PHY905 Section 4
Ion Accelerator Technology
Lecture 17

- Clean Technologies for SRF Cavities, Hydrogen Cure, and High gradient -

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17 Clean Technologies for SRF Cavities and Hydrogen Cure and High Gradient

17.1 Ultrapure Water

17.2 Degassed Water

17.3 Cleanroom assembly

17.4 Hydrogen Behavior during Chemistry

17.5 High Gradient Cavity

17.6 End Cell Study

17.7 Development of High Gradient 9-Cell Cavities

17.1 Ultrapure Water

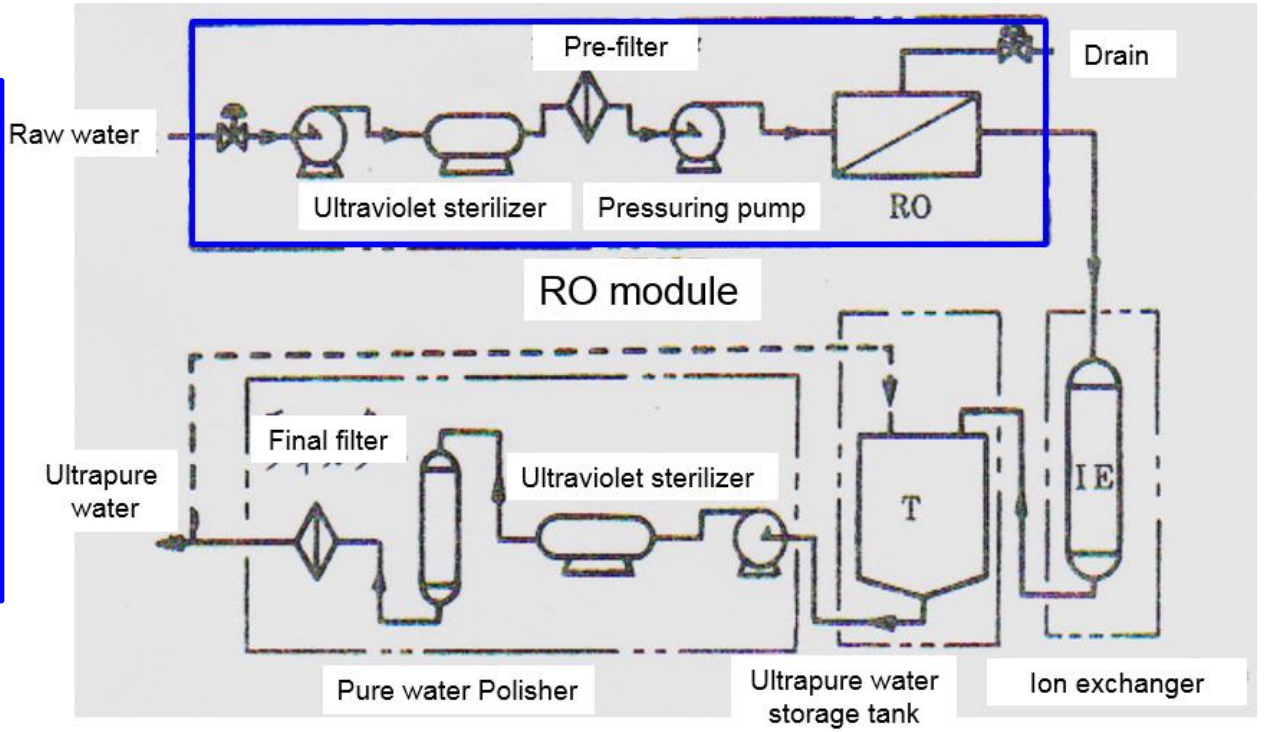
- Particles on the SRF surface are seeds of field emission.
- Hydrocarbon contamination also enhances multipcating or field emission.
- Ultrapure water is crucial to make clean SRF surface.
- Ultrapure water was applied first at Cornell early 1980's.
- Ultrapure water system was already established for semiconductor production.

Water quality:
Resistivity
18.3 MΩcm at 25^{O}C

Particle (> 0.2μm) < 50 /cc

SiO_2 < 50 ppb

TOC (total organic carbon) < 50 ppb

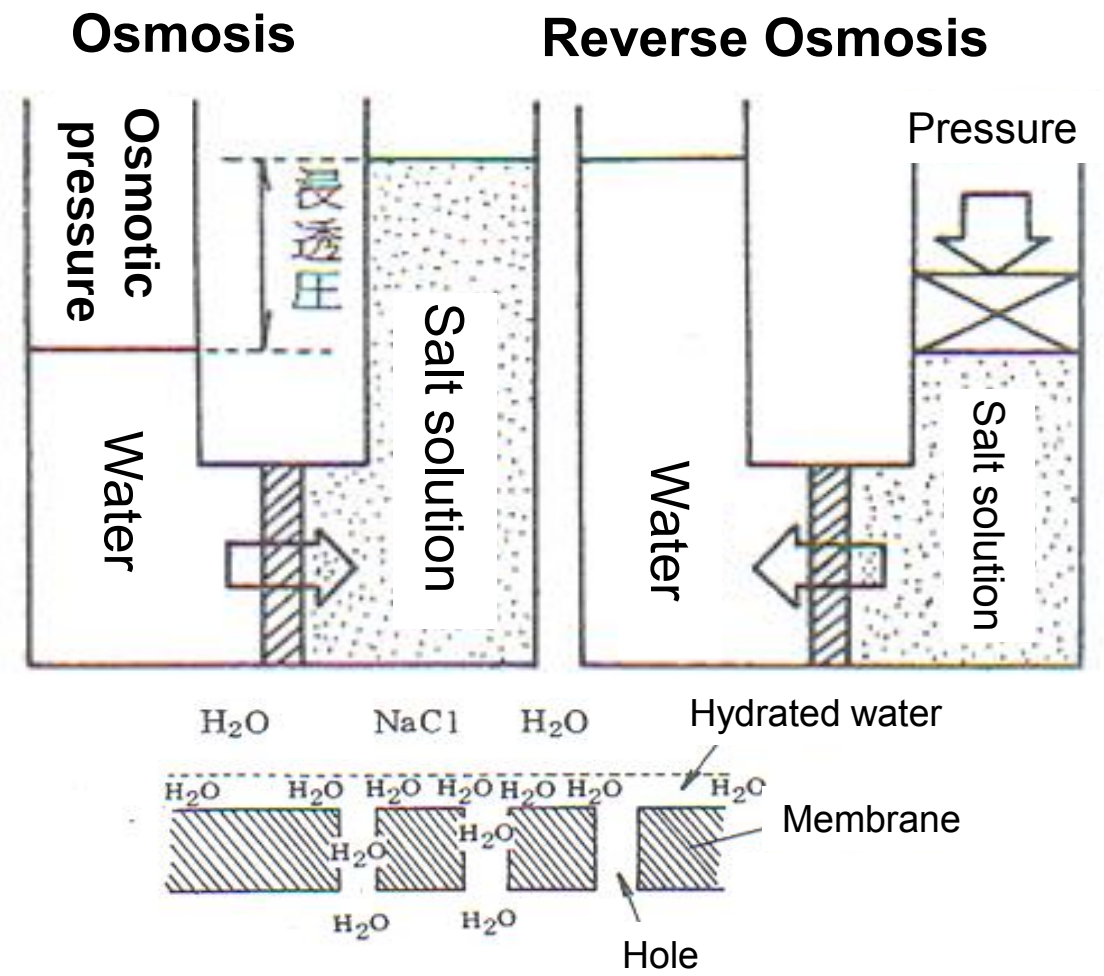


General ultrapure water system for semiconductors

Principle of Water Filtering for Ultrapure Water

Principle of water filtering

- Osmotic pressure generates when isolated water and salt solution by a semipermeable membrane.
- Oppositely, when put pressure larger than the osmotic pressure on the salt solution, water in the salt solution moves water side. This phenomena is called reverse osmosis.
- The membrane is covered by hydrated water.
- The hole size in the membrane is similar to the thickness that covered by hydrate.
- When pressurized, the water only through the hole and the dust, bacteria, ion etc. can be filtered.

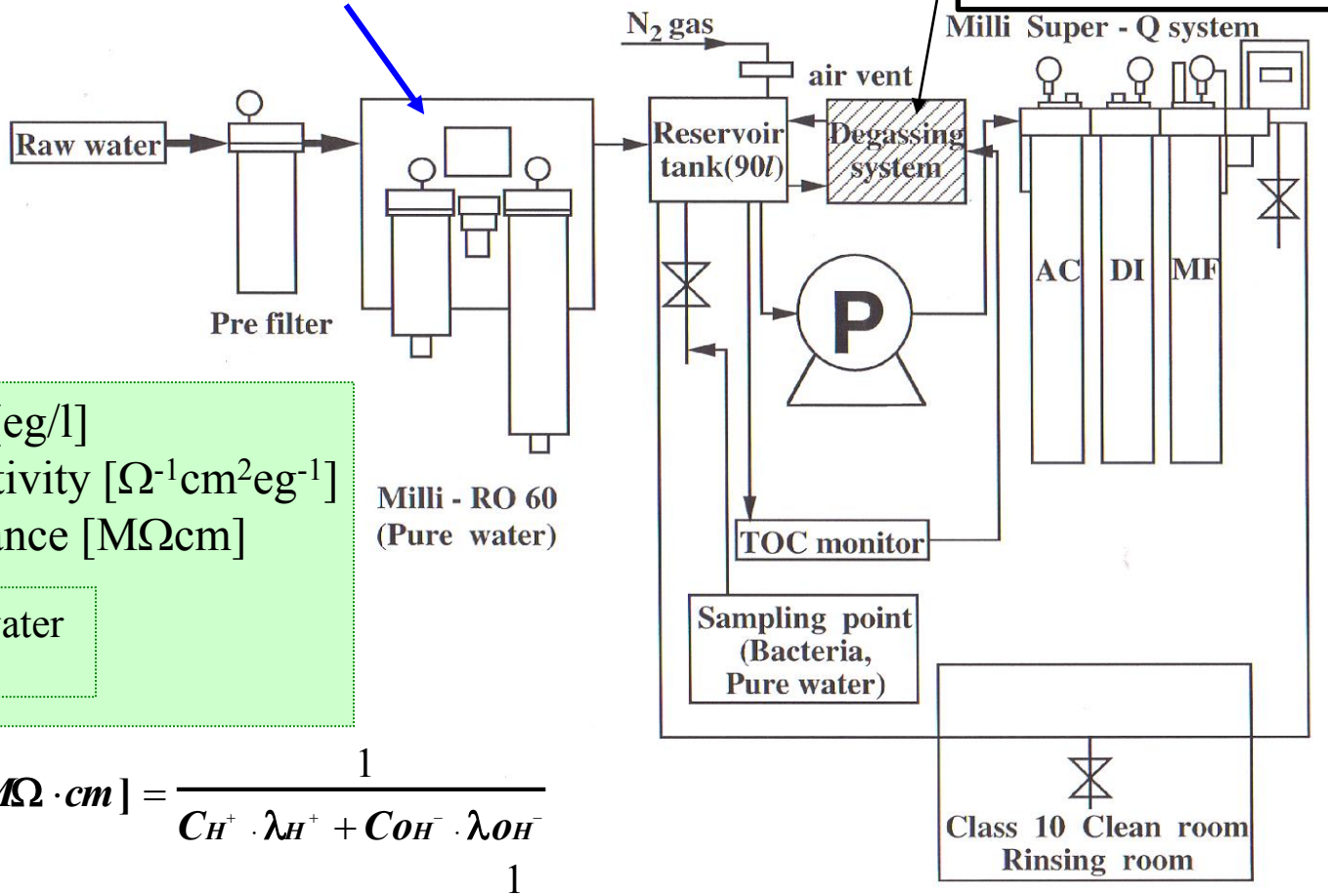


Structure of semipermeable membrane

Example of Ultrapure Water System in KEK

More than 90% of ions, particles are filtered by RO(Reverse Osmotic)

Usually no degassing system on an ultrapure making system



C: Concentration of ions [eg/l]
λ: Ion equivalent conductivity [$\Omega^{-1}cm^2eg^{-1}$]
R: Specific electric resistance [MΩcm]

For the neutralized water
$C_{H^+}=C_{OH^-}=10^{-7}$eg/l

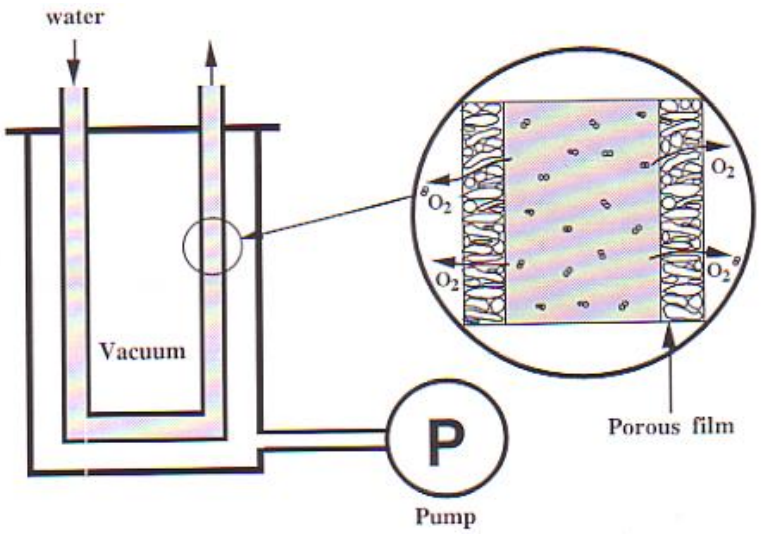
$$R = \frac{1}{\sum(C_i\lambda_i)} \qquad R[M\Omega\cdot cm] = \frac{1}{C_{H^+}\cdot\lambda_{H^+} + C_{OH^-}\cdot\lambda_{OH^-}}$$

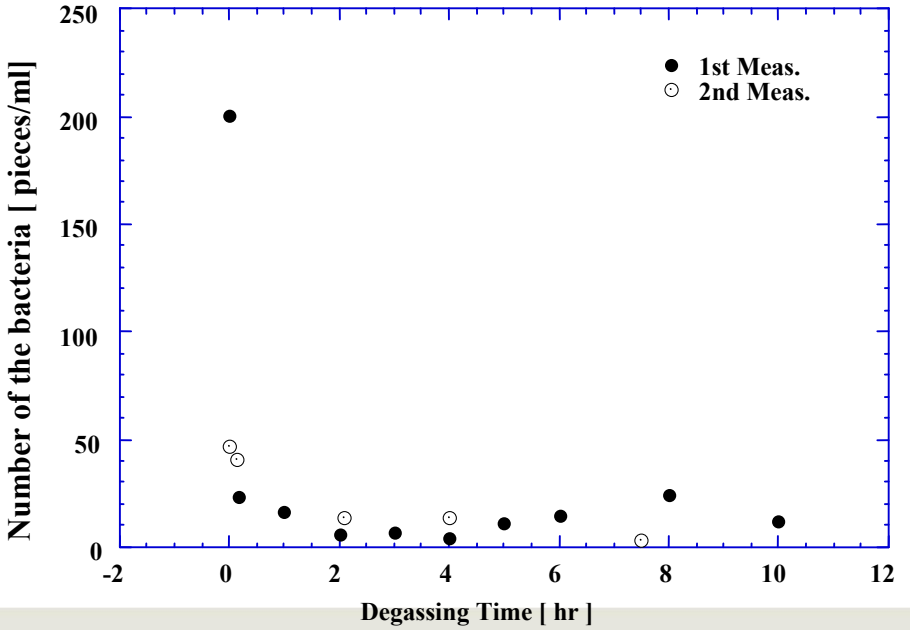
$$= \frac{1}{349.8\times10^3\times10^{-7} + 197.6\times10^3\times10^{-7}}$$

$$= \frac{1}{5.474\times10^{-2}} = 18.27[M\Omega\cdot cm] \ @\ 25\ ^0C$$

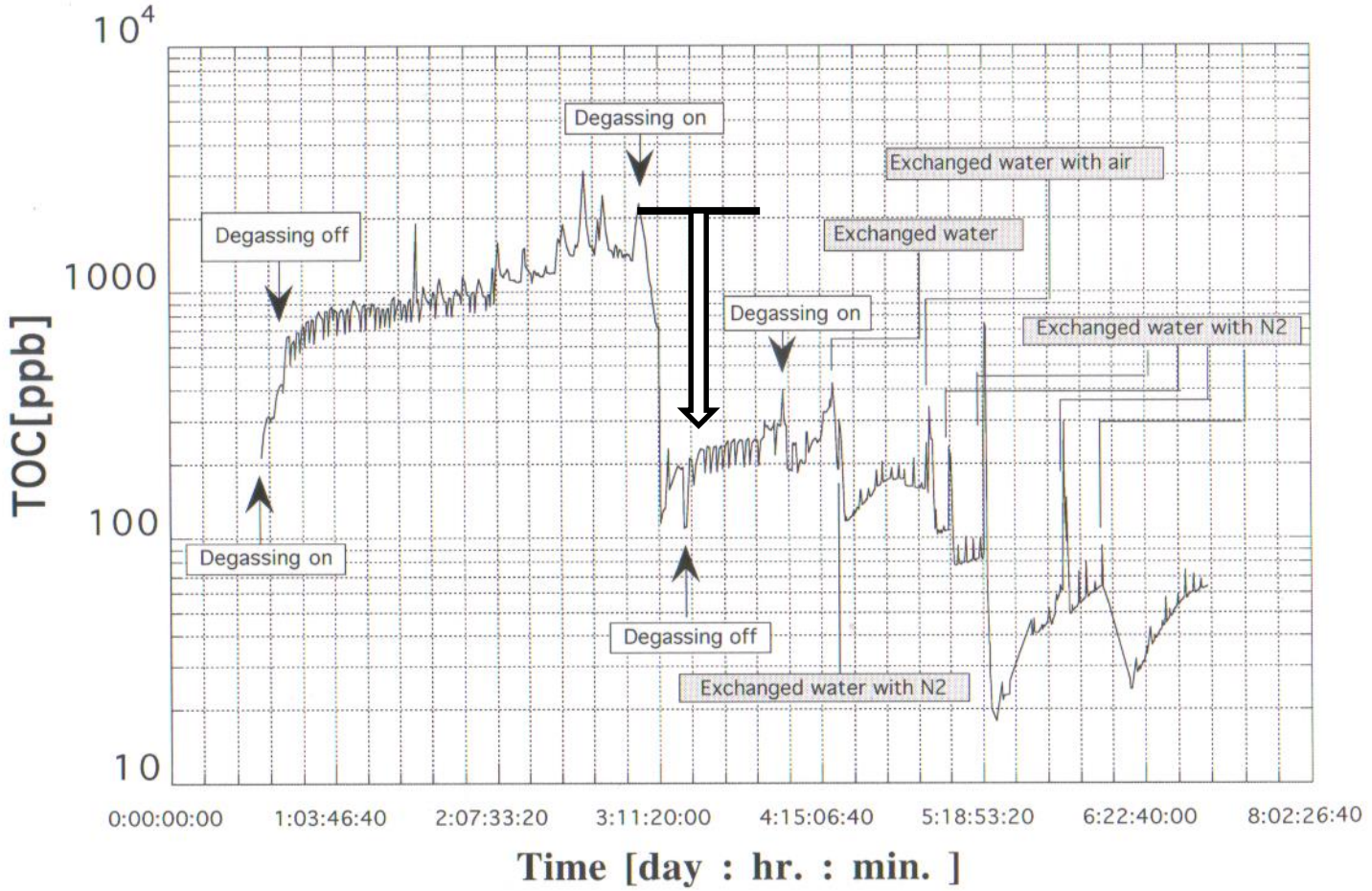
17.2 Degassed Water

- **The maintenance cost of the commercial ultrapure water system is not cheap**.
  - They have an ultraviolet sterilizer to kill bacteria in the system.
  - The filters in the system filtrate the dead bacteria, and as the result the filters are blocked off and replaced (maintenance).
  - The life of the ultraviolet lamp is not long (maintenance).
- **One cost-effective maintenance is to install degassing system in the ultrapure water system**





Degassing Effect with TOC in the Ultrapure Water



- A large impact was observed to reduce TOC by degassing at KEK.
- TOC was reduced by one order of magnitude.

17.3 Cleanroom Cavity Assembly

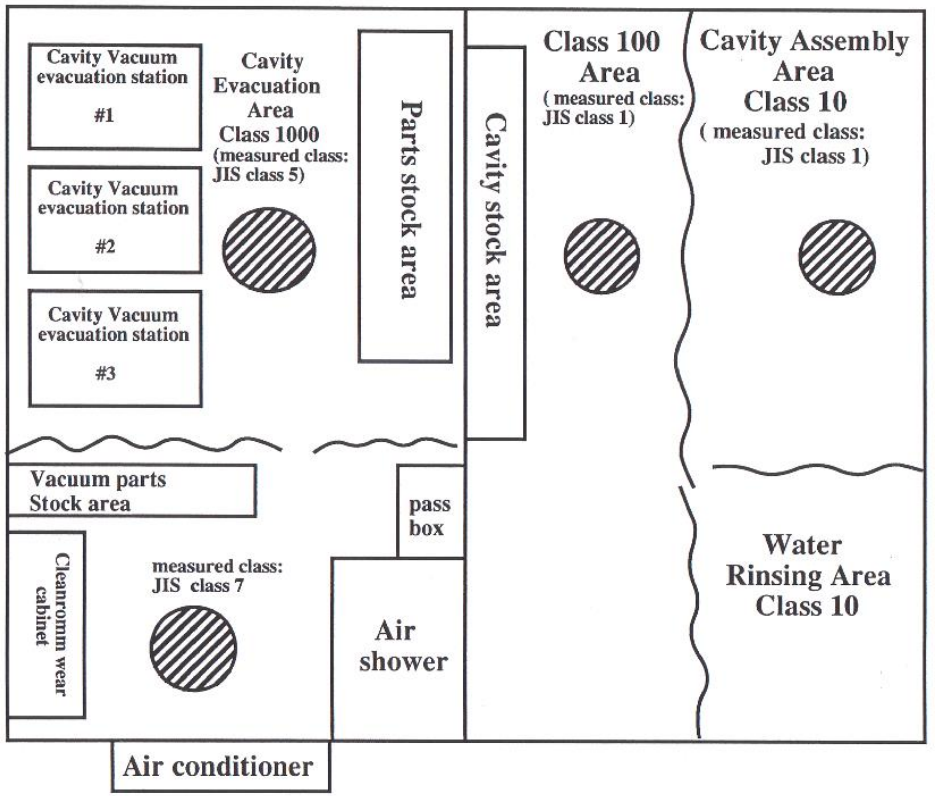
- Cleanroom cavity assembly is the same concept against particle for clean SRF surface.
- This technology was also applied at Cornell early 1980's.
- Cleanroom technology was established for semiconductor production.
- Cleanroom system is simple and robust:
  - Air circulation through high efficiency filter (HEP) for class 100 and ultra high efficiency filter (ULPA) for class 10.
- The definition of class (US NASA definition)
  - Class 100: number of particles (>0.5μm) is less than 100 pieces in one cubic feet (23.8L).
  - Class 10: number of particles (>0.5μm) is less than 10 pieces in one cubic feet (23.8L)
- ISO definition:
  - ISO 100: number of particles (>0.1μm) is less than 100 pieces (>0.5μm) in one cubic meter ($1m^3$).
  - ISO 10: number of particles (>0.1μm) is less than 10 pieces (>0.5μm) in one cubic meter ($1m^3$).

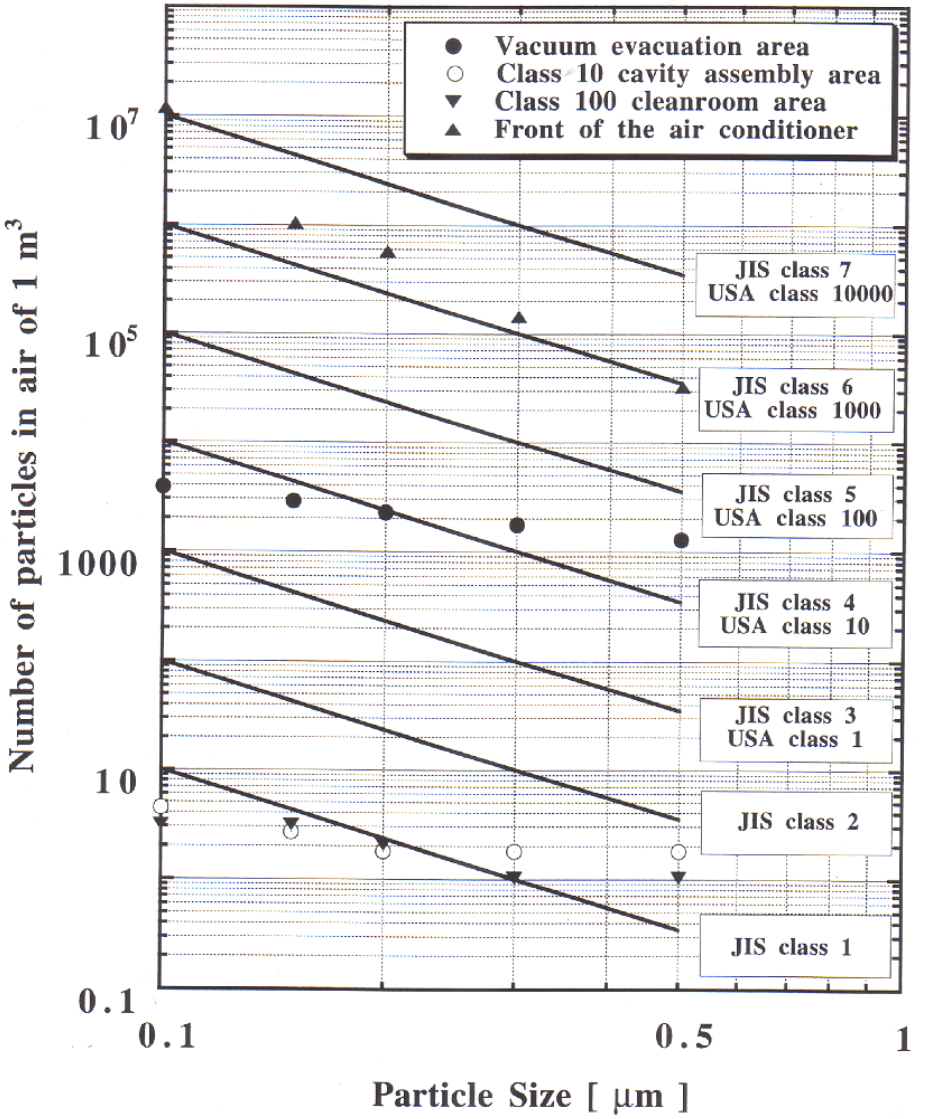
Cleanroom Cavity Assembly: Example in KEK

HEPA filter (class 100)

ULPA filter (class 10)

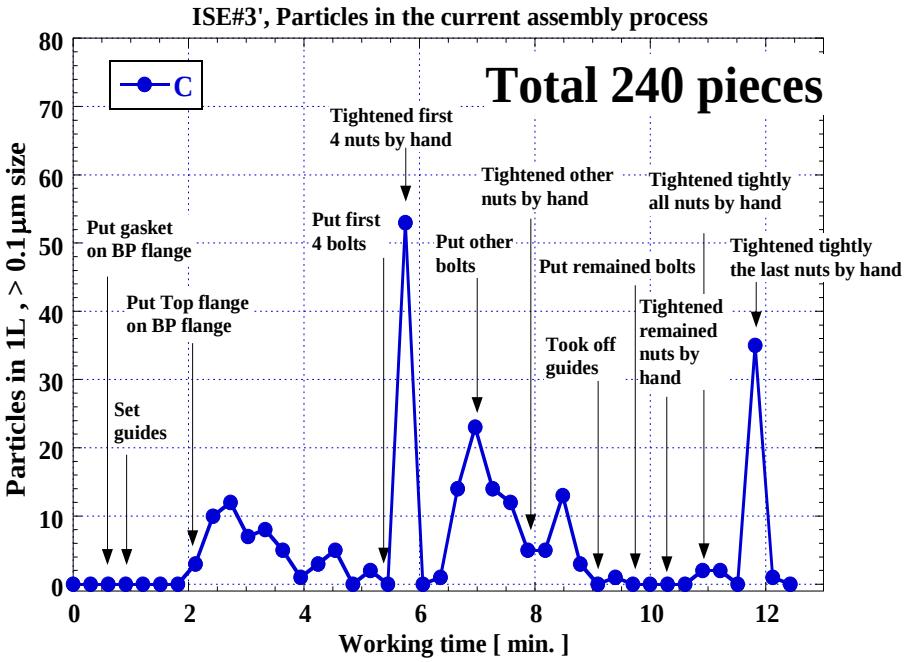
Real Cleanliness, Example KEK



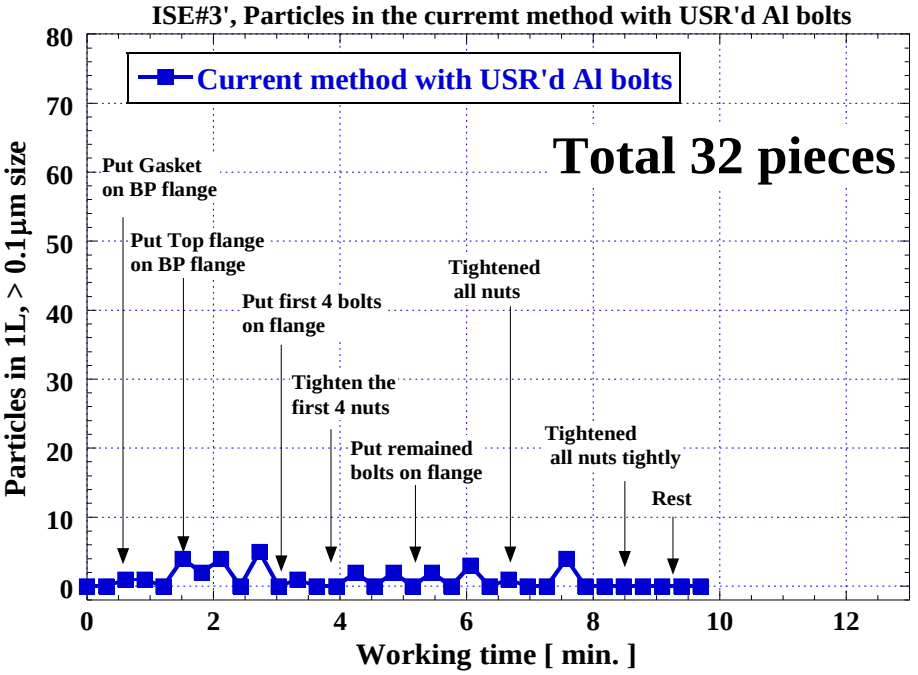


Particles during Cavity Assembly, KEK

- As expected, lots of particle generates from bolts
- Ultrasonic clean of bolts is very helpful to reduce particle contamination but not perfect !!
- Even cleanroom assembly, more care is needed !!

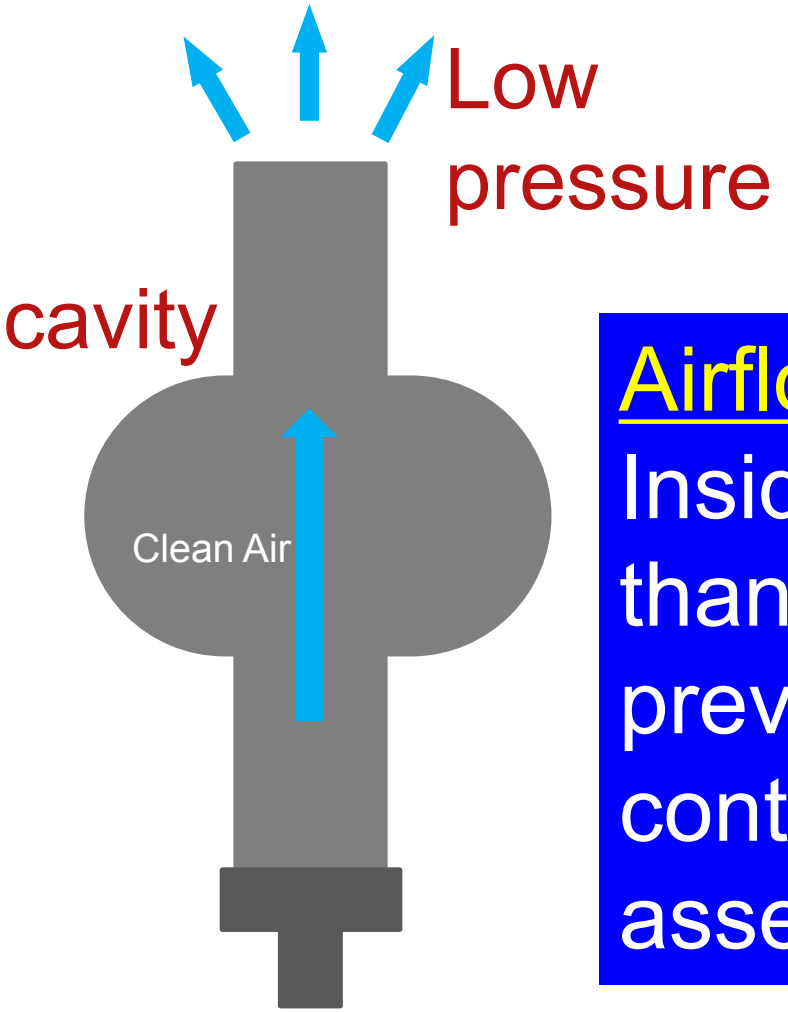


Cavity assembly using bolts without any cleaning



Cavity assembly with bolts ultrasonic cleaning

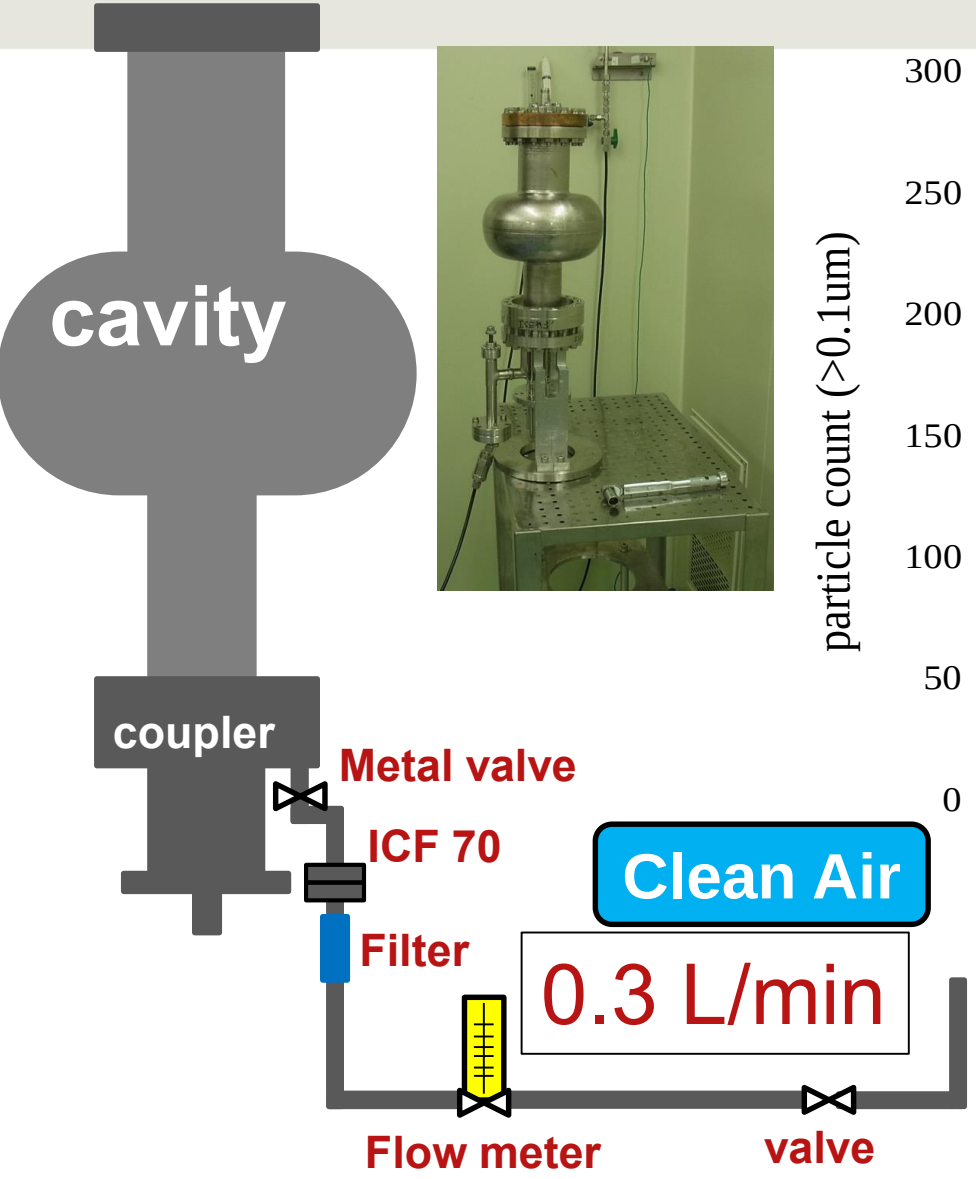
Cavity Assembly under Airflow

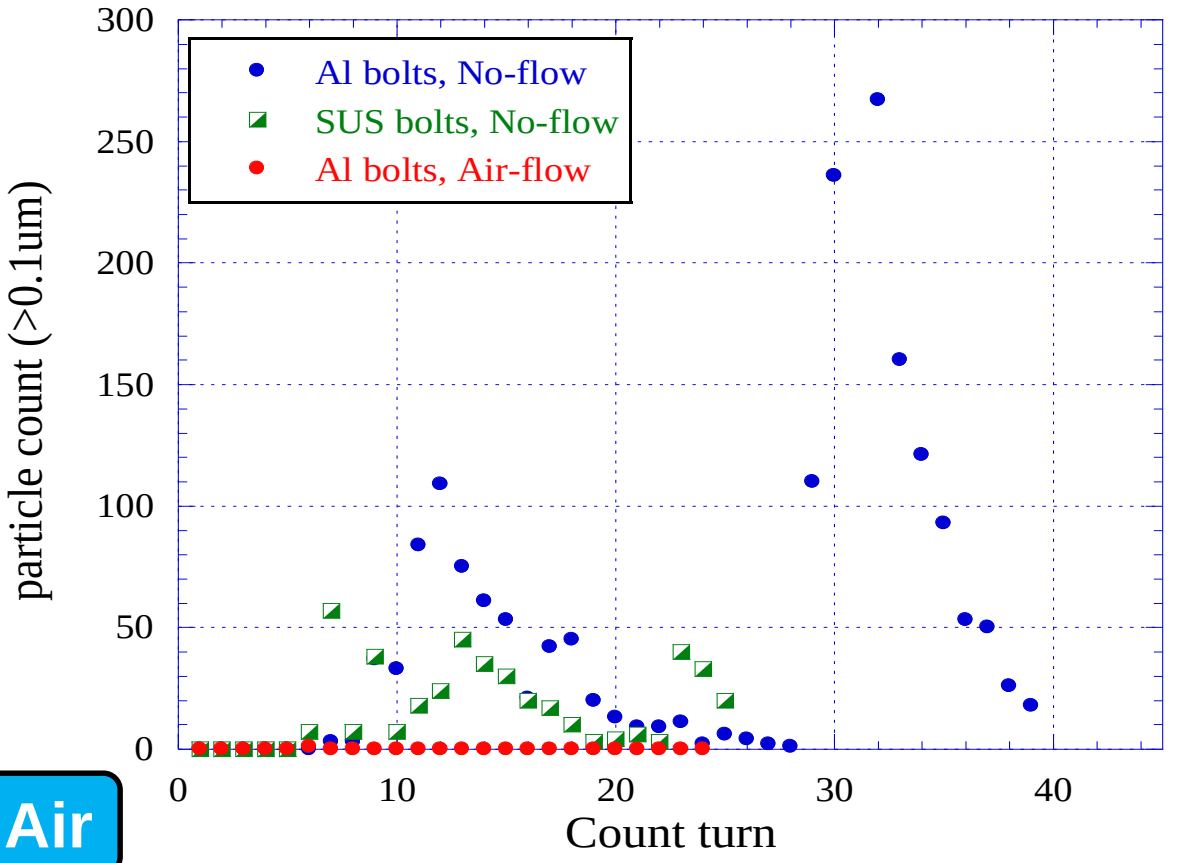


Airflow Method for assembly

Inside pressure is higher than outside pressure, then prevent the particle contamination during cavity assembly

Airflow Cavity Assembly

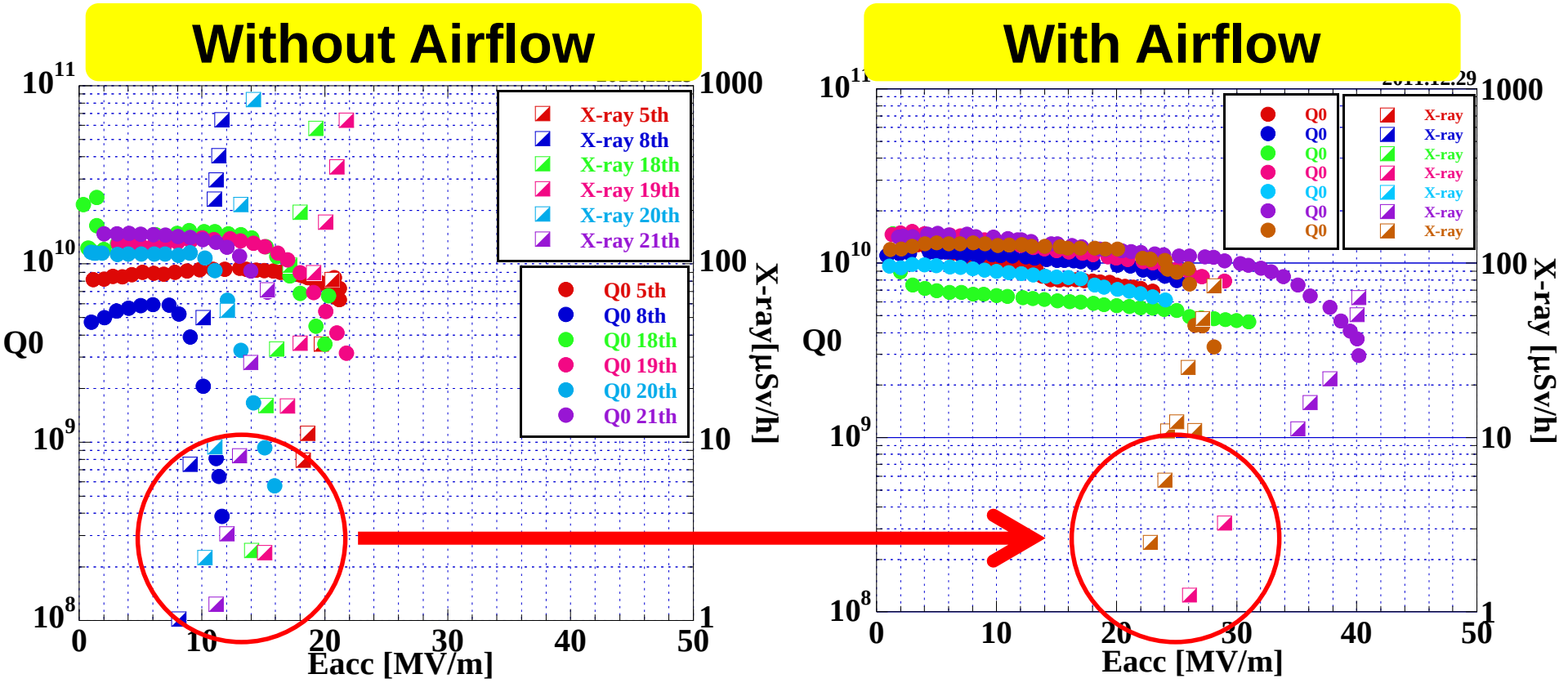




Airflow method is a **perfect cure** against the particle contamination in cavity assembly.

System of airflow method

Cavity Performance Improvement by Airflow Assembly



Adoption of Air flow method with MO-sealing cavity

17.4 Hydrogen Behavior during Chemistry
Hydrogen Q-disease-free Electropolishing

- Hydrogen is very common issue for all metal surface and vacuum technology. SRF cavity performance is very sensitive, so we can use this method.
- Here, the perfect understanding of hydrogen doping in the metal surface will be give, which will help your future studies.
- KEK took hydrogen degassing as the cure against hydrogen disease.
- Horizontal rotational EP was originally to design to eliminate the hydrogen Q-disease, but it was no time to confirm at that time (1986) due to the tight TRISTAN construction schedule.
- After the TRSTAN SRF, KEK has confirmed the horizontal rotational EP itself has no hydrogen Q-disease.
- KEK discovered Hydrogen Q-disease is caused when mechanical grinding is carried out prior to EP.
- The combination of mechanical grinding and EP is a worst scenario for the hydrogen Q-disease
- However, KEK established hydrogen free preparation method even in the combination of mechanical grinding and EP.

Investigation Coupon of Hydrogen Absorption during Various Processing

- Niobium material absorbs hydrogen during dipping EP acid, the higher acid temperature increases more adsorption.
- Hydrogen is absorbed under Intermitted EP.
- Hydrogen is not absorbed under continuous EP.
- Cathode bag protects hydrogen absorption.

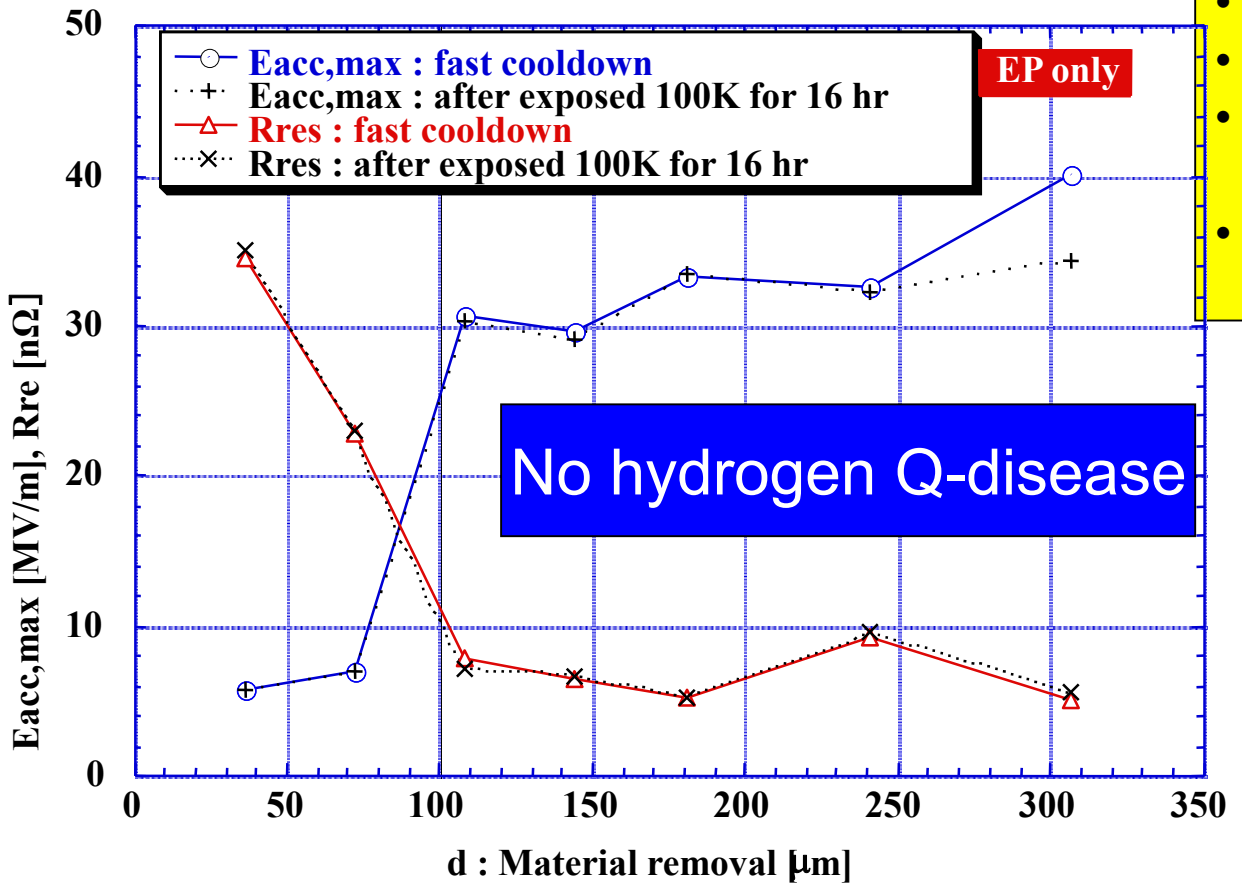
Process Number	Processing	Hydrogen concentration [ppm] (Average)	Delta (No.) –(1)
(1)	Annealing at 750^{O}C for 3 hr	0 – 1.0 (0.5)	0 (reference)
(2)	Dipping into EP acid (30^{O}C) for 3hr	4.6 – 5.7 (5.2)	+ 4.7
(3)	Dipping into EP acid (45^{O}C) for 3hr	5.2 – 6.8 (6.0)	+ 5.5
(4)	Intermitted EP 151μm	2.2 – 2.8 (2.5)	+ 2.0
(5)	Continuous EP 147μm with cathode bag	0 – 0.2 (0.1)	- 0.4
(6)	Continuous EP 151μm without cathode bag	0. 1 – 1.1 (0.6)	0.1

Investigation by Cavity of Hydrogen absorption during Various Processing

- Nb cavity absorbs hydrogen during dipping EP acid, the higher acid temperature increases more adsorption.
- Nb cavity absorbs hydrogen under Intermitted EP I
- Nb cavity absorbs hydrogen does not absorb under continuous EP.
- Cathode bag protects hydrogen absorption.

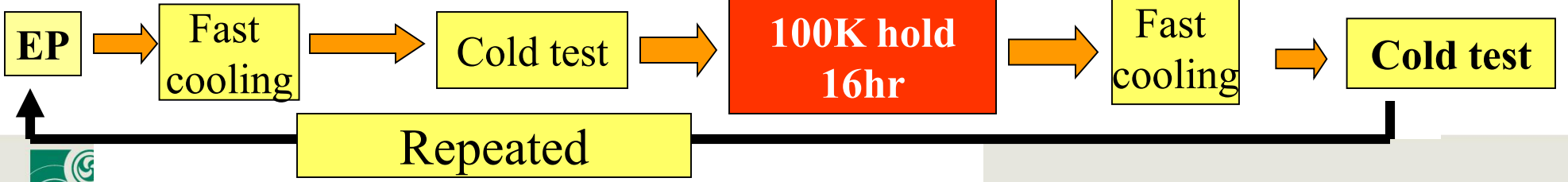
Process Number	Processing	Increased Surface resistance after 100K soaking [nΩ]
(1)	Dipping into EP acid (30^{O}C) for 3hr	+0.6
(2)	Dipping into EP acid (45^{O}C) for 3hr	+ 5.9
(3)	Continuous EP (30^{O}) 33μm	- 4.3
(4)	Intermitted EP 82μm with cathode bag	+12.6
(5)	Continuous EP 55μm with cathode bag	- 0.7
(6)	Continuous EP 110μm without cathode bag	+ 3.5

Horizontal Rotational Continuous EP Has No Hydrogen Q-Disease



- Started from a brand new cavity
- No pre-preparation prior first EP
- Repeated EP and increased the material removal up to 330 μm
- Cold tested at ~ every 50μm material removal

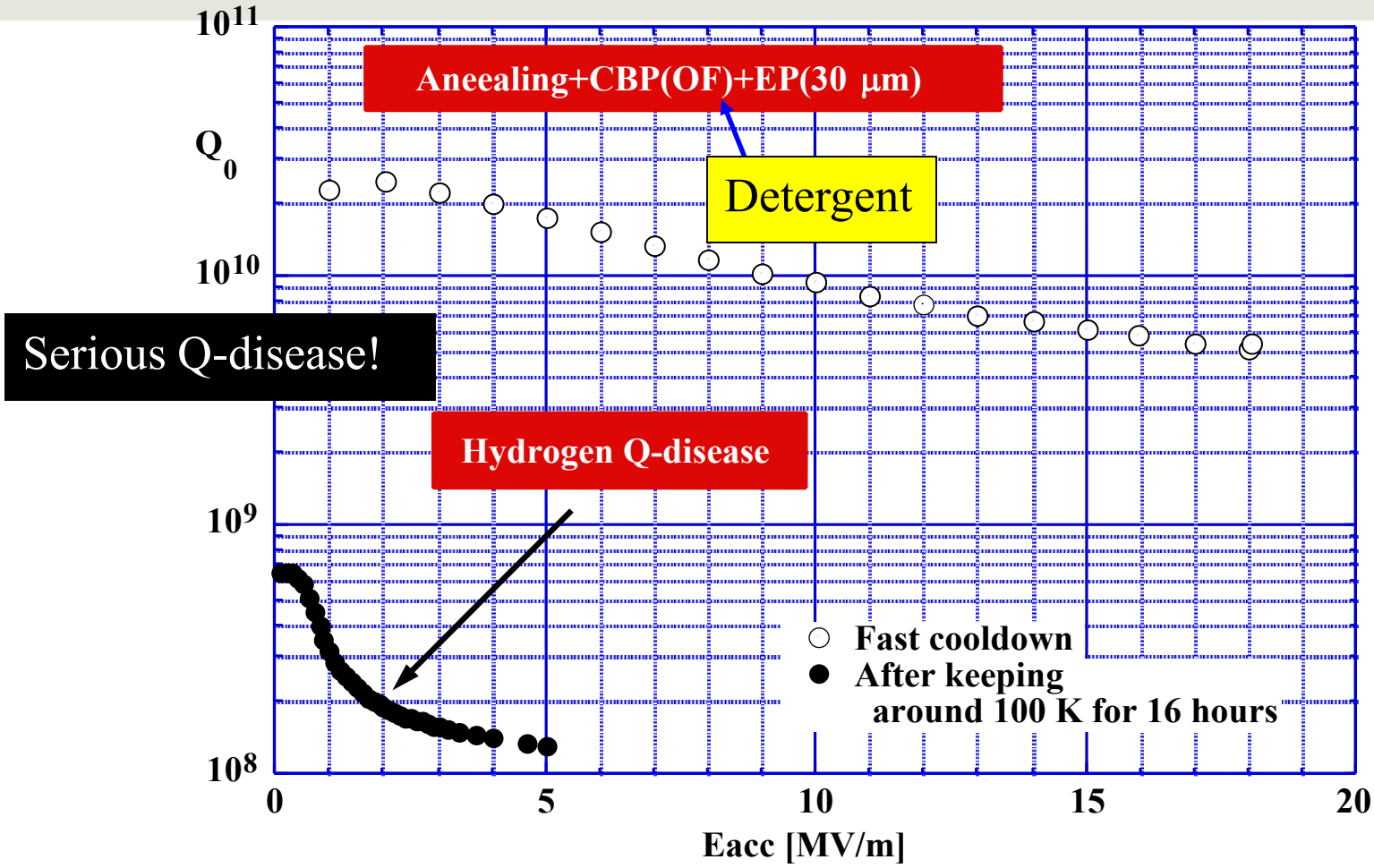
No hydrogen Q-disease even held 100K for 16 hr



Hydrogen Absorption by CBP + EP

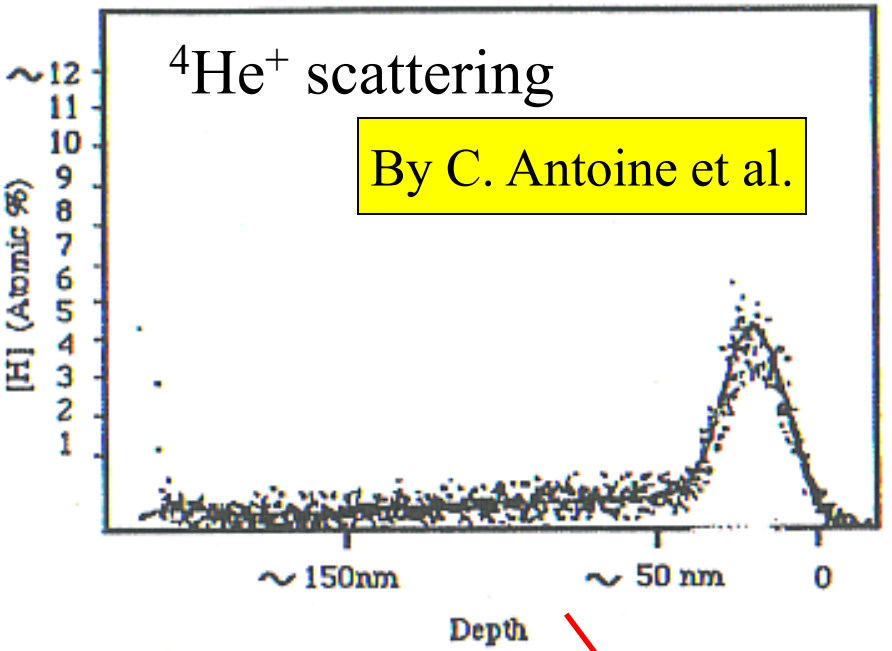
- KEK successfully validated the horizontal EP dose not produce hydrogen Q-disease.
- In the last lecture, the process: CBP + Horizontal EP (10-20μm) + Annealing + HPR produce 25MV/m but they took annealing in this procedure suspecting hydrogen Q-disease.
- How about hydrogen Q-disease with the procedure CBP+ Horizontal EP ?
- A cavity was annealed at 750^{O}C for 3hr (hydrogen degassing), then the process was tested.

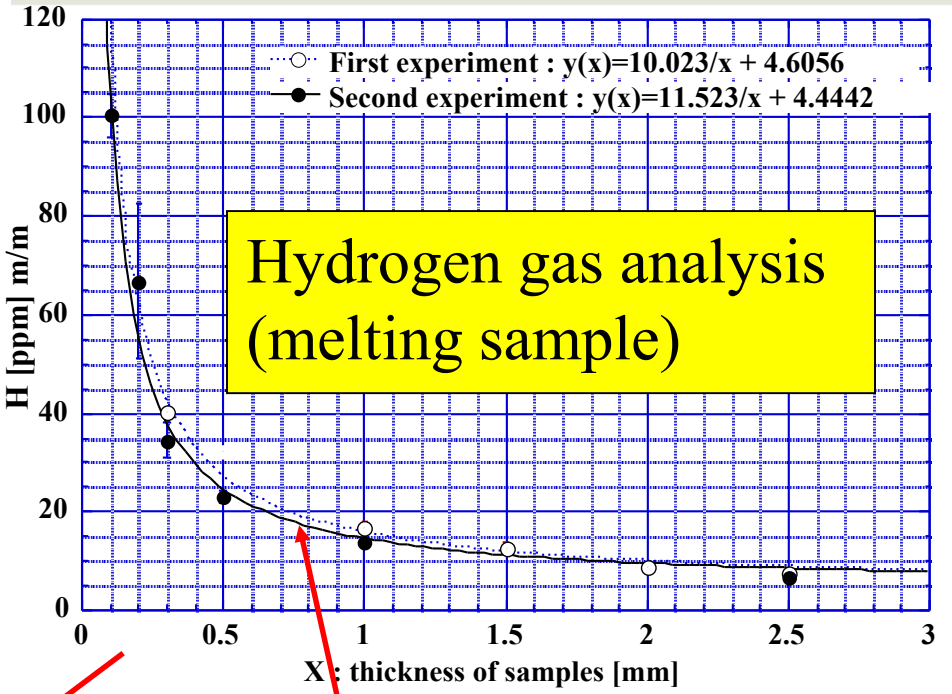
Hydrogen Absorption by CBP + EP



- **Hydrogen Q-disease was observed after 100K soaking.**
- **Even by fast cooling, light hydrogen Q-disease is observed.**
- **CBP produces hydrogen Q-disease.**

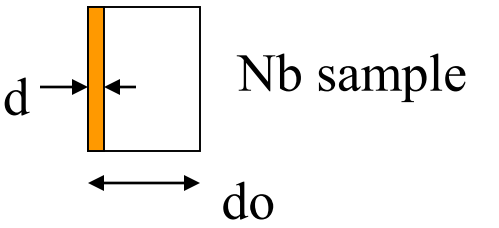
Hydrogen Trapped Site





Absorbed hydrogen located underneath of top surface

Hydrogen is trapped in the top surface layer.
Surface defects might be a trapped center.



$$W = \frac{aSd}{Sd_o\rho} = \frac{ad}{\rho} \cdot \frac{1}{d_o}$$

If hydrogen localized on the top, the hydrogen analysis result depends on sample thickness. The thinner sample has the heavier hydrogen gas concentration.

H-Gas Analysis of Nb Samples with CBP

Process	H Concentration [ppm]
CBP (no solvent)	10.9 ± 0.8
CBP (water)	79.1 ± 5.0
CBP (water+detergent)	78.0 ± 2.9
CBP ($10\%H_2O_2$)	28.4 ± 1.4
CBP (non water propyl-alcohol)	49.4 ± 2.2

CBP without water procudes less hyfrogen

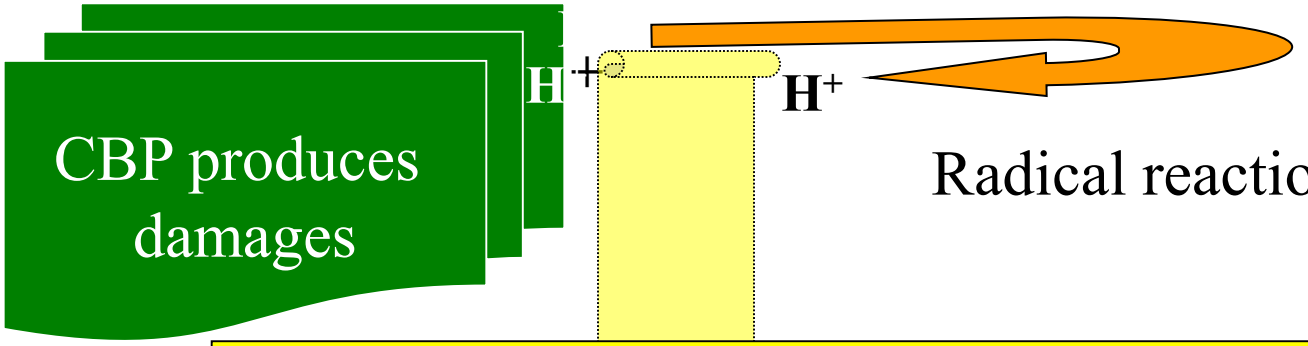
CBP with water produces heavy hydrogen

Oxide film generation mitigates hydrogen

1) Confirmed hydrogen is absorbed during CBP
2) The solution included hydrogen used CBP produces the hydrogen doping.
3) Oxidation mitigates the hydrogen doping.

Idea acquired through above experiment

Damages picks up hydrogen decomposed water



Oxidation process coves the damaged surface by oxide film and prevents the hydrogen picking up at the damage.

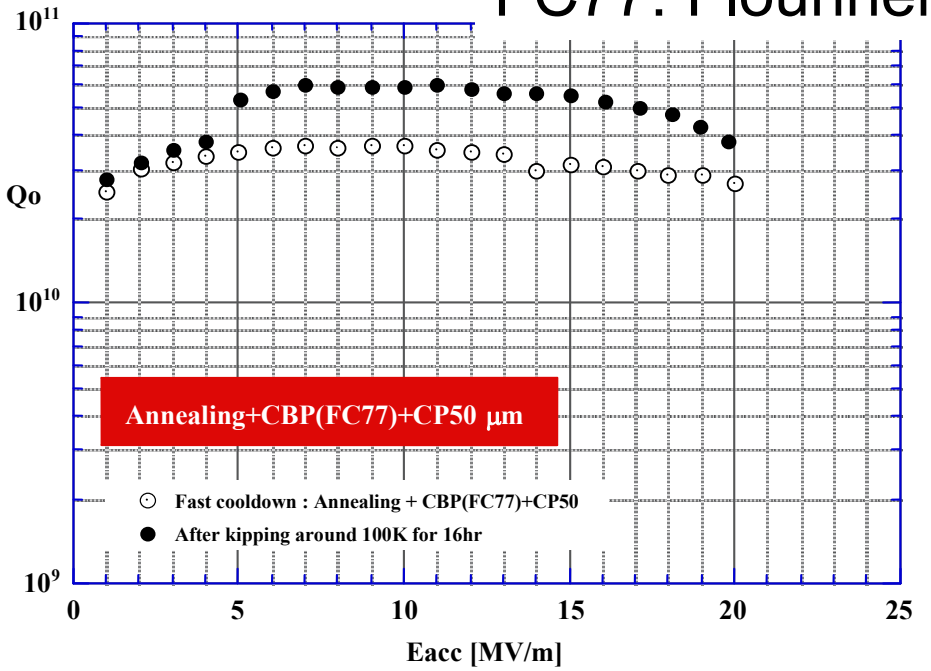
Innovation of H-free-CBP

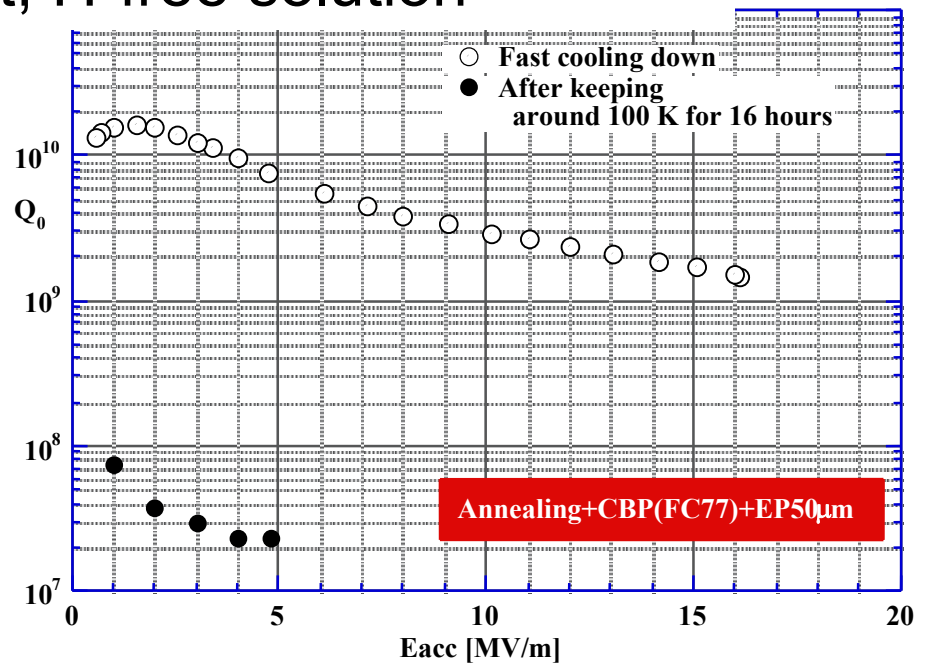
Hydrogen analisys result with niobium sample

Utilize the detergent without any hydrogen

Process	H Concentration [ppm]	Comment
CBP (FC77)	4.60± 0.80	FC77(3M-florinert):C_8F_{18}+$C_8F_{16}O$
CBP(FC77)+EP50μm	58.10± 2.95	Hydrogen Q-disease by cavity test
CBP (FC77)+CP50μm	1.02 ± 0.060	No Hydrogen Q-disease by cavity test
Annealing (750°C, 3hr)+EP50μm	5.02± 1.72	No hydrogen Q-disease by cavity test

FC77: Flourinert, H-free solution





The innovation succeeded with CP but not EP.

Hydrogen Pickup during Pre-EP

Heavy Hydrogen Q-disease happens in the Cavity Preparation Process:
Annealing + CBP(FC77)+Pre-EP(2μm)+EP(50μm)

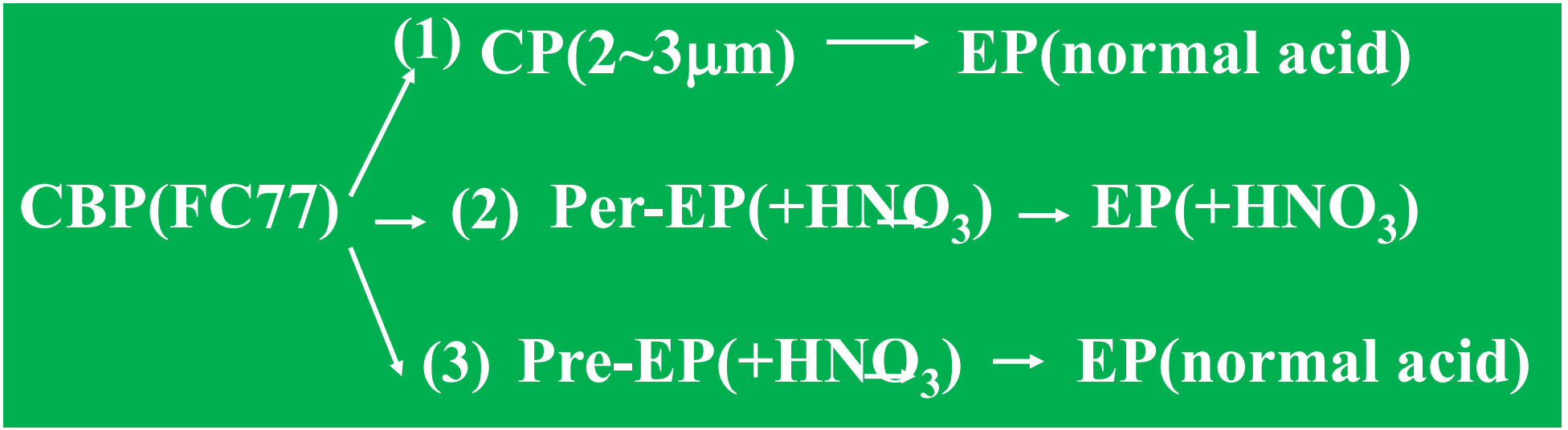
Removed abrasive contamination
Not continuous EP
No acid circulation → High Temperature

Hydrogen analysis result by samples

Process	H Concentration [ppm]	Comments
CBP (FC77) +EP50μm	3.62± 1.68	Hydrogen Q-disease by cavity test Pre-EP might pick up hydrogen.
CBP(FC77)+Pre-EP(30°C)3.25μm	5.80± 0.64	Pre-EP picks up hydrogen.
CBP(FC77)+Pre-EP(37°C)3.25μm	16.71± 3.43	Much more hydrogen is picked up at the higher temperature.

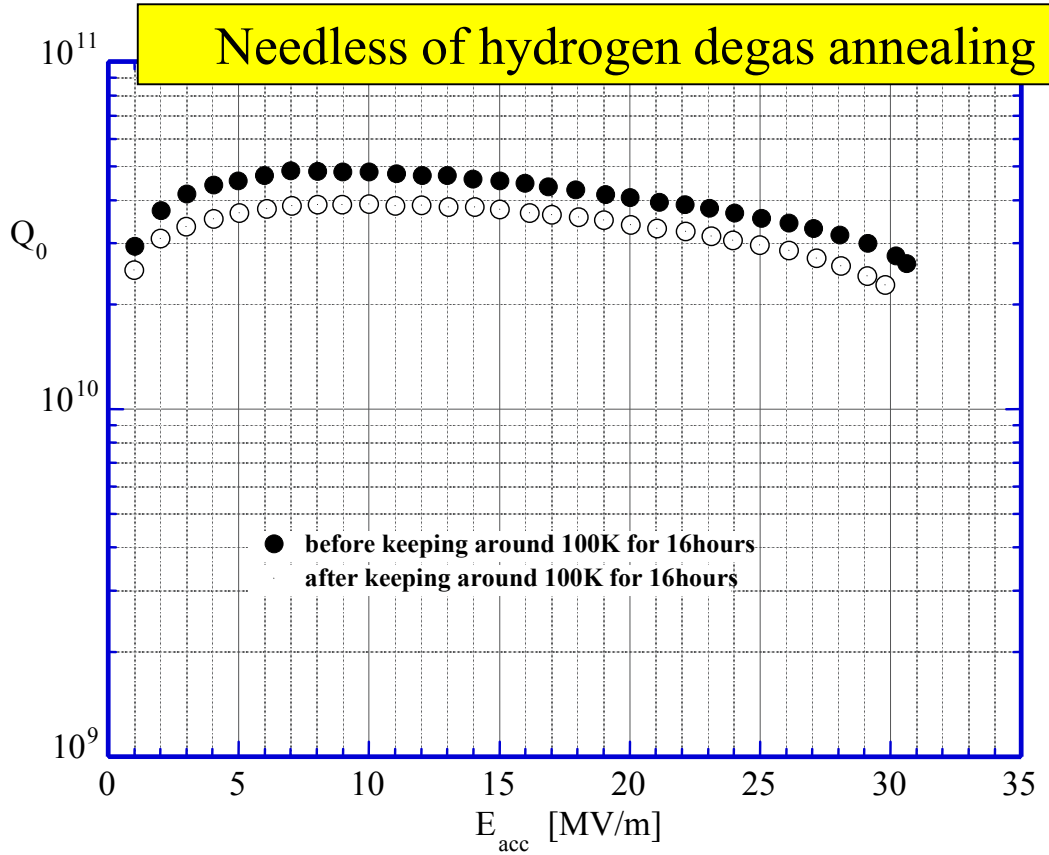
Hydrogen is picked up during Pre-EP. When the EP acid temperature the higher, the more hydrogen picked up. The hydrogen once picked up this process can not be removed by the additional EP

H-free Preparations



From the easy waste acid treatment point of view, (3) is most feasible.

Certification of the H-free Process: BCP(FC77) + Pre-EP (+1500ppm HNO_3)+EP(50μm, normal acid)



CBP(FC77)

⇓

Pre-EP(+1500ppmHNO_3)

⇓

EP(50μm, normal acid)

HNO_3 1500ppm: 1.5 cc HNO_3 /1L
EP acid

A H-free process has been successfully certified, which can eliminate the annealing for hydrogen degassing. The process become simple and cost-effective.

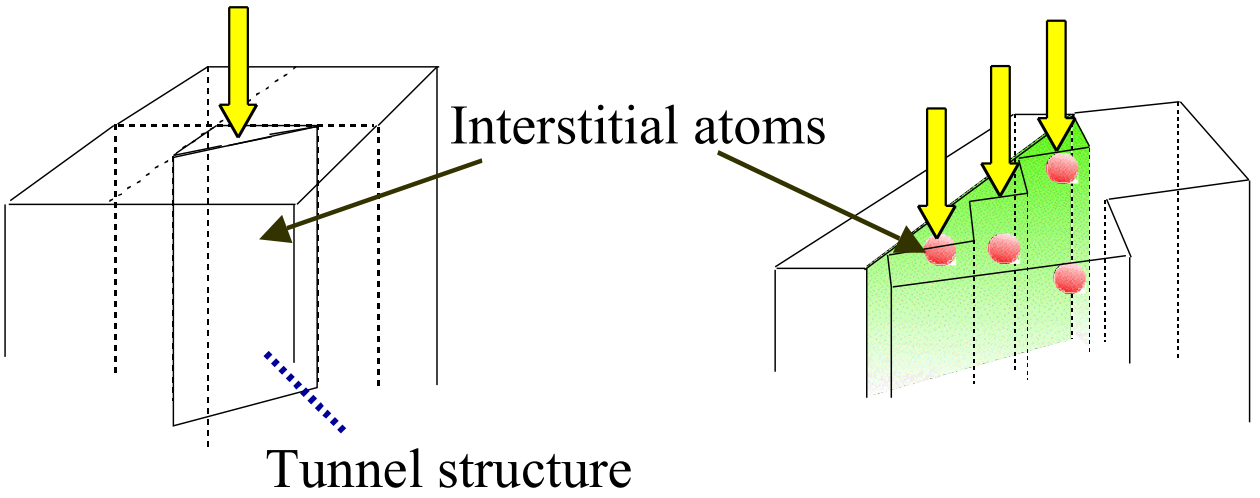
Hydrogen Behavior during Chemistry

1） The horizontal EP method was designed as that it should have no hydrogen absorption. However that was not certified during TRISAN project due to the tight construction schedule. After the TRISTAN that has been successfully certified.
2） Mechanical grinding like BP or CBP dopes hydrogen on the cavity surface, whic can not be removed additional EP.
3) The hydrogen comes from the water or detergents including hydrogen as the component.
4) When use H-free detergent like Flourinert, hydrogen is not absorbed.
5) The oxidation of the damaged surface can preserve the hydrogen doping.
6) The pre-EP used in TRISTAN project dopes hydrogen, however it can be protected by using EP acid one drop HNO_3 added, for instance 1500ppm.
7) When combined such pre-EP(HNO_3) and additional conventional horizontal EP , processing can reach the gradient 30MV/m without hydrogen Q-disease.

Hydrogen Absorption Mechanism

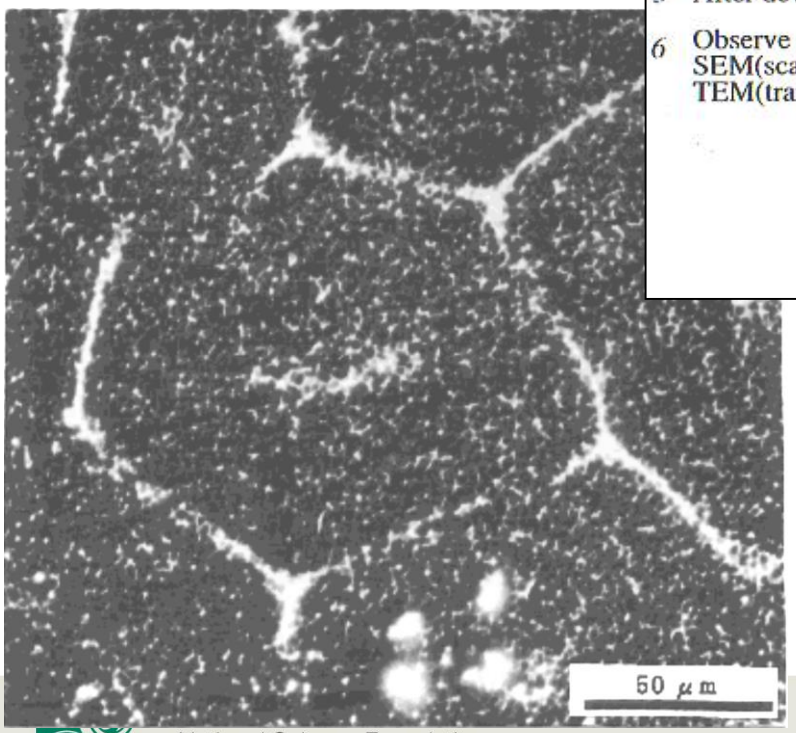
Channeling

By G.Katano



Hydrogen Trapping Sites by Tritium Autoradiography

By G.Katano et al.



Similar process as photography
Use tritium instead of Hydrogen

1 Doping tritium to sample
2 Make the photo emulsion layer on the specimen
3 Tritium decays
$H \rightarrow {}^{3}He + e^{-} + \bar{\nu}$
4 β-rays hits photo emulsion
5 After developmentsilver grains remain
6 Observe silver grains using SEM(scanning electron microscopy) or TEM(transmission electron microscopy)

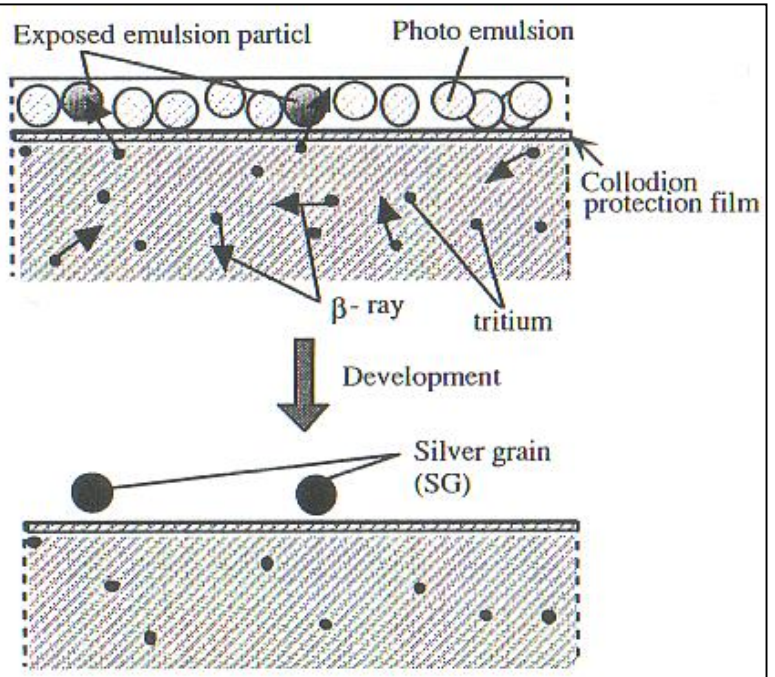
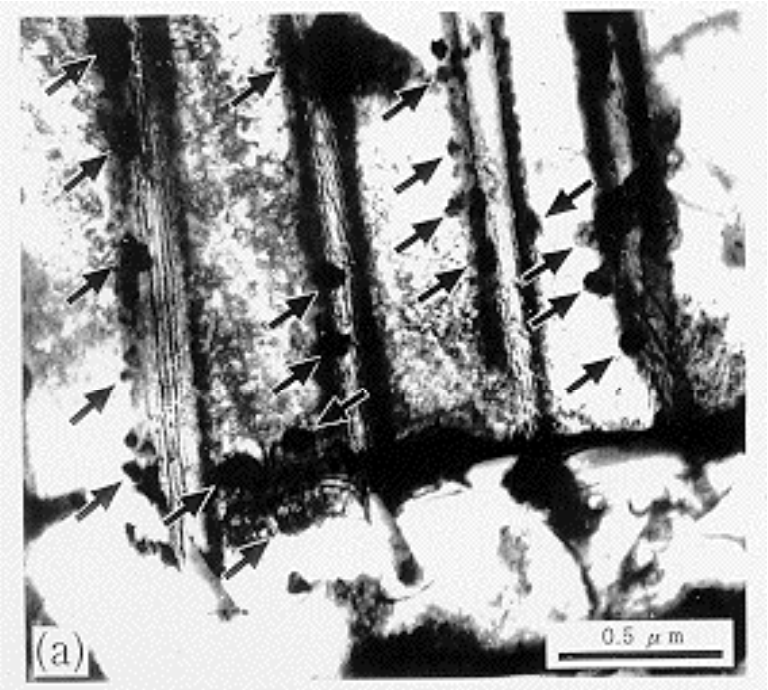


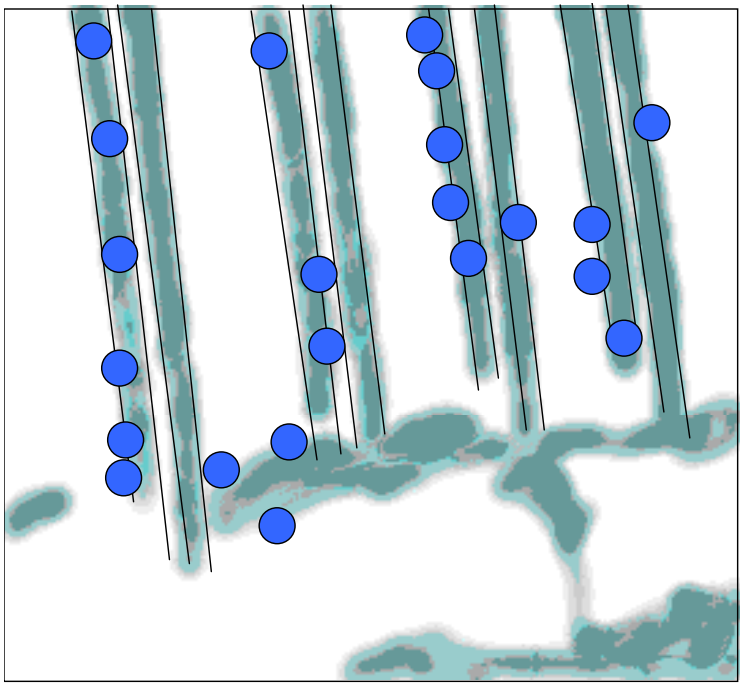
FIGURE 4. Principles of tritium autoradiograpy on metal specimen.

Tritium trapped around grain boundaries and in the grain (Carbide iron)

Visual Observation of Hydrogen Tapping Sites by Tritium Autoradiography



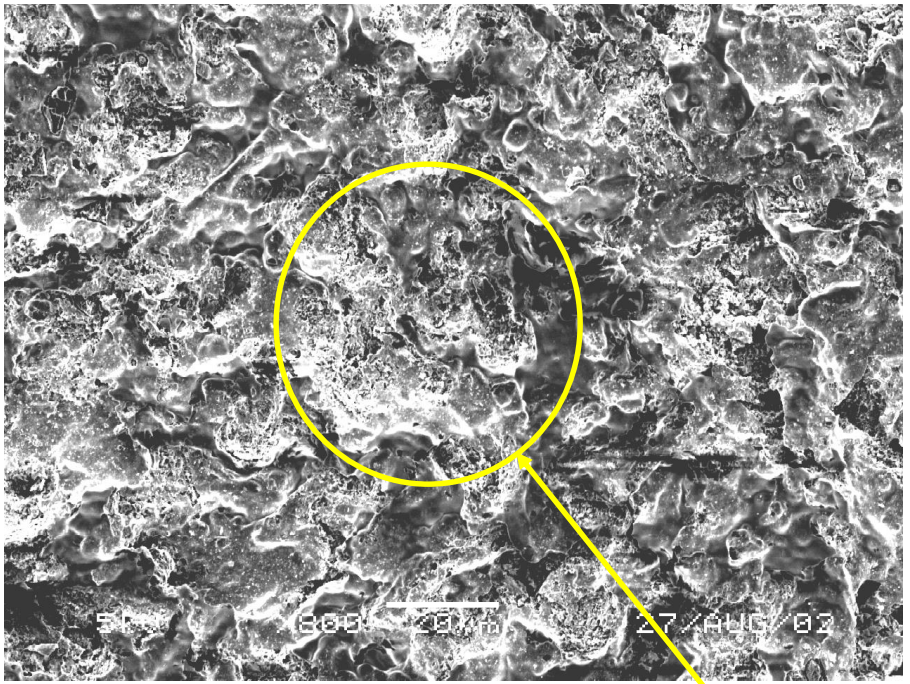
TEM image



Titanium precipitated around Ceramic: Carbide iron

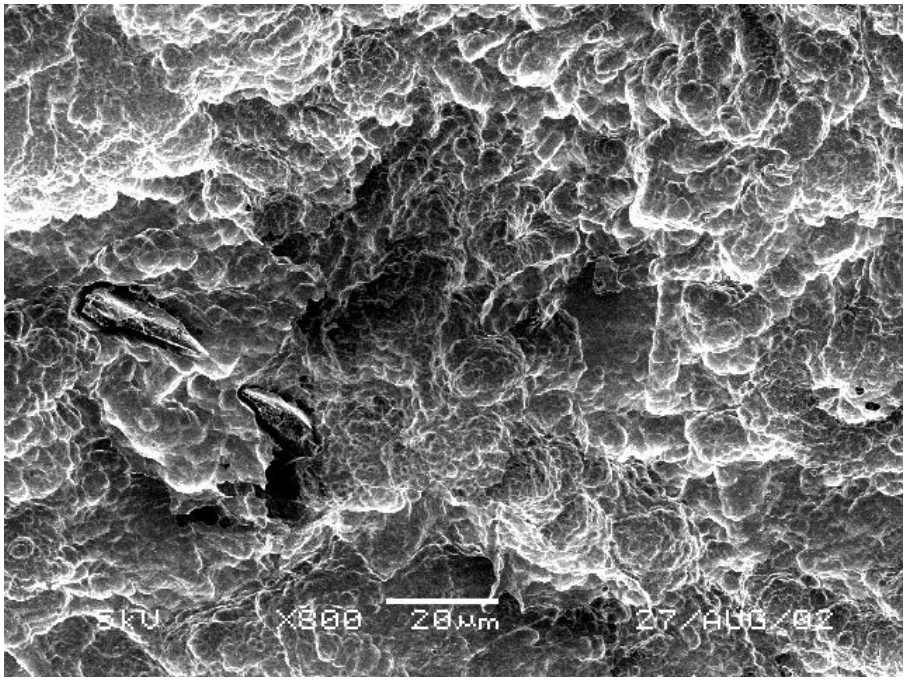
Hydrogen Absorption on Nb Surface Defects

CBP+EP 1μm



SEM image

CBP+CP 3μm



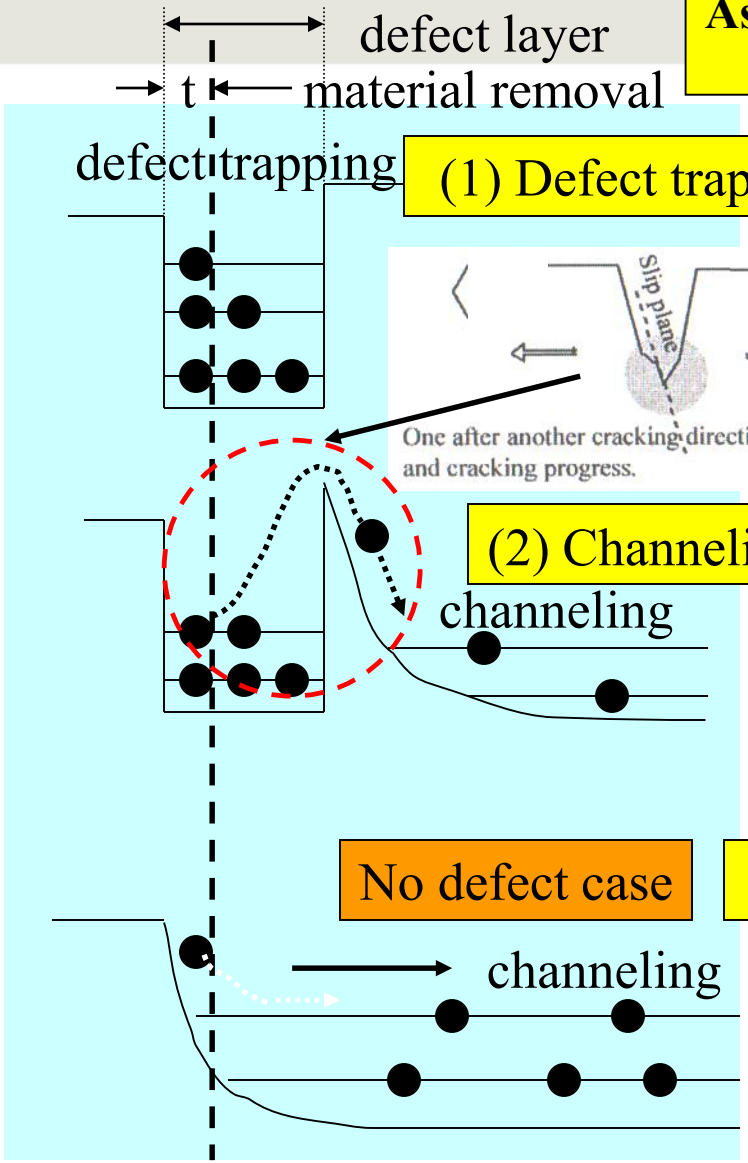
SEM image

The porous structure on the sample surface electropolished after CBP is the hydrogen trapped sites.

Hydrogen Absorption Model

Assumption : Exponential distribution with damaged depth

$$N_d(x) = N_d^0 \cdot e^{-\frac{x}{\alpha}}$$



Amount of absorbed H : C_H

$$C_H(w/w) \propto \frac{N_d}{L-t} \propto \frac{\exp(-\frac{t}{\alpha})}{L-t}$$

Amount H is proportional to remained number of damage

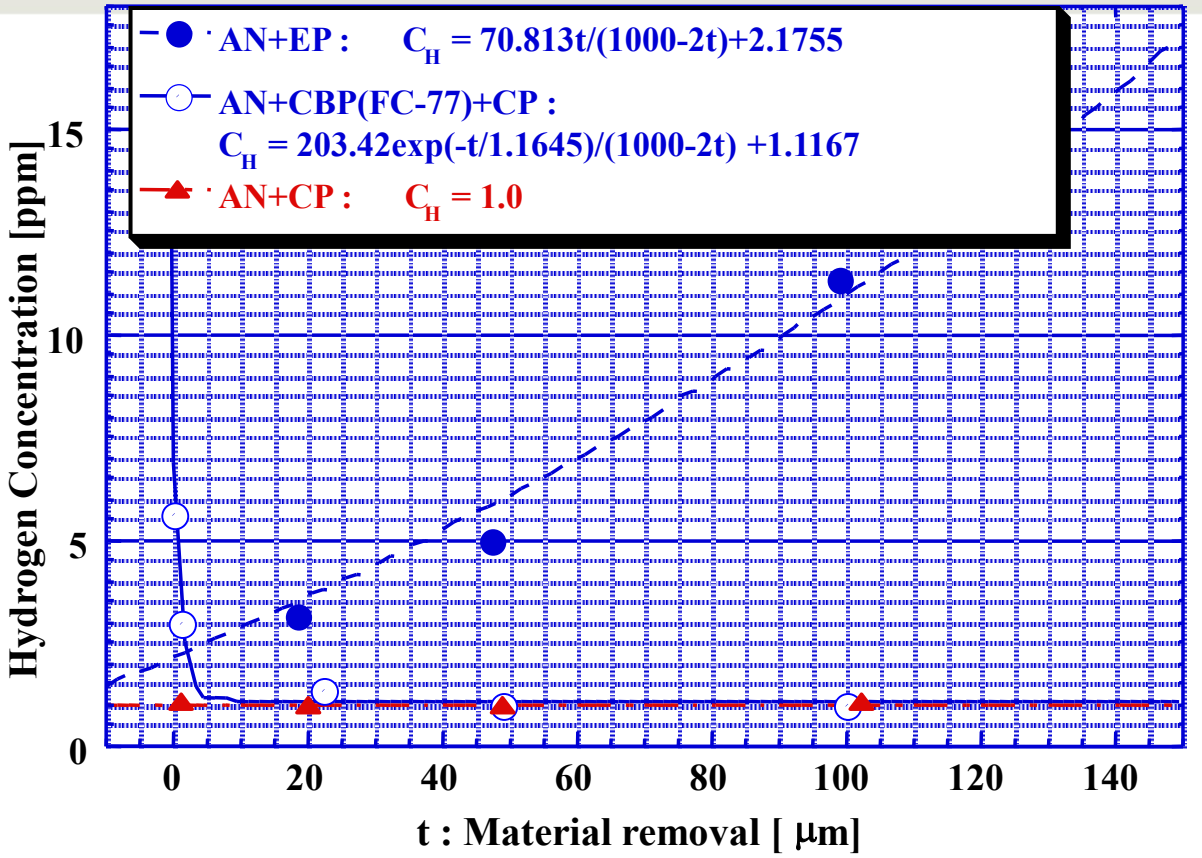
C_H is proportional to removed number of defects

$$C_H(w/w) \propto \frac{\int_0^t N_d \cdot dx}{L-t} = \frac{\int_0^t \exp(-\frac{x}{\alpha}) \cdot dx}{L-t} = \frac{[1-e^{-\frac{t}{\alpha}}]}{L-t}$$

C_H is proportional to removed material thickness

$$C_H(w/w) \propto \frac{t}{L-t}$$

Hydrogen Absorption on CP and EP

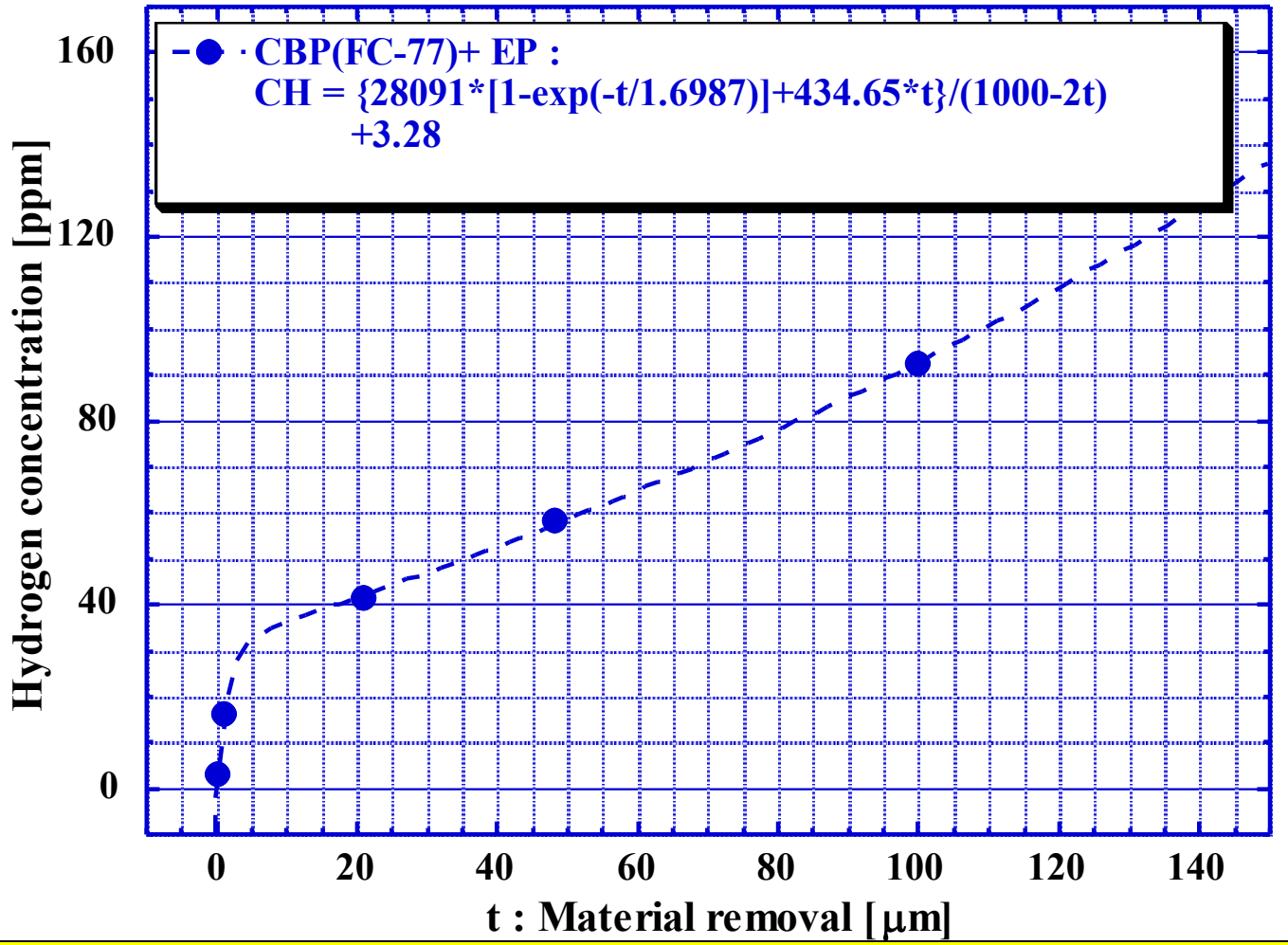


1) Well annealed niobium material dose not absorb hydrogen

2) EP(intermitted) makes channeling hydrogen absorption.

3) BCP after CBP produces defect trapped hydrogen.

Hydrogen Absorption by CBP＋EP(normal acid)



CBP+EP(normal acid) processing produces two hydrogen trapping mechanisms in parallel: defect trapping and channeling through defects.

Hydrogen Absorption in Various Mechanisms

Preparation	*Defect Trapping* $C_1' \cdot \exp(-\frac{x}{\alpha})$	*Channeling through defects* $C_1 \cdot \int_o^x \exp(-\frac{x}{\alpha})dx$	*Channeling* $C_2 \cdot x$	*Comments*
CBP(FC77)+EP(normal)	**NO**	**YES (α=1.7μm)**	**YES**	**Defects**
CBP(FC77)+CP	**YES (α=1.2 μm)**	**NO**	**NO**	**Defects Stationary oxidation process**
Annealing+EP(normal)	**NO**	**NO**	**YES**	**NO defect**
Annealing+CP	**NO**	**NO**	**NO**	**NO defects**

Oxidizer like nitric acid can oxide the defect surface and preserve the channeling through defects.

Summary of Hydrogen Absorption with SRF Nb Cavities

- **Hydrogen absorption mechanism during EP has been understood perfectly.**
- **Mechanical grinding which makes surface damages produces hydrogen absorption during the processing. The hydrogen in the detergent is absorbed on the damages. Utilizing H-free detergent can prevent the hydrogen absorption.**
- **Pre-EP used in the TRISTAN recipe produce hydrogen absorption.**
- **Using the EP acid dropped a little amount of nitric acid can eliminated the hydrogen trapping.**

17.5 High Gradient Cavity

Basic R&D for High Gradient SC Niobium Cavity in KEK L-band Group

High Gradient
SC Cavity
Eacc ~ 40MV/m

1) High pure niobium material RRR~200
2) Electropolishing (EP)
3) High Pressure Water Rinsing (HPR)
4) Baking (70~140°C)

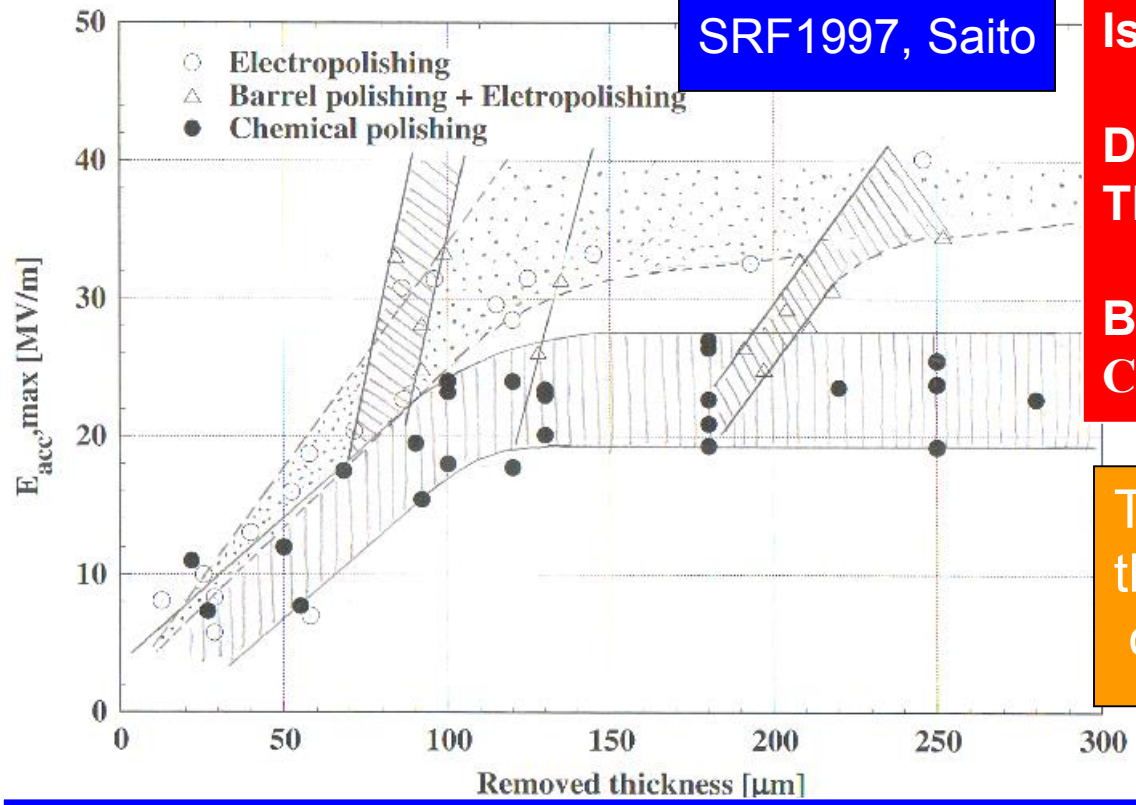
Degradation-free
Final Cavity Assembly

1) Opening vacuum with Argon Gas
2) Simple Aluminum Vacuum Sealing

Cost-Effective
Cavity Production
Method

1) Nb/Cu Clad Seamless Cavity
2) Simplified Surface Treatment

Discovery of Superiority of EP with High Gradient Performance



SRF1997, Saito

Is EP the good method for SRF ?

Dose the high cavity performance in TRISTAN cavities due to EP?

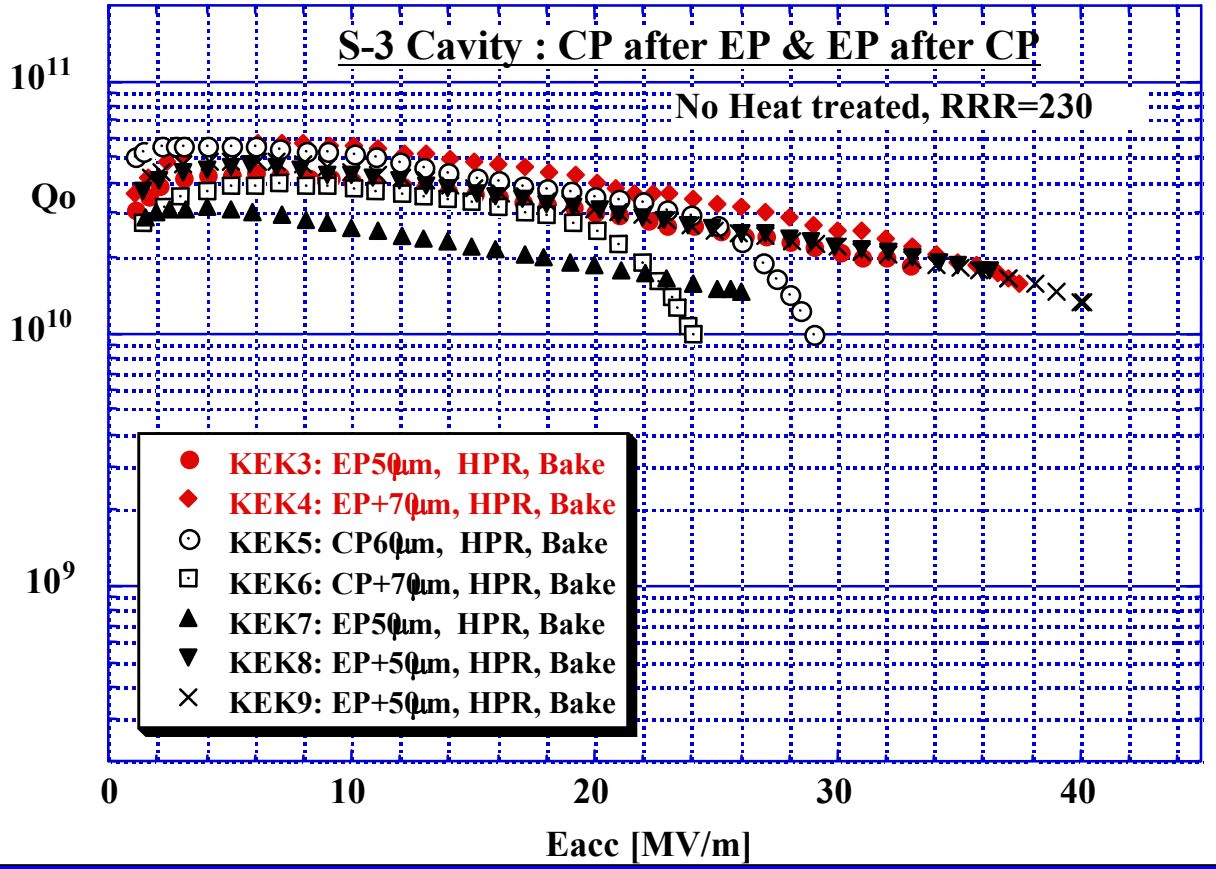
BCP is much simple and cost-effective, Can it replace to EP ?

The first step is to determine the limitation of BCP on the SRF cavity performance !!

Cavity performance was investigated with increased material removal by BCP: three cavities were used to see the statistics

1) Even removed 250mm, the gradient was limited below Eacc=20~28MV/m and saturated.
2) When electropolished the cavities with similar performance, the gradient improved quickly with EP material removals.
3) Electropolished cavities have no gradient saturation below 30 MV/m.
4) Electropolishing has confirmed to have superiority over BCP for high gradient performance

Other Fact of EP Superiority over BCP

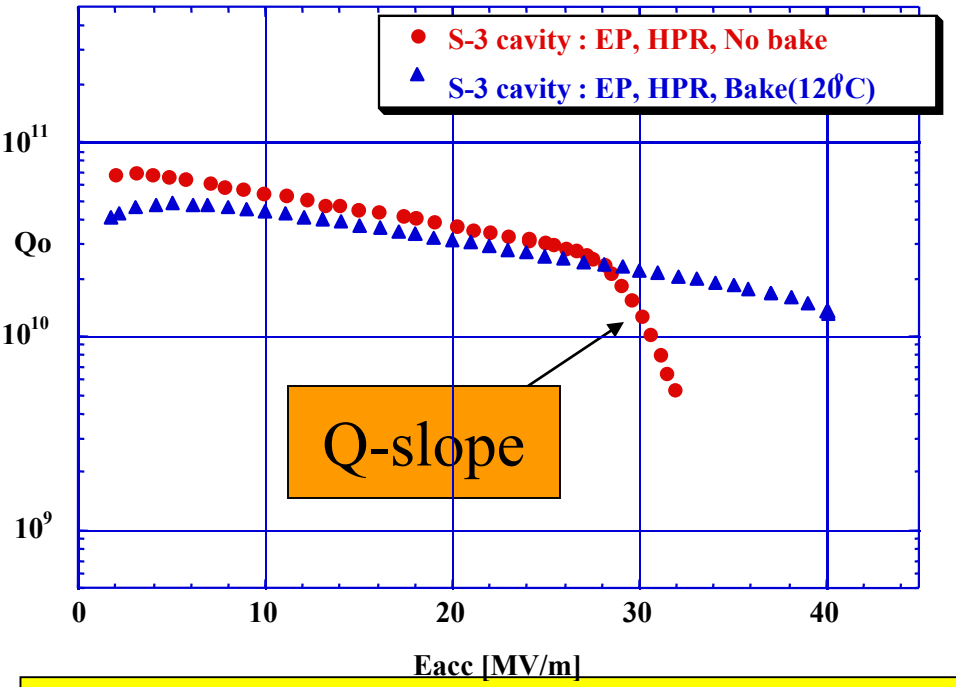


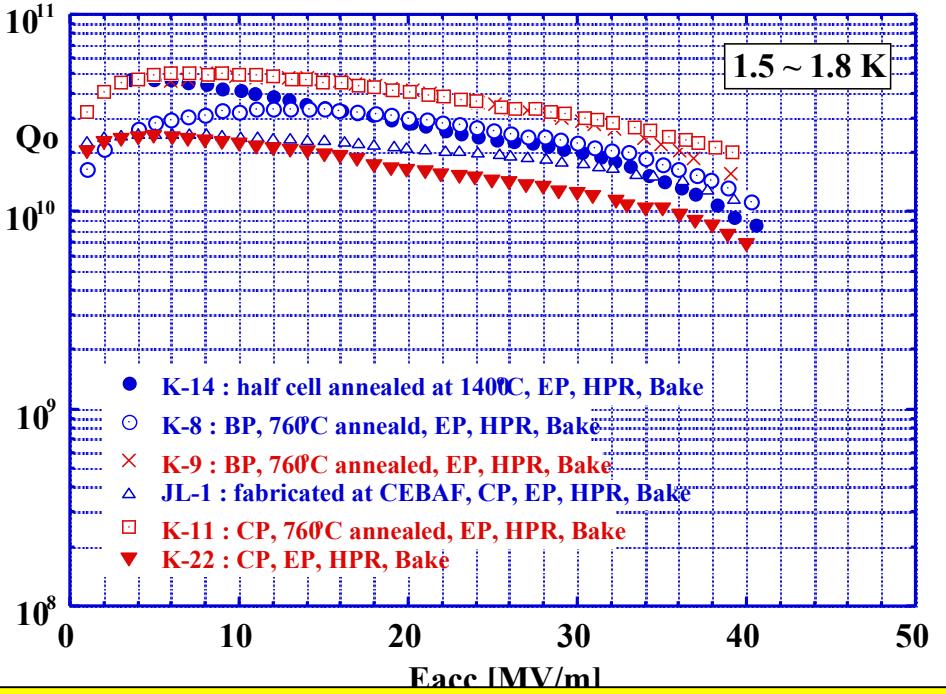
2000, E. Kako

Electropolished the cavity from Saclay repeatedly

1) Gradient was improved up to 38 MV/m with increased EP material removals.
2) Subsequently took BCP, the gradient degraded up to 24 MV/m with increased BCP material removals, of which degradation is called as high field Q-slope.
3) Again took EP, the gradient improved up to 40 MV/m with increased EP material removals.

Baking Effect with EP'ed Cavities

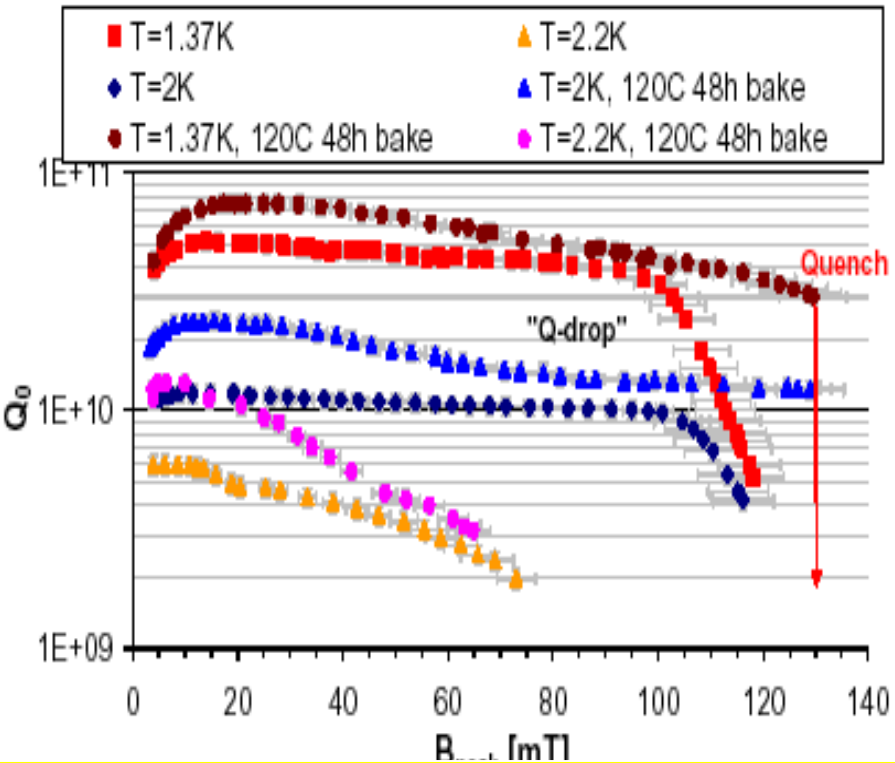


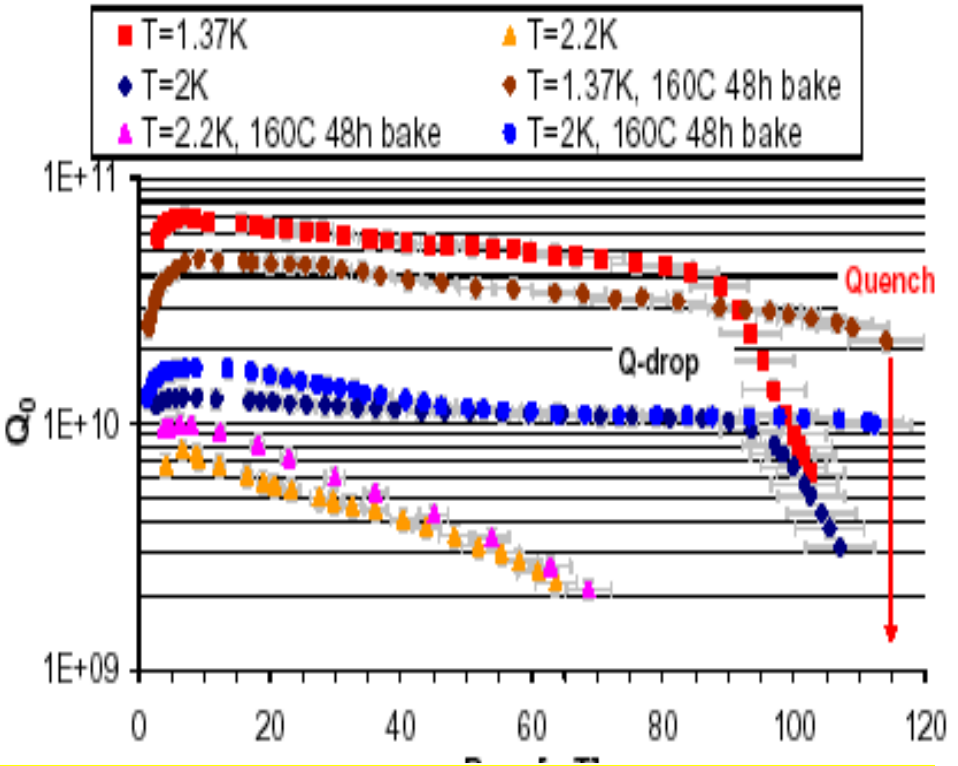


No understanding the importance of 120°C baking until 2000's

1) KEK used 120°C baking traditionally to improve vacuum quality (remove water) until then
2) Importance of the baking was discovered at DESY, 2001 after EP technology was transferred to DESY
3) EP'ed cavity has also high field Q-slope but it was perfectly eliminated by the baking。
4) KEK has reached 40 MV/m and start to be conscious the 40 MVm limitation.

Baking Effect on BCP'ed Cavities





The same question happed with BCP'ed cavities soon

1) Baking effect was observed partially
2) The improvement up to 40MV/m was not happened with BCP'ed Cavities
3) Understanding why is Didi's PhD study

Only Oxygen Diffusion Can't Explain the Limitation of 40 MV/m

Coupled Problem

Why EP'ed cavity is limited 40MV/m?
Why BCP'ed cavity is limited below 40MV/m even after baking.

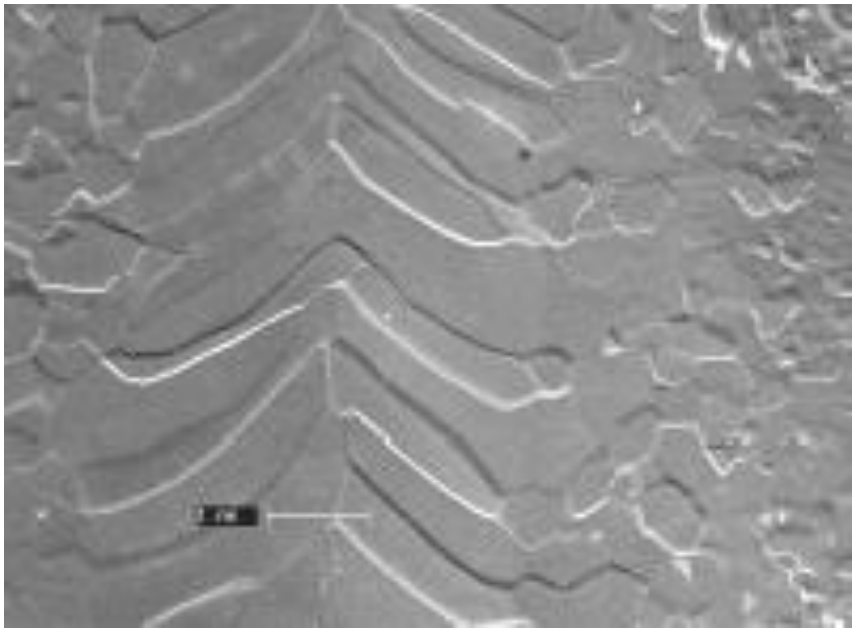
⇓ Self-consistent explain

Critical Field limits the gradient
Eacc ~ 40MV/m = 43.8x40 = 1750 Oe = Hc^{RF}
By K.Saito 2001

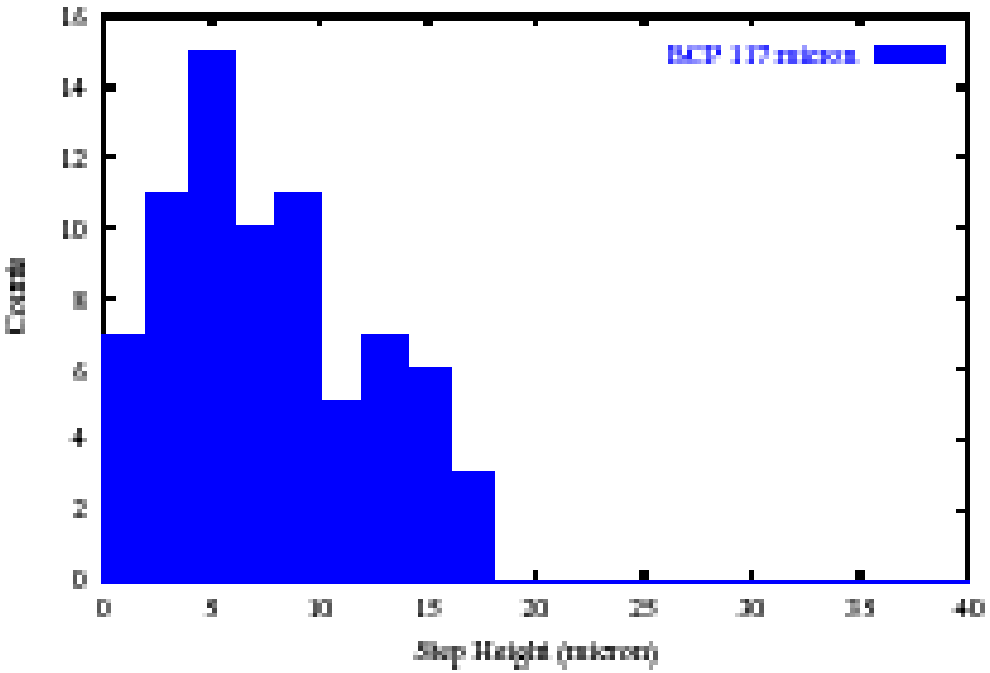
EP'ed smooth surface → **No magnetic field enhancement** → **Quench at $H_{rf}=H_C^{RF}$**

EP'ed rough surface → **Magnetic field enhancement: β_m β_m = 40/28~40/20=1.4~2** → Quench at $\beta_m \cdot H_{rf} = H_c^{RF}$

Grain Boundary Steps on EBW Seams



Equator EBW seam of Nb cavity

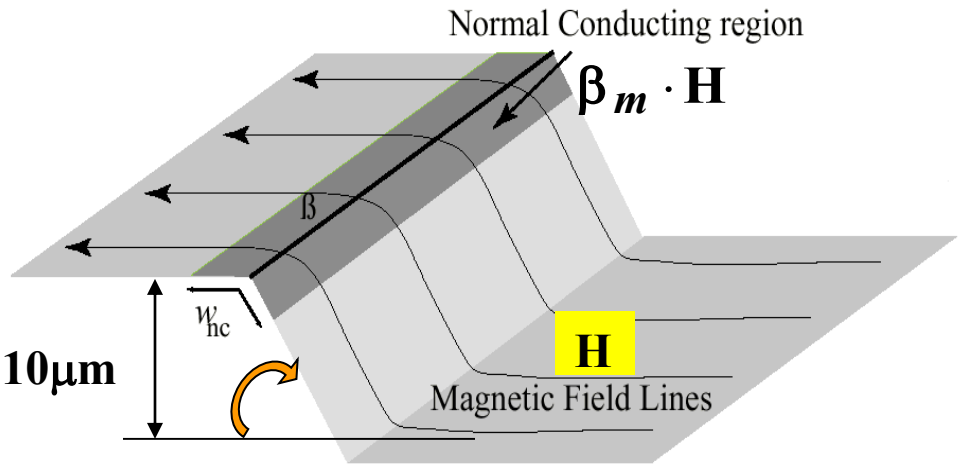


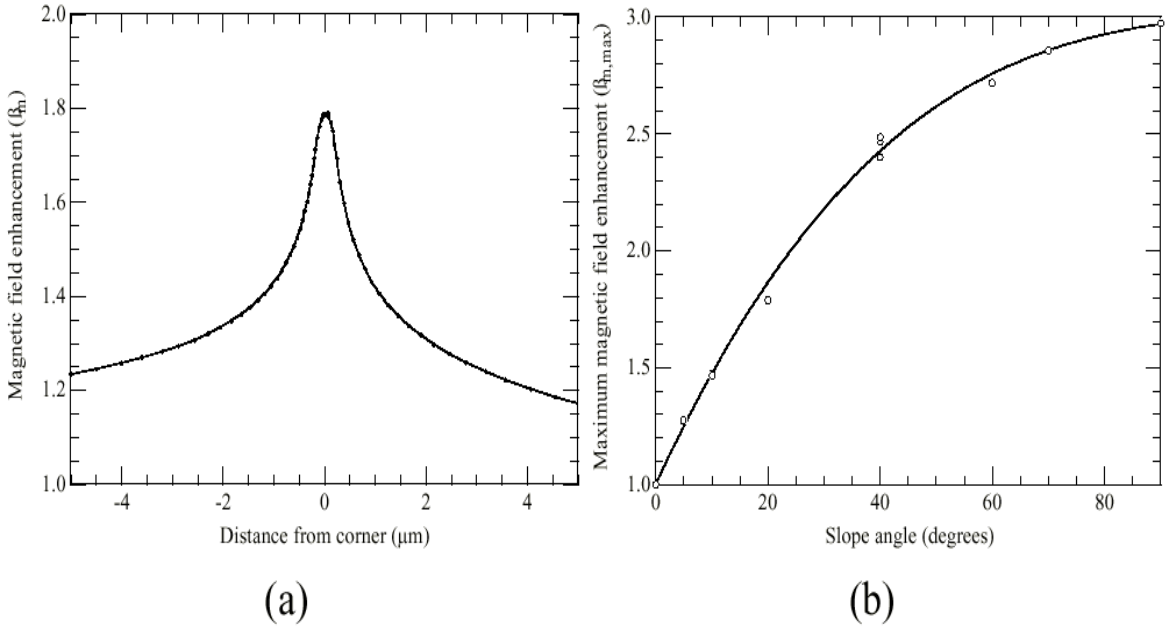
Distribution of the step height

Magnetic Field Enhancement Model on the Steps

The field enhancement β_m (1.4 – 2.0) Estimated from experimental results is consistent with simulation by J. Knobrch.

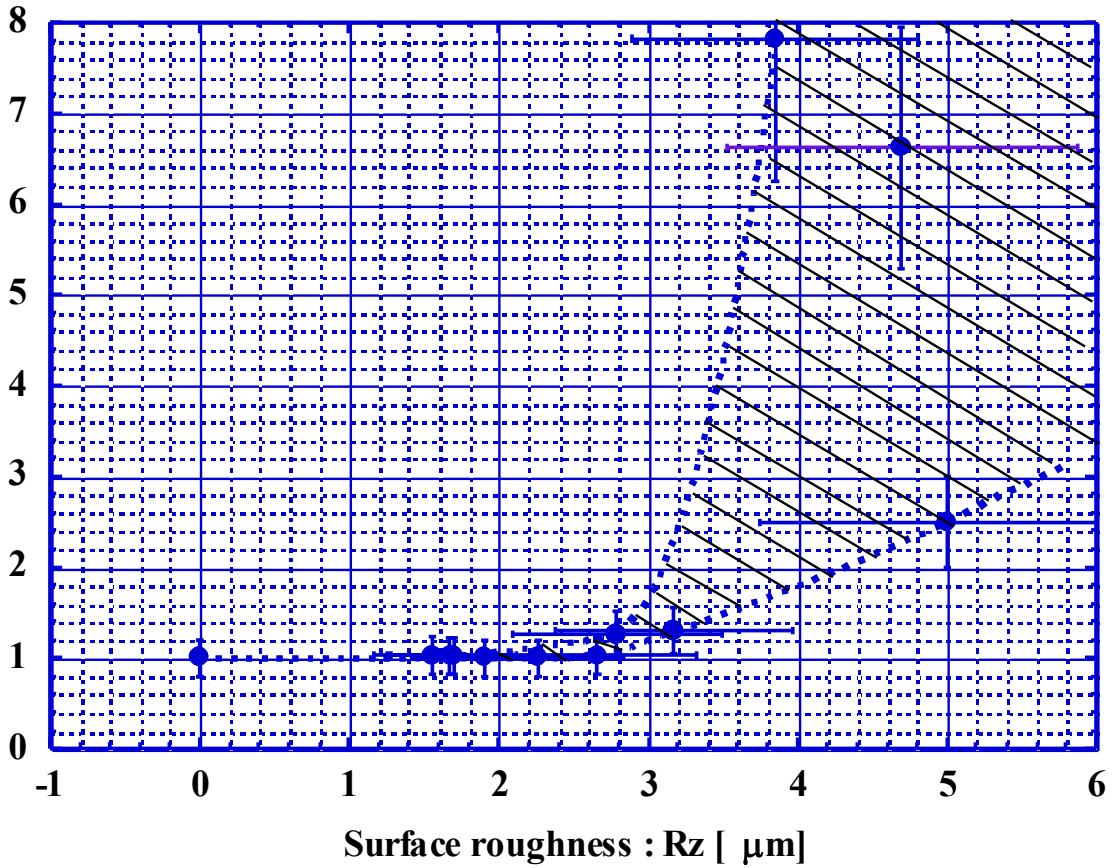
Cornell





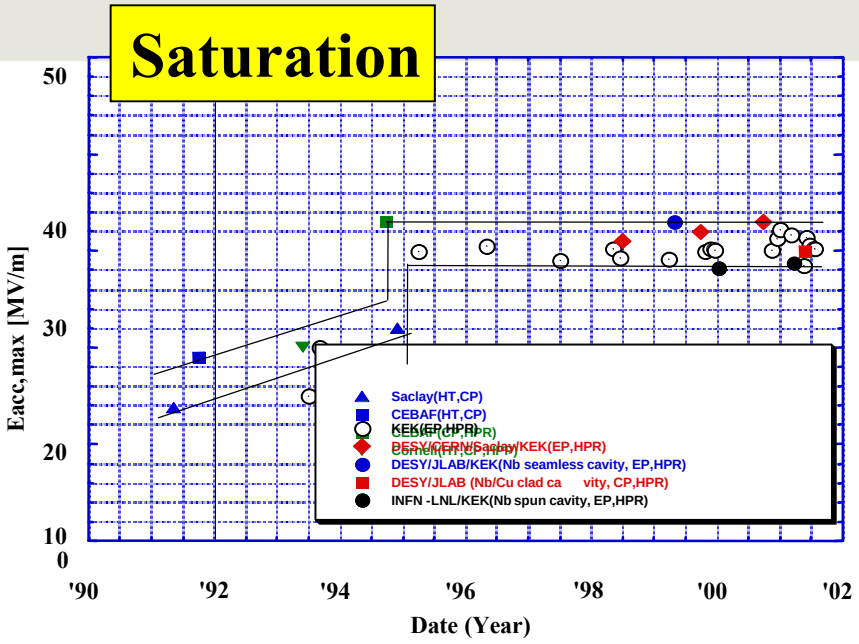
Surface Roughness Allowed High Gradient

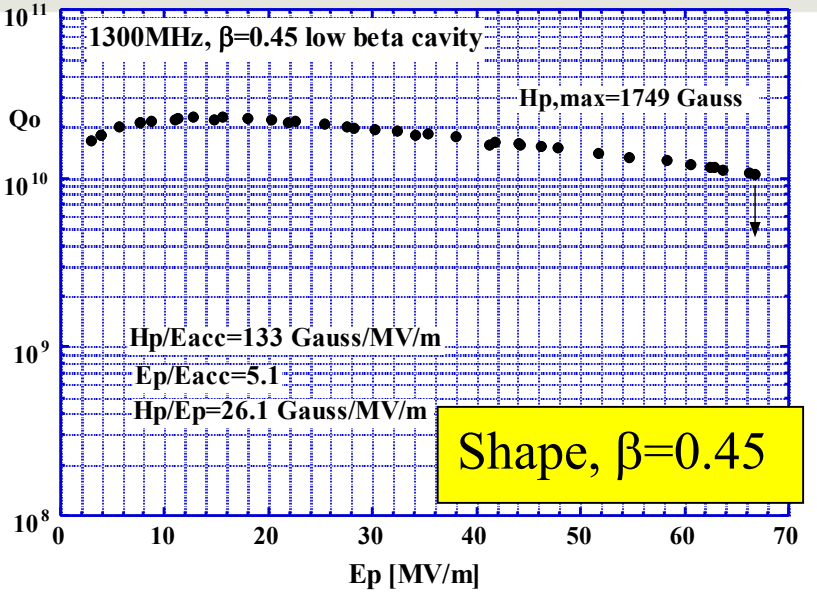
$$R_{BCS}(E_{acc}) = \frac{A}{T_B + C \cdot E_{acc}} \cdot \exp[-\frac{B\sqrt{1-\left(\frac{\beta_m H_p}{\sqrt{2}\cdot H_c}\right)^2}}{T_B + C \cdot E_{acc}}], \qquad \mathbf{H_c(Rz) = 2150\ Gauss = \beta_m(Rz)\cdot H_p}$$

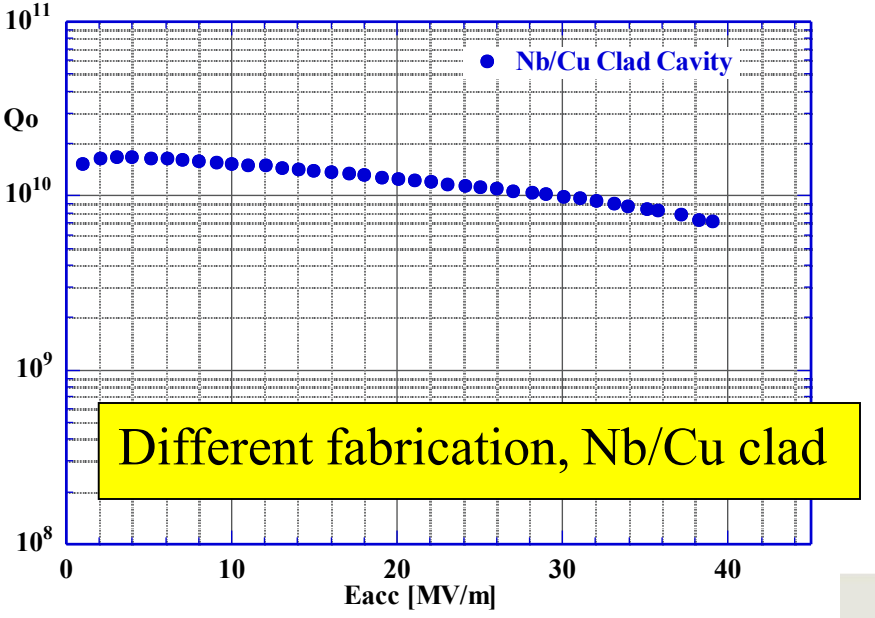


The surface roughness
Rz < 2.5μm for
1300 MHz cavities

Limitation of 1750 Oe

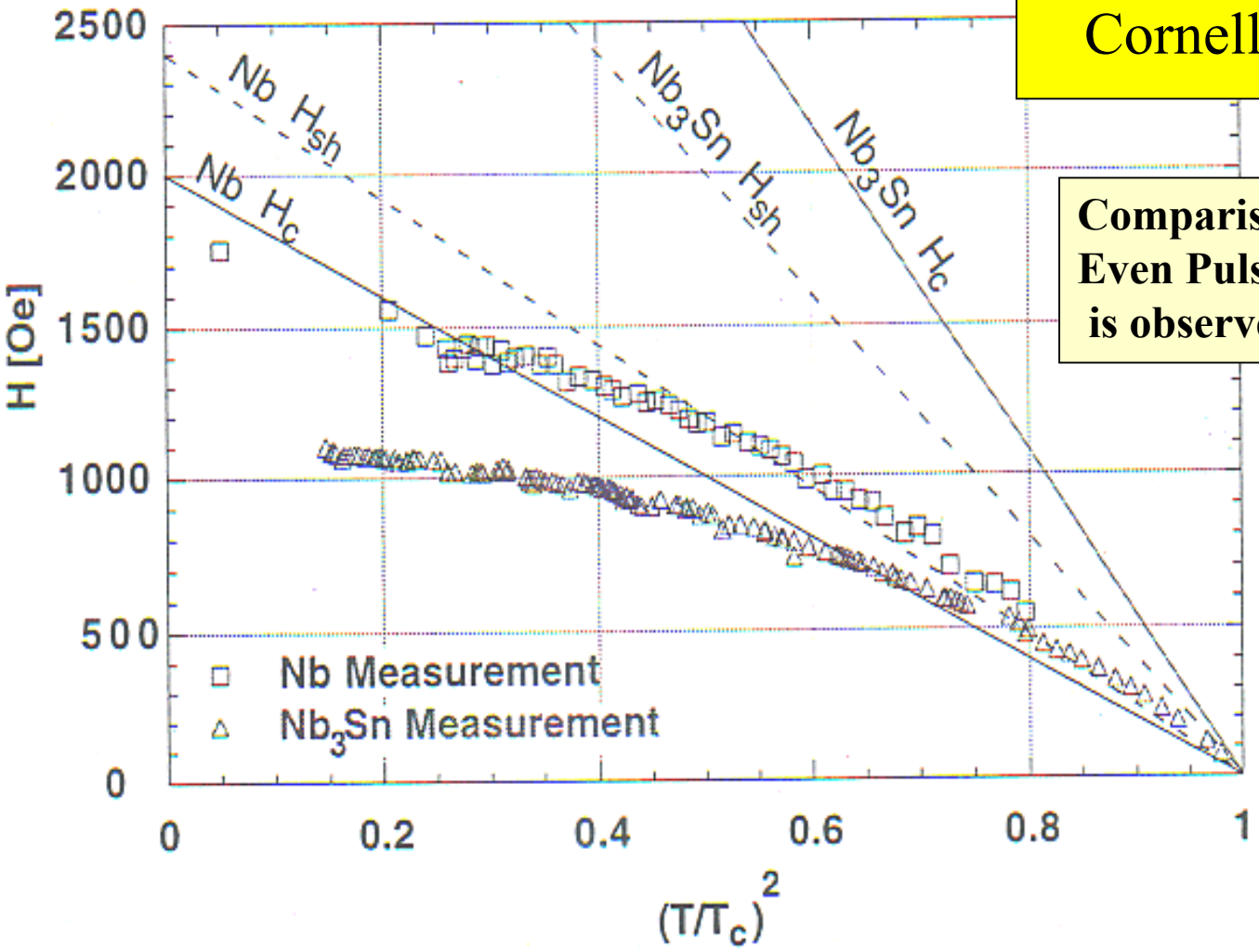






1) 1750Oe of limitation does not upgrade for those 10 years (1995 – 2002)
2) The cavity of β=0.45 low beta also limited 1750 Oe. The 1750 Oe limitation is independent on cavity shape
3) Nb/Cu clad seamless cavity also limited 1750 Oe, independent on cavity fabrication method
4) Seamless Nb bulk cavity also limit 1750 Oe.

Magnetic Critical Field Measurement by Pulsed RF at Cornell



Cornell University

Comparison with super-heating(Hsh)
Even Pulsed RF, 1750 Oe limitation is observed

What Is the Correct Model for H_C^{RF} ?

By K.Saito

$$\text{Planenucleation: } \sigma_s = \frac{1}{2}\mu\xi H_c^2 - \frac{1}{2}\mu\lambda H^2 = 0$$

$$\text{AC Application: } H \Rightarrow \frac{1}{\sqrt{2}} H$$

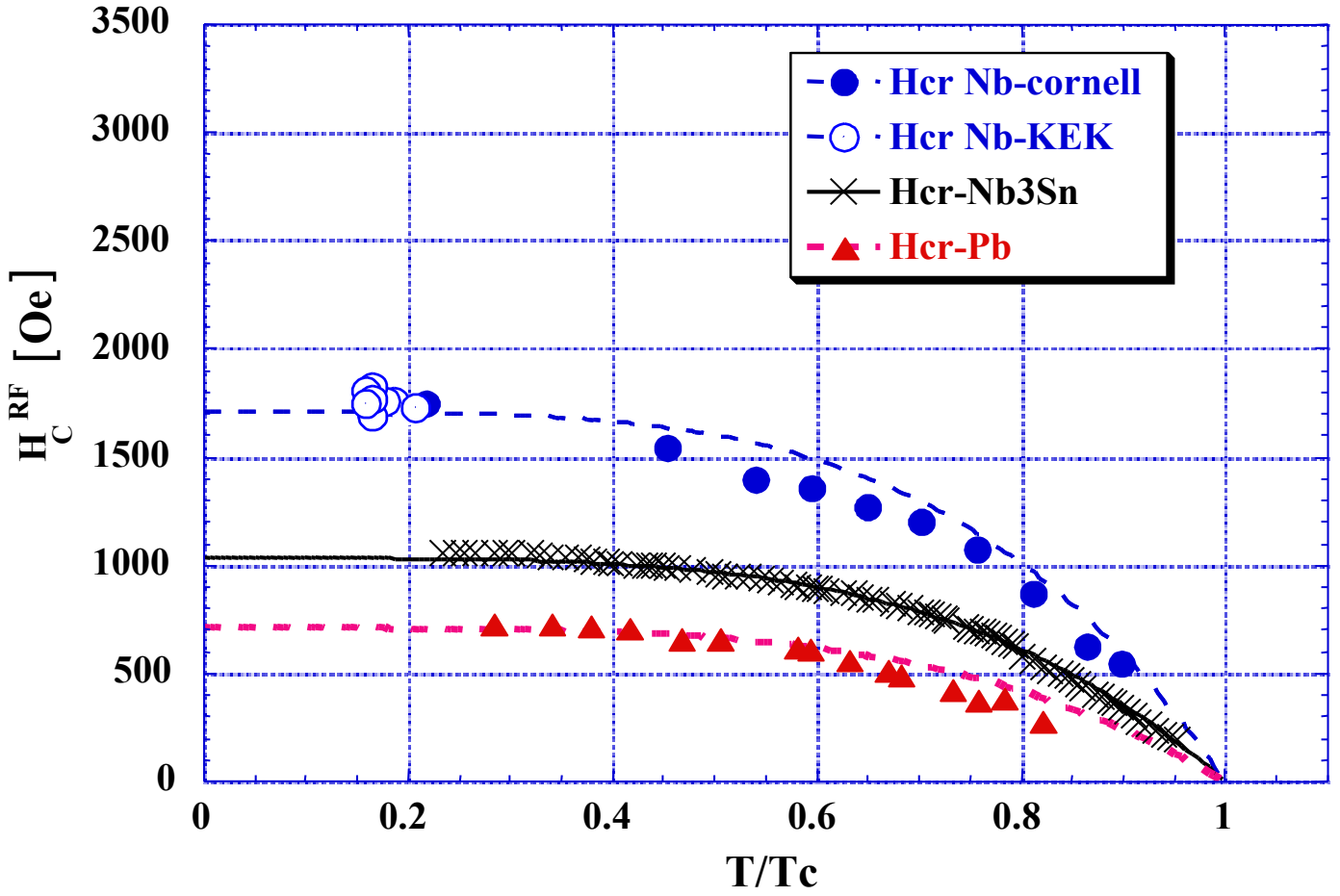
$$\sigma_s = \frac{1}{2}\mu\xi H_c^2 - \frac{1}{4}\mu\lambda H^2 = 0 \quad \therefore \; H_c^{RF} = \sqrt{2}\cdot\sqrt{\frac{\xi}{\lambda}} H_c = \frac{\sqrt{2}}{\sqrt{\kappa}} H_c$$

$$H_c^{RF}(T) = \frac{\sqrt{2}}{\sqrt{\kappa(T)}} H_c(T) = \frac{\sqrt{2}}{\sqrt{\frac{\kappa(0)}{1+\left(\frac{T}{T_c}\right)^2}}} \cdot H_c(0)\left[1-\left(\frac{T}{T_c}\right)^2\right] = \frac{\sqrt{2}H_c(0)}{\sqrt{\kappa(0)}}\sqrt{1+\left(\frac{T}{T_c}\right)^2}\cdot\left[1-\left(\frac{T}{T_c}\right)^2\right]$$

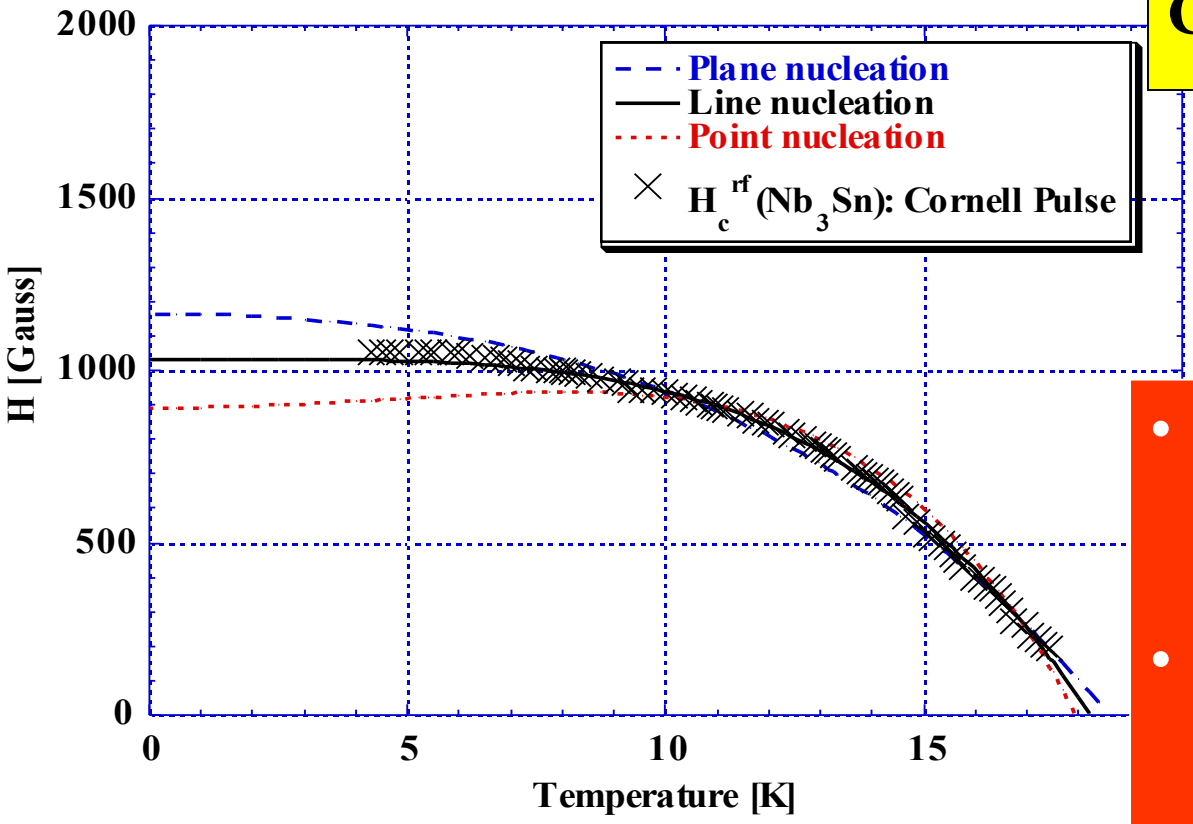
$$\text{Vortex Nucleation : } \frac{1}{2}\mu 4\pi(\xi H_c)^2 - \frac{1}{2}\mu 4\pi(\lambda\frac{H}{\sqrt{2}})^2 = 0$$

$$\therefore \; H_c^{RF} = \frac{\sqrt{2}}{\kappa} H_c \,, \; H_c^{RF}(T) = \frac{\sqrt{2}}{\kappa(T)} H_c(T) = \frac{\sqrt{2}H_c(0)}{\kappa(0)}\left[1-\left(\frac{T}{T_c}\right)^4\right]$$

Vortex Line Nucleation Model Can Fit the Experiment Results



Vortex Line Nucleation Model for Nb_3Sn Cavity

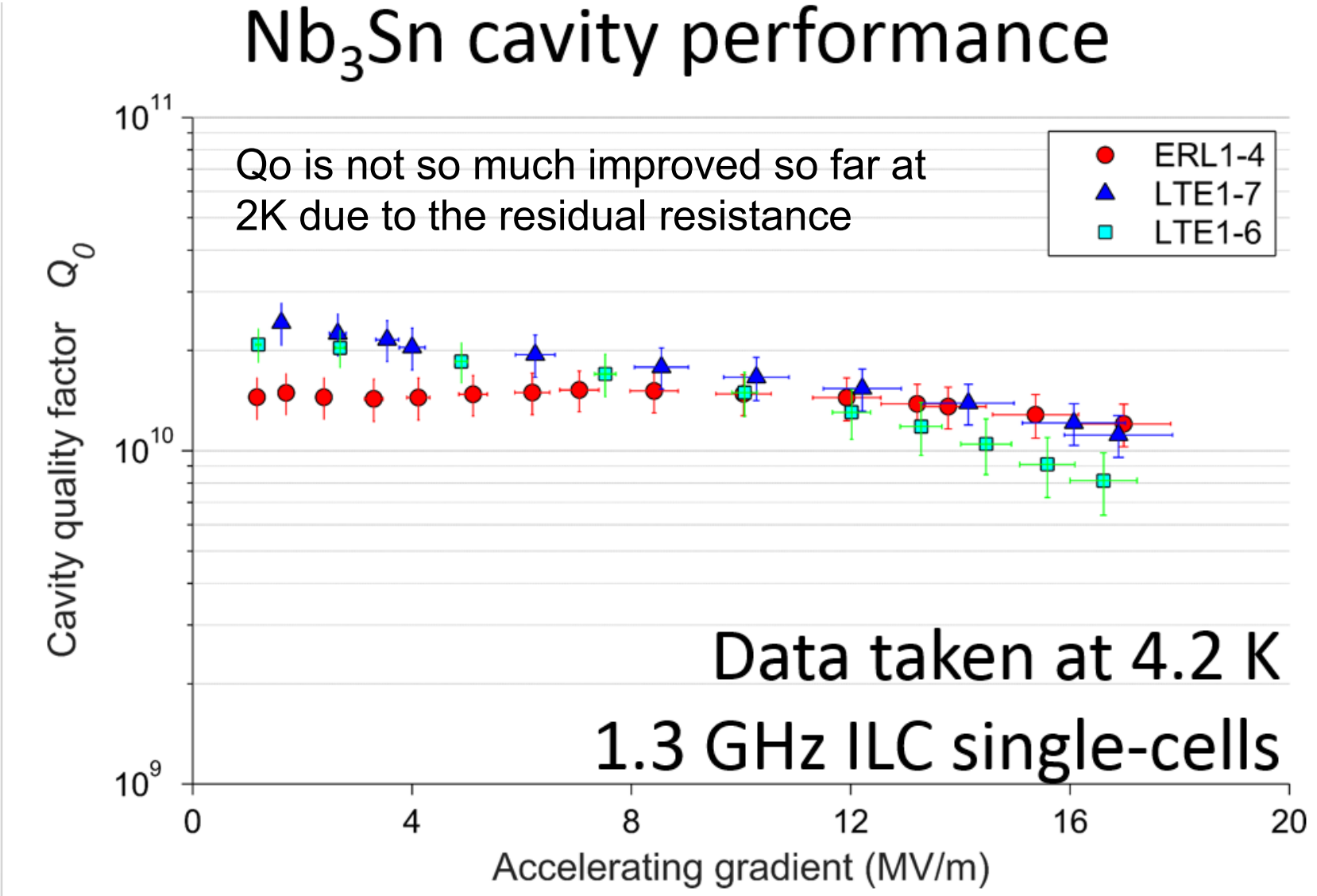


Cornell : Nb_3Sn Cavity

$$H_c^{RF}(T) = 1033.3 \cdot [\,1 - \left(\frac{T}{18.23}\right)^4\,]$$

- Nb_3Sn Cavity could not reach Eacc > 23 MV/m (1000Oe).
- If this analysis is wrong, we can a hope for > 80MV/m, and SRF community is happy

Recent R&D for Nb_3Sn at Cornell University



Summary of Gradient Limitation

- SRF niobium cavity has already reached to the RF critical magnetic field limitation
- Higher gradient could not be expected in like Nb_3Sn

  (Kenji's opinion but not for SRF community).
- Is there anyway push the gradient for SRF Nb cavity ?

Yes !!

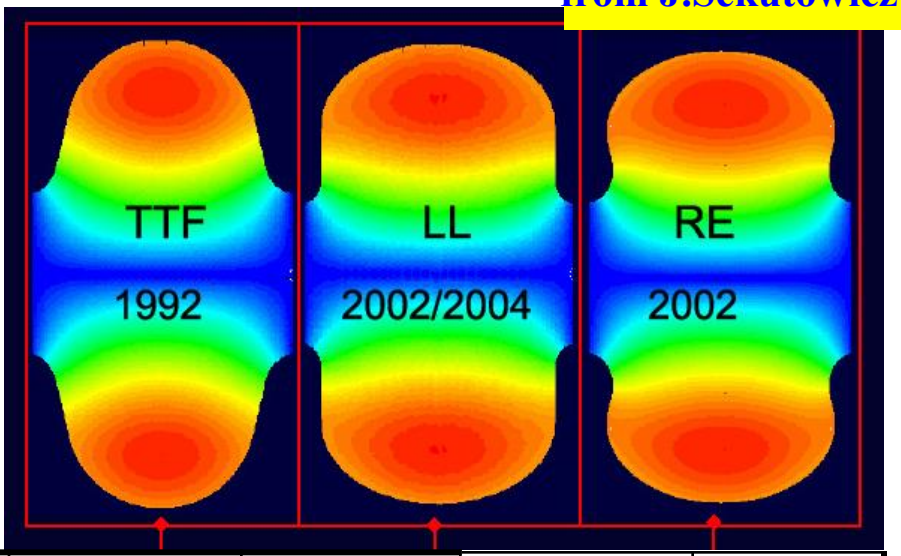
Choose high gradient Shape

Principle of 50MV/m

Cavity shape designs with low Hp/Eacc

TTF: TESLA shape
Reentrant (RE): Cornell Univ.
Low Loss(LL): JLAB/DESY
Ichiro Single(IS): KEK

from J.Sekutowicz lecture Note



	TESLA	LL	RE	IS
Diameter [mm]	**70**	**60**	**66**	**61**
Ep/Eacc	**2.0**	**2.36**	**2.21**	**2.02**
Hp/Eacc [Oe/MV/m]	**42.6**	**36.1**	**37.6**	**35.6**
R/Q [W]	**113.8**	**133.7**	**126.8**	**138**
G[W]	**271**	**284**	**277**	**285**
Eacc max	**41.1**	**48.5**	**46.5**	**49.2**

ILC WG5 Asia (high gradient R&D group) Strategy and R&D Issues

Leader K. Saito

- **Push gradient higher for the future ILC energy reach**
- **Needs enough margin on 35MV/m operation**
- **Cavity operation cost saving by 10% by LL cavity shape**
- **Industrialization : Conventional baseline fabrication and advanced Nb/Cu clad seamless cavity for cost down**

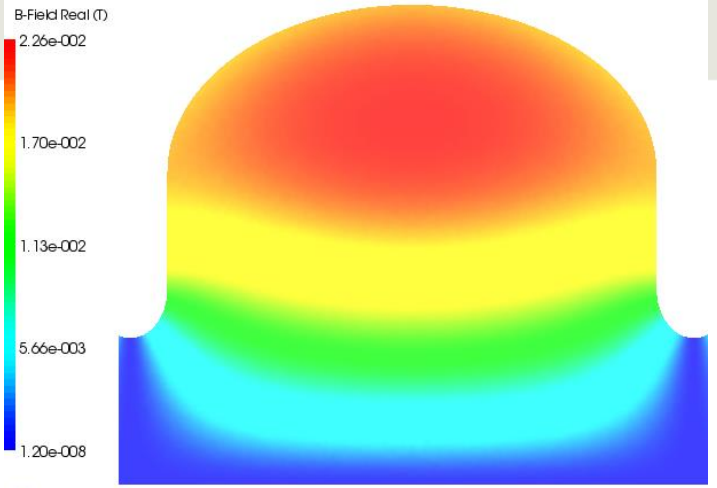
KEK decided to develop the LL shape 9-cell cavity for ILC and demonstrate the high gradient (45MV/m) module operation in STF at least by the TDR.

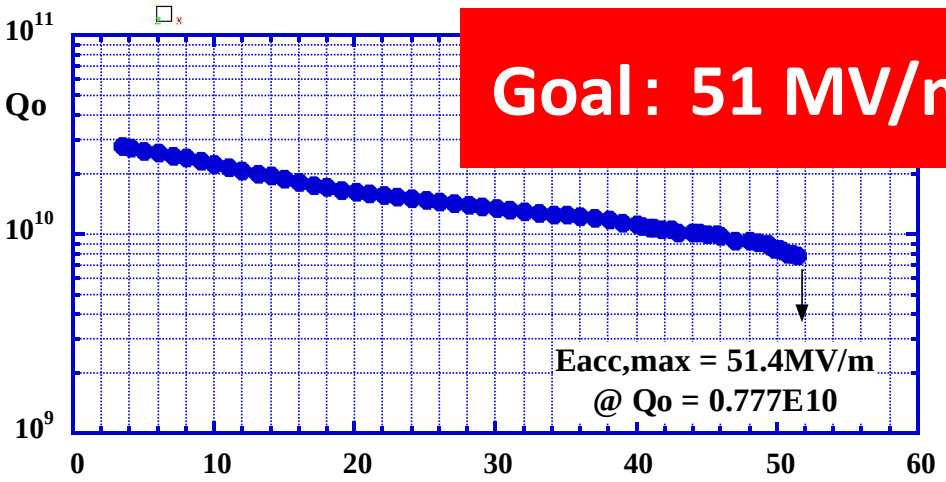
Need a wide dynamical range tuner for larger Lorenz detuning
Need a higher power (500kW) input coupler

R&D Issues :

1) **45MV/m high gradient cavity**
2) **Wide dynamical range tuner system**
3) **500kW high power coupler**
4) **Baseline fabrication, Nb/Cu clad seamless cavity fabrication**

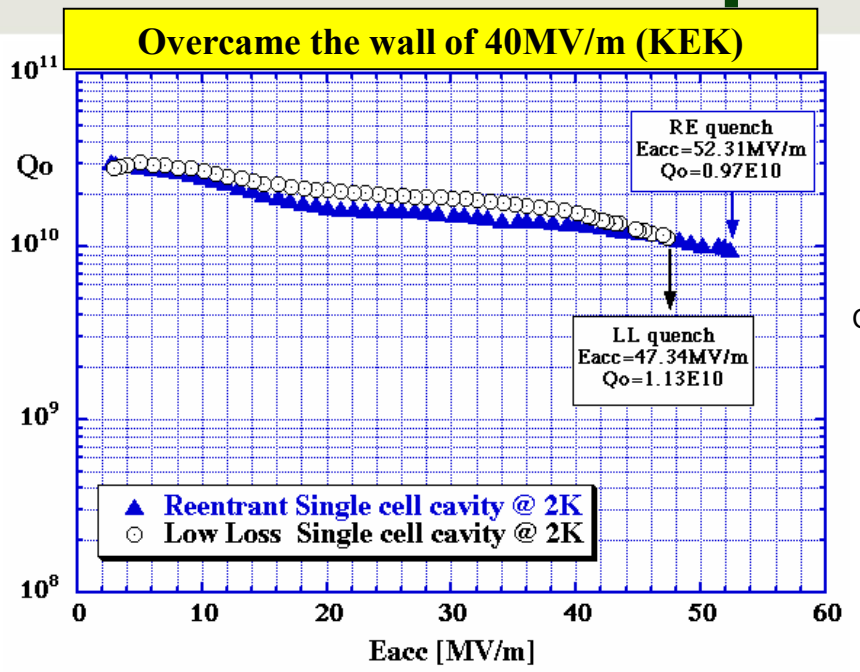
ICHIRO Cavity program in KEK for ILC

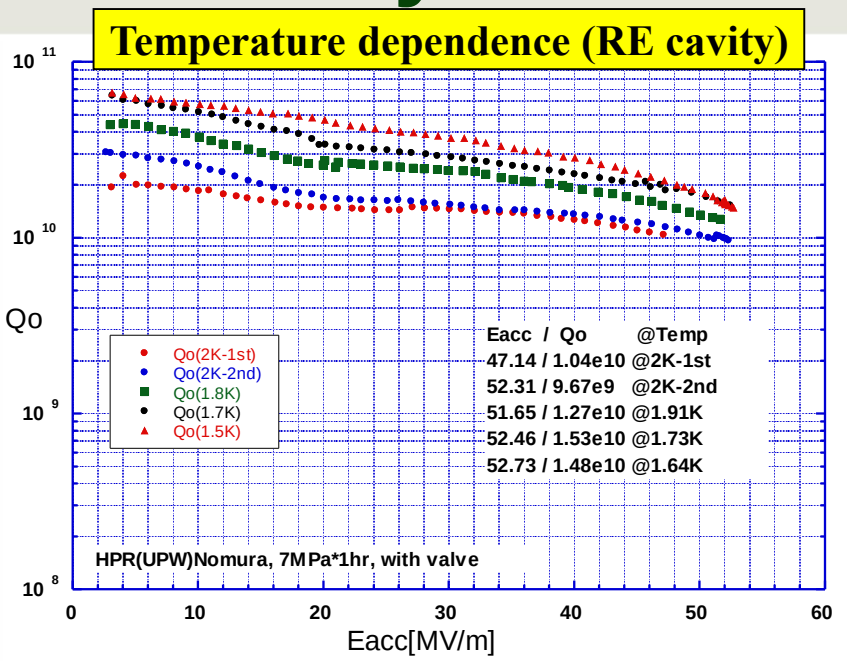




Goal: 51 MV/m!

Demonstrated 50 MV/m and the Reproducibility





Measurement results@ 2K

Low Loss @ 2K

Eacc,max	Qo @ Eacc,max
46.5	1.20E10
47.3	1.13E10
46.6	1.50E10
45.0	1.03E10
44.0	1.20E10

45.9±1.3 MV/m , Q0 = (1.21±0.18) E10

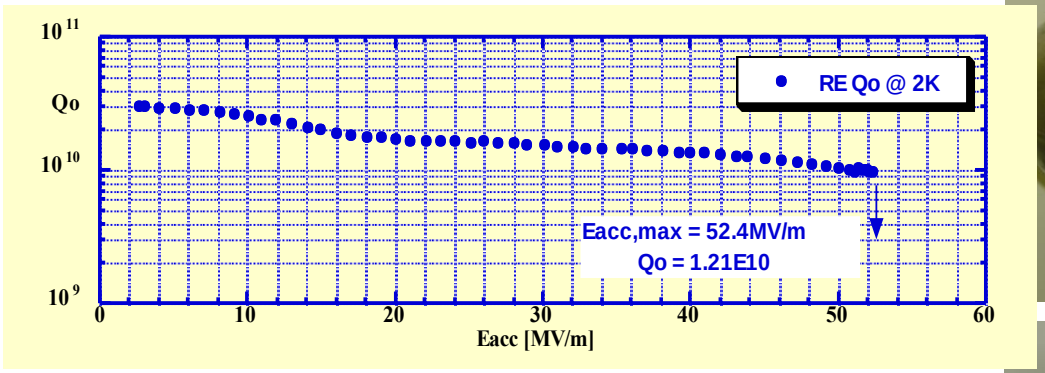
After HPR

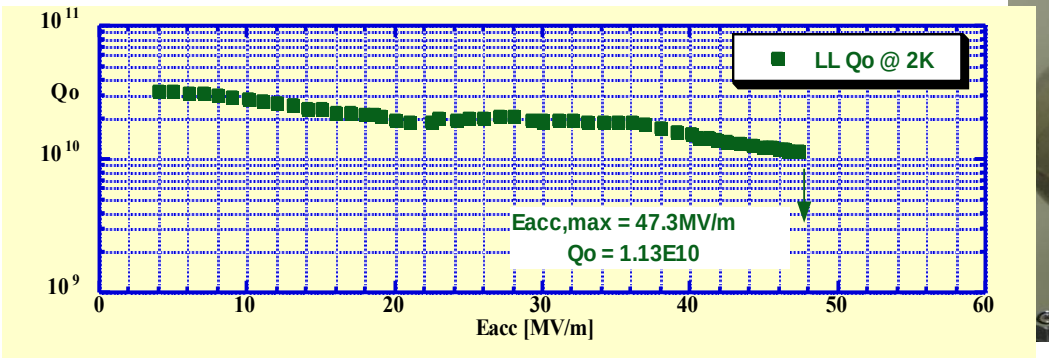
Reentrant@ 2k

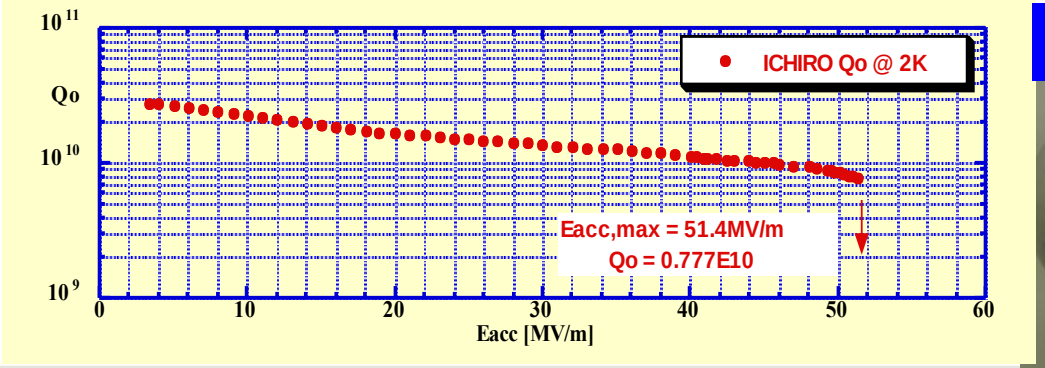
Eacc,max	Qo @ Eacc,max
51.2	0.59E10
52.3	0.97E10
51.9	1.11E10
52.4	1.21E10
50.0	0.98E10

51.6 ±1.0 MV/m, Q0 = (0.97±0.24) E10

Principle Proof of the 50MV/m







Reentrant

Diameter [mm]	60
Ep/Eacc	2.36
Hp/Eacc [Oe/MV/m]	36.1
R/Q [W]	133.7
G[W]	284
Eacc max	48.5

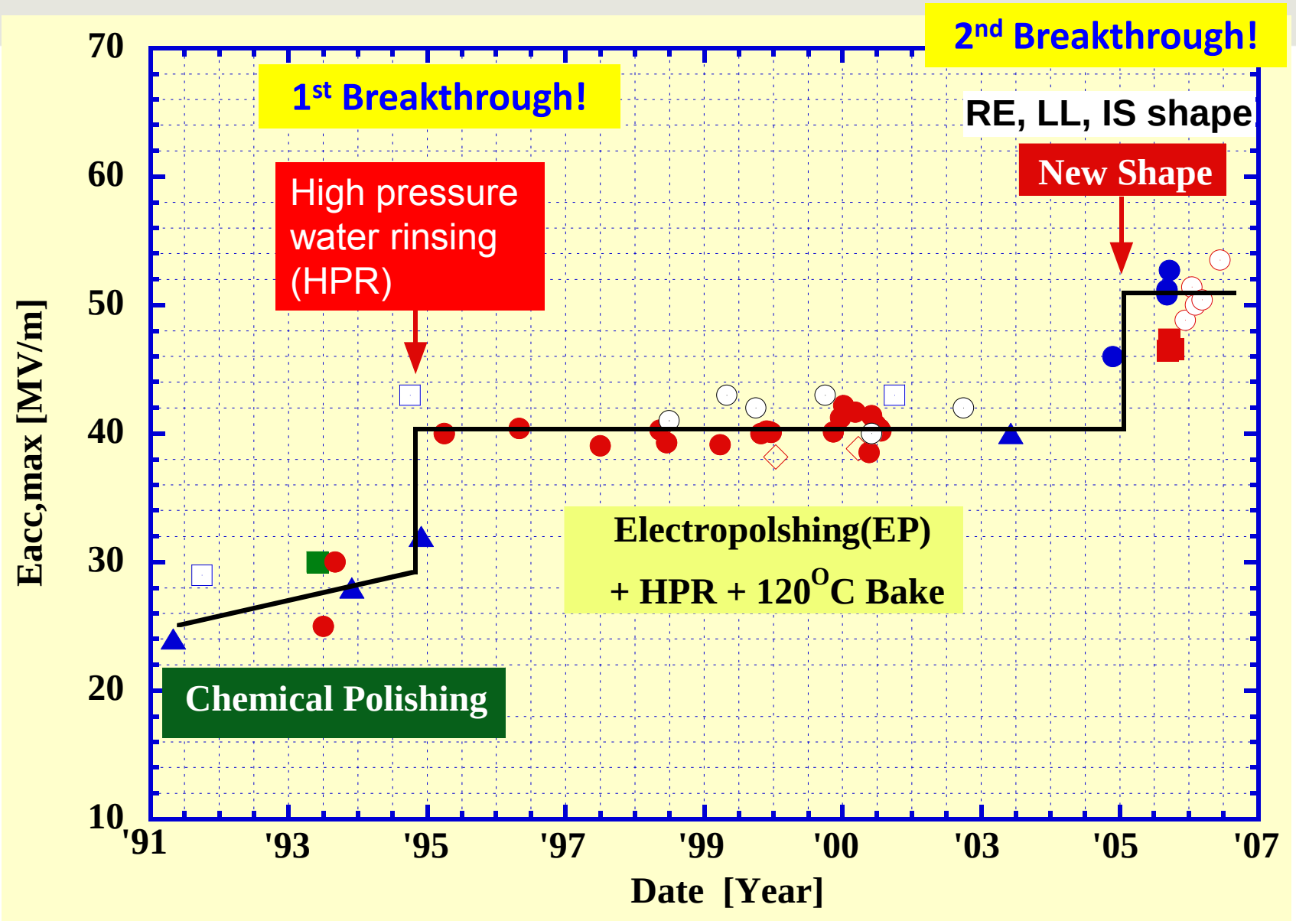
Low Loss

Diameter [mm]	66
Ep/Eacc	2.21
Hp/Eacc [Oe/MV/m]	37.6
R/Q [W]	126.8
G[W]	277
Eacc max	46.5

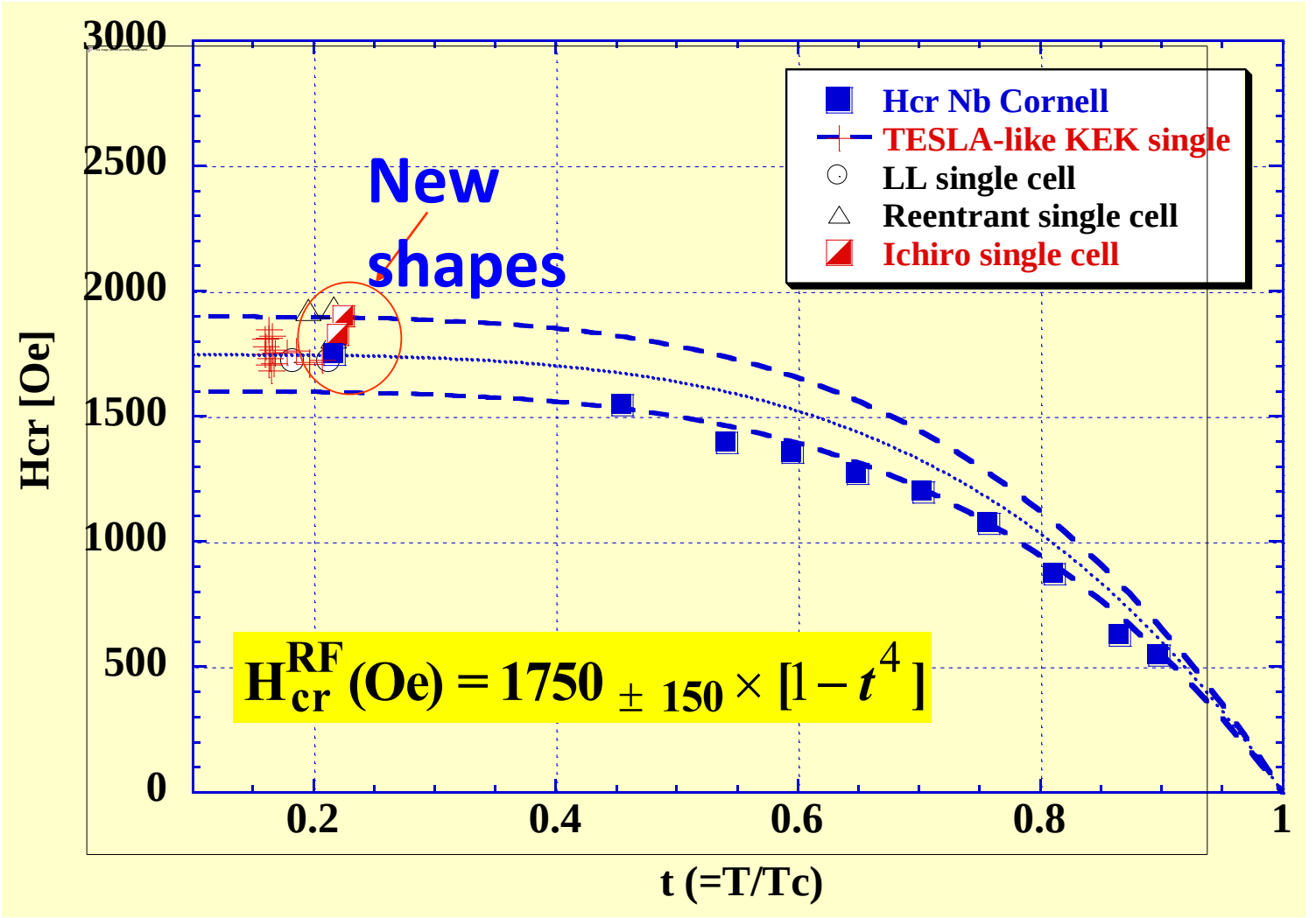
Ichiro Single

Diameter [mm]	61
Ep/Eacc	2.02
Hp/Eacc [Oe/MV/m]	35.6
R/Q [W]	138
G[W]	285
Eacc max	49.2

Breakthrough for > 50 MV/m, KEK



RF Critical Field Analysis



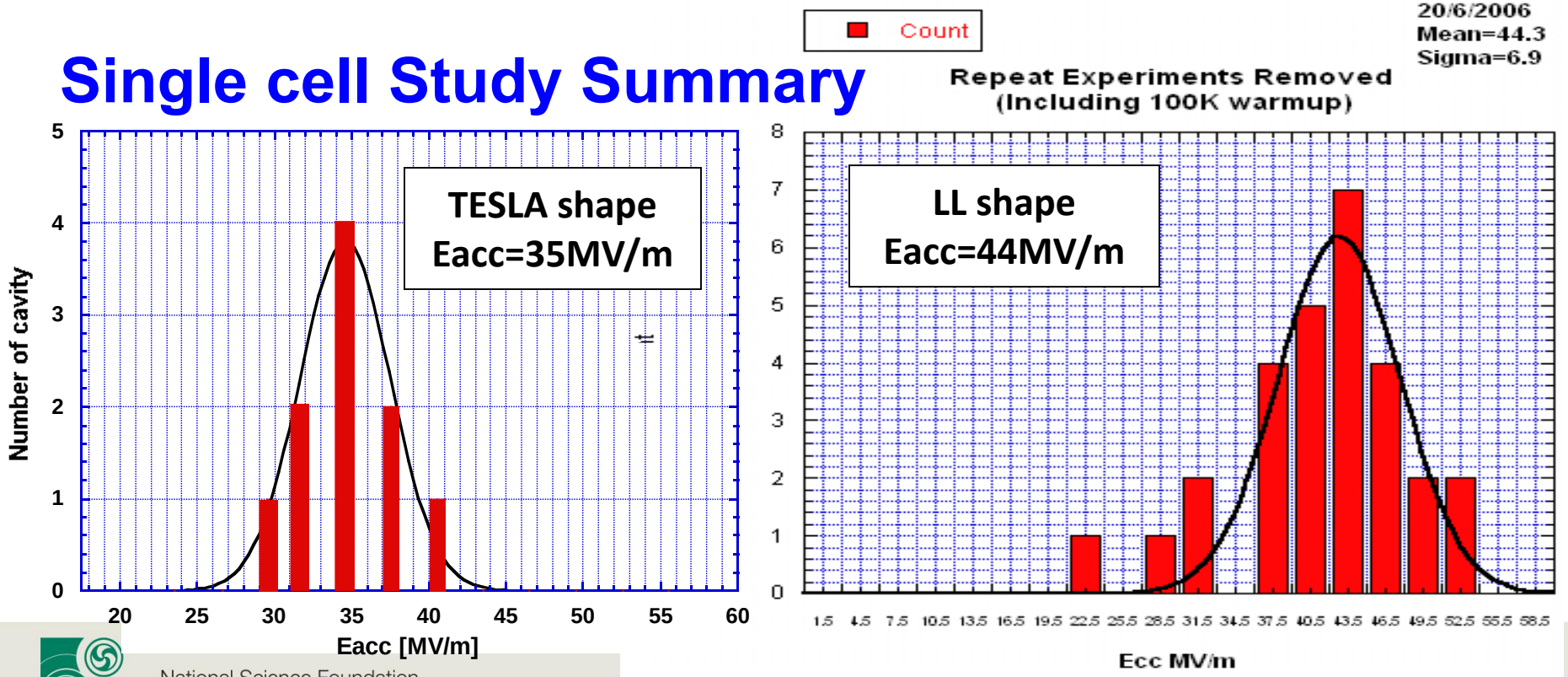
Single Cell Study Summary

- New cavity shapes with low Hp/Eacc made a breakthrough in high gradient of 50MV/m.
- Proof of reproducibility was done.
- Statistics shows IS shape is superior to TESLA shapes with high gradient.
- Establishment of recipe is ongoing

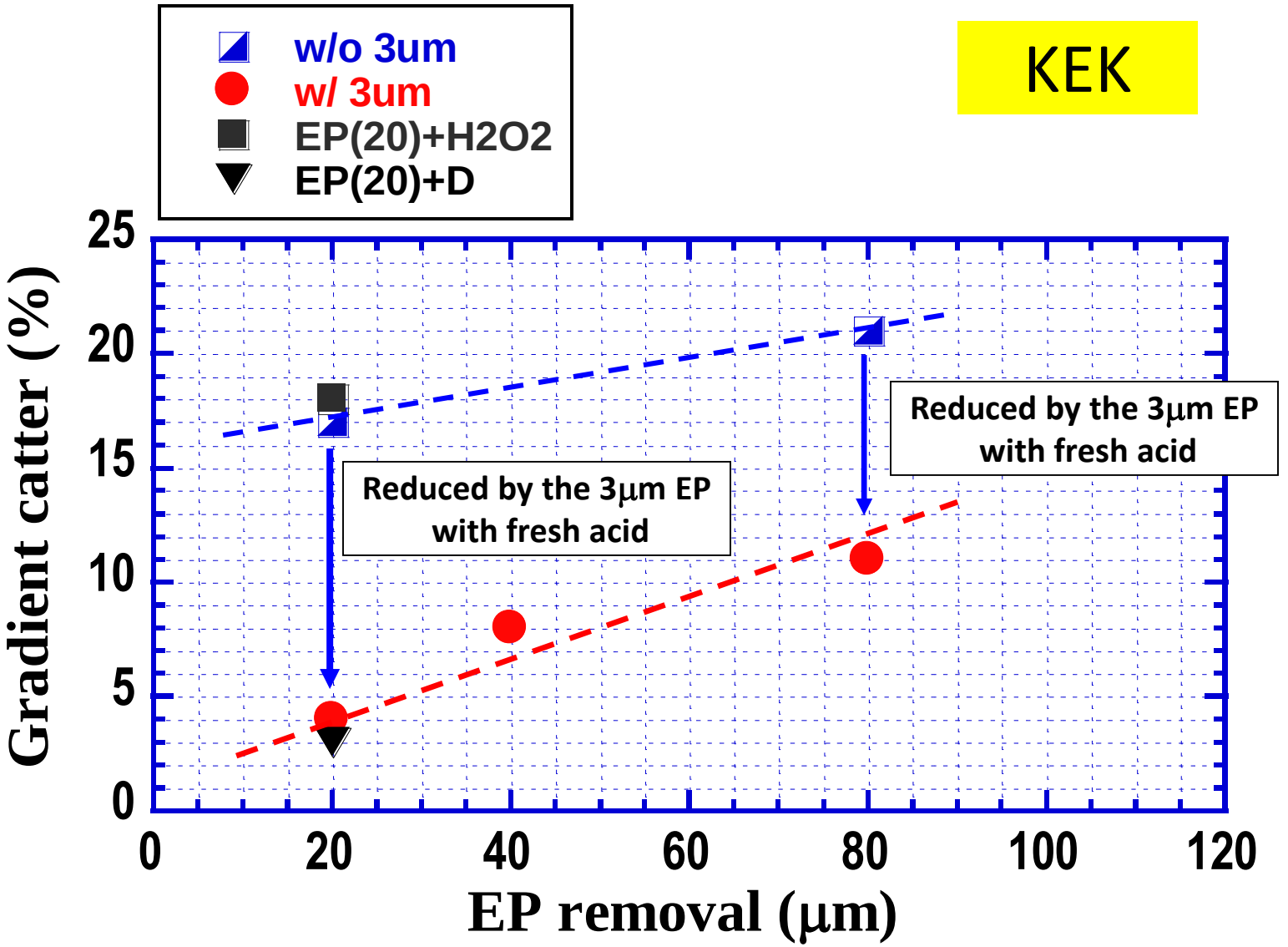
Cavities prepared by KEK recipe

Mean=44.3MV/m, Sigma=6.9 by R.S.Orr

Single cell Study Summary

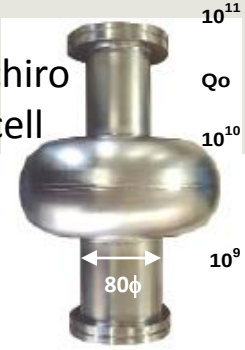


Gradient Scatter vs. EP Material Removal

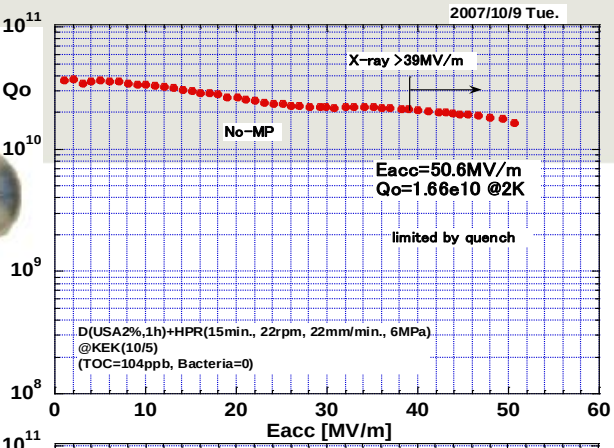


17.6 END Cell Study

New Ichiro End cell

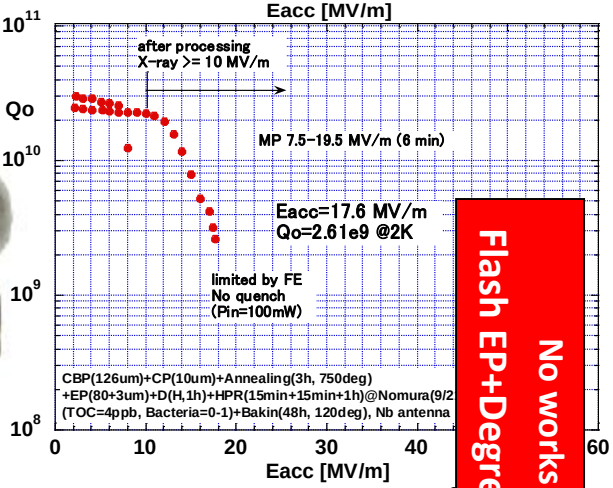


ISE#3



Just HOM cylinder

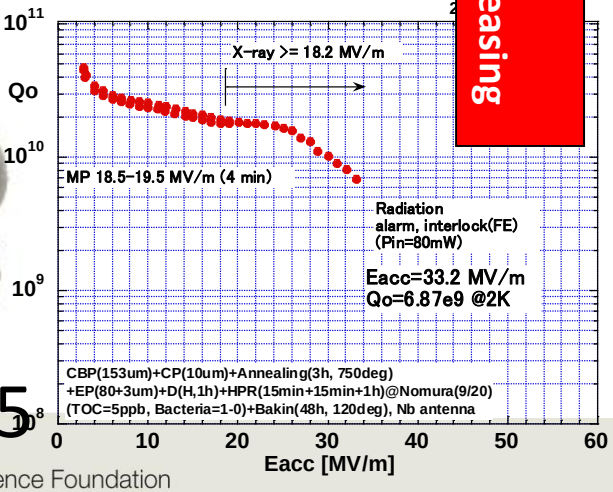
ISE#4



No works
Flash EP+Degreasing

Full HOM

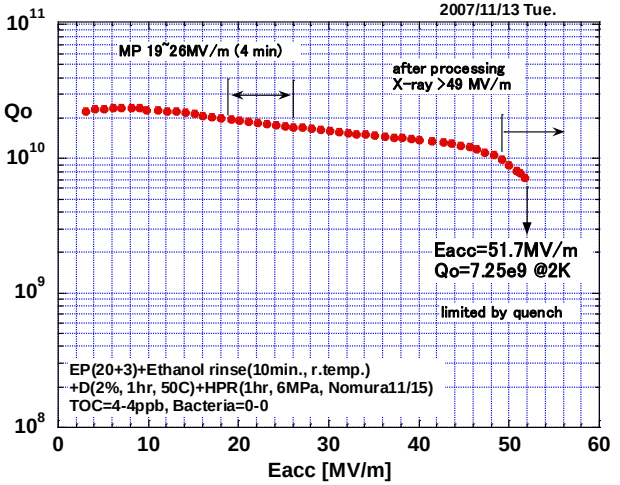
ISE#5

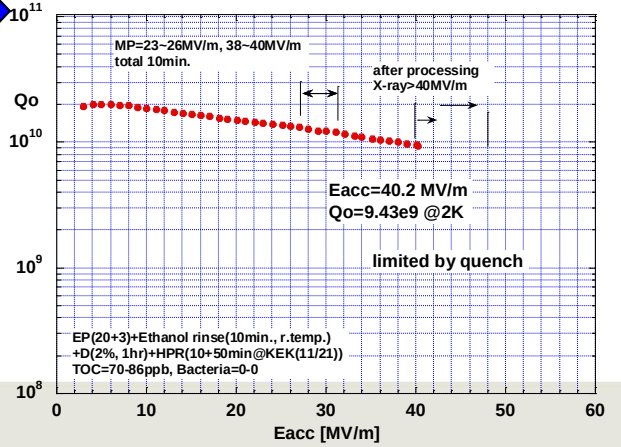


New END cell itself has no problem !

Sulfur contamination might remain on the complicated beam pipe.

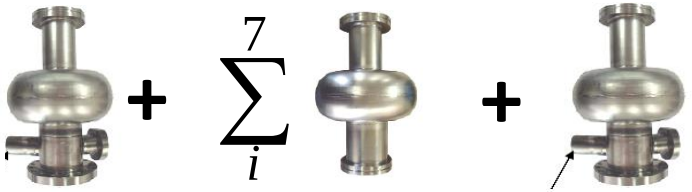
+ Ethanol Rinsing





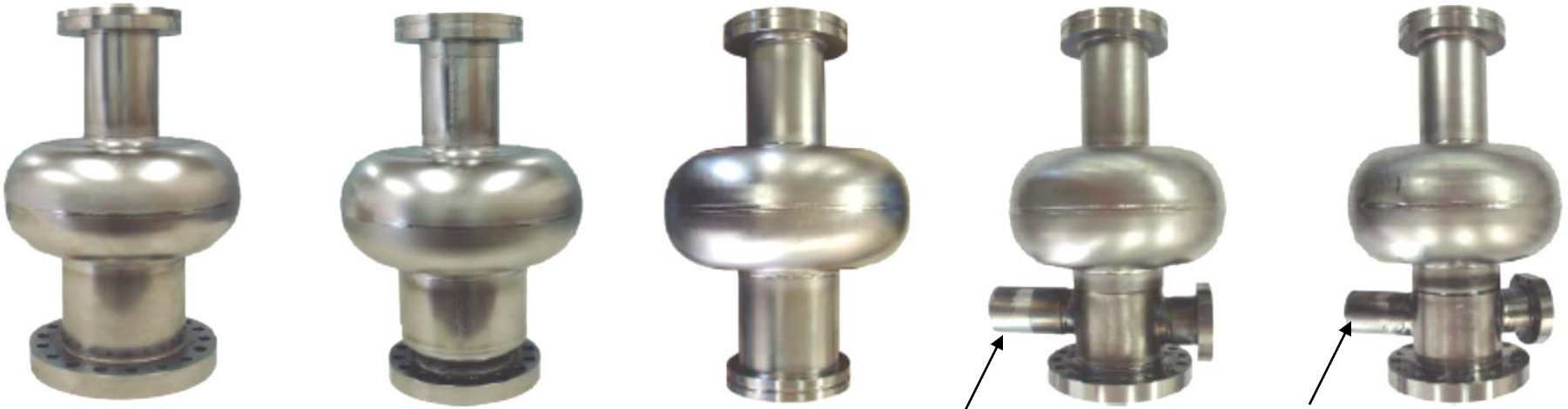
END Group Study

We have to understand why so such different result happened between single and multi-cell .

9-Cell =  = 50MV/m ?!

ISE#1 ISE#2 ISE#3 ISE#4 ISE#5

Ichiro cavity old End cell | **New Ichiro End cell**



So far (2011):

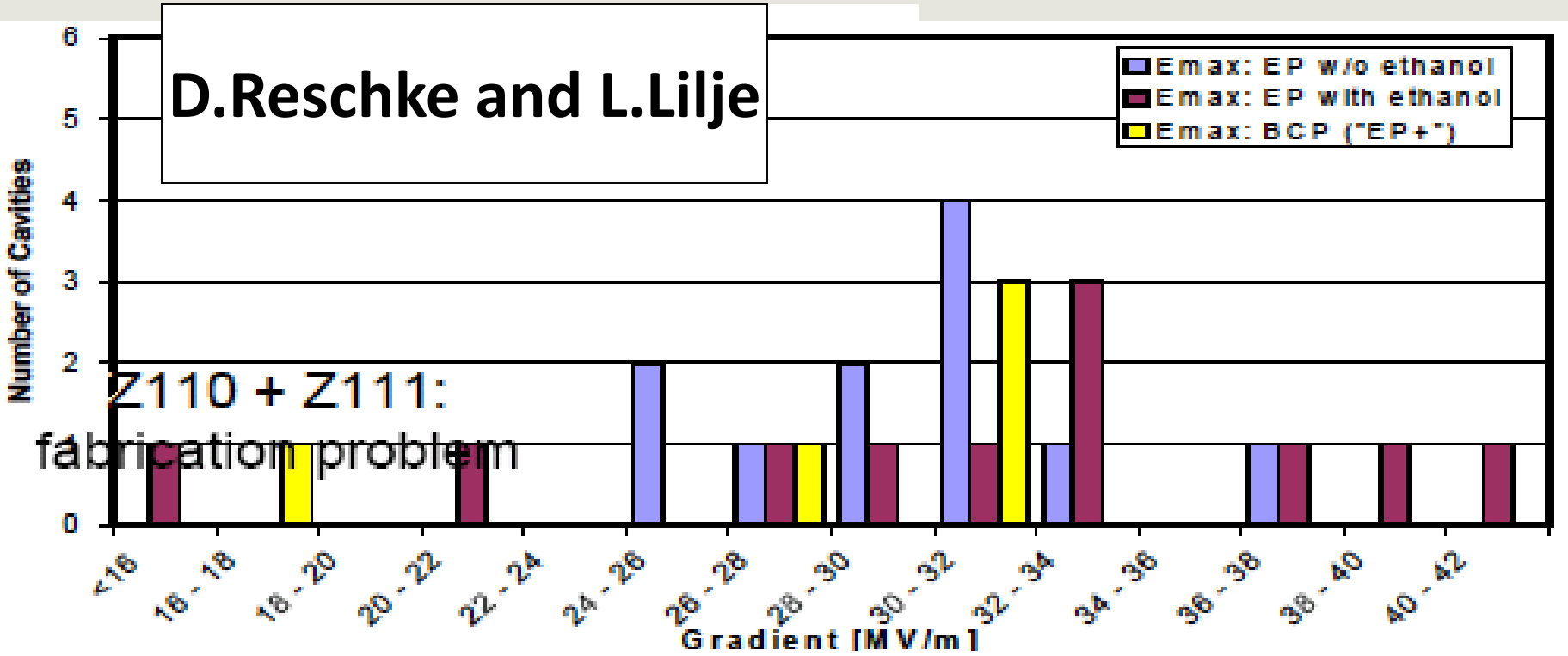
34.5MV/m **41MV/m** **50MV/m** **51MV/m** **45MV/m**

Just HOM cylinder **HOM**

Theoretical limitation : ~ 40MV/m

Theoretical limitation ~ 50MV/m

Ethanol Rinsing @ DESY 9-cell



⇒ **EP w/o eth:** $< E_{acc,max} > = (30 \pm 4)$ MV/m

$< E_{acc,usable} > = (29 \pm 3)$ MV/m

⇒ **EP with eth:** $< E_{acc,max} > = (32 \pm 6)$ MV/m (w/o Z110)

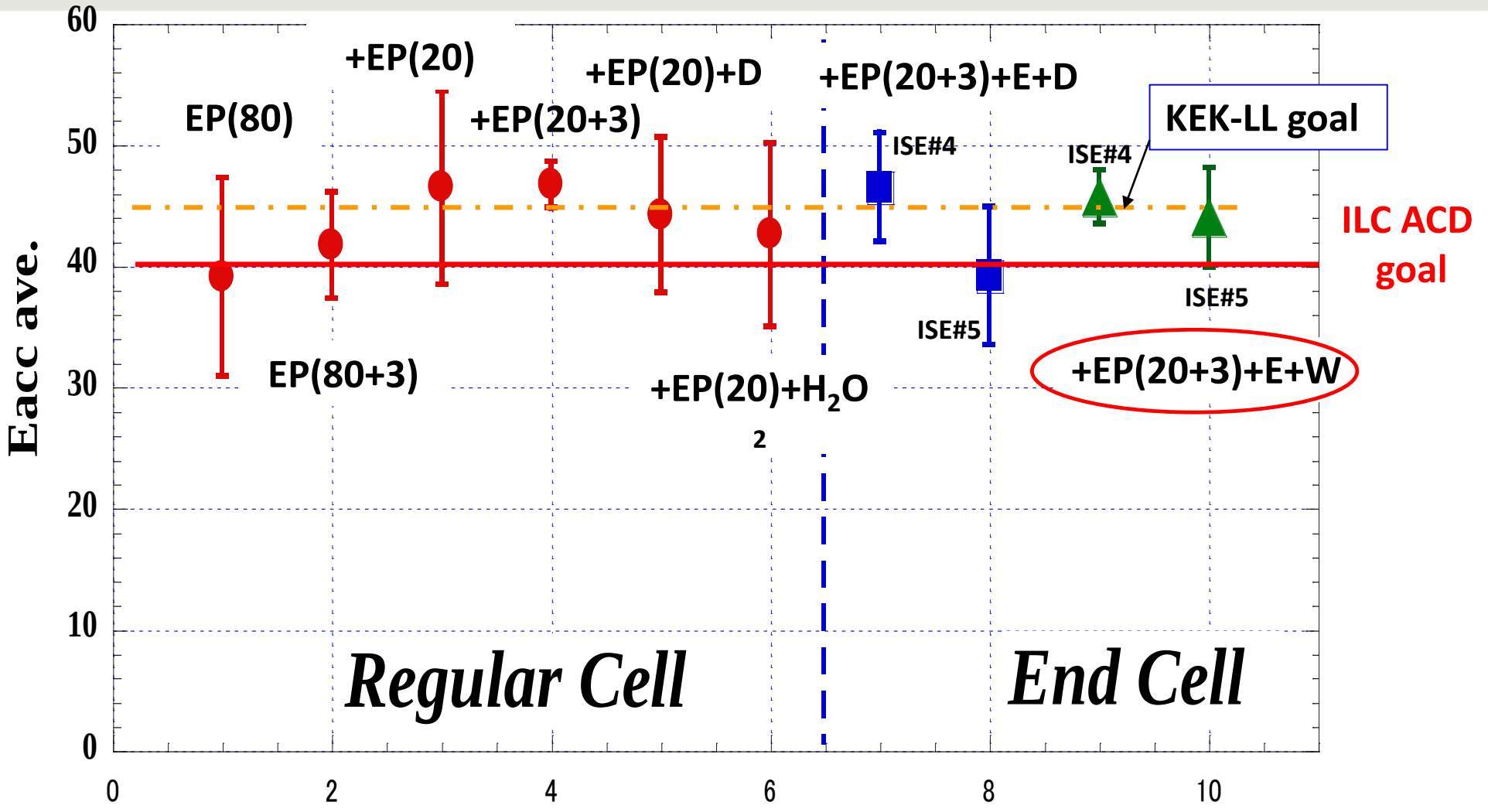
$< E_{acc,usable} > = (30 \pm 4)$ MV/m

⇒ **BCP ("EP+"):** $< E_{acc,max} > = (30 \pm 2)$ MV/m (w/o Z111)

$< E_{acc,usable} > = (29 \pm 2)$ MV/m

Ethanol rinsing is effective!

Scatter in the Max Gradient so far (2011)



Established 45MV/m Single cell cavity in 2011 with performance scatter

17.7 High Gradient 9-Cell Cavity

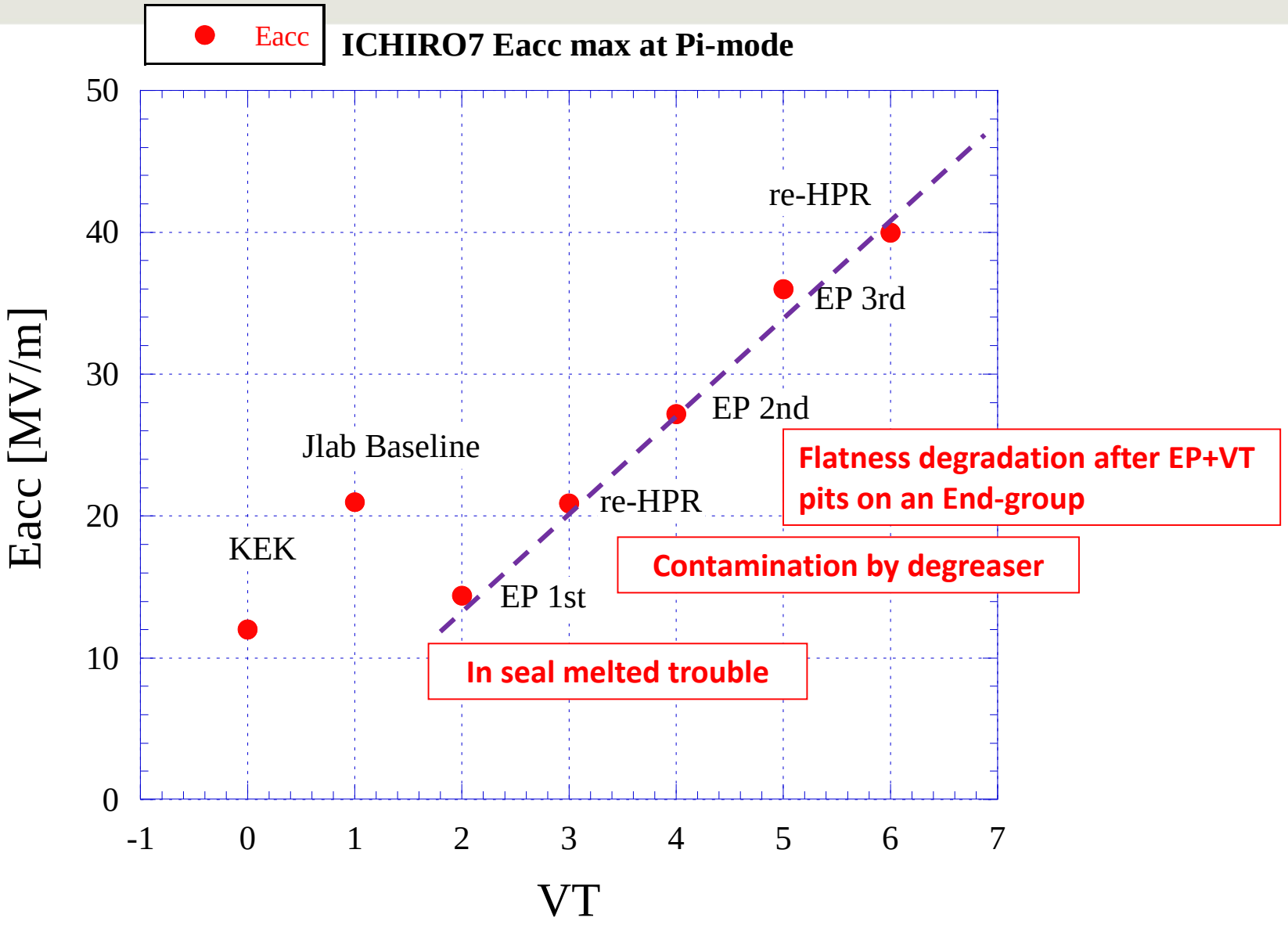
Step-II : full cavity **Ichiro#7**

w/ end groups

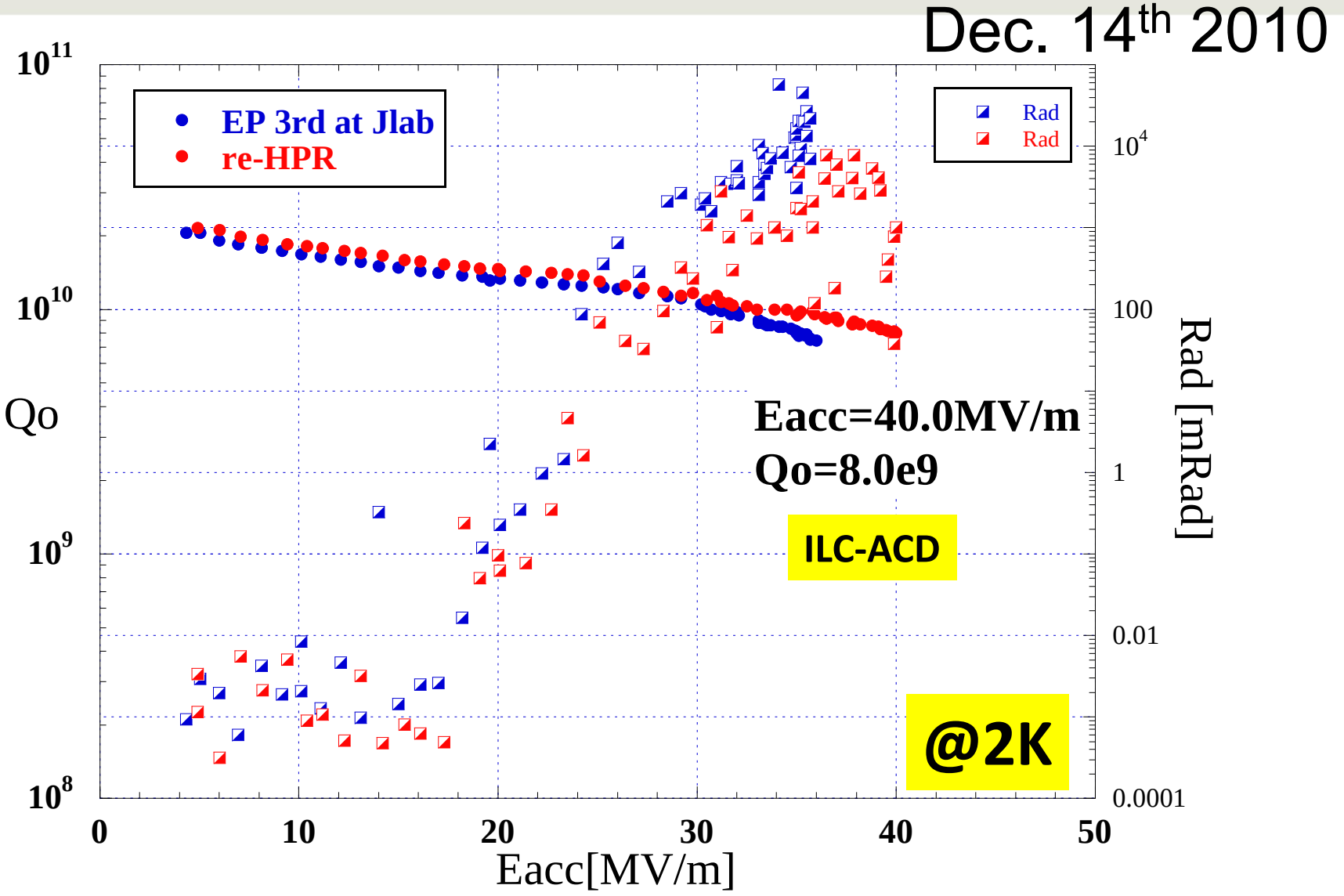
2010 Feb.	March	April	May	June	July
2weeks, Fumio, Kenji	1 RF test (baseline)			10weeks, Fumio 3 RF test (2 EP, 1 re-HPR)	Commissioning done for ICHIRO7

Aug.	Sep.	Oct.	Nov.	Dec.	2011 Jan.
	SSTIN @Jlab Fumio, Kenji		13weeks, Fumio 3 RF test (1 EP, 1 re-HPR, 1 re-test w/OSTs)		

ICHIRO#7 Study at JLab

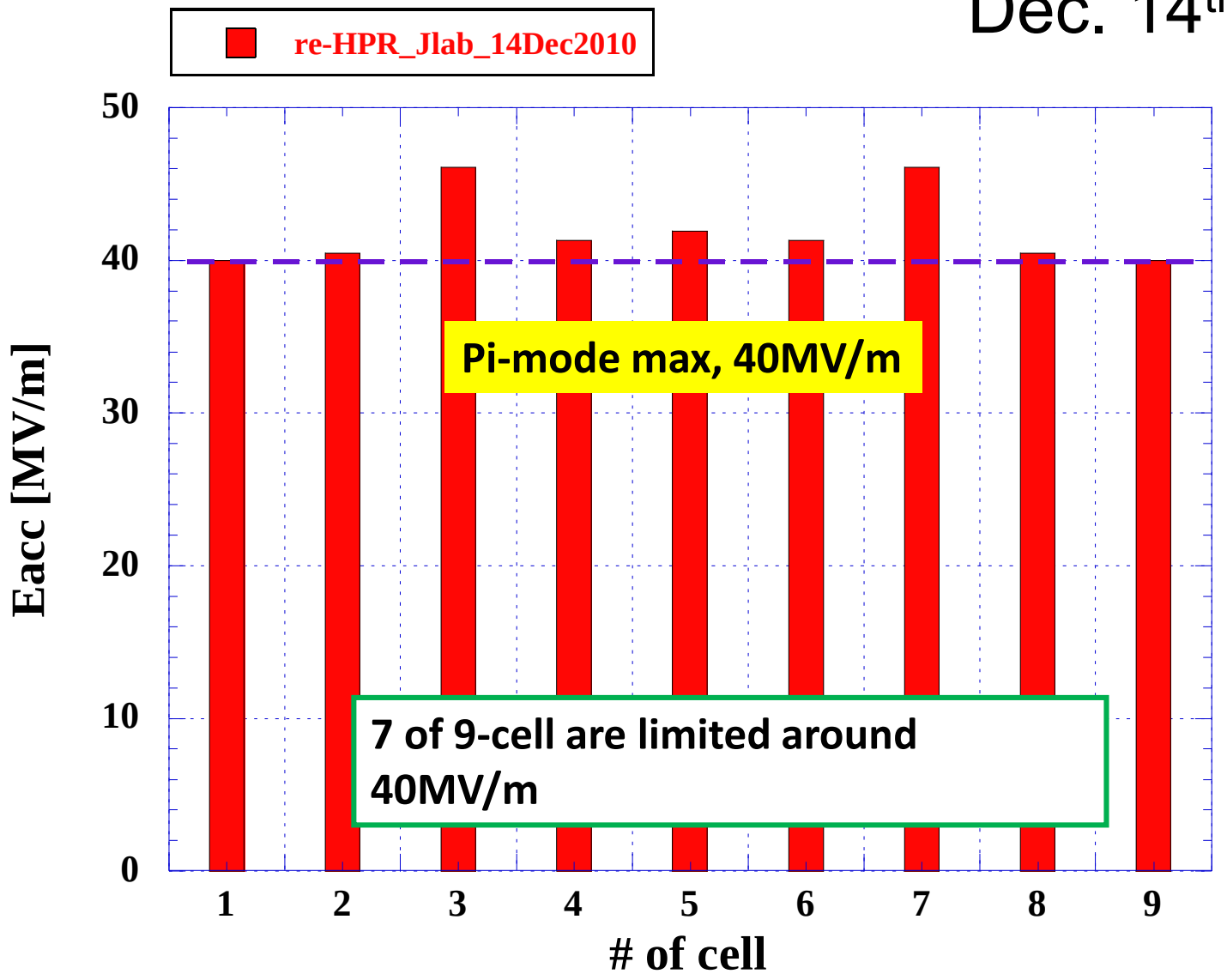


ICHIRO#7 VT After Re-HPR at Jlab



Pass-band Measurement

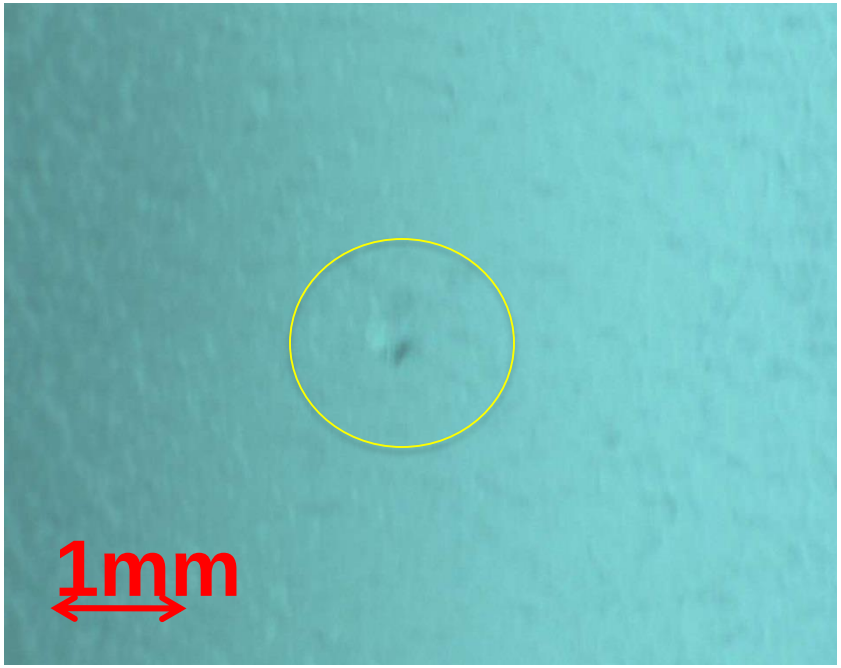
Dec. 14th 2010



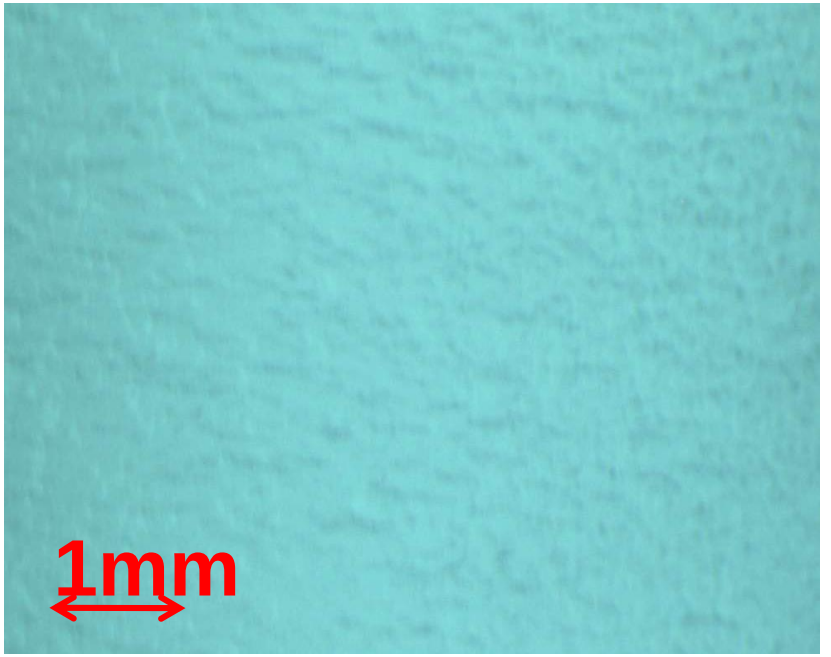
Inspection after VT

2011 Jan. 28th

Cell#8, quench location of pi-mode



quench area at pi-mode

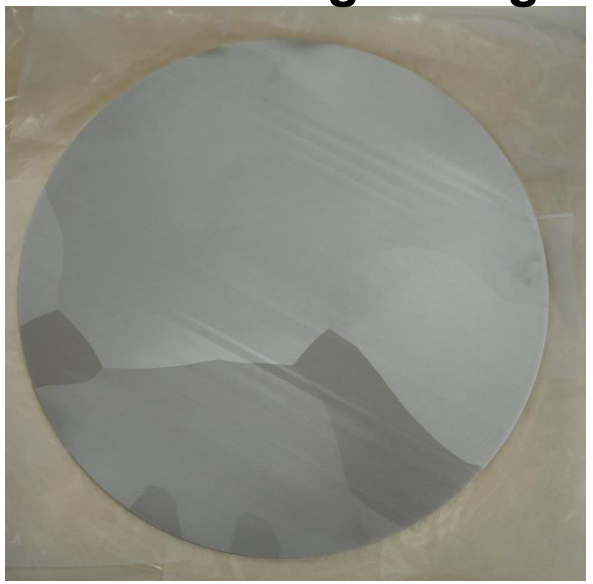


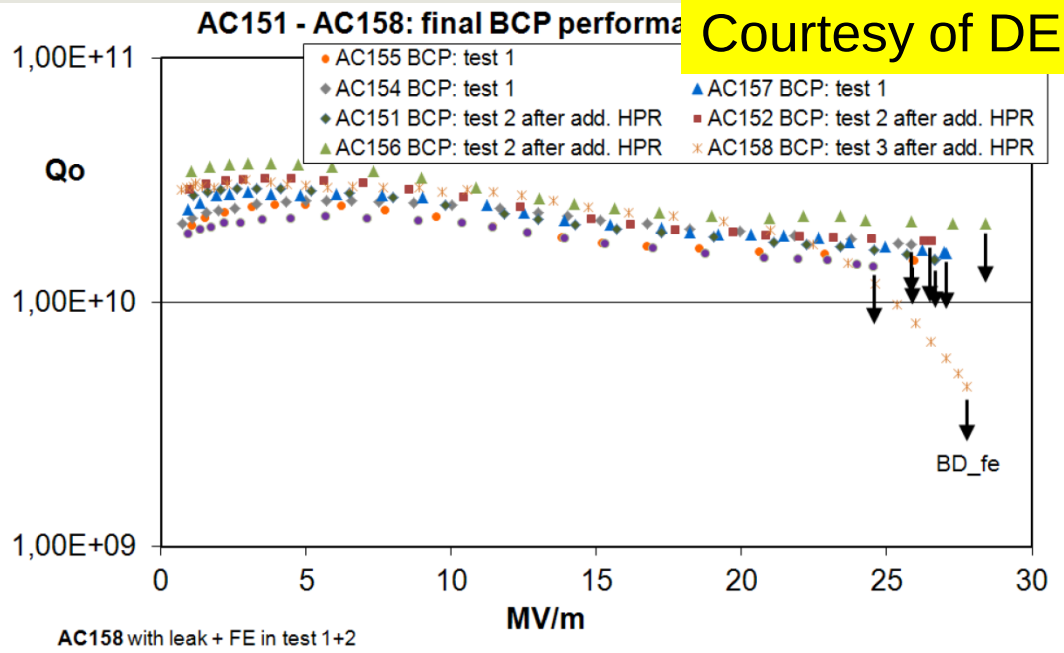
other area
for comparison

ILC LG 9-Cell Cavities Activities at DESY

Courtesy of DESY

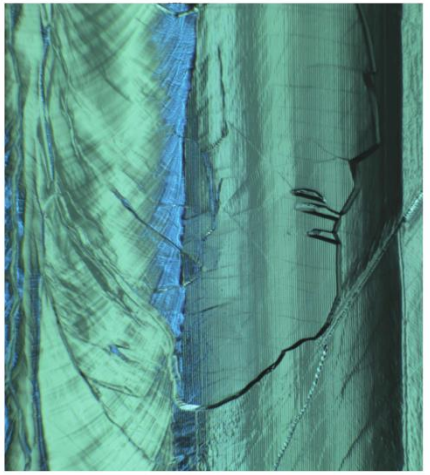
Direct slicing Nb Ingot



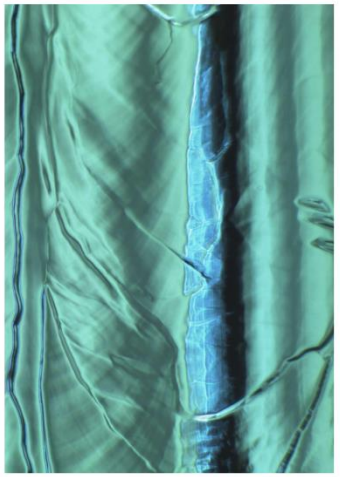


AC158 with leak + FE in test 1+2

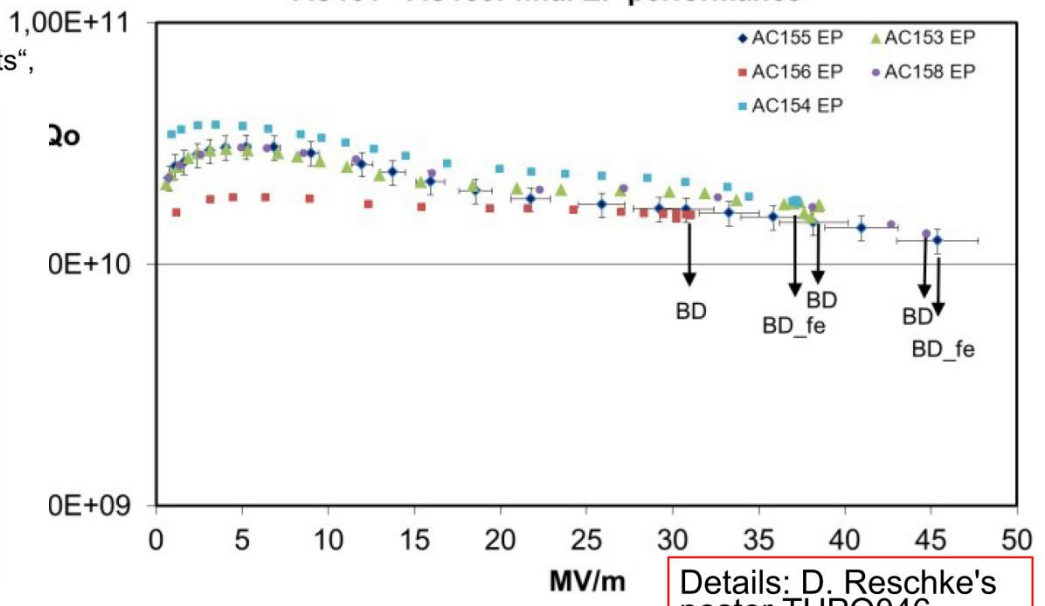
Quench-sites inspected in AC151-AC158 so far: no „obvious defects“, just etching pits (all over the cavity) and grain boundaries



After BCP: sharp edges



After EP: smoothed edges

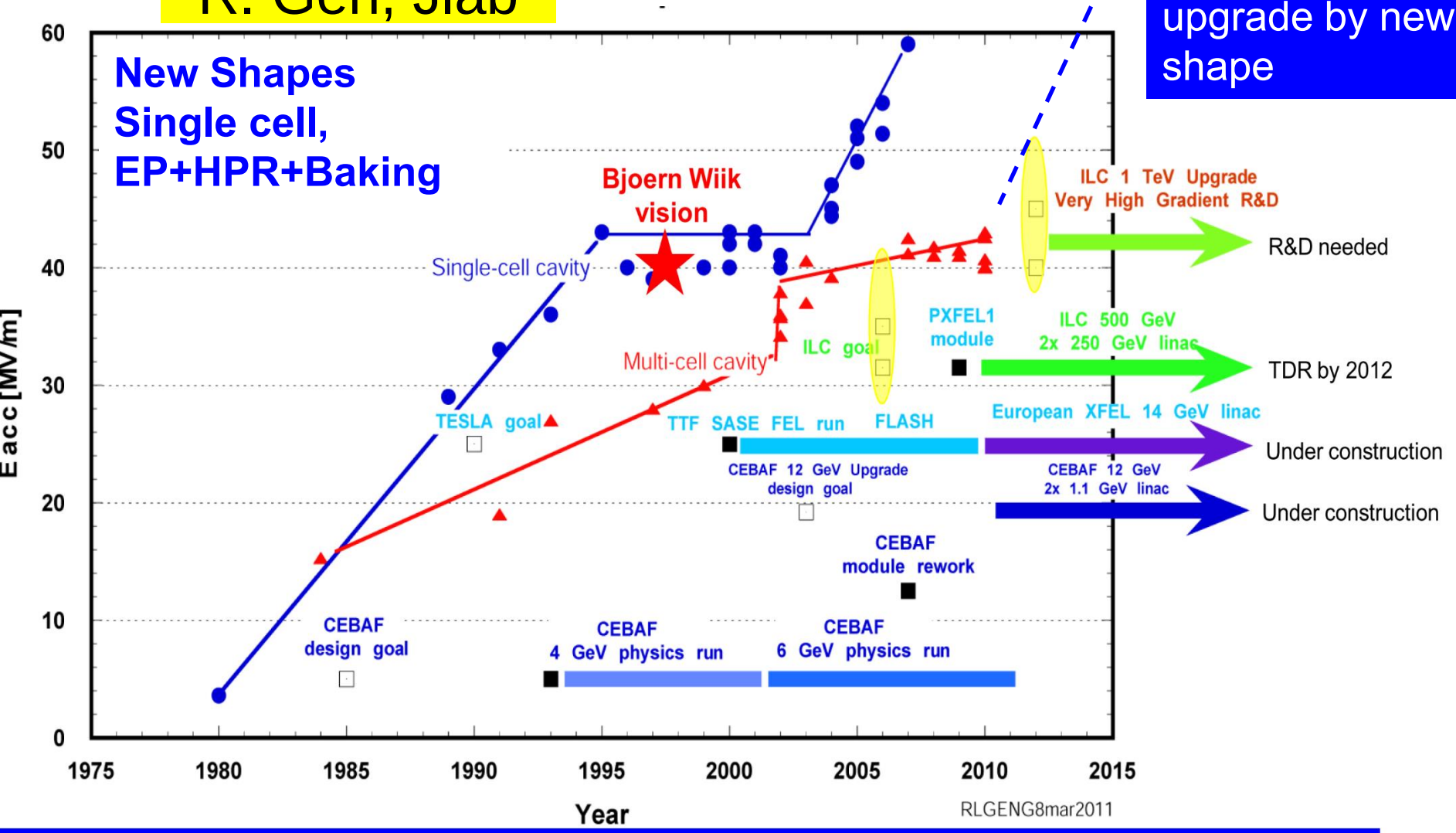


Details: D. Reschke's poster TUPO046

ILC 9-Cell High Gradient Tracking

R. Gen, Jlab

Expected gradient upgrade by new shape



Steady progress in SRF cavity gradient makes SRF an enabling technology

SRF based electron linacs (CW & pulsed) have track record of successful operations

Homework

- Homework 17.1

Recently high gradient is very much pushed for Nb SRF cavities by understanding of the fundamentals and SRF technologies.

Please describe your understanding what were keys for the high gradient evolution.

- Homework 17.2

If you are looking for new SRF material instead of Nb, what do you put your key points for your new material exploring?