First Cavity Performance Test for Nb_3Sn Superconducting Cavity by Vapor Diffusion Process at KEK

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Thin film SRF 2021

Outline

- R&D motivation
- KEK coating system
- Sample coating
- Cavity coating
- Cavity performance test
- Summary, Future works

Nb3Sn R&D at KEK

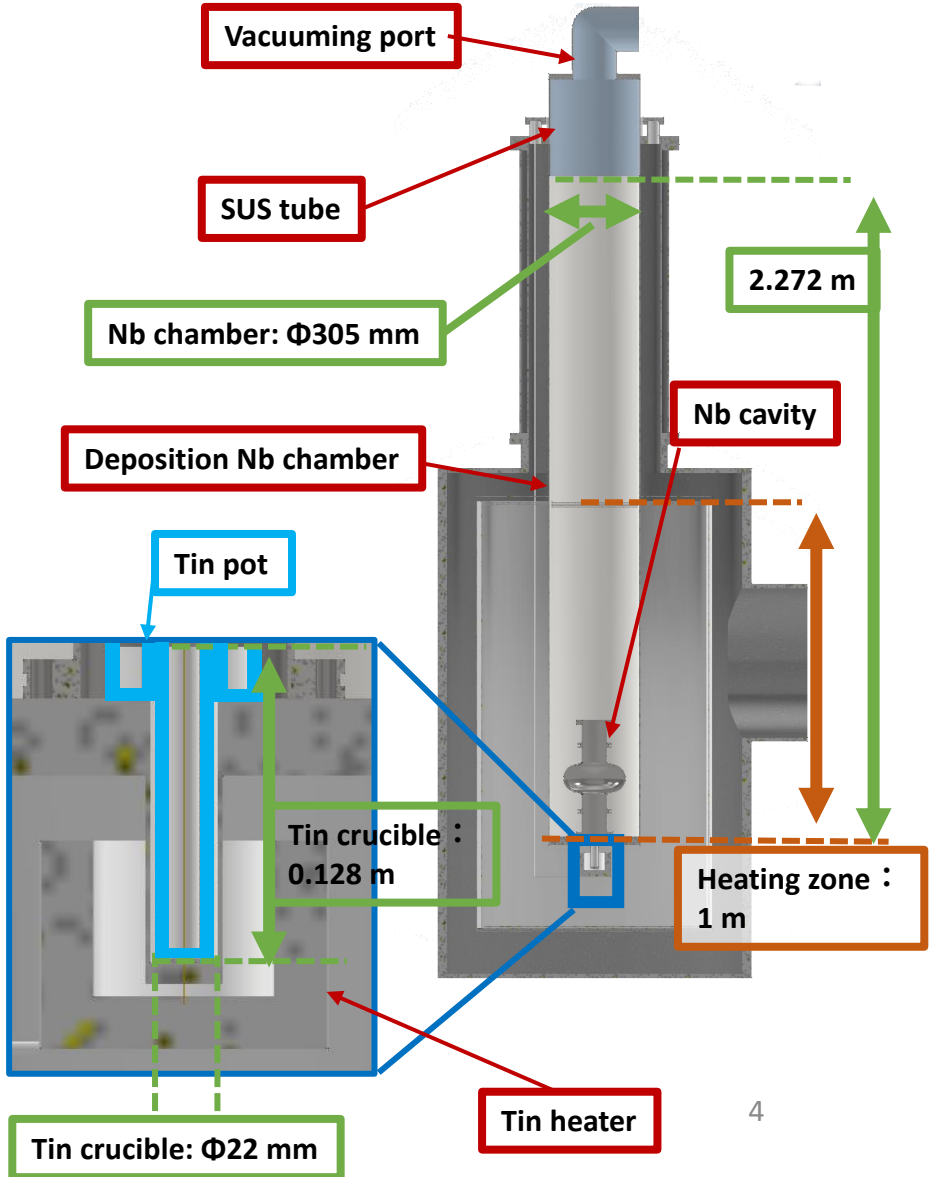
Nb3Sn vapor diffusion R&D for High-Q has just started at KEK

- Motivation
  - Development of High-Q Nb3Sn cavity
  - Compact SRF accelerator with cryocooler

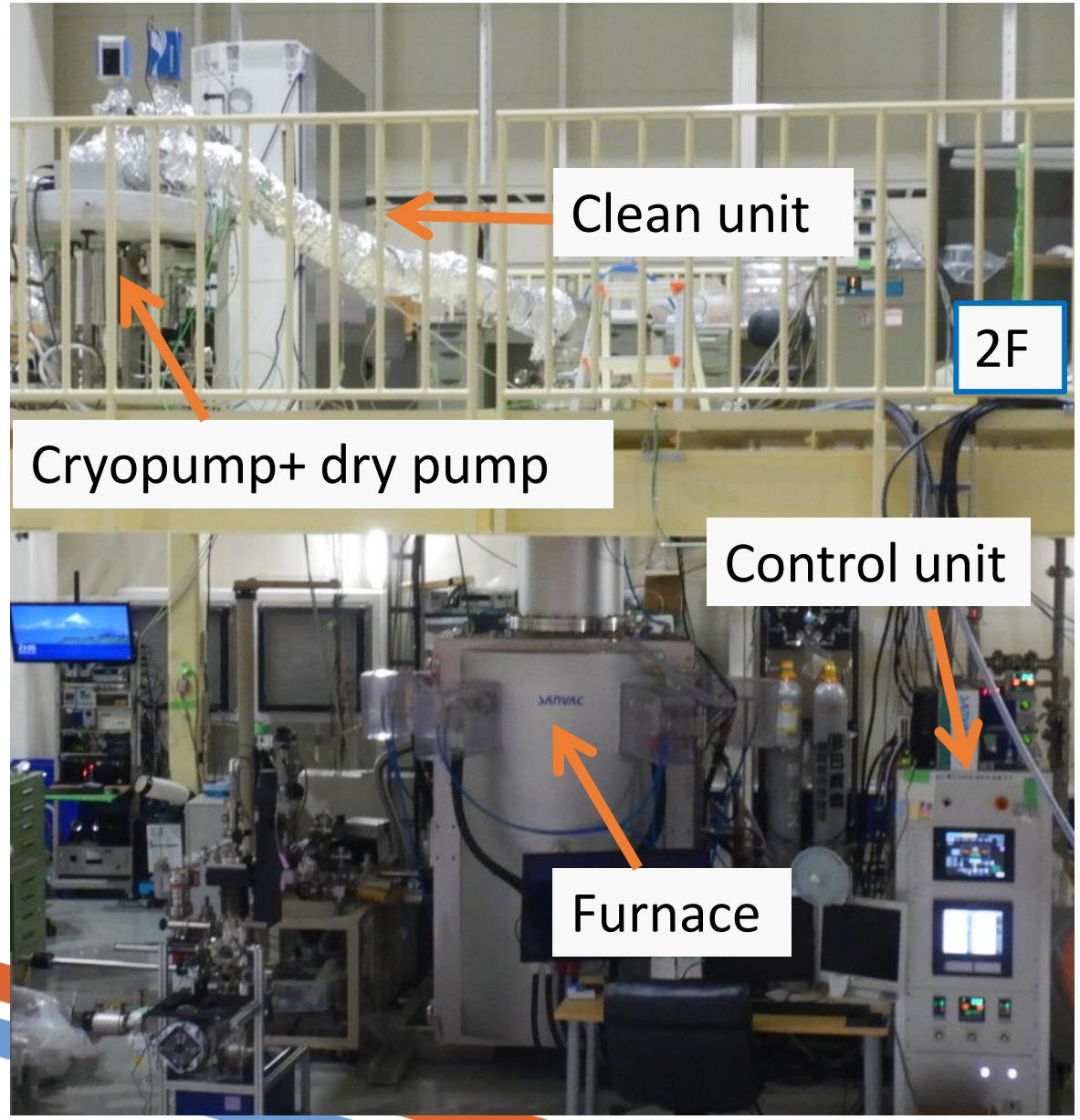
- Vapor diffusion system (Furnace, Nb coating chamber, vacuum pump and etc.) was construction.
- Coating tests were carried out.
- Characteristics of several coating samples were observed.
- A Nb cavity was coated with Nb3Sn then the performance was measured.

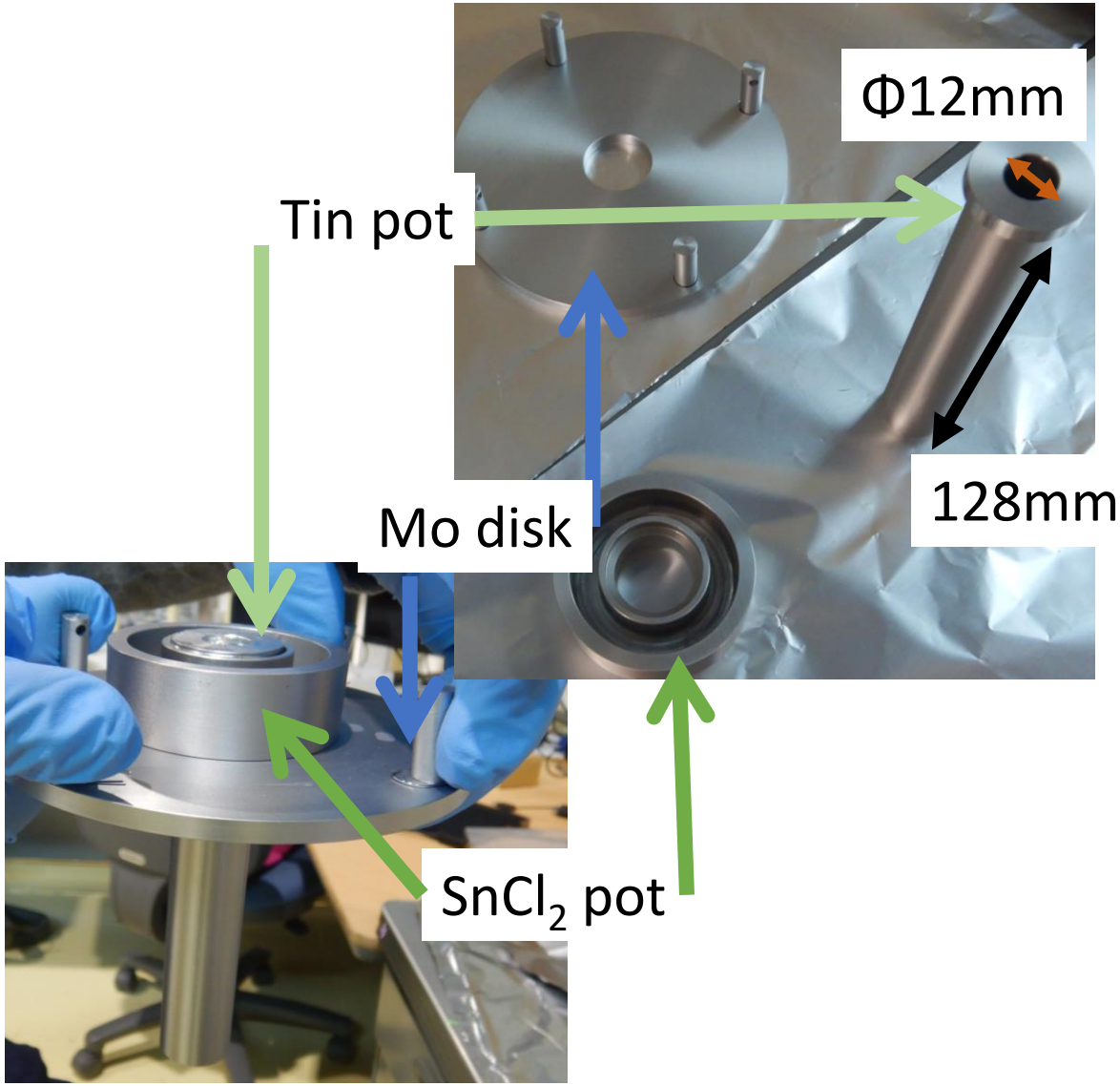
Design of KEK coating system

- Furnace temperature is 1100℃ and Tin heater temperature is above 1300℃ in coating process.
- Nb chamber vacuum and furnace vacuum are isolated.
  - Prevent contamination
- Nb chamber heatproof temperature is 1400℃.
  - Titanium flange was welded with TIG welding.
  - The chamber connects SUS vacuum port.
    - Cu gasket is used for vacuum seal.
- Tin heater is made of Mo, and rated power is 1 kW.
  - Maximum temperature ＞ 1400℃
- Vacuuming system: **Cryo pump** +Dry pump
  - Vacuum pressure ＜ 1×10^{-5} Pa at 1100℃ (furnace)
- Furnace and Tin heater are independently controlled.



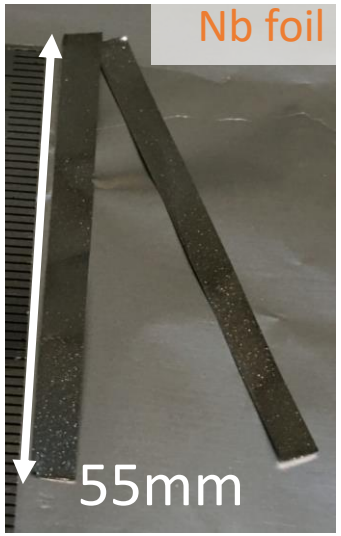
Coating system at KEK

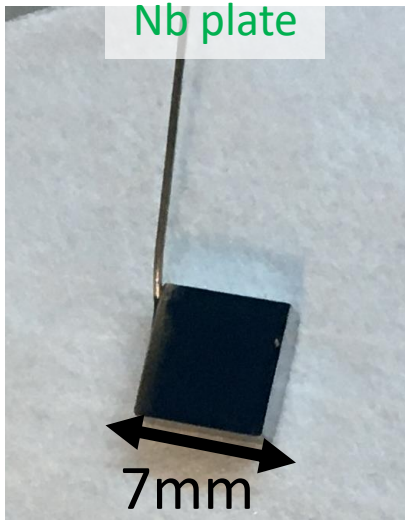




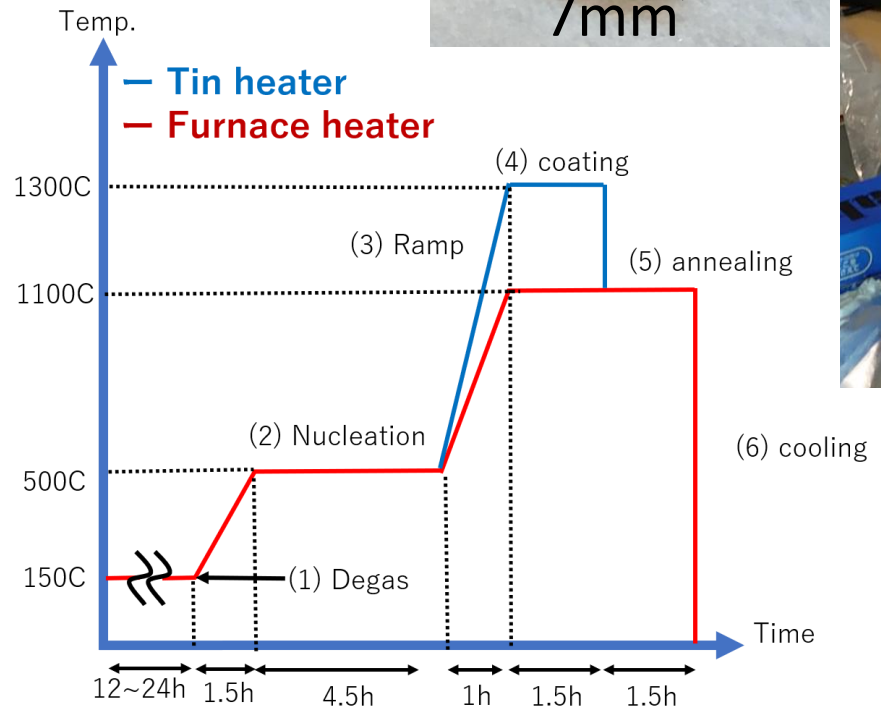
Sample coating

- Sample coating : Searching parameter for cavity
- Two types of sample are coated
  - Nb foil : RRR~30, 5 × 55 × 0.07 [mm^3], CP
    - Used for Tc measurement and cross section observation
  - Nb plate : RRR~300, 7 × 7 × 3 [mm^3], mirror polish
    - Used for surface observation
- Sample holder : made of niobium
- Sample coating parameter
  - Nucleation : 500°C 4.5 h
  - Coating : 1300°C~1500°C 1.5 h (Tin heater)
    1050°C~1200°C (Furnace)
  - Annealing : 1100°C 1.5 h or 0 h
  - Nb chamber is evacuated during entire coating process.





Sample holder with Tin pot

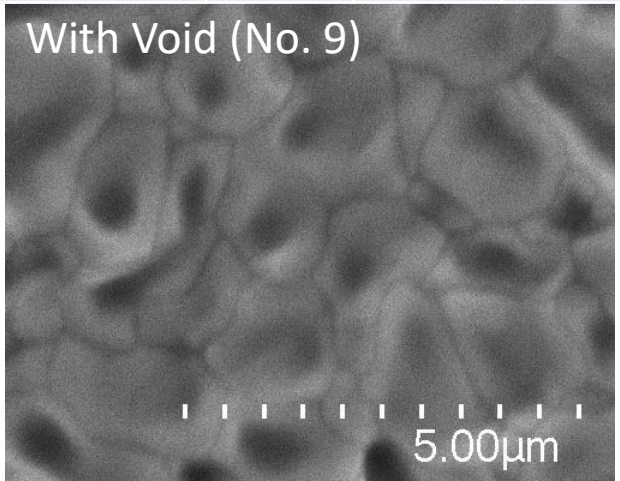


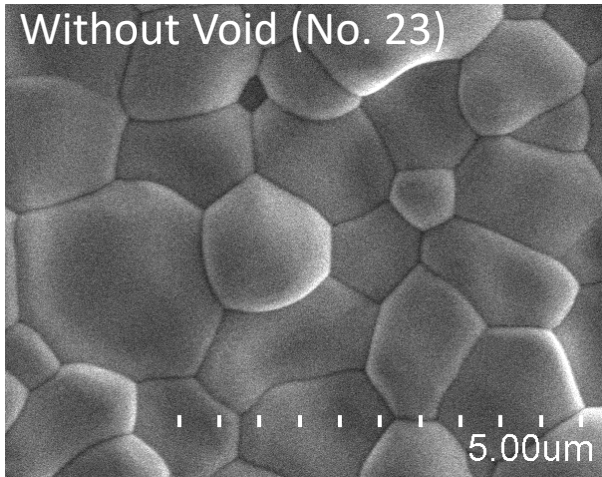
Sample coating result

- Sample was coated several parameters.
  - Coating temperature : 1050°C~1200°C (furnace)
  - Coating time : 1.5 h / 3.0 h
  - Annealing time : 1.5 h / 0 h
  - Nb foil on top of sample holder : Available/ Not available.
  - Nucleation condition and Tin pot temperature was fixed. :
    - Nucleation :500°C 4.5h
    - Tin pot . : 1400°C
- Samples with annealing have voids on surface.
- Sample coating number 23 was chosen as cavity coating parameter.
  - Coating time/ Annealing time : 3 h/0 h
  - Tin at% is around 24 at%.
  - Tc ~ 18 K
  - **There are no voids on surface.**

Typical Sample coating Result

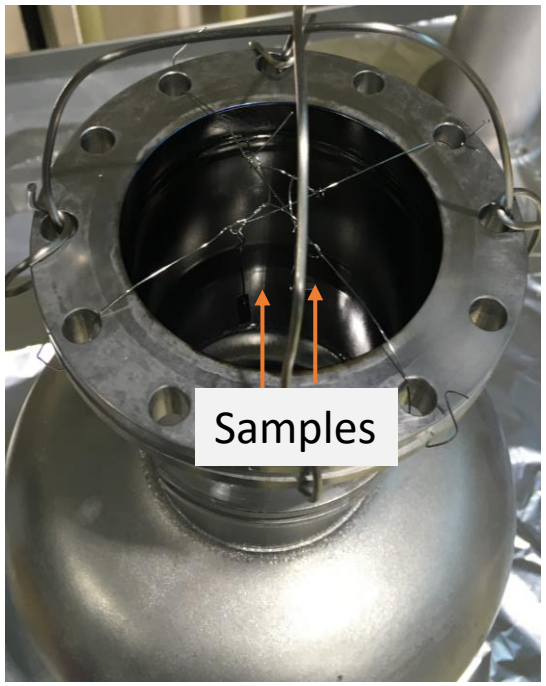
Sample Coating Num.	4	9	11	20	21	22	23
Coating Temp[C]	1200	1100	1100	1100	1050	1150	1100
Coating Time[h]	1.5	1.5	1.5	3	3	3	3
Annealing Time[h]	1.5	1.5	0	0	0	0	0
Nb foil	–	–	–	☑	☑	☑	–
Tc [K]	11.1 ±0.1	18.0 ±0.2	17.9 ±0.4	17.6 ±0.2	17.9 ±0.2	18.2 ±0.2	18.1 ±0.1
Thickness [μm]		1.7 ±0.2	1.3 ±0.3	2.7 ±0.4	2.9 ±0.3	3.5 ±1.0	1.5 ±0.3
Tin at%	20.7	25.3	23.6	23.7	24.3	24.3	24.0
Voids	☑	☑	–	–	–	–	–

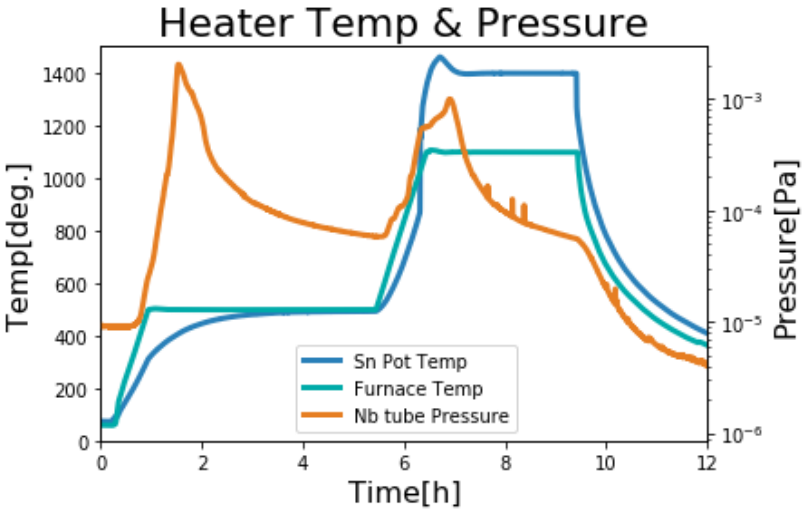


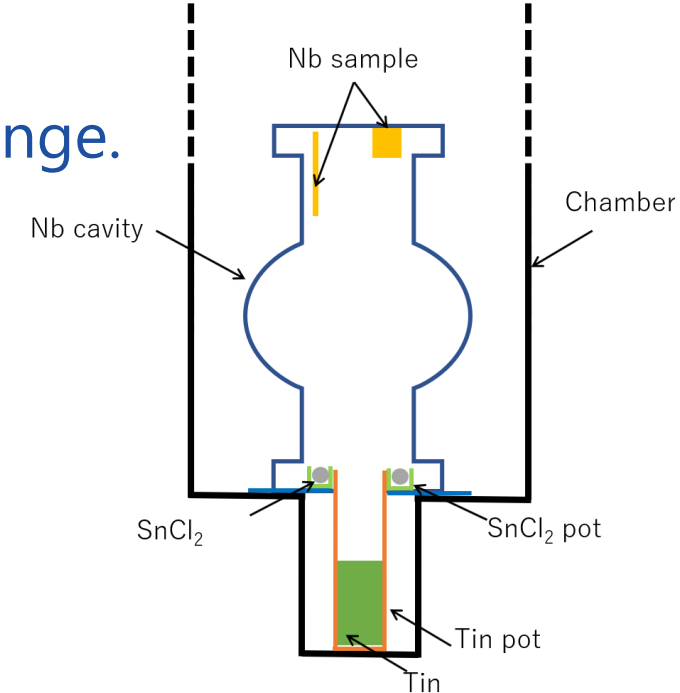


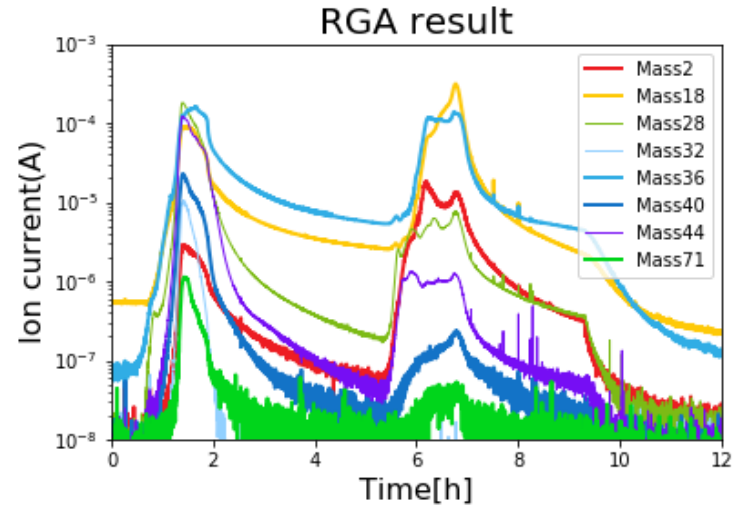
Cavity Coating

- The shape of coating cavity was a TESLA-like single cell.
- Nb3Sn coating process
  - Nucleation : 500ºC 4.5 h
  - Coating : Furnace 1100ºC 3 h
    Tin pot 1400ºC 3 h
  - Annealing : 0 h
- Nb sample was hanged on cavity flange.
  - Nb plate
  - Nb foil









Cavity Coating Result

Inside of the cavity

- Before coating : metallic luster
- After coating : matte
  - Whole inside equator was matte.

Measurement result of witness sample

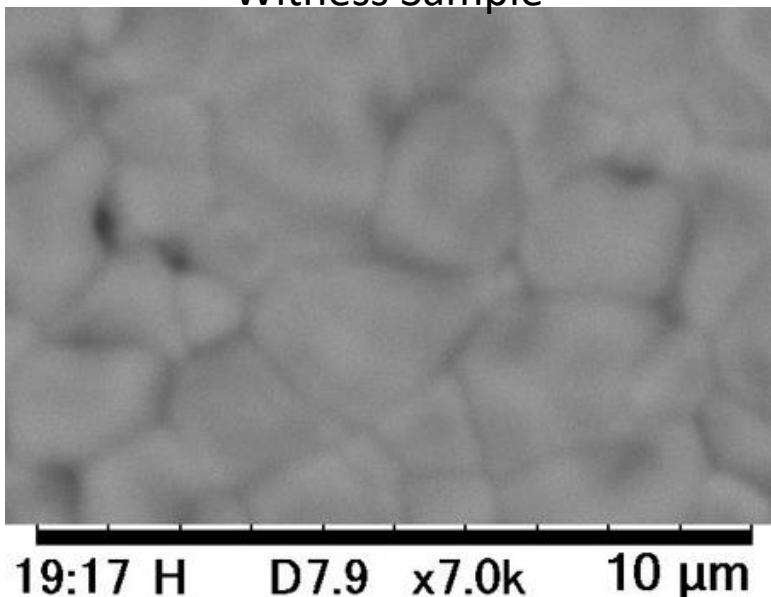
- Grain size : 1~3 μm.
- Thickness : 1.7 ± 0.4 μm.
- Composition ratio of Tin : 23.1 ± 0.4at%
- Cavity seems to be successfully coated.

	Sample(23rd)	Witness sample
Thickness [μm]	1.5 ± 0.3	1.7 ± 0.4
Tin at%	24.0	23.1 ± 0.4

Before Coating (EP2)

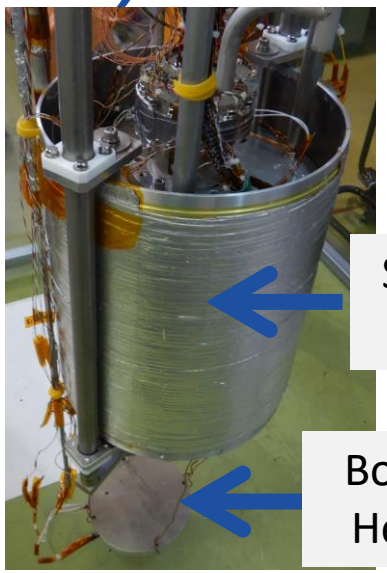
After Coating

Witness Sample



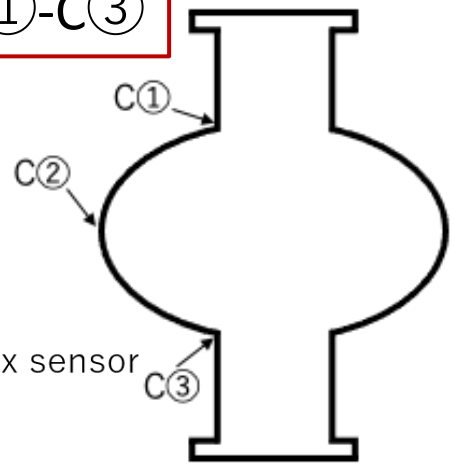
Measurement setup (Flux, RF)

- Flux expulsion when cavity became SC state was measured.
  - Flux expulsion in Fast/Slow cooling
  - External magnetic field : 0 mG, ±50 mG
- Sensor position
  - Cernox : Top/ bottom iris, Equator
  - Flux gate : 0 deg. 120 deg. 240 deg.
    - 0 deg. : Z, θ, R axis
    - 120 deg. : Z, θ, R axis
    - 240 deg. : Z, θ axis
- Solenoid coil
- Bottom heater
- Cavity temperature gradient when cavity became SC (ΔT) :
  Top iris temp. – Bottom iris temp.

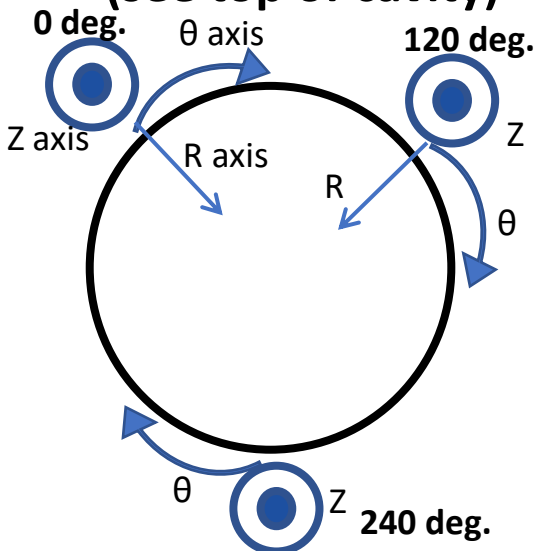


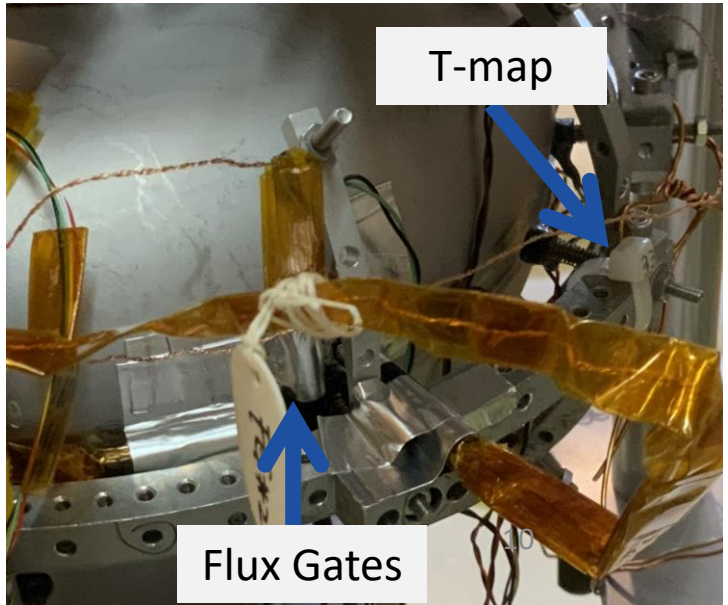
Cernox position

ΔT= C①-C③



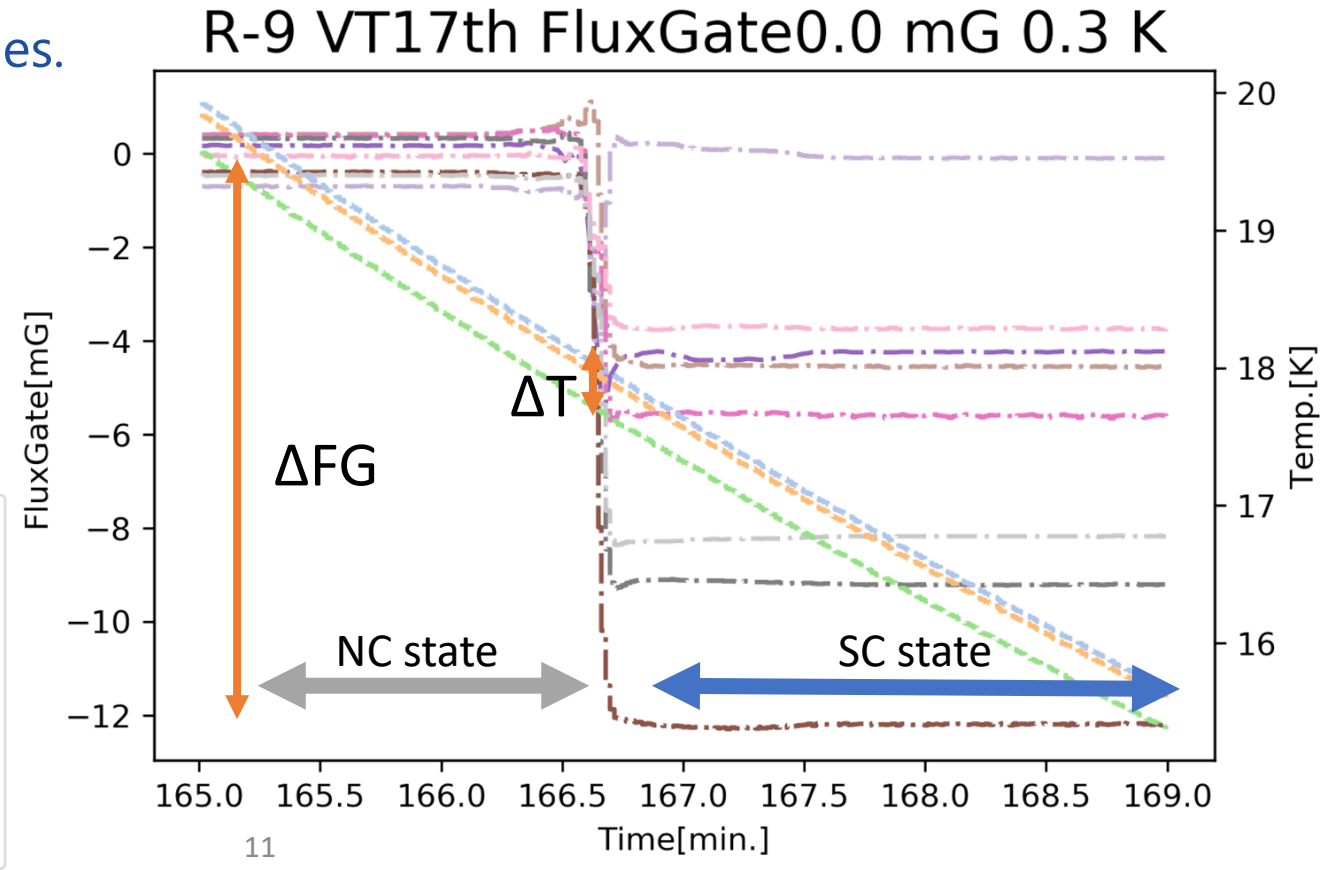
Each axis
(see top of cavity)





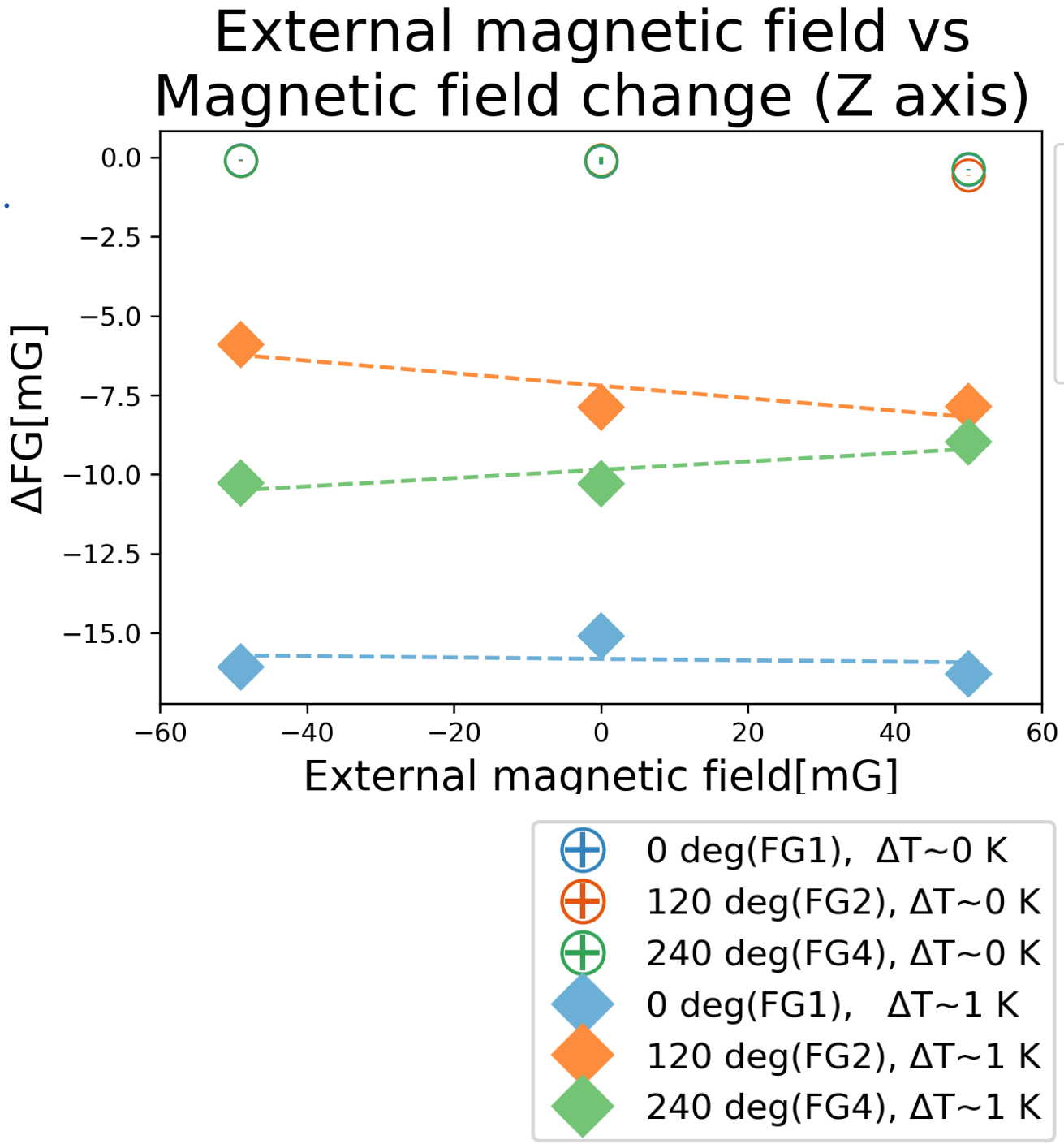
Flux Measurement

- Each magnetic filed change occurred between 17.5 K and 18 K.
- ΔT：Deference top and bottom iris.
  - Values between superconducting transition.
- ΔFG：Deference NC FGs values and SC FGs values.



Flux Measurement

- Compared ΔFGs when ΔT ~ 0 K, 1 K and each mag. Field.
  - ○ : ΔT ~ 0 K
  - ◆ : ΔT ~ 1 K
- mag. Field 0 mG : Effect of Thermal current
  - Several mG decreased.
- mag. Field ±50 mG :
  Effect of thermal current + flux expulsion
  - Similar value as 0 mG
  - No flux expulsion was measured.
  - e.g.)Nb cavity : Z axis field was enhanced 1.56 ~1.7 times. [1][2]

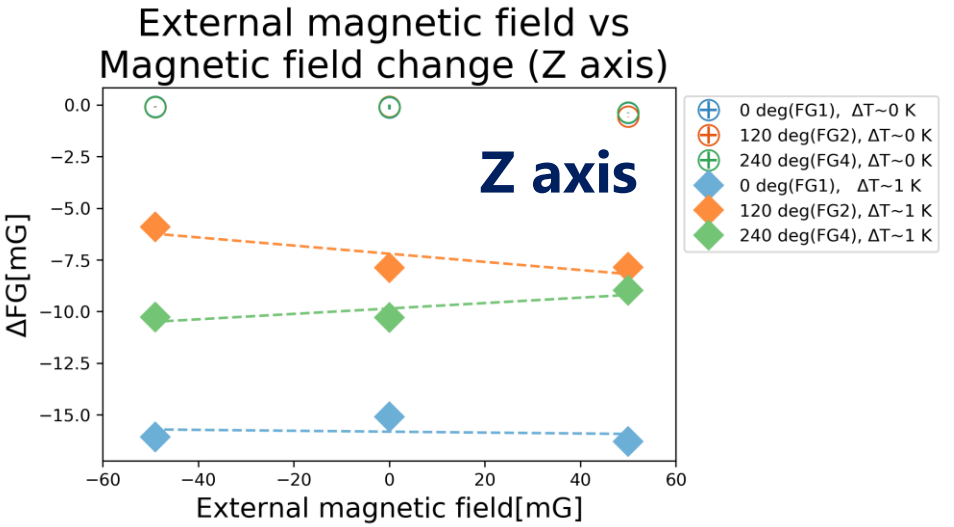


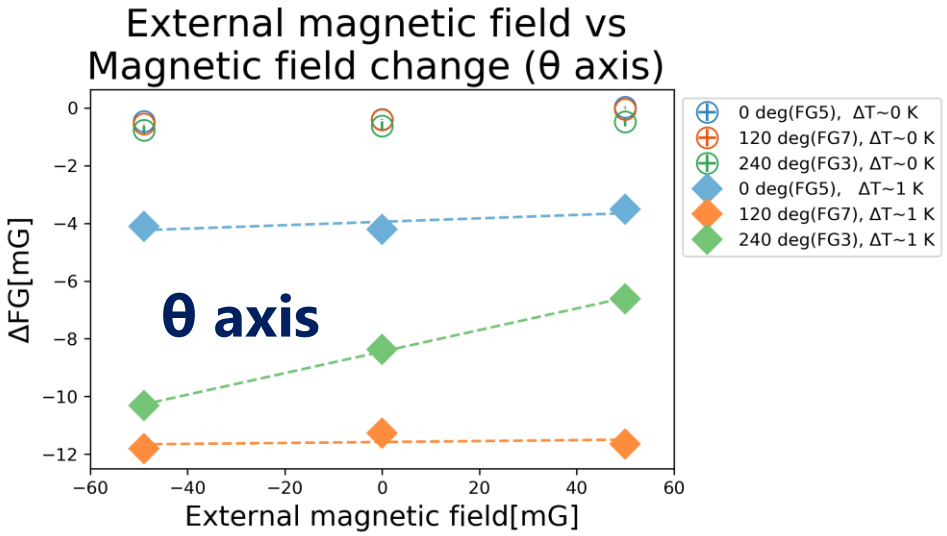
[1] Kensei Umemori, TTC 2018
[2] S.Posen et.al. , JOURNAL OF APPLIED PHYSICS 119, 213903 (2016)

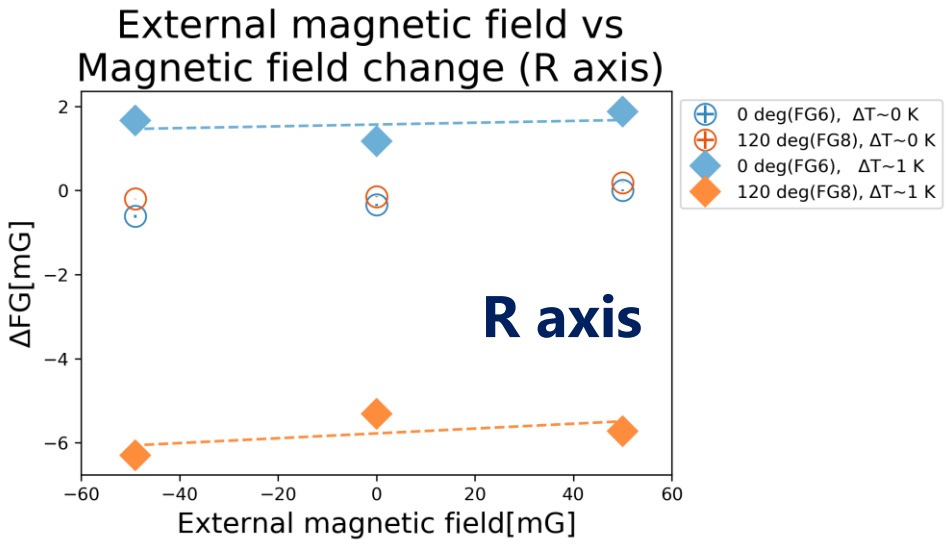
Flux measurement

- Compared ΔFGs when ΔT ~ 0 K, 1 K and each mag. Field.
  - ○ : ΔT ~ 0 K
  - ◆ : ΔT ~ 1 K
- mag. Field 0 mG : Effect of Thermal current
- mag. Field ±50 mG : Effect of thermal current ~~+ flux expulsion~~

- ΔFG of 0 mG and ±50 mG was similar in each axis.
  - Flux expulsion was not measured.
  - Effect of external magnetic field was small.



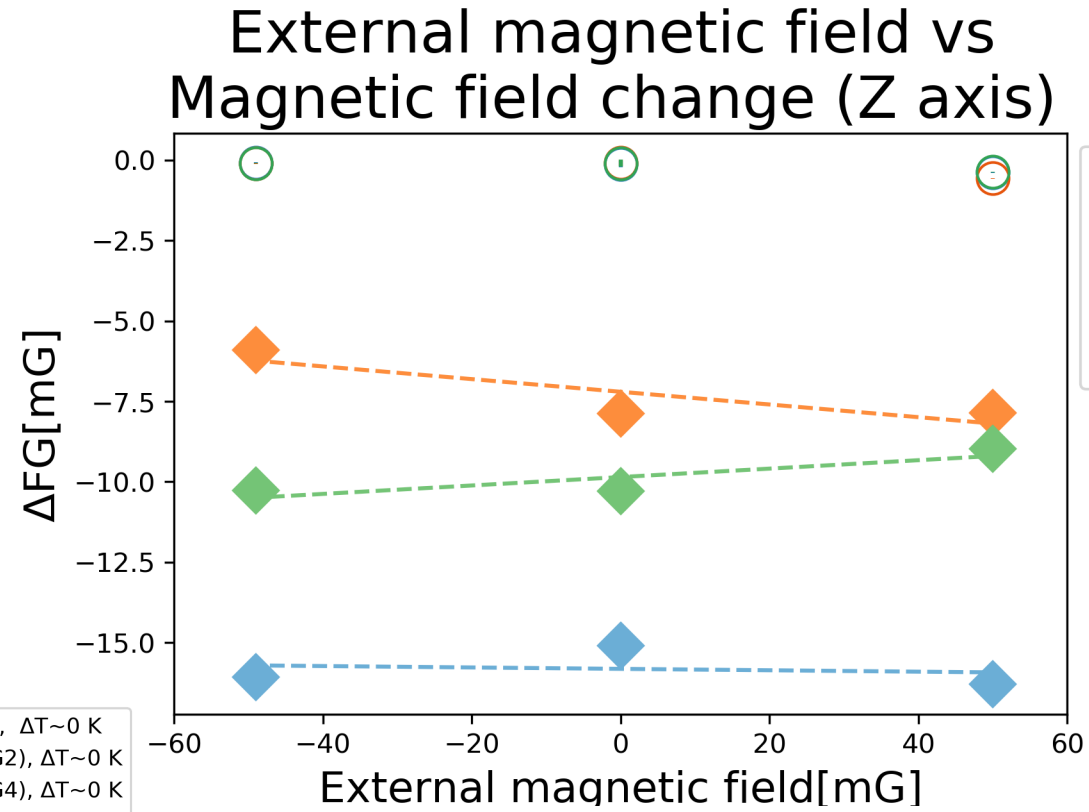




Discussion (Flux expulsion)

- **No flux change from ext. mag. field was measured.**
  - Nb cavity : Z axis field was enhanced 1.56 ~1.7 times. (Full expulsion)[1][2]
  - Nb3Sn cavity : ΔFG was not dependent on Ext. mag. field.

- **Would behavior of ΔFG be different if outside CP was applied ?**
  - Outside of the cavity was Nb3Sn. : Outside is also matte.
  - It was possible ΔFG was from thermocurrent between outside Nb_3Sn and Nb substrate.



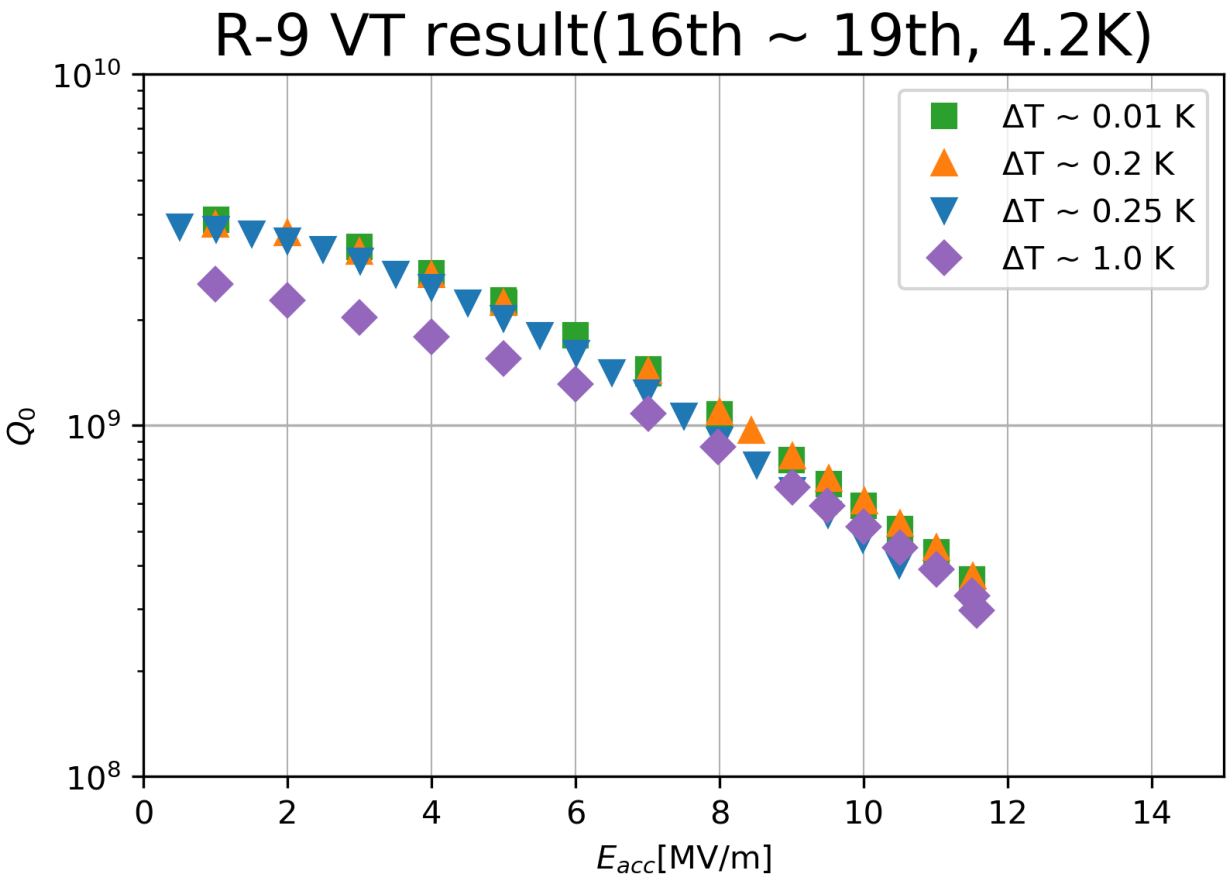
Before Coating

After Coating

[1] Kensei Umemori, TTC 2018
[2] S.Posen et.al. , JOURNAL OF APPLIED PHYSICS 119, 213903 (2016)

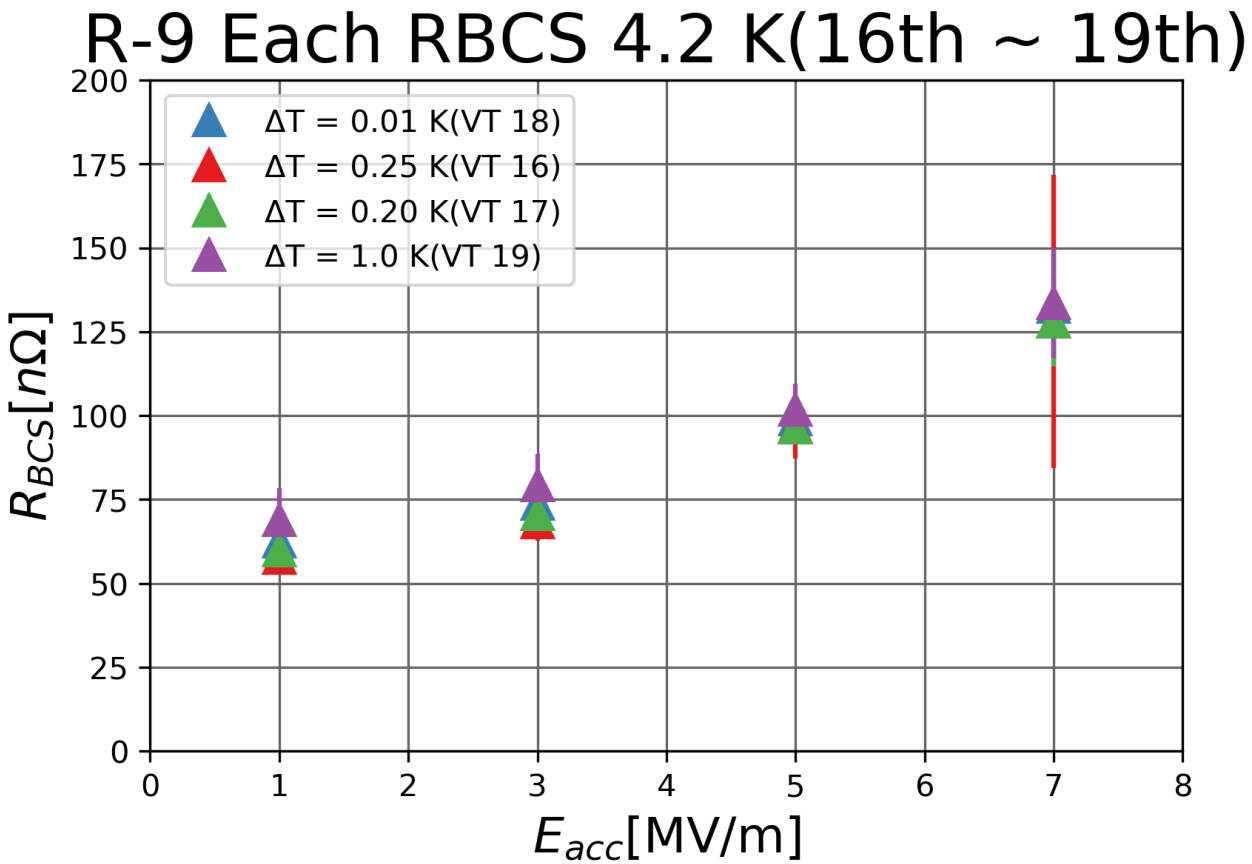
RF Measurements

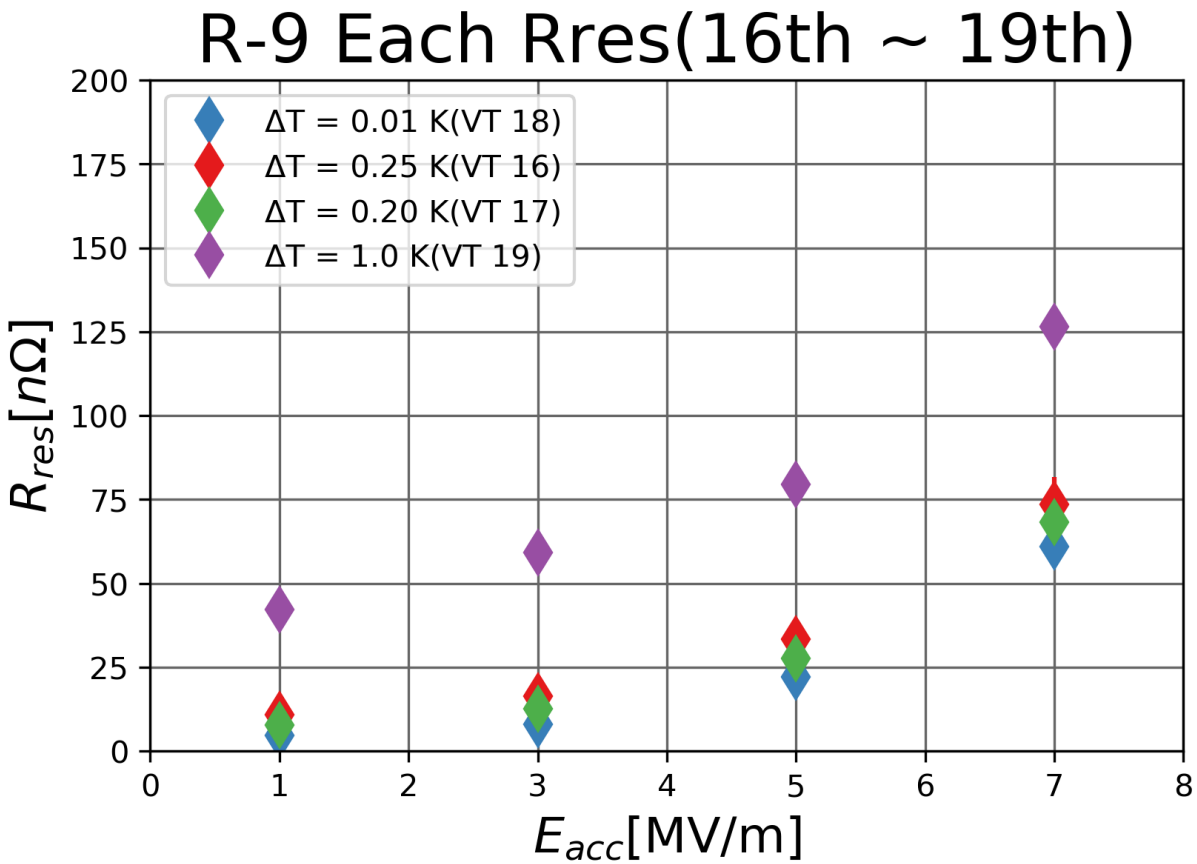
- Cavity performance was measured in each Temperature with several temperature gradient (ΔT).
  - Measurement temperature : 1.5 K ~ 4.3 K
  - ΔT : 0.01 K, 0.2 K, 0.25 K, 1.0 K
- Qo at 4.2 K 1 MV/m, ΔT = 0.01 K : 3.9 $\times 10^9$
- Qo at 4.2 K 1 MV/m, ΔT = 1.0 K : 2.5 $\times 10^9$
- Maximum Eacc was around 11.5 MV/m in each measurement.



RF Measurements

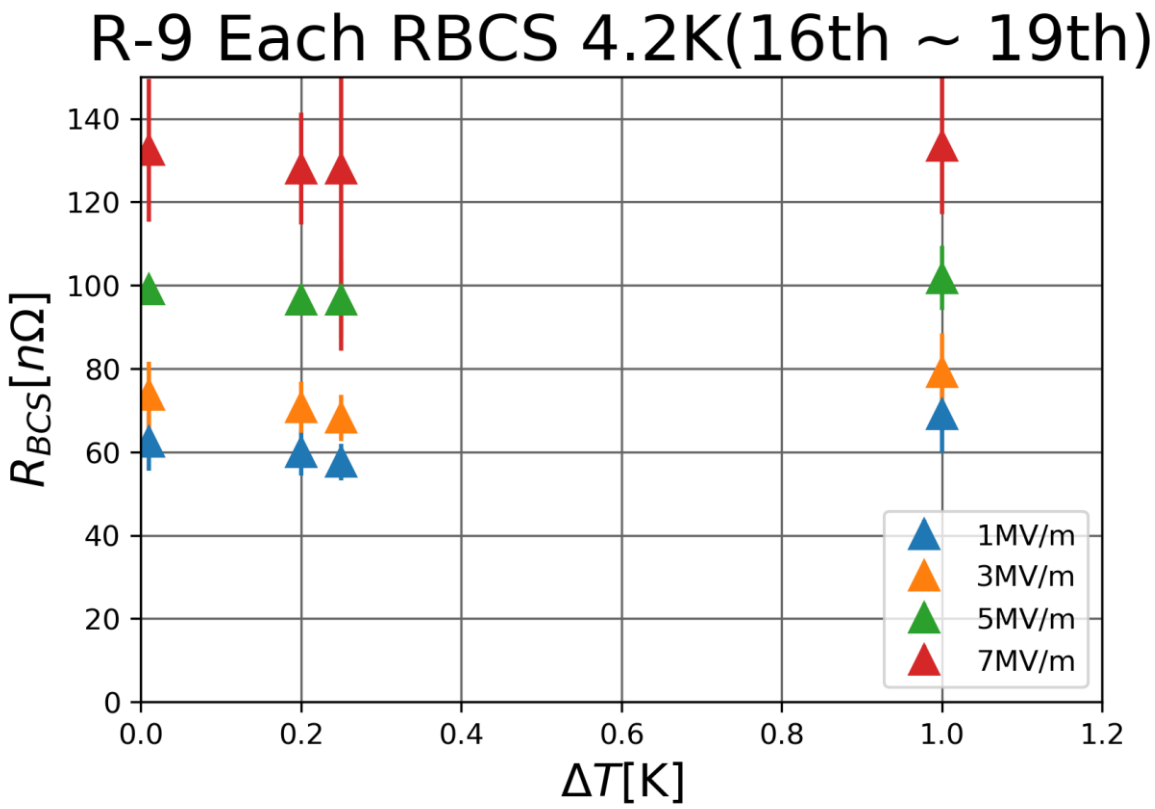
- Rs was decomposed into R_{BCS} and R_{res}.
- R_{BCS} @ 4.2 K(ΔT =0.01 K) : 62 nΩ ~ 132 nΩ
- R_{res} (ΔT =0.01 K) : 5 nΩ ~ 61 nΩ

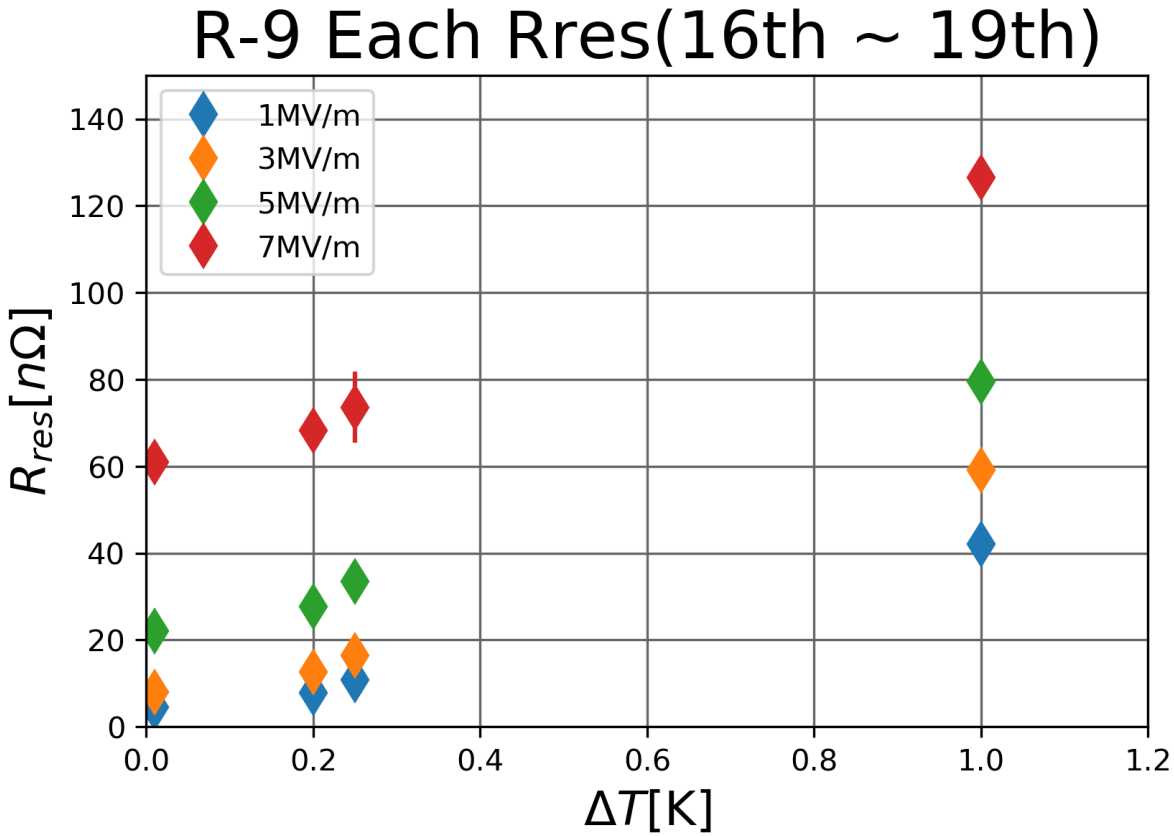




RF Measurements

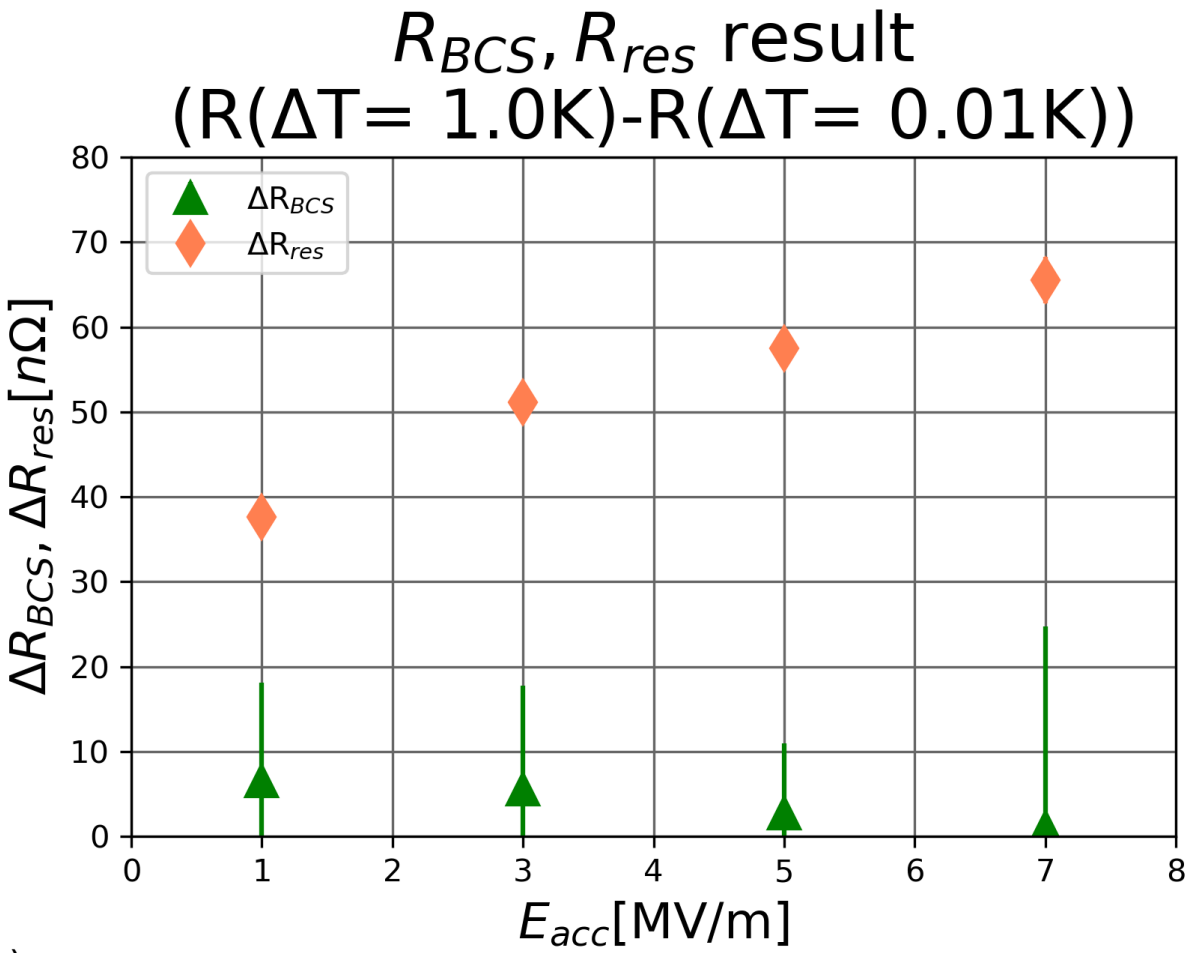
- Rs was decomposed into R_{BCS} and R_{res}.
- R_{BCS} : Week dependent on ΔT
- **R_{res} : Strong dependent on ΔT**

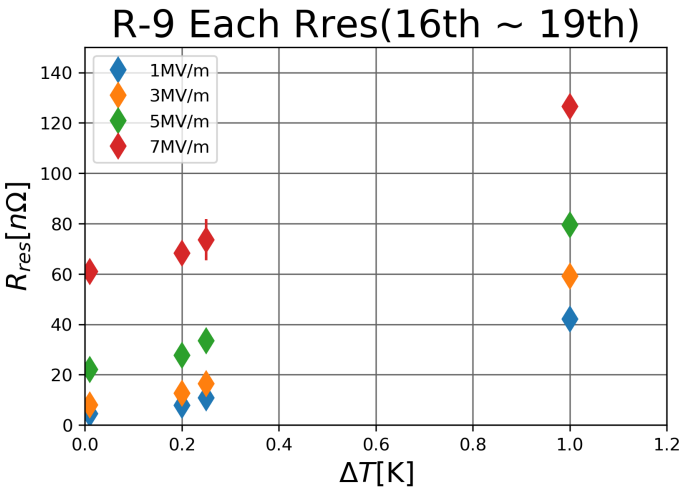


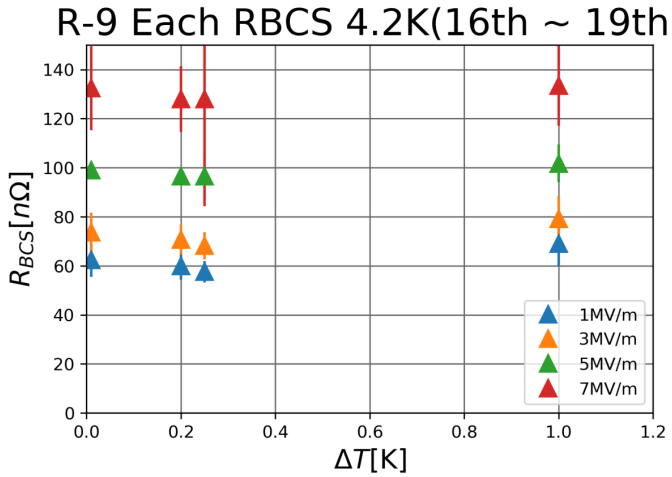


RF Measurements

- Rs was decomposed into R_{BCS} and R_{res}.
- R_{BCS} : Week dependent on ΔT
- **R_{res} : Strong dependent on ΔT**
  - **Rres increased between 40 nΩ ~ 65 nΩ**
  - **Flux from thermal current was trapped**

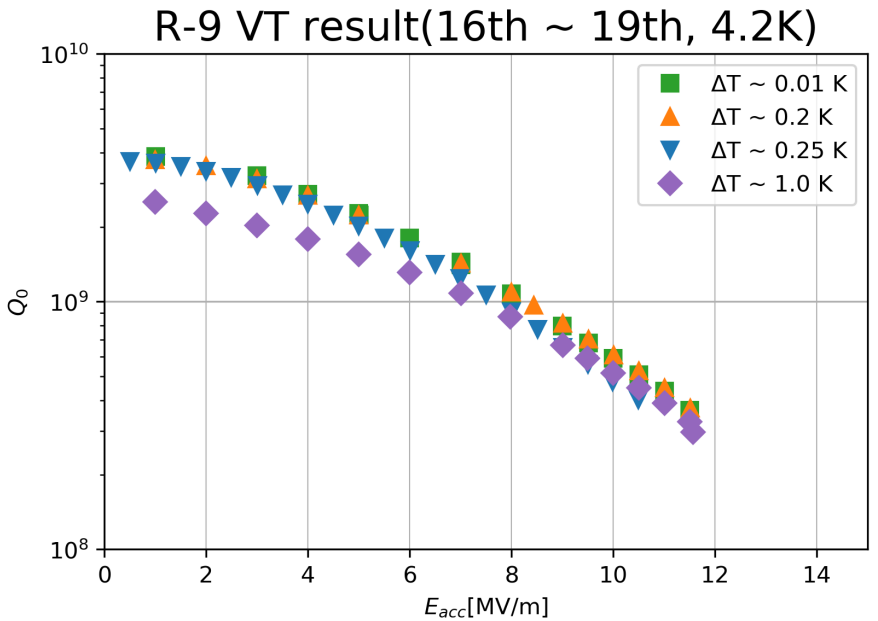


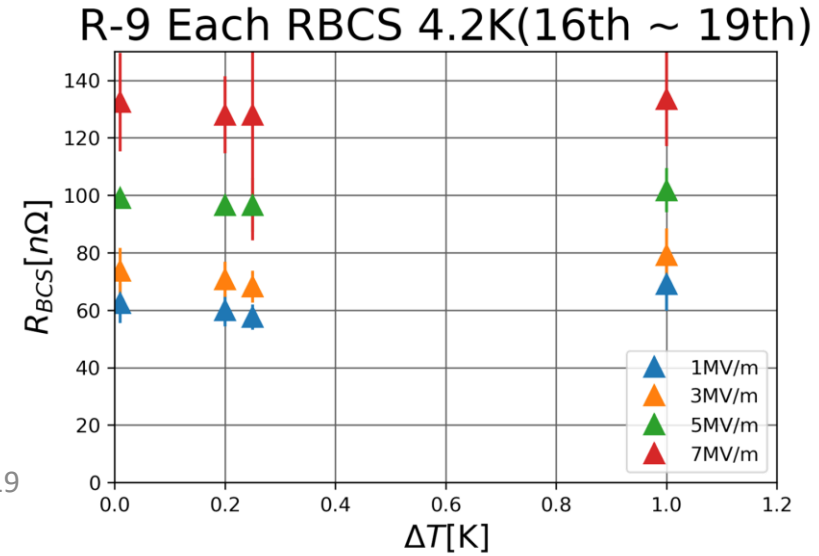


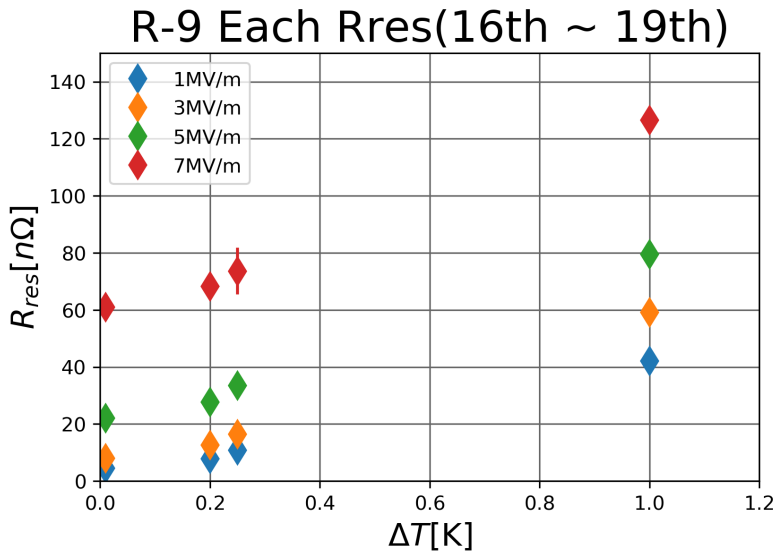


Discussion (RF measurement)

- **Qo was lower than 1×10^{10} at 4.2 K.**
  - $R_{BCS\ at\ 4.2K}$ was much higher than expected (e.g. compared to results at other labs).
    - Δ of the film was not good ?
    - Contamination of Carbon or Tin ?
  - Rs increased when Eacc increased.
- **ΔT dependent Rres was strong.**
  - Rres increased depending on ΔT.
  - Flux from thermal current was trapped.







Summary

- A vapor diffusion system was constructed at KEK.
  - Total coating system works well.
- Several samples were coated, and single cell cavity was coated.
- First Nb3Sn coating for cavity succeeded.
  - Tc of the cavity was between 17.5 K and 18 K.
  - Qo was 3.9×10^9 at 1 MV/m and 4.2 K (ΔT = 0.01 K).
  - Maximum Eacc was 11.5 MV/m.
- Flux change was measured in 0 mG / $\pm$50 mG.
  - No flux expulsion was measured.
  - Flux change was dominant on ΔT.
- R_{BCS} was higher than expected.
- Rres has strong dependent on ΔT
- Rres also has strong dependent on Eacc

Future work

- To realize high-Q of Nb3Sn cavity above 1×10^{10} at 4.2 K.
  - Furnace environment: We just built clean booth to improve clean coating environment.
  - Nb substrate: Try anodized and research other treatment before coating
  - Optimize coating parameter: Nucleation time/temp, coating time, etc.
  - Coupon cavity will be made and search the parameters.
- Details of flux change and effect of thermal current on Qo will be investigated.

Thank you for your attention !