Introduction of Superconducting RF Cavity

(2)

Recent Progress on SRF Cavity Performance

Eiji Kako (KEK, Japan)

2026 Accelerator Summer School
at Korea University
July 07, 2026'

Outline of the Lecture

1. Fundamental of SRF Cavity System

   (60 min. Lecture + 10 min. Discussion)

Break (10 min.)

2. Recent Progress on SRF Cavity Performance

   (60 min. Lecture + 10 min. Discussion)

2. Recent Progress on SRF Cavity Performance

1. Fundamental Cavity Performance
2. High Purity Niobium Production
3. Toward Higher Q and Higher Gradient
4. Performance Recovery Techniques
5. Breakthrough for the next step
6. Summary

2. Recent Progress on SRF Cavity Performance

Innovation Center for Applied Superconducting Accelerators

This lecture is based on a Review Paper by E. Kako.

Book project: New Horizons in SRF technology: towards future High-Energy Physics Colliders

About the Book:
This book will introduce the dimensions of SRF systems needed for the next generation of high-energy physics colliders. The sheer size of these systems motivates the need to reduce cost and to lower the electrical power consumption and hence the urgency to follow up on R&D paths that have the potential to significantly reduce the investment cost and environmental footprint. In subsequent contributions various R&D lines will be described that have already reduced the electrical surface resistance of superconducting resonators, used to accelerate particles in existing particle accelerators. Furthermore, emerging technologies are introduced, which are pursued in various laboratories around the world, and which promise a step change in today's performance. The theoretical background for all technologies will be introduced, their potential assessed, along with the needed R&D path and the anticipated timeline for operational readiness. As examples for a future HEP collider, the book starts with the requirements and challenges for the ILC, the Future Circular Collider study at CERN, and the muon collider. These machines will be taken as an example to illustrate the technological impact of the presented R&D initiatives.

Table of Content:

1

Chapter 4: Prospects of bulk Niobium cavities

Eiji Kako (KEK) and Akira Yamamoto (KEK)

4-1. Introduction

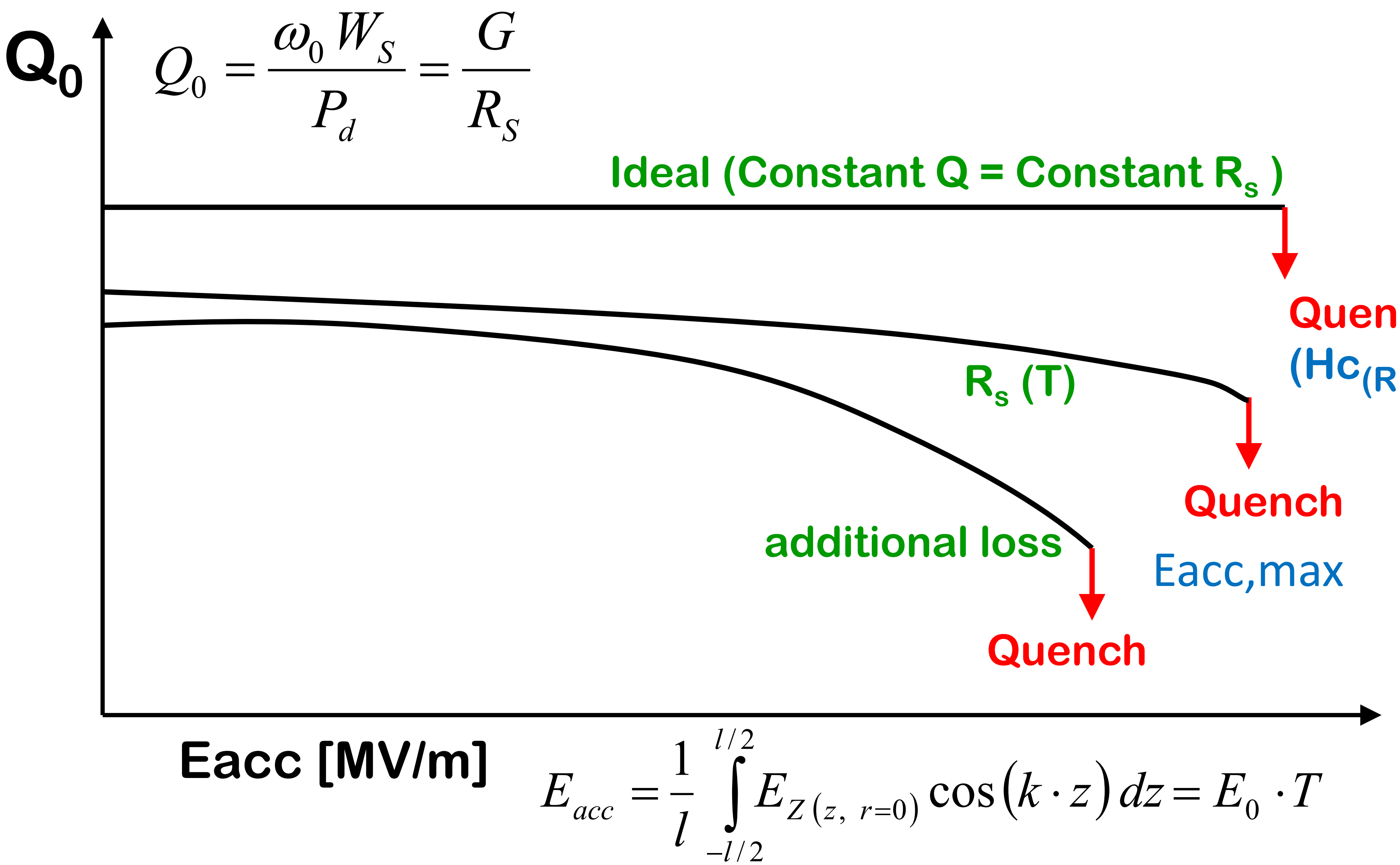
From the late 80s to the early 90s, large-scale accelerator projects using superconducting radiofrequency (SRF) cavities made of bulk niobium materials, such as TRISTAN at KEK [1], HERA at DESY [2], and CEBAF at JLab [3], were successfully constructed and operated in three regions: Asia, Europe, and Americas. Following this, the development of high accelerating gradient SRF cavities experienced remarkable progress worldwide. This was achieved through close cooperation and communication exemplified the TESLA collaboration [4] and the construction of Euro-XFEL [5], for which approximately 800 1.3 GHz 9-cell bulk niobium SRF cavities were produced. The technology for achieving higher accelerating gradient in a pulsed mode has been transferred to SRF cavity technology development for ILC [6], expected to become a global project. Recently, FRIB at MSU [7] and RAON at IBS [8] have been constructed as superconducting linear accelerators with low-beta type cavity structures for heavy ions. Furthermore, SRF accelerators such as LCLS-II HE [9] and SHINE [10] in CW operation, and ESS [11] in high duty-factor operation are under construction in the three regions. Future particle accelerator projects for high energy physics aim to build extra-ordinary large circular colliders. These projects are planned for the FCC [12] in Europe and CEPC [13] in China. Numerous SRF cavities made of bulk niobium materials have been developed and are expected for many accelerator projects worldwide. These cavities will make a significant contribution to the reliable and sustainable operation of accelerators.

Several types of accelerating structures with a wide range of operating frequency have been developed using niobium SRF cavities for worldwide accelerator projects. The cavity structures are classified by their beta-value (ratio of a particle speed to the speed of light). Low-beta structures like quarter-wave resonators (QWR), half-wave resonators (HWR) and single-spoke resonators (SSR) have been used for proton and heavy-ion acceleration with relatively low particle speed. The frequency range is mostly between 70 MHz and 350 MHz. On the other hand, elliptical structures have been used for acceleration of electrons and protons with high beta-values larger than 0.5. The frequency ranges from 500 MHz to 3.9 GHz. The development of these niobium SRF cavities requires high quality control for high purity niobium production, cavity fabrication technology, surface preparation processes, and a strict clean environment during assembly.

2. Recent Progress on SRF Cavity Performance

1. Fundamental Cavity Performance
2. High Purity Niobium Production
3. Toward Higher Q and Higher Gradient
4. Performance Recovery Techniques
5. Breakthrough for the next step
6. Summary

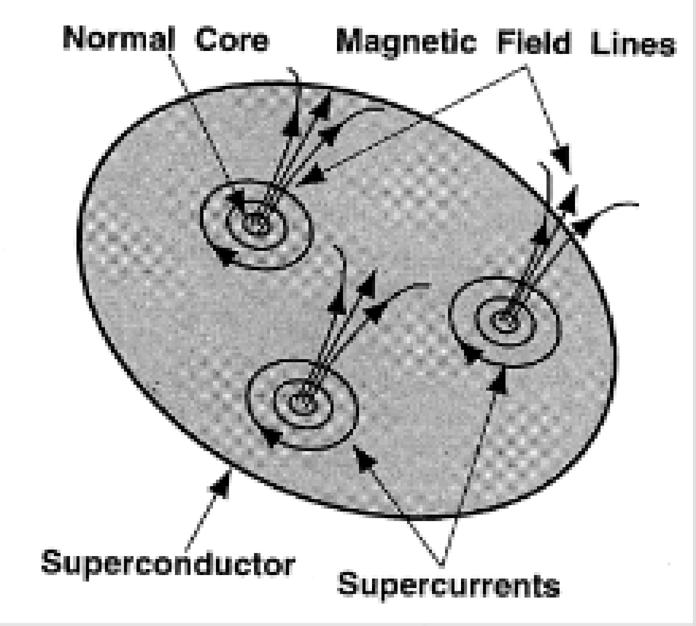
Performance of SRF cavity: Qo-Eacc curve



Cavity performance : Essential technology

- High purity Nb material (Fine-grain, Large-grain, Medium-grain)
- Forming (Hydroforming, Deep drawing, Spinning)
- Joining (EBW, TIG, LBW, Brazing, ….)
- Surface removal treatment (CP, EP, cold-EP)
- Rinsing (Detergent, Ultra-pure water, Ultra-sonic, HPR)
- Clean room environment (Slow pumping/venting)
- Assembly procedure (Robotic with AI)

Cavity performance : Residual magnetic field



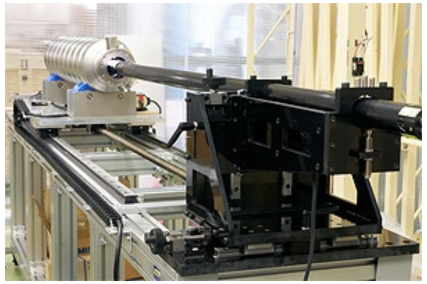
Experiment to investigate shielding effect of residual magnetic field

(0.3 nΩ / mGauss)

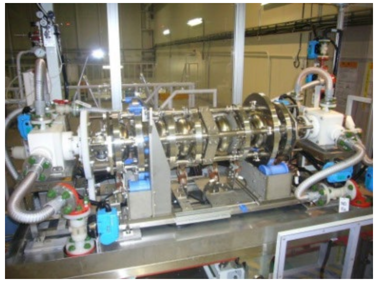
This sensitivity is strongly dependent on the surface condition.

Residual magnetic field is one of main causes of residual surface resistance, because magnetic fluxes in a normal conducting state are trapped when a transition to superconducting state occurs in a niobium cavity.

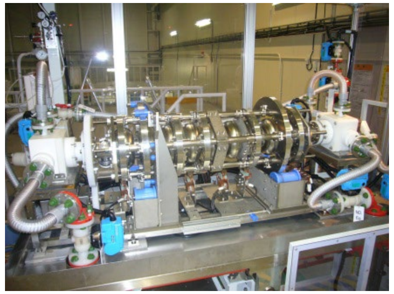
Surface preparation : indispensable preparation



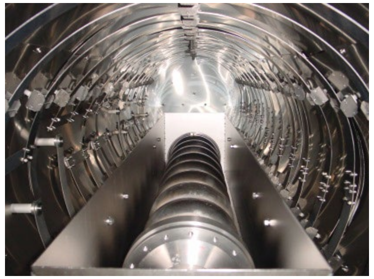
Inspection of inner surface



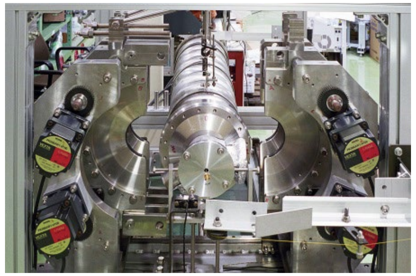
Pre-EP + EP-I (5+100 mm)



EP-II (5~20 mm)



Anneal (750°C, 3h)



Hot bath rinsing by ultra-sonic agitation with ultra-pure water

Suppression of Field Emission

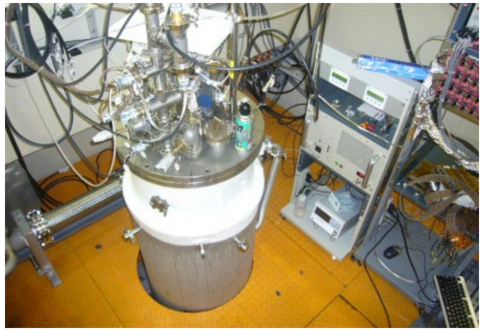
- **Rinsing by ultra-pure water**
- **Assembly in class-10 clean room**

HPR

Assembly (Class 10)

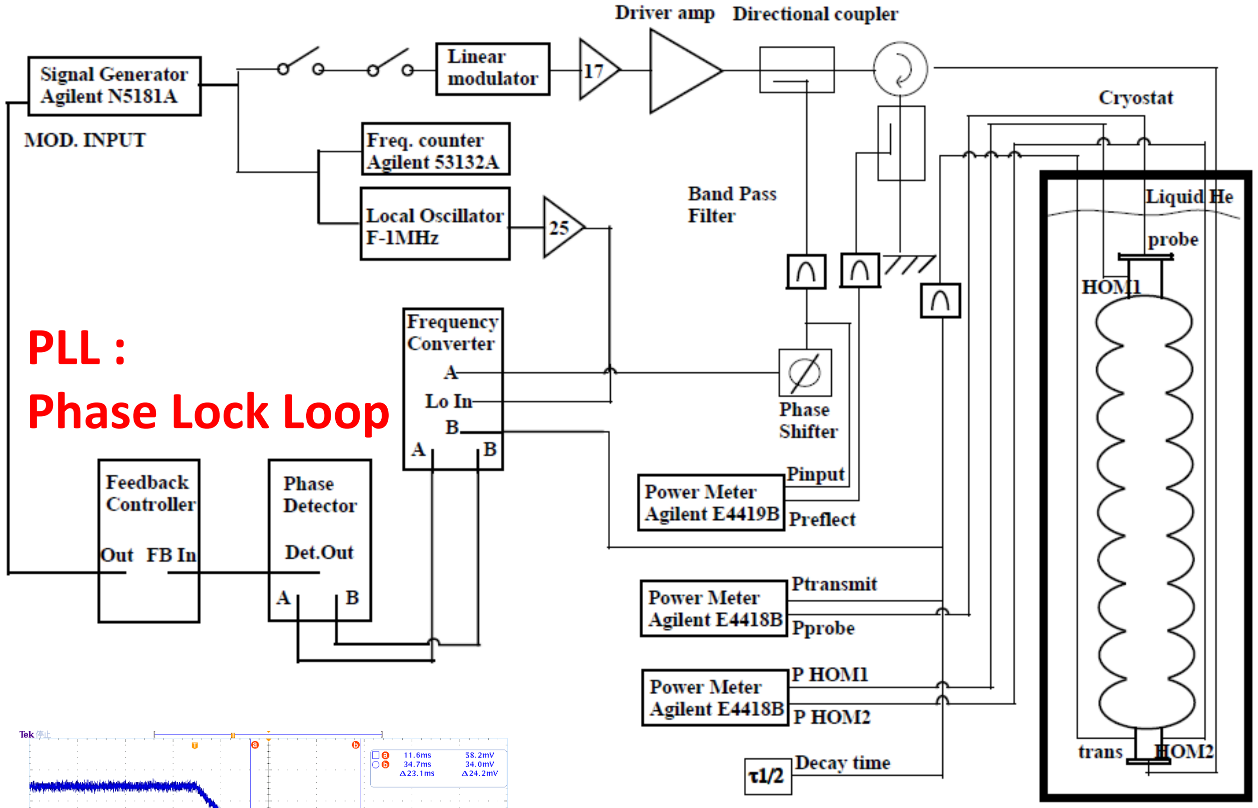
Baking (120°C, 48h) (Class 1000)

Hanging stand with T-map

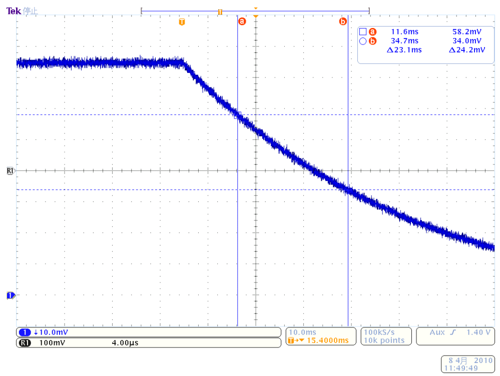


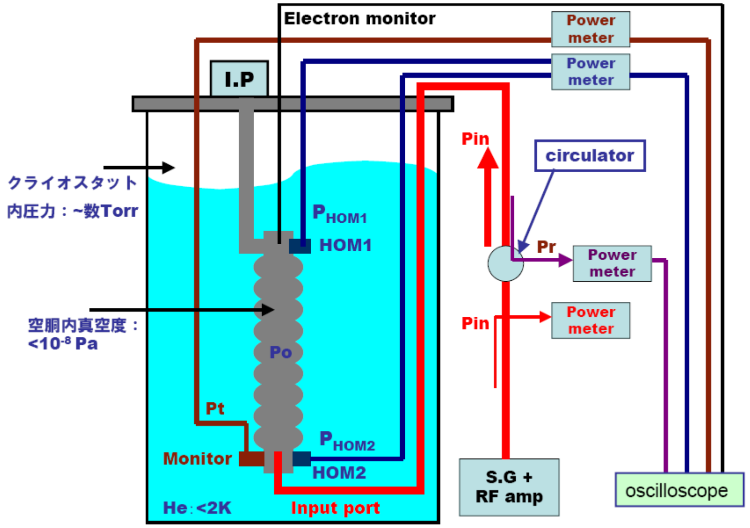
Vertical Test

RF system for Vertical Tests : VT



PLL : Phase Lock Loop





$$Q_L = 2\pi f_o \cdot \tau_{1/2} / \log_e 2$$

($t_{1/2}$: decay time of P_t)

$$P_o = P_{in} - P_{ref} - P_{ext}$$

$$\beta^* = \frac{1 \pm \sqrt{P_{ref}/P_{in}}}{1 \mp \sqrt{P_{ref}/P_{in}}}$$

$$\beta_{in} = \beta^* \cdot (1 + \beta_{ext})$$

$$\beta_{ext} = P_{ext} / P_o$$

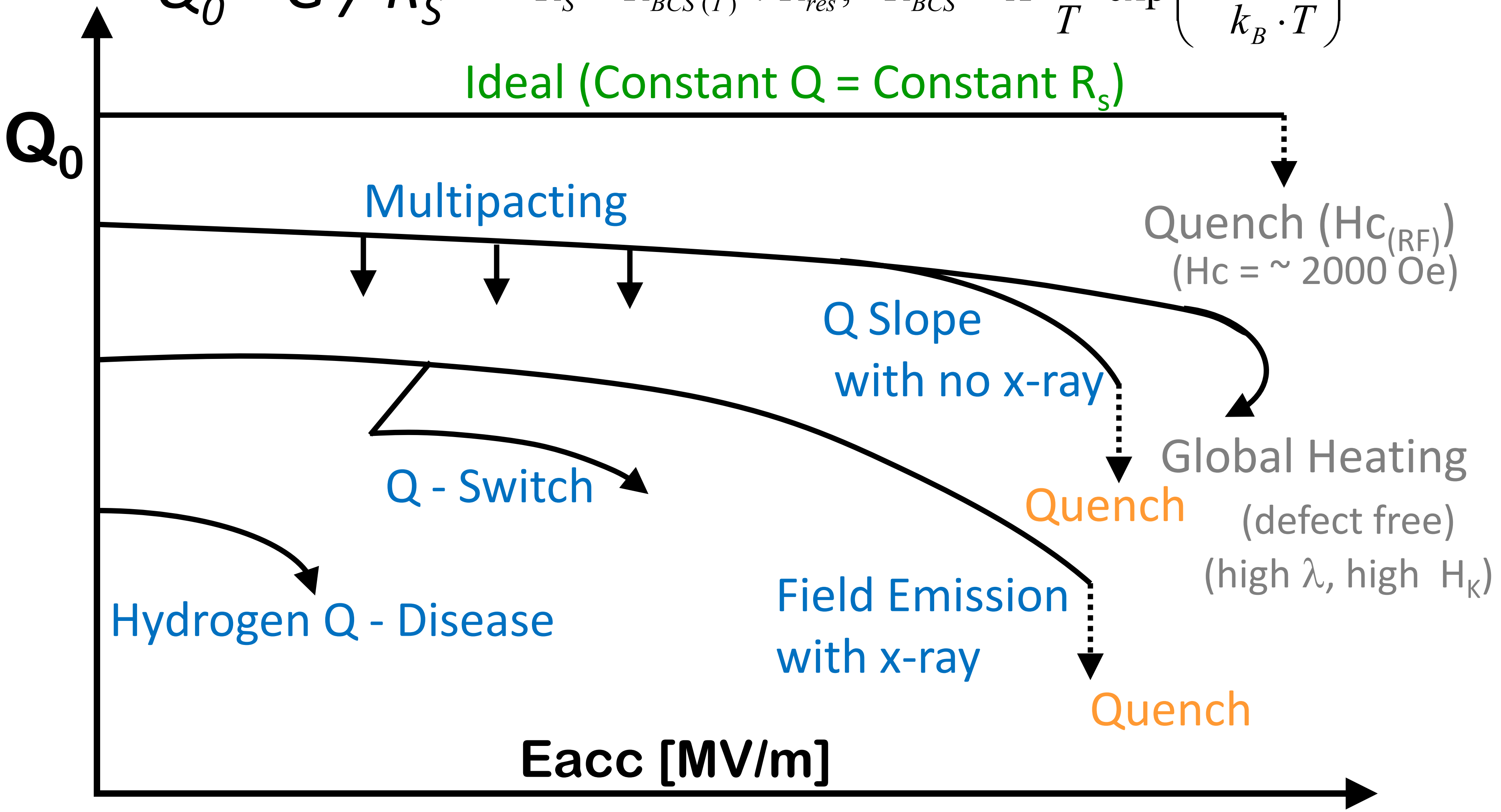
$$Q_o = Q_L \cdot (1 + \beta_{in} + \beta_{ext})$$

$$Q_{ext} = P_o \cdot Q_o / P_{ext}$$

Phenomena limiting cavity performance

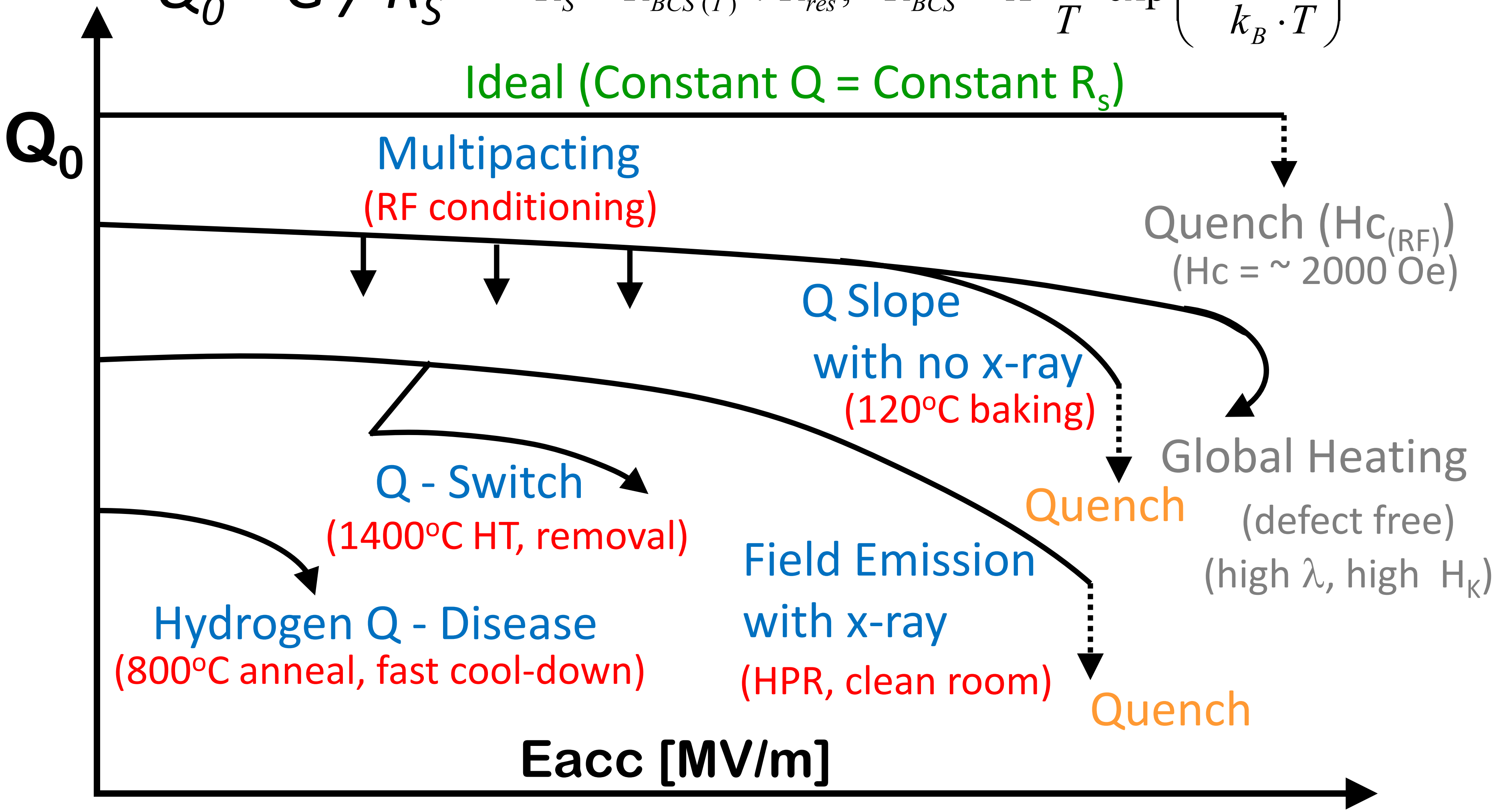
$Q_0 = G / R_S$

$$R_S = R_{BCS\,(T)} + R_{res}, \quad R_{BCS} = A\frac{\omega^2}{T}\exp\left(-\frac{\Delta}{k_B \cdot T}\right)$$



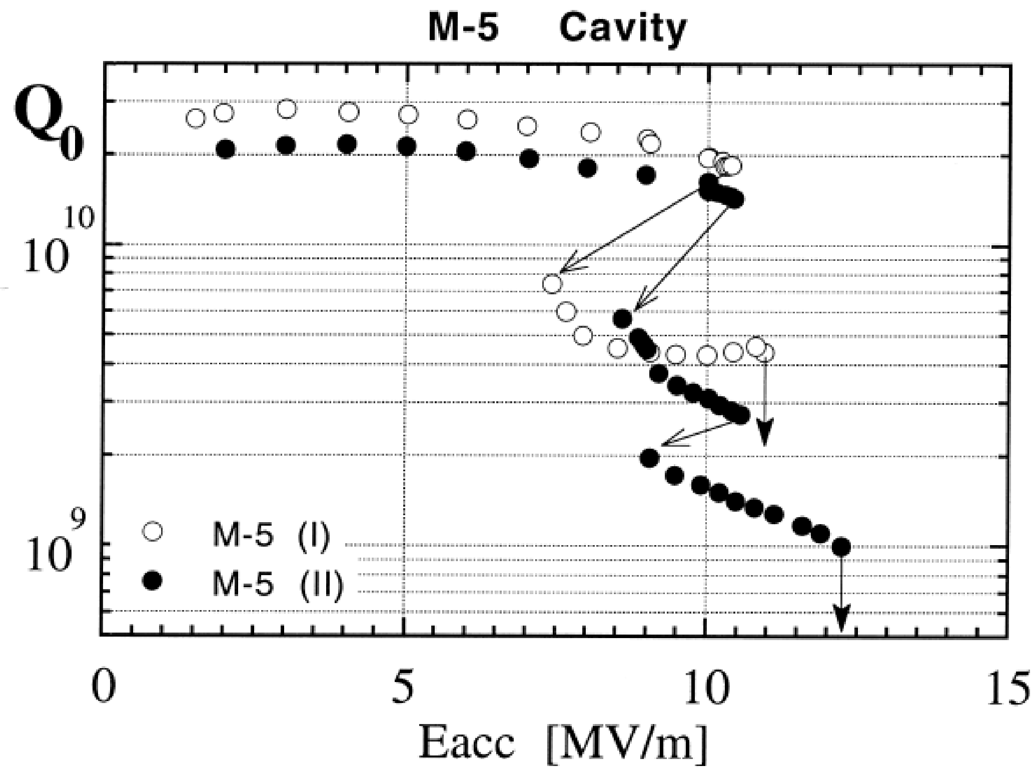
Cure methods against Performance limitation

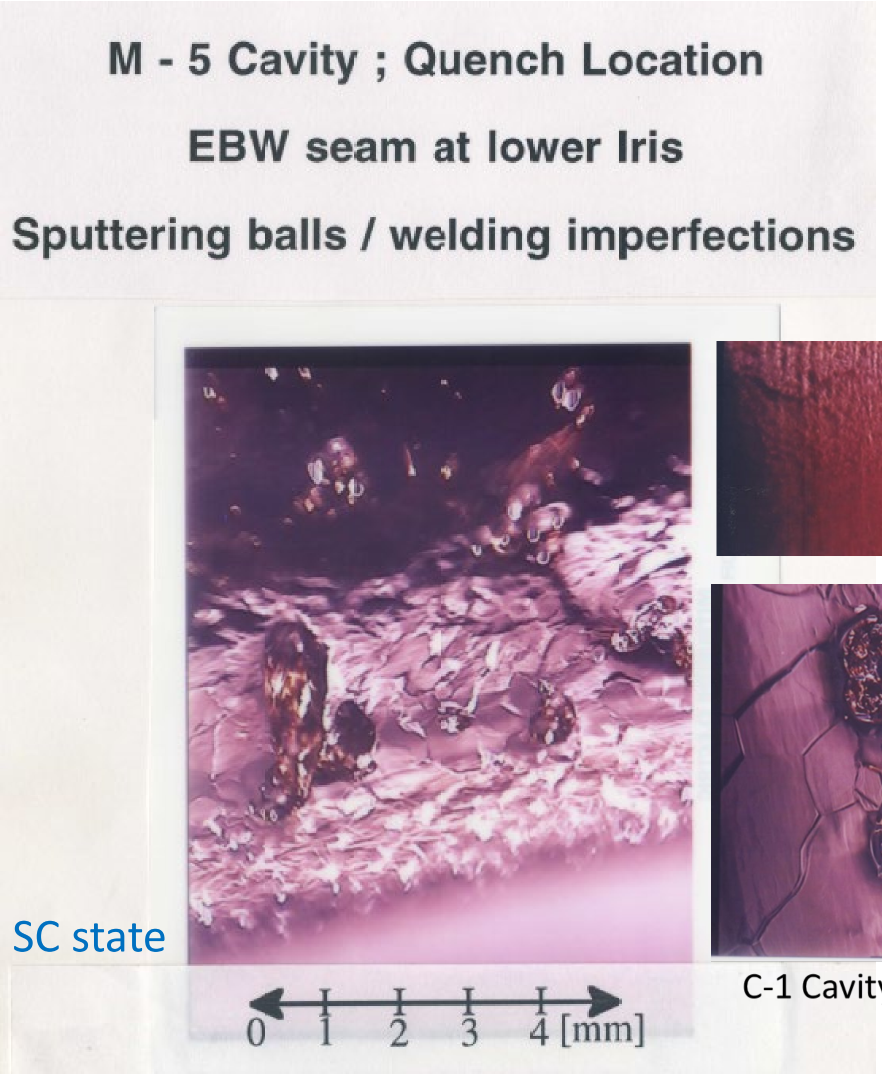
$$Q_0 = G / R_S \qquad R_S = R_{BCS\,(T)} + R_{res}, \quad R_{BCS} = A\frac{\omega^2}{T}\exp\left(-\frac{\Delta}{k_B \cdot T}\right)$$



Performance limitation : Q-switch

Q - Switch

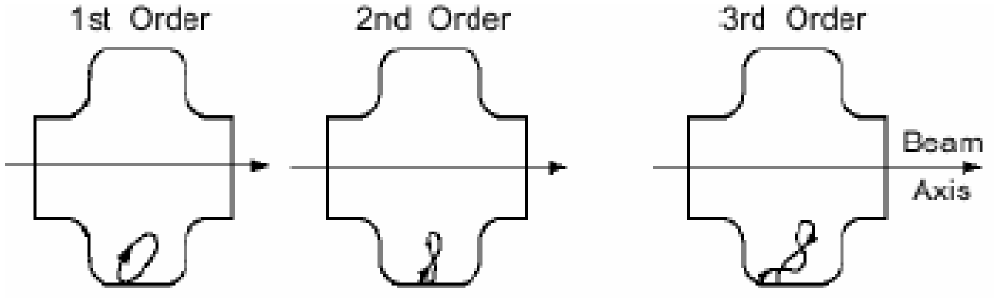




C-1 Cavity ; iris EBW (θ = 30°)

The Q-Switch is caused by heating due to the transition from an SC state to a NC state at thermally isolated defects.
Typically, around iris region, where surface currents are lower.

Performance limitation : Multipacting

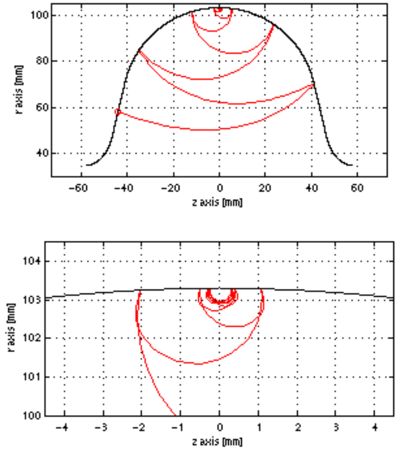


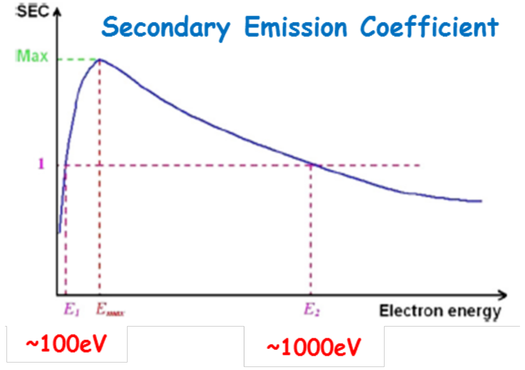
Multipacting at equator region

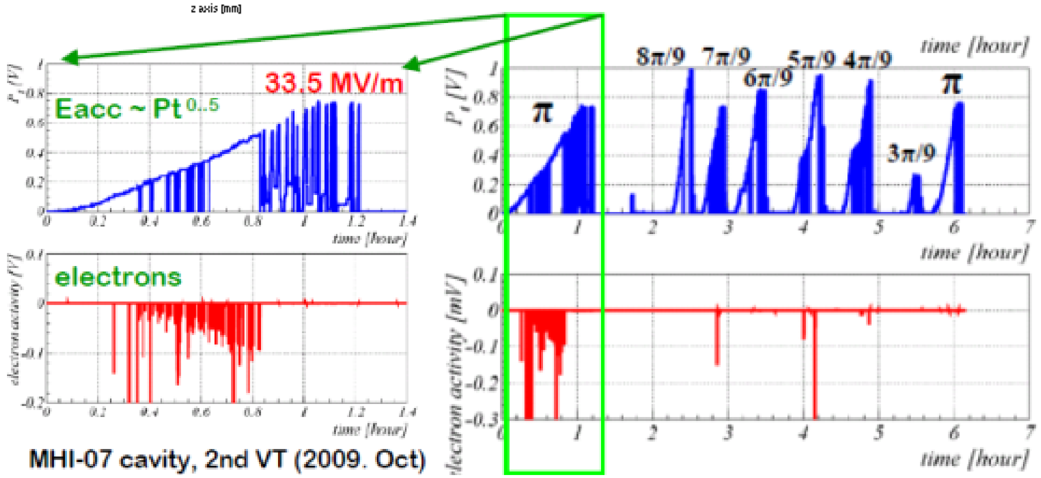
Multipacting is a low RF power, electron multiplication based on resonance breakdown phenomenon in vacuum. For a cavity shape such as a pill-box cavity, the cavity performance is frequently limited by a multipacting phenomenon around the equator region. A spherical cell shape is usually used for actual SRF cavities to suppress the multipacting phenomenon by eliminating a flat region around the equator. In the design of the cell shape, the ease of forming processes and rinsing procedures for cleaning should also be considered.

Multipacting (Clean surface is essential.)

Multipacting is usually processed-out by RF conditioning.

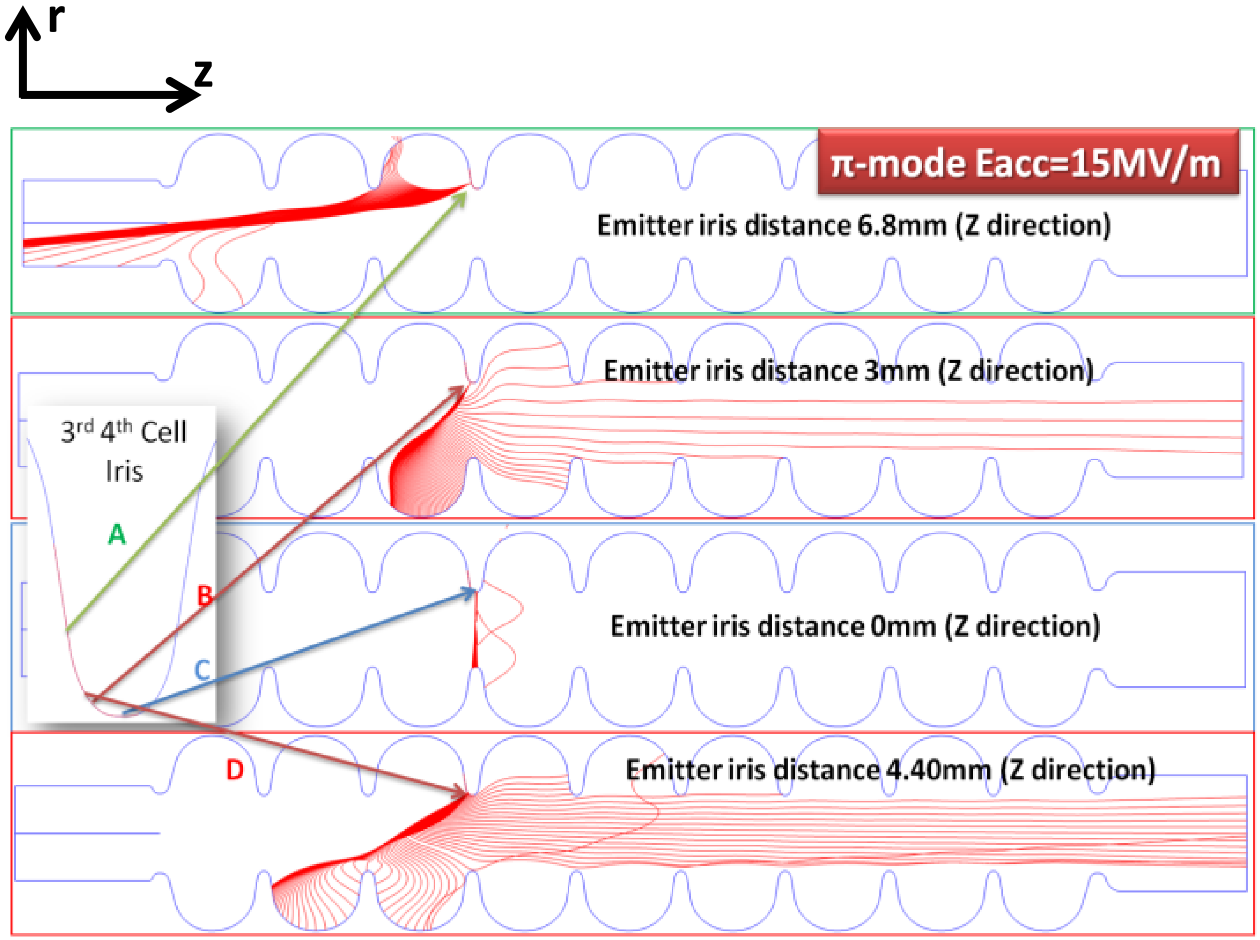






Performance limitation : Field Emission

TM010-mode

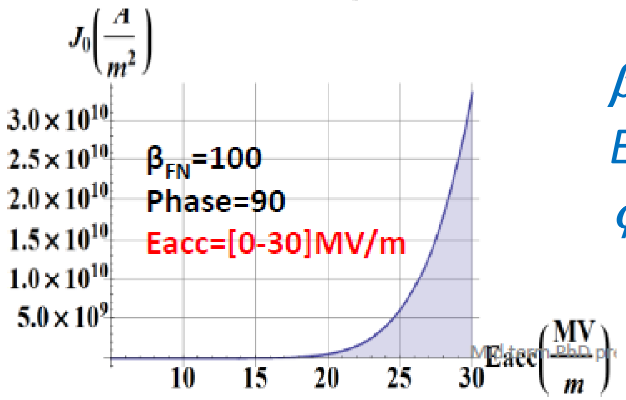


[Thesis by E. Cenri (KEK)]

Source of
field emitted electrons

Fowler – Nordheim Equation

$$J = \frac{A_{FN}(\beta_{FN} E_{surf}(t))^2}{\varphi} e^{\frac{-B_{FN}\varphi^{1.5}}{(\beta_{FN} E_{surf}(t))}} \left[\frac{A}{m^2}\right]$$

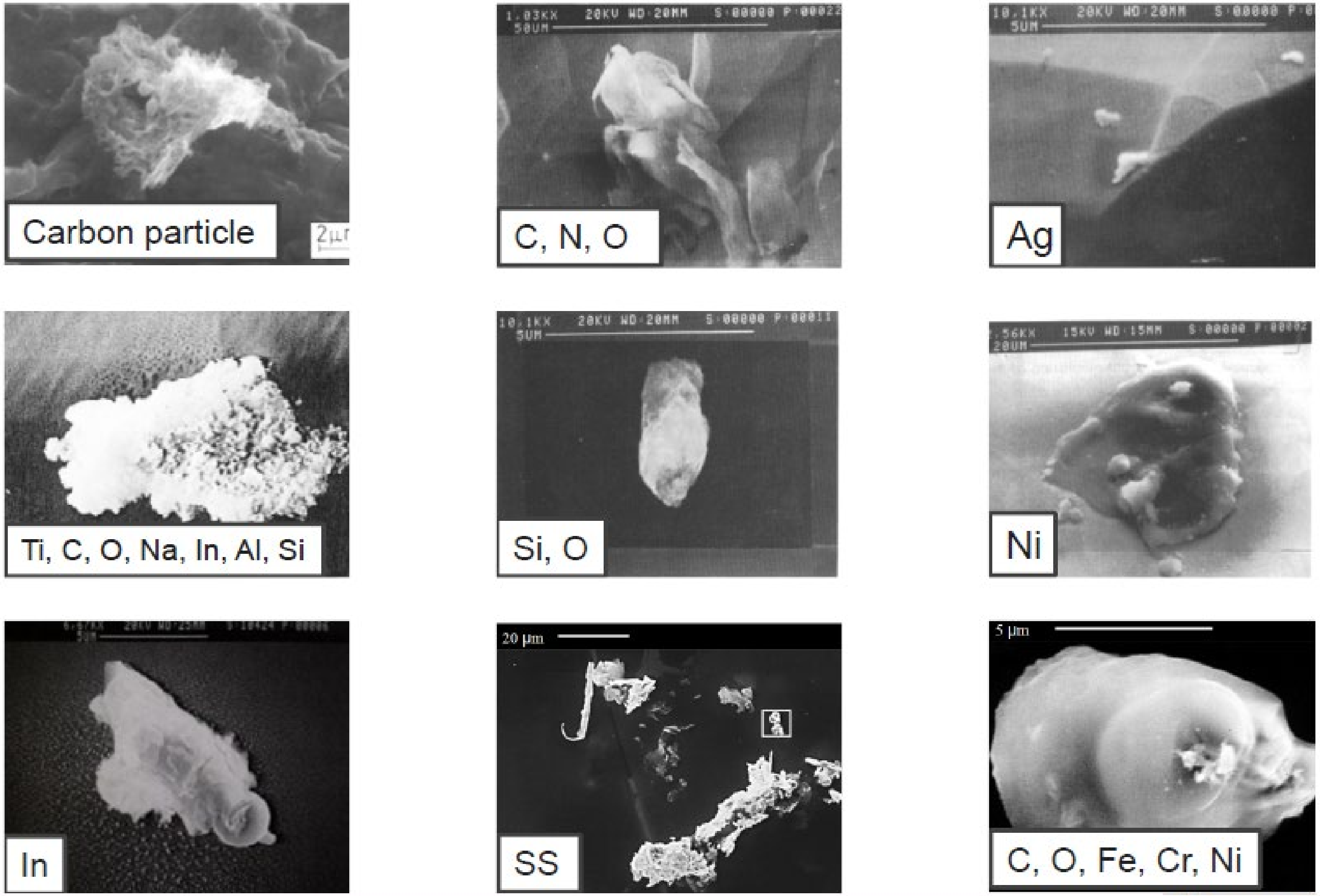


β_{FN} : field enhancement factor

E_{surf} : surface electric field

φ : work function of Nb

Sources of field emission: dust particles



5/18/2017 Martina Martinello | IPAC 2017

[by M. Martinello (FNAL)]

Performance limitation : HPR

Application from semiconductor industries to accelerator technologies.

The Evolution of Silicon Wafer Cleaning Technology

Werner Kern*

Lam Research Corporation, Advanced Research Center, San Diego, California 92126

J. Electrochem. Soc., Vol. 137, No. 6, June 1990 © The Electrochemical Society, Inc.

High-pressure fluid jet cleaning consists of a high-velocity jet of liquid sweeping over the surface at pressures of up to 4000 psi (55, 56). The liquid can be DI water or organic solvents. The shear forces effectively dislodge submicron particles and penetrate into dense topography, but damage to the wafer can result with improperly adjusted pressure (18).

[Ph. Bernard, EPAC'92 at Berlin]

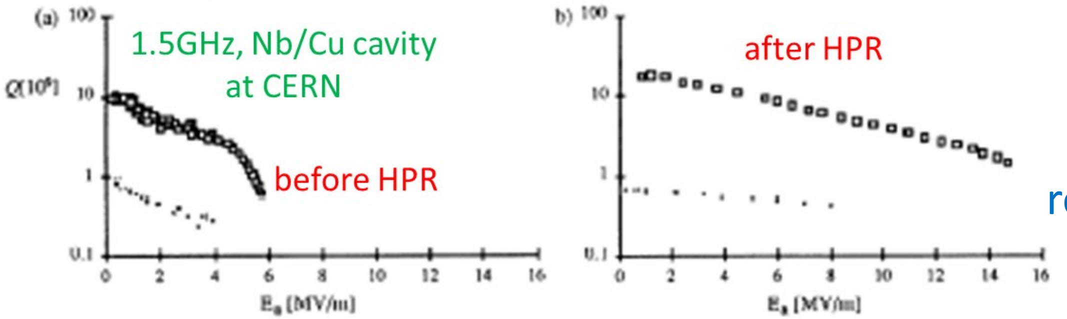


Figure 1. Q-value vs accelerating field for the fundamental mode at 4.2 K (lower) and 1.6 K (upper), a) before and b) after high-pressure water rinsing.

[P. Kneisel, SRF'93 at JLab]

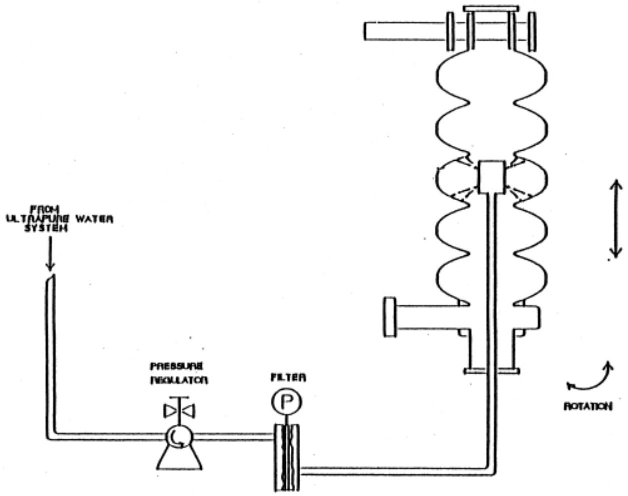


Figure 1 : Schematic of High Pressure Rinsing System

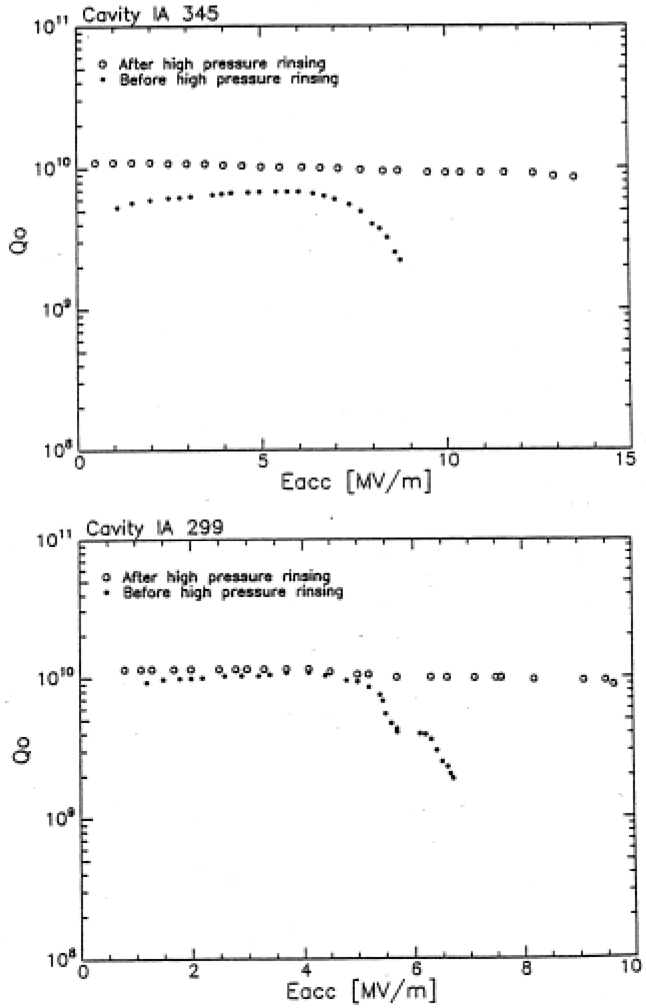
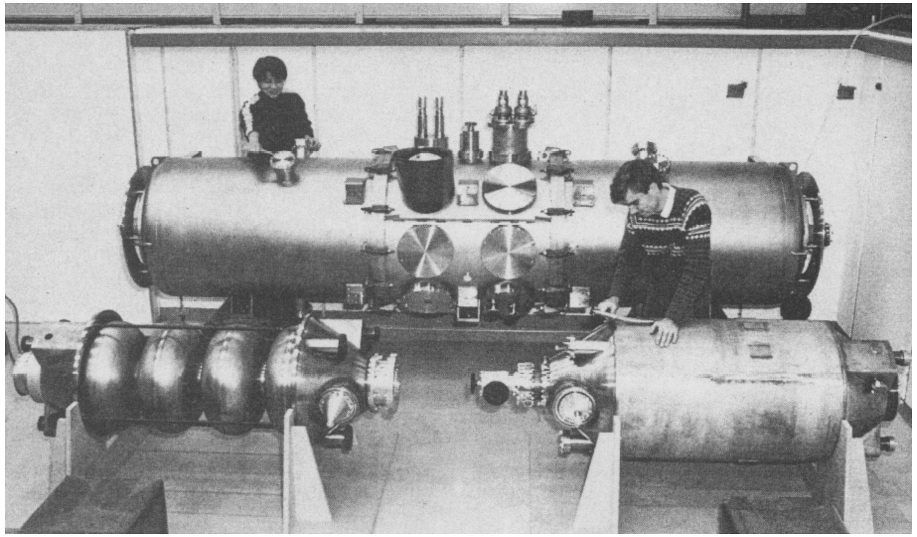


Figure 3 : Results of Production Cavity Pair IA345/IA299 before and after High Pressure Rinsing (measurements have been

Experimental results of performance recovery by high pressure water rinsing

Demonstration of the effectiveness of HPR

Performance limitation : Hydrogen Q-disease

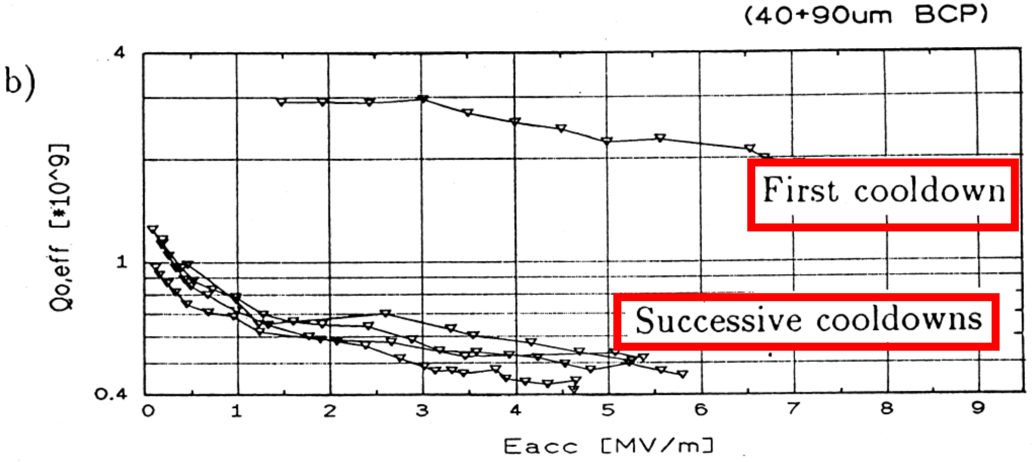


HERA cavities and cryomodule (in 1991 at DESY)

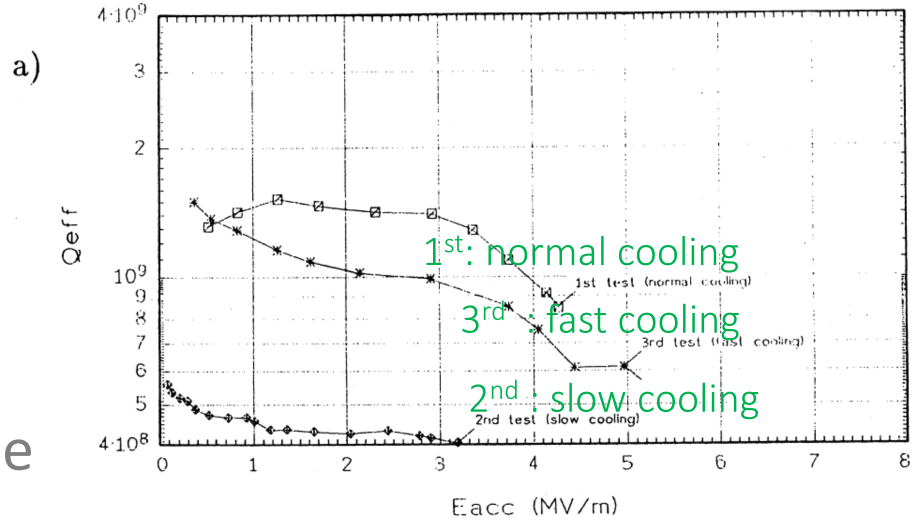
Heat capacity in the cryomodule is large, so that the fast cooling like vertical tests is very difficult.
Therefore, hydrogen Q-disease was observed in this condition.

HERA cavities (DESY) :   BCP + no Anneal → Q-disease

TRISTAN cavities (KEK) : EP + 800°C Anneal → no Q-disease

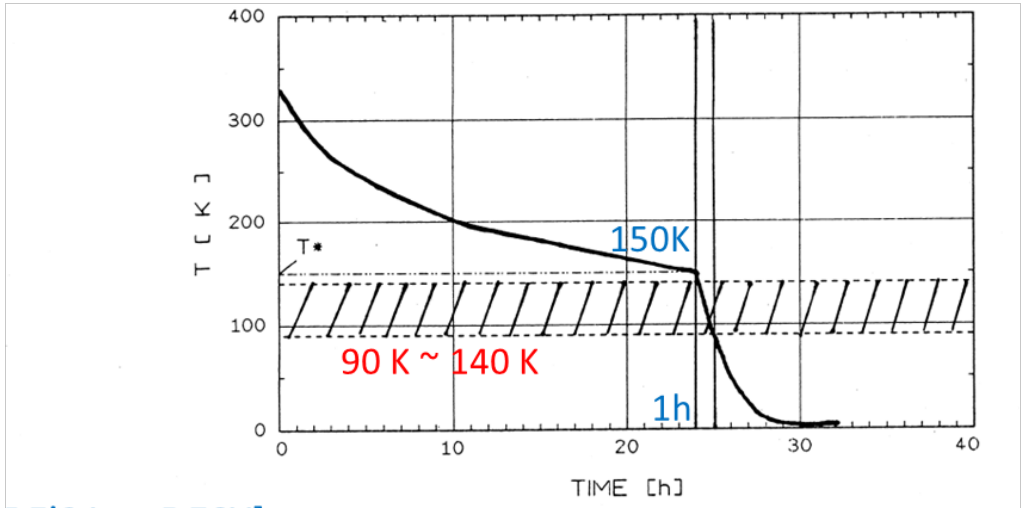


[SRF'91 at DESY]



Performance limitation : Hydrogen Q-disease

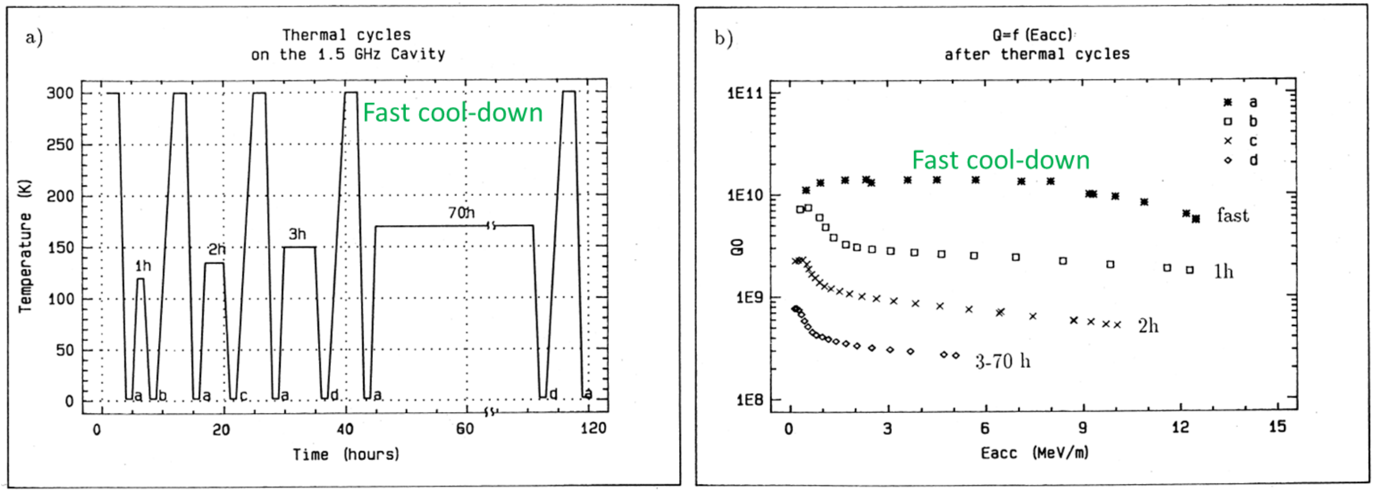
Cool-down condition in Cryomodule



[SRF’91 at DESY]

Fig. 4: Cooldown conditions to reduce the effect of the Q desease.

1.5 GHz Nb 1-cell Cavity at Saclay



Experimental results on Q-disease at DESY :

A cure method by fast cooling around dangerous temperature region from 140K to 90K

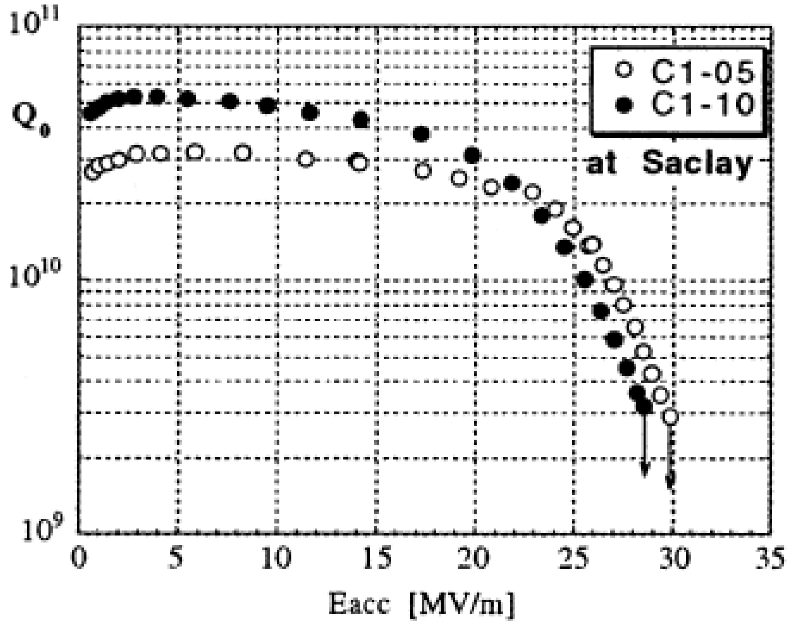
Experimental results on Q-disease at CEA-Saclay :

Another cure method is an annealing at 800^{o}C of Nb cavities for hydrogen degassing.

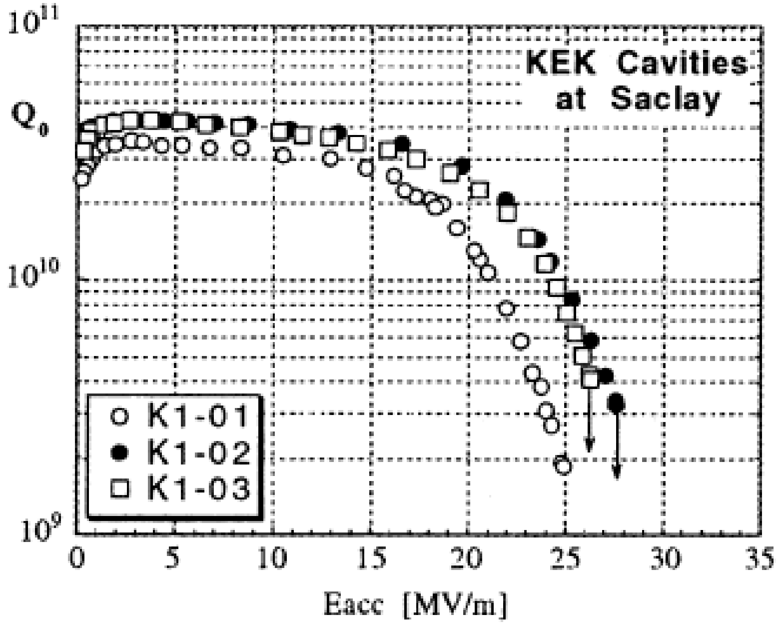
Hydrogen dissolved in a bulk niobium is precipitated on the surface layer and formed niobium-hydride composition.

Performance limitation : High field Q-slope

2 Saclay cavities tested at Saclay



3 KEK cavities tested at Saclay



[by E. Kako : SRF'97]

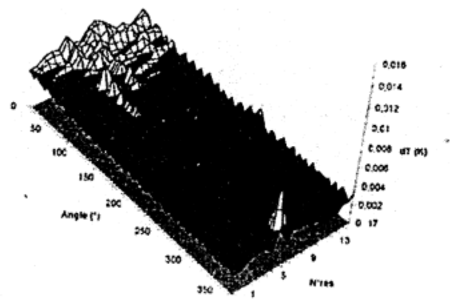


図5．C1-10空洞の表面温度分布(Eacc=29MV/m)

Q- Slope without x-ray

Reproducible observation.
Temperature rises at whole cavity surface were observed by a temperature mapping system.
(No Field Emission)

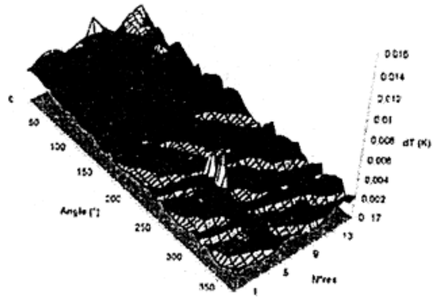
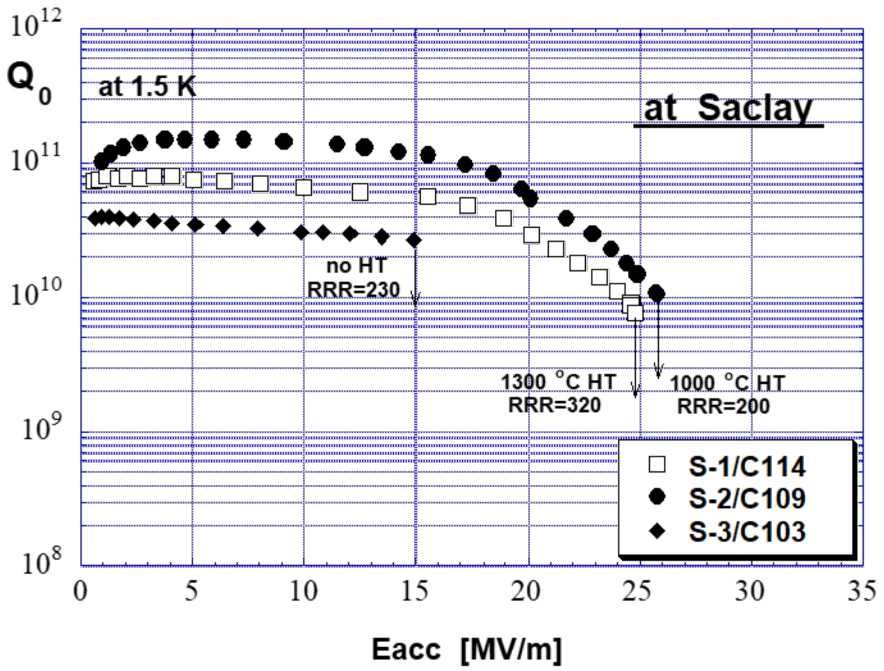


図6．K1-02空洞の表面温度分布(Eacc=28MV/m)

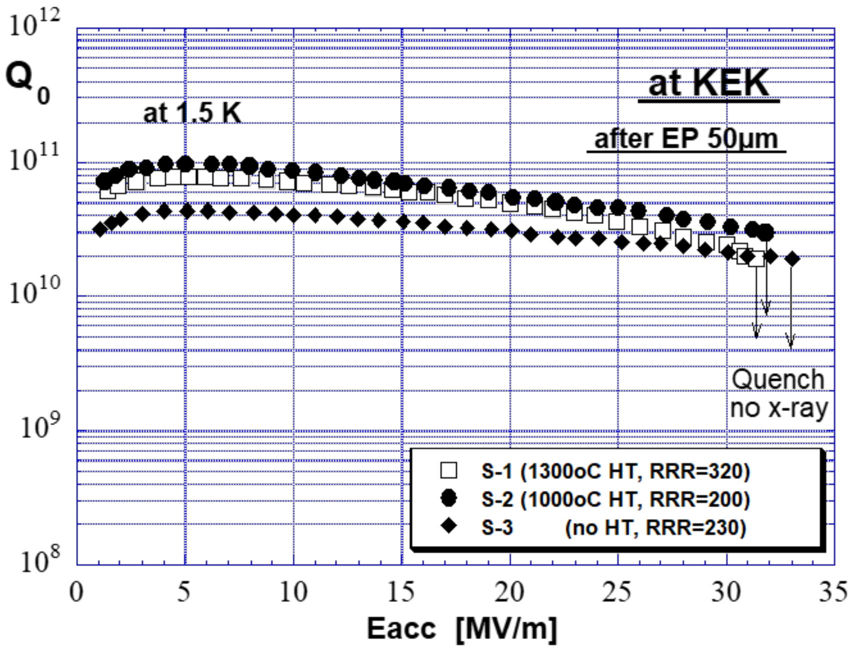
Performance limitation : High field Q-slope

Study on 1-cell cavities at KEK

Improvement of cavity performance by EP



CP cavity @ Saclay



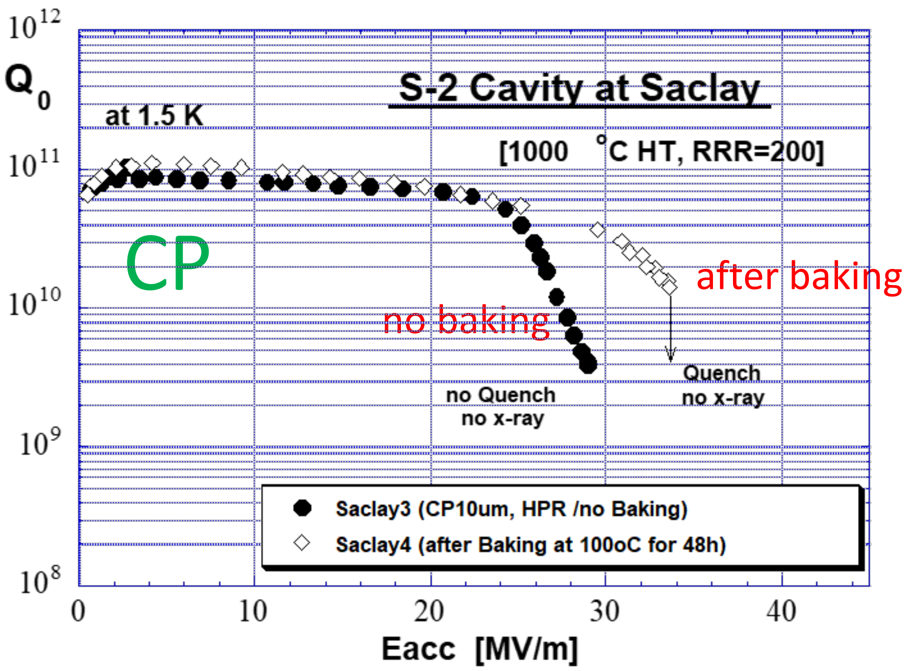
After EP @ KEK

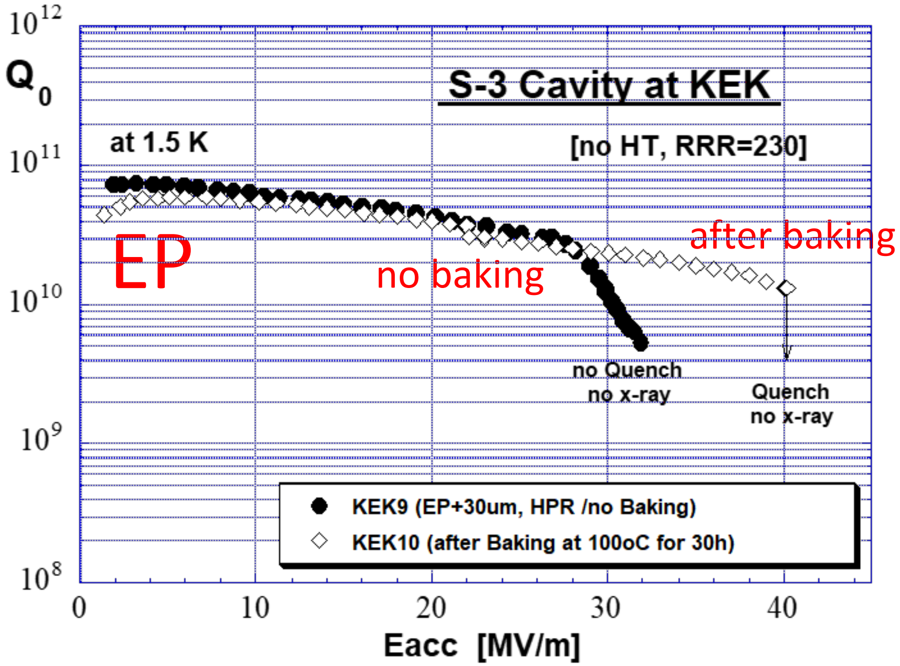
[by E. Kako : SRF'99 at Santa Fe]

Performance limitation : 120 oC Baking

Study on 1-cell cavities at KEK

Effectiveness of baking at 120ºC





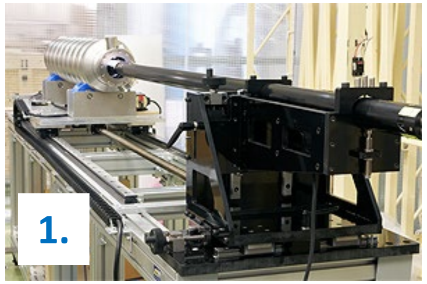
CP cavity + Natural Drying @ Saclay

EP cavity + Pumping & Baking @ KEK

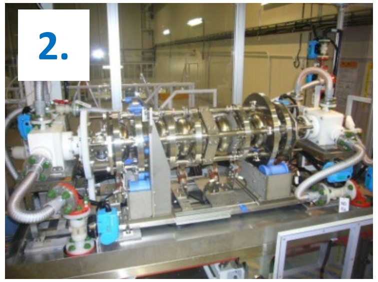
EP+120ºC Baking is an indispensable procedure to achieve >30 MV/m

(The initial purpose of baking at KEK was a drying in vacuum for a wet cavity after EP.)

Current Surface Preparation Techniques

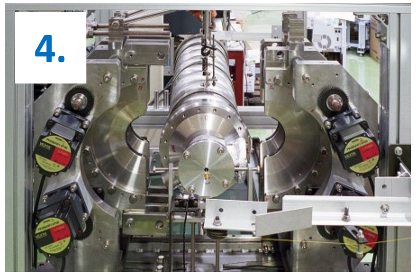


Inspection of inner surface



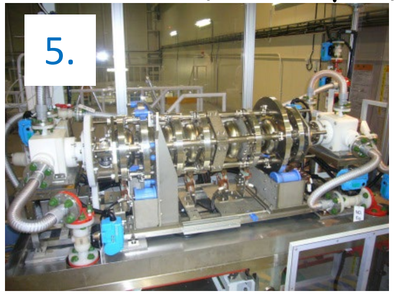
Pre-EP + EP-I (5+100 μm)

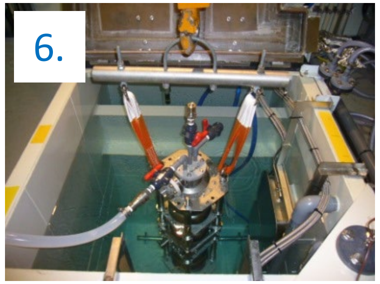
Anneal (750°C, 3h)



Pre-tuning (flatness, f_0)

EP-II (5~20 μm)

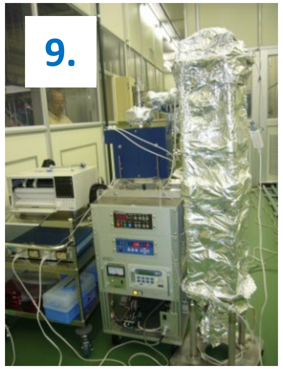




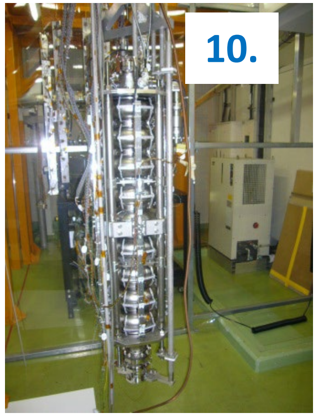
Hot bath rinsing with ultra-sonic

HPR

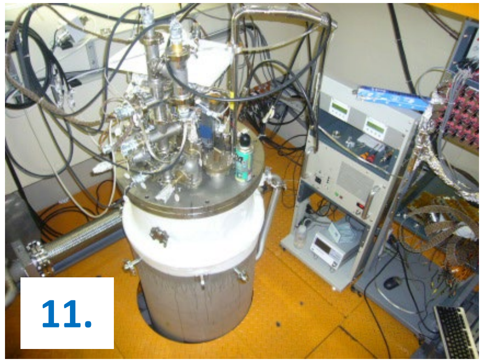
Assembly (Class 10)



Baking (120°C, 48h) (Class 1000)



Hanging stand with T-map



Vertical Test

Question (5)

What is the essential surface preparation procedures as a current standard?

Superconducting RF (SRF) Cavity

What is the essential surface preparation procedures as a current standard?

Established as an essentially important surface processing :

1. Electro-polishing: ***EP***
2. Annealing at 800^{o}C for ***hydrogen degassing***
3. High pressure water rinsing: ***HPR***
4. Assembly in ***class-10*** clean room
5. Baking at ***120^{o}C***
6. ***Clean assembling*** procedure to suppress field emission

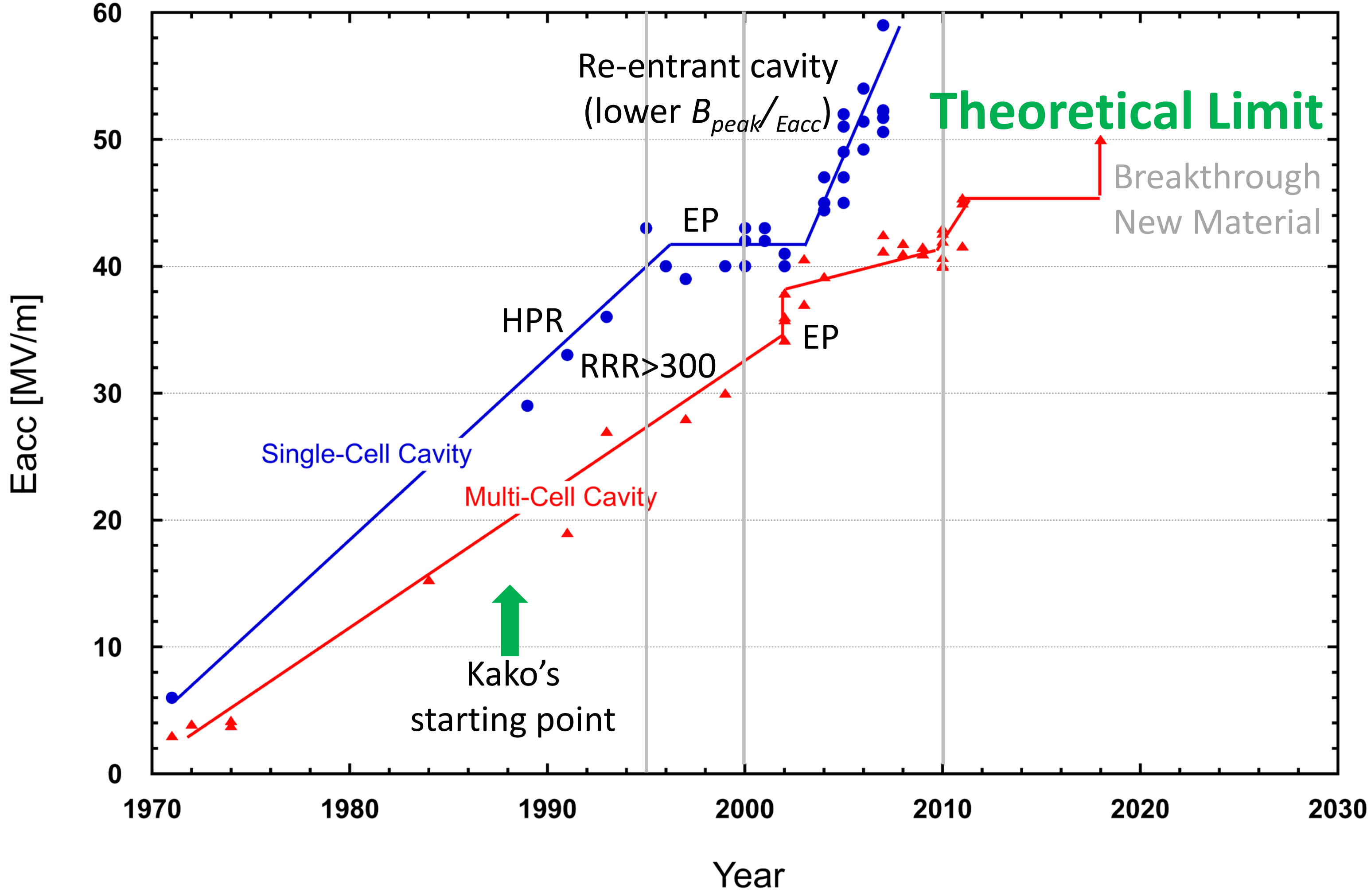
2. Recent Progress on SRF Cavity Performance

1. Fundamental Cavity Performance
2. **High Purity Niobium Production**
3. Toward Higher Q and Higher Gradient
4. Performance Recovery Techniques
5. Breakthrough for the next step
6. Summary

History achieved accelerating gradients (Eacc)

Innovation Center for Applied Superconducting Accelerators
応用超伝導加速器イノベーションセンター

Single-cell (blue) and Multi-cell (red) 1.3 GHz Bulk Niobium Cavities in 1970' - 2020'



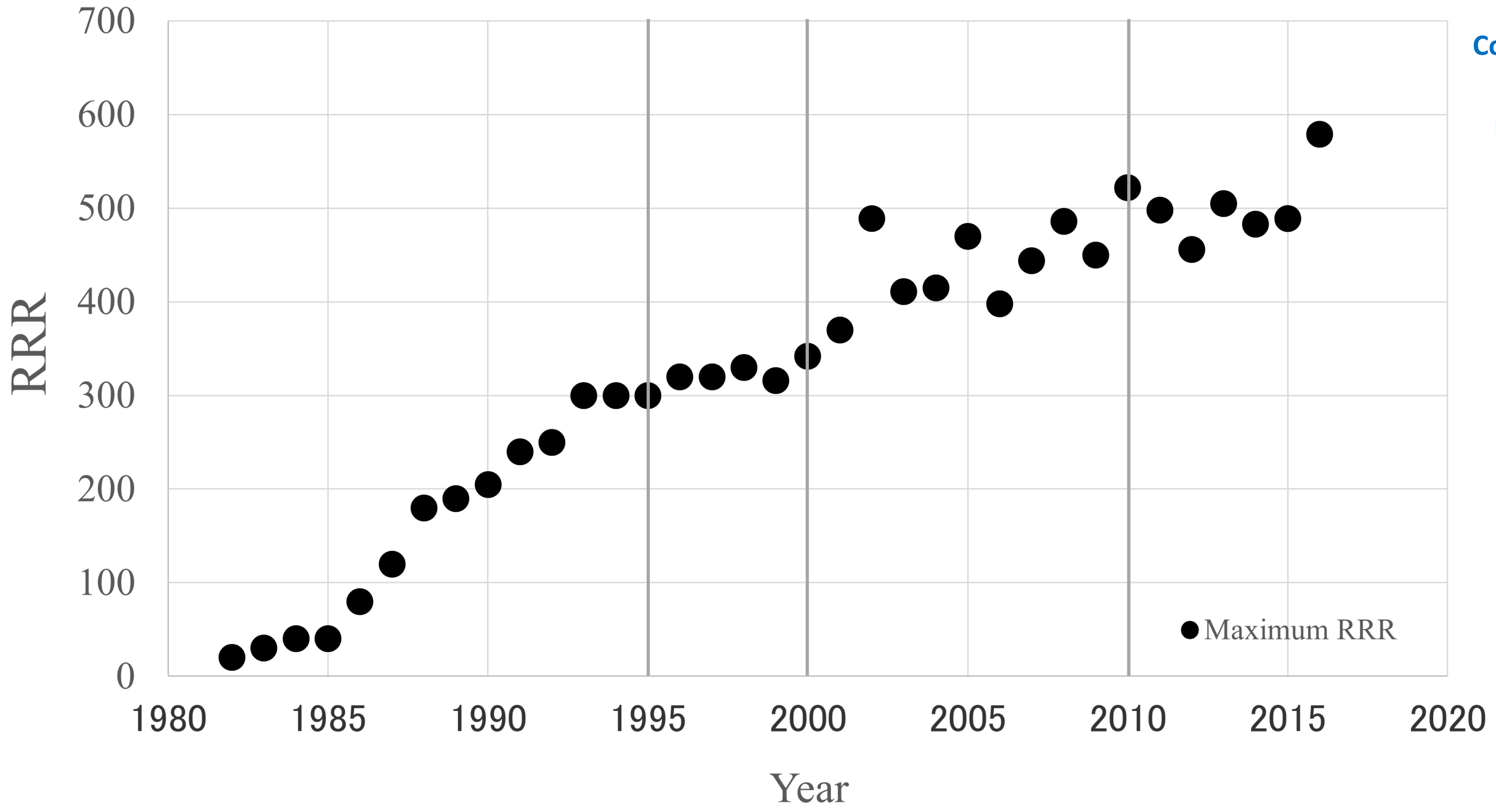
B_C ~ 190 – 200 mT

B_{peak} / E_{acc} = 4.3 mT/(MV/m)

$E_{acc, theoretical}$ = 46.5 MV/m

Courtesy of RongLi Geng (JLab, USA)

High Purity Niobium Production

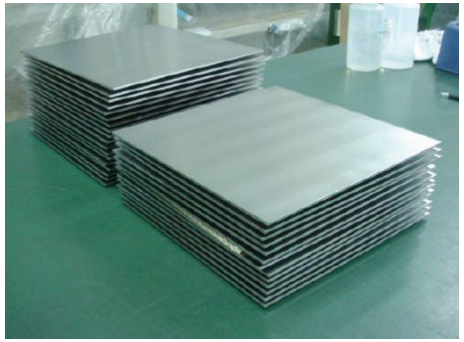


Courtesy of H. Umezawa (Tokyo-Denkai)

Niobium Sheets Production by Tokyo-Denkai

Project	Country/Region	Year	Weight (ton)	Frequency (MHz)
SNS	USA	2000-2001	2.1	805
TTF/FLASH	Germany	2002-2006	1.6	1300
Spiral-2	France	2006-2007	3.0	88
CEBAF-UG	USA	2009-2010	2.5	1500
Euro-XFEL	Europe	2011-2013	13.0	1300
FRIB	USA	2012-2014	9.6	80.5, 322
LCLS-II, 1	USA	2014-2015	5.1	1300
ESS	Europe	2017	3.8	352, 704
RIKEN	Japan	2017	0.6	73
LCLS-II, 2	USA	2017-2018	6.5	1300
SARAF	Israel	2018	1.5	176
LCLS-II, HE	USA	2020-2023	4.0	1300
SHINE	China	2022-2025	5.0	1300
Total	*	2000-2025	58.3	73-1500

Courtesy of H. Umezawa (Tokyo-Denkai)



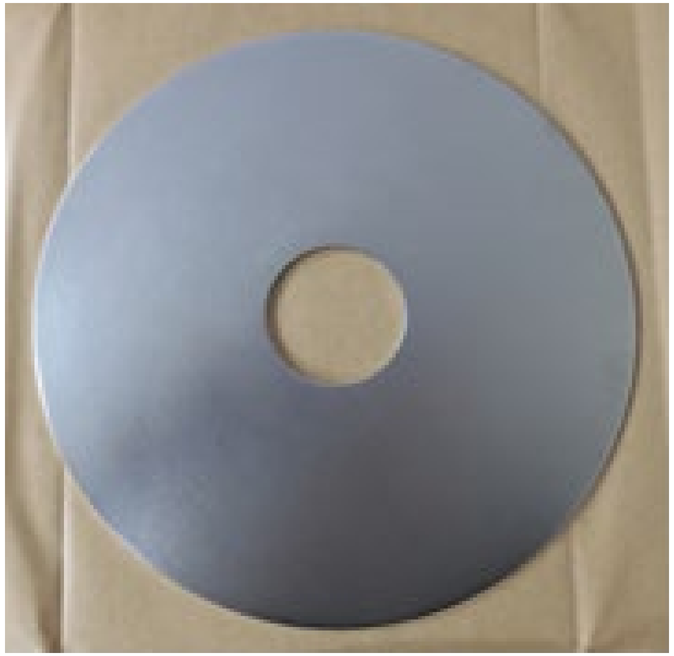
1.8 kg /sheet
for 1.3 GHz cavity

1.0 ton = 580 sheets
= 32 9-cell cavities
= 4 cryomodules

85,000 yen / kg
153,000 yen / sheet
2,754,000 yen / 9-cell cavity

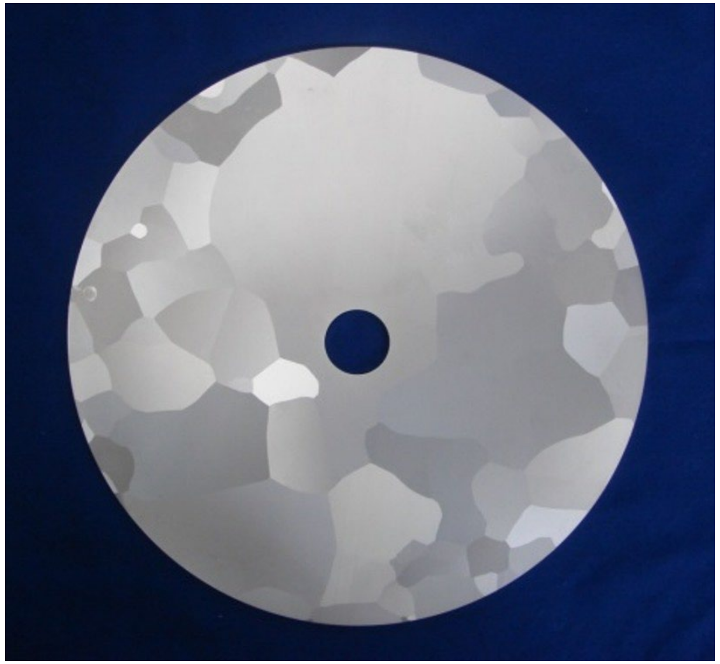
Niobium Disks for SRF Cavity Fabrication

(a)
Fine Grain



Grain size: 5 – 50 μm
Mechanical Property: unform
Manufacturing process: complex
Manufacturing cost: high
Strict quality control
Reliable cavity performance

(b)
Large Grain



Grain size: 1 – 10 cm
Mechanical Property: inhomogeneous
Manufacturing process: no forging & rolling
Manufacturing cost: significant reduction
Partial decrease in stress
Excellent cavity performance

(c)
Medium Grain

Grain size: 0.2 – 2.0 mm
Mechanical Property: isotropic
Manufacturing process: no rolling
Manufacturing cost: reduced
Suitable for large scale project
Under evaluation of cavity performance

Cavity Performance of Large-Grain SRF Cavity

Fine Grain (11, 9-cell cavities at KEK)

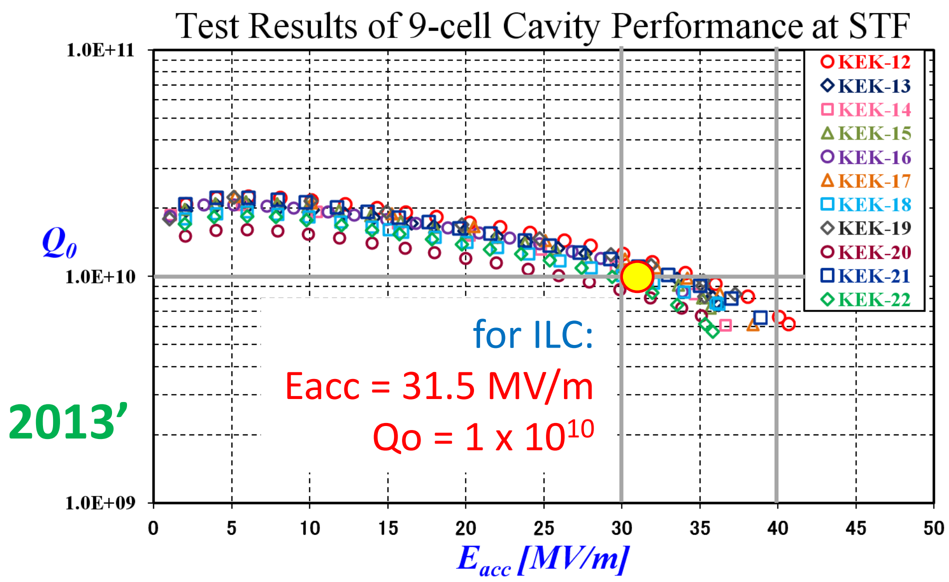


Figure 1: Best Q_0 vs. E_{acc} curves obtained from performance tests for KEK-12 through KEK-22.

Y. Yamamoto, H. Hayano, E. Kako, S. Noguchi, T. Shishido, K. Watanabe, "Achieving high gradient performance of 9-cell cavities at KEK for the international linear collider", Nuclear Inst. and Method in Physics Research A, 729 (2013) p589-595.

Large Grain (11, 9-cell cavities at DESY)

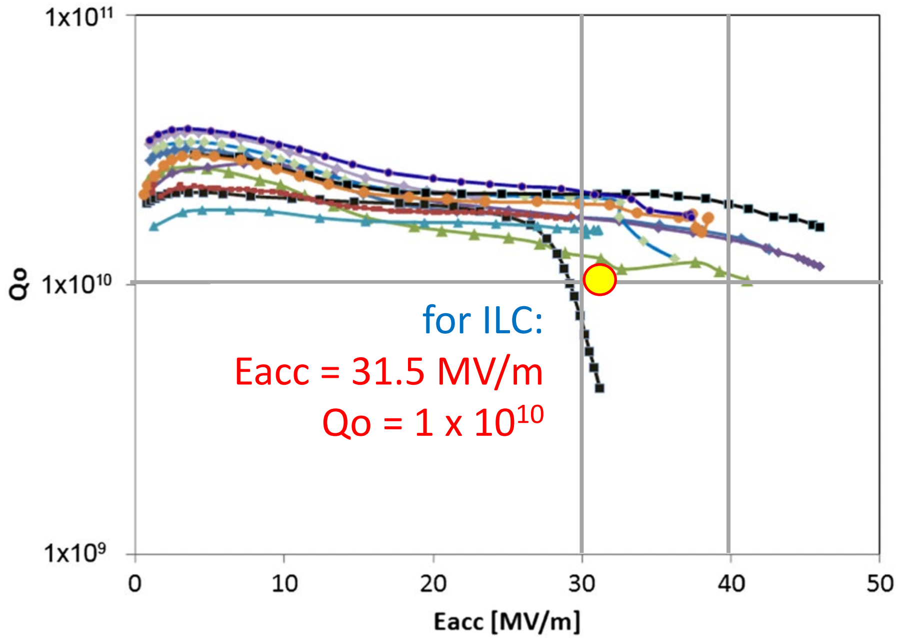


FIG. 13. Final Q0-Eacc performance of the LG cavities AC112–AC114, AC151–AC158 at 2 K after EP.

W. Singer, S. Aderhold, A. Ermakov, J. Iversen, D. Kostin, G. Kreps, A. Matheisen, W.-D. Moeller, D. Reschke, X. Singer, K. Twarowski, and H. Weise, "Development of Large Grain Cavities", PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 16, 012003 (2013)

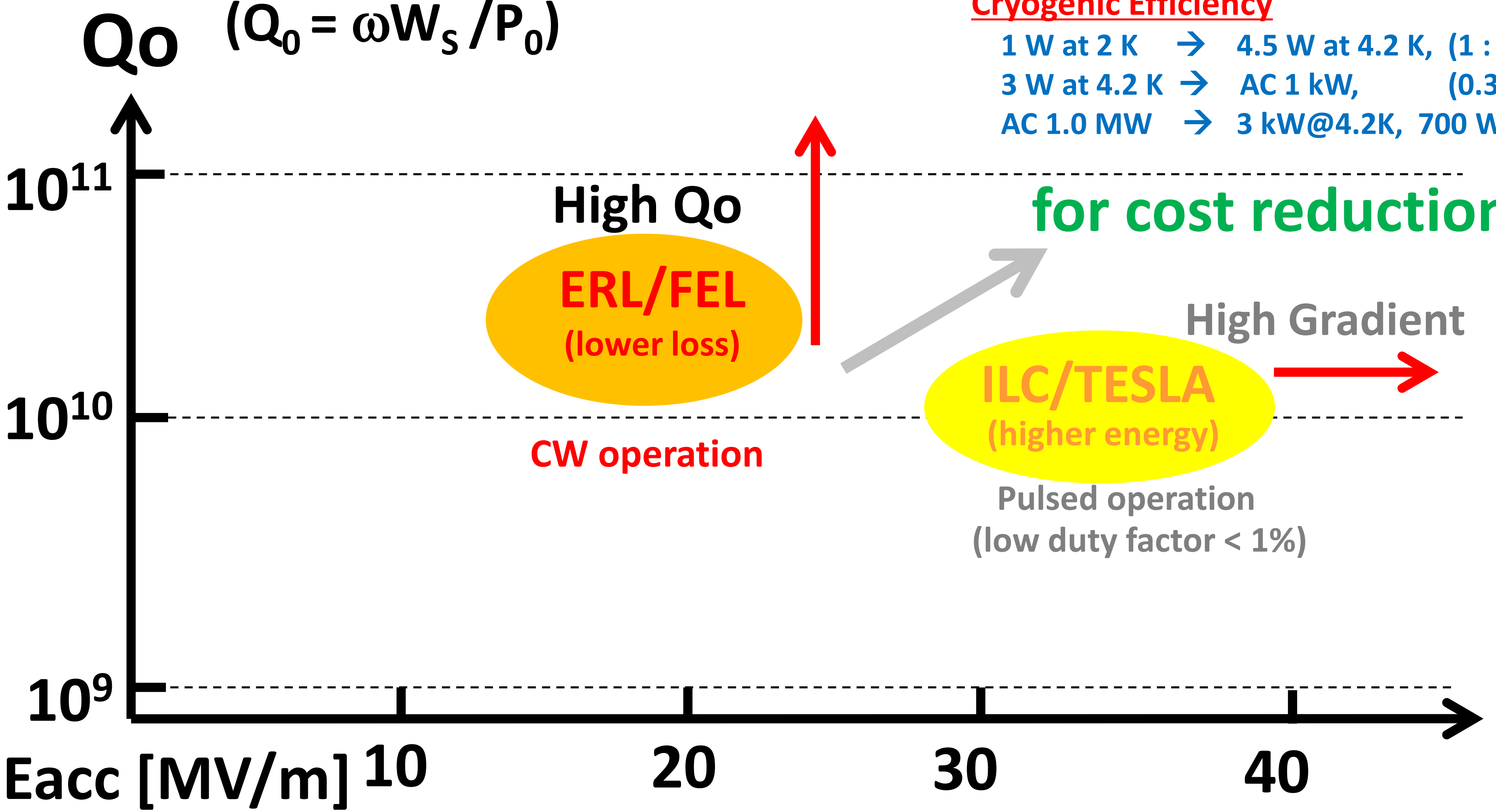
2. Recent Progress on SRF Cavity Performance

1. Fundamental Cavity Performance
2. High Purity Niobium Production
3. **Toward Higher Q and Higher Gradient**
4. Performance Recovery Techniques
5. Breakthrough for the next step
6. Summary

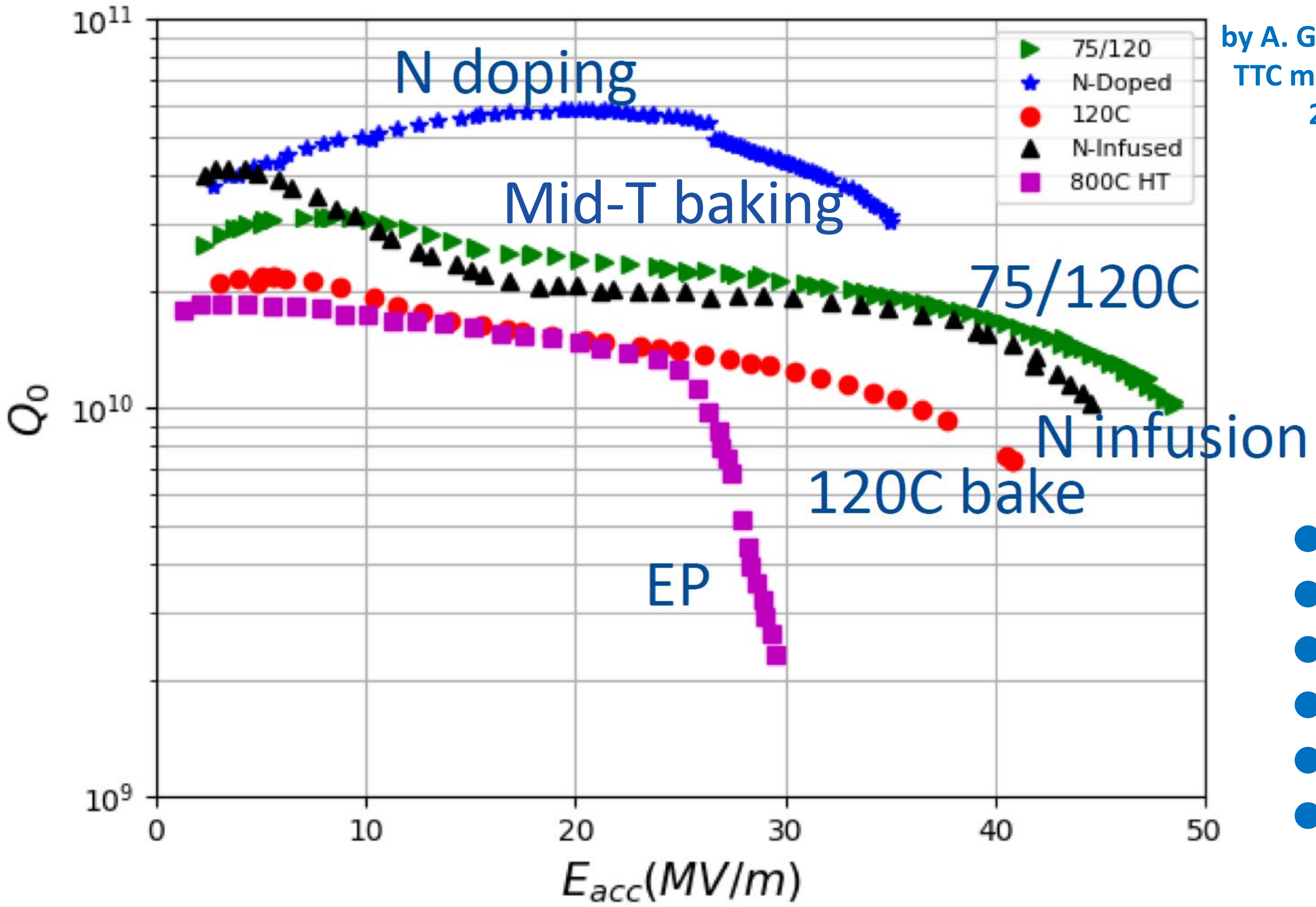
Toward higher Qo and higher Gradient

Cryogenic Efficiency

1 W at 2 K → 4.5 W at 4.2 K, (1 : 4.5)
3 W at 4.2 K → AC 1 kW, (0.3%)
AC 1.0 MW → 3 kW@4.2K, 700 W@2K



Toward higher cavity performance : high-Q, high-G

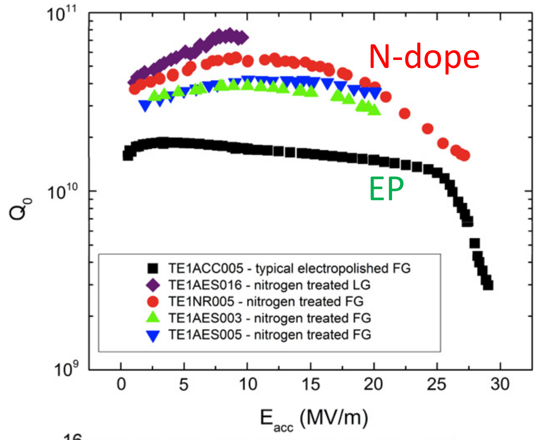


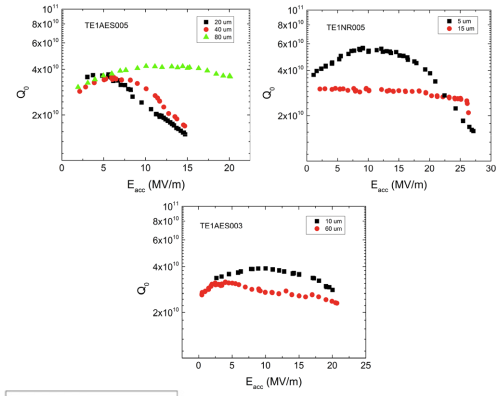
by A. Grassellino (FNAL)
TTC meeting at TRIUNF
2019 February 05

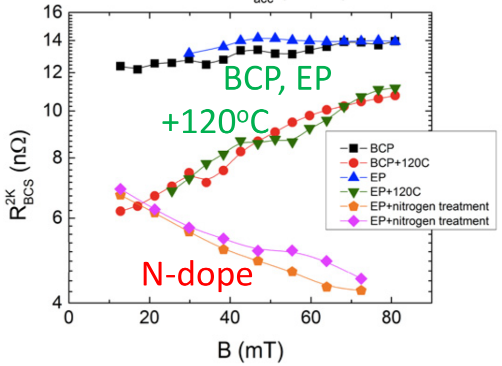
- N-doping
- N-infusion
- Two step baking
- Mid-T baking
- Cold - EP
- Fast cooling speed

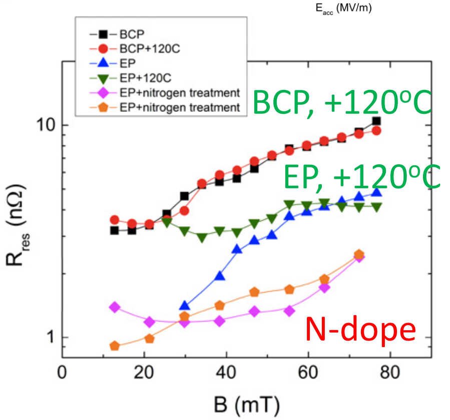
Nitrogen Doping for High-Q

The procedures of Nitrogen-Doping are annealing at 800°C in a UHV vacuum furnace for 3 hrs, followed by injection of about 2 x 10^{-2} Torr partial pressure of pure nitrogen for 10 min at 800 °C, followed by surface removal of 10-30 μm EP, HPR and RF testing.

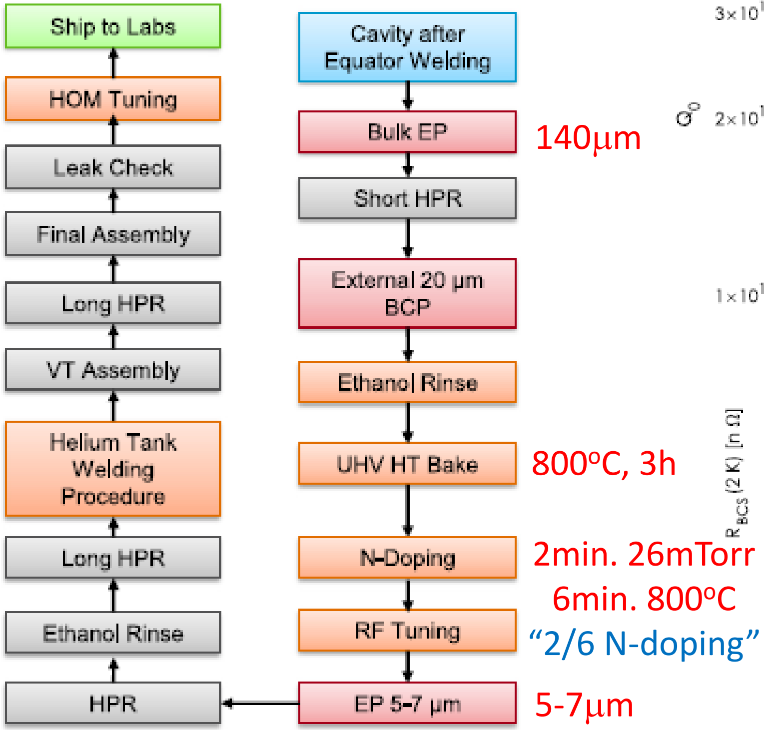


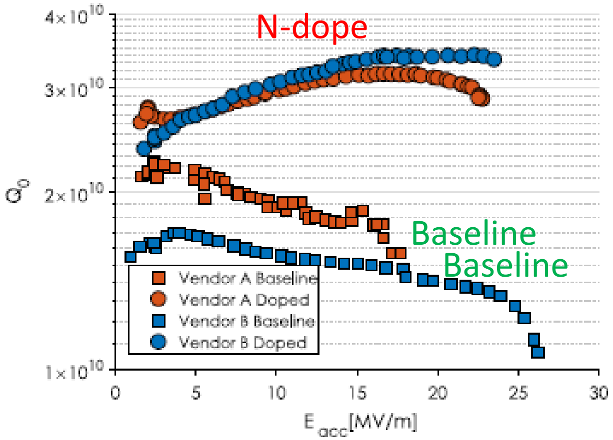


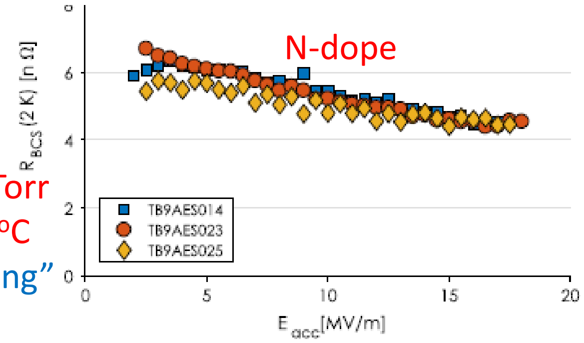




“Nitrogen and argon doping of niobium for superconducting radio frequency cavities: a pathway to highly efficient accelerating structures” by A. Grassellino (FNAL, USA), Supercond. Sci. Technol. 26 (2013) 102001







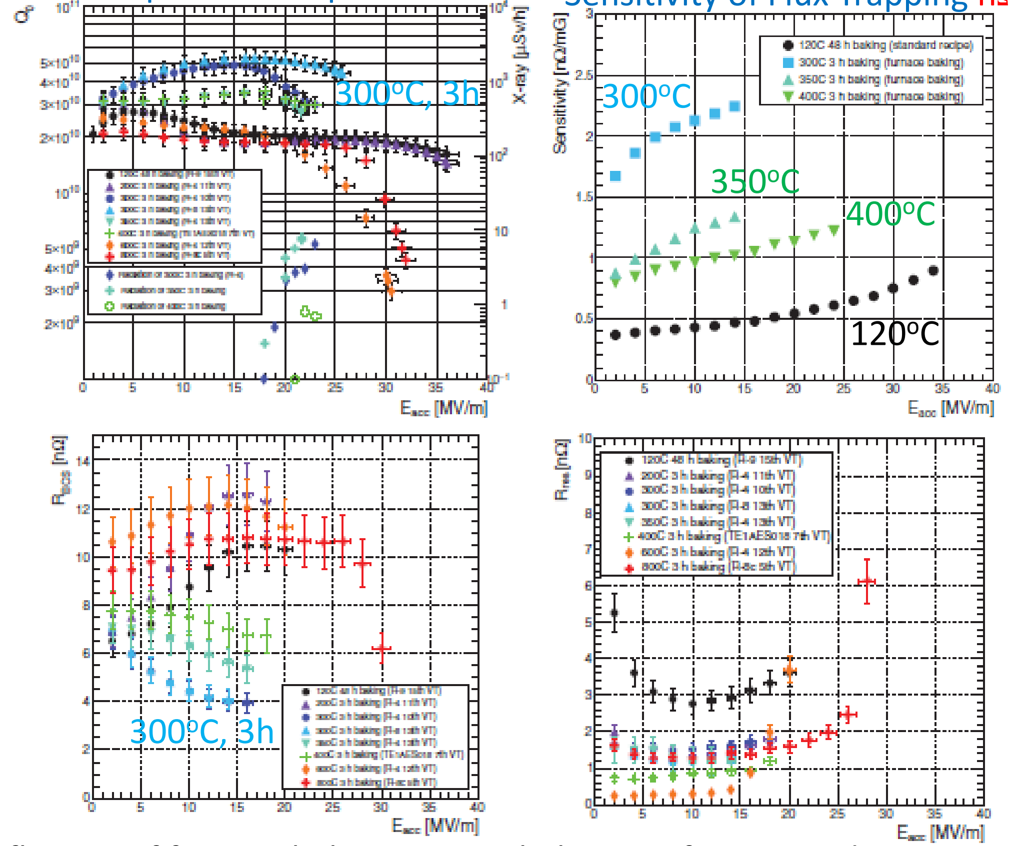
“Industrialization of the nitrogen-doping preparation for SRF cavities for LCLS-II” by D. Gonnella (SLAC, USA), NIM-A 883 (2018) p143–150.

Mid-T Baking for High-Q (1)

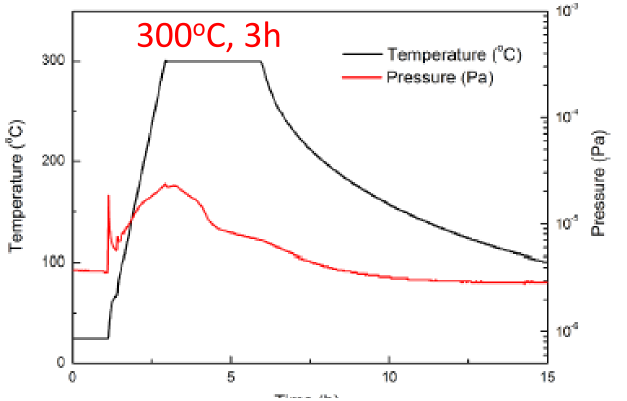
The Mid-T baking is performed as the **last step** of the cavity surface treatment. The cavities are heated **at 300ºC for 3 hours** in a UHV vacuum furnace, followed by HPR and natural drying at CR.

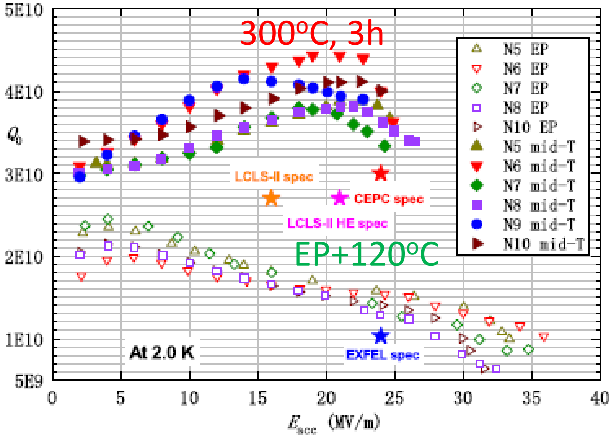
Temperature Dependence

Sensitivity of Flux Trapping nΩ/mG



“Influence of furnace baking on Q–E behavior of superconducting accelerating cavities”, by H. Ito (KEK, Japan), Prog. Theor. Exp. Phys. 2021, 071G01 (8 p).





Process of N5, N6, N7, N8, N10
- Bulk EP
- 800 °C 3 h
- Light EP
- Vertical test
- 900 °C 3 h
- Exposure to air
- Mid-T furnace baking (300ºC, 3h)
- Vertical test

Process of N9
- Bulk EP
- 900 °C 3 h
- Exposure to air
- Mid-T furnace baking (300ºC, 3h)
- Vertical test

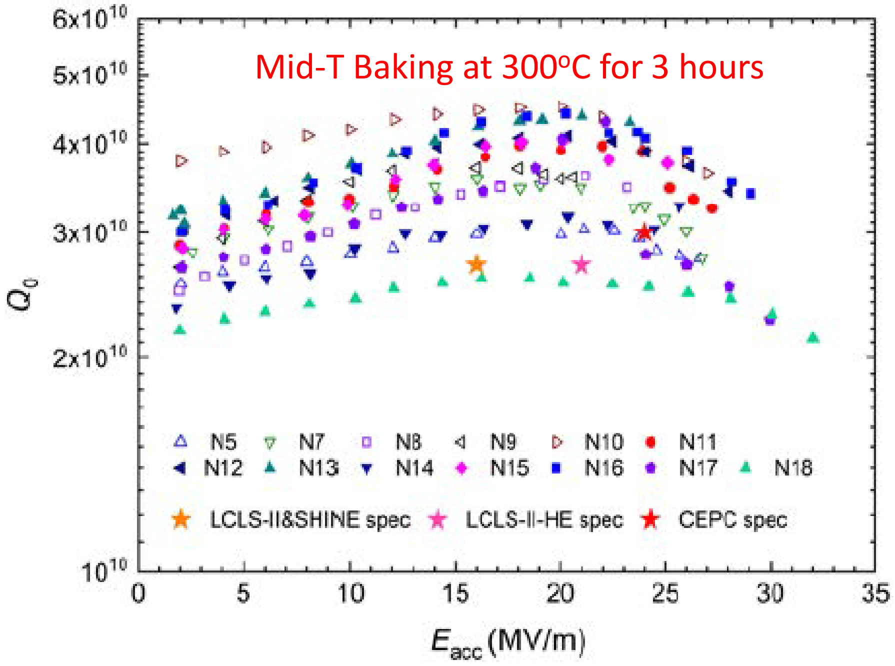
“Medium-temperature furnace baking of 1.3 GHz 9-cell superconducting cavities at IHEP”, by Feisi He (IHEP, China), Supercond. Sci. Technol. 34 (2021) 095005 (7p).

Mid-T Baking for High-Q (2)

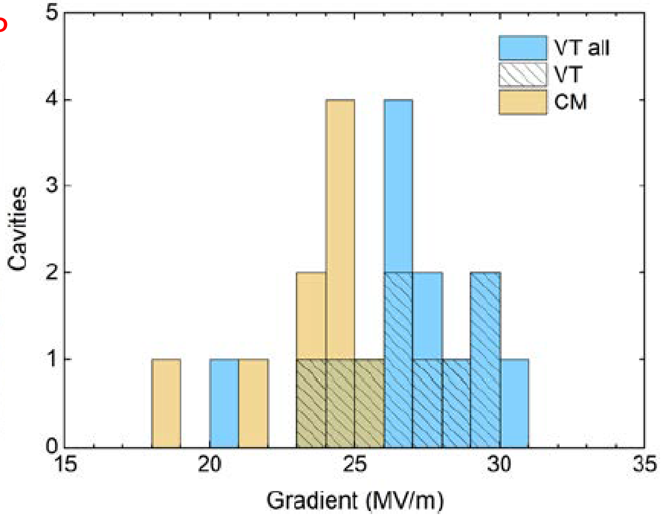
PHYSICAL REVIEW ACCELERATORS AND BEAMS **27,** 092003 (2024)

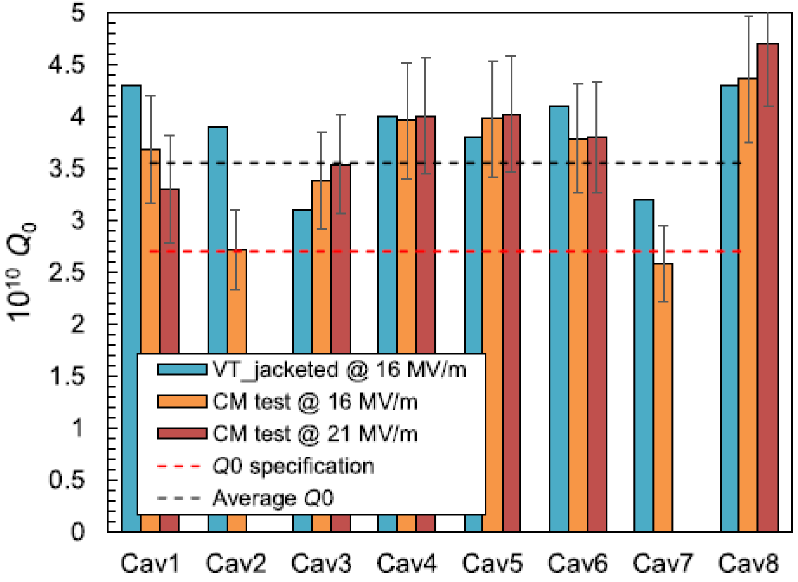
High Q and high gradient performance of the first medium-temperature baking 1.3 GHz cryomodule

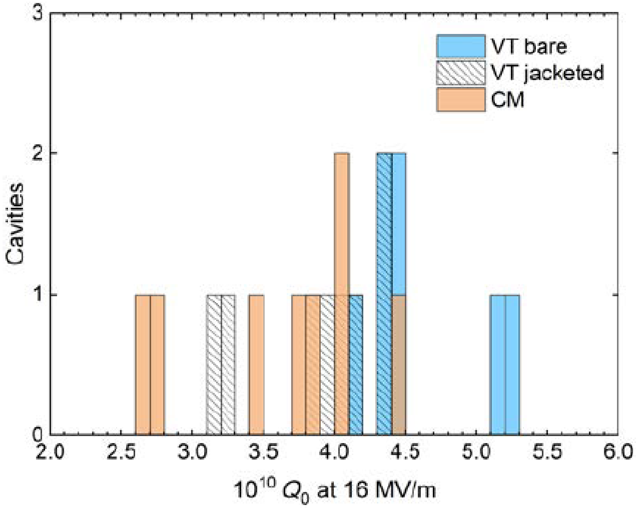
Weimin Pan,[1,2,*] Jiyuan Zhai,[1,2] Feisi He,[1,2] Rui Ge,[1,2] Zhenghui Mi,[1,2] Peng Sha,[1,2] Song Jin,[1]



First Mid-T Baking 1.3 GHz Cryomodule at IHEP



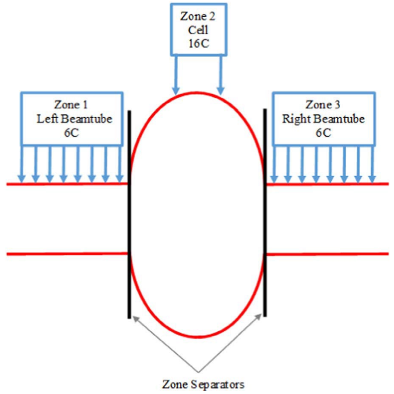


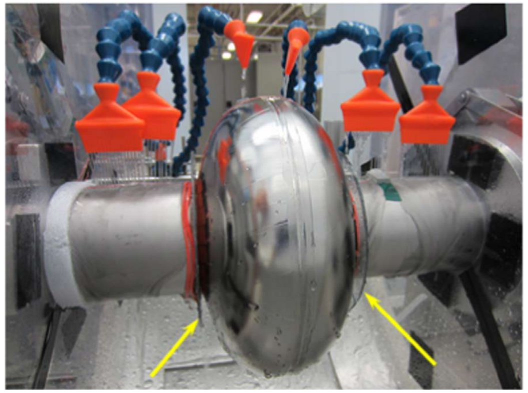


Cold-EP for High-G

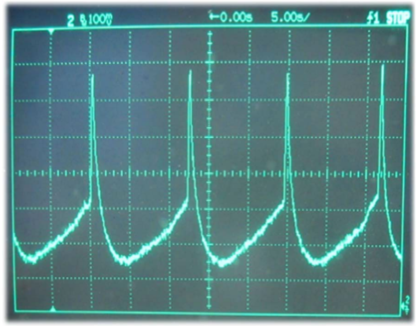
Innovation Center for Applied Superconducting Accelerators
応用超伝導加速器イノベーションセンター

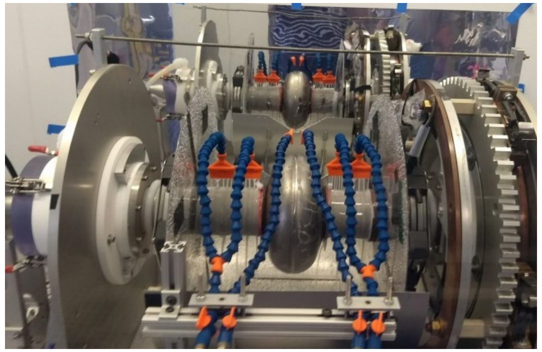
The key parameters in the cold EP are a low temperature of 15°C at the cell surface, (32°C in a standard EP) and a lower EP current of 15 A, (40 A in a standard EP). The temperature of electrolyte in the acid tank was maintained below 12°C with the chiller unit during the cold-EP process.



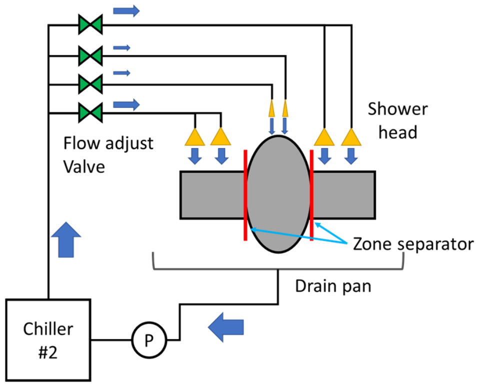


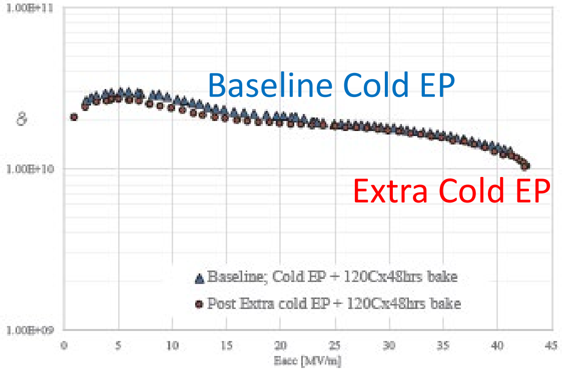
Parameter	VALUE
Voltage	18 V
Current	15 A (average)
Beamtube temperature	6 C
Cell temperature	16 C
Electrolyte temperature	6 C
Electrolyte flow rate	1 L/min
Cavity rotation speed	1 revolution/min
Electrolyte volume	12 L
Material removal rate	5 μm/h
Niobium surface current density	10 mA/cm² (average)
Open cathode area	100 cm²
Cathode surface current density	150 mA/cm² (average)





Parameters	[Unit]	Hot EP	Cold EP	Extra Cold EP
Target removal	[μm]	>10	10 or less	~30
EP voltage	[V]	18	18	18
EP current	[A]	40	15	8
Equator temp.	[degC]	32	15	-4
Beam tube temp.	[degC]	5	0	-8
Acid temp.	[degC]	20	12	4
Removal rate	[μm/hour]	13	5	3
Acid circulation	[L/min.]	1.5~2.3	1.5~2.3	1.5~2.3
Cavity rotation	[RPM]	1	1	1
Nitrogen gas flow	[L/min.]	1	1	[





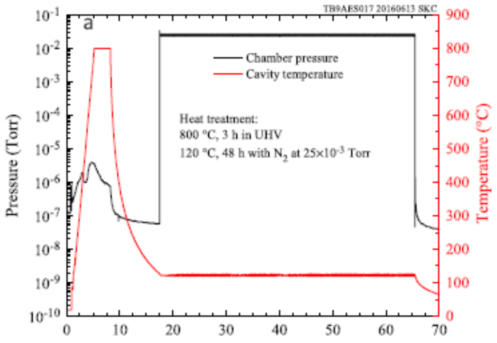
"Extreme diffusion limited electropolishing of niobium radiofrequency Cavities", by Anthony C. Crawford (FNAL, USA), NIM-A 849 (2017) p5–10.

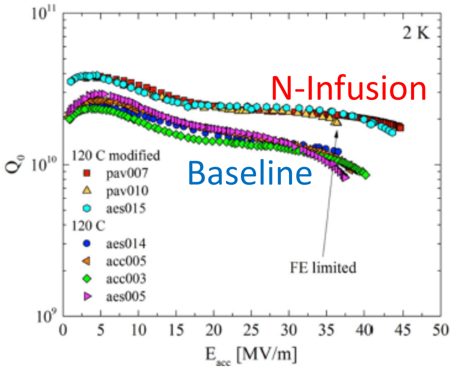
"EXTRA-COLD EP PROCESS AT FERMILAB", F. Furuta (FNAL, USA), SRF2021, East Lansing, MI, USA (2021) p230-232.

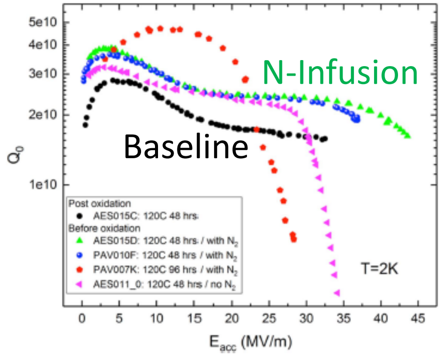
Nitrogen Infusion for High-G

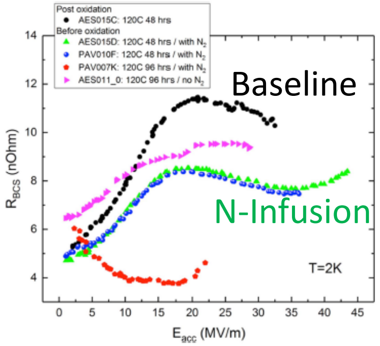
Innovation Center for Applied Superconducting Accelerators
応用超伝導加速器イノベーションセンター

After heat treatment at 800ºC for 3 hours in a UHV vacuum furnace, the temperature was lowered to a range of 120ºC and the cryopumps are shut down. Then, high-purity nitrogen gas was injected into the furnace at a pressure of ~25 mTorr, and the pressure was maintained by roughing pumps. Following the nitrogen infusion at 120ºC for 48 hours with low pressure nitrogen, only HPR was applied.

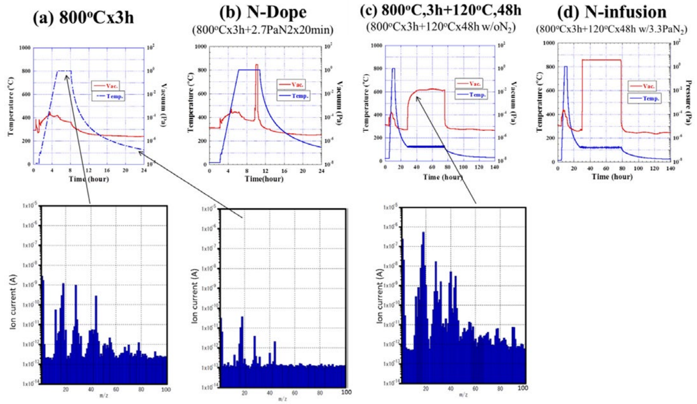


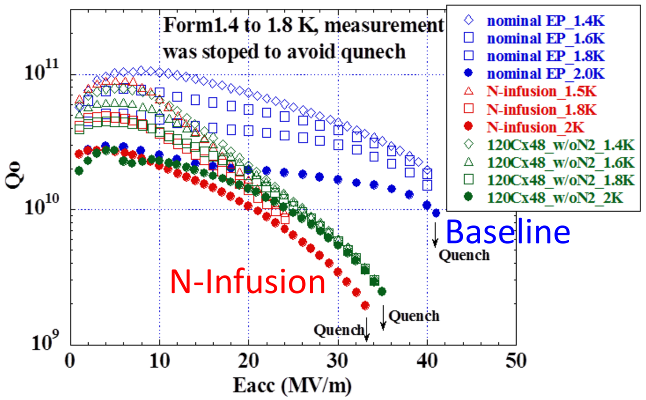


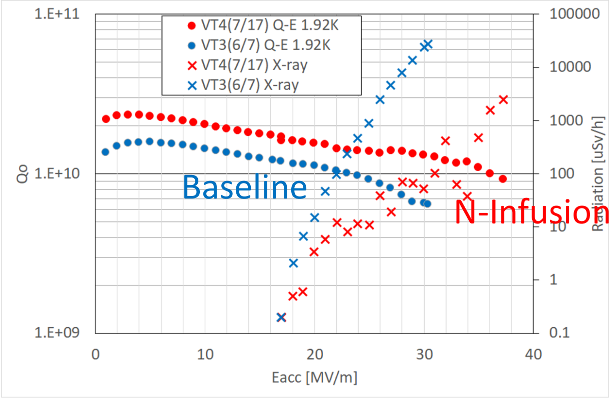




“Unprecedented quality factors at accelerating gradients up to 45MVm−1 in niobium superconducting resonators via low temperature nitrogen infusion”, by A. Grassellino (FNAL, USA), Supercond. Sci. Technol. 30 (2017) 094004 (10p).



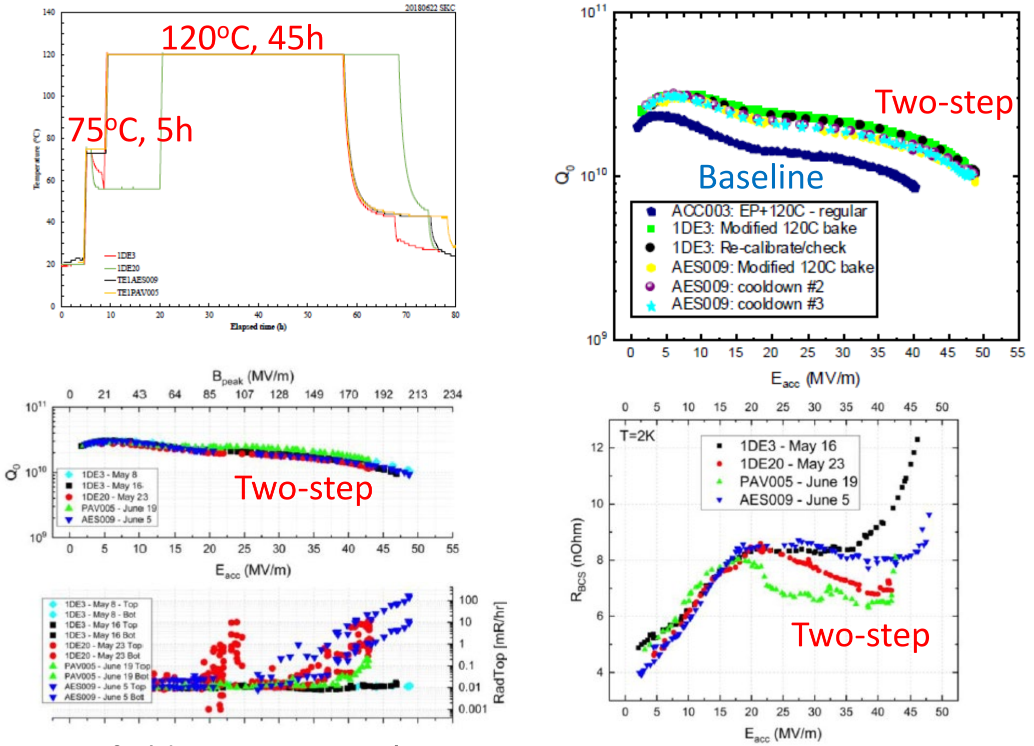




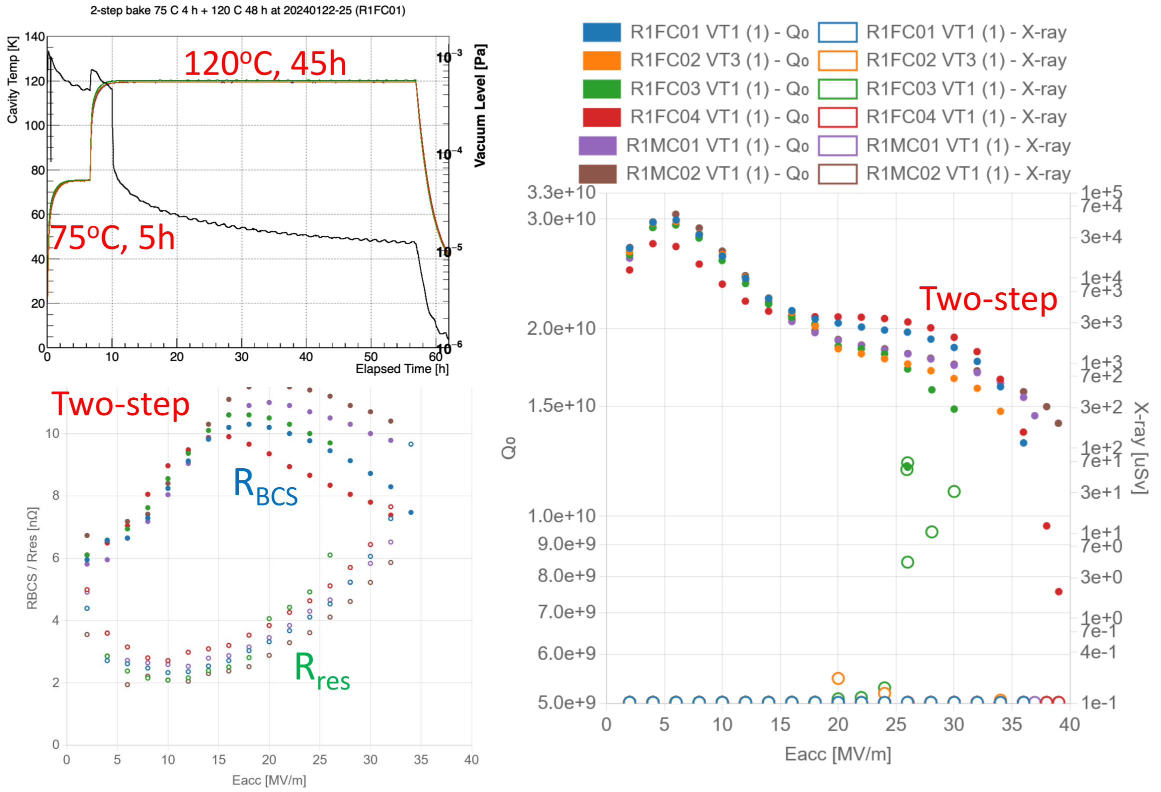
“TRIAL OF NITROGEN INFUSION AND NITROGEN DOPING BY USING JPARC FURNACE”, by T. Konomi (KEK, Japan), SRF2017, Lanzhou, China (2017) p775-778.

Two-step Baking for High-G

Two-step baking at 75°C and 120°C was accidentally discovered during a standard baking.
The discovery showed that the simple addition during the mild baking of a step at 75°C for a few hours, before the 120°C baking for 48 hours, systematically increases the quench fields.



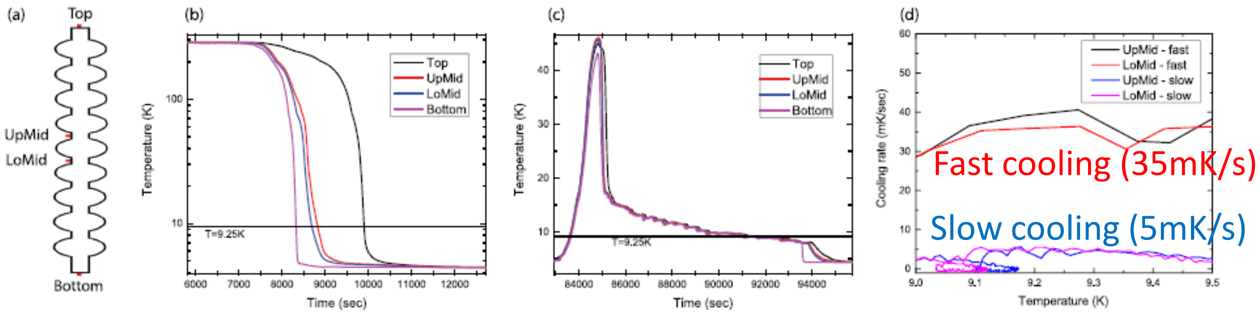
“Accelerating fields up to 49 MV/m in TESLA-shape superconducting RF niobium cavities via 75°C vacuum bake”, by A. Grassellino (FNAL, USA), https_arxiv.org_pdf1806.09824

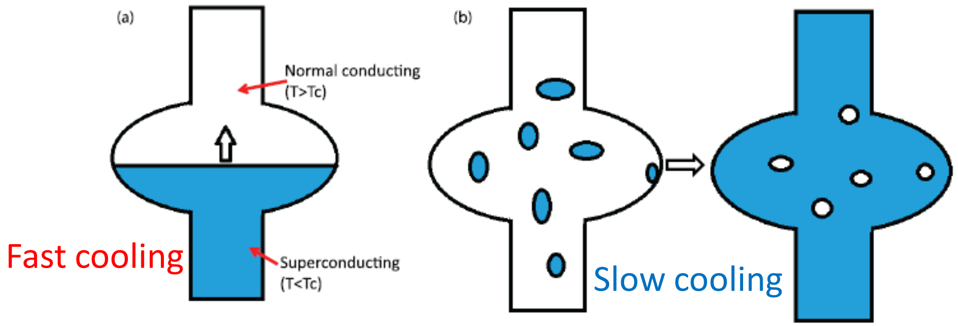


“VERTICAL TEST RESULTS FOR ITN SINGLE CELL CAVITIES”, by E. Viklund (KEK, Japan), SRF2025, Tokyo (2025) p125-128.

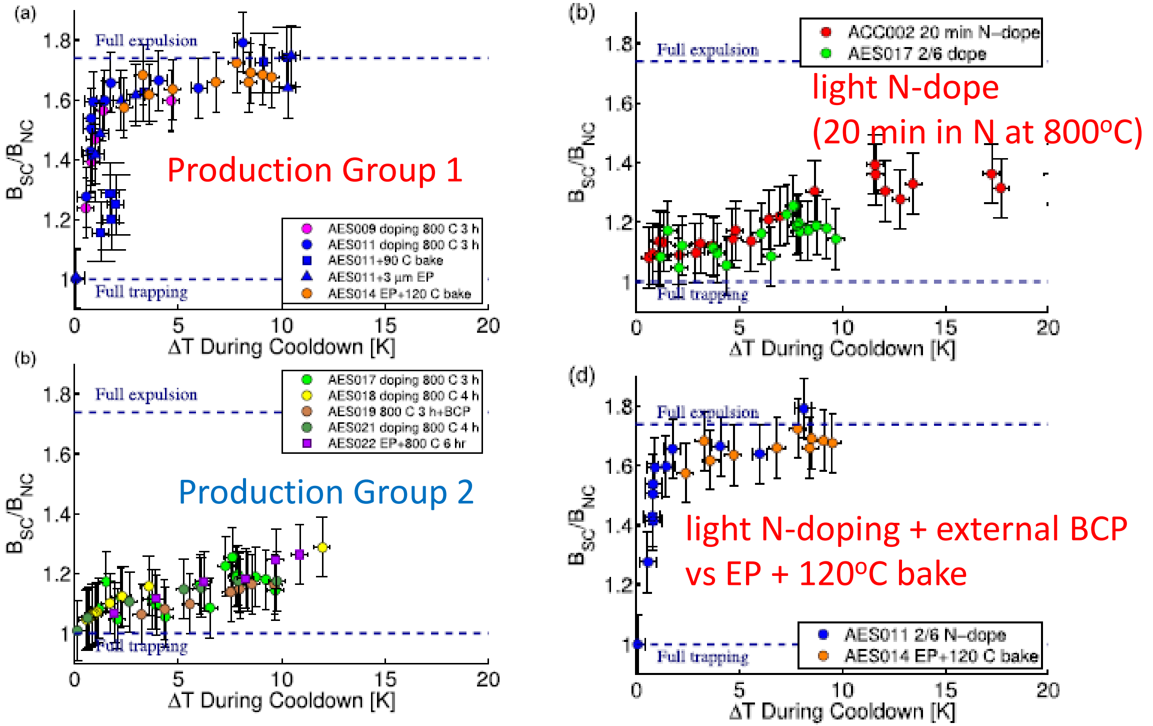
Influence of Residual Magnetic Flux (1)

Fast cool-down is highly effective for efficient expulsion of external magnetic fields.
Slow cooling leads to almost complete flux trapping and higher residual resistance,
while Fast cooling leads to much more efficient flux expulsion and lower residual resistance.





“Dependence of the residual surface resistance of superconducting radio frequency cavities on the cooling dynamics around T_c”,
by A. Romanenko (FNAL, USA), J. Appl. Phys. 115, 184903 (2014).



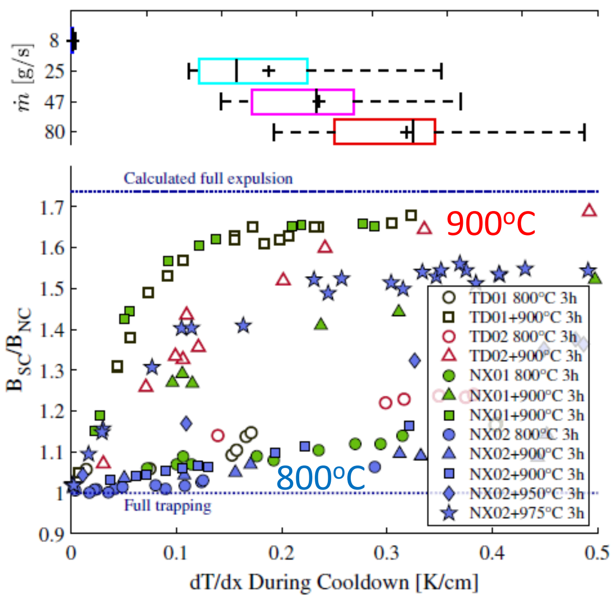
“Efficient expulsion of magnetic flux in superconducting radiofrequency cavities for high Q0 applications”,
by S. Posen (FNAL, USA), J. Appl. Phys. 119, 213903 (2016).

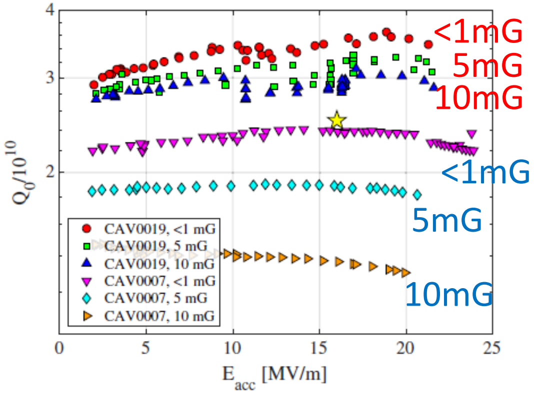
Influence of Residual Magnetic Flux (2)

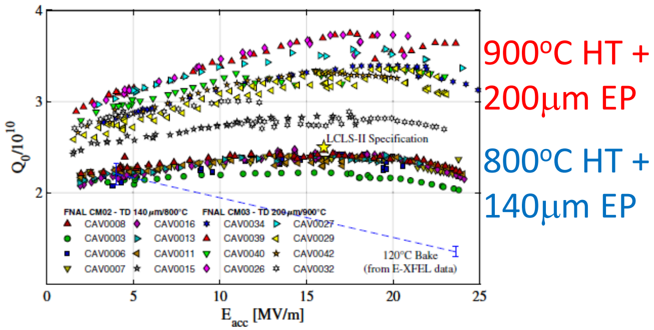
Innovation Center for Applied Superconducting Accelerators
応用超伝導加速器イノベーションセンター

It was shown that a cavity could be converted from poor expulsion behavior to strong expulsion behavior after higher heat treatment above 900^{o}C in a UHV vacuum furnace, resulting in a substantial improvement in quality factor.

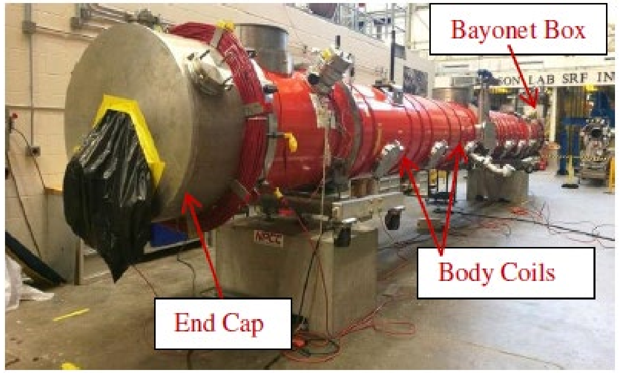
(It is preferable to control the ambient magnetic field at cavity surface less than 0.5 μT, (= 5. nG).)

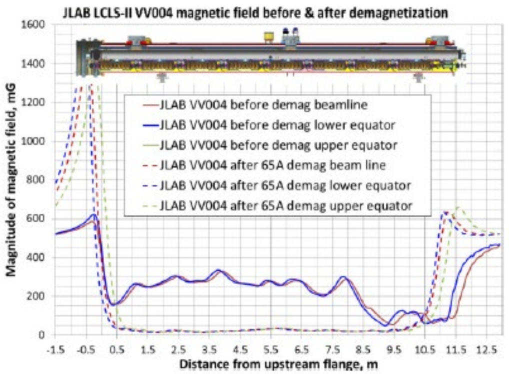


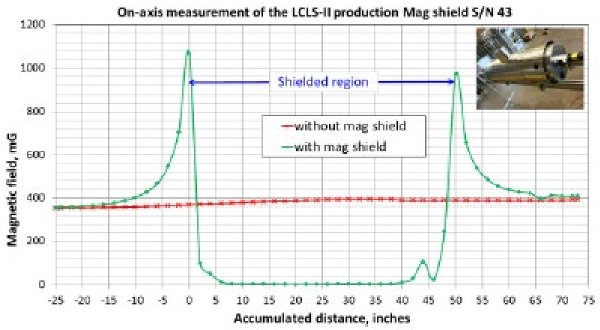


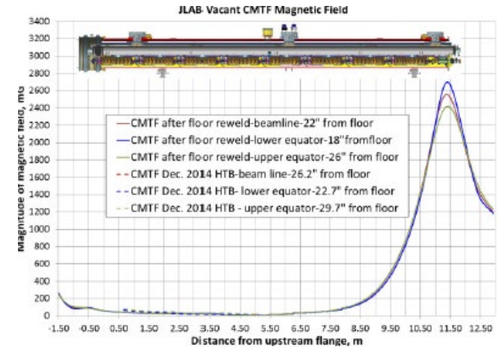


“Role of magnetic flux expulsion to reach $Q_0 > 3 \times 10^{10}$ in superconducting rf cryomodules”, by S. Posen (FNAL, USA), PHYS. REV. ACCEL. BEAMS 22, 032001 (2019)









“MAGNETIC HYGIENE CONTROL ON LCLS-II CRYOMODULES FABRICATED AT JLAB”, by G. Cheng (JLab, USA), SRF2017, Lanzhou, China (2017) p153-157.

2. Recent Progress on SRF Cavity Performance

1. Fundamental Cavity Performance
2. High Purity Niobium Production
3. Toward Higher Q and Higher Gradient
4. **Performance Recovery Techniques**
5. Breakthrough for the next step
6. Summary

Performance Recovery Techniques

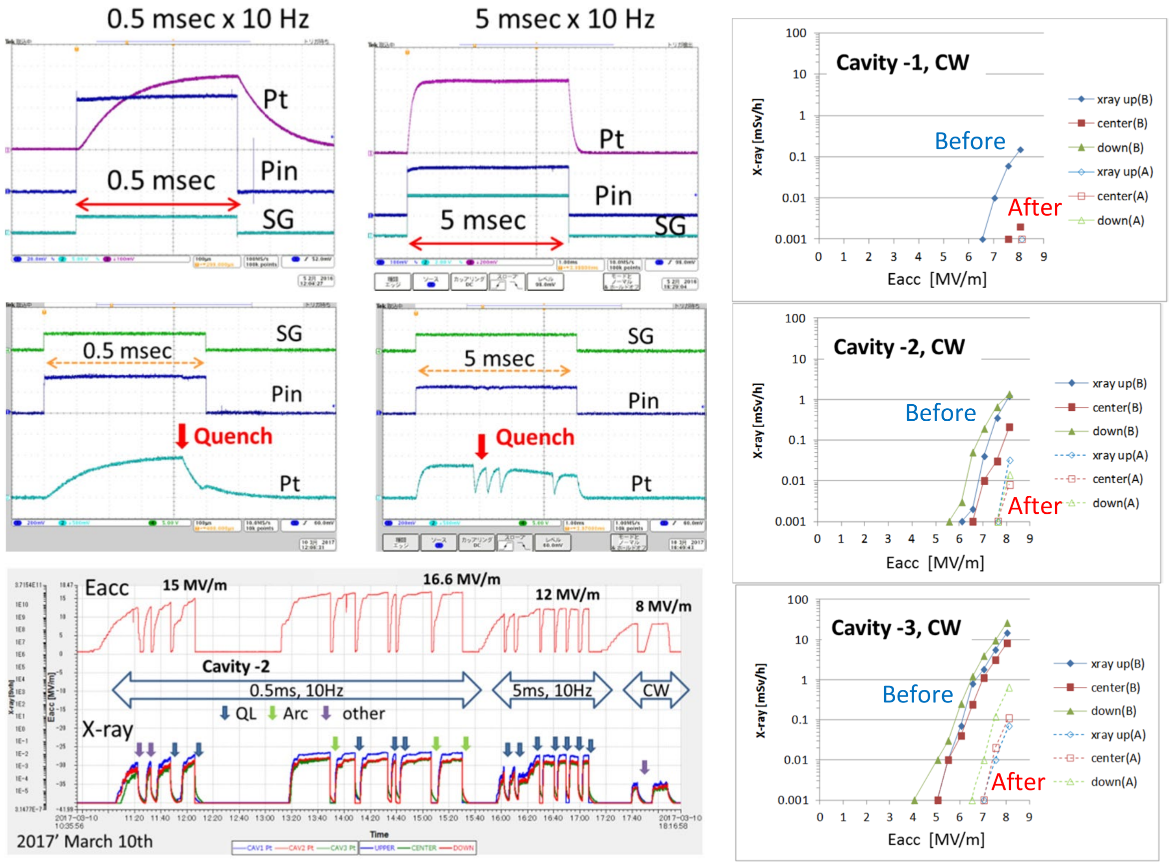
Cavity performance has been gradually degraded due to contaminated particles in Cryomodules during long term beam operation.

→ In-situ performance recovery is a key technology!

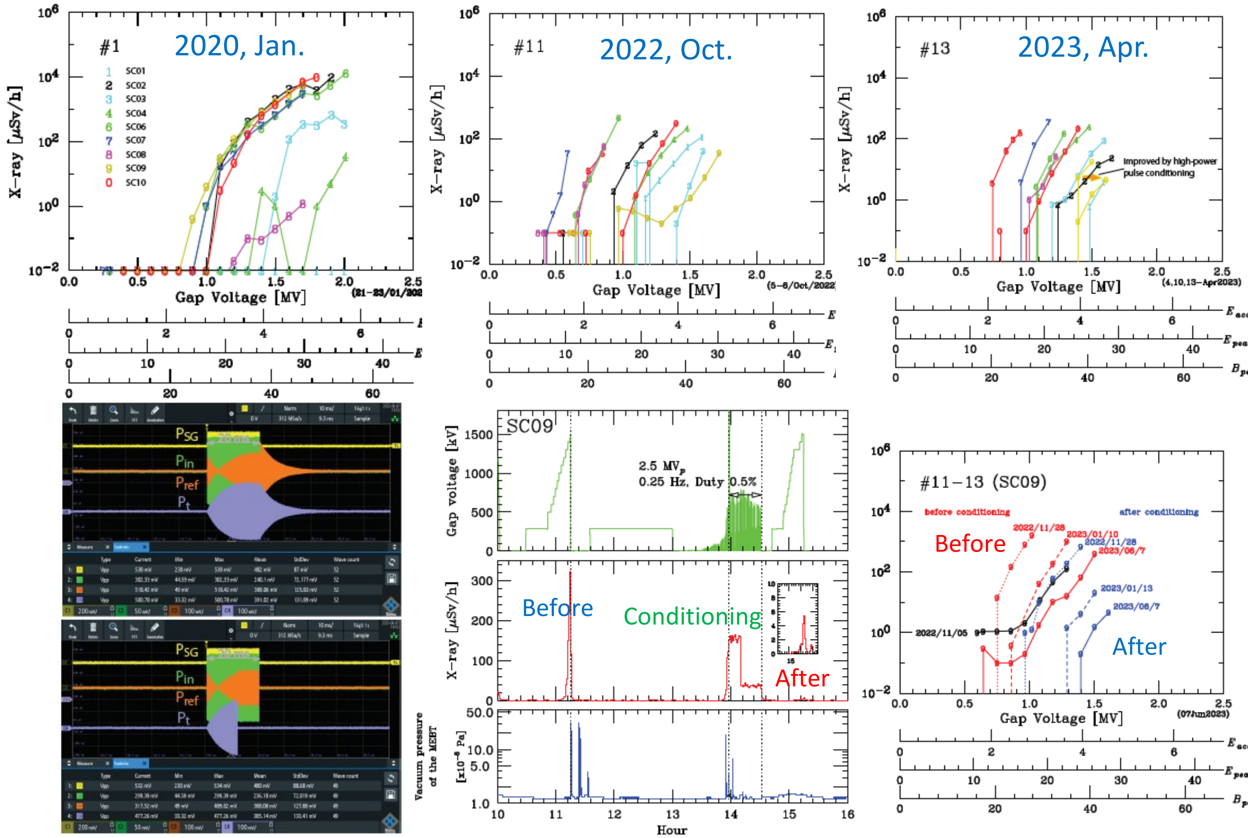
- High-power RF Pulsed Conditioning
- Helium Processing
- Plasma Processing
- Ozone Gas Processing

High-power RF Pulsed Conditioning

High-power RF conditioning with a short pulse at low temperature in CW cryomodules is effective to mitigate field emission and reduce x-ray radiation level.



Three 1.3 GHz 2-cell Cavities in cERL: SRF2017 by E. Kako (KEK)

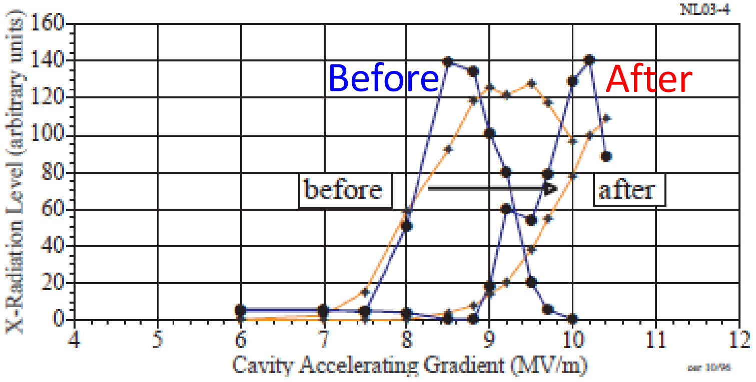


Ten 73 MHz QWR Cavities in SRILAC: SRF2023 by N. Sakamoto (RIKEN)

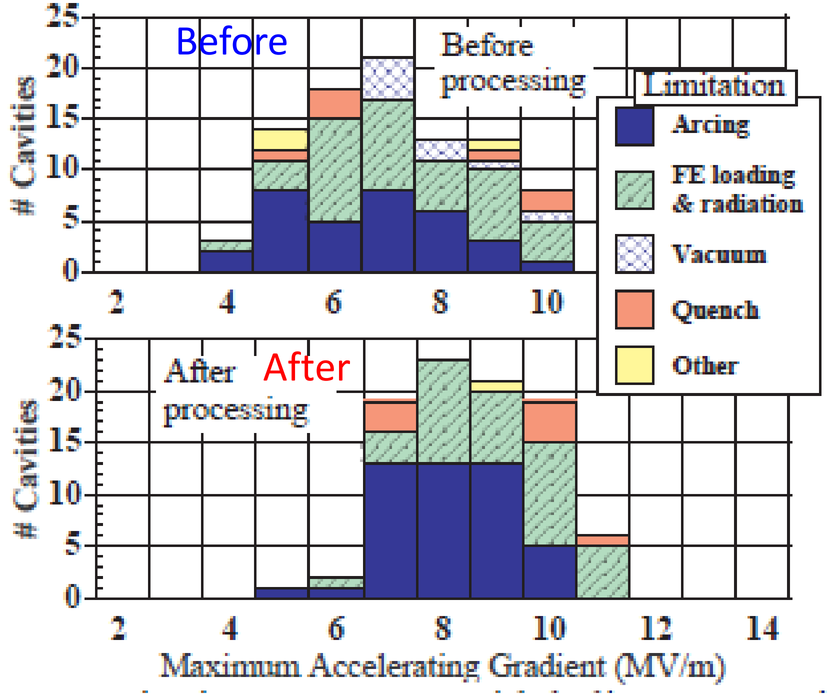
Helium Processing

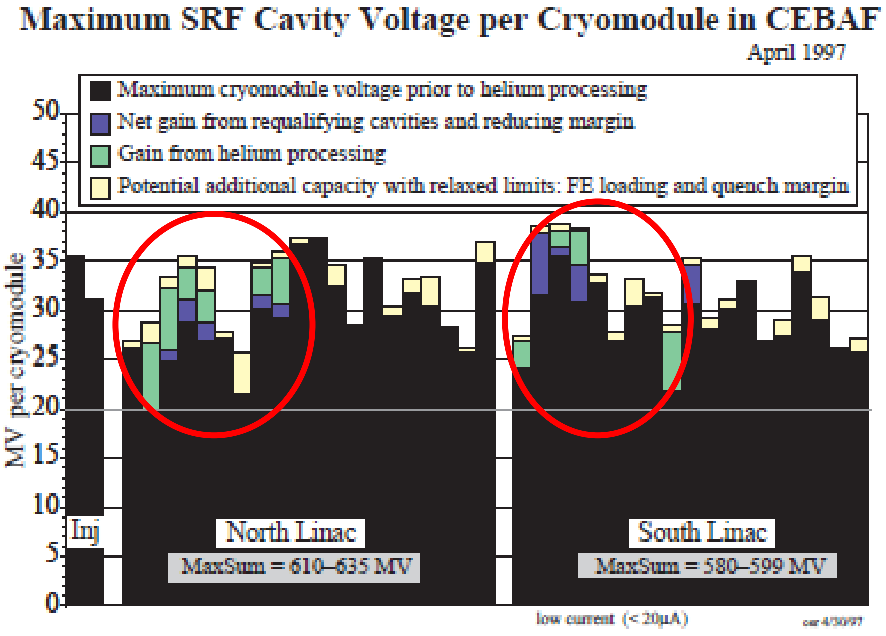
Helium processing is conducted at cryogenic temperature using inert gas, with gas pressure around 0.1 mTorr and an electric field level in the order of 10 MV/m.

(After the helium processing, warming up to 20 K was conducted for removal of the remaining helium gas inside the cavities.)



Cavity # in NL03	E_{acc} (MV/m)	Q_0 ($\times 10^9$)	
		Before	After
2	7.7	1.5	3.3
4	8.7	2.5	4.1
6	6.8	2.1	>5.3
8	8.8	2.85	4.7

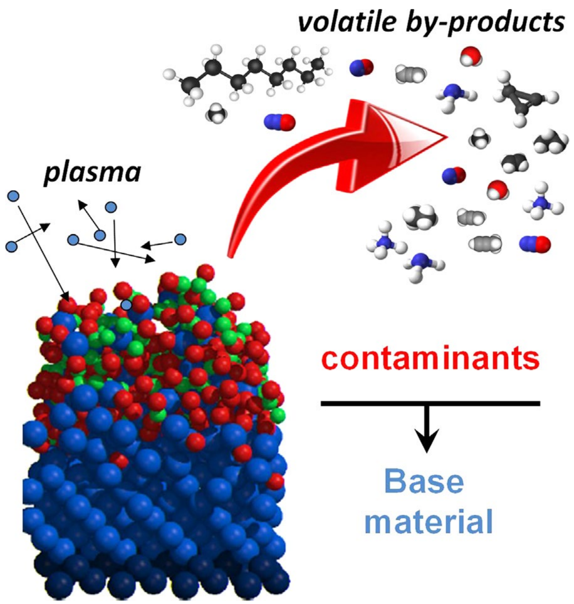


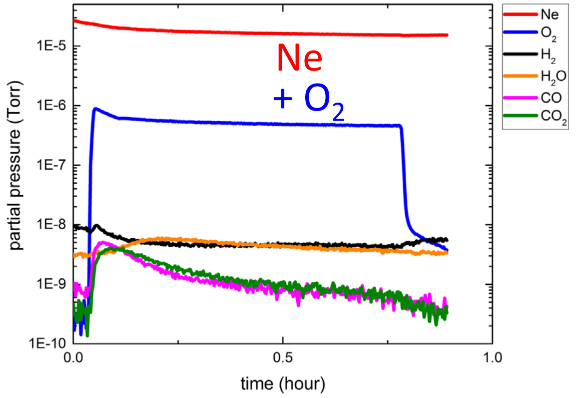


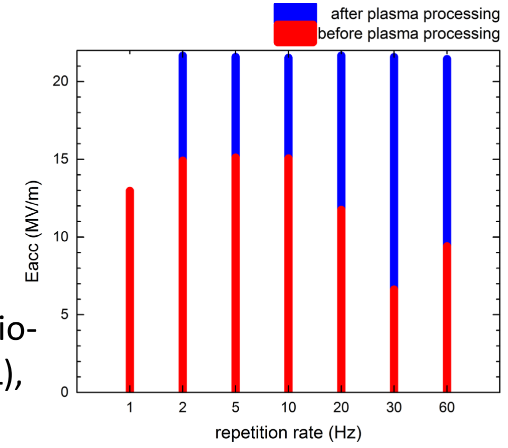
CEBAF 1.5 GHz 5-cell cavities: PAC1997 by C. E. Reece (Jlab)

Plasma Processing

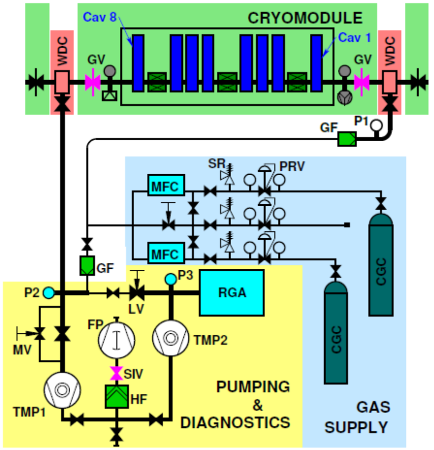
Plasma processing is performed at room temperature using a chemically reactive plasma with gas pressures of about 100 mTorr and electric field levels of around 0.01 MV/m. (This technique increased the work function of the cavity surface and removed hydrocarbons on the cavity inner surface.)

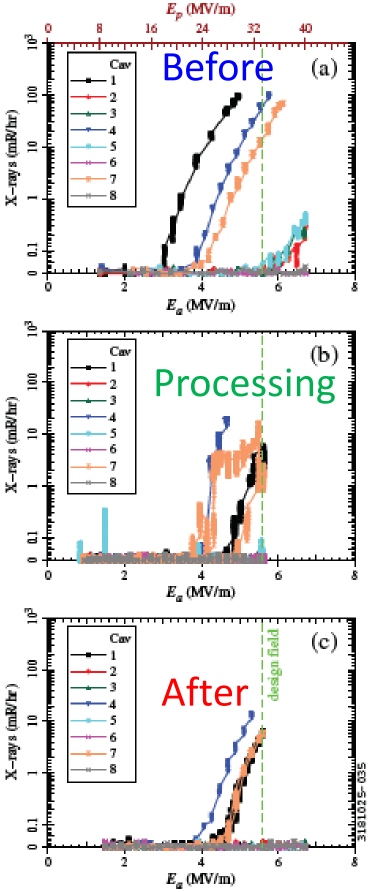






"In-situ plasma processing to increase the accelerating gradients of superconducting radio-frequency cavities", by M. Doleans (SNS/ORNL), NIM-A 812 (2016) p50–59.



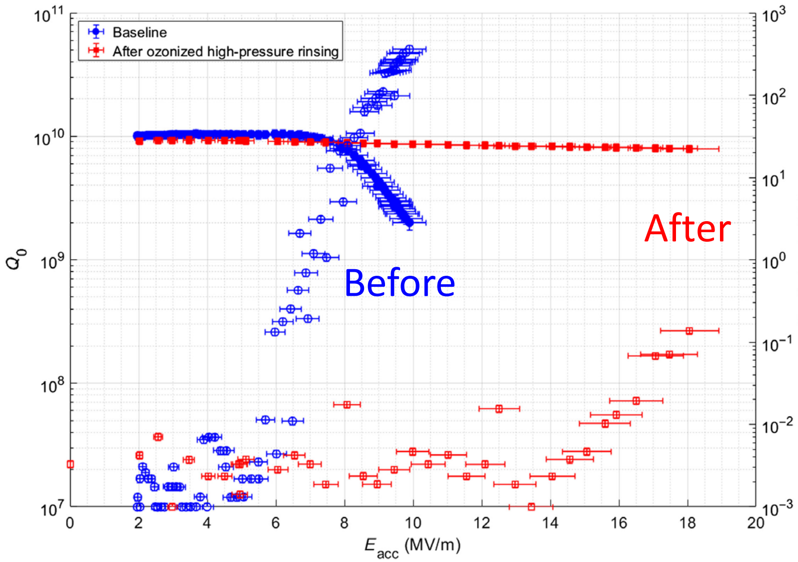


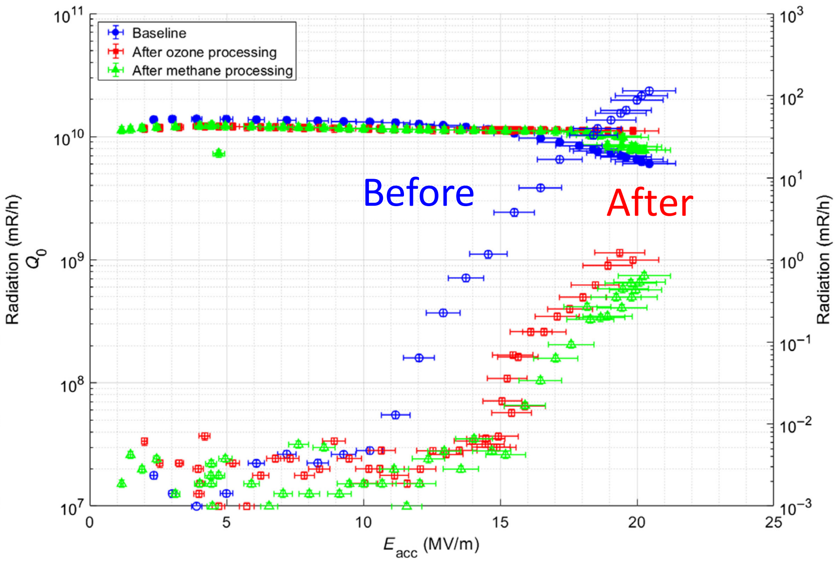
"Plasma Processing of FRIB Low-beta Cryomodules Using Higher-Order-Modes", by P. Tutt (FRIB, USA), SRF2025, Tokyo (2025) p293-299.

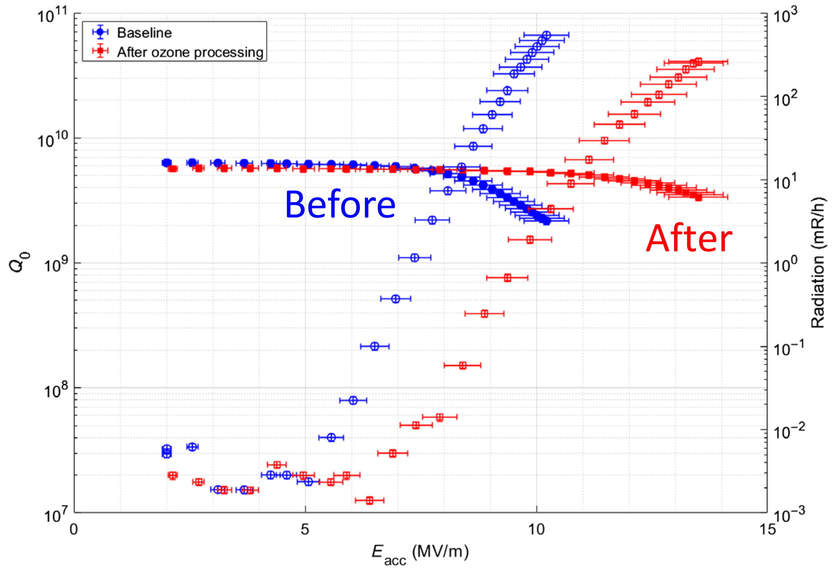
Ozone Gas Processing

iCASA Innovation Center for Applied Superconducting Accelerators
応用超伝導加速器イノベーションセンター

In-situ ozone-gas processing was performed at room temperature without RF power with a concentration of 6 wt% in an oxygen gas flow of 1 l/min. Chemical reactions with ozone-gas remove organic and some inorganic surface contaminants. (The ozone-gas processing is a simple cleaning method for cavities and cryomodules already installed into accelerators.)







“Reducing field emission in superconducting cavities with ozone”
By Roger Ruber (JLab), USA),
PHYSICAL REVIEW ACCELERATORS AND BEAMS 27, 122001 (2024)

2. Recent Progress on SRF Cavity Performance

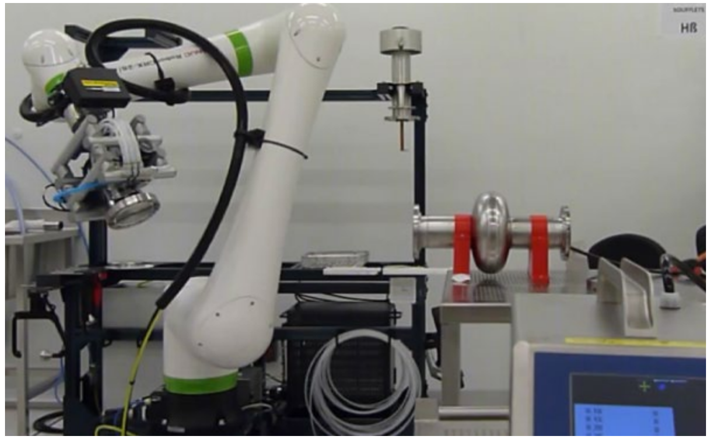
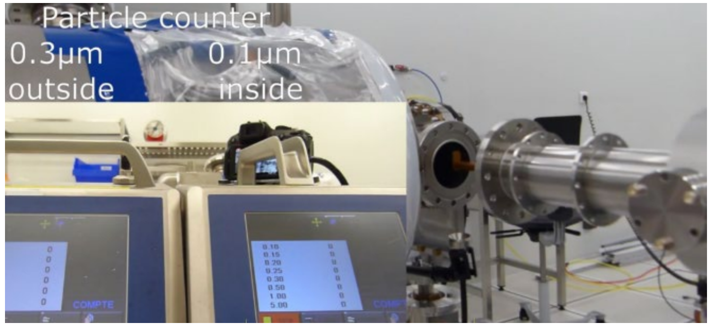
1. Fundamental Cavity Performance
2. High Purity Niobium Production
3. Toward Higher Q and Higher Gradient
4. Performance Recovery Techniques
5. **Breakthrough for the next step**
6. Summary

Breakthrough for the next Step

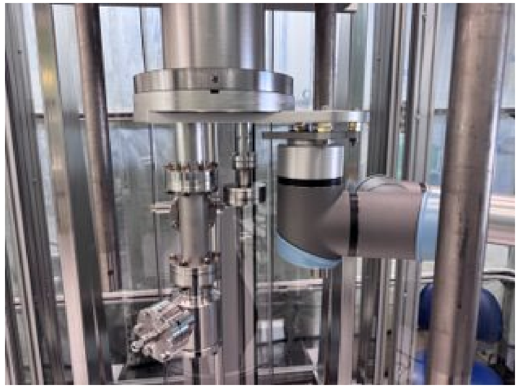
- Robotic Technology with AI
- New Cavity Structure
- New Superconducting Material
- Young Power for Innovation

Robotic Technology with AI

Contaminated particles causing field emissions are generated by the presence of workers in a cleanroom. → Robot-assisted automation assembly technology is required.

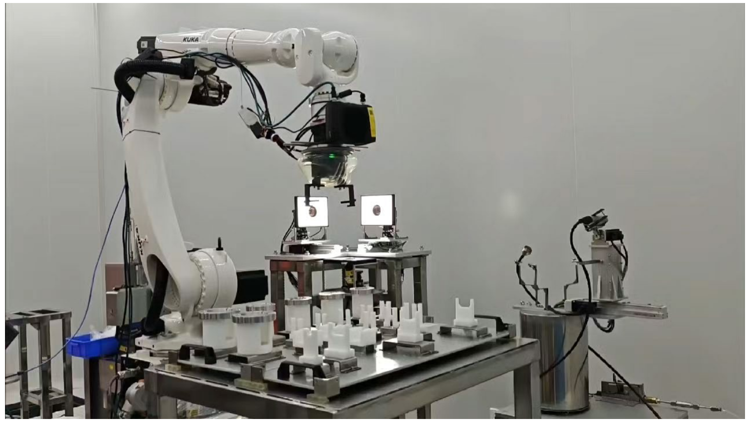
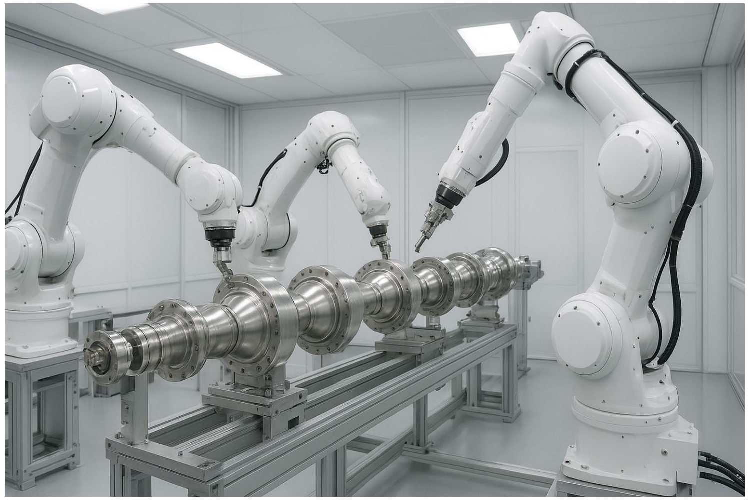
at CEA (France)

at FNAL (USA)



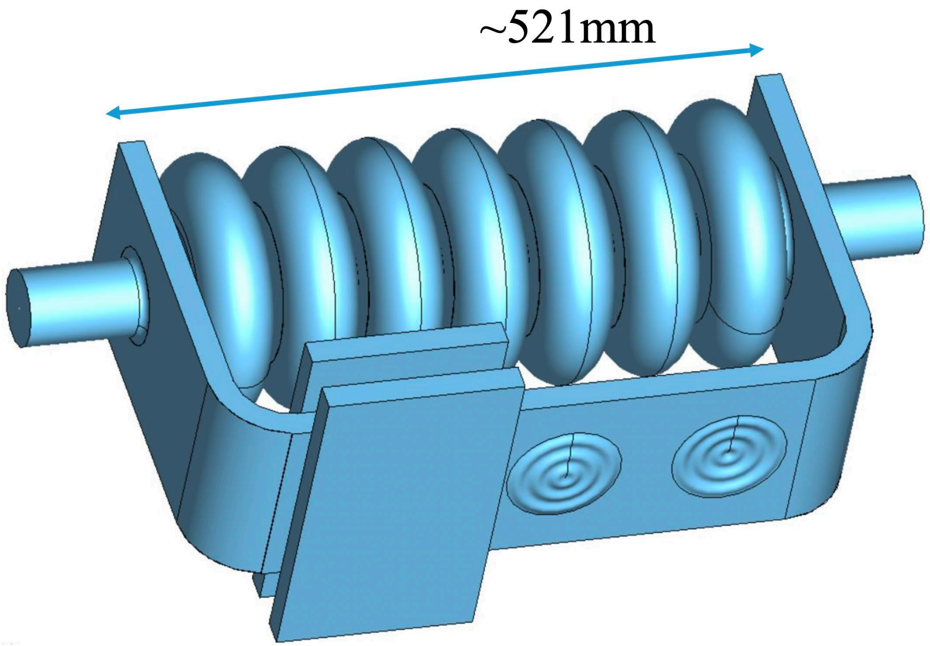

at IMP (China)

"STATUS OF ROBOTICS AND AUTOMATION IN THE SRF COMMUNITY AND REAL APPLICATIONS", L. L. Popielarski, FRIB/MSU, SRF2025 (2025) p589.

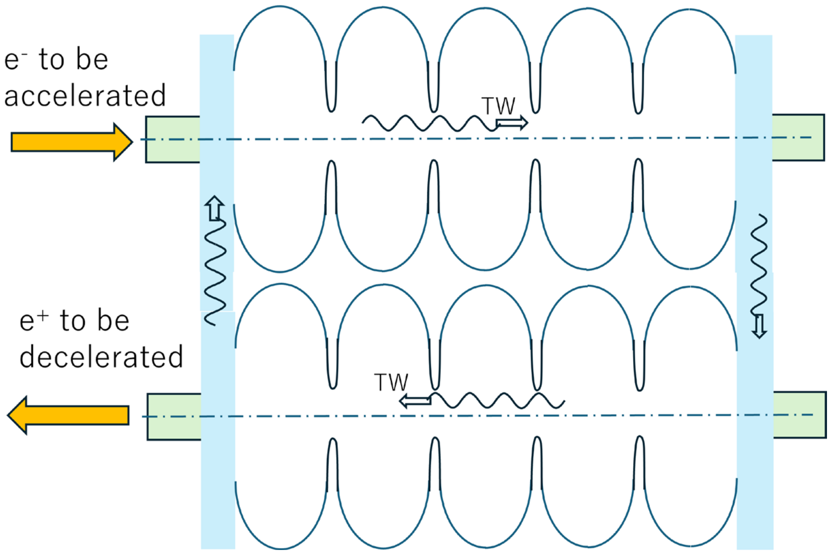
New Cavity Structures for Extremely High-G

Traveling wave (TW) technology can push the accelerating field of a niobium SRF cavity beyond the fundamental limit for SW structures to 70 MV/m or more.



Traveling Wave Cavity Structure

Courtesy of Fumio Furuta and Sergey Kazakov
Fermilab (USA)



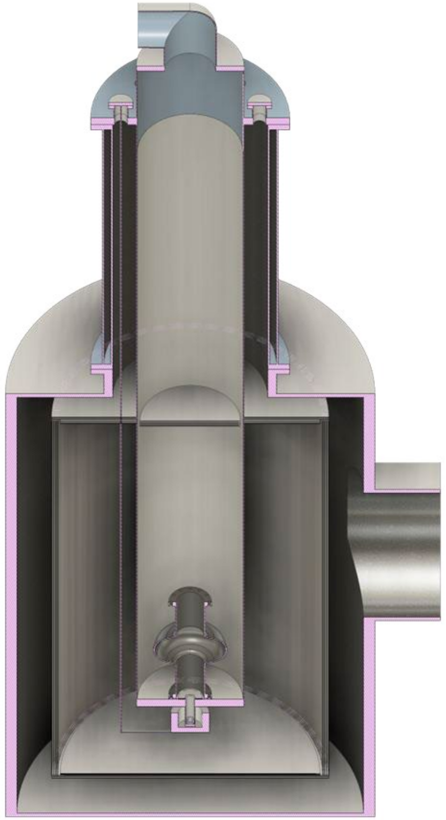
Twin-Axis Cavity
with Traveling Wave Type Structure

Courtesy of Kaoru Yokoya, KEK (Japan)

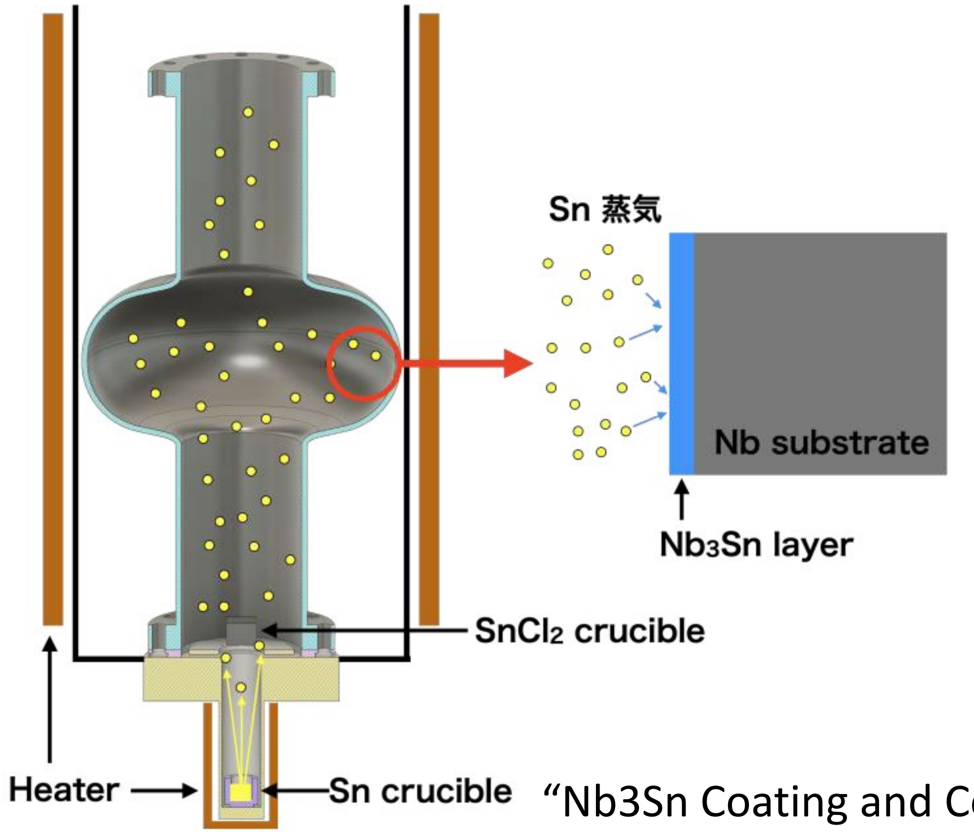
New Superconducting Material (Nb_3Sn)

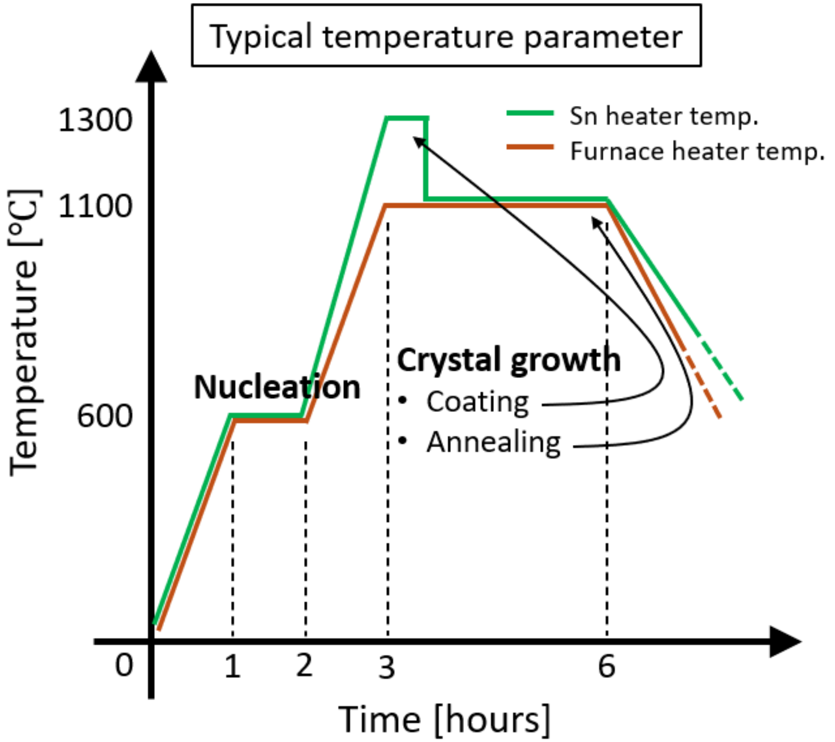
Nb_3Sn Coating on Niobium Cavity by Vapor Diffusion Method:

Nucleation of Sn ($SnCl_2$) at 600°C → Crystal Growth of Nb_3Sn layer at 1300°C → Annealing at 1100°C for 3 hours.



High Temperature Vacuum Furnace (1300°C)



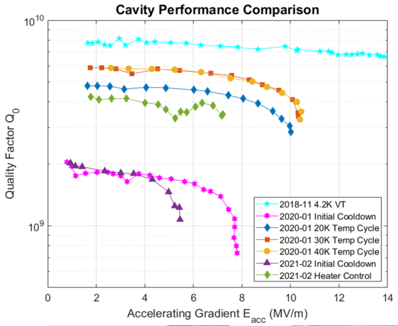


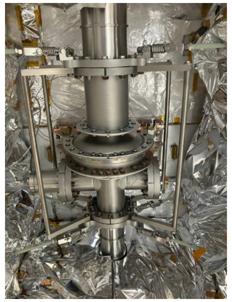
"Nb3Sn Coating and Conduction Cooling R&D at KEK", SRF2025 by T. Yamada (KEK, Japan)

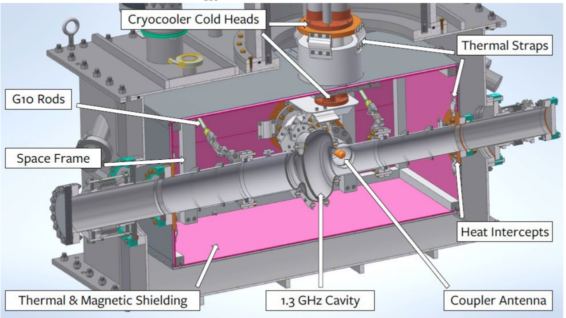
New Superconducting Material (Nb_3Sn)

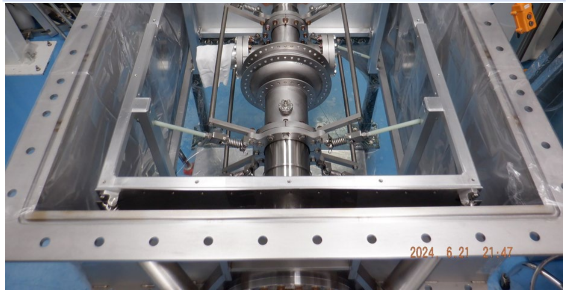
Innovation Center for Applied Superconducting Accelerators
応用超伝導加速器イノベーションセンター

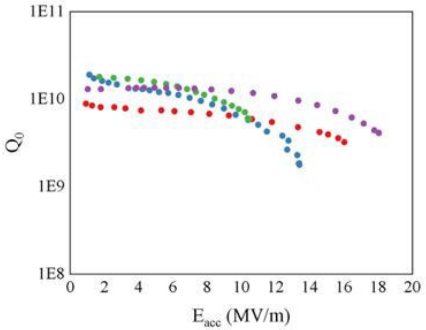
Nb_3Sn (T_c=18.3K) cavity can be cooled by a cryocooler (He-free system). SRF2025 (WEA04, WEA05, WEA06)

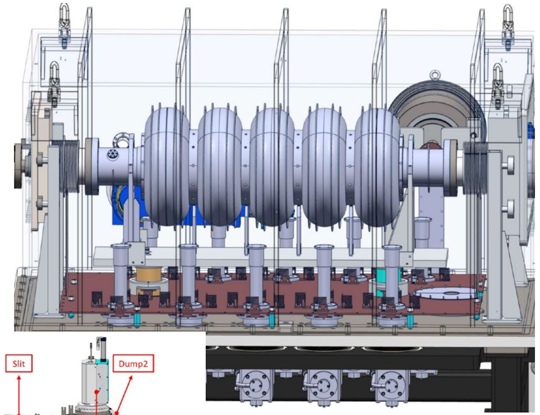


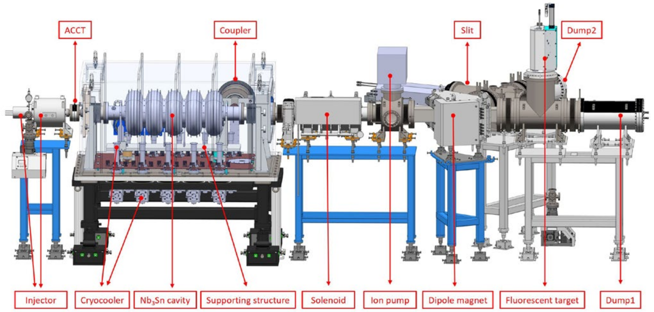


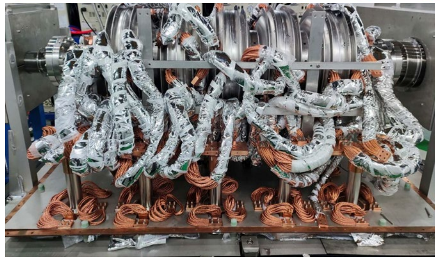


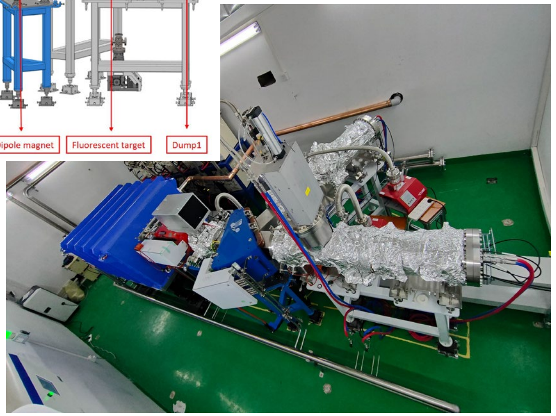


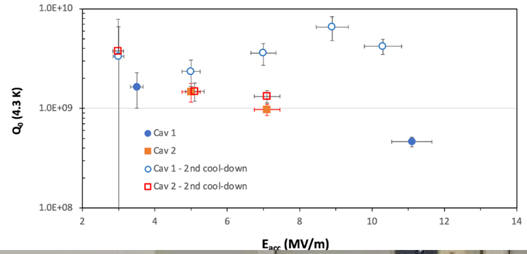


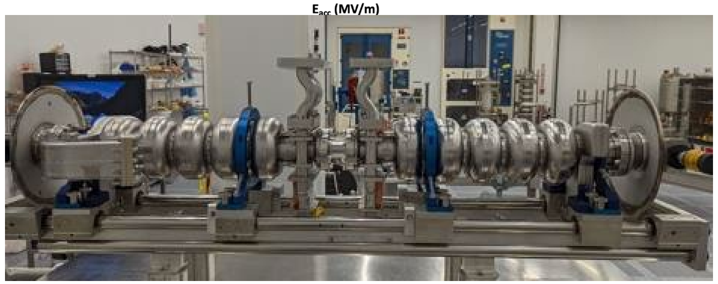


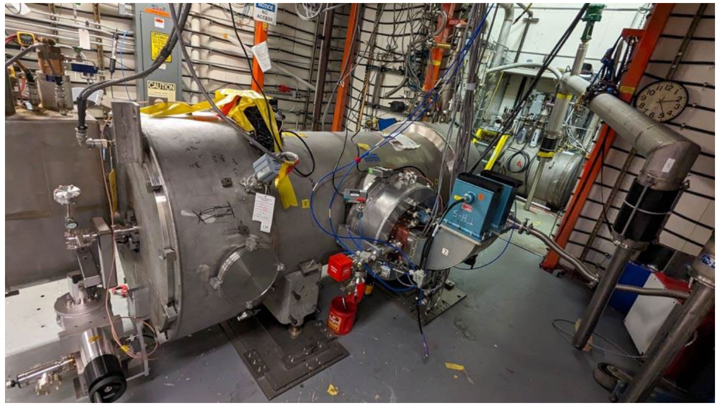












Cornell (USA): 1.3 GHz 1-cell cavity
Conduction cooling by 1 Cryocooler

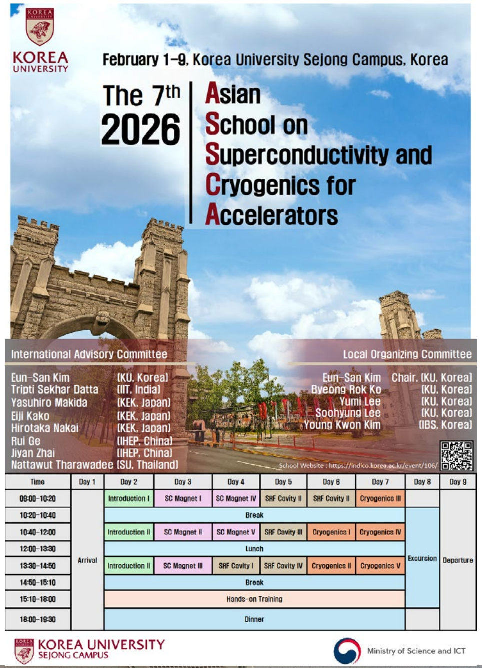
IMP (China): 650 MHz 5-cell cavity
Conduction cooling by 10 Cryocoolers

Jlab (USA): Two 1.5 GHz 5-cell Cavities
Cooling by Liq. Helium at 4.3K

Young Power for Innovation

TTC2025 at IBS, Korea

ASSCA2026 at Korea University



SRF2025 at Tokyo Univ., Japan

1. Fundamental Cavity Performance
2. High Purity Niobium Production
3. Toward Higher Q and Higher Gradient
4. Performance Recovery Techniques
5. Breakthrough for the next step
6. Summary

Summary

- Essential surface preparations including EP, 800^{o}C HT, HPR, 120^{o}C baking and clean assembly was confirmed in many 1.3 GHz 1-cell/9-cell cavities.
- R&D efforts towards Higher-Q and Higher-Gradient of SRF cavity performances have continued to produce new results and open exciting possibilities.
- Higher-Gradient must be accompanied by measures to mitigate field emission in SRF cavities installed in cryomodules.
- Related technologies must be saved development costs and power consumption.
- In the longer-timescale (longer 10-years), TW SRF structures are anticipated to be developed and gradients to be increased to ~70 MV/m or more.

Thank you for your attention.

I believe you are interested in SRF cavity developments.
We welcome your visit to KEK.

Emeritus Prof. Eiji Kako

iCASA, Accelerator Laboratory,
KEK, Japan
voice: +81-29-864-5200 ex. 4325
fax: +81-29-864-3182
email: eiji.kako@kek.jp

Thank you!

Questions !