# SRF multilayer thin-film R&D at KEK

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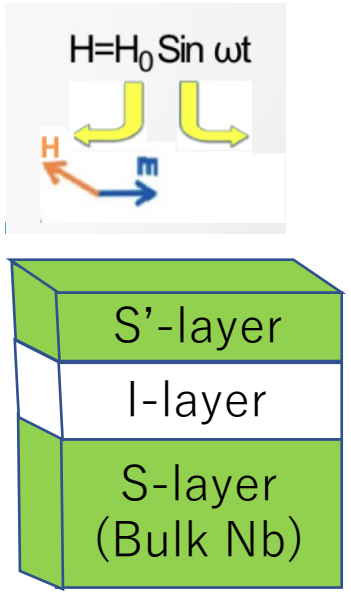
# Introduction

- The maximum accelerating gradient of superconducting cavity is limited by the magnetic field at which vortex avalanche occurs.
  - In this presentation, we calls such magnetic field as "effective $H_{c1}$", **$H_{c1,eff}$.**
- Recently proposed theory predicts that $H_{c1,eff}$ is pushed up by Superconductor-Insulator-Superconductor structure (**S'-I-S structure**)[1][2][3][4].
- This method potentially provide the basis for the next-generation SRF technology.
- In this presentation, I will report on the status of SRF multi-layer thin-film R&D at KEK from 2018 to 2023.




[1] A. Gurevich, Appl. Phys. Lett. 88, 012511 (2006). [2] T. Kubo, Y. Iwashita, and T. Saeki, Appl. Phys. Lett. 104, 032603 (2014).
[3] A. Gurevich, AIP Adv. 5, 017112 (2015). [4] T. Kubo, Supercond. Sci. Technol. 30, 023001 (2017).

# History of SRF multilayer R&D at KEK

- We performed SRF multi-layer thin-film R&D according to the ULVAC-KEK collaboration from 2018 to the middle of 2020.
- This collaboration provided us the significant progress as follows:

**1. $H_{c1,eff}$ measurement of S'IS sample consisting of NbN(50-800 nm)-SiO2-Nb (presented in SRF2019)**

**2. Development of Nb3Sn thin-film coating method for SIS structure**

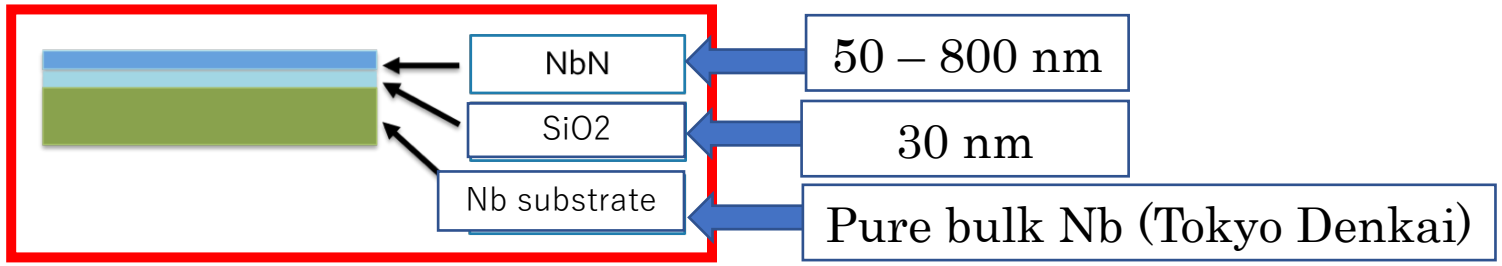
**3. Development of Nb sputtering apparatus to coat the inside of 3 GHz cavity**

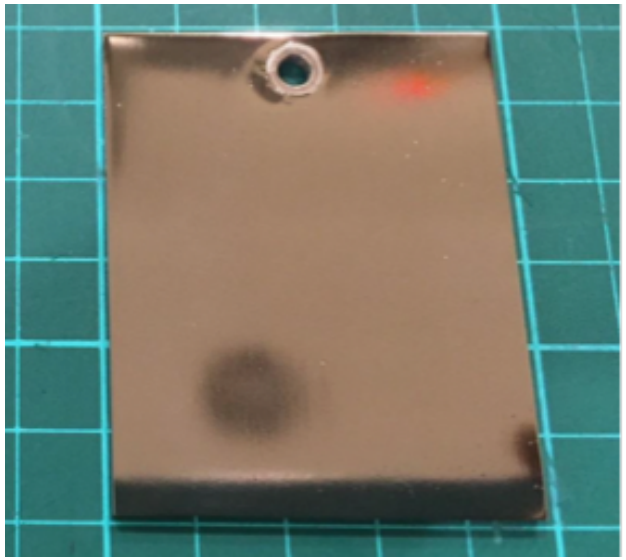
**I will explain obtained results in the followings.**

# Result of ULVAC-KEK collaboration

1. **$H_{c1,eff}$ measurement of S'IS sample consisting of NbN(50-800 nm)-SiO2-Nb (SRF2019 presentation)**
2. Development of Nb3Sn thin-film coating method for S'IS structure
3. Development of Nb sputtering apparatus to coat the inside of 3 GHz cavity

# S-I-S' sample used in this study

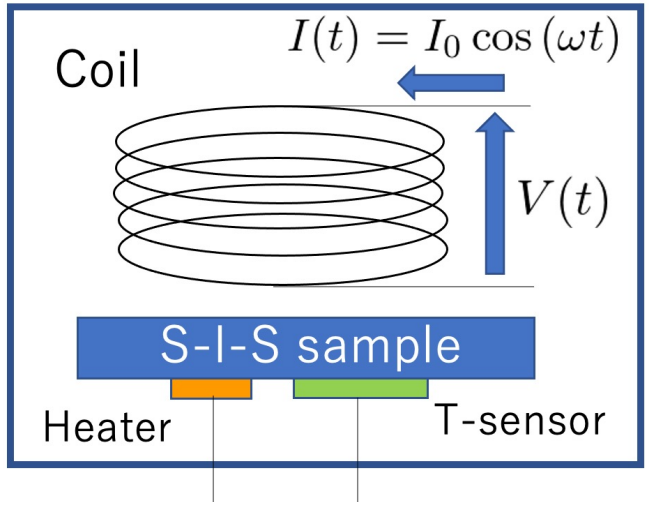


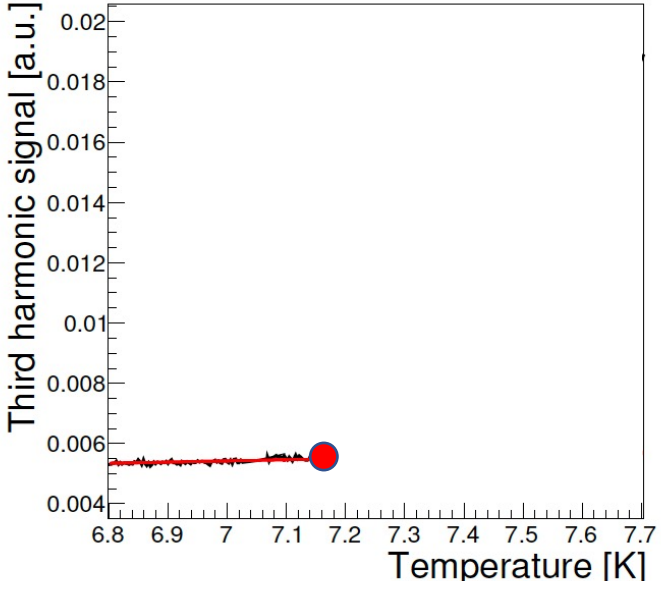



- $NbN/SiO_2$ thin-film with various thicknesses is formed on pure bulk Nb [5].
- This sample is fabricated by ULVAC, Inc. with **DC magnetron sputtering**.

[5] R. Ito, T. Nagata, et al., LINAC 2018 Proceedings, TUPO050

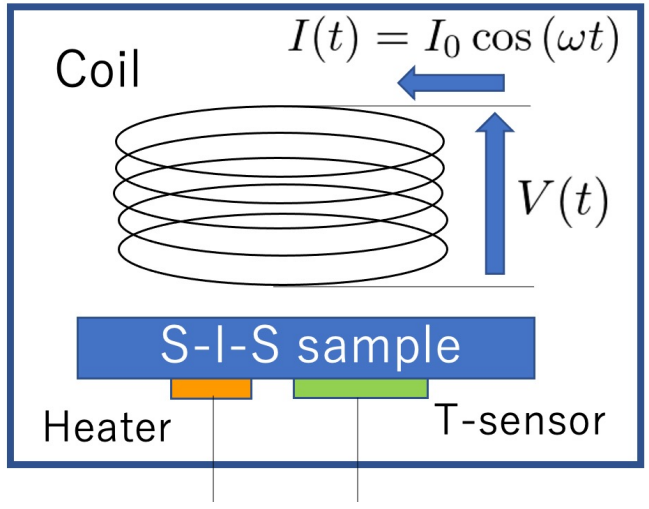
# Third harmonic measurement

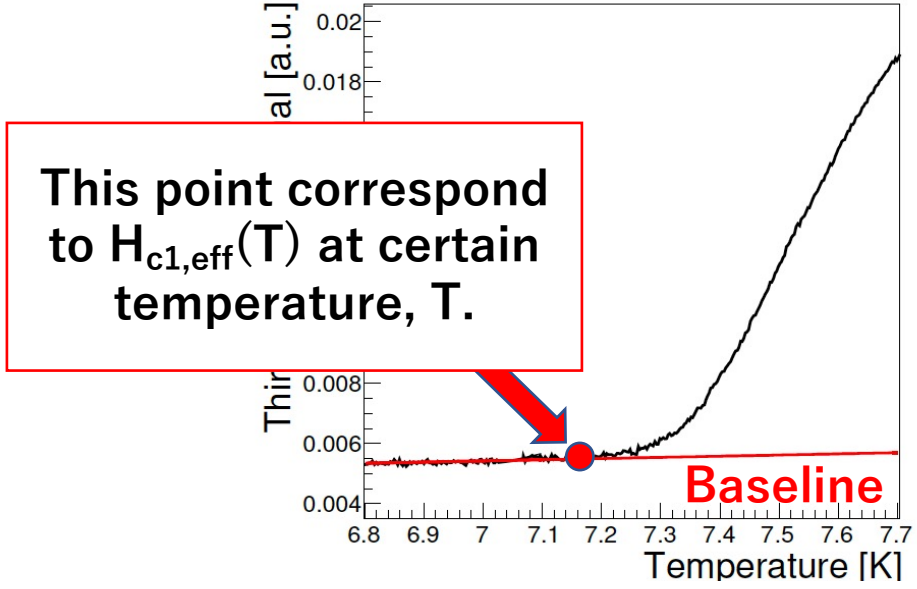



- **Coil** set just above **S-I-S sample** where the drive current $I0 \cos(\omega t)$ is flown, which can apply an AC magnetic field **$H_0$cos(ωt)** to S-I-S samlpe**.**
- Voltage of the coil V(t) and temperature of S-I-S sample are monitored while gradually increasing temperature.
- The third harmonic voltage v3($t$) = V3 cos ($3\omega t$) suddenly rises at the moment when H0 exceeds the effective Hc1 of the sample at a certain temperature.
- By repeating measurements for different H0, we can clarify the temperature dependence of the effective Hc1.

# Third harmonic measurement

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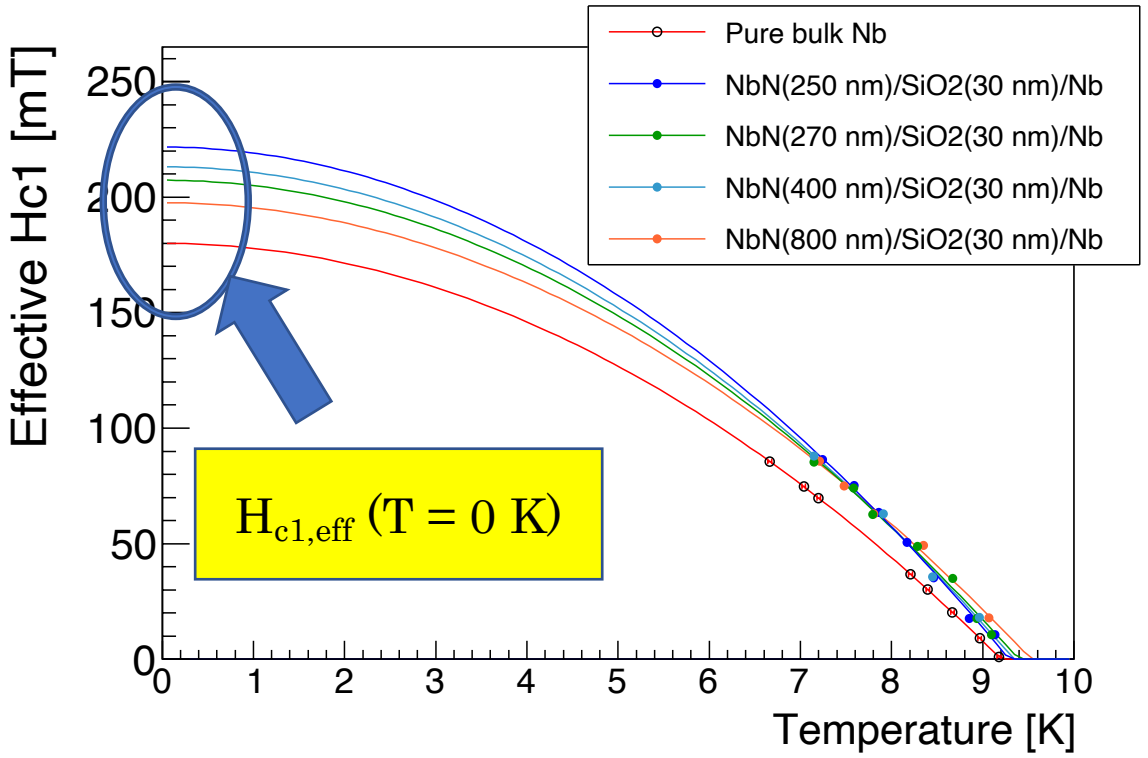
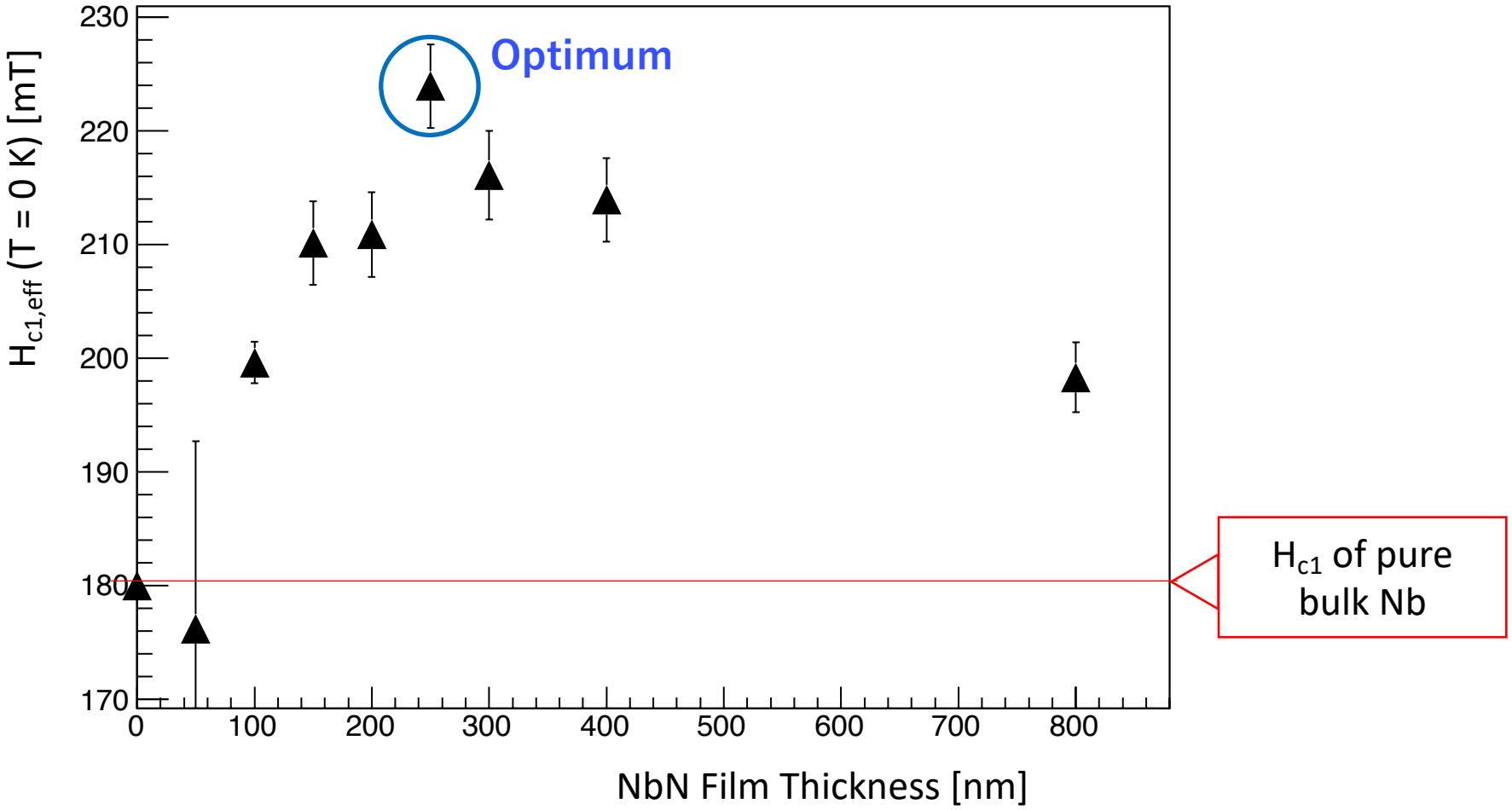
# The measurement result of the effective Hc1




- Finally, the temperature dependence of $H_{c1,eff}$ are fitted with Hc1 curve:
  - $Hc1(T) = Hc1(0)(1-(T/Tc)^2)$
- Hc1(0) can be used for the criterion to evaluate the performance of Hc1.

# Analysis Result of $H_{c1}$

**Effective Hc1 of S'IS sample as a function of NbN film thickness is shown below**



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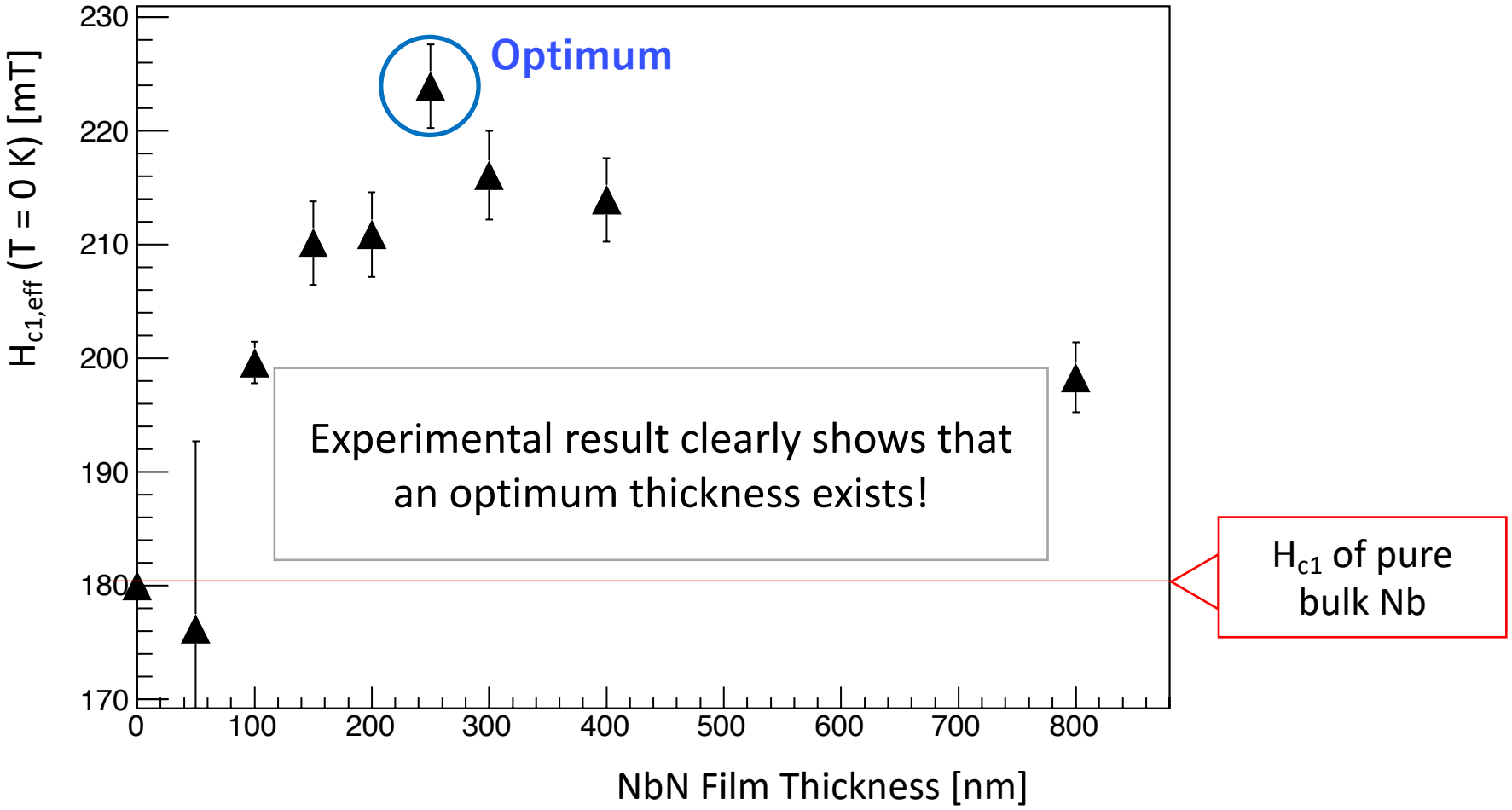

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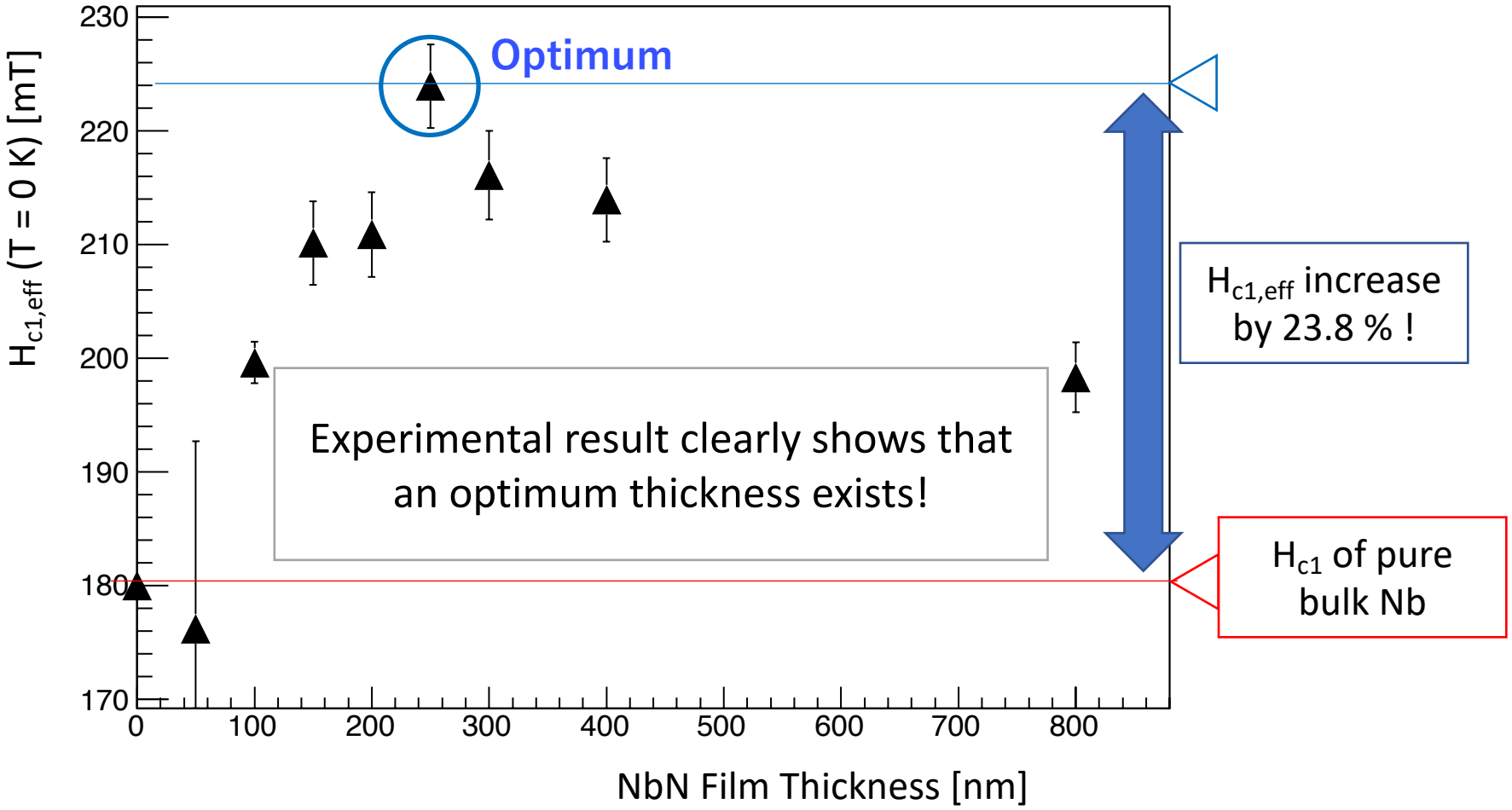
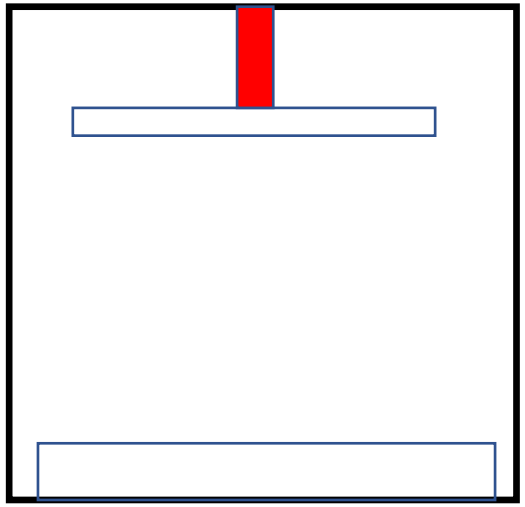


# Result of ULVAC-KEK collaboration

1. $H_{c1,eff}$ measurement of S'IS sample consisting of NbN(50-800 nm)-SiO2-Nb (SRF2019)
2. **Development of Nb3Sn thin-film coating method for S'IS structure**
3. Development of Nb sputtering apparatus to coat the inside of 3 GHz cavity

# Result of ULVAC-KEK collaboration (2)



- ULVAC developed Nb3Sn thin-film coating method for S'IS structure by DC magnetron sputtering described as follows.
  - **On top of the vacuum chamber:**
    - The stage that can rotate as revolution.
    - Substrates are attached to the stage.
  - **On bottom of the vacuum chamber:**
    - Nb and Sn targets are mounted.
  - Applying DC power to targes and flowing argon gas at certain gas pressure, DC magnetron sputtering occur,

→Nb and Sn flux are emitted from targets into top substrate

→Nb and Sn layers are alternatively piled up by several angstroms.

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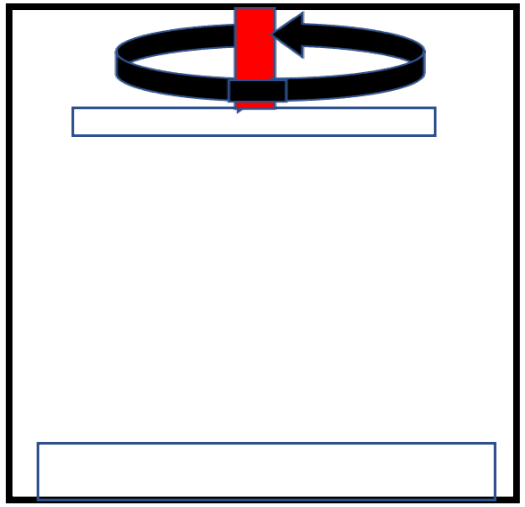

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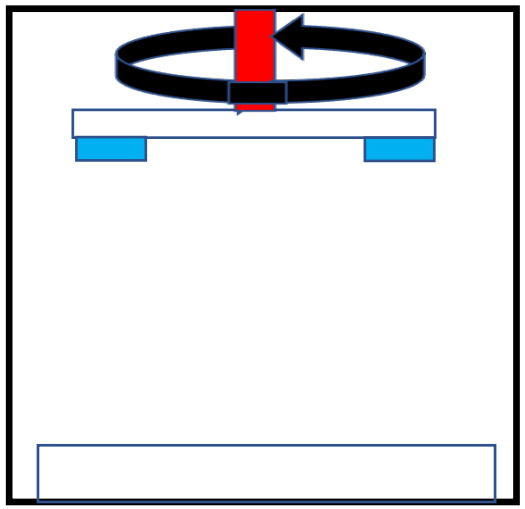

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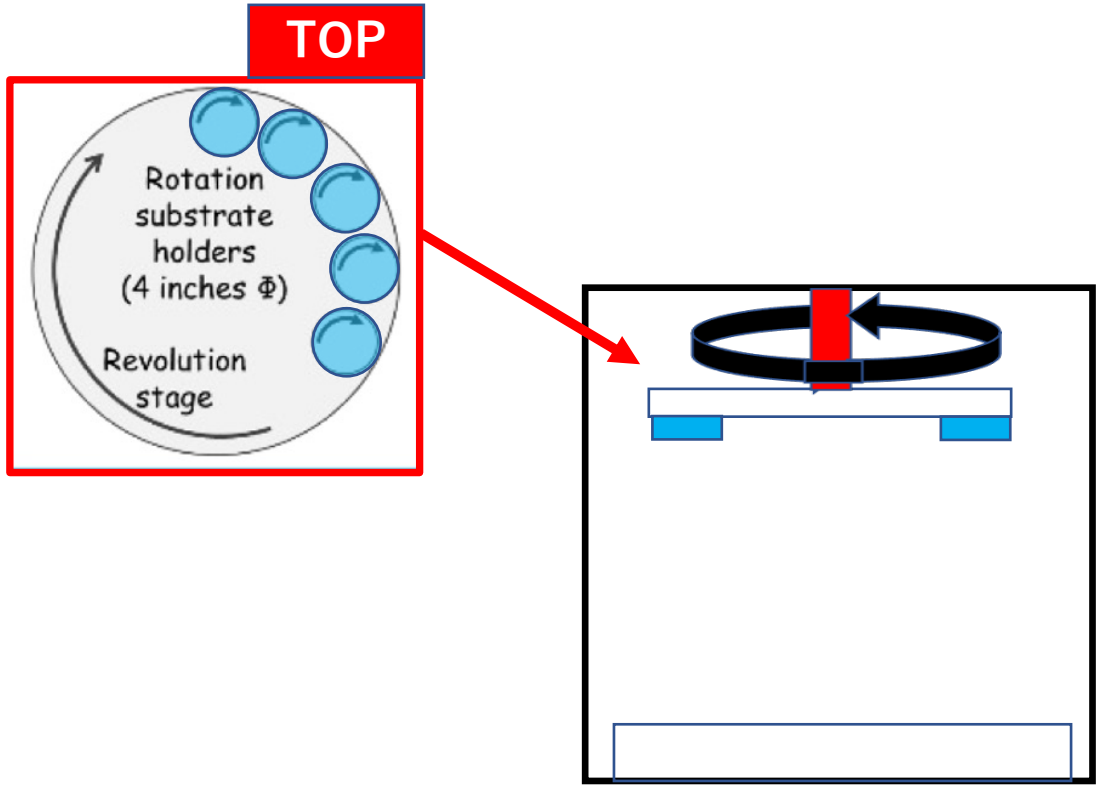


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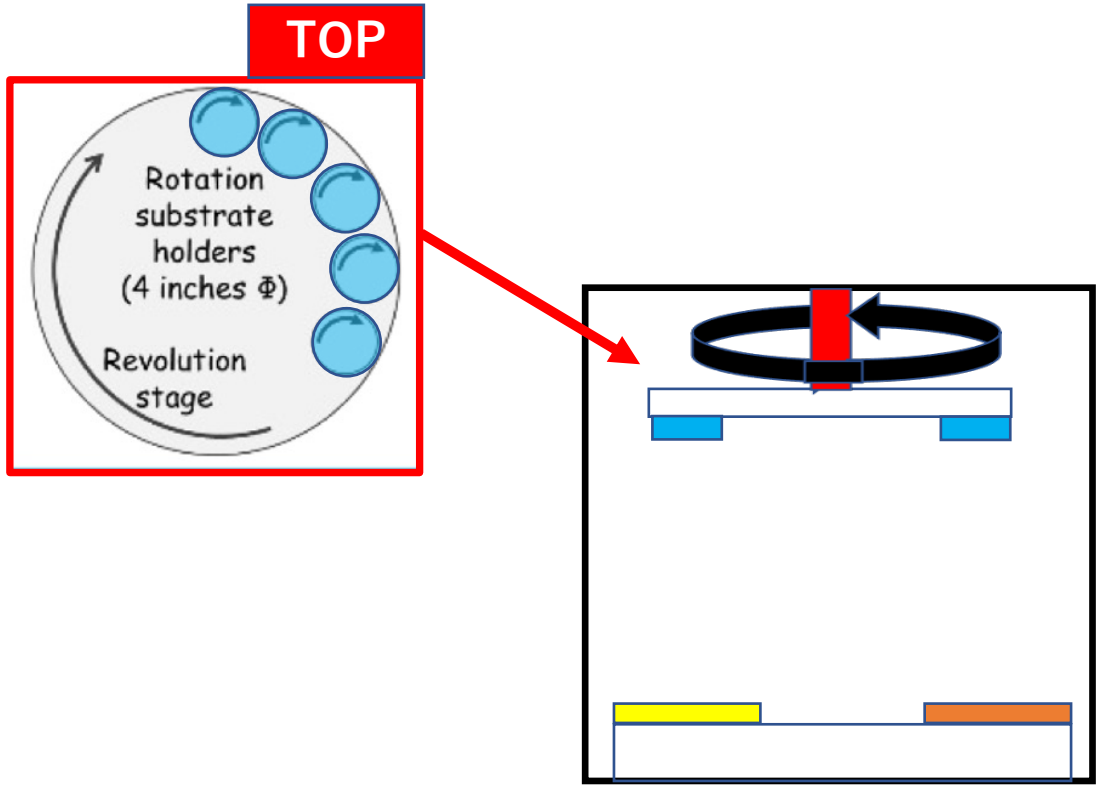


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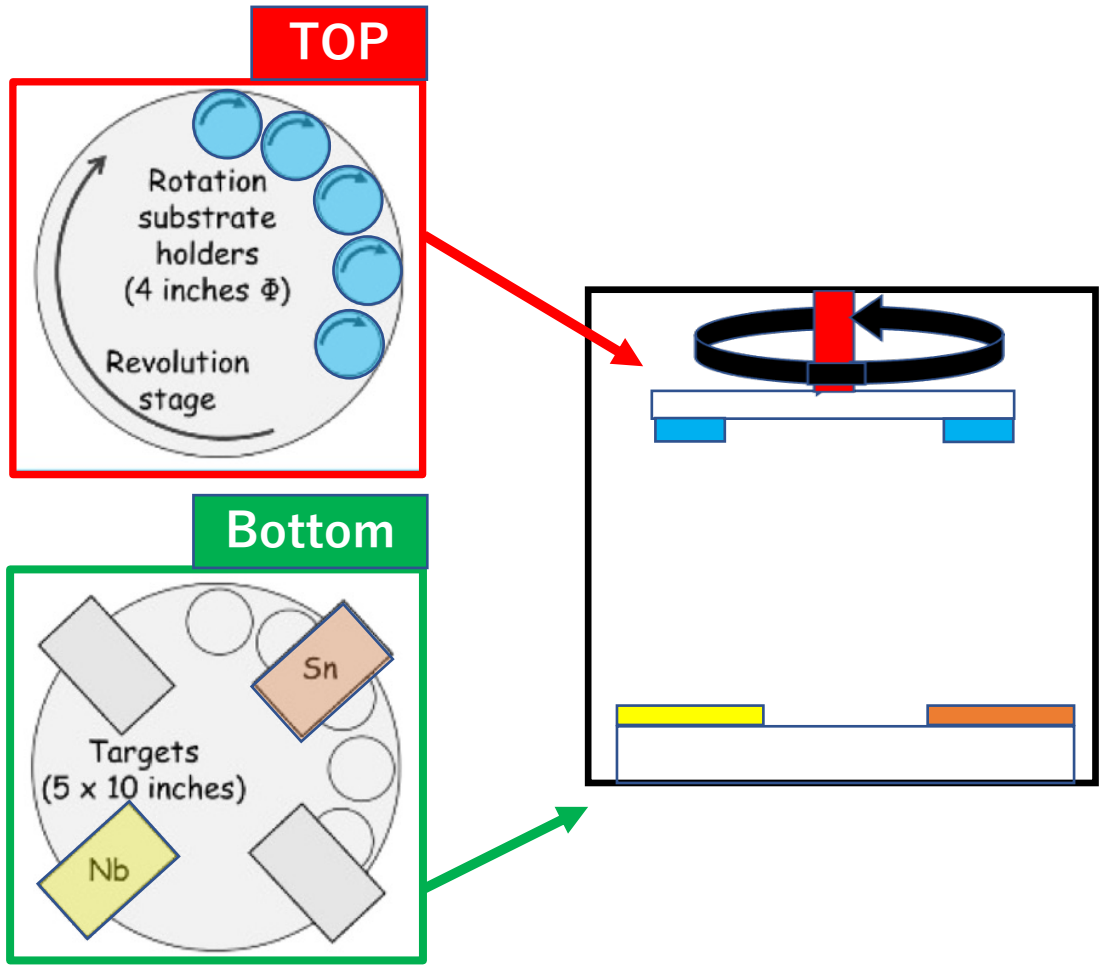


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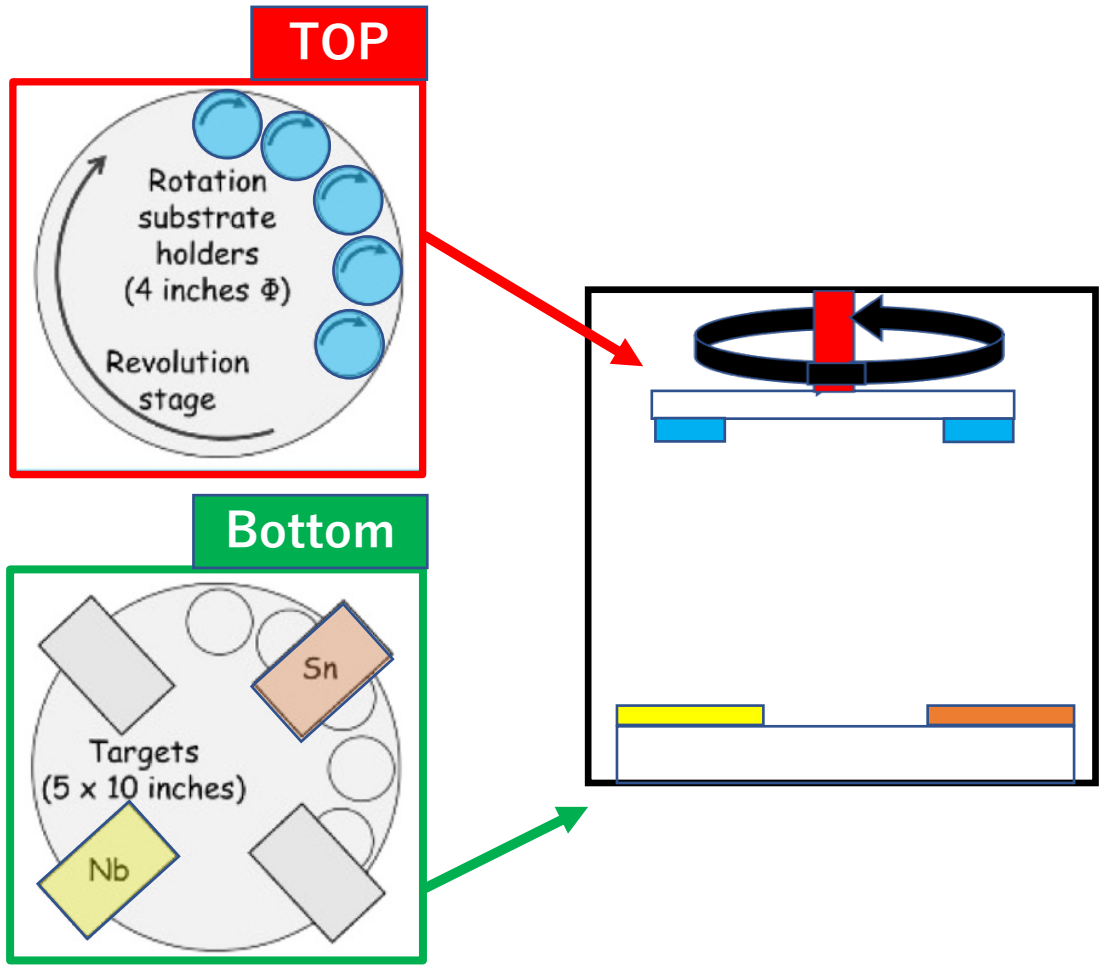


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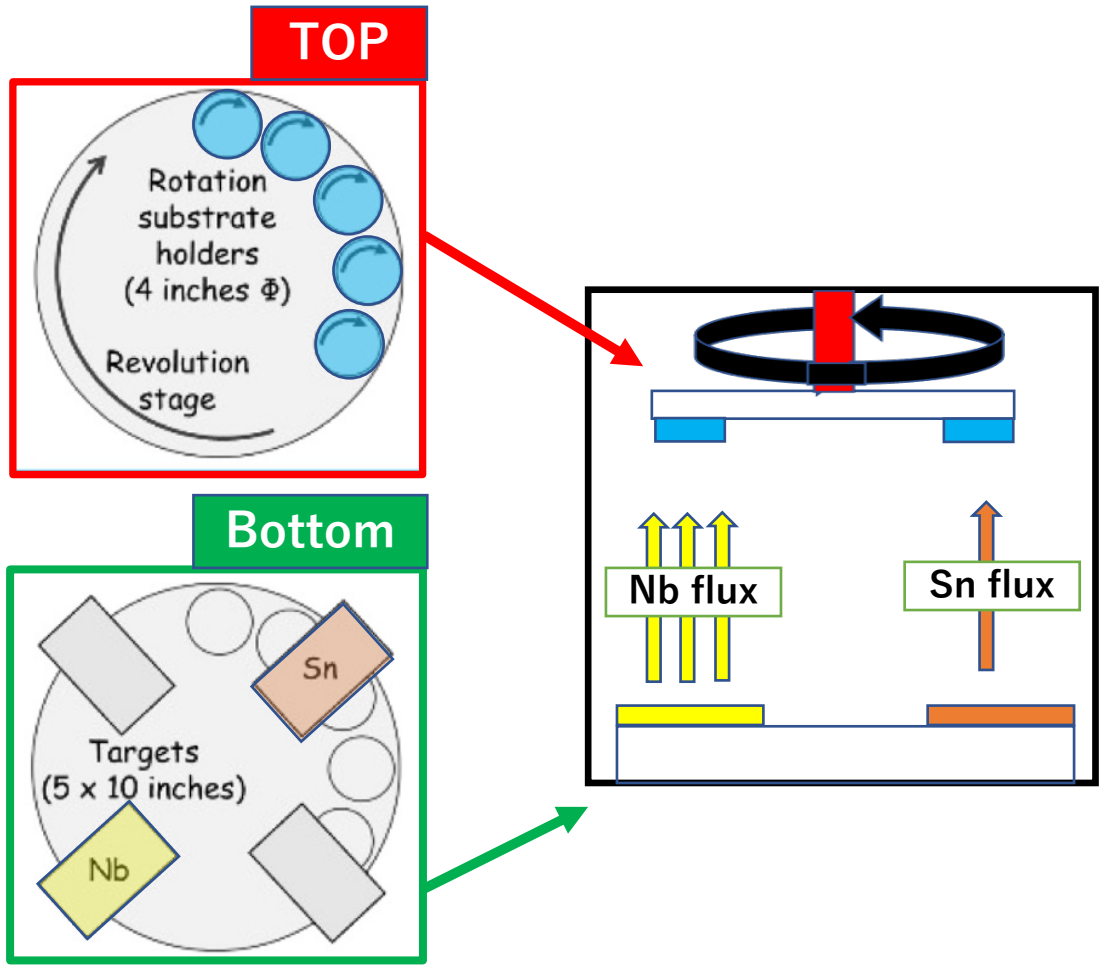


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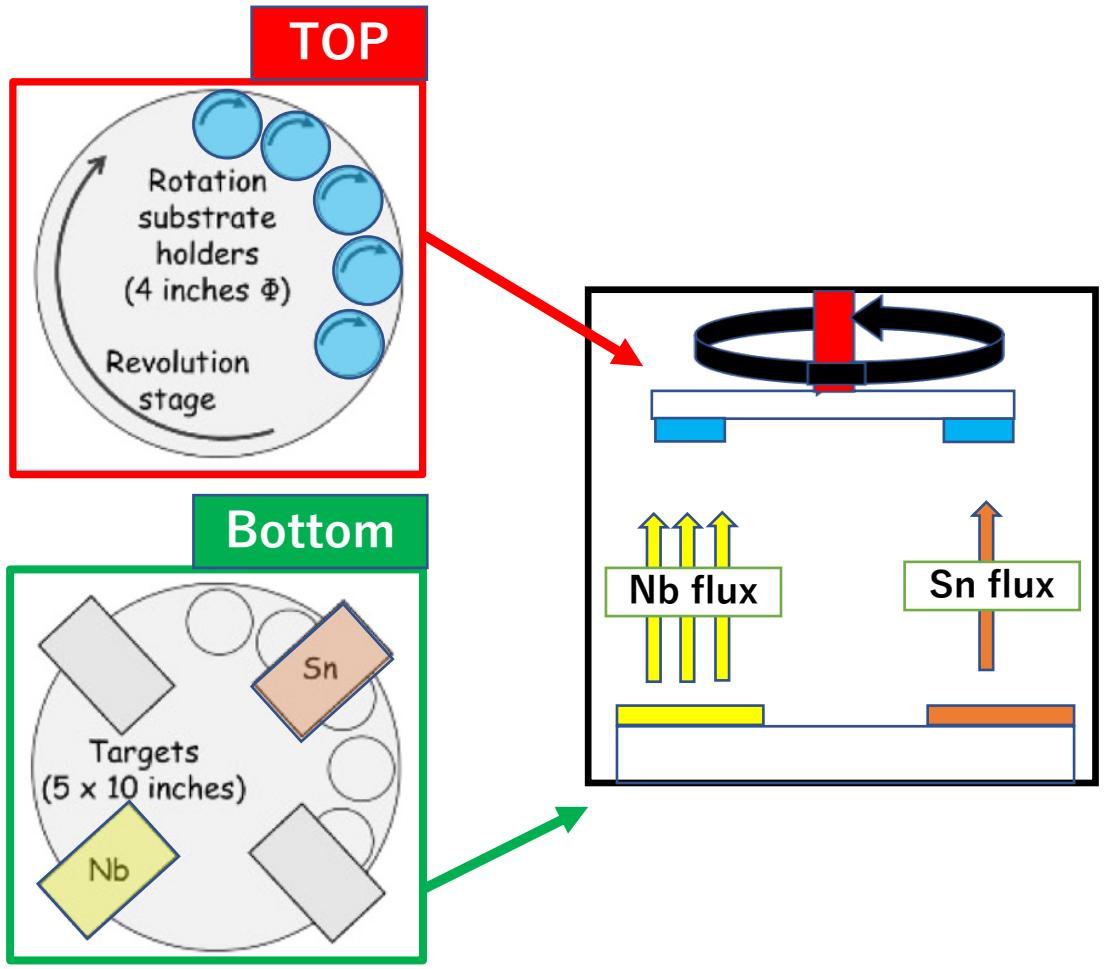


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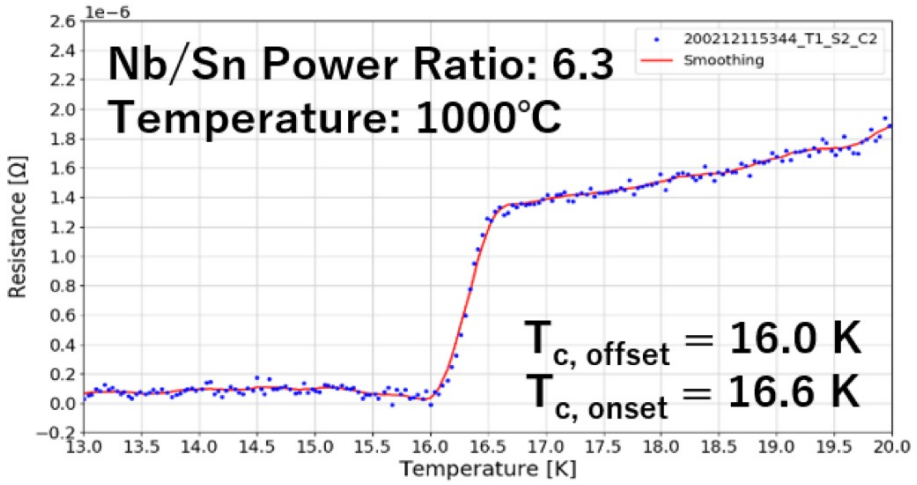


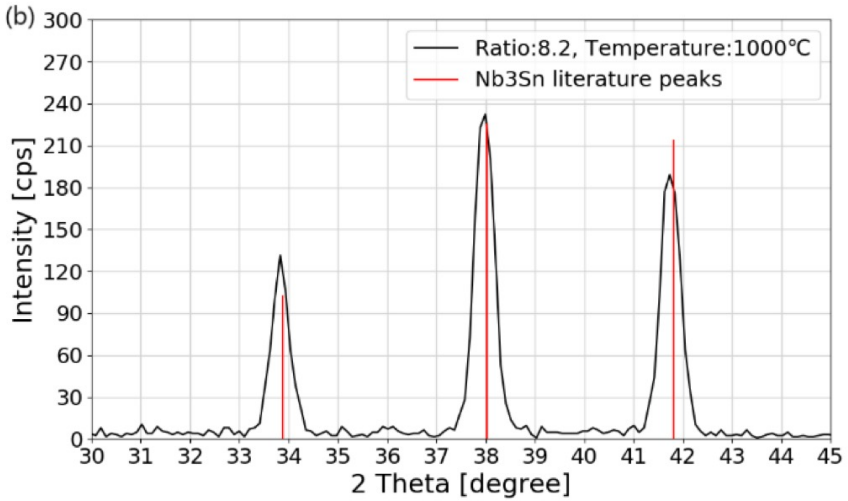


- **Finally, by annealing samples in the temperature range from 600 ℃ to 1000℃, we can synthesize Nb3Sn.**
- RRR measurement clearly show SC-transition at certain temperature.
- We estimate a Sn atomic percentage and a lattice constant by XRD measurement.

# Discussion point

**The highest Tc of our samples is ~16.6 K, less than 18 K.**

- We have not yet created the Nb3Sn film with the ideal Sn atomic percentage and the lattice constant.
  - Ideal Sn atomic percent: 25 %
  - Ideal lattice constant: 0.533 Å

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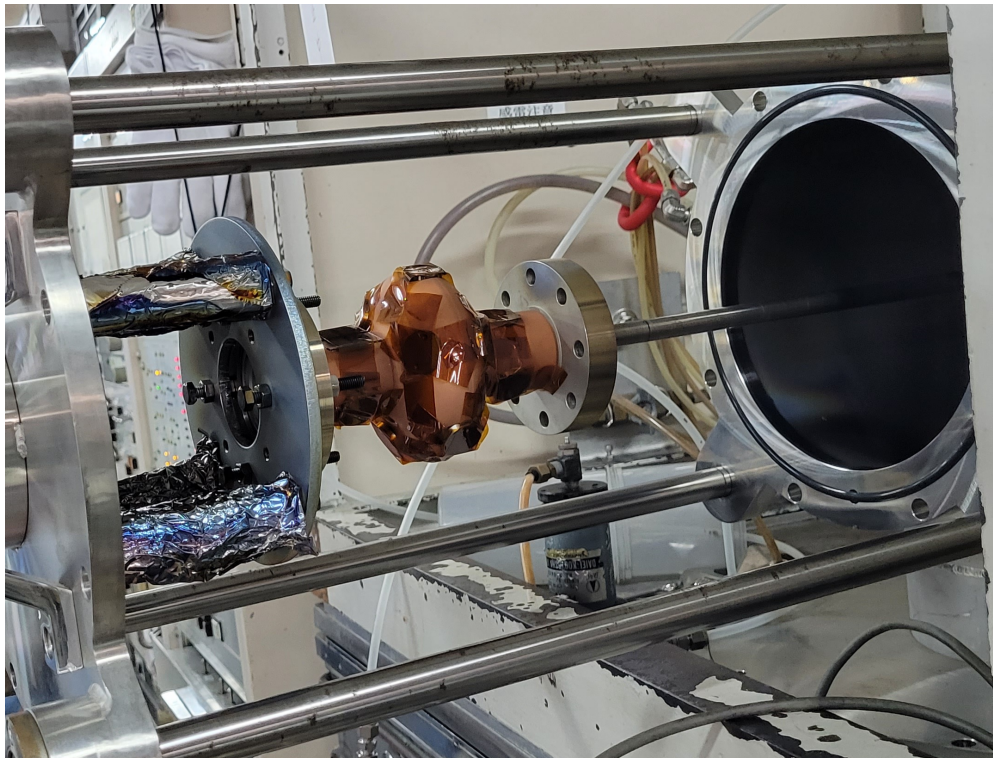

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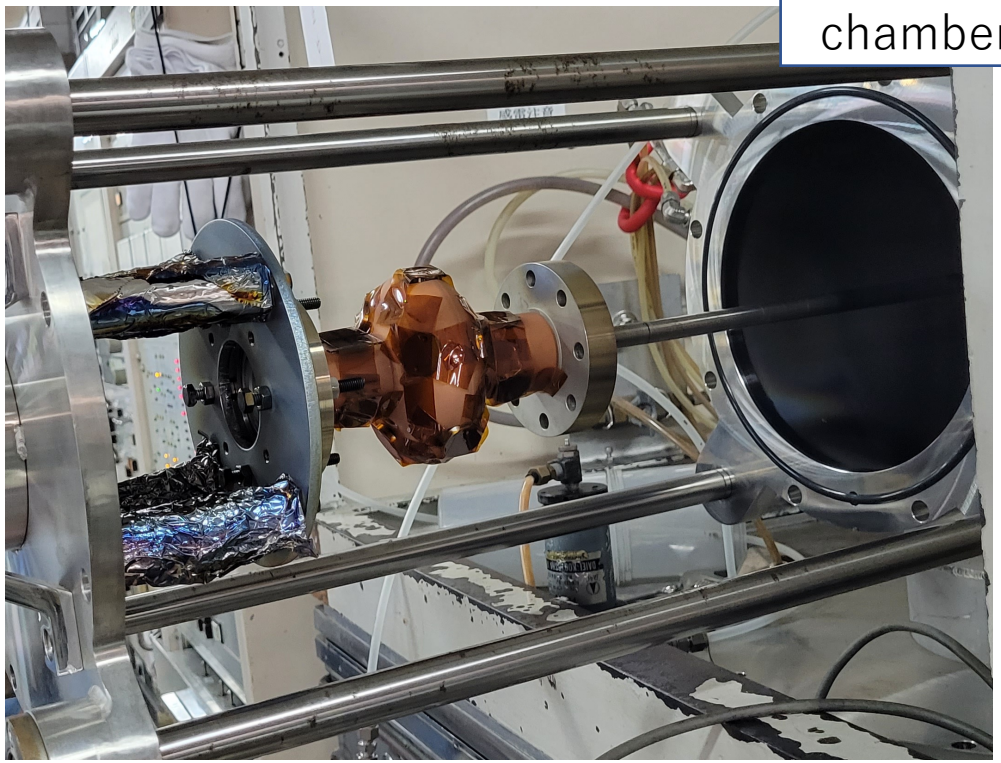

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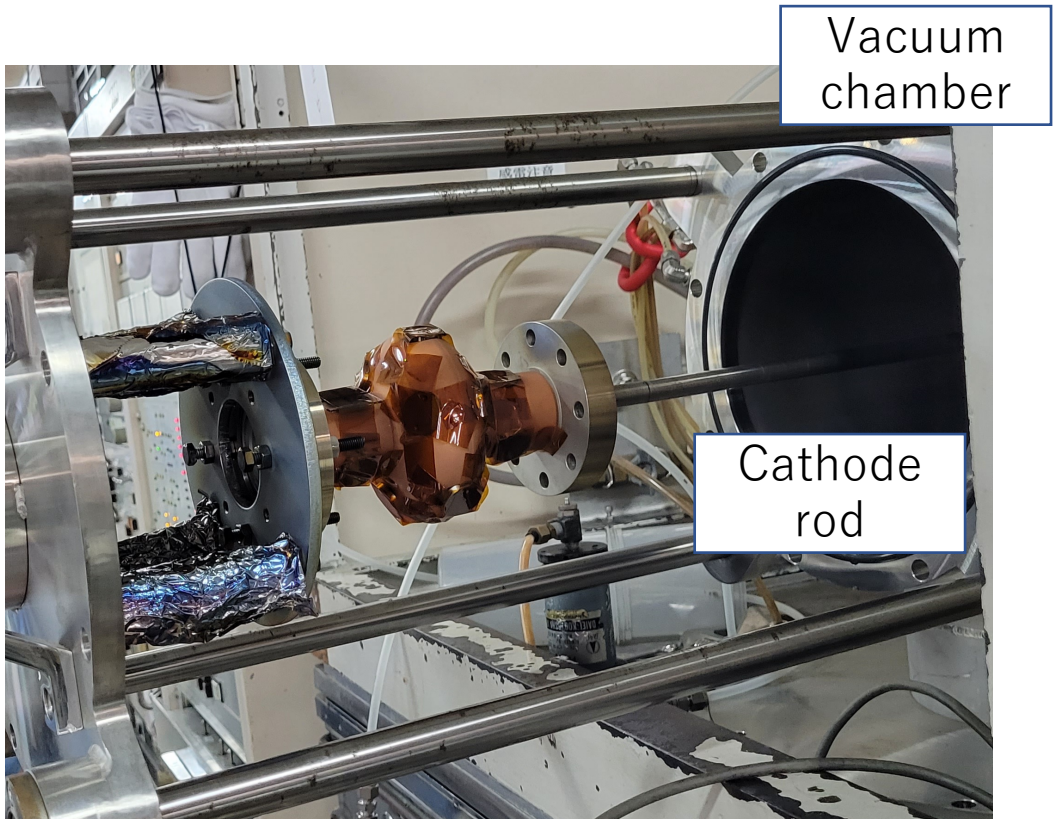

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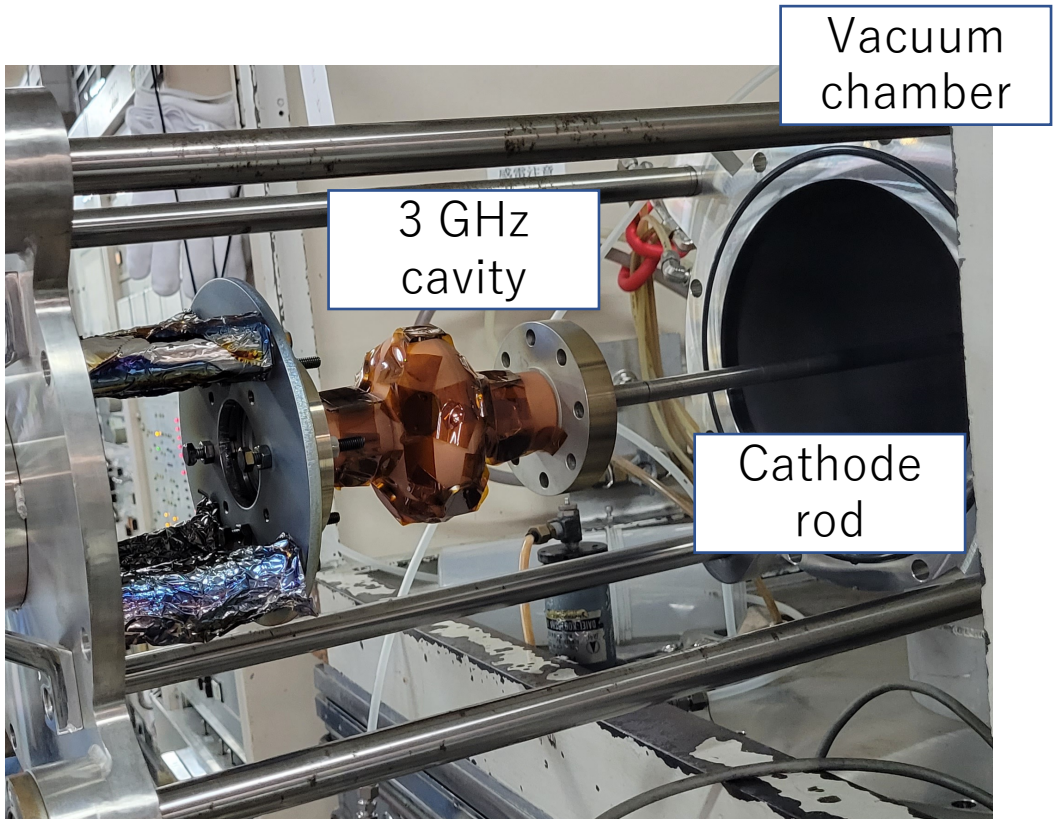

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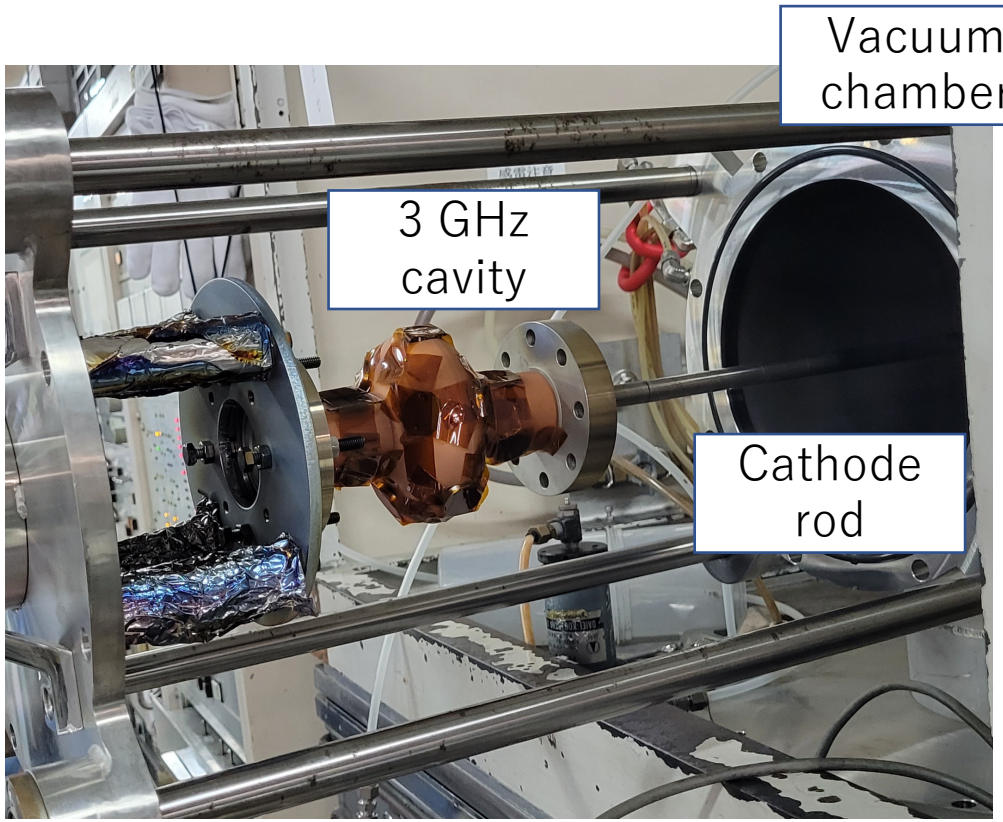


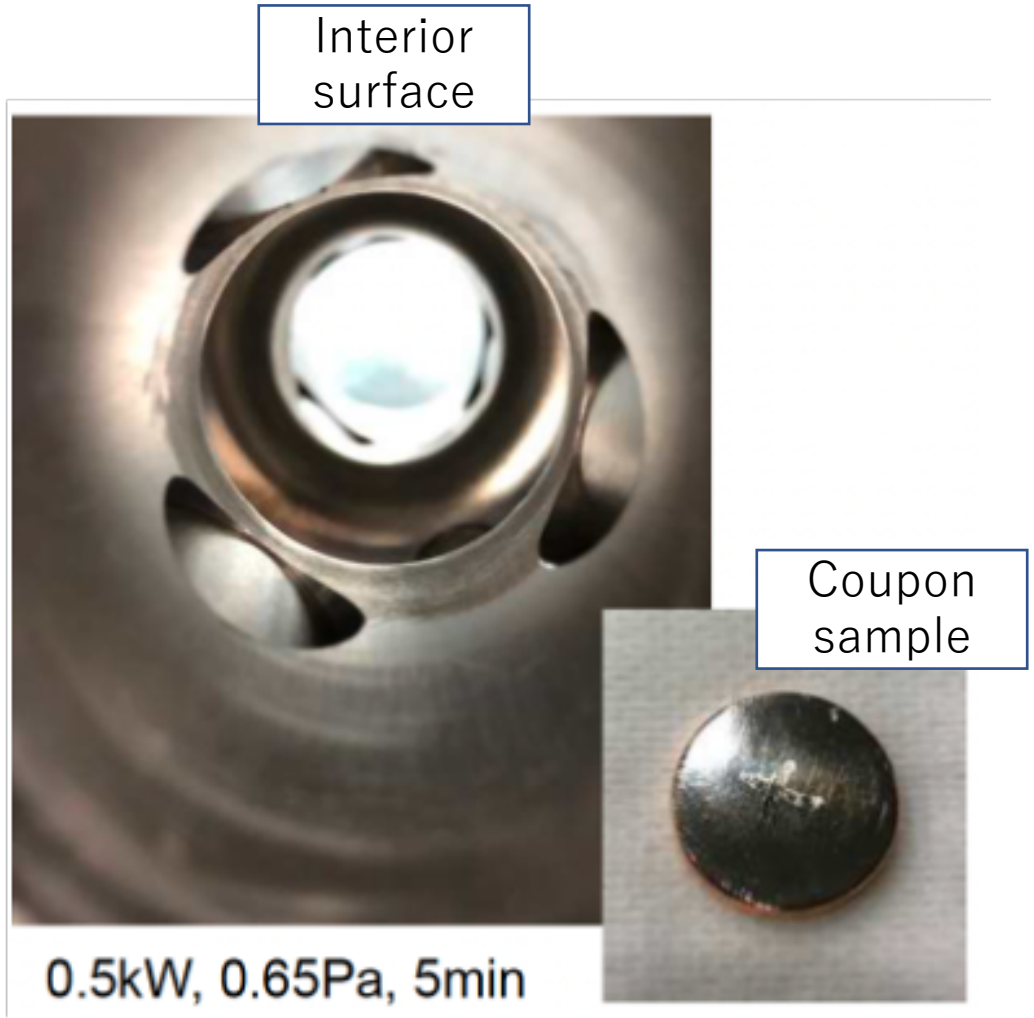

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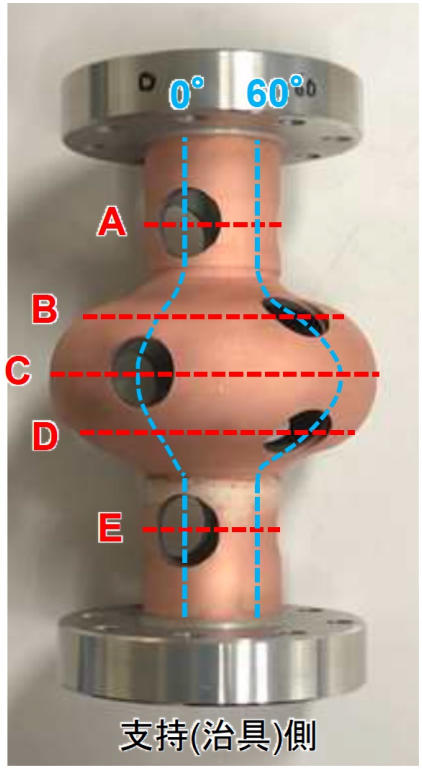
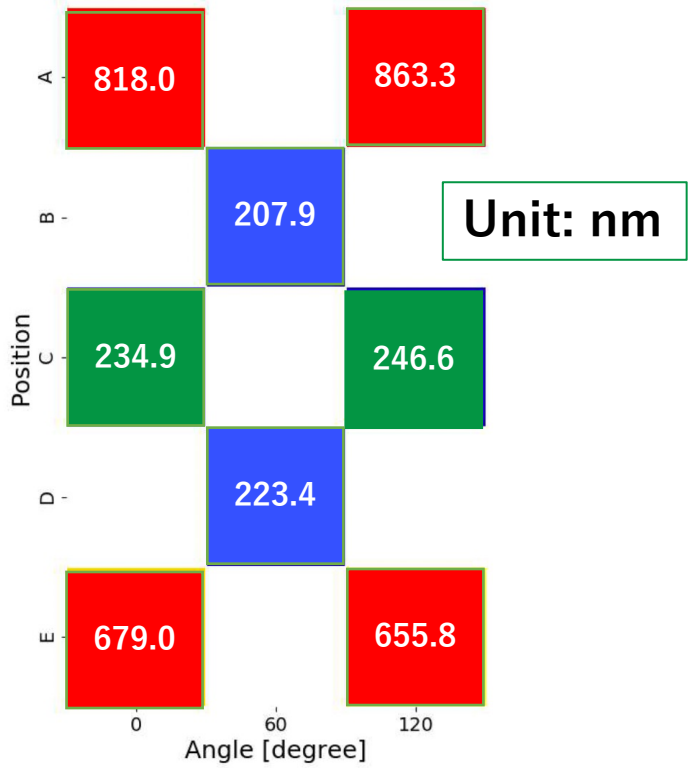
- We evaluated the film thickness distribution from the sputtering test to the cupon cavity as left figure.




- We evaluated film thickness on several points from A to E.
  - **A,E**: Iris position
  - **C**: Equator position
  - **B,D**: the middle point between equator and iris.
- Vertical axis:
  - position of reference point (A-E)
- Horizontal axis:
  - azimuthal angle of 3 GHz cavity
- Thickness is shown in the colored square.

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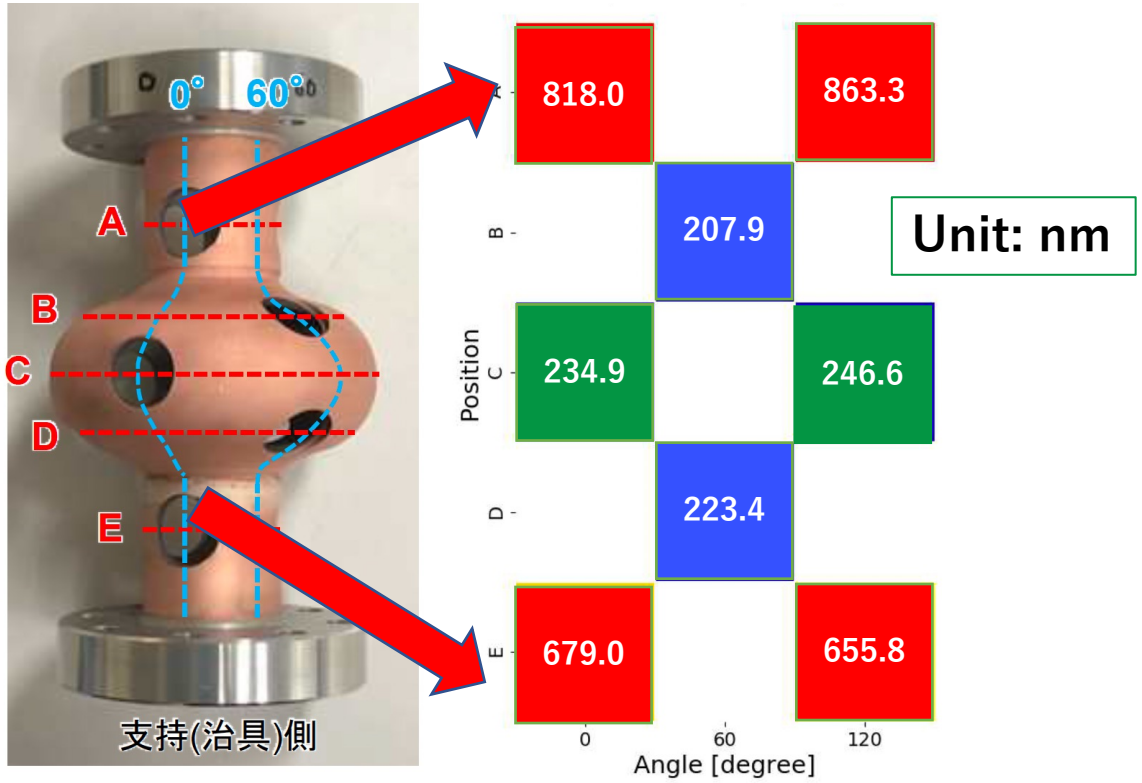


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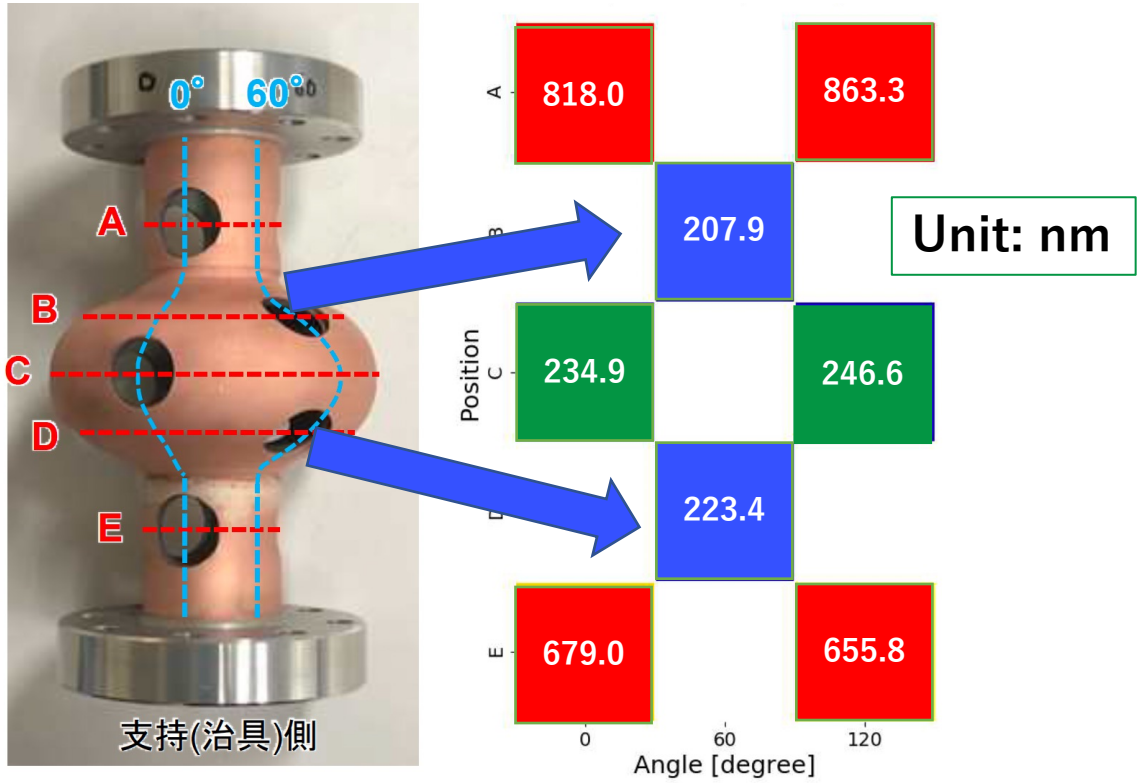


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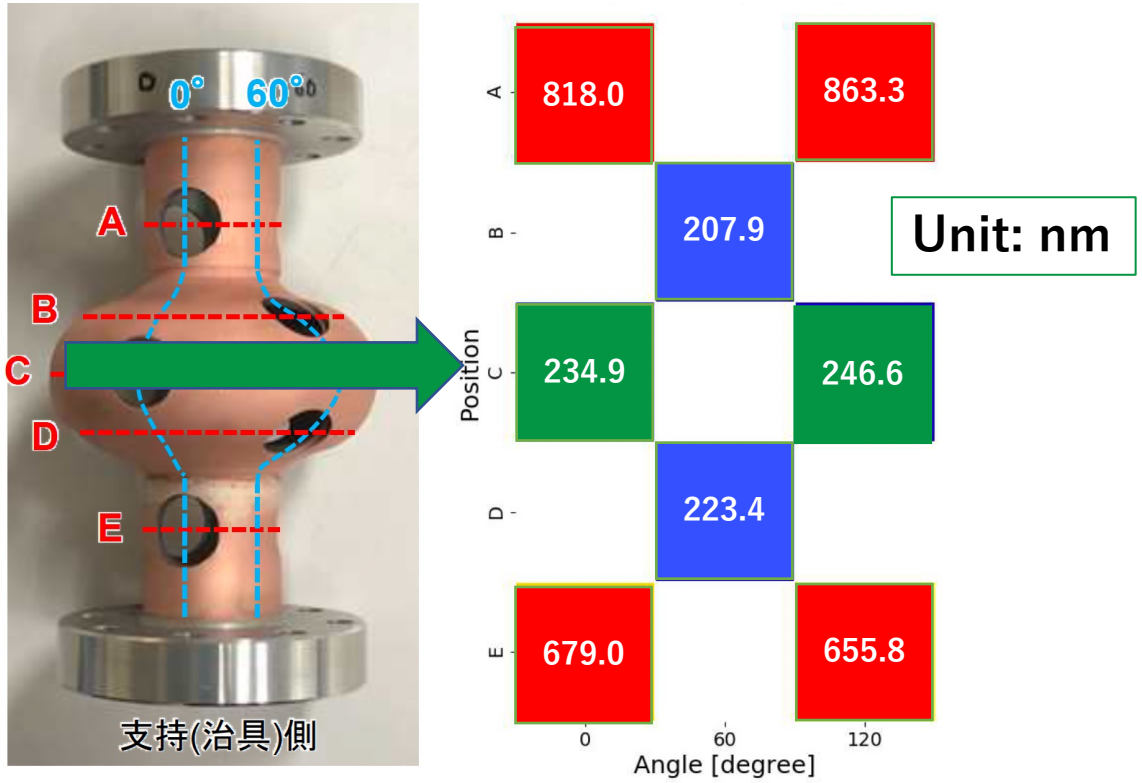


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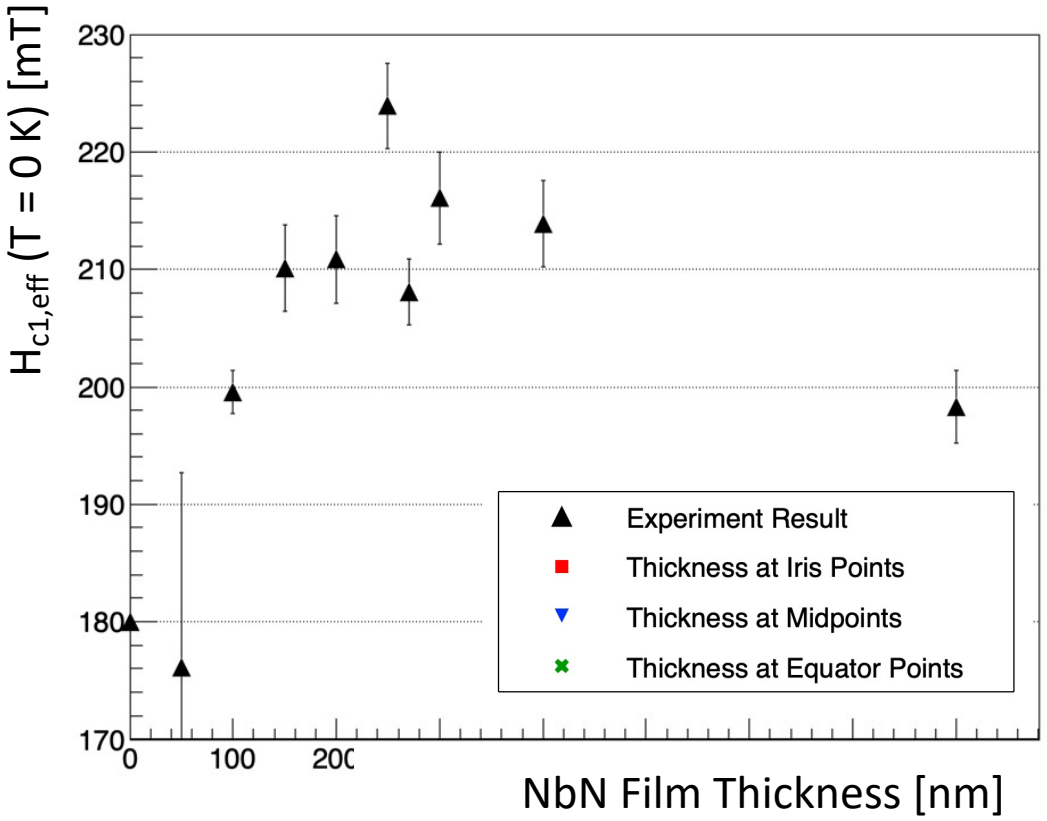


- **For reference, data points of Nb film thickness is superimposed in the $H_{c1,eff}$ of NbN-SiO2-Nb as a function of NbN film thickness.**
  - For ease of viewing, the vertical value is chosen to be 228 mT.
- The data point of equator, at which the strongest surface B-field occur, is overlapped with the point of the maximum effective Hc1 of S'IS structure.

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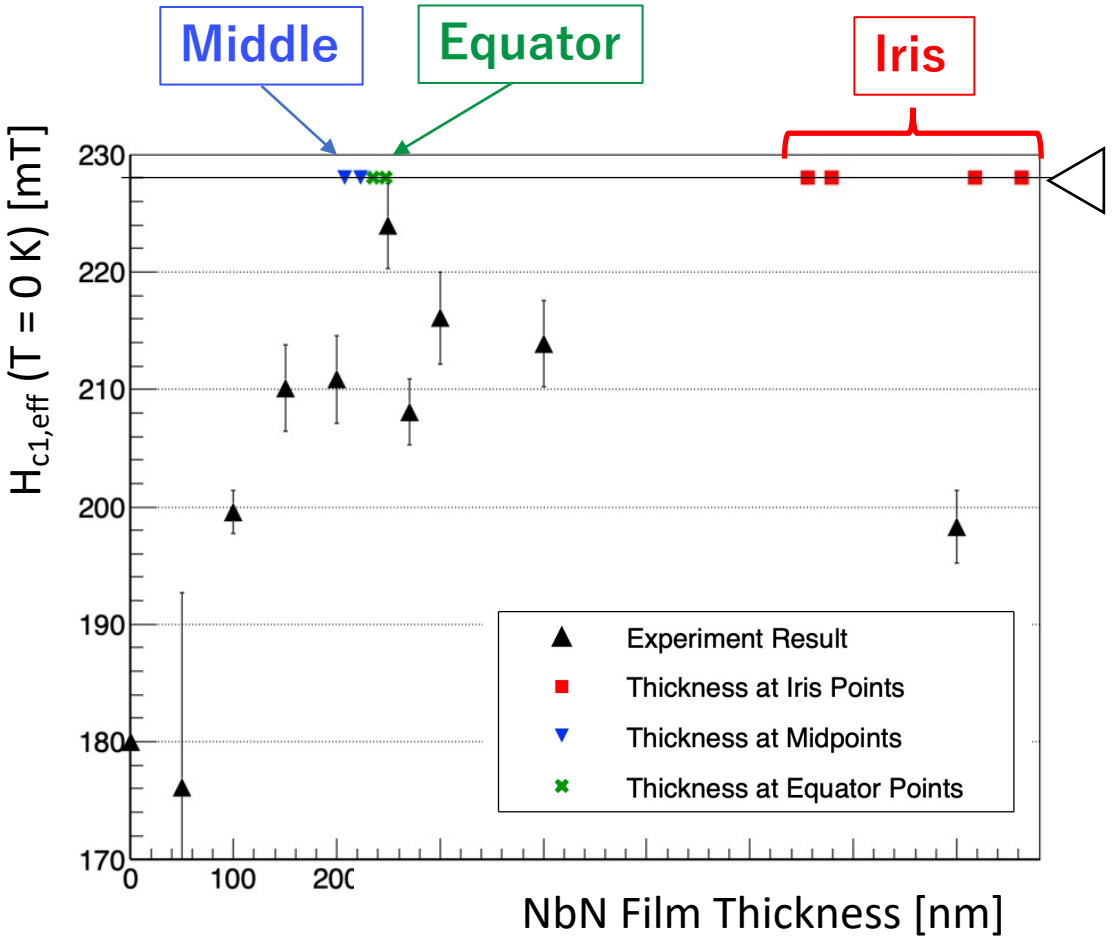


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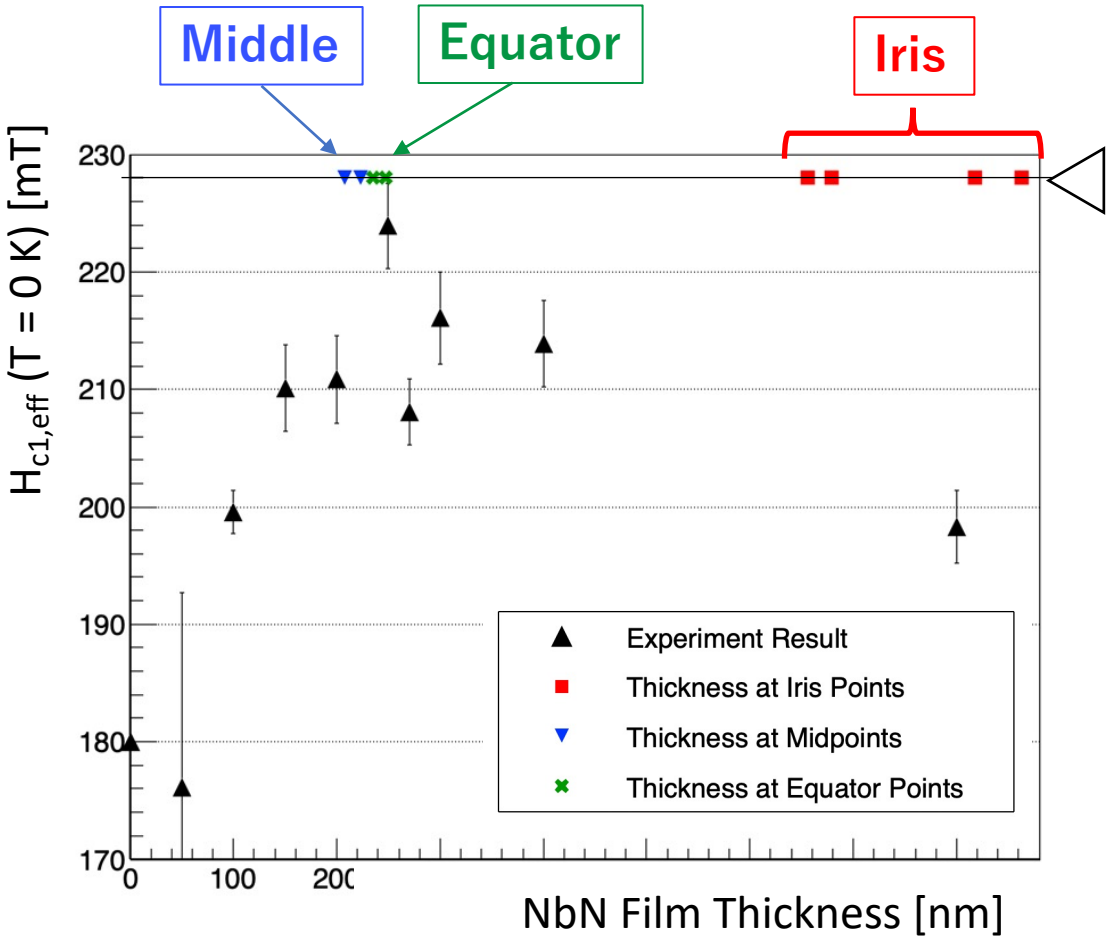


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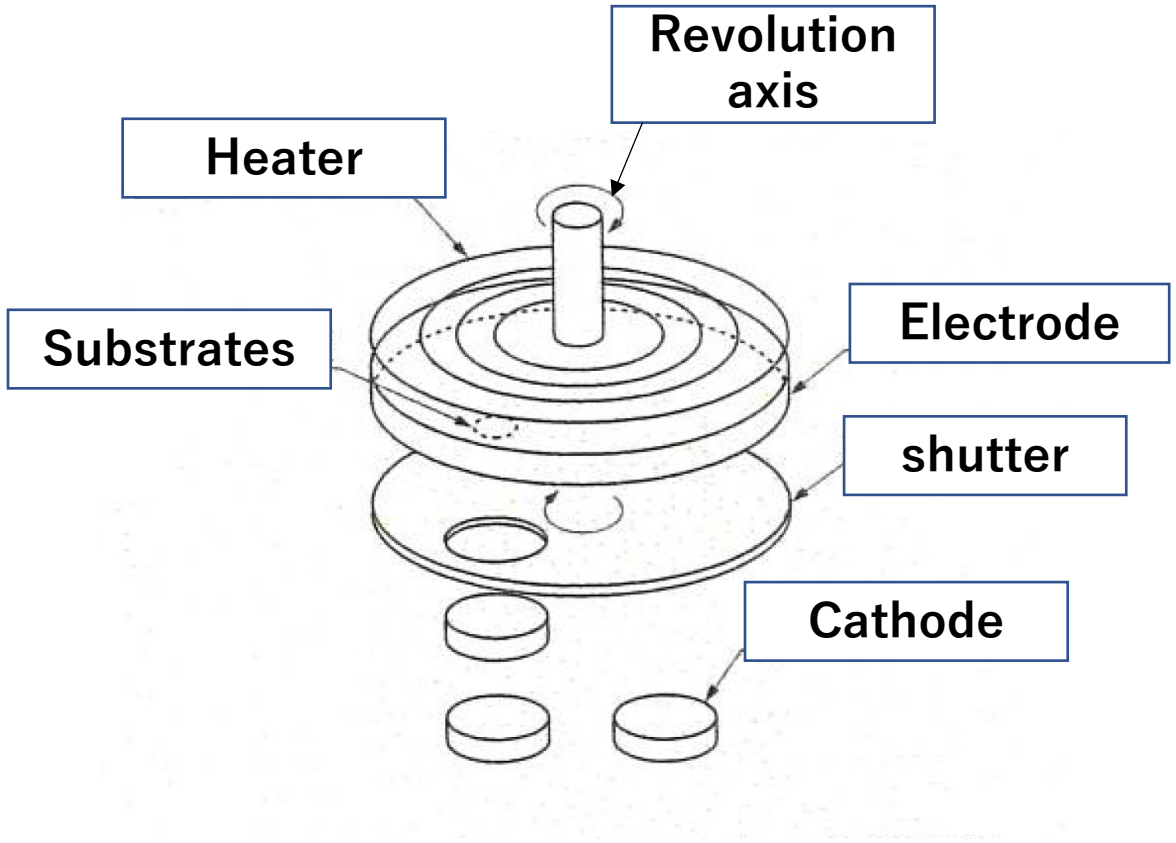
# Beyond KEK-ULVAC collaboration

# Beyond ULVAC-KEK collaboration

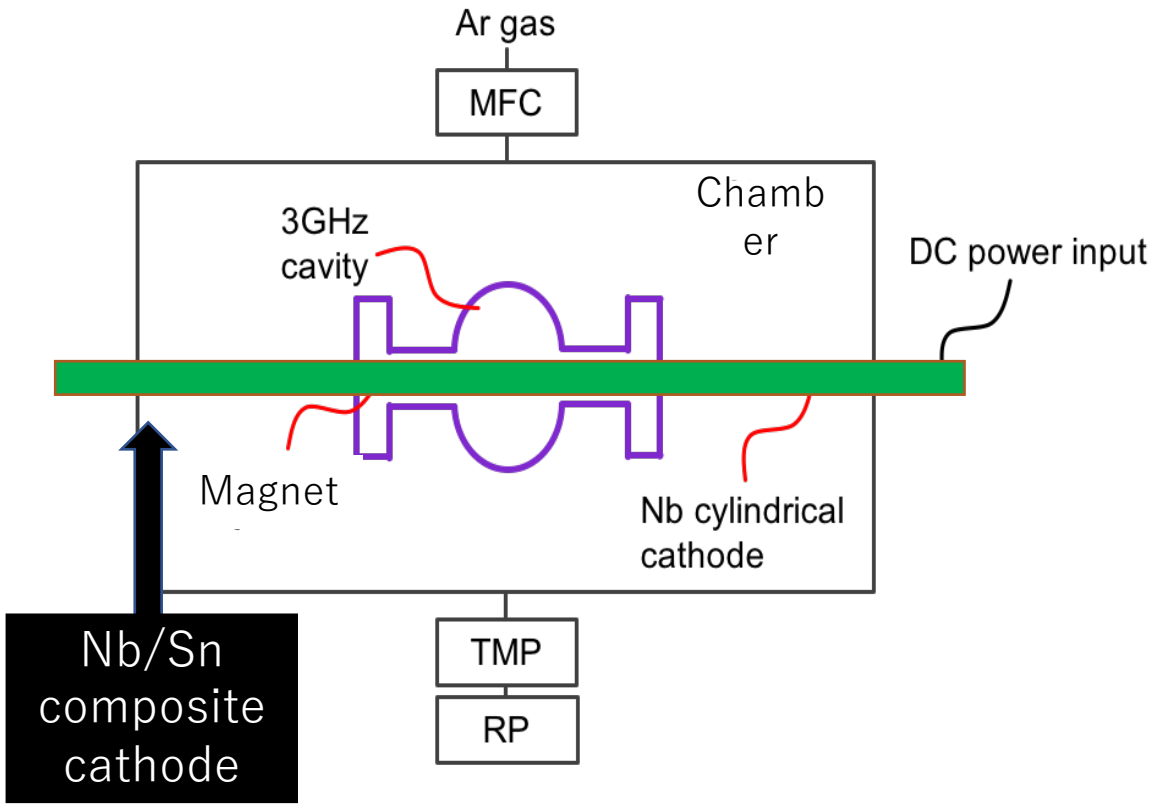
- Because ULVAC-KEK collaboration ended in the middle of 2020, we decided to proceed the film-formation research by ourselves.
- This year, we finally get the grant (KAKENHI KIBAN-A) to introduce new sputtering apparatus that can apply the Nb3Sn multilayer coating method.

# Beyond ULVAC-KEK collaboration (1)



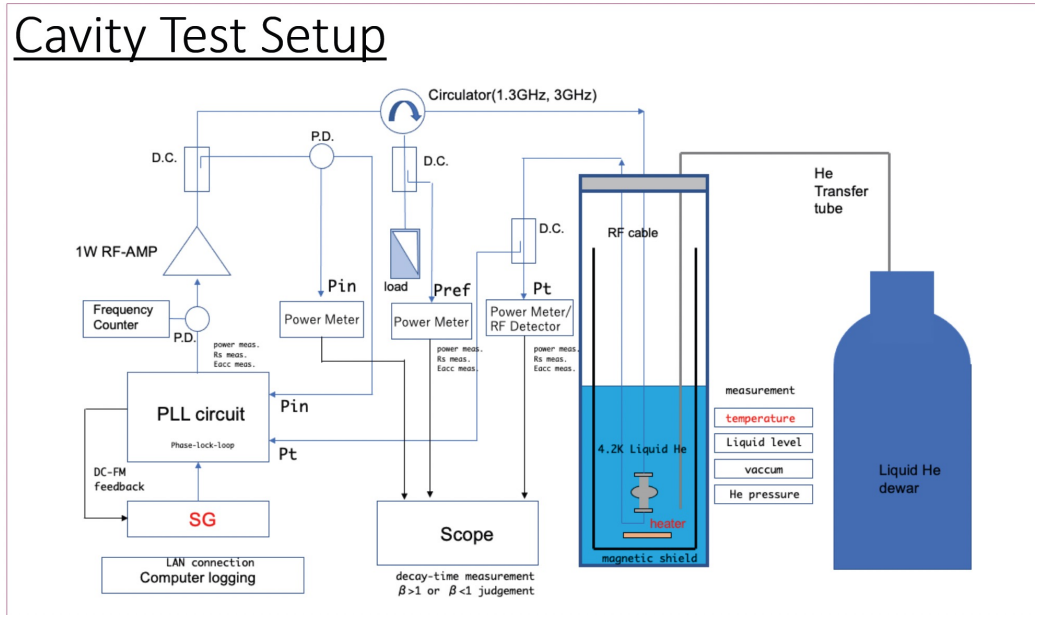

- KEK introduce the sputtering apparatus, SH-450 (ULVAC inc.).
- SH-450 is capable of Nb3Sn coating method almost same as developed by ULVAC-KEK collaboration.
  - In addition, temperature control of substrate is possible.
  - RF sputtering and HIPIMS are also possible only by replacing DC power sources.

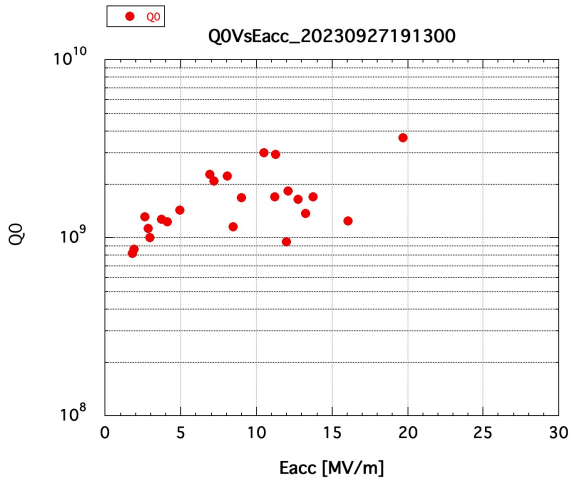
# Beyond ULVAC-KEK collaboration (2)




- Nb3Sn coating method can be applied to the inside of 3 GHz cavity.
- **Nb/Sn composite cathode** is the key.
- Development of the special cathode is ongoing.

# VT setup for 3 GHz cavity at KEK STF




- This year, we prepared VT setup for 3 GHz cavity at KEK STF for evaluation of the cavity performance with S'IS structure.
- We performed the first VT of a 3 GHz cavity made of a pure bulk Nb on Sep 27.
  - Treatment
    - BCP and 120 °C bake for 48 h
    - No anneal (we missed)
- Problem
  - RF feedback system was unstable if Eacc is greater than 20 MV/m.
- We are developing new RF feedback system designed to be work stably.

# Summary

- We performed SRF multi-layer thin-film R&D by the ULVAC-KEK collaboration from 2018 to mid of 2020.
  - Measuring $H_{c1,eff}$ of NbN(50-800 nm)-SiO2 (30 nm)-Nb sample

  → We demonstrated that $H_{c1,eff}$ at 0 K is increased by 23.8 % at the optimum thickness.
  - Development of Nb3Sn coating method for S'IS structure

  → We created Nb3Sn-Nb sample with Tc = 16.6 K by DC magnetron sputtering.
  - Development of Nb sputtering apparatus

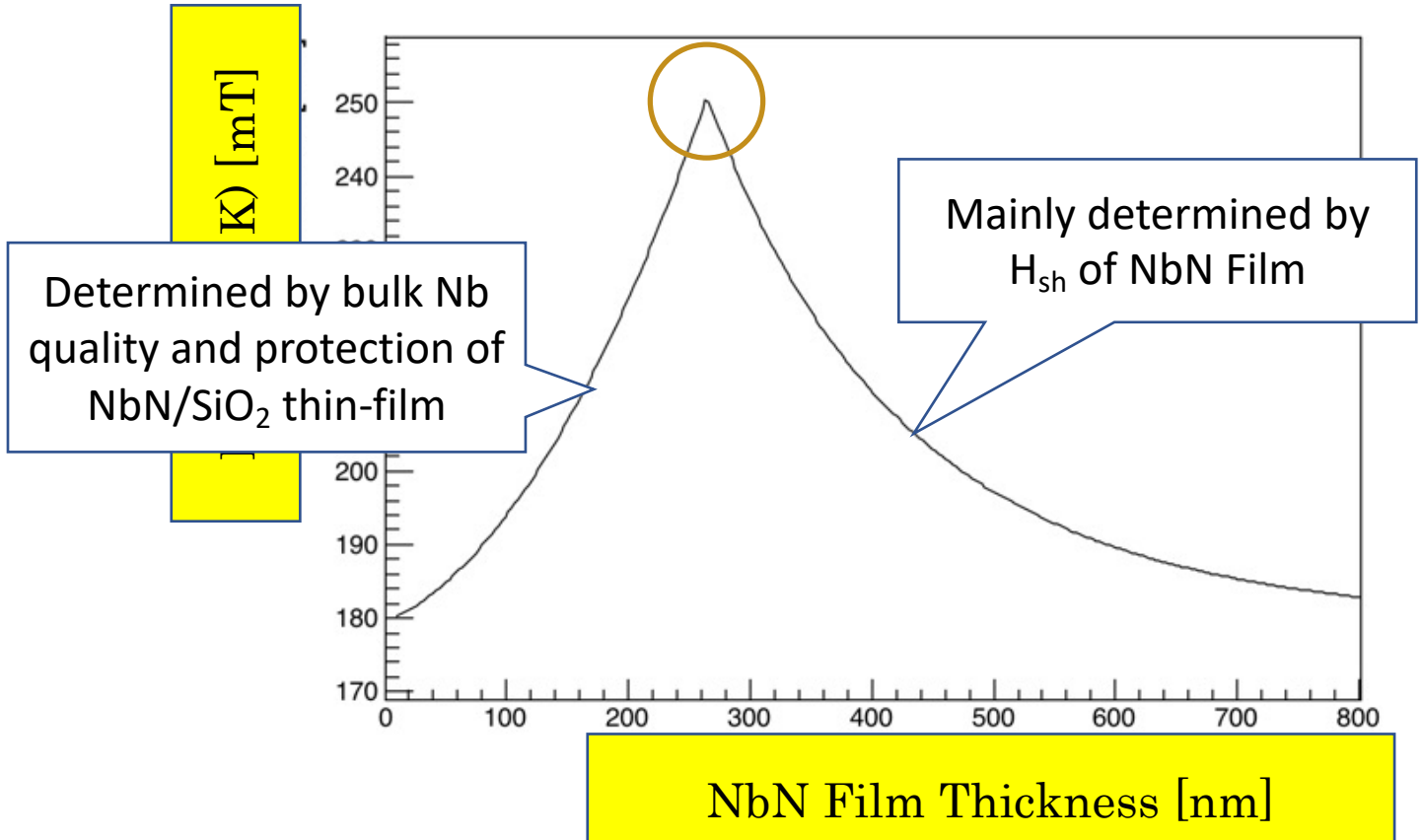
  →We successfully coat the inside of 3 GHz cavity.
- This year, KEK introduced new sputtering system for Nb3Sn multi-layer coating.
  - SH450 allow us to apply the Nb3Sn coating method same as developed by ULVAC-KEK collaboration.
  - Development of Nb/Sn composite cathode is ongoing.
- VT system at 2 K for 3 GHz cavity is being prepared.

Thank you for you attention

# Backup

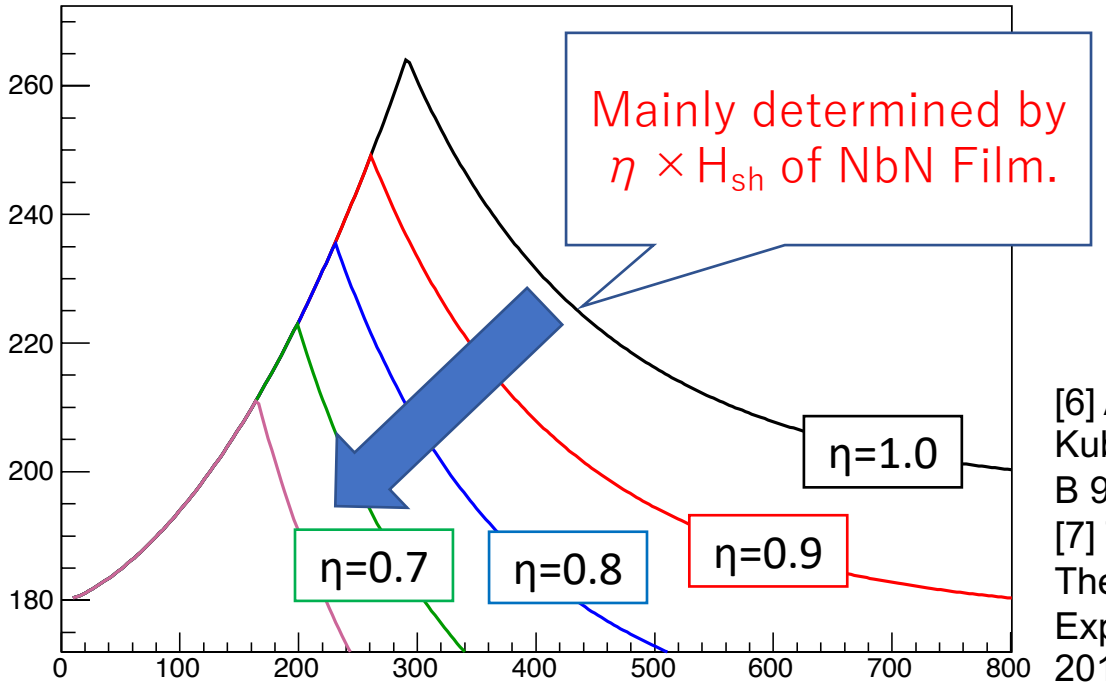
# Theory

- Theoretical calculation ($H_{c1,eff}$ vs NbN thickness) is plotted below:
  - Optimum thickness exists, which is the same as experiment.
  - London penetration depth λ of NbN film is calculated by the electrical resistivity ρ and the critical temperature $T_c$.
  - $H_c$ of NbN is taken from literature (C Geibel et.al, (1985) J. Phys. F: Met. Phys. 15 405).



# Theory

- The performance of NbN film deteriorates due to the effect of the imperfect surfaces such as surface defects and roughness and so on.
- This effect is included as the parameter η [6][7].
  - η =1 (Black line) is the ideal case, while η < 1 (other colors) is not so.

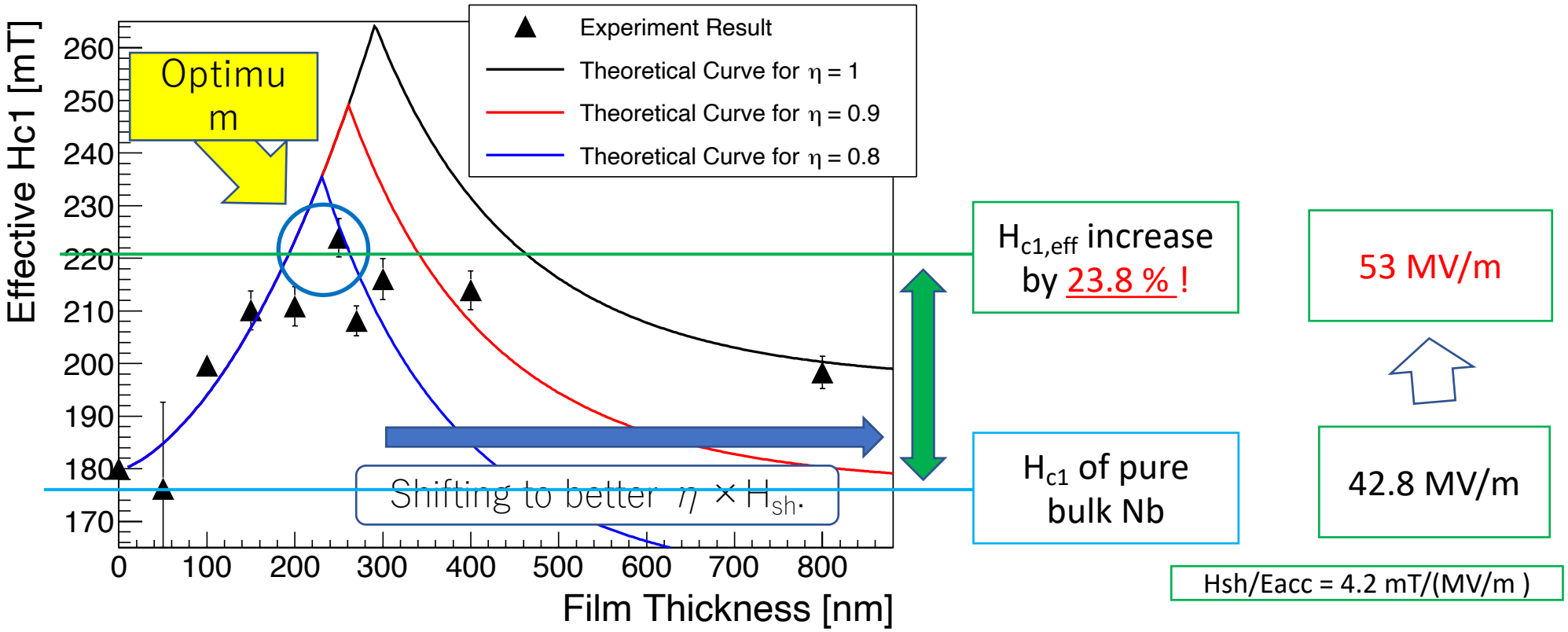




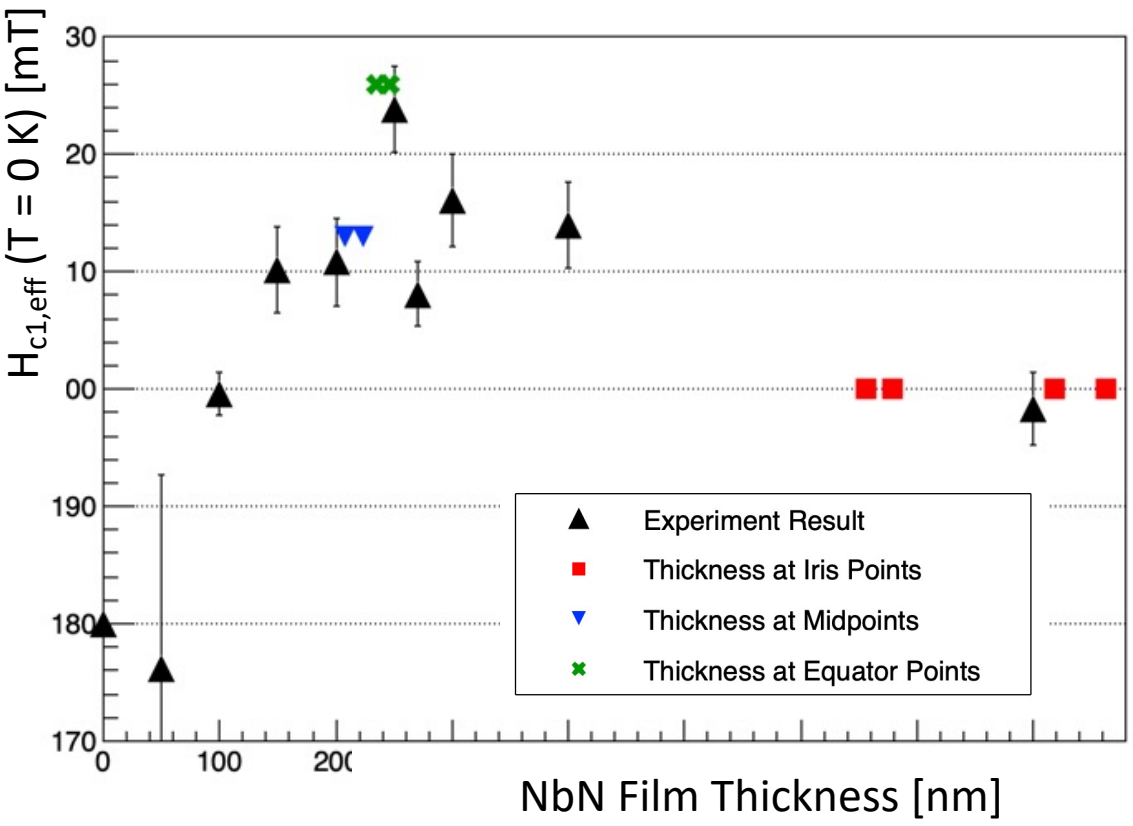
[6] A. Gurevich and T. Kubo, Physical Review B 96, 184515 (2017)
[7] T. Kubo, Progress of Theoretical and Experimental Physics 2015, 063G01 (2015)

# Comparison of data and theory

- Experimental result and theoretical curve are superimposed below.



# Discussion point

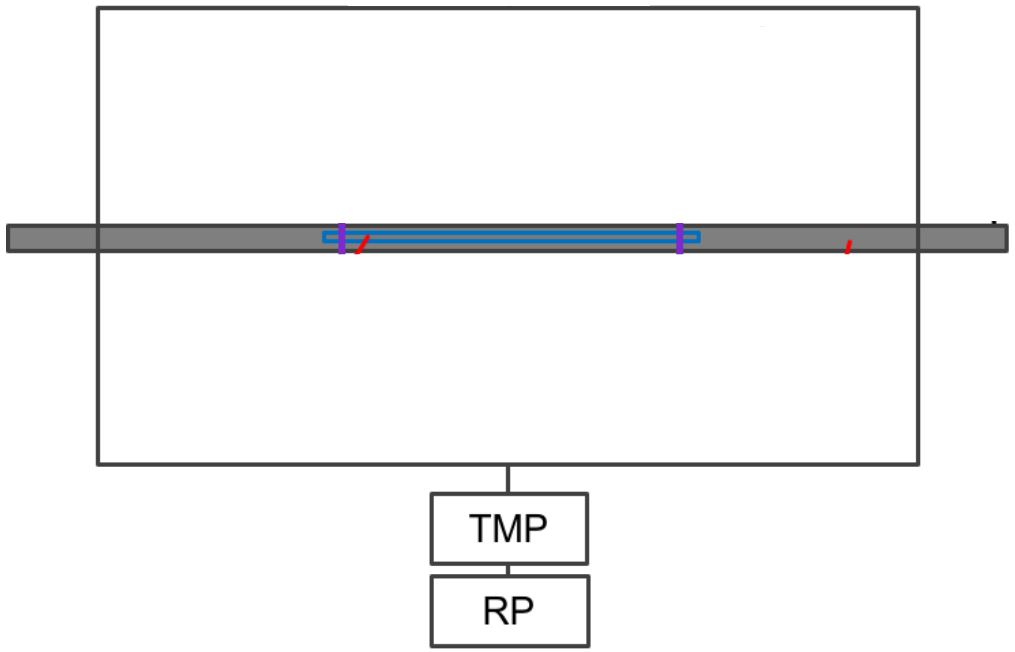



- For reference, data points of Nb film thickness is superimposed in the $H_{c1,eff}$ of NbN-SiO2-Nb as a function of NbN film thickness.
  - Vertical axis is arbitrary. So, a data point of film thickness is shown near $H_{c1,eff}$.
- **$H_{c1,eff}$ at SC film thickness at the closest point is summarized as follows:**

| | Equator | Middle | Iris |
|---|---|---|---|
| Hc1,eff | 223 mT (optimum) | 210 mT | 200 mT |

# Main Result of ULVAC-KEK collaboration (3)

- Schematic illustration of Nb sputtering apparatus is shown below.




- Components
  - Vacuum chamber
  - Argon gas flow
  - Nb cathode
  - Permanent Magnet
  - 3 GHz cavity
  - DC power source

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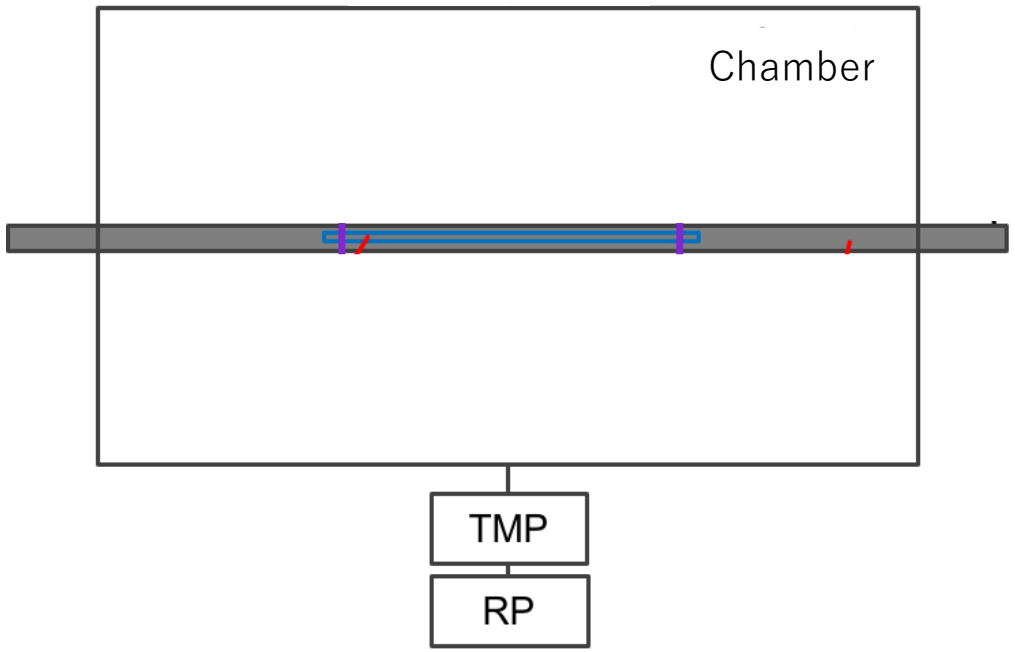


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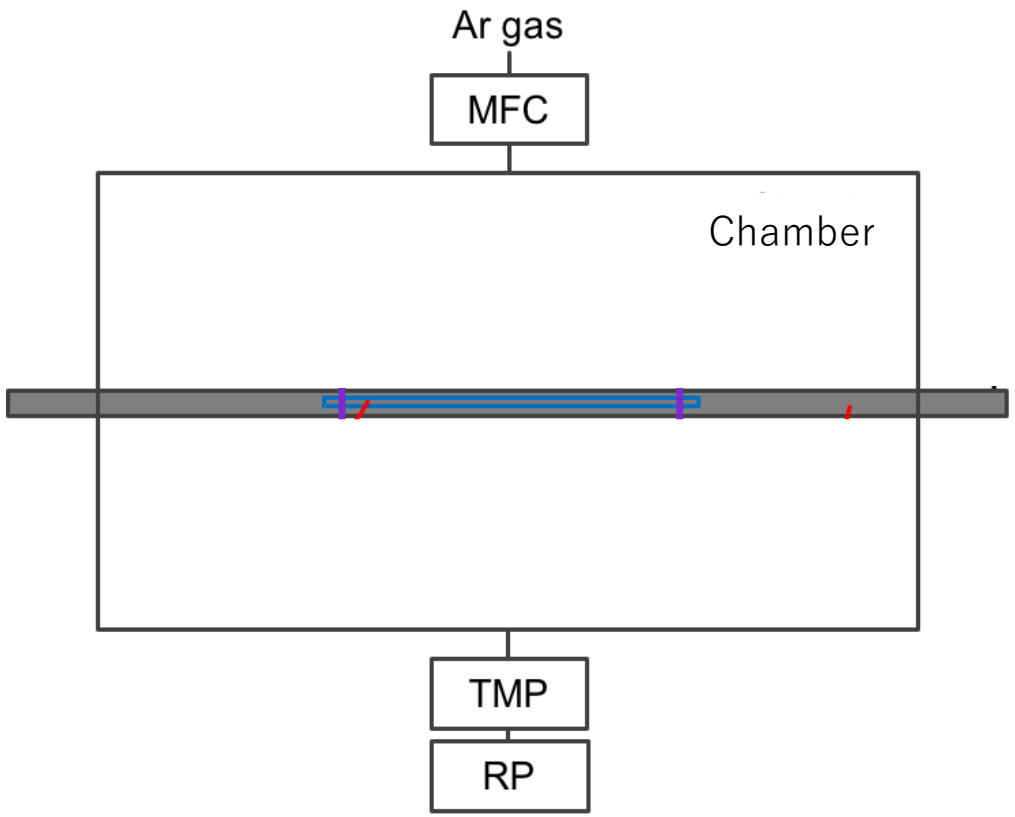


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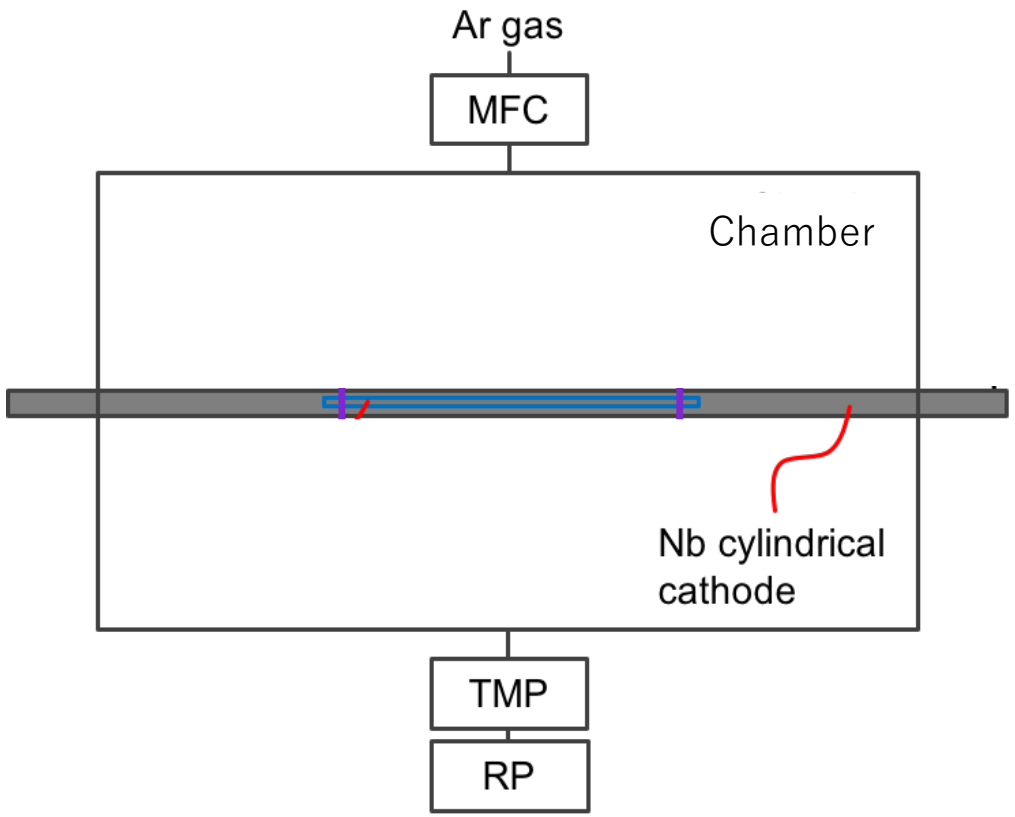


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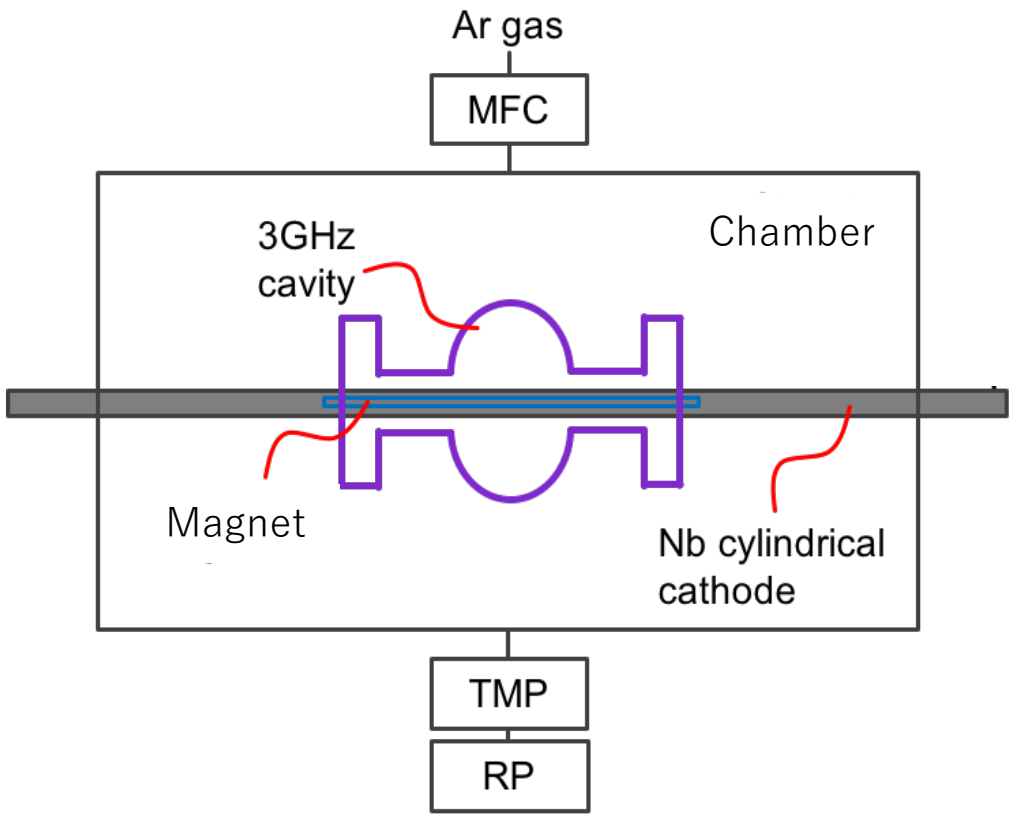


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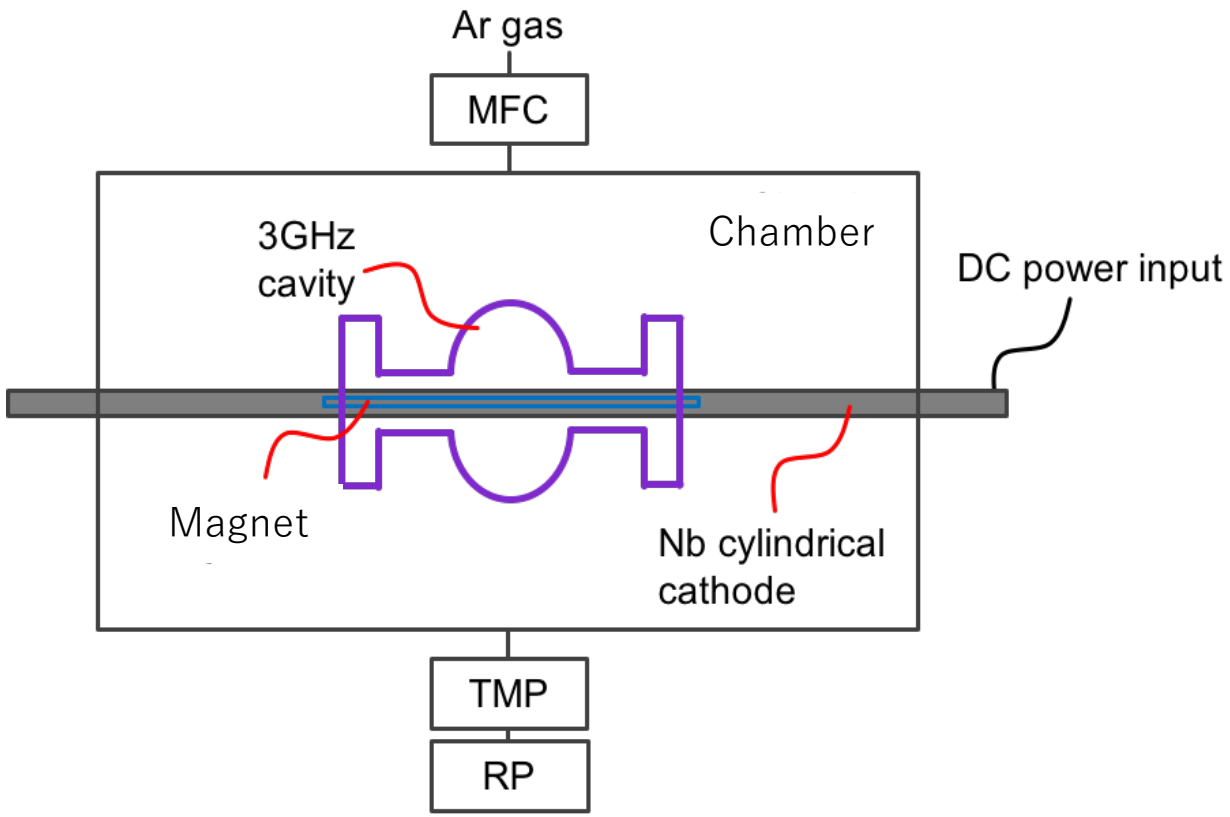


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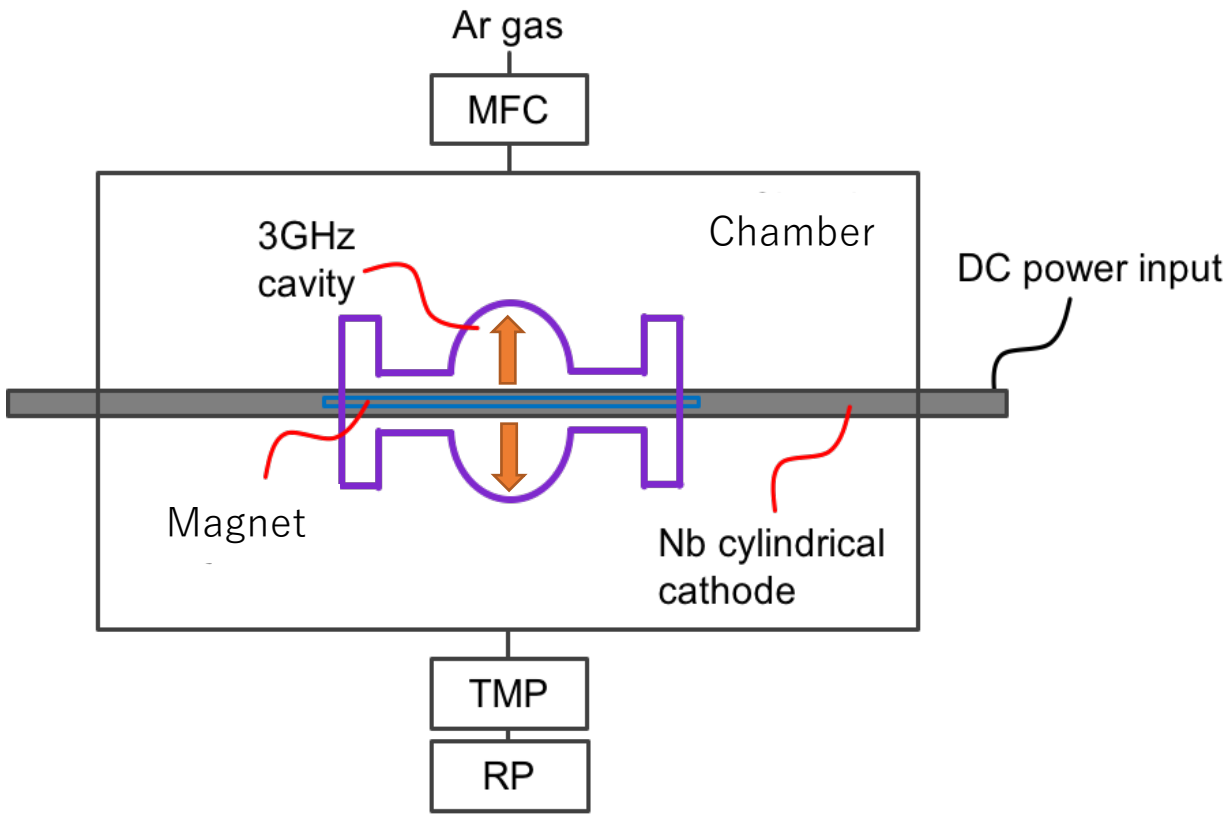


- Components
  - Vacuum chamber
  - Argon gas flow
  - Nb cathode
  - Permanent Magnet
  - 3 GHz cavity
  - DC power source
- **The inside of 3 GHz cavity is coated with Nb thin-film by DC magnetron sputtering.**