

# Beyond the-state-of-the-art SRF cavities with advanced surface preparation

**CNRS/IN2P3/IJCLab**

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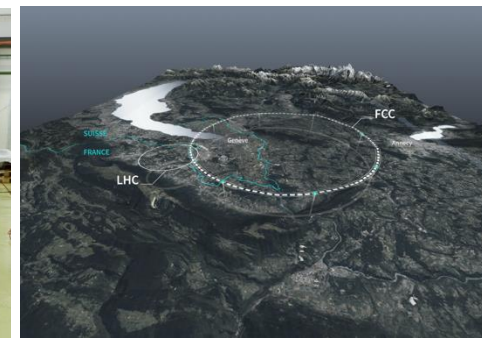
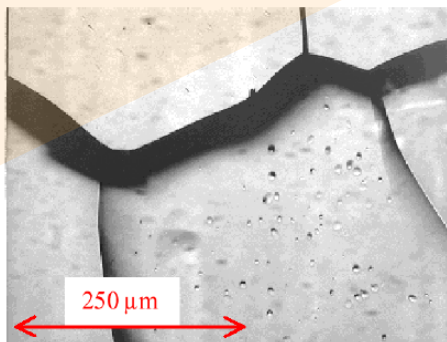
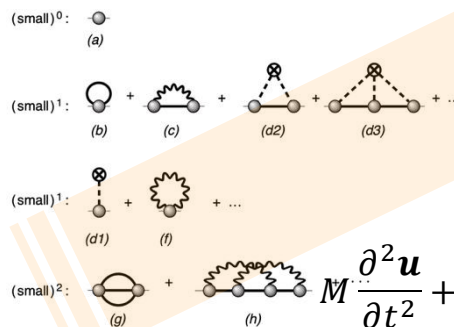
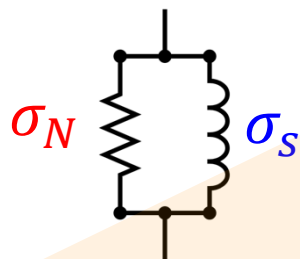
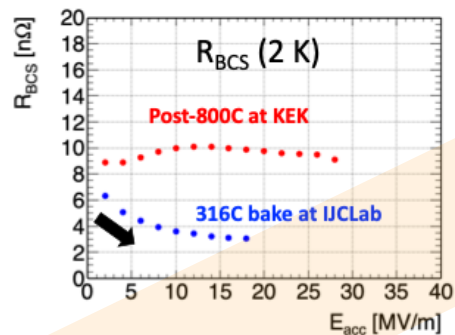
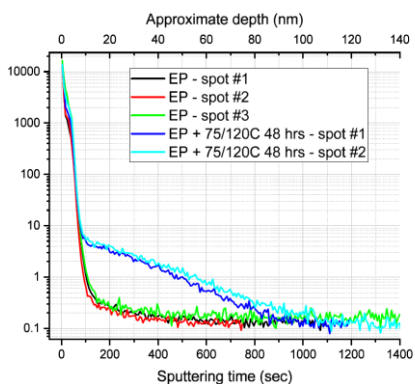
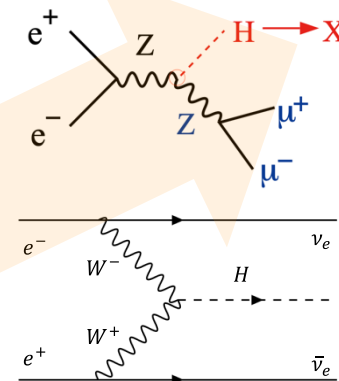
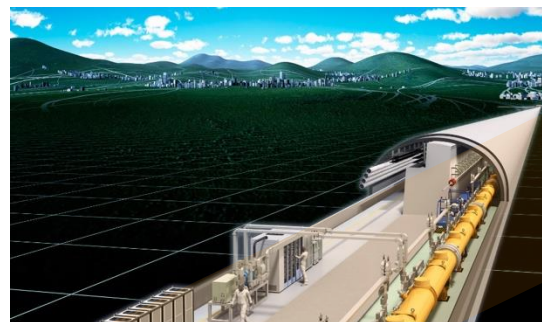
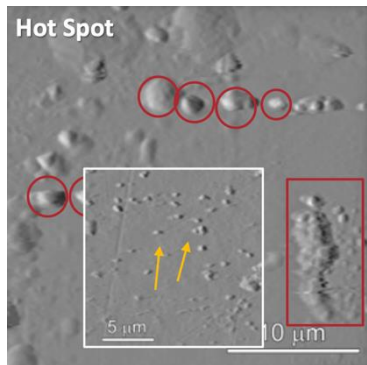


## Outline

- Superconducting RF cavities for future accelerators
- Previous collaborative activities in 2024-2025 Feb
- New results in 2025 Sep-Nov
- Theoretical approach
- Highlights of SRF2025 conference
- Plan of 2026
- Conclusion



# Accelerators: from superconductivity to particle physics

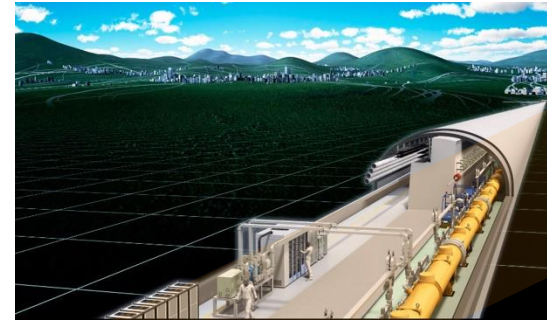
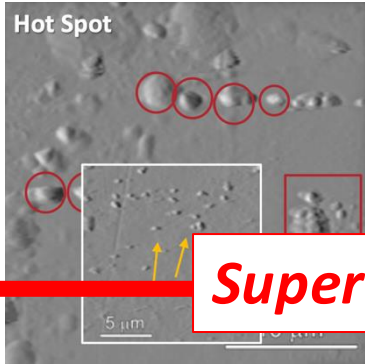


$$M \frac{\partial^2 \mathbf{u}}{\partial t^2} + \eta \frac{\partial \mathbf{u}}{\partial t} - \epsilon \frac{\partial^2 \mathbf{u}}{\partial z^2} + \nabla U(z, u) = \mathbf{J}_{RF}(z, u) \times \mathbf{B}_{ext}$$

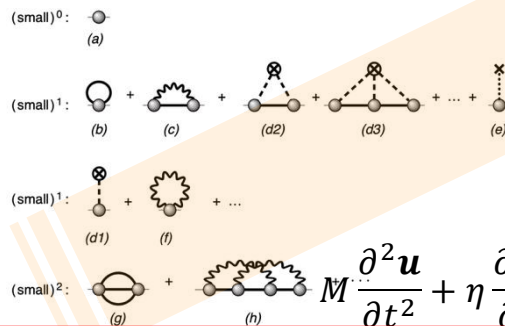
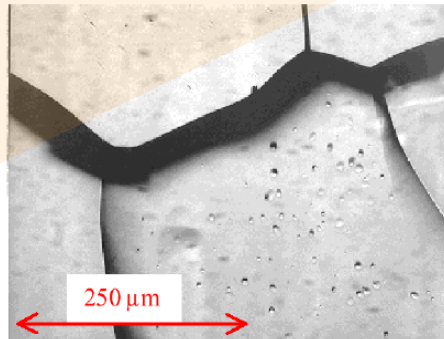
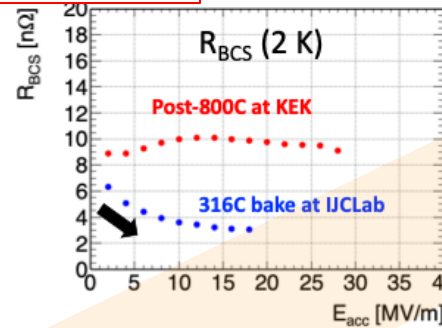
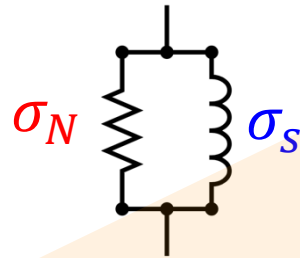
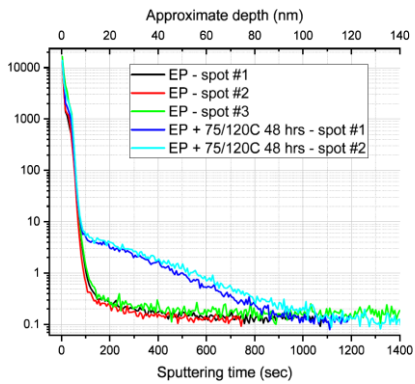


# Accelerators: from superconductivity to particle physics

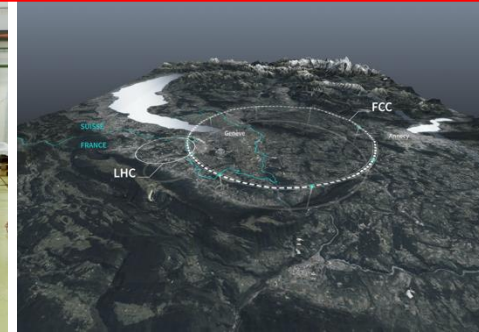
*particle physics*



## *Superconductivity physics*



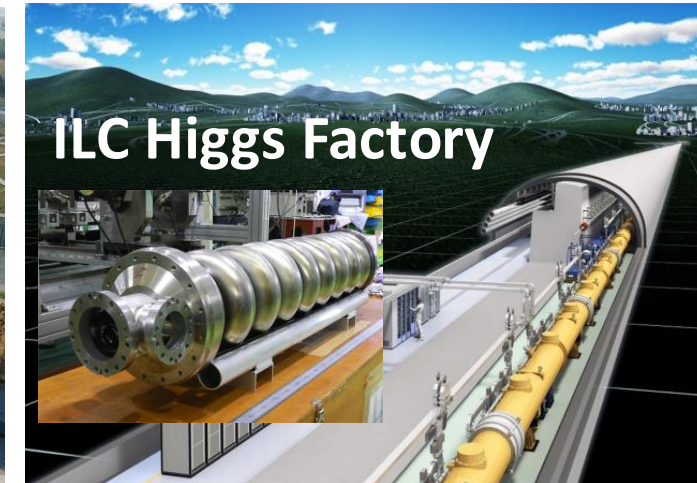
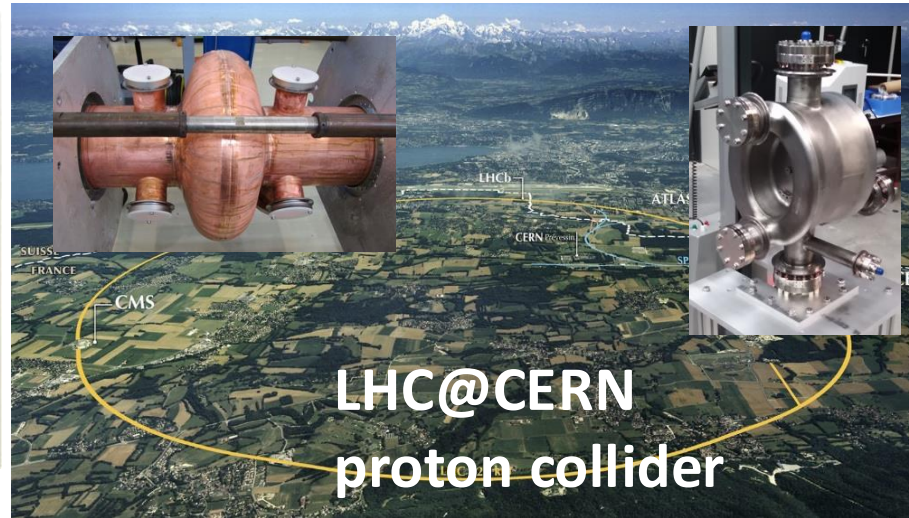
$$M \frac{\partial^2 \mathbf{u}}{\partial t^2} + \eta \frac{\partial \mathbf{u}}{\partial t} - \epsilon \frac{\partial^2 \mathbf{u}}{\partial z^2} + \nabla U(z, u) = \mathbf{J}_{RF}(z, u) \times \mathbf{B}_{ext}$$



- Particle physics
  - relativistic QFT
- Superconductivity
  - nonrelativistic QFT
  - Cooper pairs = Higgs



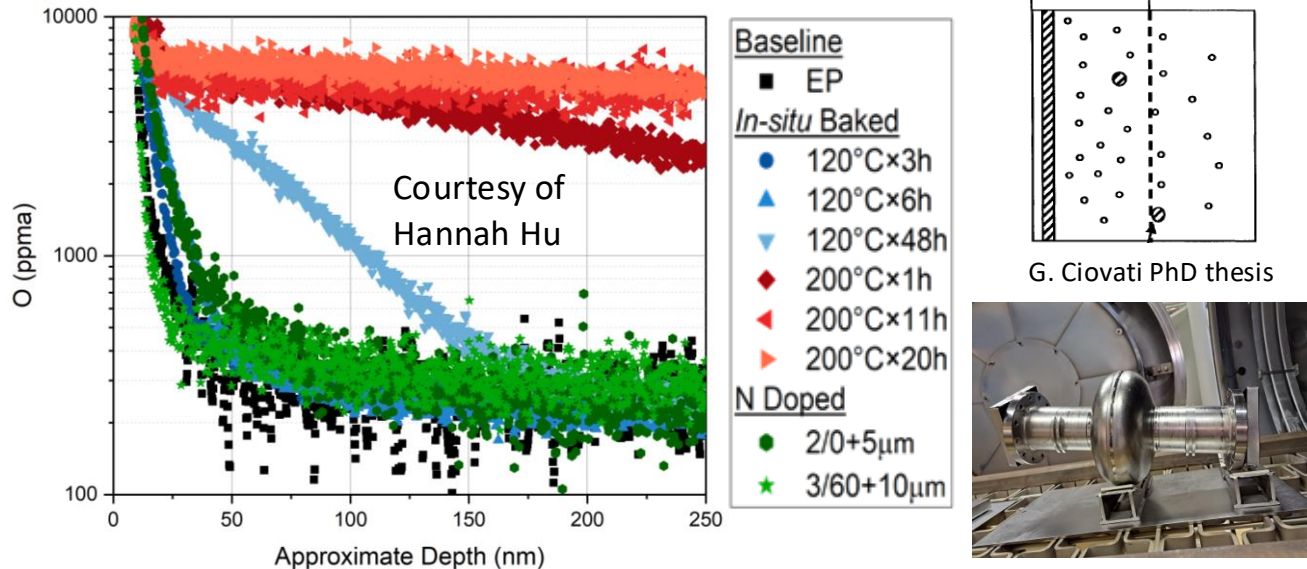
# Superconducting RF cavities in present and future accelerators



SRF is the technology of today → most probably next colliders



## Bulk niobium with surface engineering

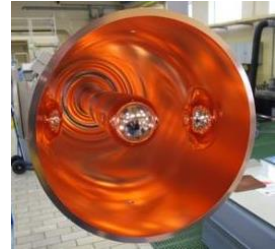
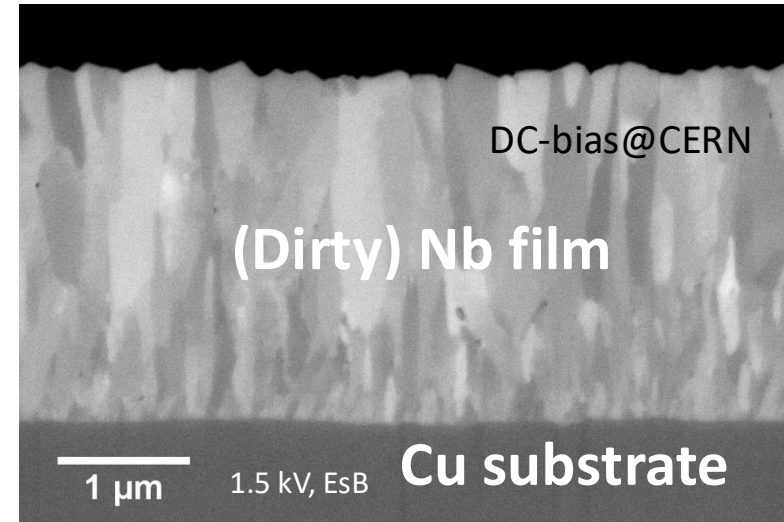


Baseline for most accelerator projects, engineering, **R&D in theoretical aspects**

Main scope of this proposal

→ Promising for future colliders with mystery in fundamental aspects

## Thin films on substrates



LEP II, LHC, SOLEIL, ALPI, HIE-ISOLDE, FCCee Z/H/W, **R&D in material science**



## Key parameters of SRF cavities

Accelerating gradient  $E_{acc}$  gives power loss  $P_c$

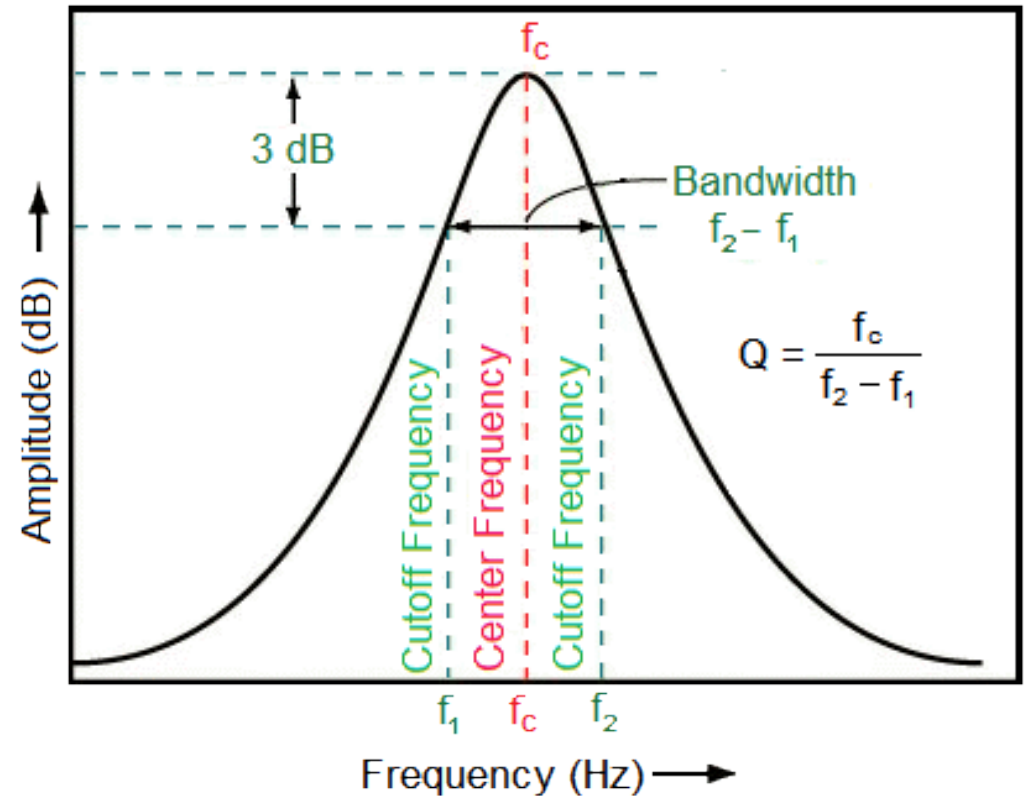
$$P_c \propto \frac{E_{acc}^2}{Q_0}$$

$P_c$  is minimized by higher quality factor  $Q_0$  →

$Q_0$  can be derived from surface resistance  $R_s$

Experimental observable  $Q_0 \propto \frac{1}{R_s}$  From quantum theory of superconductivity

<http://lossenderosstudio.com/glossary.php?index=q>



Fundamental research of SRF: compare experimental ( $E_{acc}$ ,  $Q_0$ ) and theoretical  $R_s(E_{acc})$



- CW machines need high Q
- LC needs high Gradient

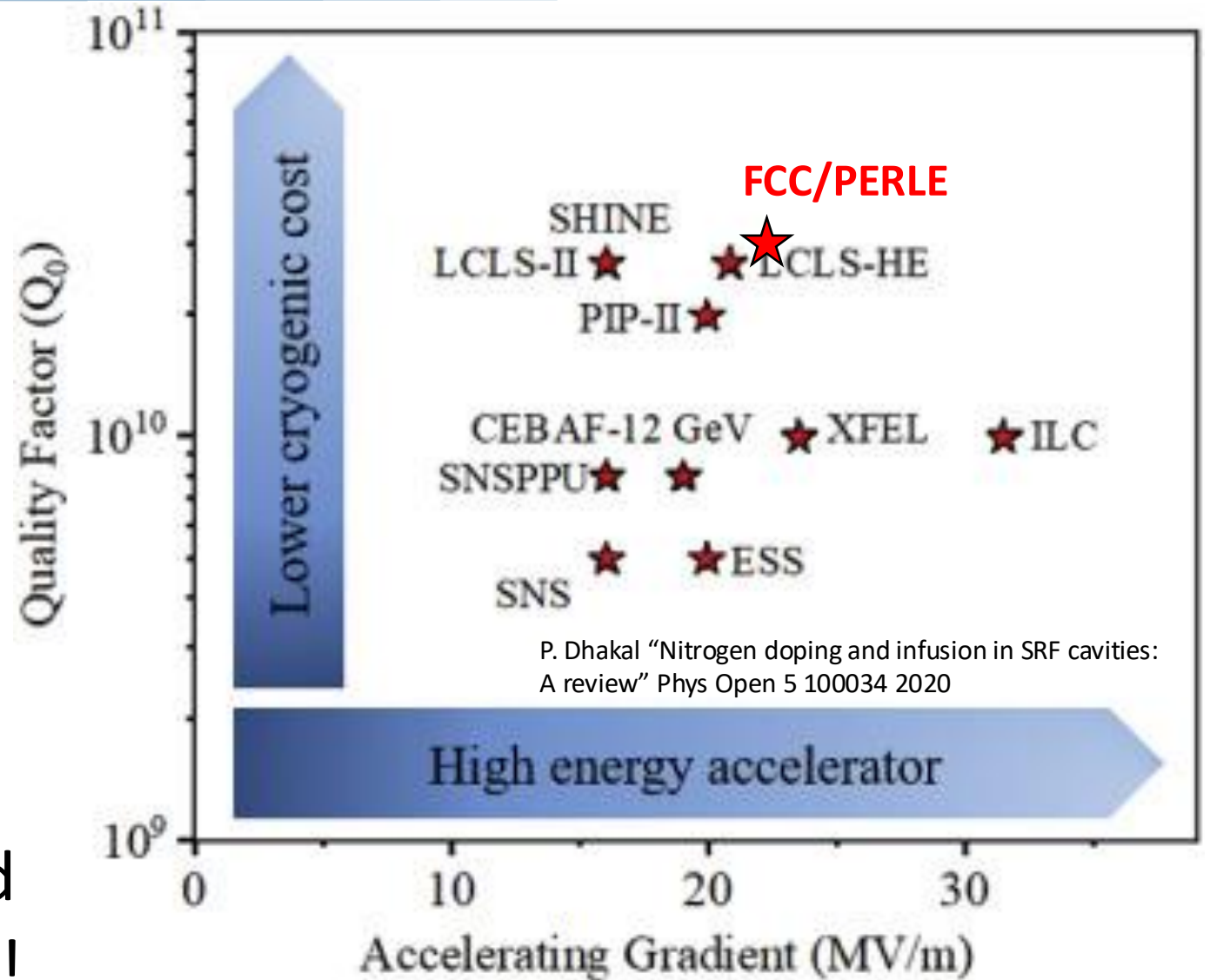
We have recipes

- Chemical etching
- Baking/doping

For either high-Q/high-G

***But do not know why***

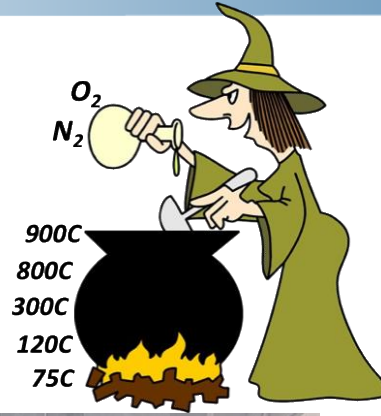
→ We want to understand and scientifically optimize them!





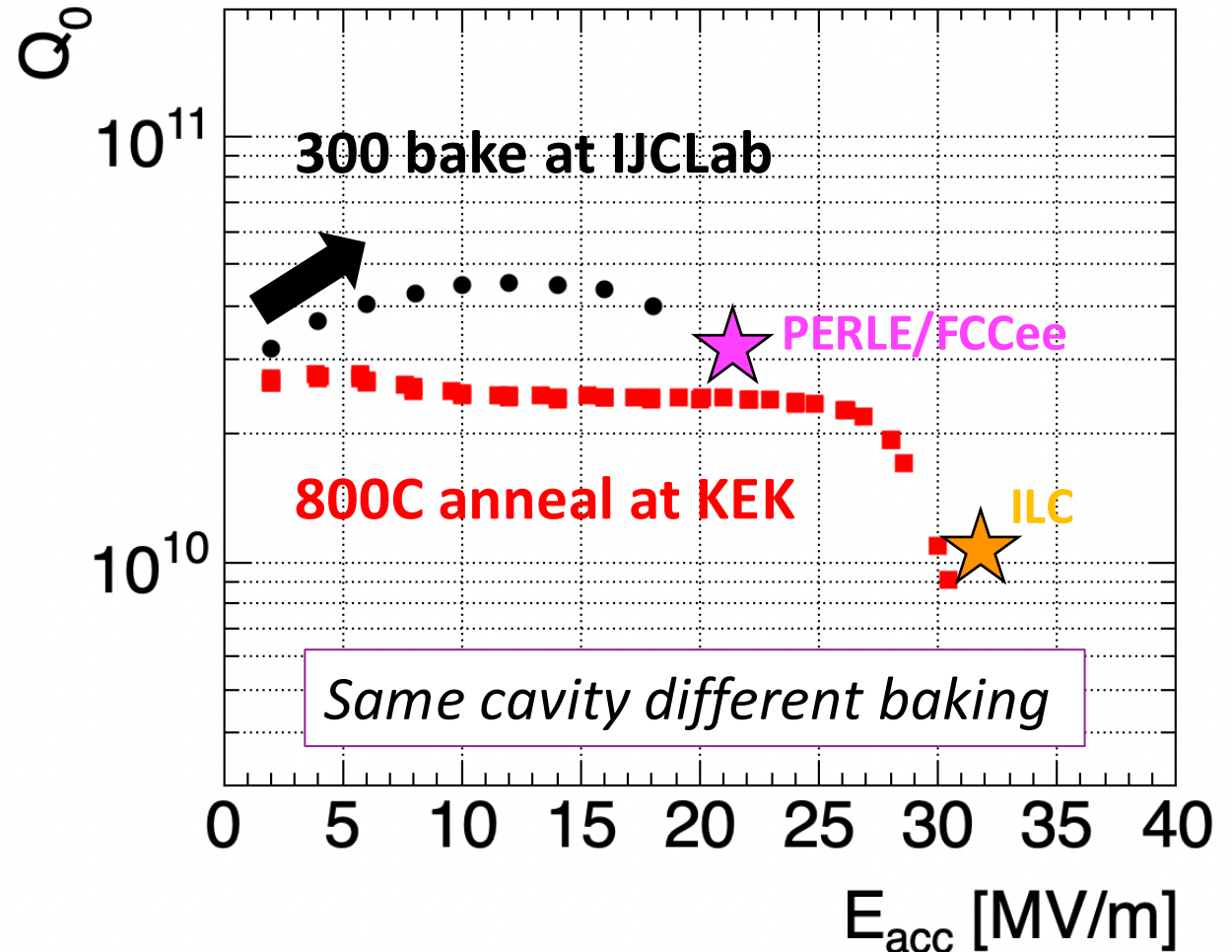
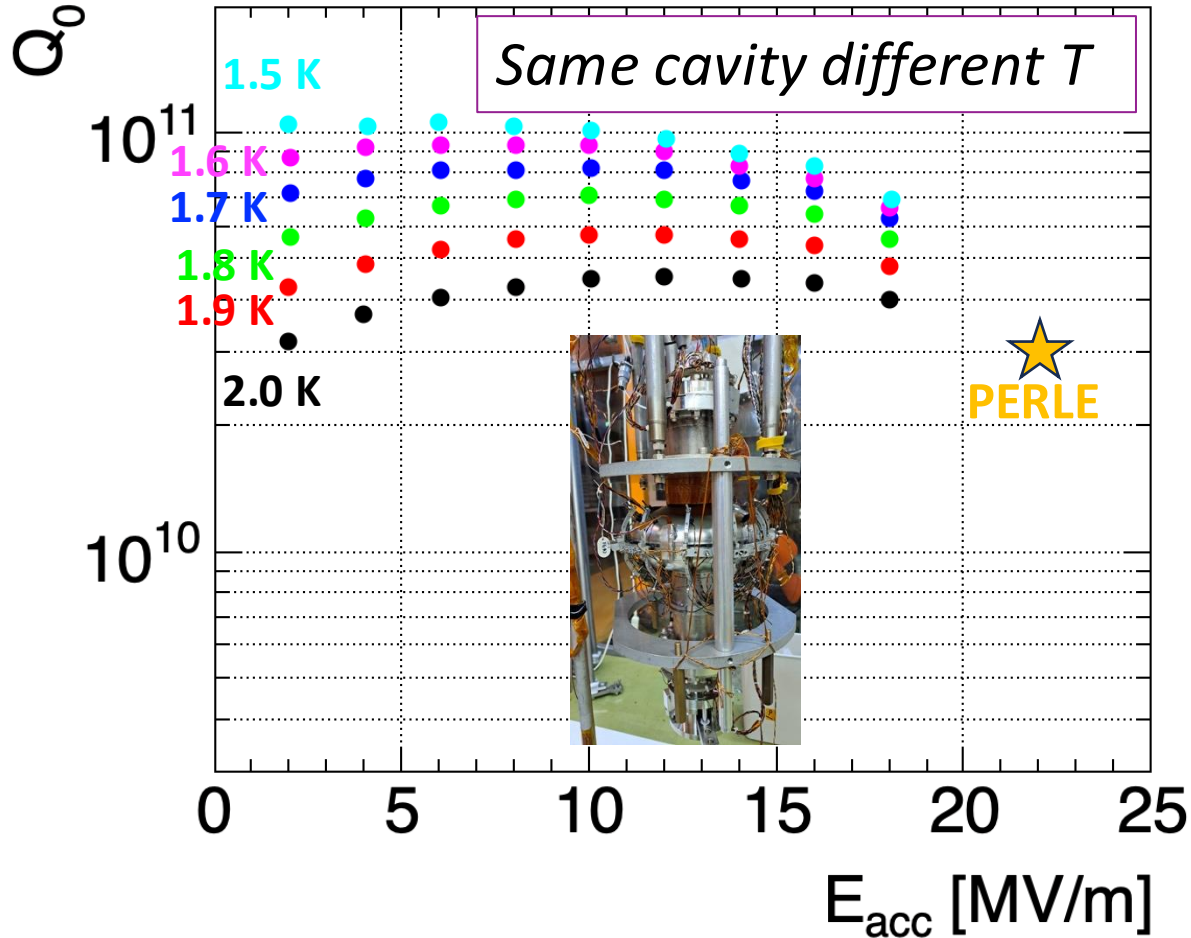
# Chaudron for black magic

High-Q/high-G  
can be switched  
by baking process





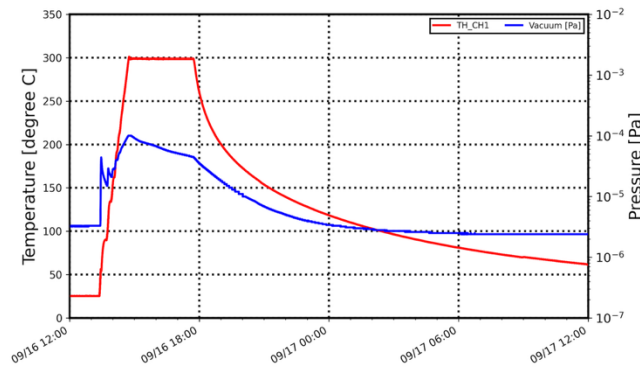
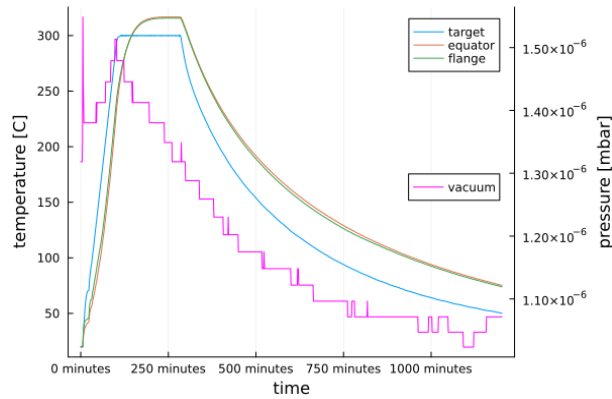
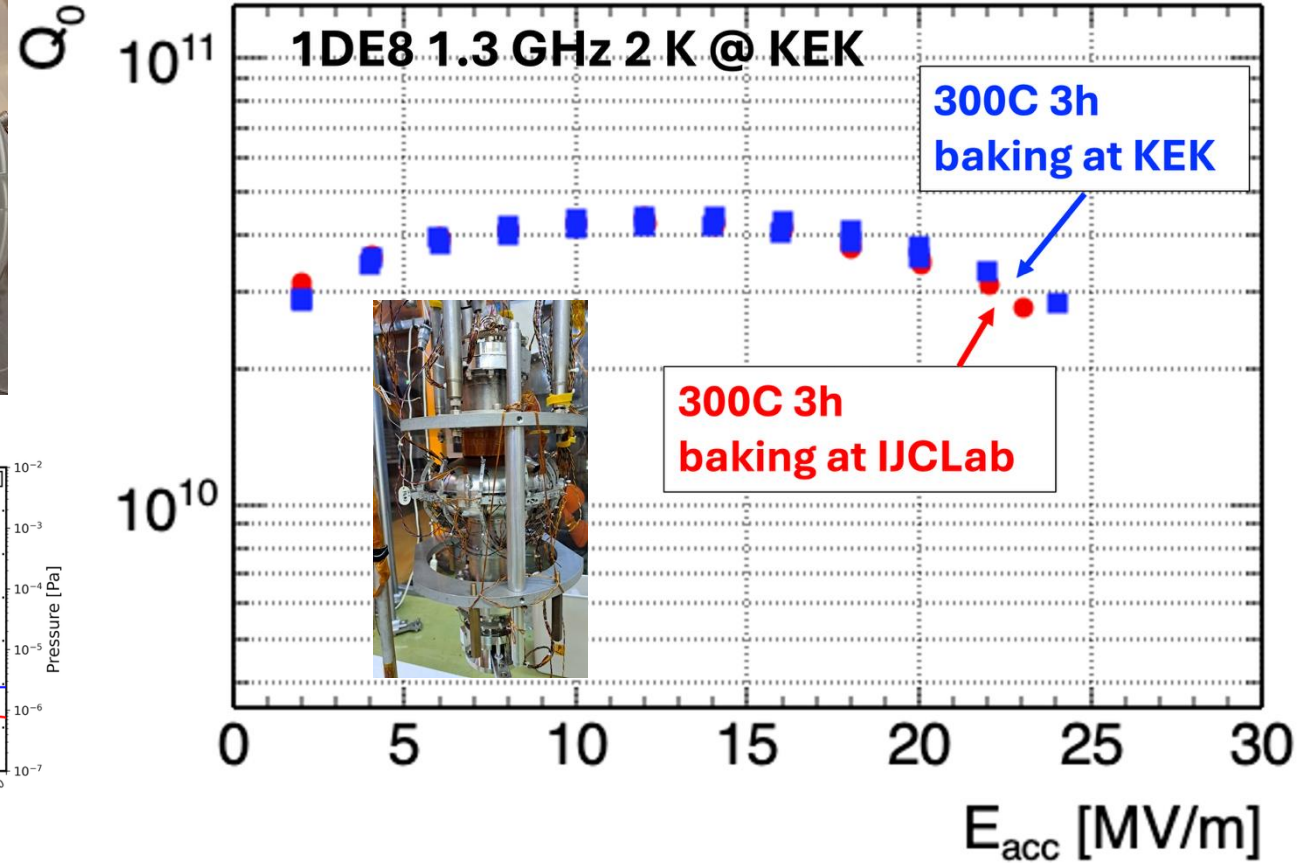
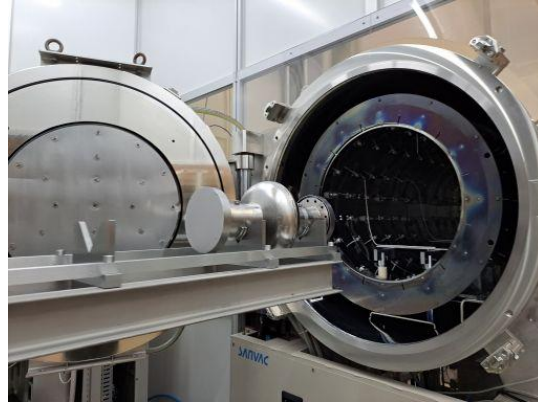
# Results in 2024-2025 Feb under FJPPN collaboration



- Excellent performance with 300C bake by IJCLab and tested by KEK
- High-Q recipe can be reset by high-G recipe demonstrated by 800C annealing by KEK



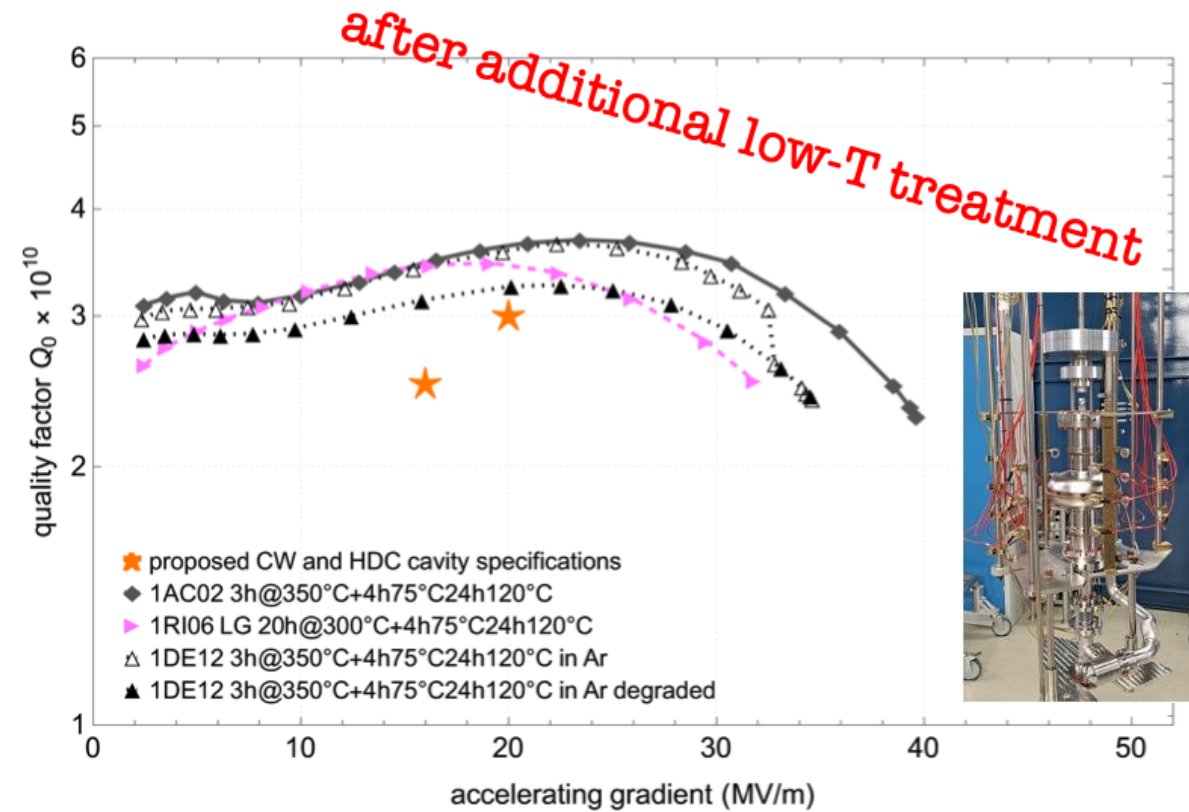
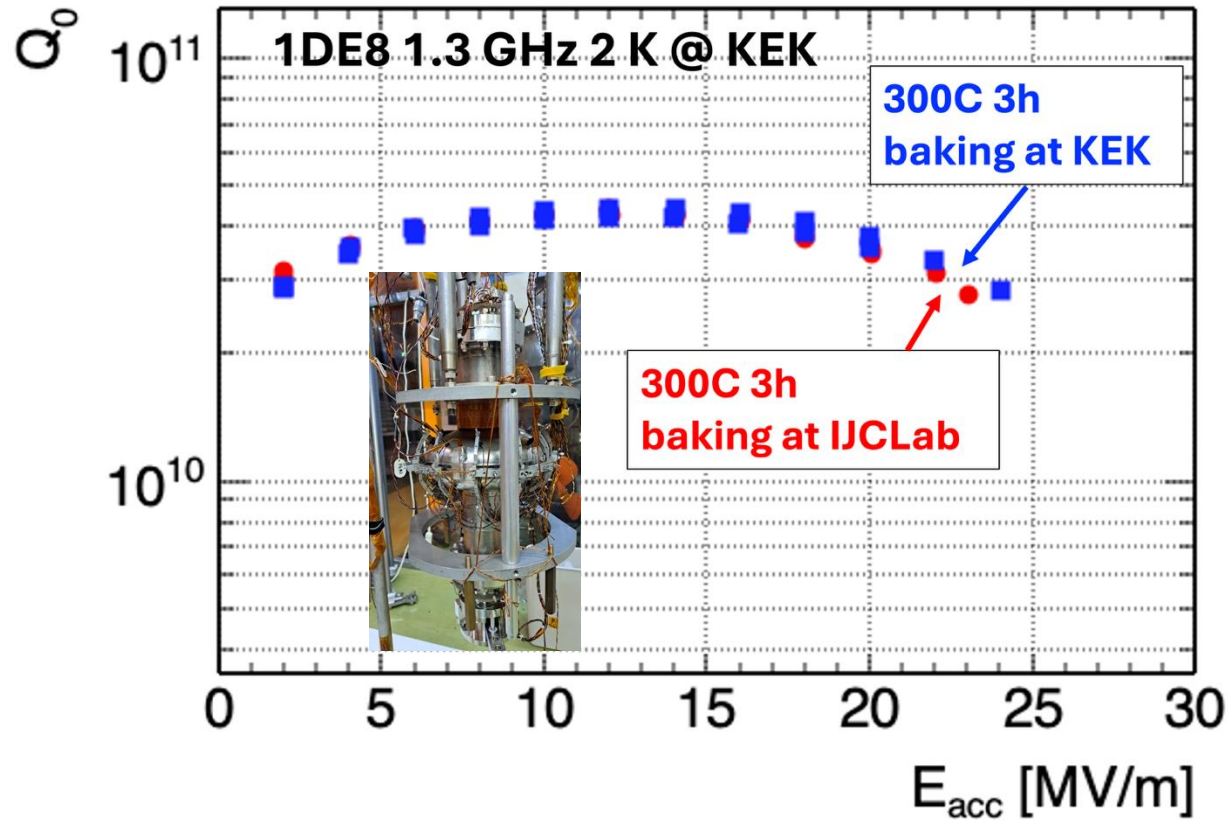
# New results in 2025 Sep-Nov: IJCLab vs KEK



- Systematic comparison of baking process in IJCLab and KEK
- Multiple differences (eg vacuum...) were identified → however, the cavity results were exactly identical 😊



# Perspective in 2026: KEK → IJCLab + DESY



- KEK has not reproduced the high-gradient results of DESY
- The furnaces in KEK and IJCLab are comparable but less clean than the one in DESY (?)
- Systematic comparison among KEK and DESY will be coordinated by IJCLab

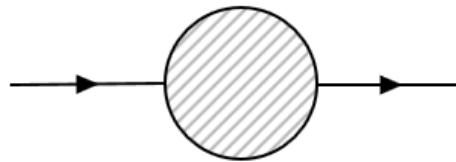
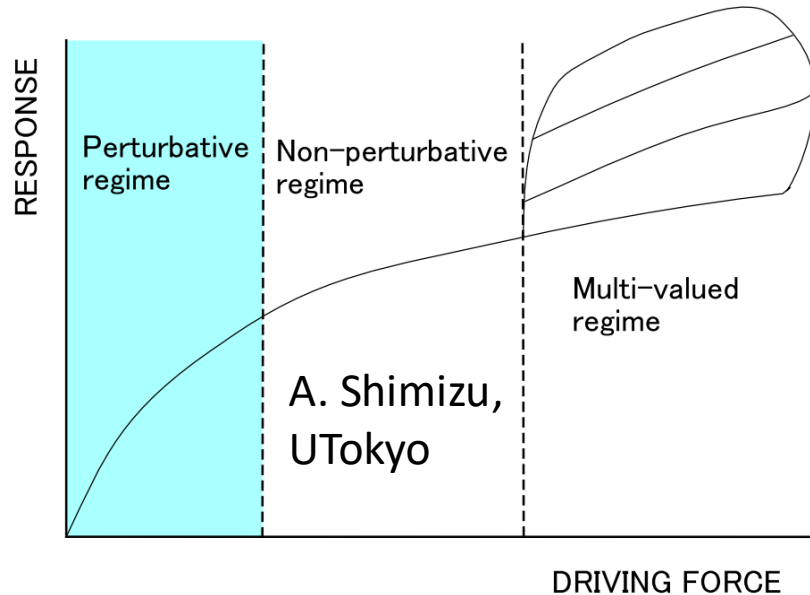


Quantum mechanical **derivation** of  $R_S$  requires quantum many body theory

$$\mathcal{H} = \mathcal{H}_0 + \mathcal{H}_{RF}(t)$$

If the RF field is "small"

(Suspicious in our case...)



$$= \text{equilibrium} \text{---} \text{wavy line} \text{---} \text{equilibrium} + \text{First order perturbation} \text{---} \text{wavy line} \text{---} \text{Higher order terms ignored} \text{---} \text{wavy line} \text{---} + \dots$$

The responding current is given by the **equilibrium state** (fluctuation-dissipation theorem)

$\mathcal{H}_0$  : Fermi Liquid  $\rightarrow$  Ohm's law

$\mathcal{H}_0$  : BCS  $\rightarrow$  Mattis Bardeen

Linear response theory (1<sup>st</sup> order perturbation)  $\rightarrow$  no field dependence in  $Q_0$



# Fundamental question: origin of anti-Q-slope

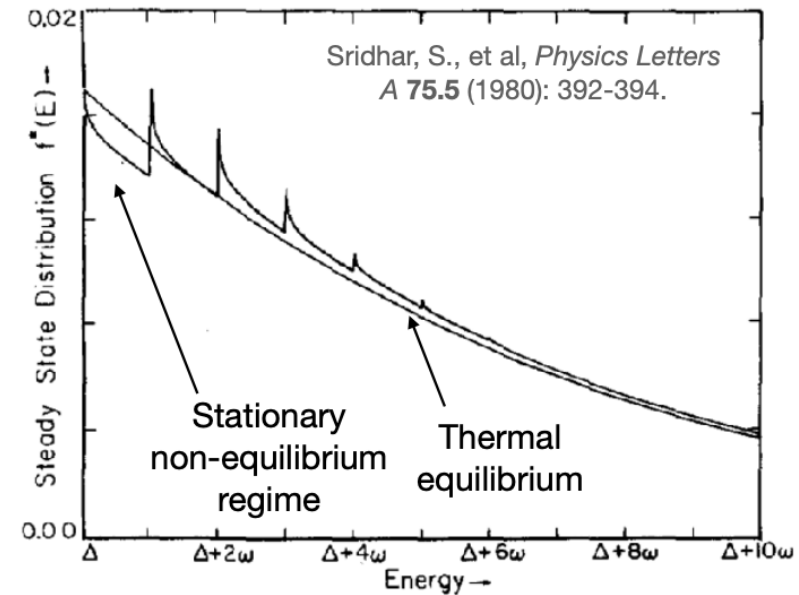
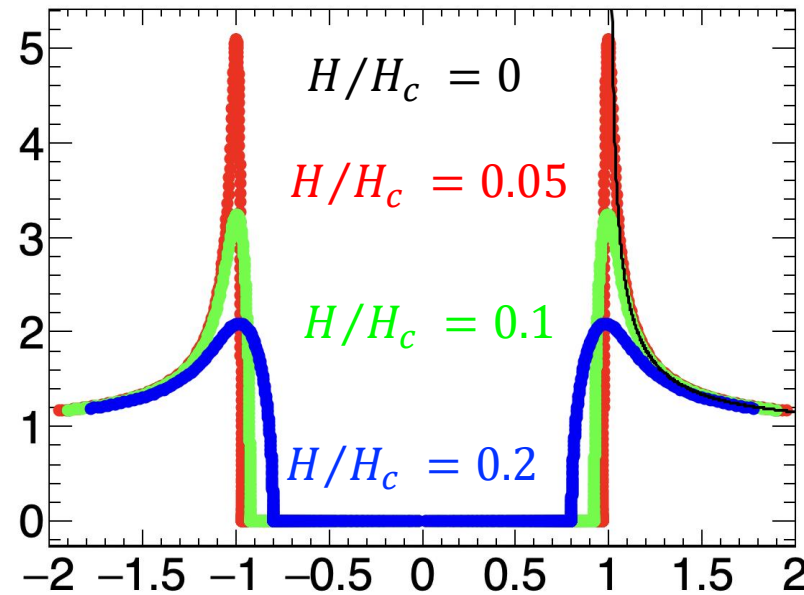
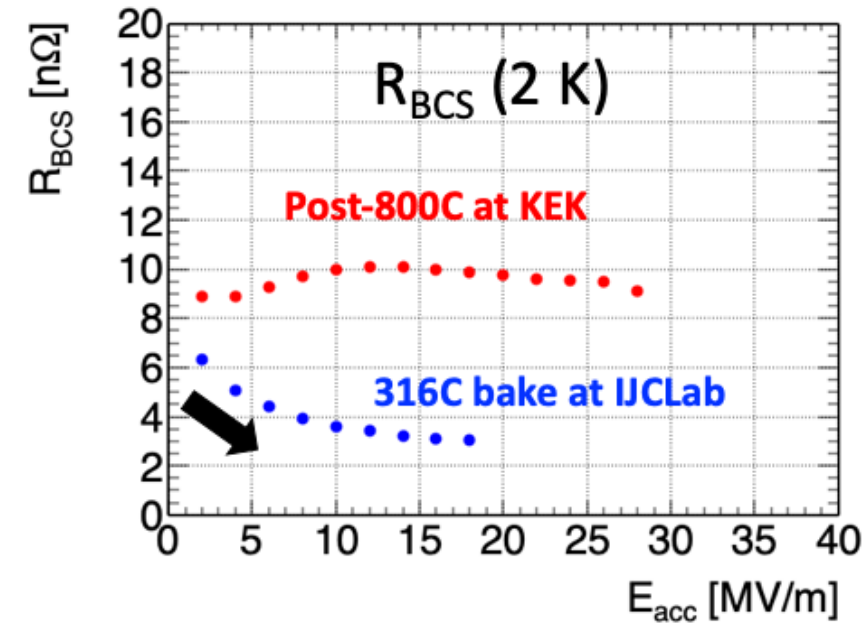
$$\frac{1}{Q_0(E_{acc})} \propto R_s(E_{acc}) \sim \hbar\omega \int_{\Delta}^{\infty} d\varepsilon N(\varepsilon)N(\varepsilon + \hbar\omega) \times [f(\varepsilon) - f(\varepsilon + \hbar\omega)]$$

(Simplified working ansatz...)

Anti-Q-slope

Smearing of  $N(E_{acc})$ ?

Non-equilibrium  $f(E_{acc})$ ?



Highly non-linear **nonequilibrium** phenomena to be addressed in this collaboration



# SRF2025 conference in The University of Tokyo



**SRF2025  
TOKYO**

22<sup>ND</sup> INTERNATIONAL CONFERENCE  
ON RF SUPERCONDUCTIVITY

September 21-26, 2025

Hot topic 2

*Development toward extremely high performance superconducting cavities*

**2K Nb: High-G > 50 MV/m**  
**Non 2K || non Nb: > 25 MV/m**

Convener:  
Akira Miyazaki

Panelists:  
Claire Antoine, Jinfang Chen, Takayuki Kubo, Sam Posen, Genfa Wu

**2K Nb: High-Q >  $5 \times 10^{10}$**   
**Non 2K || non Nb: >  $2 \times 10^{10}$**

- State-of-the-art
  - Understandings of bulk Nb (our research!)
  - Practicalities
- Future directions
  - Travelling wave
  - Thin Films (partially our research!)



**France-Japan collaboration for high-Q / high-G SRF cavities**


**IJCLab**  
Irène Joliot-Curie  
Laboratoire de Physique des 2 Infinis

**CEA**  
Commissariat à l'Énergie Atomique

**KEK**  
High Energy Accelerator Research Organization

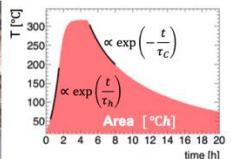
A. Miyazaki<sup>1</sup>, M. Fouaidy<sup>1</sup>, N. Gandolfo<sup>1</sup>, D. Longuevergne<sup>1</sup>, G. Oiry<sup>1</sup>, M. Vannson<sup>1</sup>, L. M. Vogt<sup>1</sup>, M. Soudrier<sup>2</sup>, E. Canni<sup>2</sup>, F. Ezzaneou<sup>2</sup>, G. Jullien<sup>2</sup>, L. Maurice<sup>2</sup>, T. Hara<sup>3</sup>, M. Omei<sup>3</sup>, H. Ito<sup>3</sup>, K. Umemori<sup>3</sup>  
<sup>1</sup>IJCLab Université Paris-Saclay, <sup>2</sup>CNRS/IN2P3/IJCLab Université Paris-Saclay, <sup>3</sup>CNRS/IN2P3/IJCLab Université Paris-Saclay, <sup>4</sup>KEK/JACoM Université Paris-Saclay, <sup>5</sup>KEK/JACoM Université Paris-Saclay, <sup>6</sup>Physique des Accélérateurs, <sup>7</sup>Accélérateur Physics

**Heat Treatment in clean vacuum furnaces**




→ Systematic analysis of impacts from different furnaces and test stands for mid-T bake

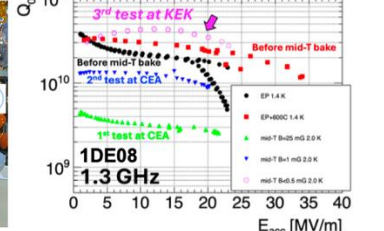
**Parametrization of HT**



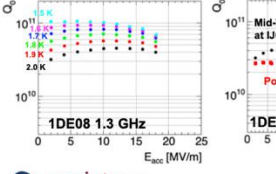
**Vertical tests in France and Japan**



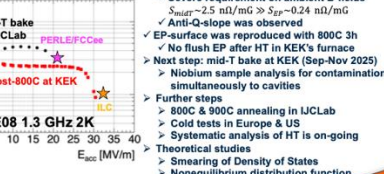
**Results in 2024**



**Anti-Q-slope**



**Reset by 800C 3h**



✓ 1<sup>st</sup> demonstration of mid-T bake in IJCLab furnace with 1.3 GHz 1-cell cavity (from DESY)  
 ✓ Severe requirement on ambient B-fields  
 $S_{\text{micro}} > 2.5 \text{ nT/mG} \gg S_{\text{EP}} \sim 0.24 \text{ nT/mG}$   
 ✓ Anti-Q-slope was observed  
 ✓ EP-surface was reproduced with 800C 3h  
 ✓ No flush EP after HT in KEK's furnace  
 ➢ Next step: mid-T bake at KEK (Sep-Nov 2025)  
 ➢ Niobium sample analysis for contamination simultaneously to cavities  
 ➢ Further steps  
 ➢ 800C & 900C annealing in IJCLab  
 ➢ Cold tests in Europe & US  
 ➢ Systematic analysis of HT is on-going  
 ➢ Theoretical studies  
 ➢ Smearing of Density of States  
 ➢ Nonequilibrium distribution function  
 ➢ Joint-PhD program  
 CNRS-UChicago

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UMR 9012, CNRS, Université Paris-Saclay, Université Paris Cité

EAJADE

www.ijclab.in2p3.fr

Leading role in the SRF community enabled by FJPPN / TYL!



# SRF2025 highlight: progress in anti-Q-slope theory

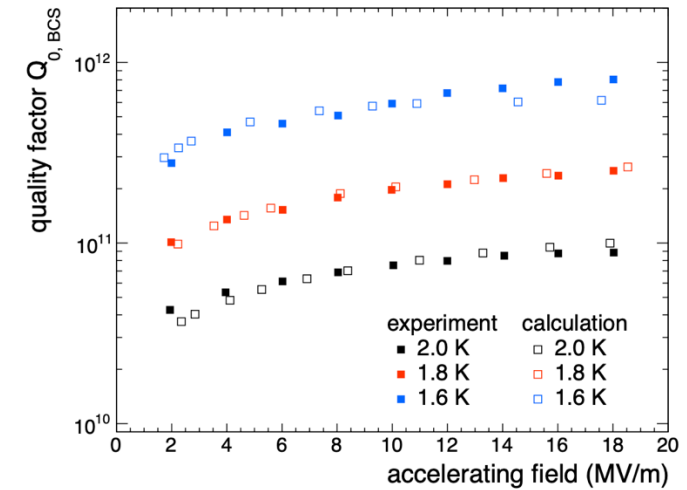
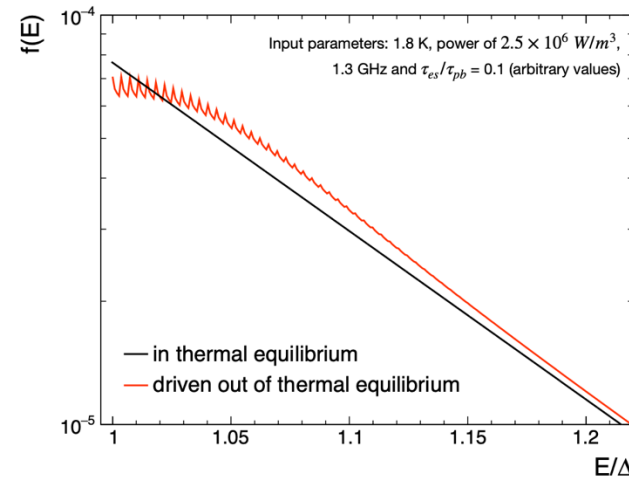
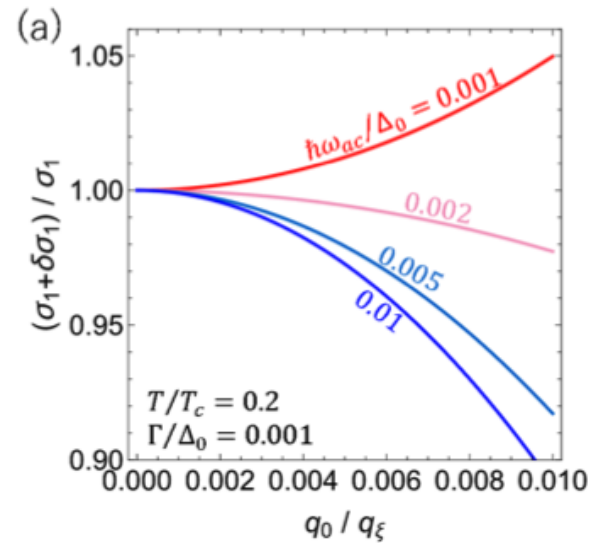
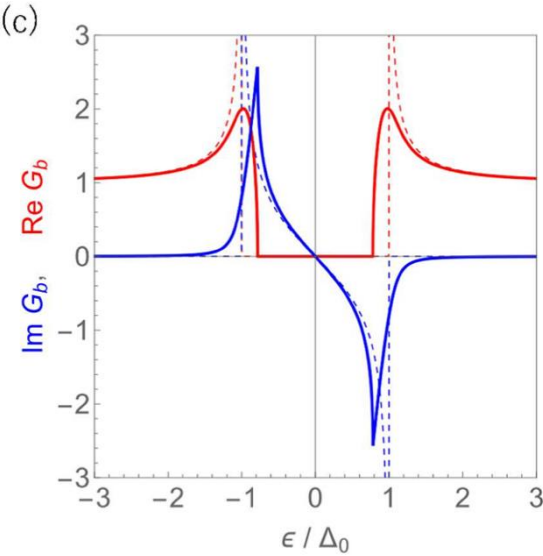
Takayuki Kubo

“nonequilibrium corrections and Higgs mode in superconducting devices: unravelling the pronounced **anti-Q-slope** in high-frequency regime and current-dependent kinetic inductance”

Antonio Bianchi

“Investigation of **anti-Q-slope** and Q-slope effects in SRF cavities: a unified theoretical framework”

**Data taken at KEK via FJPPN**



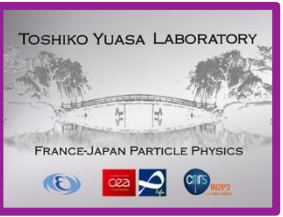
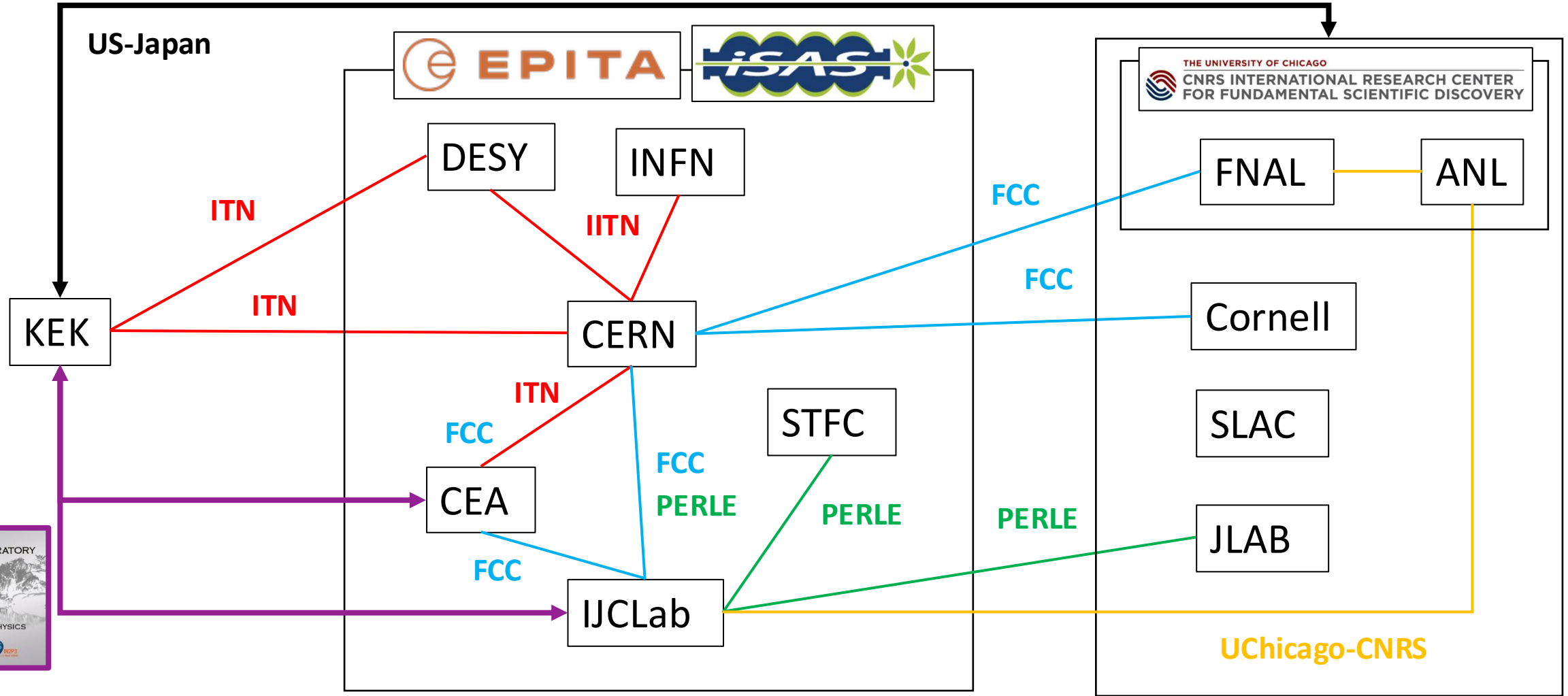
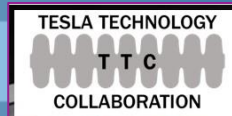
Phys Rev. Appl. 24 064061 (2025)  
Phys Rev. Appl. 23 054091 (2025)

doi:10.18429/JACoW-SRF2025-THA05  
Journal publication in preparation

Two competing hypotheses → experimental tests!



# FJPPN in the global SRF collaboration



- We are **financially** linking laboratories for the SRF studies (TTC is only for technology and no funding...)
- **FJPPN is the critical ingredient that gives a direct link between Japan and France**



# Expected activities in 2026

- Participation in LCWS2026 [FR → JP]
  - Akira Miyazaki & Axel Perez-Ruiz will come to KEK
  - Experiments with an extended stay
- Participation in TTC2026 [JP → FR]
- Experiment at DESY [JP → FR → DE]
  - The cavity is being shipped from KEK to DESY
  - Another cavity from KEK may be tested as well
- Theoretical collaboration
  - Takayuki Kubo: Higgs mode
  - Investigating to include Hikaru Ueki (LSU → Kyoto)

## International Workshop on Future Linear Colliders 2026

2026年11月9日～13日  
KEK

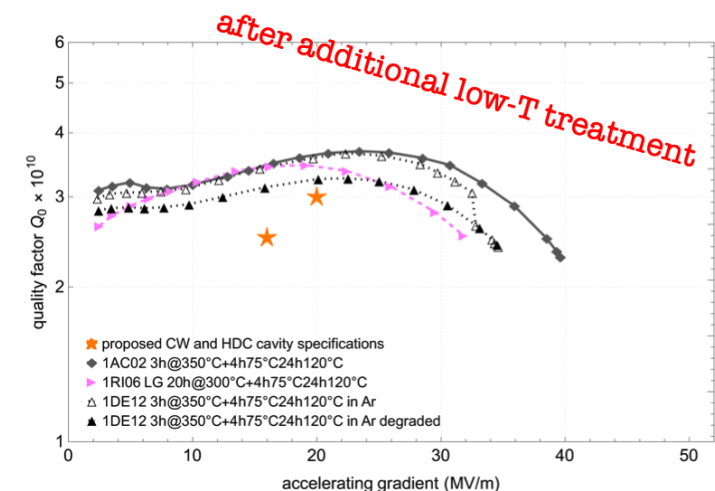
検索単語を入力

## TTC 2026 Meeting

CEA – CNRS – Université Paris-Saclay

9 – 12 June 2026

Ecole CentraleSupélec, Gif-sur-Yvette, France





# Conclusions

- SRF cavities are the core of next particle accelerators
- Exchange cavities / furnace heat treatment / cavity testing in different laboratories
  - The same results were obtained with a cavity treated by IJCLab and KEK!
  - Next step: DESY
- We do not know how SRF cavities work scientifically
  - Nonequilibrium nonlinear phenomena!
- SRF2025
  - Leading role in the community
  - Progress in nonequilibrium nonlinear theory for SRF cavities
- Activities in 2026
  - LCWS2026 at KEK
  - Cavity testing at DESY
- FJPPN is a seed funding that fills the missing link in the global collaboration among US, EU, and JP
- Multiple European funded projects are starting but Japan needs to be included!
  - Are KEK-Kyoto researchers eligible to French / European funding through TYL?
  - Are French researchers eligible to KAKENHI through TYL?