Introduction of SRF Cavity System

Eiji Kako (KEK, Japan)

ASSCA2025 at IHEP
March 26, 2025’

Outline of the Lecture

1. Introduction
2. Fundamental of SRF Cavity
3. Overview of SRF Cavity System
4. Fabrication and Surface Preparation
5. Cavity Performances
6. Summary

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Introduction of Lecturer

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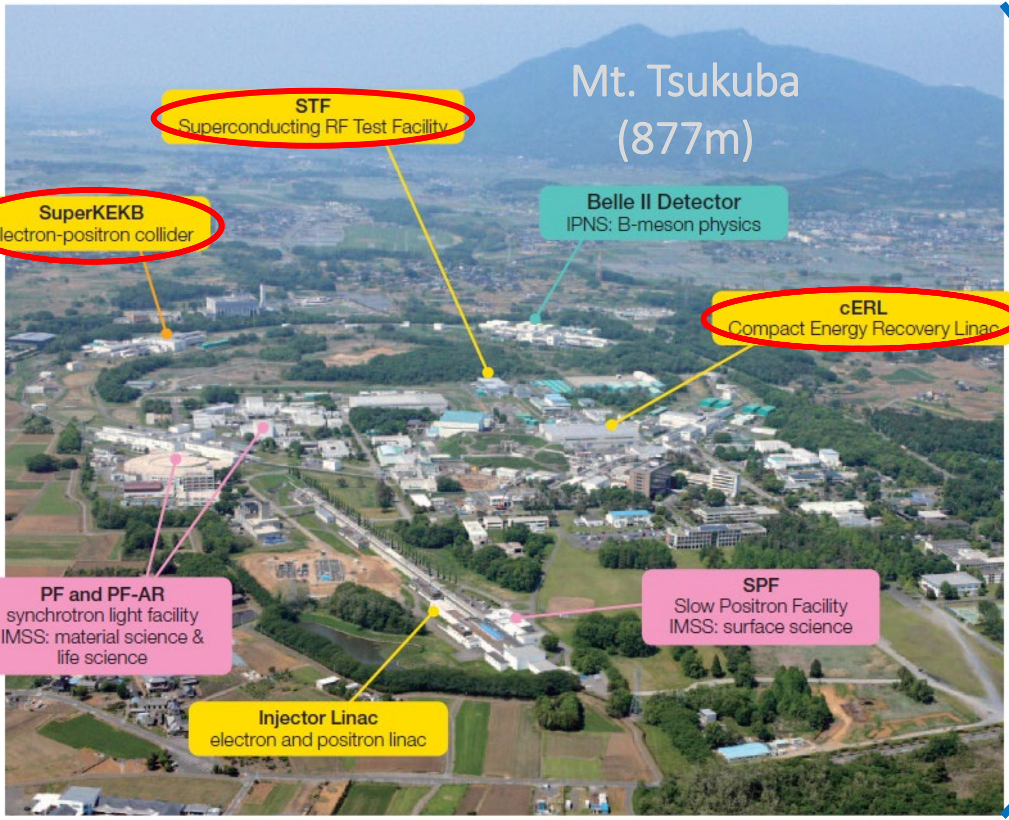
Introduction of KEK

High Energy Accelerator Research Organization

KEK



Tsukuba Campus
(Electron Accelerator)

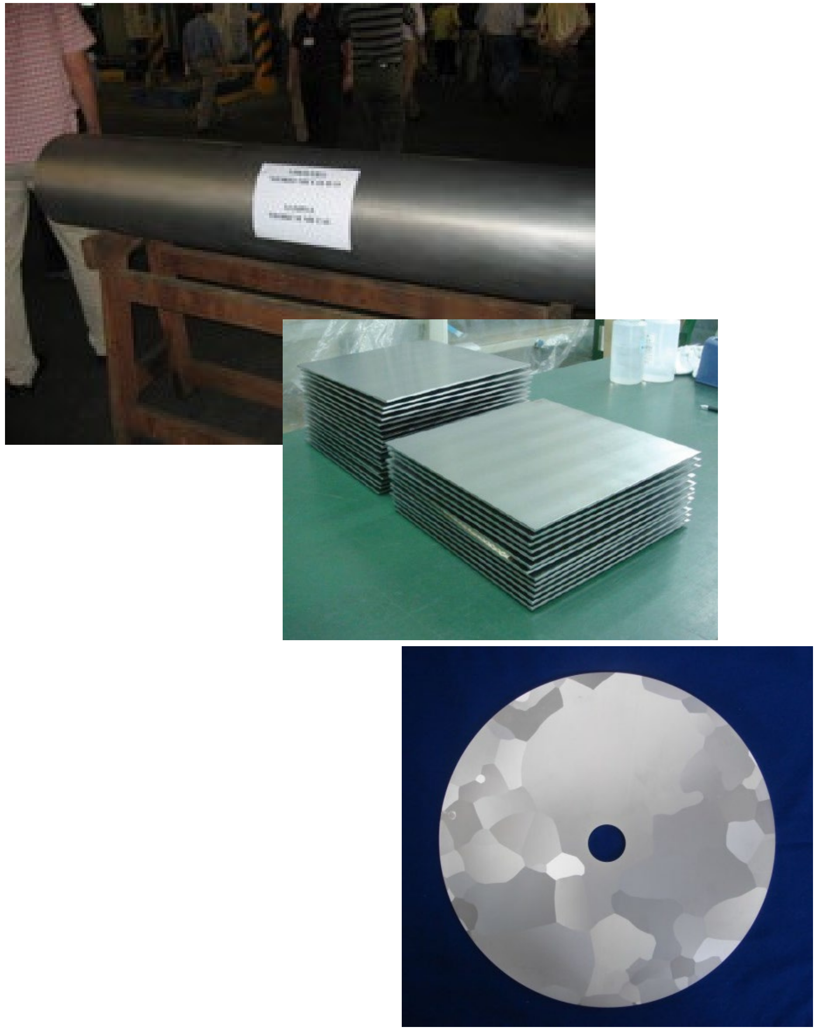
J-PARC

Tokai Campus
(Proton Accelerator)

Introduction of Superconducting Cavity

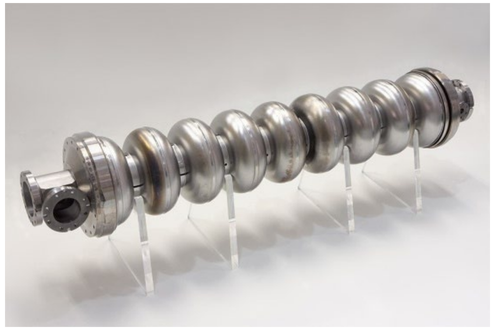
My life at KEK for 38 years.

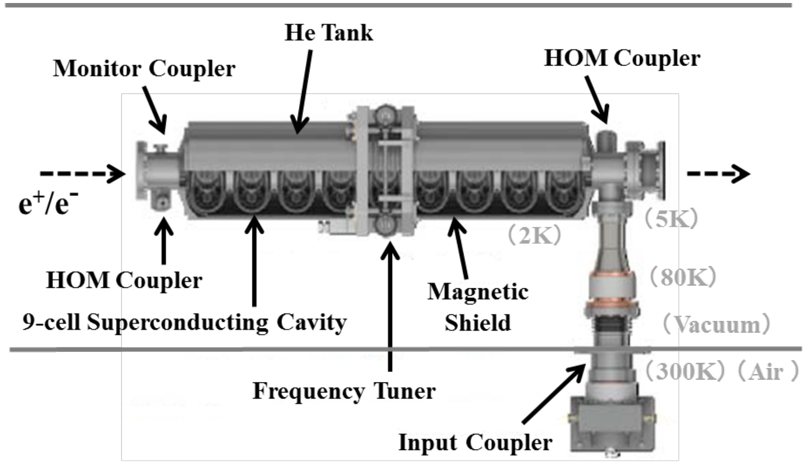
Superconducting RF (SRF) Cavity



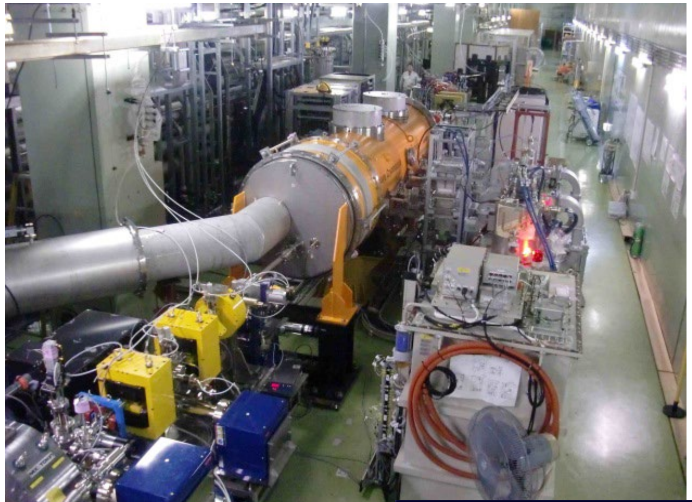
Niobium Material

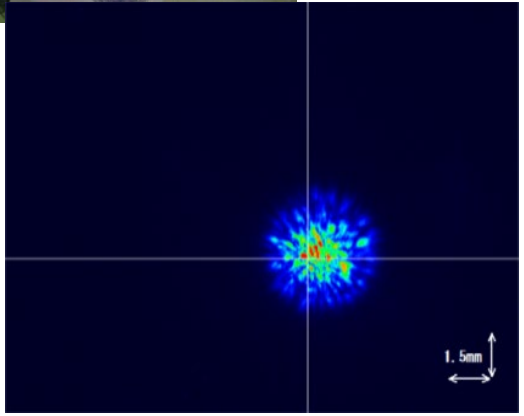
Cavity





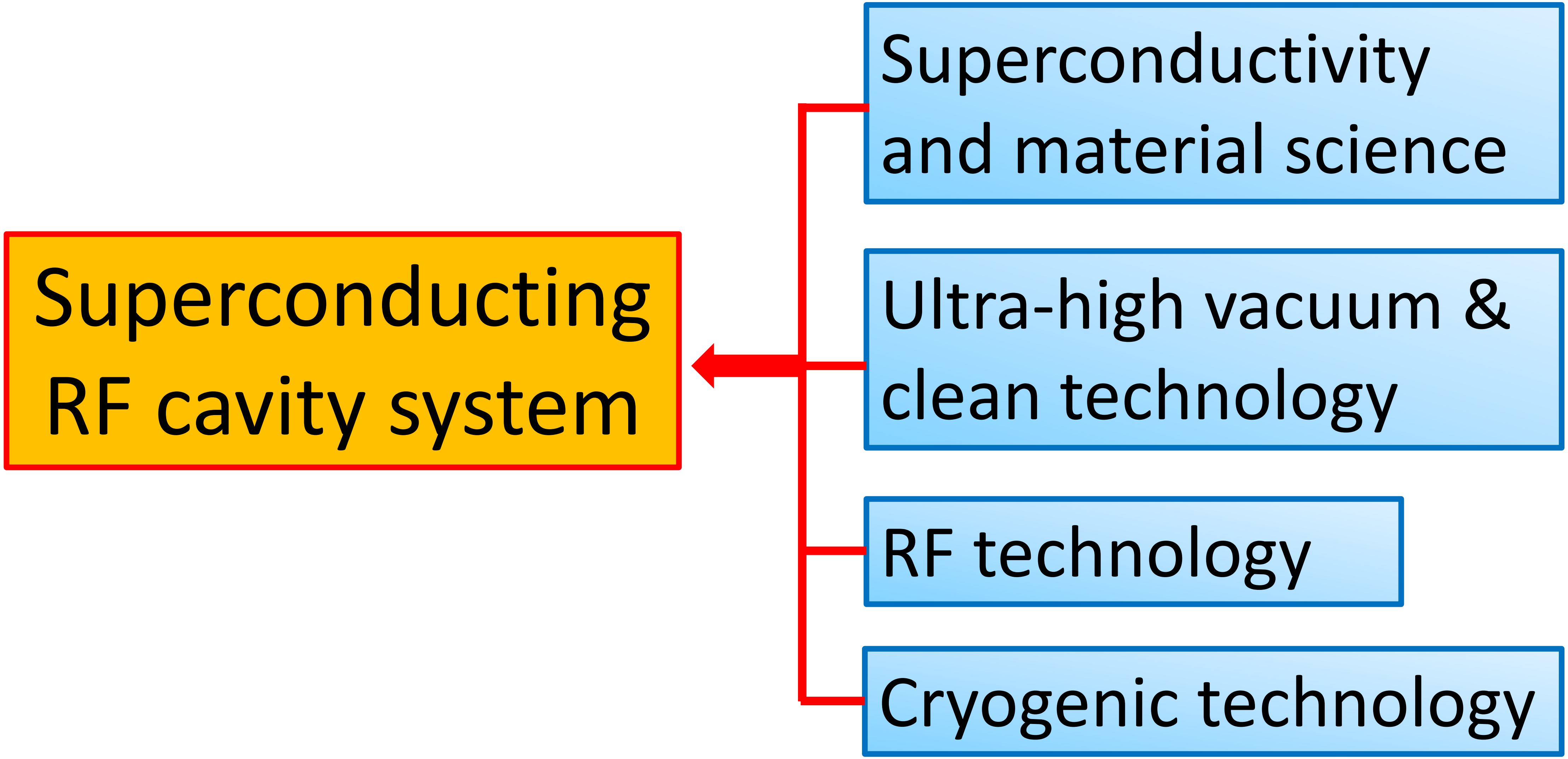
Cryomodule





Stable Beam Operation

Superconducting RF (SRF) Cavity



Superconducting RF cavity system

Superconductivity and material science

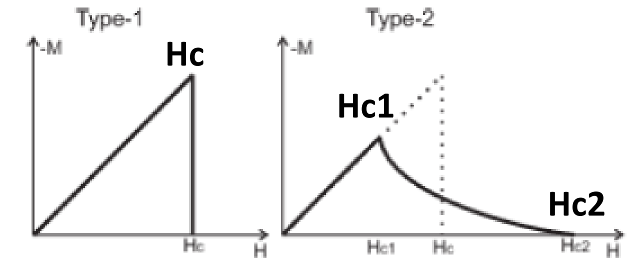
Ultra-high vacuum & clean technology

RF technology

Cryogenic technology

Typical Properties of Superconductor

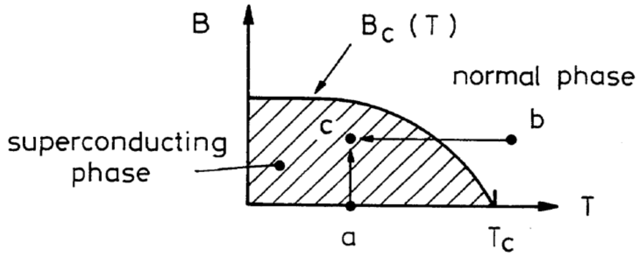
Type-1, Type-2 Superconductor



Pb

Nb, Nb3Sn

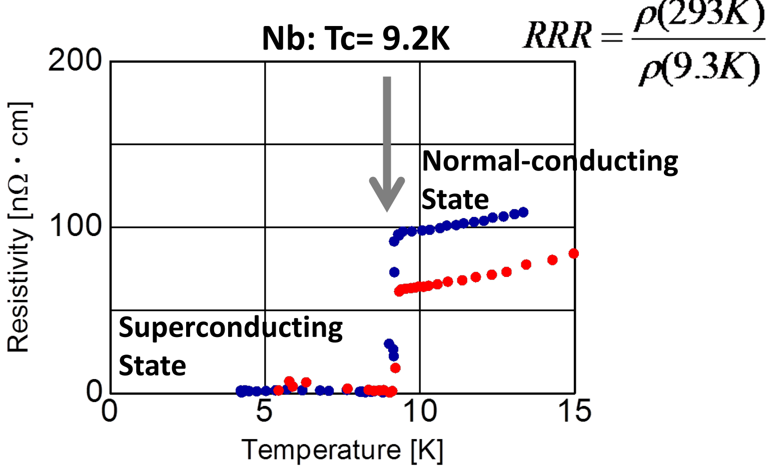
Phase diagram



$$H_{c1}(T) = H_{c1}(0) \times (1-(T/T_c)^2)$$

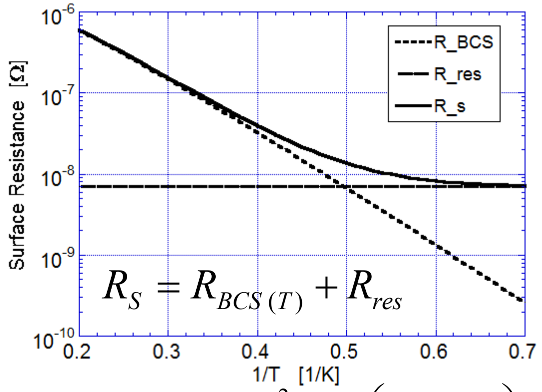
T < Tc/2

DC Resistivity



$$RRR = \frac{\rho(293K)}{\rho(9.3K)}$$

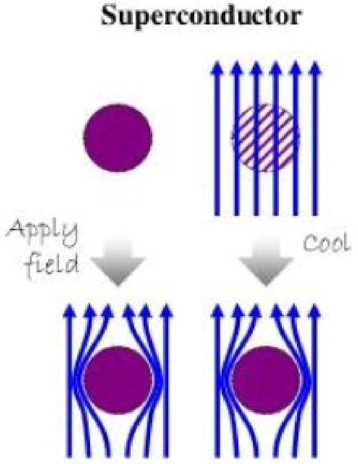
RF Surface Resistance



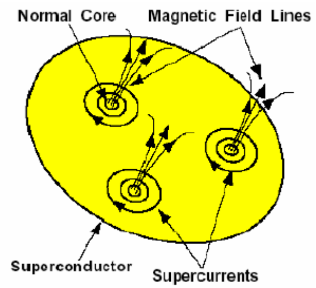
$$R_S = R_{BCS\,(T)} + R_{res}$$

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

Meissner effect

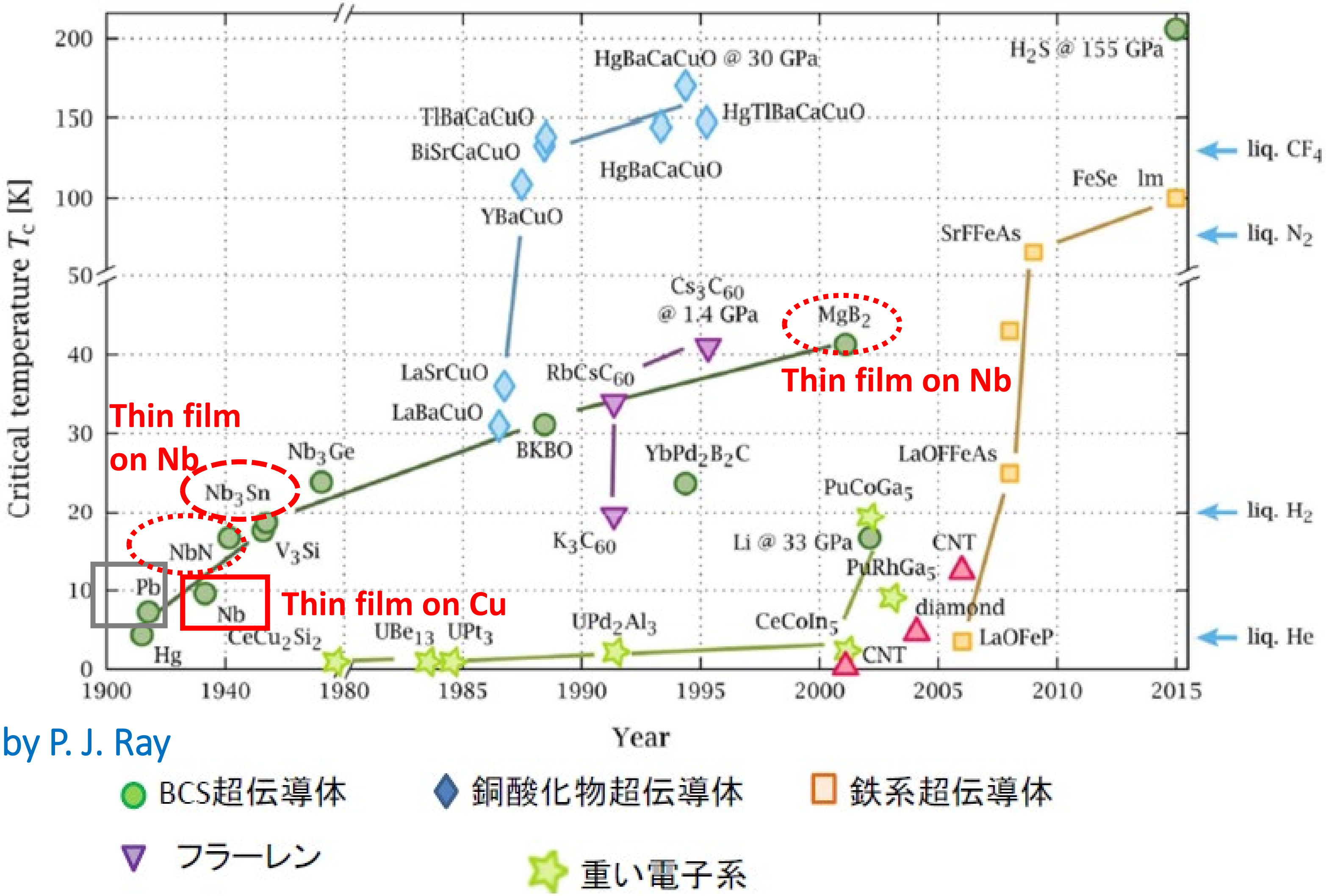


Flux trapping



R_{res} = 0.3~0.4 [nΩ /mG]

Critical Temperatures of Superconductors



Thin film on Nb

Thin film on Nb

Thin film on Cu

by P. J. Ray

	T c	H c (0)	λ
Nb	9.2 K	0.20 T	40 nm
NbN	16.2 K	0.23 T	~350 nm
Nb$_3$Sn	18 K	0.54 T	~100 nm
MgB$_2$	40 K	0.43 T	140 nm

Question (1)

What is the advantage using Niobium for SRF cavities?

Superconducting RF (SRF) Cavity

What is the advantage using Niobium for SRF cavities?

- Suitable critical temperature (*Tc*) at 9.2 K

  → Cooling by liquid He: at 4.2 K and at 2.0 K

- Availability of high purity Niobium metal

  → Production by Electron Beam (EB) melting

- Better fabrication property from Niobium sheets

  → Forming by deep drawing and joining by EB welding

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Rest Energy of Particles

1 Joule = 1 Nm= 1 kgm^2/sec^2

1 eV = 1.6 x 10^{-19} Joule

c = 2.9979 x 10^8 m/sec

m_e = 0.9109 x 10^{-27} g ; mass of electron

m_p = 1.6925 x 10^{-24} g ; mass of proton

Rest Energy

$E_e = m_e c^2 = 0.511$ MeV

$E_p = m_p c^2 = 938$ MeV

Kinetic Energy of Particles

Rest Energy $E_0 = m_0 c^2 \quad (v = 0)$

$(v > 0)$

$$\boxed{E = \frac{m_0 c^2}{\sqrt{1-(v/c)^2}} = \frac{m_0 c^2}{\sqrt{1-\beta^2}} = m_0 \gamma c^2}$$

Kinetic Energy $E_K = m_0 \gamma c^2 - m_0 c^2 = m_0 c^2 (\gamma - 1)$

$$\gamma = 1 \Big/ \sqrt{1-\beta^2} \qquad \boxed{\beta = v/c}$$

$\beta < 0.5 \quad (v << c)$

Low-β

$\beta \approx 0.5 \sim 0.7$

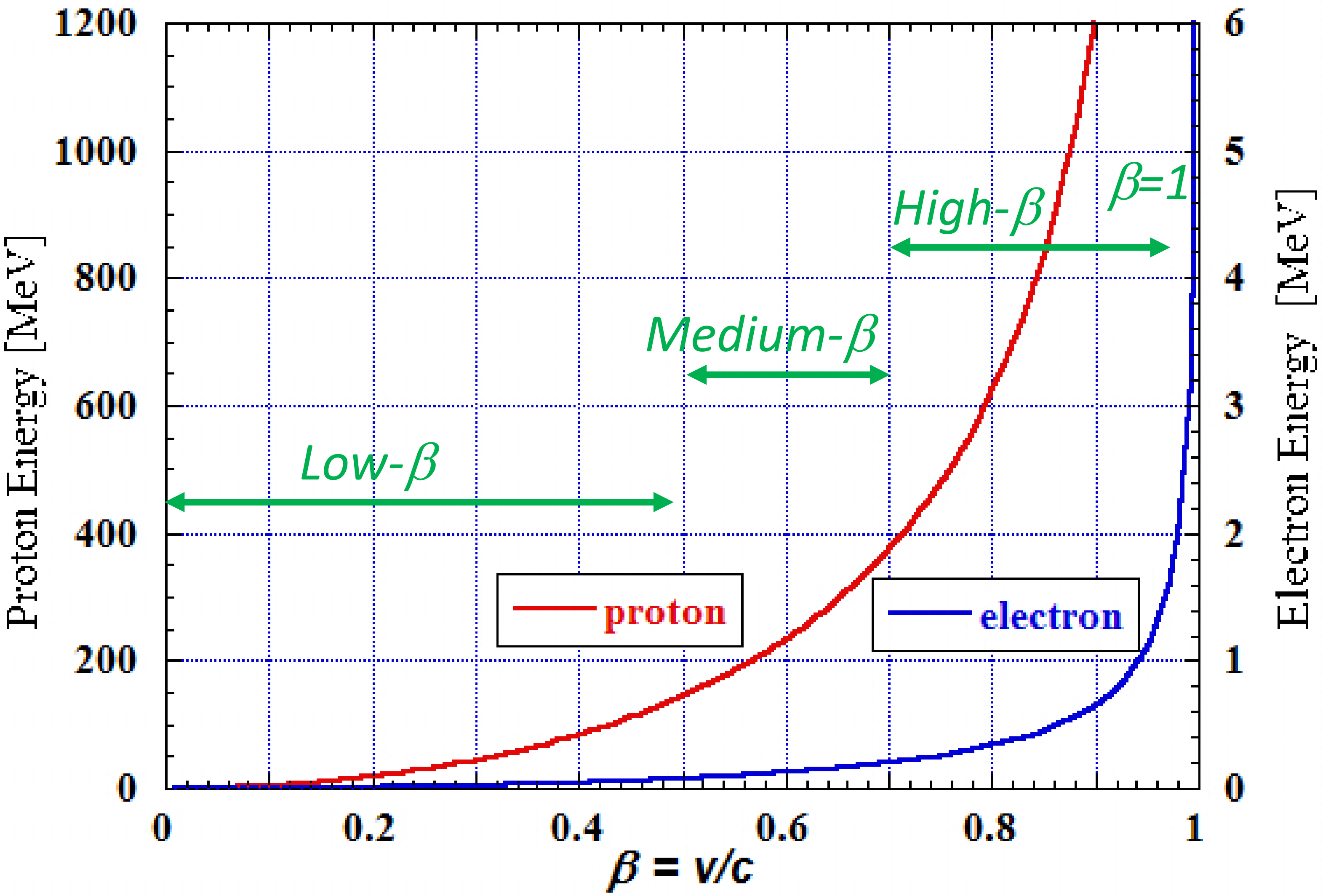
Medium-β

$\beta \approx 1 \quad (v \approx c)$

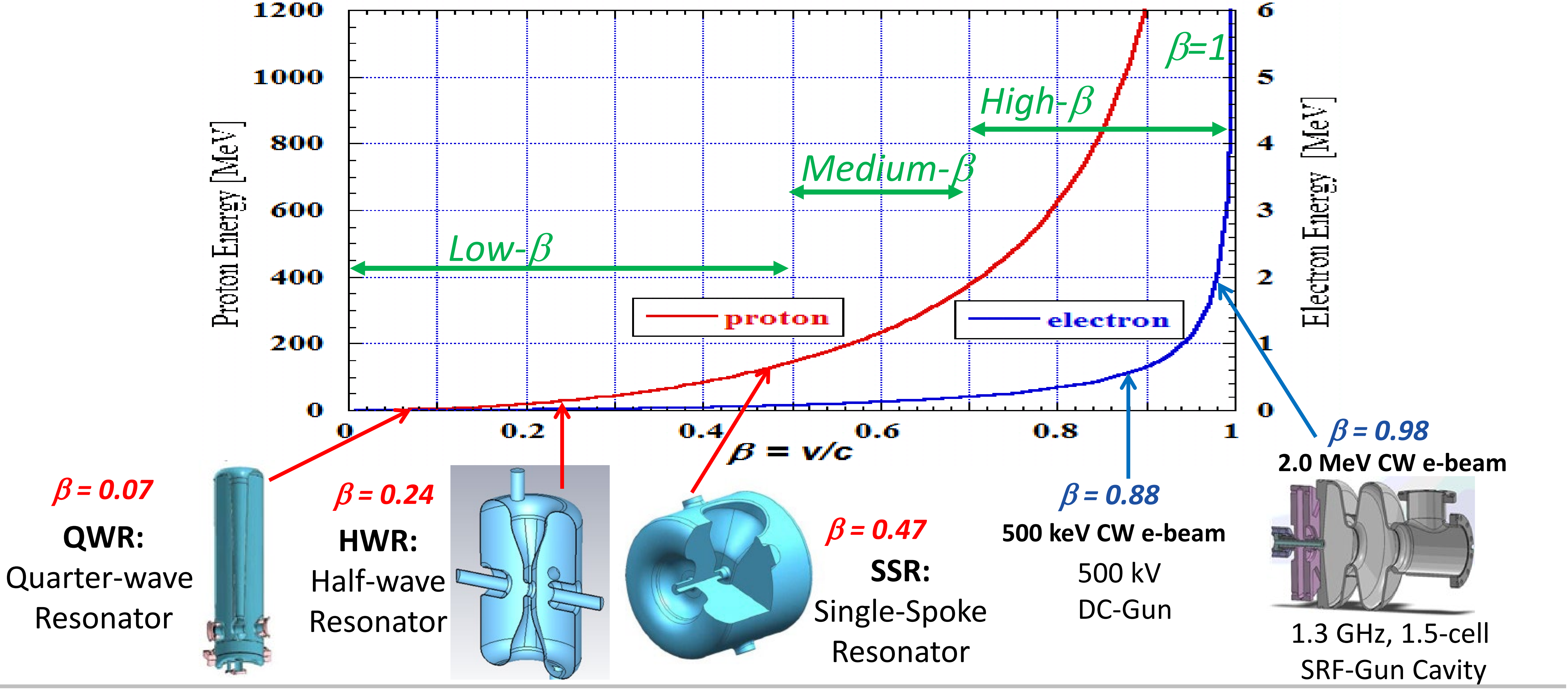
$\beta > 0.7$

High-β

Kinetic Energy of Protons and Electrons



Accelerating Structures for Proton and Electrons



β = 0.07

QWR:
Quarter-wave
Resonator

β = 0.24

HWR:
Half-wave
Resonator

β = 0.47

SSR:
Single-Spoke
Resonator

β = 0.88

500 keV CW e-beam

500 kV
DC-Gun

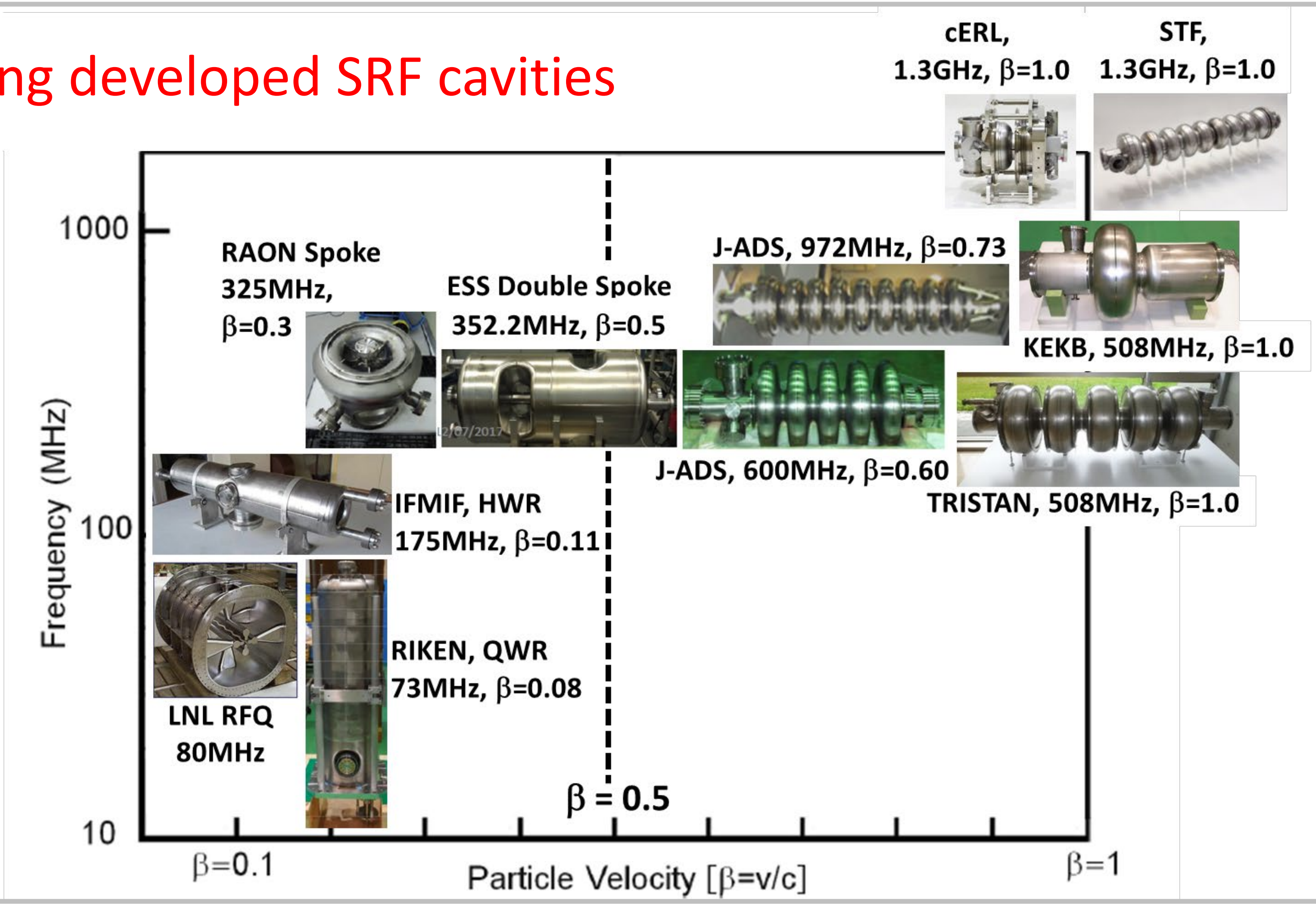
β = 0.98

2.0 MeV CW e-beam

1.3 GHz, 1.5-cell
SRF-Gun Cavity

Accelerating Structures for Proton/Ions and Electrons

Existing developed SRF cavities



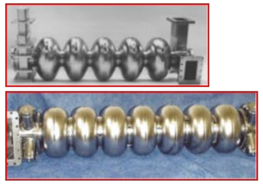
(IHEP : CEPC)

SRF Cavity Production in Worldwide Projects

Elliptical multi-cell cavities

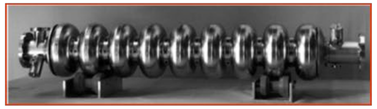

FERMI 3.9 GHz


S-DALINAC 3 GHz


CEBAF 1.5 GHz


HEPL 1.3 GHz


CESR 0.5 GHz

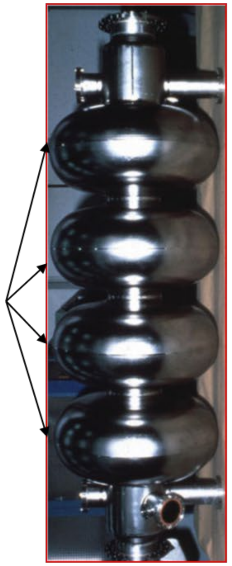

TESLA/ILC 1.3 GHz


SNS ß=0.61,0.81, 0.805 GHz


HERA 0.5 GHz


KEK-B 0.5 GHz


TRISTAN 0.5 GHz


LEP 0.352 GHz

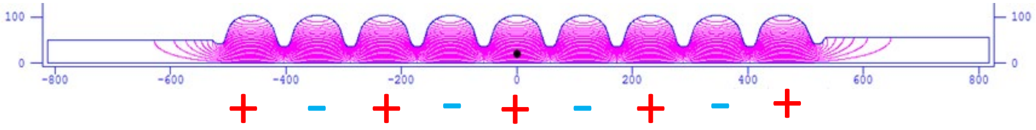
Quarter Wave Resonators (QWR)

Half Wave Resonators (HWR)

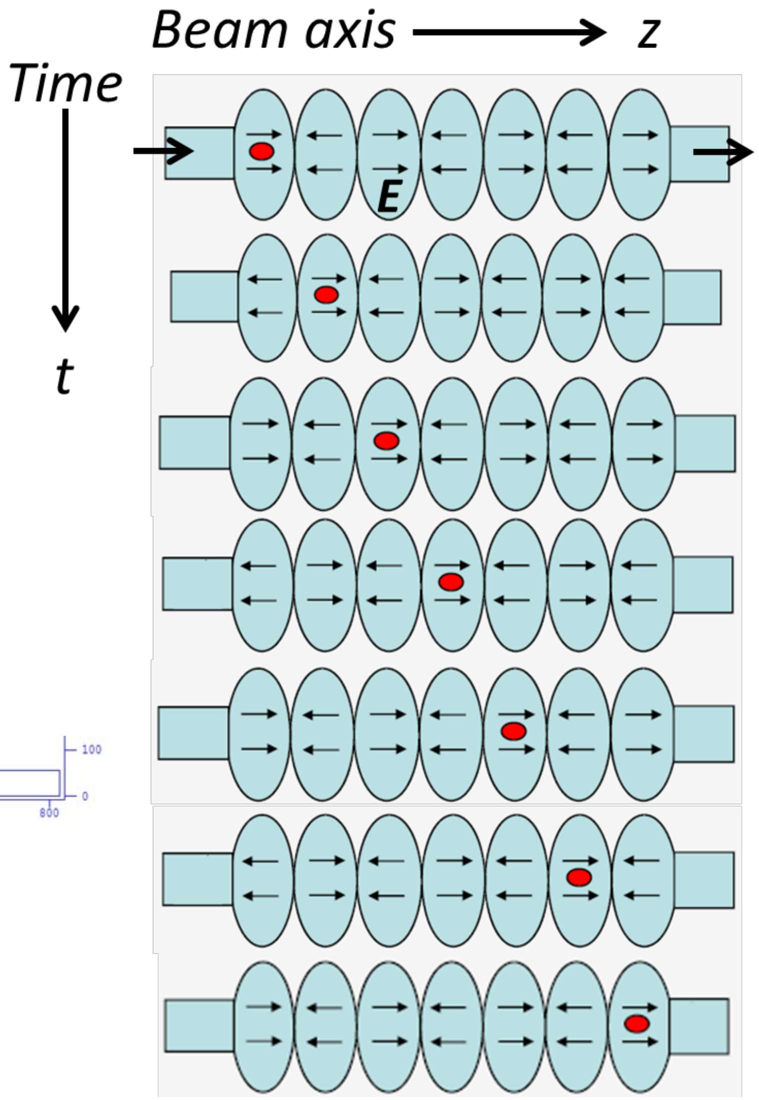
Spoke cavities

Beam Acceleration by RF Fields (v = c)

1.3 GHz, 9-cell Cavity



Accelerating Electric Field
(TM010 π-mode)



$$z = v \cdot t$$

$$E = E_0 \sin(\omega t)$$
$$= E_0 \sin(k z)$$

Synchronized condition

$$v = c, \ (\beta = 1)$$

$$f = \frac{\omega}{2\pi} = \frac{c}{\lambda}$$

Electromagnetic field in an RF cavity

Several important equations and useful formulas are now introduced in order to better understand the behavior of the electromagnetic fields inside an RF cavity:

- Maxwell's equations:

$$div\,\vec{B} = 0 \qquad div\,\vec{D} = \rho \qquad rot\,\vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \qquad rot\,\vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

- Wave equation:

$$\nabla^2 \vec{H} = \sigma \mu \frac{\partial}{\partial t} \vec{H} + \varepsilon \mu \frac{\partial^2}{\partial t^2} \vec{H}$$

- Helmholtz equation:

$$\nabla^2 \vec{H} + k^2 \vec{H} = 0$$

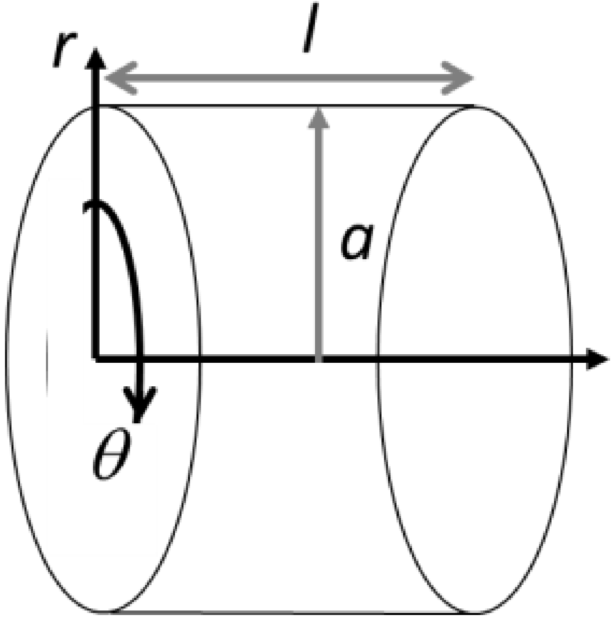
$$\nabla^2 \vec{E} + k^2 \vec{E} = 0$$

- Bessel equation and Bessel functions:

$$\frac{d^2 R}{dr^2} + \frac{1}{r}\frac{dR}{dr} + \left({k_c}^2 - \frac{n^2}{r^2} \right) R = 0 \qquad J_{n\ (k_c r)} = \sum_{m=0}^{\infty} \frac{(-1)^m (k_c r/2)^{n+2m}}{m!\ (n+m)!}$$

Pill-Box Cavity

The following important RF parameters for the case of the pill-box cavity are calculated analytically from the fundamental equations obtained in the previous formulas.



A pill-box cavity, (circular cylindrical resonator): The symbol *a* and *l* represents the radius and the cavity length of the pill-box cavity, respectively.

- Resonant frequency: f_0
- Stored energy: W_S
- RF loss (dissipation power): P_d
- RF surface resistance: R_S
- Quality factor: Q
- Geometrical factor: G
- Transit-time factor: T
- Accelerating gradient: E_{acc}
- Shunt impedance: R_{sh}
- R over Q: R/Q
- Energy gain

Accelerating mode (TM010)

TM_{010} mode is known as "accelerating mode". The boundary conditions of electromagnetic fields of the accelerating mode inside a pill-box cavity can be written as follows:

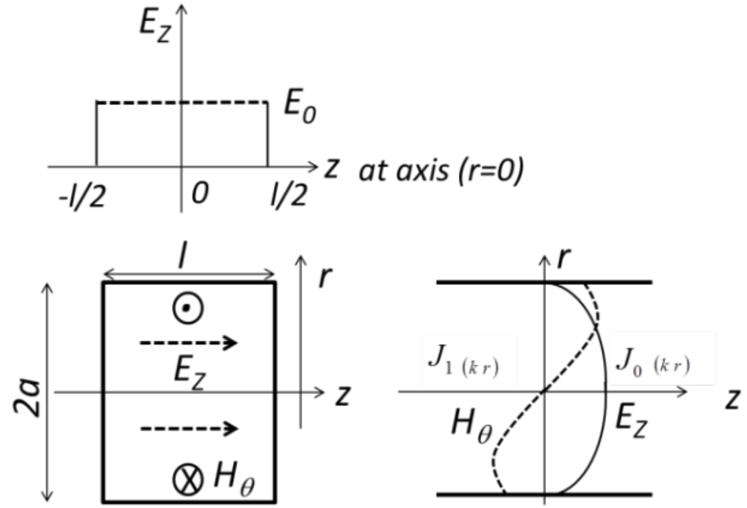
$$\boxed{\begin{aligned} H_z &= 0, \\ E_r &= 0, \\ H_r &= 0, \\ E_\theta &= 0. \end{aligned}}$$

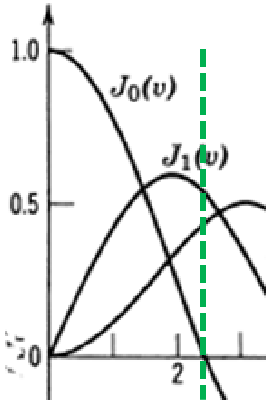
Only two components of $E_z(r)$ and $H_\theta(r)$ exist.

$$\boxed{\begin{aligned} E_{z(r)} &= E_0 \, J_{0\,(kr)} \cos \omega t \\ H_{\theta(r)} &= -\left(\frac{E_0}{Z_0}\right) J_{1\,(kr)} \sin \omega t \end{aligned}}$$

where the following relation holds:

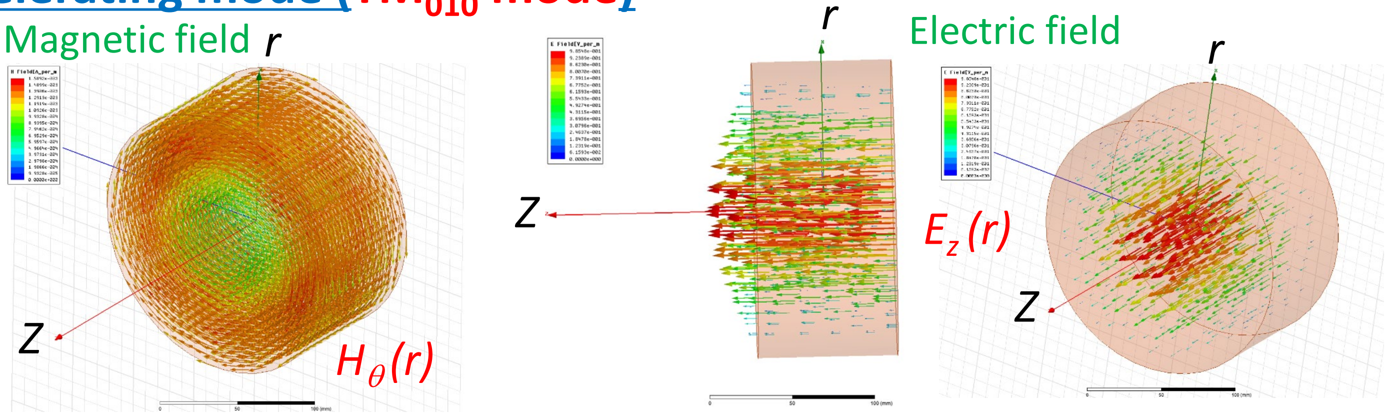
$$Z_0 = E_0/H_0 = (\mu_0/\varepsilon_0)^{0.5} = 120\,\pi = 377\ \Omega\,.$$





Bessel functions

Accelerating mode (TM_{010} mode)



Summary of Main RF Parameters (1)

The essential RF parameters can be summarized as follows:

- Electric RF field ***E*** [V/m]:

$$\vec{E}\exp\left(j\omega t\right)$$

- Magnetic RF field ***H*** [A/m]:

$$\vec{H}\exp\left\{j\left(\omega t+\frac{\pi}{2}\right)\right\}$$

- Accelerating gradient ***E_{acc}*** [V/m]:

$$E_{acc}=\frac{1}{l}\int_{-l/2}^{l/2}E_{Z\,(z,\ r=0)}\cos\left(k\cdot z\right)dz$$

- RF Loss / Dissipated RF power ***P_d*** [W]:

$$P_d=\frac{R_S}{2}\int^{A}\left|\vec{H}\right|^2 dA$$

Summary of Main RF Parameters (2)

- Stored energy ***W***

$$W_S = \frac{\mu_0}{2}\int^{V}\left|\vec{H}\right|^2 dV = \frac{\varepsilon_0}{2}\int^{V}\left|\vec{E}\right|^2 dV$$

- Quality factor ***Q***:

$$Q = \frac{\omega_0 W_S}{P_d} = \frac{G}{R_S}$$

- Geometrical factor ***G*** [Ω]:

$$G = \omega_0\,\mu_0\,\frac{\int^{V}\left|\vec{H}\right|^2 dV}{\int^{A}\left|\vec{H}\right|^2 dA}$$

- Effective shunt impedance ***R*** [Ω]:

$$R_{sh} = \frac{V_{acc}^2}{P_d} = \frac{E_{acc}^2}{P_d}L_{cavity}^2$$

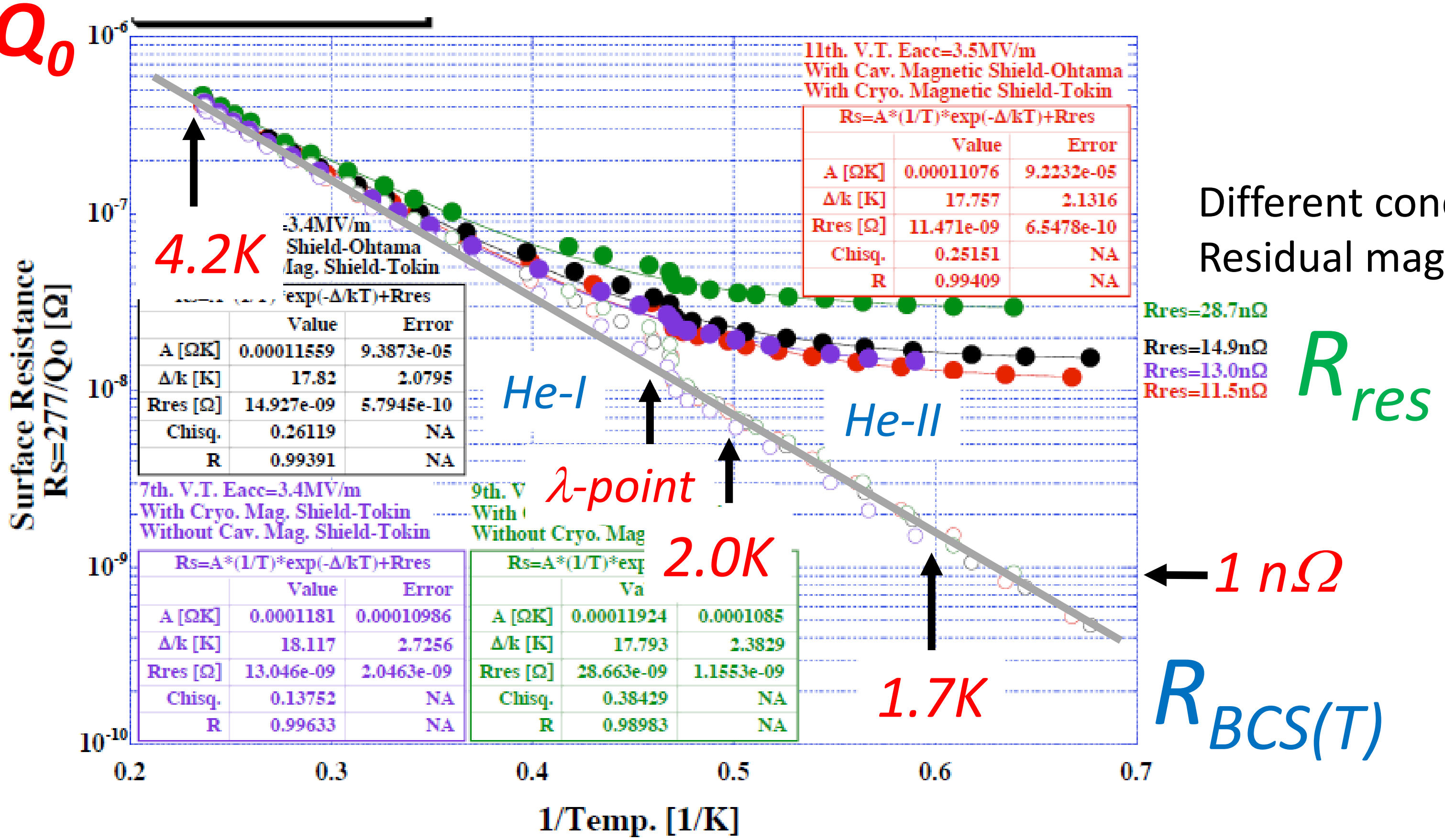
- ***R/Q*** [Ω]:

$$\left(\frac{R}{Q}\right) = \frac{E_{acc}^2}{\omega W_S}L_{cavity}^2$$

Temperature Dependence of Surface Resistance

1.3 GHz, 9-cell
Superconducting Cavity

$R_S = G/Q_0$



Rs=A*(1/T)*exp(-Δ/kT)+Rres		
	Value	Error
A [ΩK]	0.00011076	9.2232e-05
Δ/k [K]	17.757	2.1316
Rres [Ω]	11.471e-09	6.5478e-10
Chisq.	0.25151	NA
R	0.99409	NA

exp(-Δ/kT)+Rres		
	Value	Error
A [ΩK]	0.00011559	9.3873e-05
Δ/k [K]	17.82	2.0795
Rres [Ω]	14.927e-09	5.7945e-10
Chisq.	0.26119	NA
R	0.99391	NA

Rs=A*(1/T)*exp(-Δ/kT)+Rres		
	Value	Error
A [ΩK]	0.0001181	0.00010986
Δ/k [K]	18.117	2.7256
Rres [Ω]	13.046e-09	2.0463e-09
Chisq.	0.13752	NA
R	0.99633	NA

Rs=A*(1/T)*exp		
	Va	
A [ΩK]	0.00011924	0.0001085
Δ/k [K]	17.793	2.3829
Rres [Ω]	28.663e-09	1.1553e-09
Chisq.	0.38429	NA
R	0.98983	NA

Different condition of
Residual magnetic field

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

Surface resistance of RF Cavity: Cu and Nb

Normal-conducting Cavity ;

- *Surface resistance;* R_S $[\Omega]$

$$R_S = \sqrt{\frac{\omega\,\mu}{2\,\sigma}} = \frac{1}{\sigma\,\delta} \quad [\Omega]$$

$f = 1.3$ GHz, $G = 270\ \Omega$

Cu (20°C) ; $\sigma = 0.58 \times 10^{8}$ $[1/\Omega\,\mathrm{m}]$

$R_S = 9.4\ \mathrm{m}\Omega$, ($\delta = 1.8\ \mu\mathrm{m}$)

$Q = G / R_S = 2.9 \times 10^{4}$

Superconducting Cavity ;

- *Surface resistance;* R_S $[\Omega]$

$$R_S = R_{BCS\,(T)} + R_{res}$$

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

$f = 1.3$ GHz, $G = 270\ \Omega$

Nb (2K) ; $R_{BCS} = 7$ $[\mathrm{n}\Omega]$

$R_{res} = 7$ $[\mathrm{n}\Omega]$

$R_S = 14\ \mathrm{n}\Omega$, ($\lambda_0 = 44$ nm)

$Q = G / R_S = 1.9 \times 10^{10}$

R_{BCS} : *BCS resistance*

R_{res} : *Residual surface resistance*

k_B : *Boltzmann constant*

Δ : *Gap energy of Cooper pair*

Question (2)

What is the advantage of superconducting cavities?

Superconducting RF (SRF) Cavity

What is the advantage of superconducting cavities?

- low surface loss → higher Q → higher Ws
- high acceleration gradient

  → higher energy in smaller space
- better efficiency to beam power

  → smaller RF power source
- ***CW operation at higher fields***

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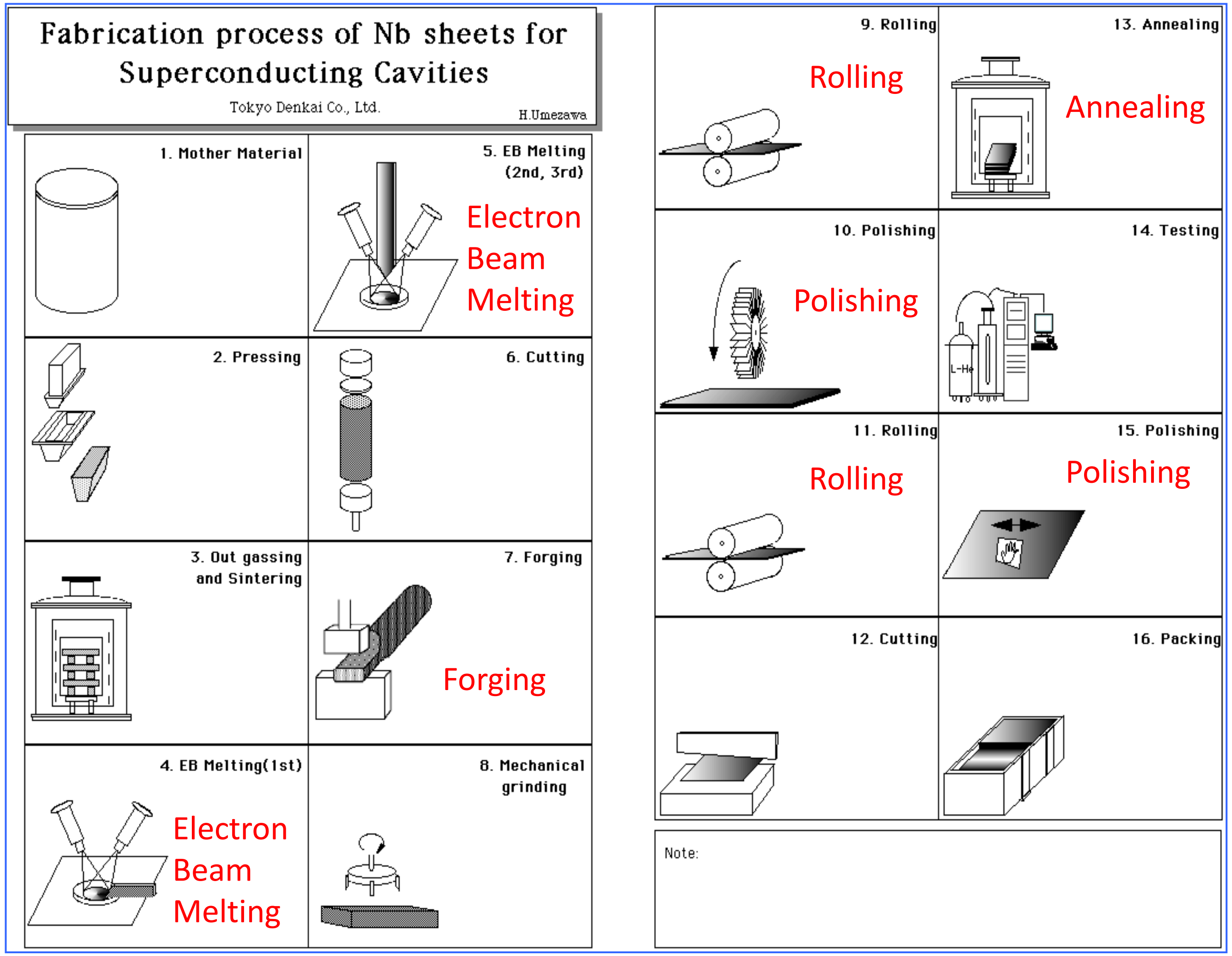
Fabrication Process of Nb Sheets

Electron Beam Melting



Fabrication process of Nb sheets for Superconducting Cavities

Tokyo Denkai Co., Ltd.

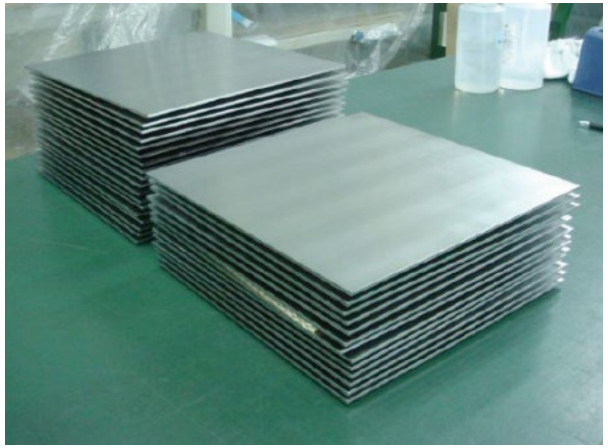
H.Umezawa

1. Mother Material
2. Pressing
3. Out gassing and Sintering
4. EB Melting(1st)
5. EB Melting (2nd, 3rd)
6. Cutting
7. Forging
8. Mechanical grinding
9. Rolling
10. Polishing
11. Rolling
12. Cutting
13. Annealing
14. Testing
15. Polishing
16. Packing

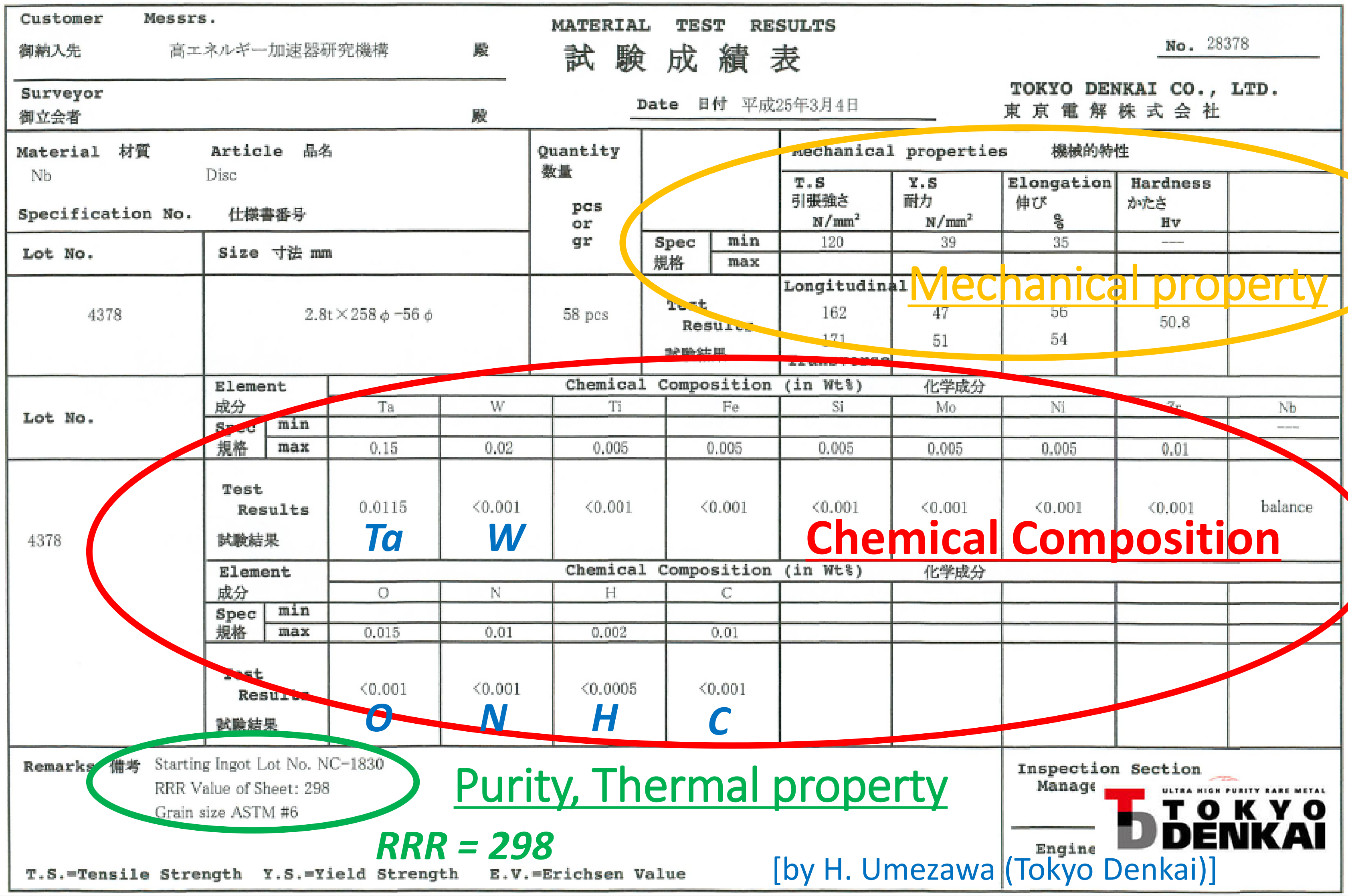
Note:

[by H. Umezawa (Tokyo Denkai)]

ULTRA HIGH PURITY RARE METAL
TOKYO DENKAI



Material certification of Nb: (Mill sheet)



Customer Messrs.
御納入先 高エネルギー加速器研究機構 殿

Surveyor
御立会者 殿

MATERIAL TEST RESULTS
試 験 成 績 表

No. 28378

Date 日付 平成25年3月4日

TOKYO DENKAI CO., LTD.
東 京 電 解 株 式 会 社

Material 材質 Nb	Article 品名 Disc	Quantity 数量 pcs or gr	
Specification No. 仕様書番号			
Lot No.	Size 寸法 mm		
4378	2.8t×258φ−56φ	58 pcs	

Mechanical properties 機械的特性

		T.S 引張強さ N/mm²	Y.S 耐力 N/mm²	Elongation 伸び %	Hardness かたさ Hv	
Spec 規格	min	120	39	35	---	
	max					
Test Results 試験結果	Longitudinal	162	47	56	50.8	
	Transverse	171	51	54		

Chemical Composition (in Wt%) 化学成分

Lot No.	Element 成分		Ta	W	Ti	Fe	Si	Mo	Ni	Zr	Nb
	Spec 規格	min									---
		max	0.15	0.02	0.005	0.005	0.005	0.005	0.005	0.01	
4378	Test Results 試験結果		0.0115	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	balance

Chemical Composition (in Wt%) 化学成分

Element 成分		O	N	H	C
Spec 規格	min				
	max	0.015	0.01	0.002	0.01
Test Results 試験結果		<0.001	<0.001	<0.0005	<0.001

Remarks 備考 Starting Ingot Lot No. NC-1830
RRR Value of Sheet: 298
Grain size ASTM #6

Inspection Section
Manager
Engineer

ULTRA HIGH PURITY RARE METAL TOKYO DENKAI

T.S.=Tensile Strength Y.S.=Yield Strength E.V.=Erichsen Value

Mechanical property

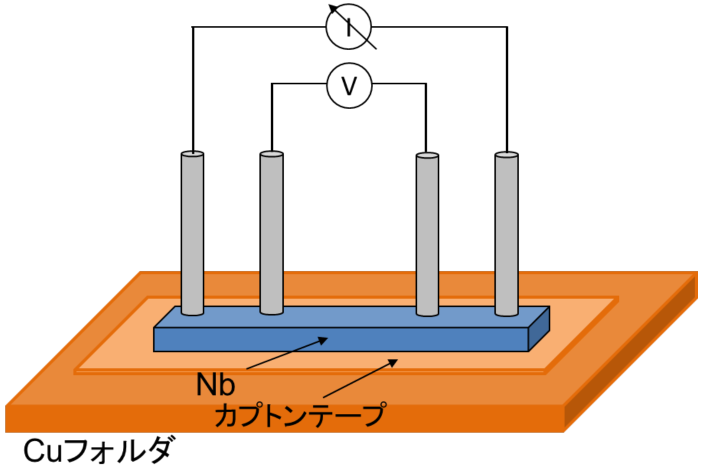
Chemical Composition

Purity, Thermal property

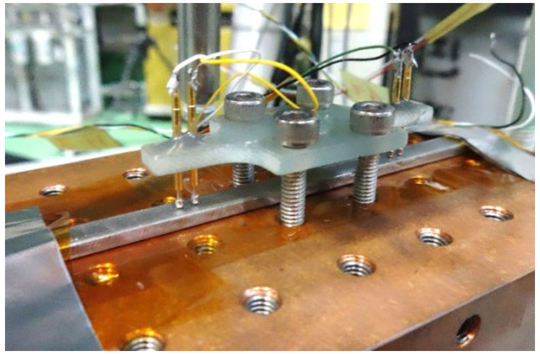
RRR = 298

[by H. Umezawa (Tokyo Denkai)]

Characteristics of Nb materials: (RRR)



RRR measurement system



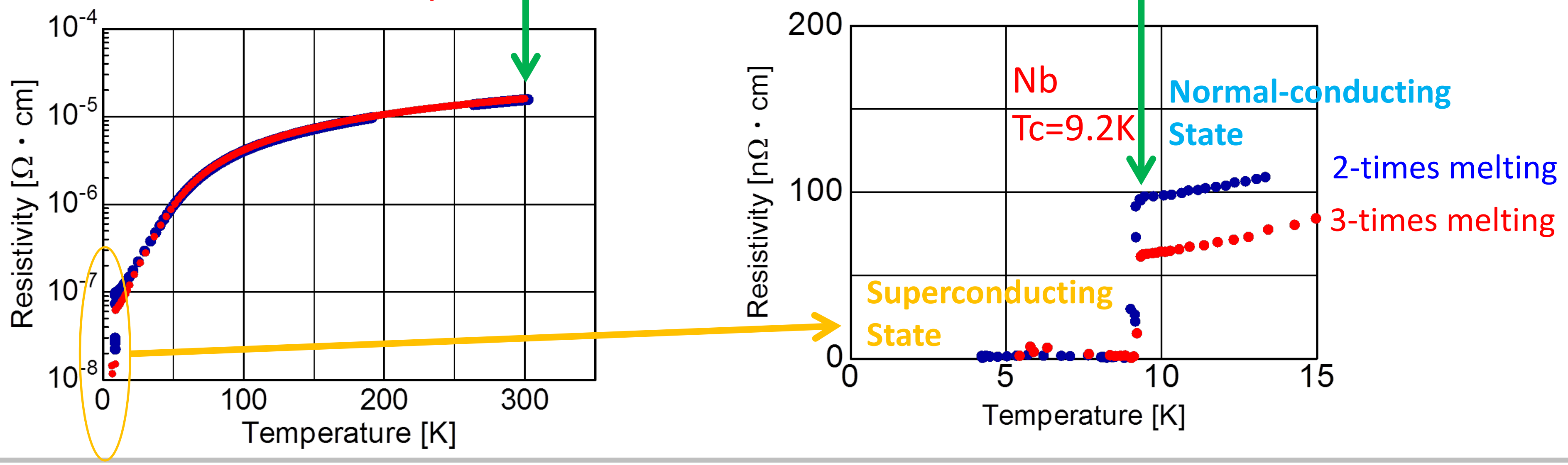
Residual Resistance Ratio

$$RRR = \frac{\rho(300\mathrm{K})}{\rho(9.2\mathrm{K})}$$

ρ (300K) = 2x10^{-5} Ω cm
ρ (300K) = 2x10^{-5} Ω cm

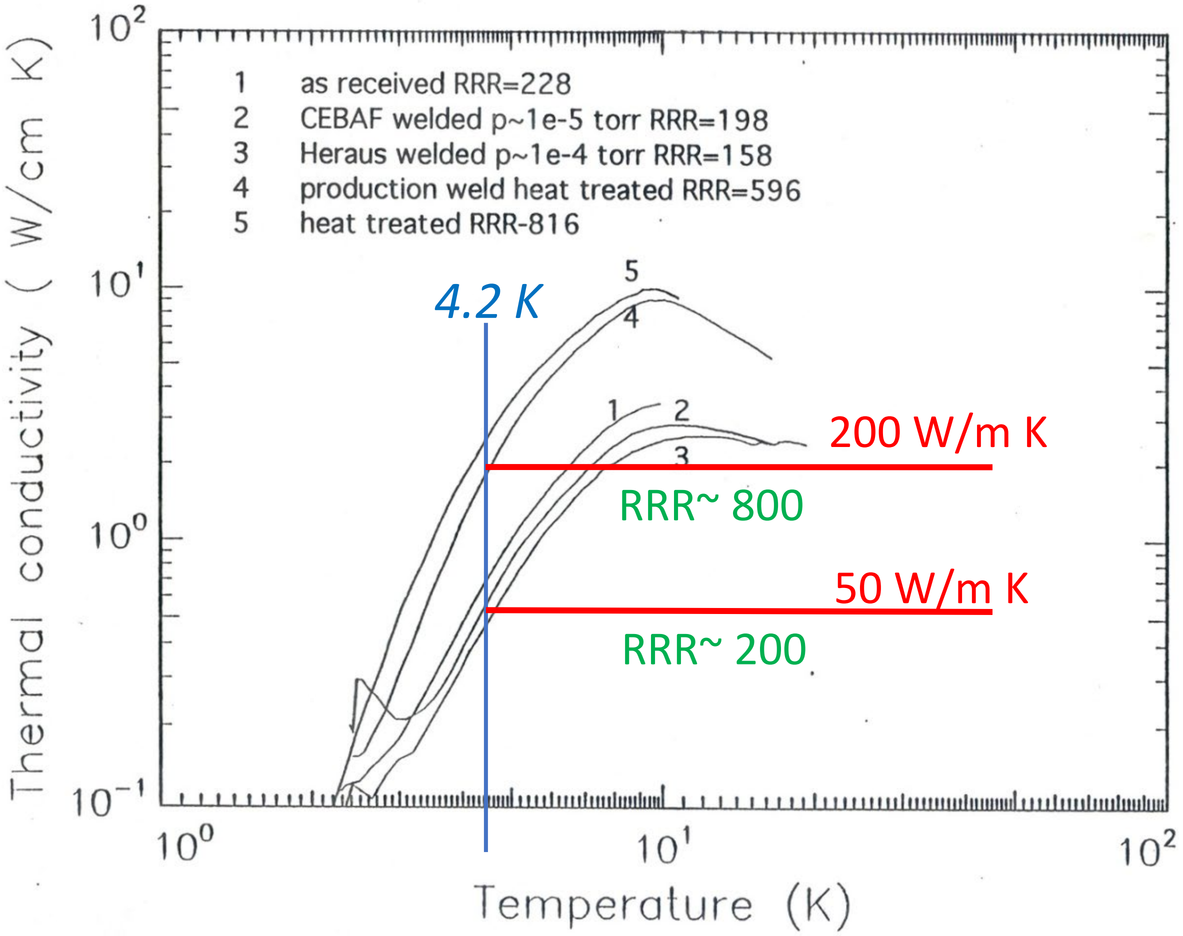
ρ (9.2K) = 1x10^{-7} Ω cm
ρ (9.2K) = 6x10^{-8} Ω cm

RRR = 200
RRR = 330



Material Properties: Thermal conductivity

Thermal conductivity of Nb



RRR : *Residual Resistance Ratio*

$$RRR = \frac{\rho(300\mathrm{K})}{\rho(9.2\mathrm{K})}$$

κ*: *Thermal Conductivity

$$\kappa_{(4.2K)} \approx RRR/4$$

$$[W/m \cdot K]$$

Wiedemann-Franz's law

$$\boxed{\kappa \propto \sigma = \frac{1}{\rho}}$$

H

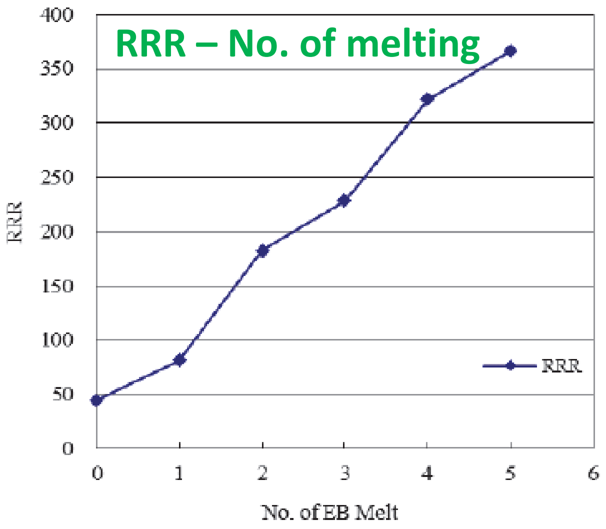
H_{quench} **: *Quench field***

$$\boxed{H_{quech} = \sqrt{\frac{4\,\kappa\,(T_c - T_{He})}{a\;R_{defect}}}}$$

R_{defect} : *Resistivity of Defect*
a : *Radiaus of Defect*
T_c : *Critical Temperature*
T_{He} : *He Temperature*

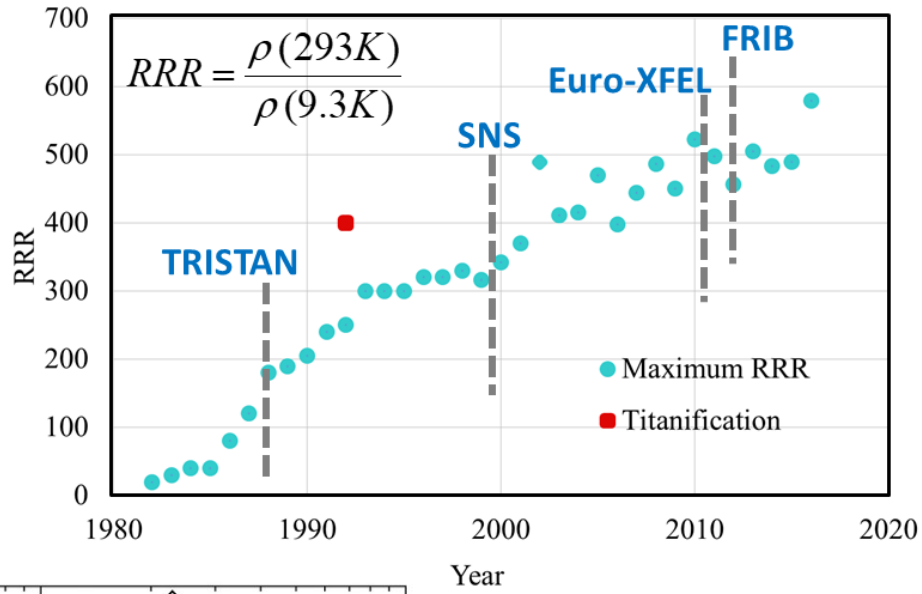
High RRR niobium with high thermal conductivity is preferable for achieving higher accelerating gradient.

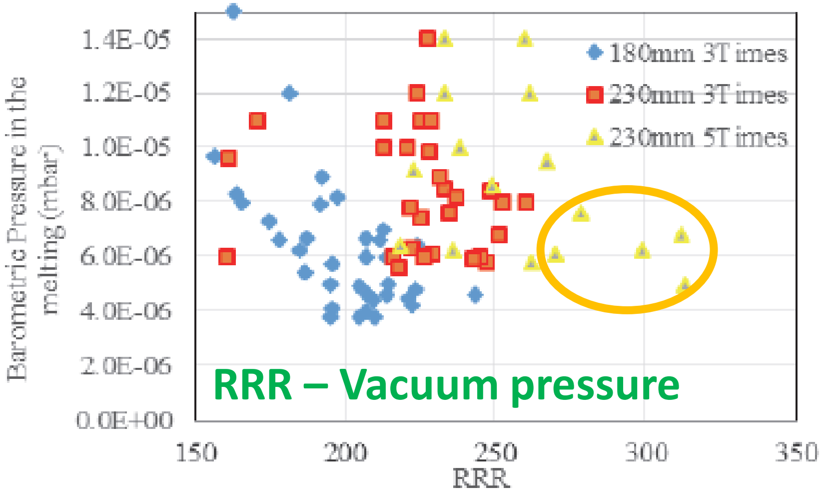
Characteristics of Nb materials: (Improvement of RRR)

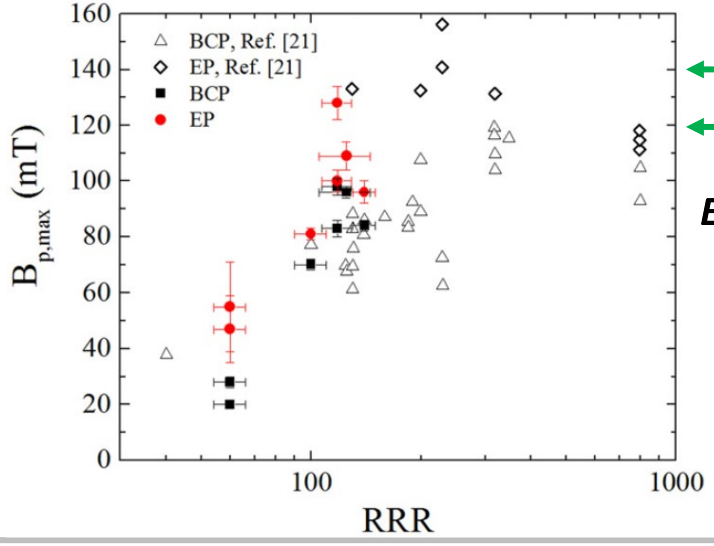


ULTRA HIGH PURITY RARE METAL
TOKYO DENKAI

[by H. Umezawa (Tokyo Denkai)]







← 35 MV/m

← 30 MV/m

E_{acc} (MV/m) = $B_{p,max}$ (mT) / 4.3

Performance improvement for 25 years at KEK

TRISTAN 508MHz 5-cell Cavity

He temperature at 4.2 K
CW operation

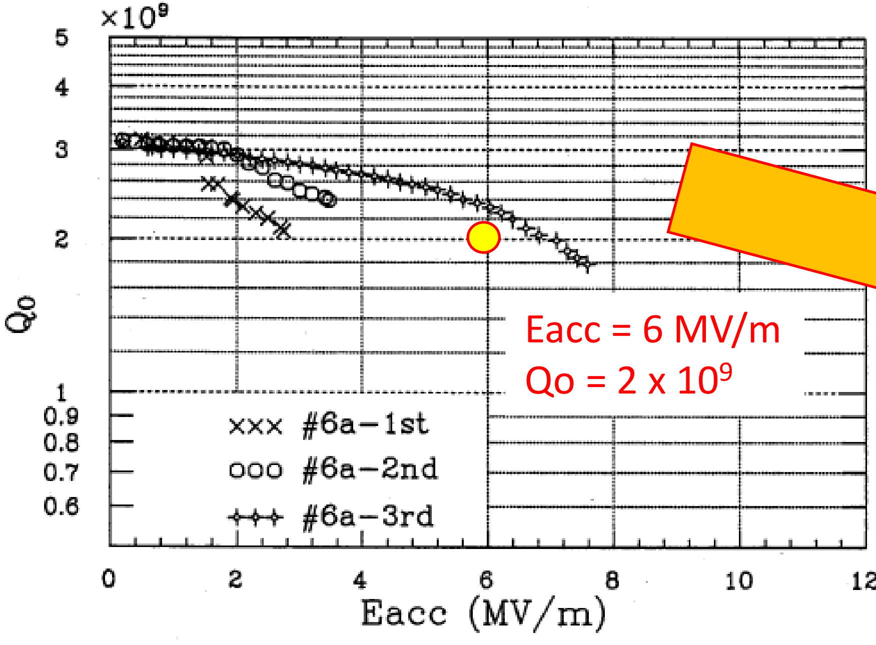


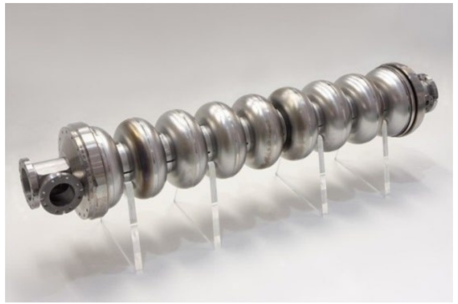
Figure 7: Qo and Eacc of TRISTAN #6a cavity.

1989’

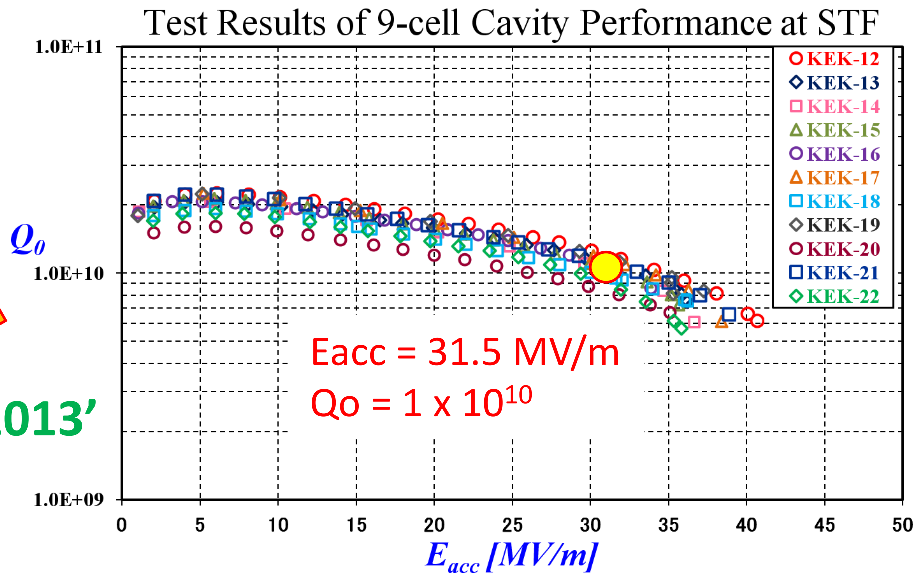
Eacc = 6 MV/m
Qo = 2×10^9

[T. Furuya, SRF’89]

STF 1.3GHz 9-cell Cavity



He temperature at 2.0 K
1 ms, 5 Hz pulsed operation



2013’

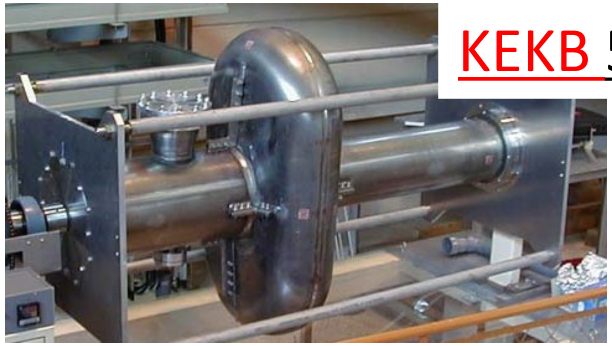
Eacc = 31.5 MV/m
Qo = 1×10^{10}

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

[Y. Yamamoto, NIM-A (2013)]

SRF cavities developed at KEK

TRISTAN
508MHz 5-cell Cavity



KEKB 508MHz Crab Cavity

KEKB 508MHz 1-cell Cavity

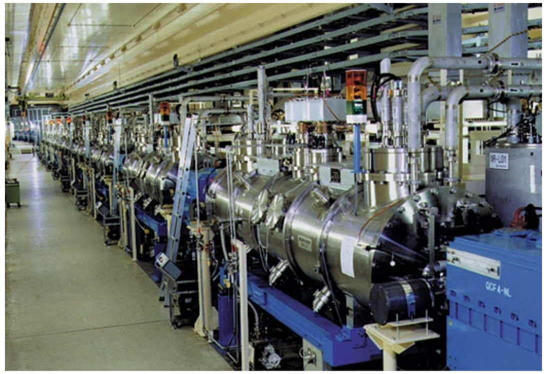
J-ADS 972MHz
9-cell Cavity
(β=0.73)

cERL Injector
1.3GHz 2-cell Cavity

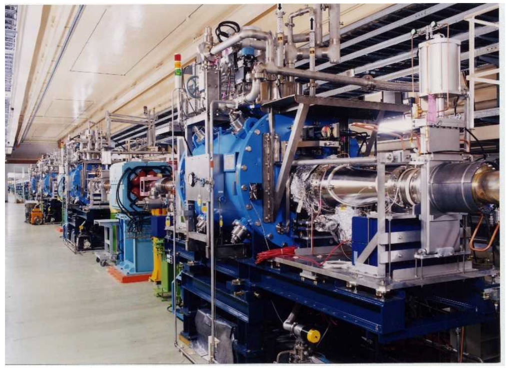
cERL ML 1.3GHz 9-cell Cavity

STF 1.3GHz 9-cell Cavity

Cryomodules developed at KEK



TRISTAN 508MHz Cryomodule



KEKB
508MHz Cryomoudle

KEKB Crab Cryomoudle

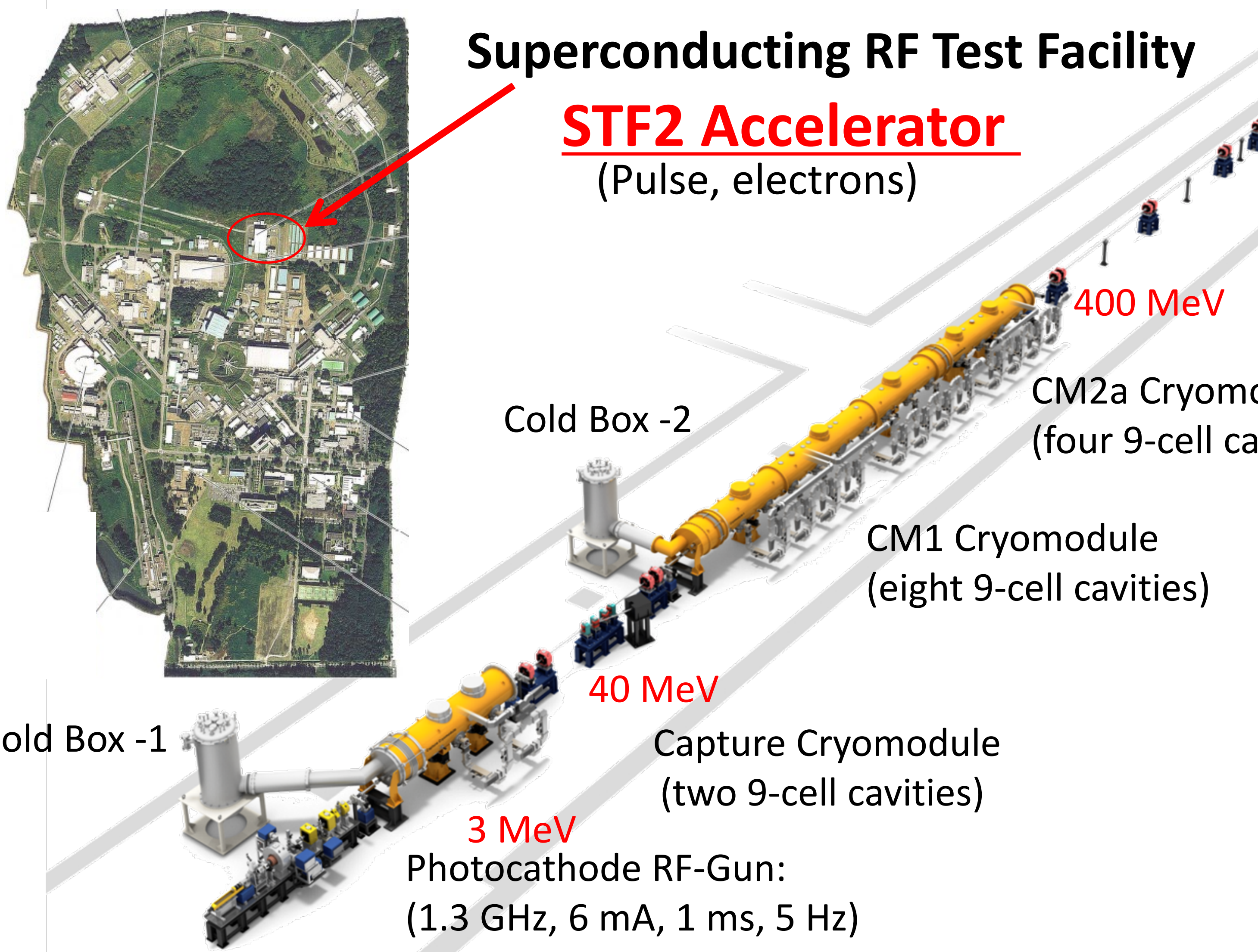
J-ADS 972MHz
Cryomodule

cERL 1.3 GHz
Injector Cryomodule

cERL 1.3 GHz
ML Cryomodule

STF 1.3GHz Cryomodule

STF at KEK for future Linear Collider (ILC)



Superconducting RF Test Facility

STF2 Accelerator
(Pulse, electrons)

12 kW
Beam Dump

400 MeV

CM2a Cryomodule
(four 9-cell cavities)

Cold Box -2

CM1 Cryomodule
(eight 9-cell cavities)

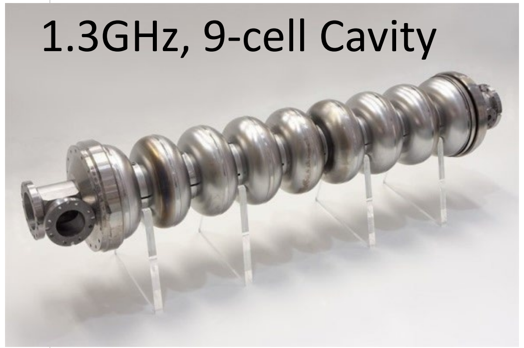
40 MeV

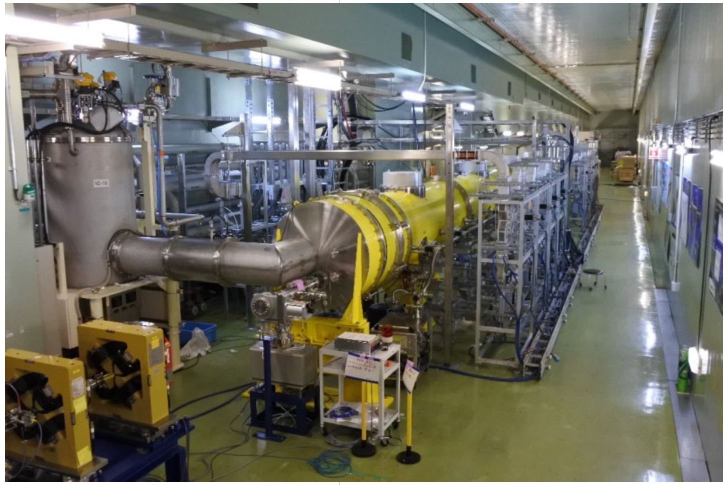
Cold Box -1

Capture Cryomodule
(two 9-cell cavities)

3 MeV

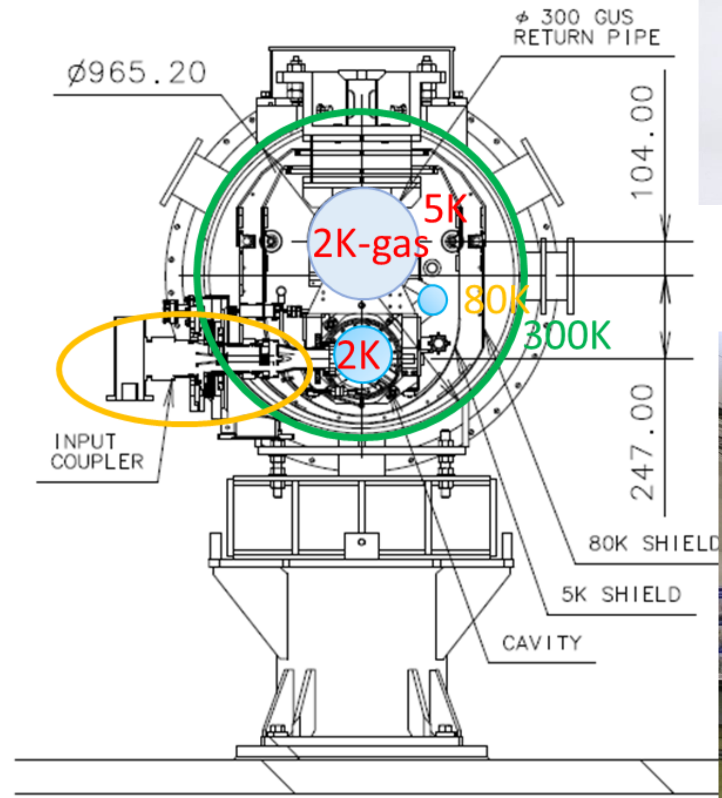
Photocathode RF-Gun:
(1.3 GHz, 6 mA, 1 ms, 5 Hz)


1.3GHz, 9-cell Cavity



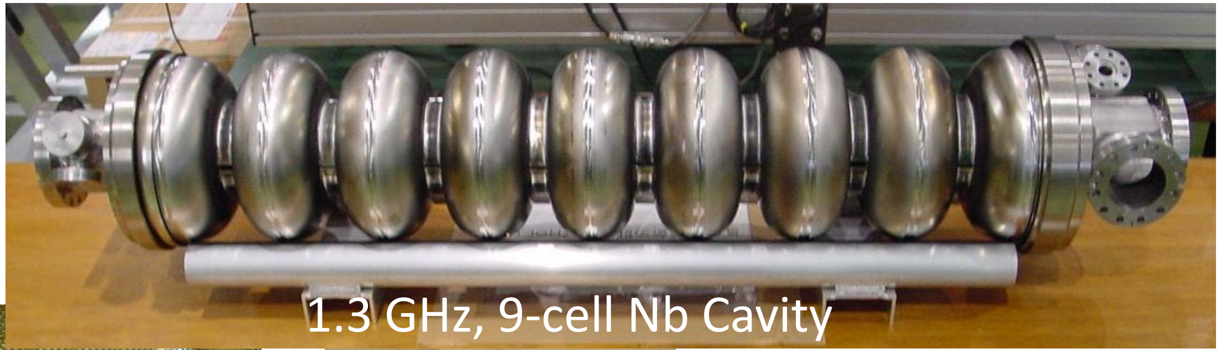
Superconducting RF cavity system for STF

Cryomodule



STF Cryomodule

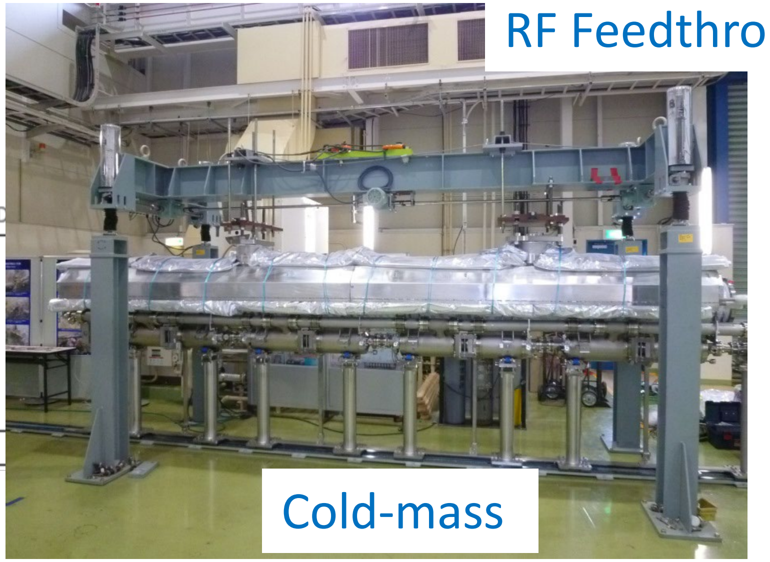
Input Couplers



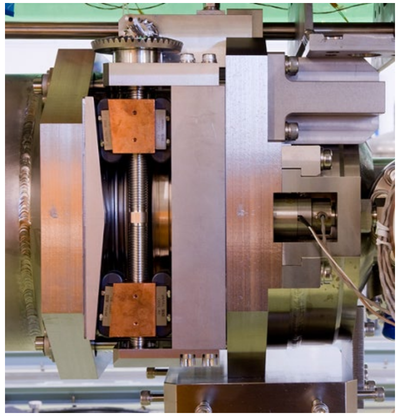
1.3 GHz, 9-cell Nb Cavity

RF Feedthroughs

HOM Couplers



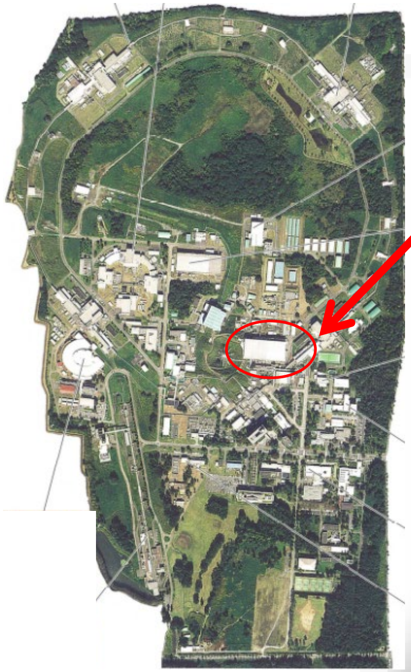
Cold-mass



Slide-Jack Tuner

Magnetic Shield
& He Jacket (Ti)

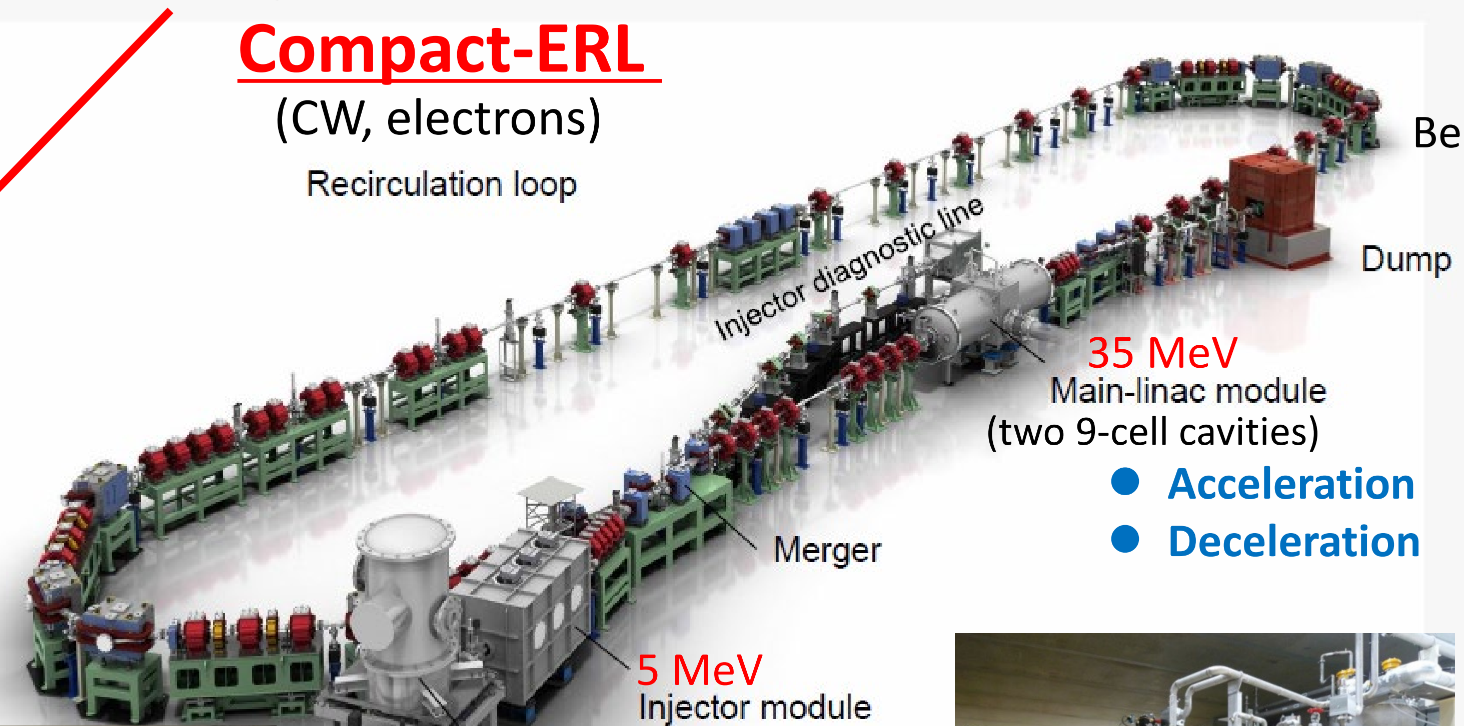
cERL at KEK for future Light Source: ERL



Energy Recovery LINAC

Compact-ERL

(CW, electrons)



50 kW
Beam Dump

35 MeV
Main-linac module
(two 9-cell cavities)

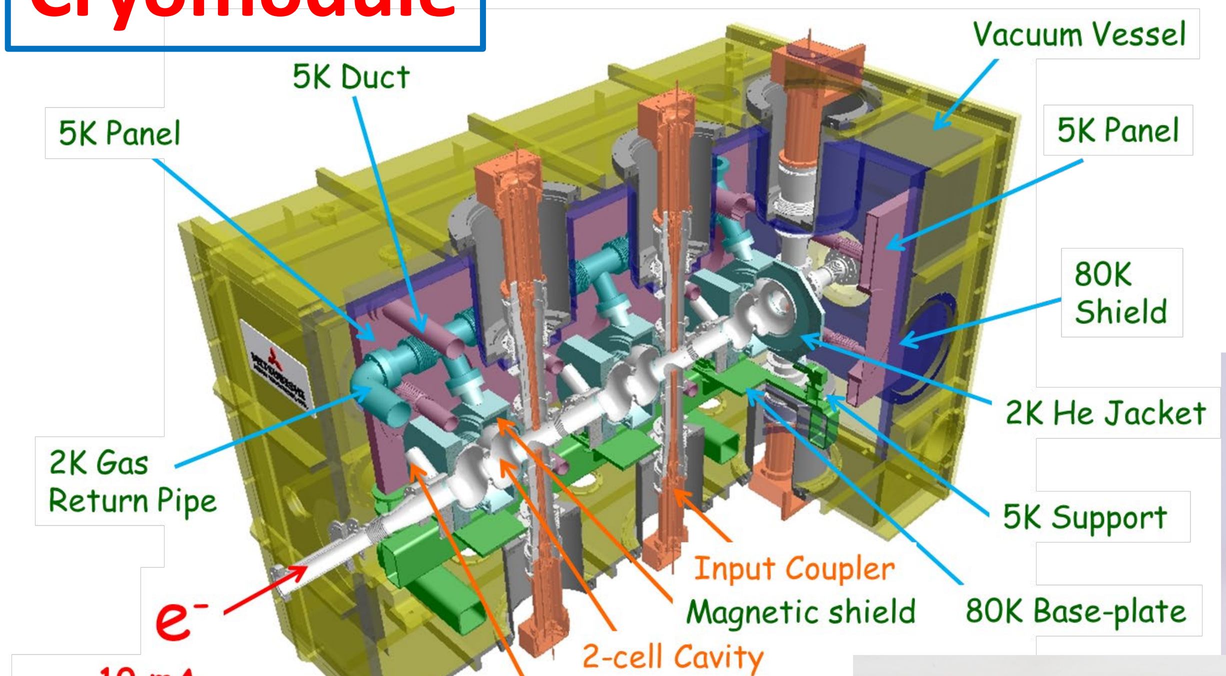
- **Acceleration**
- **Deceleration**

5 MeV
Injector module
(three 2-cell cavities)

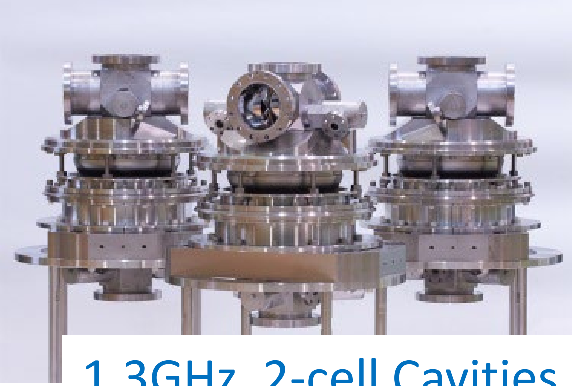
0.5 MeV
Photocathode DC gun
(500 kV, CW, 10 mA)

Superconducting RF cavity system for cERL

Cryomodule



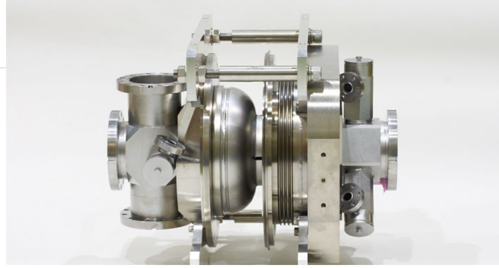
cERL Injector Cryomodule



1.3GHz, 2-cell Cavities

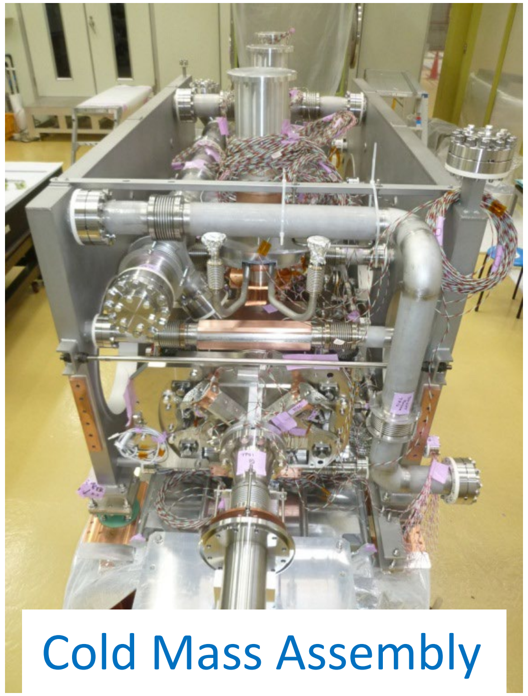
Slide-Jack Tuner

Input Couplers



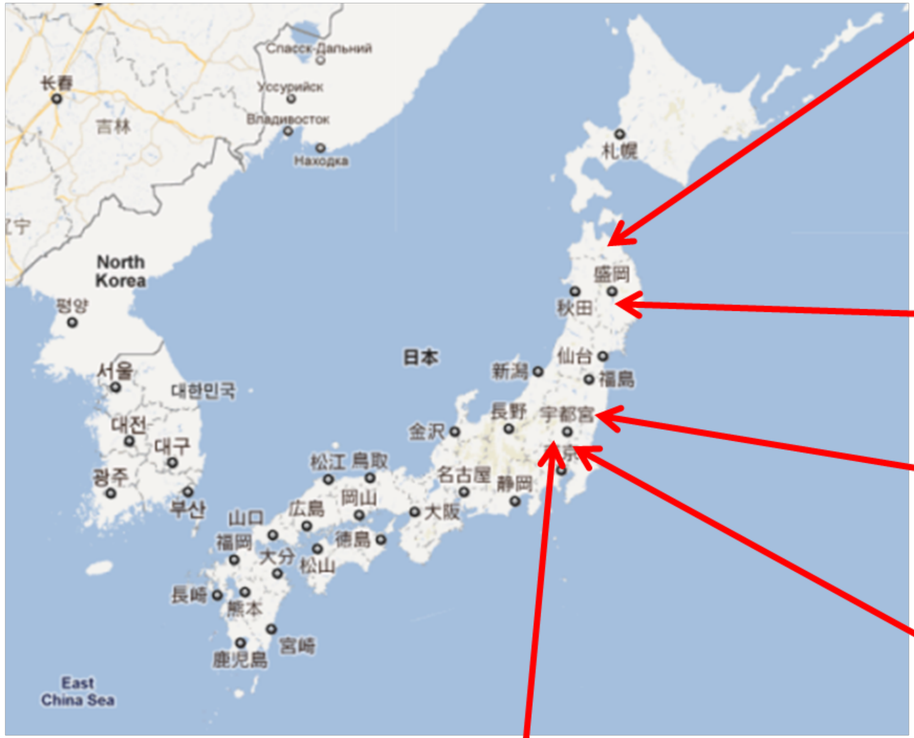
1.3GHz, 2-cell Cavity

HOM Couplers



Cold Mass Assembly

Superconducting Accelerator Projects in Japan



QST-Rokkasho

● IFMIF-LIPAc (deuterons)
8 : 175MHz, HWR

A-FNS (deuterons)
8+10+12+12 : 175MHz, HWR

ILC (e^- e^+ collider)
8000 : 1.3GHz, 9-cell cavity

JAEA-Tokai

ADS (protons)

KEK-Tsukuba

🟩 SuperKEKB (e^- e^+ collider)
8 : 508MHz, 1-cell cavity

🟩 cERL (elecrons)
3 : 1.3GHz, 2-cell cavity
2 : 1.3GHz, 9-cell cavity

🟩 STF2 (electrons)
2+12 : 1.3GHz, 9-cell cavity

Multi-MW SC Proton Driver (protons)

RIKEN-Nishina

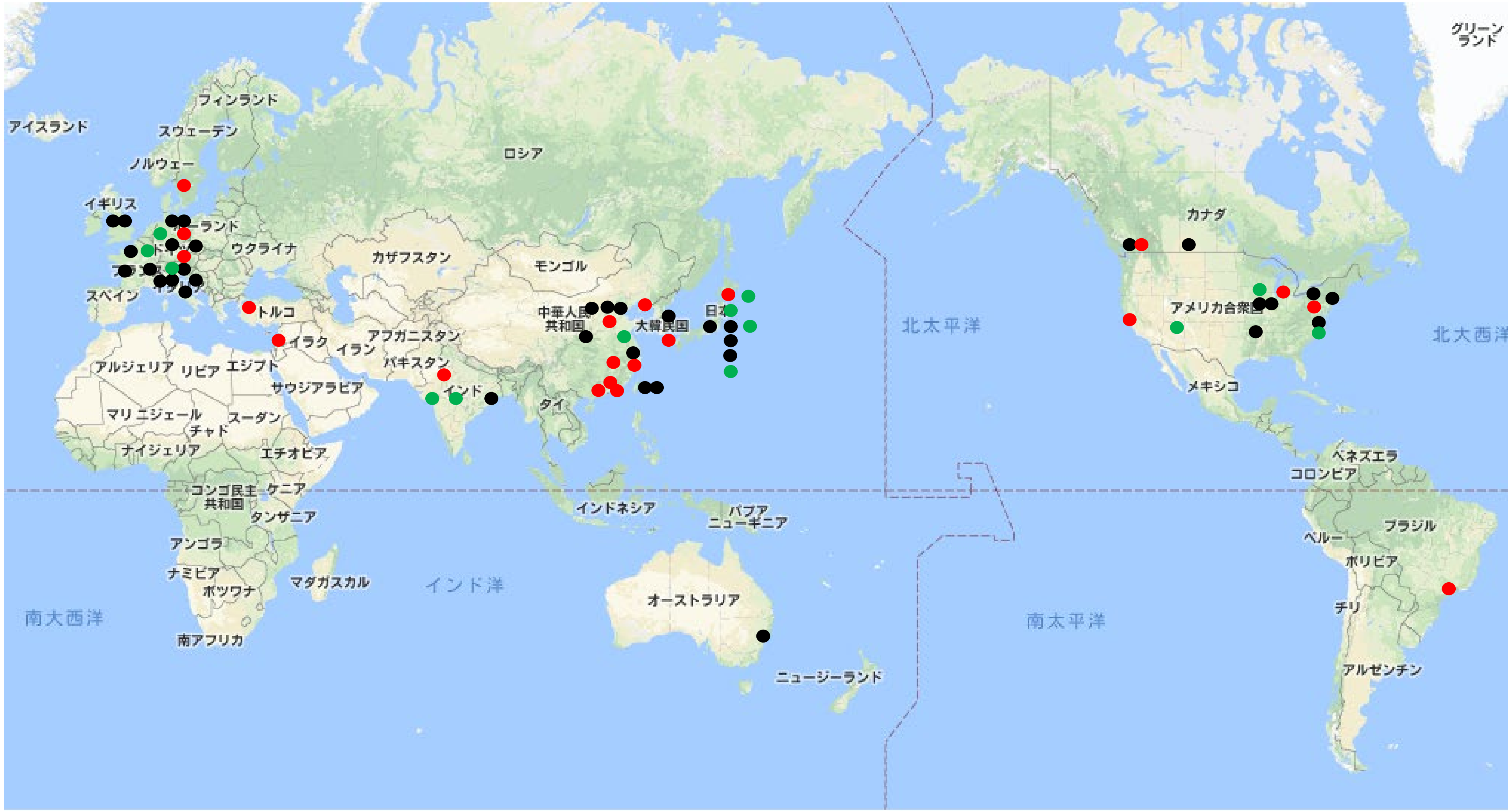
🟩 SRILAC (heavy ions)
4+4+2 : 73MHz, QWR

🟩 operation
● under construction

No. of cavity : frequency : cavity structure

underline: future project

Superconducting Accelerator Projects in World



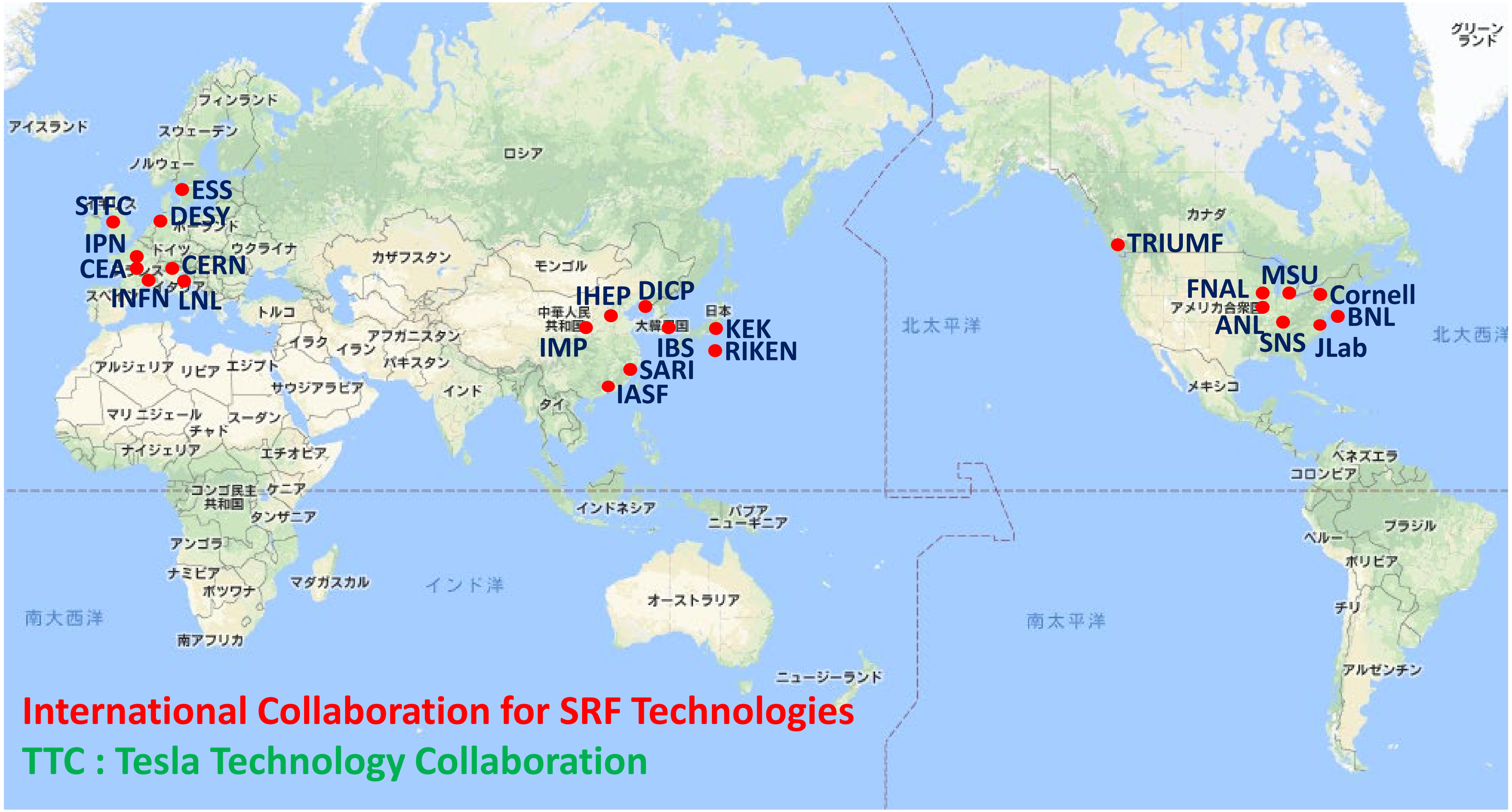
● **Operation** ● **Construction** ● **Future Plan**

Superconducting Accelerators in Worldwide

- **Elemental Particle Physics:** (S-KEKB, BEPC, LHC, CEPC, FCC)
- **Radiation Light Source:** (DIAMOND, CLS, TPS, SLS, PLS, NSLS-II, HEPS, HALF, SAPS)
- **LINACs for Nuclear Physics:** (CEBAF, S-DALINAC)
- **LINACs for Free Electron Laser:** (FLASH, E-XFEL, LCLS-II, SHINE, DALS, S3FEL)
- **Energy Recovery LINACs:** (cERL, bERLinPro, CBETA, PERLE)
- **Proton LINACs for N. Source & ADS:** (SNS, ESS, CESS, CiADS, MIRRHA, J-ADS)
- **Proton LINACs for Neutrino Experiments :** (PIP-II, HIPrDr-KEK)
- **Deuteron LINACs for Nuclear Fusion:** (IFMIF-LIPAc, A-FNS, DONES)
- **Heavy Ions LINACs:** (ISAC-II, SPIRAL-2, RILAC, FRIB, RAON, HIAF)
- **Linear Colliders for High Energy Physics** (STF, FAST, ILC)

Operation
Construction
Future Plan

Main Accelerator Laboratories for SRF R&D



International Collaboration for SRF Technologies

TTC : Tesla Technology Collaboration

- Cryogenics (Liq. He)
- Surface preparation
- Vacuum Furnace
- HPR
- Clean room
- VT

Question (3)

Why our international collaboration is important for R&D of superconducting cavities?

Superconducting RF (SRF) Cavity

Why our international collaboration is important for R&D of superconducting cavities?

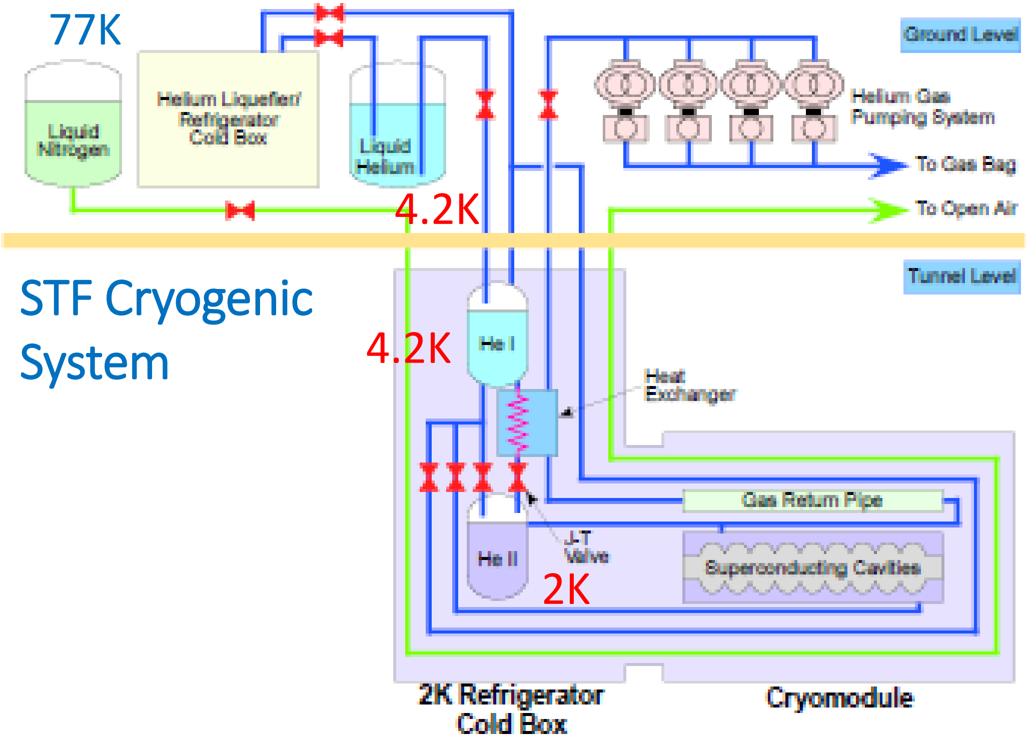
- To advance SRF technology R&D and related accelerator studies across the broad diversity of scientific applications.
- To keep open and provide a bridge for communication and sharing of ideas, developments, and testing across associated projects.
- Free and open exchange of scientific and technical knowledge, expertise, engineering designs, and equipment.
- New developments are reported, recent findings are discussed, and technical issues concluded.

Outline of the Lecture

1. Introduction
2. Fundamental of SRF Cavity
3. Overview of SRF Cavity System
4. **Fabrication and Surface Preparation**
5. Cavity Performances
6. Summary

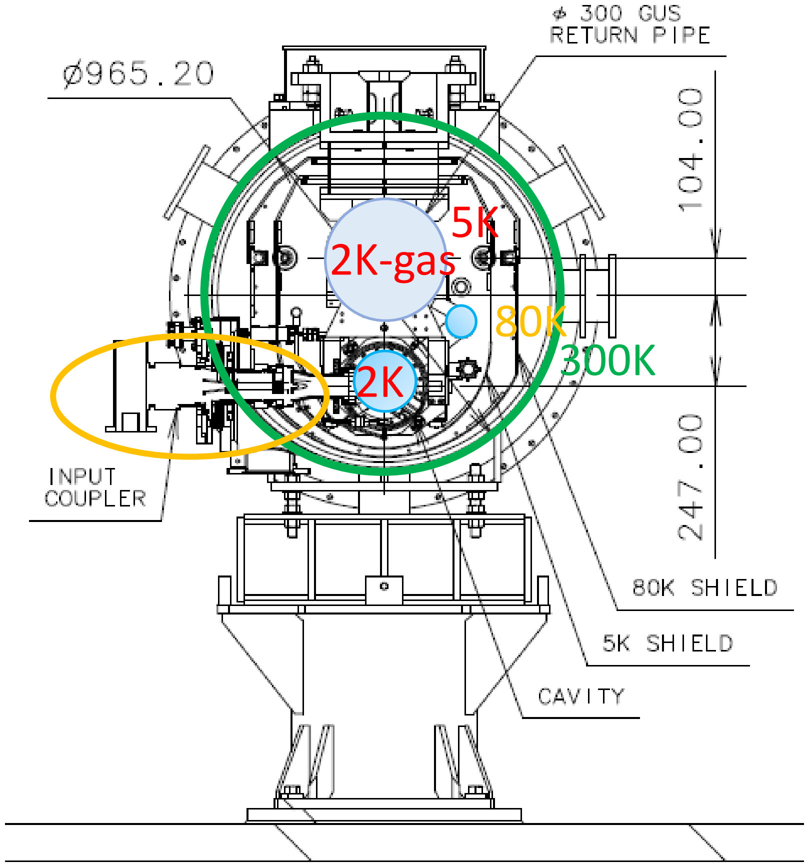
Superconducting RF Cavity System (1)

Refrigerator



STF Cryogenic System

Cryomodule



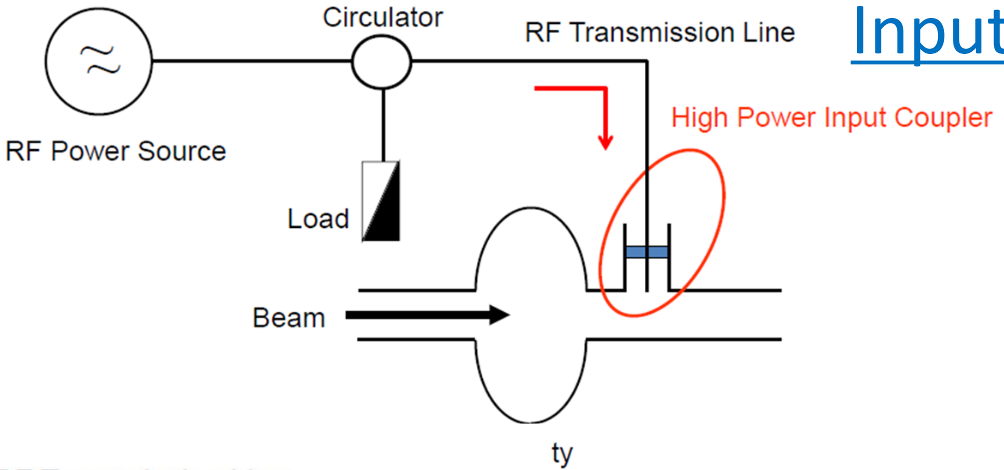
STF Cryomodule

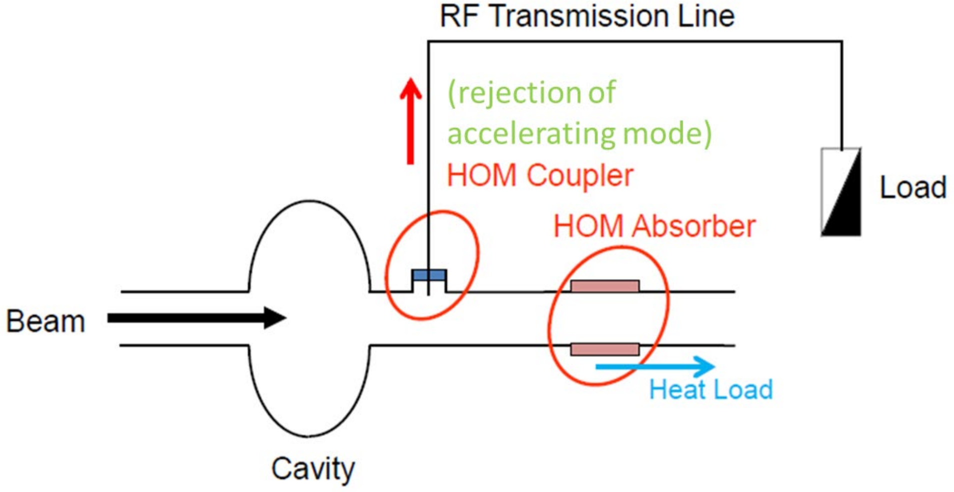
Cryogenic Efficiency

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

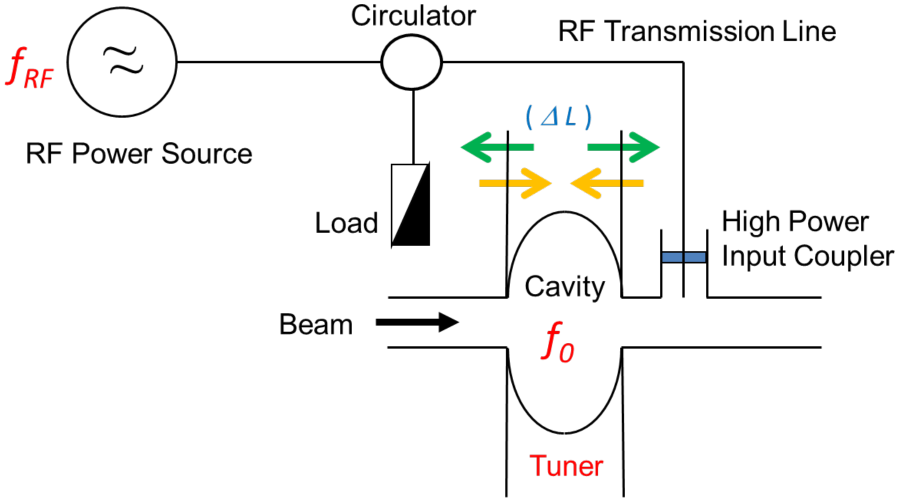
Superconducting RF Cavity System (2)

Input coupler





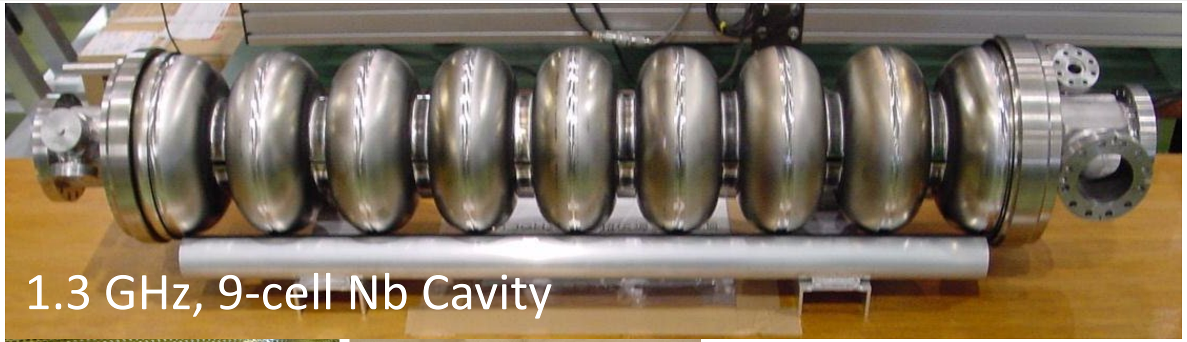
HOM coupler and absorber



Frequency Tuner

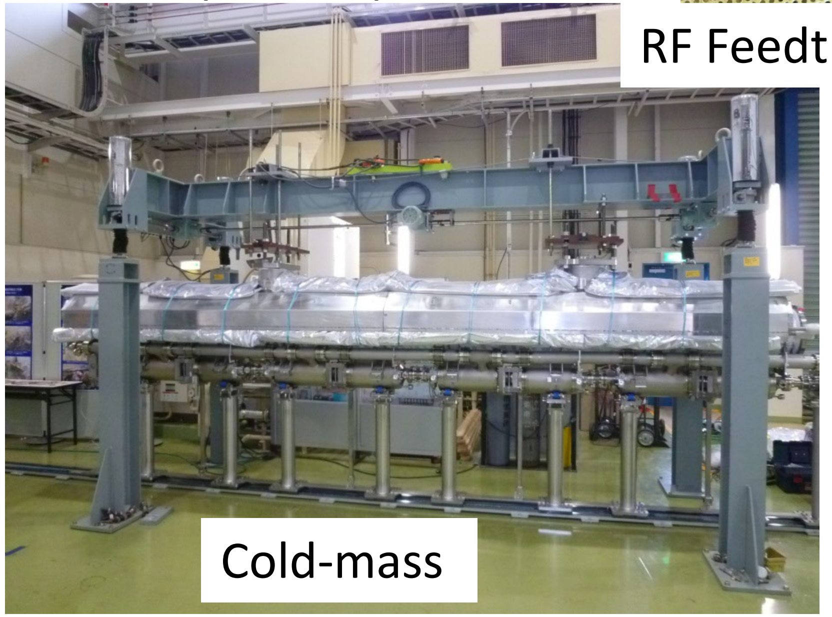
Superconducting RF Cavity System (3)

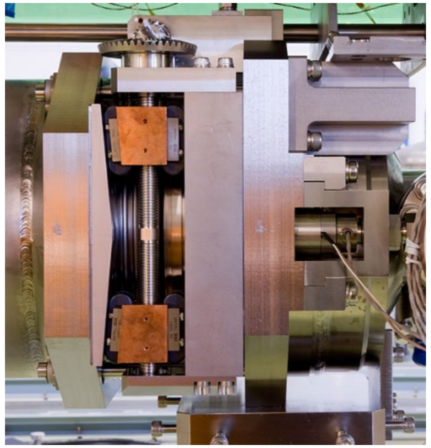

Input Coupler


1.3 GHz, 9-cell Nb Cavity


RF Feedthrough

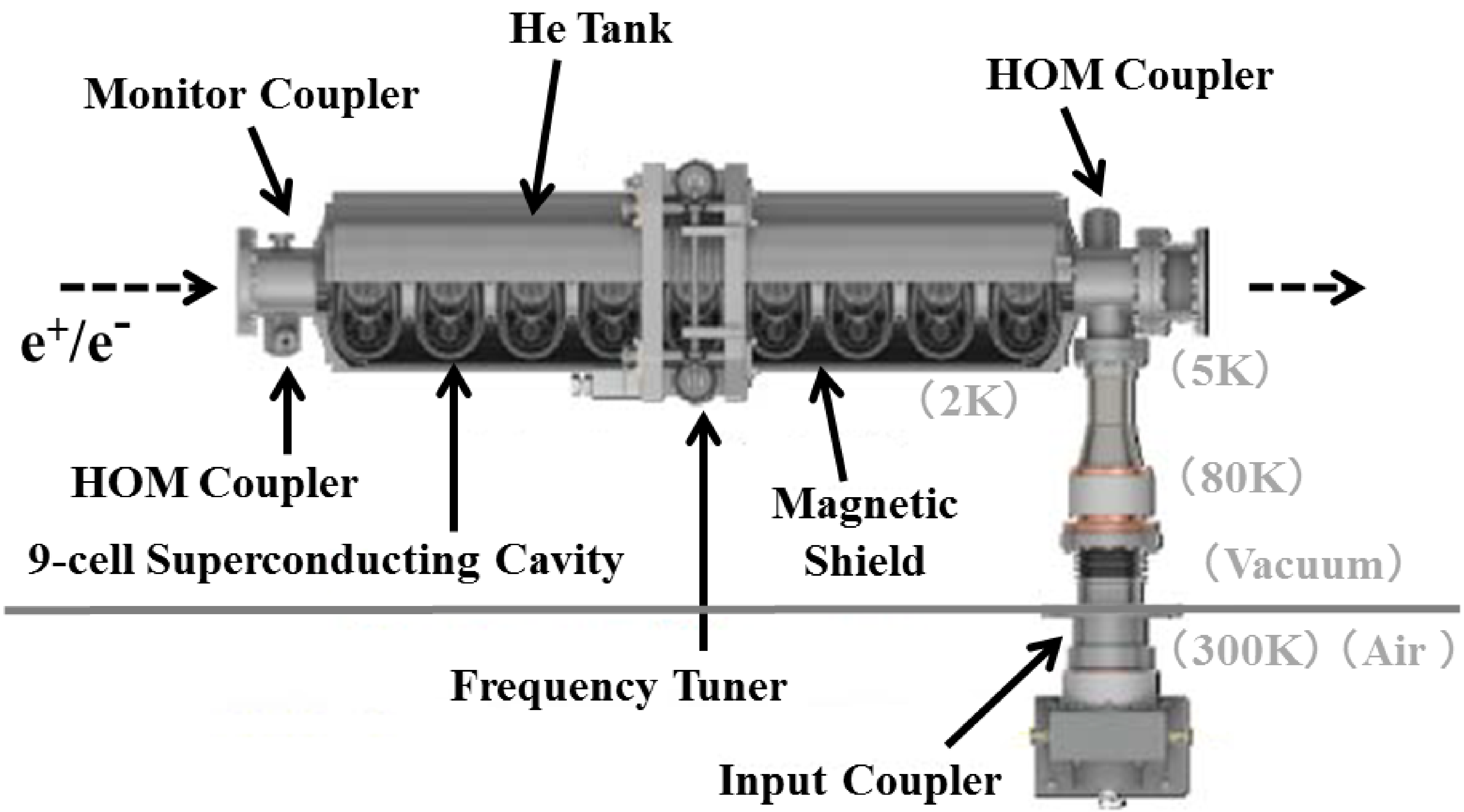

HOM Coupler


Cold-mass


Slide-Jack Tuner


Magnetic Shield
He Jacket (Ti)

Superconducting RF Cavity System (4)



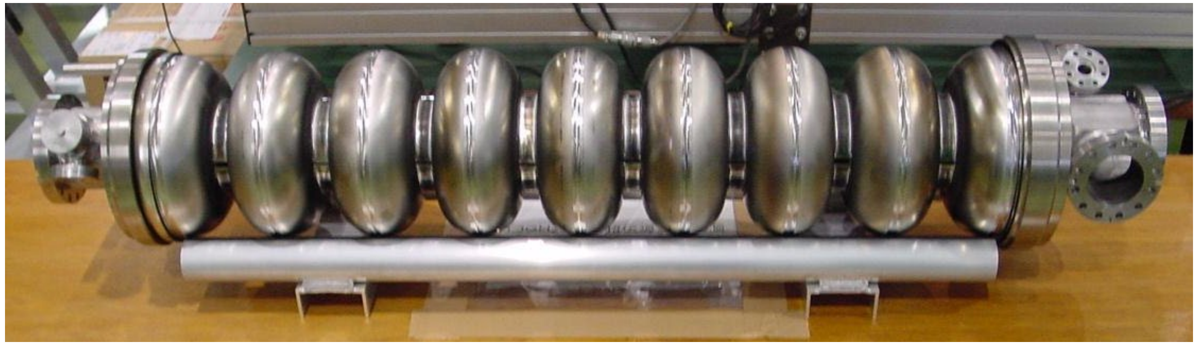
STF 9-cell SRF Cavity Package

Superconducting RF Cavity System (5)

Center-cells
(Tokyo Denkai ; RRR~300 Nb)

Forming and joining properties of Nb

(Deep drawing , EBW: electron beam welding)



Cavity fabrication companies in the world

PAVAC INDUSTRIES INC.

Advanced Energy Systems, Inc.

NIOWAVE
www.niowaveinc.com

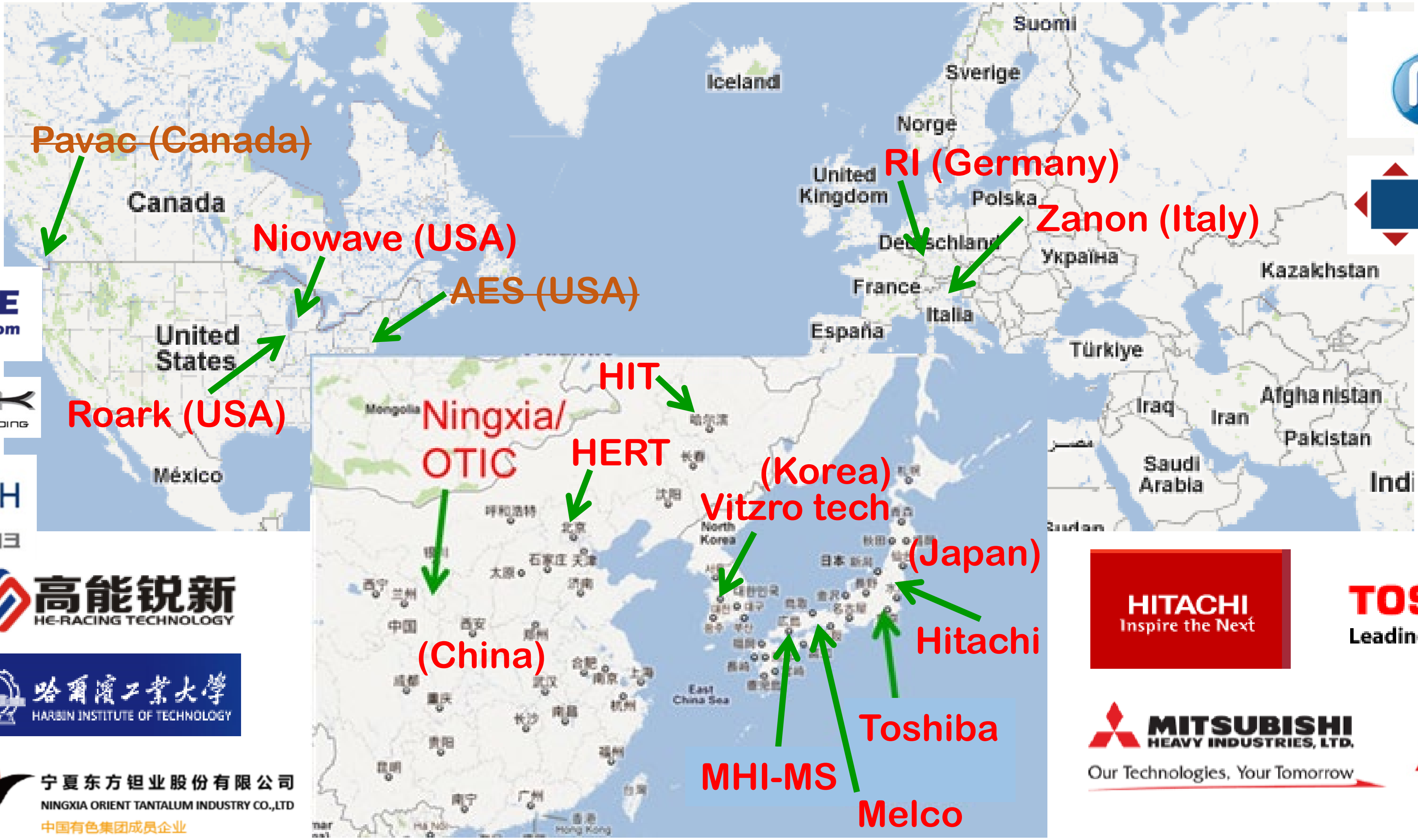
ROARK
COMPLEX FABRICATION · EB WELDING

VITZRO TECH
주식회사 비츠로테크

高能锐新
HE-RACING TECHNOLOGY

哈爾濱工業大學
HARBIN INSTITUTE OF TECHNOLOGY

宁夏东方钽业股份有限公司
NINGXIA ORIENT TANTALUM INDUSTRY CO.,LTD
中国有色集团成员企业



research instruments

Zanon
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Inspire the Next

TOSHIBA
Leading Innovation >>>

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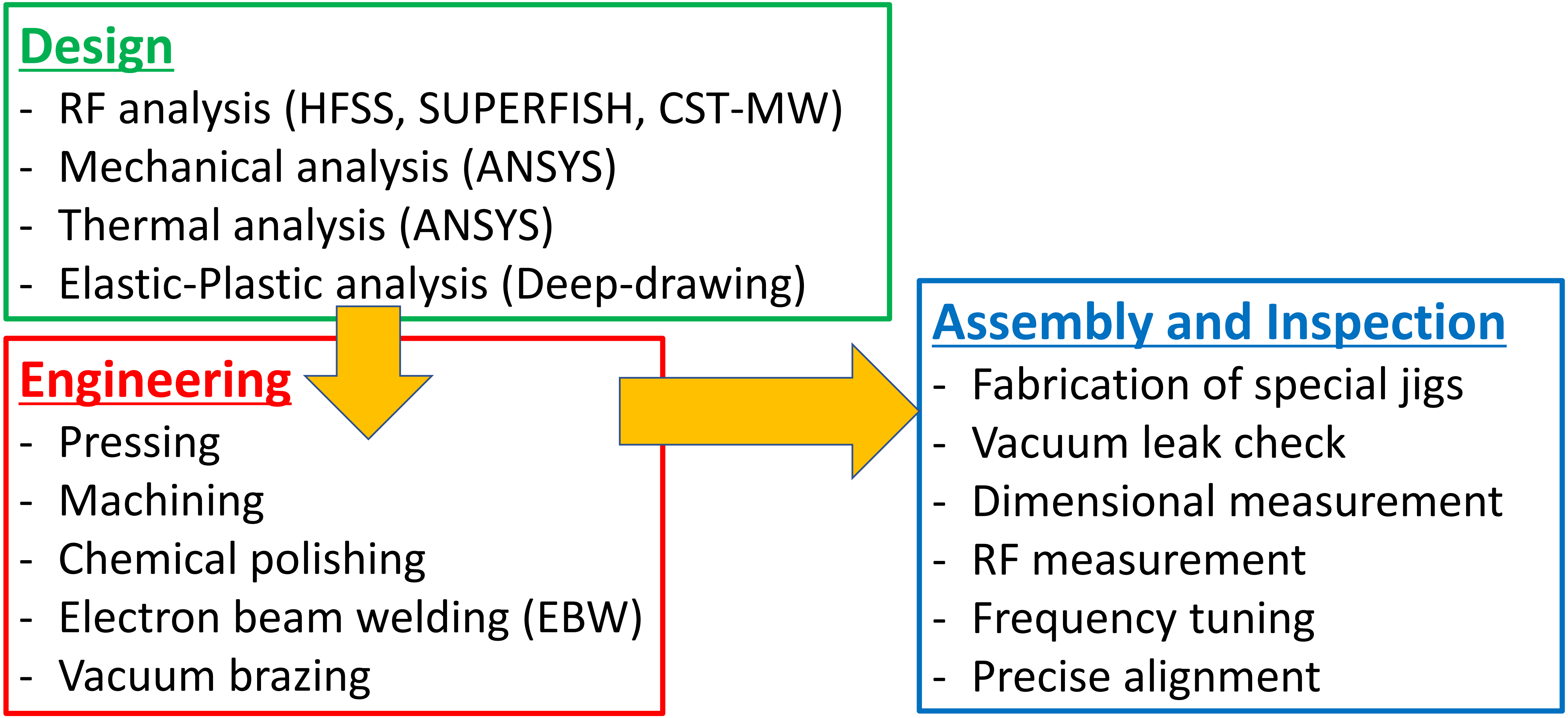
MITSUBISHI ELECTRIC

Essential technologies for cavity fabrication



Design
- RF analysis (HFSS, SUPERFISH, CST-MW)
- Mechanical analysis (ANSYS)
- Thermal analysis (ANSYS)
- Elastic-Plastic analysis (Deep-drawing)

Engineering
- Pressing
- Machining
- Chemical polishing
- Electron beam welding (EBW)
- Vacuum brazing

Assembly and Inspection
- Fabrication of special jigs
- Vacuum leak check
- Dimensional measurement
- RF measurement
- Frequency tuning
- Precise alignment

Special cavity fabrication tools developed by DESY

TESLA 1.3 GHz 9-cell cavity

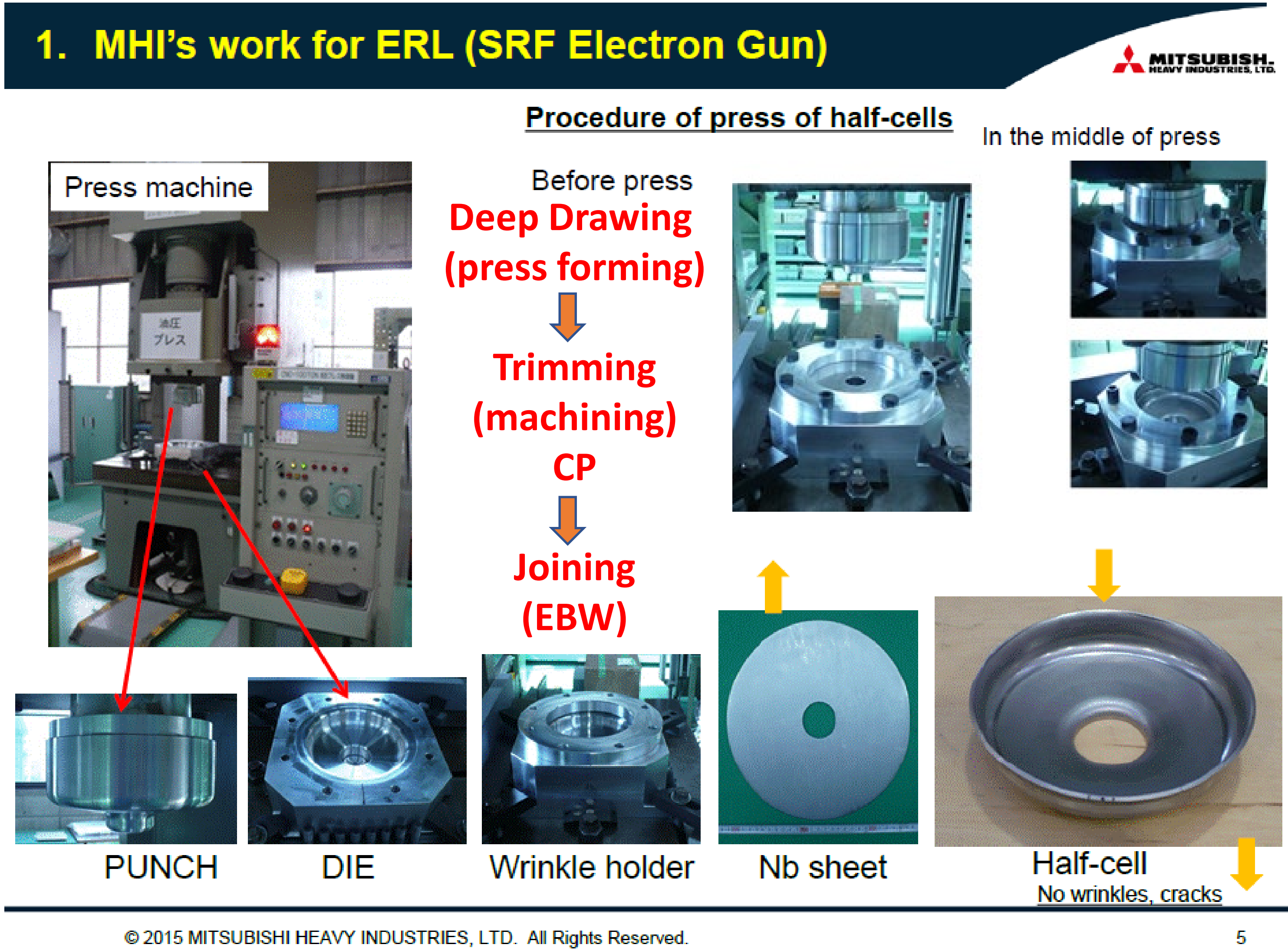
DESY

Eddy current scan of Nb sheet

Frequency measurement of half-cell/dumb-bell

Automatic pre-tuning machine

Fabrication Process of Nb Cavities



1. MHI's work for ERL (SRF Electron Gun)

Procedure of press of half-cells

Press machine

Before press

In the middle of press

Deep Drawing (press forming)

⇩

Trimming (machining)

CP

⇩

Joining (EBW)

No wrinkles, cracks

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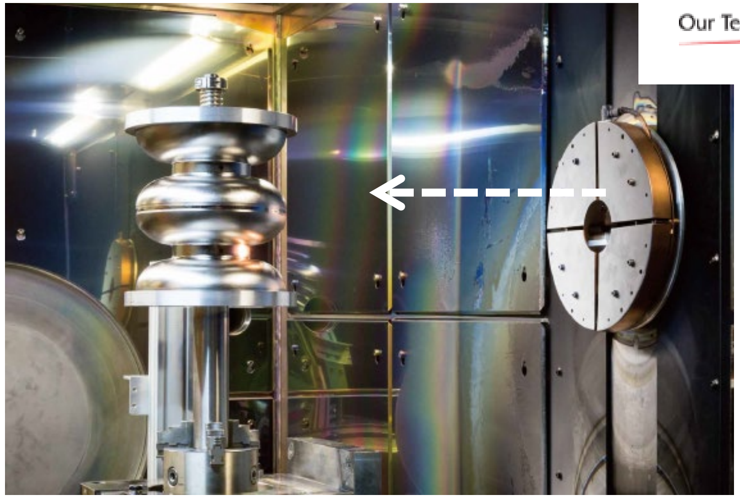
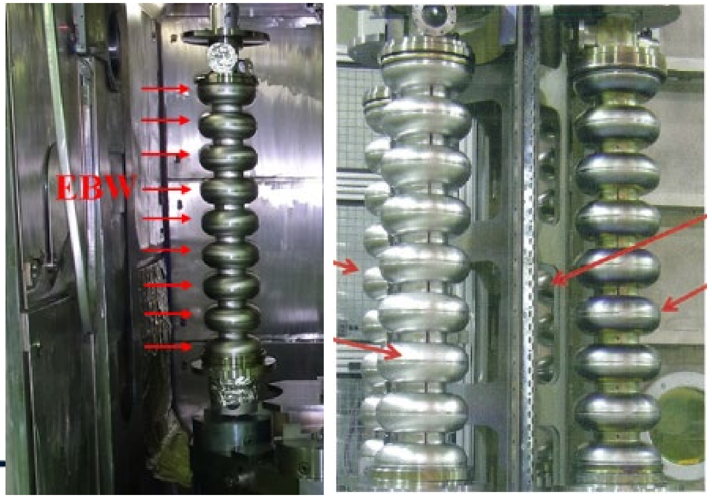
5

Electron Beam Welding (EBW)

MITSUBISHI HEAVY INDUSTRIES, LTD.
Our Technologies, Your Tomorrow

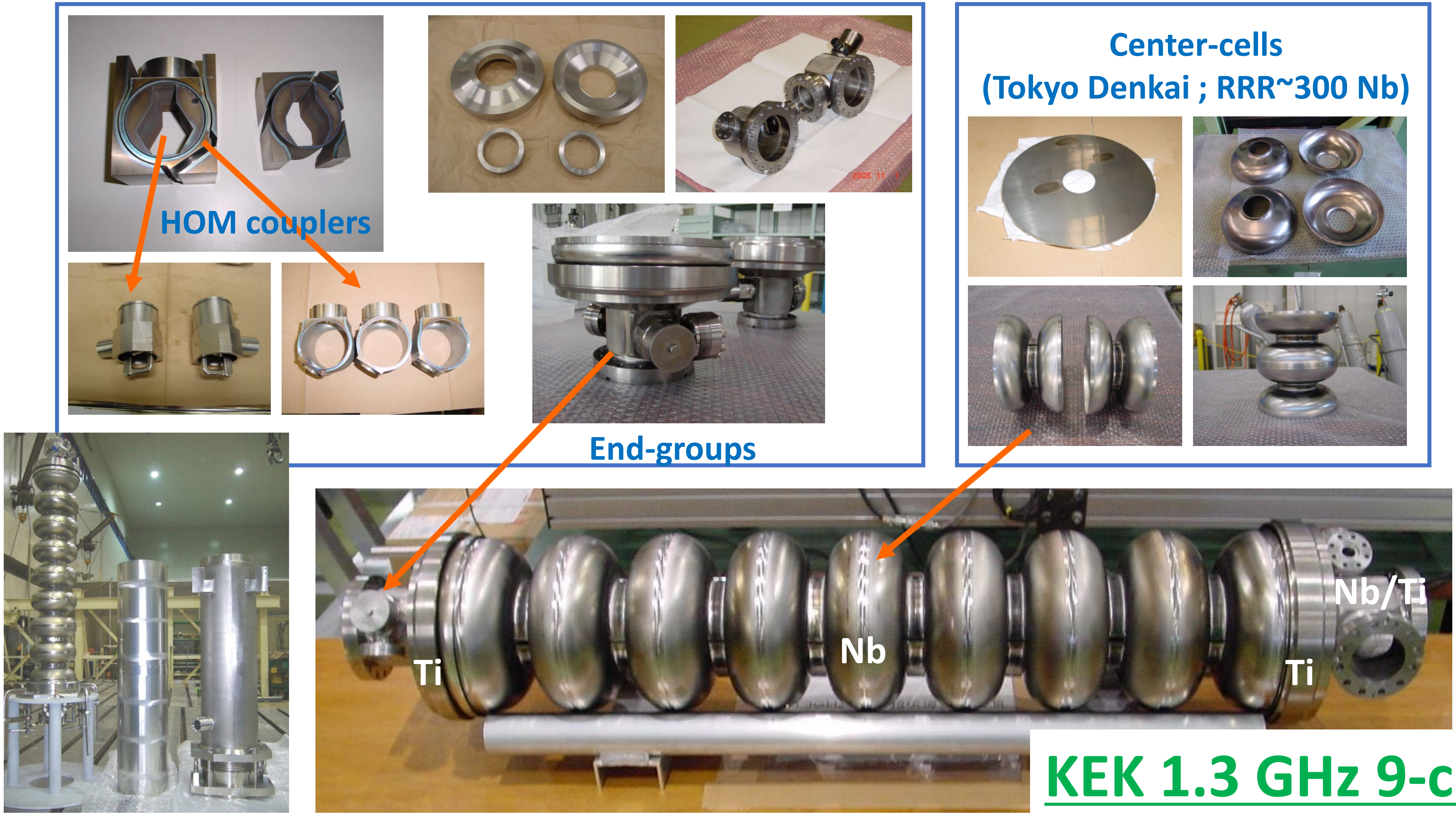
by K. Sennyu (MHI-MS)





Special Technology
4 x 9-cell cavities
(all 36 EBW seams)
per
1 vac. Pumping
at MHI-MS

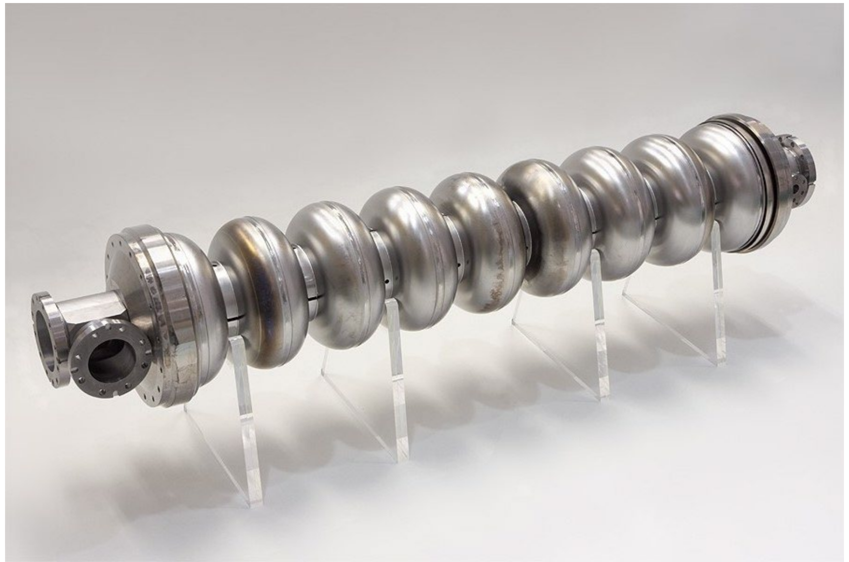
Cavity fabrication (EBW: electron beam welding)

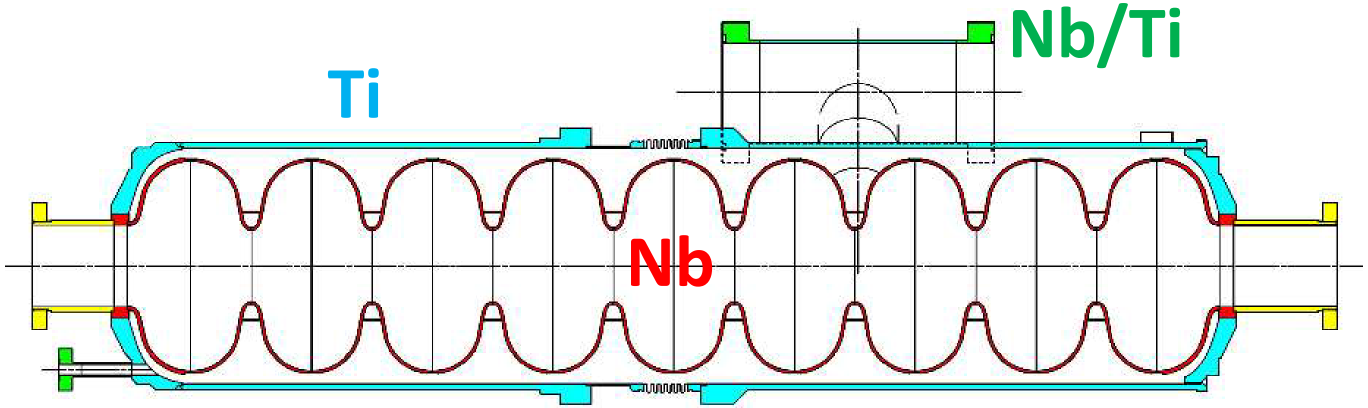


KEK 1.3 GHz 9-cell cavity

Materials and joining methods in SRF cavity

KEK 1.3 GHz 9-cell cavity

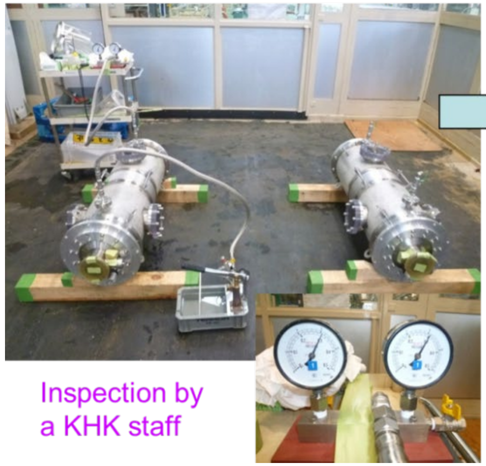




Materials	Joining Methods
Nb	(Cavity cells)
Ti	(He Tank)
Nb/Ti	(Flanges)
Nb - Nb Joining	EBW, LBW
Nb - Ti Joining	EBW
Ti - Ti Joining	TIG
Nb/Ti - Ti Joining	TIG
Nb/Ti - Nb Joining	EBW, LBW

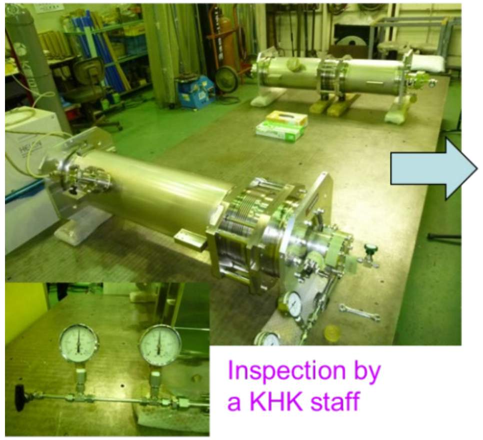
High pressure gas safety low in Japan

Nb Cavity
at 1.5 times of design pressure
(test with water : 0.3 MPa)



Inspection by
a KHK staff

Cavity unit with Jacket
at 1.25 times of design pressure
(test with He gas : 0.25 MPa)

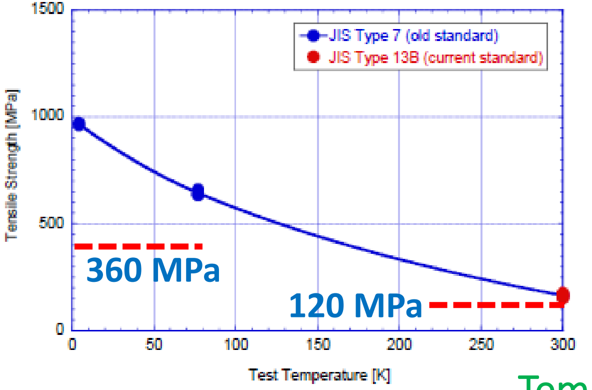


Inspection by
a KHK staff

Cavity string assembly

Mechanical properties of Nb, Ti and Nb/Ti (EBW-joints)

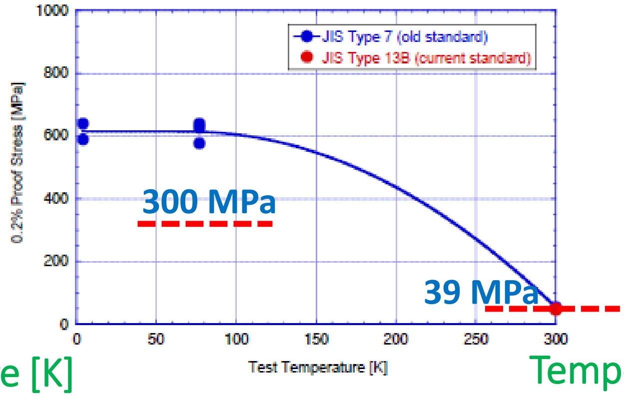
Tensile strength of Nb



Temperature [K]

Fig. (5)a Tensile strength of Nb.

0.2% Proof Stress of Nb



Temperature [K]

Fig. (5)b 0.2% proof stress of Nb.

Charpy Impact Value of Nb

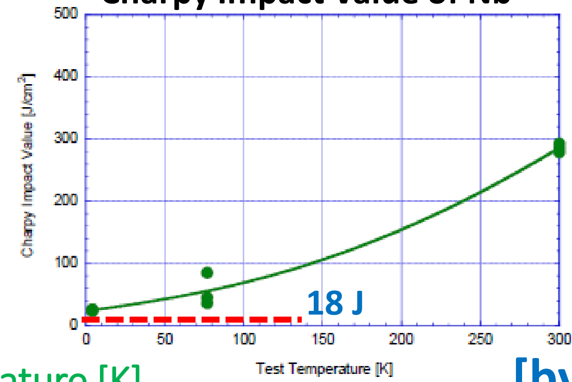
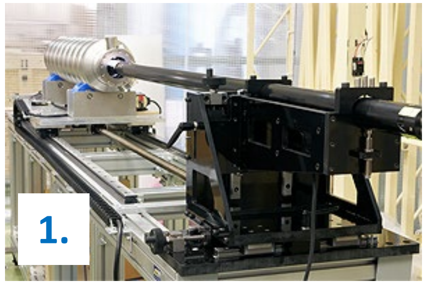


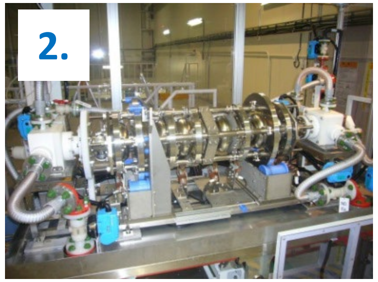
Fig. 5(b) Charpy impact value of Nb (10 mm wide).

[by H. Nakai (KEK)]

Surface treatment (smooth and clean)

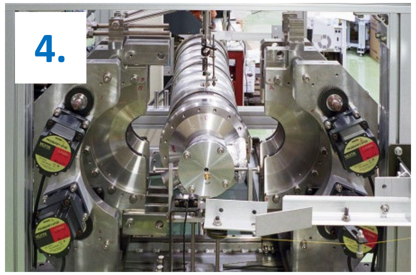


Inspection of inner surface

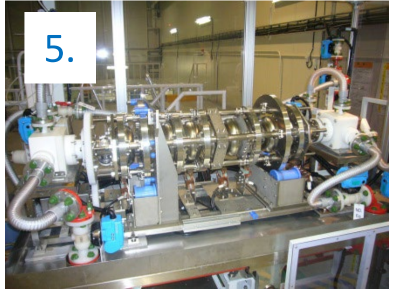


Pre-EP + EP-I (5+100 μm)

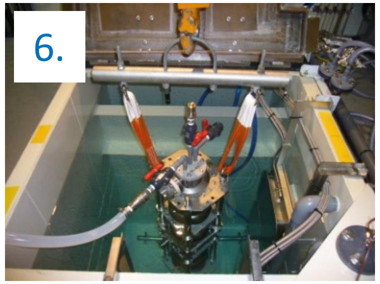
Anneal (750°C, 3h)



Pre-tuning (flatness, f_0)



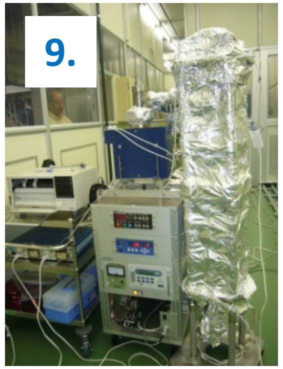
EP-II
(5~20 μm)



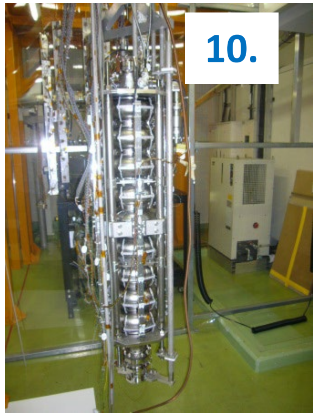
Hot bath rinsing with ultra-sonic

HPR

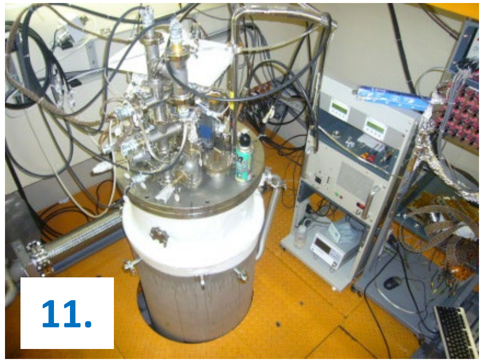
Assembly (Class 10)



Baking (120°C, 48h)
(Class 1000)



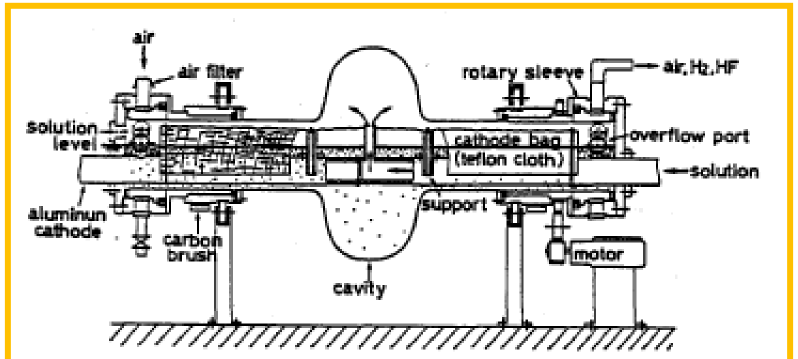
Hanging stand with T-map



Vertical Test

Electro-polishing: EP

Electro-polishing Device

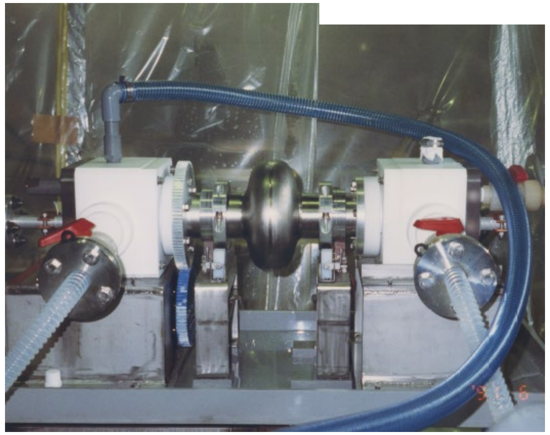


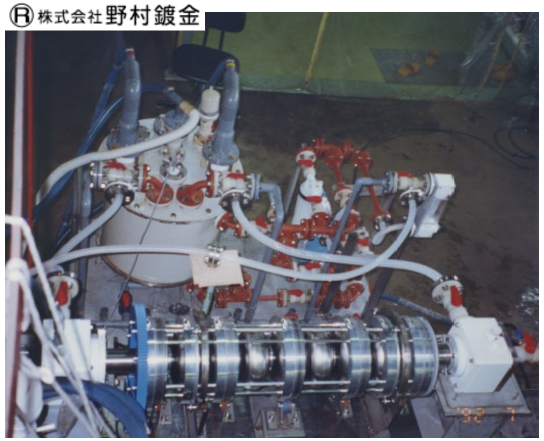
by K. Saito (4th SRF-WS in 1989')

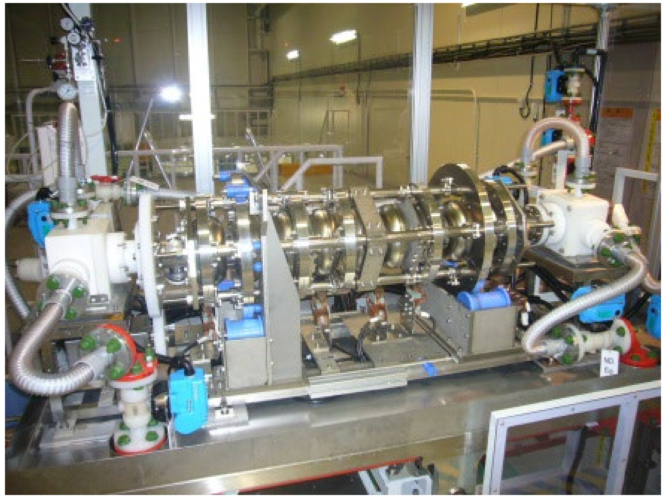
1993'

NOMURA PLATING
Ⓡ株式会社野村鍍金

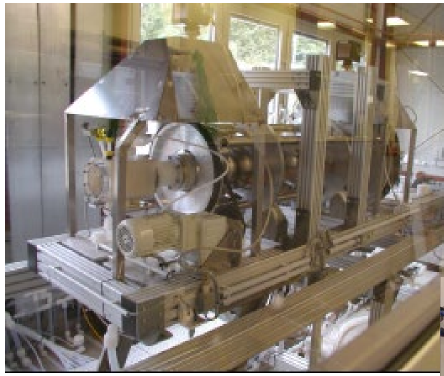
1998'



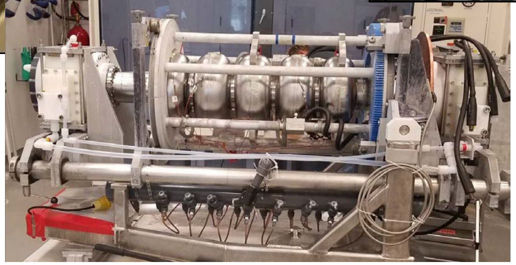




2006' STF/KEK



DESY



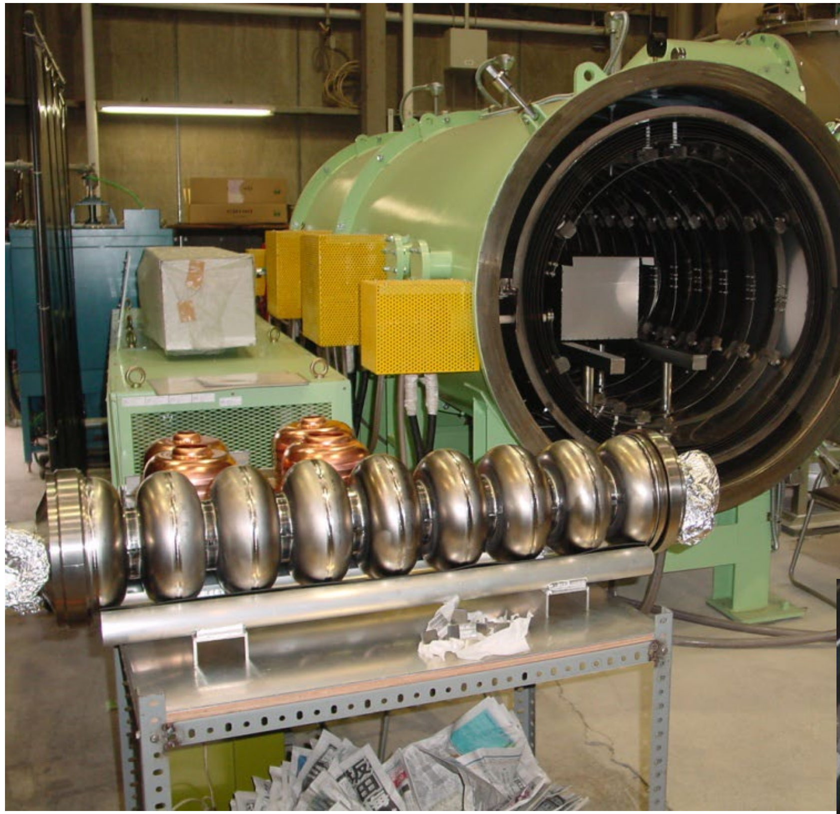
JLab

ANL/
FANL

E. ZANON/DESY
Ningxia/IHEP
Wuxi/SINAP

RI/
DESY

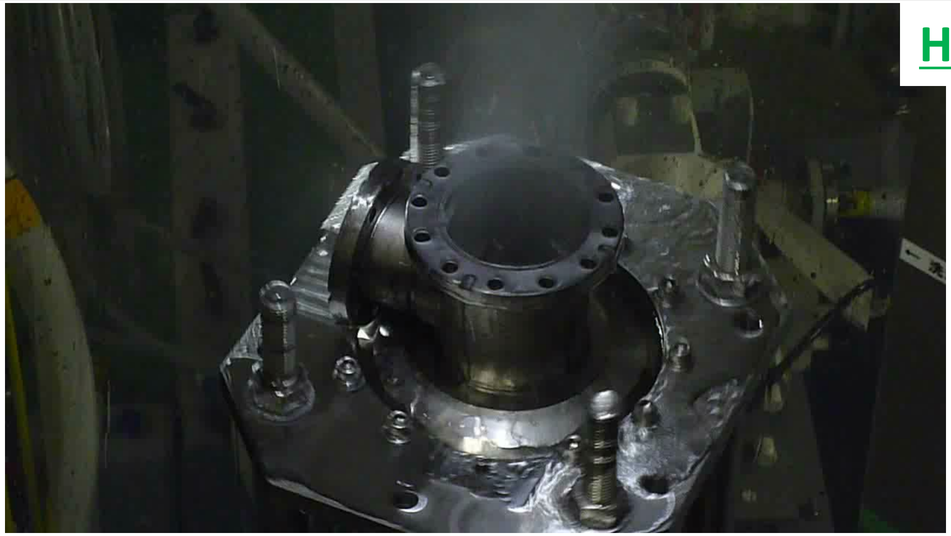
Vacuum furnace for heat treatment



Vacuum furnace with diffusion-pump
for hydrogen degassing:
max. temp. = 800 ^{o}C
1. x10^{-4} Pa at RT

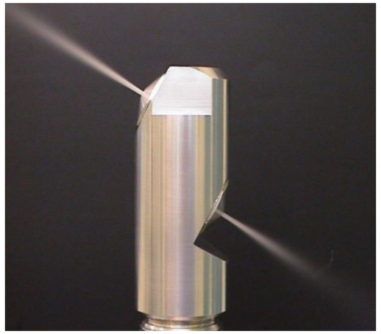
New clean vacuum furnace with cryopump
for N-doping and N-infusion:
max. temp. = 1200 ^{o}C
1. x10^{-6} Pa at RT

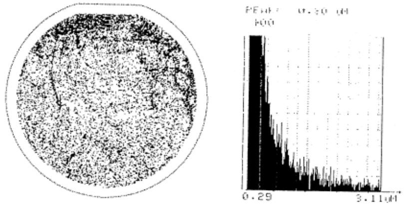
High pressure rinsing: HPR



Pressure = 8 MPa

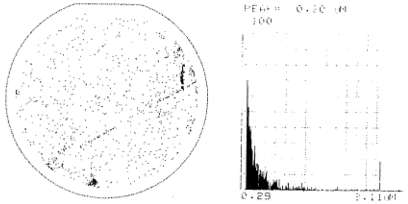
Purity = 18 MΩ・cm





Particle size	Count
0.30-1.20 μm	5825
1.20-2.01 μm	405
2.01-3.00 μm	2720
> 3.00 μm	1069
Total	10019

Fig. 6 Residual particles on a wafer surface after the TRISTAN final rinsing.



Particle size	Count
0.30-1.20 μm	646
1.20-2.01 μm	52
2.01-3.00 μm	282
> 3.00 μm	37
Total	1017

Fig. 7 Residual particle on a wafer surface after HPR.

by K. Saito (SRF91')

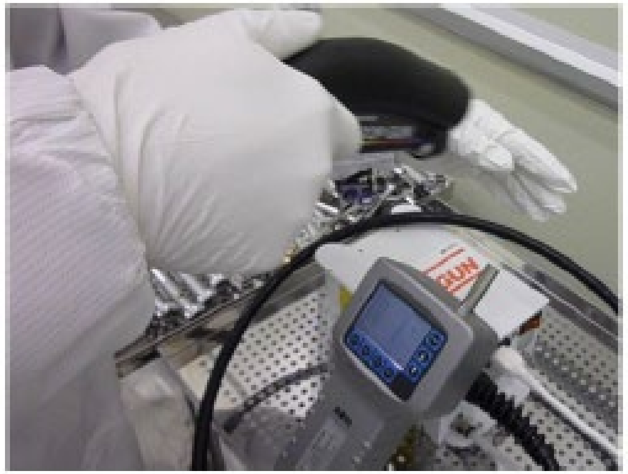
HPR-1 at STF

Nozzle: fixed
Cavity: rotation, up/down

HPR-2 at COI

Nozzle: rotation
Cavity: up/down

Cleanroom Assembly (class-10, ISO-4)



- Parts cleaning
- UPW rinsing
- Ultra-sonic bath
- Ionized gun
- Particle counter
- Ar gas flow

Question (4)

What is the essential technologies for achieving higher cavity performance?

Superconducting RF (SRF) Cavity

What is the essential technologies for achieving higher cavity performance?

Essential technologies for higher performance:

- **Smooth Surface**
- **Clean Surface**
- **Clean Environment**

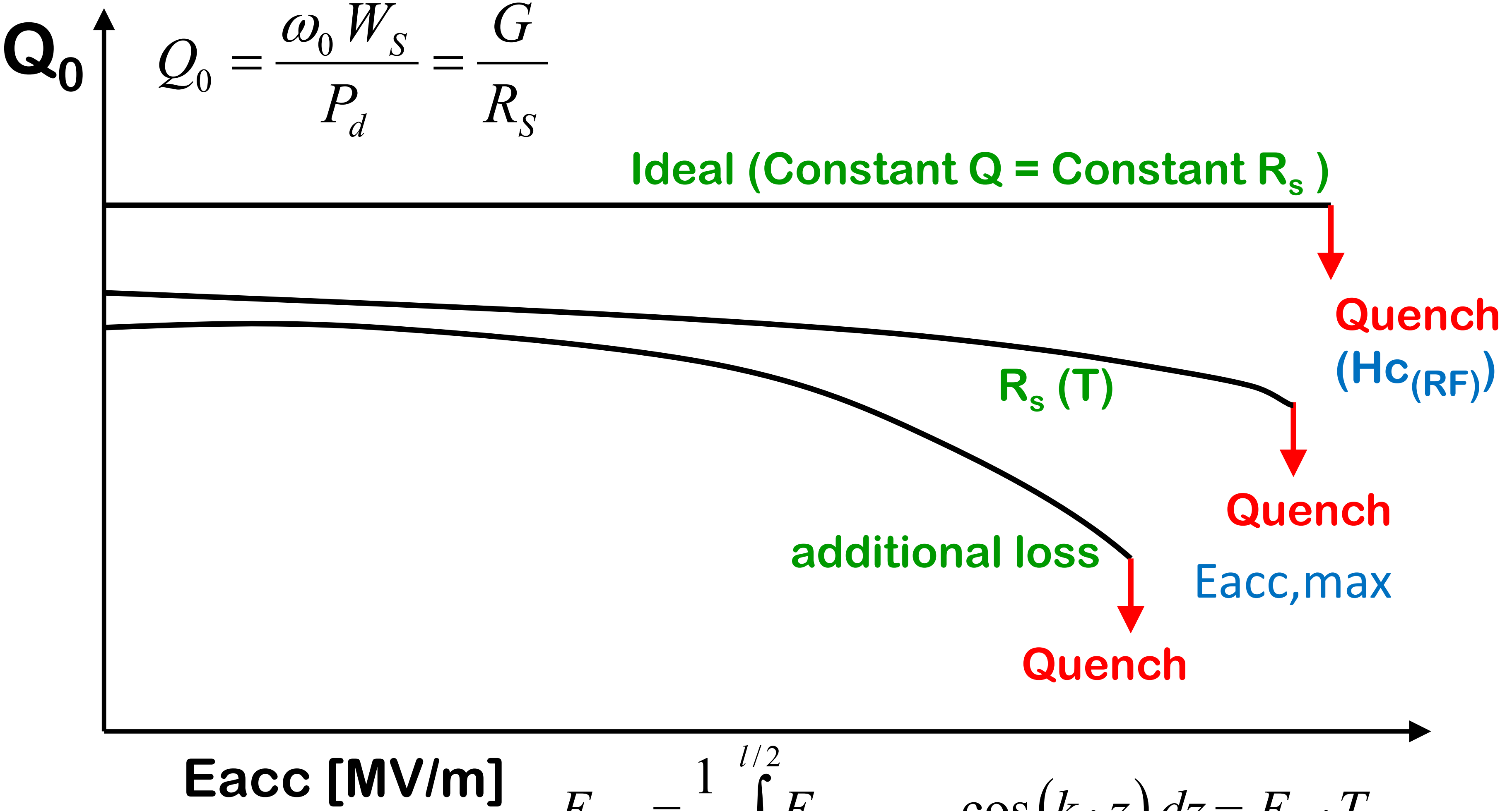
To achieve higher performance

- avoid Thermal Quench caused by surface defects
- suppress Field Emission due to dust contamination

Outline of the Lecture

1. Introduction
2. Fundamental of SRF Cavity
3. Overview of SRF Cavity System
4. Fabrication and Surface Preparation
5. **Cavity Performances**
6. Summary

Performance of SRF cavity: Qo-Eacc curve



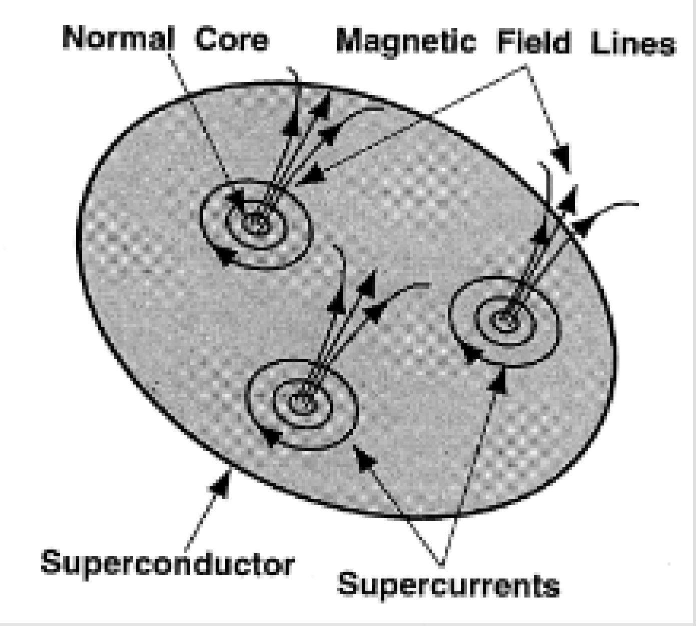
$$Q_0 = \frac{\omega_0 W_S}{P_d} = \frac{G}{R_S}$$

$$E_{acc} = \frac{1}{l} \int_{-l/2}^{l/2} E_{Z\,(z,\ r=0)} \cos\left(k \cdot z\right) dz = E_0 \cdot T$$

Cavity performance : Essential technology

- High purity Nb material (Fine-grain, Large-grain)
- Forming (Hydroforming, Deep drawing, Spinning)
- Joining (EBW, TIG, LBW, Brazing, ….)
- Surface removal treatment (CP, EP)
- Rinsing (Detergent, Ultra-pure water, US, HPR)
- Clean room environment
- Assembly procedure

Cavity performance : Residual magnetic field



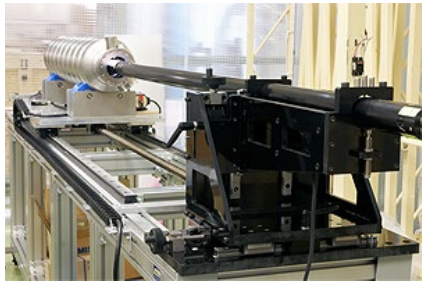
Experiment to investigate shielding effect of residual magnetic field

(0.3 nΩ / mGauss)

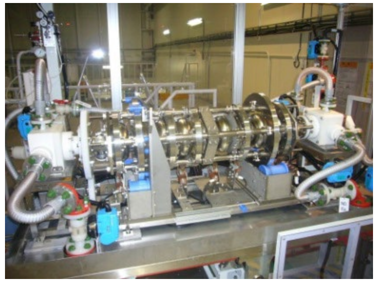
This sensitivity is strongly dependent on the surface condition.

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.

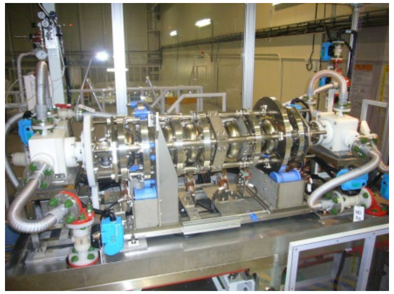
Surface preparation : indispensable preparation



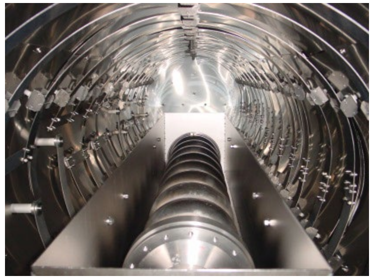
Inspection of
inner surface



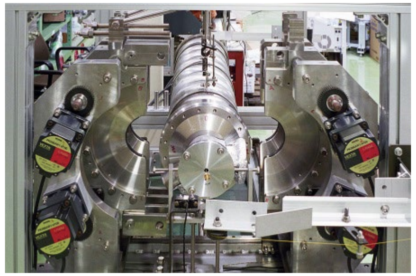
Pre-EP + EP-I (5+100 mm)



EP-II
(5~20 mm)



Anneal (750°C, 3h)



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

Suppression of Field Emission

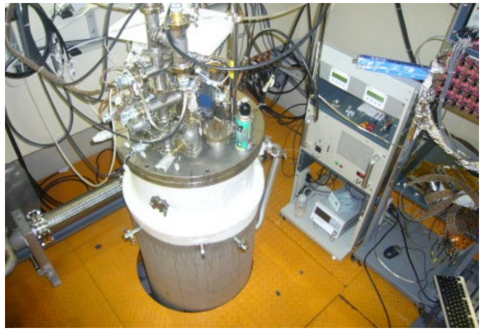
- **Rinsing by ultra-pure water**
- **Assembly in class-10 clean room**

HPR

Assembly (Class 10)

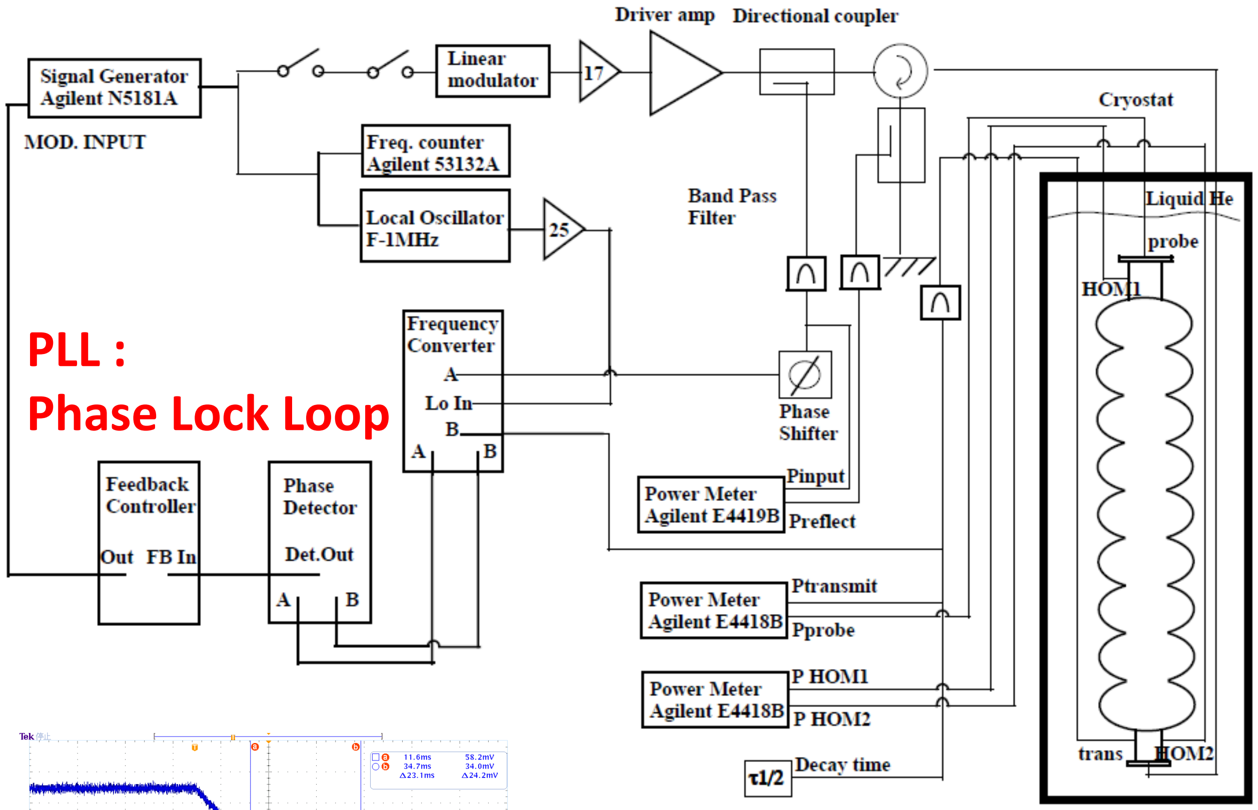
Baking (120°C, 48h)
(Class 1000)

Hanging stand with T-map

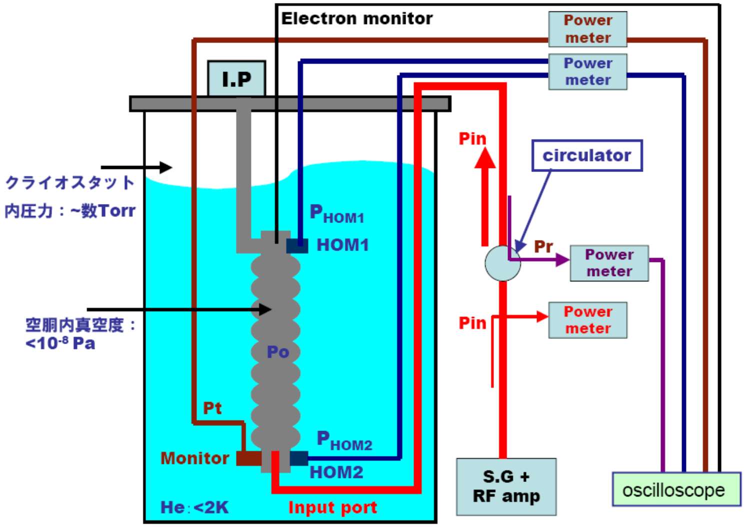


Vertical Test

RF system for Vertical Tests : VT



PLL :
Phase Lock Loop



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

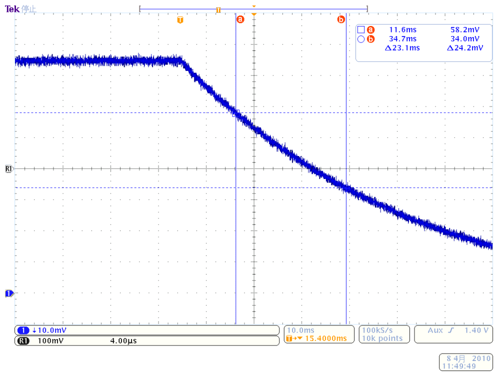
$$\beta^* = \frac{1 \pm \sqrt{P_{ref}/P_{in}}}{1 \mp \sqrt{P_{ref}/P_{in}}}$$

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

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

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

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



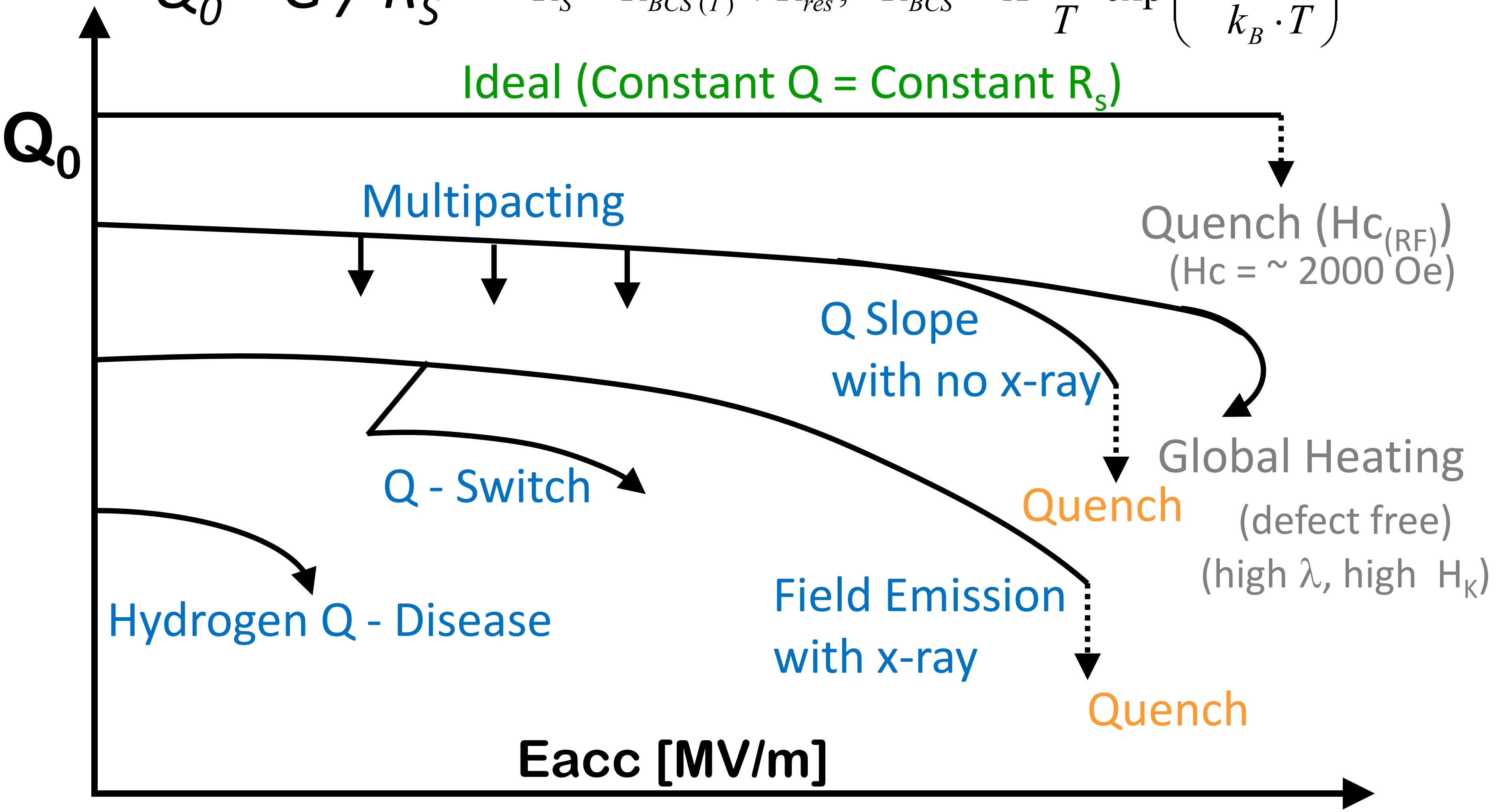
$$Q_L = 2\,\pi\, f_o \cdot \tau_{1/2} / \log_e 2$$

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

Phenomena limiting cavity performance

$$Q_0 = G / R_S$$

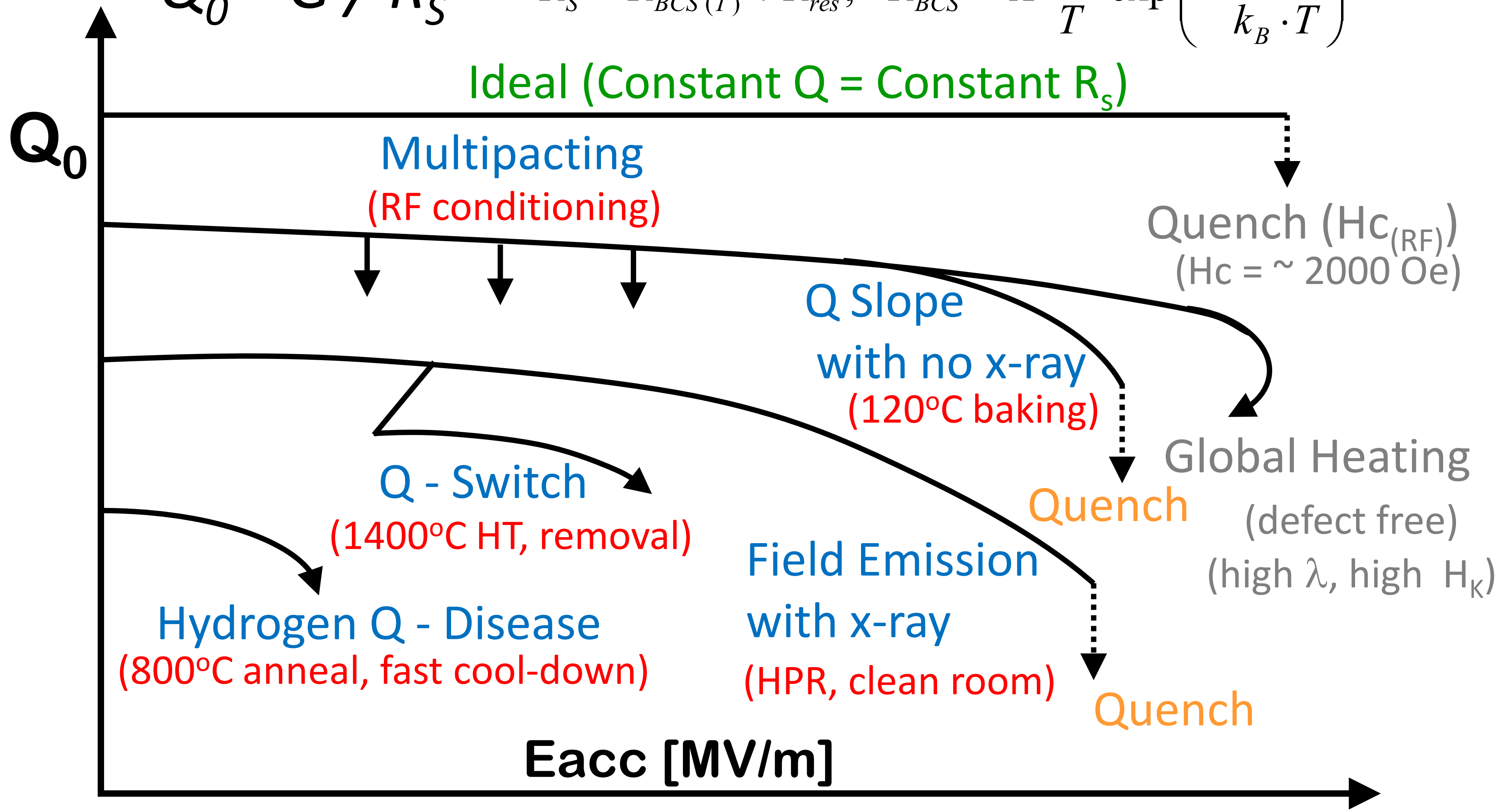
$$R_S = R_{BCS\,(T)} + R_{res}, \quad R_{BCS} = A \frac{\omega^2}{T} \exp\left(- \frac{\Delta}{k_B \cdot T} \right)$$



Cure methods against Performance limitation

$$Q_0 = G / R_S$$

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



Ideal (Constant Q = Constant R_S)

Multipacting
(RF conditioning)

Quench ($Hc_{(RF)}$)
(Hc = ~ 2000 Oe)

Q Slope
with no x-ray
(120°C baking)

Global Heating
(defect free)
(high λ, high H_K)

Quench

Q - Switch
(1400°C HT, removal)

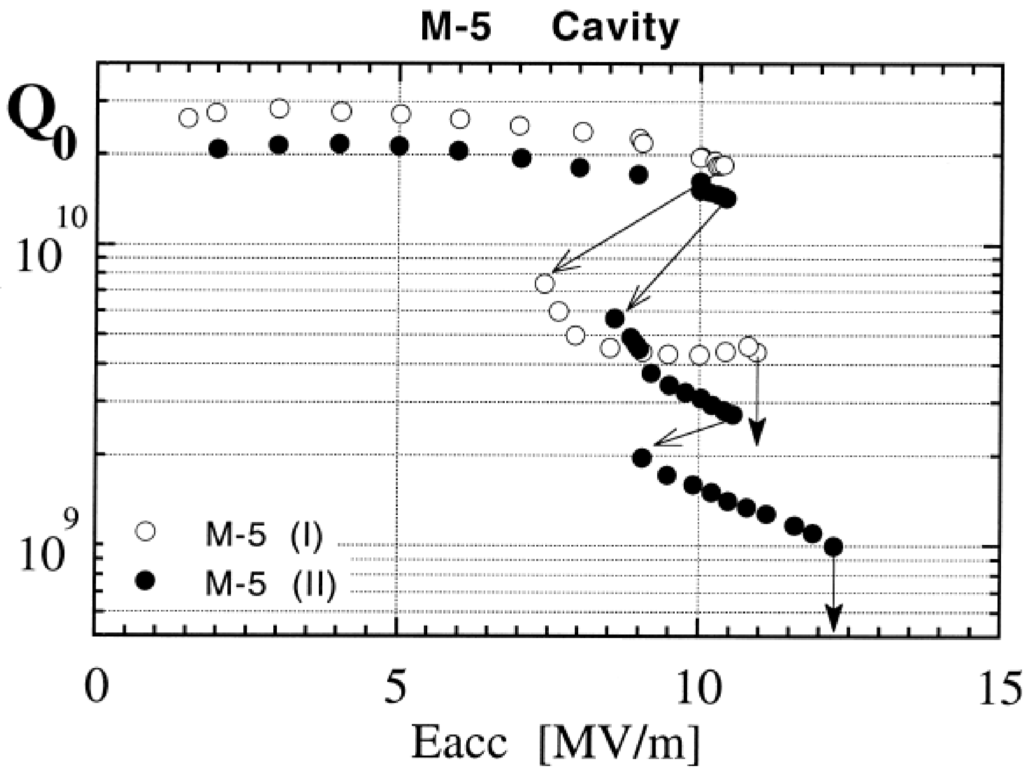
Field Emission
with x-ray
(HPR, clean room)

Quench

Hydrogen Q - Disease
(800°C anneal, fast cool-down)

Performance limitation : Q-switch

Q - Switch

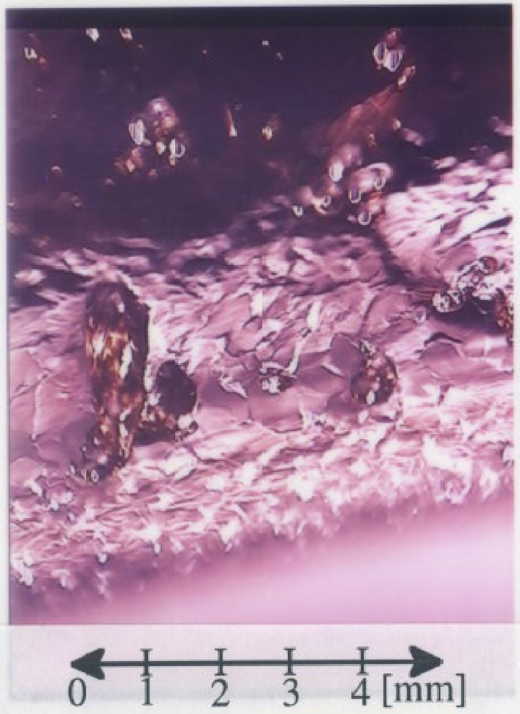


The Q-Switch is caused by heating due to the transition from an SC state to a NC state at thermally isolated defects.
Typically, around iris region, where surface currents are lower.

M - 5 Cavity ; Quench Location

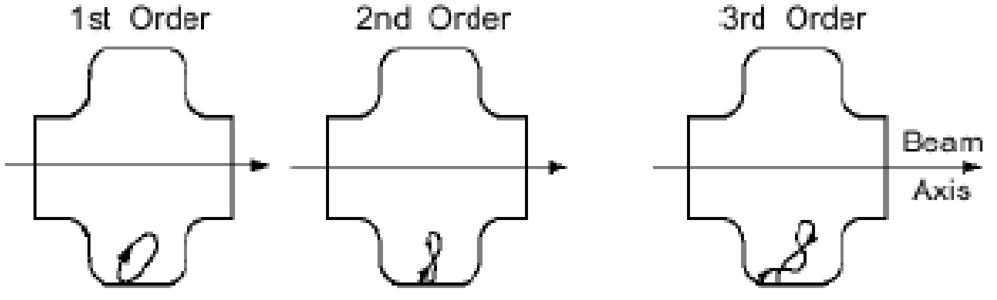
EBW seam at lower Iris

Sputtering balls / welding imperfections



C-1 Cavity ; iris EBW (θ = 30°)

Performance limitation : Multipacting

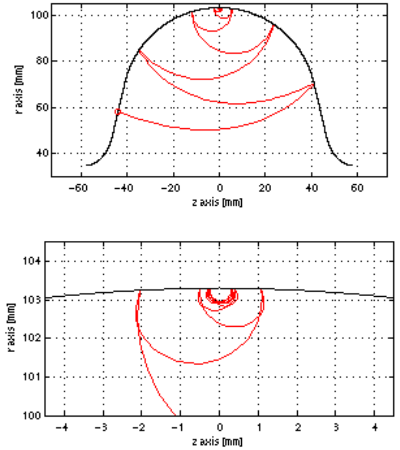


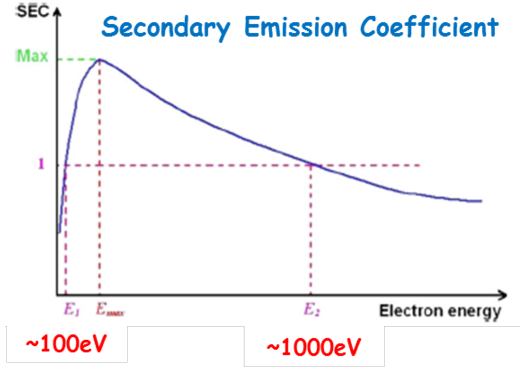
Multipacting at equator region

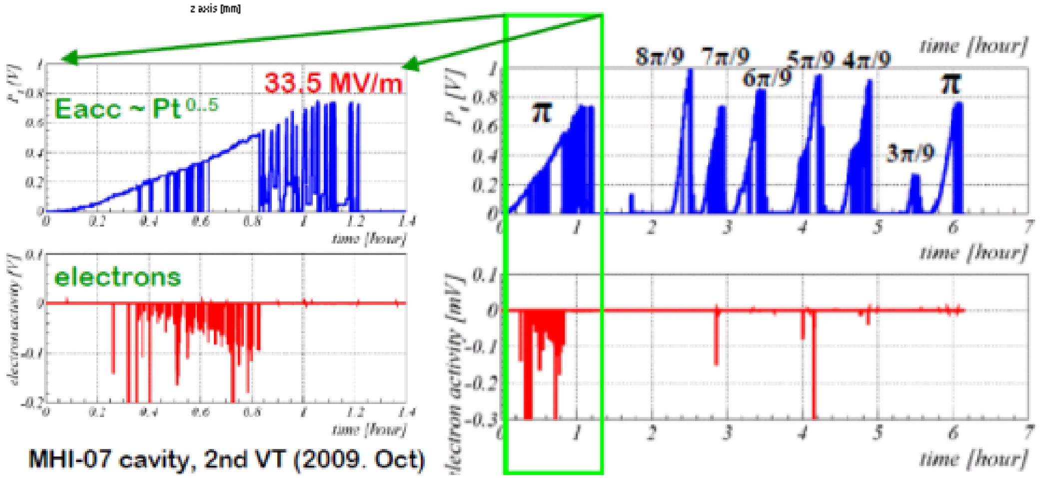
Multipacting is a low RF power, electron multiplication based on resonance breakdown phenomenon in vacuum. For a cavity shape such as a pill-box cavity, the cavity performance is frequently limited by a multipacting phenomenon around the equator region. A spherical cell shape is usually used for actual 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.



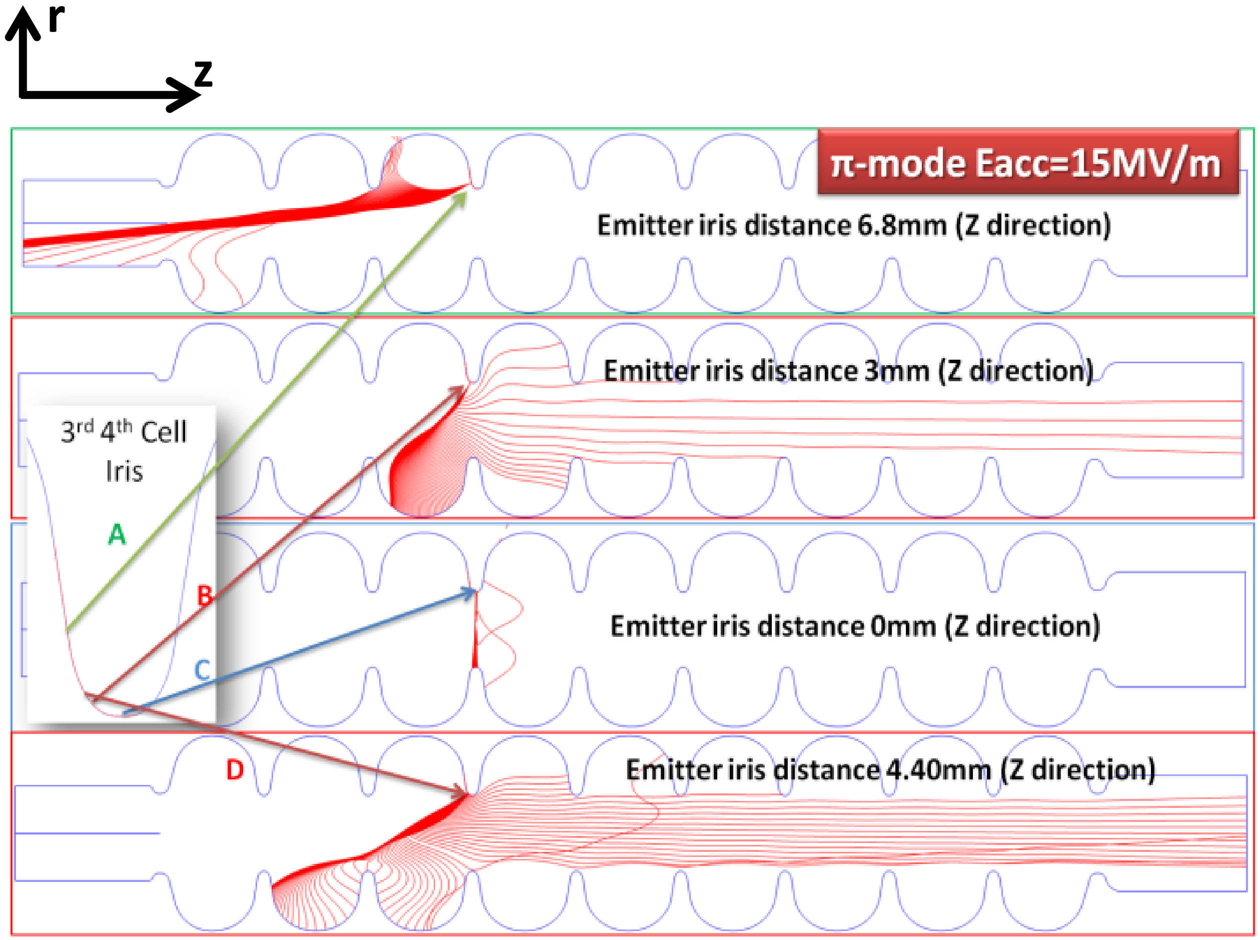




MHI-07 cavity, 2nd VT (2009. Oct)

Performance limitation : Field Emission

TM010-mode

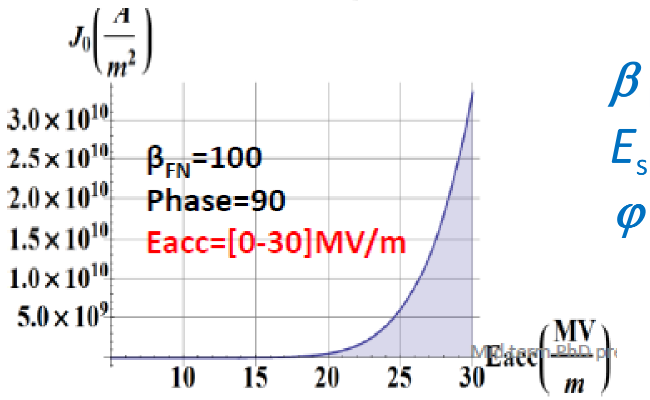


[Thesis by E. Cenri (KEK)]

Source of
field emitted electrons

Fowler – Nordheim Equation

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

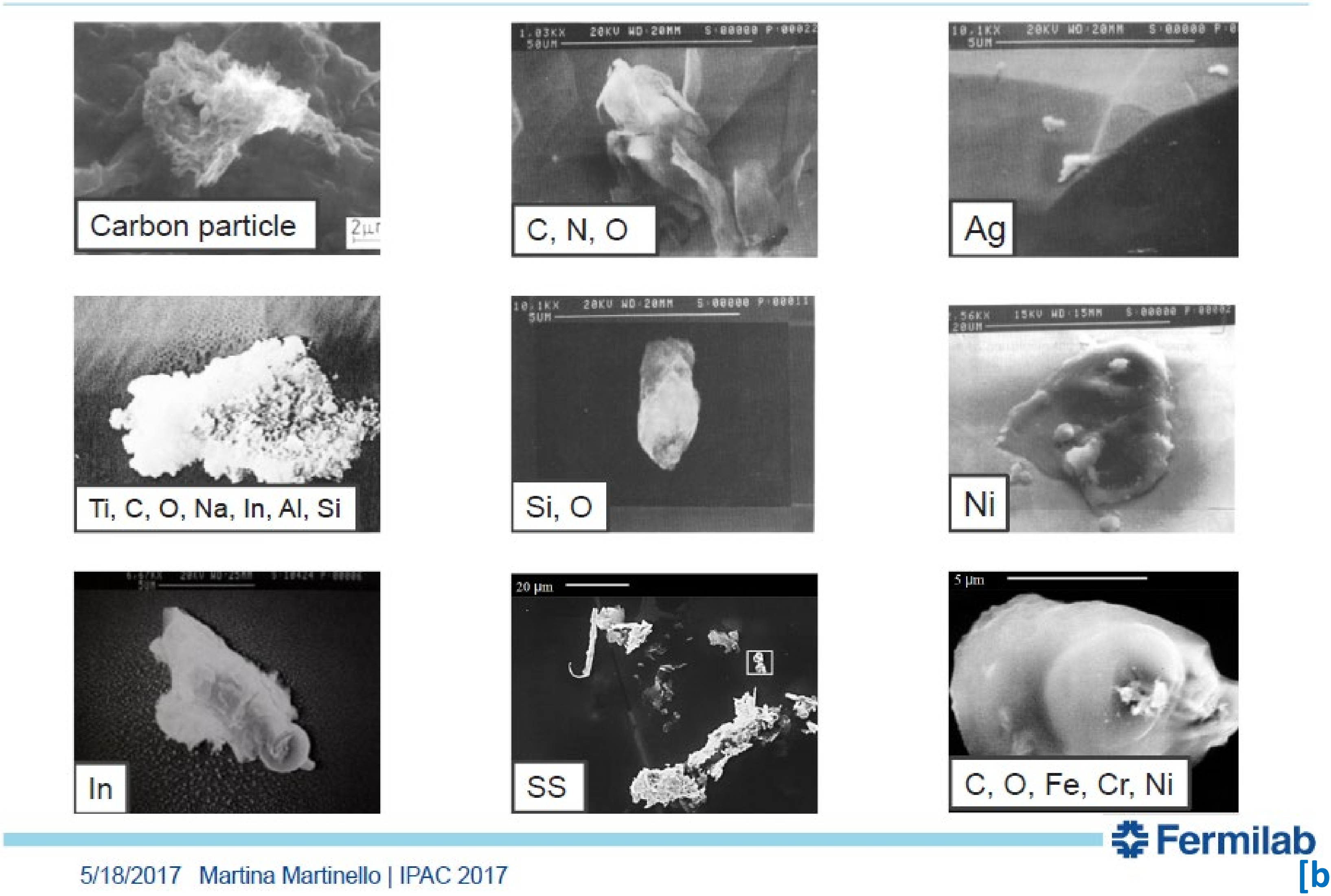


β_{FN} : field enhancement factor

E_{surf} : surface electric field

φ : work function of Nb

Sources of field emission: dust particles



Carbon particle

C, N, O

Ag

Ti, C, O, Na, In, Al, Si

Si, O

Ni

In

SS

C, O, Fe, Cr, Ni

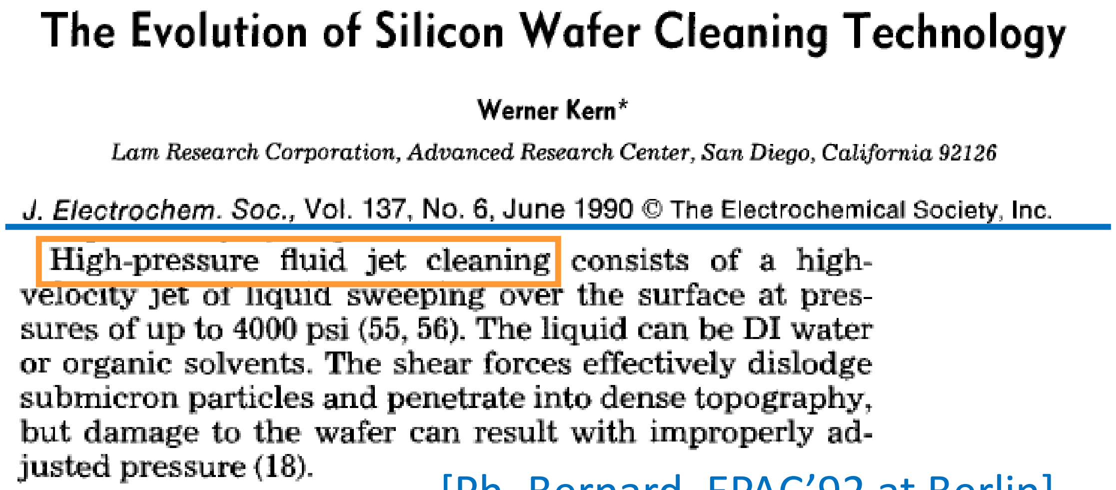
Fermilab

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

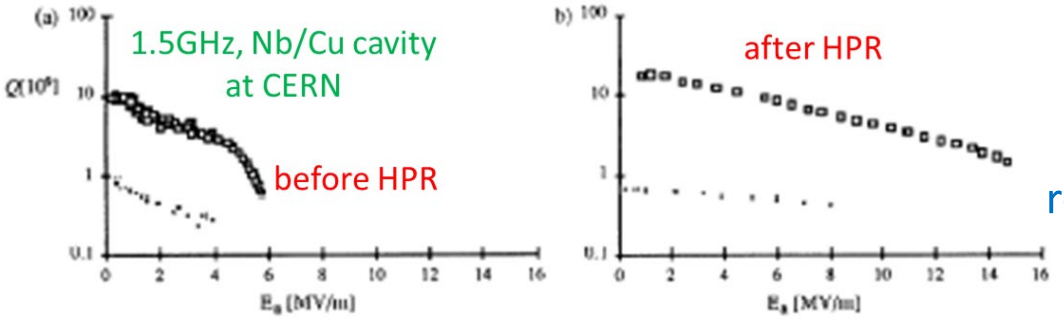
Werner Kern*

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]



1.5GHz, Nb/Cu cavity
at CERN

before HPR

after HPR

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]

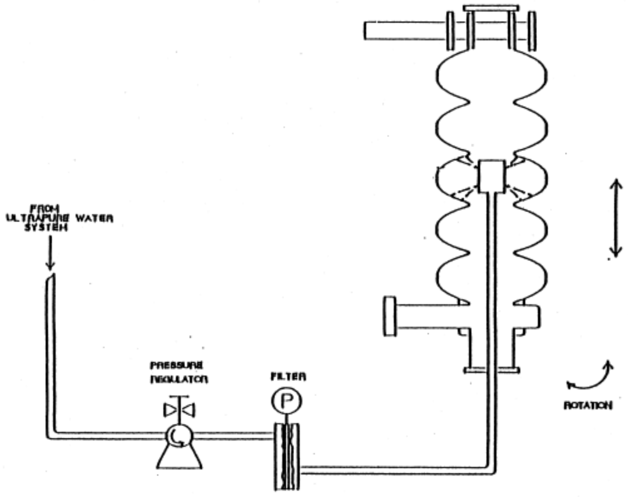


Figure 1 : Schematic of High Pressure Rinsing System

Experimental results of performance recovery by high pressure water rinsing

Demonstration of the effectiveness of HPR

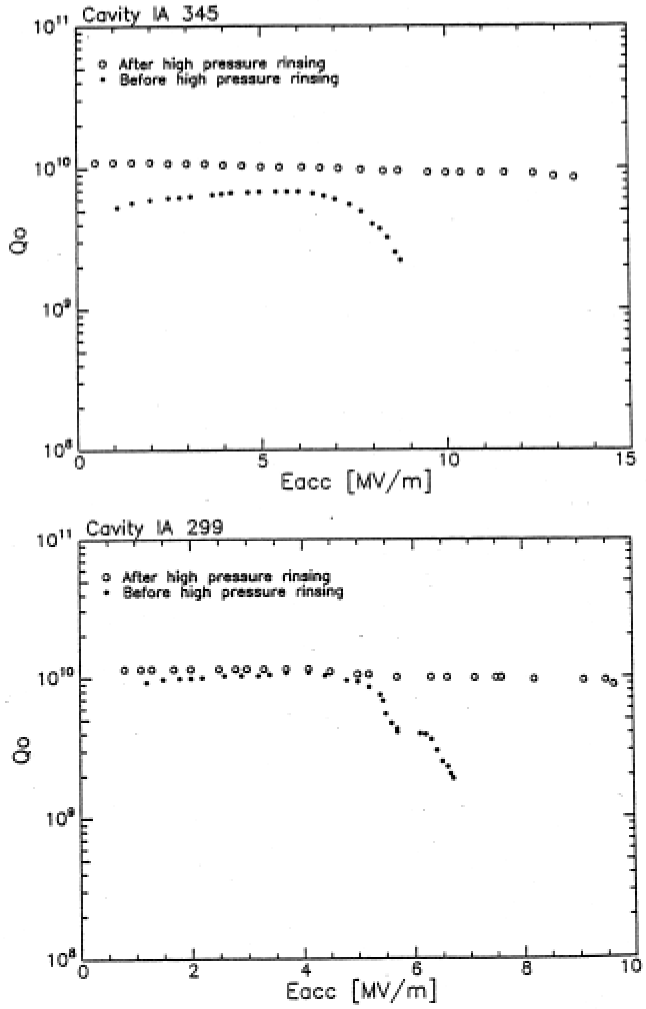
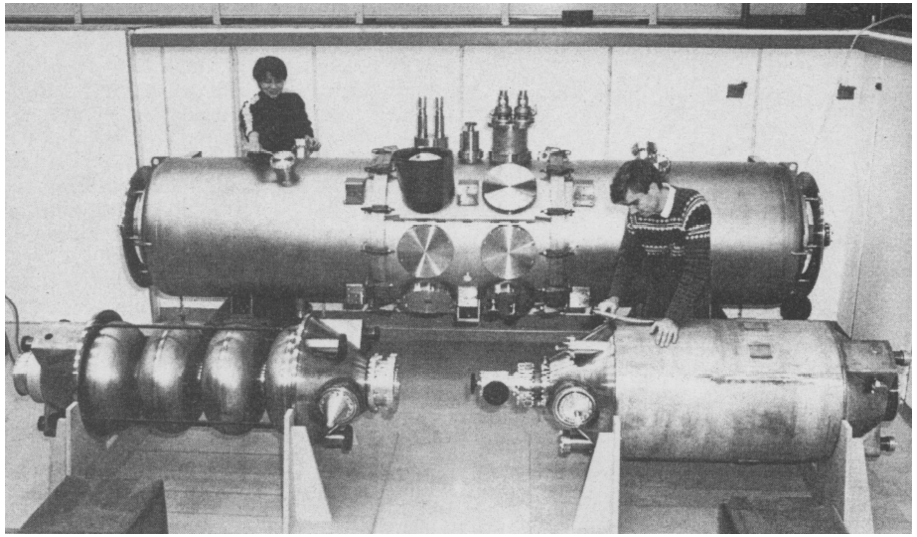


Figure 3 : Results of Production Cavity Pair IA345/IA299 before and after High Pressure Rinsing (measurements have been

Performance limitation : Hydrogen Q-disease

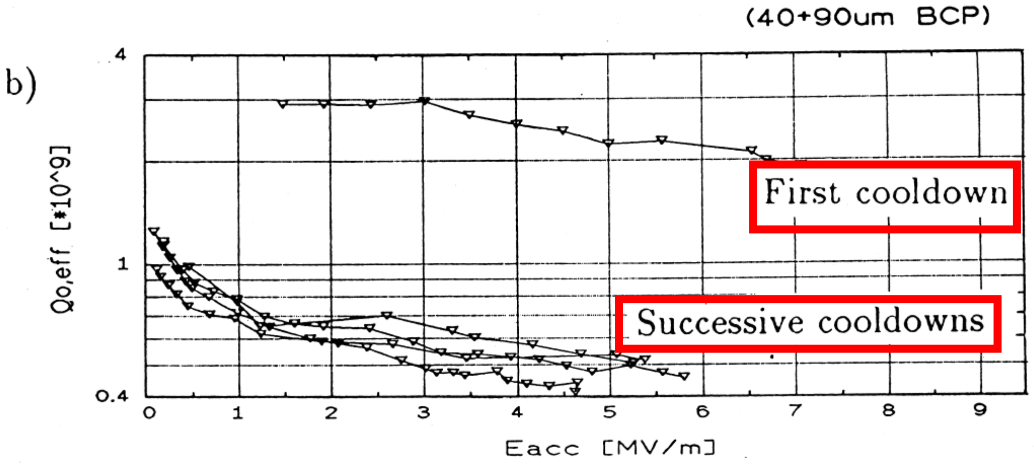


HERA cavities and cryomodule (in 1991 at DESY)

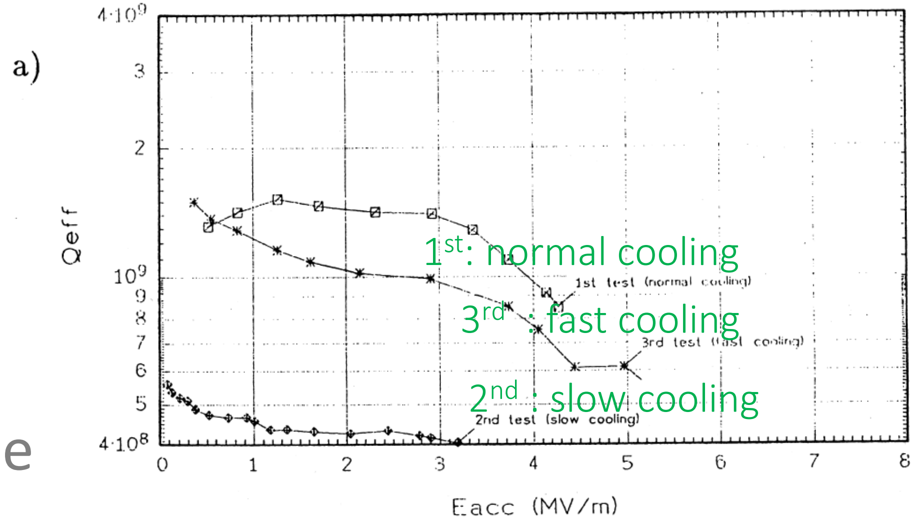
Heat capacity in the cryomodule is large, so that the fast cooling like vertical tests is very difficult.
Therefore, hydrogen Q-disease was observed in this condition.

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

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

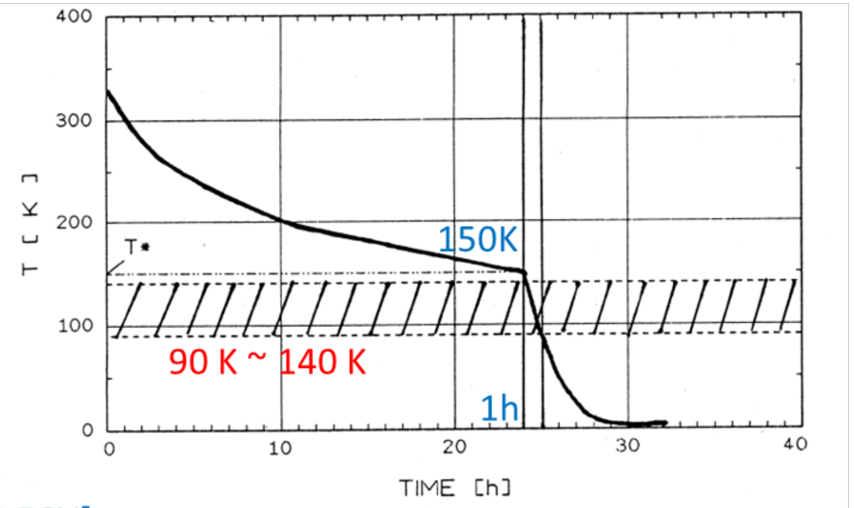


[SRF’91 at DESY]



Performance limitation : Hydrogen Q-disease

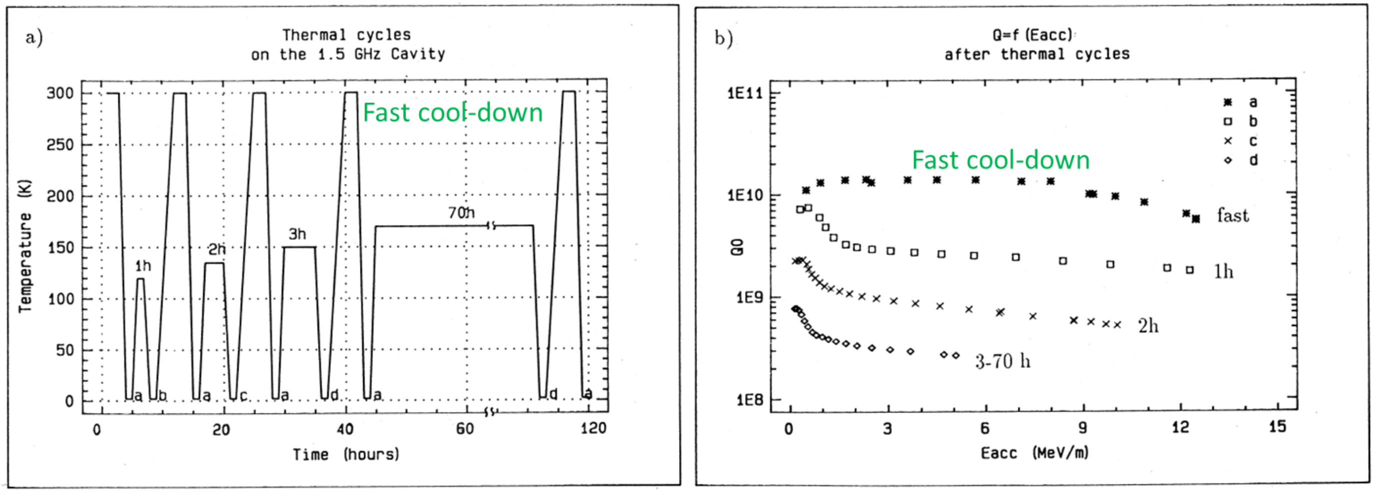
Cool-down condition in Cryomodule



[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

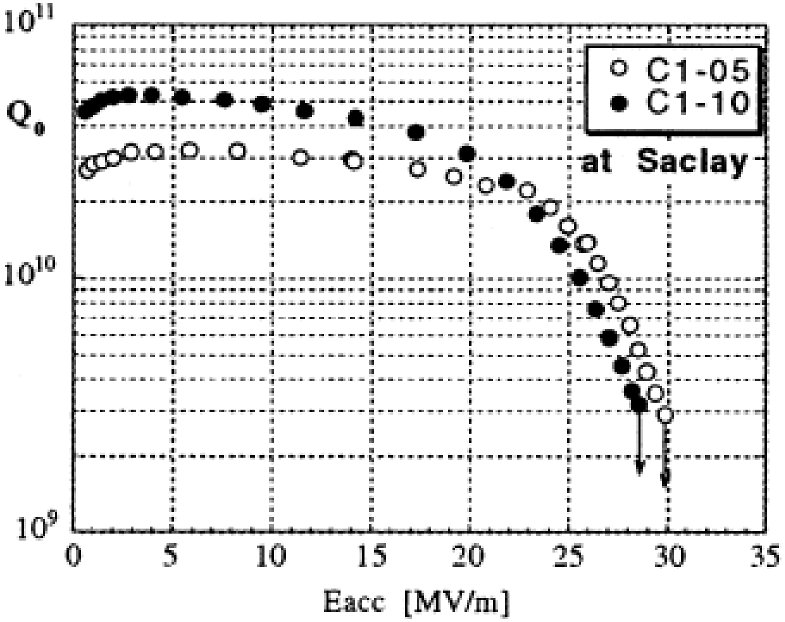
Experimental results on Q-disease at CEA-Saclay :

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

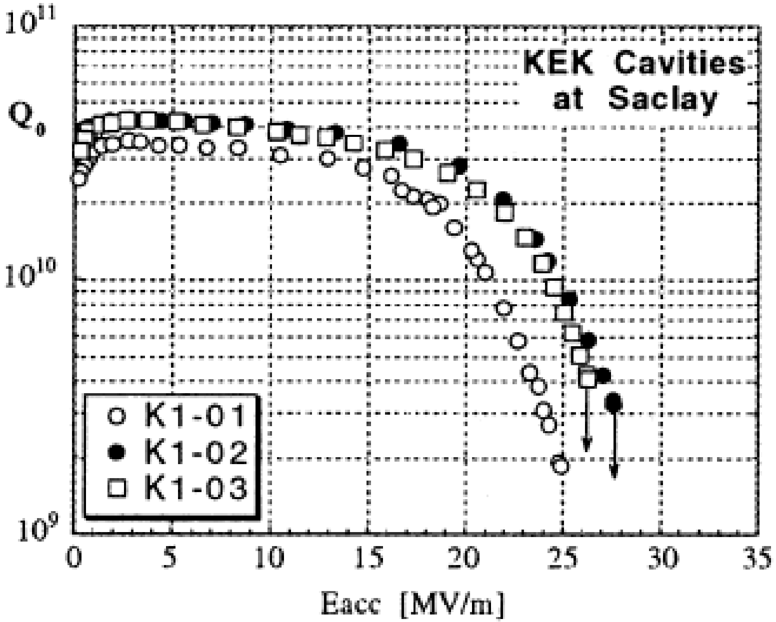
Hydrogen dissolved in a bulk niobium is precipitated on the surface layer and formed niobium-hydride composition.

Performance limitation : High field Q-slope

2 Saclay cavities tested at Saclay



3 KEK cavities tested at Saclay



[by E. Kako : SRF'97]

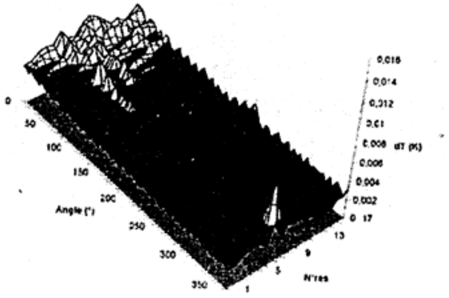


図5．C1-10空洞の表面温度分布(Eacc=29MV/m)

Q- Slope without x-ray

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

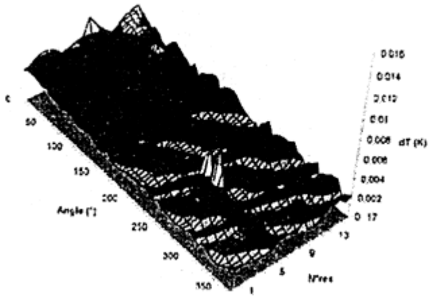
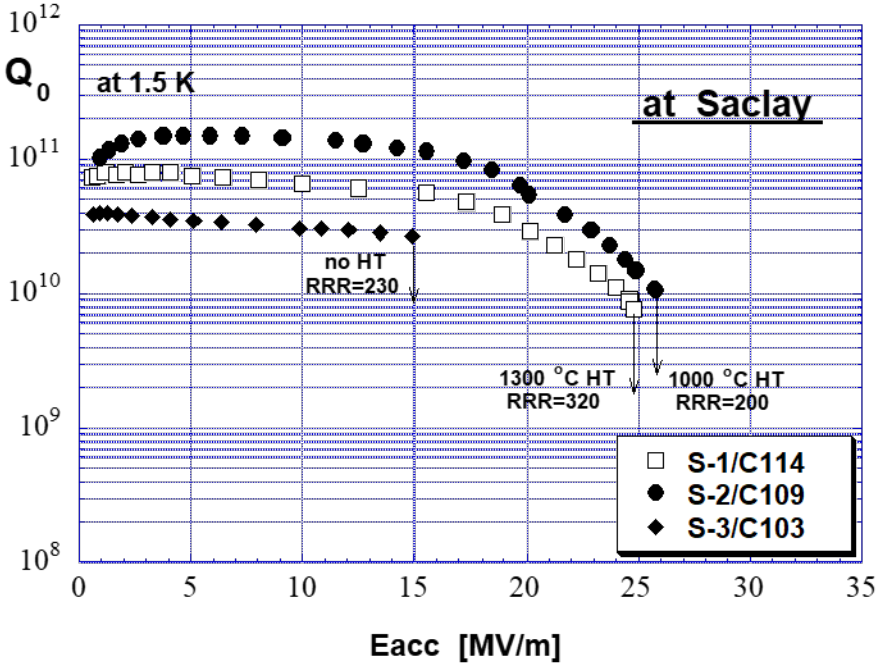


図6．K1-02空洞の表面温度分布(Eacc=28MV/m)

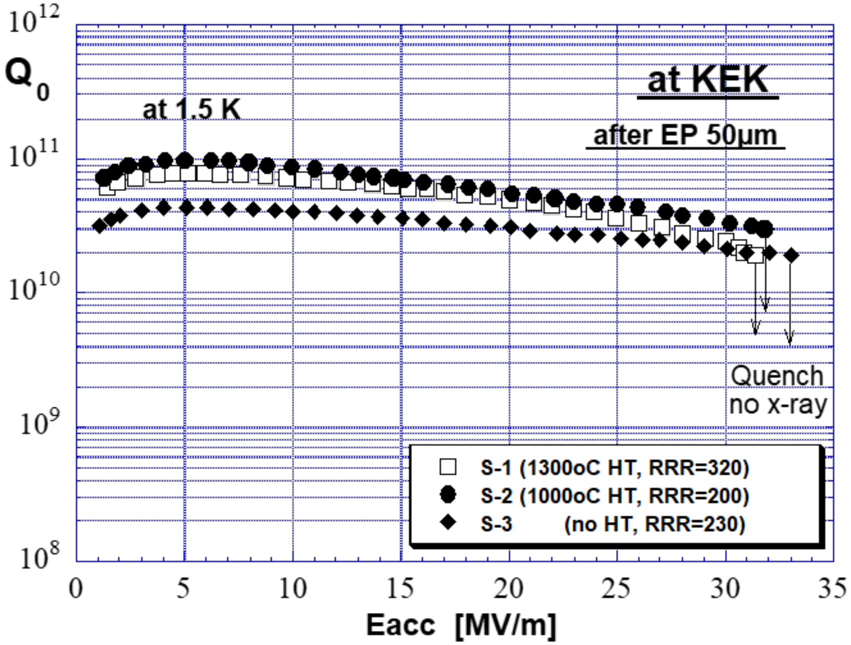
Performance limitation : High field Q-slope

Study on 1-cell cavities at KEK

Improvement of cavity performance by EP



CP cavity @ Saclay



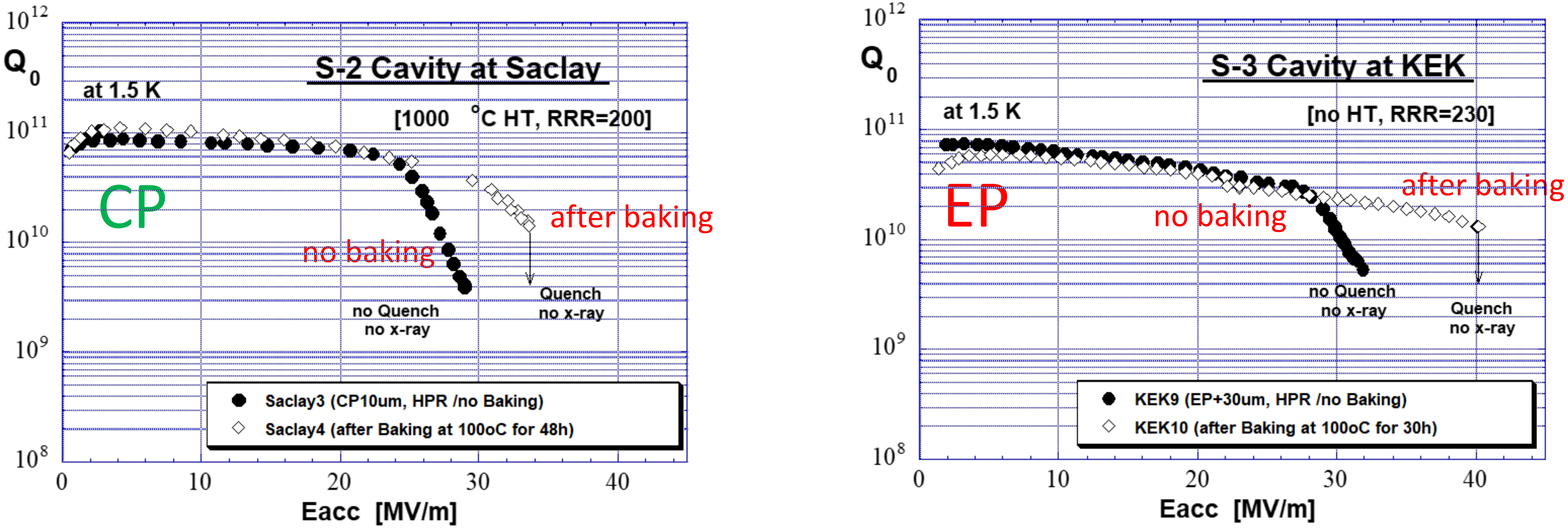
After EP @ KEK

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

Performance limitation : 120 oC Baking

Study on 1-cell cavities at KEK

Effectiveness of baking at 120°C



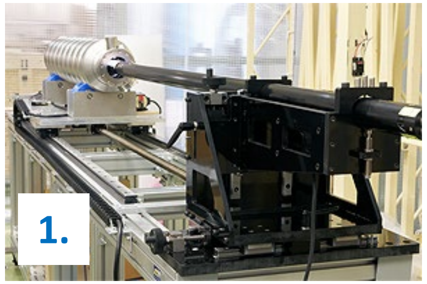
CP cavity + Natural Drying @ Saclay EP cavity + Pumping & Baking @ KEK

EP+120°C 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.)

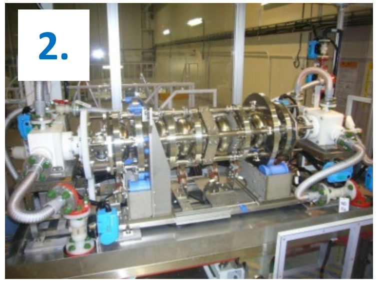
Current Surface Preparation Techniques

1.



Inspection of inner surface

2.

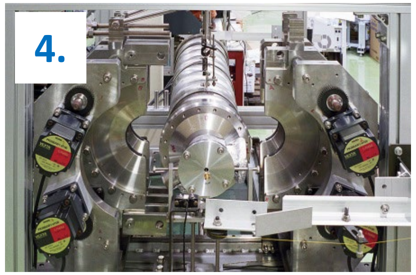


Pre-EP + EP-I (5+100 μm)

3.

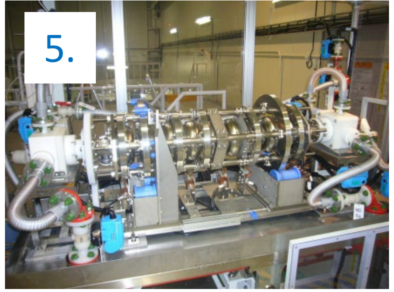
Anneal (750°C, 3h)

4.



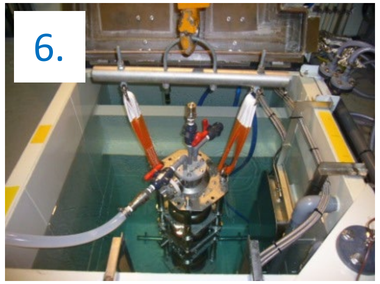
Pre-tuning (flatness, f_0)

5.



EP-II
(5~20 μm)

6.



Hot bath rinsing with ultra-sonic

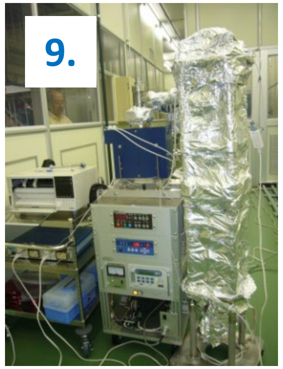
7.

HPR

8.

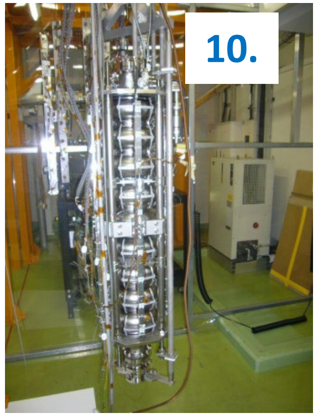
Assembly (Class 10)

9.



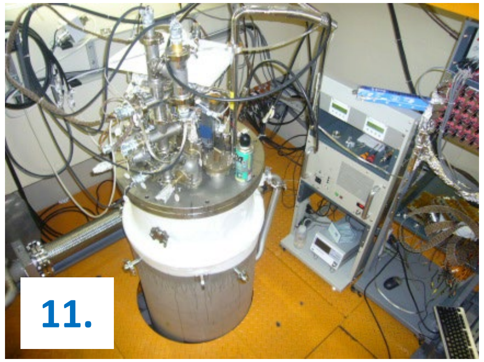
Baking (120°C, 48h)
(Class 1000)

10.



Hanging stand with T-map

11.



Vertical Test

Question (5)

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

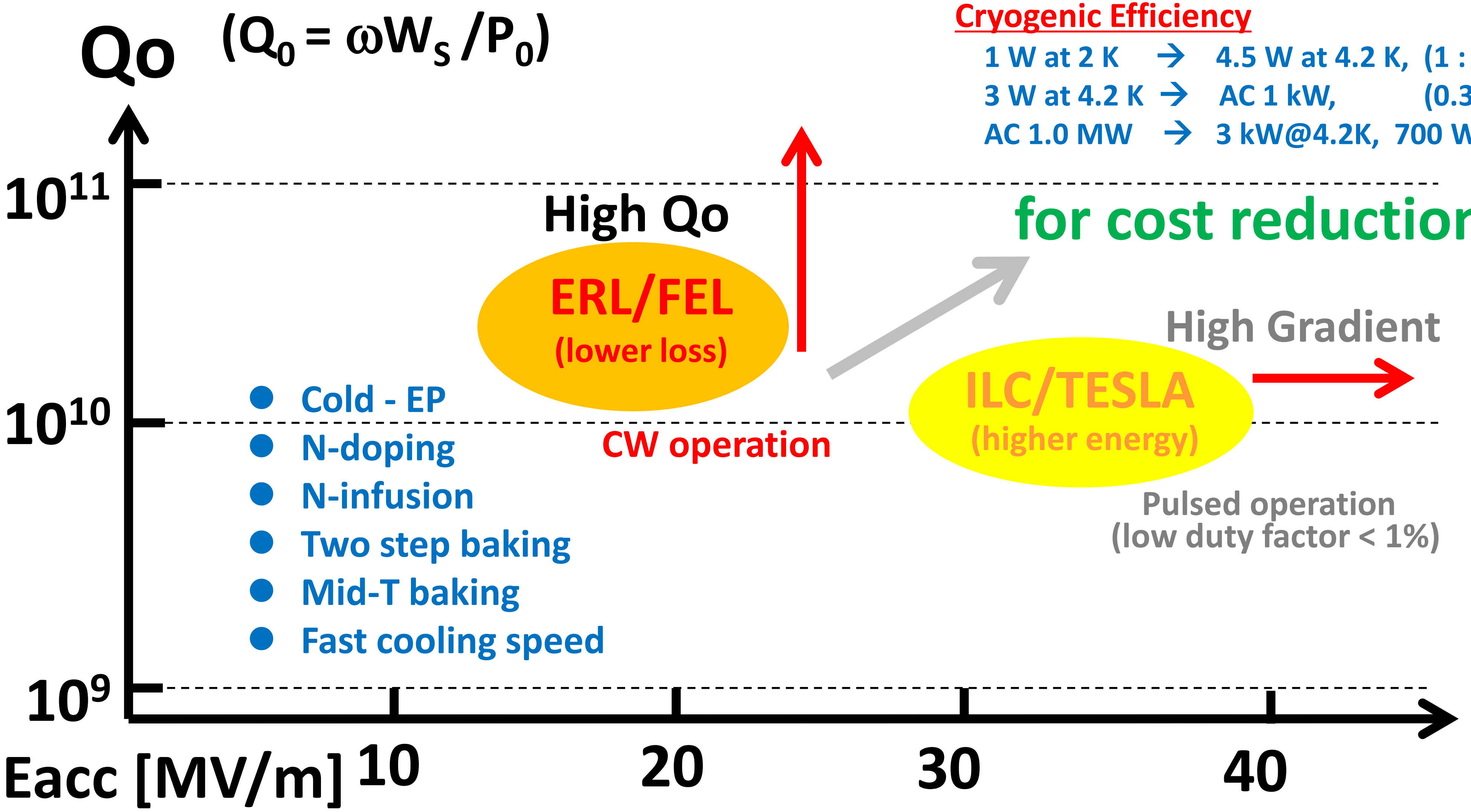
Superconducting RF (SRF) Cavity

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

Toward higher Qo and higher Eacc



$(Q_0 = \omega W_S / P_0)$

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

High Qo

ERL/FEL
(lower loss)

CW operation

for cost reduction

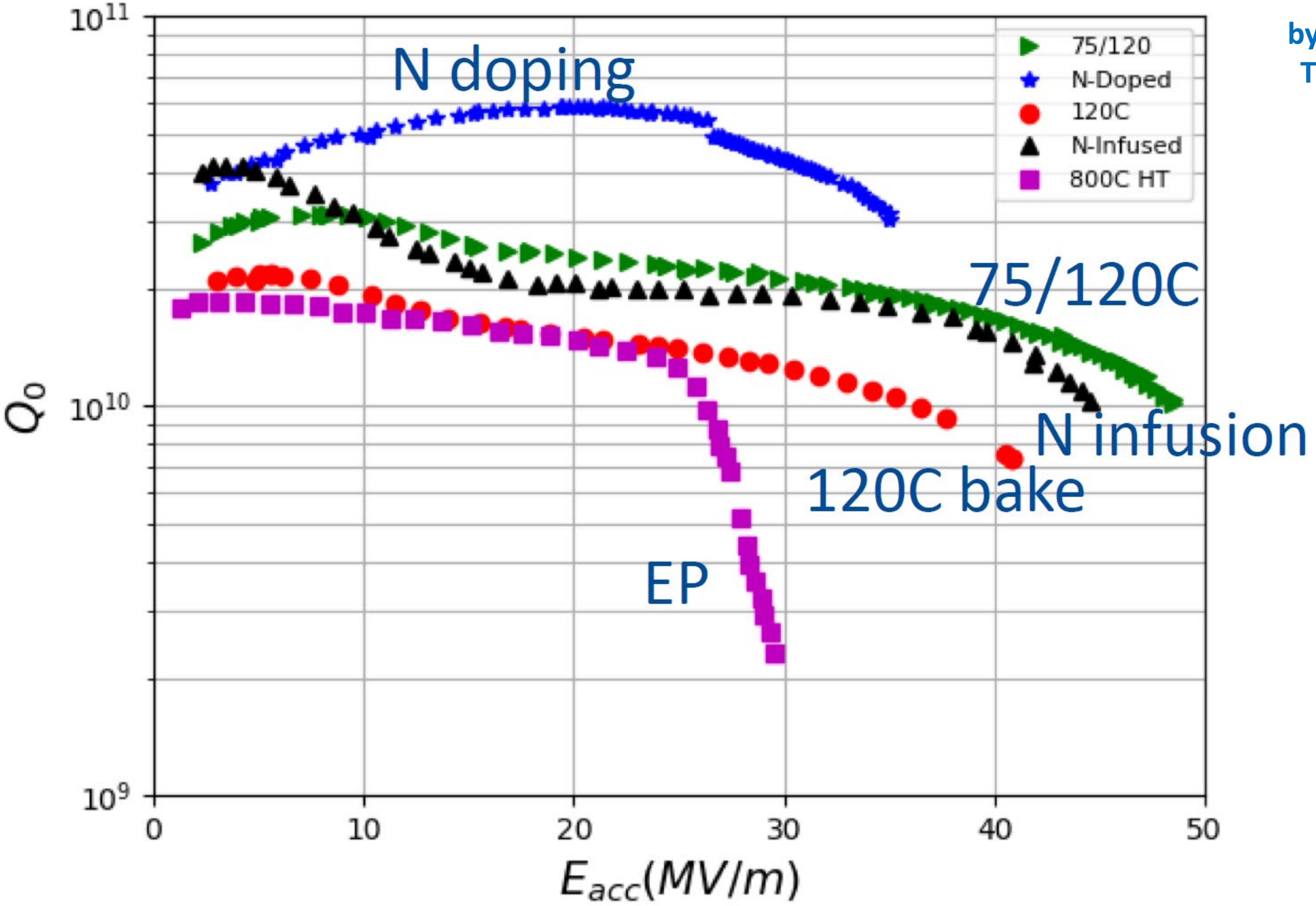
High Gradient

ILC/TESLA
(higher energy)

Pulsed operation
(low duty factor < 1%)

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

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



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

Recent developments toward higher performance

1. Reliable operation at higher gradient (High-G)
   - Improvement of clean environment to suppress field emission:
     a. Development of slow pumping/venting system
     b. Development of local clean booth
   - Performance recovery of degraded cavity:
     a. Surface cleaning by He-processing at low temperature
     b. Surface cleaning by plasma processing using glow discharge
     c. High power pulsed RF conditioning
2. High-Q technology for reducing cryogenic losses
   - Nitrogen doping at 800 ^{o}C + EP
   - Nitrogen infusion at 800+120 ^{o}C + (no EP)
   - Development of lower residual magnetic field components
3. Possible operation at 4.2K
   - Nb_3Sn thin film on Nb cavity with higher Tc and higher Hc

Outline of the Lecture

1. Introduction
2. Fundamental of SRF Cavity
3. Overview of SRF Cavity System
4. Fabrication and Surface Preparation
5. Cavity Performances
6. Summary

Summary

- Fundamental knowledge of RF electromagnetic fields in the SRF cavities is absolutely important in the first step of R&D in SRF technologies.
- Essential surface preparations including EP, 800°C HT, HPR, 120°C baking and clean assembly was confirmed in many 1.3 GHz 1-cell/9-cell cavities.
- High power input couplers and HOM couplers/absorbers are one of the most critical components of an SRF cavity system and include varieties of key technologies in design, fabrication, conditioning and operation.
- International collaboration is essentially important for R&D of superconducting cavities.

Thank you for your attention.

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

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email: eiji.kako@kek.jp

Thank you!

Questions !

Superconducting RF (SRF) Cavity

Superconducting RF (SRF) Cavity