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

CNRS/IN2P3/IJCLab

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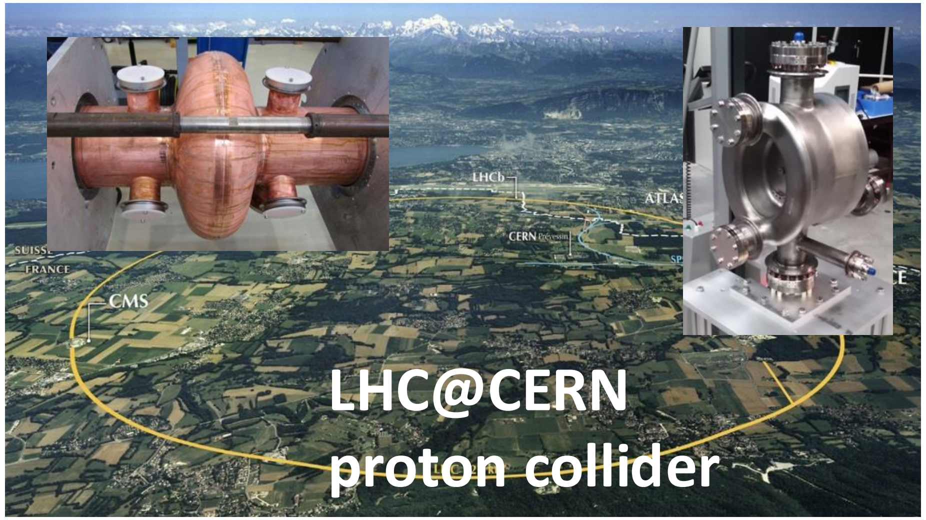
Outline

- Superconducting RF cavities for present and future accelerator projects
- Mystery in SRF cavity performance
- Previous collaborative activities
- Theoretical approach: new collaboration
- Global collaboration
- Plan of 2025
- Conclusion

Superconducting cavities in present and future accelerators



SRF is the technology of today → most probably next colliders

Project demands

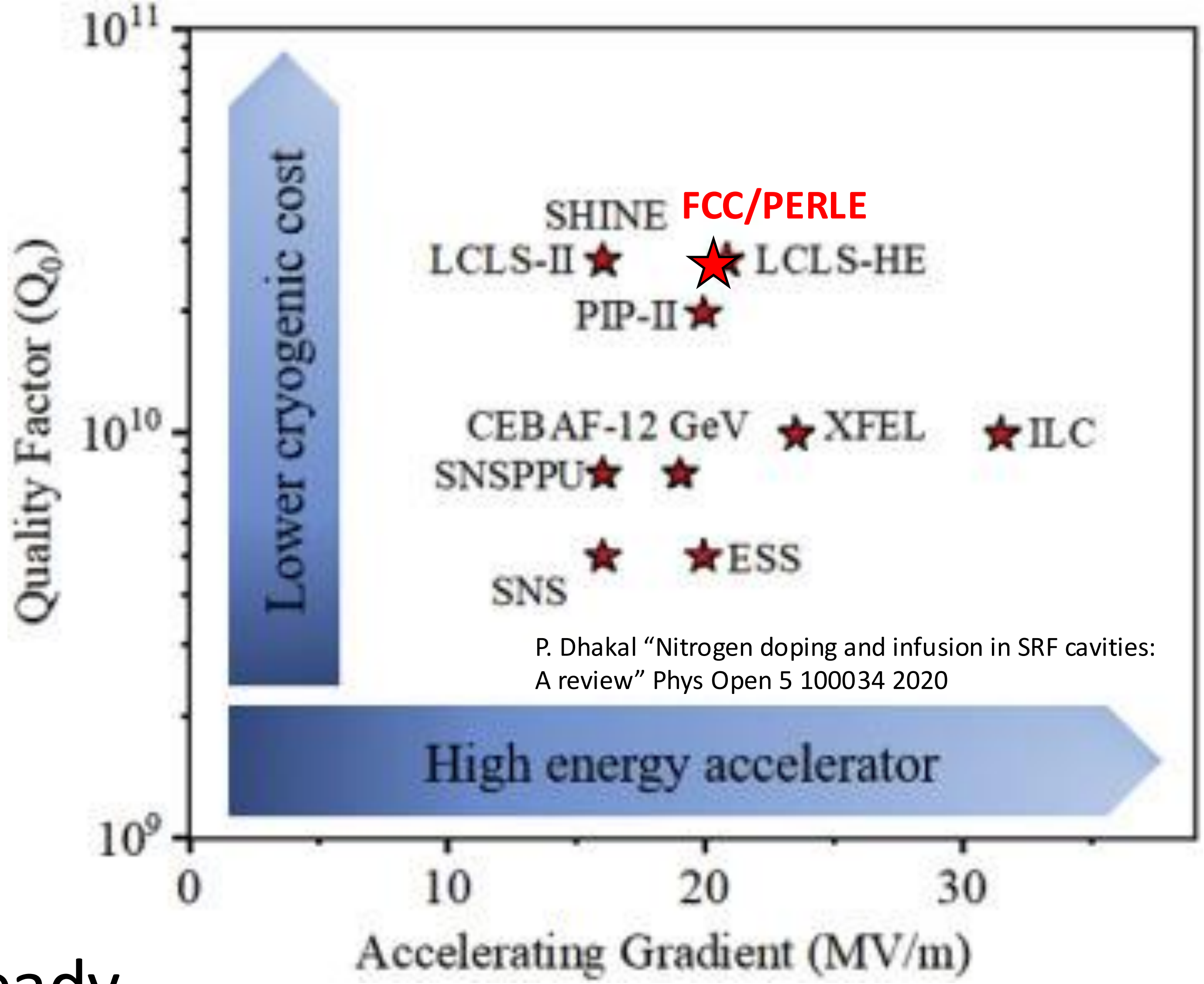
- CW machine (circular or high current linac) needs high Q
- ILC needs high gradient

<u>We need state-of-the-art</u>

- Chemical etching
- Baking/doping

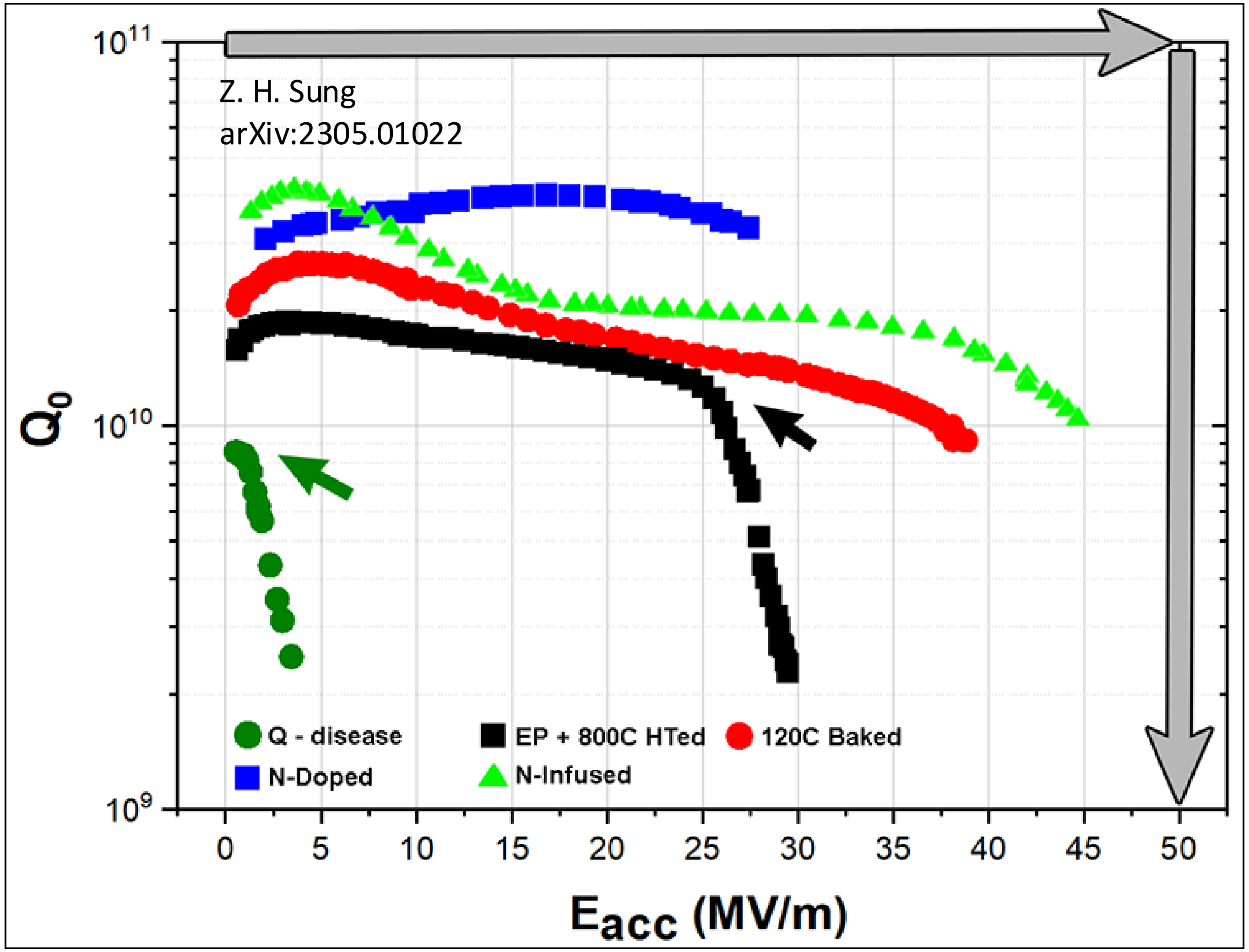
in **industry**

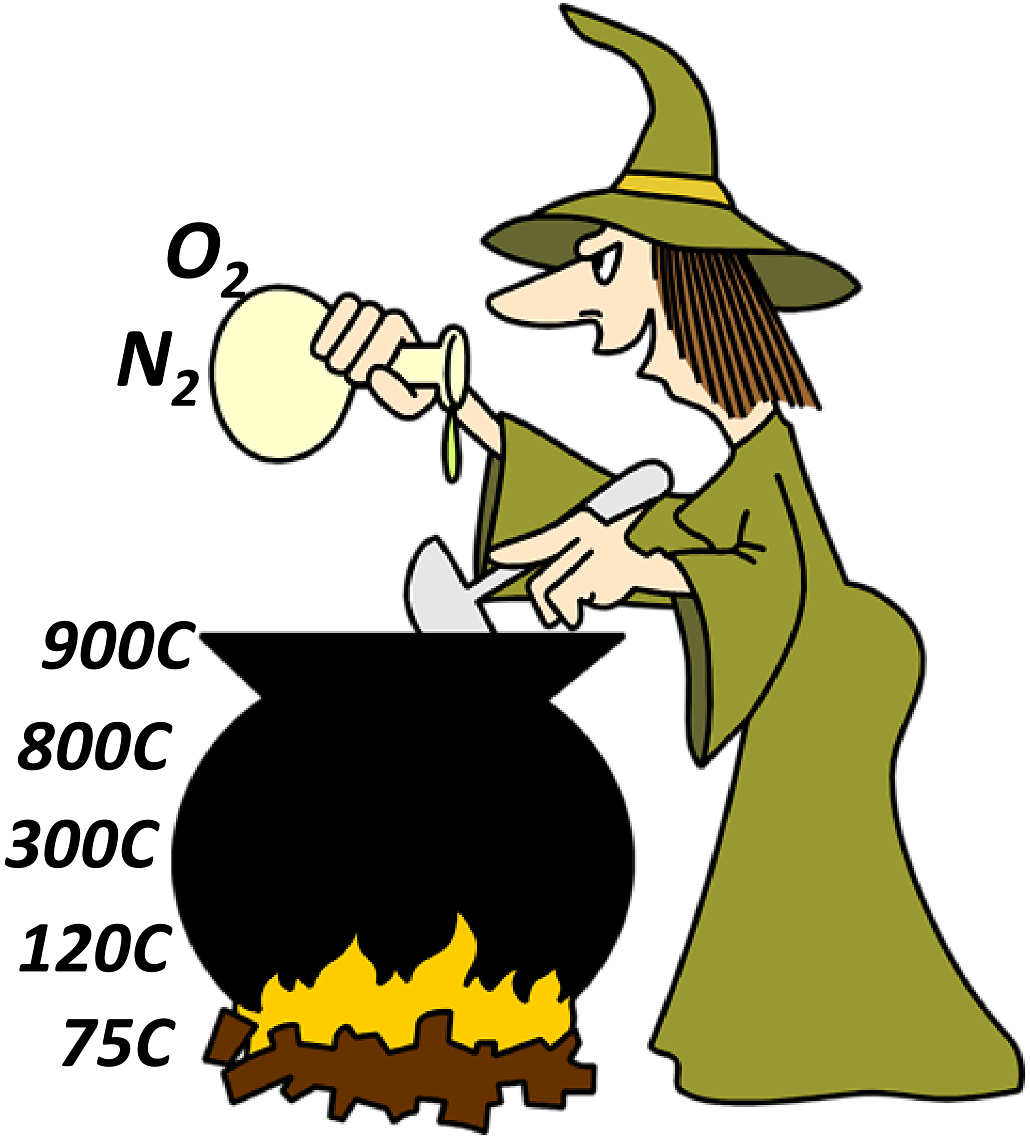
→ They are ***in principle*** ready



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

Why just "In principle (?) ready" → *Black magic*

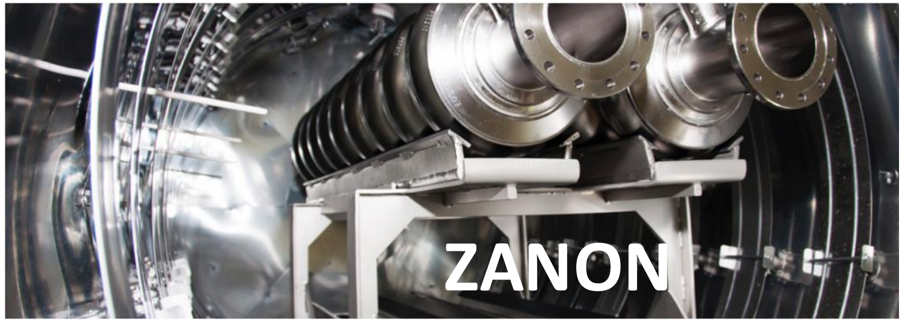




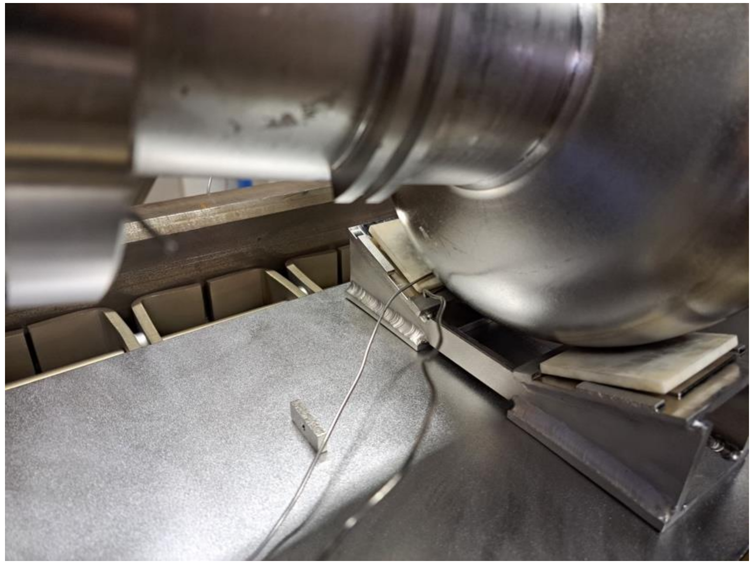
We know it works (in some labs) but do not know why

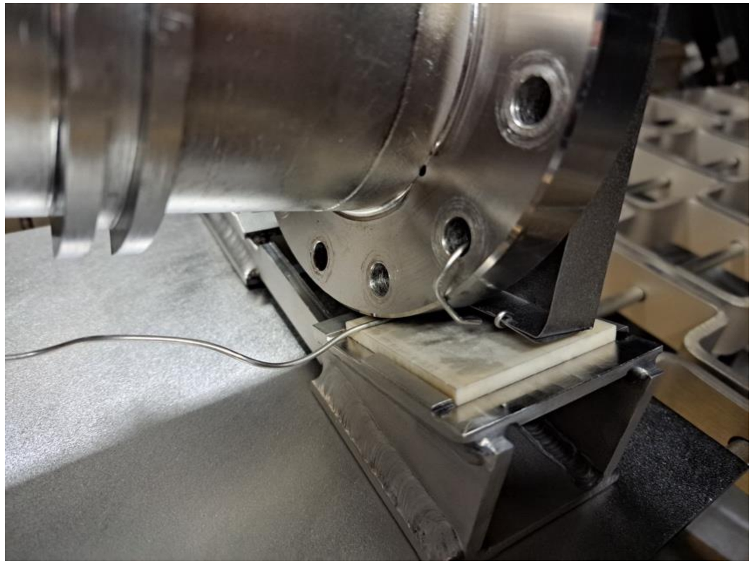
Chaudron for black magic

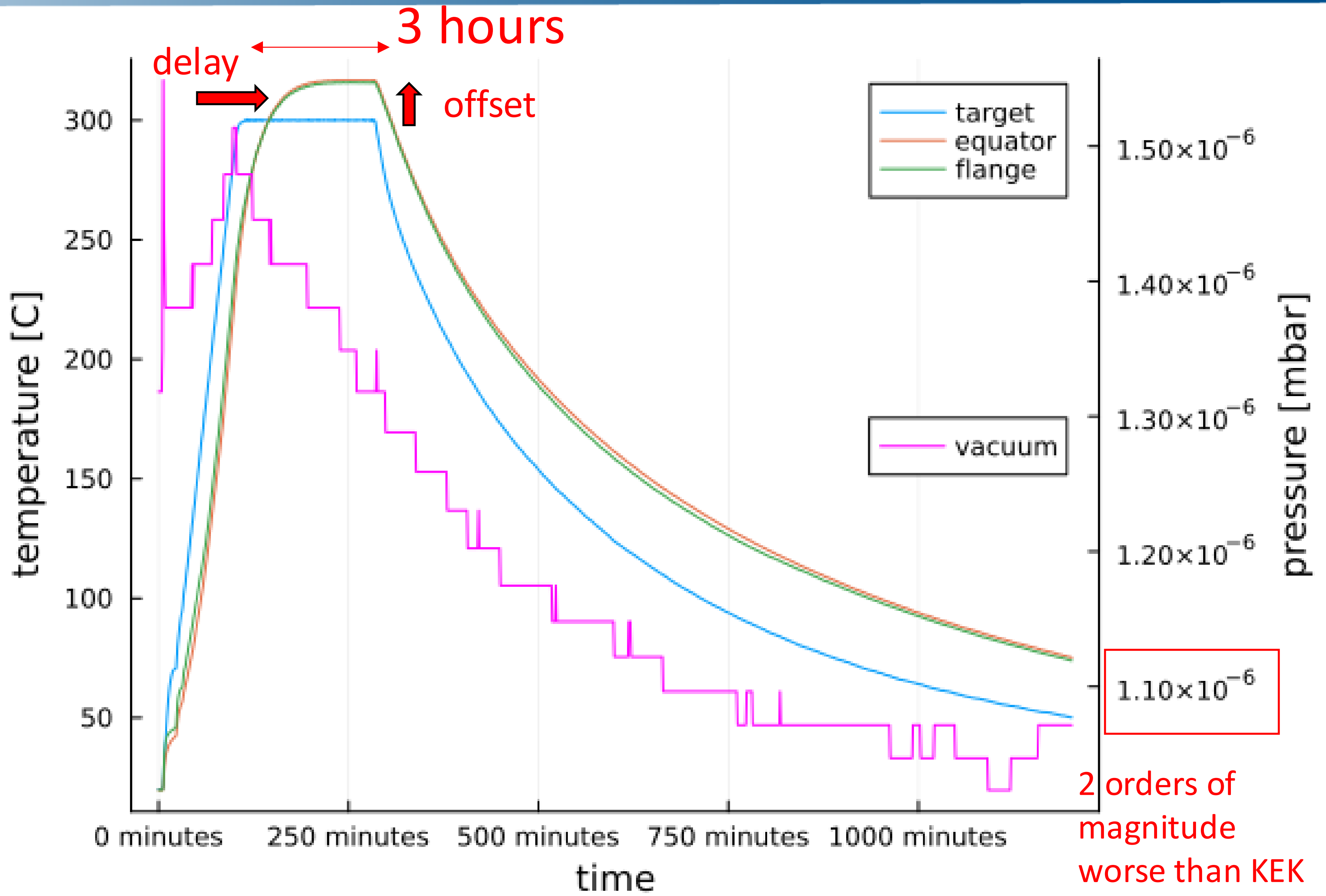
- Clean vacuum furnace (cryopump) over the world including industry
- Systematic comparison of working parameters or even definition of parameters is challenging without collaboration



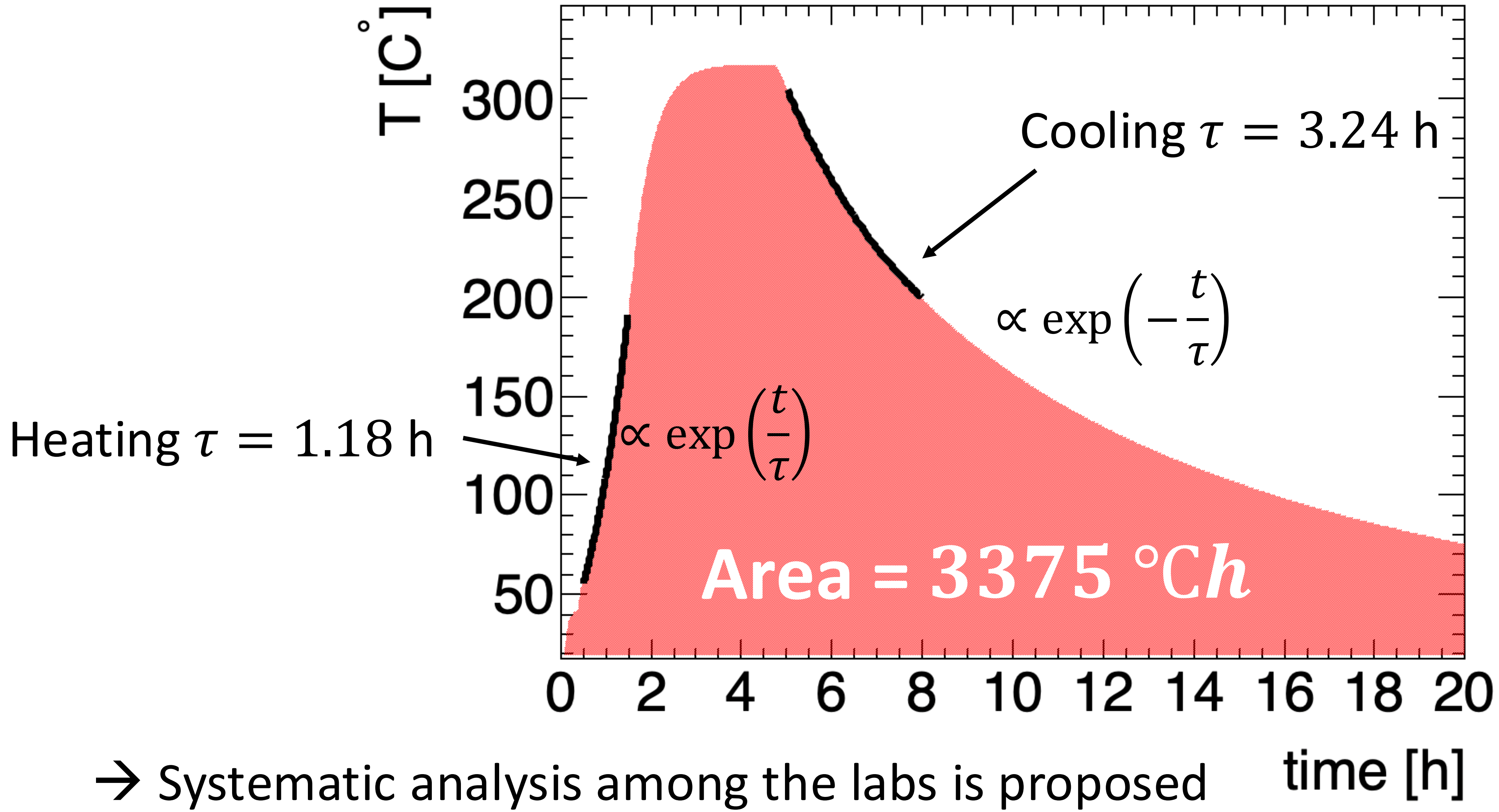
1^{st} try in IJCLab







2 orders of magnitude worse than KEK

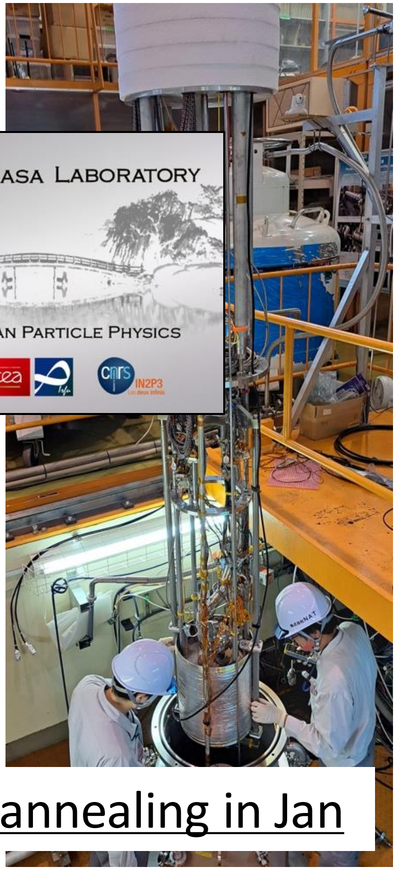


→ Systematic analysis among the labs is proposed

Cavity measurement at cold with collaboration

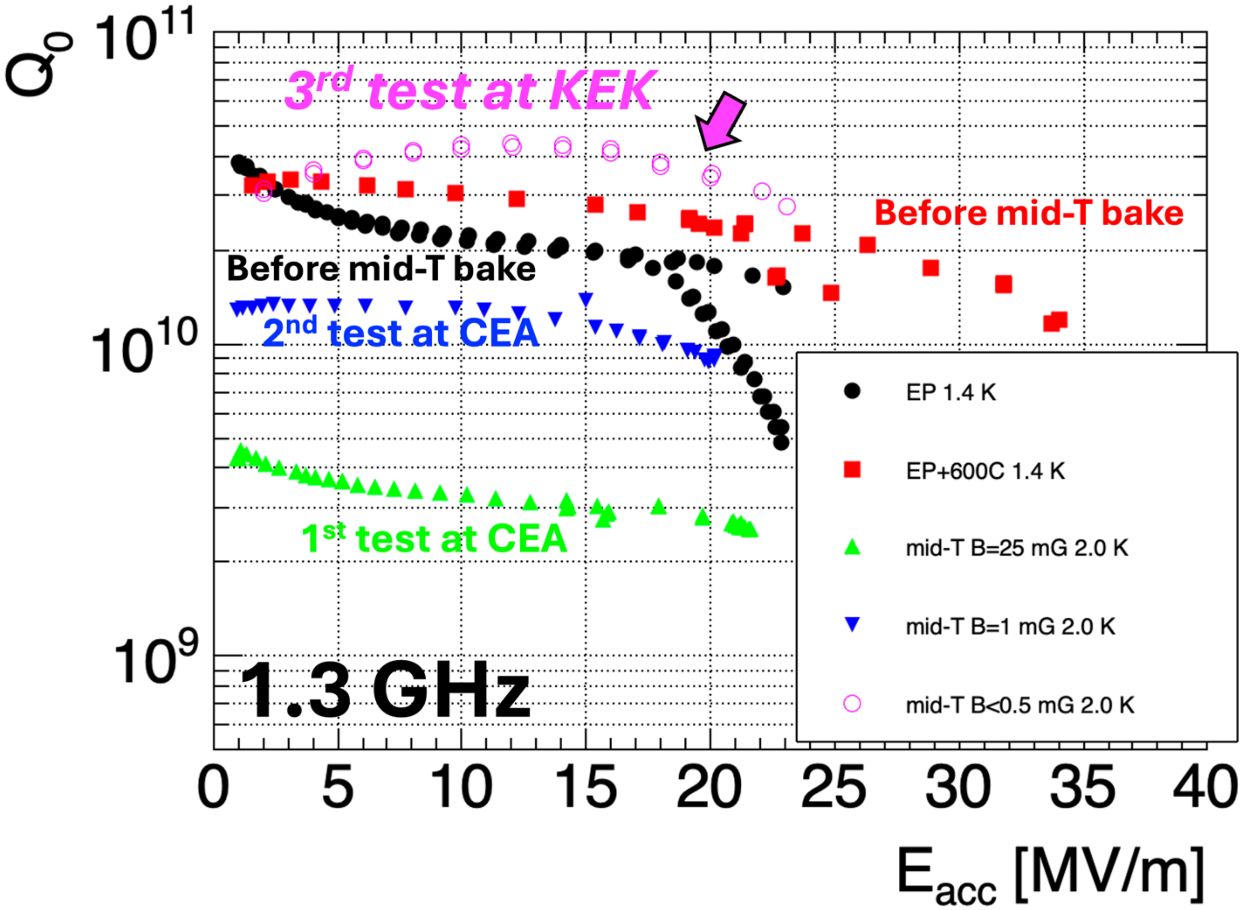
1st (June) and 2nd (July) tests at CEA Saclay

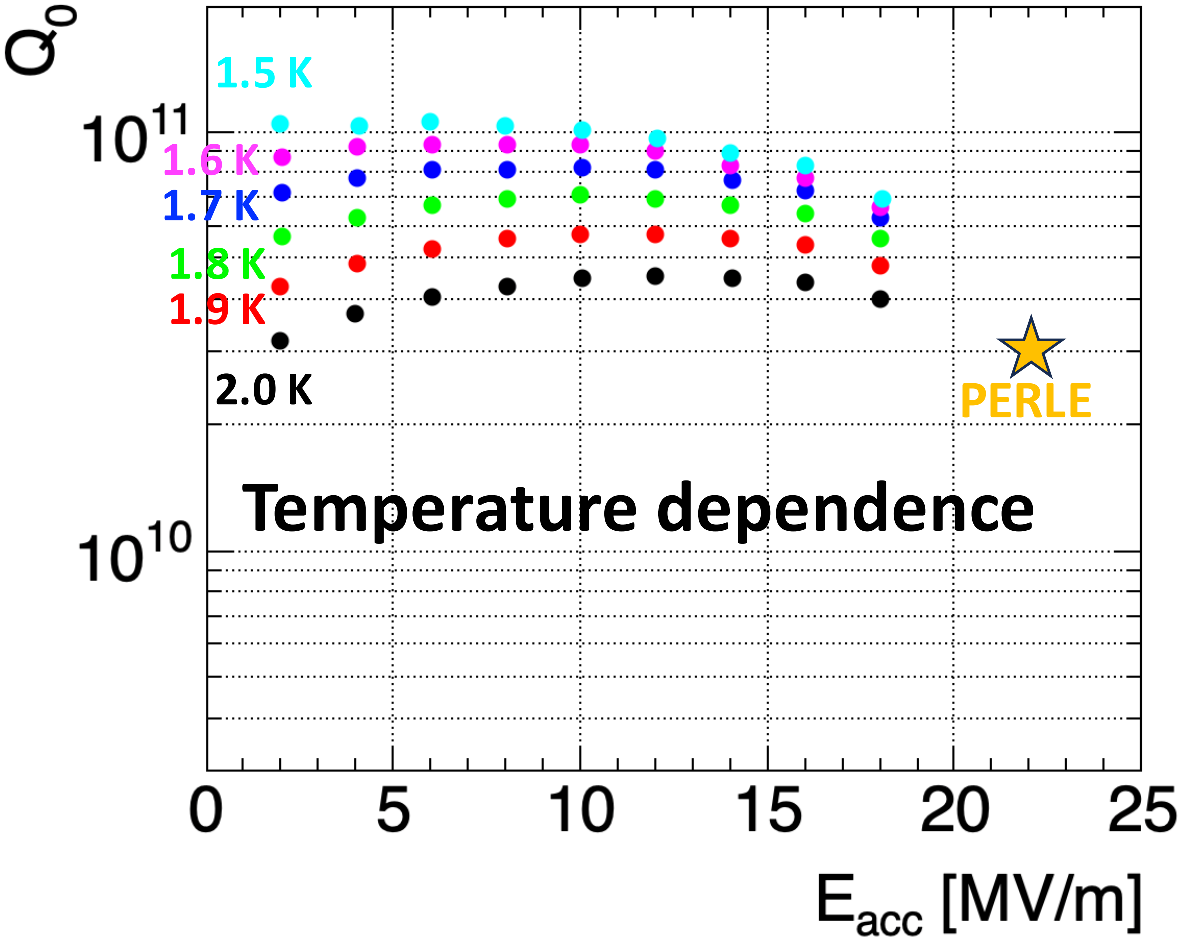
3rd test at KEK-STF: Sep 30 – Oct 11



4th test at KEK-STF: Feb 2025 after 800C annealing in Jan

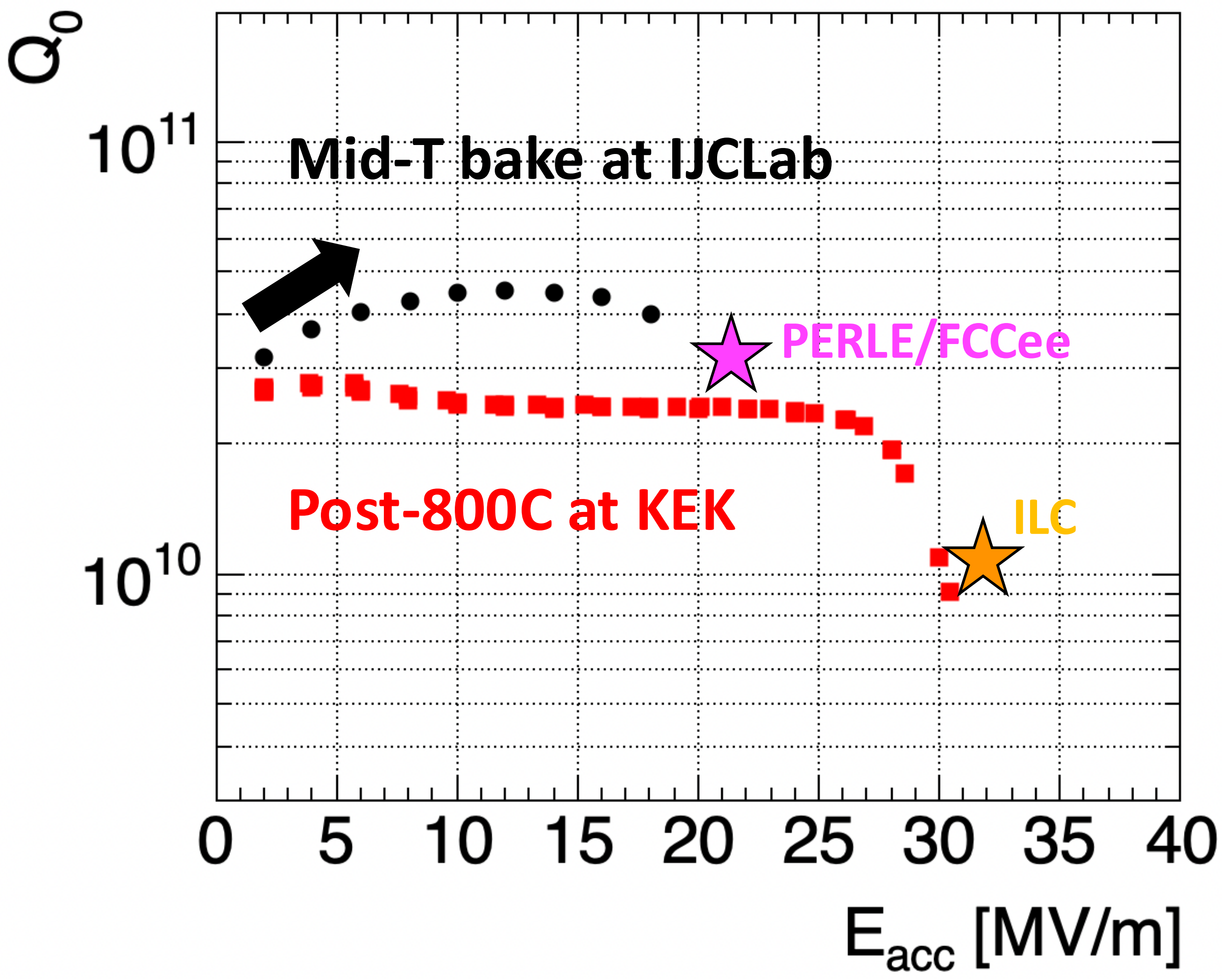
Activities in 2024 (FR → JP): cavity measurement

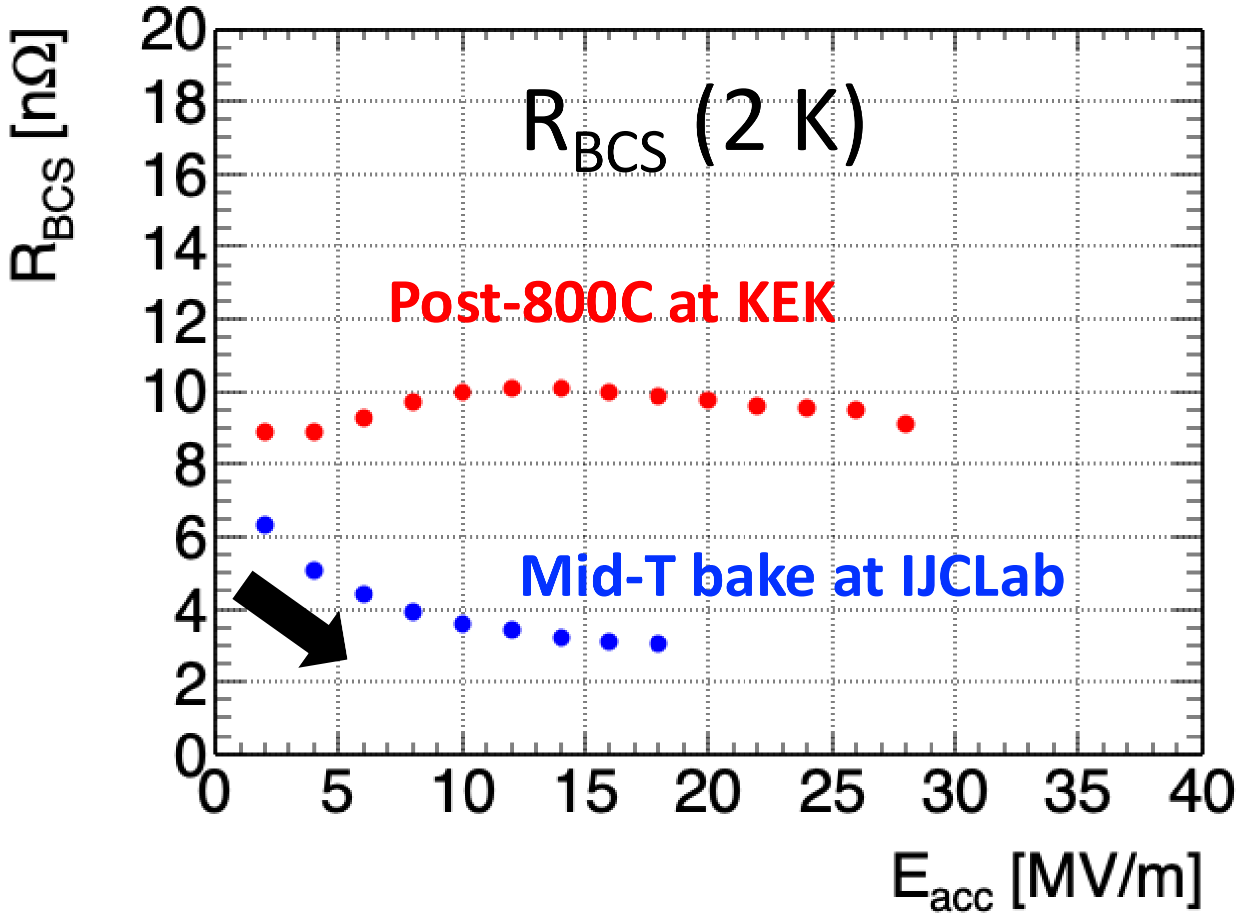




- Measurement result at CEA was not excellent ← magnetic fields issue
- One week measurement after ERL2024 → excellent result at KEK in reduced magnetic fields

Switch OFF/ON the *anti-Q-slope*





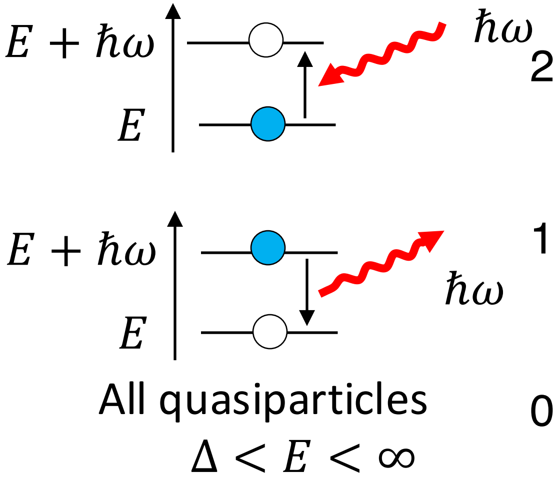
Increase in Q / decrease in R by the RF field is a peculiarly nonlinear phenomenon

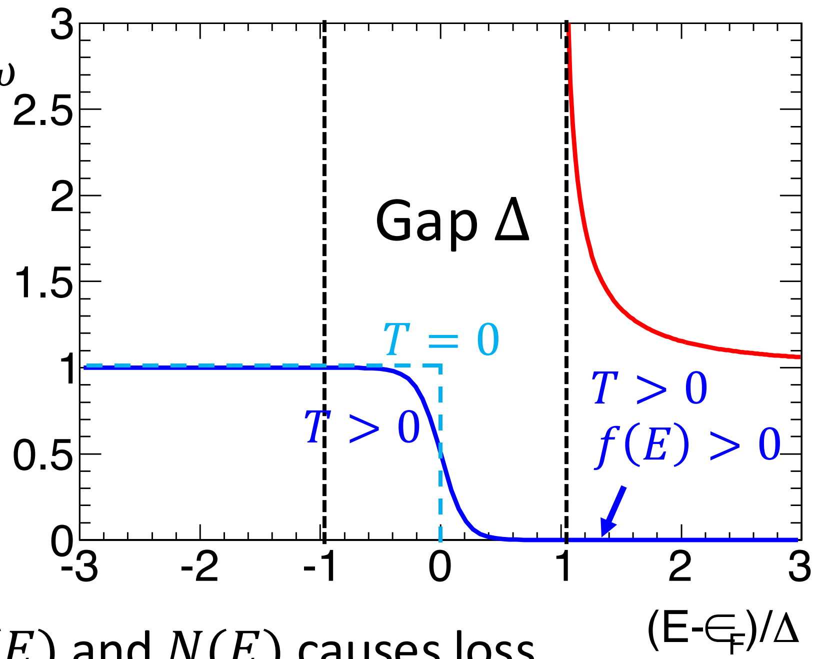
→ anti-Q-slope → critical for FCC-type applications

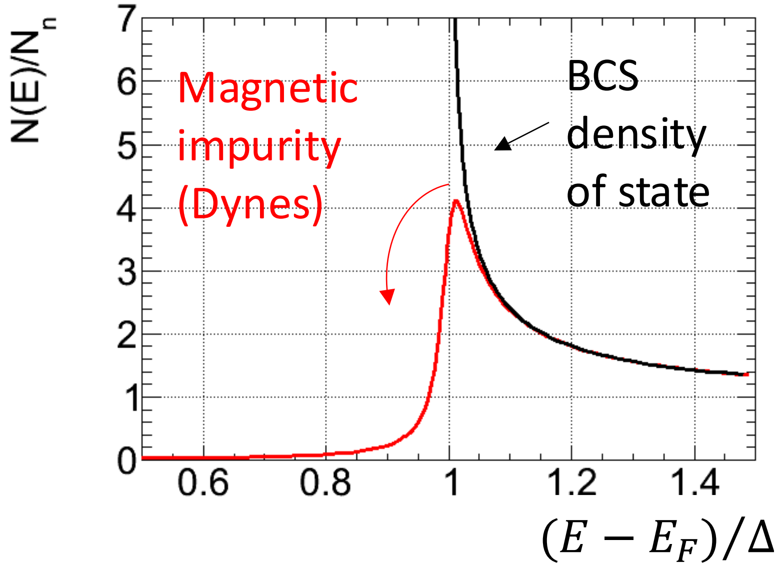
High-Q (low R_s) theory: Homogeneous disorder

Quasiparticle loss

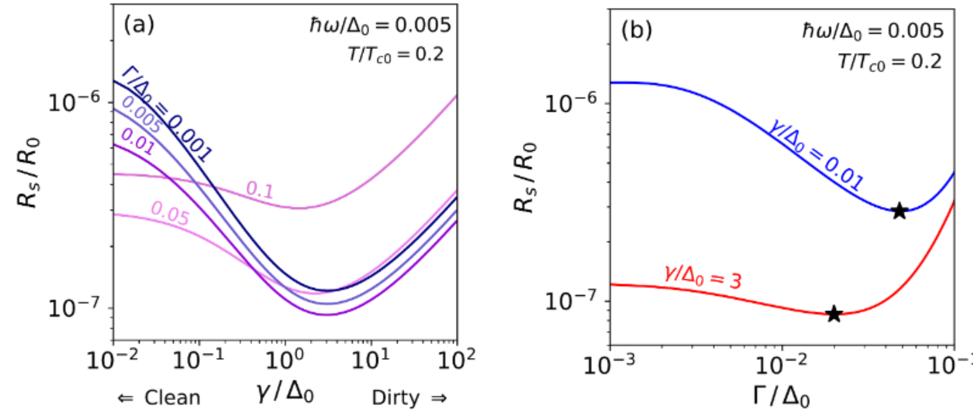
$$R_s = R'_{BCS}(T;\omega;\gamma,\Gamma) \propto \hbar\omega \int_{\Delta}^{\infty} dE\,[f(E) - f(E+\hbar\omega)] \times N(E)N(E+\hbar\omega) = R_{BCS} + R_{res}$$







Takayuki Kubo, Phys. Rev. Applied 17, 014018, 2022



Non-magnetic scattering

Magnetic scattering

<u>The overlap between $f(E)$ and $N(E)$ causes loss</u>

The pole at Δ cause R_{BCS}; the states below Δ causes R_{res}

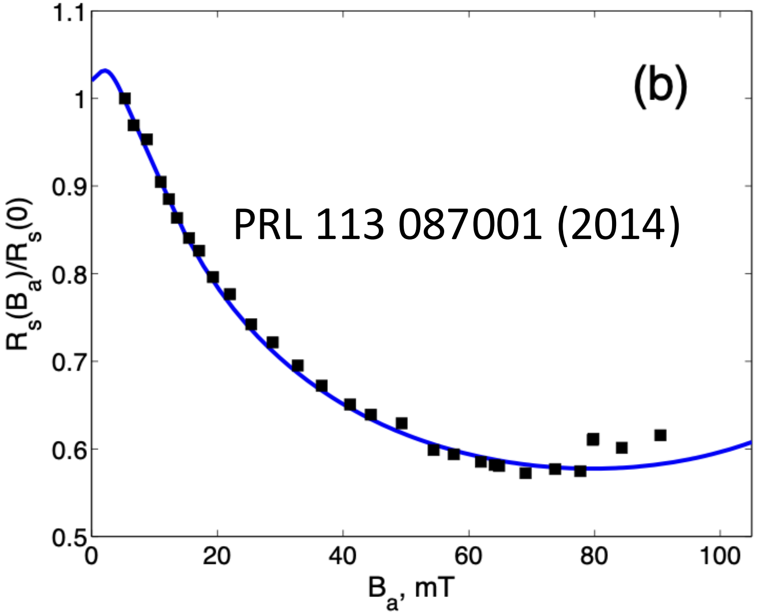
→ Smearing of $N(E)$ decreases R_{BCS} and increases R_{res}

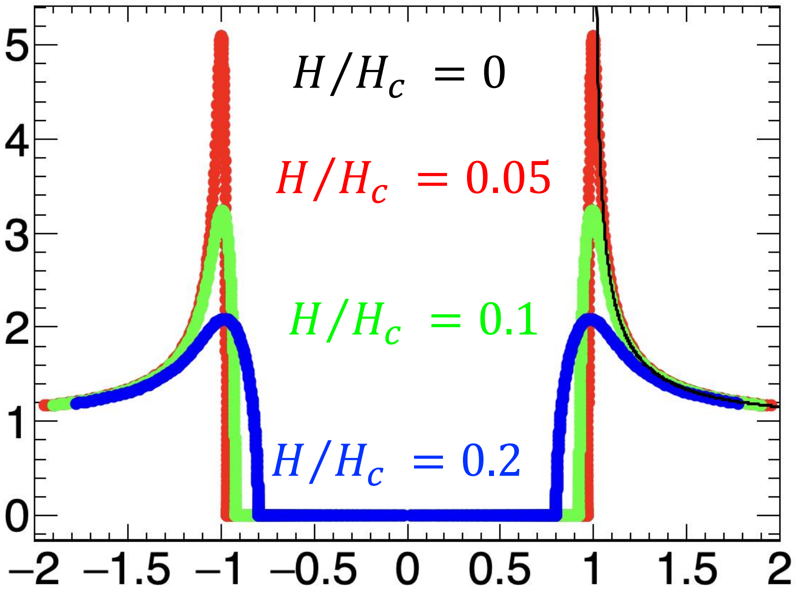
→ Combination of magnetic (O?) and nonmagnetic (N?) **impurity scattering** can control a minimum of $R_{BCS} + R_{res}$

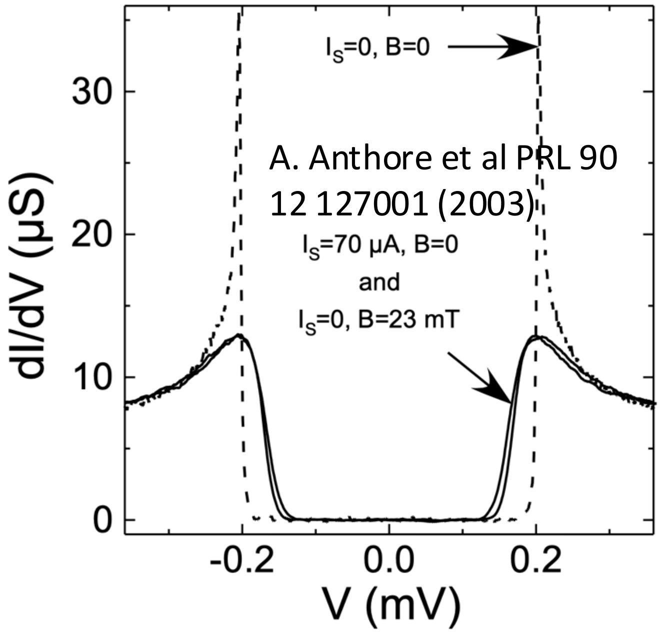
The theory is valid only at low field (1st order perturbation)

Gurevich-Kubo theory for anti-Q-slope

Smearing of $N(E)$ → R_{BCS} ↓ caused by field not impurity







- DC field is known to smear $N(E)$ → reduction of net number of thermally excited quasi-particles
- Extrapolation of DC result to RF may be justified relaxation time of SC is faster than RF (quasi-DC approximation)
- Eliashberg excitation of $f(E)$

$$f_0 > 1.73/2\pi\tau_E \sim 15\ \mathrm{GHz} \gg 1\ \mathrm{GHz\ (SRF)}$$

→ Extrapolation of DC may be valid for SRF

Energy relaxation time

Metal	T_c (K)	$\tau_E{}^a$ (s)	k_BT_c (μeV)	γ_r (μeV)
Zn	0.88	$9.3\ 10^{-8}$	76	$7.1\ 10^{-3}$
Al	1.18	$1.3\ 10^{-8}$	102	$5.2\ 10^{-2}$
In	3.41	$9.5\ 10^{-11}$	294	6.9
Sn	3.72	$2.7\ 10^{-10}$	321	2.4
Nb	9.25	$\boxed{1.8\ 10^{-11}}$	798	37

1 GHz corresponds to $\hbar\omega$ = 4.1 μeV.

Mooij, J. E. Enhancement of Superconductivity, chap. 9, 191–287 (Plenum Press, New York, 1981).

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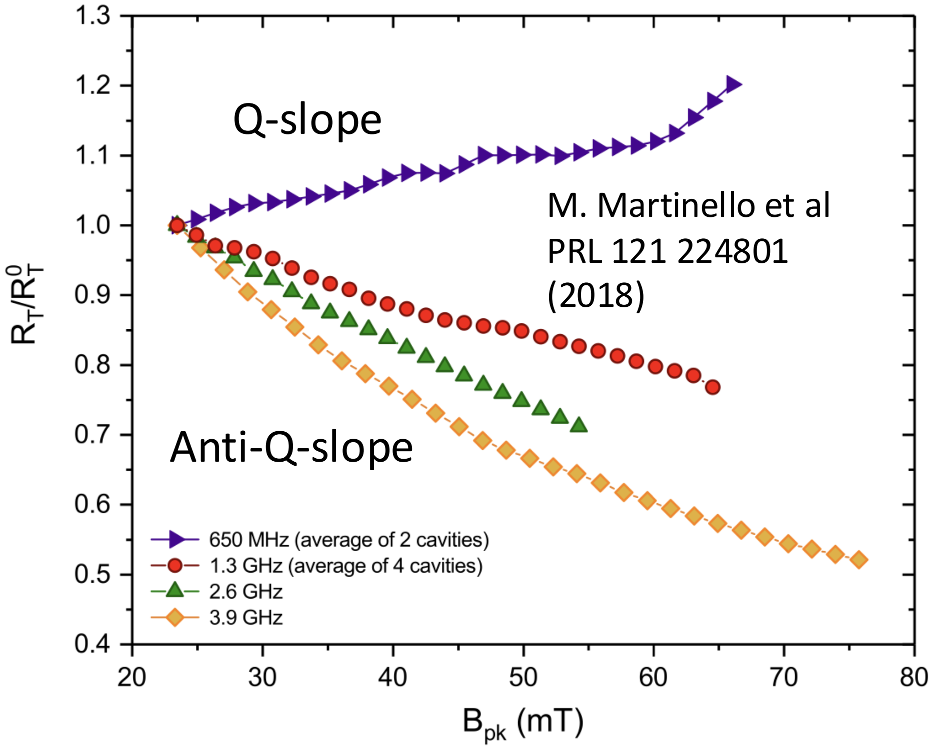
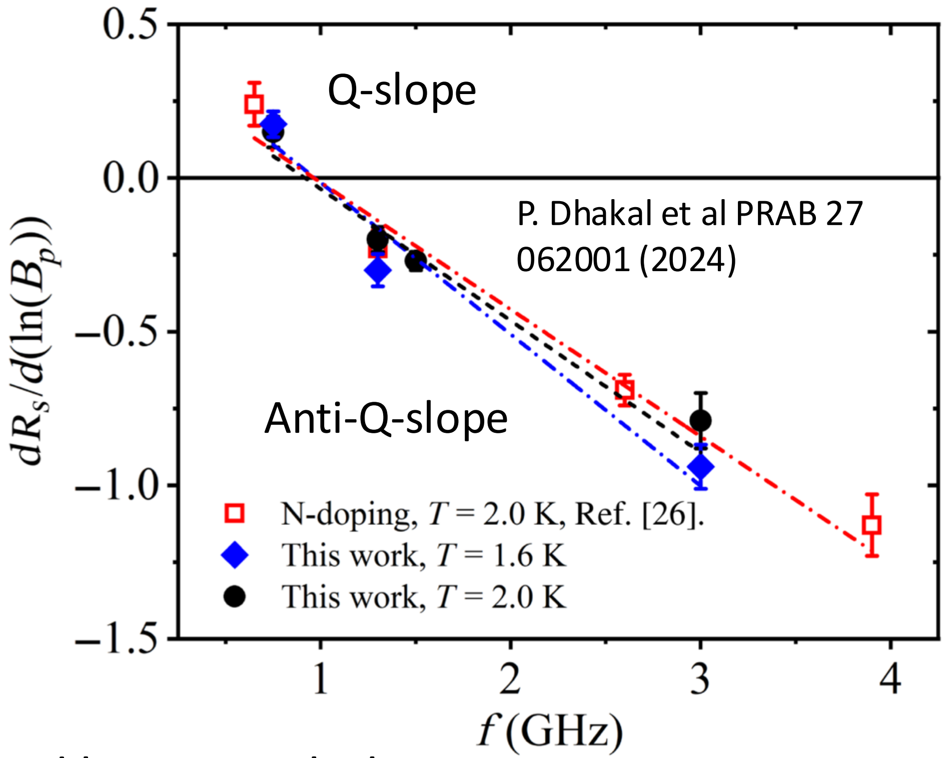
Frequency dependence of anti-Q-slope theory





- Frequency dependence (higher/lower 1 GHz) was NOT explained by Gurevich theory
- Electron-photon relaxation time $\tau_{e,ph} \sim 0.23$ ns $\gg \tau_E = 18$ ps (energy relaxation time)
- If the relaxation process is dominated by $\tau_{e,ph}$, corresponding cross-over is **1.2 GHz**

→ Possible enhancement of superconductivities could cause anti-Q-slope?

Dobrovolskiy, et al. Commun Phys 3, 64 (2020).

- Extension of Gurevich theory (+ impurity self-energy and Higgs mode) enhances anti-Q-slope at higher frequency WITHIOUT $\tau_{e,ph}$ discussions (T. Kubo arXiv:2408.00334)

→ Quantitative study is the next research direction

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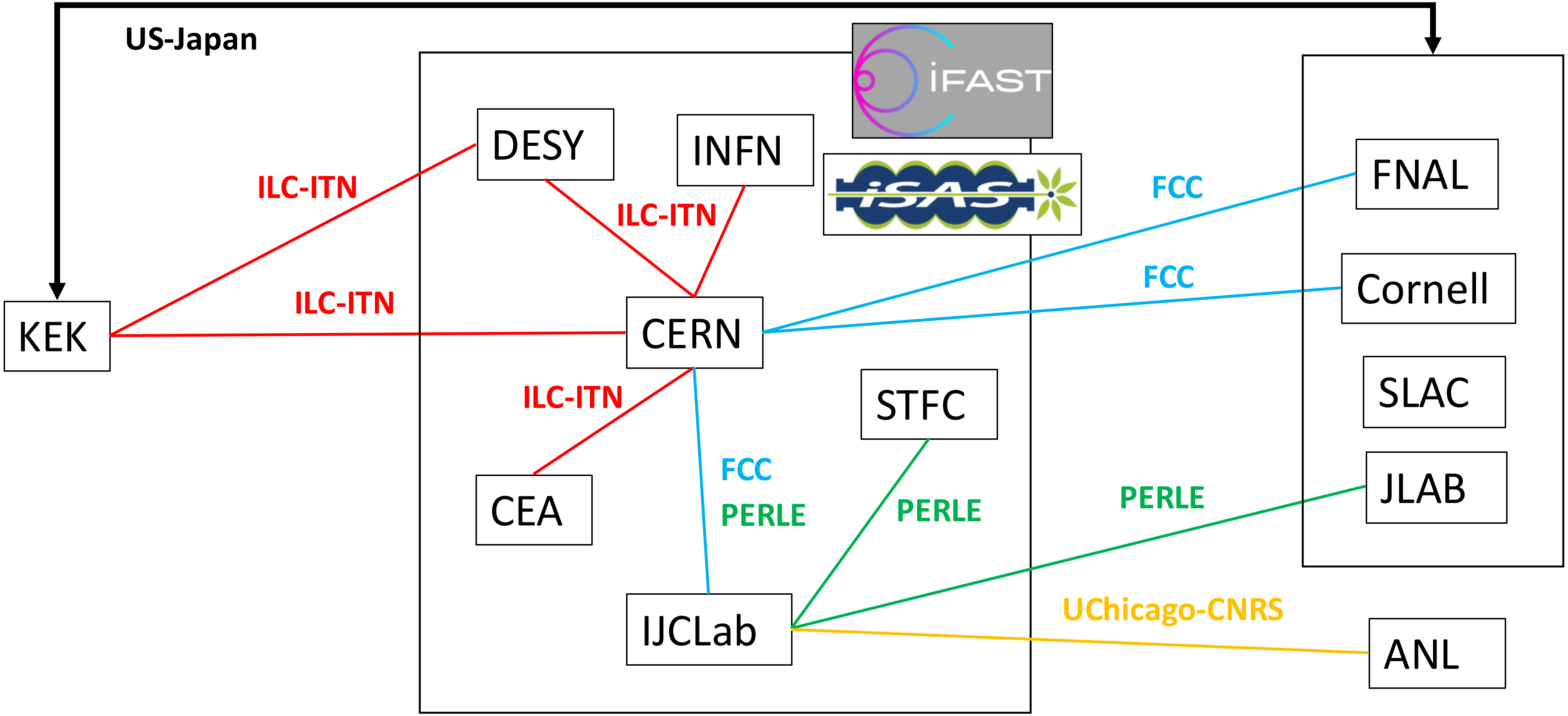
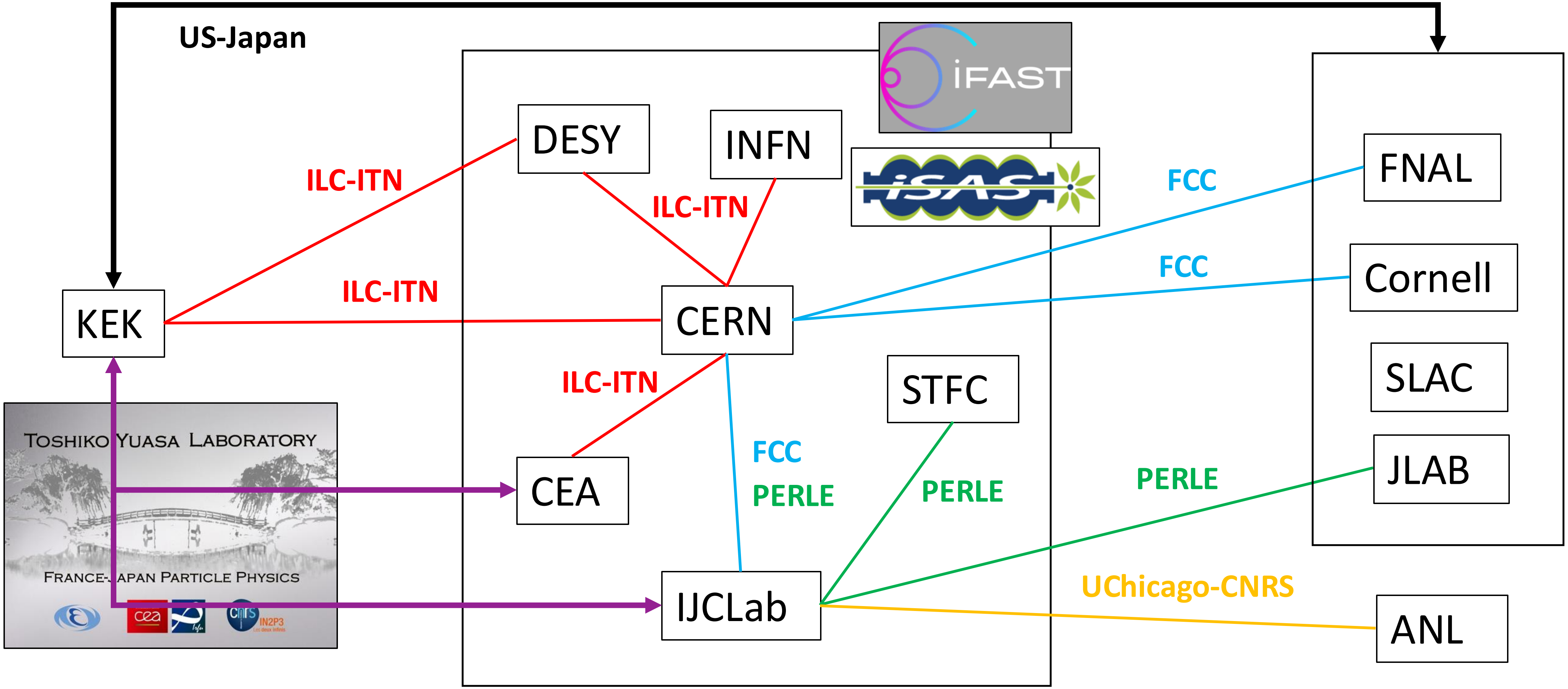
FJPPN in the global SRF collaboration



- We are ***financially*** linking laboratories for the SRF studies (TTC is only for technology and no funding…)
- FJPPN is the critical ingredient that closes the missing link

FJPPN in the global SRF collaboration



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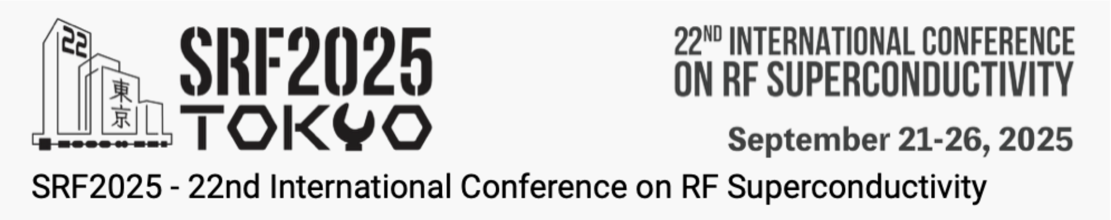
Expected activities in 2025

- Participation in SRF2025 conference [FR→ JP]
  - Akira Miyazaki is a convener of Hot Topic session “development toward extremely high performance superconducting cavities ”
  - Extend the stay at KEK before/after SRF2025 [FR→JP]
  - Heat treatment of the cavity at KEK
  - Revisit KEK in November 2025
  - Cavity preparation (IJCLab clean room technician) works with KEK people inside clean room
  - Cavity testing (Akira Miyazaki)



- Hayato Ito / Kensei Umemori visit IJCLab (time slot to be discussed…LCWS2026?) [JP→FR]
  - Participation in heat treatment with IJCLab vacuum furnace
  - Seminar on heat treatments at KEK
- Theoretical collaboration
  - Takayuki Kubo helps Akira Miyazaki to implement numerical codes
- Matching fund EAJADE will co-finance the travel with FJPPN
- Starting point for larger grant application (?)

Conclusions

- SRF cavities are the core of next particle accelerators
- We are more or less sure of how to make good cavities but we do not know how they work scientifically and systematically
  - Nonequilibrium nonlinear phenomena!
  - Challenge in comparing parameters of different laboratories
- Exchange cavities / furnace heat treatment / cavity testing in different laboratories
  - A successful example is IJCLab-CEA-KEK collaboration 2024
  - The key was bilateral financial scheme: European funding + FJPPN (ERL)
- Based on the success in 2024, we propose to decoupled SRF cavities from ERL
  - SRF collaboration will focus on more general scientific aspects of superconducting physics
  - ERL collaboration will focus on beam dynamics, photocathode, more specific and practical aspects
- FJPPN is the last piece of puzzle that fills the missing link in the global collaboration among US, EU, and JP

PhD job opening for high-Q cavity study

INSPIRE HEP

jobs

Fundamental studies of superconducting radiofrequency cavities [CNRS-UChicago joint-PhD program]

U. Paris-Saclay • Europe

physics.acc-ph | cond-mat | physics | PhD • Experiments: CERN-FCC

Deadline on Jun 30, 2025

- Systematic data analysis of SRF cavity data over the world
- Comparison to nonequilibrium superconductivity theories
- Contact: Akira.Miyazaki@ijcalb.in2p3.fr