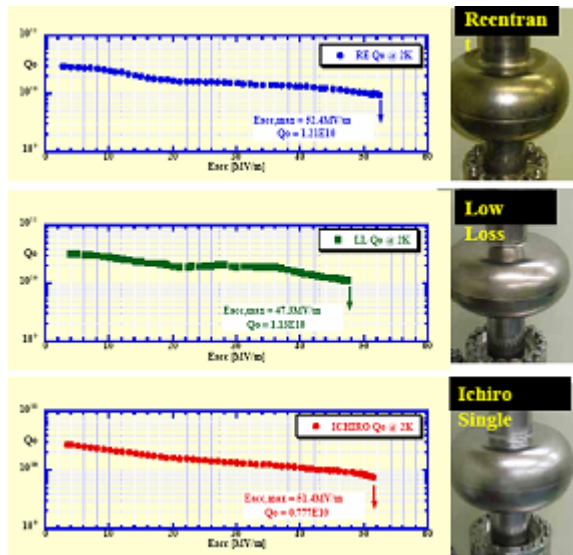


Fig.23: Proof of principal for 50MV/m high gradient

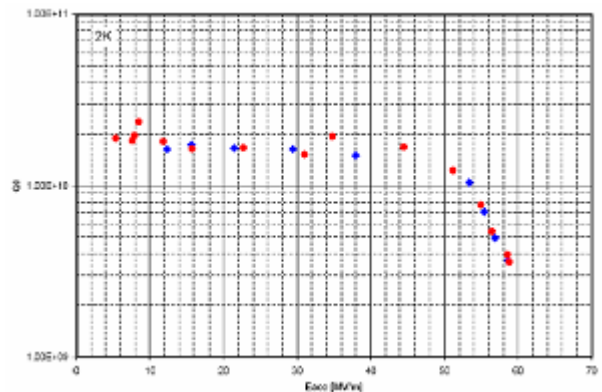


Fig.24: World record of the high gradient so far

cavity to Cornell. The other cavity was treated in KEK using WG5-Asia best recipe and tested. The gradient was limited 48MV/m by field emission due to the HPR pumping contamination mentioned before. After this measurement, they sent it back filling clean air. At Cornell, taking degreasing and HPR, they measured it. The result is shown in Fig.24. They have reached 59MV/m, which is the world record on SRF niobium cavity so far.

### History of Improvement of High Gradient

Fig.25 shows the history of high gradient improvement on 1.3 GHz single cell niobium cavities since 1991. Between 1991 and 1994, gradient improved gradually. High pure niobium material development, improve of preparation, and high peak power processing are pushed up the gradient. In 1995, HPR was routinely used in preparation and field emission was remarkably suppressed. Thus, we made a breakthrough from 30MV/m to 40MV/m. However, after that gradient saturated around 40MV/m and this performance was mainly produced by EP. Between 1995 and 2003 we faced Q-slope issue and understood the baking procedure can eliminate it, especially EP case. To date the cavity fabricated from large grain or single crystal niobium material can produce high gradient by even BCP but the result is no different from that of EP. In 2005, another breakthrough happened from 40 to 50MV/m by the high gradient shape as mentioned above. This is still continued even until now.

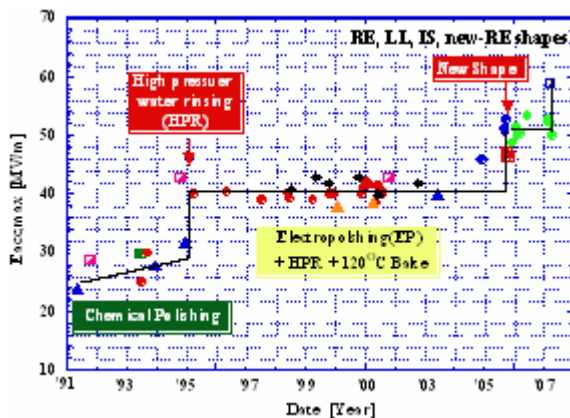


Fig.25: History of high gradient on SRF niobium cavity

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