PHY905 Section 4
Ion Accelerator Technology
Lecture 8
- SRF Cavity Fabrication and Cold Test -

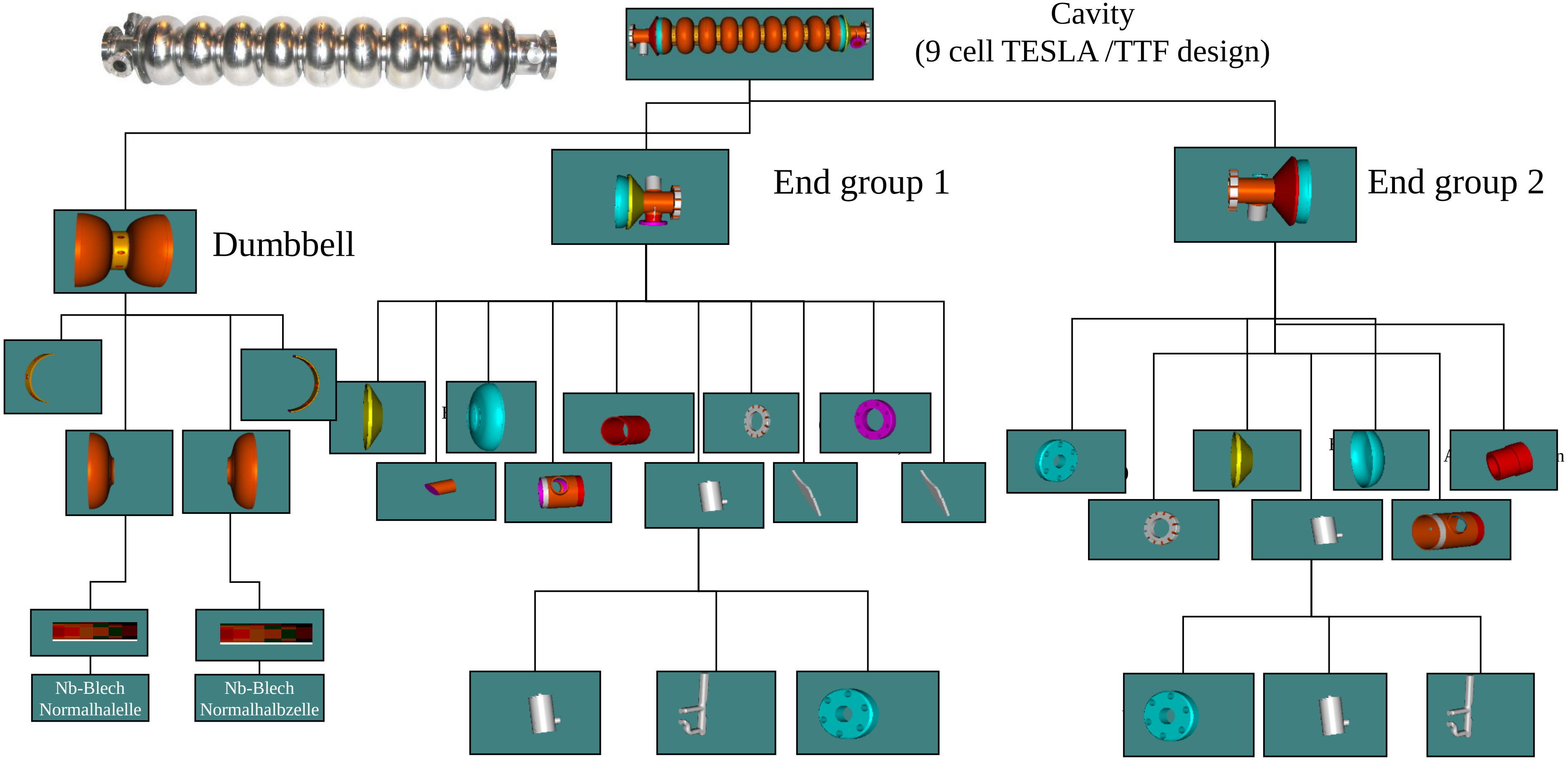
Yoshishige Yamazaki, Kenji Saito, Steve Lidia
National Superconducting Cyclotron and Facility for Rare Isotope Laboratory
Michigan State University

SRF Cavity Fabrication and Cold Test

- SRF cavity fabrication
  - 8.1 Cavity components (ILC cavity example)
  - 8.2 Current cavity fabrication method
    - Dumbbell fabrication
    - Beam pipe fabrication
    - End group fabrication
    - Nb/Stainless bonding
  - 8.3 Nb film coated copper cavity

- SRF cavity cold test
  - 8.4 Theory of RF measurement of SRF cavities
  - 8.5 RF measurement system

8.1 Cavity components, ILC cavity example

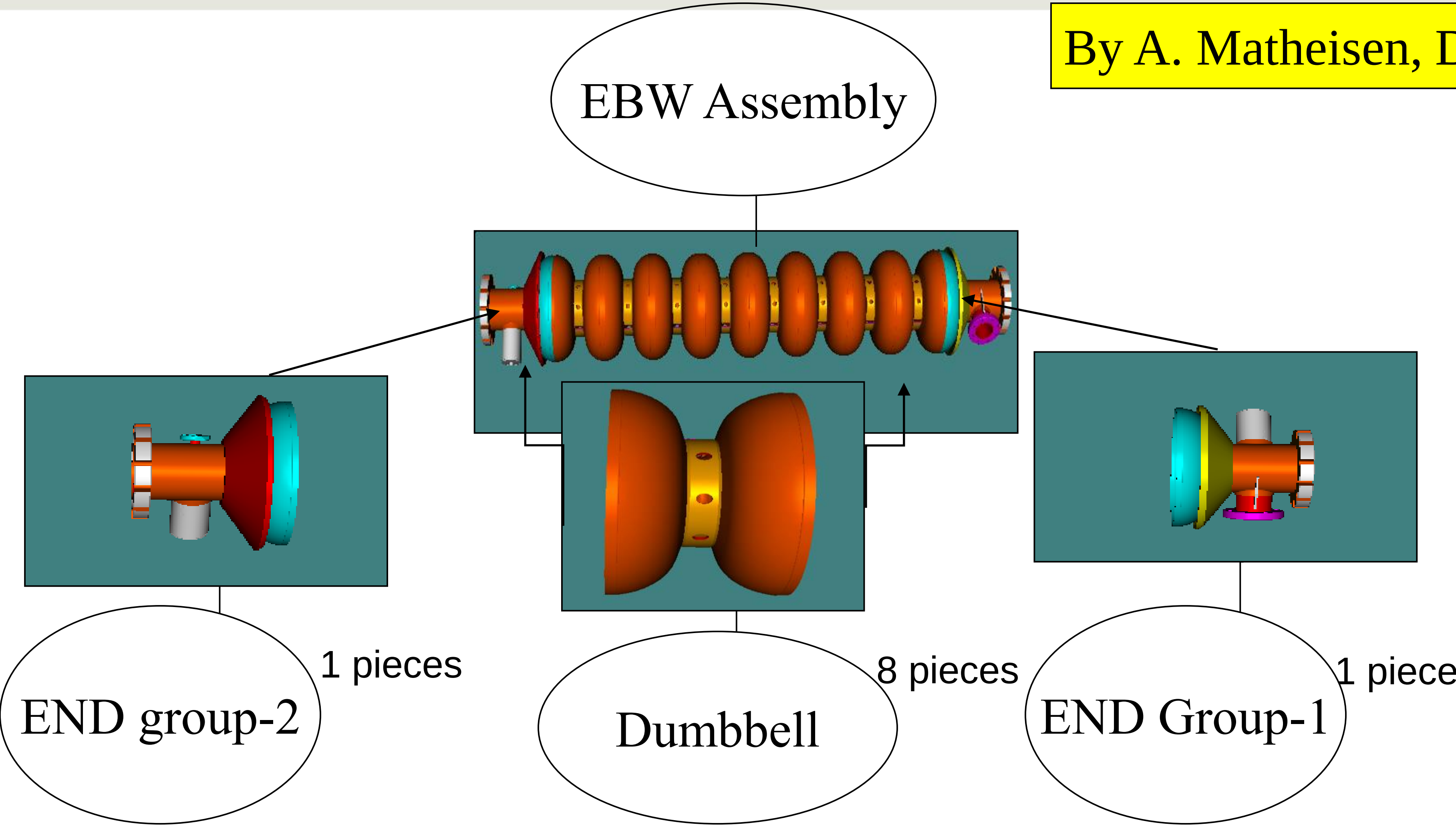


Cavity fabrication and preparation sequences
for the TESLA / TTF cavities at DESY

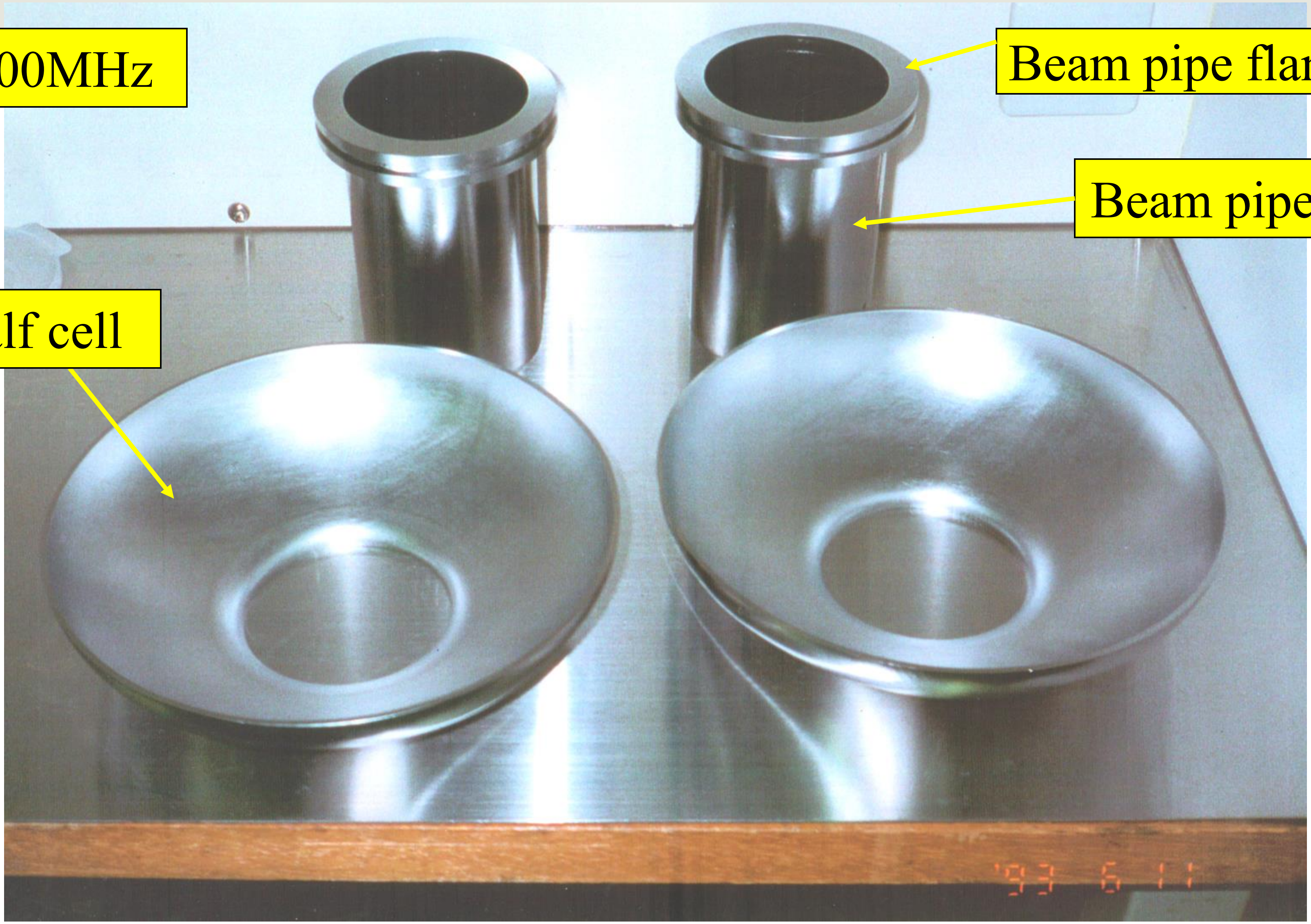
1st ILC workshop at KEK Tsukuba Japan
A. Matheisen
for DESY and the TESLA Collaboration

Grouping of fabrication process for ILC cavities

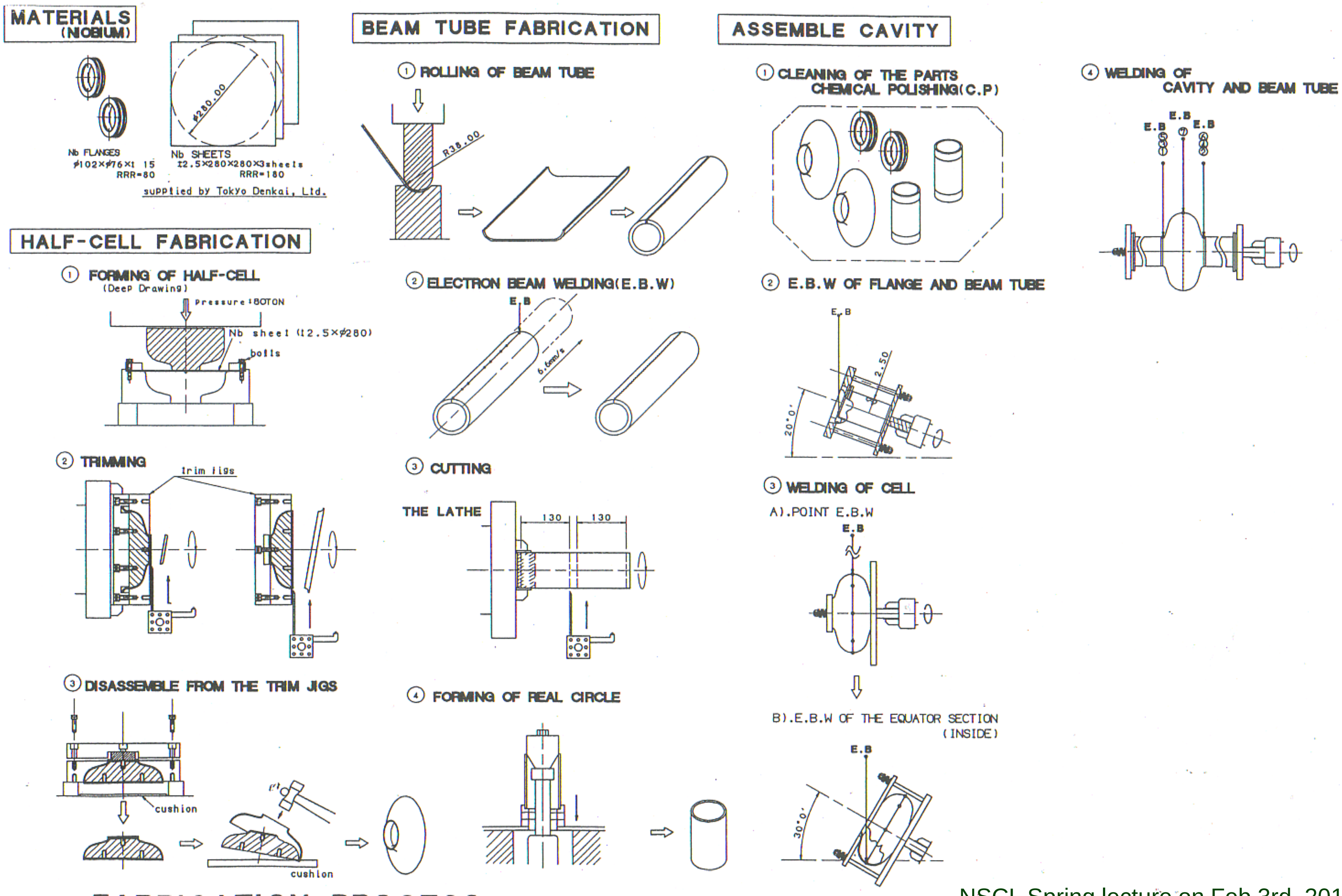
By A. Matheisen, DESY



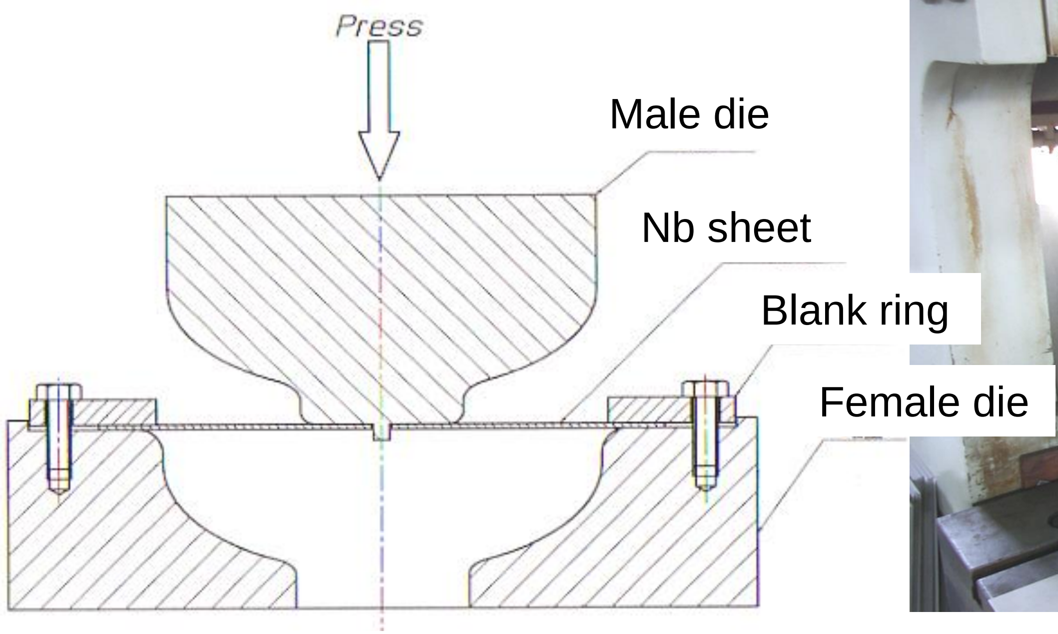
Single cell cavity parts



8.2 Current cavity fabrication flow



8.3 Dumbbell fabrication (Ichiro 9-cell)
Half cell forming (deep drawing)

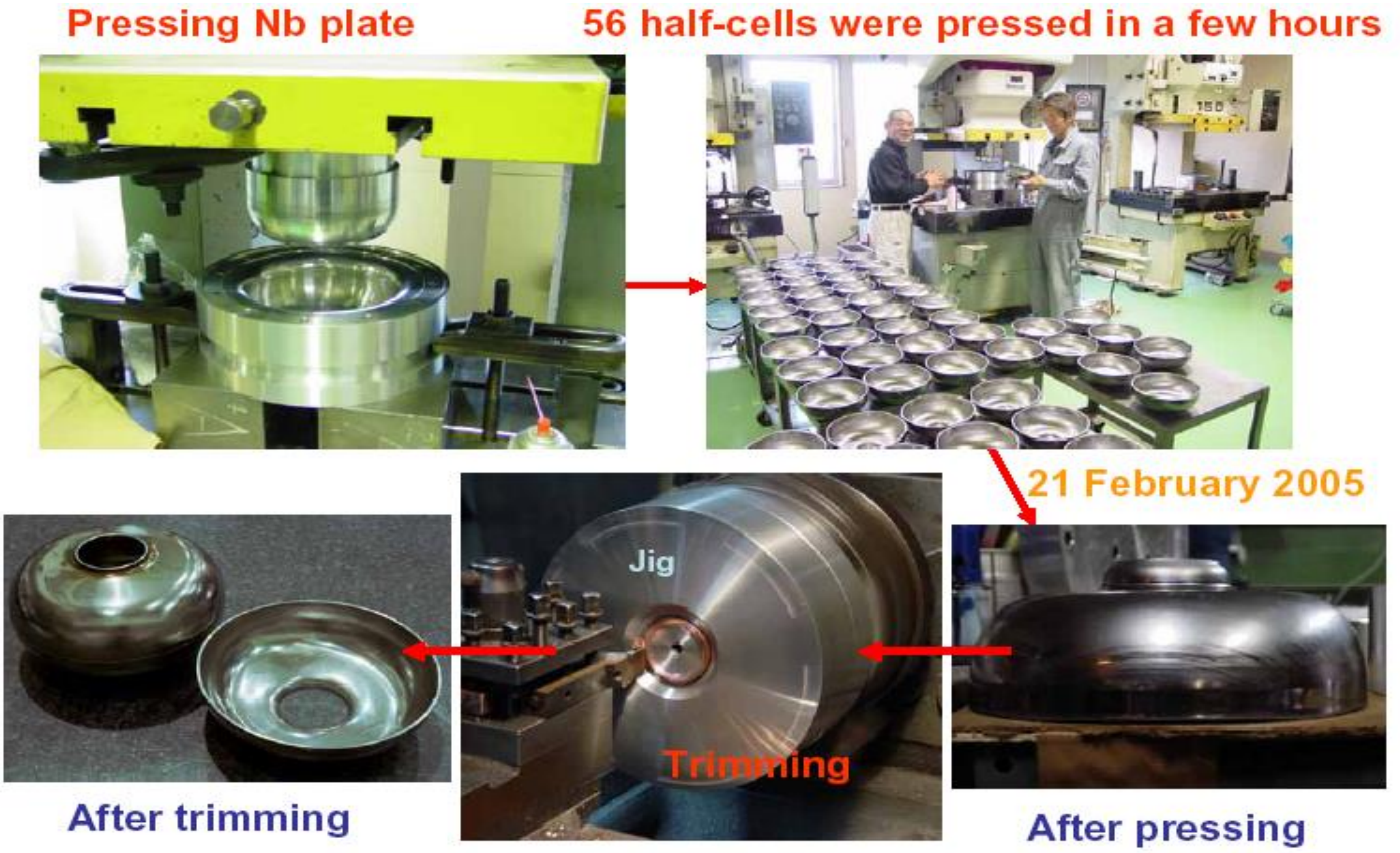


80 t press for 2.8t niobium half cell (1300MHz)
280 mm diameter niobium sheet

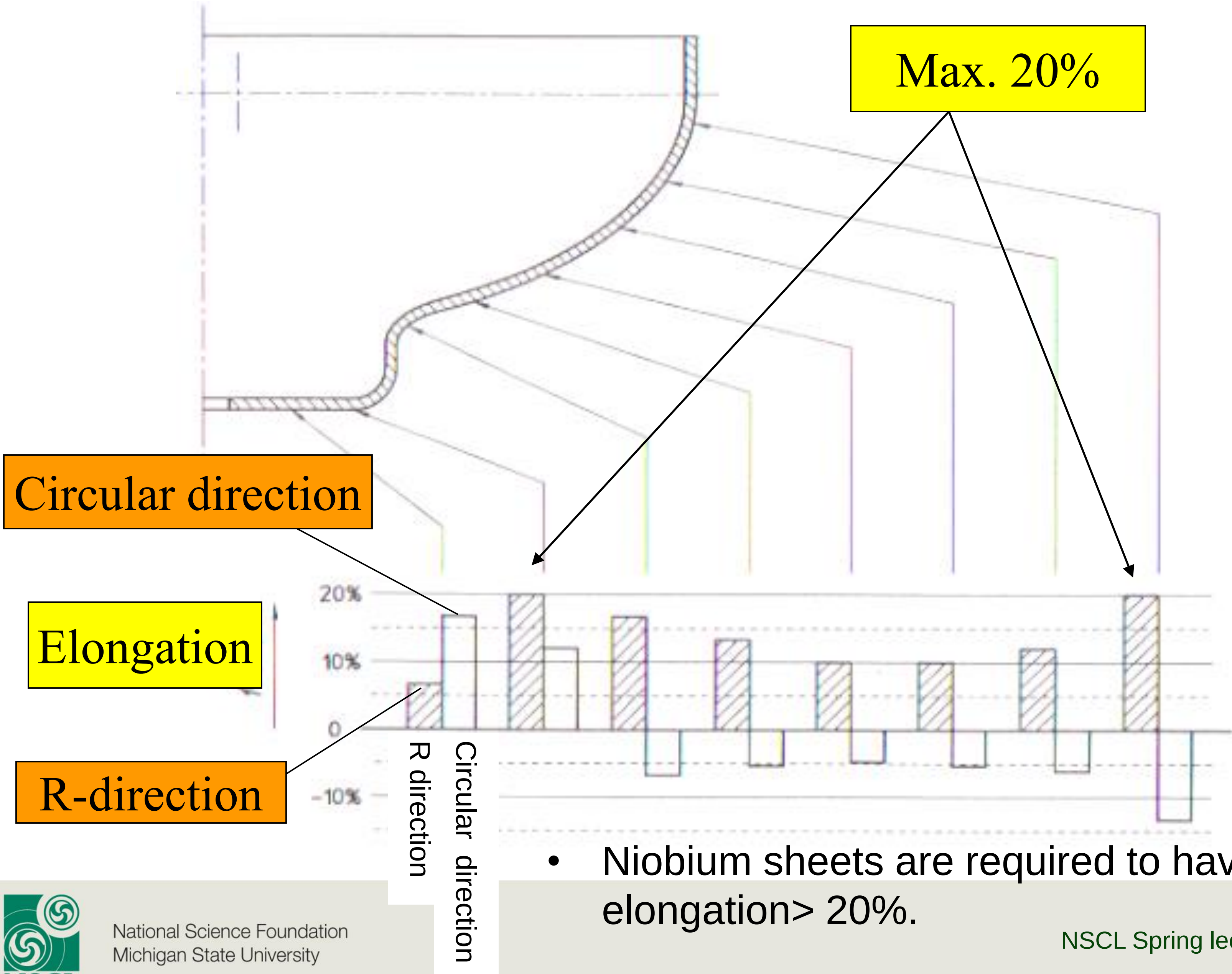
Deep drawing die and trimming fixtures

- Design of deep drawing dies and trimming fixtures
  - The design of dies are not the same as the RF cavity design. Need a special attention for the design.
  - Spring back or material deformation during the forming are considered in the design
- Fabrication by NC machine using hard Aluminum alloy (JIS2000).

Half cell forming (deep drawing) and trimming

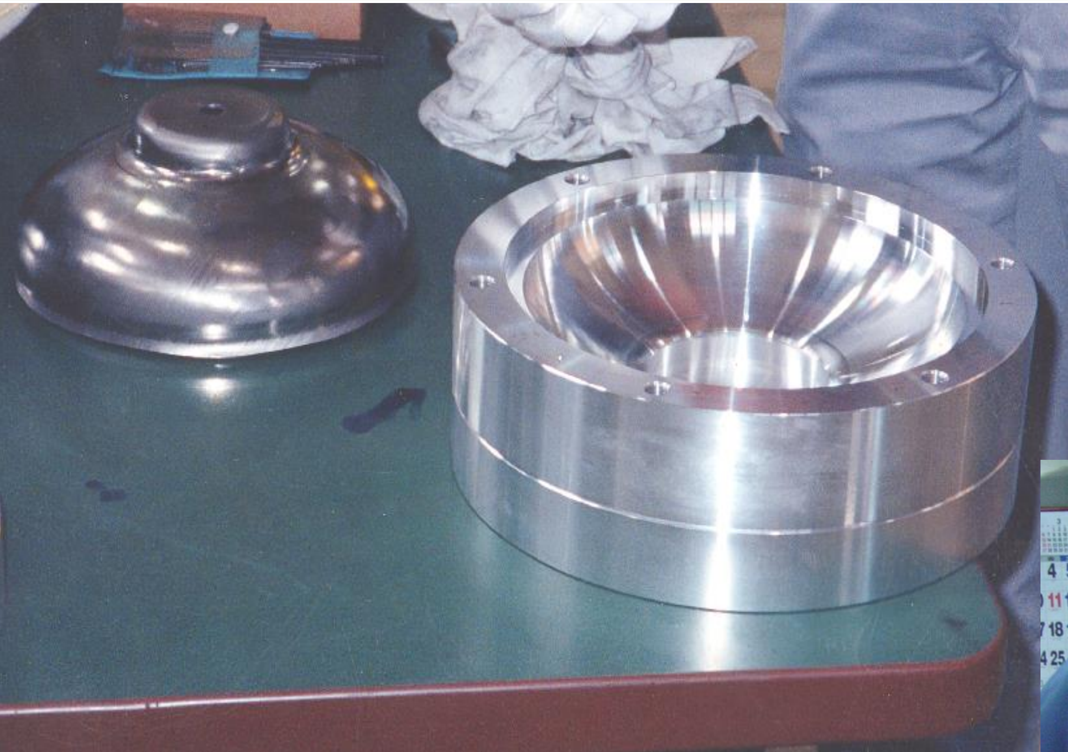


Local elongation



- Niobium sheets are required to have an elongation> 20%.

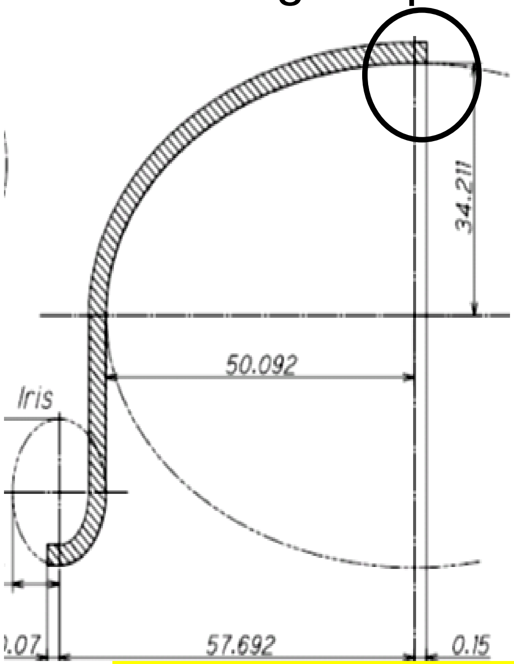
Trim dies and view of trimming work

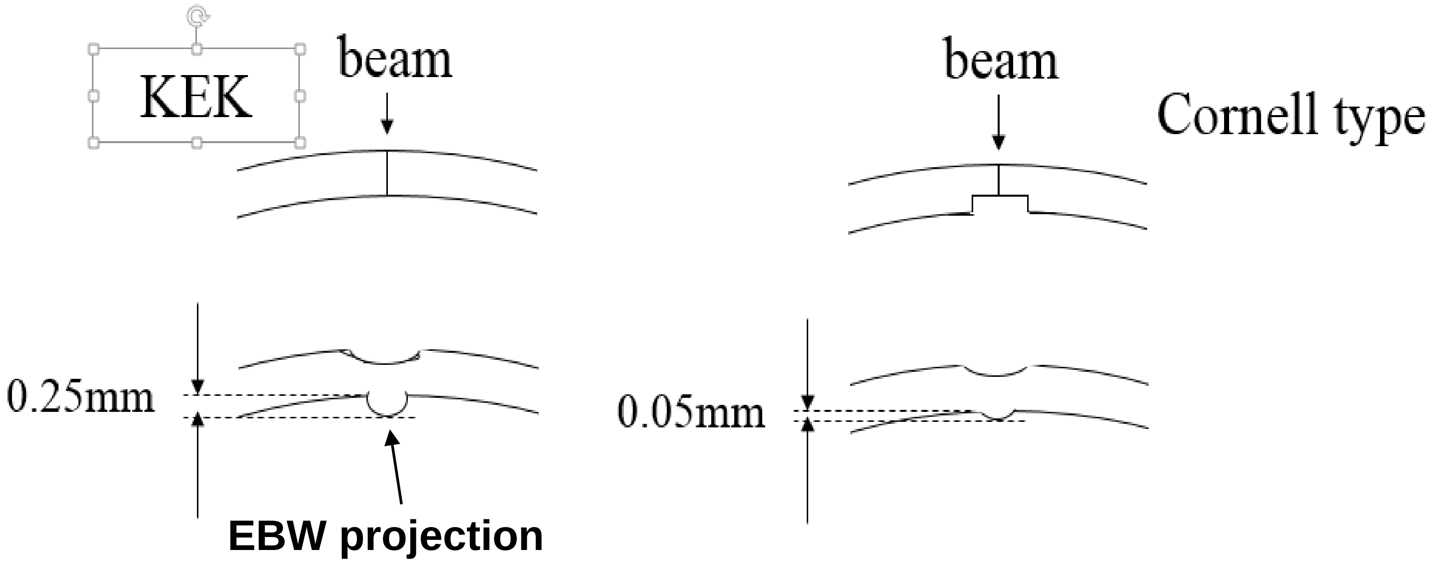


石塚製作所 (Family company)

Trimming shape

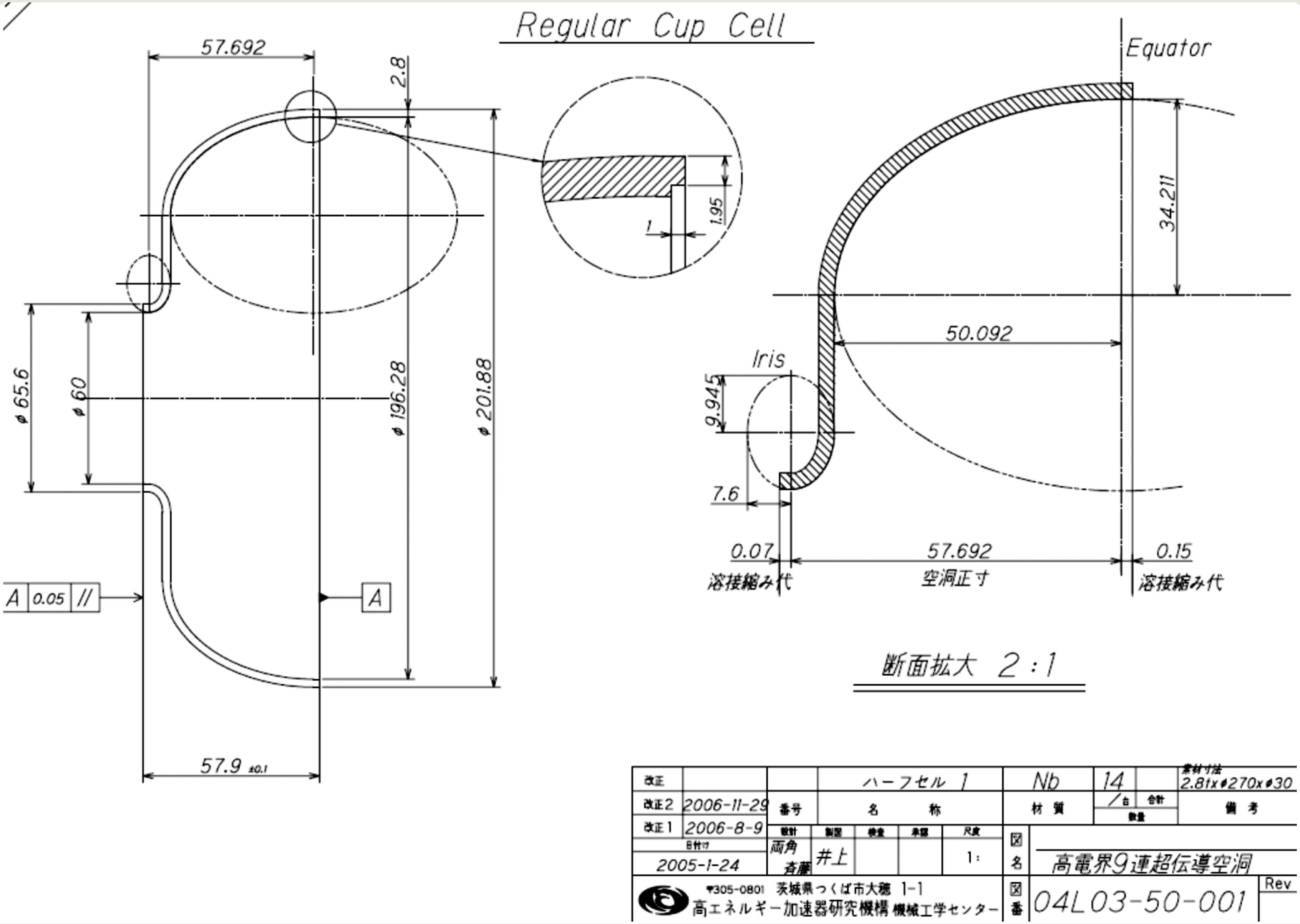
- Smooth surface is preferred at the equator (high RF current region) to eliminate the EBW defects.
- The projection (EBW seam) on inner surface by melted niobium should be considered as much as small when made EBW from top.
- The EBW shrinkage offset is also considered for the trimming.
- Trimming shape is considered of these things.



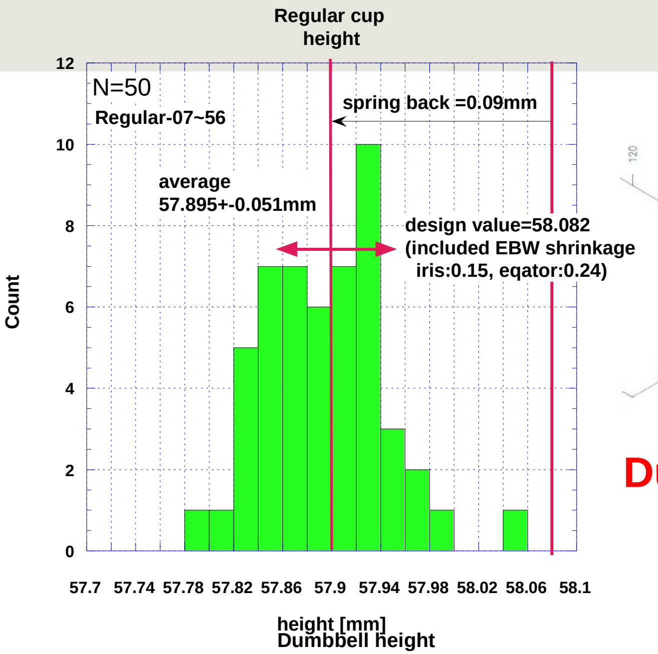


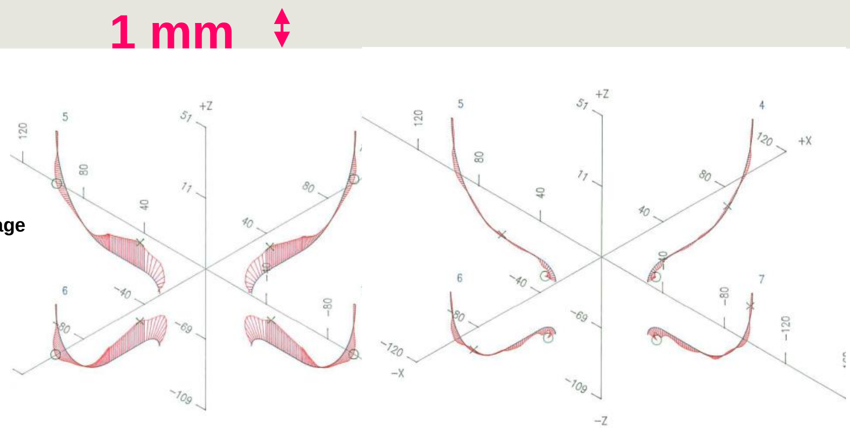
- Cornell trimming shape is very useful to smooth the EBW seam.

Improved trimming shape



Dimensional measurement post trimming

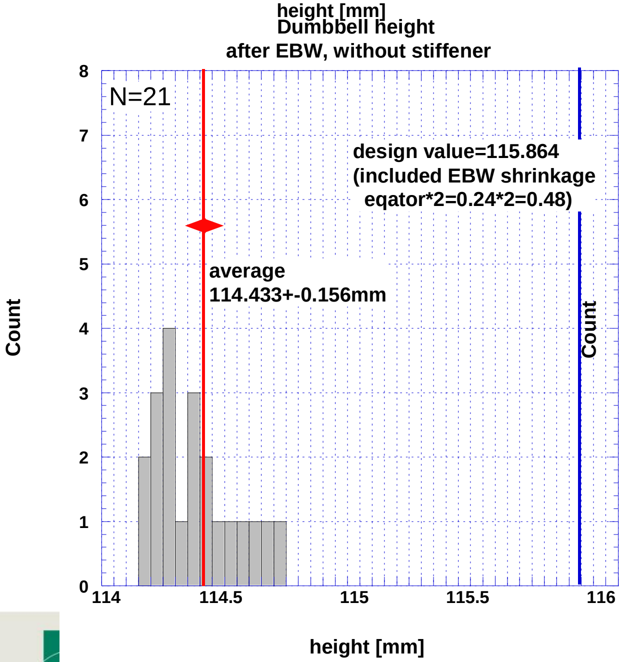


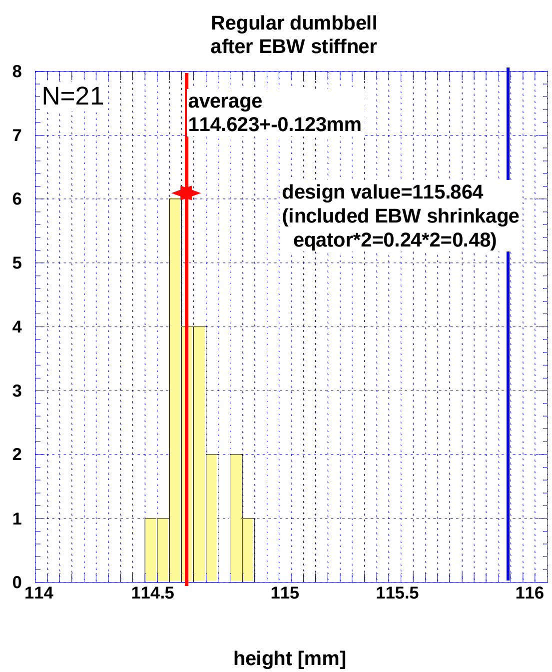


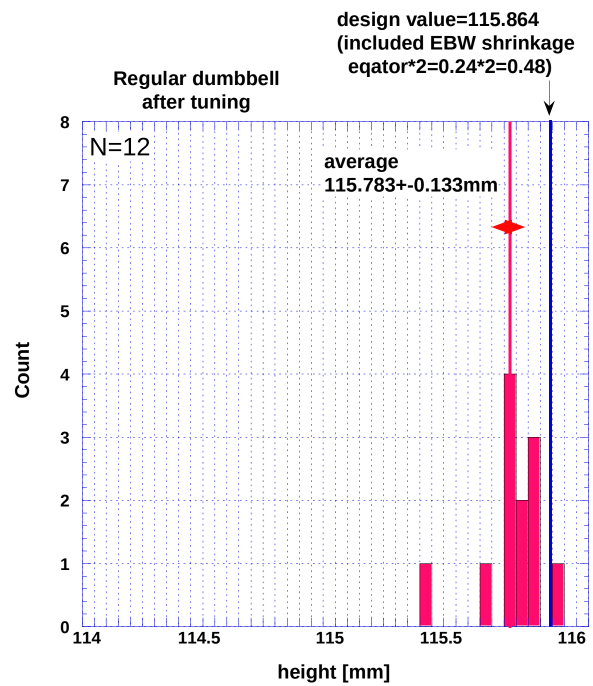
Dumbbell EBW

After stiffener EBW on dumbbell and tuning

Machining error: 50µm
Half cell spring back :90µm
EBW shrinkage
0.42 ± 0.13mm @ equator
0.15 ± 0.04mm @ iris
Dumbbell fabrication error ~80µm after tuning
9-cell length error: 0.7~0.1mm

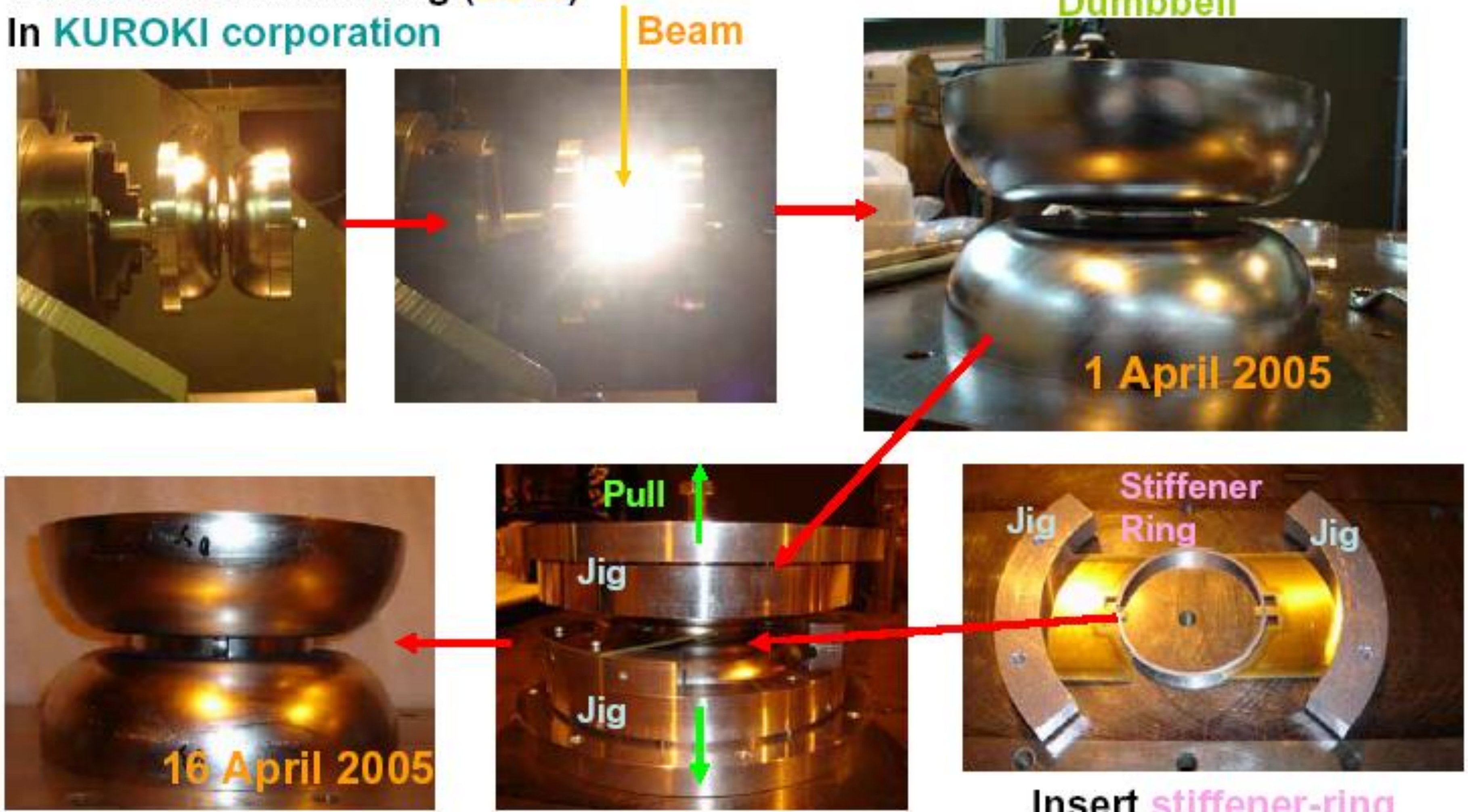






EBW assembly of dumbbell with stiffener ring

Electron Beam Welding (EBW)
In KUROKI corporation



Dumbbell with stiffener-ring after EBW.

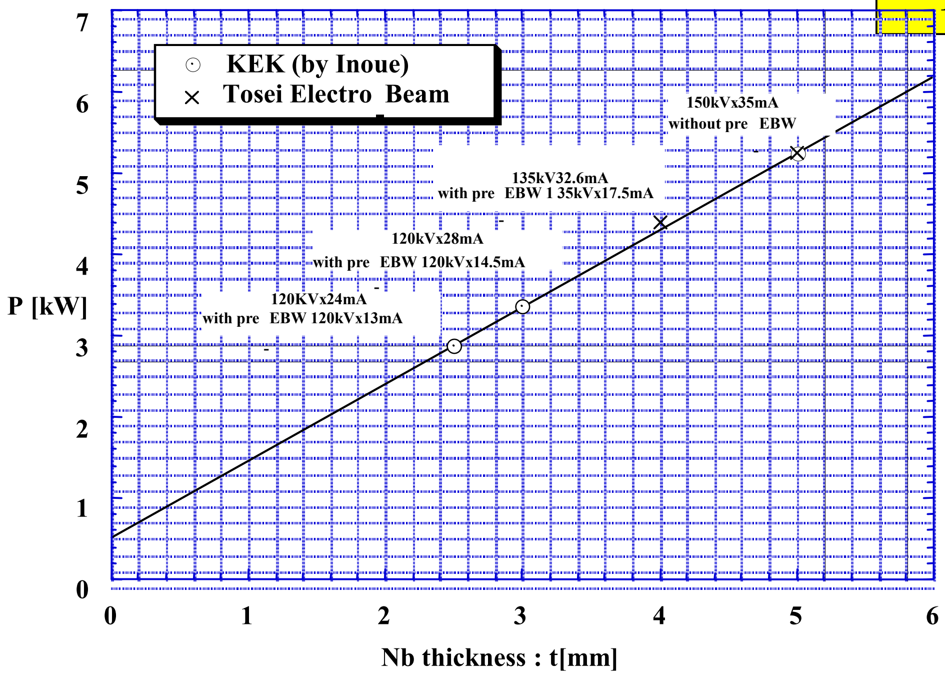
Pull and extend dumbbells to insert stiffener-ring.
=> EBW (dumbbell + ring)

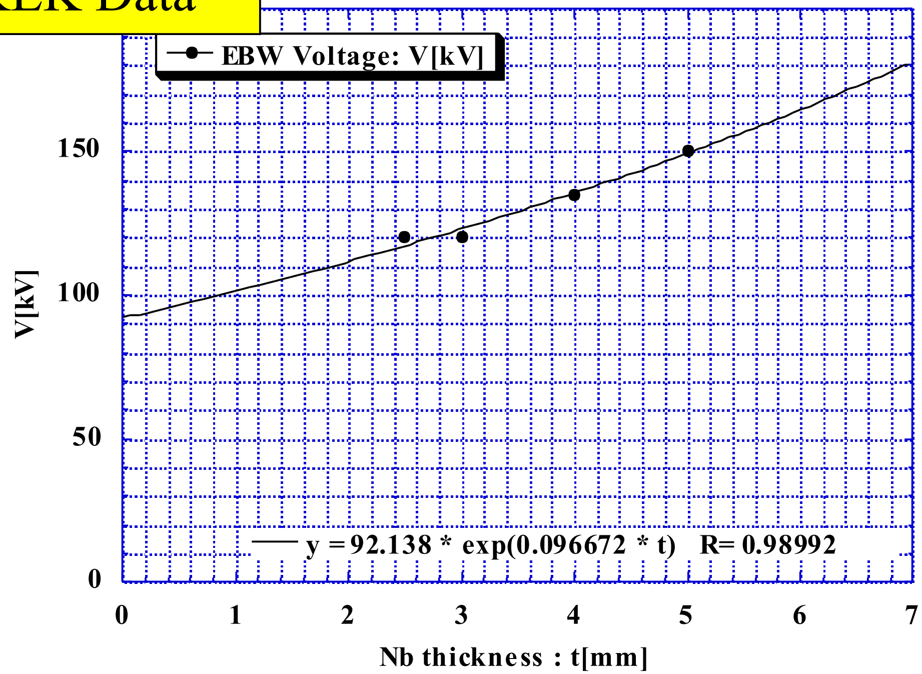
Insert stiffener-ring into the iris part of dumbbell.

EBW conditions with NEC EBW machine : high voltage type

- EBW machine has two types: High voltage and High current
  - High voltage machine is suitable for thicker sheet welding but easy to make sputter balls
  - High current machine produce smoother EBW seam but welding seam is usually wide
  - Focusing/defocusing of the beam is another important parameter
- Full penetrated welding is required

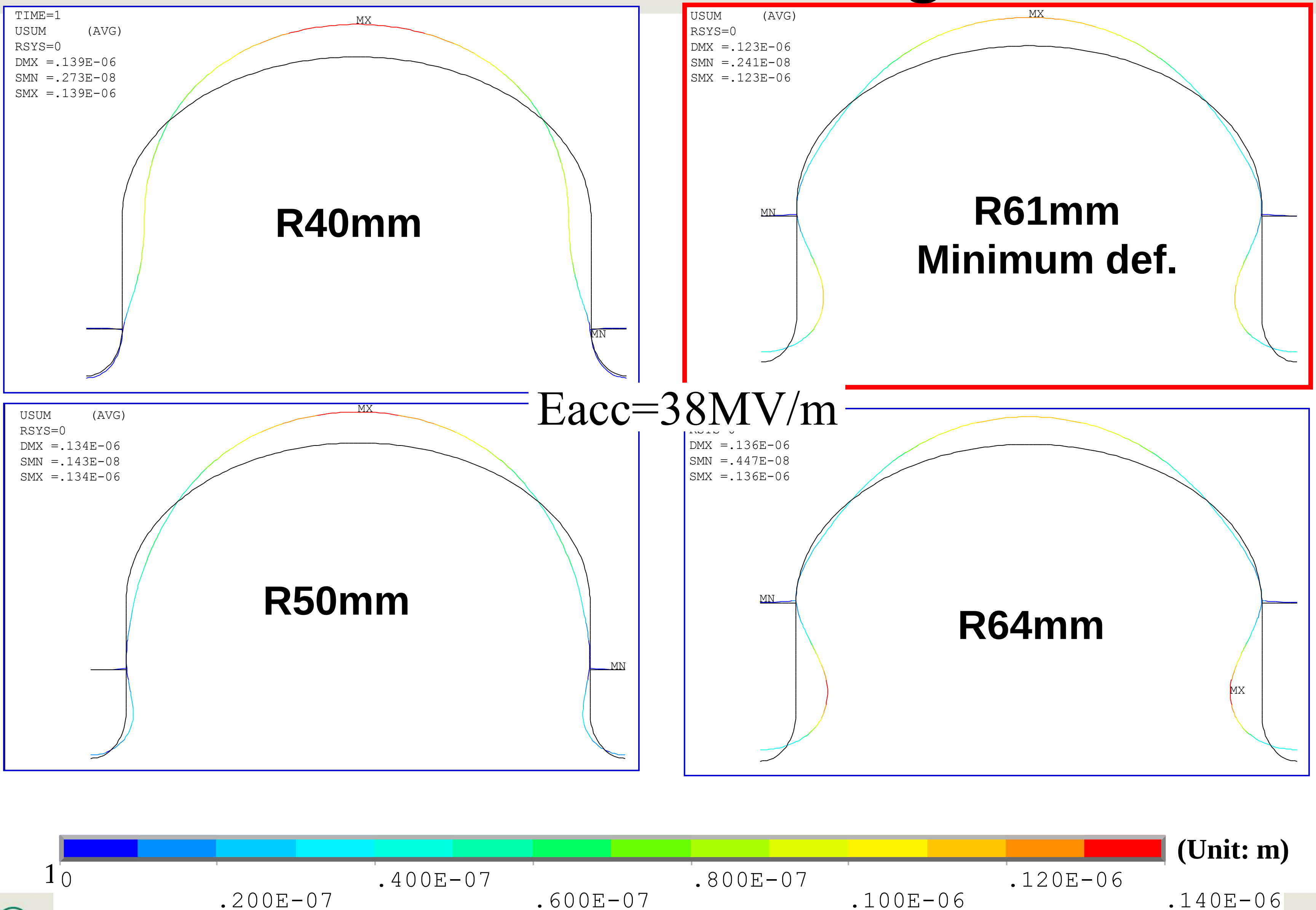
KEK Data





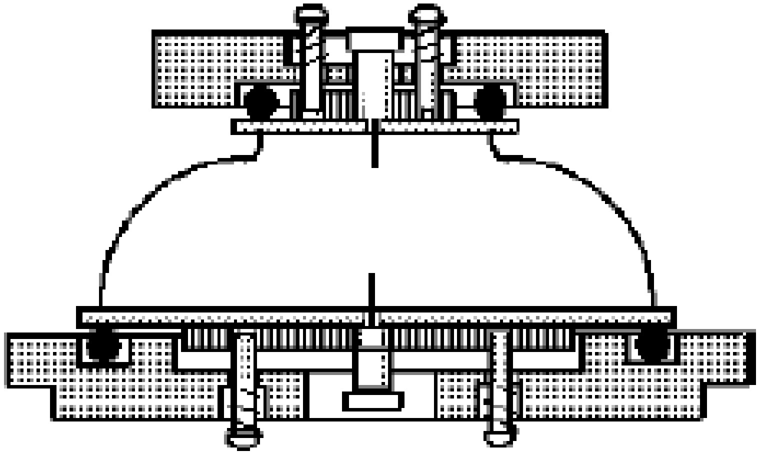
Optimum Location for stiffener ring against Lorentz detuning

by H.Yamaoka



Dumbbells and END cups

Example of Inspection (frequency check) @ DESY



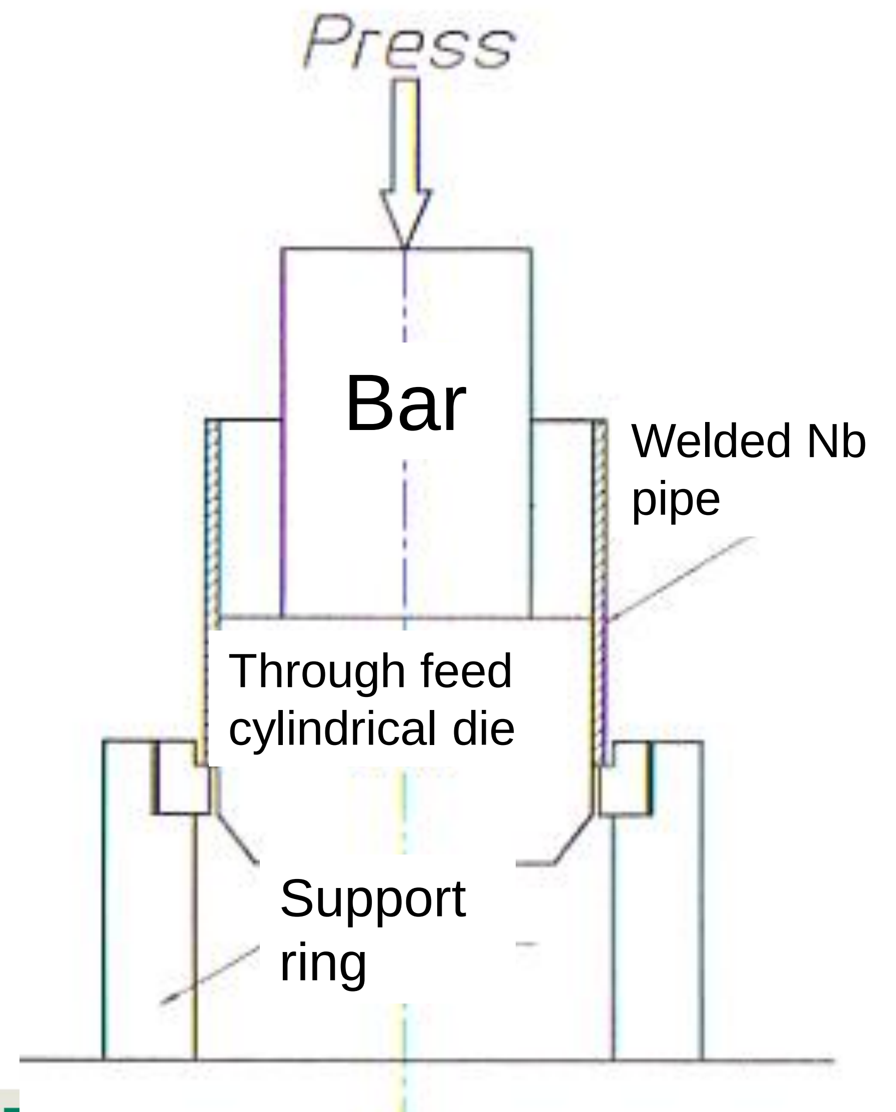
Beam pipe fabrication: thicker sheet case

Nb thickness: 4t ~ 6t

Rounding and EBW of beam pipe tube

After EBW

Centering of tubes after EBW



Completed niobium tubes

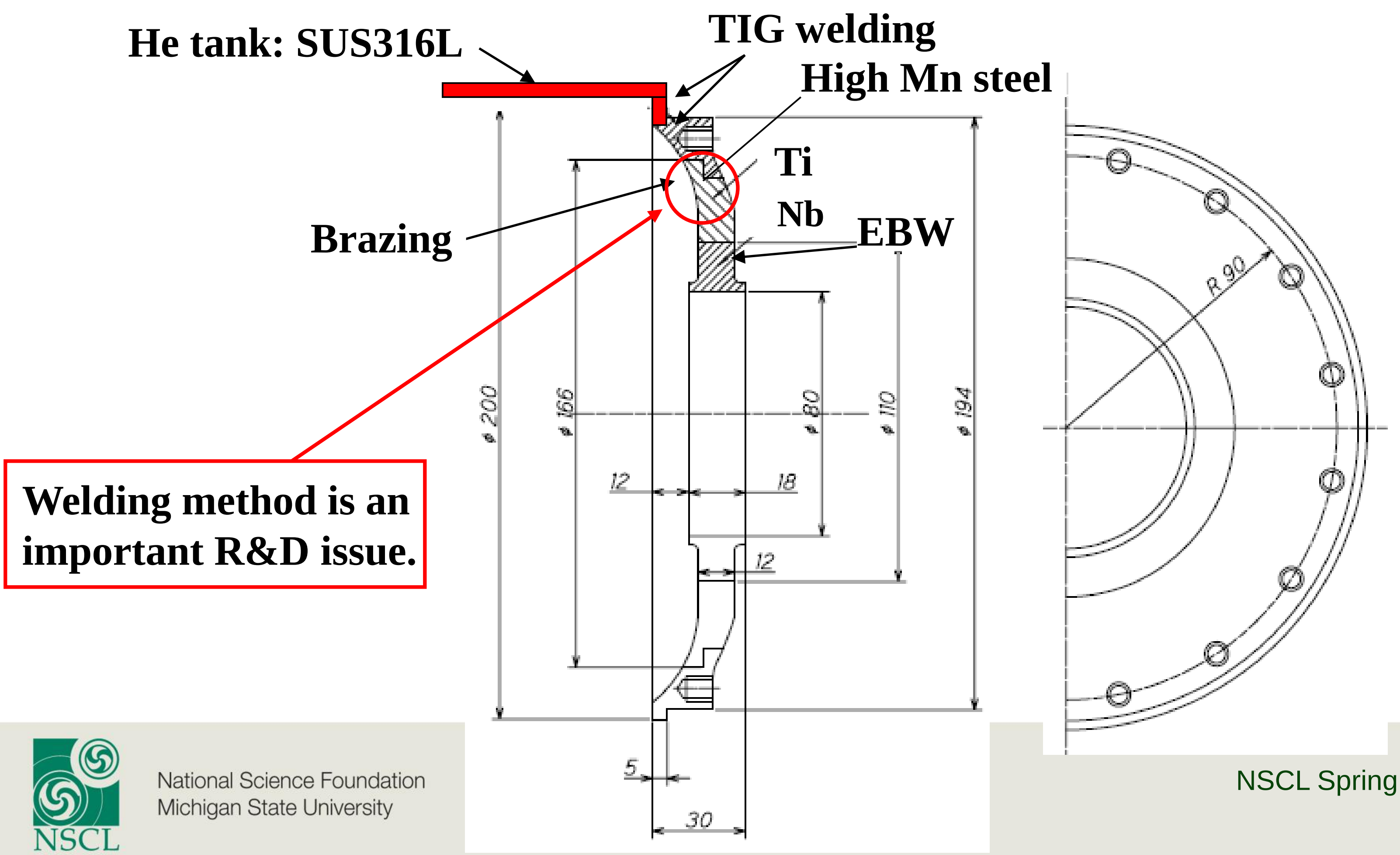
End group fabrication: HOM couplers parts

END group parts

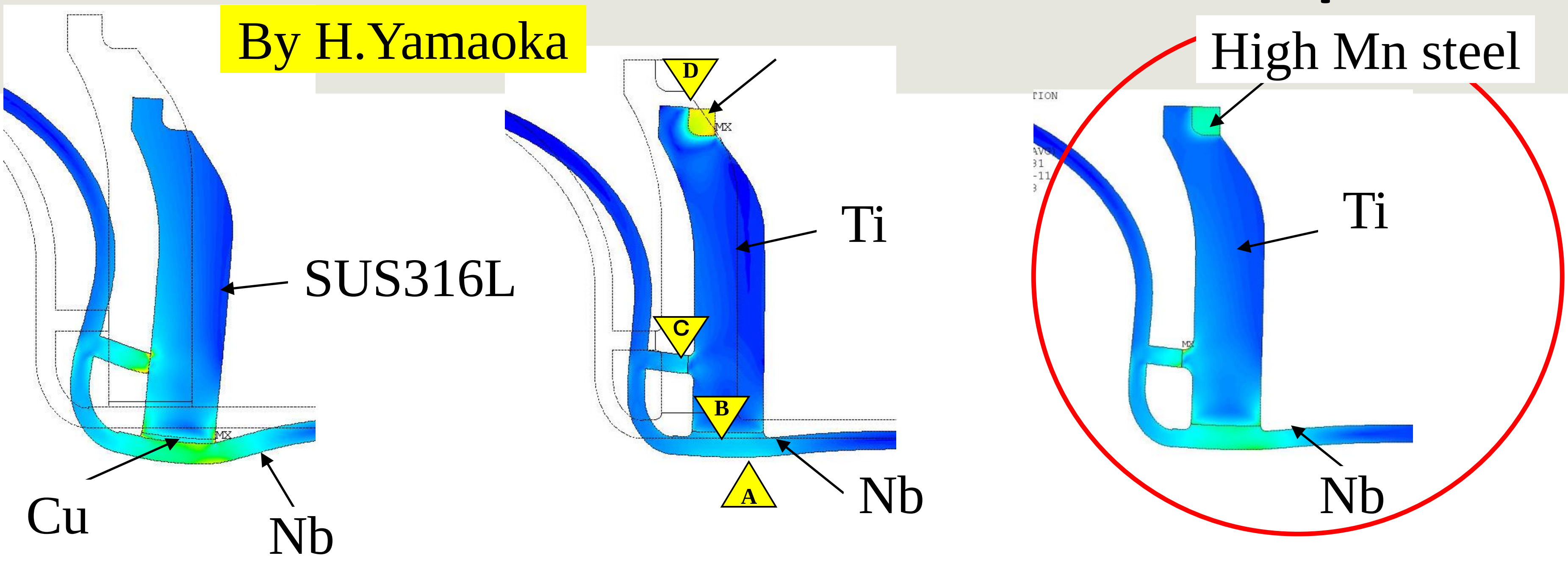
END half cells and Helium vessel base plate

Design of End base plate

- End group is connected to the helium jacket.
- Depending on the helium vessel material (for instance Stainless), special joining is required. Needs welding between different materials.
- Nb (Beam pipe) → End plate (Ti) → High Mn steel (end plate) → Helium jacket (Stainless)



Cure for the thermal stress at the base plate



Nb/Cu/SUS316L **Nb/Ti+SUS316L** **Nb/Ti+High Mn steel**

Stress concentration (Max.)

	A [MPa]	B [MPa]	C [MPa]	D [MPa]
Nb/Cu/SUS316L	250	500	500	
Nb/Ti/SUS316L	100	100	200	470
Nb/Ti/High Mn Steel	100	100	200	80

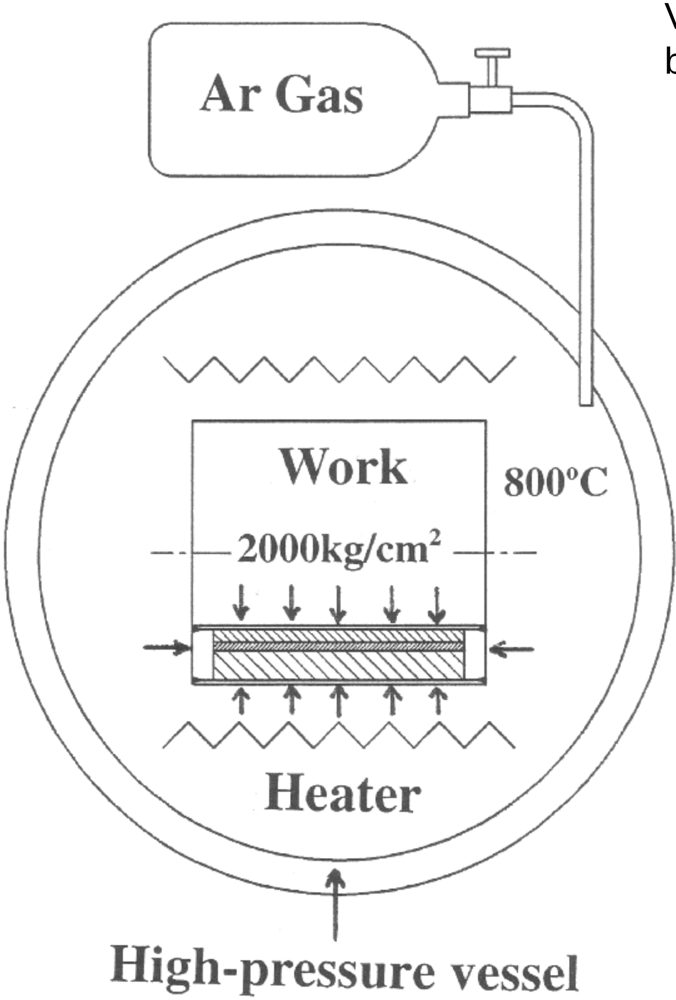
Thermal expansion coefficient

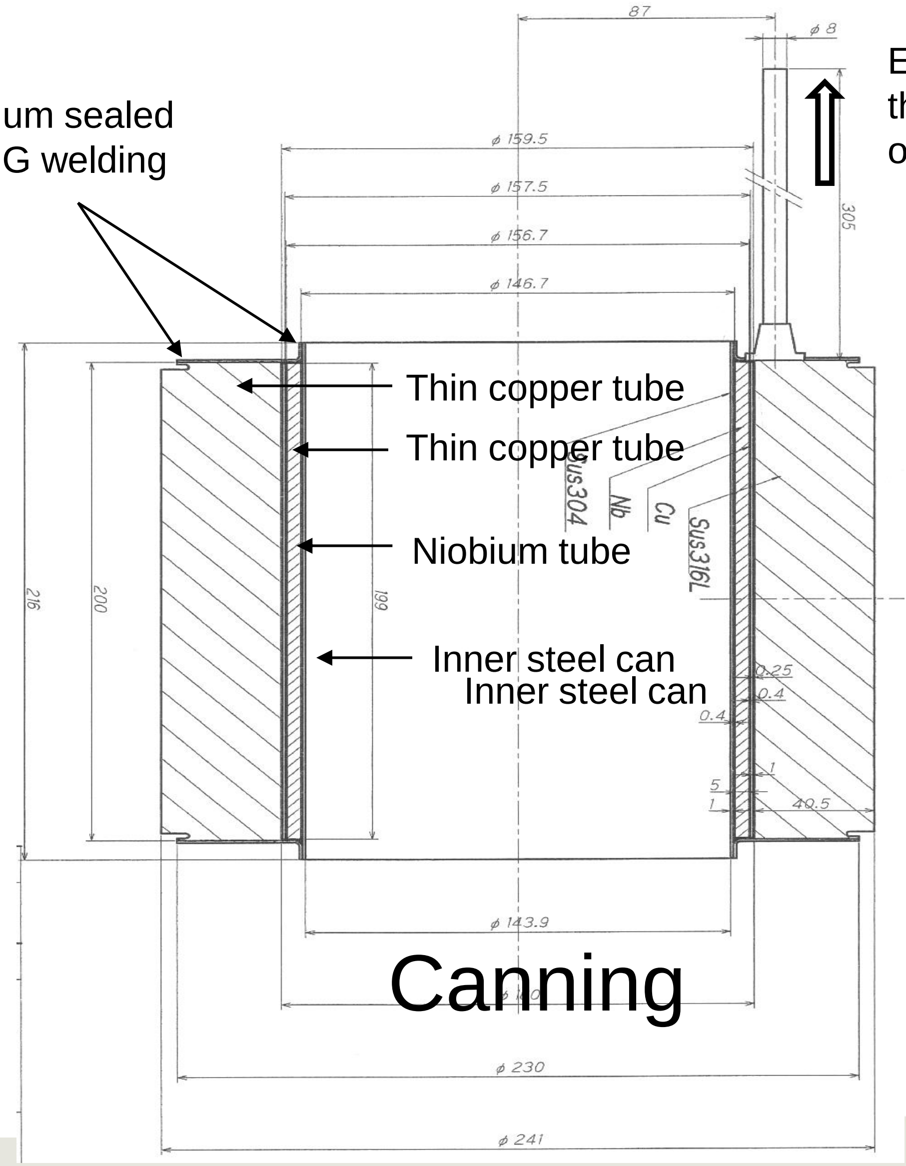
	$\alpha = \frac{\int_{77K}^{300K} \alpha(T)dT}{300-77}$ [E-6/K]
SUS316L	16.0
Cu	17.0
High Mn steel	9.8
Ti	8.4
Nb	5.0

EBW of End group

SFC (vendor)

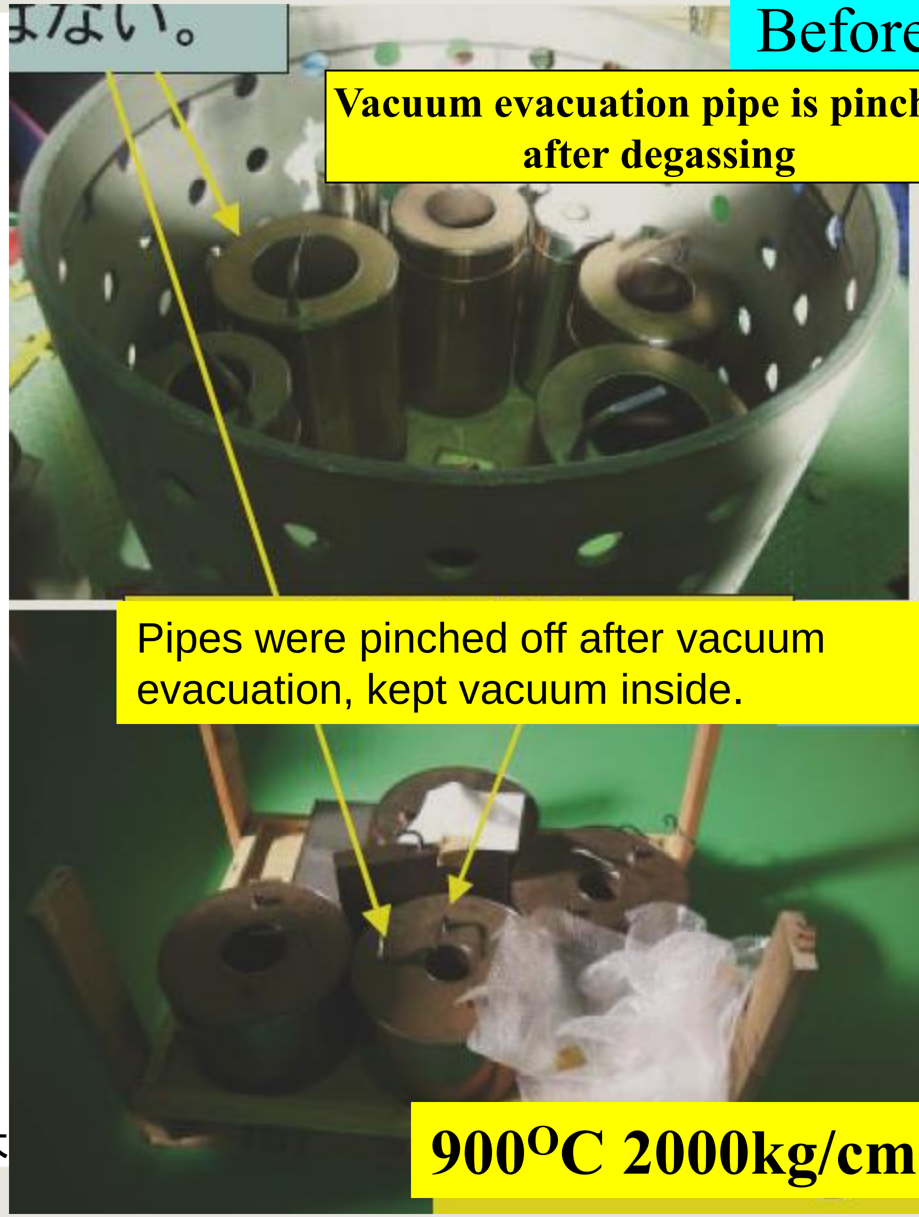
Nb/SUS bonding example:
HIP(Hot isostatic Pressing)





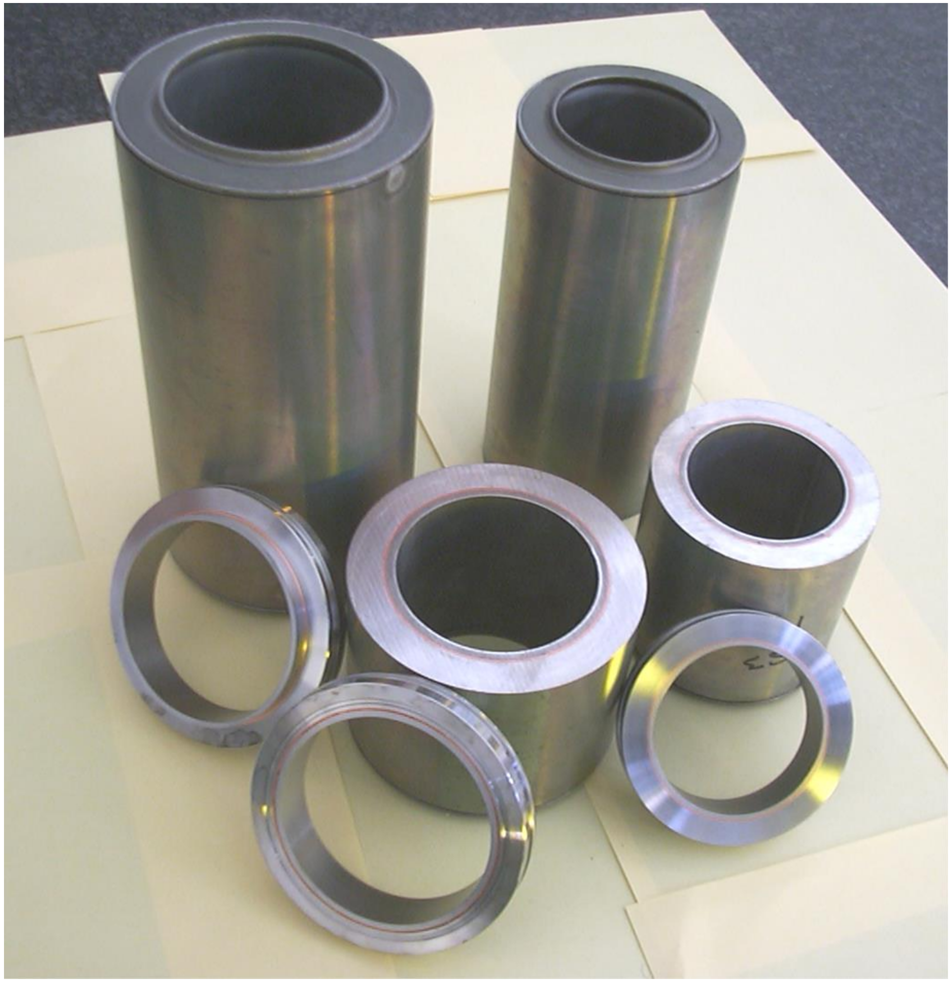
HIP System

HIP装置　金属技研（株）水戸営業所
Kinzoku Giken Co. Ltd



900^{O}C 2000kg/cm^2

Nb/stainless HIP bonded tubes

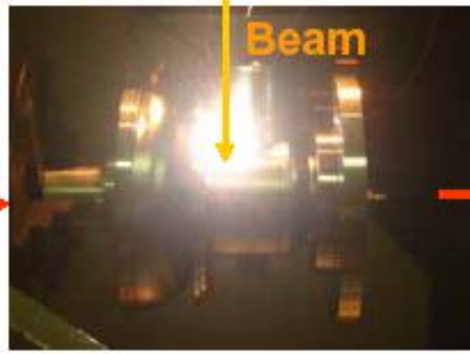


End gropes of ILC cavities

EBW cavity assembly

EBW of dumbbells

EBW of end-beam-pipe



End-beam-pipes with HOM and flanges

EBW of end-beam-pipes and cell-part

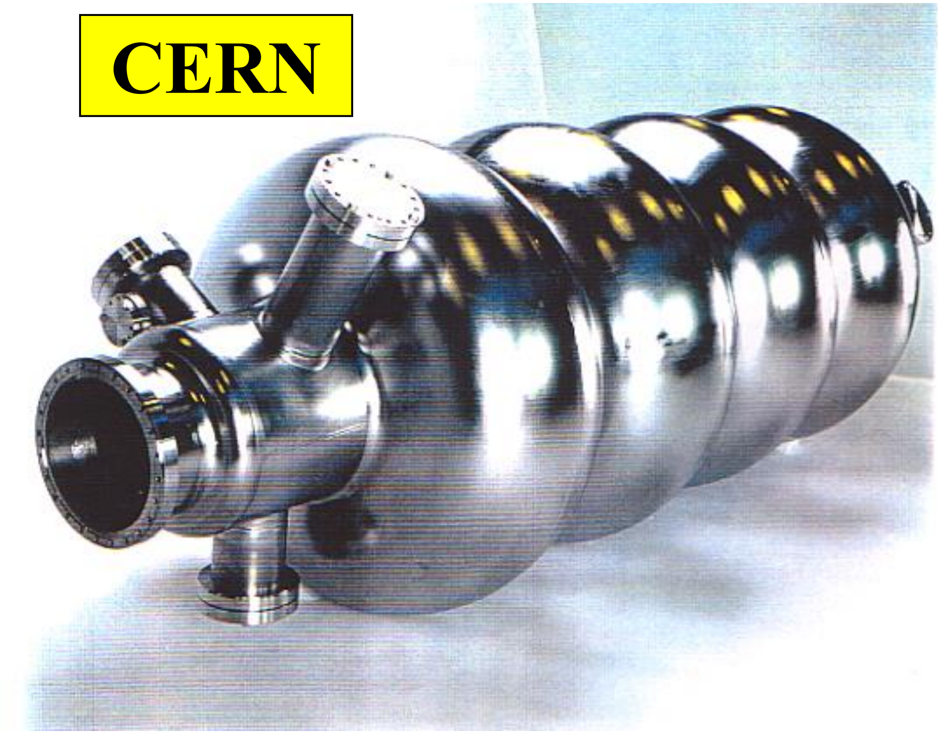
Four 9-cell ICHIRO high-gradient LL Cavities were successfully delivered to KEK ! (4 July 2005)

Completed Ichiro 9-cell cavity (naked cavity)

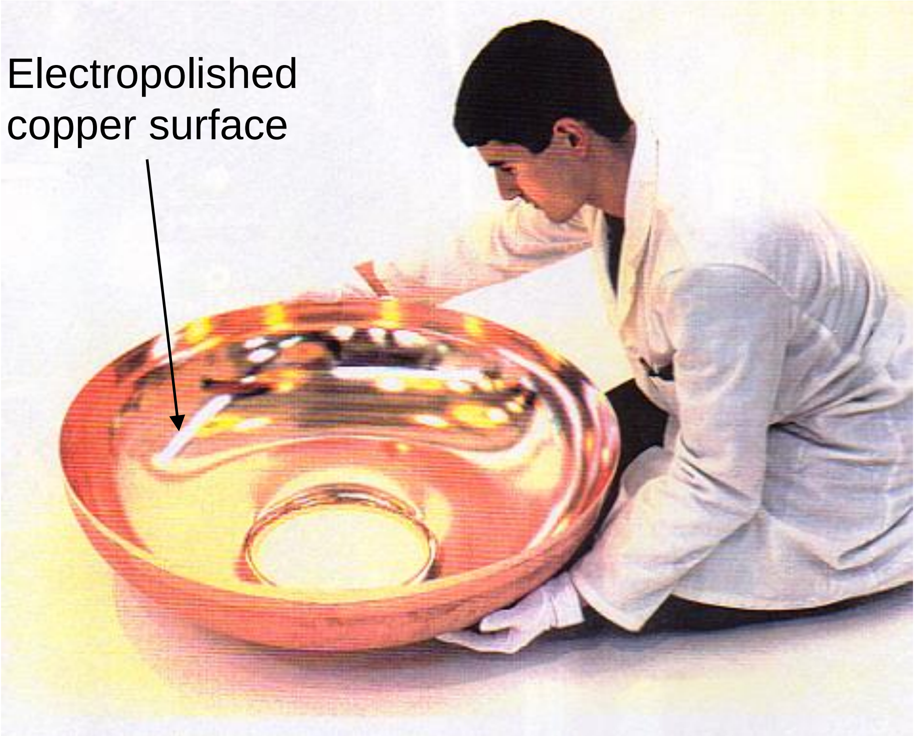
黒木溶接工業（株）
Kuroki Kogyo Co. Ltd.

8.3 Nb film coated copper cavity : CERN 352MHz cavity

- LEP-II (CERN) 352MHz has large diameter and needs lots of niobium material, as the result the material cost is very high.
- CERN developed niobium coated (~ 2μm) copper cavity instead of niobium bulk cavity in end of 1980's

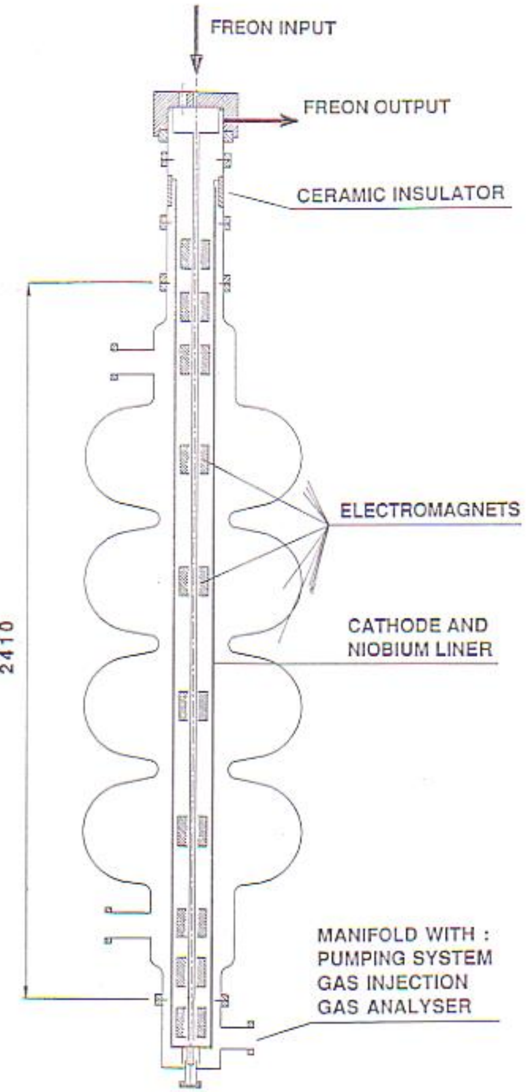


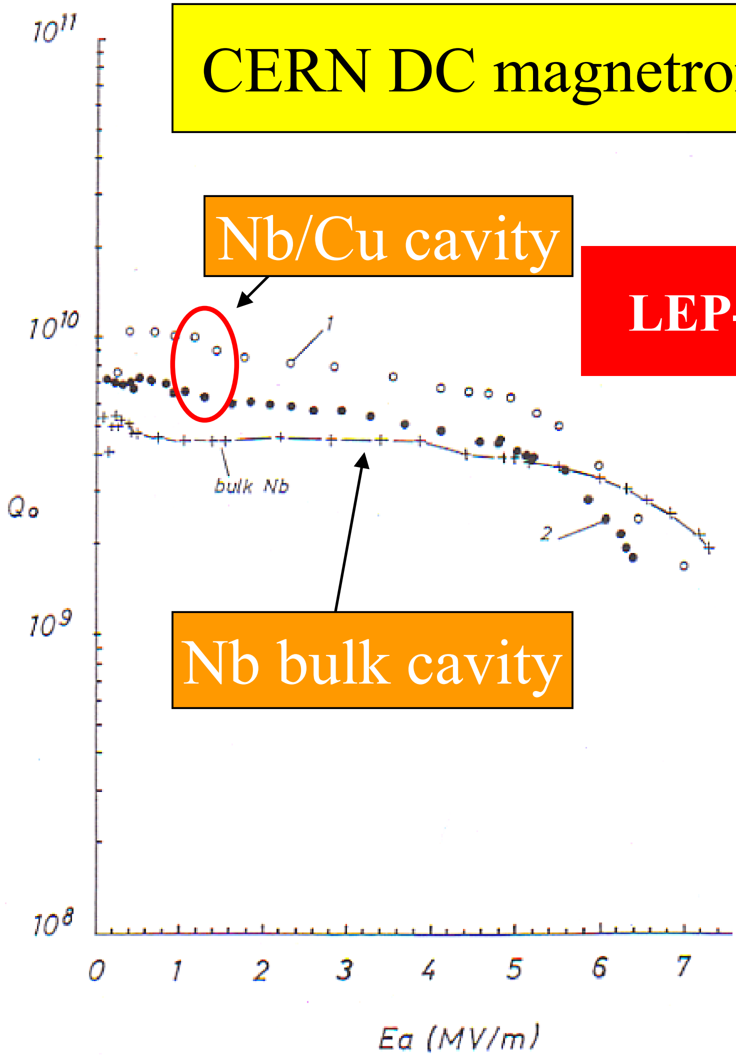
LEP-II 352MHz niobium bulk cavity



Copper substrate half cell before EBW (electropolished)

Nb film coating method at CERN and the cavity performance



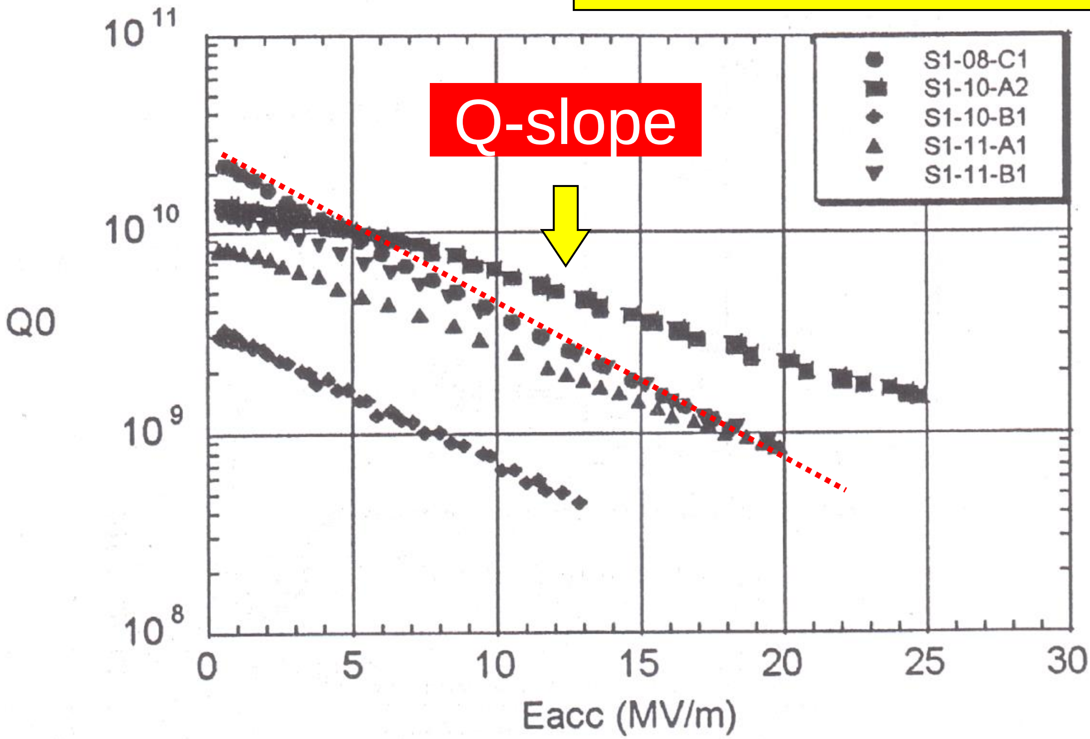


LEP-II is almost Nb coated cavities

- Qo is higher than niobium bulk cavities at lower field < 5MV/m.
- Less sensitive against flux trapping. No needs for magnetic shield around the cavity
- Bulk/Nb coated cavity both have similar performance at 5MV/m.

Application for high gradient cavities
Steep Q-slope in Nb coated cavities

Saclay 1500MHz



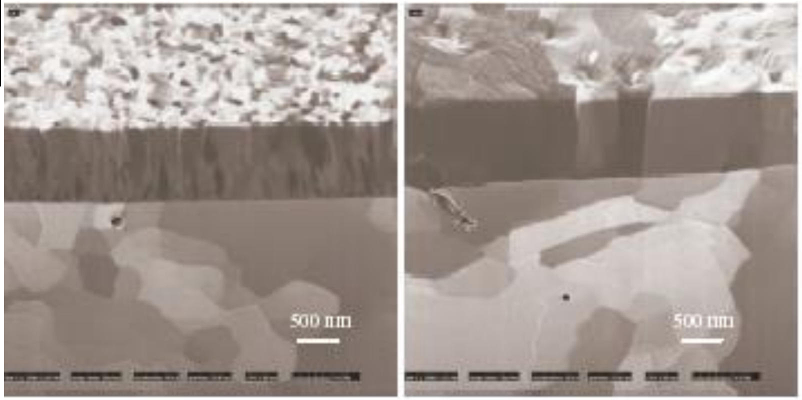


Figure 4: Cross sectional FIB images of niobium films on oxidised (left) and oxide-free (right) copper substrates

- Nb coated cavity: expected Qo ~ $1x10^9$ at Eacc 30MV/m, lower than more than one magnitude.
- Nb bulk cavity: Qo ~ 1.5 $x10^{10}$

Very intensive studies have been continued for last 25 years but we still have no solution.

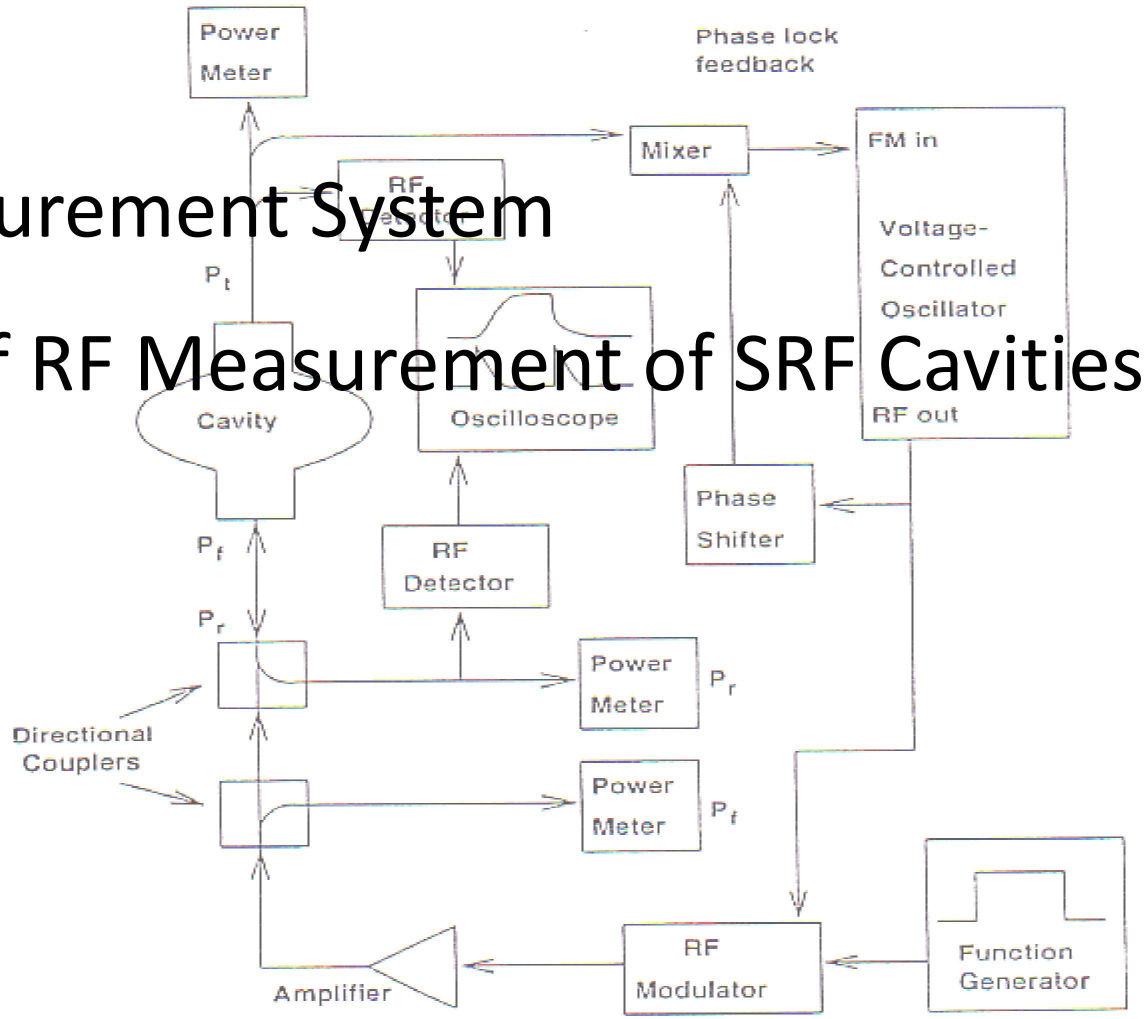
Welding technology for SRF

Bonding technology	Feature	Application Nb/Nb Nb/other
Argon welding (ITG)	Argon gas, established Okay for thick material	No NO
Brazing	Vacuum／Hydrogen gas, brazing wire, Okay for thick material	NO YES
EBW	Vacuum, established Okay for thicker material	YES NO (except for Ti)
Hot isostatic pressing (HIP)	High pressure･High temperature, complicate	YES YES
Laser Welding	Air/Argon gas Simple, Low efficient	Yes (need statistics) ?

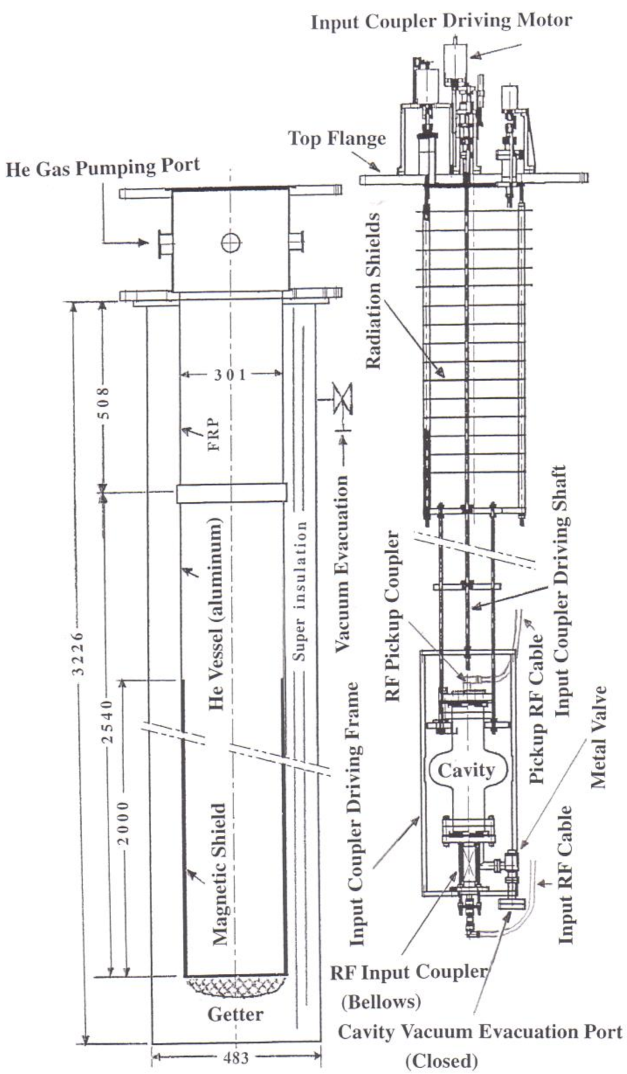
SRF cavity cold test

8.4 RF Measurement System

8.5 Theory of RF Measurement of SRF Cavities



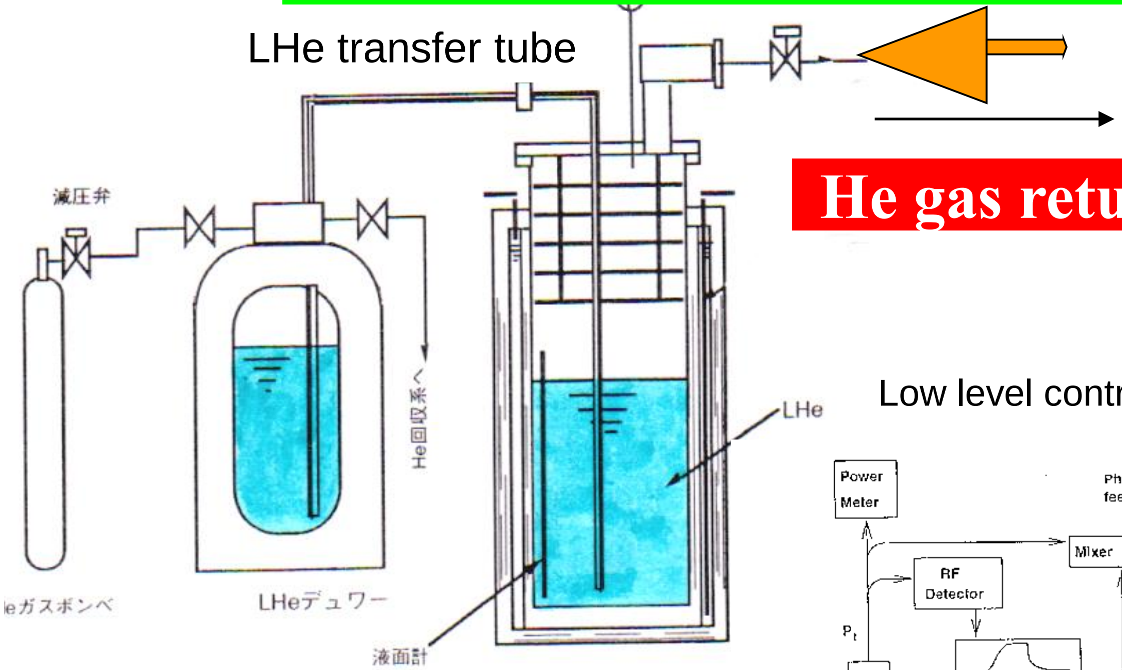
8.4 SRF cavity cold test system



Vertical Dewar　Vertical stand

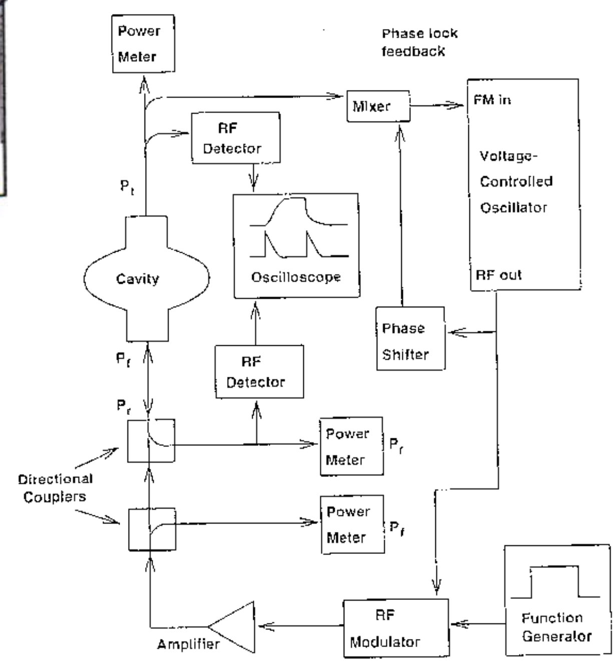
Evacuation pump for He gas to cool down 2K

LHe transfer tube



He gas return line

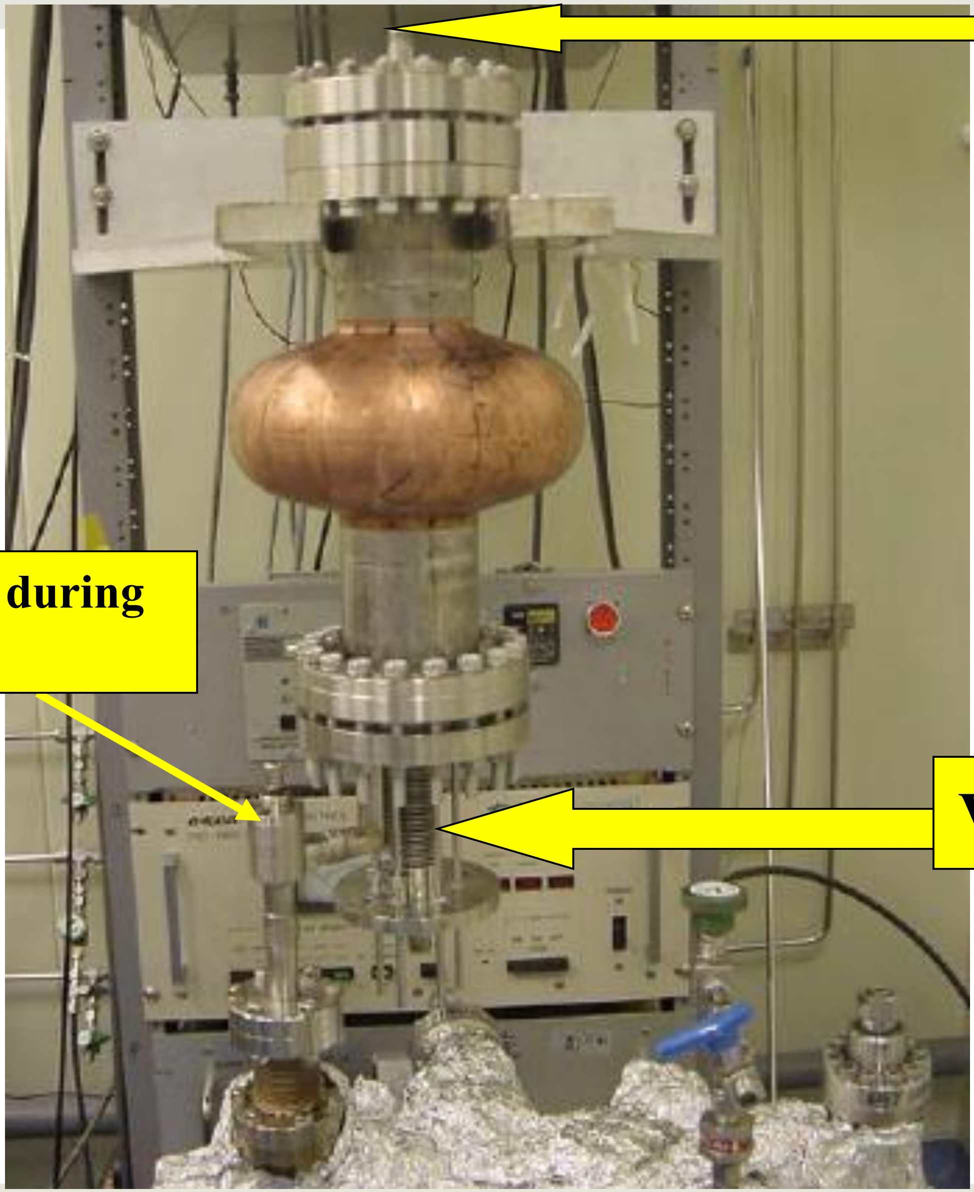
Low level control system



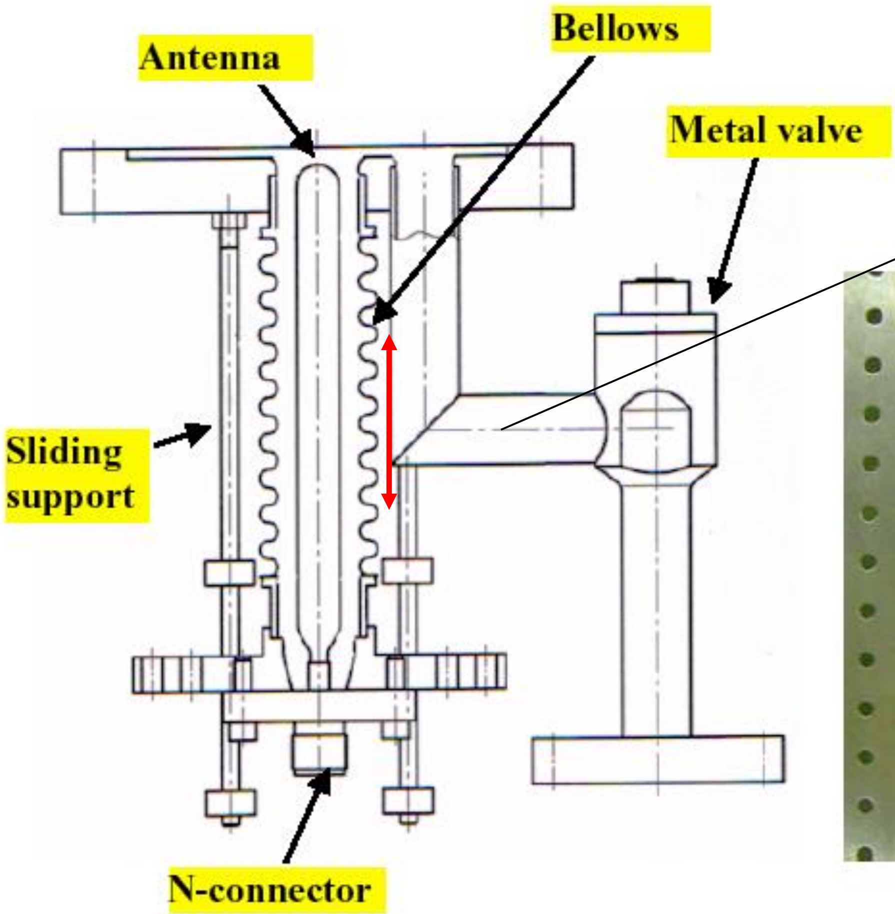
Thermal conductivity[W／mK]

Material	300K - 4K
Copper	550
Aluminum	250
Stainless	10.3
Brass	67
GFRP	0.35
Teflon	0.24
Pilexgrass	0.67

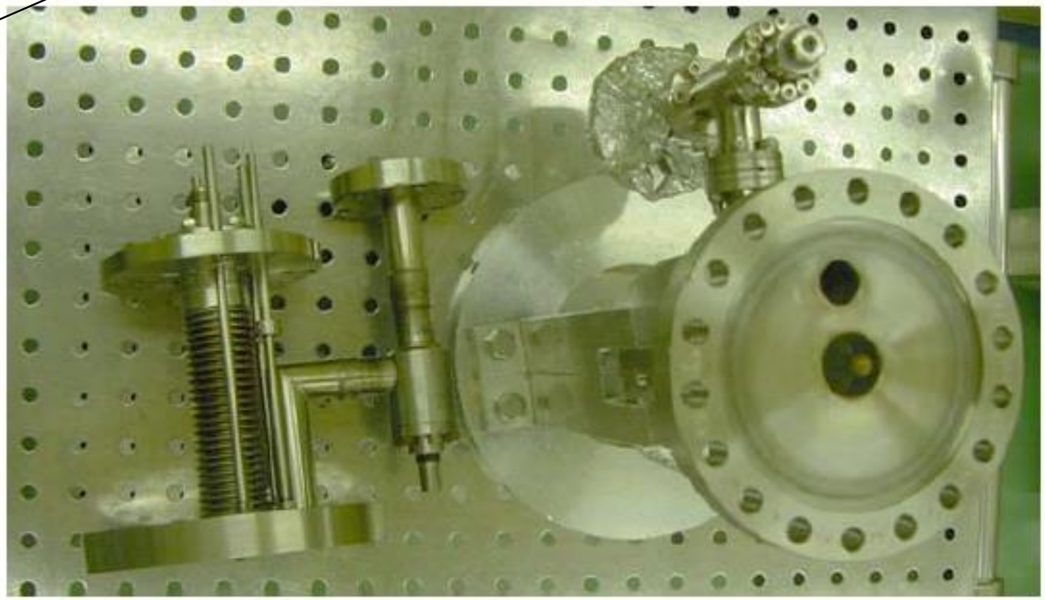
SRF Cavity（Nb/Cu clad cavity)



Variable RF input coupler

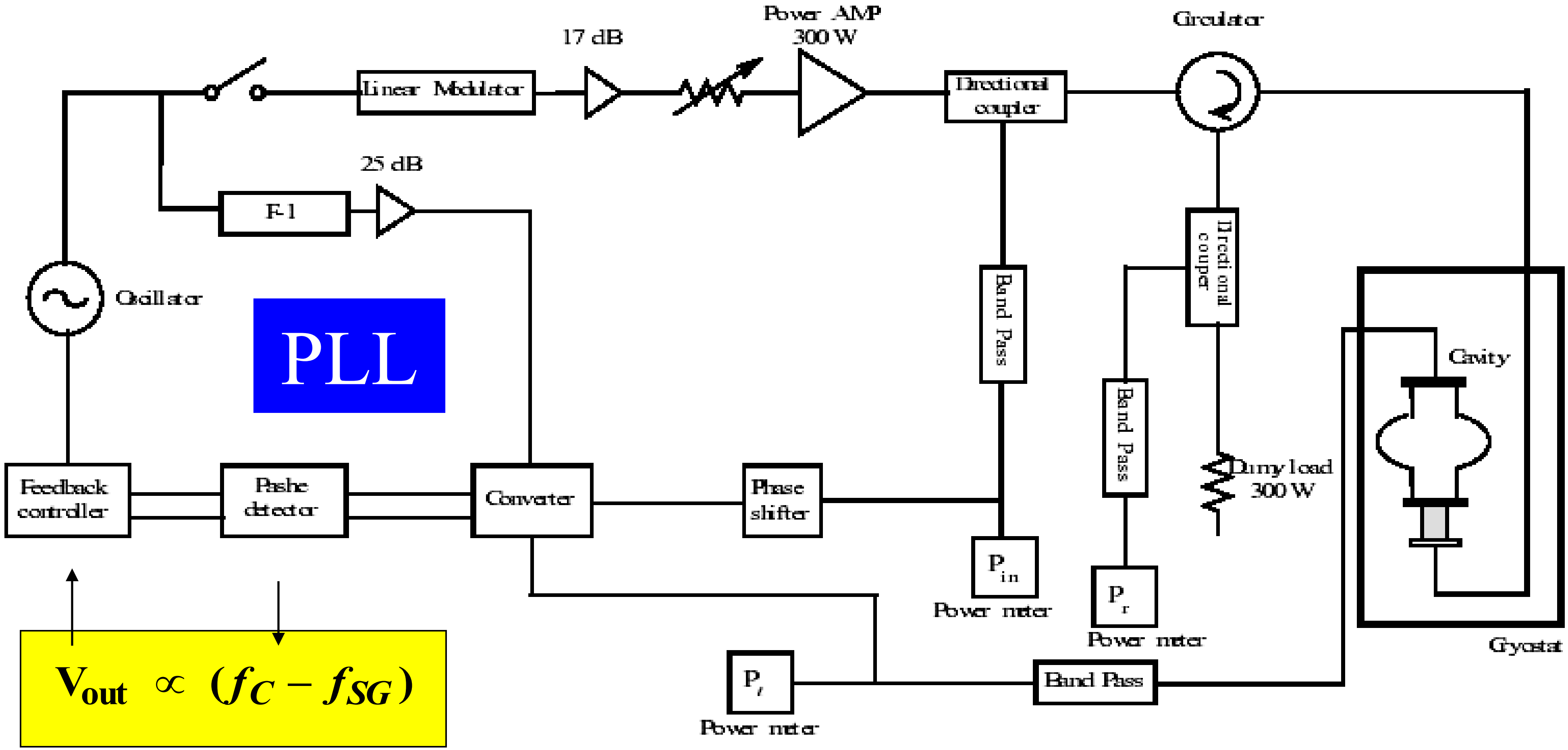


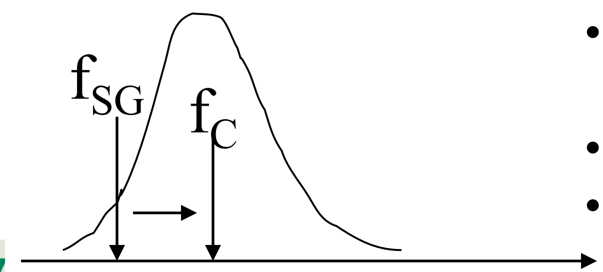
Vacuum evacuation port



Variable input coupler for the vertical test in KEK

Low level control system

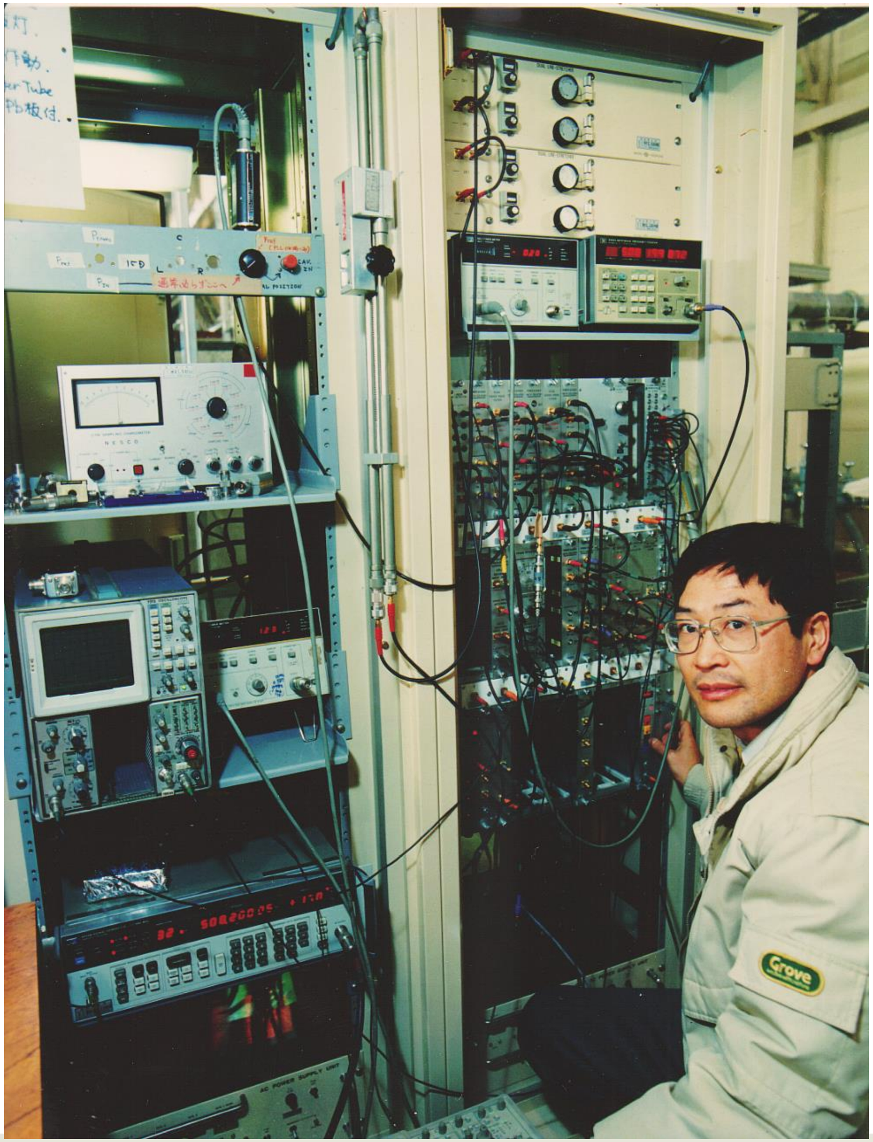




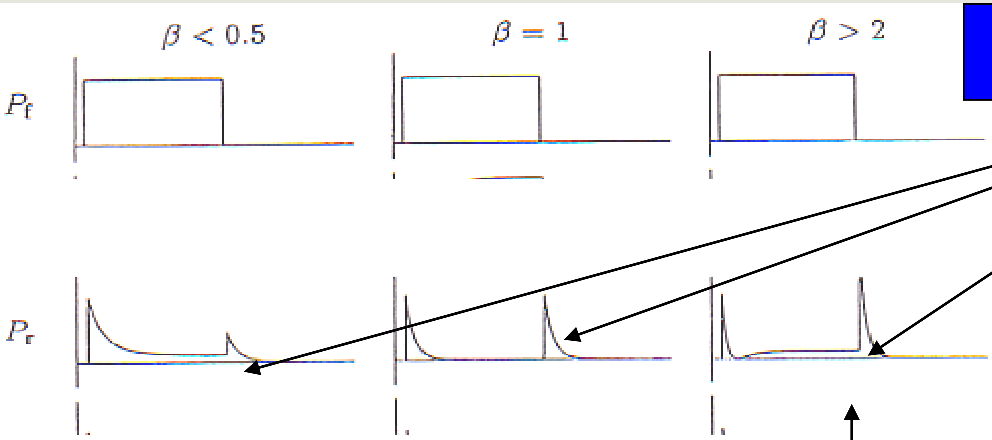
- Cavity frequency is oscillating due to the environment noise (vibration of the floor)
- RF frequency has to follow the cavity frequency
- Cavity resonant frequency is fed back to the RF generator by PLL (Phase lock loop)

RF System example (very old)

TRISTAN



8.5 Theory of measurement



Pulse method

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

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

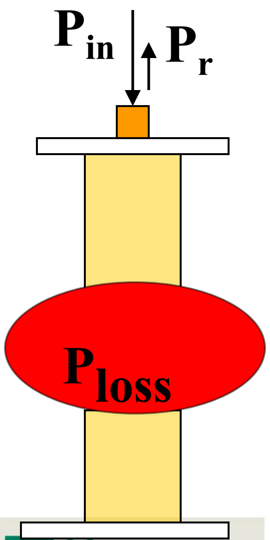
t = 0

One-port

Decay time : $\tau_{1/2}$

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

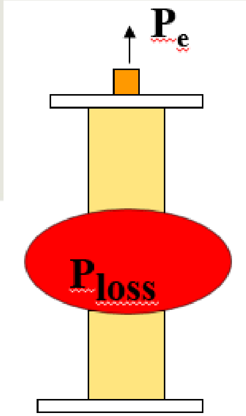
$$\ln(2) = \frac{2\pi f}{Q_L} \tau_{1/2}$$



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

- Q_L is very high in SRF cavities and can not use bandwidth measurement
- Q_L is measured from damping time measurement of the stored energy

One-Port cavity



After RF off

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

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

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

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

Calculate from equivalent circuit

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

Distinguish from wave form Pr

$\tau_{1/2}$, P_{in}, P_r — **Measurement value**

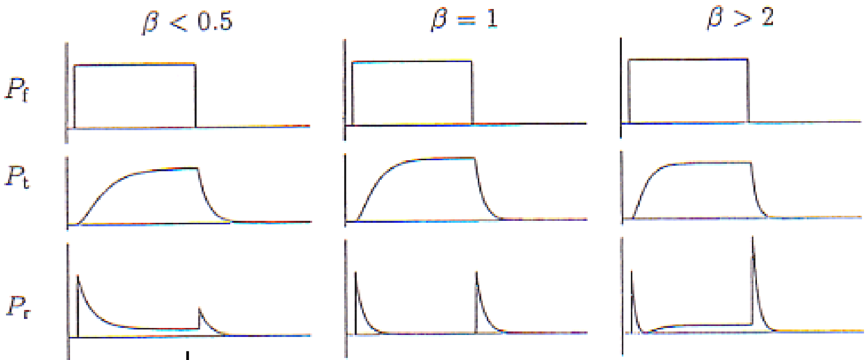
Calculation Q_L, β_{in}

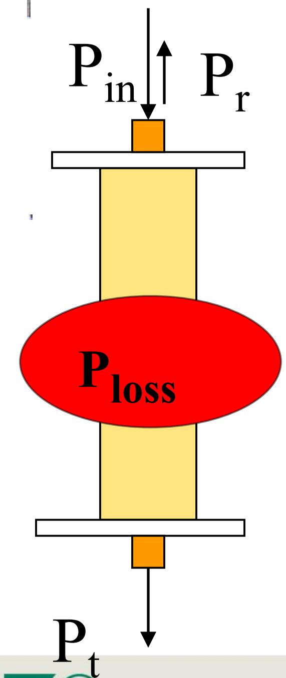
Calculation Qo

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

Two-Port cavity

- Actually two port measurement is more convenient for gradient measurement





Measureable

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

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

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

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

Measureable

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

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

$$(\text{over} > 1 / \text{under} < 1)$$

Two-Port Cavity measurement, continued

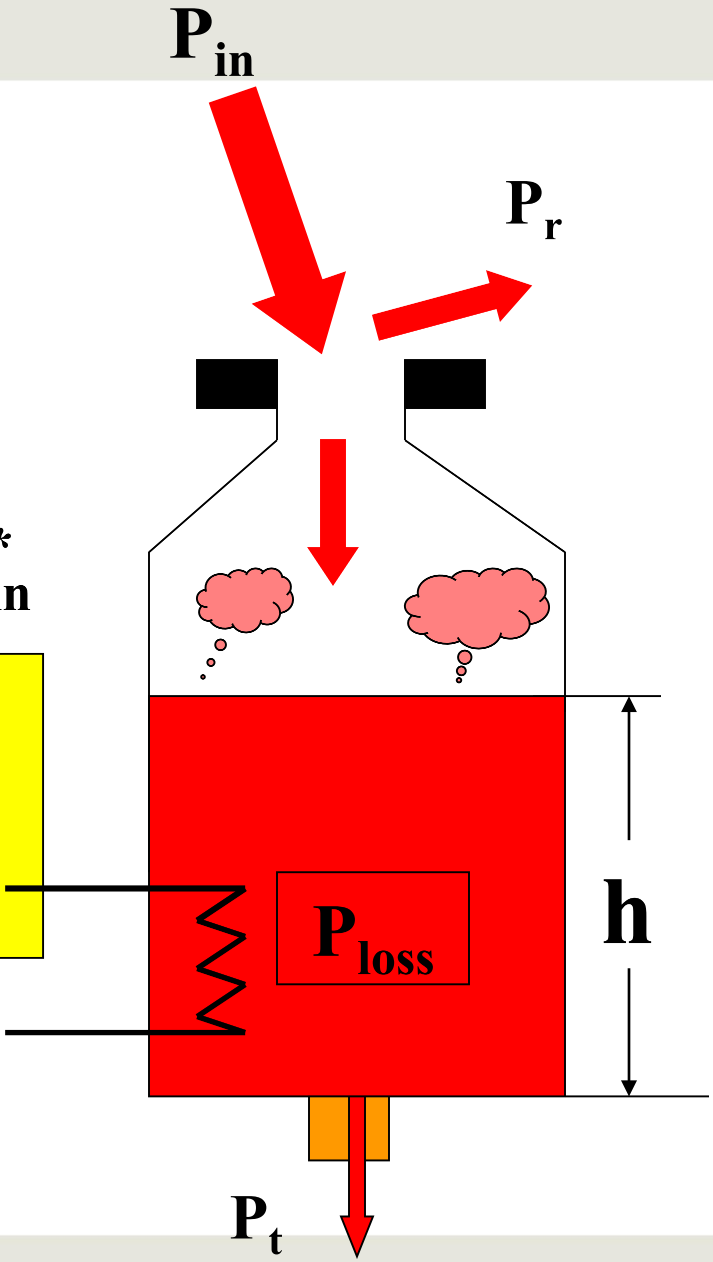
$$Q_o^* = \frac{Q_o}{(1+\beta_t)} = (1+\beta_{in}^*)\cdot Q_L$$

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

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

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

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



Steady state : h= constant ⇦ U constant

Calculation of accelerating gradient

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

$$= \left(E_{acc} \cdot d_{eff}\right)^2$$

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

$$= Z \cdot \sqrt{Q_O \cdot P_{loss}}$$

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

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

Summary of calculation of Q_O

Measured parameters:

Steady state :CW

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

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

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

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

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

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

$$Q_t = Q_O / \beta_t$$

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

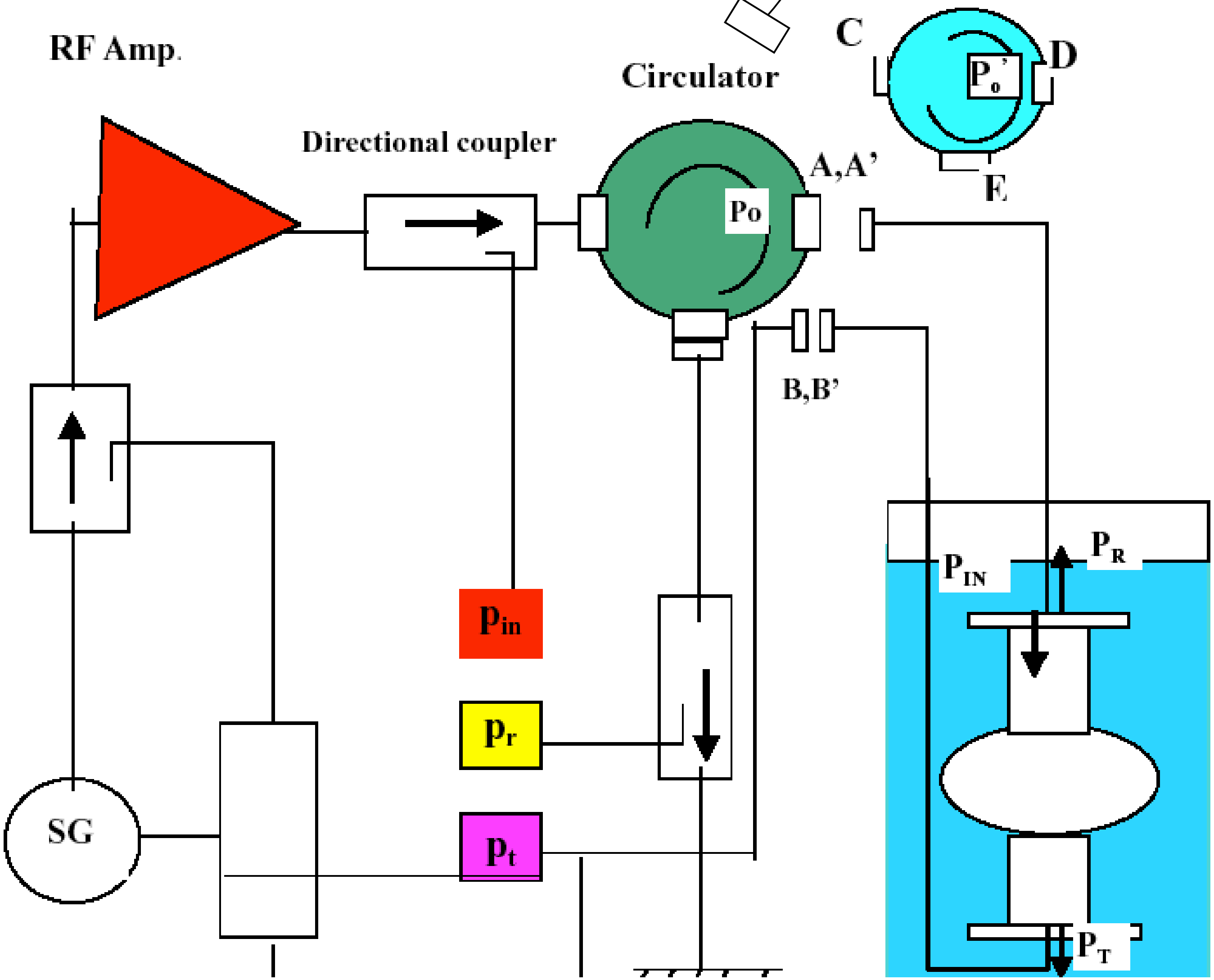
$$Q_O = (1 + \beta_{in} + \beta_t)\, Q_L$$

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

Cable calibration

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'

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

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

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

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

$P_R = c_r \cdot p_r$

$P_T = c_t \cdot p_t$

Homework 4

I. Cable correction

Cable correction measurement
p_{in}=55.5μW, p_o=50.0mW,
p_r=10.72μW, p_t=3.04mW

p_o'=39.0mW, p_{in}'=22.6mW
p_t'=27.9mW

II. Calculation of Qo and Eacc

Measured power and decay time
f = 1303.590529 MHz
$\tau_{1/2}$ = 23.6 msec
Coupling: over
p_{in} = 3.11 mW,
p_r = 192 nW,
p_t = 0.142 mW
He pressure = 758.1 torr

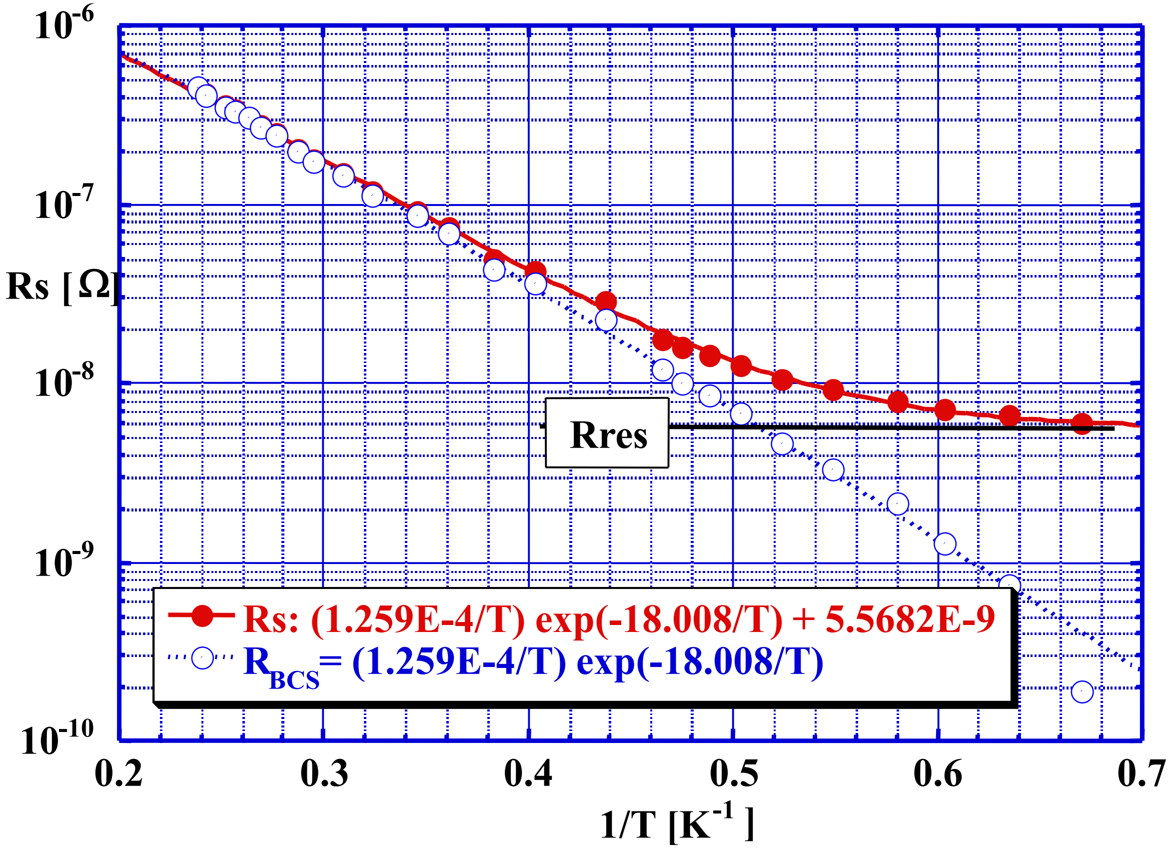
4.1 Calculate cable correction factor Cin, Cr, Ct using the data I.

4.1 Calculate Q_L, Q_{in}, Q_O, β_{in}, β_t, R_S, Eacc, measurement result for 1300MHz single cell Nb SRF cavity at 4.2K. Calculate the cable correction factors using these results.

Measurement of temperature dependence of SRF surface resistance

$$R_S = \frac{\Gamma}{Qo}$$

Γ = 271 Ω for TTF single cell cavity



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

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

Measurement of Qo vs Eacc curve