Course B: Superconductive RF

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LC school 2013

5 - 15 Dec. 2013, Antalya, Turkey

Course B: Superconductive RF
RF Test of Cavity

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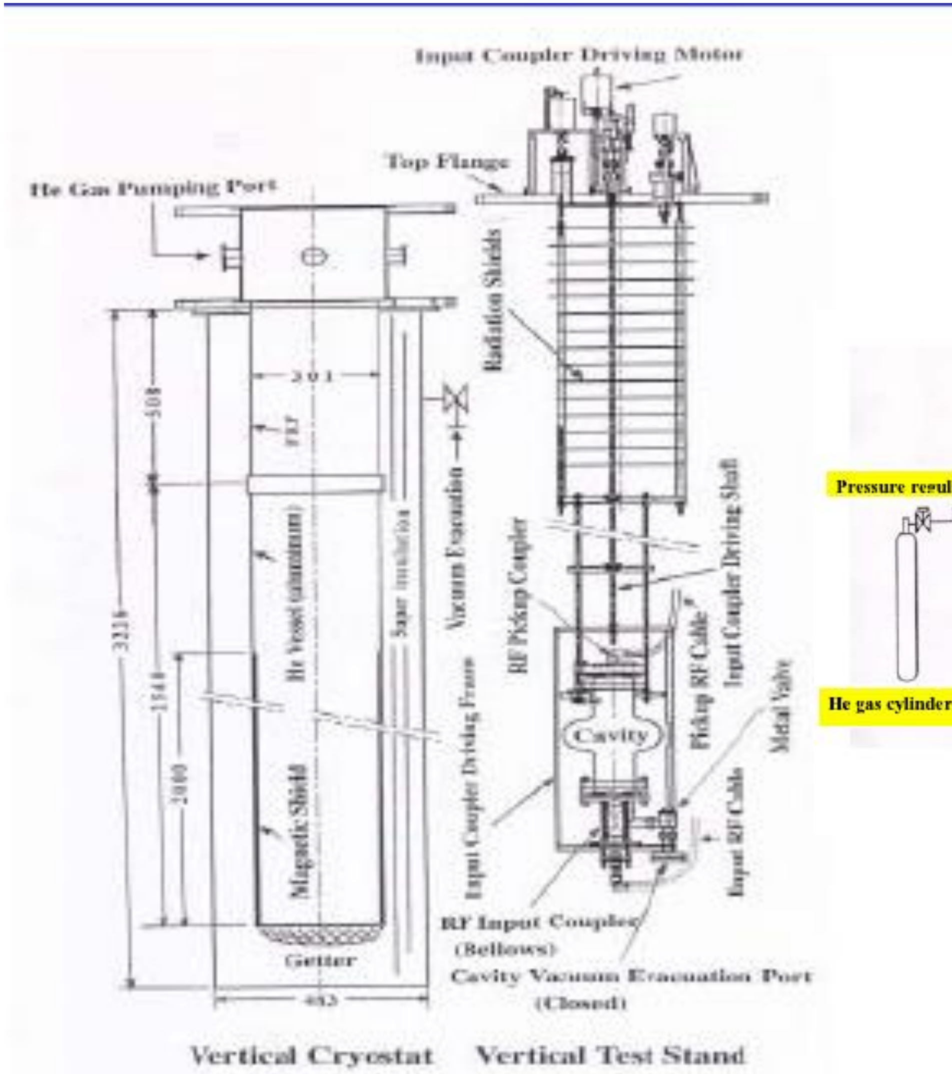
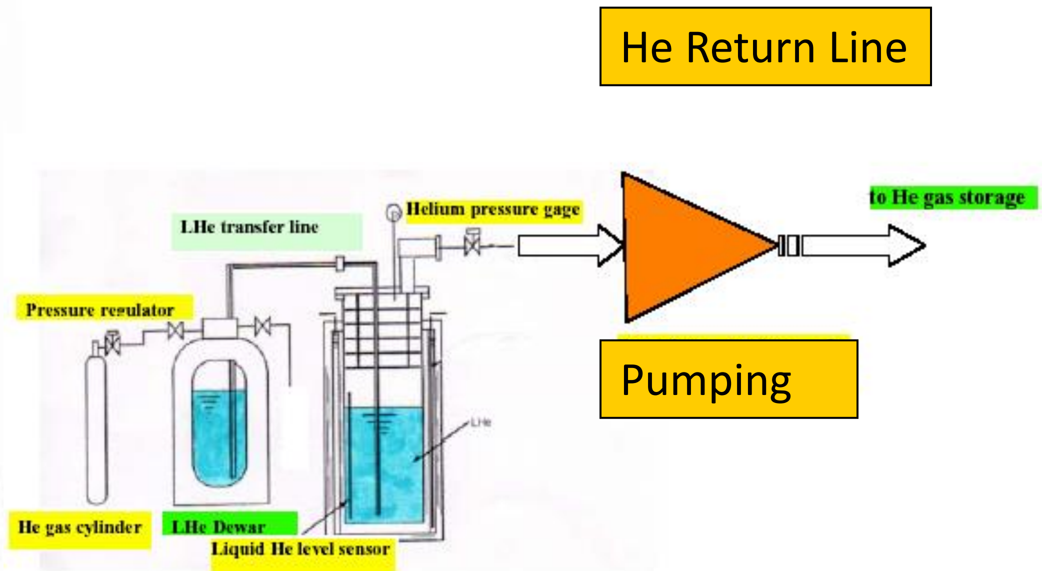
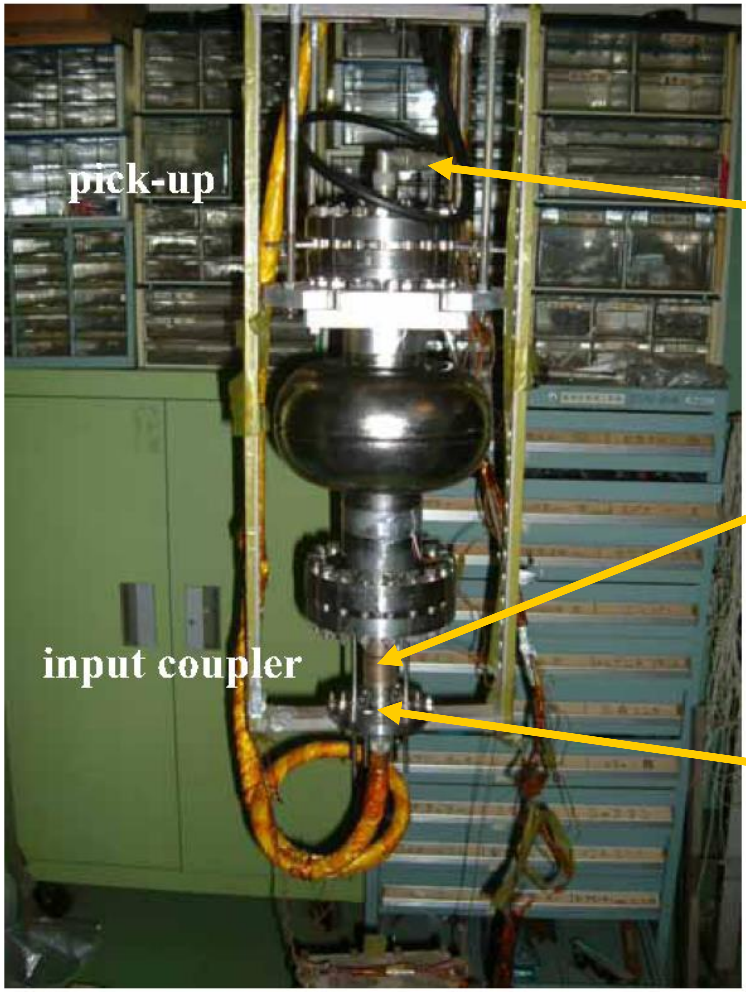
12 Dec. 2013, Antalya, Turkey

RF Test Cryostat (Vertical Test)





Cavity Preparation Stand

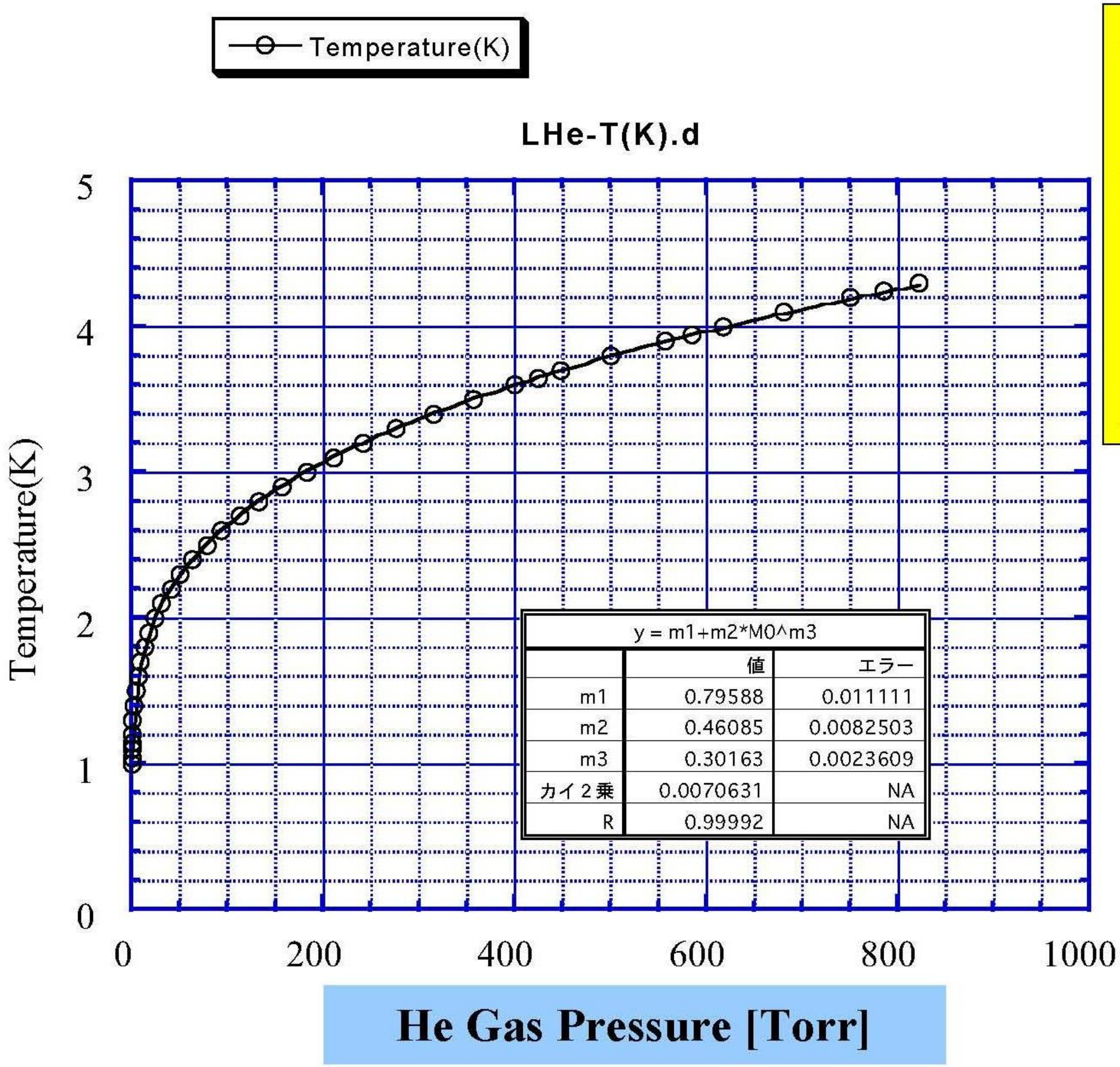


Pickup coupler

Input coupler

Metal valve for vacuum

Temperature of Liquid He (P vs. T)



	値	エラー
m1	0.79588	0.011111
m2	0.46085	0.0082503
m3	0.30163	0.0023609
カイ２乗	0.0070631	NA
R	0.99992	NA

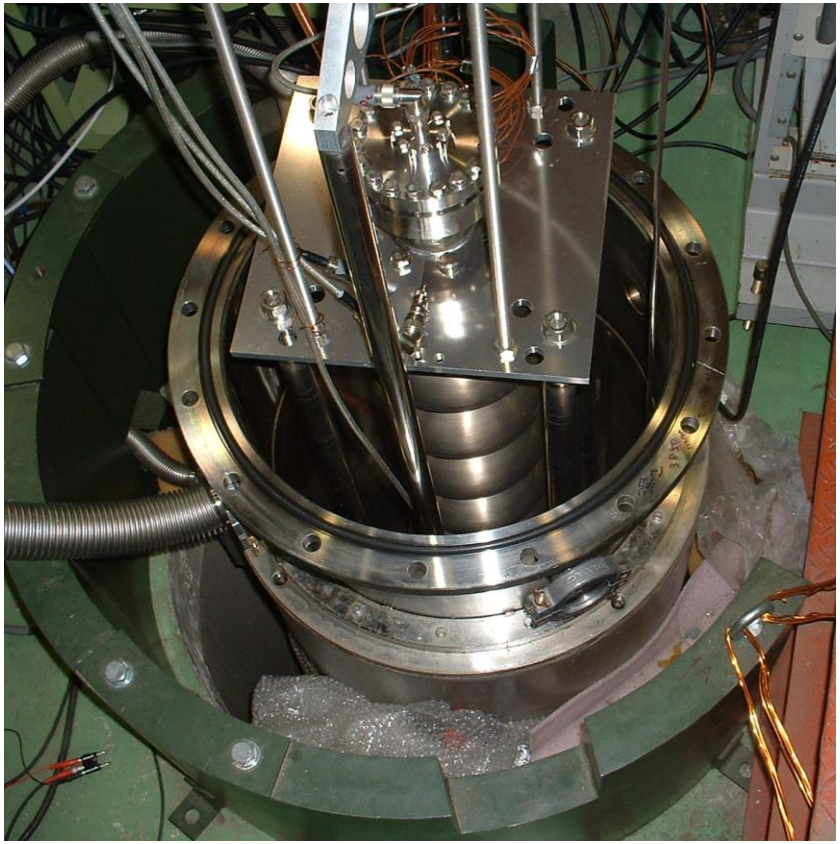
4.25 K = 760 Torr

λ-point :

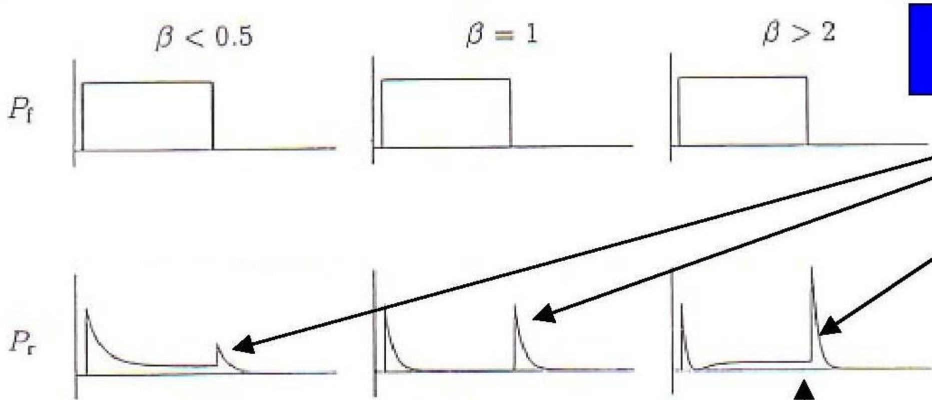
2.1773K = 38.41 Torr

2K = 23.77 Torr

Cryostat for Vertical Test



Theory of Measurement



Pulse method

$$P_t(t) = P_o \exp(-\frac{\omega}{Q_L} t)$$

$$\omega = 2\pi f, \quad Q_L : \text{Loaded Q}$$

t = 0

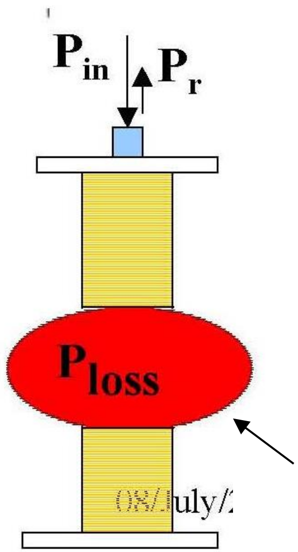
One-port

Measure the period during when P becomes half .

Decatime : $\tau_{1/2}$

$$P_t(\tau_{1/2}) = \frac{1}{2} P_o = P_o \exp(-\frac{\omega}{Q_L} \cdot \tau_{1/2})$$

$$\ln(2) = \frac{2\pi f}{Q_L}$$



$$Q_L = 2\pi f \cdot \frac{\tau_{1/2}}{\ln(2)}$$

Ploss = heat caused by RF field in the cavity.

One-Port Cavity

Ploss = consumption on cavity wall

Pe = Power that goes out from port when Pin=0

$$Q_O \equiv \frac{\omega U}{P_{loss}},$$

$$Q_L \equiv \frac{\omega U}{P_{loss} + P_e} = \frac{\omega U}{P_{loss}\left(1 + \frac{P_e}{P_{loss}}\right)}$$

(for one port)

(When **P**in = 0)

$$= \frac{Q_O}{(1+\beta_{in})}$$

$$Q_O = (1+\beta_{in}) \cdot Q_L$$

Calculation of Equivalent Circuit

$$\beta_{in} \equiv \frac{1 \pm \sqrt{P_r / P_{in}}}{1 \mp \sqrt{P_r / P_{in}}}$$

(over > 1 / under < 1)

(When **P**in > 0)

$$\beta_{in} \equiv \frac{P_e}{P_{loss}}$$

(When **P**in = 0)

The wave shape of Pr

$\tau_{1/2}$, P_{in}, P_r — Measured values

Calculation → Q_L, β_{in}

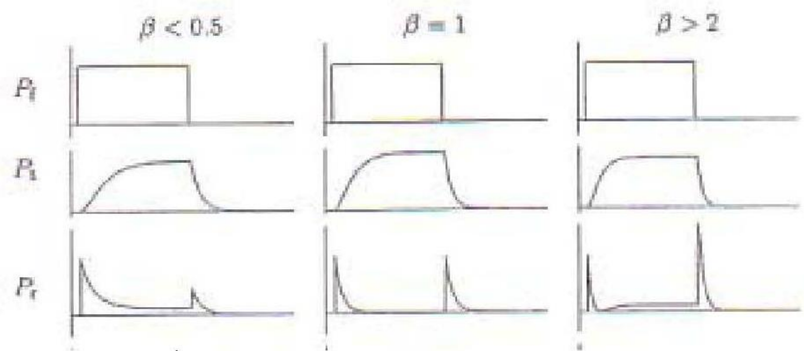
Calculation → Qo

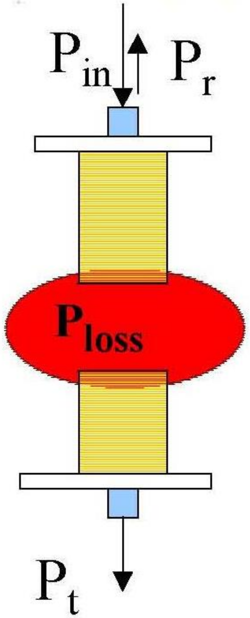
$$R_s = \frac{\Gamma}{Q_o}$$

Geom. factor

Surface resistance

Two-Port Cavity





$$P^*_{loss} = P_{loss} + P_t$$ Ploss of one-port

$$Q^*_o = \frac{\omega U}{P^*_{loss}} = \frac{\omega U}{P_{loss} + P_t}$$

$$= \frac{\omega U}{P_{loss}\left(1 + \frac{P_t}{P_{loss}}\right)}$$

Measured value

$$= \frac{Q_o}{(1+\beta_t)} \quad \because \; \beta_t \equiv \frac{P_t}{P_{loss}}$$

$$= (1+\beta^*_{in})Q_L$$

When **P**in = any.

Measured value

$$\beta^*_{in} = \frac{1 \pm \sqrt{P_r / P_{in}}}{1 \mp \sqrt{P_r / P_{in}}}$$ (over > 1 / under < 1)

(When **P**in > 0)

$$\beta^*_{in} \equiv \frac{P_e}{P^*_{loss}}$$ (When **P**in = 0)

$Q_L = \omega U / (P_{loss} + P_e + P_t)$
$= Q_0 / (1+\beta_{in} + \beta_t)$ when $P_{in} = 0$

$$Q_o^* = \frac{Q_o}{(1+\beta_t)} = (1+\beta_{in}^*)\cdot Q_L$$

$$Q_o = (1+\beta_{in}^*)\cdot(1+\beta_t)\cdot Q_L$$
$$= \left[1+(1+\beta_t)\cdot\beta_{in}^* + \beta_t\right]\cdot Q_L$$

$$Q_0 = (1+\beta_{in} + \beta_t)\cdot Q_L \Leftrightarrow \beta_{in} = (1+\beta_t)\cdot\beta_{in}^*$$

$$Q_o \equiv \frac{\omega U}{P_{loss}},\ Q_t \equiv \frac{\omega U}{P_t} = \frac{\omega U / P_{loss}}{P_t / P_{loss}} = \beta_t^{-1}\cdot Q_o$$

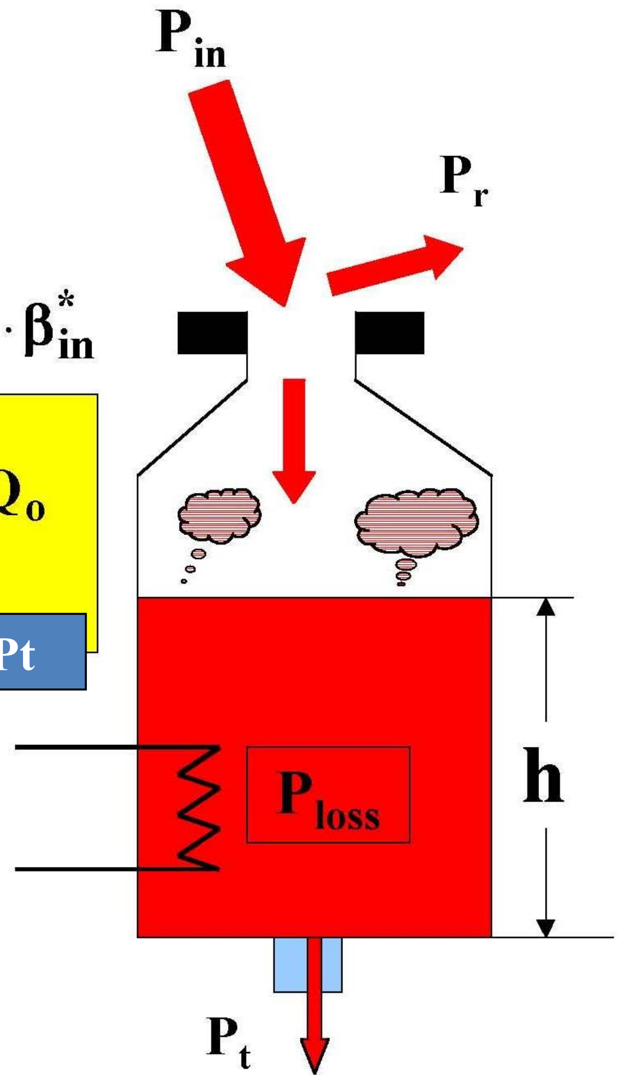
$$\omega U = Q_o\cdot P_{loss} = Q_t\cdot P_t$$

$Q_t = Q_0 \cdot P_{loss} / P_t$

$$P_{loss} = P_{in} - P_r - P_t$$

Pin, Pr, Pt : Measured values

Stable Status : h=const ⇐ U const



Calculation of Acceleration Gradient

$$R_{sh} = \frac{V^2}{P_{loss}} \qquad \because\ V = E_{acc} \cdot d_{eff}$$

Rsh = Shunt impedance

deff = Effective length of cavity along the beam axis.

$$= (E_{acc} \cdot d_{eff})^2 \ / \ P_{loss}$$

$$E_{acc} = \frac{1}{d_{eff}} \cdot \sqrt{R_{sh} \cdot P_{loss}} = \frac{1}{d_{eff}} \cdot \sqrt{\left(R_{sh}/Q_O\right) \cdot (Q_O \cdot P_{loss})}$$

$$= Z\sqrt{Q_O \cdot P_{loss}} \quad \text{(One-port)}$$

$$= Z\sqrt{Q_t \cdot P_t} \quad \text{(Two-port)}$$

$R_{sh}/Q_O = V^2/\omega U$

Not dependent on material

$$\because Q_t = \frac{\omega U}{P_t} = \frac{Q_o \cdot P_{loss}}{P_t}, \quad Q_o \cdot P_{loss} = Q_t \cdot P_t$$

Set $Q_t \gg Q_0$ ($P_t \ll P_{loss}$).
Qt is constant during the measurement if using a fixed antenna.
Z is independent of surface resistance (material of cavity).

Summary:

Measured parameters:

$f, \tau_{1/2} \rightarrow$

$P_{in}, P_r, P_t \rightarrow$

Stable state (CW)

$$Q_L = 2\pi f \tau_{1/2}/\ln(2)$$

$$\beta_{in}^* = \frac{1 \pm \sqrt{\frac{P_R}{P_{IN}}}}{1 \mp \sqrt{\frac{P_R}{P_{IN}}}}$$

$$P_{loss} = P_{in} - P_r - P_t$$

$$\beta_t = P_t/P_{loss}$$

$$Q_t = Q_O/\beta_t$$

$$\beta_{in} = (1+\beta_t)\beta_{in}^*$$

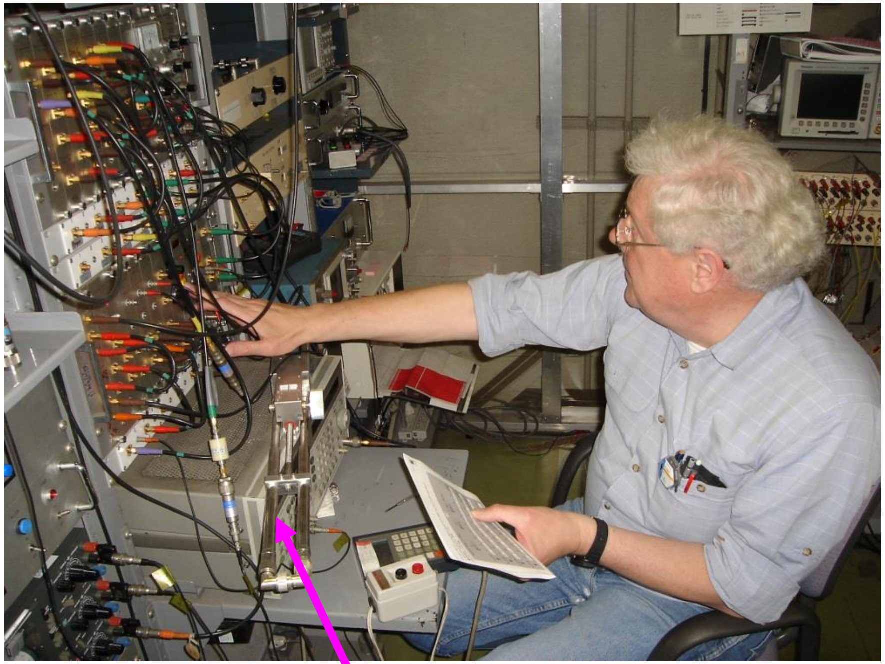
$$Q_O = (1+\beta_{in}+\beta_t)\, Q_L$$

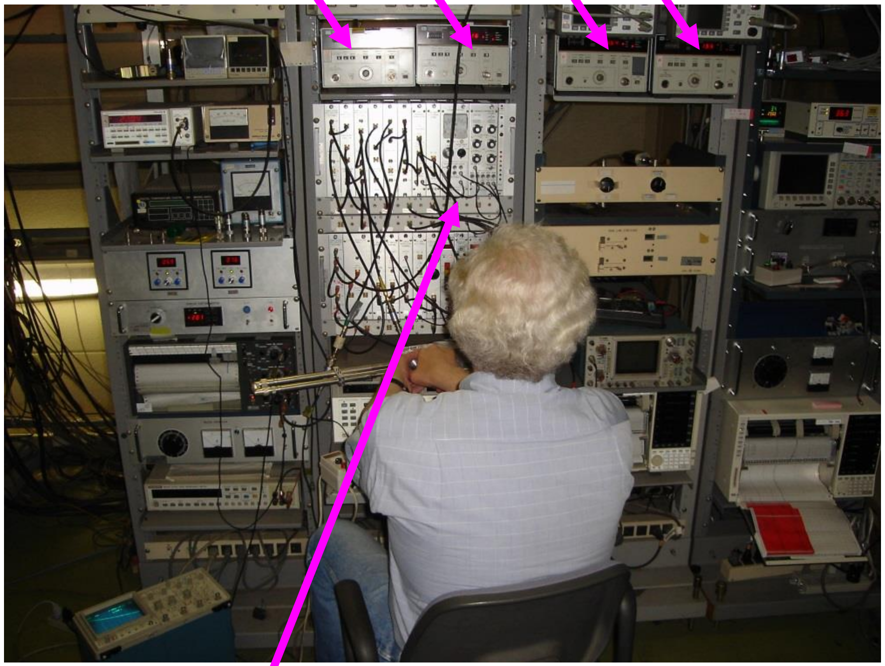
$$R_s = \frac{\Gamma}{Q_o}$$

$$Eacc = Z \cdot \sqrt{P_t \cdot Q_t}, \qquad Q_o = Q_t \beta_t$$

Control Room of Vertical Test (VT)

Power-meter (Pin, Pr, Pt)





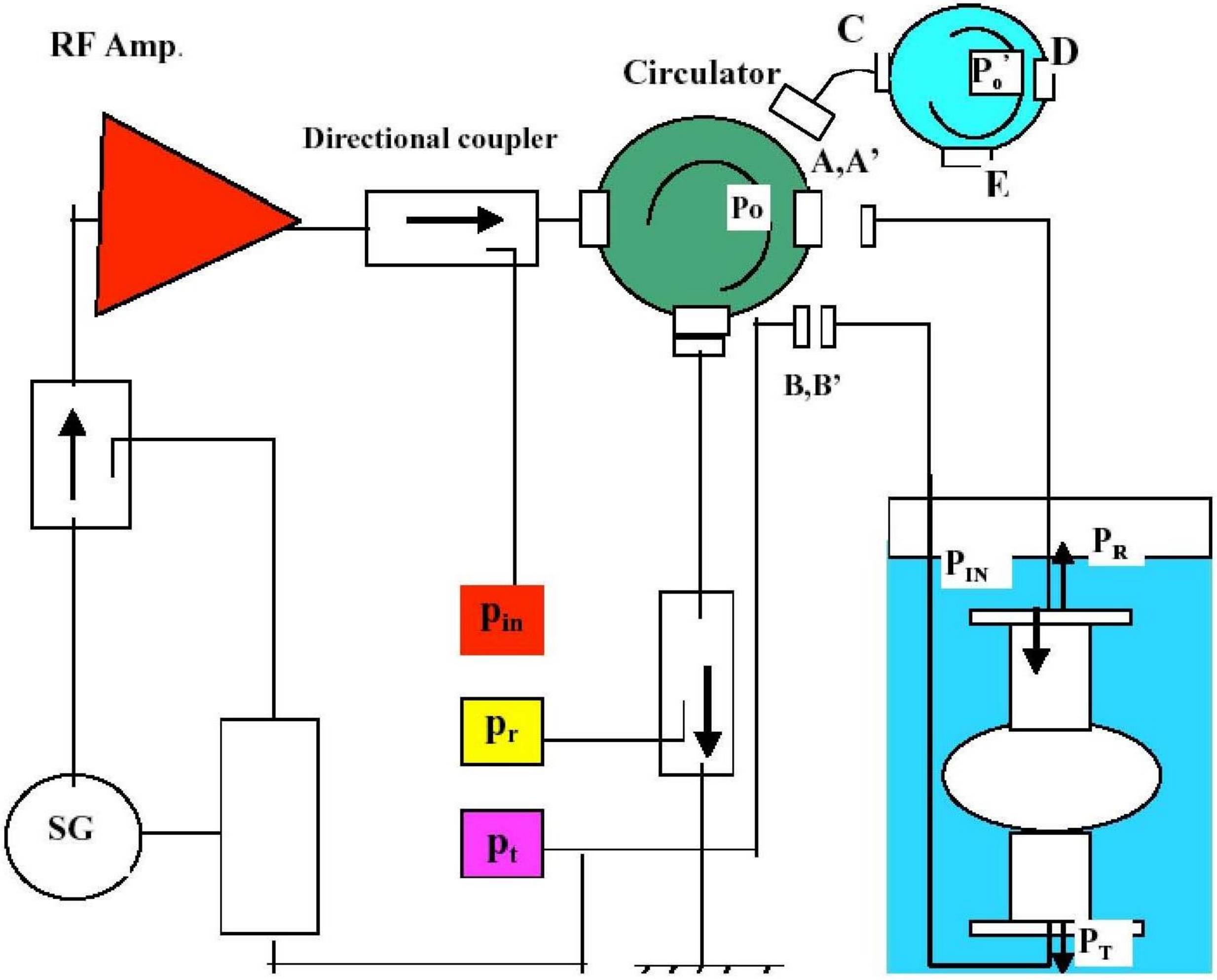
Signal Generator (SG)

Feed-back system (PLL)

Cable Correction

p_{in}, p_r, p_t : measured in the measurement room

P_{IN}, P_R, P_T : Power at the cavity (cooled), $P_{IN} = c_{in} \cdot p_{in}$, $P_R = c_r \cdot p_r$, $P_T = c_t \cdot p_t$



p_{in}, P_O at A,

p_r: short A

p_t : connect B to A

P_O/p_{in}, P_O/p_r, P_O/p_t

P_O' at E : connect A and C , and short D

p_{in}' at E : connect D to A'

p_t' at E : connect D to B'

$C_{in}=(P_O/p_{in})\cdot(p_{in}'/P_O')^{1/2}$

$C_r=(P_O/p_r)\cdot(P_O'/p_{in}')^{1/2}$

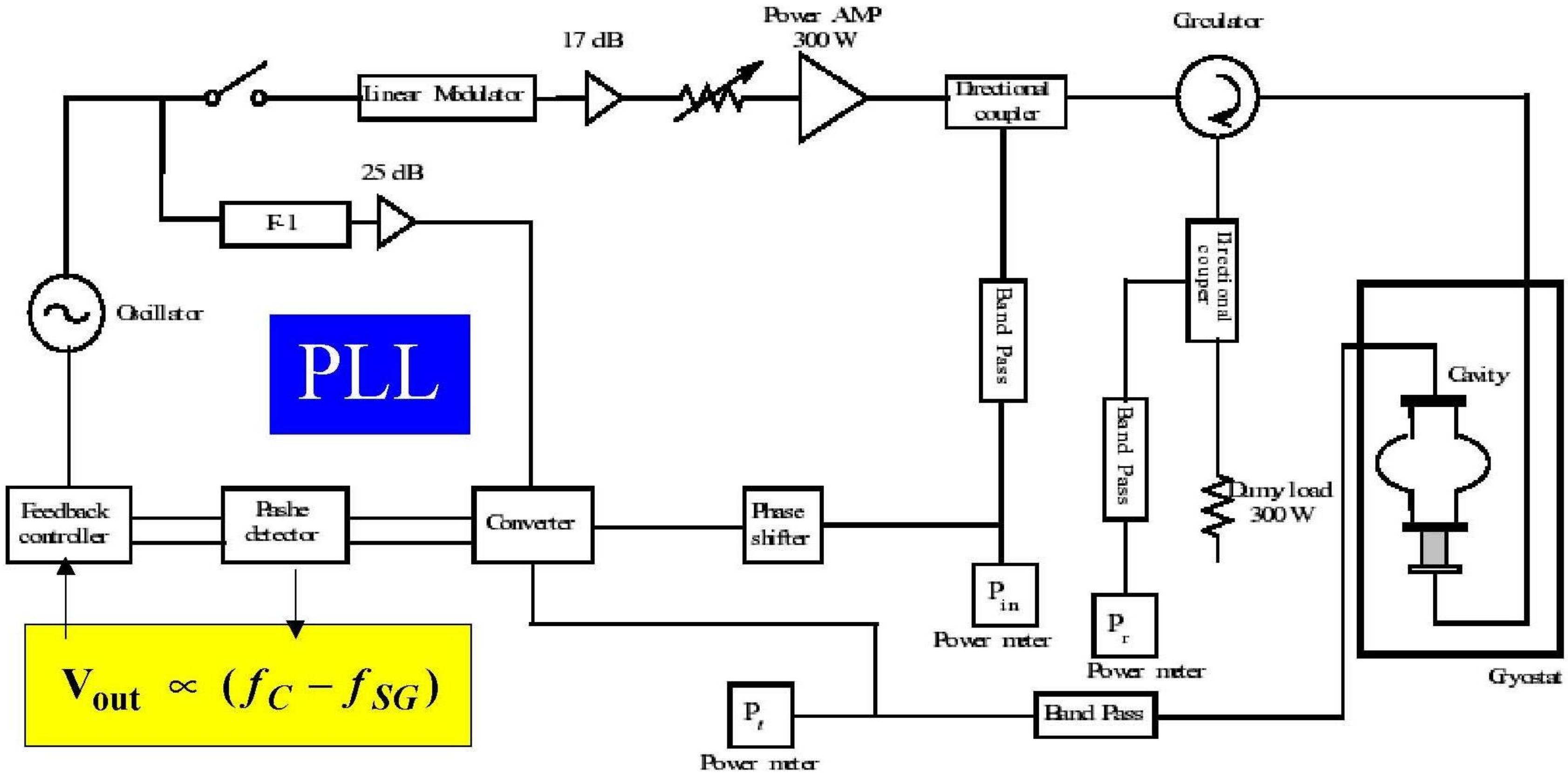
$C_t=(P_O/p_t)\cdot(P_O'/p_t')^{1/2}$

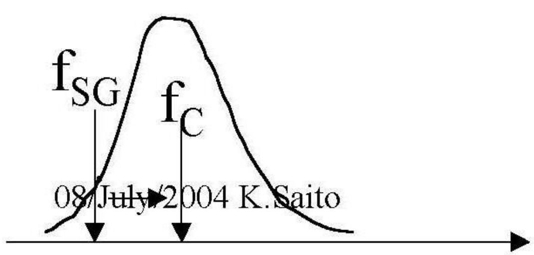
$P_{IN} = c_{in} \cdot p_{in}$

$P_R = c_r \cdot p_r$

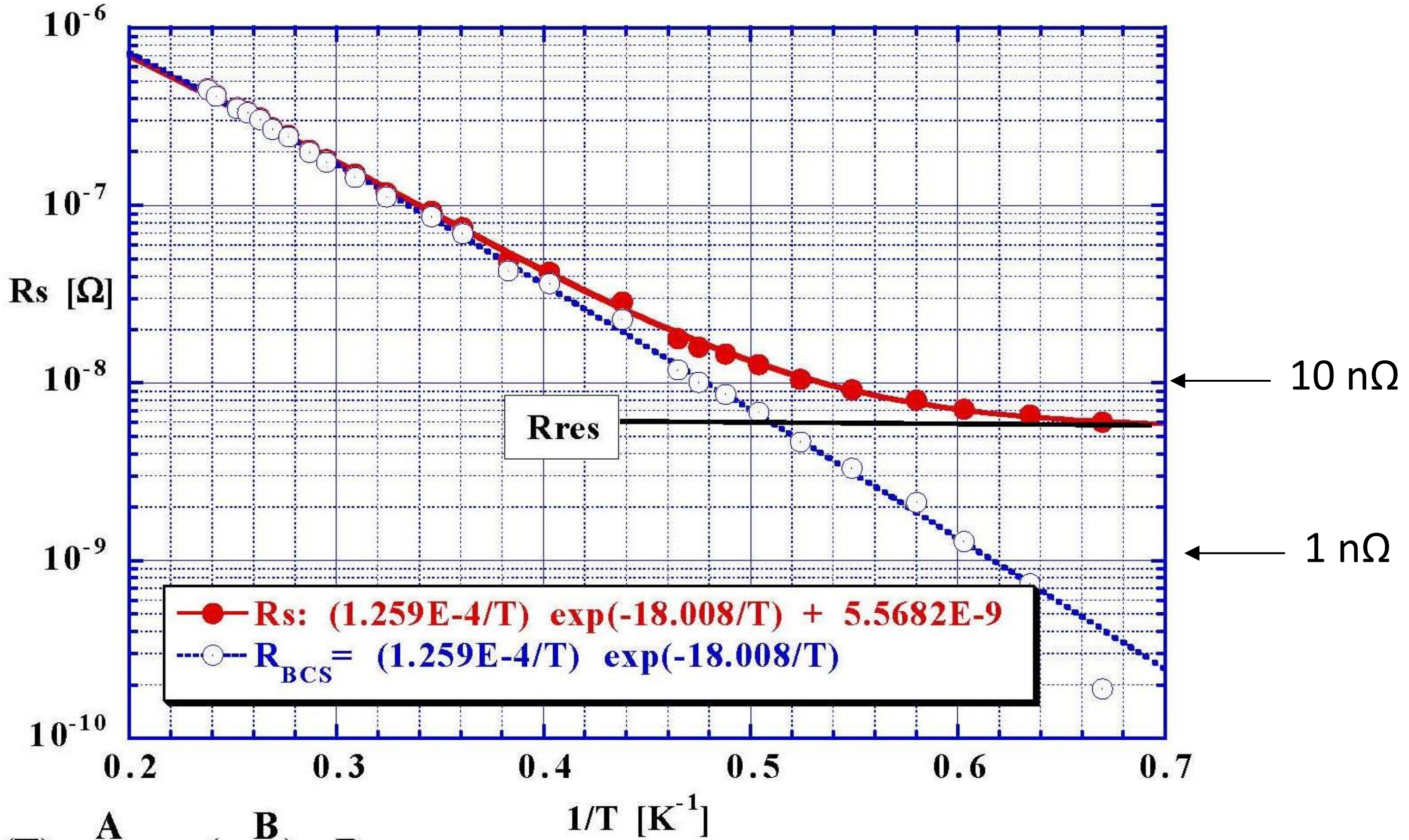
$P_T = c_t \cdot p_t$

Feed Back System





Measurement of Surface Resistance (Dependence on T)

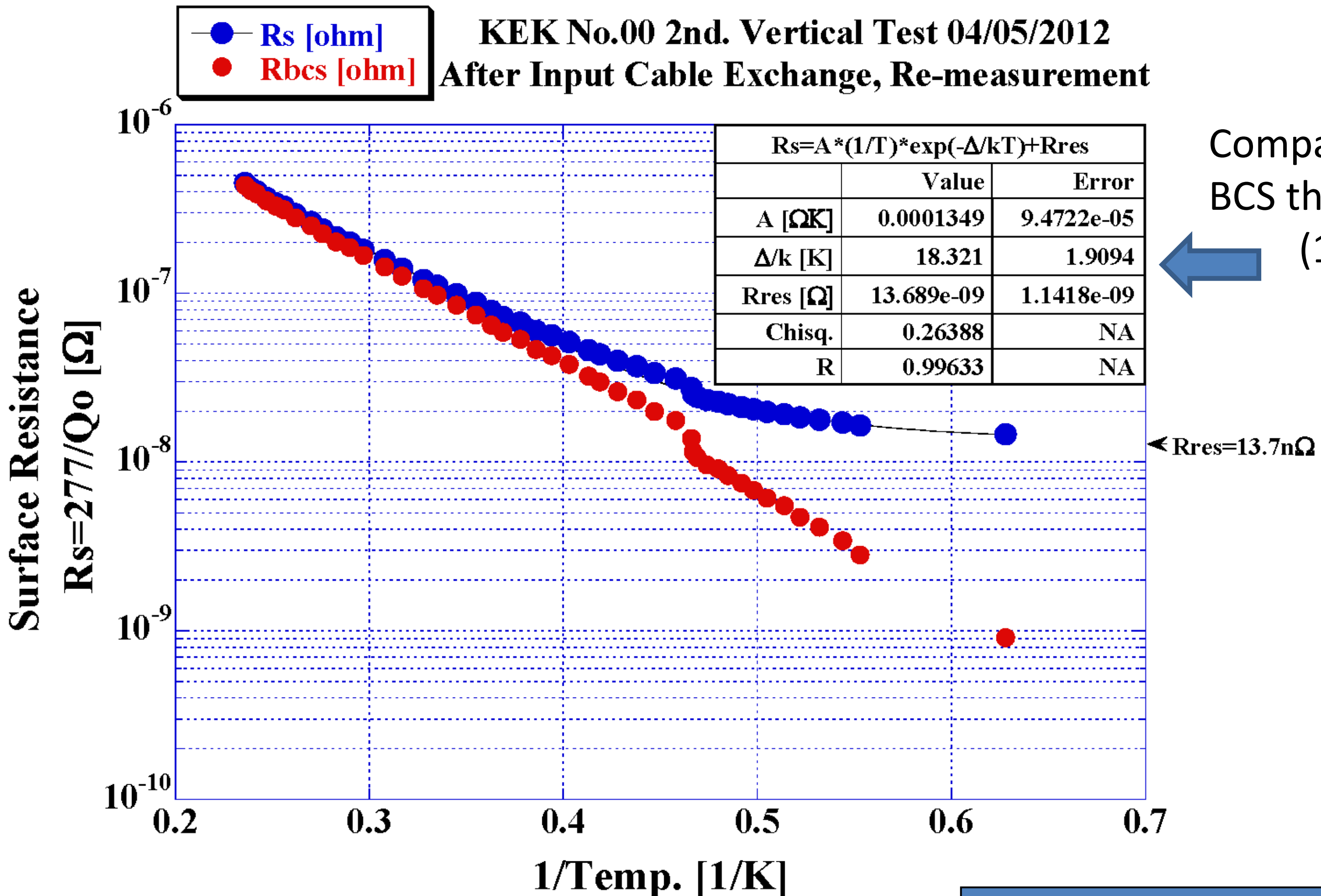


$$R_s - \text{fit} : R_s(T) = \frac{A}{T} \cdot \exp(-\frac{B}{T}) + R_{res}$$

$$B = \frac{\Delta}{k_B}$$ = 17.67 (BCS theory)

Rs = Γ/ Q0 is plotted

Measurement of Surface Resistance (Dependence on T)

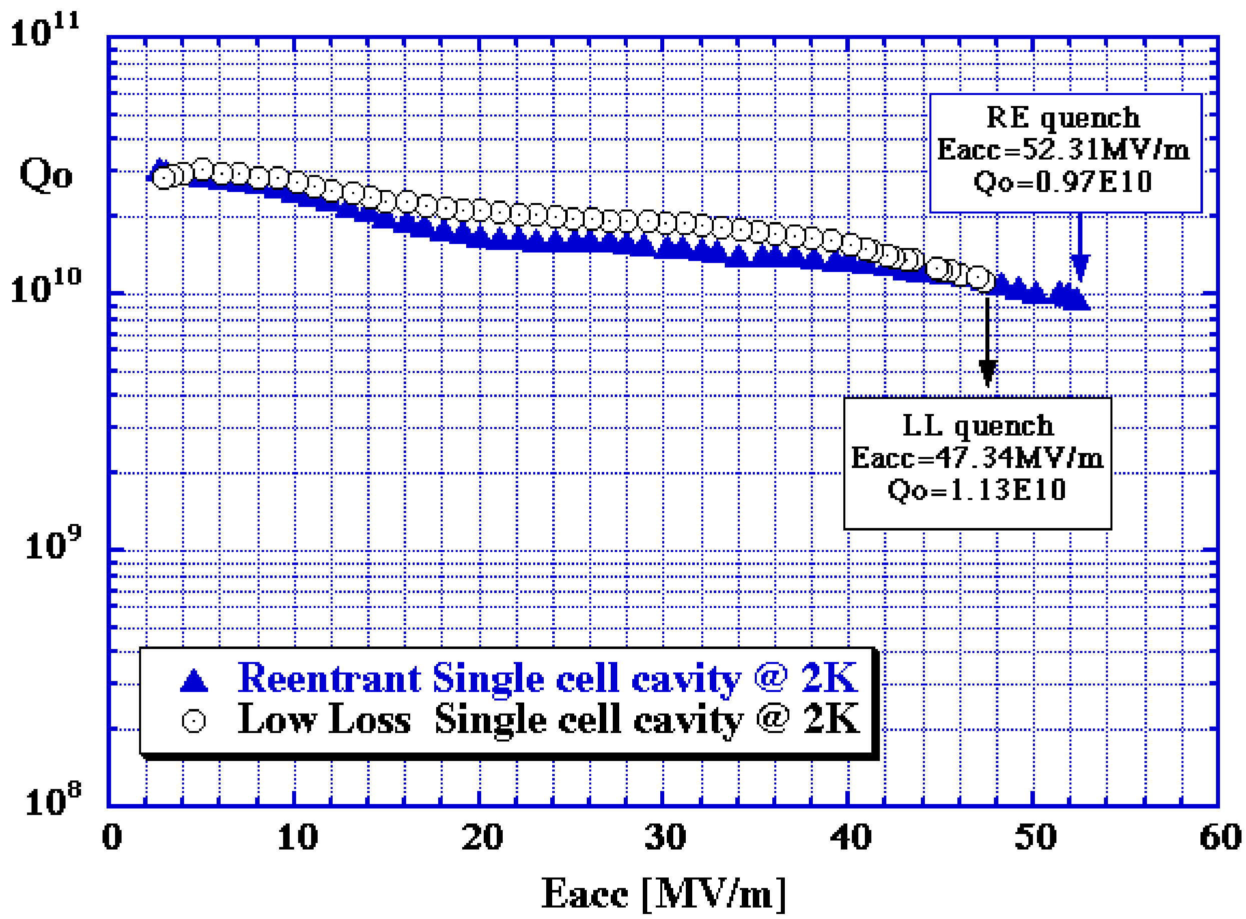


Compare with BCS theory (17.67)

Rs = Γ/ Q0 is plotted

Qo vs Eacc

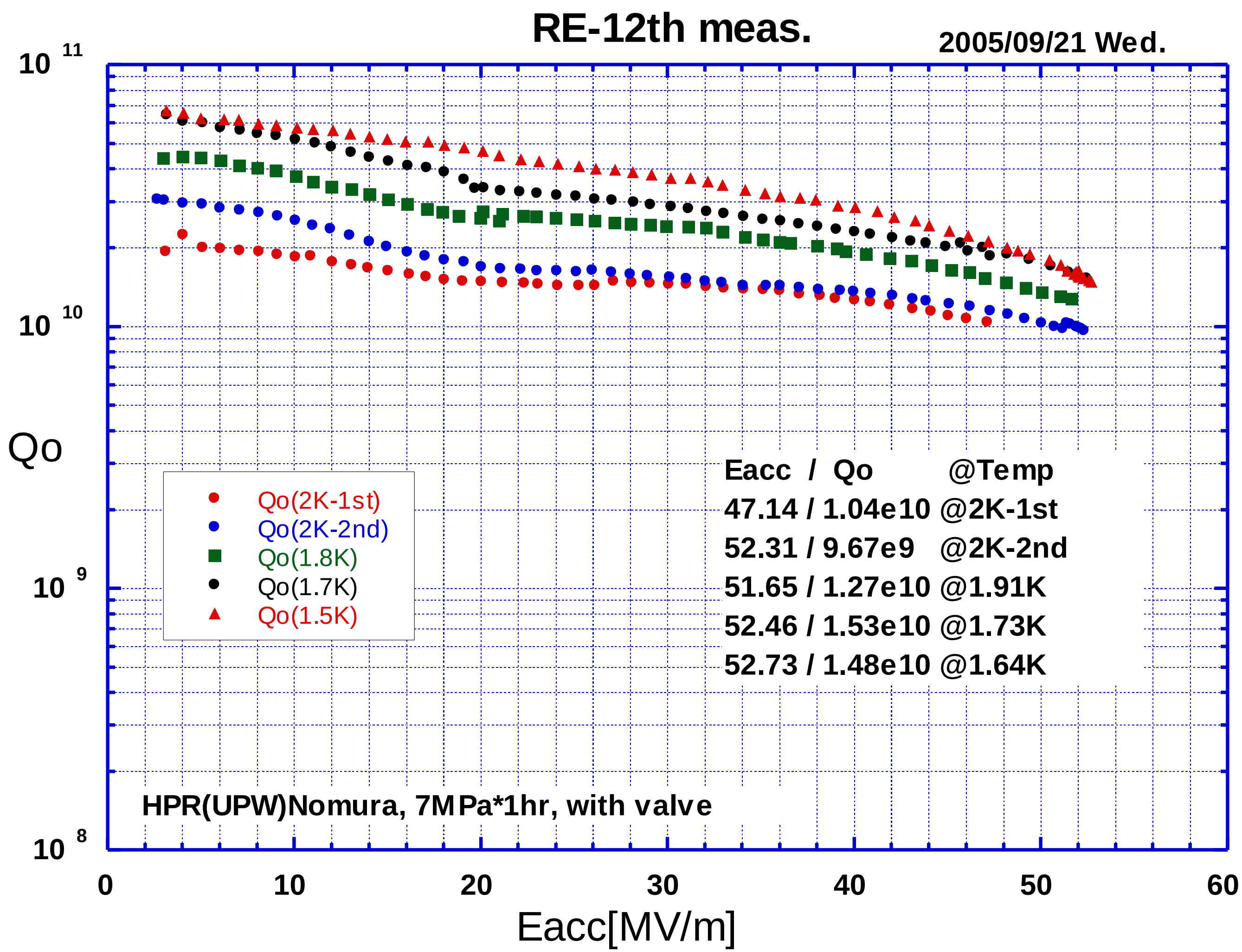
Eacc > 45 MV/m with new-shape at KEK



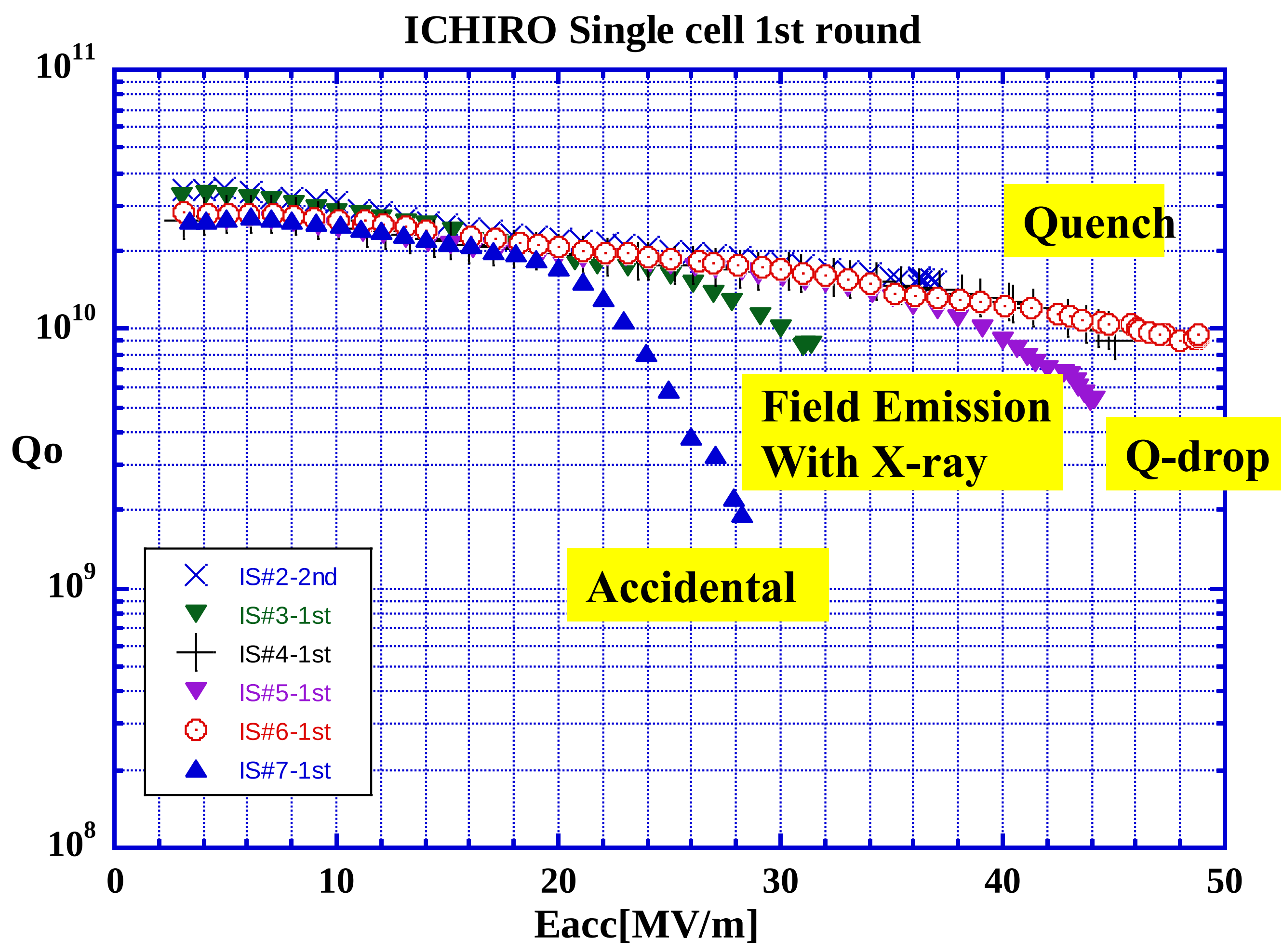
Eacc = Z sqrt(Qt･Pt) , Q0 = Qt ･ Pt / Ploss

Q0 vs Eacc（T dependence）

Temperature dependence (RE cavity)

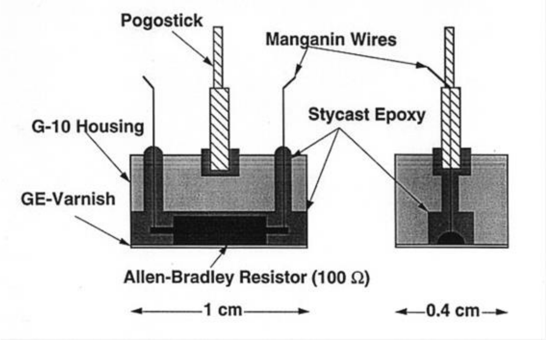


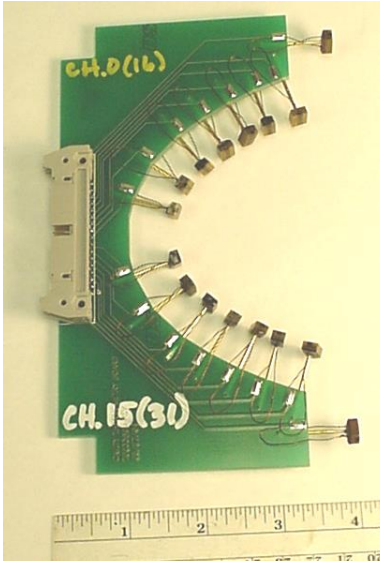
Q0 vs Eacc（Limitation）

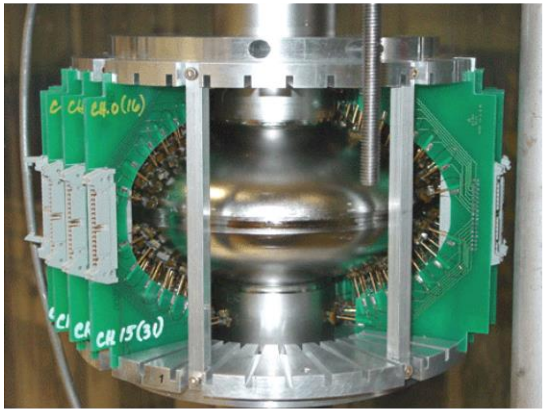


T-Mapping (1)

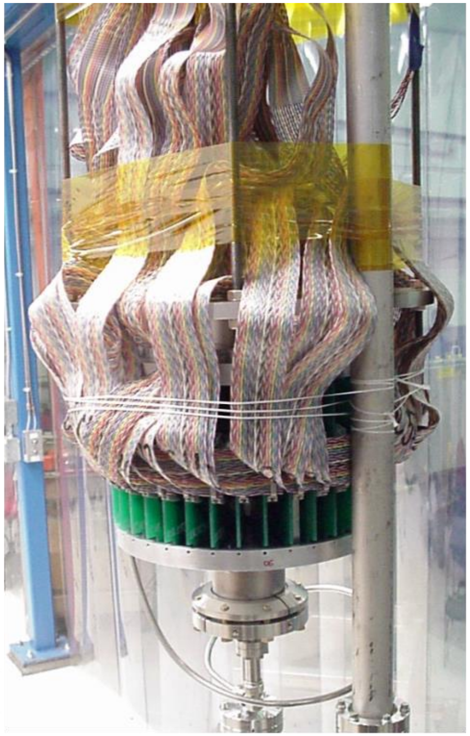
T-mapping system: ~600 Allen-Bradley C-resistors



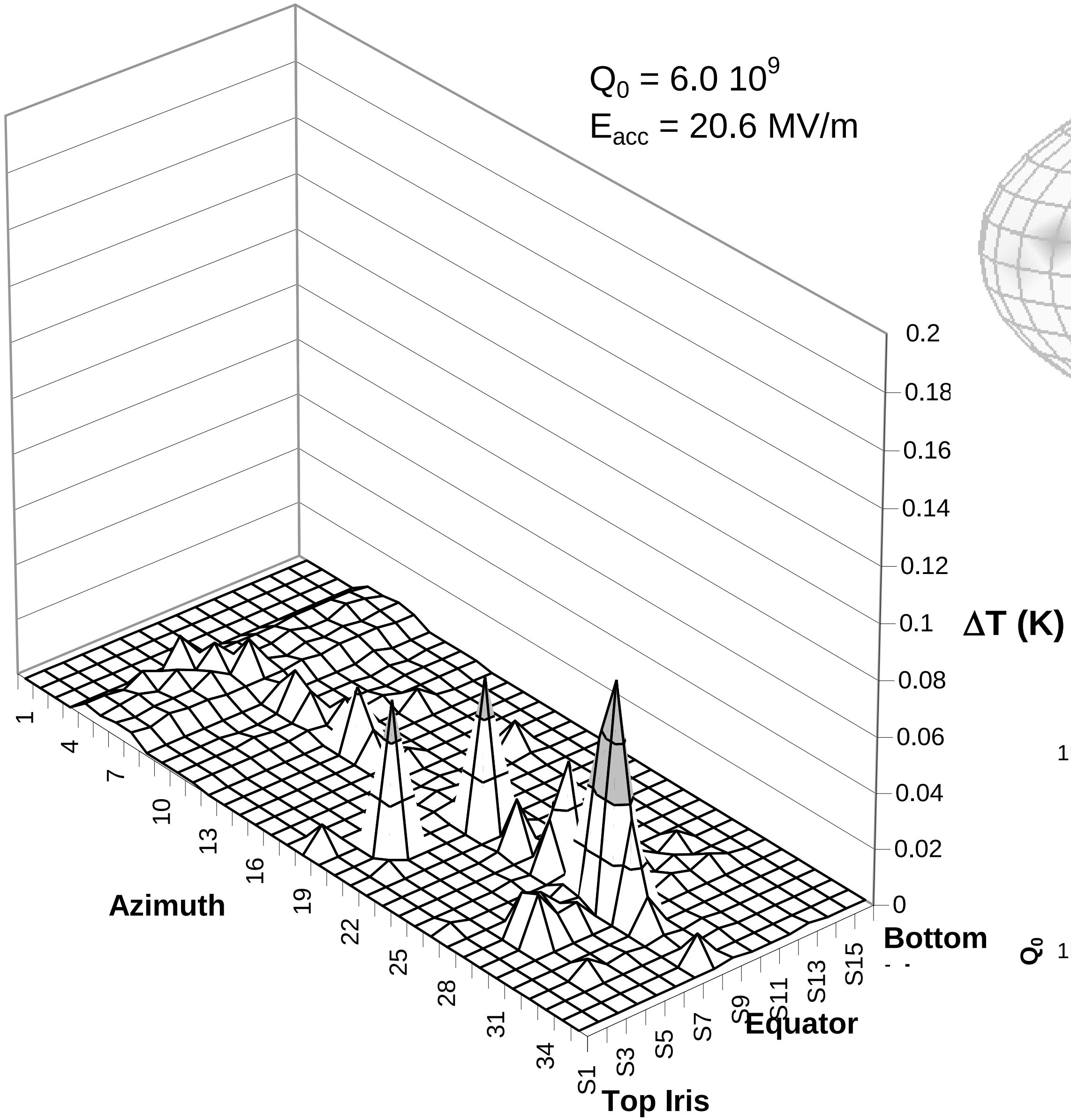




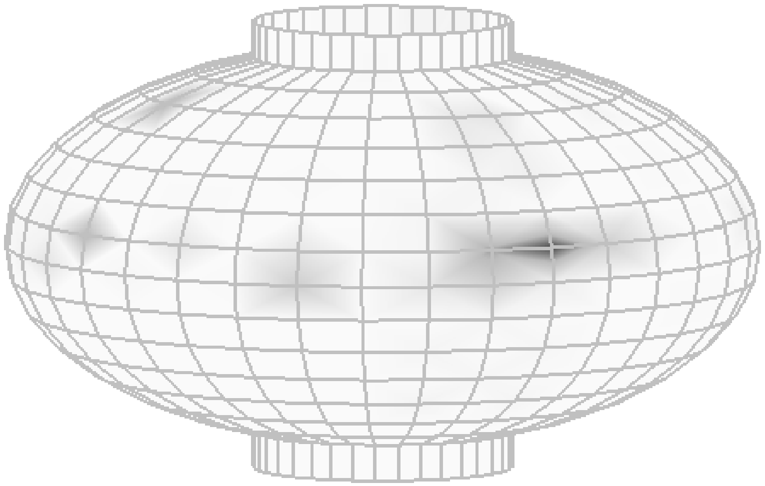
a)

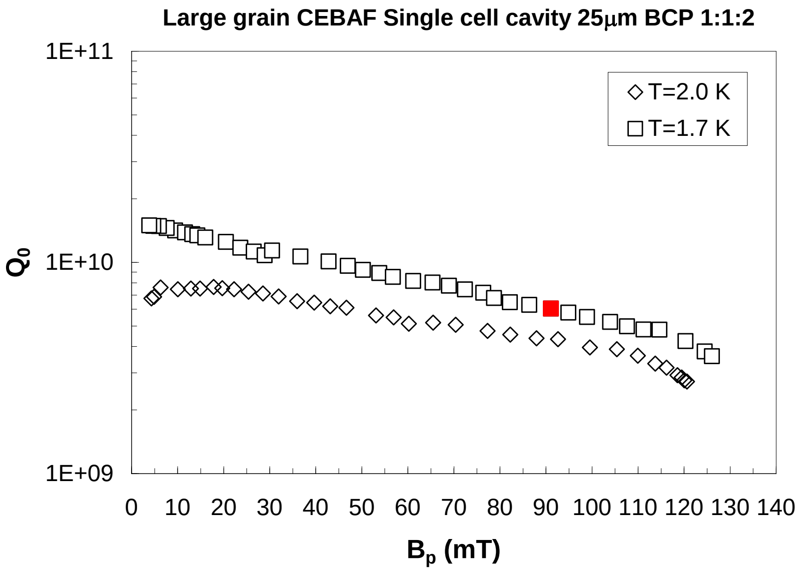


b
)



Q$_0$ = 6.0 10^9
E$_{acc}$ = 20.6 MV/m
ΔT (K)
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Azimuth
1
4
7
10
13
16
19
22
25
28
31
34
S1
S3
S5
S7
S9
S11
S13
S15
Top Iris
Equator
Bottom



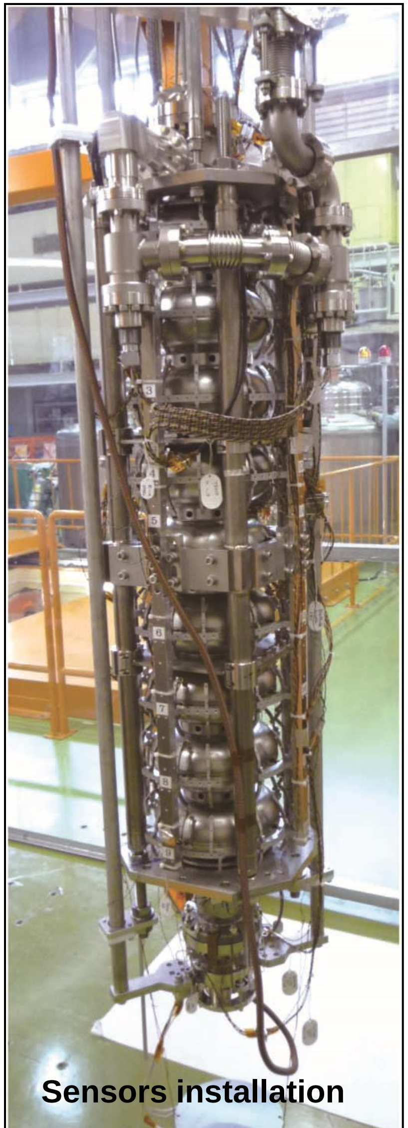


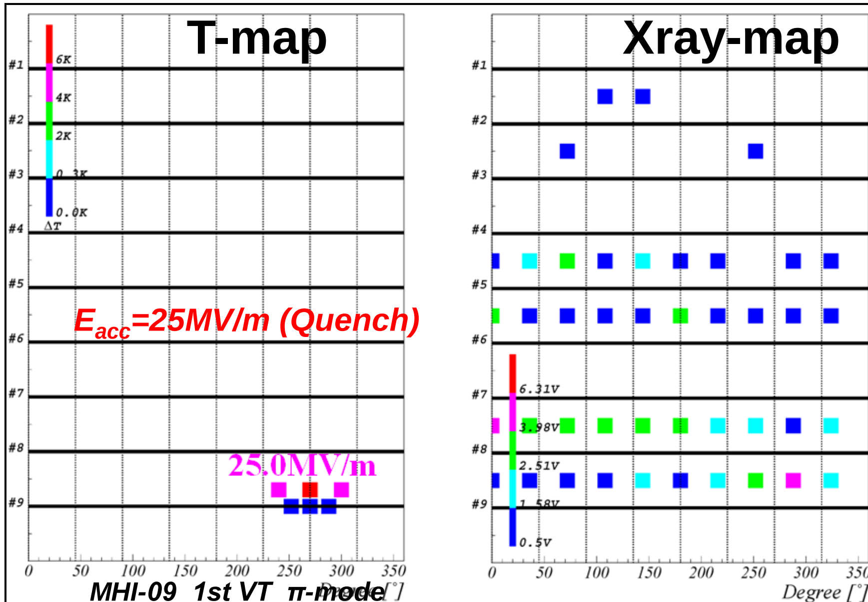
Large grain CEBAF Single cell cavity 25μm BCP 1:1:2
T=2.0 K
T=1.7 K
Q$_0$
1E+11
1E+10
1E+09
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
B$_p$ (mT)

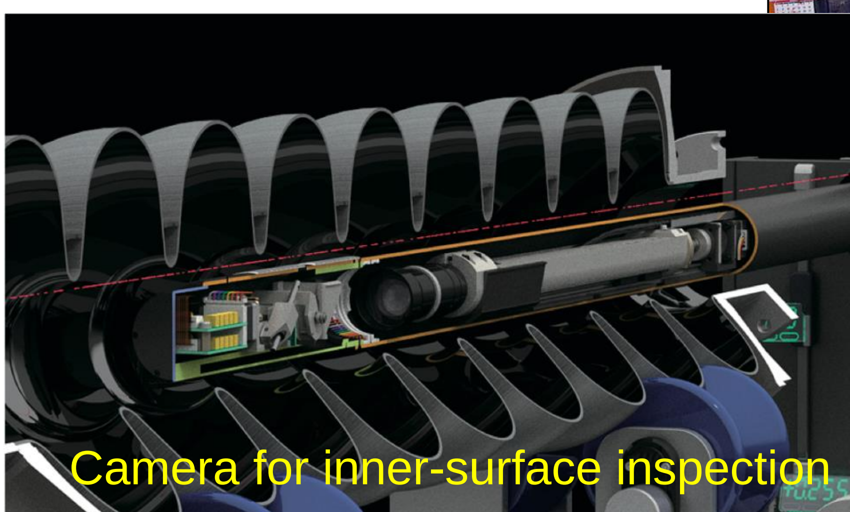
Acceptance test of cavity

Temperature and X-ray maps of cavity are obtained during each test.

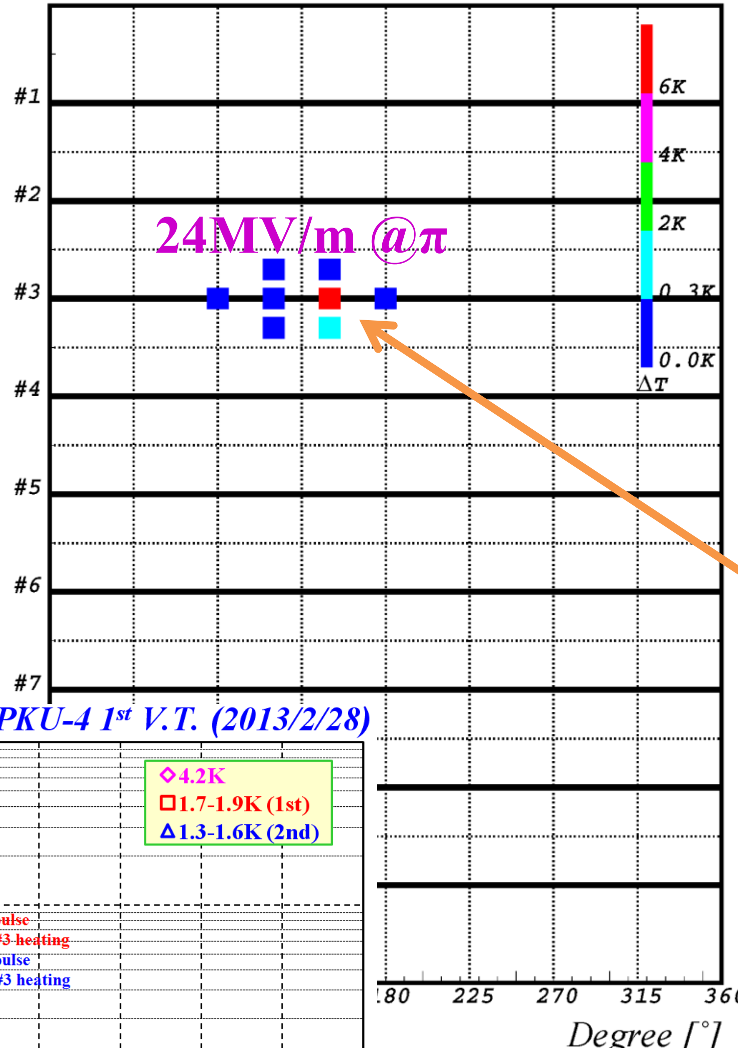
T-map & Xray-map, together with pass-band mode measurement, location of quench is identified. Inspection camera visualize what's happen inside.

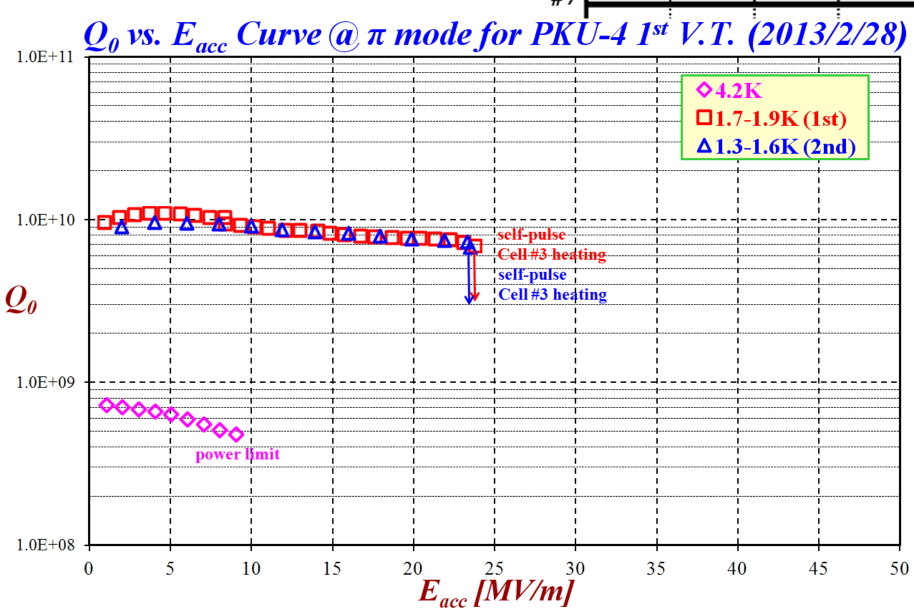


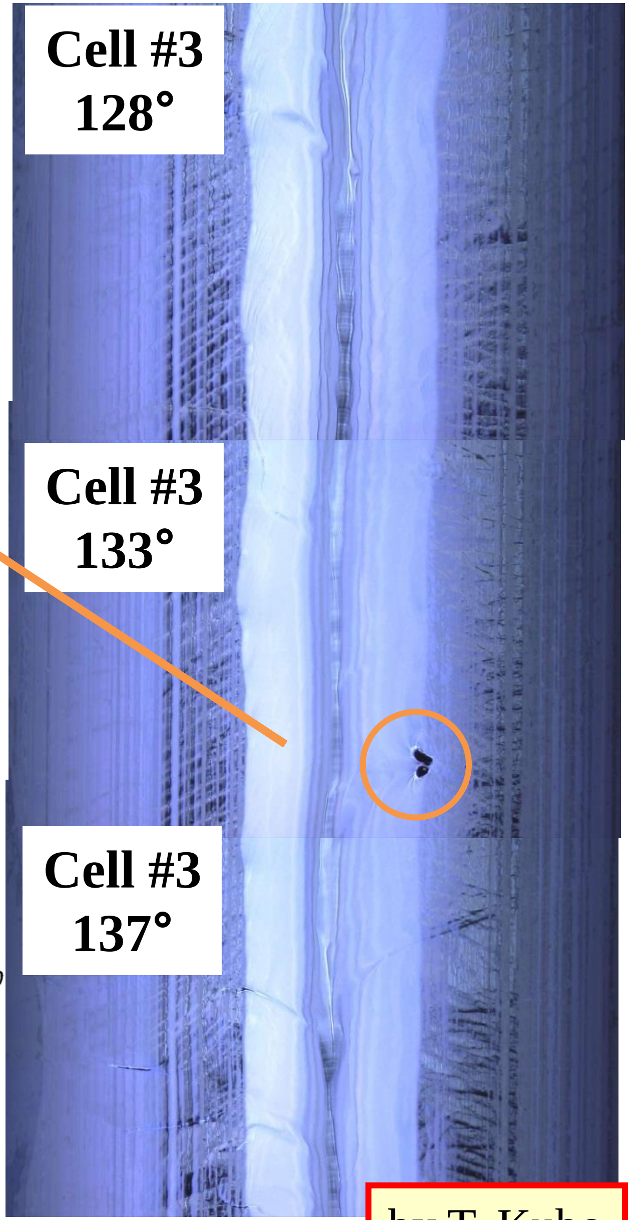




PKU-04 cavity

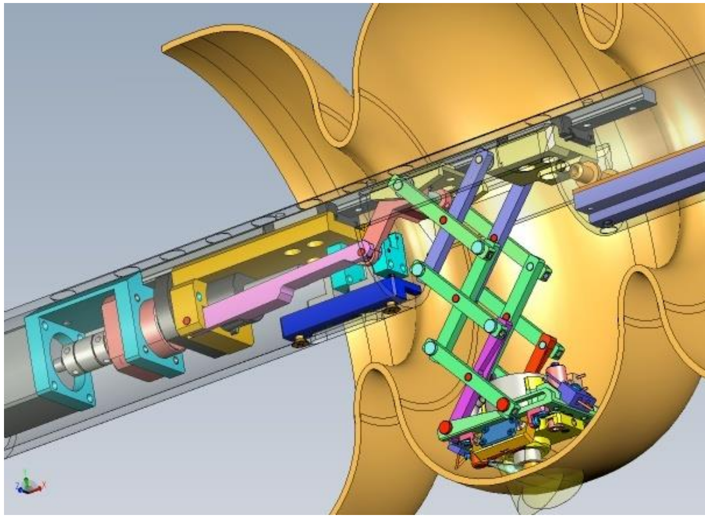


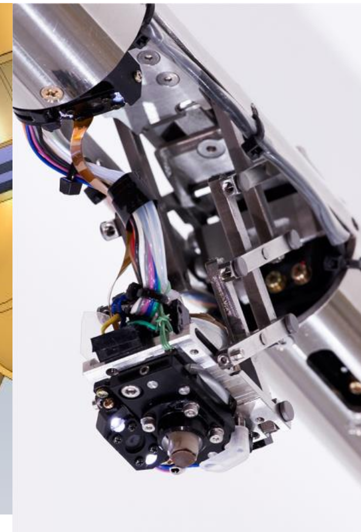




by T. Kubo

Local grinding at KEK



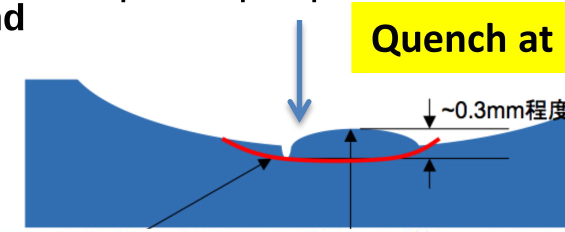


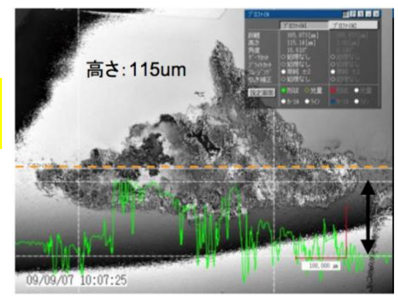
Grinding only for pit, without touching other surface

diamond powder compound with water in between were used.

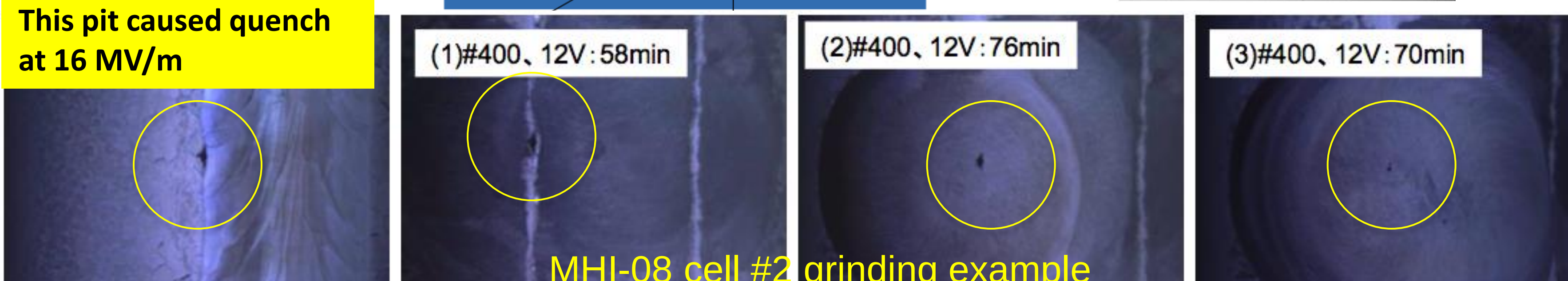
~115µm depth pit in MHI-08 cavity

Quench at 16 MV/m





This pit caused quench at 16 MV/m



MHI-08 cell #2 grinding example

Q-drop and In-situ Baking

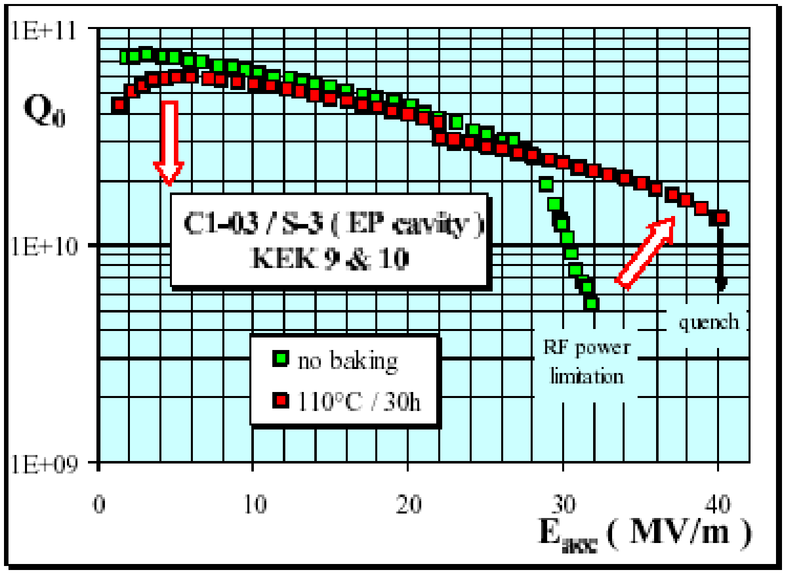
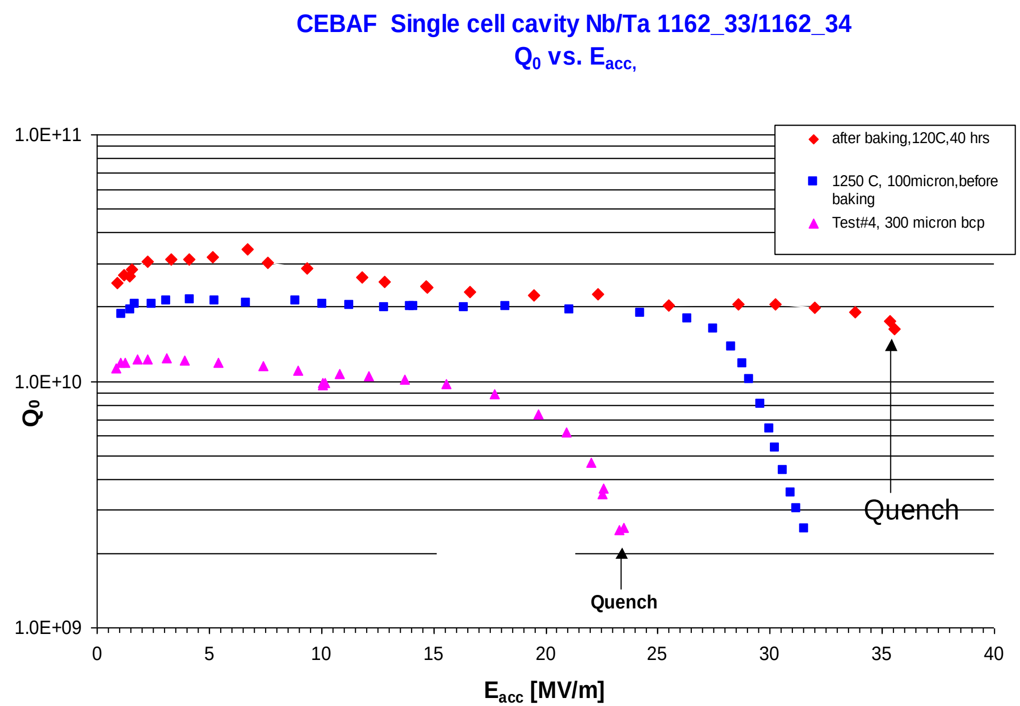


Figure 4: Baking effect on C1-03 Saclay cavity (electropolished and tested at KEK) [9].

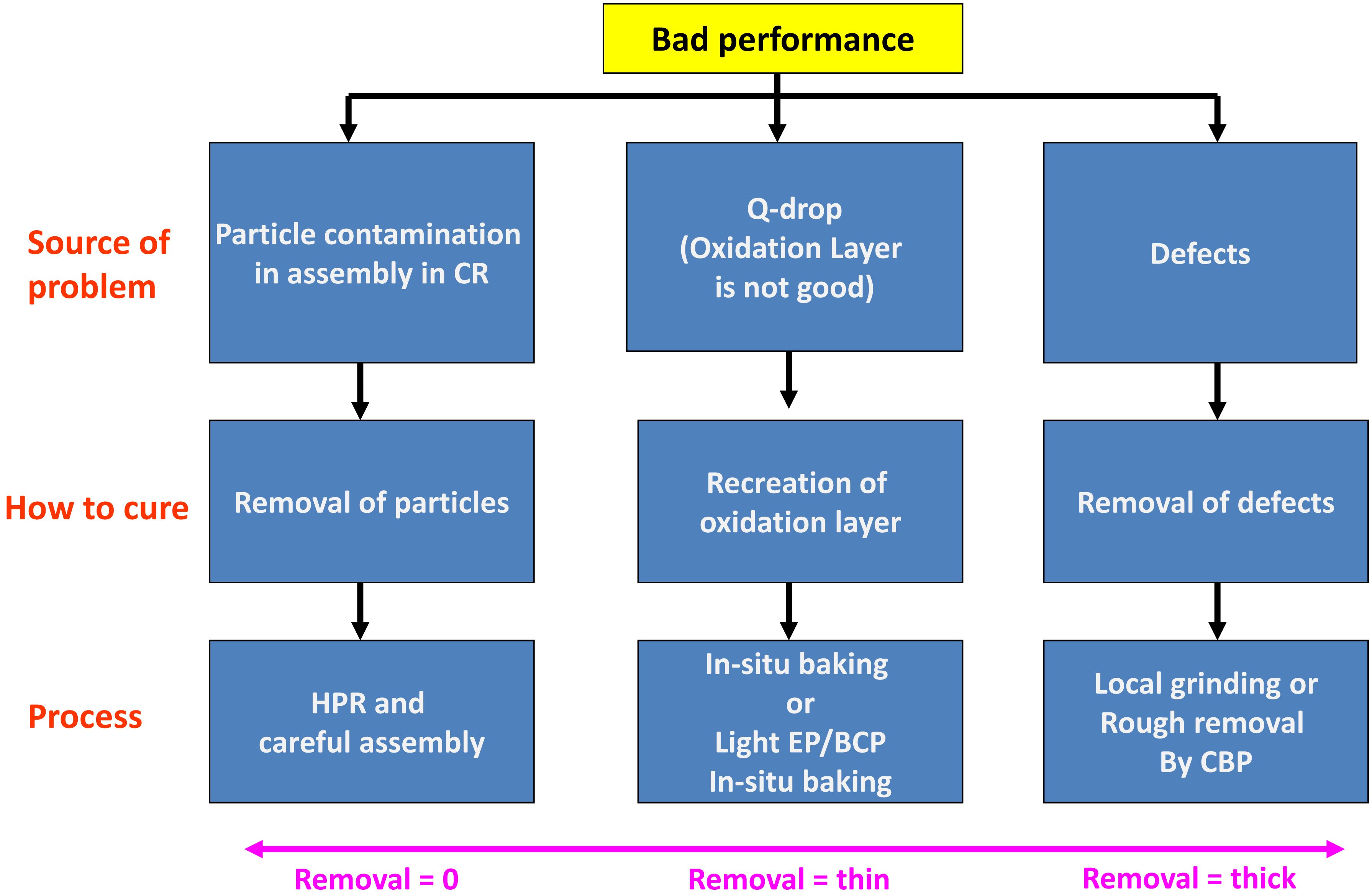
[B.Visentin,SRF2003]

electropolished

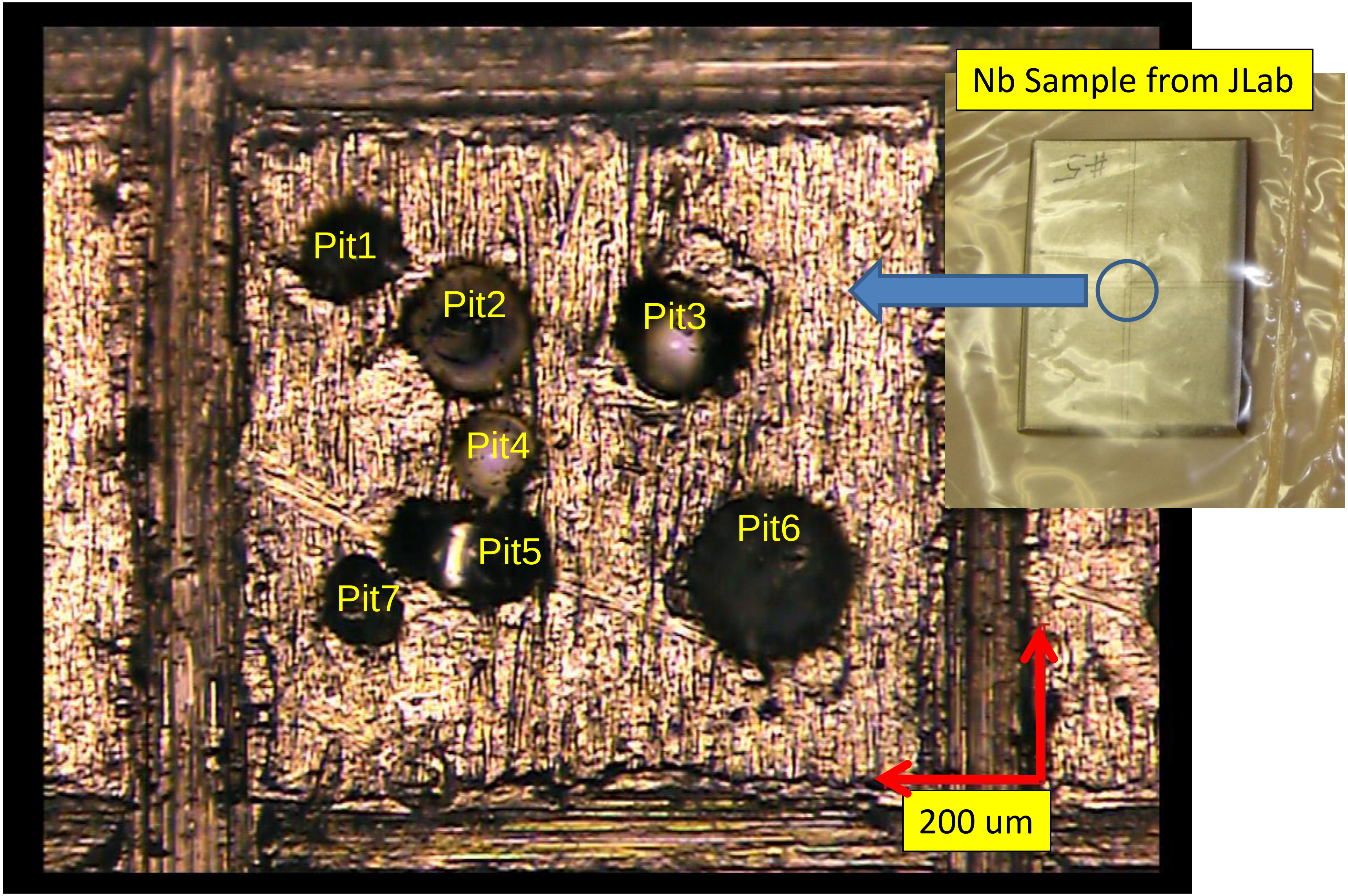
Buffered Chemical Polished(1:1:1)



How to cure bad cavities (1/2)

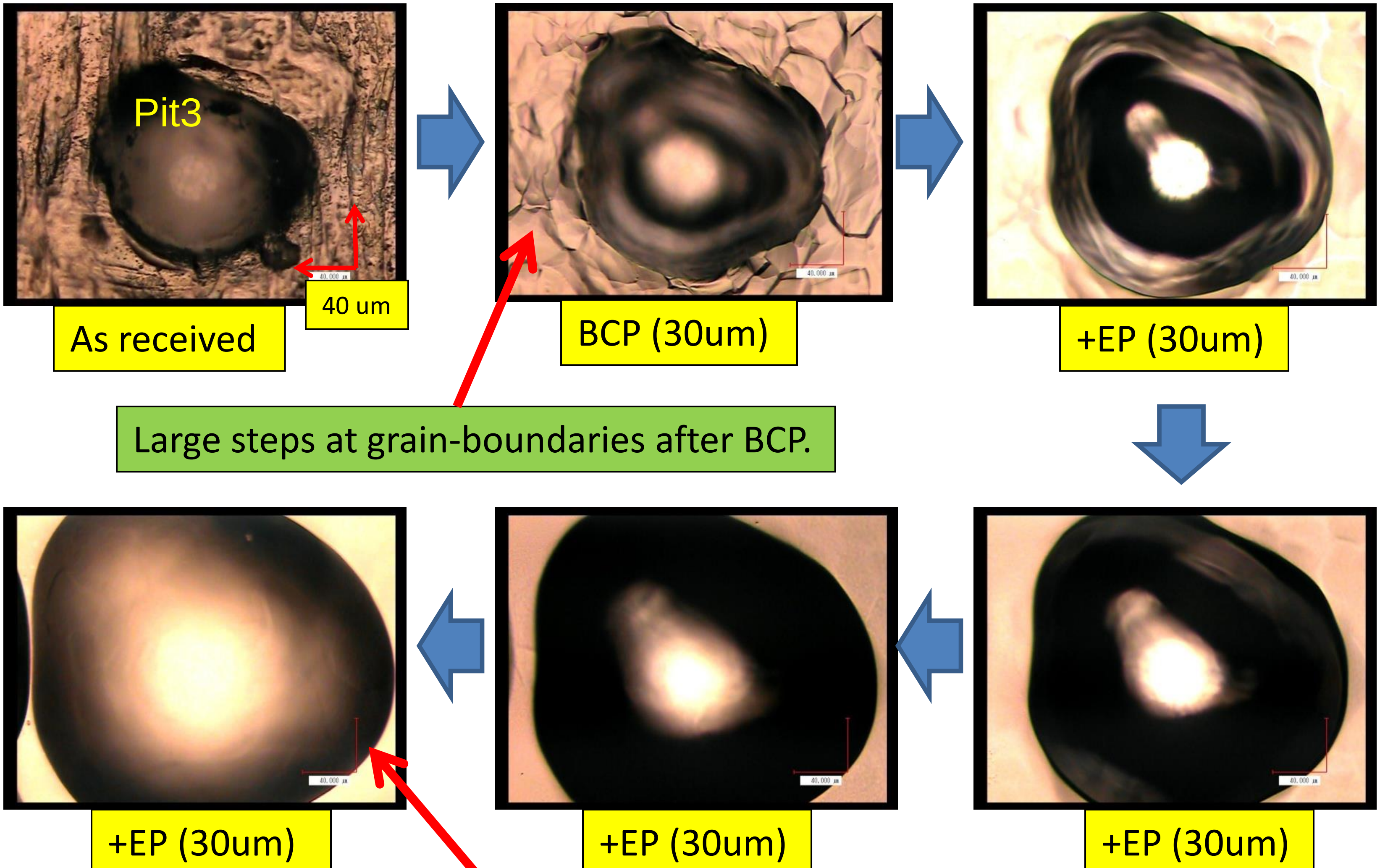


Nb sample with artificial pits from JLab



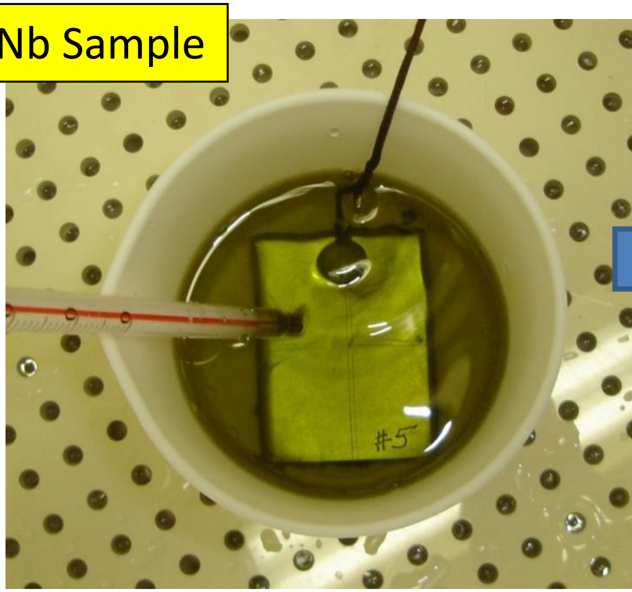
On interested surface of both samples, there are marked lines for purpose of location referencing.

JLab Nb sample with artificial pits

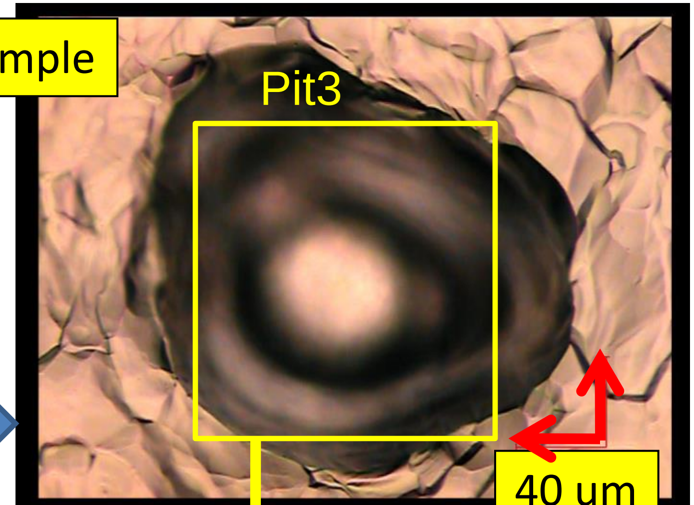


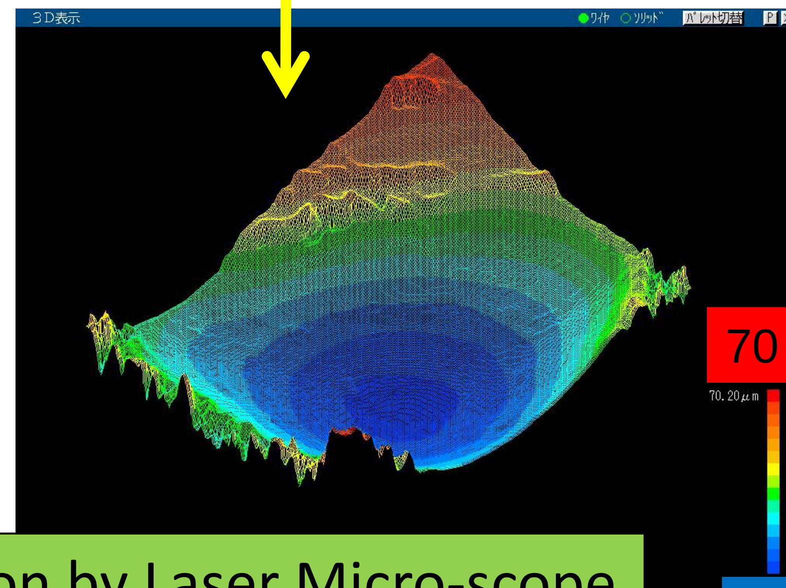
After BCP(30um)+EP(120um), still the edge of pit is sharp!

Jlab Nb sample with artificial pits



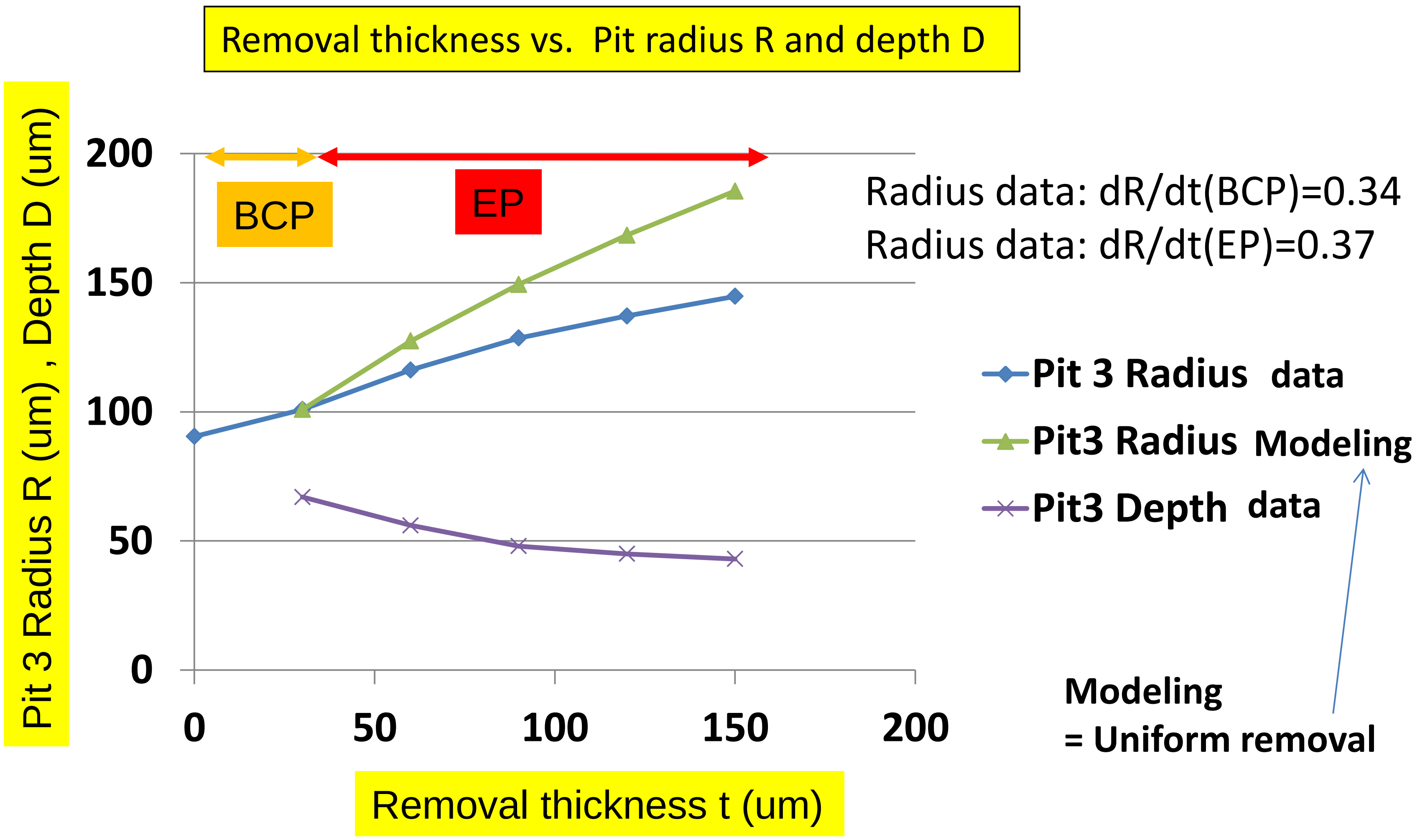
BCP (30um) at STF/KEK





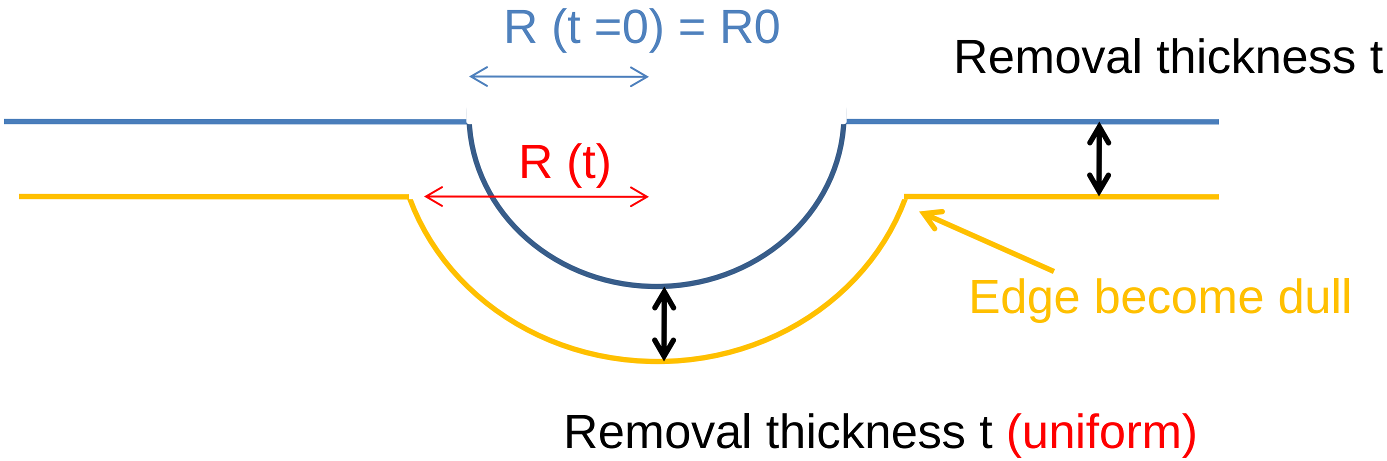
Observation by Laser Micro-scope

JLab Nb sample with artificial pits



Jlab Nb sample-1 with artificial pits

Radius for Uniform Removal Modeling

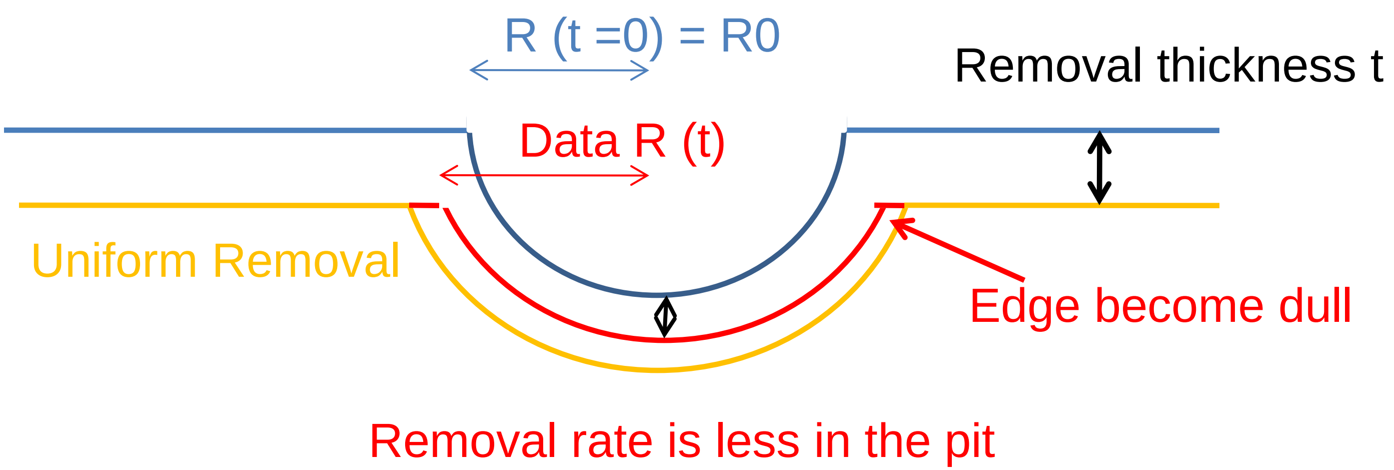


$$R(t) = SQRT\ (\ R0 \times R0 + 2 \times R0 \times t\ )$$

In this modeling, the depth of pit is constant / no change.

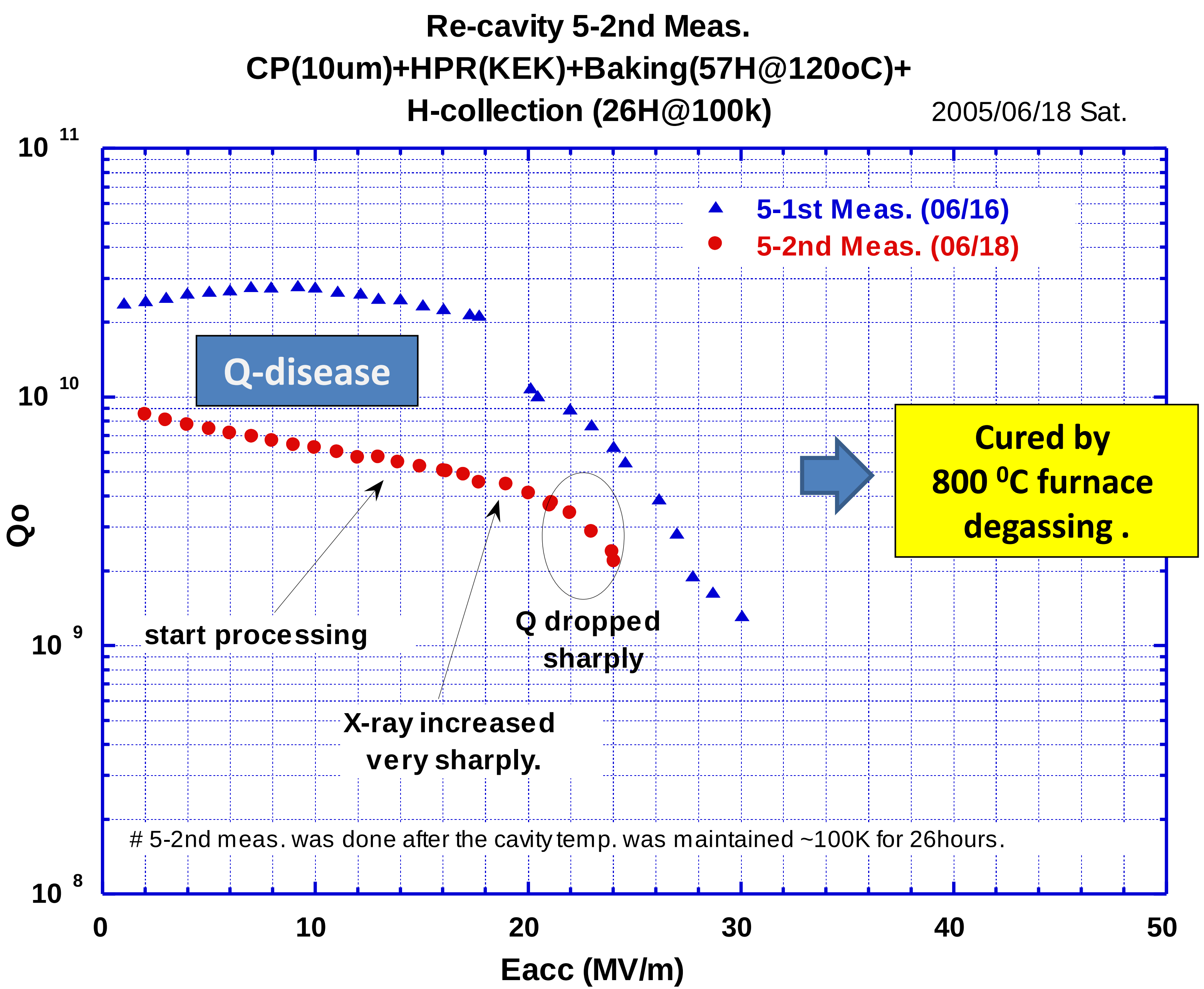
Jlab Nb sample with artificial pits

Measured Radius and Depth

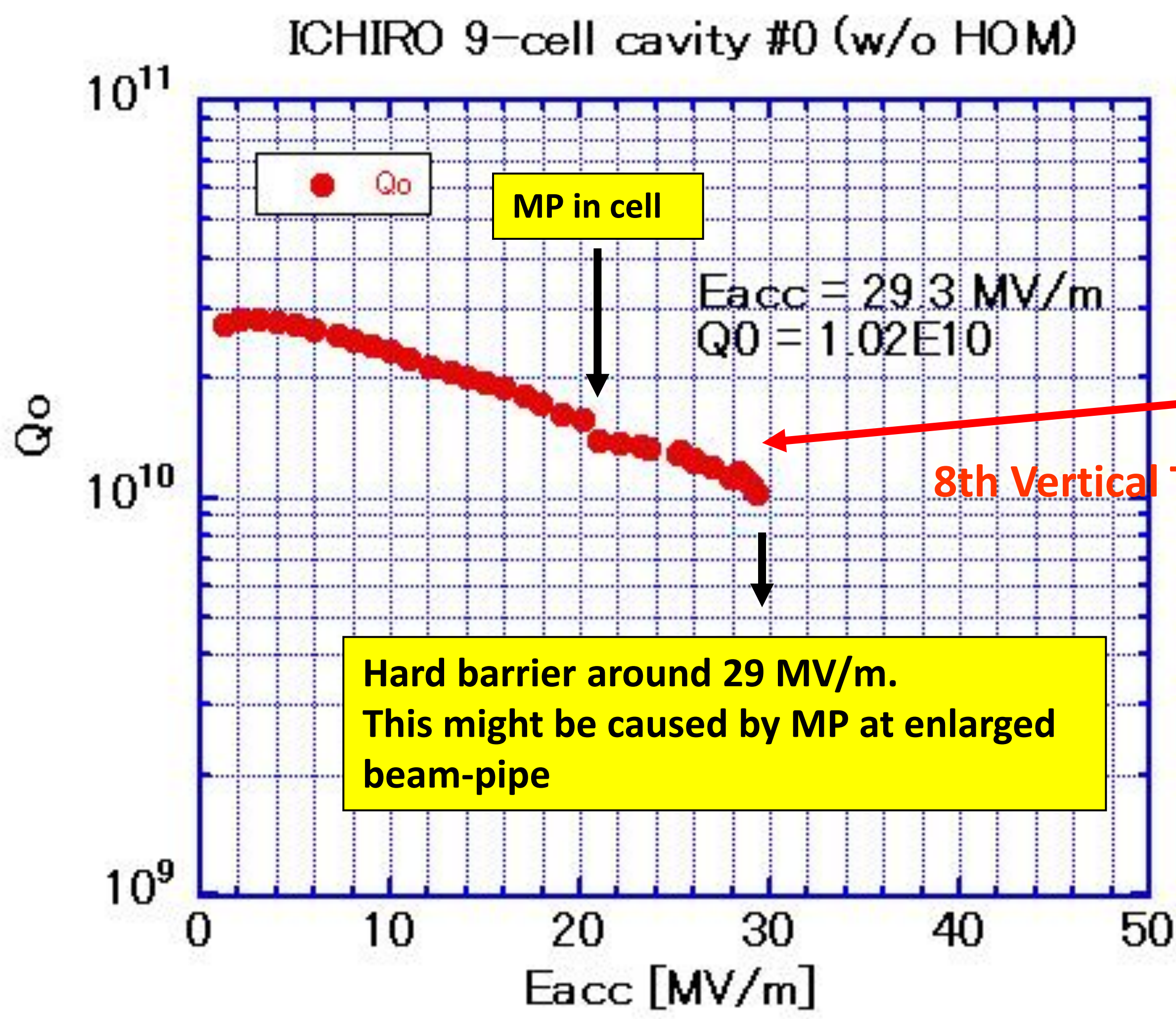


Radius increases slowly and the depth becomes shallower.

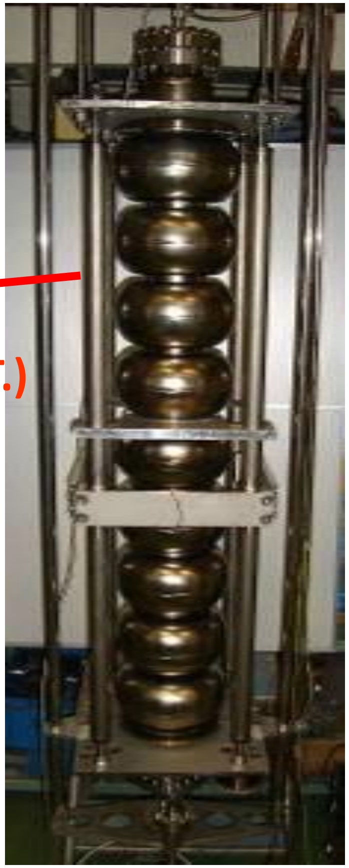
However, EP seems not to round the edge of pit very effectively / selectively.
EP is not all mighty. All pits should be removed before EP process mechanically.


Re-cavity 5-2nd Meas.
CP(10um)+HPR(KEK)+Baking(57H@120oC)+
H-collection (26H@100k)
2005/06/18 Sat.
5-1st Meas. (06/16)
5-2nd Meas. (06/18)
Q-disease
Cured by
800 ^{0}C furnace
degassing .
start processing
Q dropped
sharply
X-ray increased
very sharply.
5-2nd meas. was done after the cavity temp. was maintained ~100K for 26hours.
Qo
Eacc (MV/m)
10^{11}
10^{10}
10^{9}
10^{8}
0
10
20
30
40
50

ICHIRO 9-cell 1st cavity (#0) w/o HOM



ICHIRO 9-cell 1st Cavity #0 w/o HOM

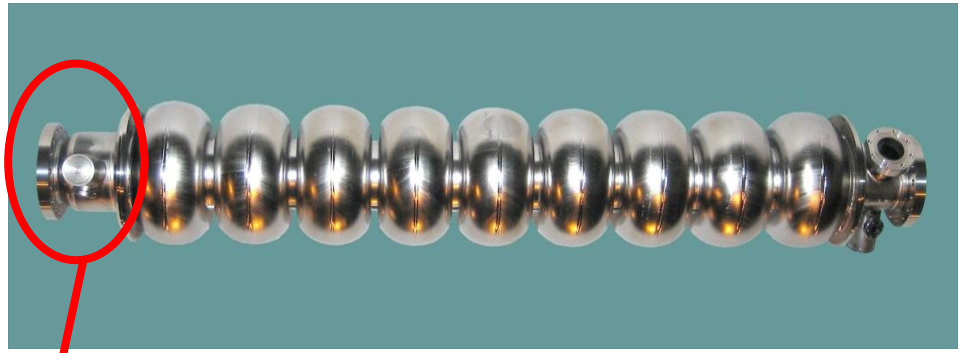


8th Vertical Test (V.T.)

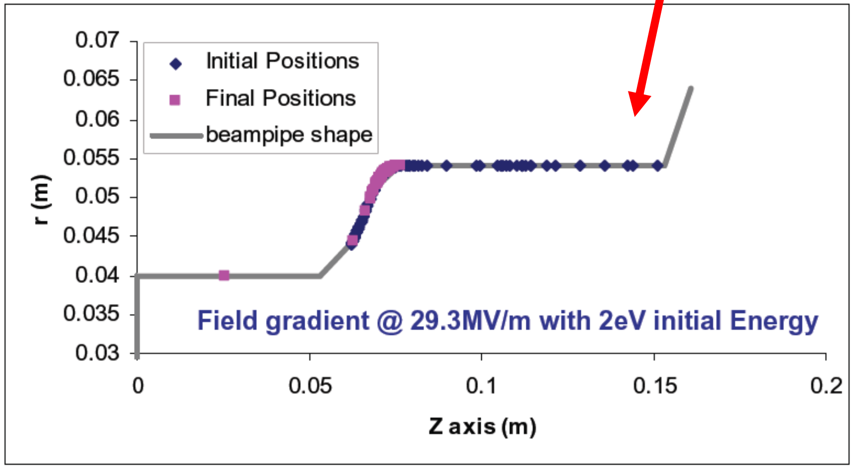
No Q-disease was found.

Multi-pacting simulations by L. Ge at SLAC

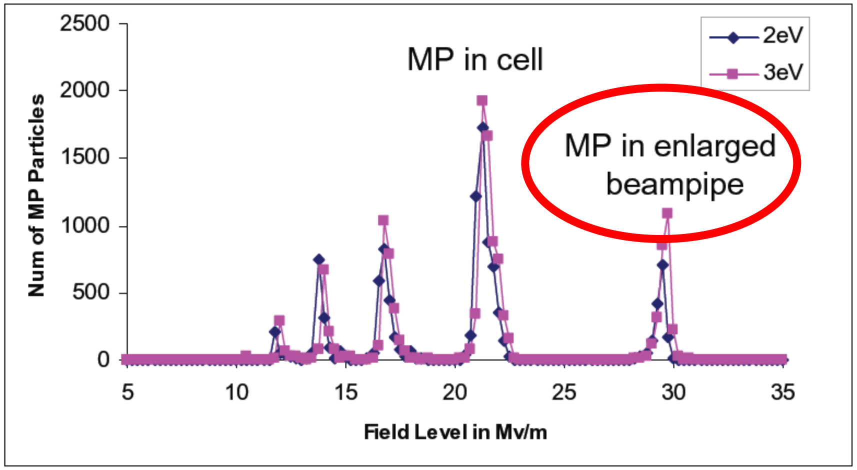
Multi-pacting points were found at the taper part of enlarged beam-pipe from simulation.



- MP Particles Distribution (surviving 50 impacts)



- MP in end-group of ICHIRO Cavity with enlarged beam-pipe



How to cure bad cavities (2/2)