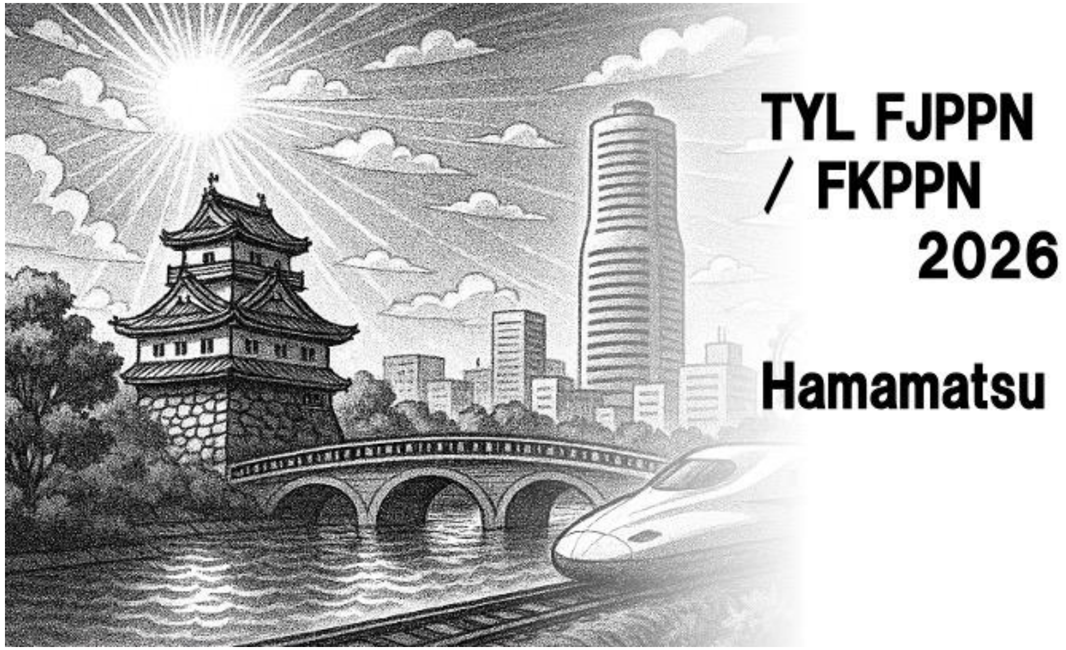
A_RD_25:
Continued Effort Towards Ultimate Performance for Accelerator Cavities



Overview of the project

A_RD_25	**Title: A_RD_25 Continued effort towards ultimate performance for accelerator cavities**					
	French Group			**Japanese Group**		
	name (Family name, First name)	**title**	**lab.**[1]	**name** (Family name, First name)	**title**	**lab.**[22]
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	Thomas PROSLIER	Dr.	IRFU/CEA	Takayuki SAEKI	Dr.	KEK
PIs:	Grégoire JULLIEN	Mr.	IRFU/CEA	Ryo KATAYAMA	Dr.	KEK
	Enrico CENNI	Dr.	IRFU/CEA	Takeyoshi GOTO	Dr.	KEK
Members:	Fabien EOZENOU	Mr.	IRFU/CEA	Yasuhiro FUWA	Dr.	JAEA
				Yoshihisa IWASHITA	Dr.	U. Osaka RCNP

In order to establish the scientific basis for high-performance SRF (Superconducting Radio Frequency) cavities, this project pursues a unified approach that combines cavity fabrication, surface-treatment development (such as EP: Electro-Polishing), thin film deposition technique, and theoretical understanding.

Continued Effort Towards Ultimate Performance for Accelerator Cavities

Activities in 2025 and Plan for 2026

1.	Theoretical Analysis	T. Kubo
2.	Nb_3Sn Thin Film Formation	R. Katayama
3.	3GHz cavity	Y. Fuwa
4.	EP with organic solvent	T. Goto
5.	EP with depleted HF mixture	F. Eozenou
6.	Atomic Layer Deposition	Y. Kalboussi & T. Proslier
7.	Faint Magnetic Shielding	Y. Iwashita

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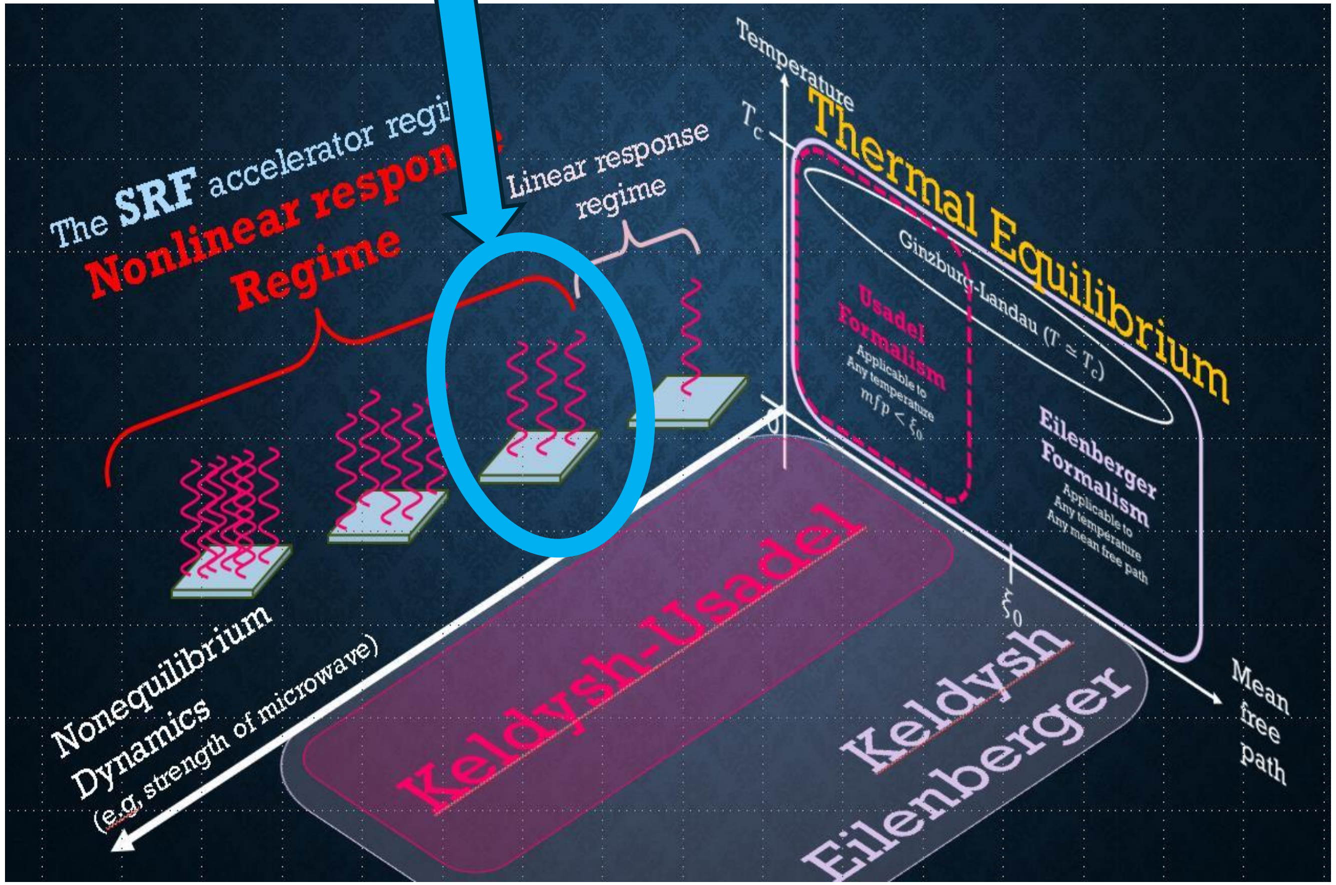
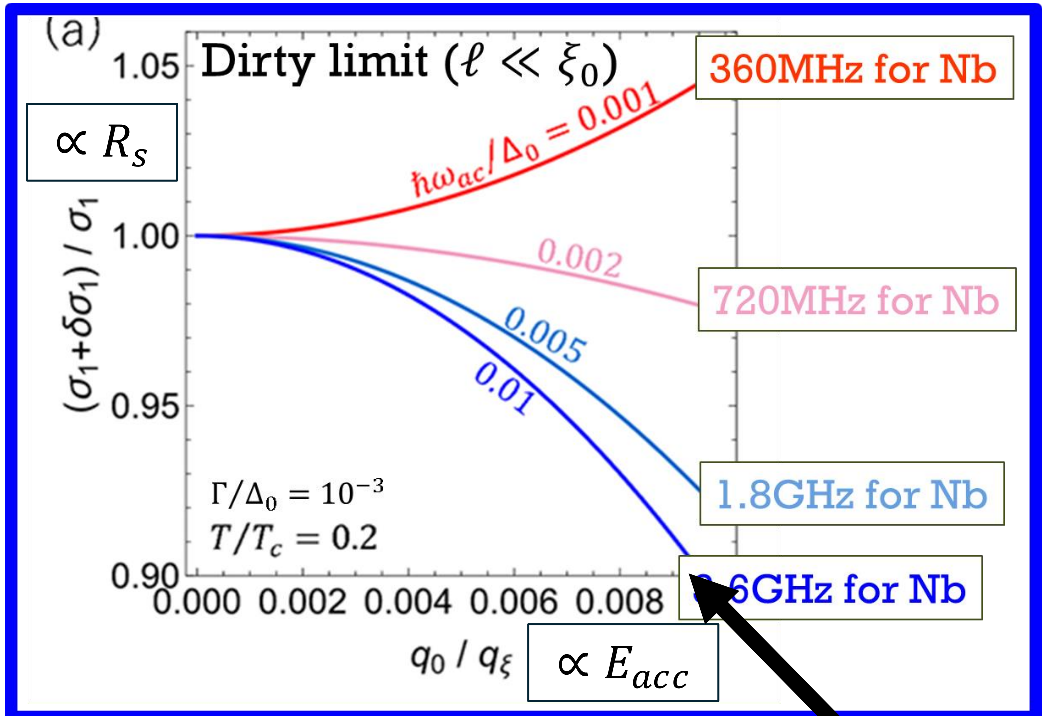
Achievement in 2025: Amplitude-dependent Electromagnetic response

The nonlinear behavior routinely observed in SRF Q-E curves is a **problem of nonequilibrium superconductivity under extremely strong rf electromagnetic fields**. Linear-response theories such as Mattis-Bardeen are no longer sufficient. Kubo addressed this long-standing problem using the Keldysh-Usadel theory, **a microscopic theory of nonequilibrium superconductivity**, by including electromagnetic perturbations up to **third order**.



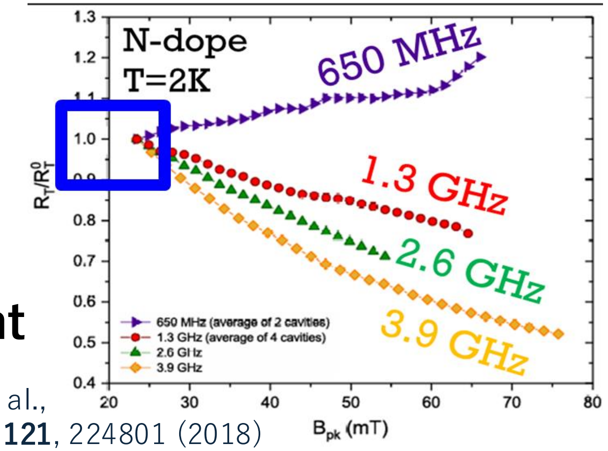


Theory T. Kubo, Phys. Rev. Applied **24**, 064061 (2026)

Note: this corresponds to **a few** (mT)

Anti R_{BCS} slope at $f \gtrsim 1$ GHz

Experiment



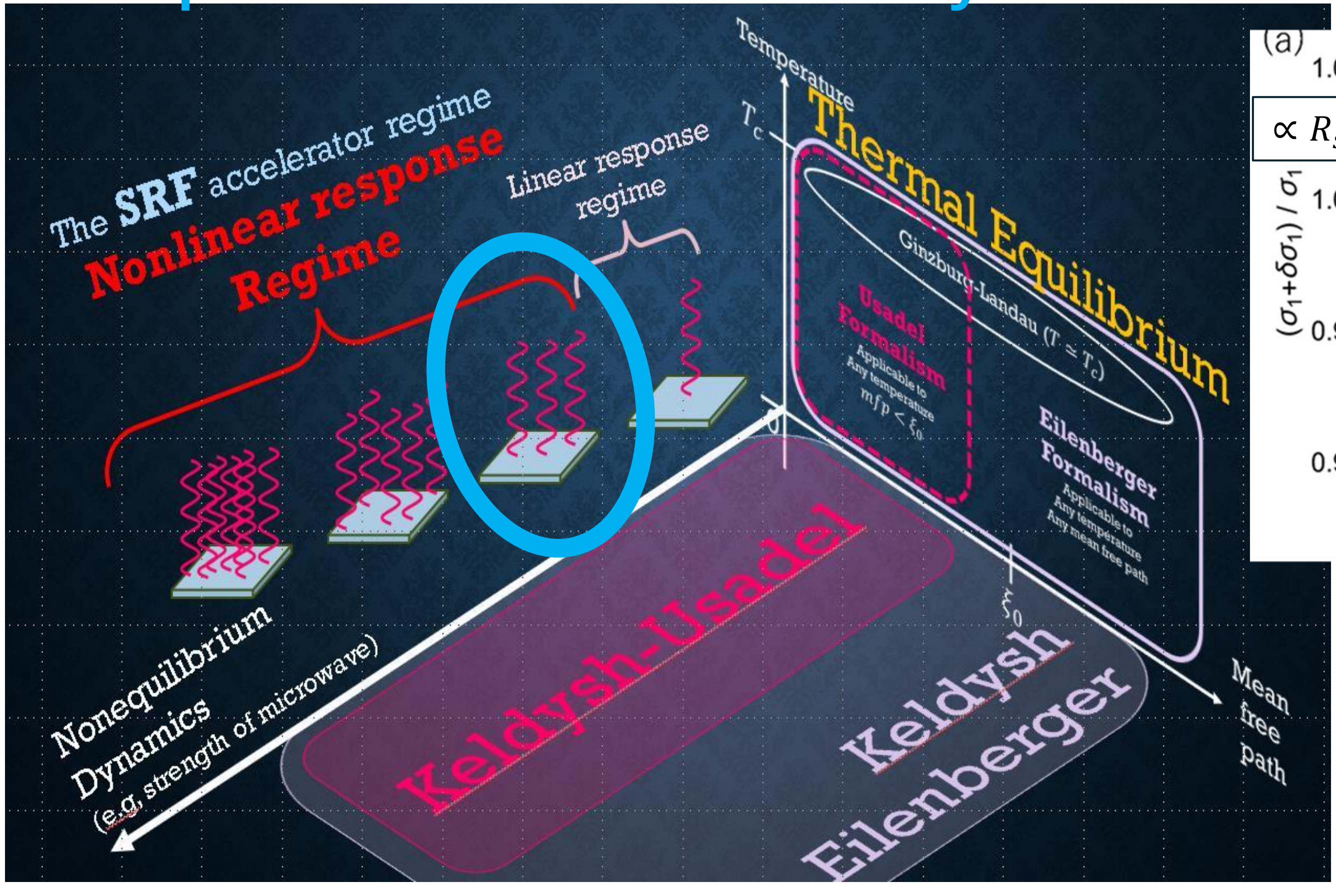
M. Martinello et al., Phys. Rev. Lett. **121**, 224801 (2018)

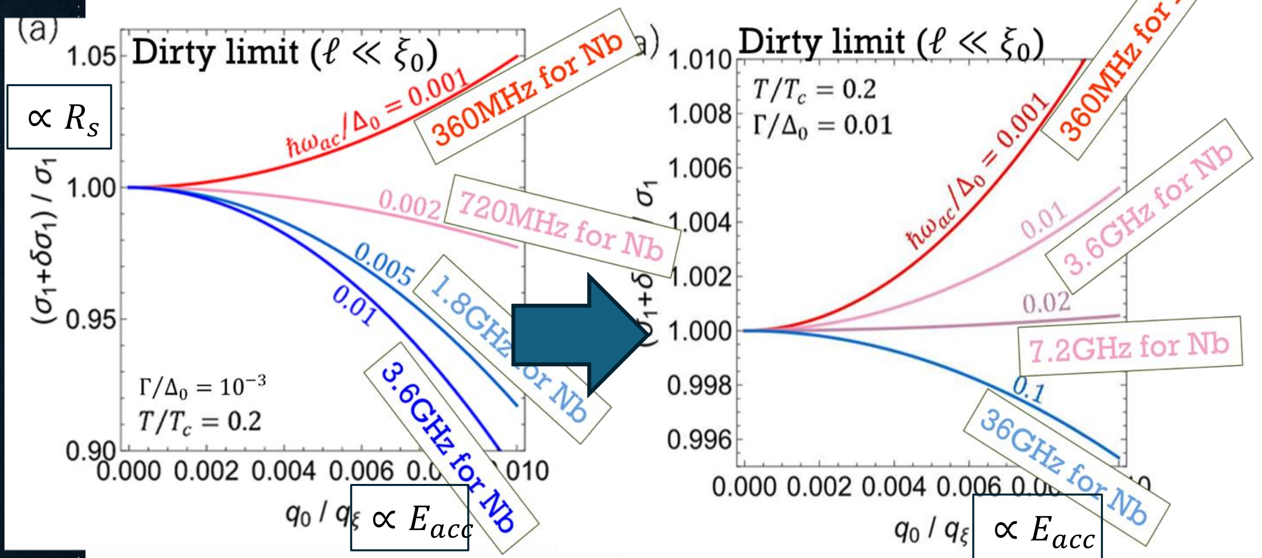
Theoretical prediction and the 2026 target

- Even when Γ is not as small as in N-doped cavities, the anti- R_{BCS} behavior can become visible by increasing the frequency.
- **We will revisit existing Q-E measurements and tunneling-spectroscopy data, and compare them with the theory.**

The inelastic scattering rate affects the "switching frequency" of R_{BCS} slope

$\Gamma/\Delta_0 = 0.001$ (e.g., **nitrogen dope**) → $\Gamma/\Delta_0 = 0.01$





Anti R_{BCS} slope at $f \gtrsim 1$ GHz → **Anti R_{BCS} slope at $f \gtrsim 10$ GHz**

T. Kubo, Phys. Rev. Applied **24**, 064061 (2026)

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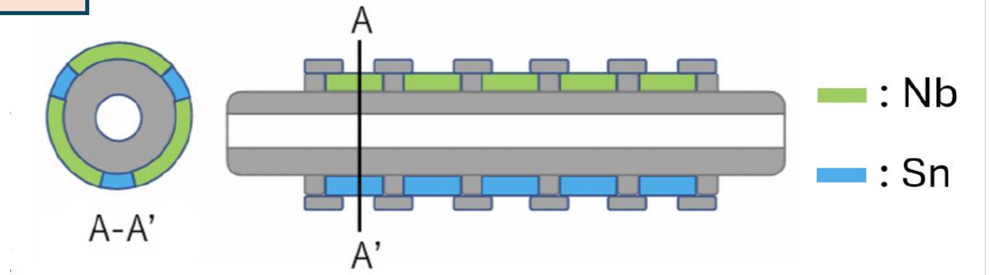
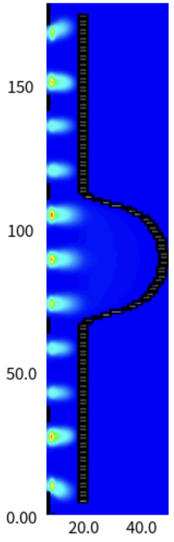
Simulation Study for Nb3Sn Film Formation Assuming DC-Magnetron Sputtering

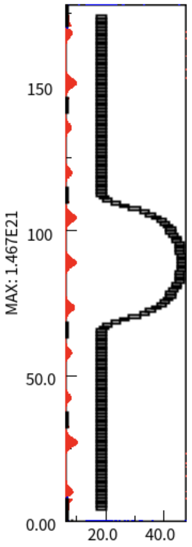
T.Sasaki



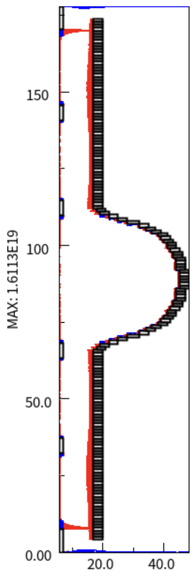
Design concept of a special Nb-Sn mixed cathode for Nb3Sn film-formation by high-temperature annealing



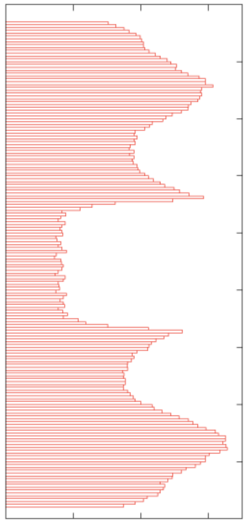
Ar+ generation rate [/m3/sec]



Ar+ flux [/m2/sec]



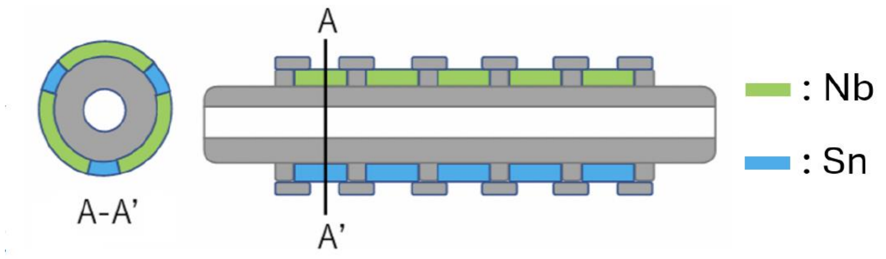
Nb flux [/m2/sec]

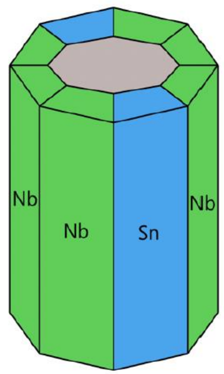


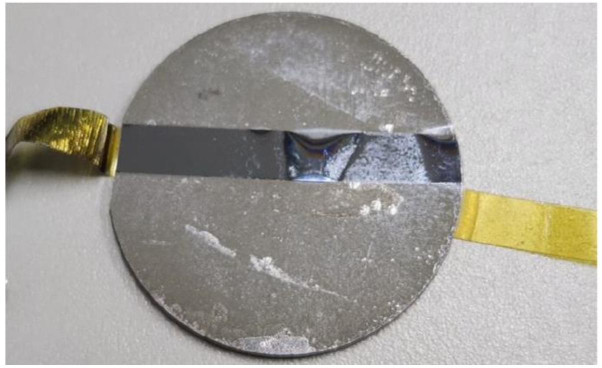
Flux distribution on surfaces [/m2/sec]

- Sputtering simulations were performed to investigate the film-formation conditions required to achieve an Nb:Sn mixing ratio of 3:1 for Nb3Sn coating inside a 3 GHz cavity by DC magnetron sputtering.
- We performed the simulations using software modules proviede by PEGASAS Software Inc.
- Nb and Sn flux distributions emitted from pure Nb and Sn cathodes were evaluated on the cavity inner surface.
- Based on the obtained results, a candidate design for an Nb-Sn mixed cathode was proposed to achieve the desired Nb3Sn precursor layer.

Sputtering Test Using a Prototype Bi-Metal Mixed Cathode







- We fabricated a special cathode base that we can cover with two metals, as shown in the left figure.
- This structure corresponds to a prototype Nb-Sn mixed cathode for creating Nb3Sn precursor layer.
- We assembled a SUS-Al mixed cathode and performed a film-formation test in the KEK sputtering apparatus.
- As a result, formation of an SUS-Al mixed film on a silicon wafer was confirmed, as shown in the lower-left figure.

Plan for 2026

- We will complete the development of an Nb-Sn mixed cathode capable of producing an Nb:Sn = 3:1 precursor layer and fabricate Nb3Sn films on the inner surface of our 3 GHz cavity.
- Further sputtering simulations and detailed surface analyses will be conducted to optimize the deposition and annealing conditions for Nb3Sn synthesis.

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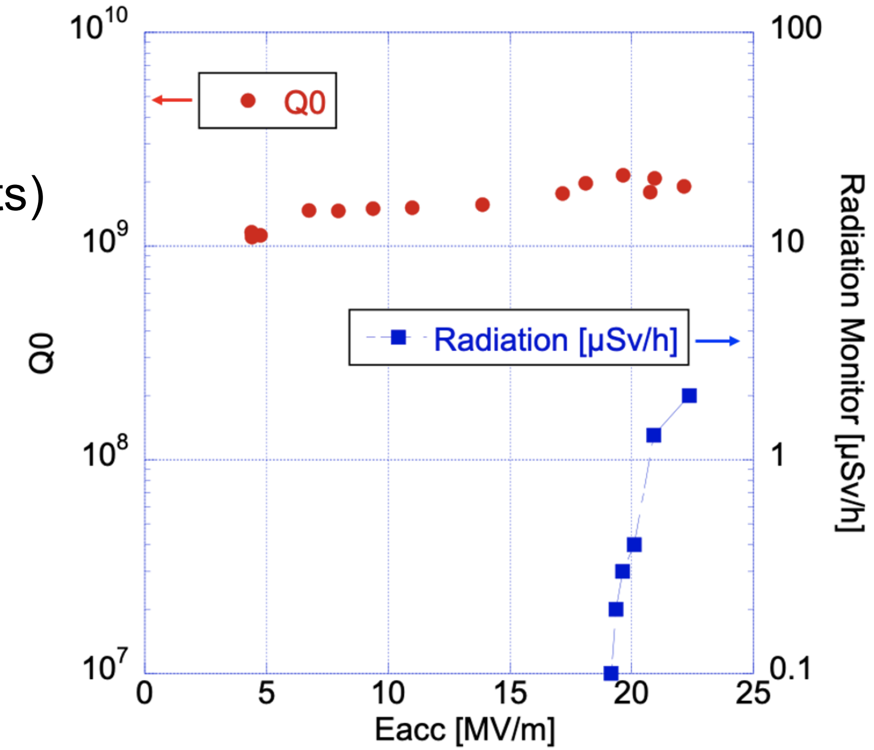
[2025] Vertical Test of a 3GHz cavity

Vertical test (VT) was performed to measure the RF performance of a (bare) 3 GHz cavity at KEK-STF.

Surface Treatment Process
- BCP (30 μm)
- EP1 (100 μm, < 50℃)
- Annealing (900 ℃, 3h)
- (Mechanical polishing to remove defects)
- EP2 (30μm, < 20℃)
- High-Pressure Rince
- Assembly in Clean Room
- Baking (120℃, 48h)

Result
- E_{acc} ~ 22 MV/m
- Q_0 ~ 2 x 10^9 (@ 2K)

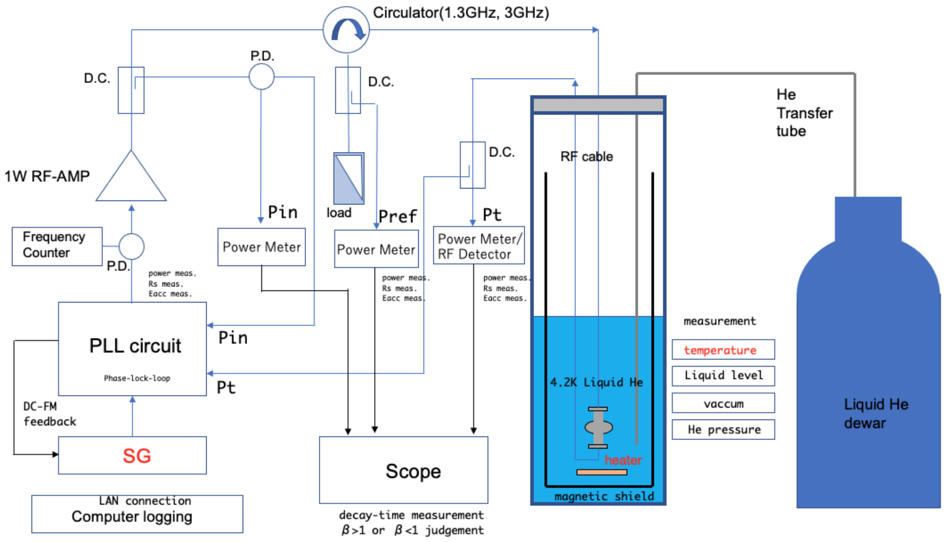
[3 GHz cavity No. 1 in 2 K liquid-He]

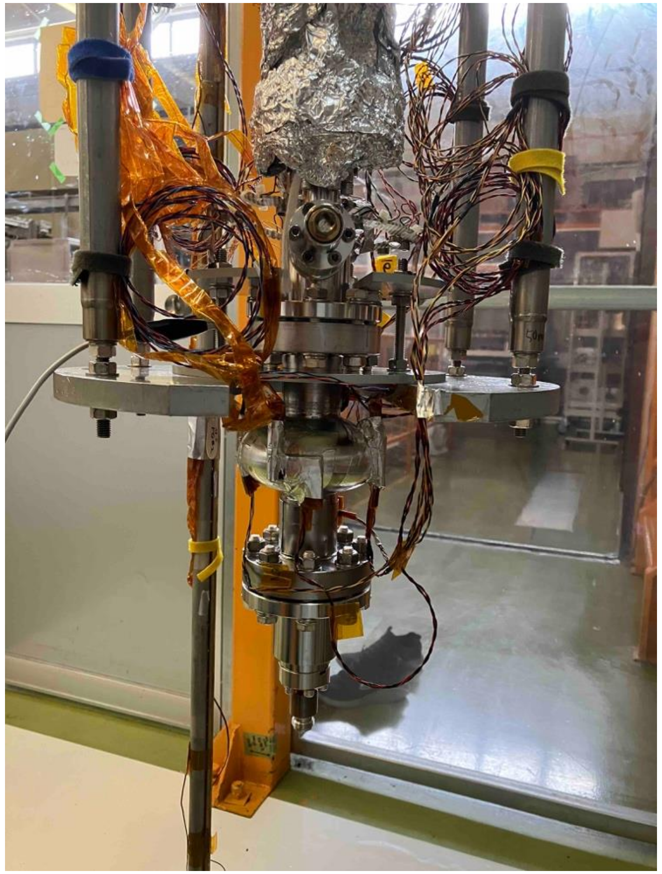


[2026 plan] 3GHz cavity

To efficiently conduct tests on cavities coated with thin films, we will establish the necessary infrastructure for 3 GHz cavity testing, such as,

- RF control system
- Data acquisition system
- Data analysis system
- …





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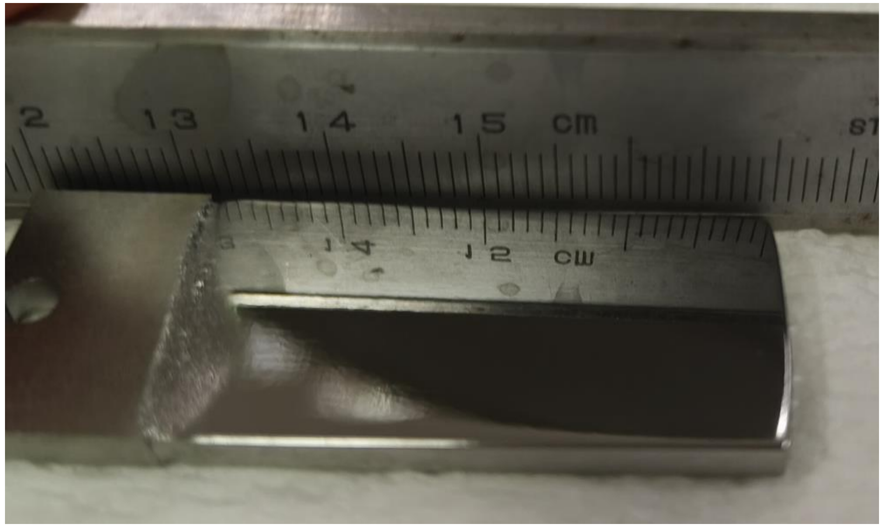
Development of organic solvent EP for higher gradient Nb cavity

1) very safe to handle the electrolyte solution
2) higher gradient performance by generating much more pristine Nb surface

- Hydrogen storage in the Vacancy and defect is much reduced.
- Vacancy formation during EP reaction becomes much less.
- Skipping 120 °C 48 hr baking of Nb cavity results in no oxygen diffusion on the surface.

sanding and CP

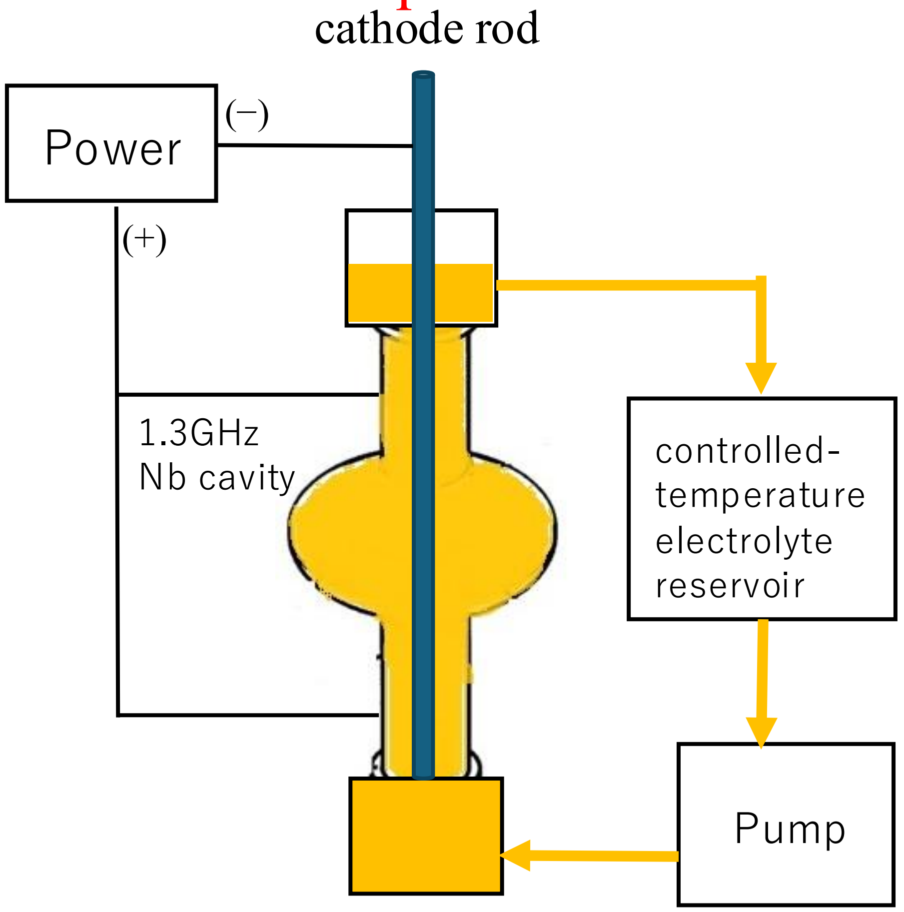
organic solvent EP



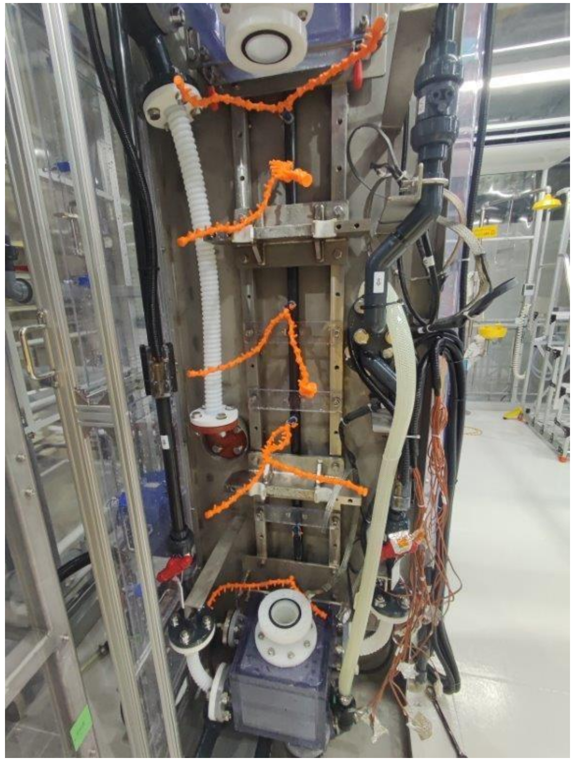
electrolyte: confidential due to patent application
conditions: 16 cm^2 (both sides), 20 °C, 24 V 180 min, ~50 $mAcm^{-2}$, 36 μm/hr, total ~100 μm polished.

Both sides of the Nb substrate have a perfectly mirror-like finish!!

Plan for 2026: scale up to 1.3 GHz 1 cell cavity



cavity stand at COI



- For a larger sample area, the experimental conditions will be more optimized for single cell cavity. (surface area: ~1000 cm^2)

Difficulties:

>> The cathode has a smaller surface area than the anode (cavity).

>> The distance between the cathode and the anode varies depending on the location of the cavity.

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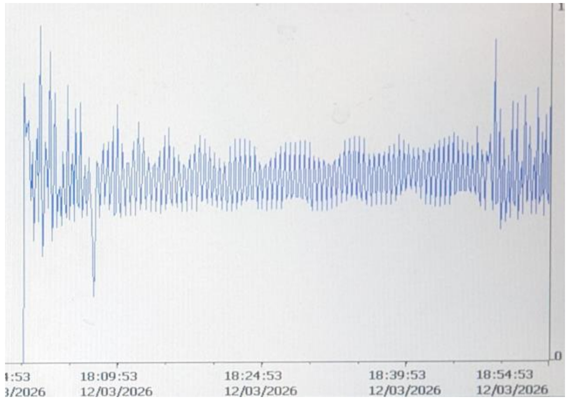
EP WITH DEPLETED HF MIXTURE
CAVITY EXPERIMENT (1Cell 1.3 GHz)

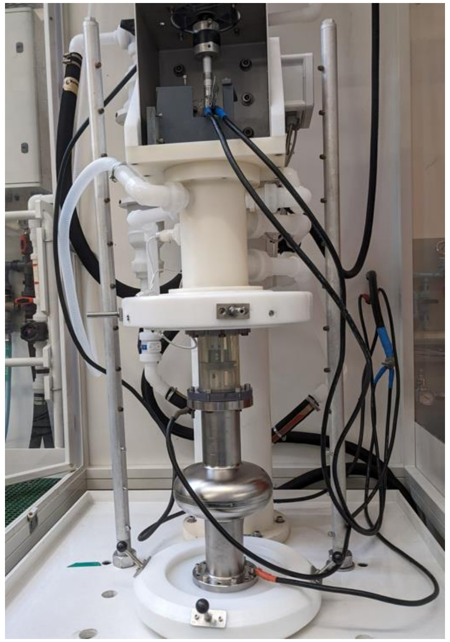
RI02 after bulk VEP



Current oscillations during treatment

Motivation:
- Reduced H uptake
To be analyzed
- Improved Safety
- Lowered toxicity

- Vertical EP Treatment at room temperature, **no cooling**
- 200µm Bulk EP done on pristine cavity RI02
- **Easy temperature control** vs standard mixture
- 0.1µm/min removal rate achieved
- **Oscillations** of the current depending on voltage
- **Uniform removal along the cavity**
- **Shiny aspect, no bubble trace observed**: Promising results
- Next: 800° C x 3h Heat treatment prior to flash VEP.
- The cavity will be tested at 2K at KEK: comparison with ILC recipe



Proposal for FY2026

Test of RI02 cavity at 2K at KEK (no baking).

Depending on the result, the next treatment may vary accordingly:

- Baking with standard parameters (120°C-48h)
- Additional VEP
- Baking with ‘2-step’ recipe (75°C-120°C)
- Additional horizontal recipe
- Mid-T baking
- …

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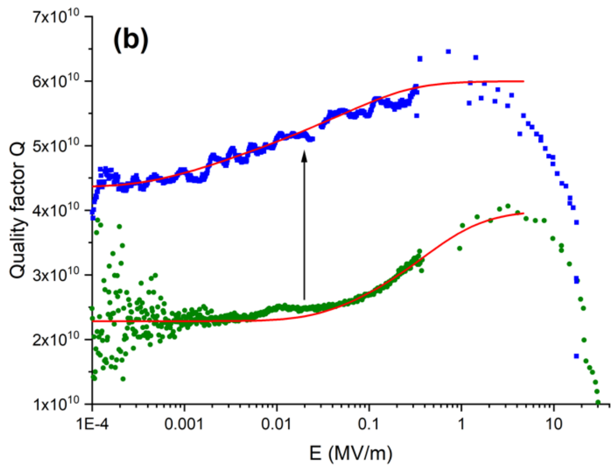
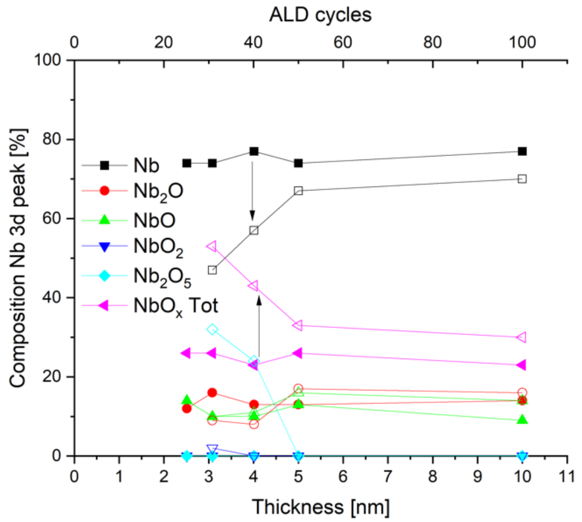
ALD oxides and thermal treatements to mitigate Nb_2O_5

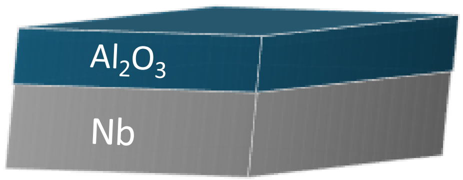
Y.kalboussi & T.Proslier

Al_2O_3 Thin films

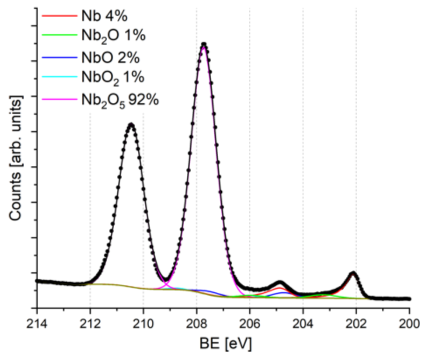
Al_2O_3-10nm- 650° C- 10hrs



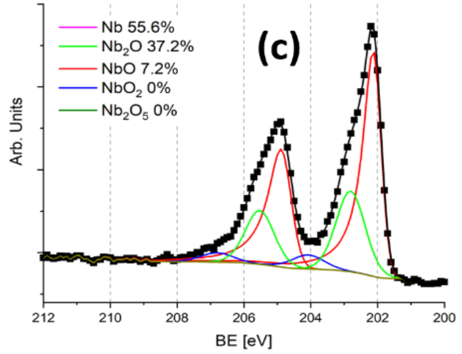




Nb after EP + HPR



Nb after ALD + TT

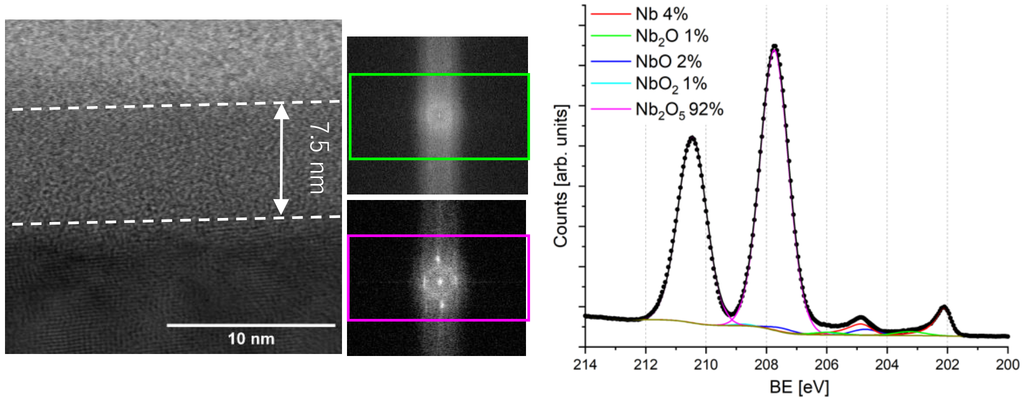


- The 10 nm Al_2O_3 film + annealing at 650°C for few hours significantly improves the quality factors of the Nb cavity in the low field regime.
- Optimization of the Al_2O_3 thickness -> Ok down to 2.5 nm.
- Other oxides such as ZrO_2 and Ta_2O_5 are being studied.

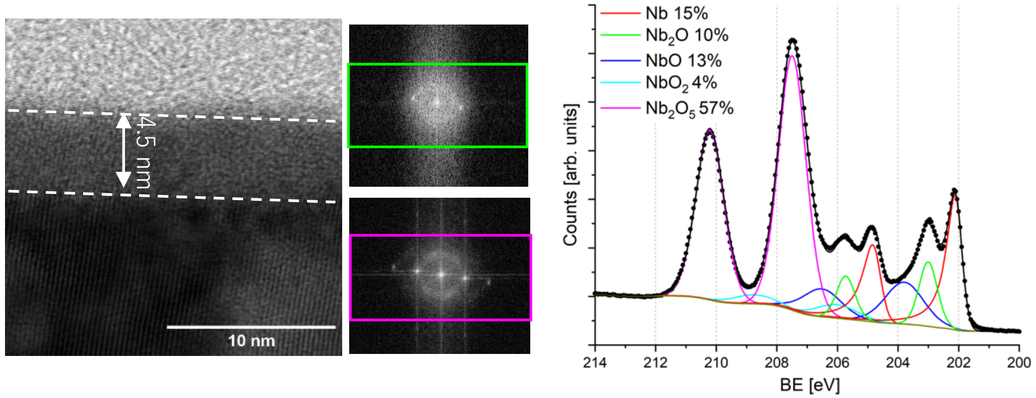
[1] Y. Kalboussi et al, "Reducing two-level system dissipations in 3D superconducting niobium resonators by atomic layer deposition and high-temperature heat treatment," Applied Physics Letters, 2024, 124 (13), pp. 134001. (10.1063/5.0202214). (hal-04470953). https://doi.org/10.1063/5.0202214

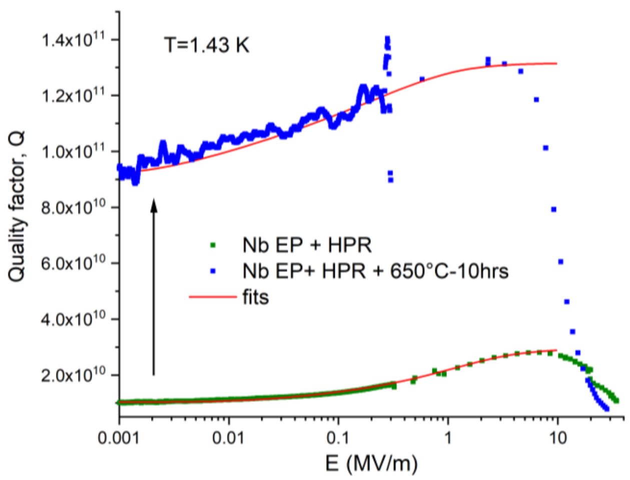
Changing NbO_x structure by thermal treatements

➢ Nb EP + HPR



➢ Nb EP + HPR + 650° C-10hrs + HPR





- World record Q values at low fields after air exposure and high pressure water rinsing (!)
- σ_{TLS} and $\tan(\delta_{TLS})$ decreased by a factor 10.
- Change in chemical / structure of the native NbO_x with indication of NbO_X (?) and Nb_2O_5 crystals.
- Other thermal treatements are being investigated

✓ Proposal for FY2026:

RF test 1,3 Ghz cavities with new ALD coating/thermal treatements at KEK at high fields to correlate their performance with chemical and physical changes at the surface.

[2] Kalboussi, Y., Curci, I., Miserque, F., Troadec, D., Brun, N., Walls, M., ... & Proslier, T. (2025). Crystallinity in niobium oxides: A pathway to mitigate two-level-system defects in niobium three-dimensional resonators for quantum applications. *Physical Review Applied*, *23*(4), 044023. https://doi.org/10.1103/PhysRevApplied.23.044023

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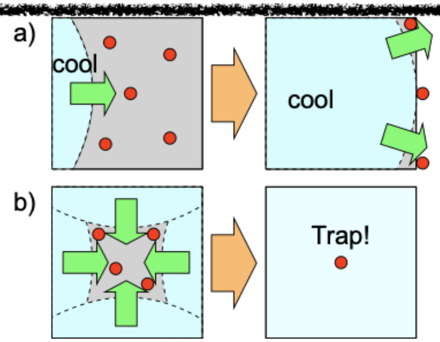
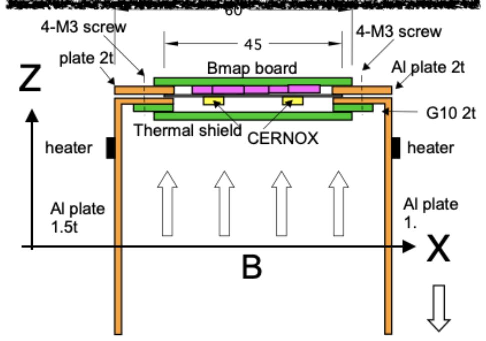
Faint Magnetic Shield by Meissner Effect
— Preview of Result —

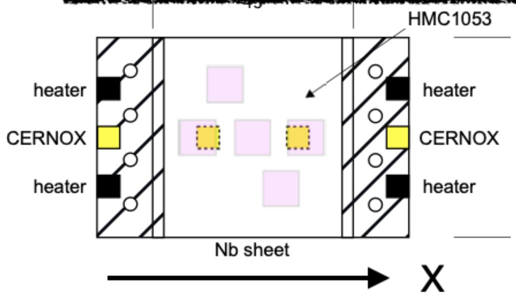
Flux may be trapped in Nb.



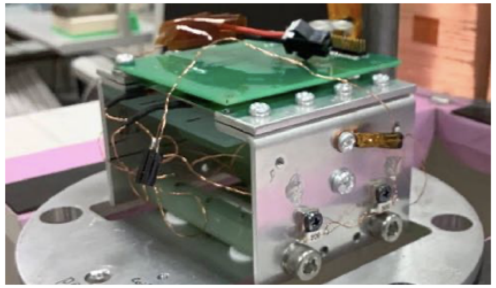
Side view of sensor layout



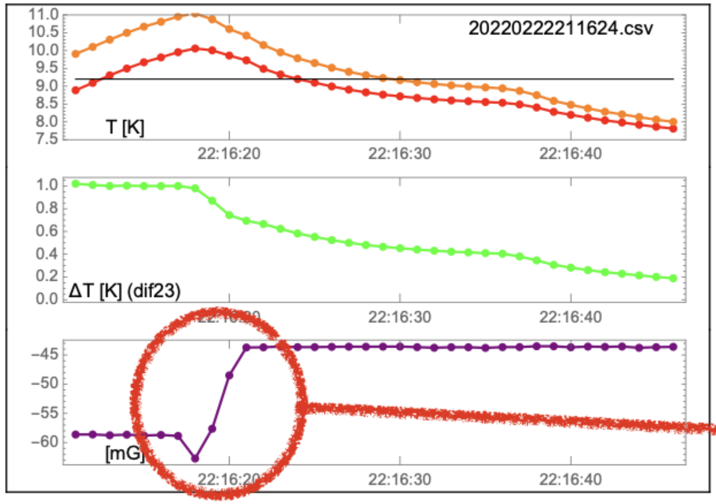
Top view of sensor layout



Experimental setup



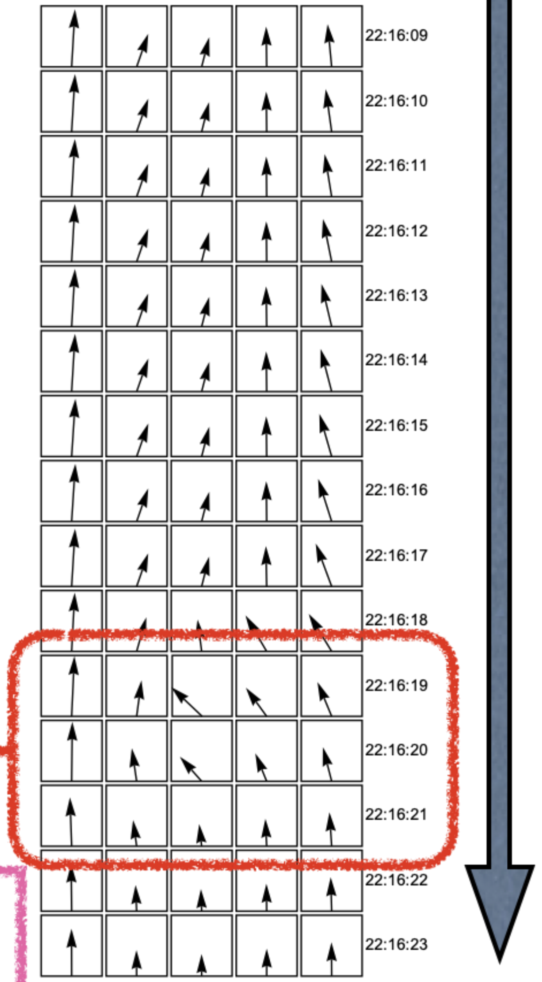
Temperature change and flux jump



2026: Next plan is to realize RRR measurement on the same setup.

Vector plot of (Bx, Bz) component

Time



Summary

Achievement in 2025

- **Theoretical Understanding:**
  Established microscopic theory for nonlinear electromagnetic response using Keldysh-Usadel framework.
- **Nb_3Sn Sputtering:**
  Completed simulations for Nb:Sn (3:1) flux distribution and successfully tested SUS-Al mixed cathode prototypes.
- **Vertical Test of 3 GHz cavity:**
  Achieved $E_{\mathrm{acc}} \sim 22\ \mathrm{MV/m}$ and $Q_0 \sim 2 \times 10^9$ for a bare 3GHz cavity at 2K.
- **Surface Treatment:**
  Developed organic solvent EP and depleted HF mixture EP.
- **ALD:**
  Investigated thermal treatments for ALD-coated surface.
- **Fain Magnetic Shielding:**
  Performed preliminary experiment for shielding with the Meissner effect of Nb.

R&D effort is continued towards ultimate cavity performance.