Lecture B2:
Superconductive RF

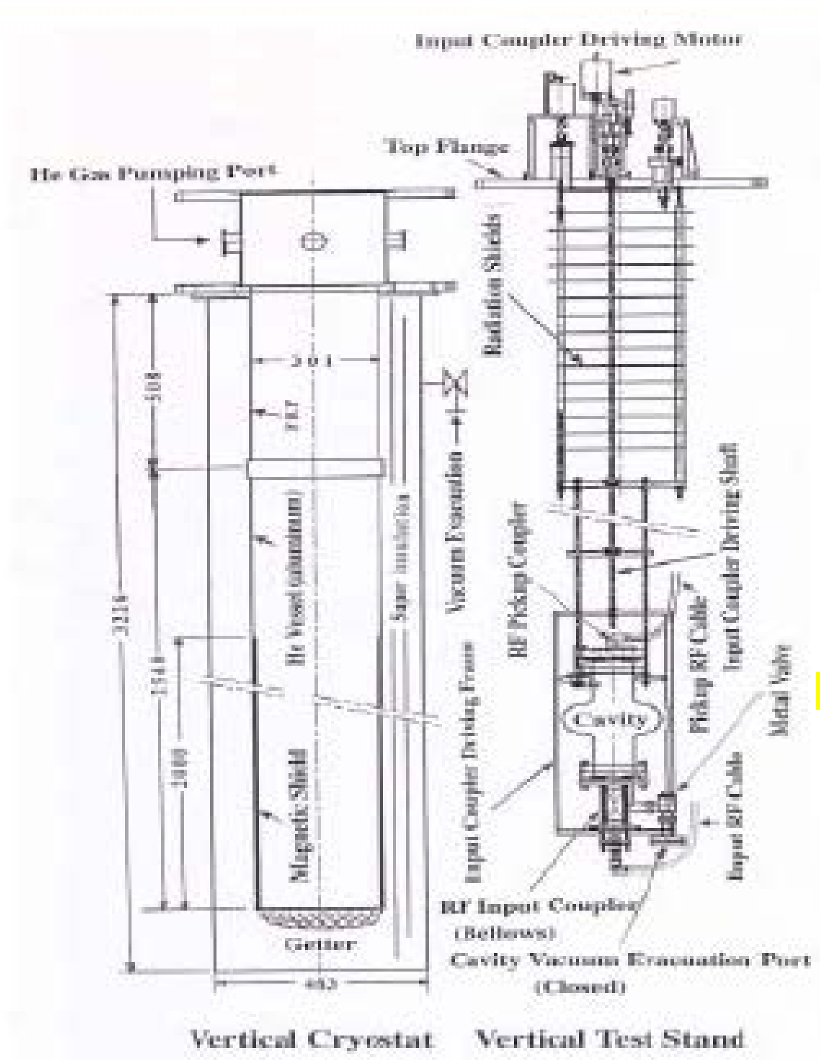
RF Test of Cavity

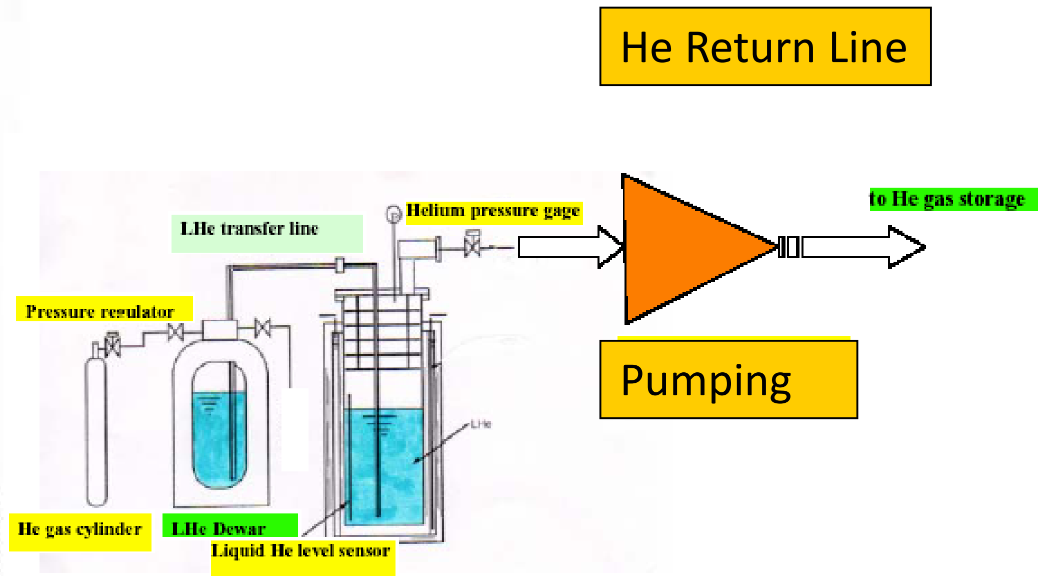
T. Saeki (KEK)

LC school 2015

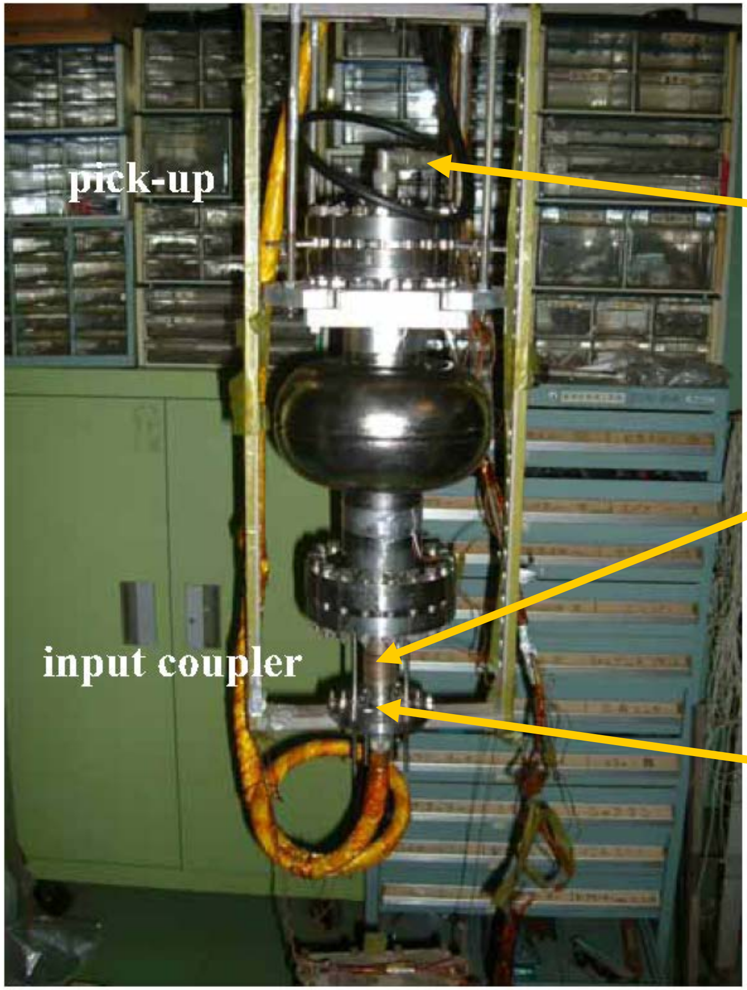
27 Oct. - 6 Nov. 2015, Whistler, Canada

RF Test Cryostat (Vertical Test)





Cavity Preparation Stand

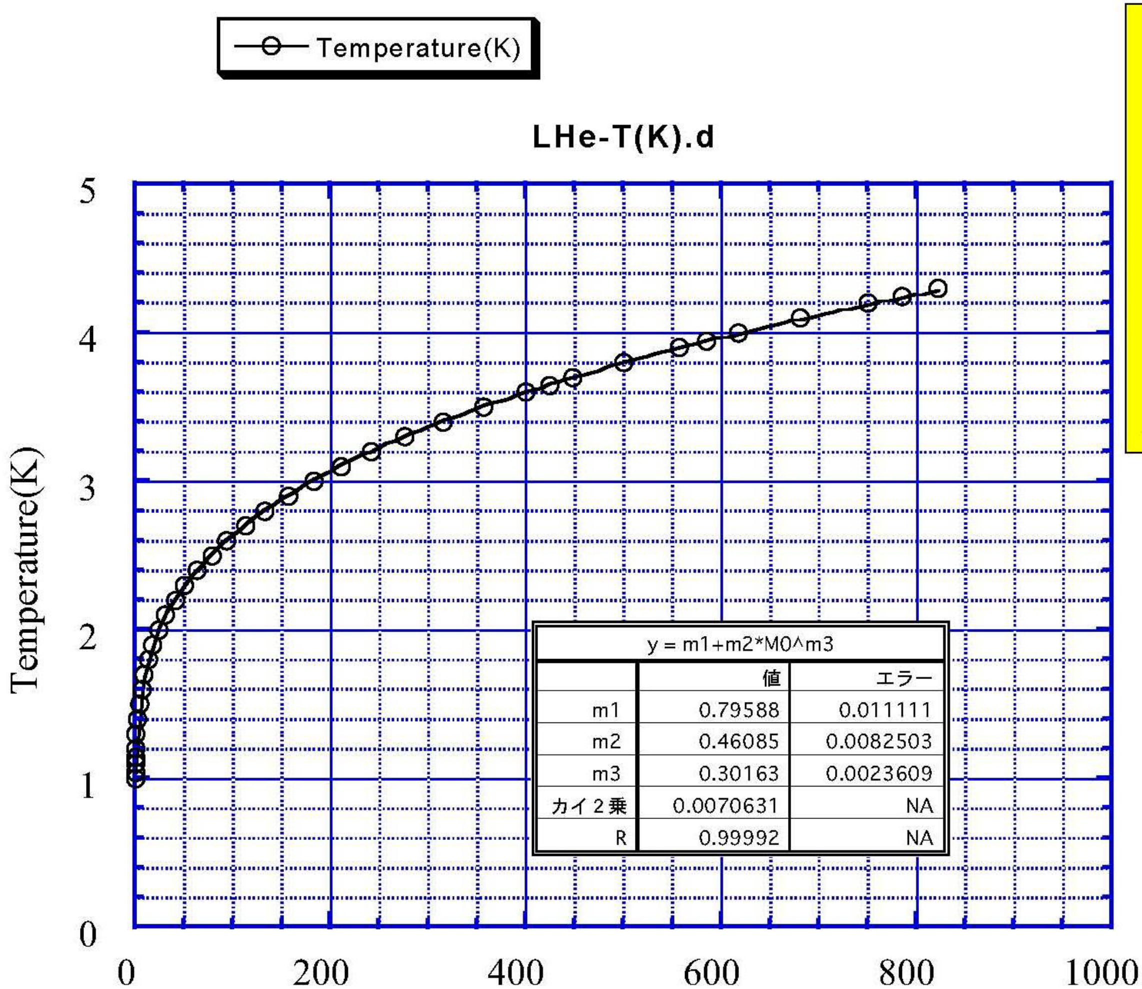


Pickup coupler

Input coupler

Metal valve for vacuum

Temperature of Liquid He (P vs. T)



He Gas Pressure [Torr]

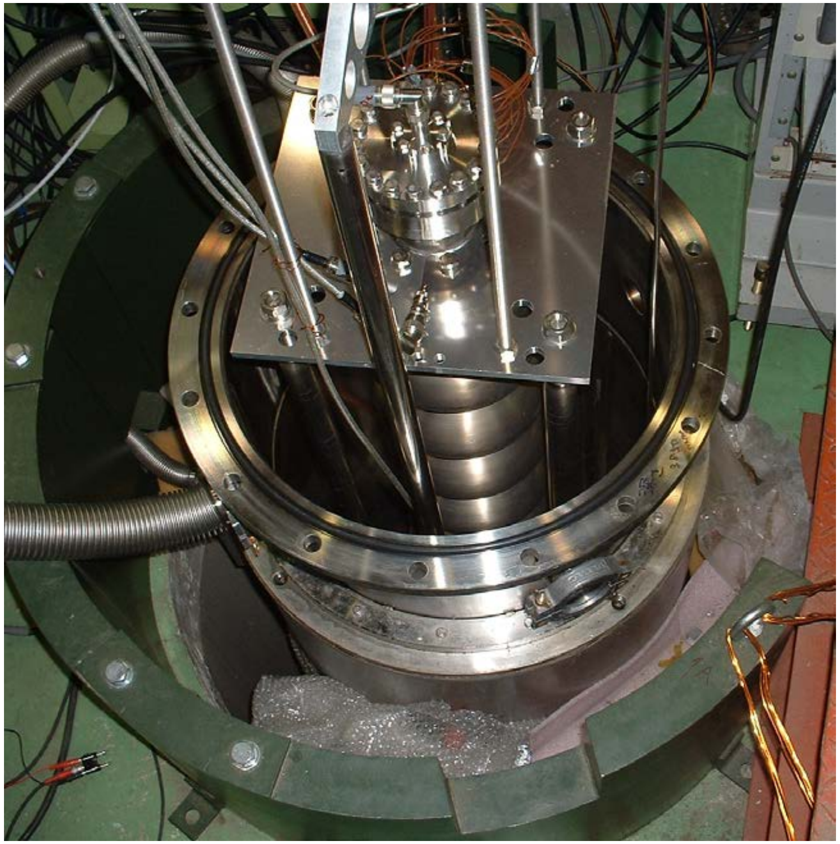
4.25 K = 760 Torr

λ-point :

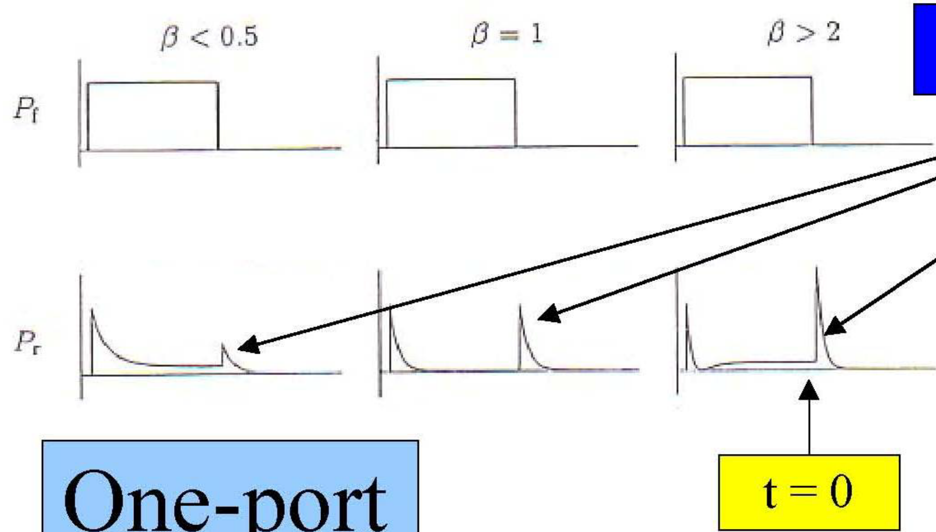
2.1773K = 38.41 Torr

2K = 23.77 Torr

Cryostat for Vertical Test



Theory of Measurement



Pulse method

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

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

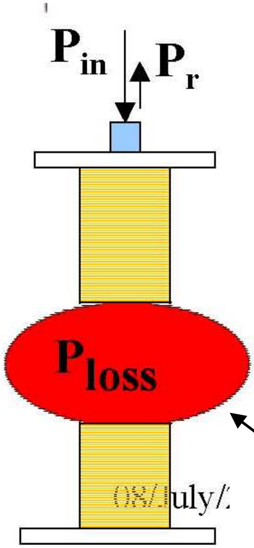
One-port

Measure the period during when P becomes half .

Decatime : $\tau_{1/2}$

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

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



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

Ploss = heat caused by RF field in the cavity.

One-Port Cavity

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

Ploss = consumption on cavity wall
Pe = Power that goes out from port when Pin=0

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

(for one port)
(When **P**in = 0)

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

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

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

Calculation Q_L, β_{in}

Calculation of Equivalent Circuit

The wave shape of Pr

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

(over > 1 / under < 1)

(When **P**in > 0)

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

(When **P**in = 0)

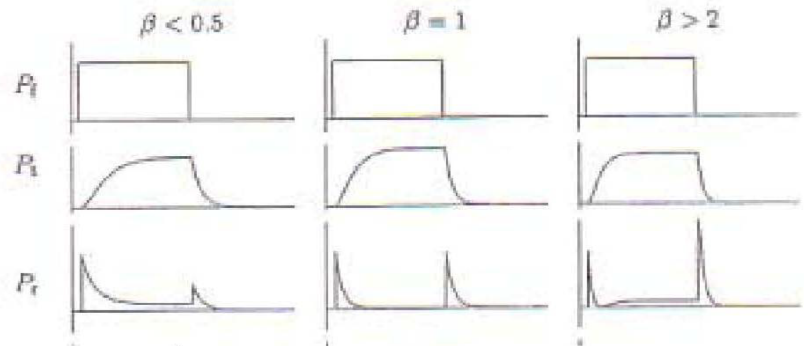
Calculation Q_O

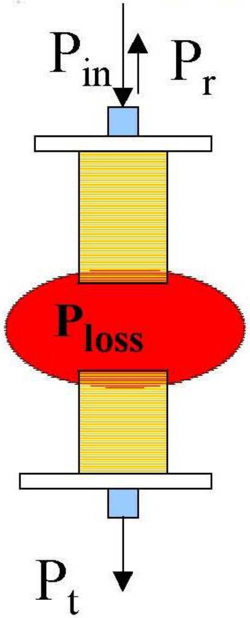
$$R_s = \frac{\Gamma}{Q_o}$$

Geom. factor

Surface resistance

Two-Port Cavity





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

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

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

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

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

Measured value

Measured value

When **P**in = any.

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

(When **P**in > 0)

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

$$Q_L = \omega U / (P_{loss} + Pe + Pt)$$
$$= Q_0 / (1+\beta in + \beta t) \quad \text{when } Pin = 0$$

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

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

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

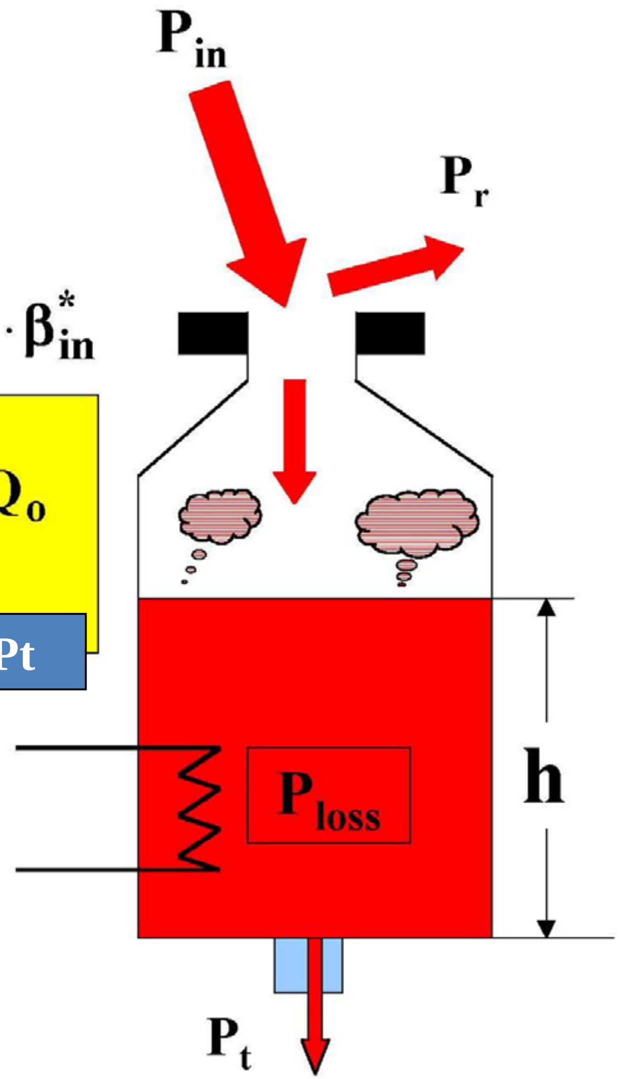
$$Q_o \equiv \frac{\omega U}{P_{loss}},\ Q_t \equiv \frac{\omega U}{P_t} = \frac{\omega U / P_{loss}}{P_t / P_{loss}} = \beta_t^{-1}\cdot Q_o$$
$$\omega U = Q_o \cdot P_{loss} = Q_t \cdot P_t$$

$$Qt = Q_0 \cdot P_{loss} / Pt$$

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

Pin, Pr, Pt : Measured values

Stable Status : h=const ⇐ U const



Calculation of Acceleration Gradient

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

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

Rsh = Shunt impedance

deff = Effective length of cavity along the beam axis.

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

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

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

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

Not dependent on material

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

Set Qt >> Q_0 (Pt << Ploss).
Qt is constant during the measurement if using a fixed antenna.
Z is independent of surface resistance (material of cavity).

Summary:

Measured parameters:

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

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

Stable state (CW)

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

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

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

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

$$Q_t = Q_O / \beta_t$$

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

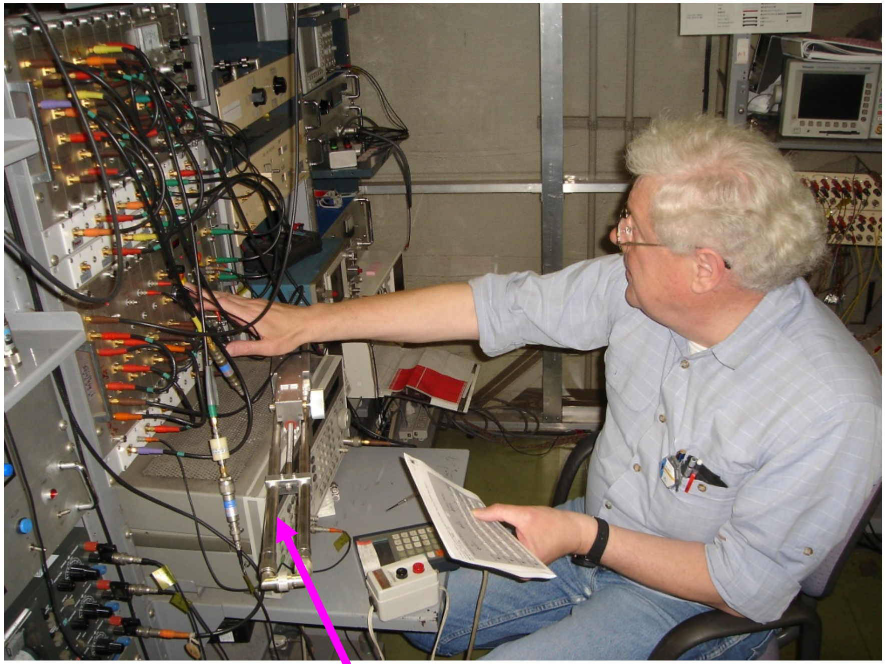
$$Q_O = (1 + \beta_{in} + \beta_t)\, Q_L$$

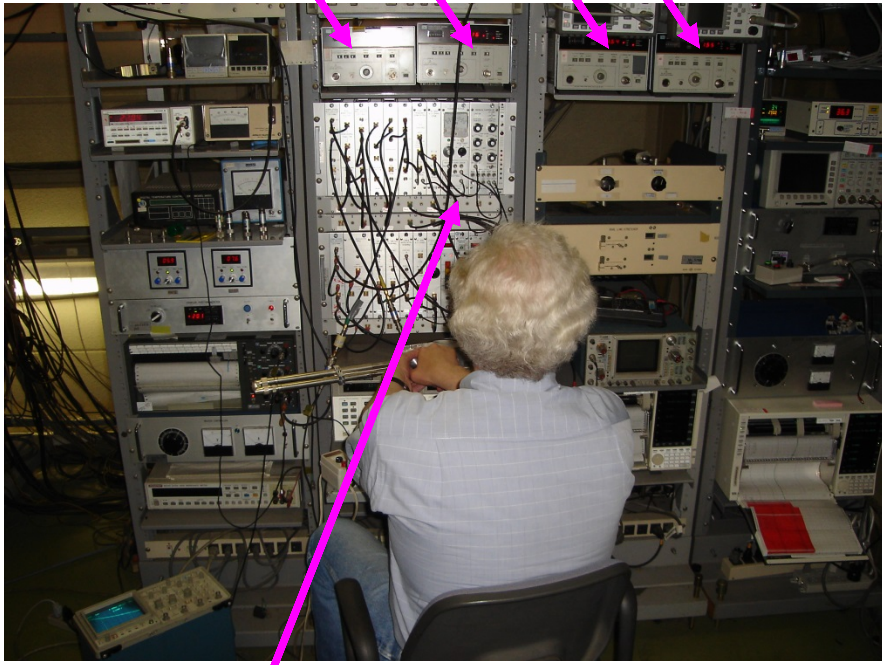
$$R_s = \frac{\Gamma}{Q_o}$$

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

Control Room of Vertical Test (VT)

Power-meter (Pin, Pr, Pt)





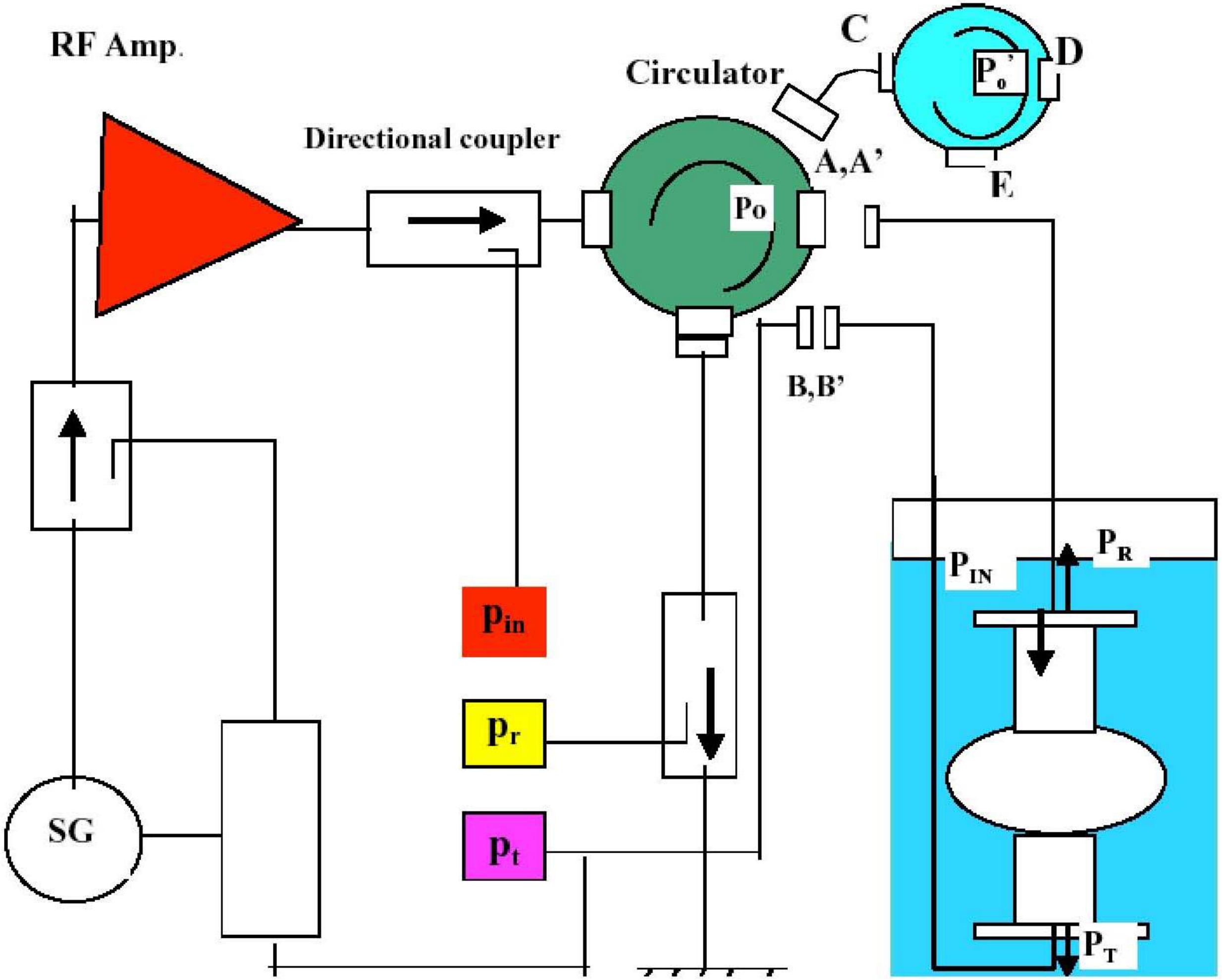
Signal Generator (SG)

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'

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

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

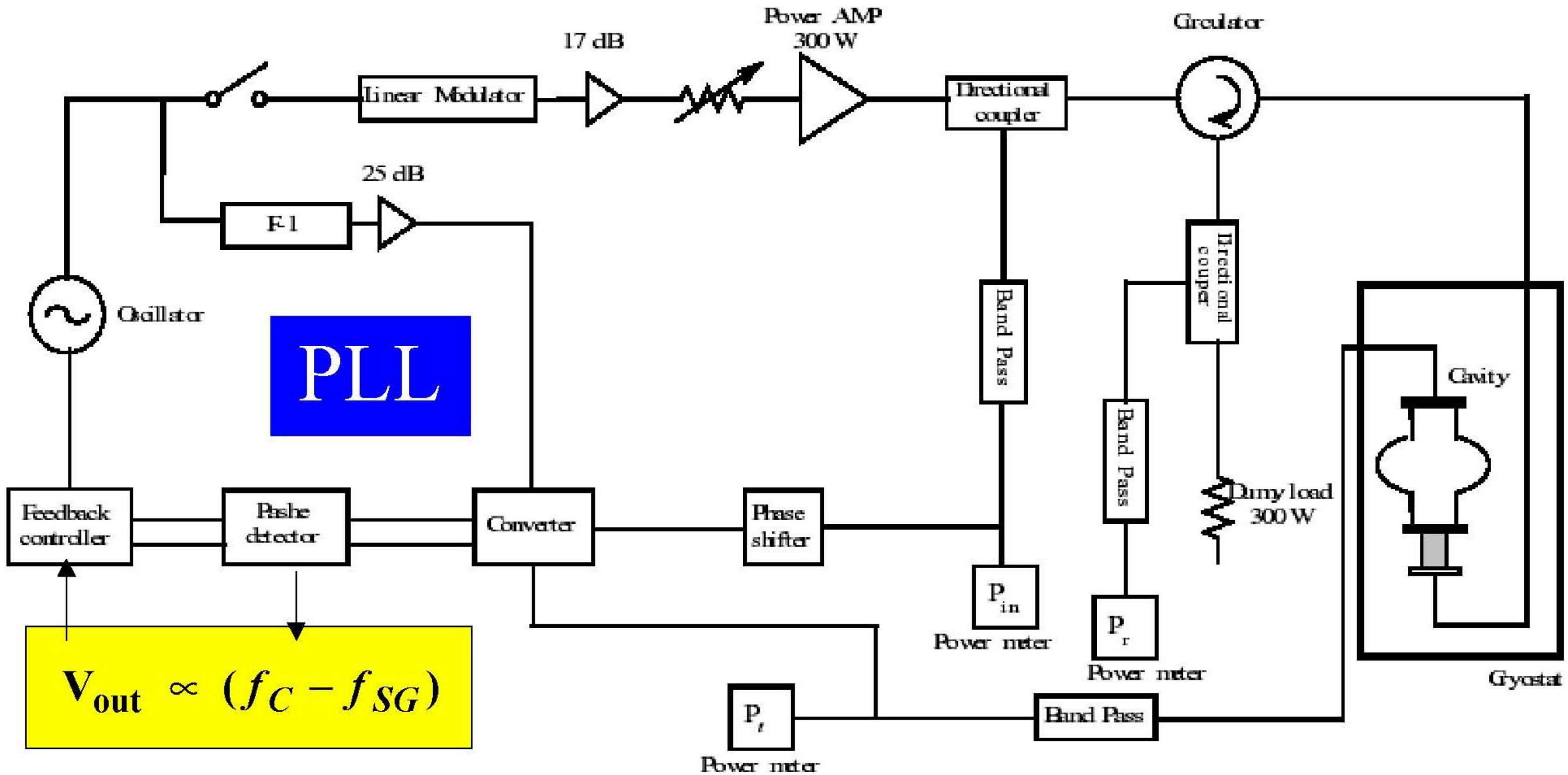
$C_t=(P_O/p_t) \cdot (P_O'/p_t')^{1/2}$

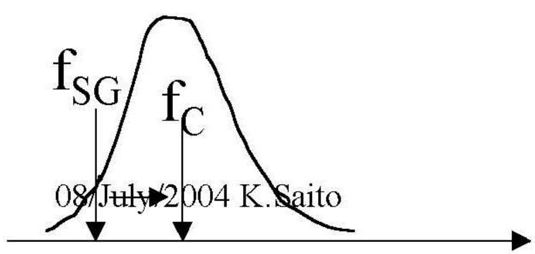
$P_{IN} = c_{in} \cdot p_{in}$

$P_R = c_r \cdot p_r$

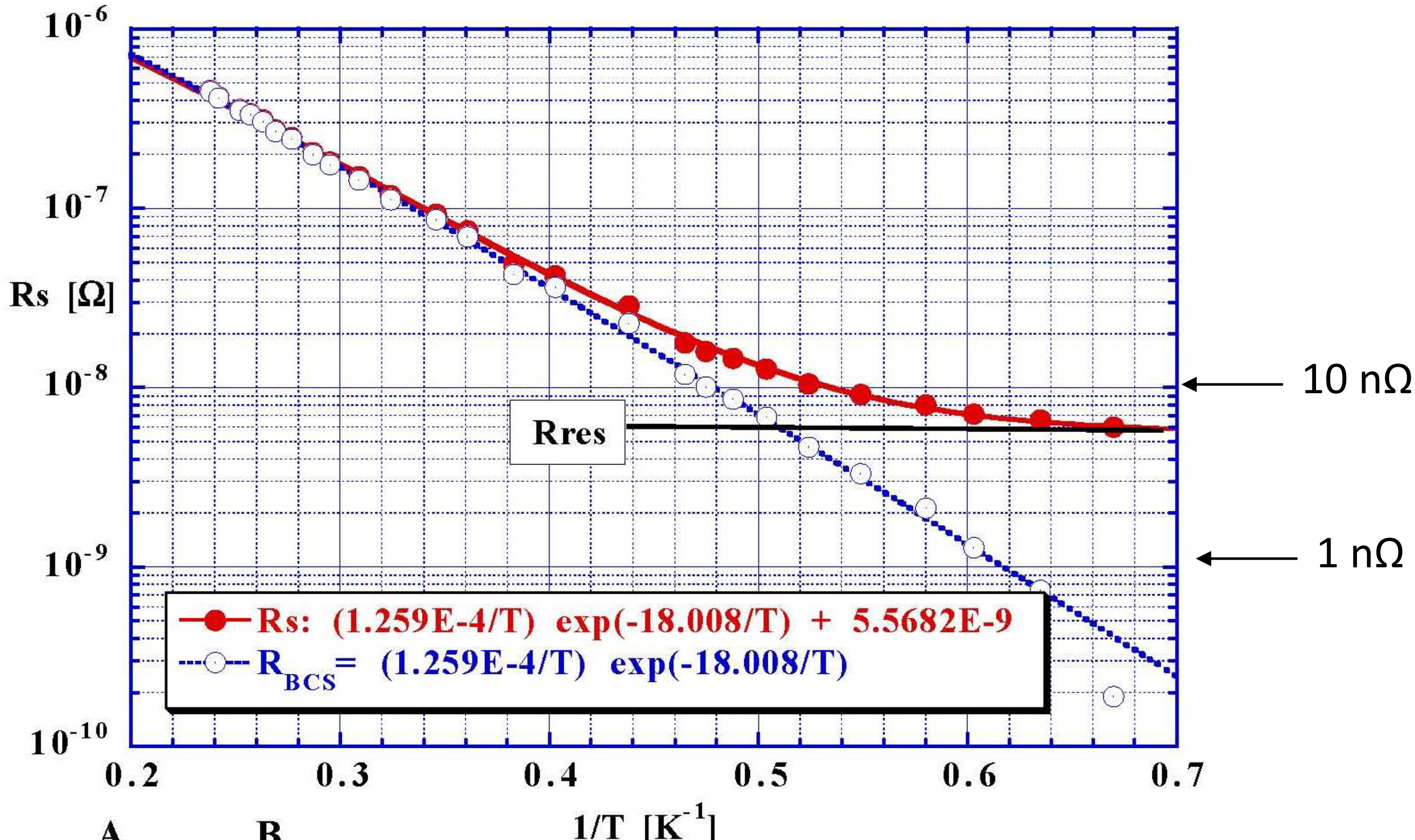
$P_T = c_t \cdot p_t$

Feed Back System





Measurement of Surface Resistance (Dependence on T)

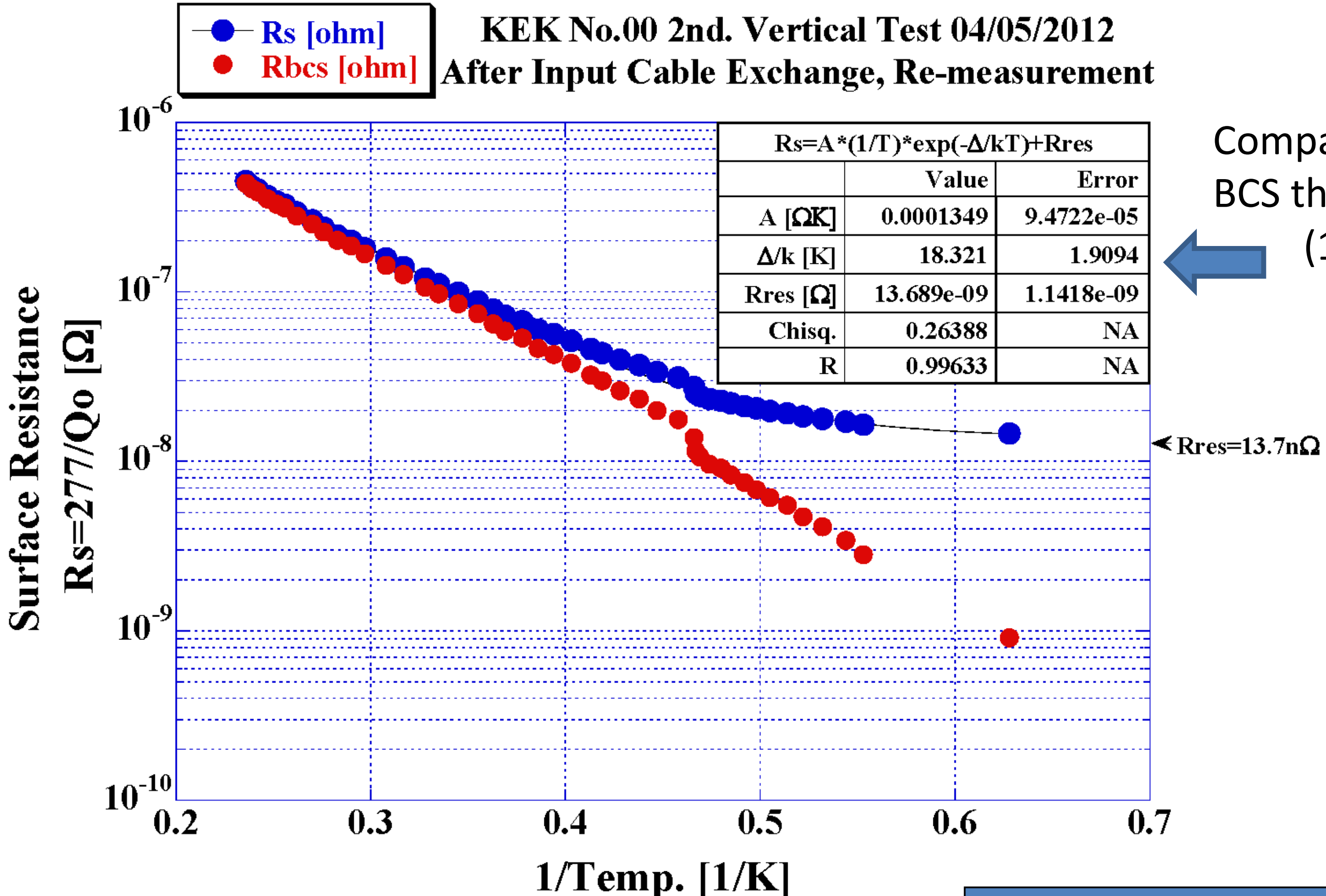


$$R_s - \text{fit}: R_s(T) = \frac{A}{T} \cdot \exp(-\frac{B}{T}) + R_{res}$$

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

Rs = Γ/ Q0 is plotted

Measurement of Surface Resistance (Dependence on T)

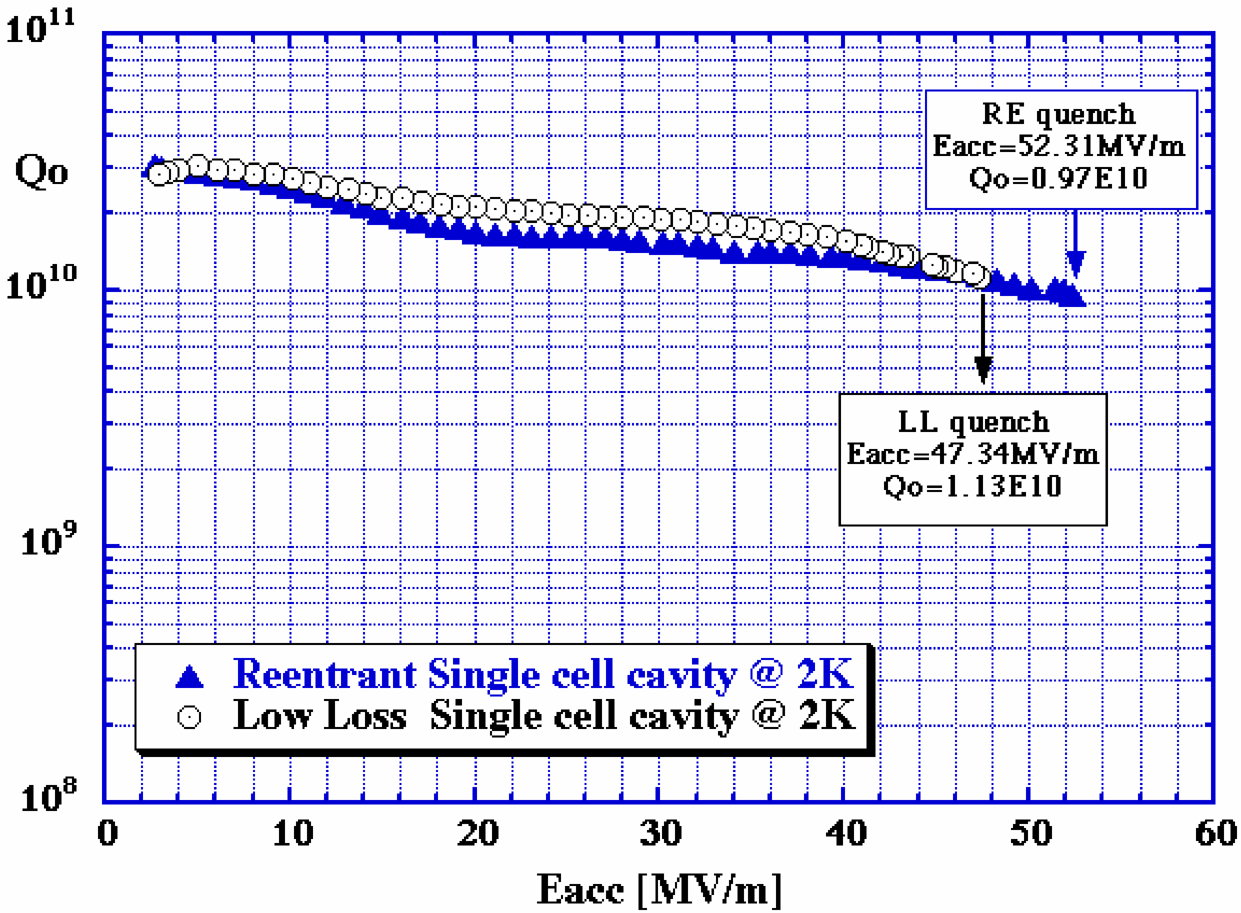


Compare with BCS theory (17.67)

Rs = Γ/ Q0 is plotted

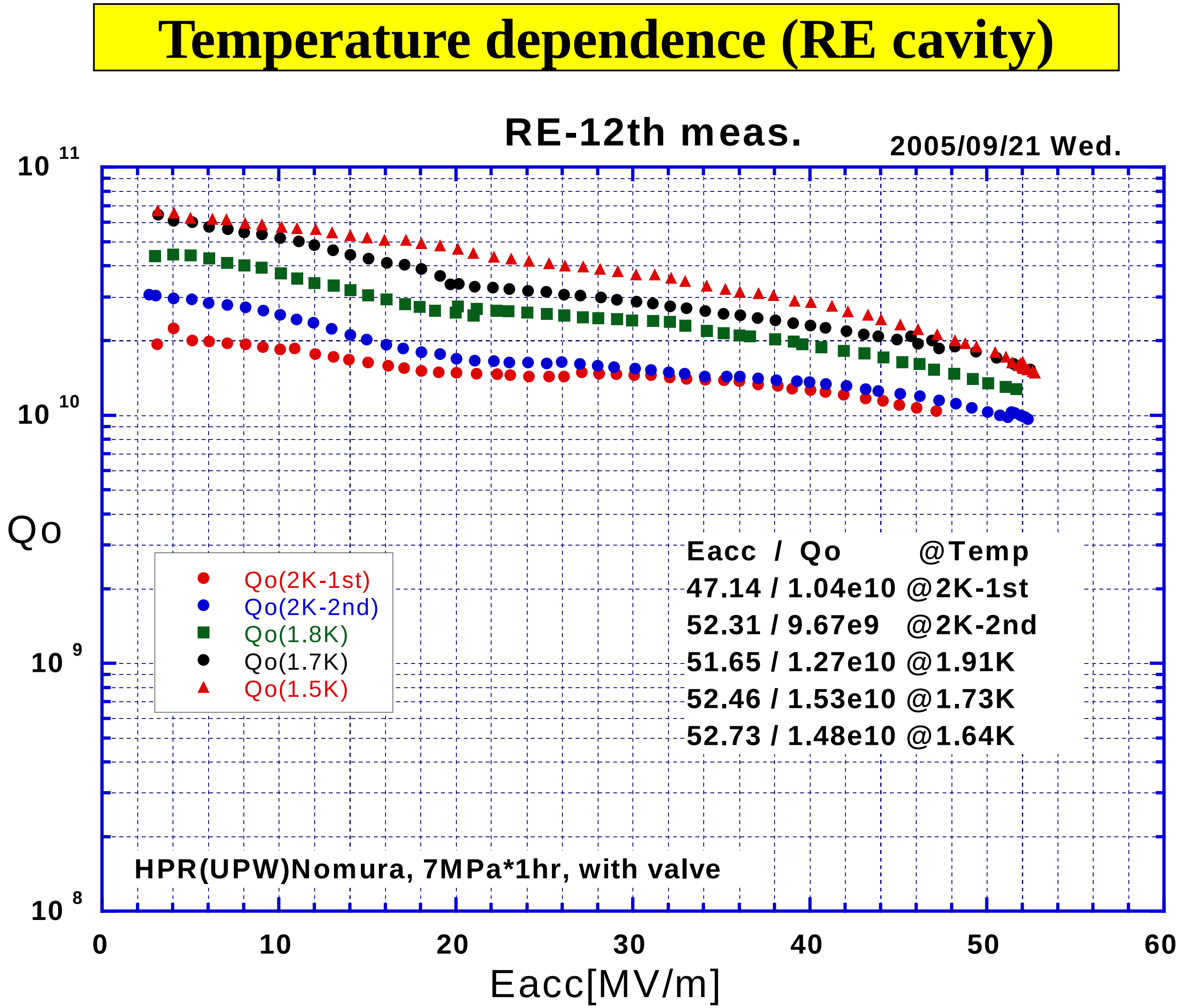
Qo vs Eacc

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

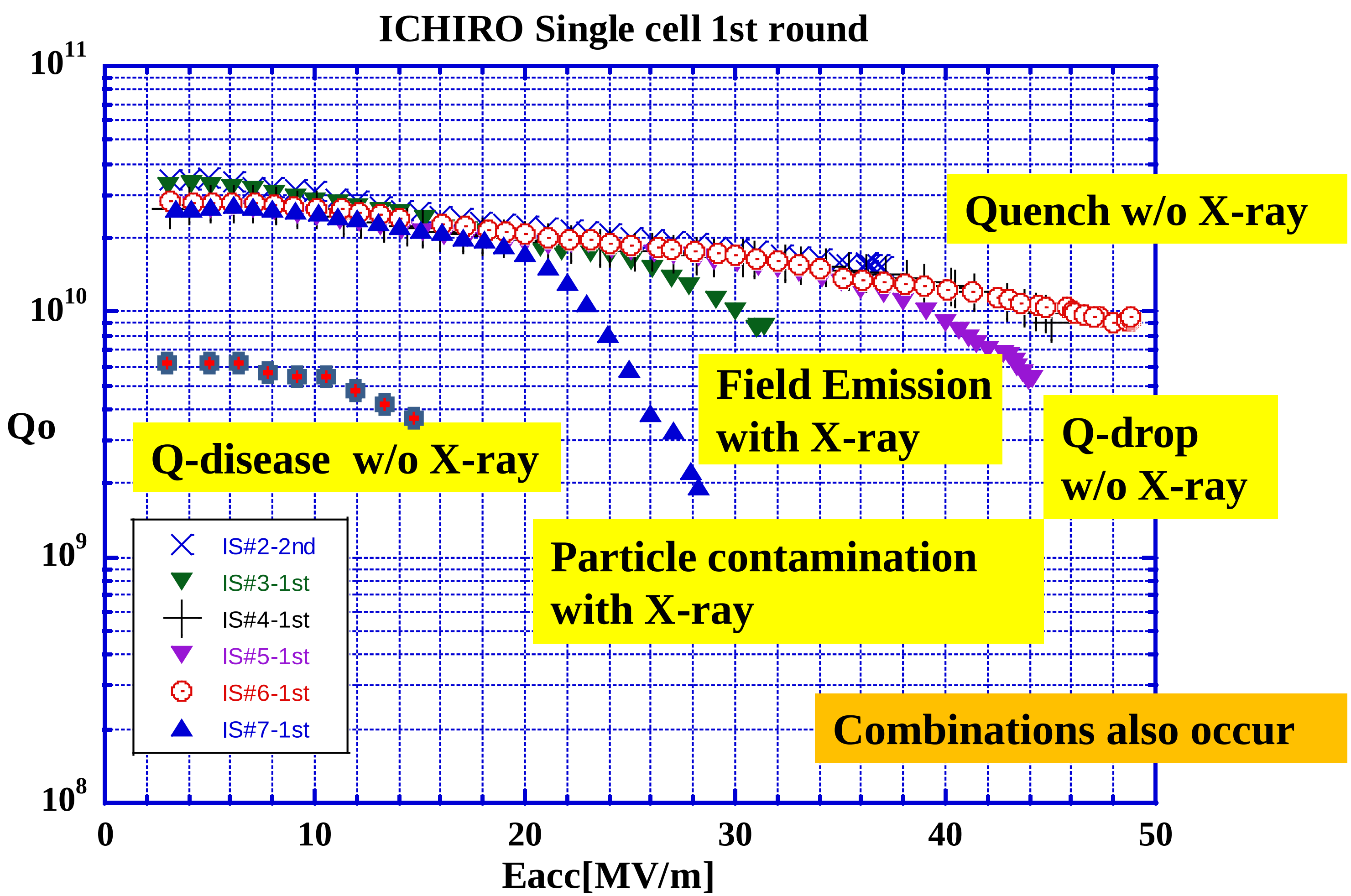


Eacc = Z sqrt(Qt･Pt) , Q0 = Qt ･ Pt / Ploss

Q0 vs Eacc（T dependence）

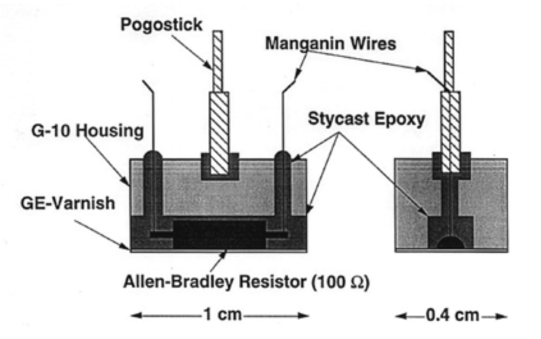


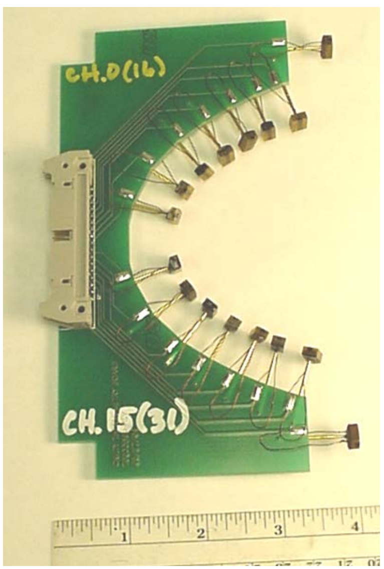
Q0 vs Eacc（Limitation）

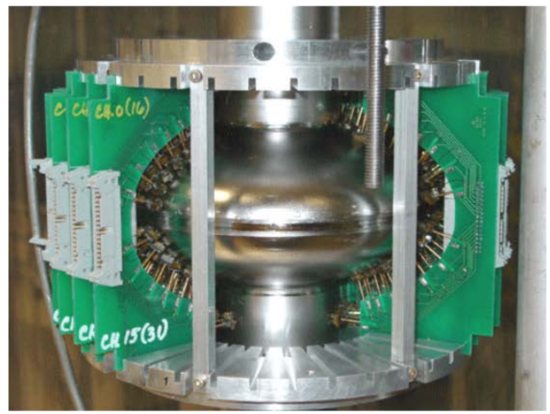


T-Mapping (1)

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

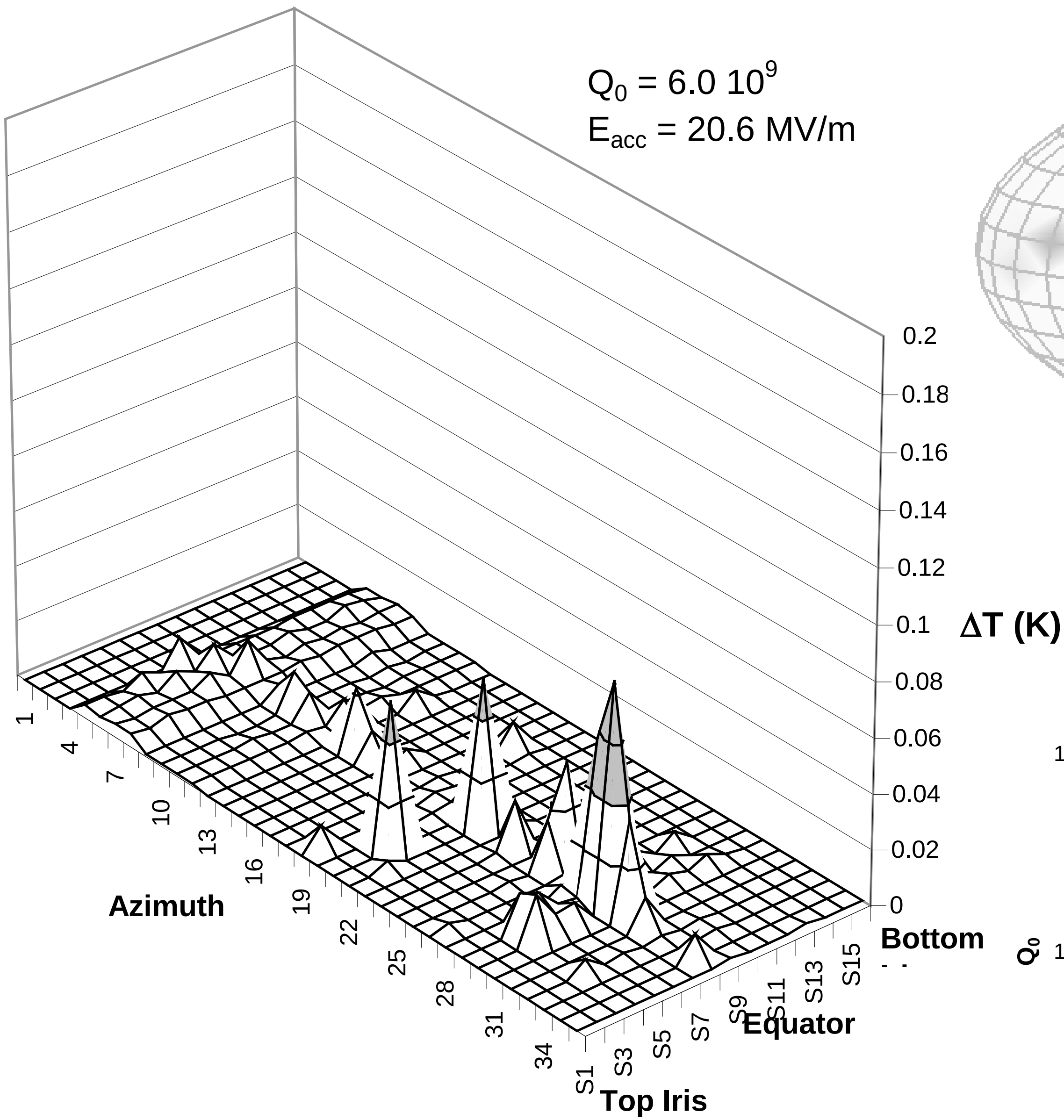




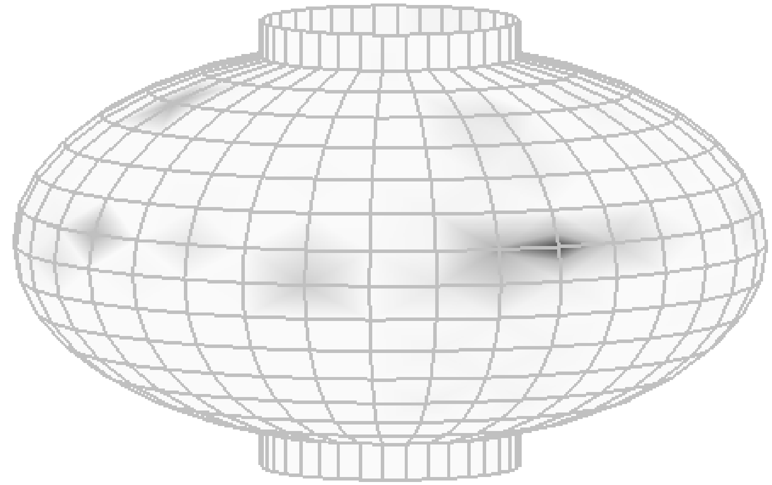


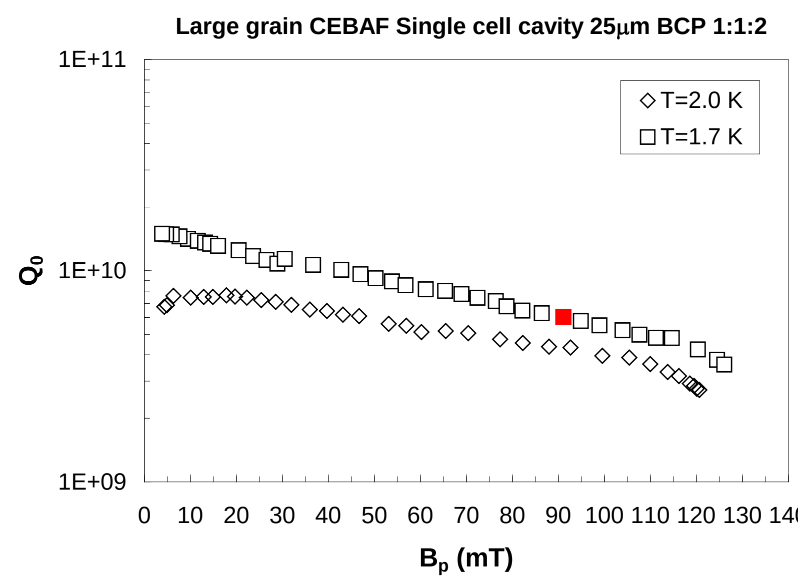
a)

b
)



Q0 = 6.0 10^9
Eacc = 20.6 MV/m
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
ΔT (K)
1
4
7
10
13
16
19
22
25
28
31
34
Azimuth
S1
S3
S5
S7
S9
S11
S13
S15
Top Iris
Equator
Bottom





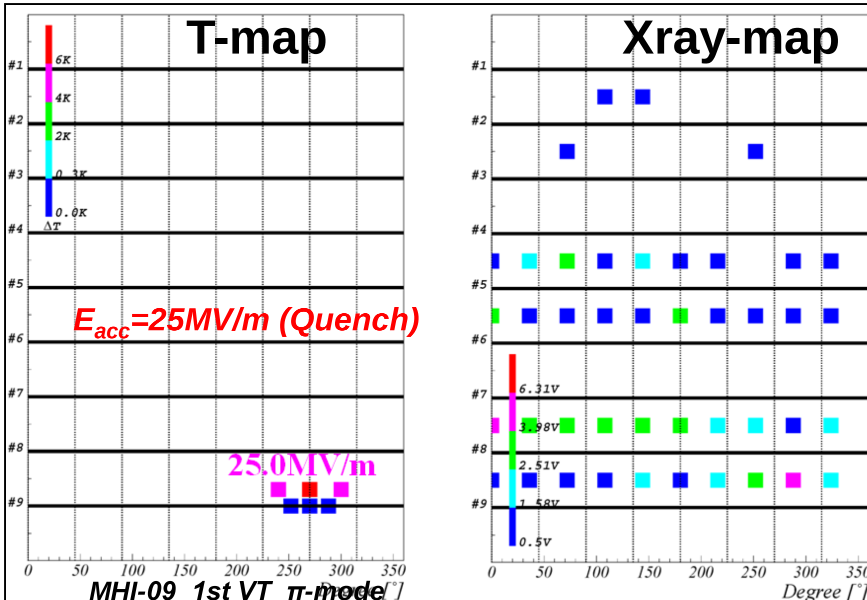
Large grain CEBAF Single cell cavity 25µm BCP 1:1:2
1E+11
1E+10
1E+09
Q0
T=2.0 K
T=1.7 K
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Bp (mT)

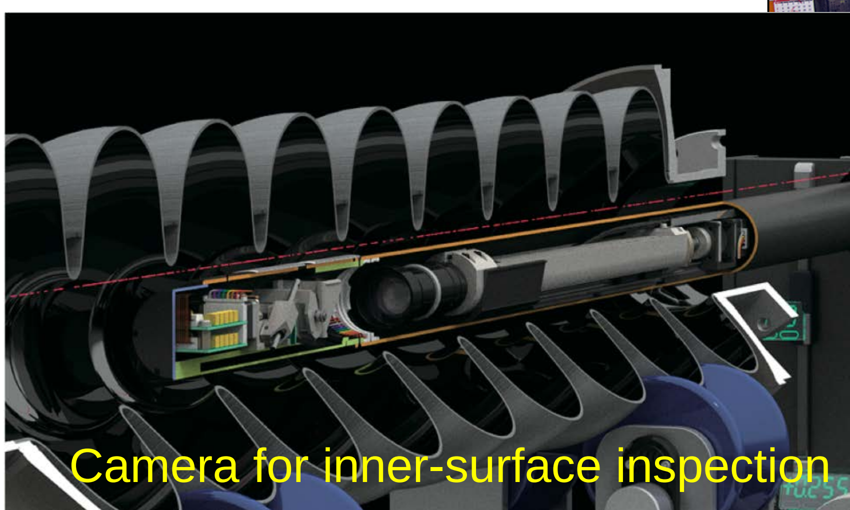
Acceptance test of cavity

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

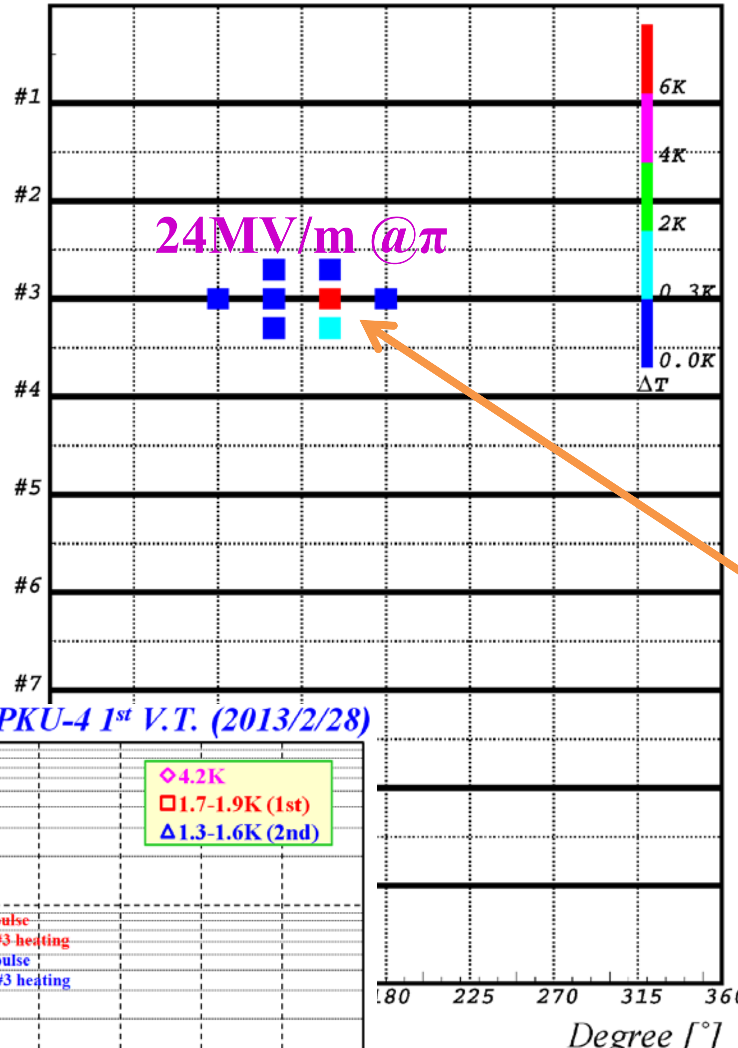
T-map & Xray-map, together with pass-band mode measurement, location of quench is identified.
Inspection camera visualize what's happen inside.

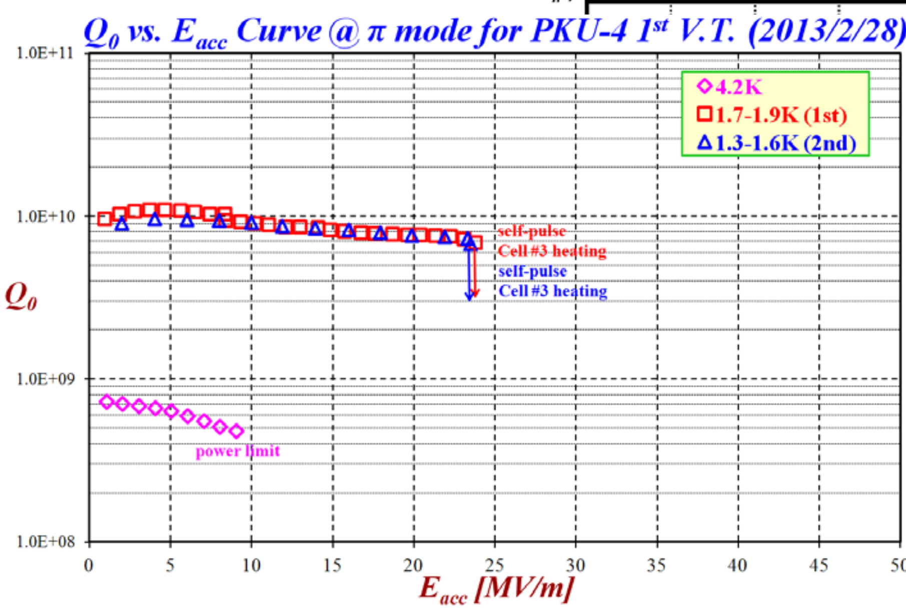

Sensors installation

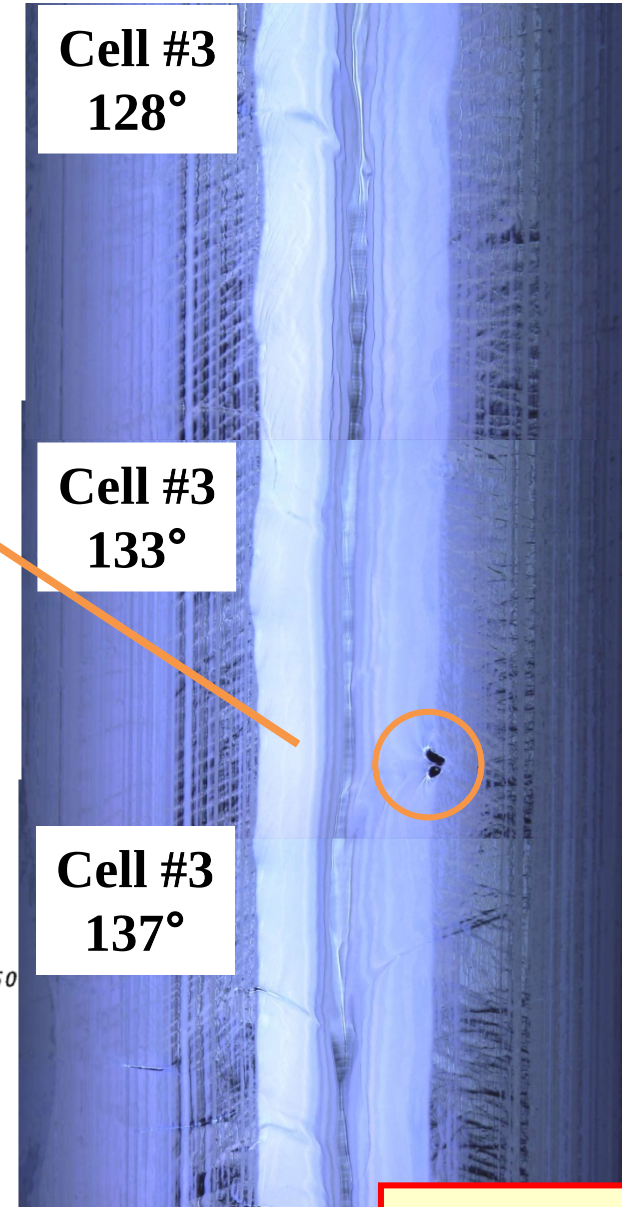



Camera for inner-surface inspection

PKU-04 cavity

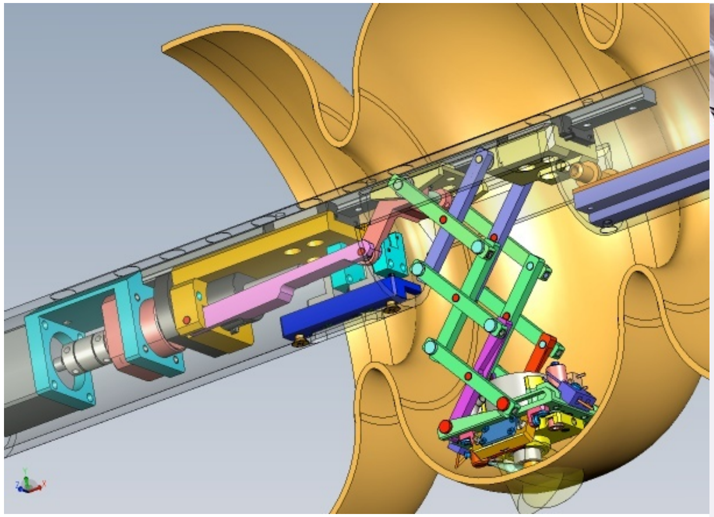


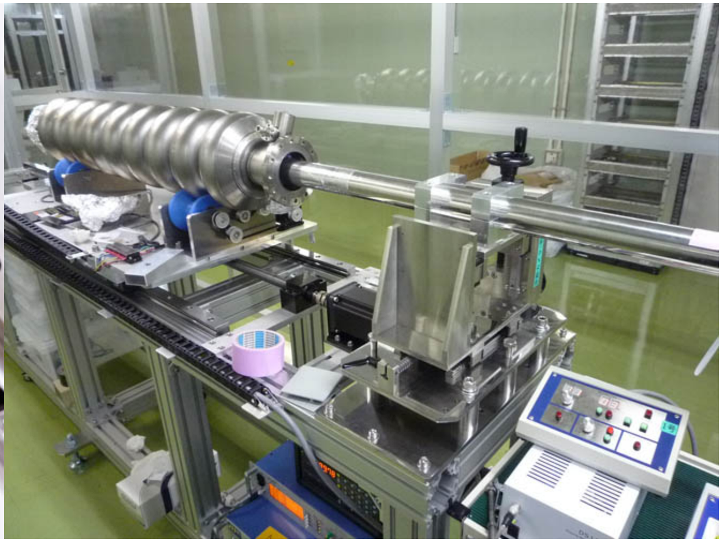




by T. Kubo

Local grinding at KEK



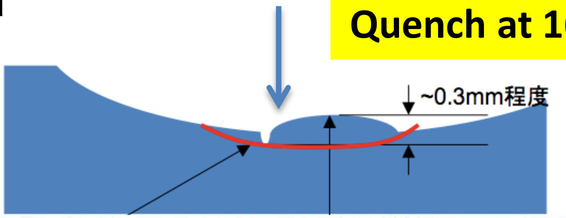


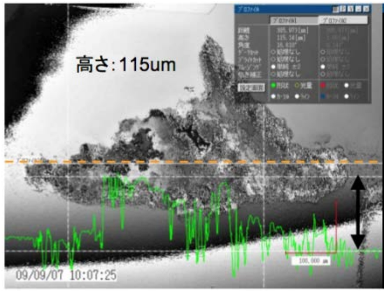
Grinding only for pit, without touching other surface

diamond powder compound with water in between were used.

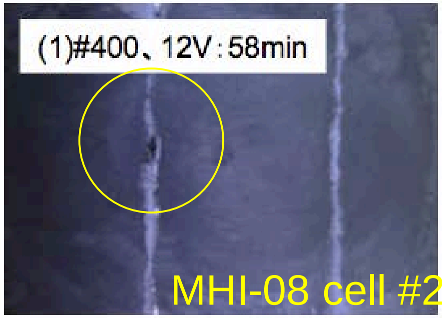
~115µm depth pit in MHI-08 cavity

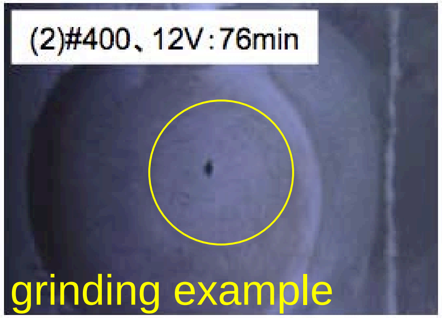
Quench at 16 MV/m

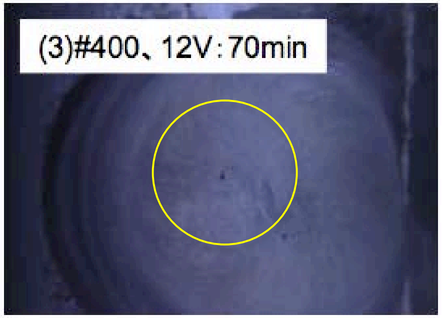




This pit caused quench at 16 MV/m







MHI-08 cell #2 grinding example

Q-drop and In-situ Baking

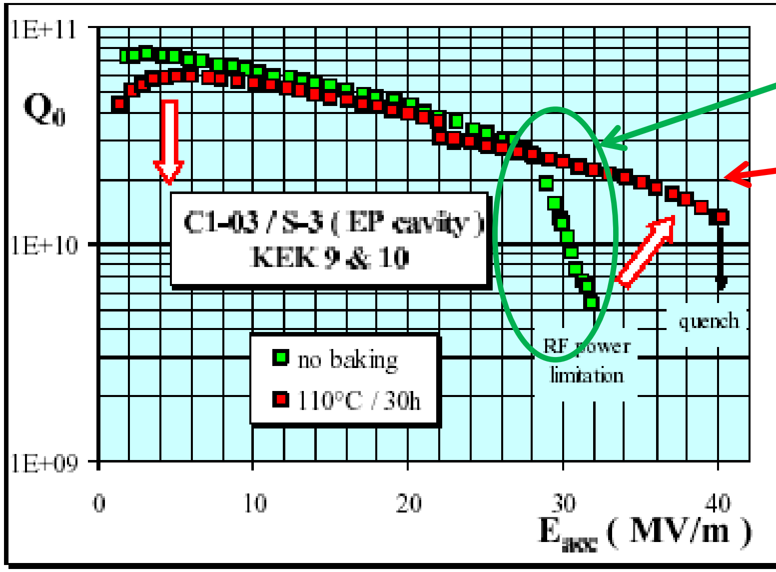


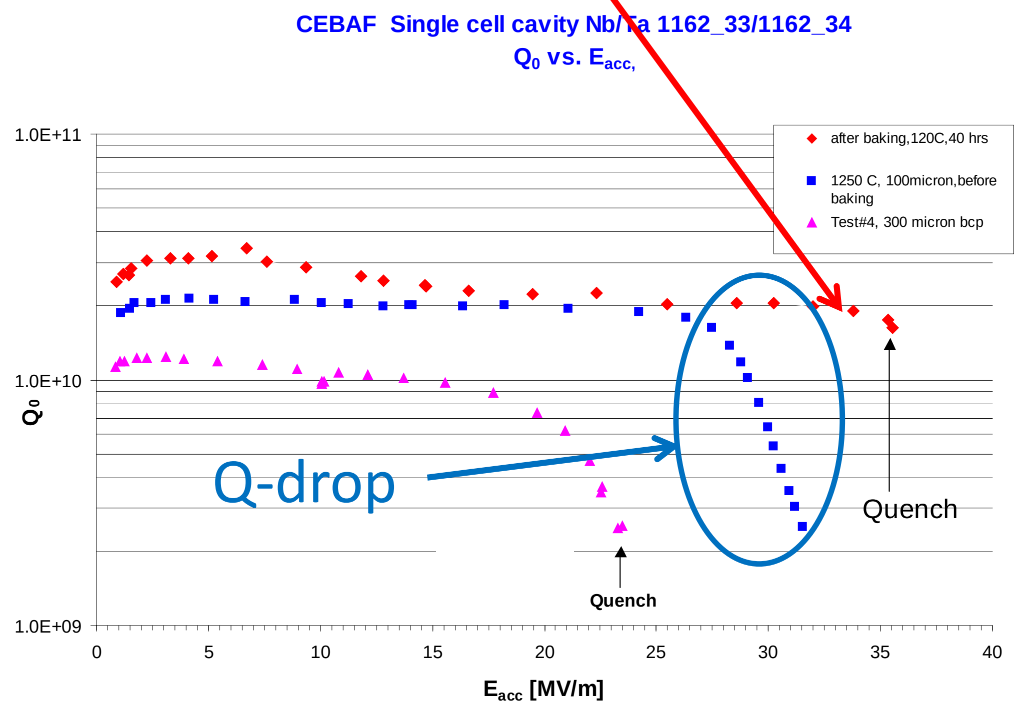
Figure 4: Baking effect on C1-03 Saclay cavity (electropolished and tested at KEK) [9].

[B.Visentin,SRF2003]

electropolished

Q-drop

Q-drop was recovered by in-situ baking



Q-drop

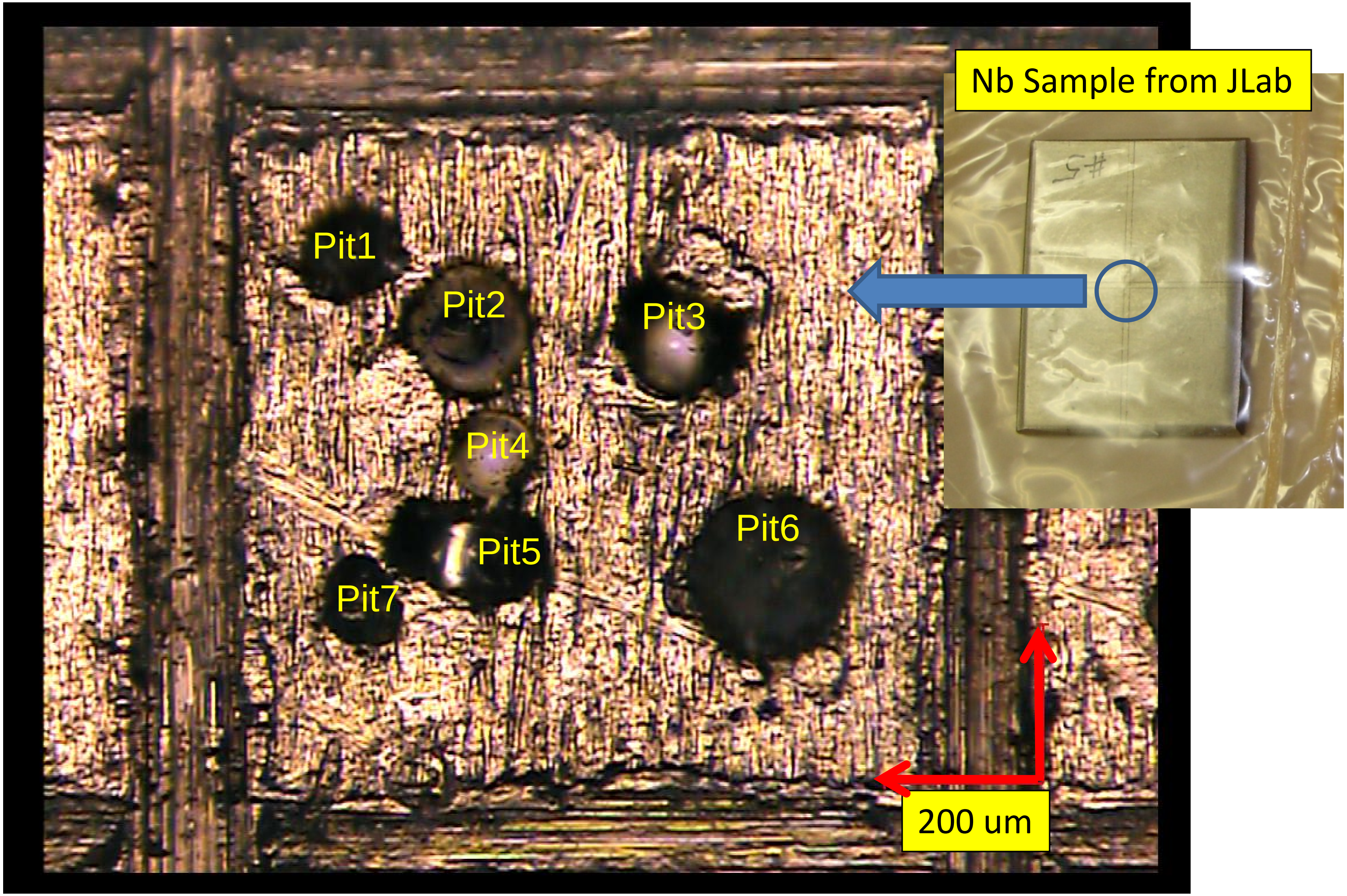
Buffered Chemical Polished(1:1:1)

How to cure bad cavities (1/2)

Bad performance

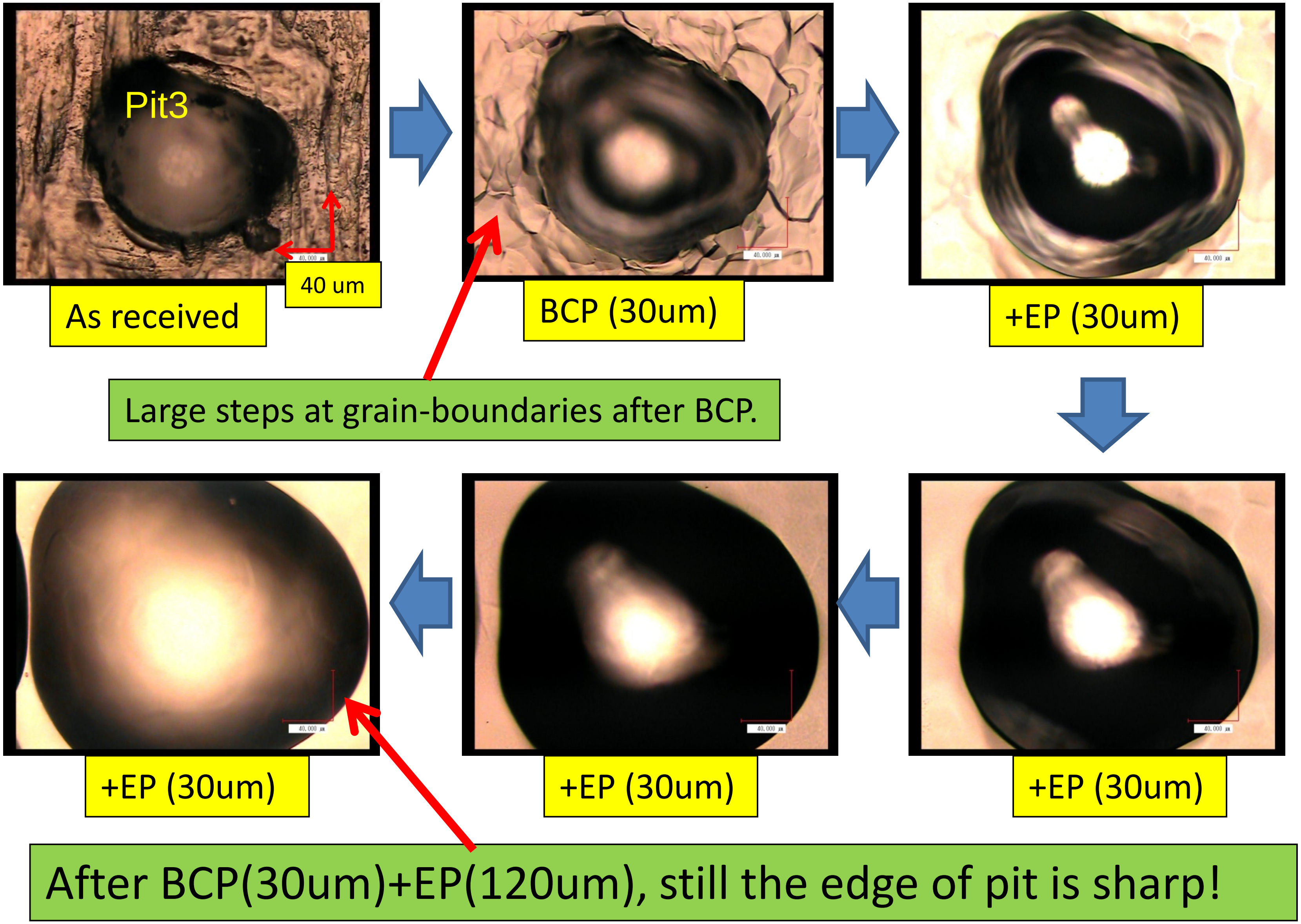
Source of problem	Particle contamination in assembly in CR	Q-drop (Oxidation Layer is not good)	Defects just after fabrication
How to cure	Removal of particles	Recreation of oxidation layer	Removal of defects
Process	HPR and careful assembly	In-situ baking or Light EP/BCP In-situ baking	Local grinding or Rough removal By CBP
	Removal = 0	Removal = thin	Removal = thick

Nb sample with artificial pits from JLab

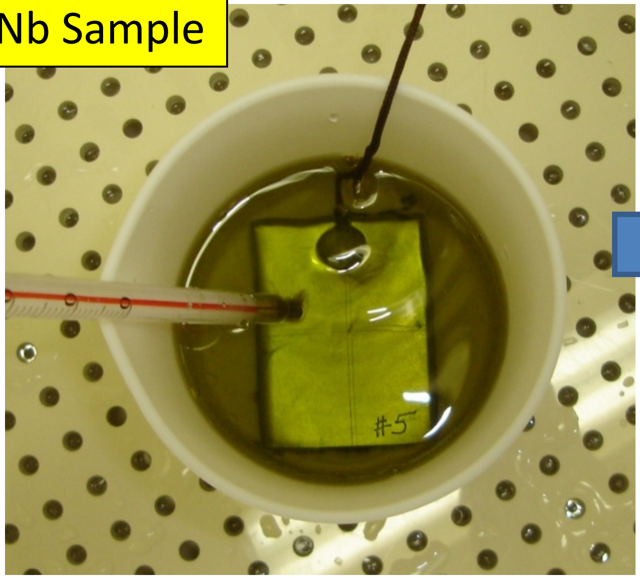


On interested surface of both samples, there are marked lines for purpose of location referencing.

JLab Nb sample with artificial pits

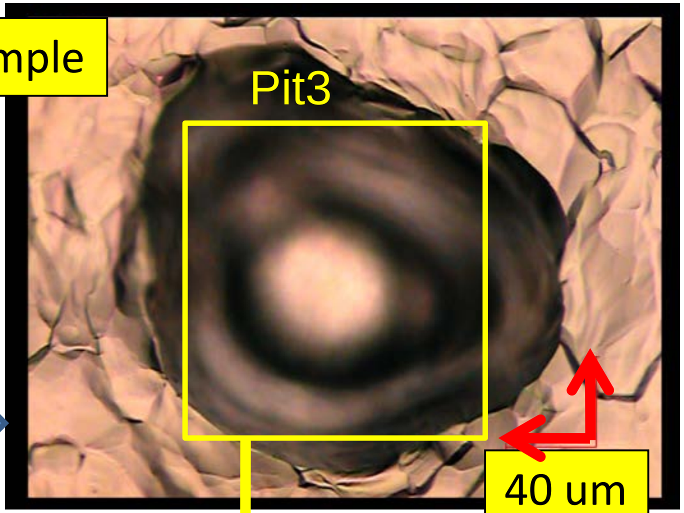


Jlab Nb sample with artificial pits



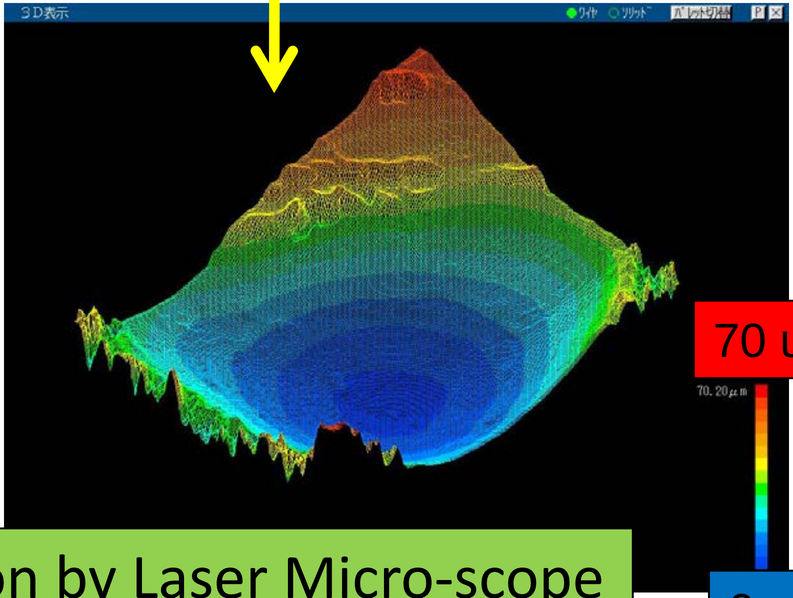
Nb Sample

BCP (30um) at STF/KEK



Nb Sample

40 um

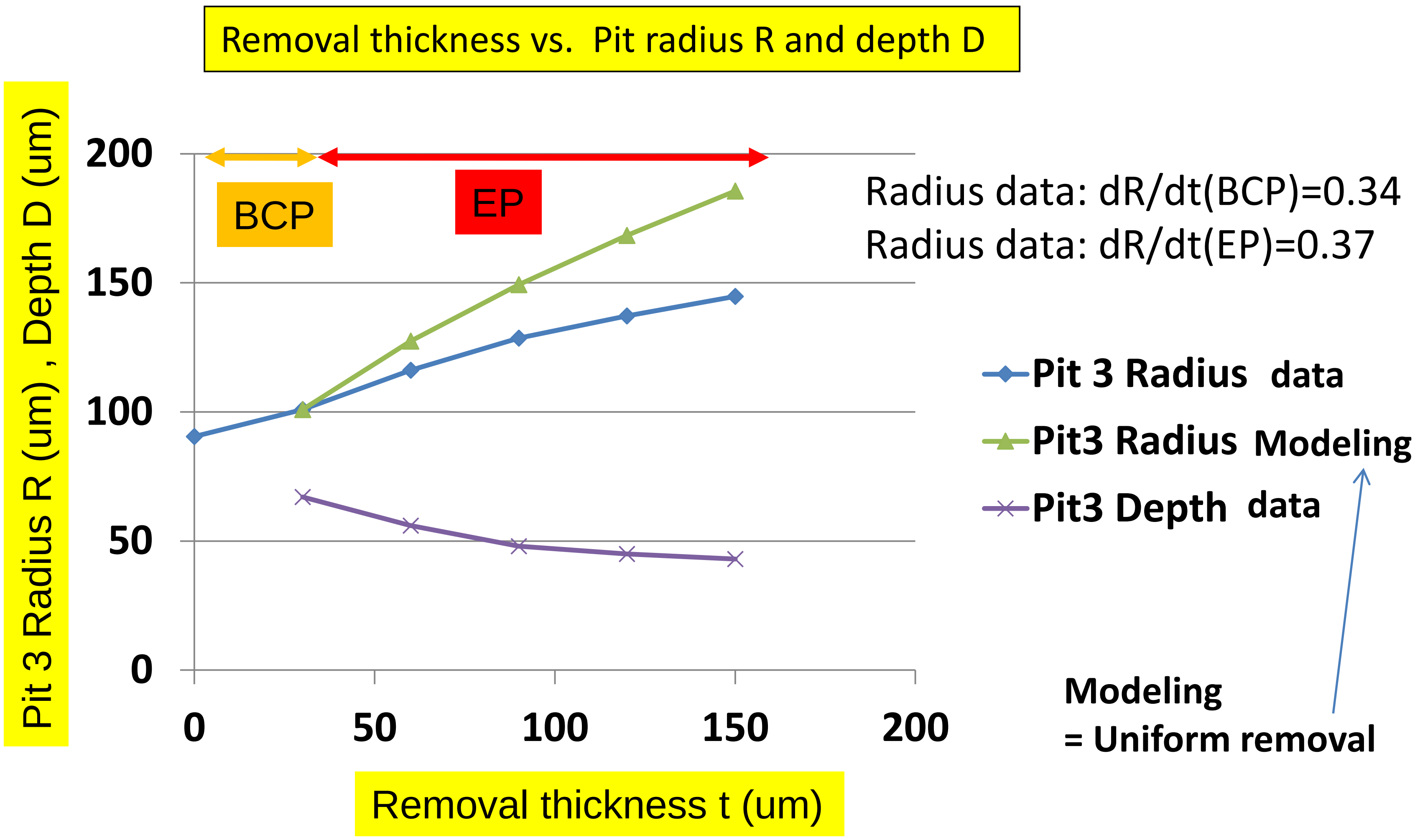


70 um

0 um

Observation by Laser Micro-scope

JLab Nb sample with artificial pits

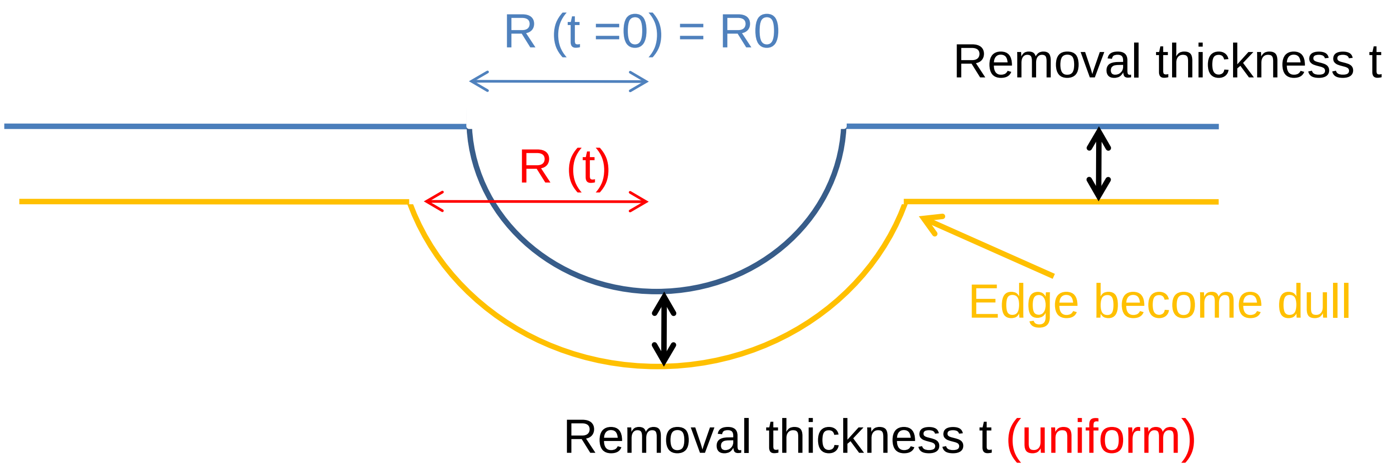


Radius data: dR/dt(BCP)=0.34
Radius data: dR/dt(EP)=0.37

Modeling
= Uniform removal

Jlab Nb sample-1 with artificial pits

Radius for Uniform Removal Modeling

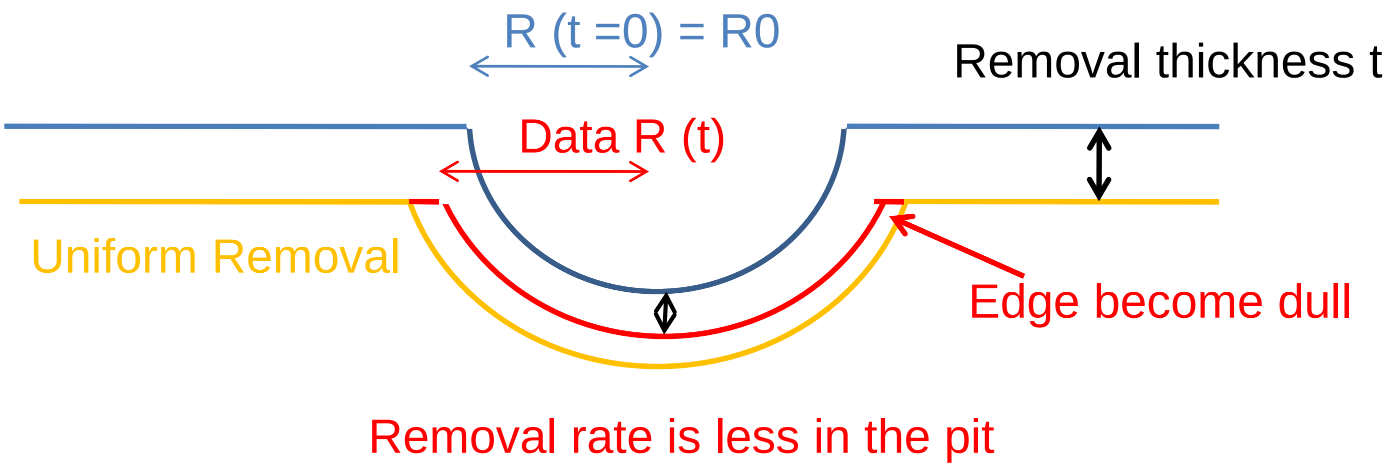


R(t) = SQRT (R0 x R0 + 2 x R0 x t)

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

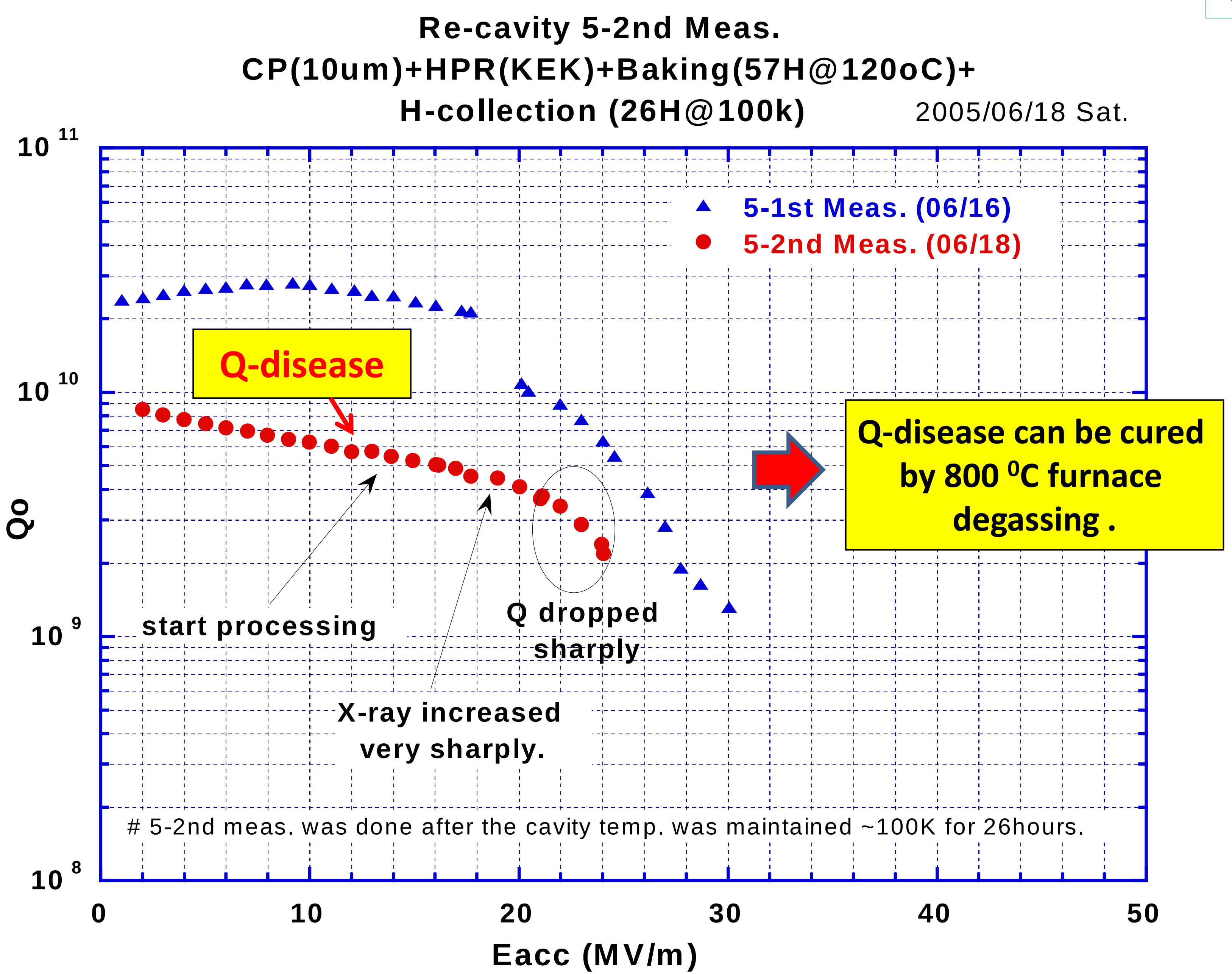
Jlab Nb sample with artificial pits

Measured Radius and Depth

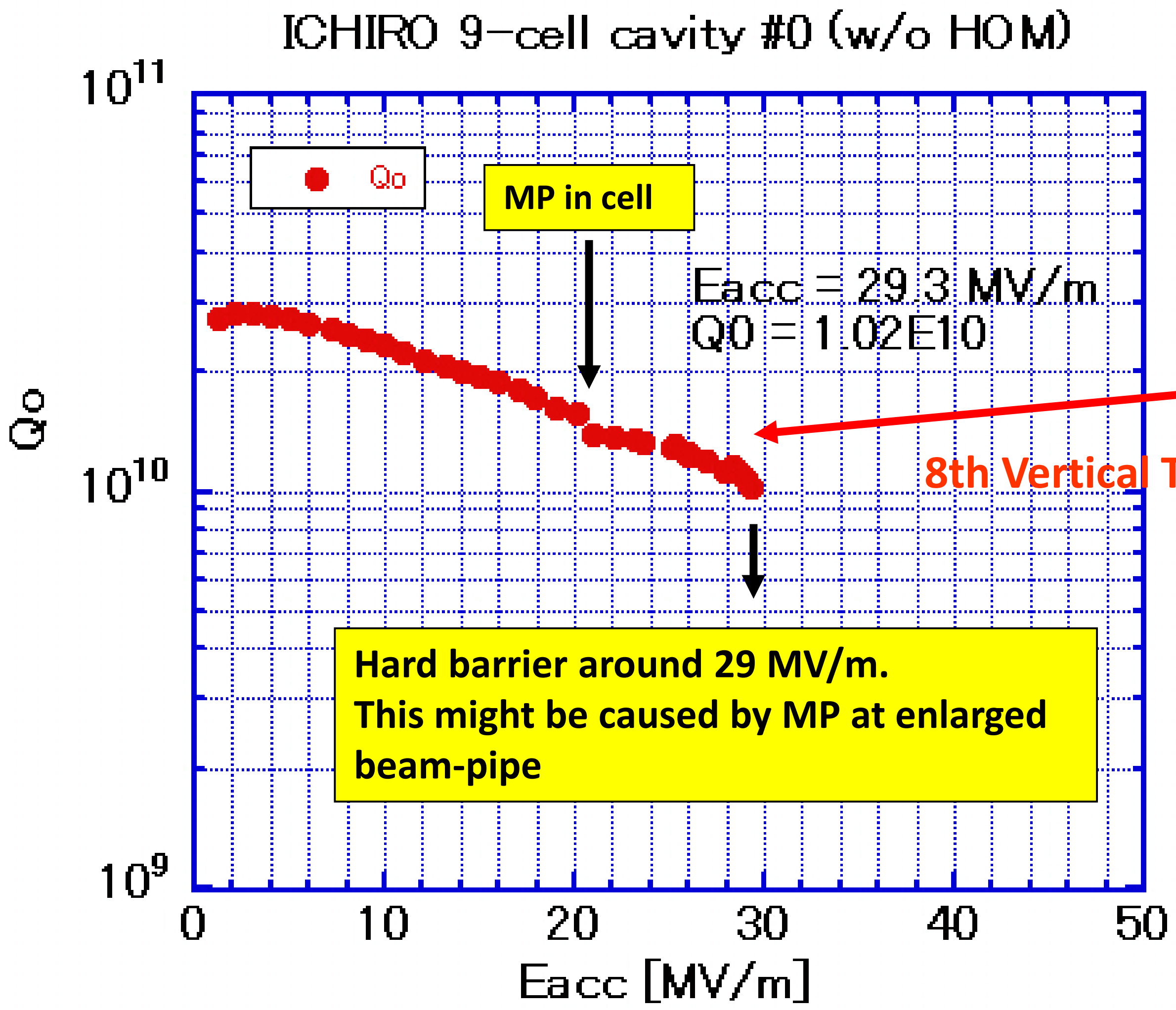


Radius increases slowly and the depth becomes shallower.

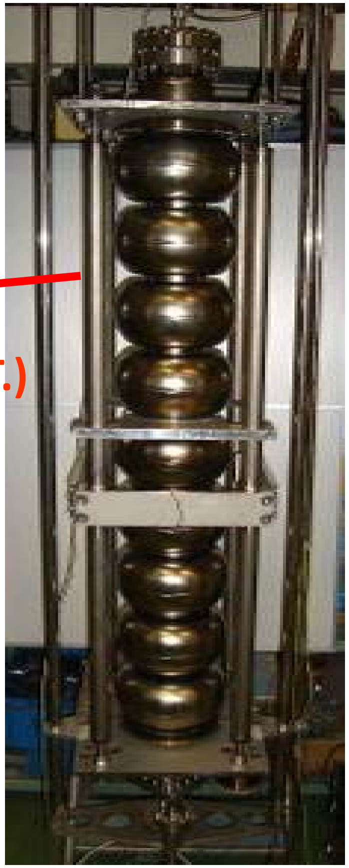
However, EP seems not to round the edge of pit very effectively / selectively.
EP is not all mighty. All pits should be removed before EP process mechanically.


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
Q-disease can be 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



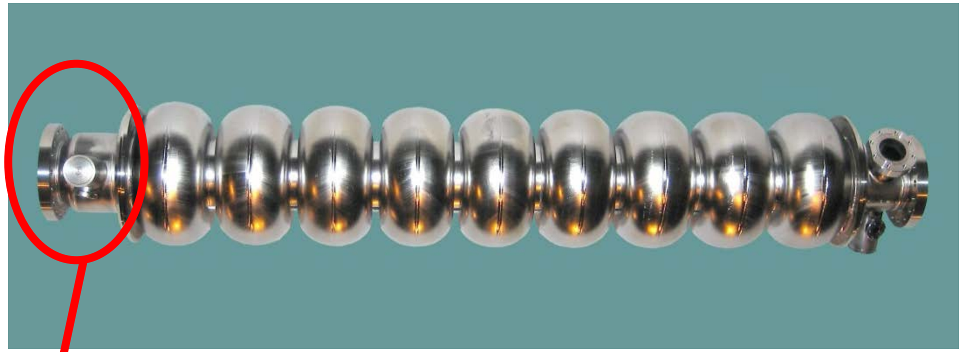
ICHIRO 9-cell 1st Cavity #0 w/o HOM



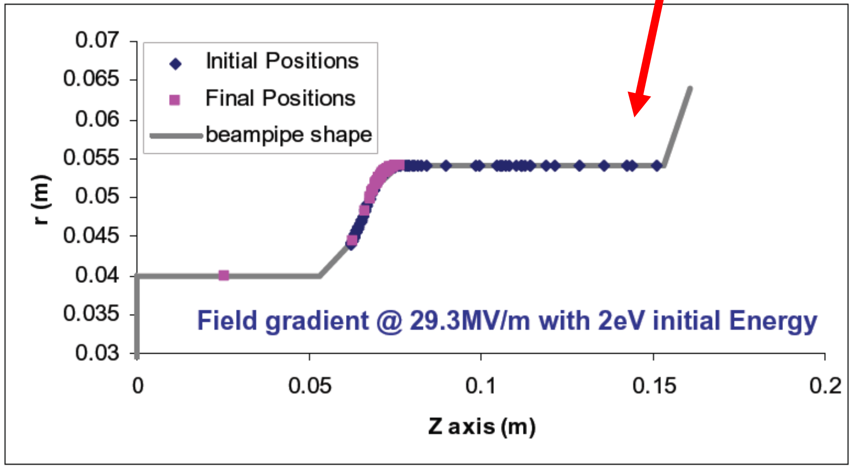
No Q-disease was found.

Multi-pacting simulations by L. Ge at SLAC

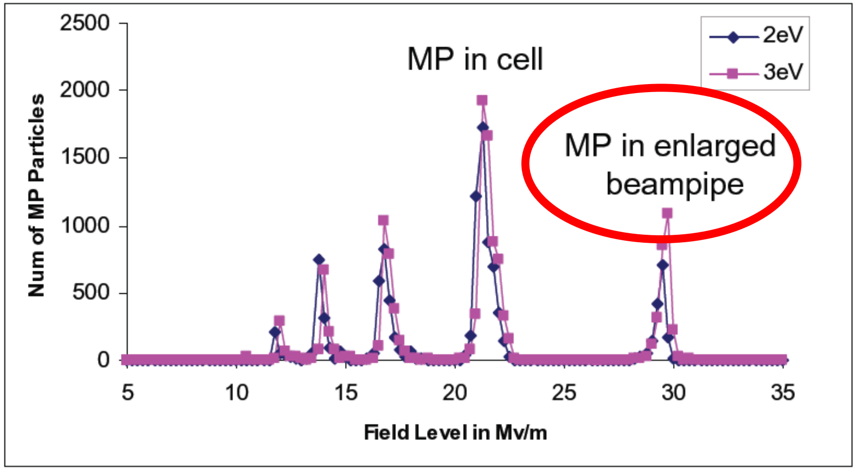
Multi-pacting points were found at the taper part of enlarged beam-pipe from simulation.



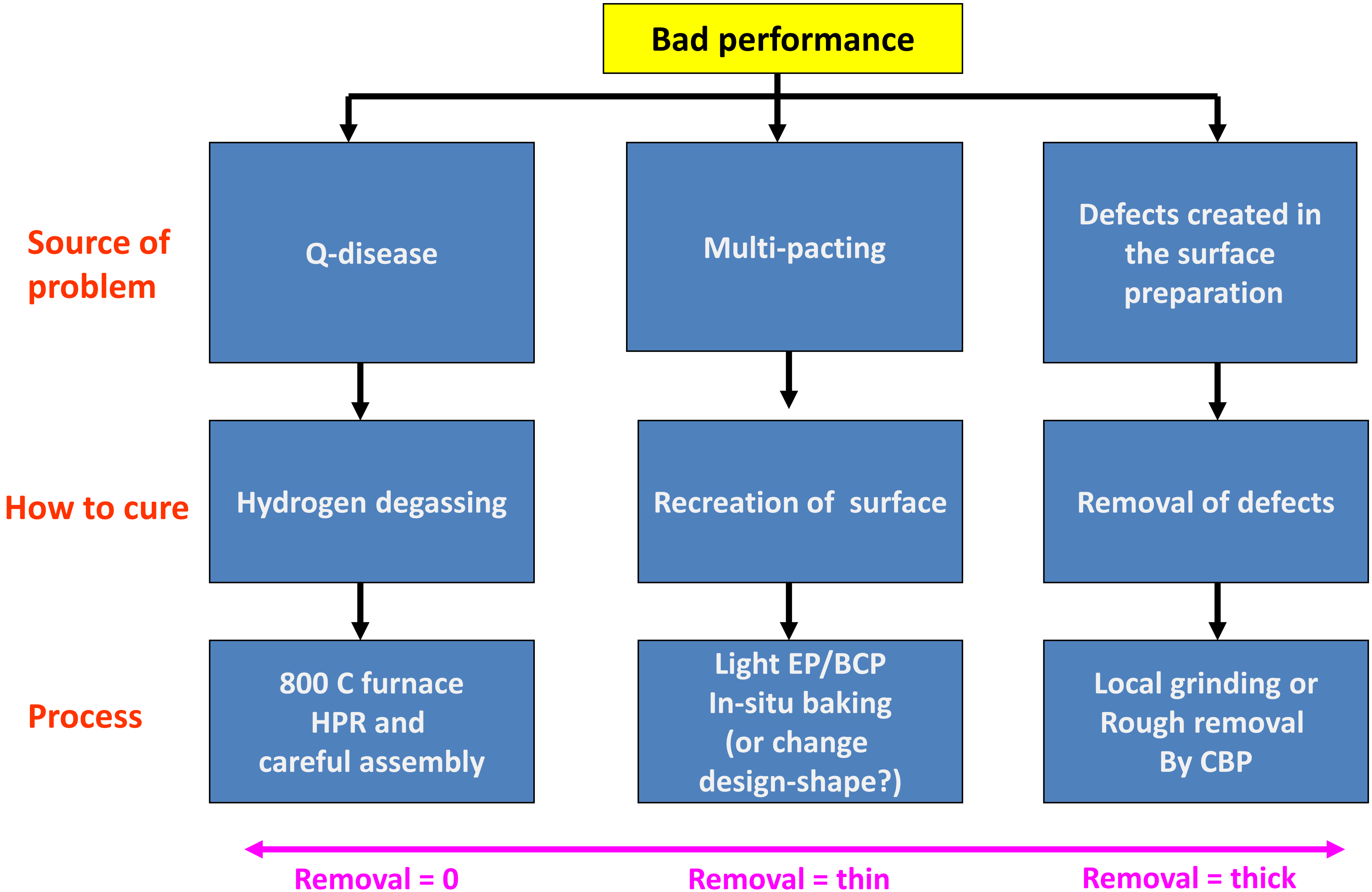
- MP Particles Distribution (surviving 50 impacts)



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



How to cure bad cavities (2/2)



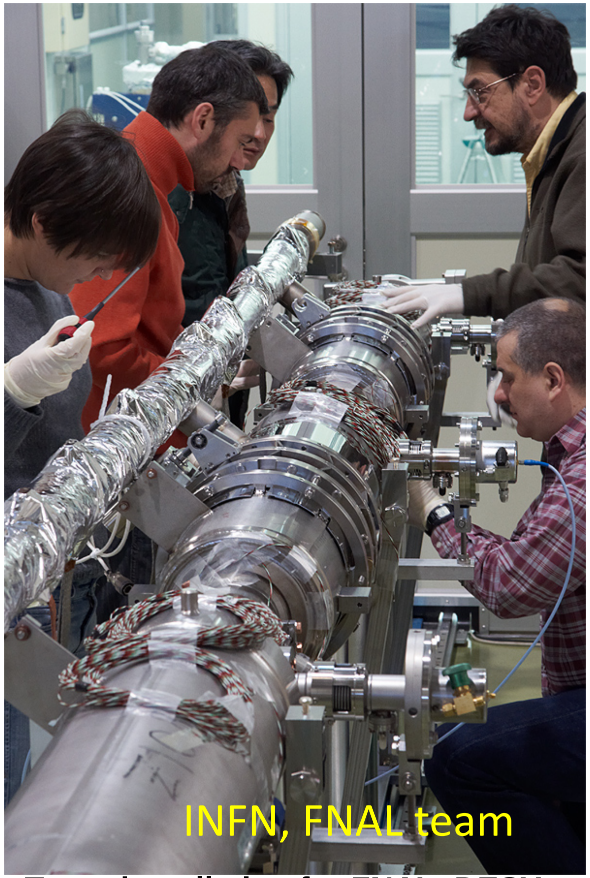
Cavities assembly for Cryomodule C

Two cavities from FNAL, two cavities from DESY,

FNAL, DESY team assembled 4 cavities, INFN, FNAL team installed blade tuners and Saclay tuners.

Tug Arkan
Brian Smith
Marco Battistoni
Manuela Schmoekel
Patrick Schilling

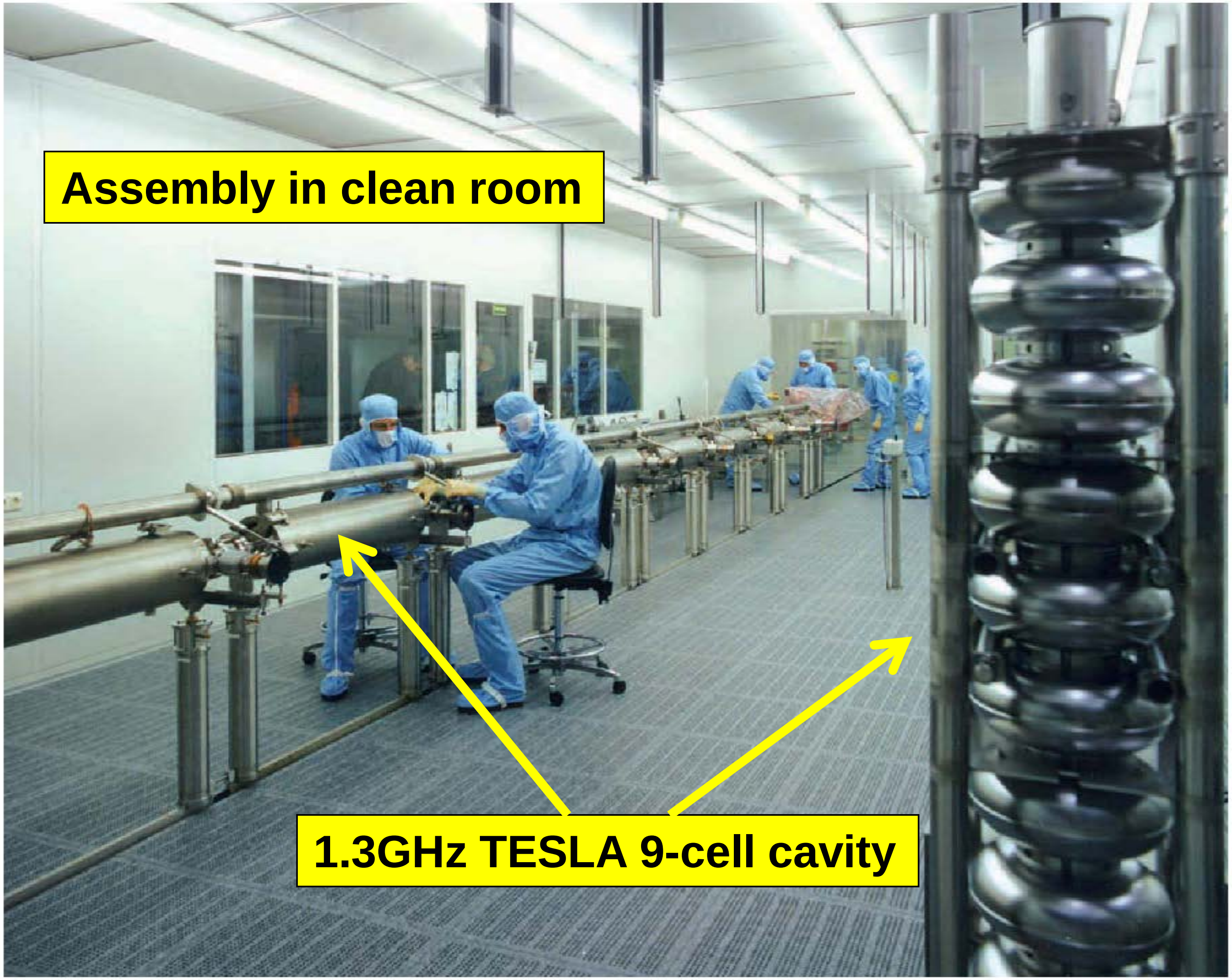
cavity connection in clean room for module installation



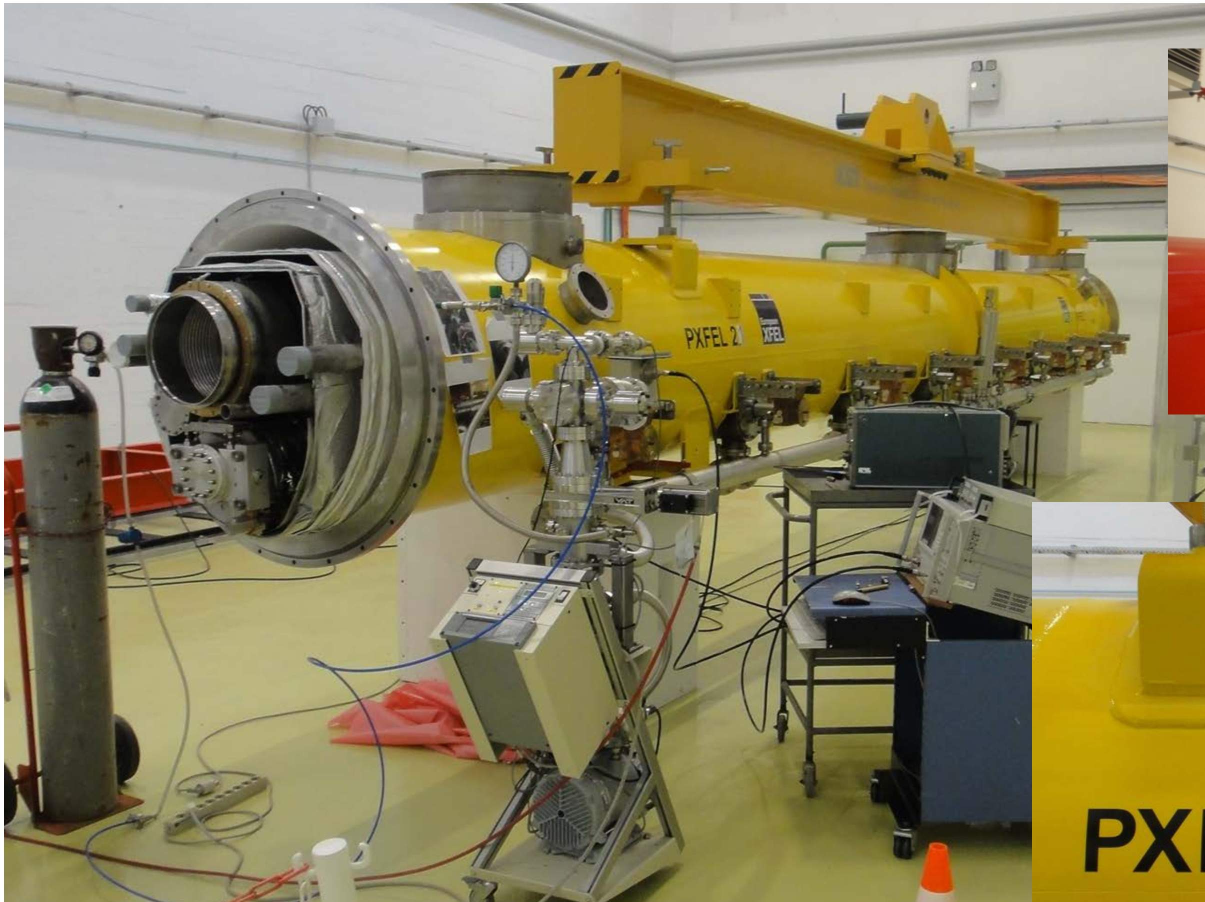
Tuner installation for FNAL, DESY cavities at outside of clean room

Carlo Pagani
Angelo Bosoti
Rocco Pararella
Serena Barbanotti

Cavity-String Assembly in Clean Room (DESY)



Saclay (March 2011)



7 March 2011 at Saclay

PXFEL 2.1 (DESY >>> Saclay >>> transportation to DESY within a few weeks)

The finished L1 section