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

CNRS/IN2P3/IJCLab

Akira Miyazaki, David Longuevergne, Axel Perez-Ruiz

CEA/IRFU

Enrico Cenni

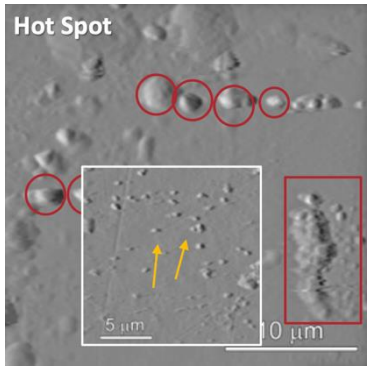
KEK/iCASA

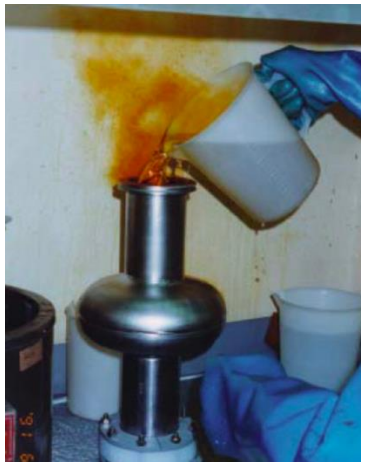
Kensei Umemori, Takayuki Kubo, Hayato Ito

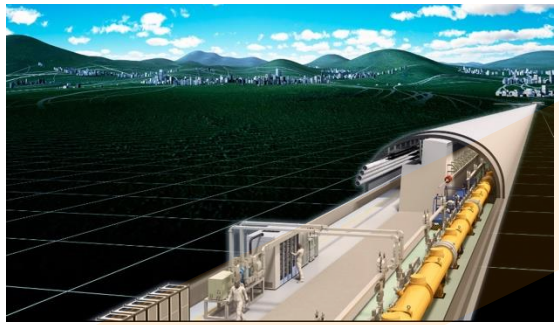
Outline

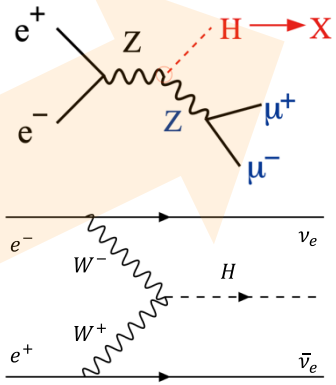
- Superconducting RF cavities for future accelerators
- Previous collaborative activities in 2024-2025 Feb
- New results in 2025 Sep-Nov
- Theoretical approach
- Highlights of SRF2025 conference
- Plan of 2026
- Conclusion

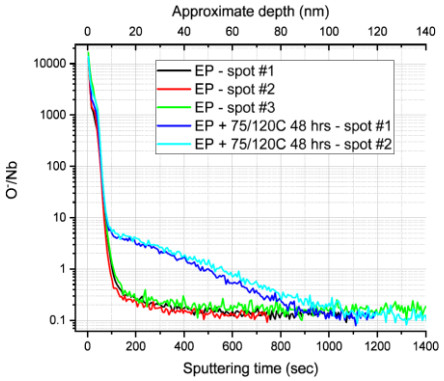
Accelerators: from superconductivity to particle physics

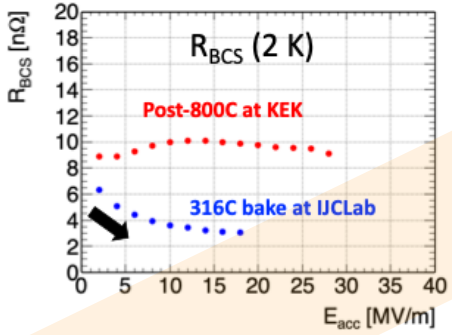


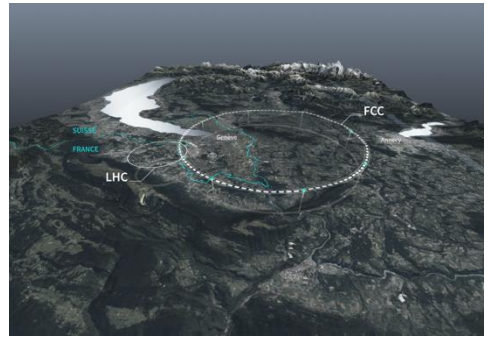


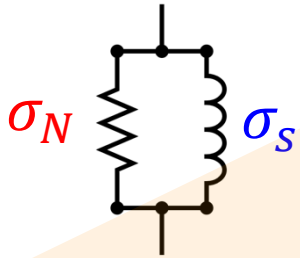


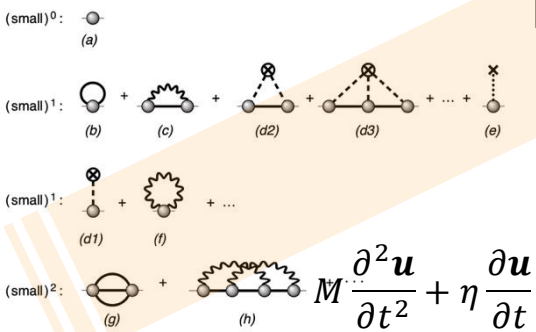


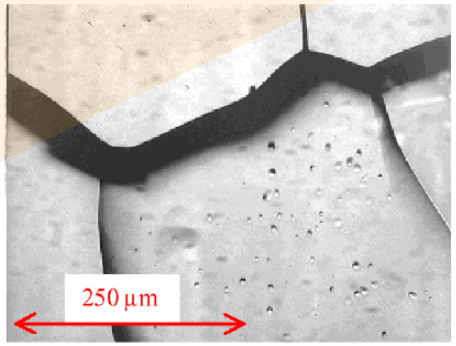








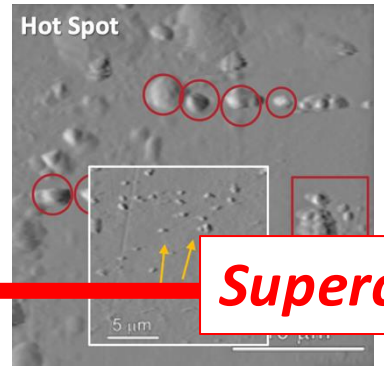


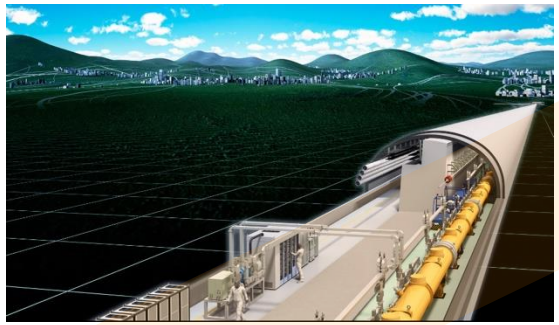


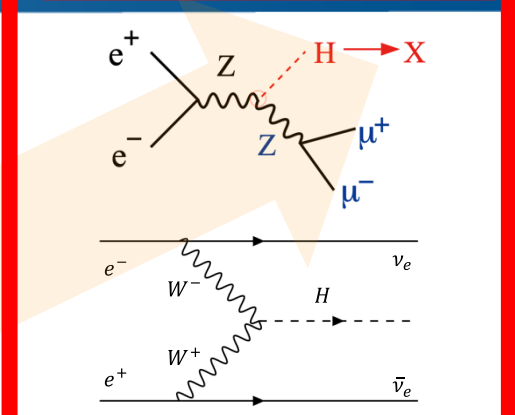
$$M\frac{\partial^2 \boldsymbol{u}}{\partial t^2} + \eta\frac{\partial \boldsymbol{u}}{\partial t} - \epsilon\frac{\partial^2 \boldsymbol{u}}{\partial z^2} + \nabla U(z,u) = \boldsymbol{J}_{RF}(z,u) \times \boldsymbol{B}_{\text{ext}}$$

Accelerators: from superconductivity to particle physics

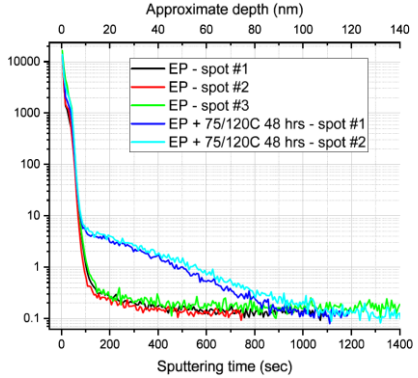
particle physics

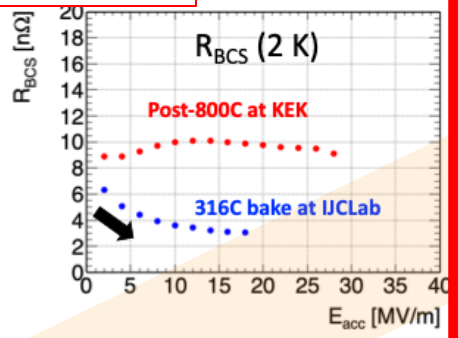


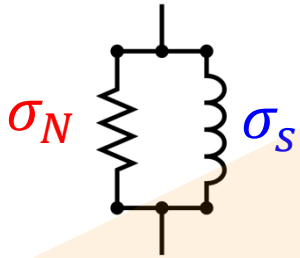


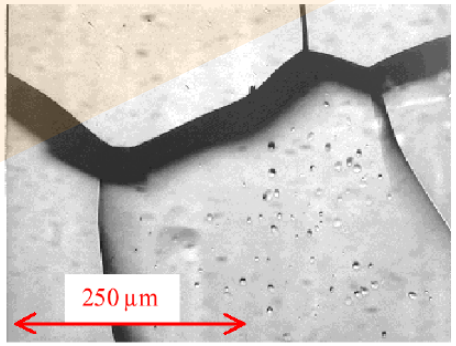


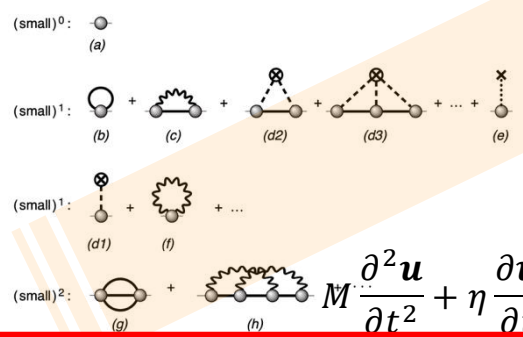
Superconductivity physics



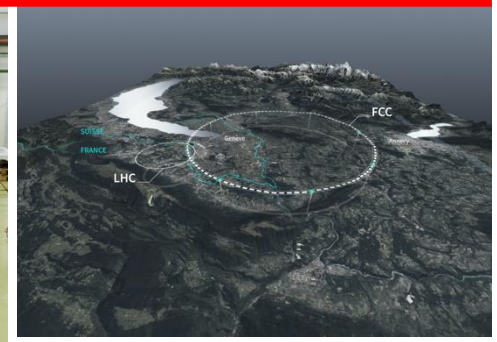






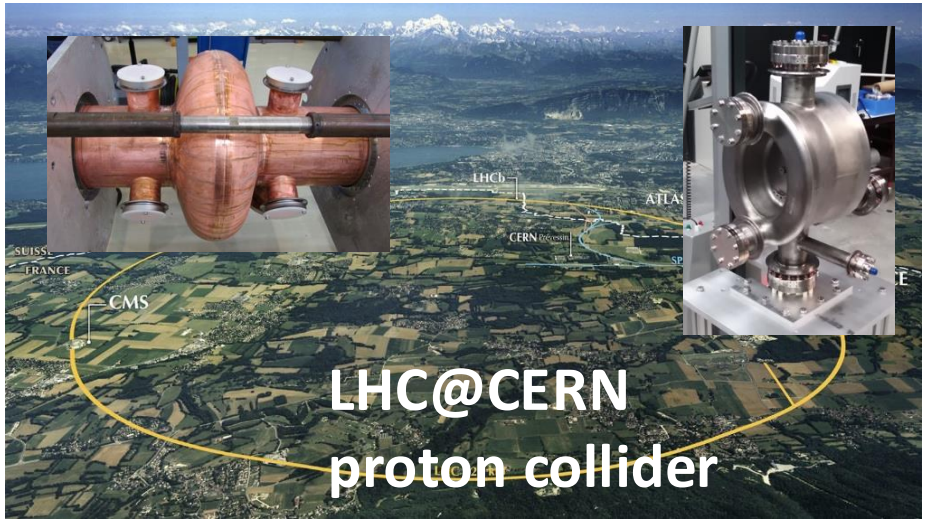


$$M\frac{\partial^2 \boldsymbol{u}}{\partial t^2} + \eta\frac{\partial \boldsymbol{u}}{\partial t} - \epsilon\frac{\partial^2 \boldsymbol{u}}{\partial z^2} + \nabla U(z,u) = \boldsymbol{J}_{RF}(z,u) \times \boldsymbol{B}_{\text{ext}}$$



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

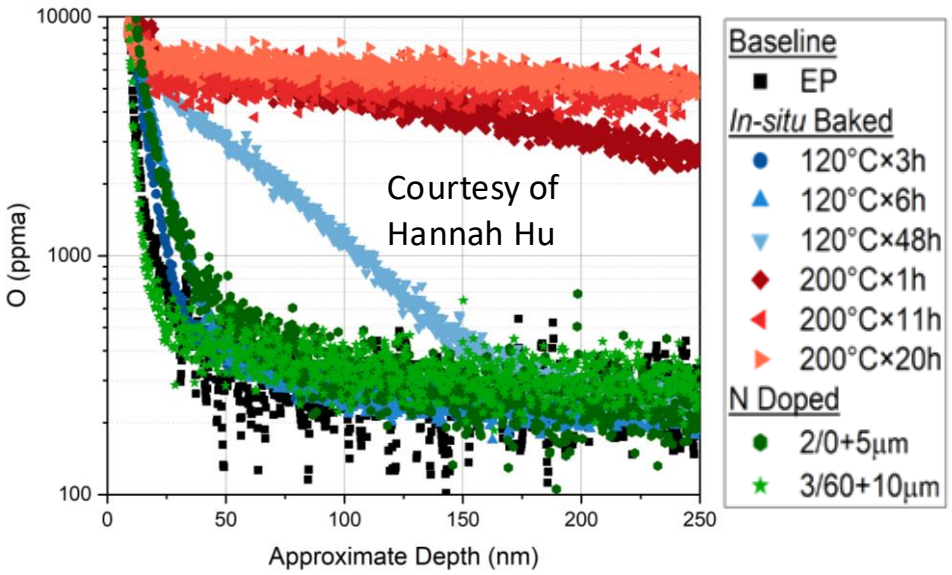
Superconducting RF cavities in present and future accelerators

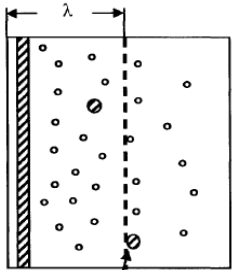


SRF is the technology of today → most probably next colliders

Two options in SRF cavities

Bulk niobium with surface engineering

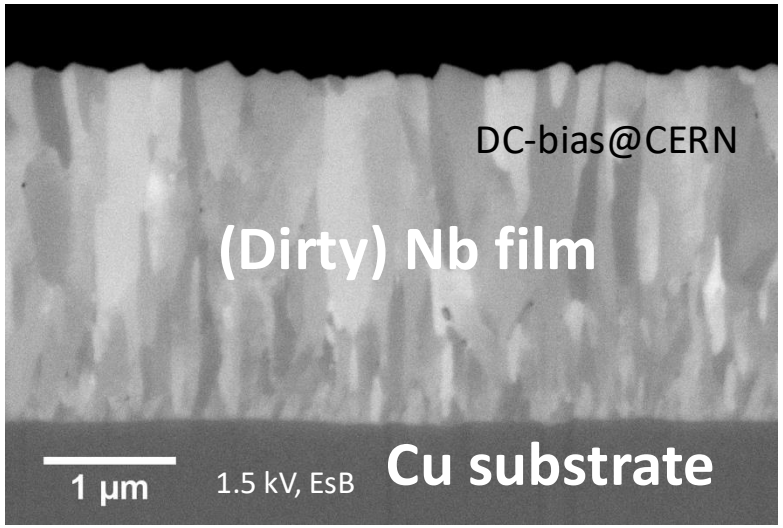




G. Ciovati PhD thesis

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

Thin films on substrates



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

Main scope of this proposal

→ Promising for future colliders with mystery in fundamental aspects

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 →

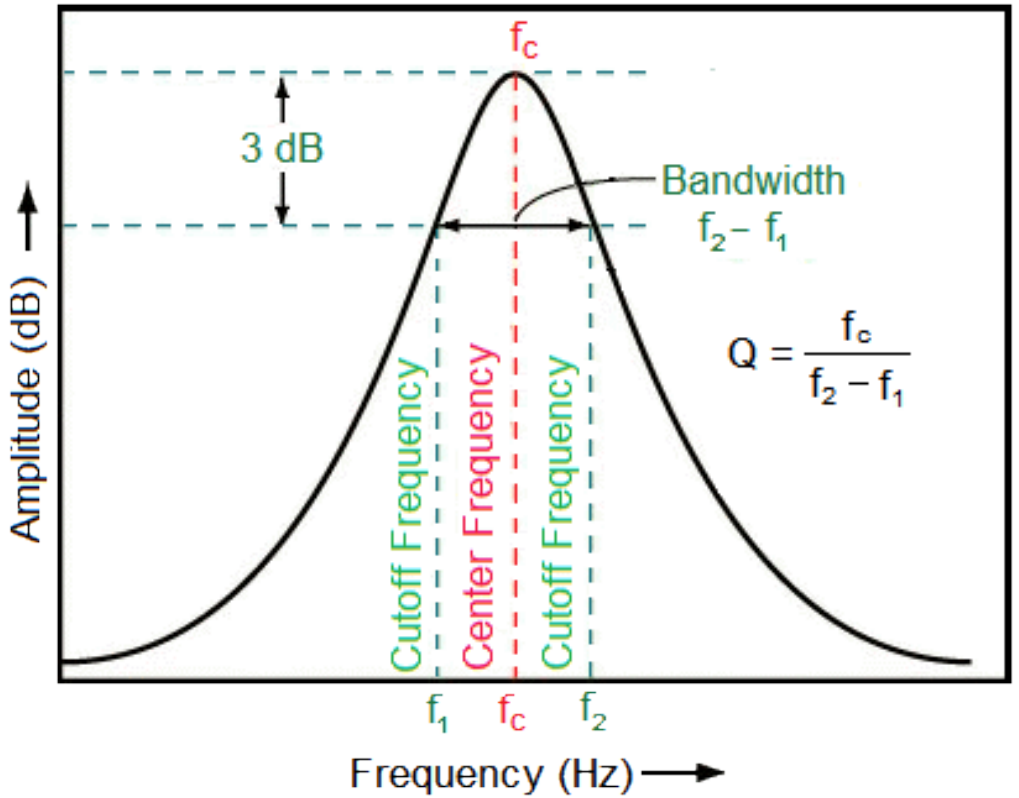
Q_0 can be derived from surface resistance R_s

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 $R_s(E_{acc})$

7

Project demands and market

- CW machines need high Q
- LC needs high Gradient

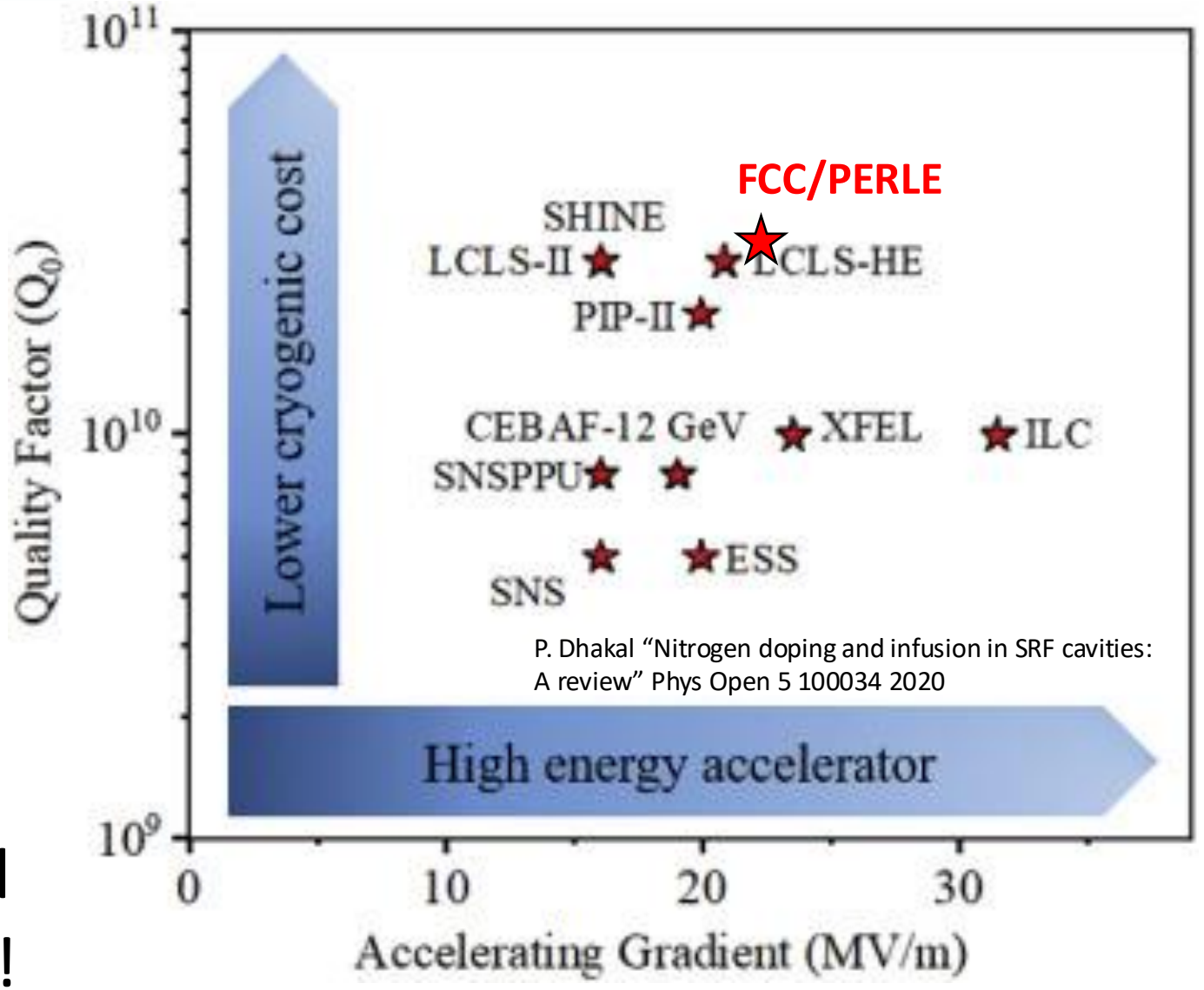
We have recipes

- Chemical etching
- Baking/doping

For either high-Q/high-G

But do not know why

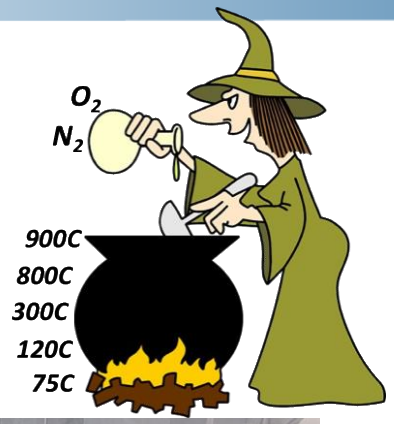
→ We want to understand and scientifically optimize them!

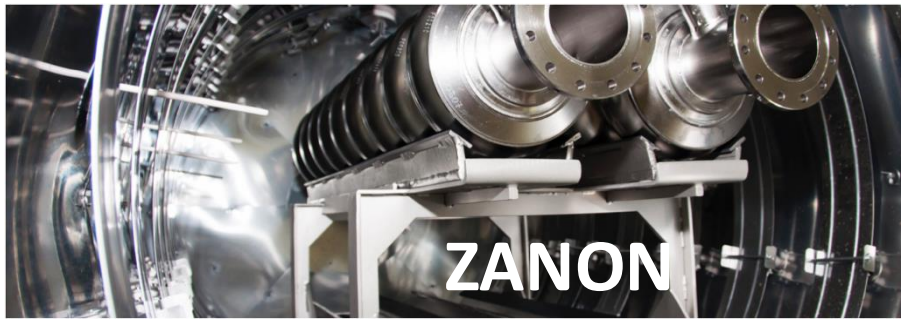


P. Dhakal "Nitrogen doping and infusion in SRF cavities: A review" Phys Open 5 100034 2020

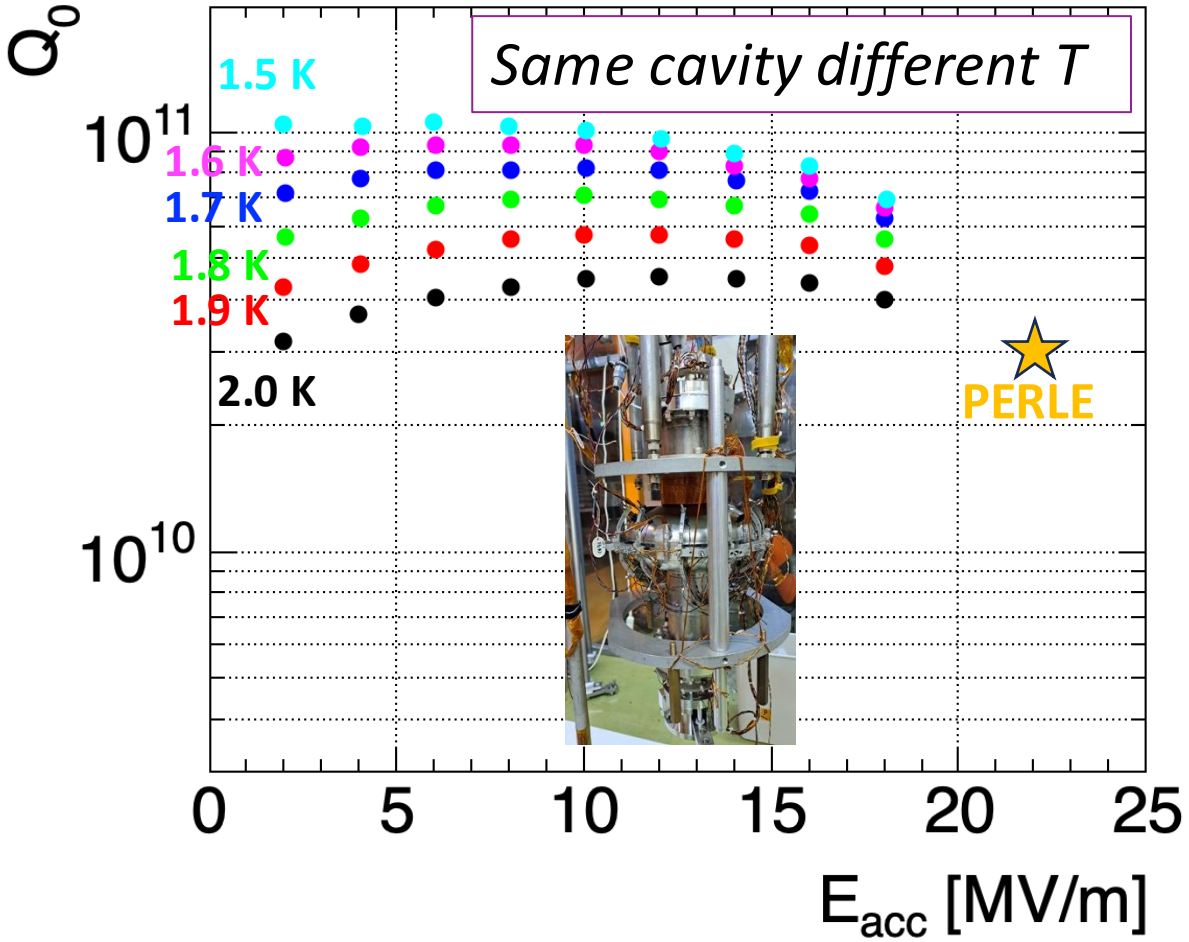
Chaudron for black magic

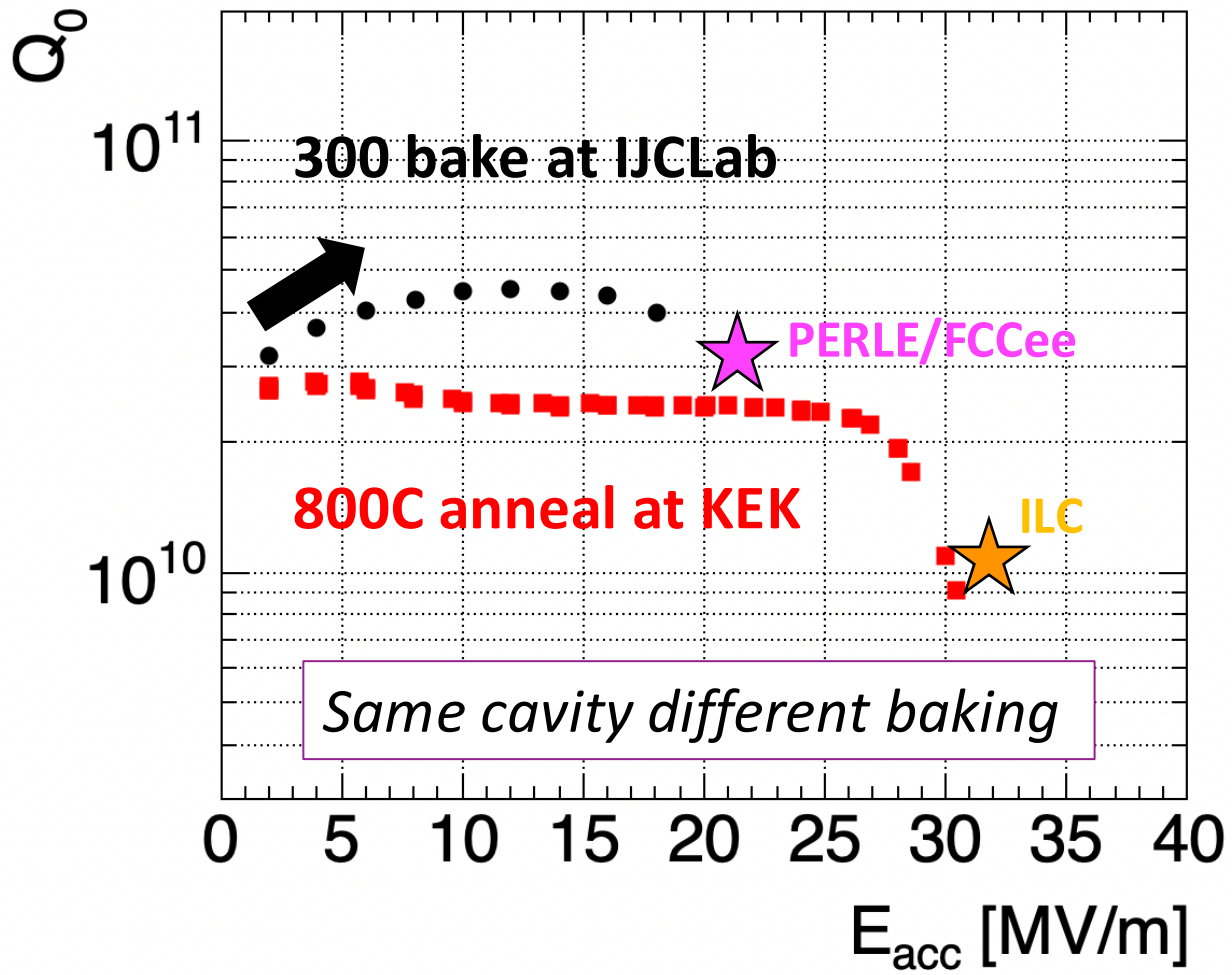
High-Q/high-G
can be switched
by baking process





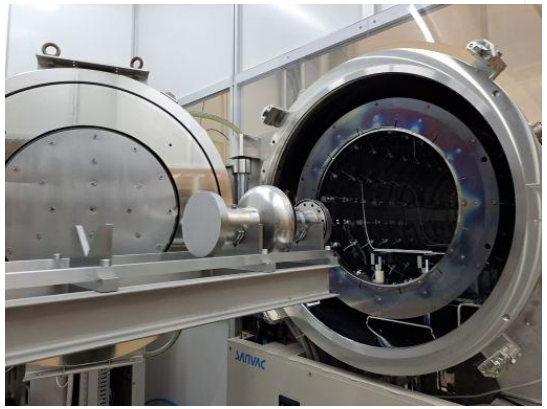
Results in 2024-2025 Feb under FJPPN collaboration

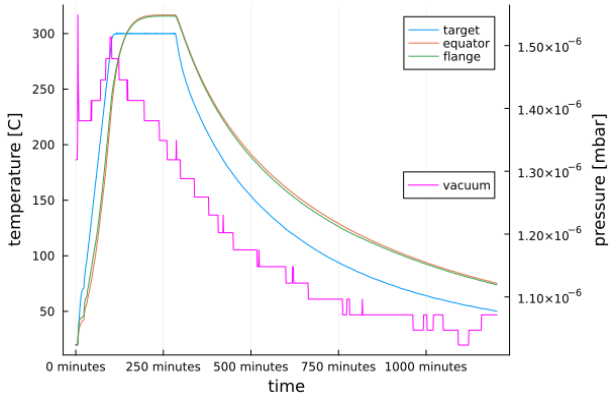


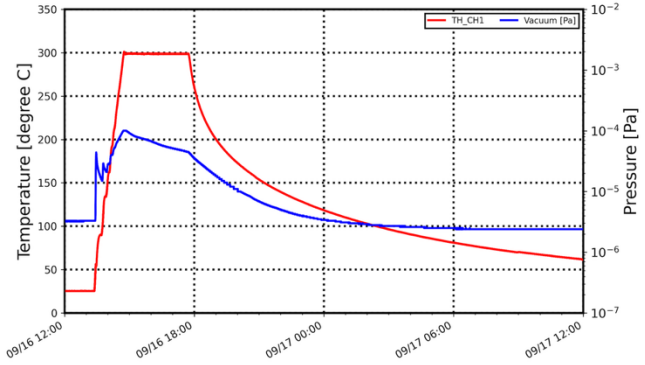


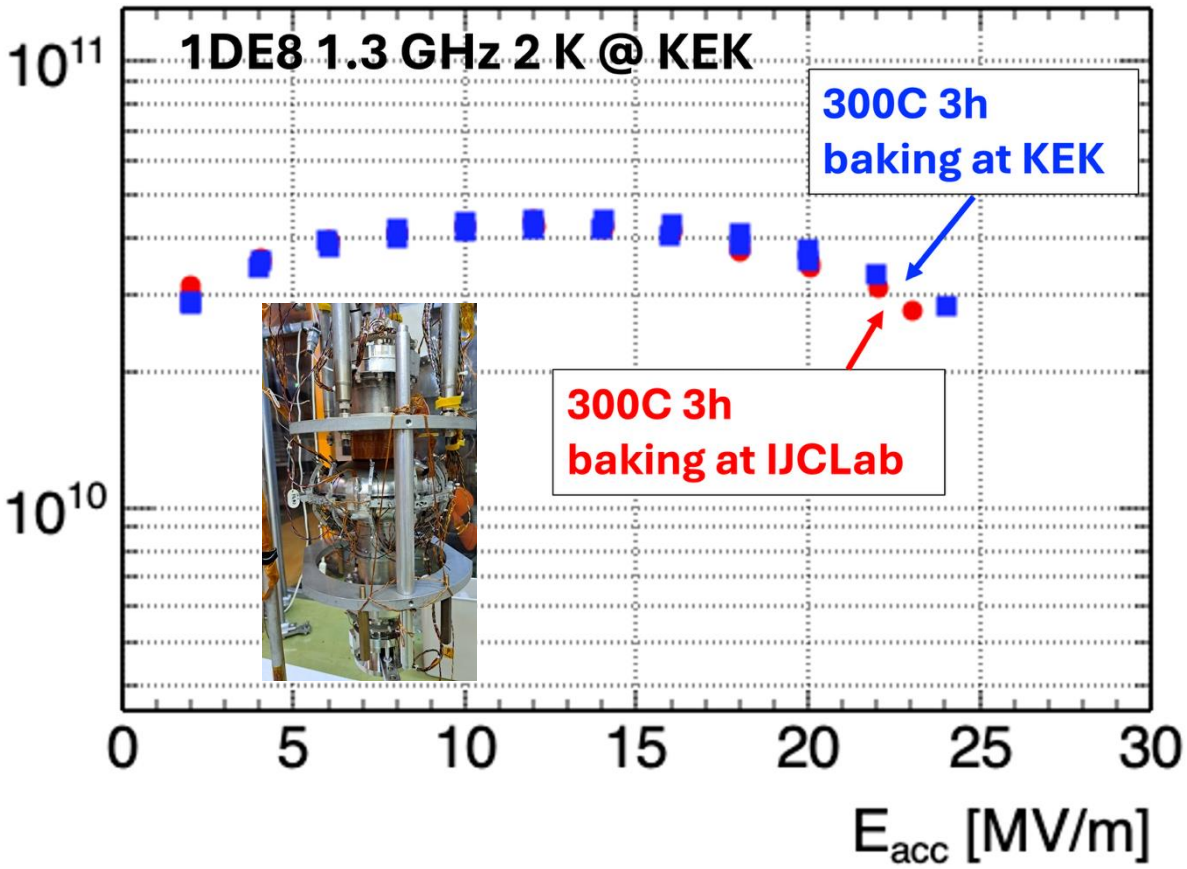
- Excellent performance with 300C bake by IJCLab and tested by KEK
- High-Q recipe can be reset by high-G recipe demonstrated by 800C annealing by KEK

New results in 2025 Sep-Nov: IJCLab vs KEK



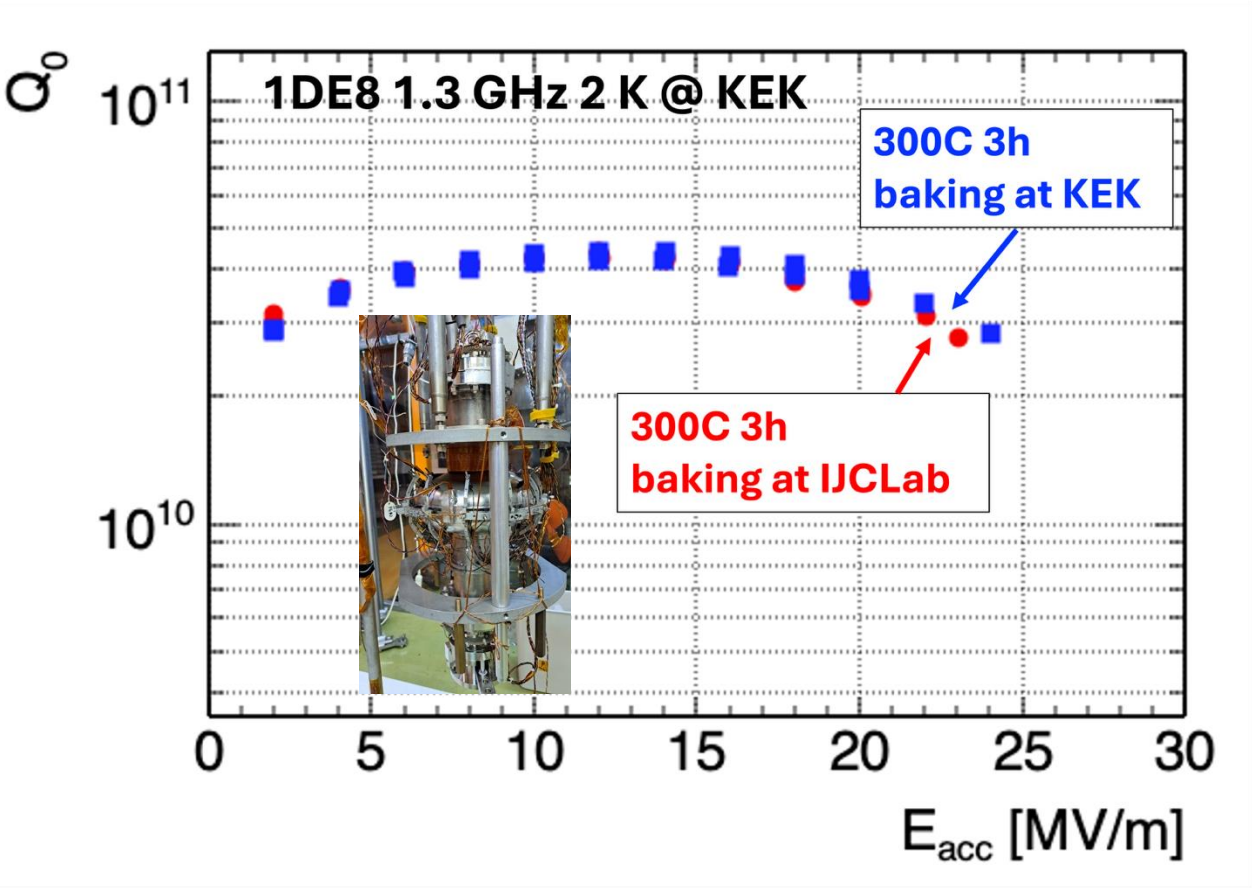


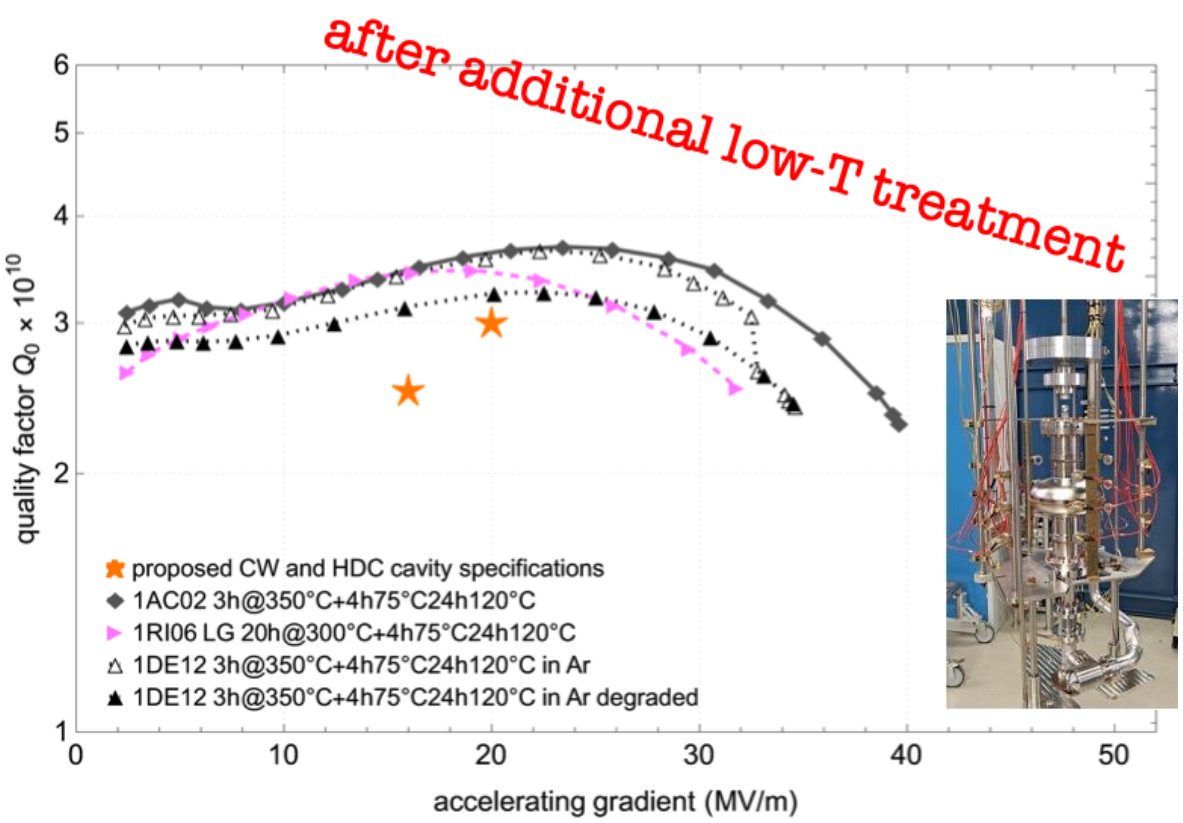




- Systematic comparison of baking process in IJCLab and KEK
- Multiple differences (eg vacuum…) were identified → however, the cavity results were exactly identical ☺

Perspective in 2026: KEK → IJCLab + DESY





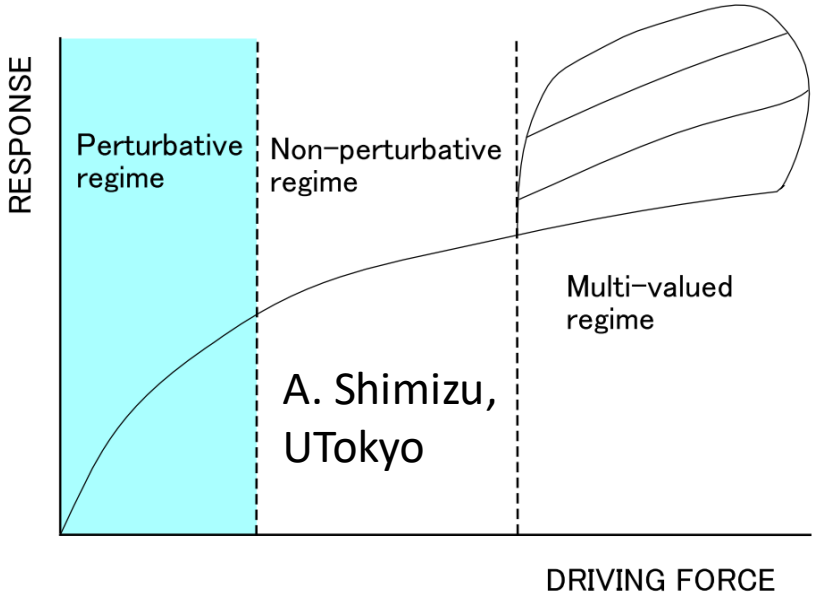
- KEK has not reproduced the high-gradient results of DESY
- The furnaces in KEK and IJCLab are comparable but less clean than the one in DESY (?)
- Systematic comparison among KEK and DESY will be coordinated by IJCLab

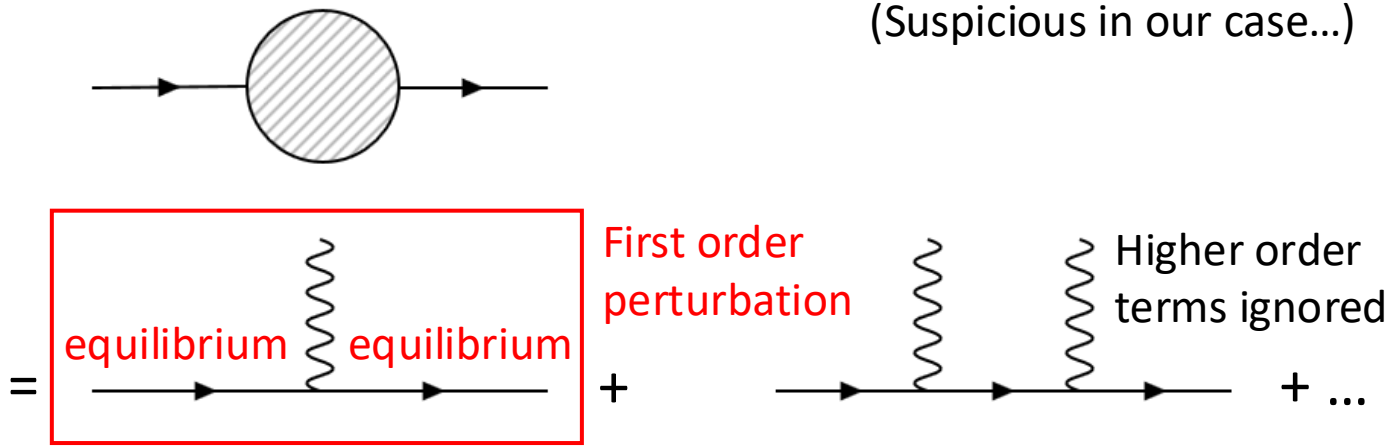
Quamtum mechanical ***derivation*** of R_s requires quantum many body theory

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

If the RF field is "small"

(Suspicious in our case…)





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

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

$\mathcal{H}_0$: BCS → Mattis Bardeen

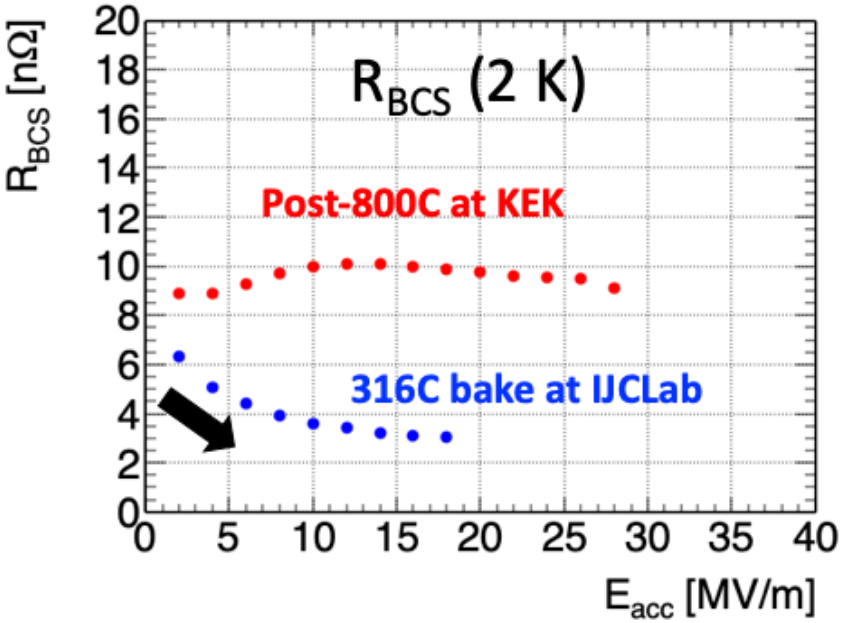
Linear response theory (1st order perturbation) → no field dependence in Q_0

Fundamental question: origin of anti-Q-slope

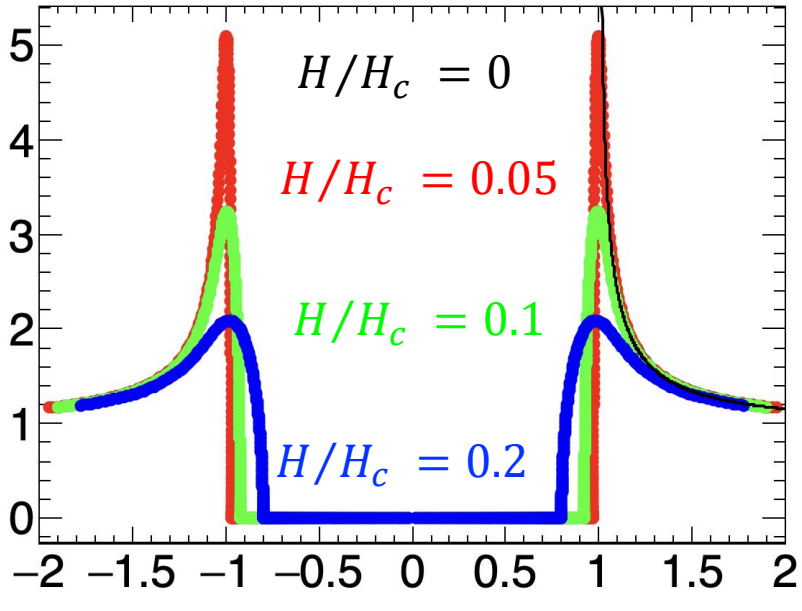
(Simplified working ansatz…)

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

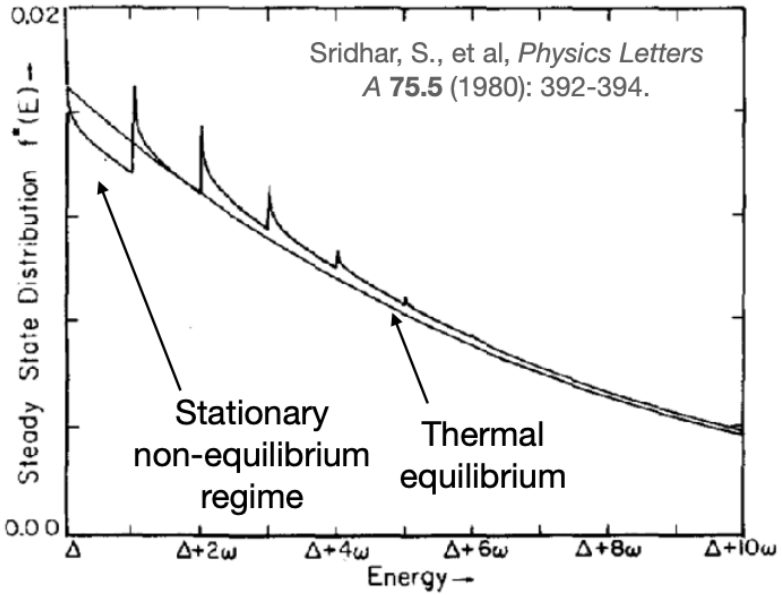
Anti-Q-slope



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

22ND INTERNATIONAL CONFERENCE ON RF SUPERCONDUCTIVITY

September 21-26, 2025

Hot topic 2

Development toward extremely high performance superconducting cavities

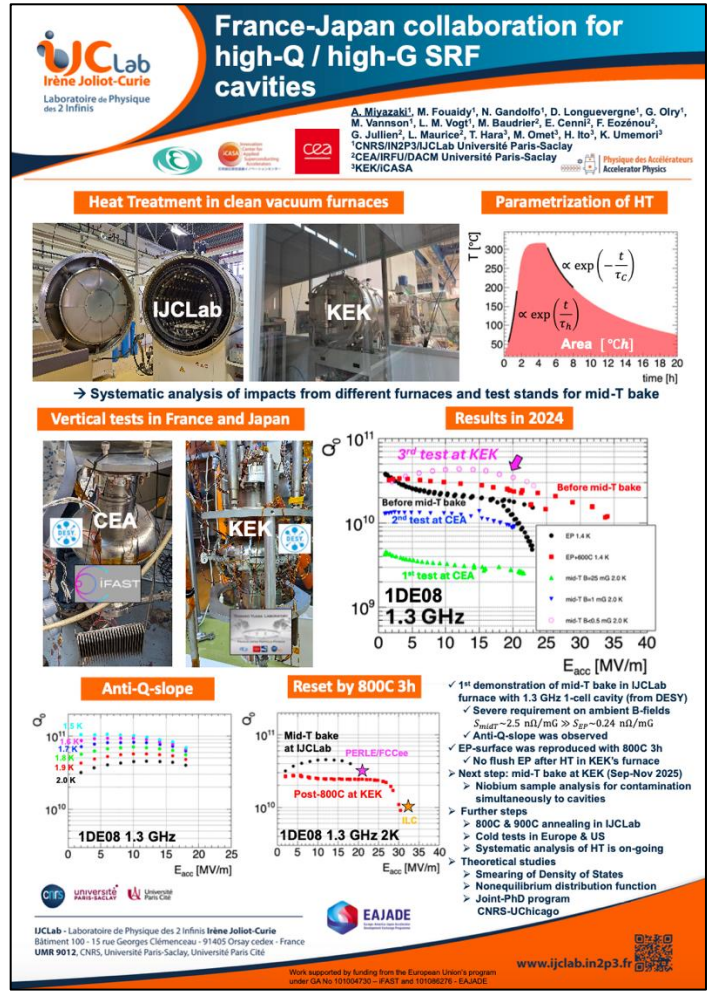
2K Nb: High-G > 50 MV/m
Non 2K || non Nb: > 25 MV/m

Convener:
Akira Miyazaki

Panelists:

2K Nb: High-Q > 5×10^{10}
Non 2K || non Nb: > 2×10^{10}

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



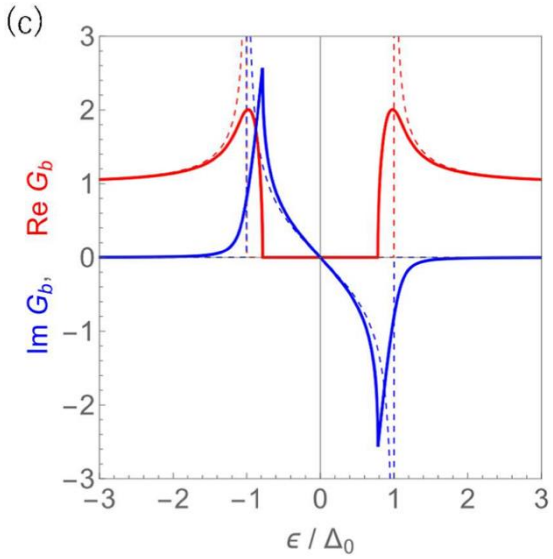
- State-of-the-art
  - Understandings of bulk Nb (our research!)
  - Practicalities
- Future directions
  - Travelling wave
  - Thin Films (partially our research!)

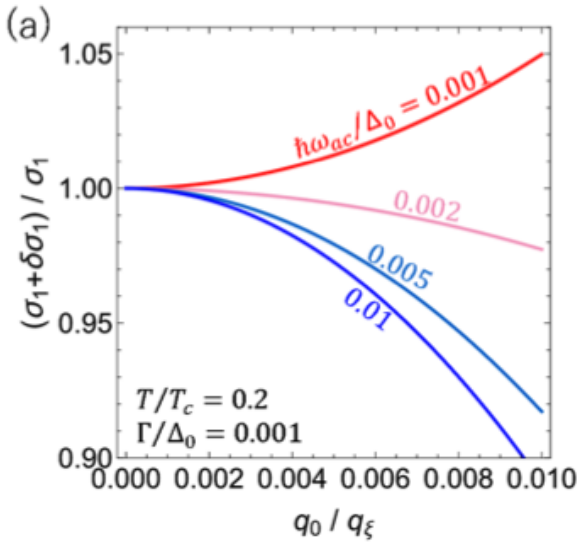
Leading role in the SRF community enabled by FJPPN / TYL!

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"*



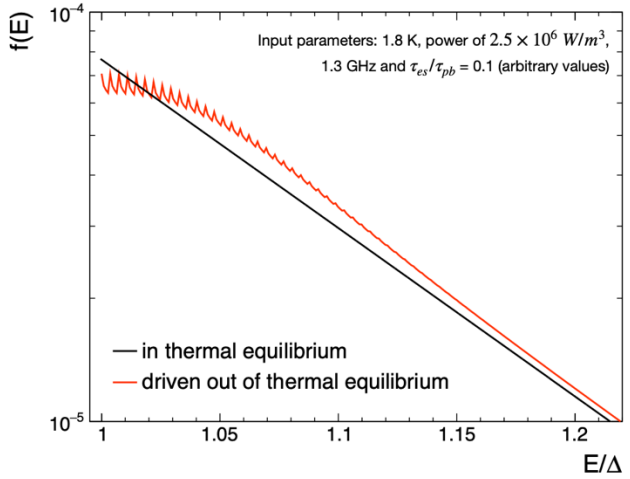


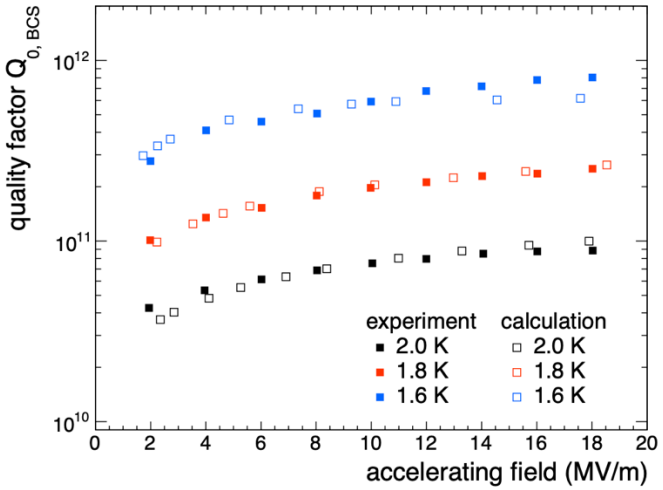
Phys Rev. Appl. 24 064061 (2025)
Phys Rev. Appl. 23 054091 (2025)

Antonio Bianchi

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

Data taken at KEK via FJPPN

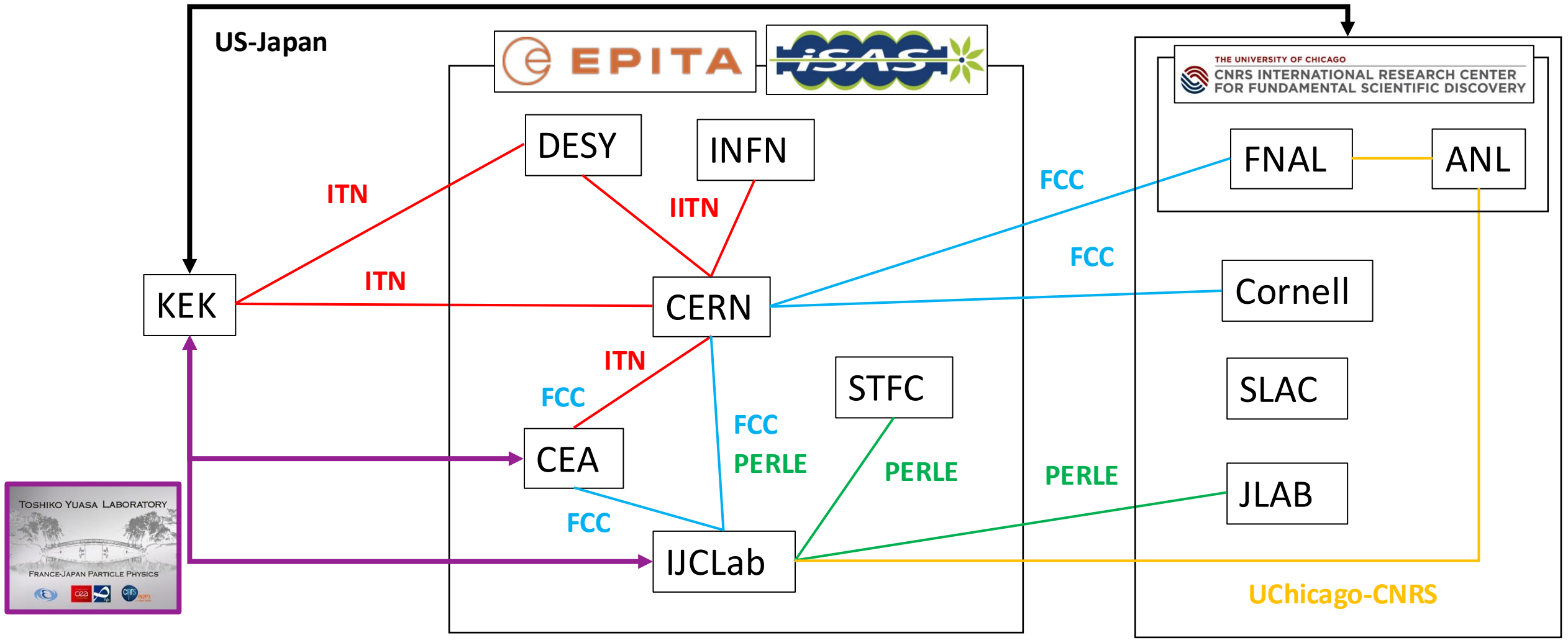




doi:10.18429/JACoW-SRF2025-THA05
Journal publication in preparation

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

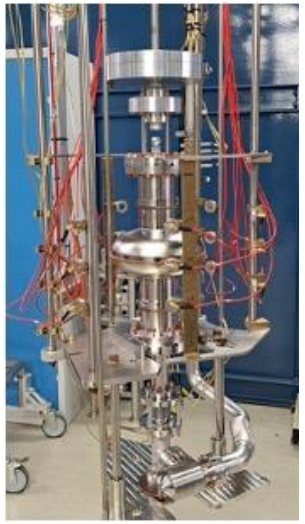
- Participation in LCWS2026 [FR→ JP]
  - Akira Miyazaki & Axel Perez-Ruiz will come to KEK
  - Experiments with an extended stay
- Participation in TTC2026 [JP→FR]
- Experiment at DESY [JP → FR → DE]
  - The cavity is being shipped from KEK to DESY
  - Another cavity from KEK may be tested as well
-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

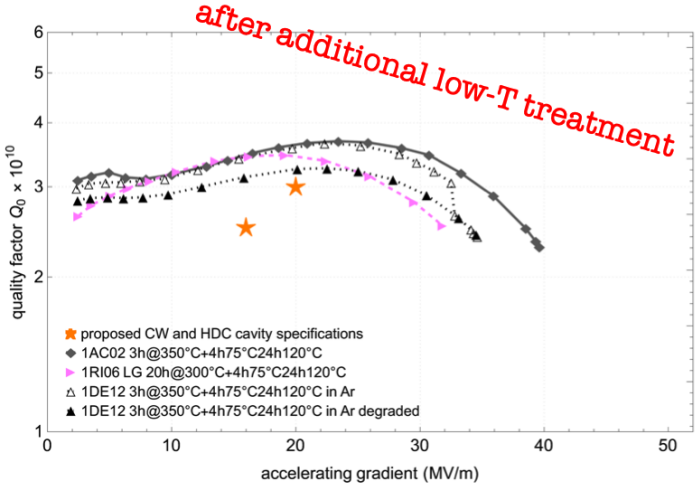
International Workshop on Future Linear Colliders 2026

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 CentraleSupelec, 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 obtain 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?