Superconducting RF - II

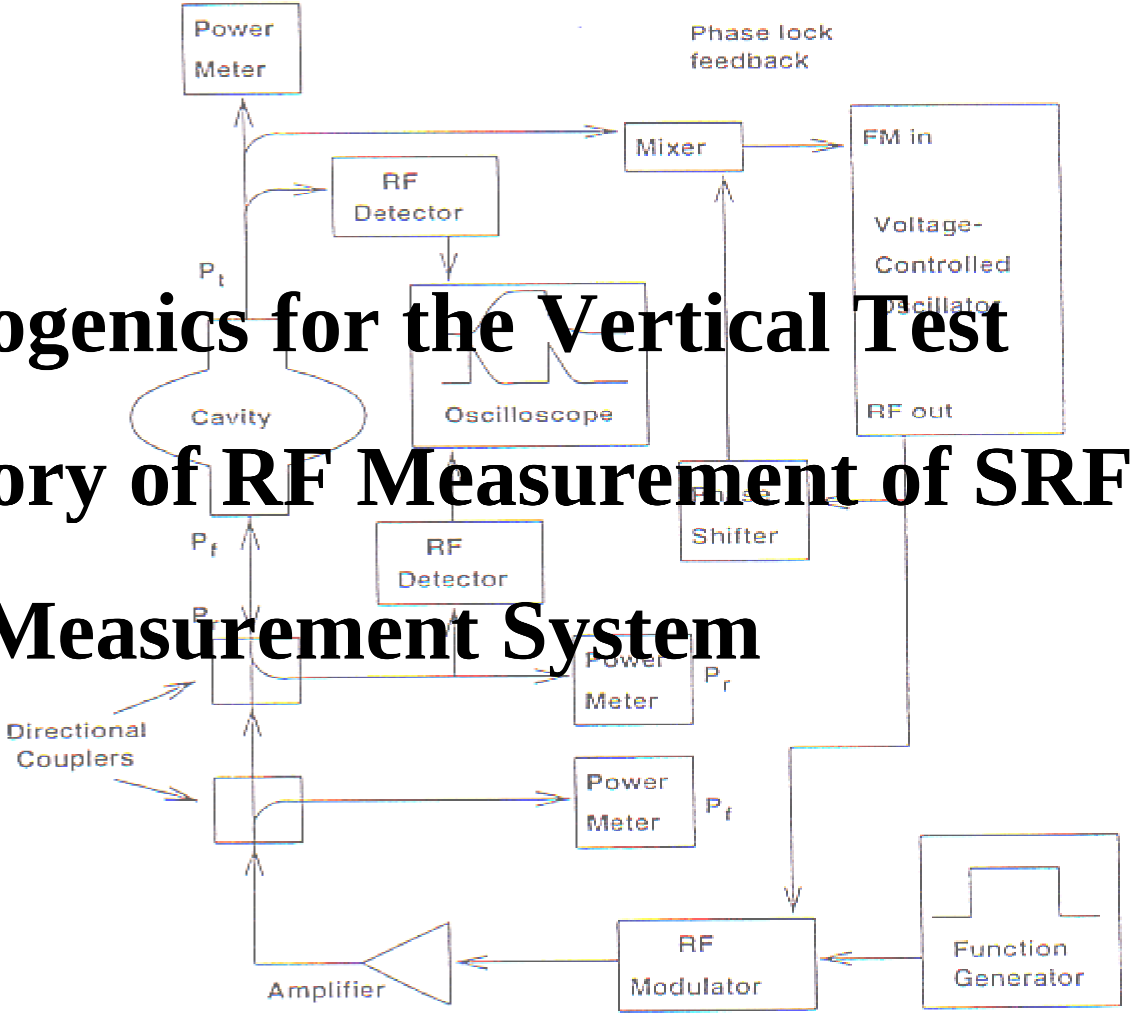
- Basics for SRF Technology -

K.Saito, KEK

13. Performance Measurement (Vertical Test)

14. Cavity R&D for ILC

13. Performance Evaluation (Vertical Test)

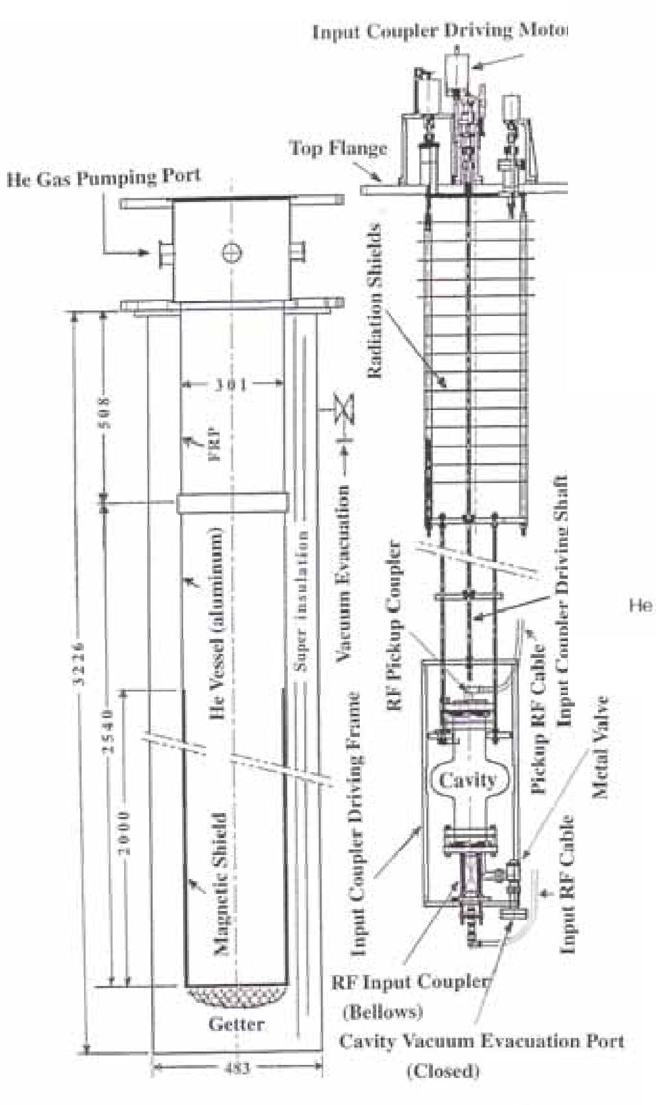


13.1 Cryogenics for the Vertical Test

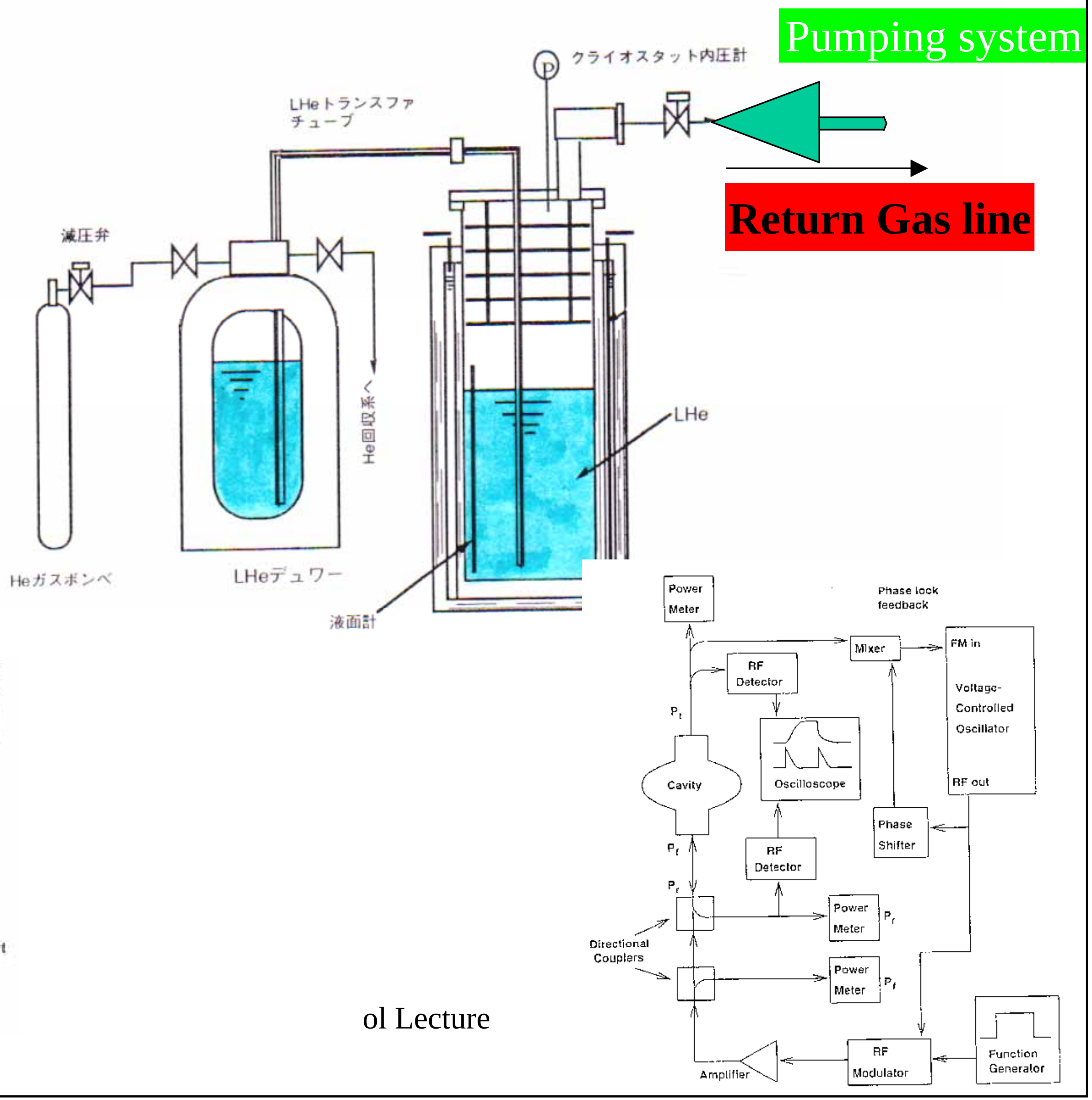
13.2 Theory of RF Measurement of SRF Cavities

13.3 RF Measurement System

13.1 Cryogenics System for Vertical Test



Vertical Cryostat Vertical Test Stand



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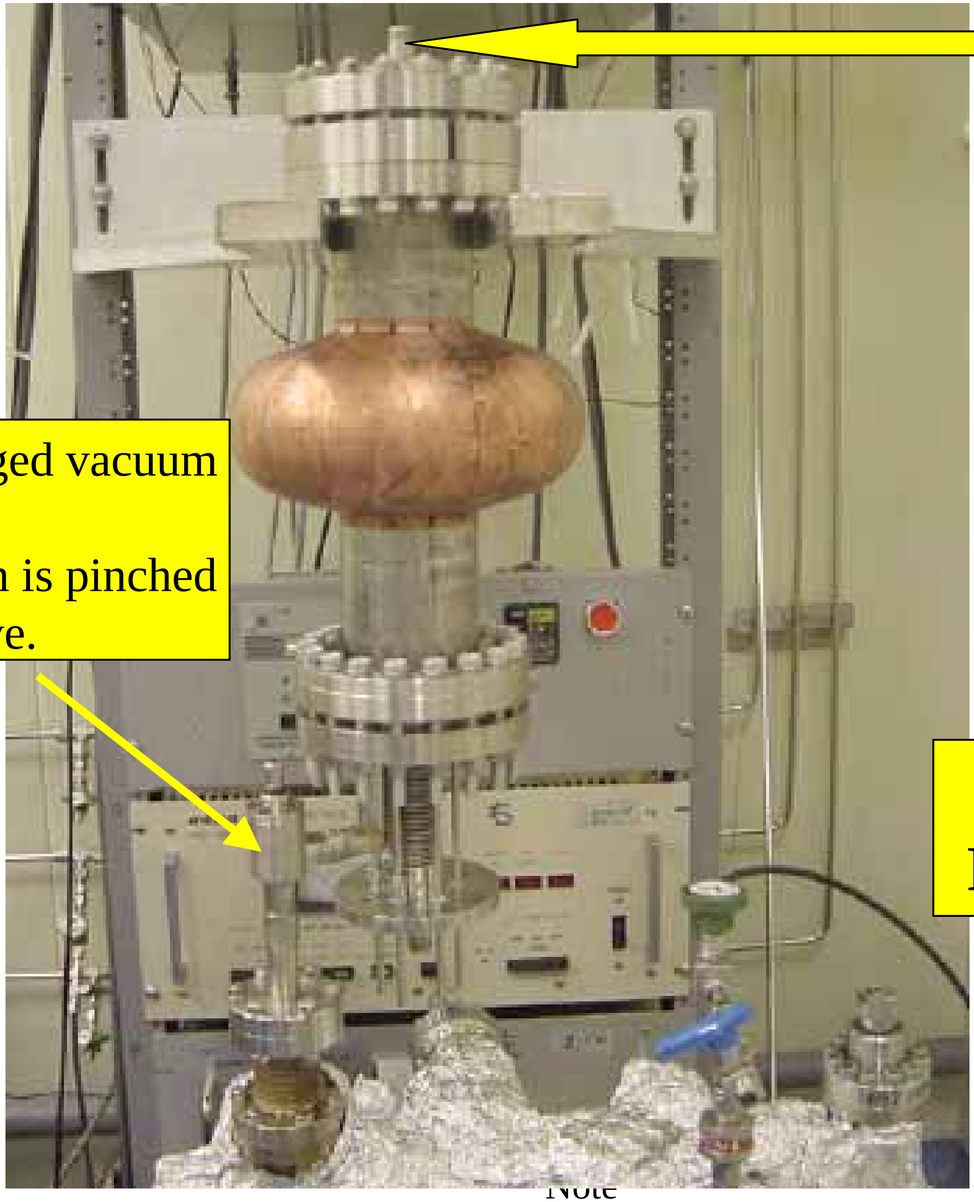
SRF Cavity (a Nb/Cu clad cavity)

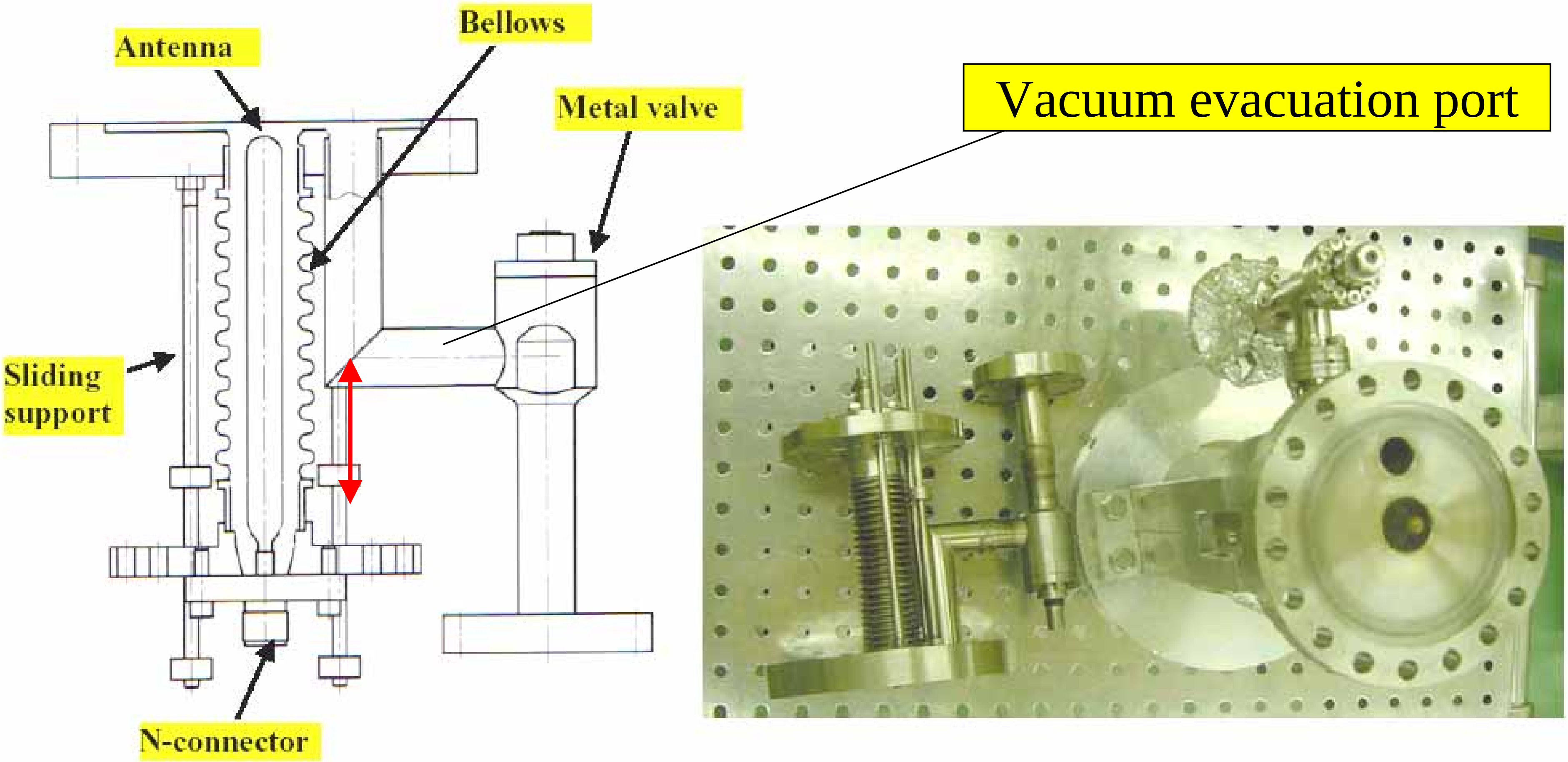


Pickup coupler

A SRF cavity hanged vacuum evacuation stand.
The cavity vacuum is pinched off by a metal valve.

Variable RF Input coupler

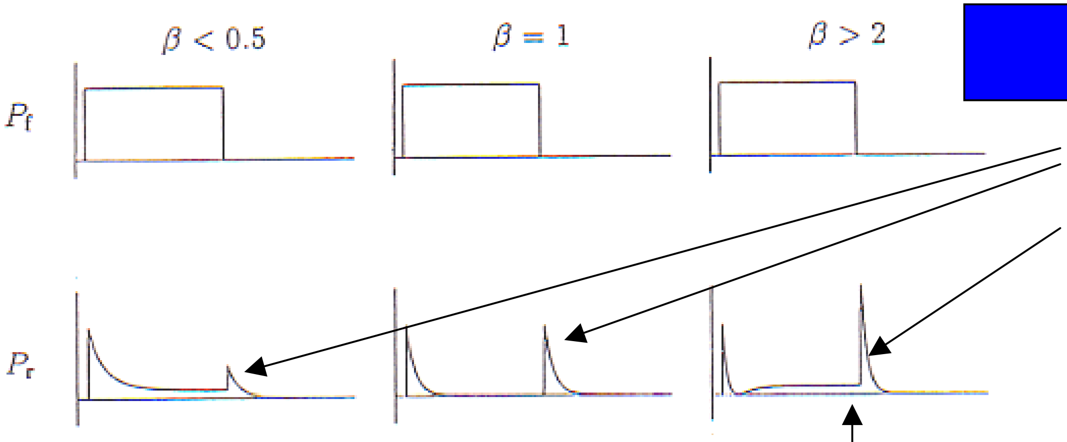
Structure of the Variable RF Input Coupler



Variable input coupler for the vertical test in KEK

13.2 Theory of RF Measurement of SRF Cavities

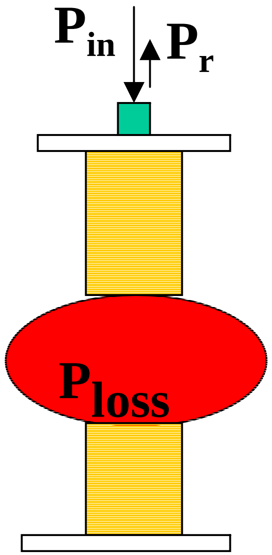
Pulse method



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

$\omega = 2\pi f$, Q_L : Loaded Q

One-port



Decatime : $\tau_{1/2}$

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

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

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

One-Port Cavity

$$\left.\begin{matrix}\tau_{1/2}\\ P_{in}\\ P_r\end{matrix}\right\}\ \text{Measurement}$$

Calculation Q_L, β_{in}

Calculation Qo

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

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

$$Q_L \equiv \frac{\omega U}{P_{loss} + P_e} = \frac{\omega U}{P_{loss}\left(1 + \frac{P_e}{P_{loss}}\right)} \quad \text{(for one port)}$$

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

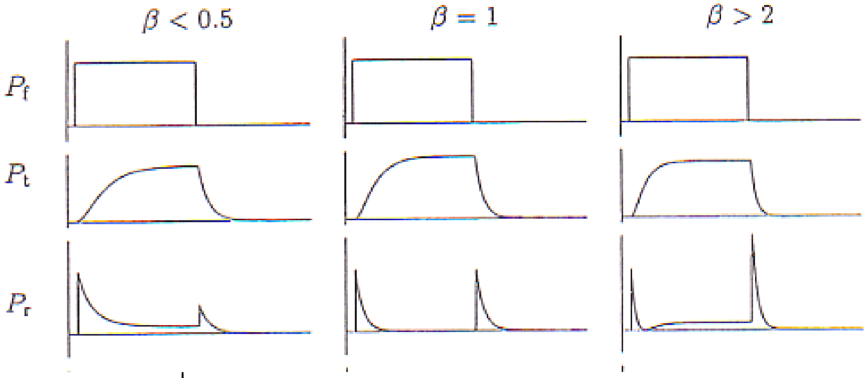
$$Q_O = (1+\beta_{in}) \cdot Q_L$$

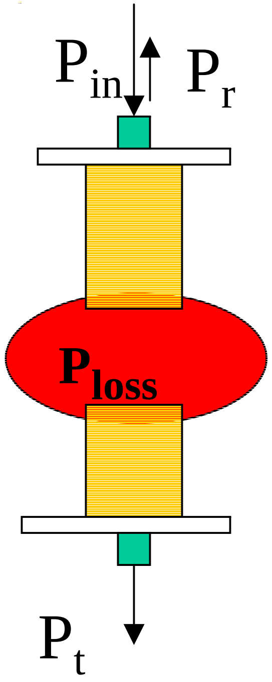
Equivalent Circuit model

Judgment from Pr

$$\beta_{in} \equiv \frac{P_e}{P_{loss}} = \frac{1 \pm \sqrt{P_r / P_{in}}}{1 \mp \sqrt{P_r / P_{in}}} \quad \text{(over > 1 / under < 1)}$$

Two-Port Cavity





$$P^*_{loss} = P_{loss} + P_t$$

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

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

measurement

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

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

measurement

$$\beta^*_{in} = \frac{1 \pm \sqrt{P_r / P_{in}}}{1 \mp \sqrt{P_r / P_{in}}}$$

(over > 1/ under < 1)

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

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

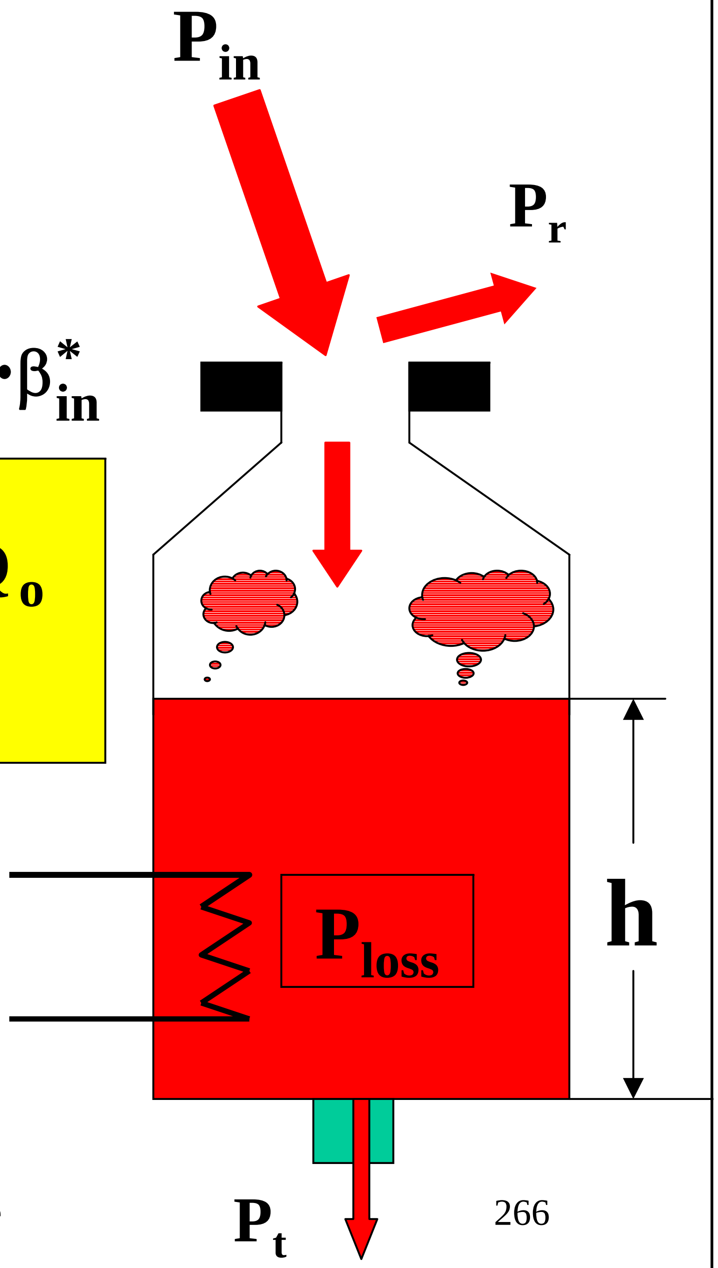
$$= \left[1+(1+\beta_t)\cdot\beta_{in}^* + \beta_t\right]\cdot Q_L$$

$$= \left(1+\beta_{in}+\beta_t\right)\cdot Q_L \quad \because\ \beta_{in} \equiv (1+\beta_t)\cdot\beta_{in}^*$$

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

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

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



Stationary state：h = const ⇐ U const

Calculation of Gradient

Exercise VIII.

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

$$= \frac{(Eacc \cdot d_{eff})^2}{P_{loss}}$$

$$Eacc = \frac{1}{d_{eff}} \cdot \sqrt{R_{sh} \cdot P_{loss}} = \frac{\sqrt{R_{sh} / Q_O}}{d_{eff}} \cdot \sqrt{Q_O \cdot P_{loss}} = Z \cdot \sqrt{Q_O \cdot P_{loss}}$$

$$= Z \cdot \sqrt{Q_t \cdot P_t}$$

$$\because\ Q_O \cdot P_{loss} = Q_t \cdot P_t$$

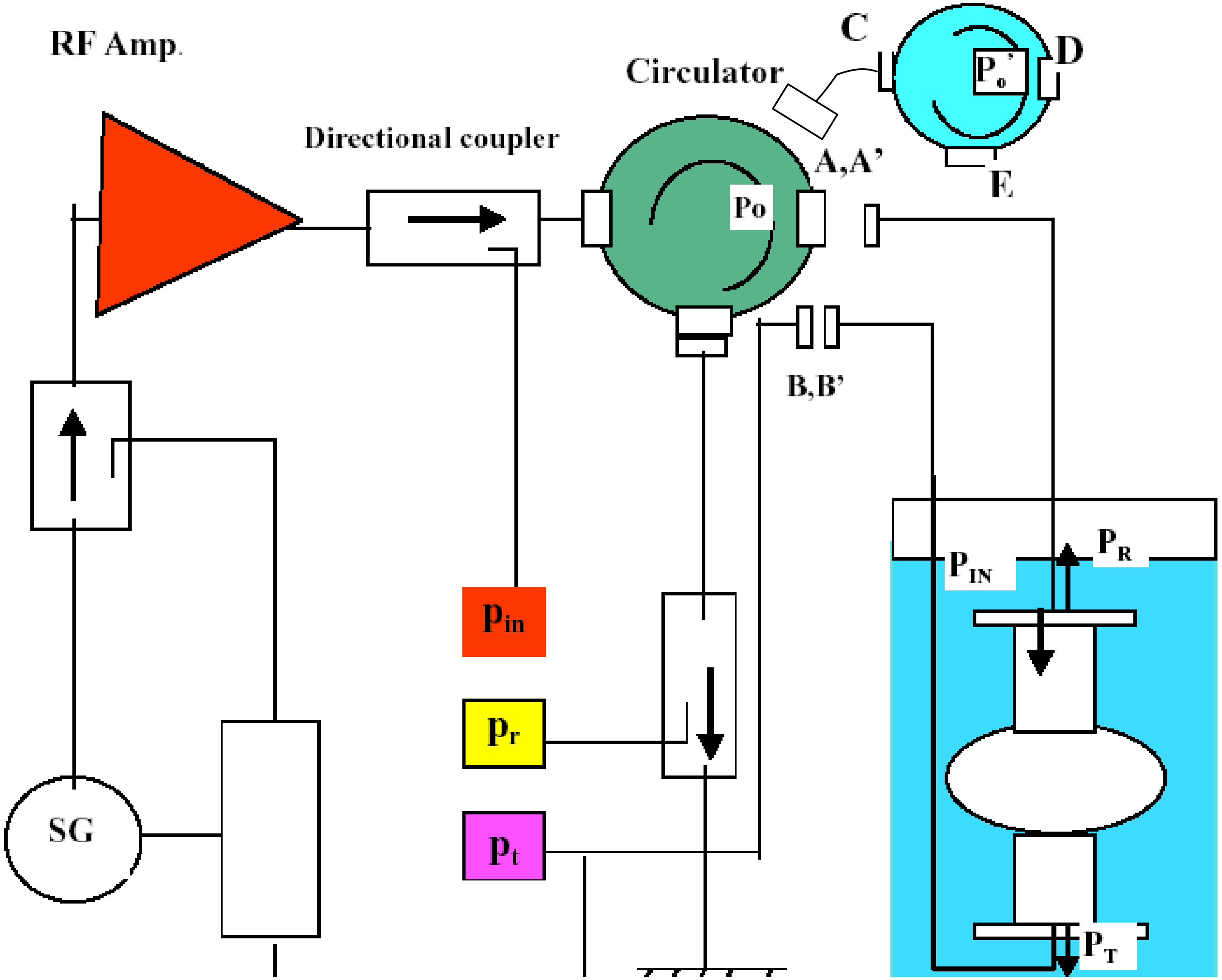
Once measured the Q_t, you can calculate Eacc directly from P_t and Q_t.
Q_O is also directly calculated from them.
You don’t need to measure the decay time for every gradient.

Cable Correction

Exercise VII.

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'

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

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

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

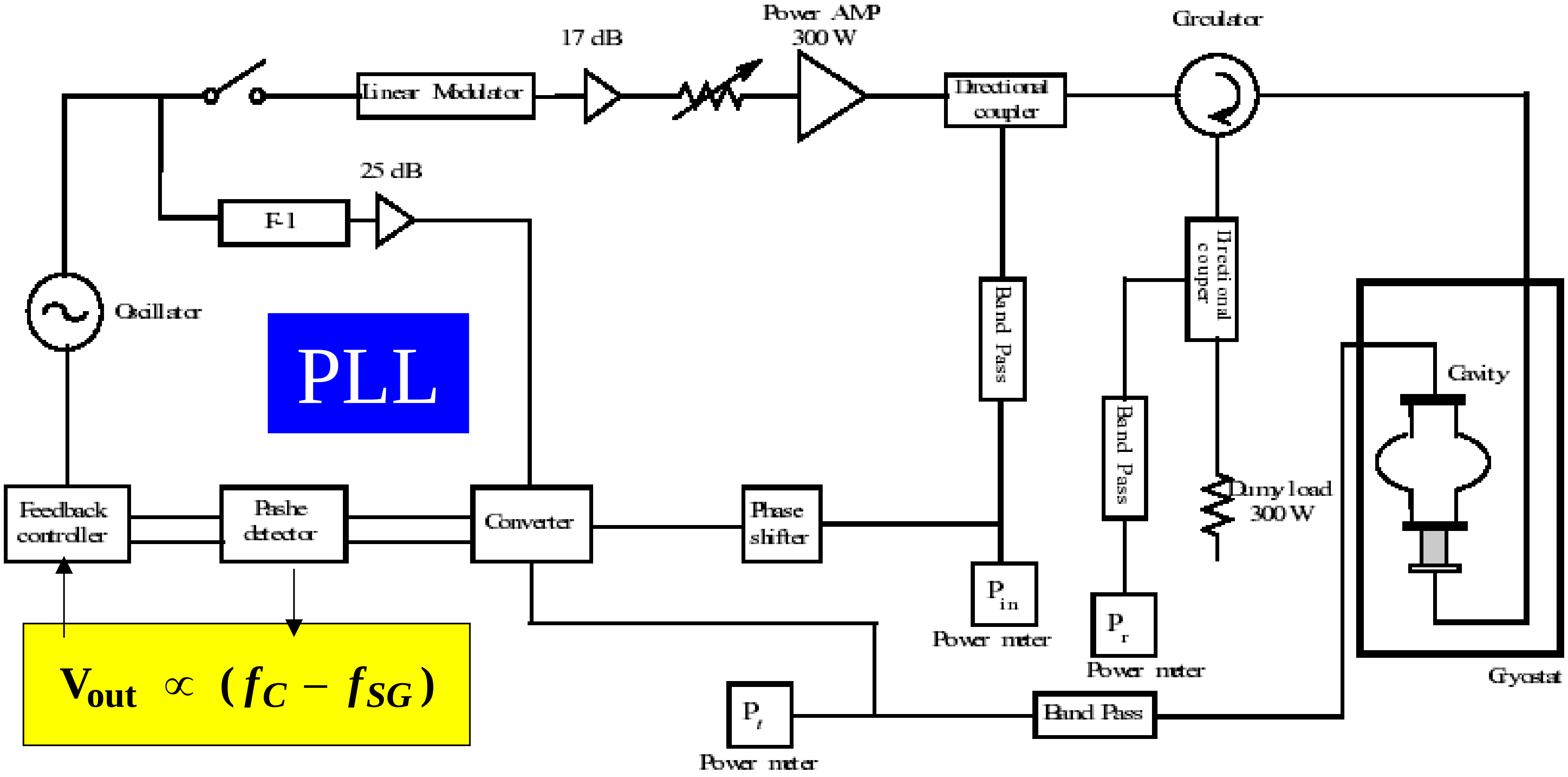
$P_{IN} = c_{in} \cdot p_{in}$

$P_R = c_r \cdot p_r$

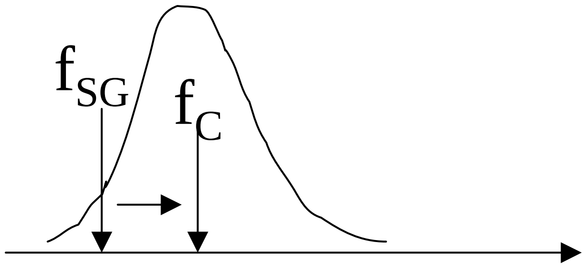
$P_T = c_t \cdot p_t$

Note

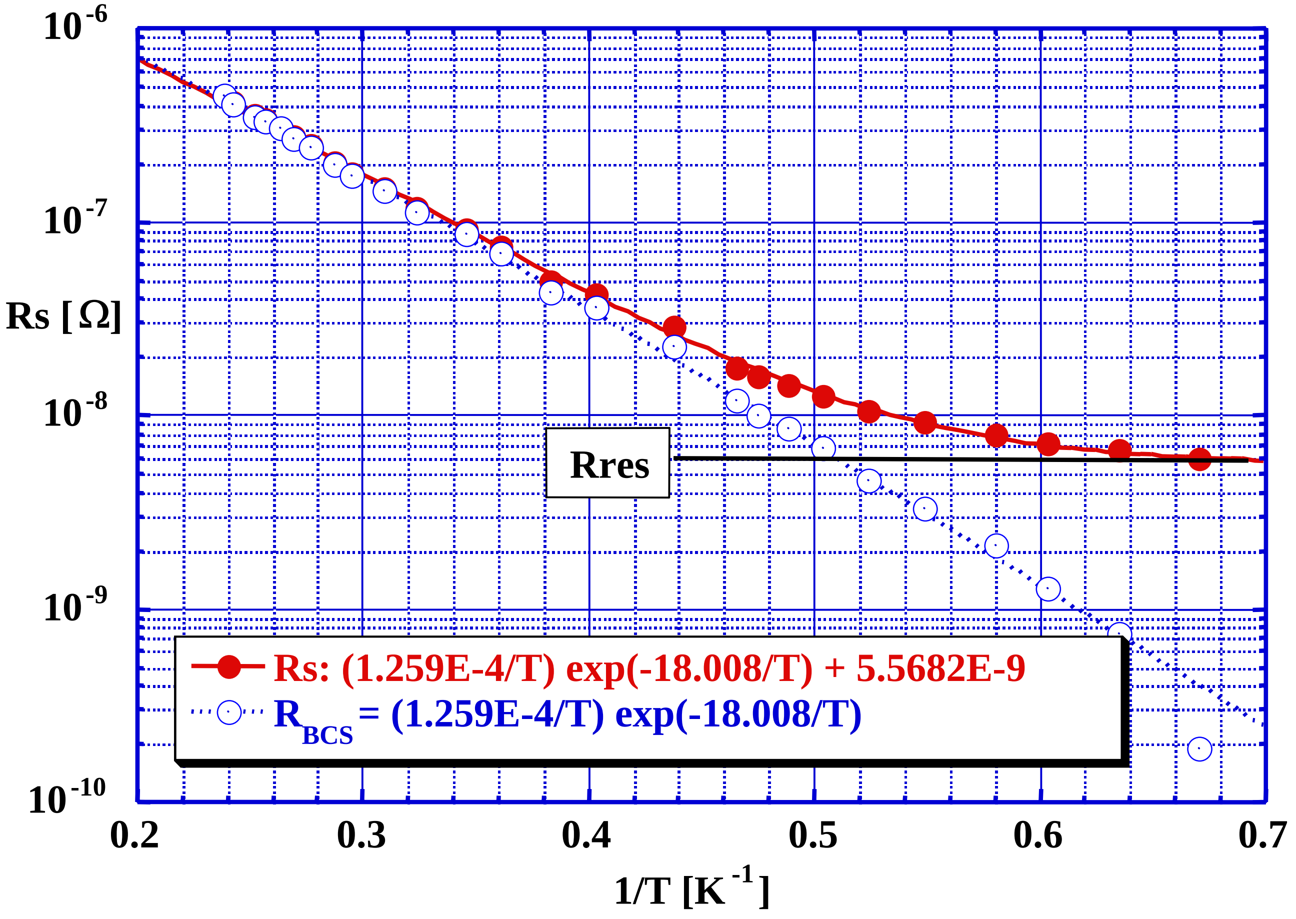
13.3 RF Measurement System



$V_{out} \propto (f_C - f_{SG})$



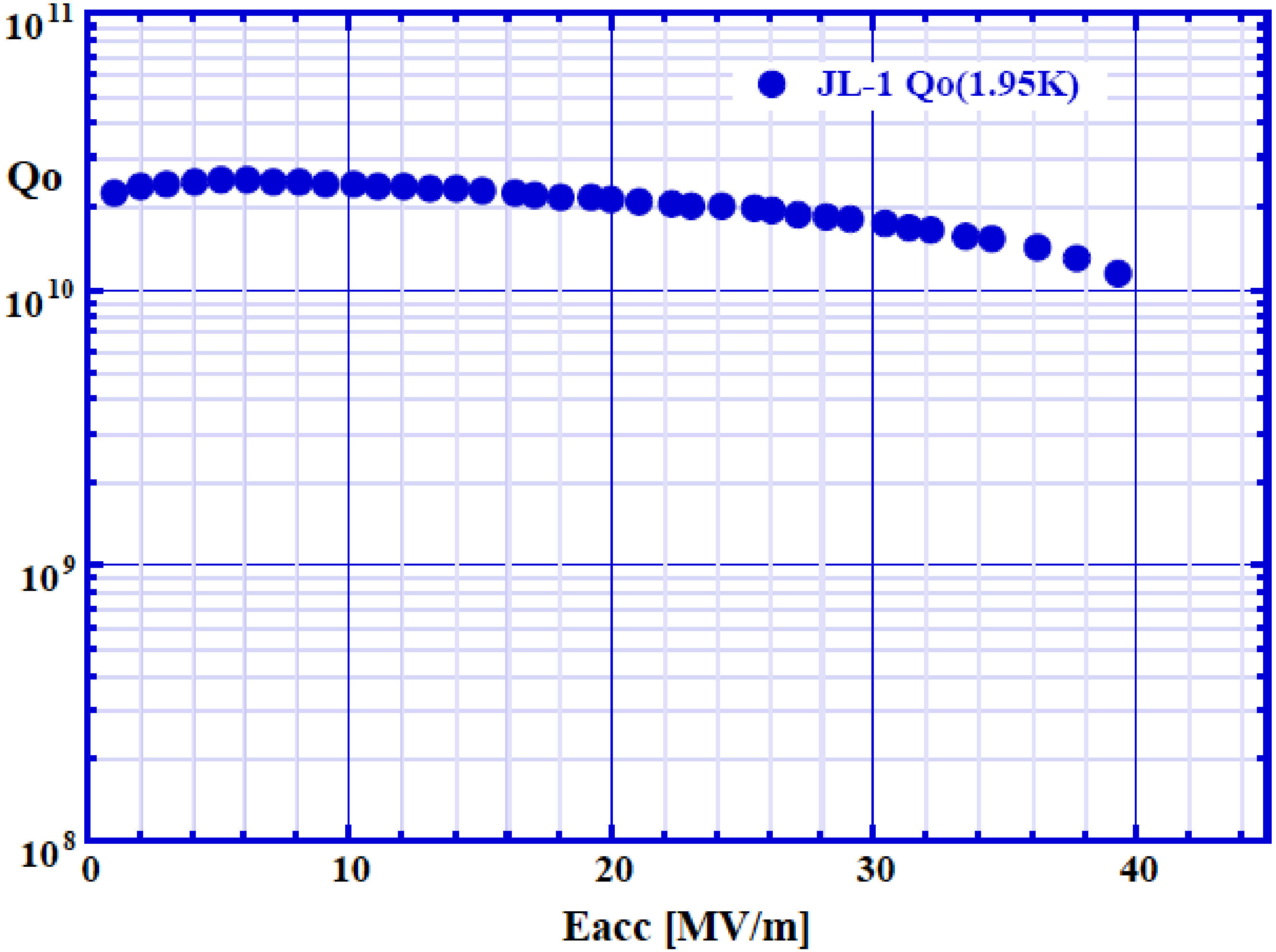
Measurement of Surface Resistance



$$R_S - \mathrm{fit}: R_S(T) = \frac{A}{T} \cdot \exp\left(-\frac{B}{T}\right) + R_{res}$$

$$B = \frac{\Delta}{k_B}$$

High Gradient Measurement Qo-Eacc curve



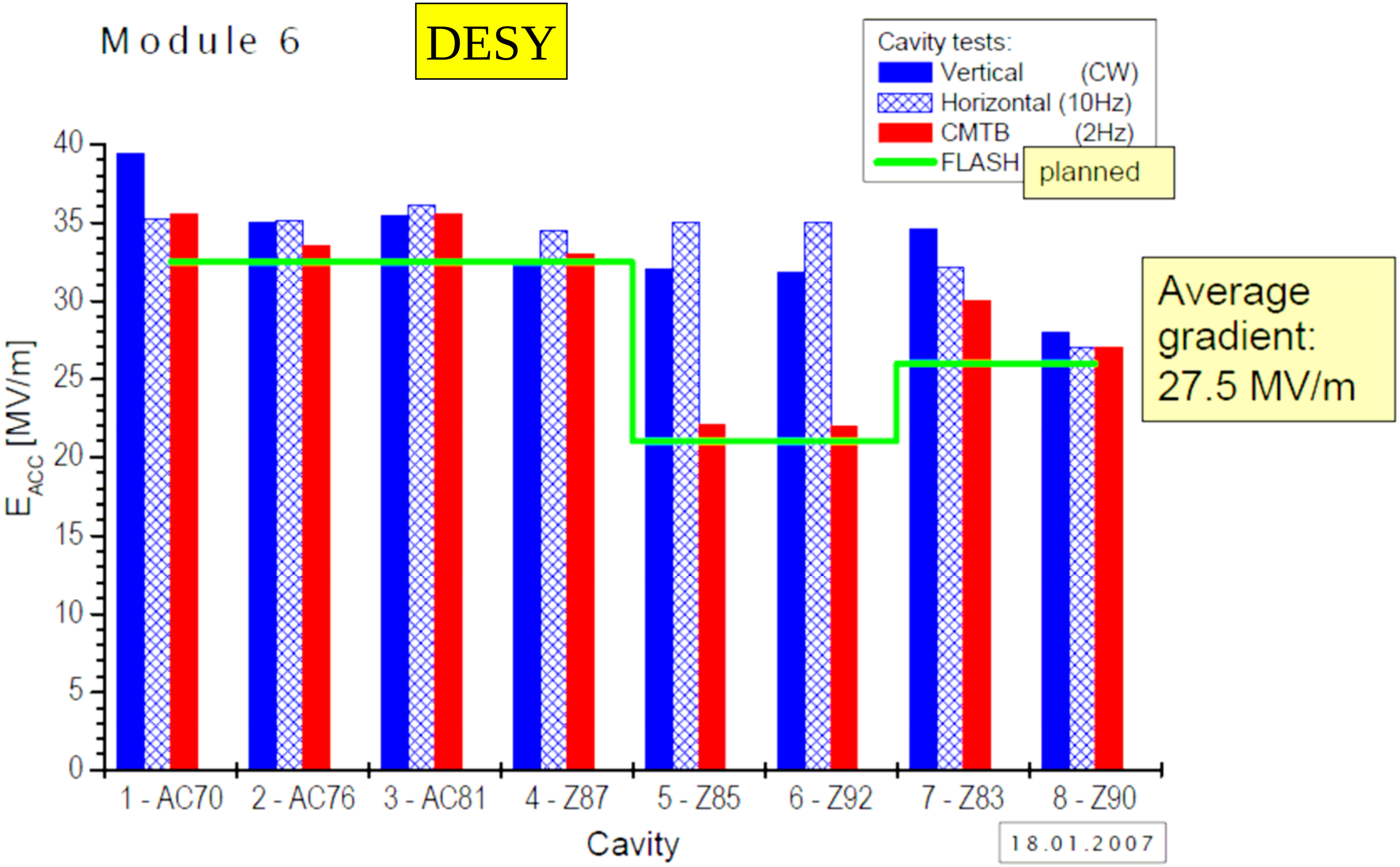
12. Cavity R&D for ILC
- High Priority issues -

12.1 Establish the preparation method for the reproducible 35MV/m

12.2 Lorentz Detuning issue
- END Group design
- Lorentz Detuning Compensation by Piezo

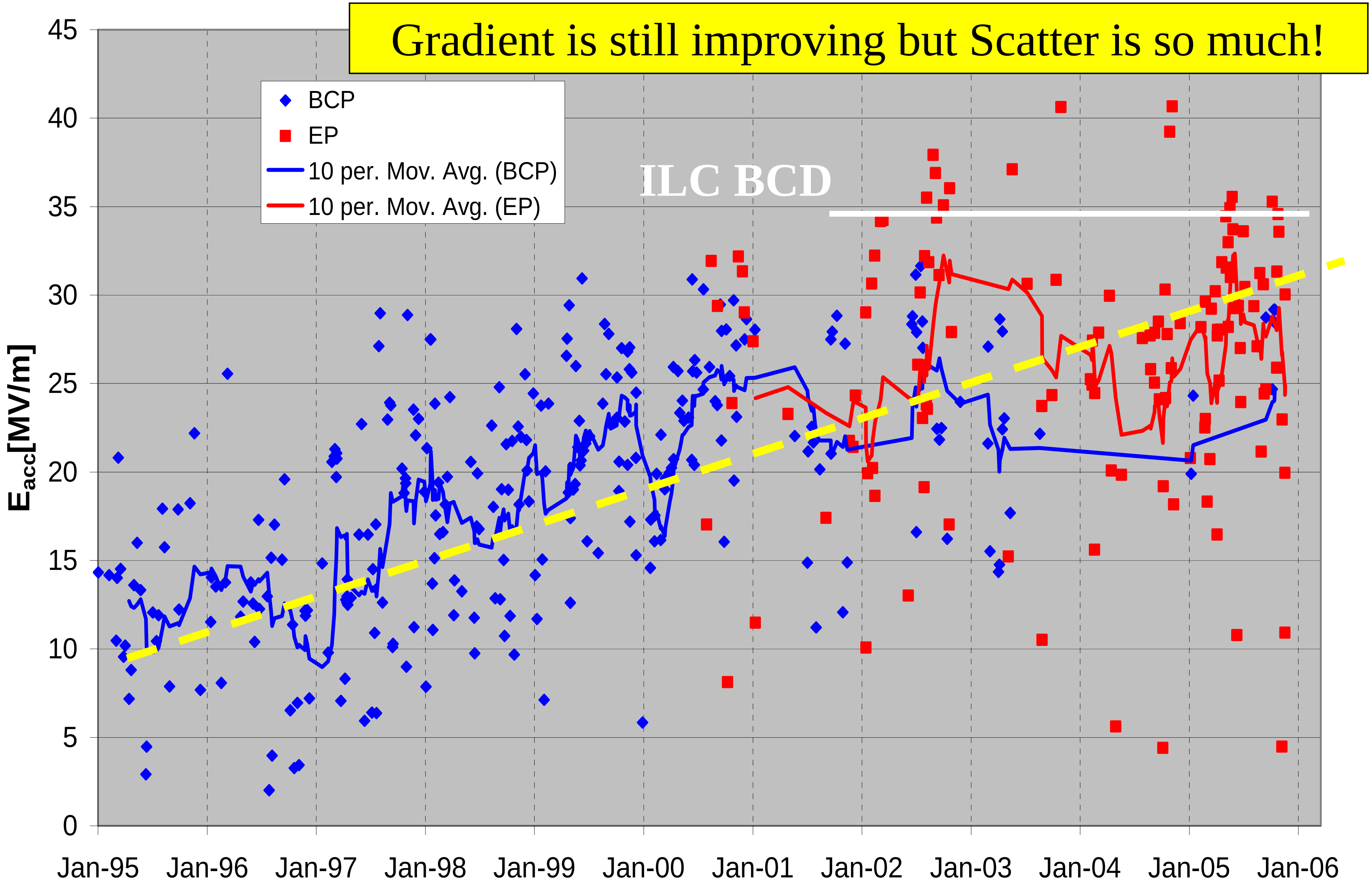
12.3 Cavity Fabrication Cost Reduction
- Large Grain Nb material
- Seamless cavity

35MV/m High Gradient Cryomodule Demonstration @ DESY



Scatter at DESY E_{acc} vs. time

Gradient is still improving but Scatter is so much!

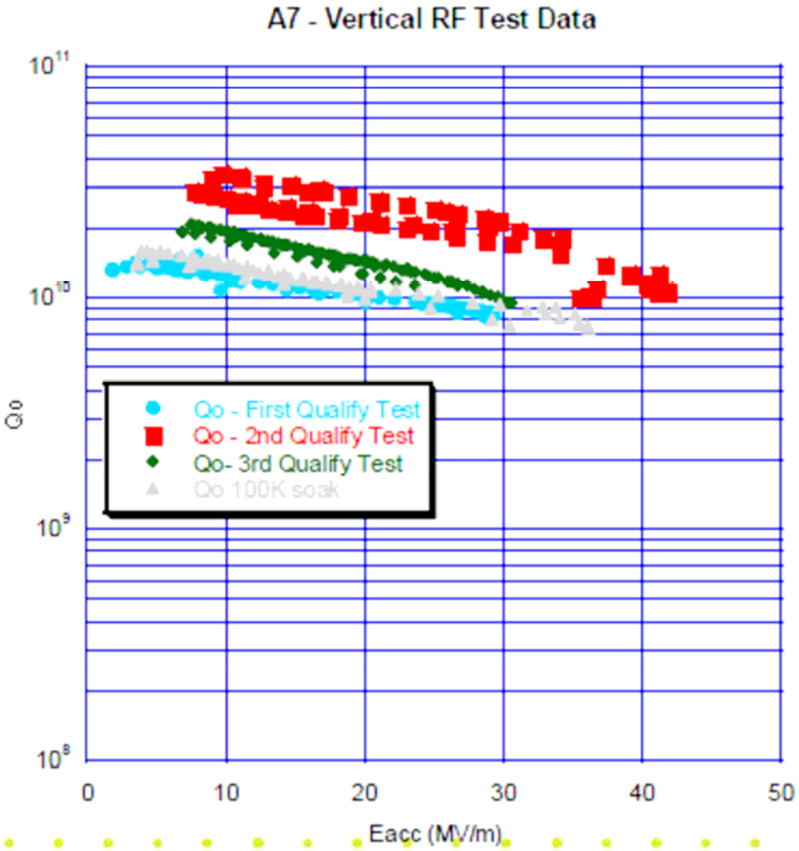


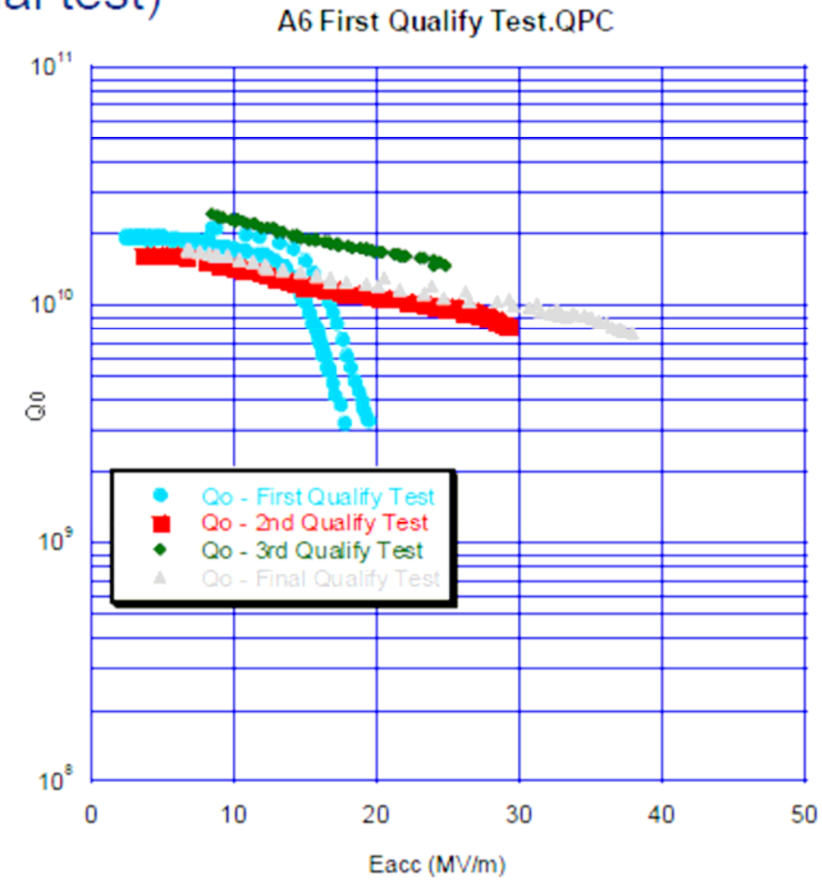
40MV/m Performance by Degreasing

ILC 9-cell cavity S0 tight loop test

By J.Mammosser

- Second candidate rinse
  - Ultrasound degrease
- All curves but one limited by quench
- Field emission in one test (A6 final test)



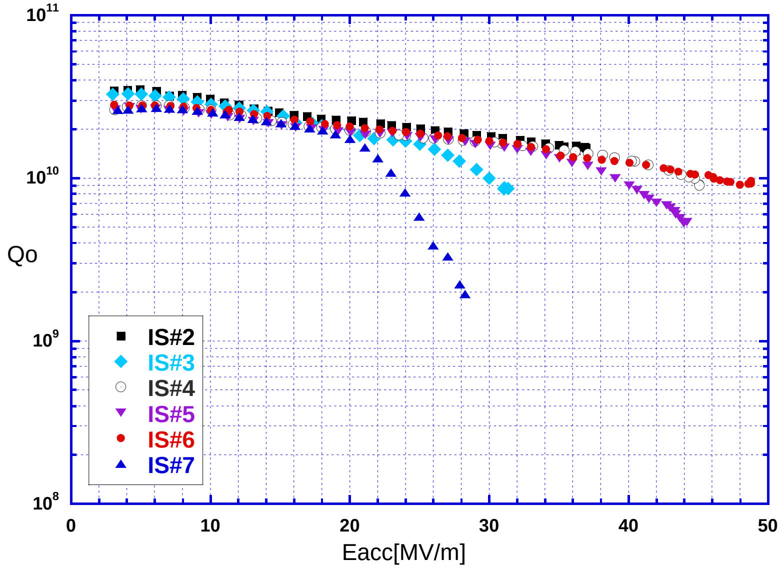


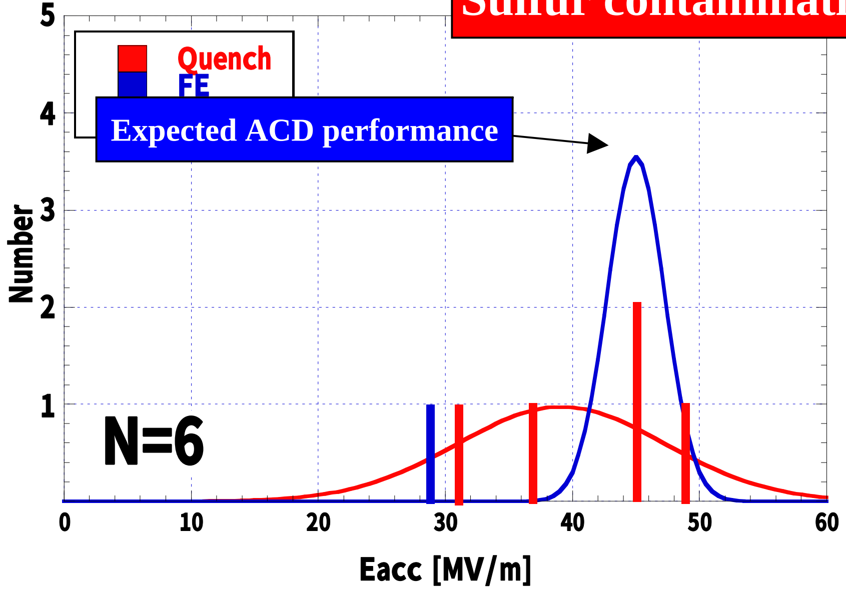
CBP(100μm)+CP(10μm)+Anneal(3hr@750^{O}C)+EP(80μm)+HPR+Baking

Single cell cavity study @ KEK

Large scatter!

Sulfur contamination?





Ave. Eacc=39.1±8.2MV/m

Scattering:20%, Acceptability@40MV/m(ACD):50%

		IS#2	IS#3	IS#4	IS#5	IS#6	IS#7
EP(80)	Eacc	36.90	31.40	45.10	44.20	48.80	28.30
	Qo	1.53e10	8.66e9	9.07e9	5.38e9	9.64e9	1.94e9

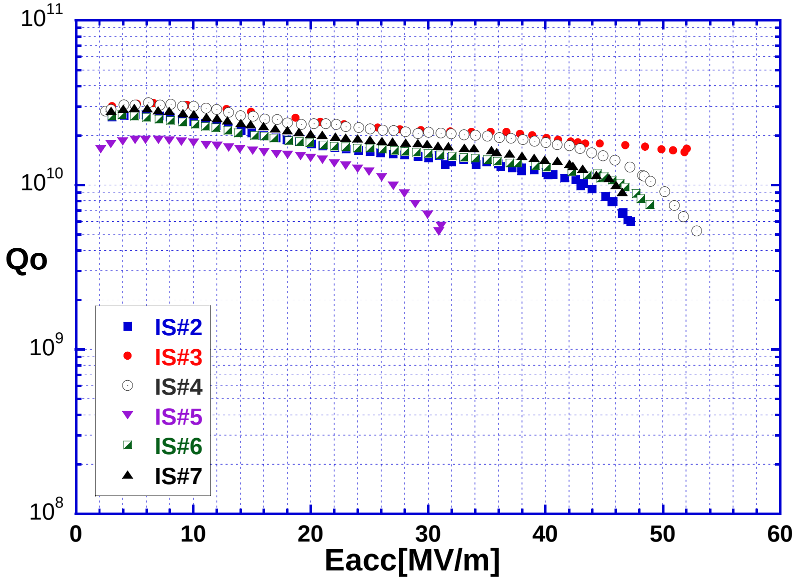
Development of the preparation with reproducible 35MV/m

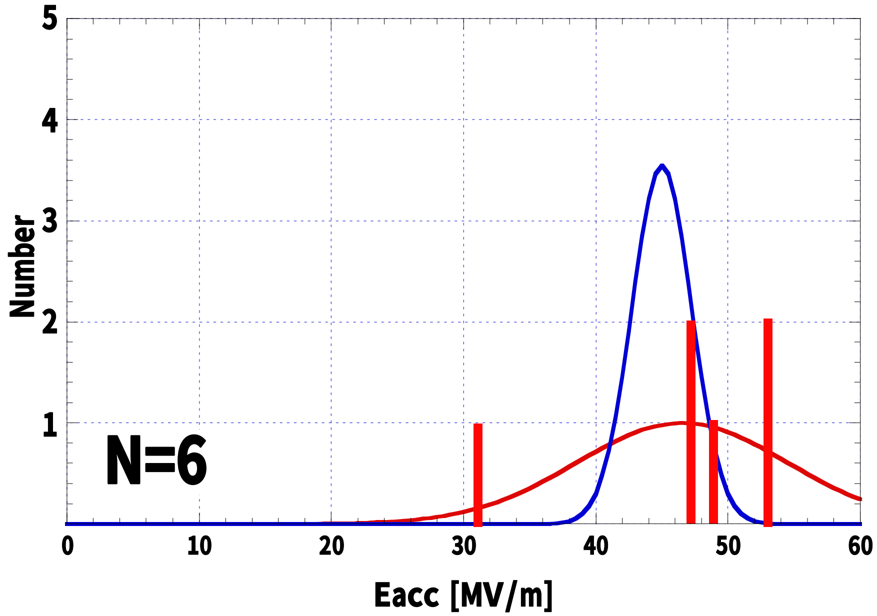
S0 Single Cell Study @ KEK on 21 Apr 2007

	Eacc,max [MV/m] / Qo @ Eacc,max									Emax average [MV/m]	Scatt. [%]	MP	Acceptability @ 40M V/m [%]
	IS#2	IS#3	IS#4	IS#5	IS#6	IS#7	IS#8	CLG#1	CLG#2				
CBP+CP+AN+EP(80) +HPR+ Bake	36.9	31.4	45.1	44.2	48.8	28.3				39.1 ± 8.2	21	Yes	50
	1.53E10	8.66E9	9.07E9	5.38E9	9.64E9	1.94E9							
CBP+CP+AN+ EP(80+3 fresh) +HPR+Bake		42.0	46.1	44.3	34.3	39.3			43.8	41.7 ± 4.4	11	Yes	67
		9.72E9	9.47E9	1.08E10	8.56E9	1.03E10			3.46E9				
CBP+CP+AN+ EP(40+3 fresh) +HPR+Bake	43.9						49.2*			46.6 ± 3.7	8	Yes	100
	9.47E9						4.33E9						
+EP(20)+HPR+Bake	47.2	52.2	52.9	31.1	48.9	46.5				46.4 ± 8.0	17	Yes	83
	5.98E9	1.51E10	5.23E9	5.21E9	7.56E9	9.03E9							
+EP(20+3 fresh)+HPR +HF+Bake	47.1	44.7	47.8		48.6	43.9		47.9		46.7 ± 1.9	4	Yes	100
	1.06E10	9.80E9	7.80E9		8.00E9	1.17E10		1.00E10					
+EP(20)+H_2O_2+HPR+ Bake	52.3			34.1	43.4	40.9				42.7 ± 6.0	18	Light	50
	1.09E10			1.37E10	1.39E10	3.01E9							
+EP(20)+Degreasing (US)+HPR+ Bake	50.1	52.2								51.2 ±1.5	2.9	Lights	100
	7.80E10	7.08E9											
Others Megasonic													

IS: Ichiro center cell shape, Tokyo Denkai polycrystalline Nb material
CLG: NingXia Large grain, Ichiro center cell shape

+EP(20μm)+HPR+Baking





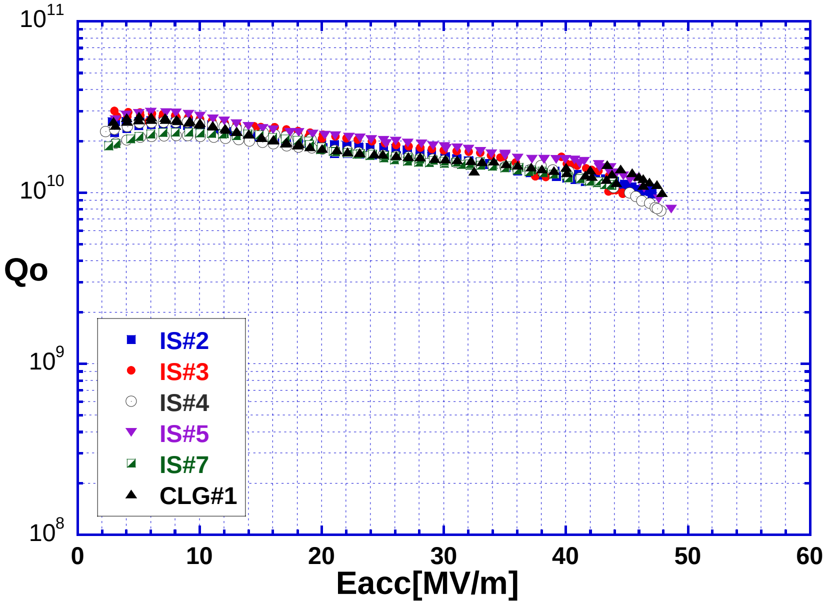
Light EP is effective to increase Eacc average,
but large scatter appears again.

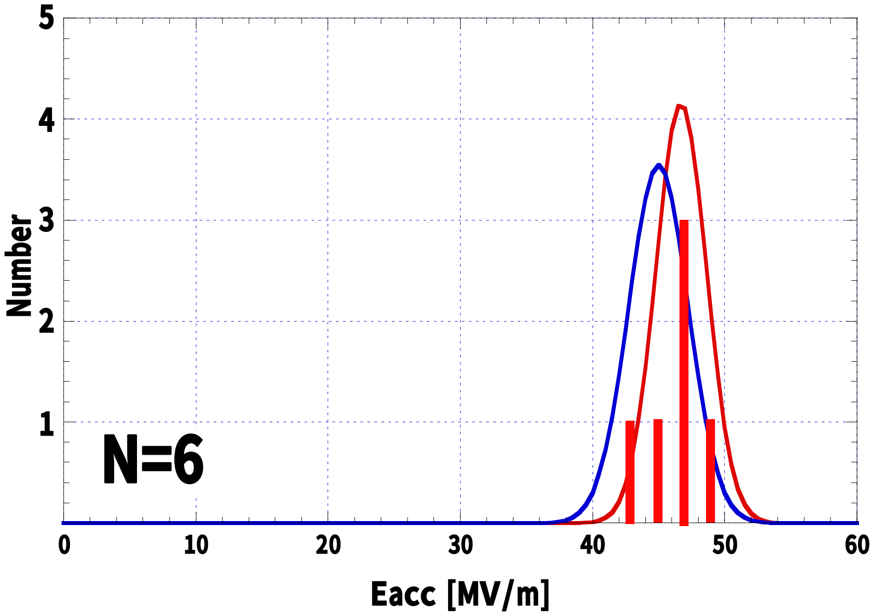
Ave. Eacc=46.5±8.0MV/m

Scattering:17%, Acceptability@40MV/m(ACD):83%

		IS#2	IS#3	IS#4	IS#5	IS#6	IS#7
+EP(20)	Eacc	47.24	52.44	52.91	31.10	48.92	46.53
	Qo	5.98e9	1.51e10	5.23e9	5.21e9	7.56e9	9.03e9

+EP(20μm)+EP(3μm, fresh, closed) +(HF*or No HF)+HPR+Baking





HF rinsing is no effective.

Light EP +EP(3) is effective for both high gradient and narrow scatter.

Ave. Eacc=46.7±1.9MV/m

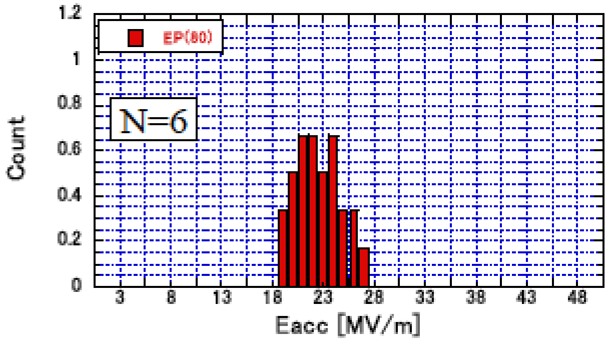
Scattering:4%, Acceptability@40MV/m(ACD):100%

		IS#2	IS#3	IS#4	IS#6	IS#7	CLG#1
+EP(20+3) +HF*	Eacc	47.07	44.67*	47.82	48.60*	43.93*	47.90*
	Qo	1.06e10	0.98e10	0.78e10	0.80e10	1.17e10	1.0e10

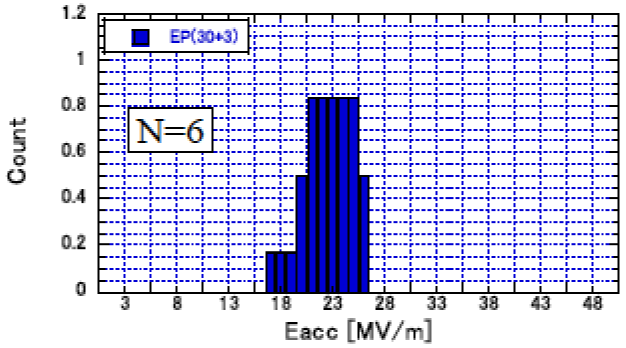
Multipacting

Probability of X-ray appearance

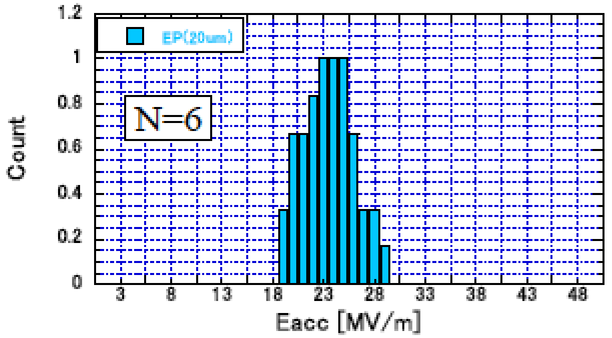
EP(80um)



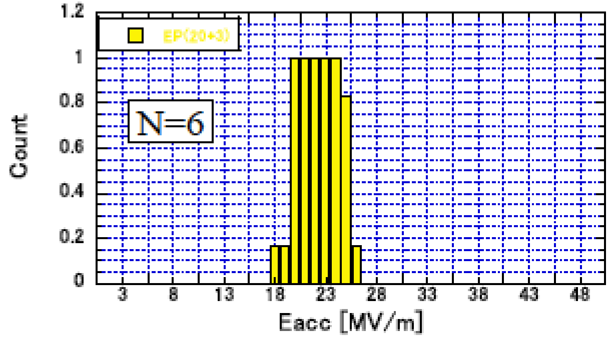
EP(80+3um)



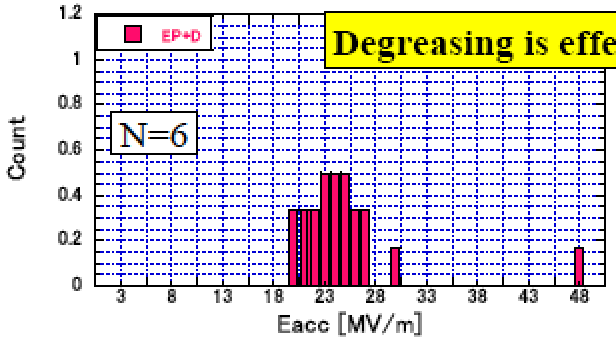
EP(20um)



EP(20+3um)

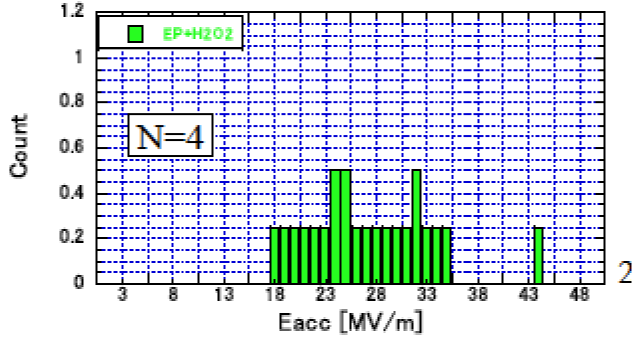


EP(20um)+Degreasing

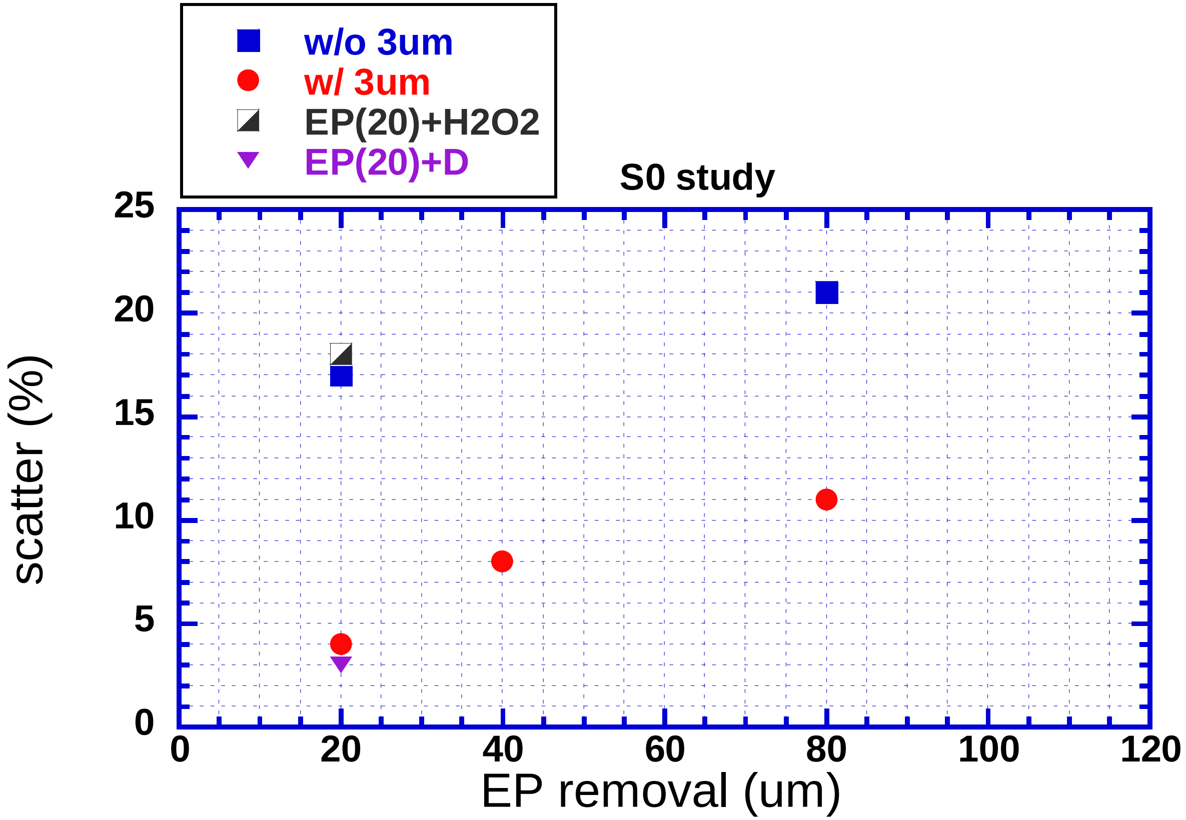


Degreasing is effective !

EP(20um)+H2O2



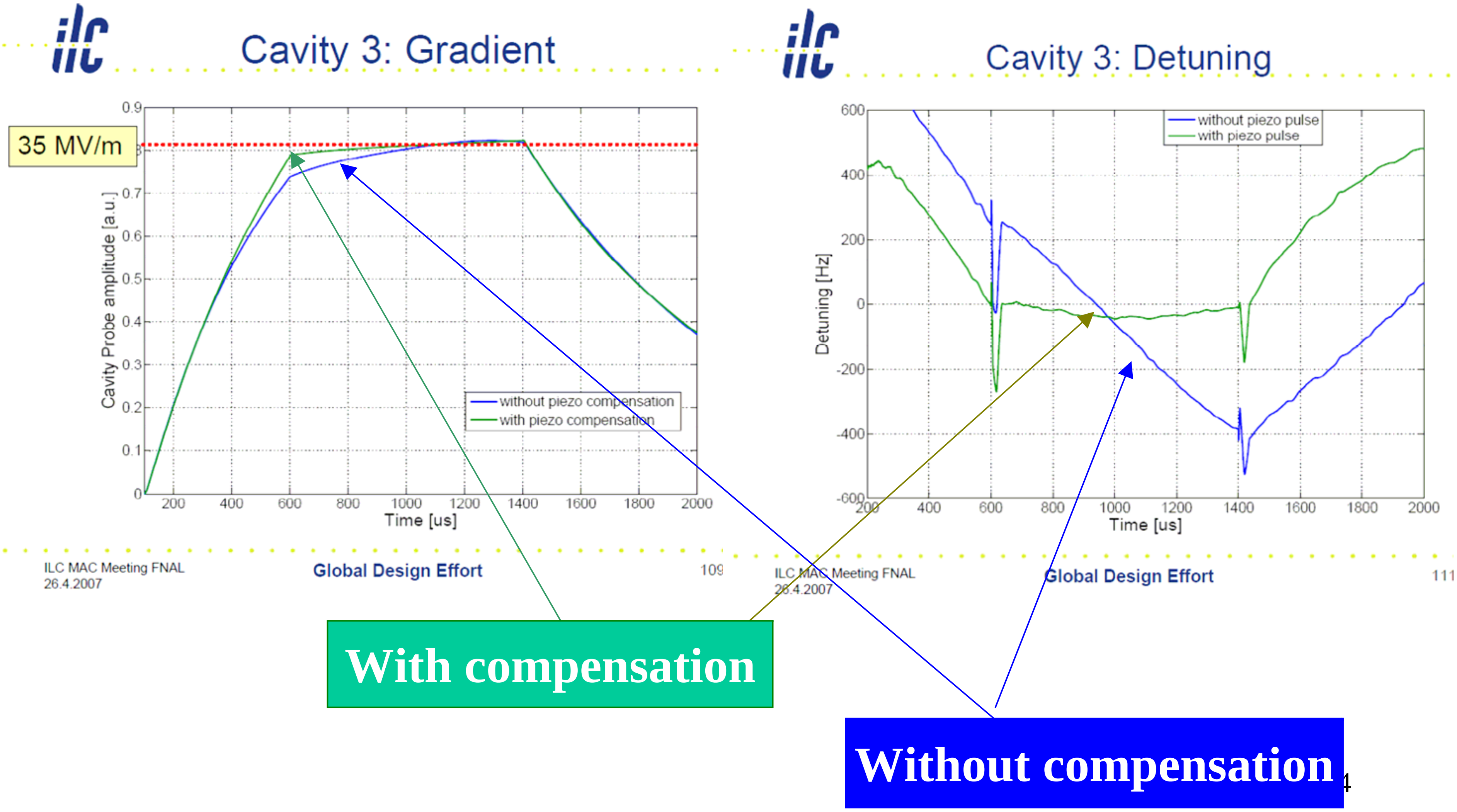
Eacc max scattering



	EP(20)	EP(20+3)	EP(80)	EP(80+3)	EP(20)+H_2O_2	EP(20)+D
Eacc ave	46.5±8.0	46.7 ±1.9	39.1±8.2	41.7±4.4	42.6±7.6	51.2±1.4
Scatter(%)	17	4	21	11	18	3
N	6	6	6	6	4	2

Lorentz Detuning Compensation by Piezo

Demonstration of Lorentz detuning compensation @ 35MV/m operation


Cavity 3: Gradient

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Cavity 3: Detuning

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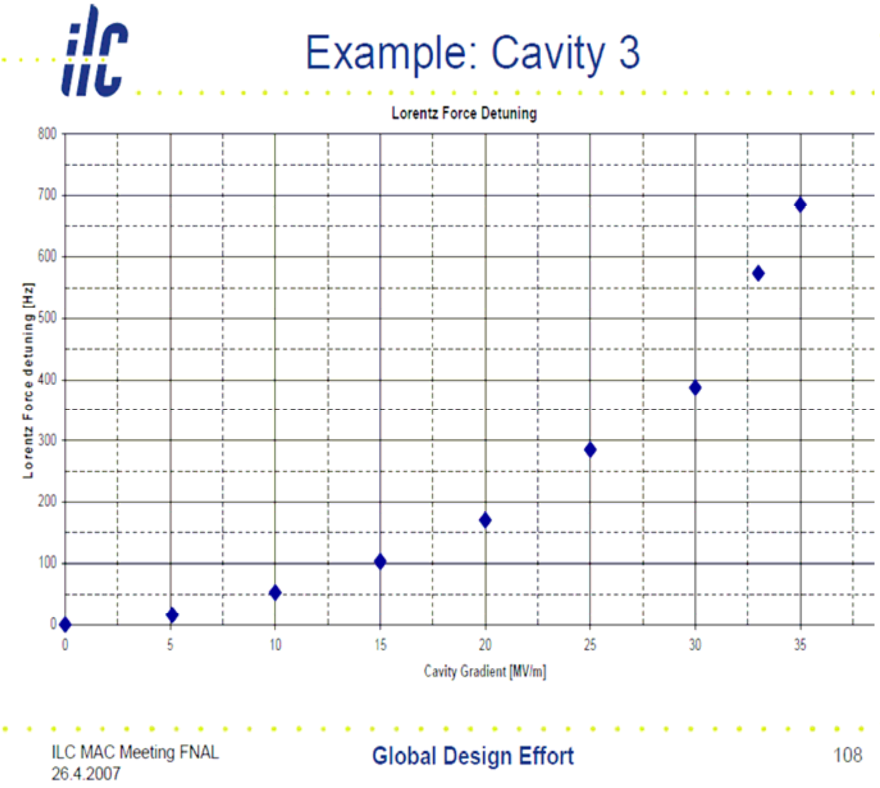
With compensation

Without compensation

Lorentz Detuning @ 35MV/m (TESLA shape)

$$\Delta f = \kappa_L \cdot E_{acc}{}^2, \quad \kappa_L = 1Hz/(MV/m)^2$$



Example: Cavity 3

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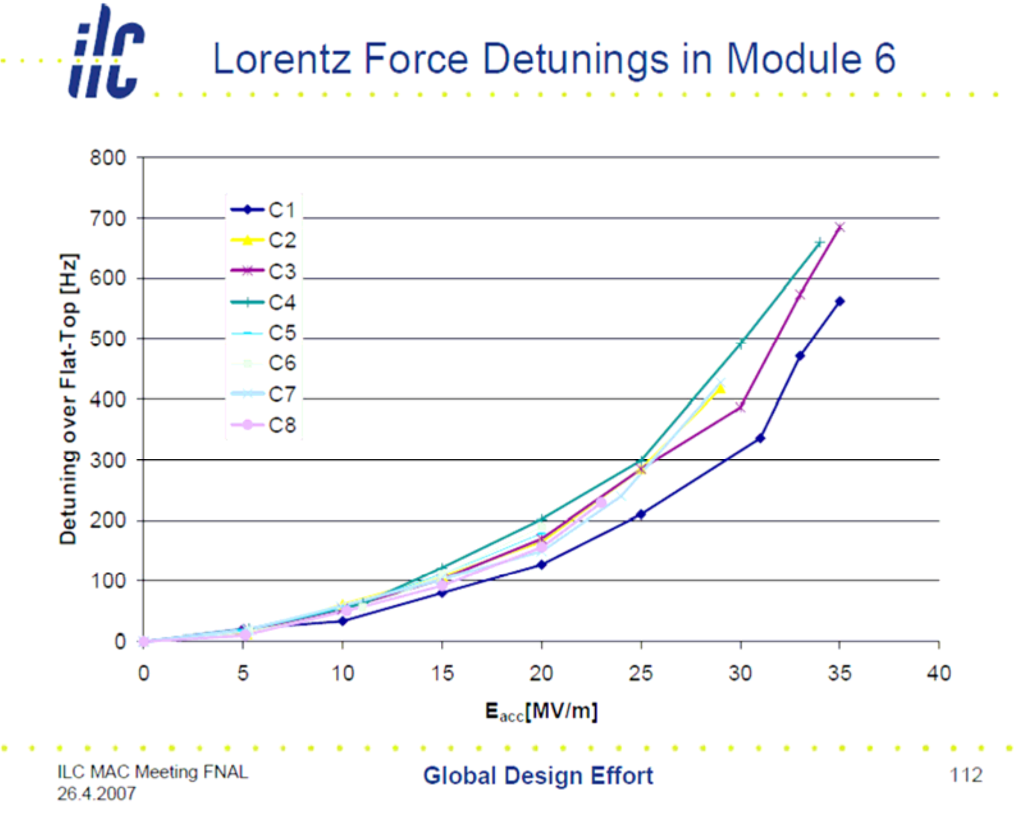

Lorentz Force Detunings in Module 6

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Cavity Fabrication Cost Reduction Issues

Large Grain/Single Crystal Niobium

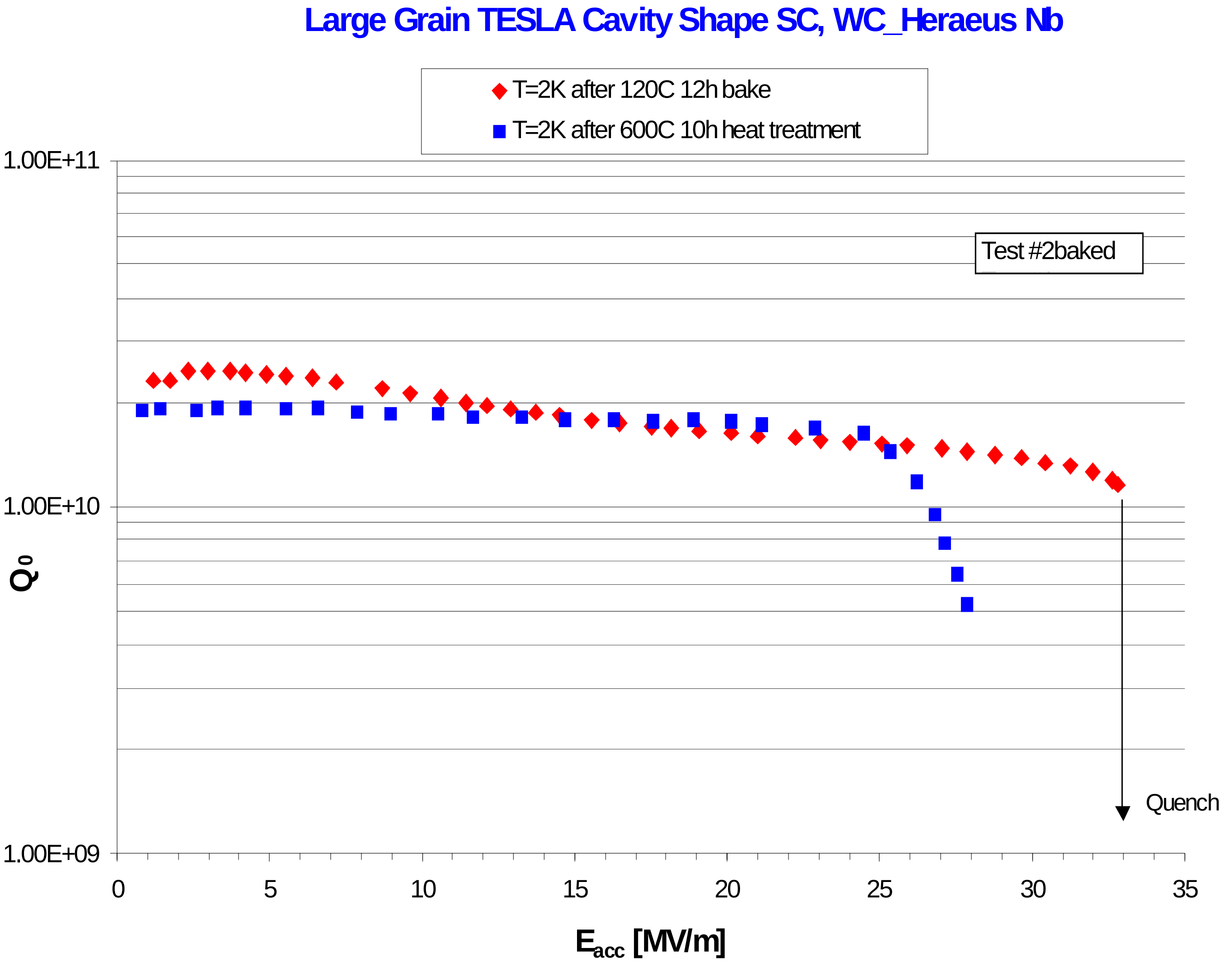
Potential Advantages

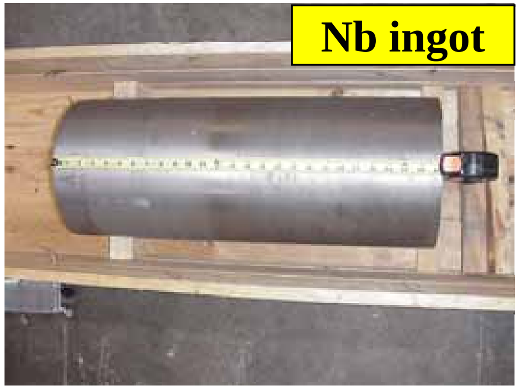
By P.Kneisel

- Reduced costs
- Comparable performance
- Very smooth surfaces with BCP, no EP necessary
- Possibly elimination of “in situ” baking because of “Q-drop” onset at higher gradients
- Possibly very low residual resistances (high Q’s), favoring lower operation temperature (B. Petersen), less “cryo power” and therefore lower operating costs
- Higher thermal stability because of “phonon-peak” in thermal conductivity
- Good or better mechanical performance than fine grain material (e.g. predictable spring back..)
- Less material QA (eddy current/squid scanning)

Material R&D for ILC

Large grain niobium cavity R&D in Jlab





Large grain Nb sheet production can bring a cost down.
BCP could produce 35MV/m gradient and it brings further cost down.

Large Grain/Single Crystal Niobium at JLAB

By P.Kneisel and G.Rao

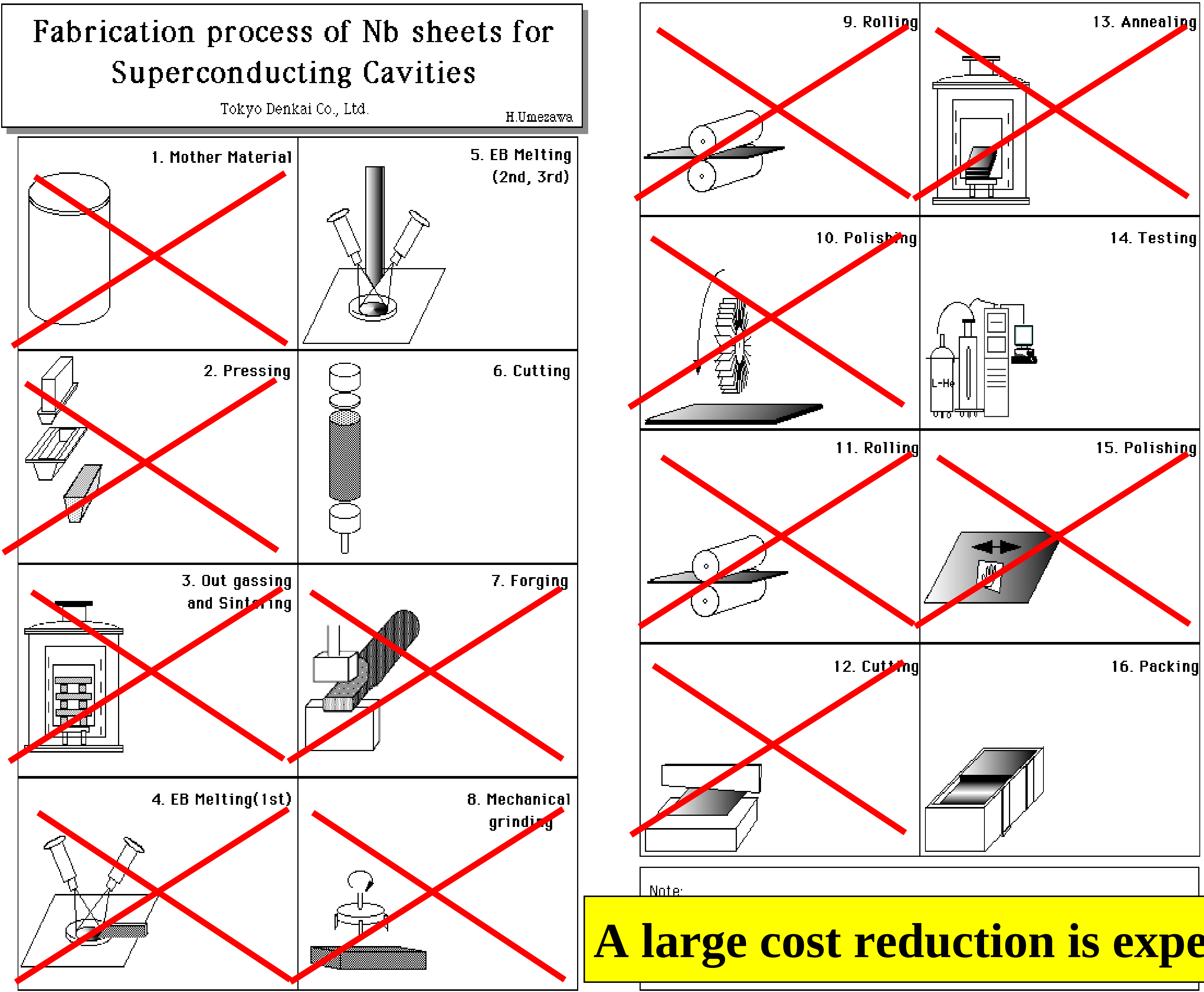
Discs from Ingot

Cavity

$E_{peak}/E_{acc} = 1.674$

$H_{peak}/E_{acc} = 4.286$ mT/MV/m

Single Crystal / Large Grain Nb Production



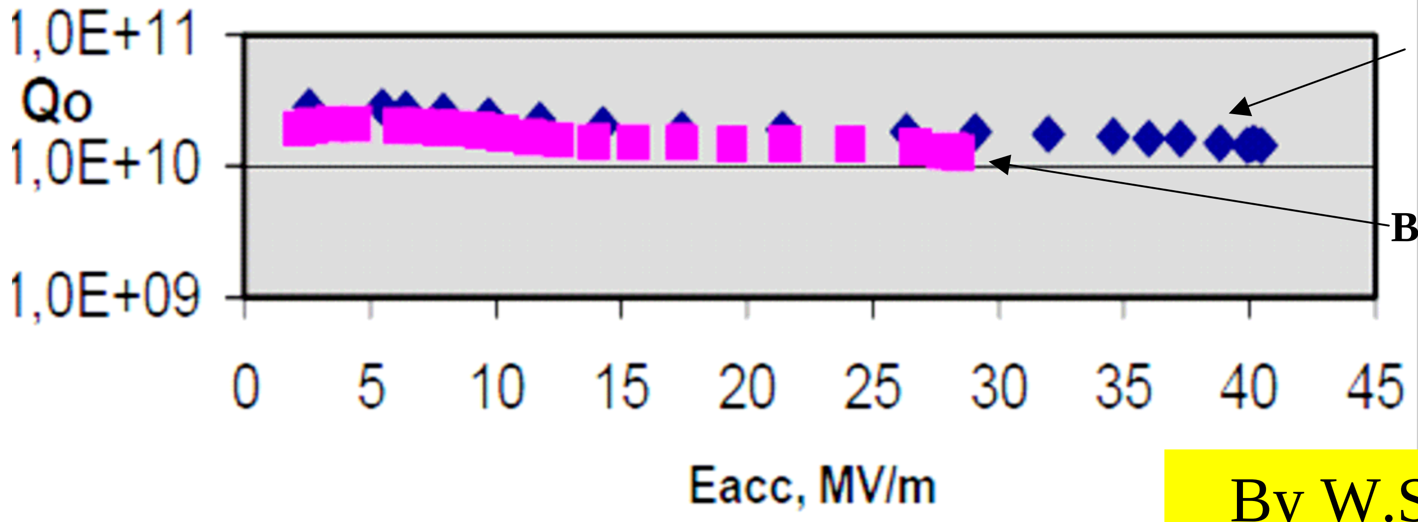
Fabrication process of Nb sheets for Superconducting Cavities

Tokyo Denkai Co., Ltd.

H.Umezawa

A large cost reduction is expected !

Large grain Nb cavity is close to the ILC BCD performance but The scatter still ~10%

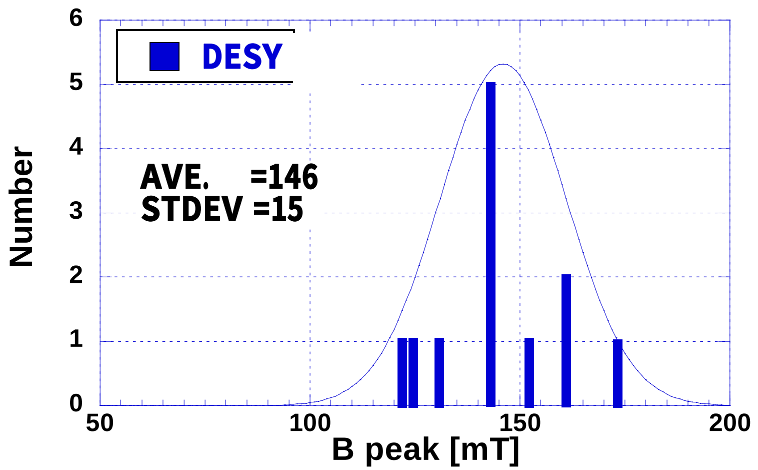


single cell cavity
EP150µm

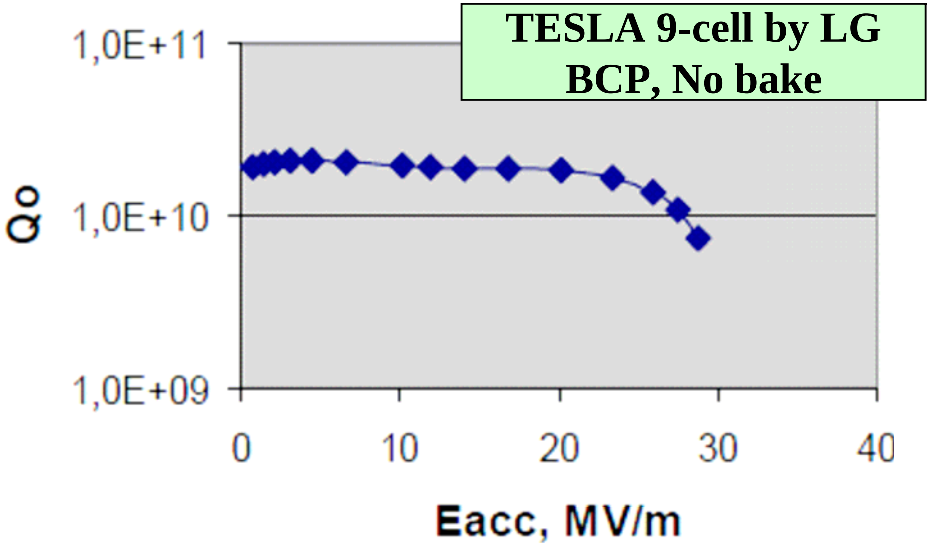
BCP after the EP

By W.Singer

Statistics of LG with single cell cavity @ DESY

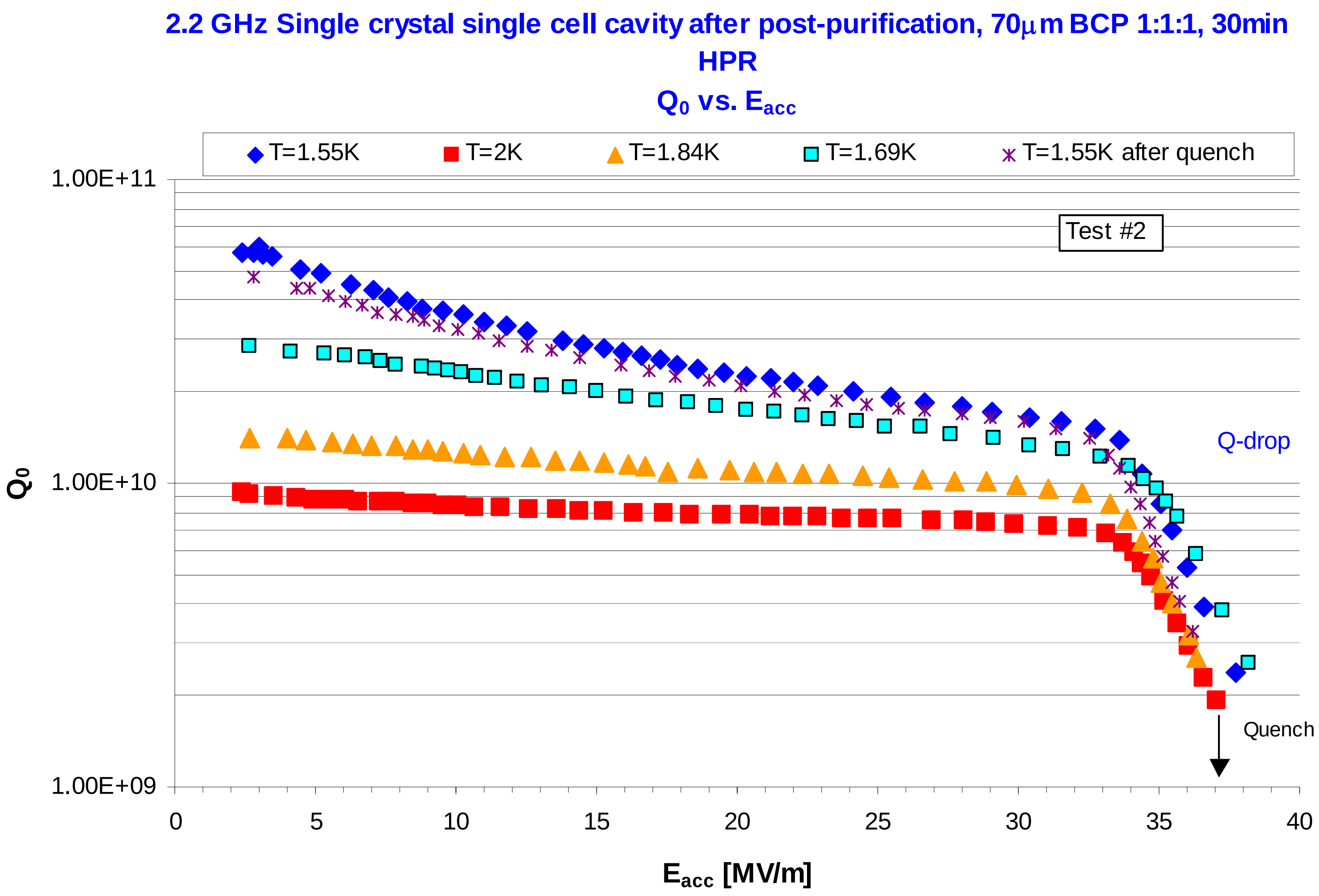


Eacc ave=34.3±3.5MV/m(10.3%)



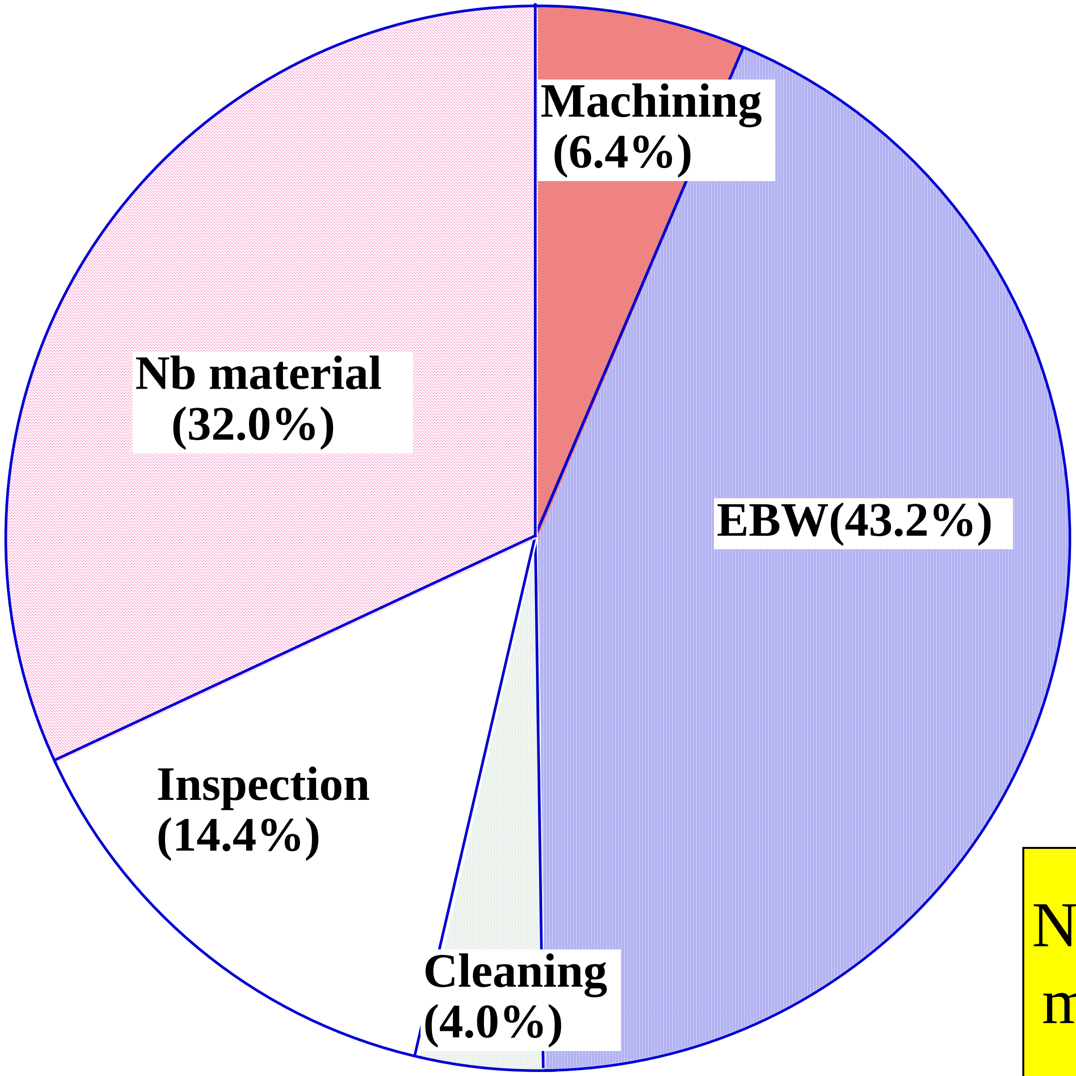
TESLA 9-cell by LG
BCP, No bake

Single Crystal Cavity



Nb Seamless or
Nb/Cu Clad Seamless Cavity

Example of the cost breakdown for in-house fabrication



Cost Breakdown for naked cavity

N~1

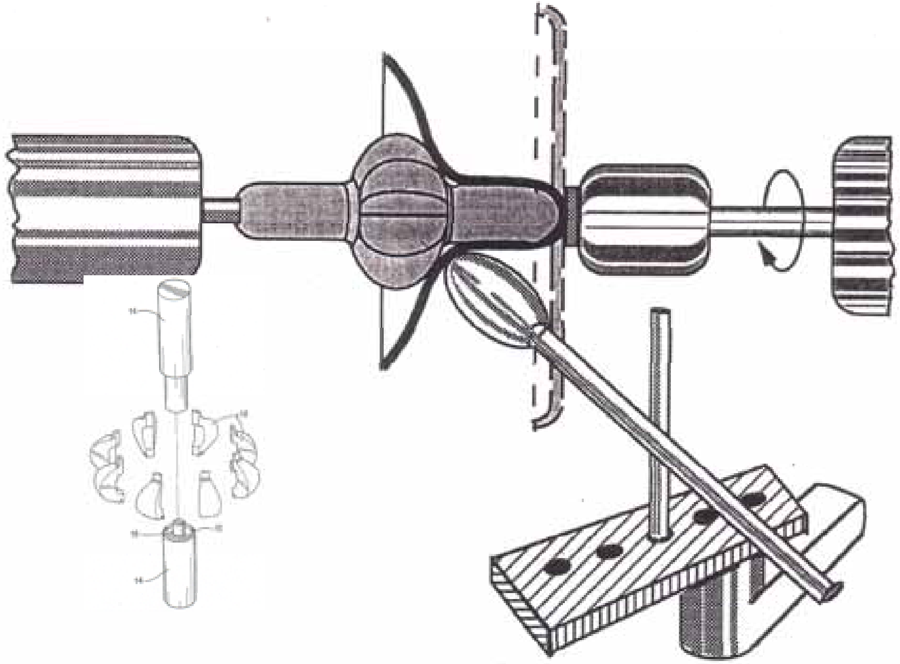
	Labor level	Single price
Nb material	-	X ¥／kg
Machining	L	L ¥／hr
EBW	H*	Machine charge H* ¥／hr
Cleaning	M	M ¥／hr
Inspection	H	H／hr

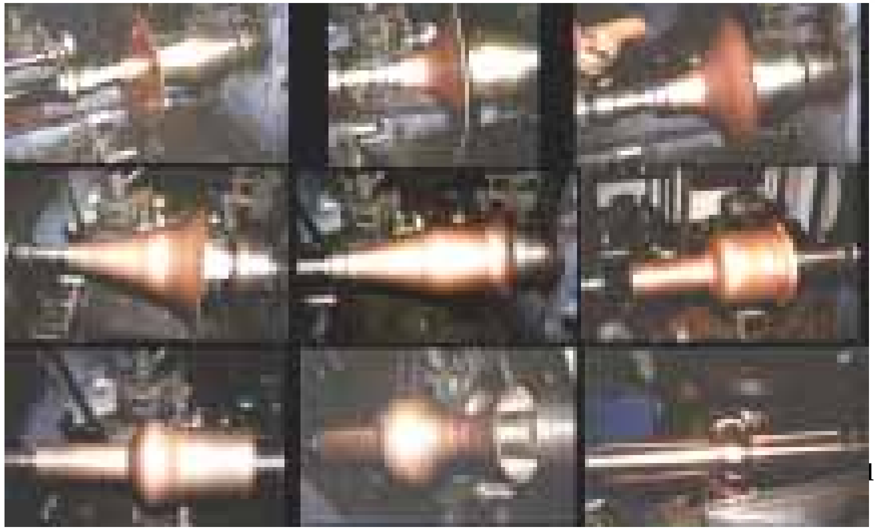
Not included: jig cost, design, management expenses, profit, consuming tax, and so on.

Seamless Cavity Technology by Spinning in Italy(INFN-LNL)

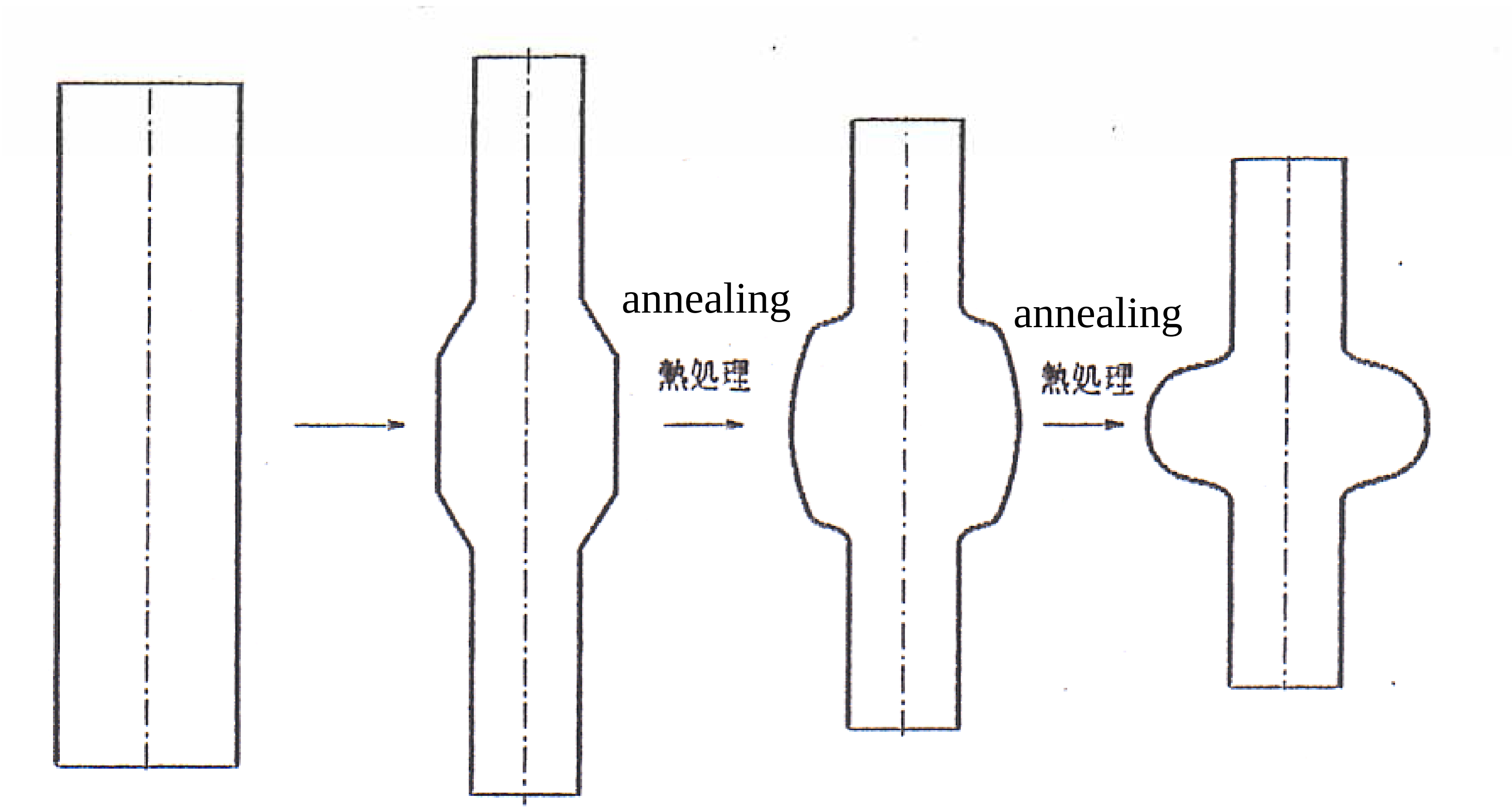
Starting material: Nb sheet

By V.Palmieri



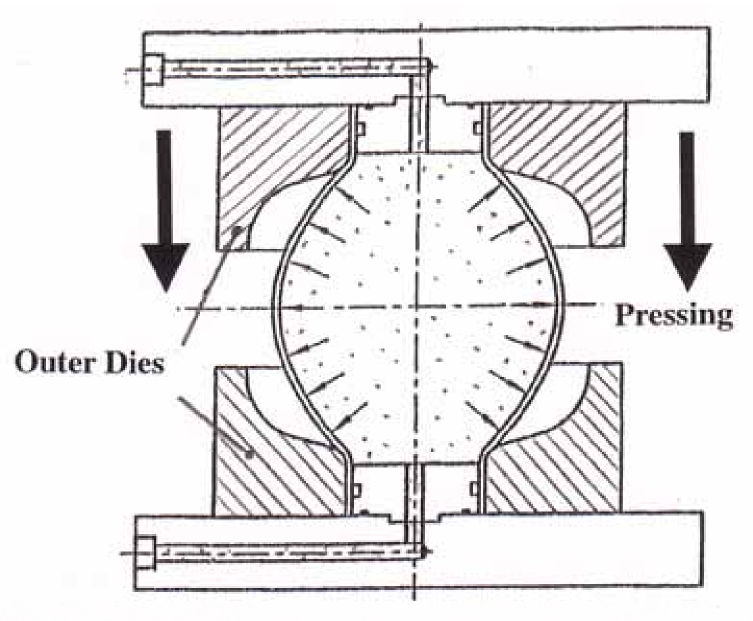


Fabrication Process in KEK for Hydroforming



Seamless pipe   Necking   Hydroforming (50%) Hydroforming (100%)

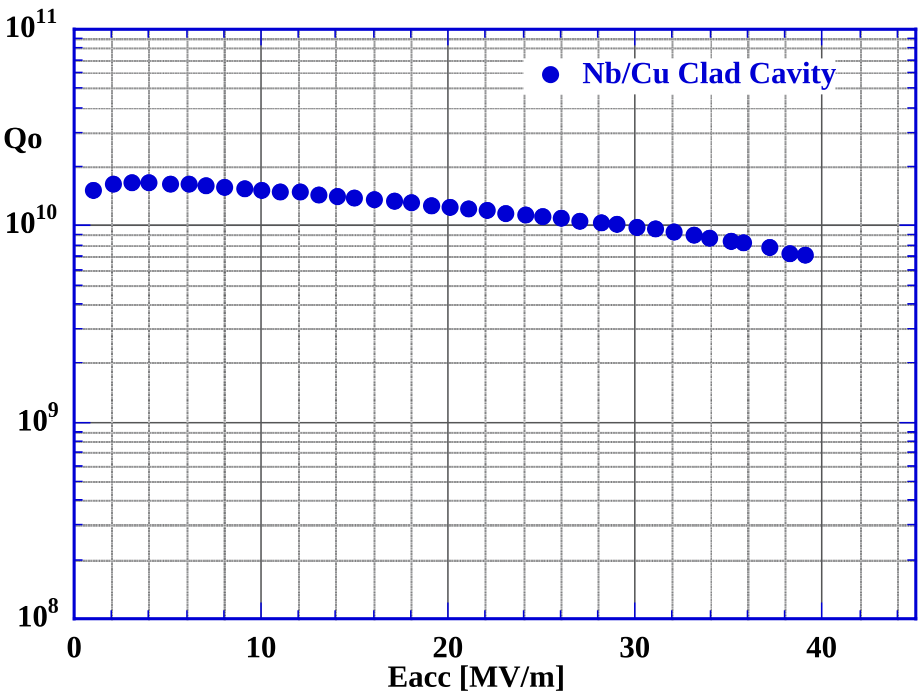
Hydroforming of Nb Bulk Cavity in DESY



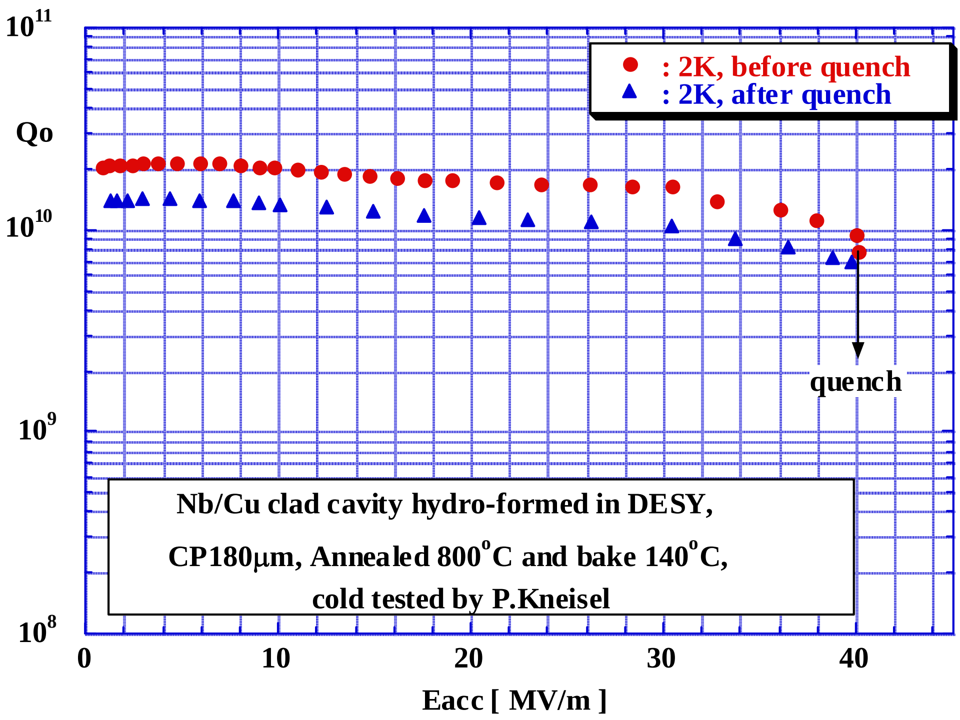
DESY 3-cell Seamless x 3 Cavity

Cavity Performance

KEK/Shin Nittetsu Co. Ltd/DESY



JLAB/DESY/KEK



Nb/Cu clad cavity hydro-formed in DESY,
CP180μm, Annealed 800°C and bake 140°C,
cold tested by P.Kneisel

Very Reliable performance on High Gradient !

Nb/Cu Clad Cavity @ KEK

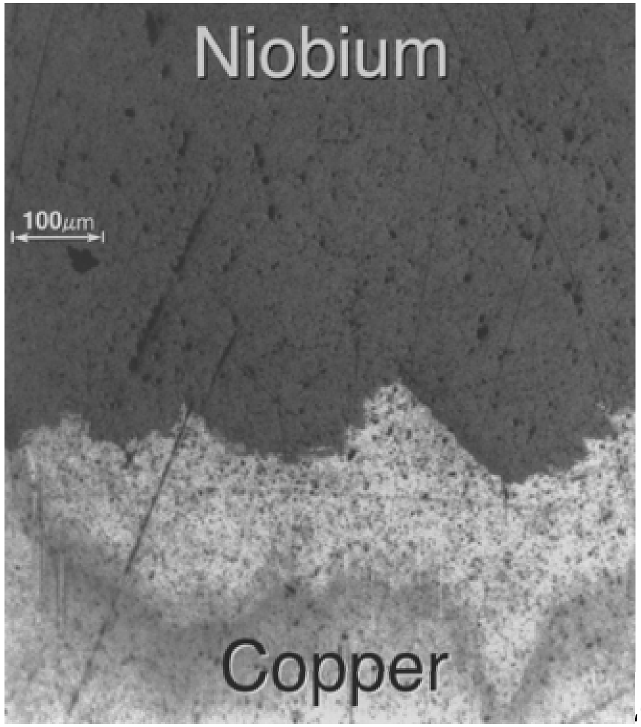
Use EP

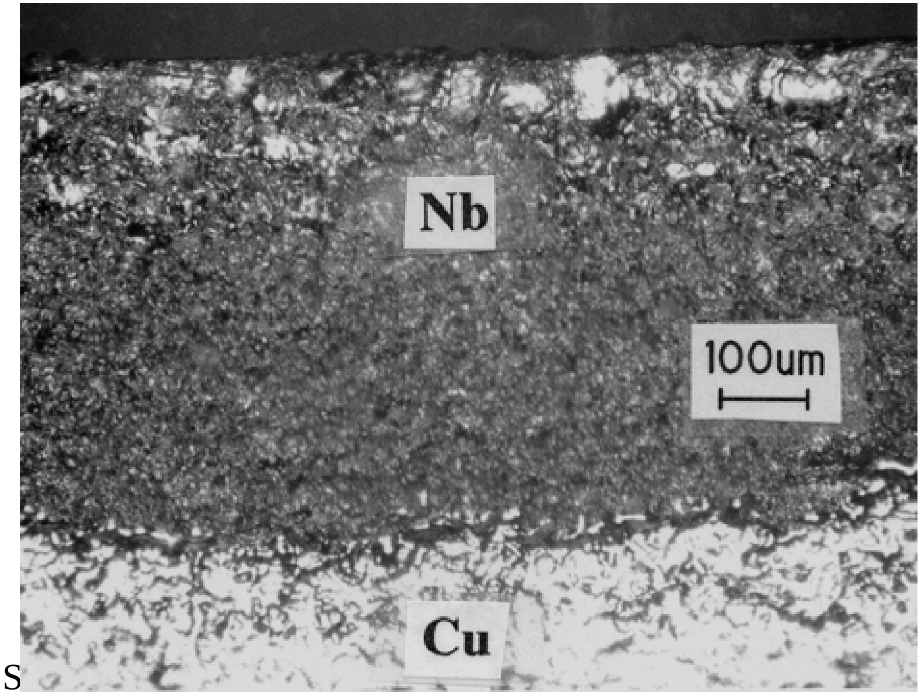
Coupled Issues

1) **Eliminate EBW**
2) **Reduce amount Nb**
3) **Guarantee cavity performance**

Keep bulk Nb property

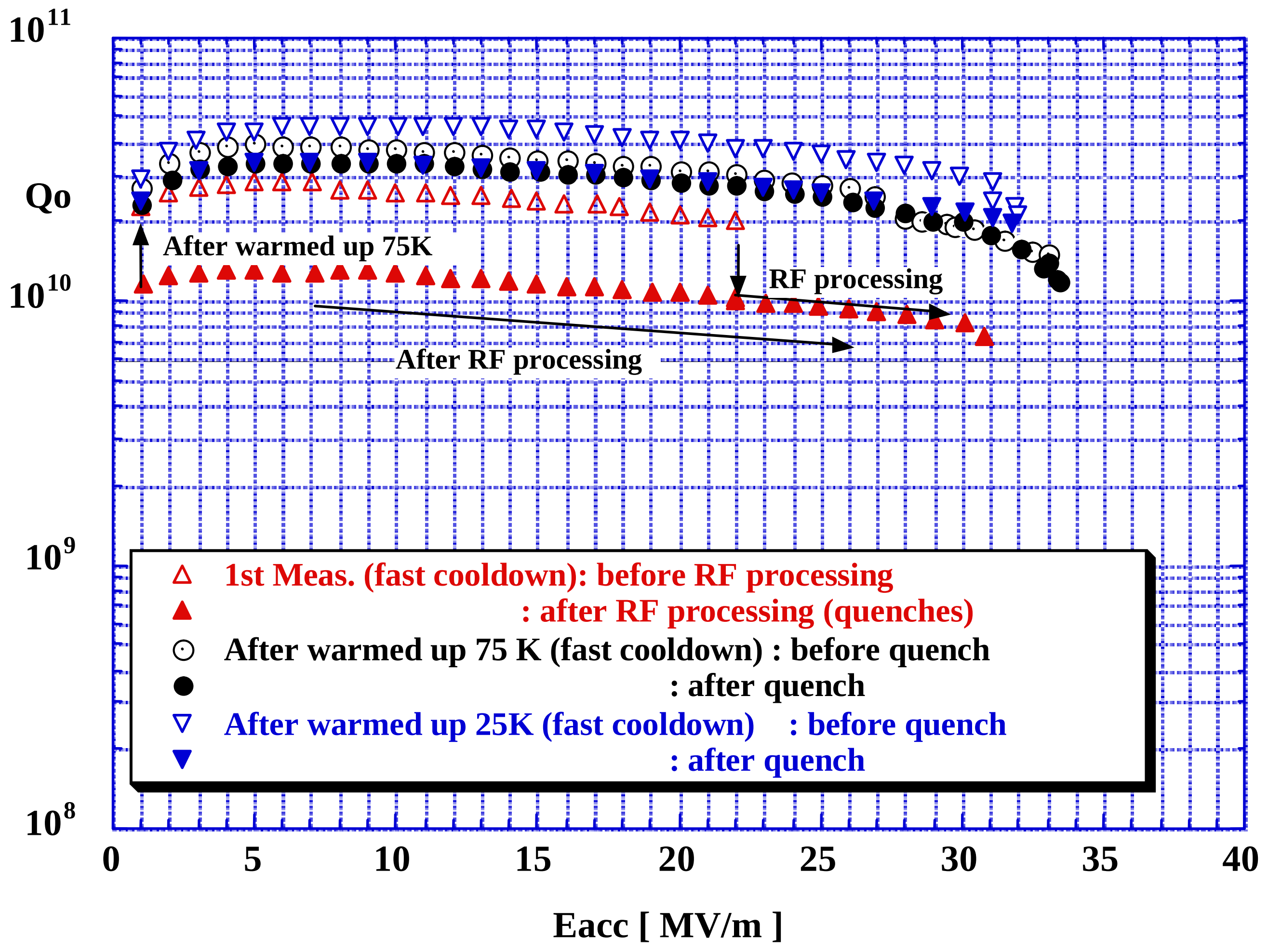
Bond tick copper pipe
on thinner Nb pipe
Use Hydroforming





Hydroforming of Nb/Cu Clad Cavity in KEK

Flux Trapping Issue



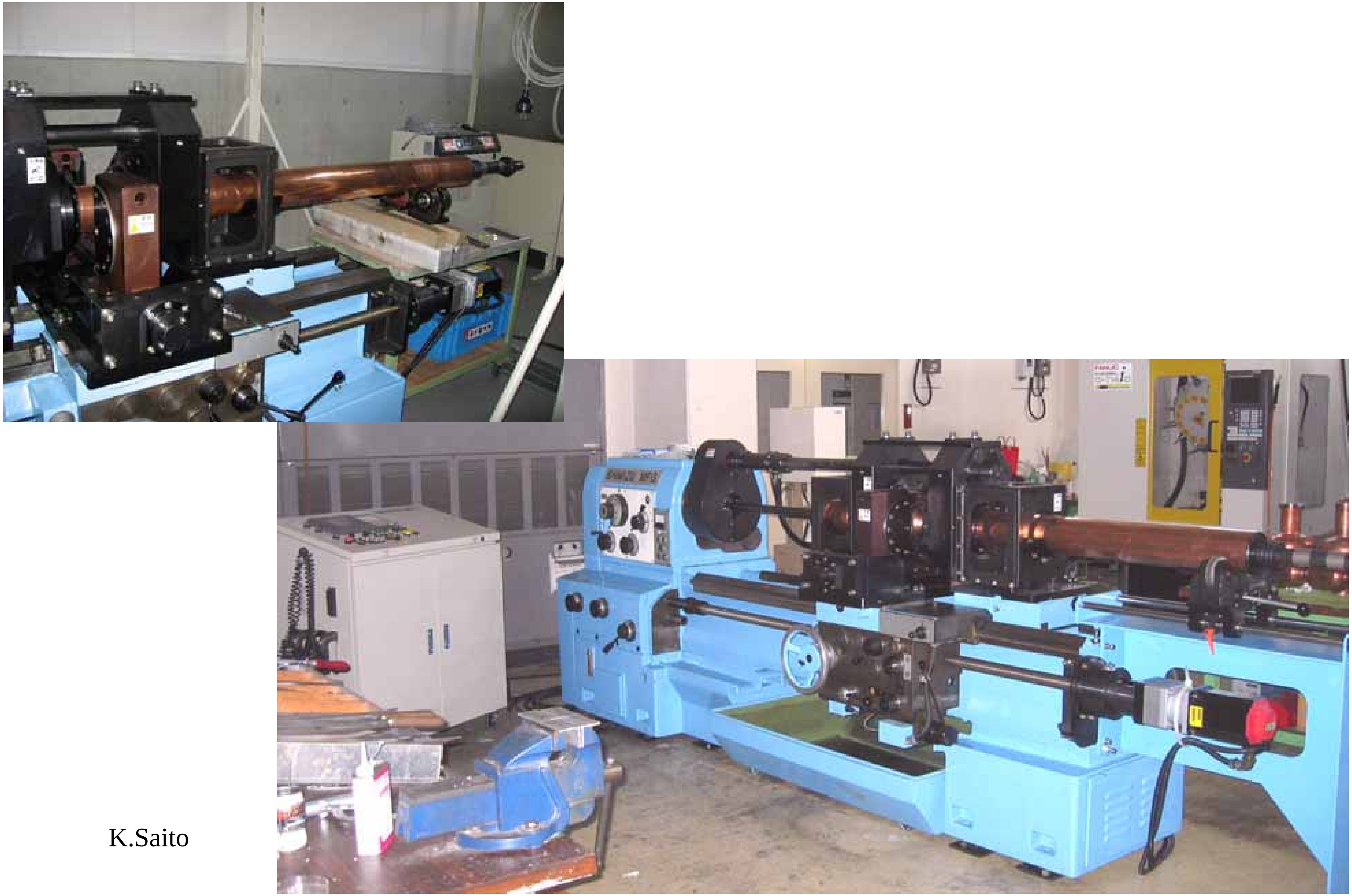
Nb/Cu Clad Seamless Pipes

Shin Nittetsu Co. Ltd /KEK

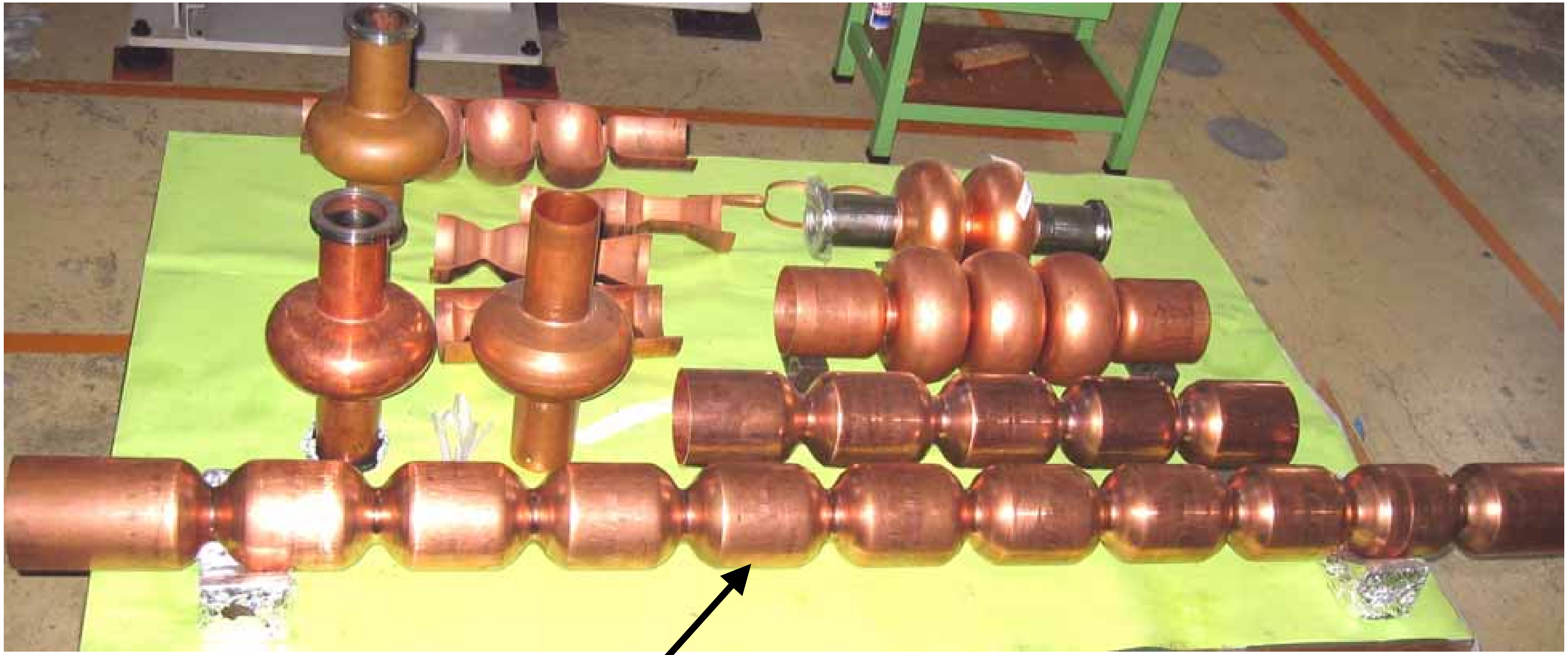
Seamless ICHIRO 3-cell Cavity (Copper model)

KEK Machinery Center

9-cell Necking machine



Necked 9-Cell



Necked 9-Cell