Introduction of Superconducting RF Cavity

(1)

Fundamental of SRF Cavity System

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)

1. Fundamental of SRF Cavity System

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

Introduction of Lecturer

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A Korean-Language Textbook

과학기술정보통신부 가속기인력양성사업

2026 가속기 여름학교

(가속기 및 빔라인 미래인재 양성 교육단)

■ 목표

방사광 가속기 및 중이온 가속기 분야의 우수 인력 양성을 위해, 대학원생들이 관련 분야를 이해하고 그에 수반한 전망을 직접 체험할 수 있도록 하여 미래를 선도할 가속기 인재 발굴 및 교육 기반 조성

■ 가속기 여름학교 일정 [7월 6일(월) ~ 7월 10일(금)]

시간	7/6 (월) 좌장 : 박종식	7/7 (화) 좌장 : 이수형	7/8 (수) 좌장 : 이유미	7/9 (목) 좌장 : 고병륵	7/10 (금) 좌장 : 고병륵
09:30 ~ 10:40	등록 및 개회 12:30 ~ 13:30	Fundamental of SRF Cavity System (Eiji Kako, KEK)	IRIS Beam Dynamics 1 (전동오, IBS)	IRIS Overall (정연세, IBS)	Heavy-Ion Therapy (곽정원, 아산병원)
10:50 ~ 12:00		Recent Progress on SRF Cavity Performance (Eiji Kako, KEK)	IRIS Beam Dynamics 2 (전동오, IBS)	IRIS SRF Cavities (윤준영, IBS)	Beam Position Monitors (이수형, 고려대 세종)
13:30 ~ 14:40	포항 가속기 현황 (김창범, PAL)	ECR Ion Source (이병섭, KBSI)	4GSR Beam Dynamics 1 (김재현, PAL)	IRIS Cryogenics (신재희, IBS)	-
14:50 ~ 16:00	경주 양성자 가속기 현황 (권혁중, KAERI)	Proton Therapy (이세병, 국립암센터)	4GSR Beam Dynamics 2 (김재현, PAL)	IRIS RF other than SRF Cavities (설경태, IBS)	-
16:10 ~ 17:20	오창 방사광 가속기 현황 (전철호, KBSI)	Manufacturing SRF Cavity and Cryomodule (한준호, KAT)	입자가속기와 과학기술의 발전 (박향규, 고려대 세종)	IRIS – Beam Diagnostics (권장원, IBS)	-

장 소 고려대학교 세종캠퍼스, 과학기술 제1관 234호

주 관 고려대학교 세종캠퍼스 가속기과학과 및 가속기연구센터

공동주최 고려대학교 세종캠퍼스 KOREA UNIVERSITY SEJONG CAMPUS, POSTECH POHANG UNIVERSITY OF SCIENCE AND TECHNOLOGY, UST 과학기술연합대학원대학교 UNIVERSITY OF SCIENCE & TECHNOLOGY, 청주대학교, 충북대학교, 부산대학교 PUSAN NATIONAL UNIVERSITY, 성균관대학교, 연세대학교 YONSEI UNIVERSITY, 울산과학기술원 ULSAN NATIONAL INSTITUTE OF SCIENCE AND TECHNOLOGY, 조선대학교 CHOSUN UNIVERSITY, KAIST 한국과학기술원 Korea Advanced Institute of Science and Technology, 한양대학교 HANYANG UNIVERSITY, 광주과학기술원, 고려대학교 KOREA UNIVERSITY, 서강대학교 SOGANG UNIVERSITY, 동국대학교 dongguk university, 서울대학교, KNU 강원대학교

후 원 NRF 한국연구재단, 과학기술정보통신부 Ministry of Science and ICT

등록비 무료, 중식 제공 참여학생 기숙사1인 1실 (신청요) 홈페이지 – QR Code참조

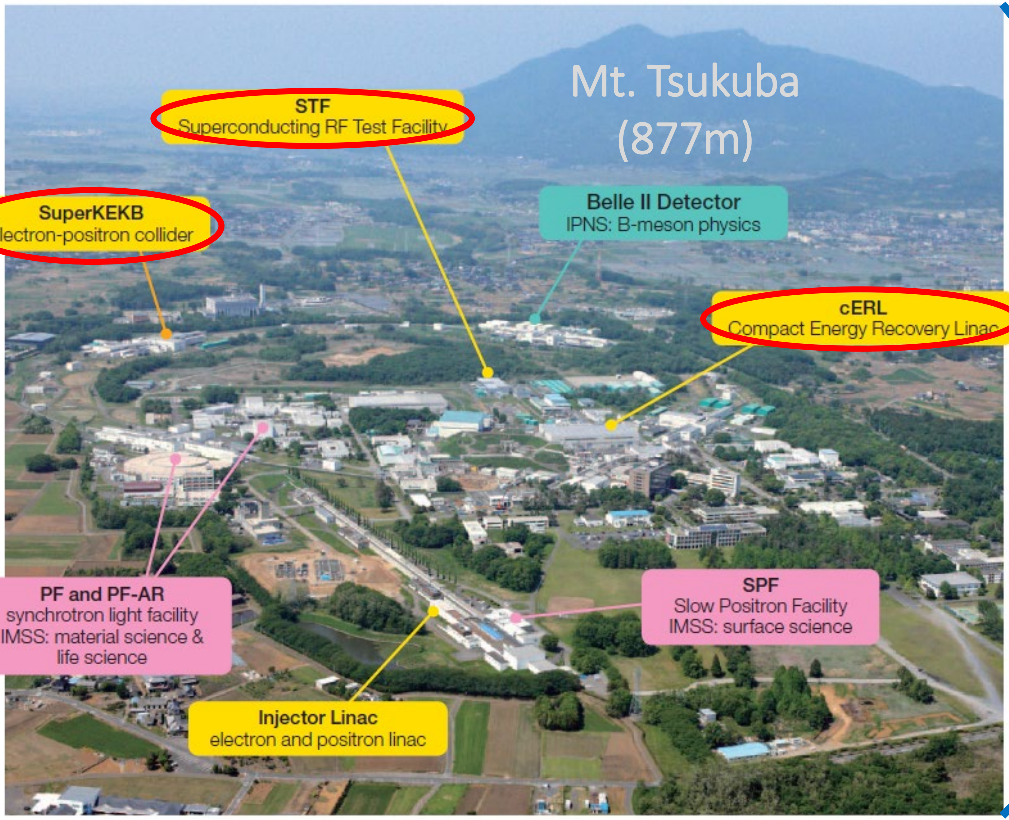
- Original Author:
  Prof. Eiji Kako (KEK)
- Translator:
  Prof. Eun-San Kim
  (Korea University)

Price: 25,000 KRW (Won)

Introduction of KEK

High Energy Accelerator Research Organization

KEK



Tsukuba Campus
(Electron Accelerator)

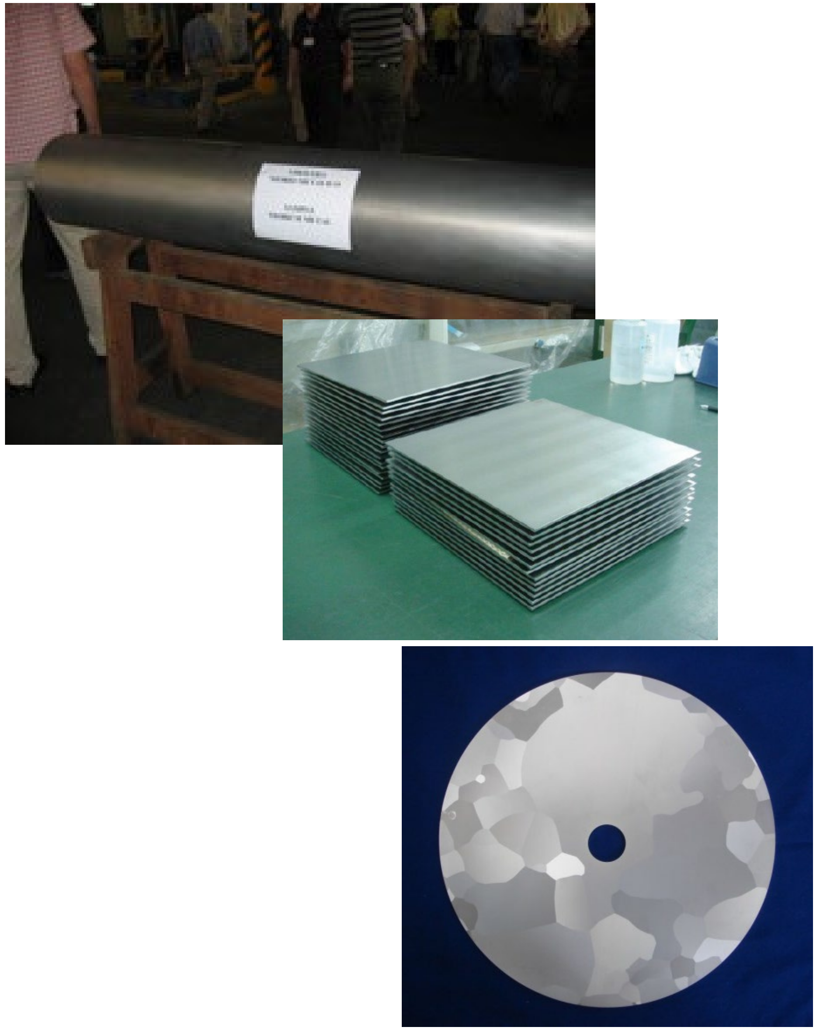
J-PARC

Tokai Campus
(Proton Accelerator)

Introduction of Superconducting Cavity

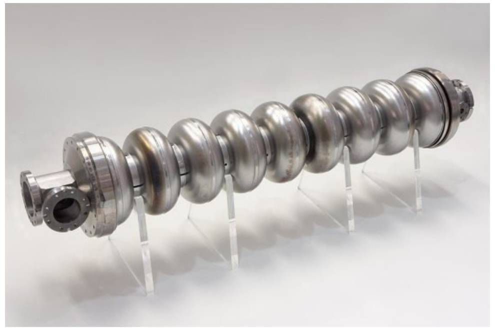
My experience on SRF Cavity for 39 years.

Superconducting RF (SRF) Cavity

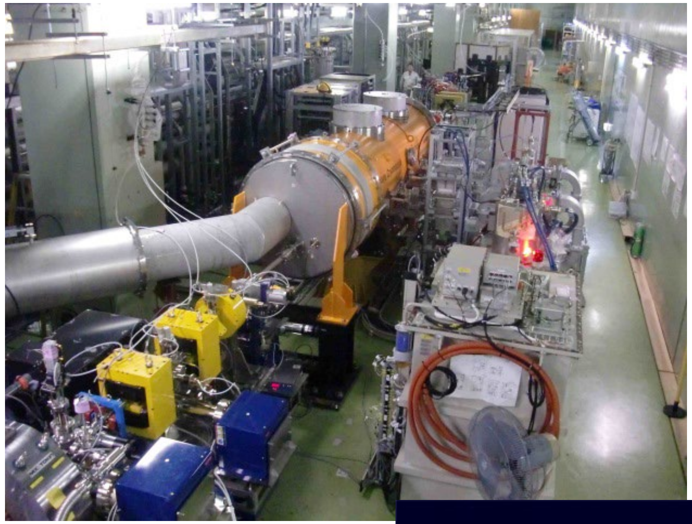


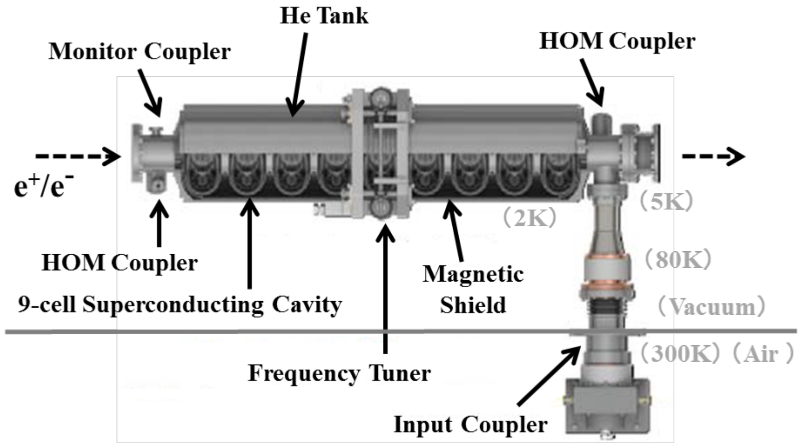
Niobium Material

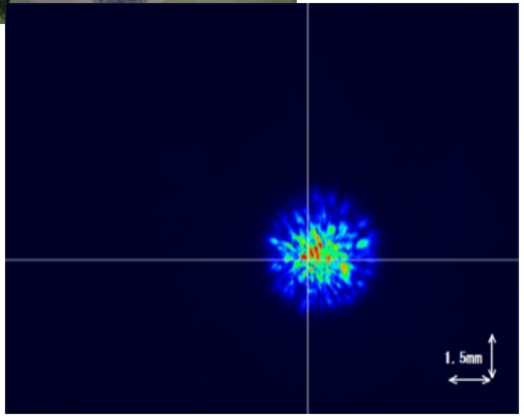
Cavity



Cryomodule







Stable Beam Operation

Superconducting RF (SRF) Cavity

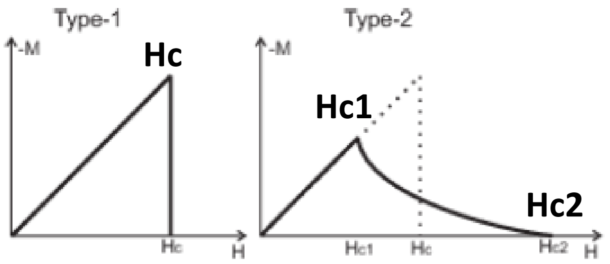
Superconducting RF cavity system

- Superconductivity and material science
- Ultra-high vacuum & clean technology
- RF technology
- Cryogenic technology

Typical Properties of Superconductor

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

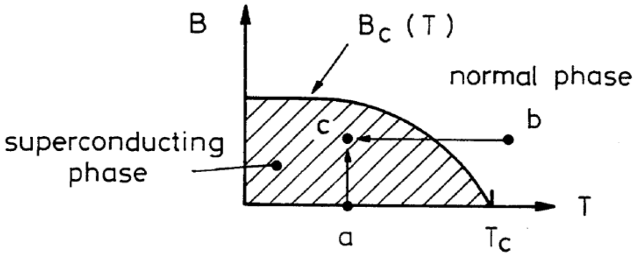
Type-1, Type-2 Superconductor



Pb

Nb, Nb3Sn

Phase diagram

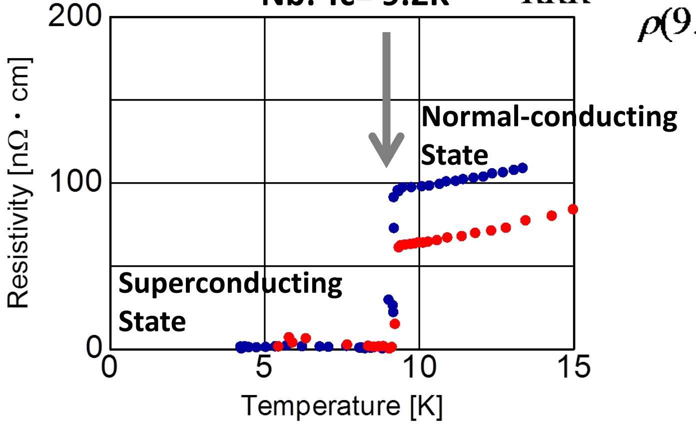


$H_{c1}(T) = H_{c1}(0) \times (1-(T/T_c)^2)$

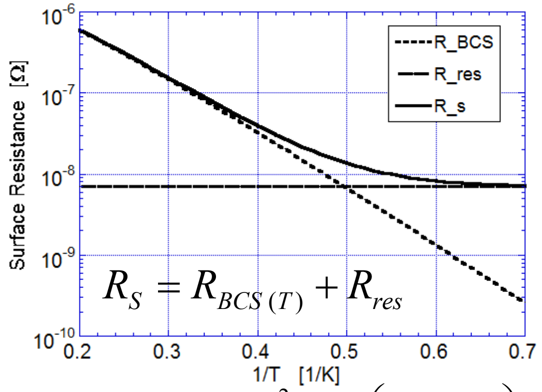
T < Tc/2

DC Resistivity

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



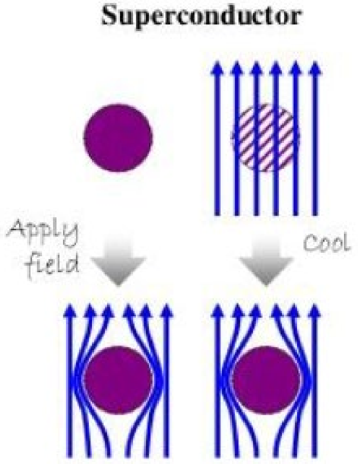
RF Surface Resistance



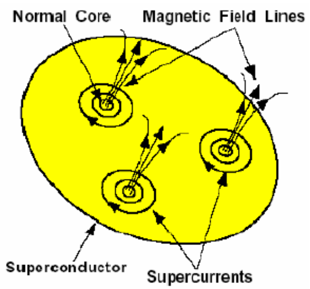
$$R_S = R_{BCS\,(T)} + R_{res}$$

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

Meissner effect



Flux trapping



R_{res} = 0.3~0.4 [nΩ /mG]

Critical Temperatures of Superconductors

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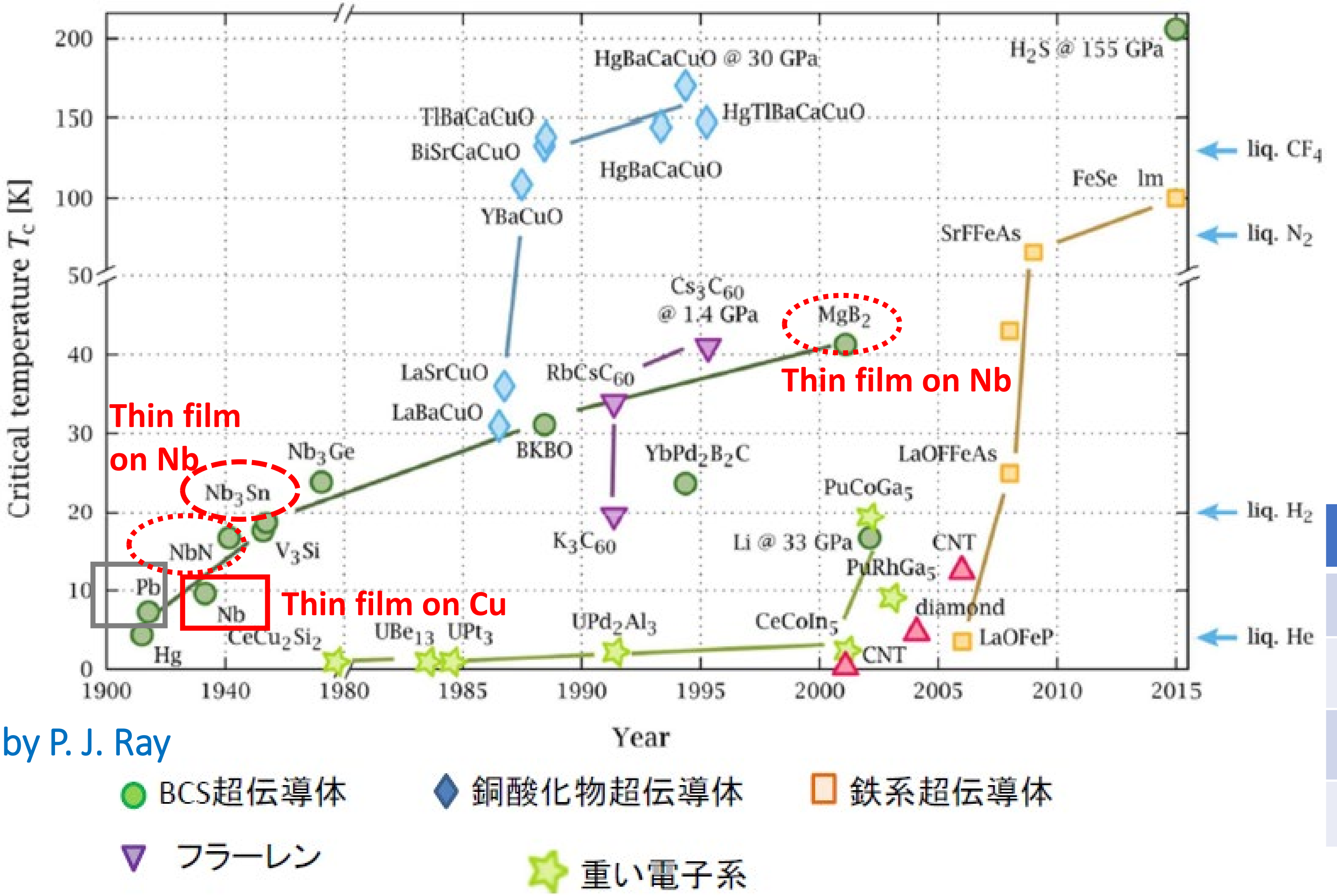

by P. J. Ray

	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_3Sn	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

$1 \text{ Joule} = 1 \text{ Nm} = 1 \text{ kgm}^2/\text{sec}^2$

$1 \text{ eV} = 1.6 \times 10^{-19} \text{ Joule}$

$c = 2.9979 \times 10^{8} \text{ m/sec}$

$m_e = 0.9109 \times 10^{-27}$ g ; mass of electron

$m_p = 1.6925 \times 10^{-24}$ g ; mass of proton

Rest Energy

$E_e = m_e c^2 = 0.511 \text{ MeV}$

$E_p = m_p c^2 = 938 \text{ MeV}$

Kinetic Energy of Particles

Rest Energy

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

$$(v > 0) \quad \boxed{E = \frac{m_0 c^2}{\sqrt{1-(v/c)^2}} = \frac{m_0 c^2}{\sqrt{1-\beta^2}} = m_0 \gamma c^2}$$

Kinetic Energy

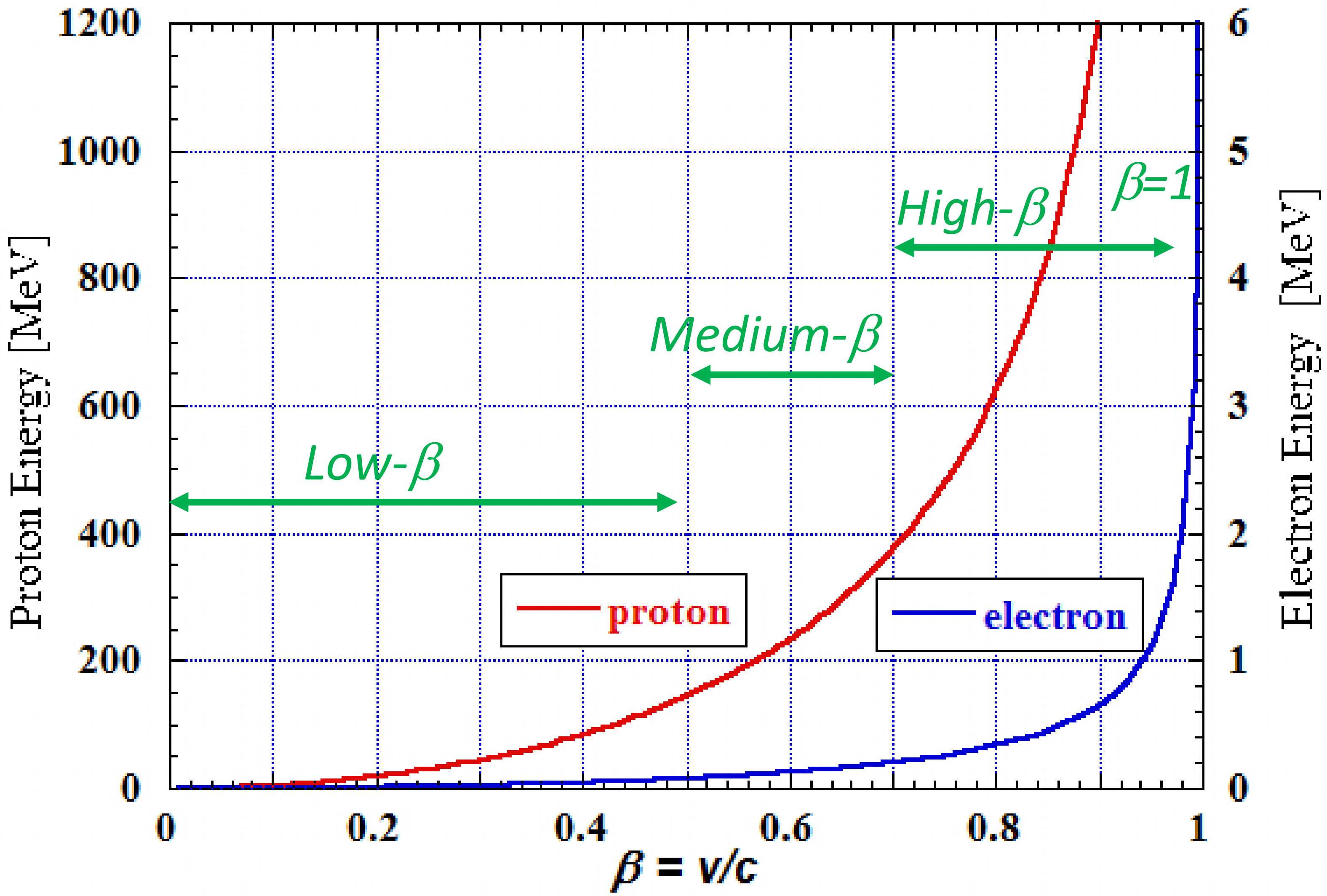
$$E_K = m_0 \gamma c^2 - m_0 c^2 = m_0 c^2 (\gamma - 1)$$

$$\gamma = 1 \Big/ \sqrt{1-\beta^2}$$

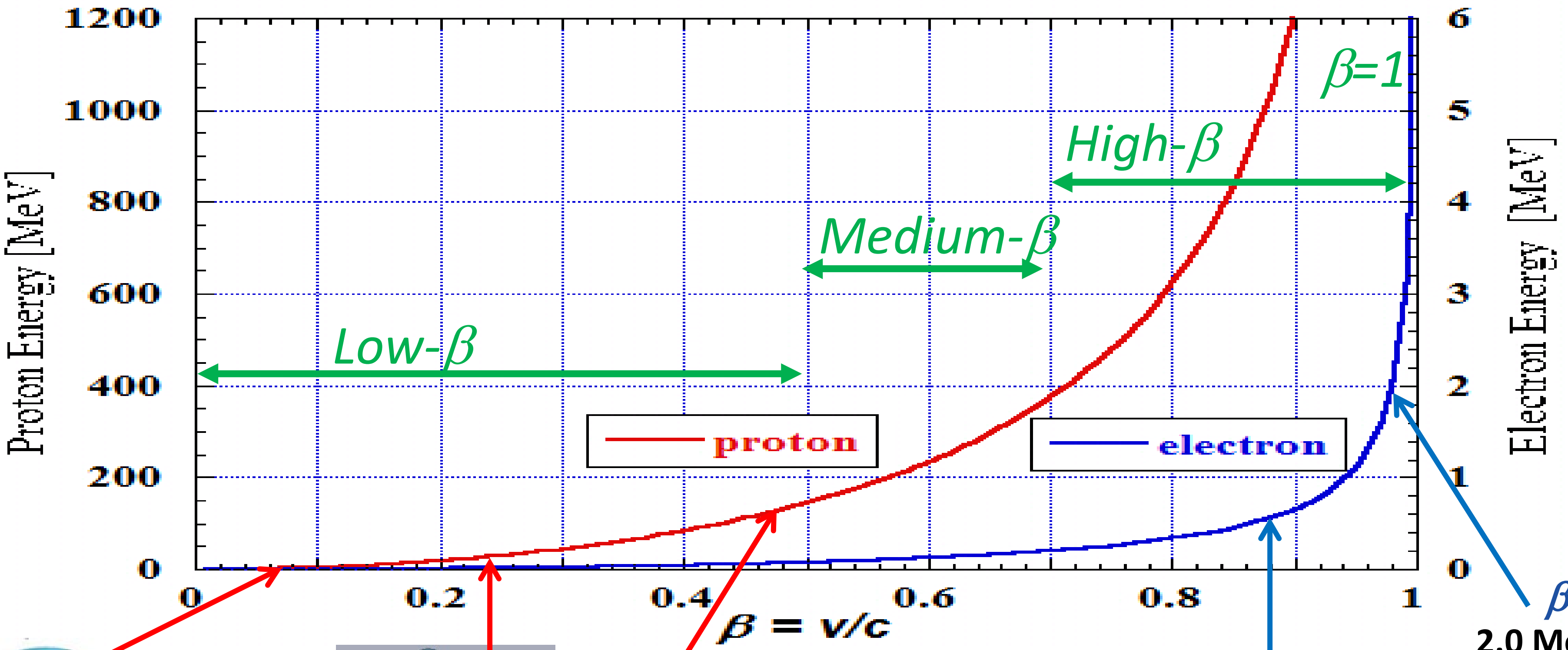
$$\boxed{\beta = v/c}$$

		$\beta \approx 1 \quad (v \approx c)$
$\beta < 0.5 \quad (v << c)$	$\beta \approx 0.5 \sim 0.7$	$\beta > 0.7$
Low-β	*Medium-β*	*High-β*

Kinetic Energy of Protons and Electrons



Accelerating Structures for Proton and Electrons



***β* = 0.07**

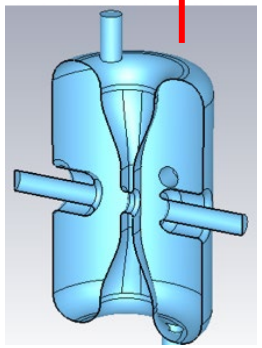
QWR:

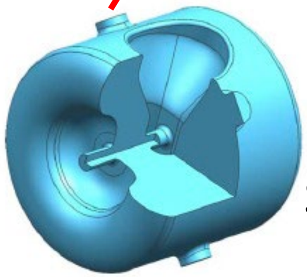
Quarter-wave Resonator

***β* = 0.24**

HWR:

Half-wave Resonator





***β* = 0.47**

SSR:

Single-Spoke Resonator

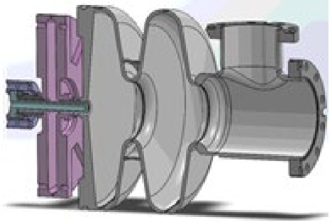
***β* = 0.88**

500 keV CW e-beam

500 kV DC-Gun

***β* = 0.98**

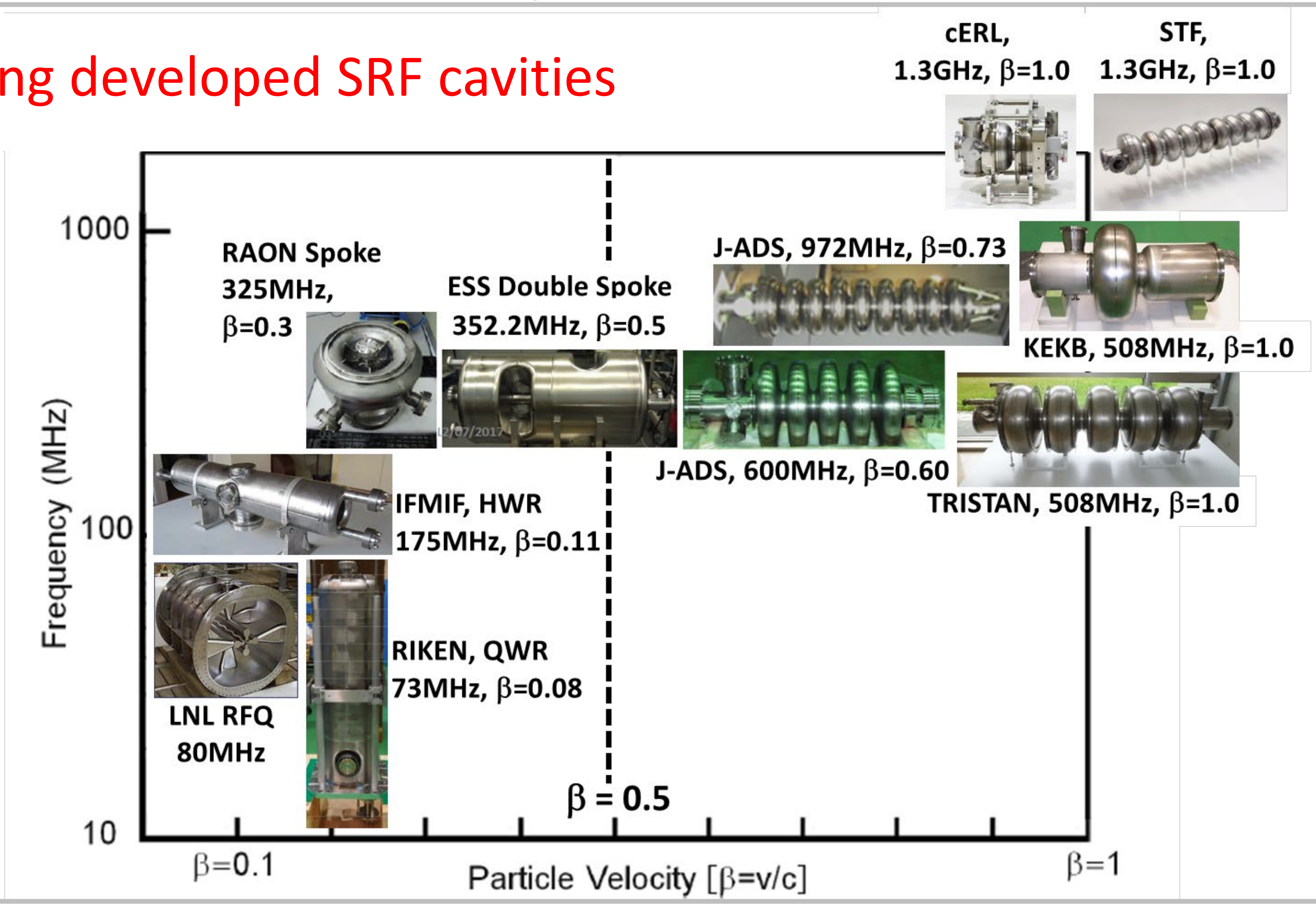
2.0 MeV CW e-beam



1.3 GHz, 1.5-cell SRF-Gun Cavity

Accelerating Structures for Proton/Ions and Electrons

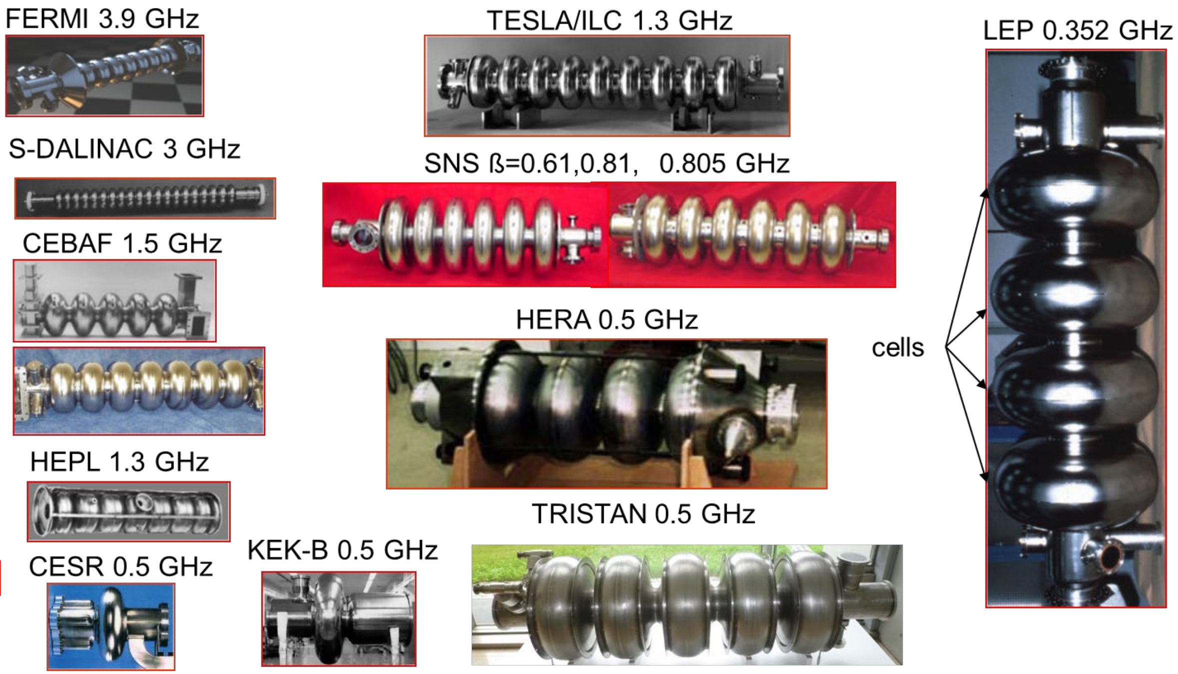
Existing developed SRF cavities



(IHEP : CEPC)

SRF Cavity Production in Worldwide Projects

Elliptical multi-cell cavities



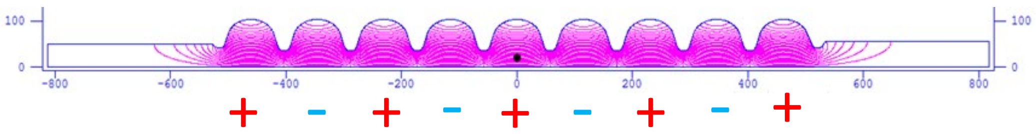
Half Wave Resonators (HWR)

Spoke cavities

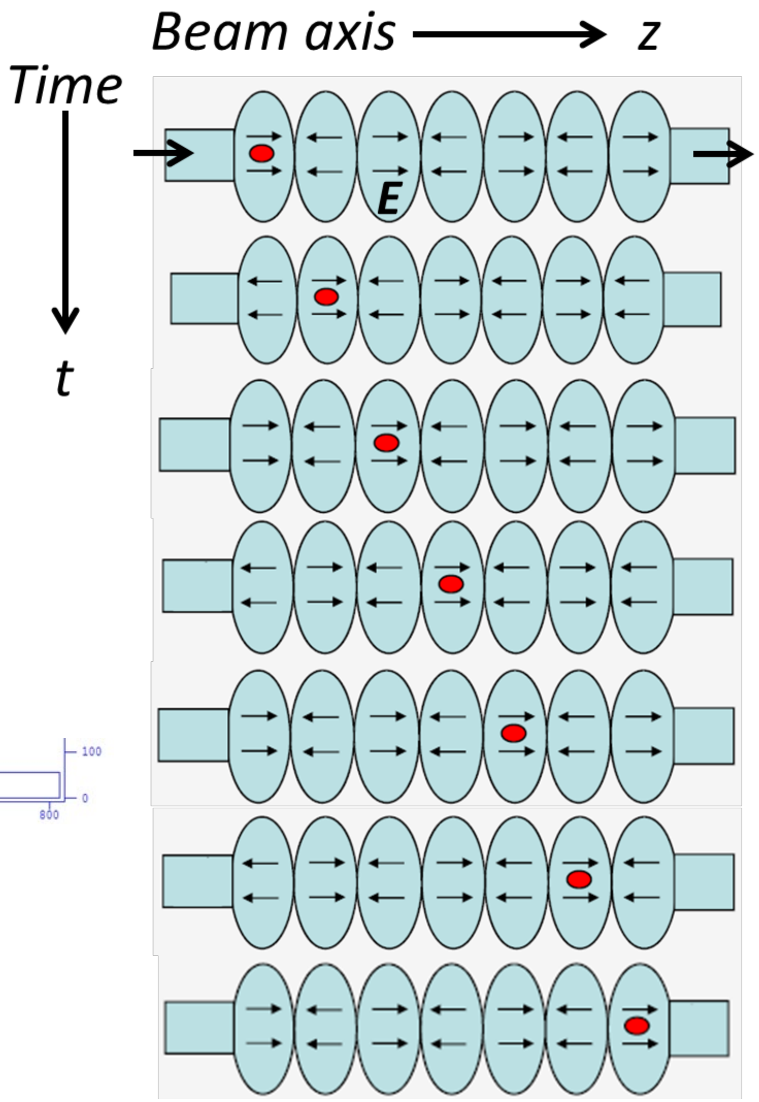
Quarter Wave Resonators (QWR)

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:

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

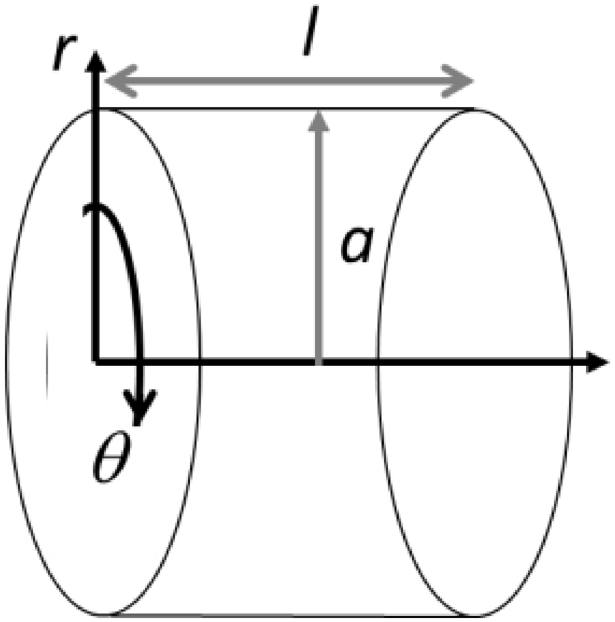
$$\nabla^2 \vec{E} + k^2 \vec{E} = 0$$

- 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.



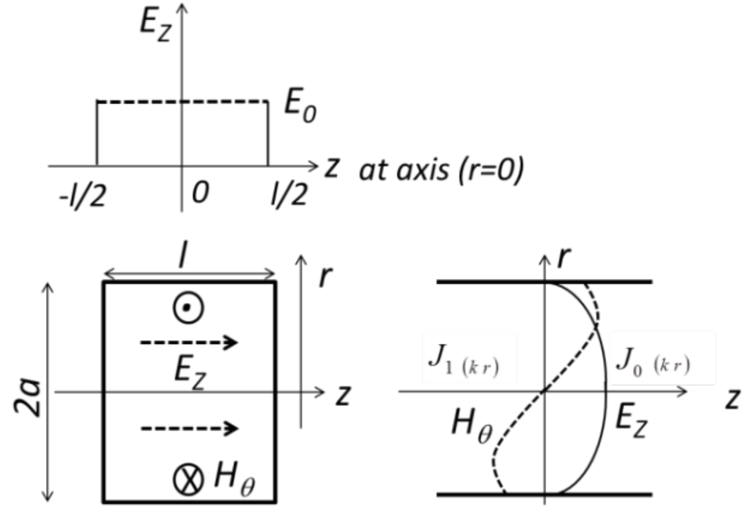
A pill-box cavity, (circular cylindrical resonator): The symbol *a* and *l* represents the radius and the cavity length of the pill-box cavity, respectively.

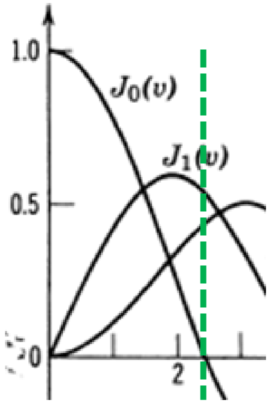
- Resonant frequency: f_0
- Stored energy: W_S
- RF loss (dissipation power): P_d
- RF surface resistance: R_S
- Quality factor: Q
- Geometrical factor: G
- Transit-time factor: T
- Accelerating gradient: E_{acc}
- Shunt impedance: R_{sh}
- R over Q: R/Q
- Energy gain

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:

$$H_z = 0, \quad E_r = 0, \quad H_r = 0, \quad E_\theta = 0.$$





2.405

Bessel functions

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

$$E_{z(r)} = E_0 \, J_{0\,(kr)} \cos \omega t$$

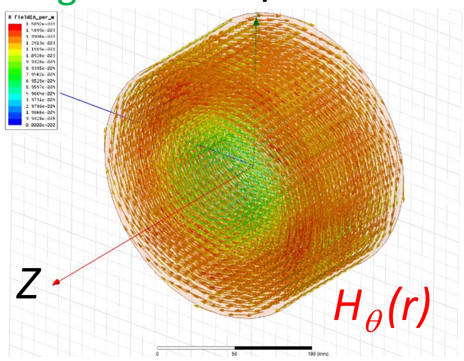
$$H_{\theta(r)} = -\left(\frac{E_0}{Z_0}\right) J_{1\,(kr)} \sin \omega t$$

where the following relation holds:

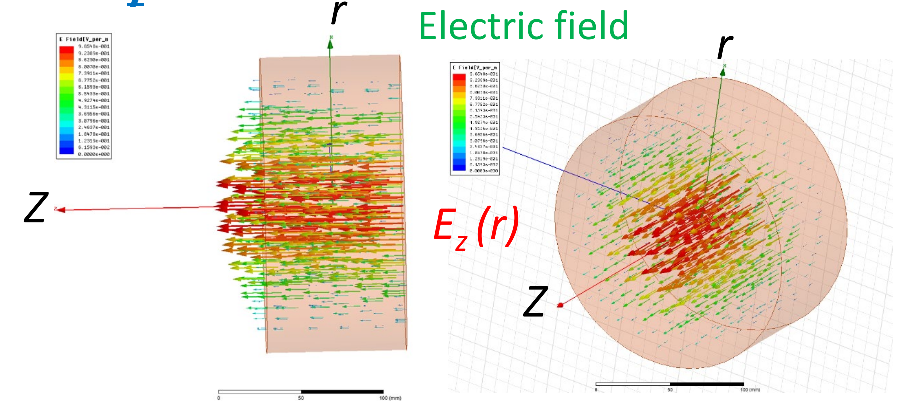
$$Z_0 = E_0/H_0 = (\mu_0/\varepsilon_0)^{0.5} = 120\,\pi = 377\,\Omega\,.$$

Accelerating mode (TM_{010} mode)

Magnetic field



Electric field



Summary of Main RF Parameters (1)

The essential RF parameters can be summarized as follows:

- Electric RF field ***E*** [V/m]: $\vec{E}\exp(j\omega t)$

- 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]:

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

- 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_S [J]:

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

- 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_{sh} [Ω]:

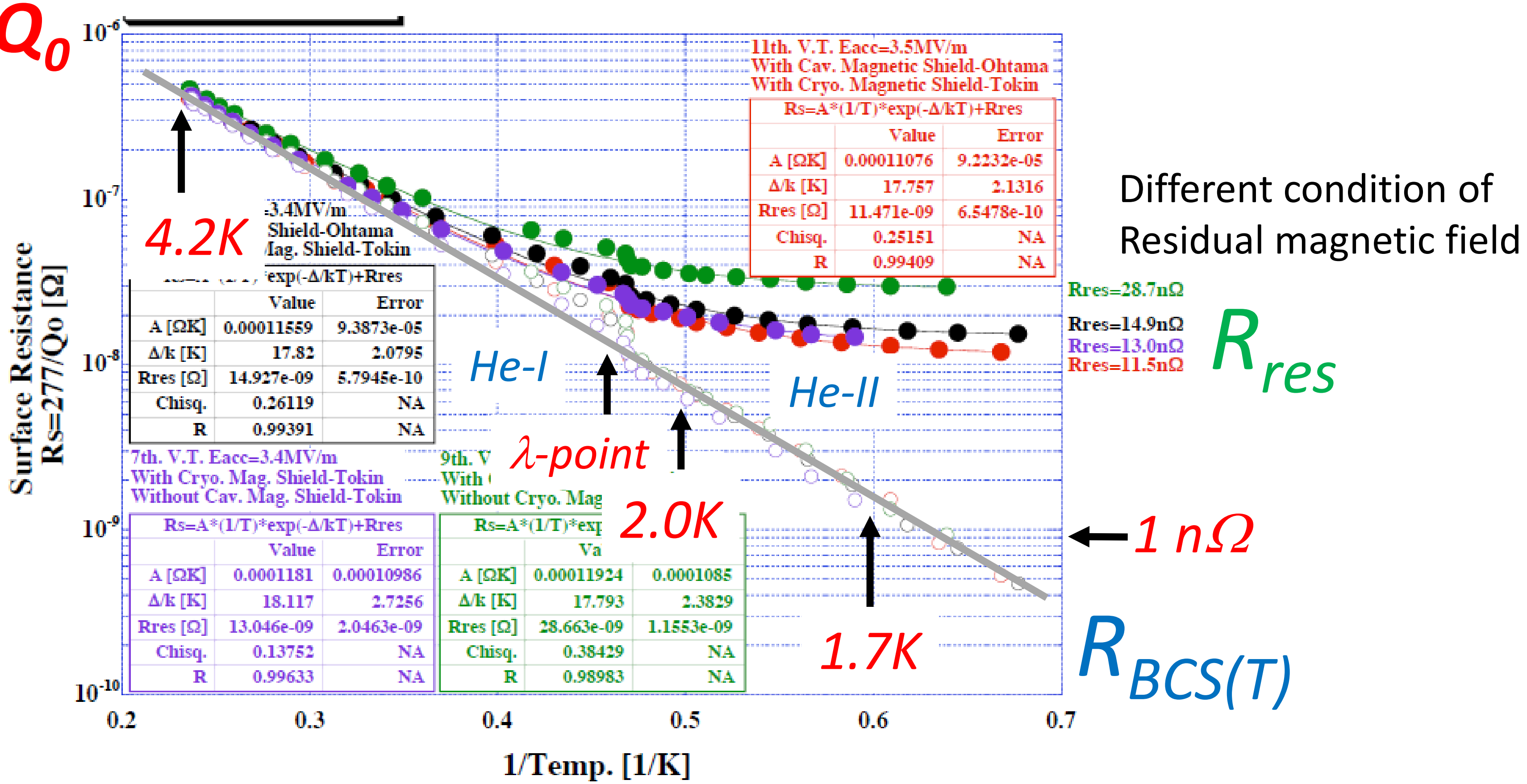
$$R_{sh} = \frac{V_{acc}^2}{P_d} = \frac{E_{acc}^2}{P_d} L_{cavity}^2$$

- 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



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

Surface resistance of RF Cavity: Cu and Nb

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Normal-conducting Cavity ;

- *Surface resistance;* R_S [Ω]

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

f = 1.3 GHz, *G* = 270 Ω

Cu (20^{o}C) ; σ = 0.58 x 10 ^{8} [1/Ω m]

R_S = 9.4 mΩ, (δ = 1.8 μm)

Q = *G* / R_S = 2.9 x 10 ^{4}

Superconducting Cavity ;

- *Surface resistance;* R_S [Ω]

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

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

f = 1.3 GHz, *G* = 270 Ω

Nb (2K) ; R_{BCS} = 7 [nΩ]

R_{res} = 7 [nΩ]

R_S = 14 nΩ, (λ_0 = 44 nm)

Q = *G* / R_S = 1.9 x 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

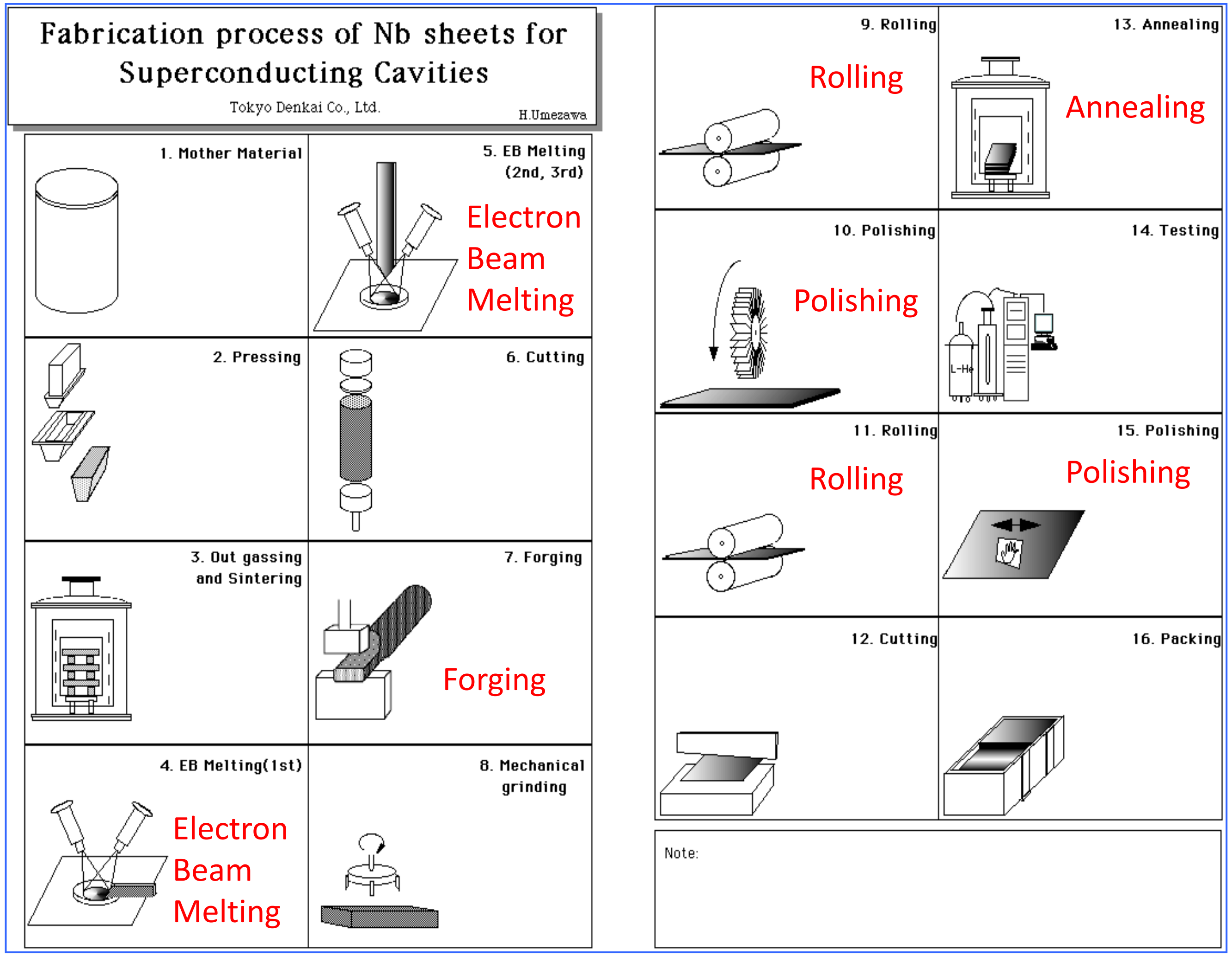
  → higher energy in smaller space
- better efficiency to beam power

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

Fabrication Process of Nb Sheets

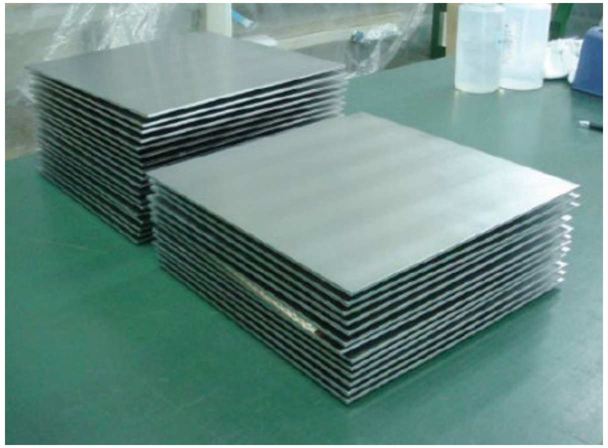
Innovation Center for Applied Superconducting Accelerators
iCASA
応用超伝導加速器イノベーションセンター

Electron Beam Melting



[by H. Umezawa (Tokyo Denkai)]

ULTRA HIGH PURITY RARE METAL
TOKYO DENKAI



Material certification of Nb: (Mill sheet)

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

Customer Messrs.
御納入先 高エネルギー加速器研究機構 殿

MATERIAL TEST RESULTS
試 験 成 績 表

No. 28378

Surveyor
御立会者 殿

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	Article 品名	Quantity 数量
Nb	Disc	pcs or gr
Specification No. 仕様書番号		

Lot No.	Size 寸法 mm	Quantity
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	

Mechanical property

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

Ta W

Chemical Composition

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

O N H C

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

Purity, Thermal property

RRR = 298

Inspection Section Manager

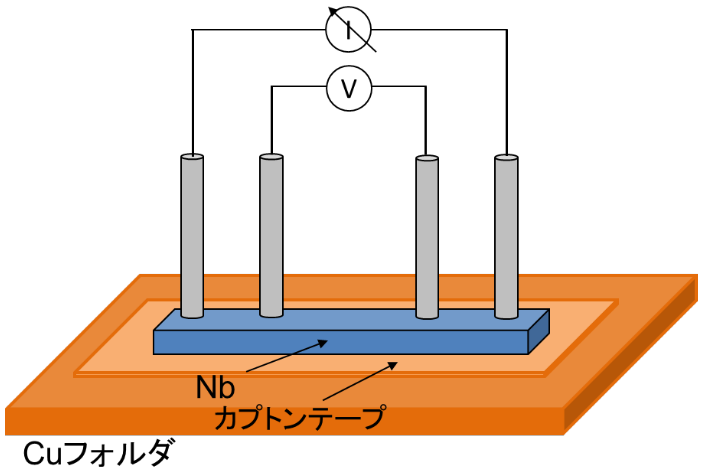
Engineer

ULTRA HIGH PURITY RARE METAL TOKYO DENKAI

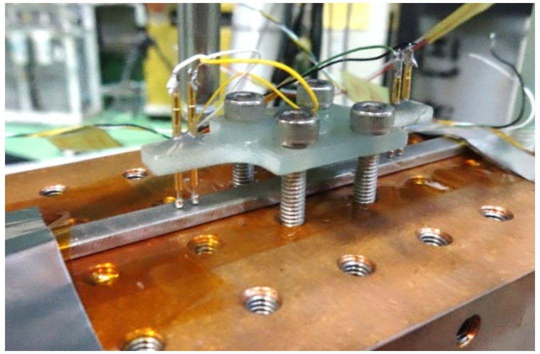
T.S.=Tensile Strength Y.S.=Yield Strength E.V.=Erichsen Value

[by H. Umezawa (Tokyo Denkai)]

Characteristics of Nb materials: (RRR)



RRR measurement system



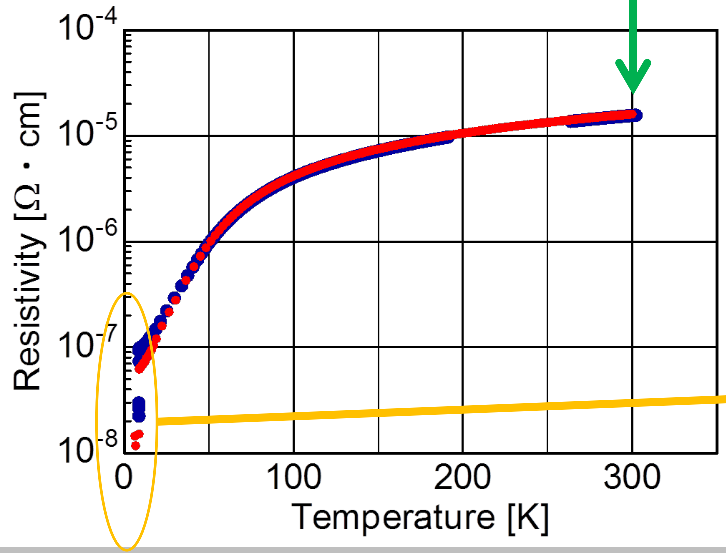
Residual Resistance Ratio

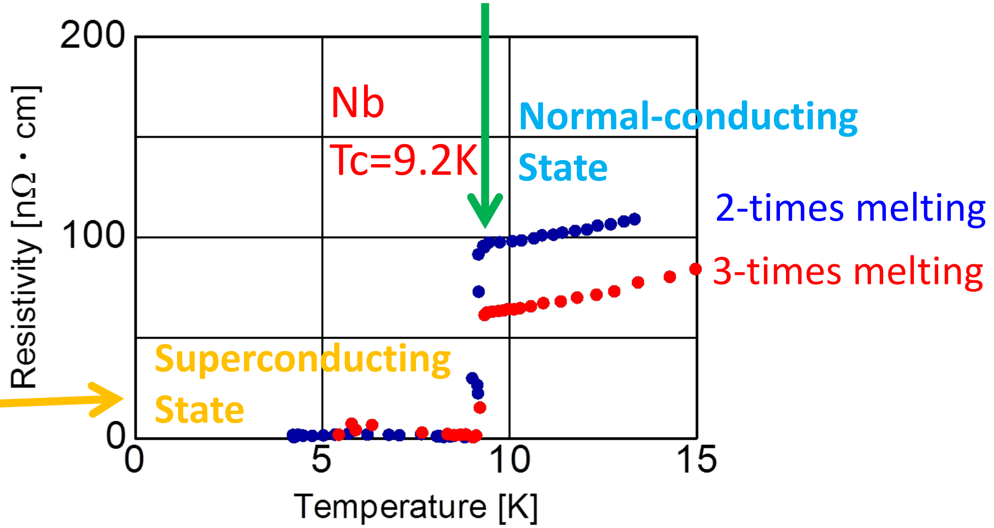
$$RRR = \frac{\rho(300\mathrm{K})}{\rho(9.2\mathrm{K})}$$

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

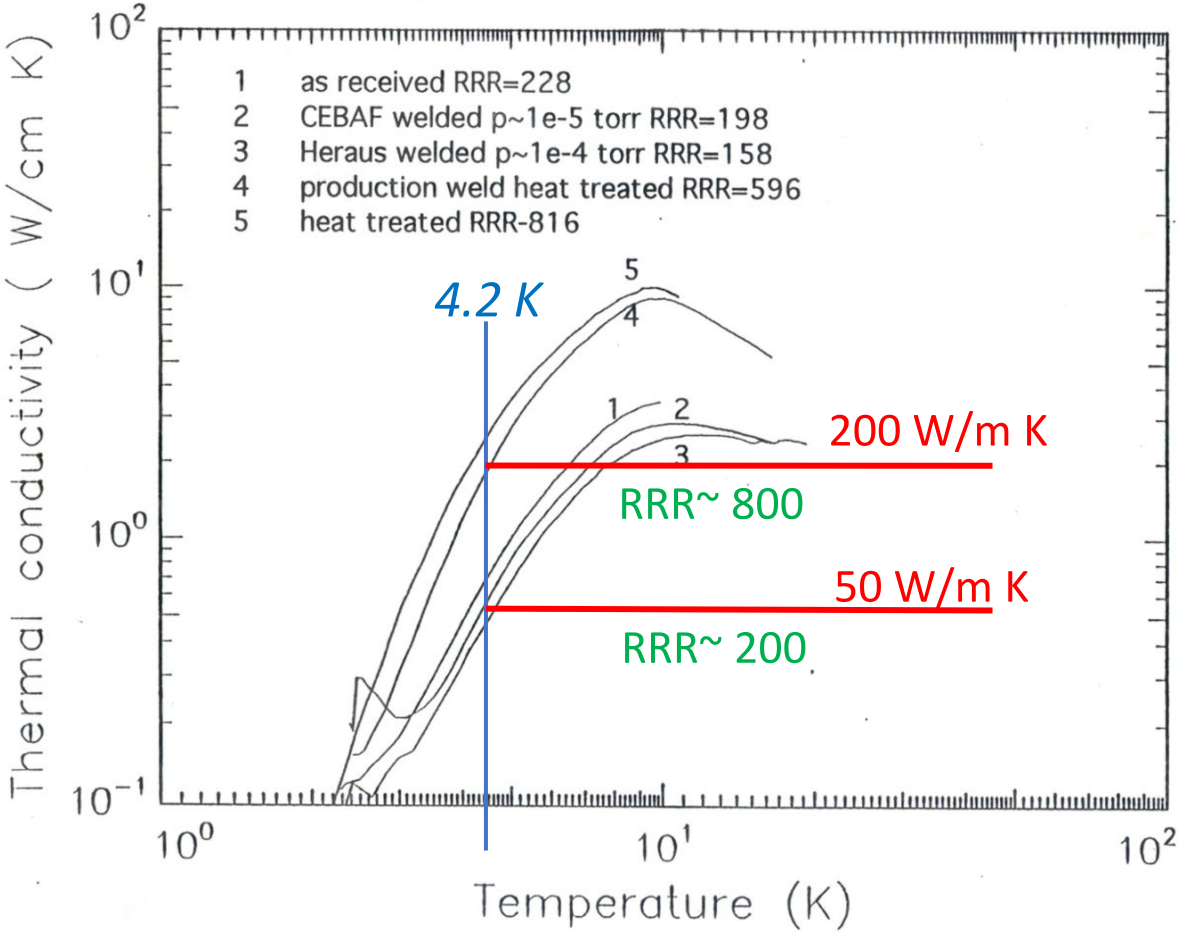
RRR = 200
RRR = 330





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

$$\kappa_{(4.2K)} \approx RRR/4 \quad [W/m \cdot K]$$

Wiedemann-Franz's law

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

H_{quench}* : *Quench field

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

R_{defect} : *Resistivity of Defect*

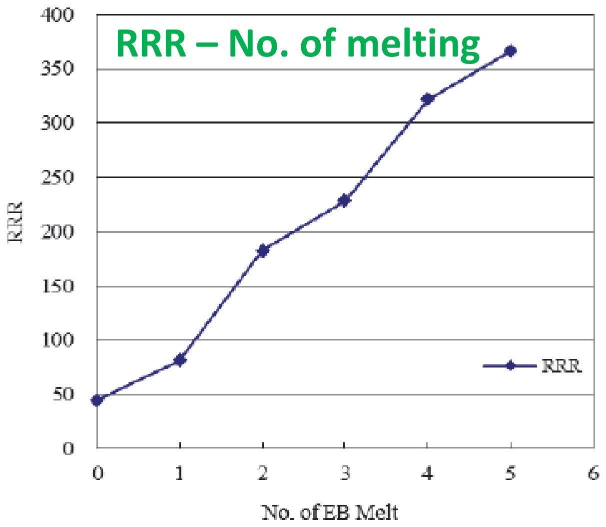
a : *Radiaus of Defect*

T_c : *Critical Temperature*

T_{He} : *He Temperature*

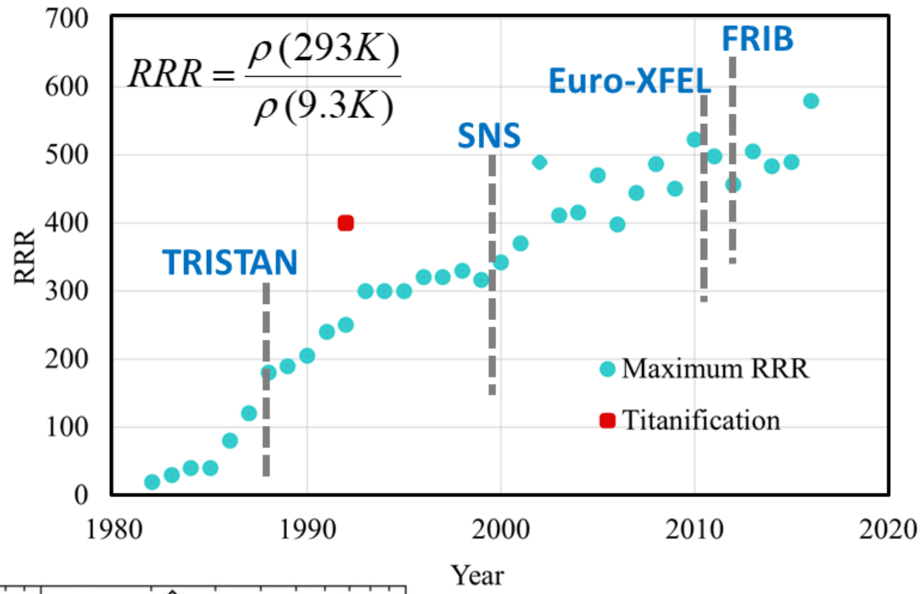
High RRR niobium with high thermal conductivity is preferable for achieving higher accelerating gradient.

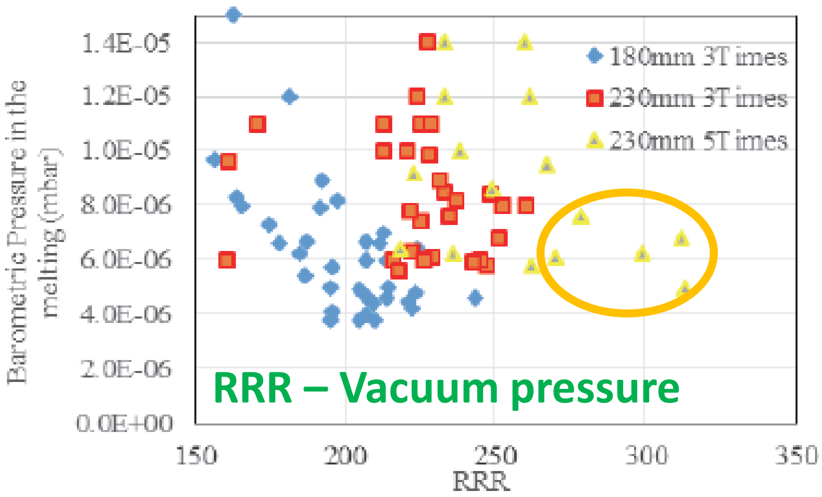
Characteristics of Nb materials: (Improvement of RRR)

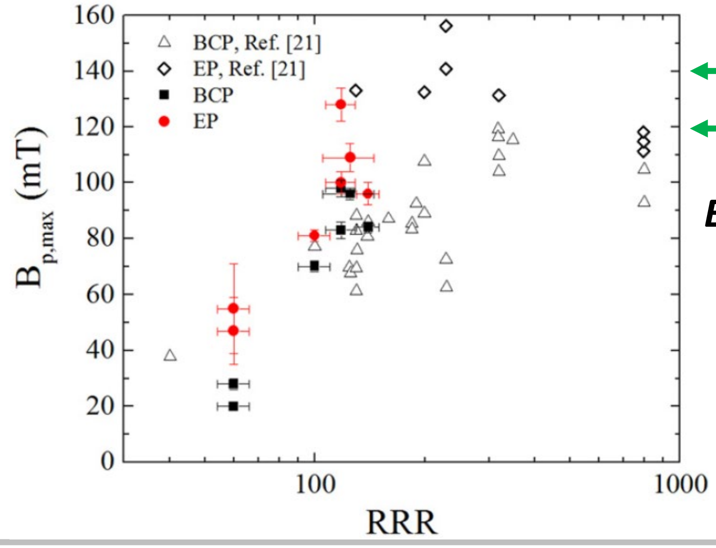


ULTRA HIGH PURITY RARE METAL
TOKYO DENKAI

[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

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

TRISTAN 508MHz 5-cell Cavity

He temperature at 4.2 K
CW operation

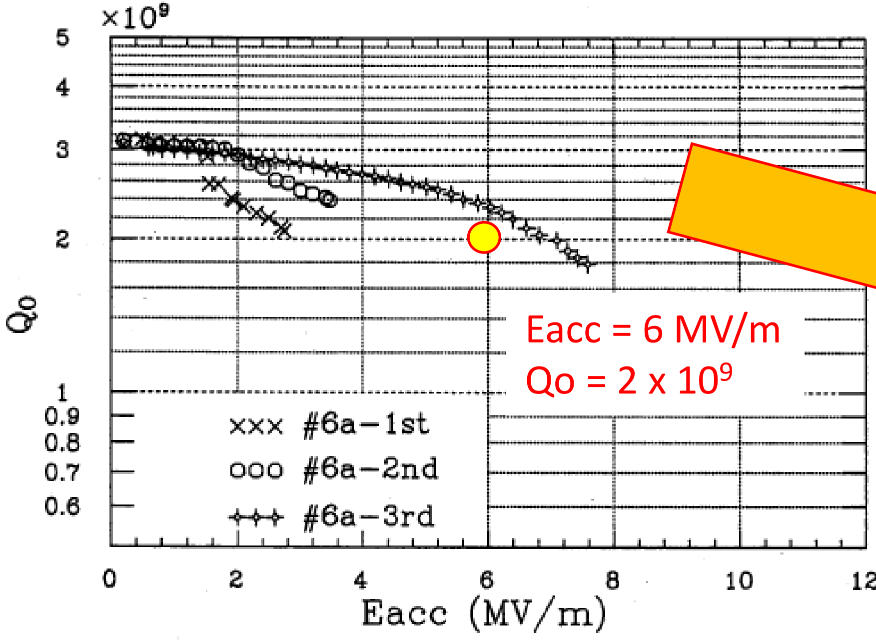


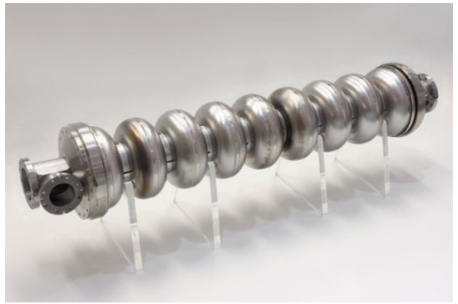
Figure 7: Qo and Eacc of TRISTAN #6a cavity.

1989'

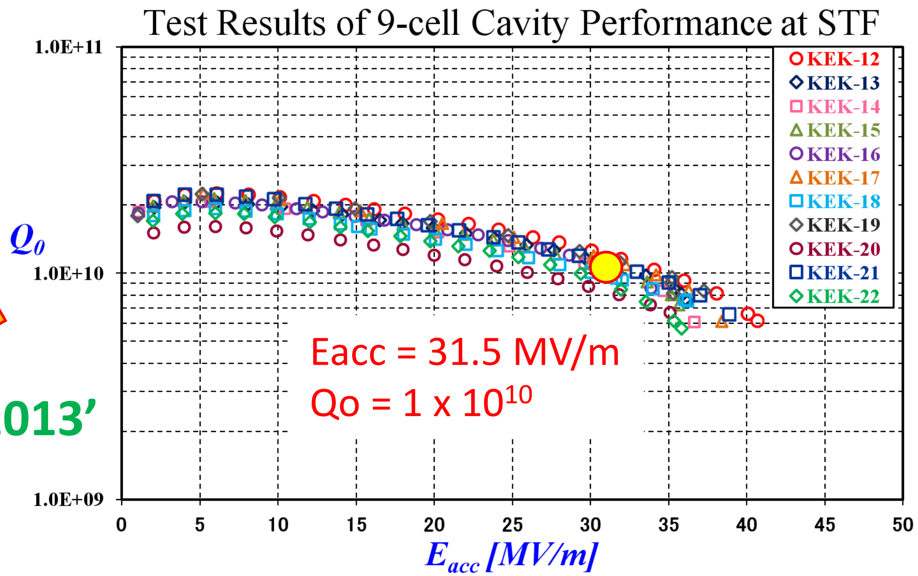
Eacc = 6 MV/m
Qo = 2 x 10^9

[T. Furuya, SRF'89]

STF 1.3GHz 9-cell Cavity



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



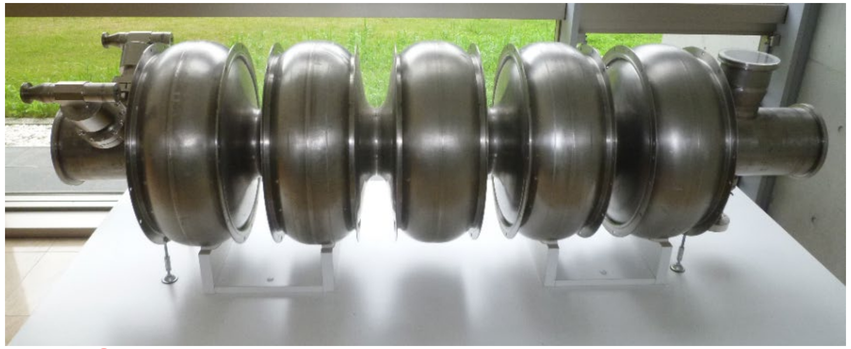
2013'

Eacc = 31.5 MV/m
Qo = 1 x 10^{10}

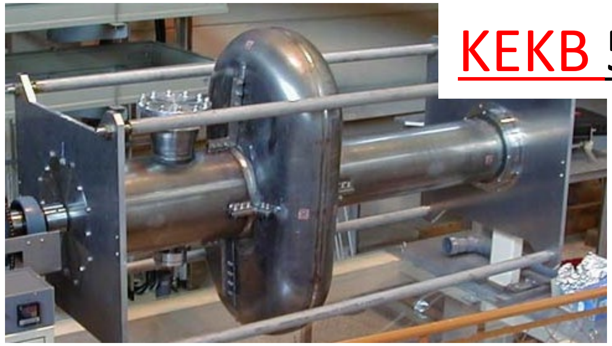
Figure 1: Best Q_0 vs. E_{acc} curves obtained from performance tests for KEK-12 through KEK-22.

[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)

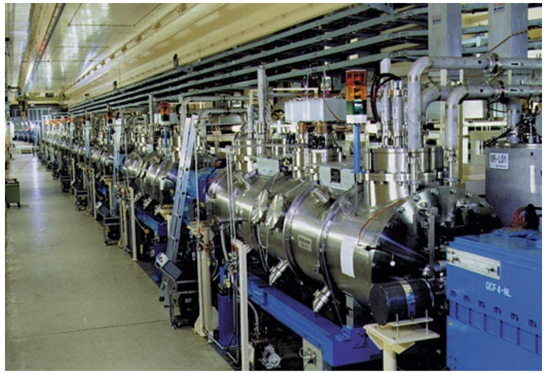
cERL Injector
1.3GHz 2-cell Cavity

cERL ML 1.3GHz 9-cell Cavity

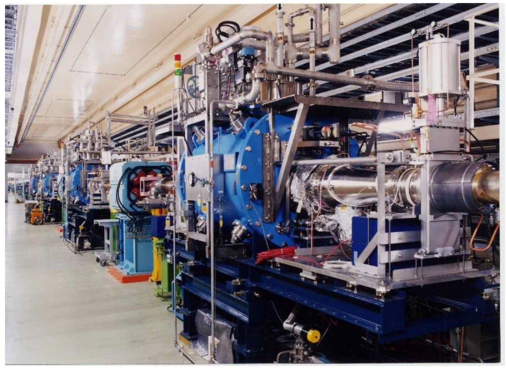
STF 1.3GHz 9-cell Cavity

Cryomodules developed at KEK

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



TRISTAN 508MHz Cryomodule



KEKB
508MHz Cryomoudle

KEKB Crab Cryomoudle

J-ADS 972MHz
Cryomodule

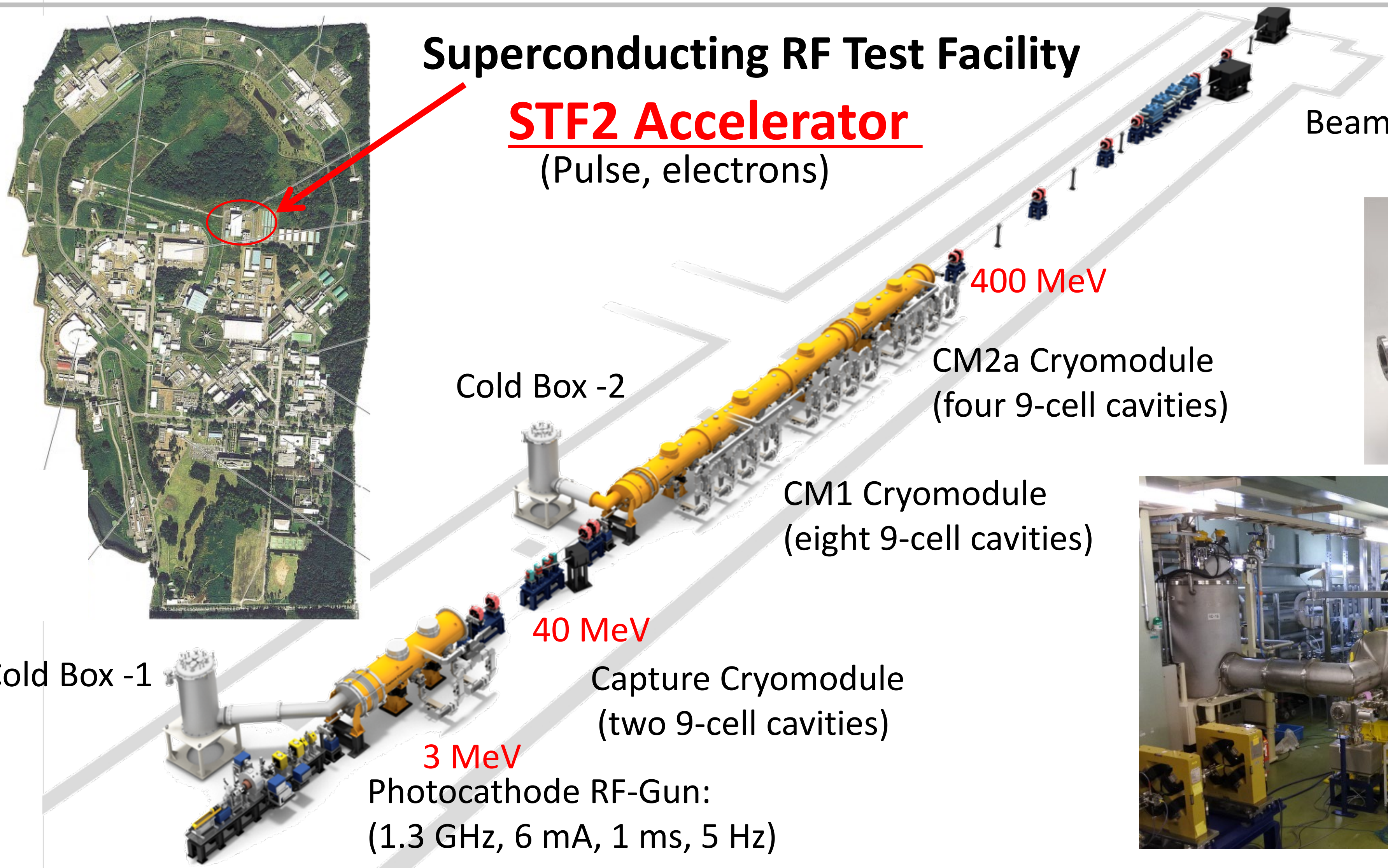
cERL 1.3 GHz
Injector Cryomodule

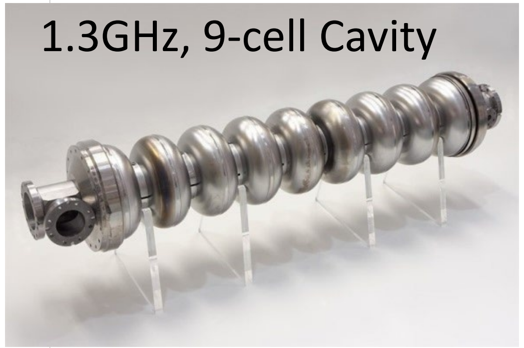
cERL 1.3 GHz
ML Cryomodule

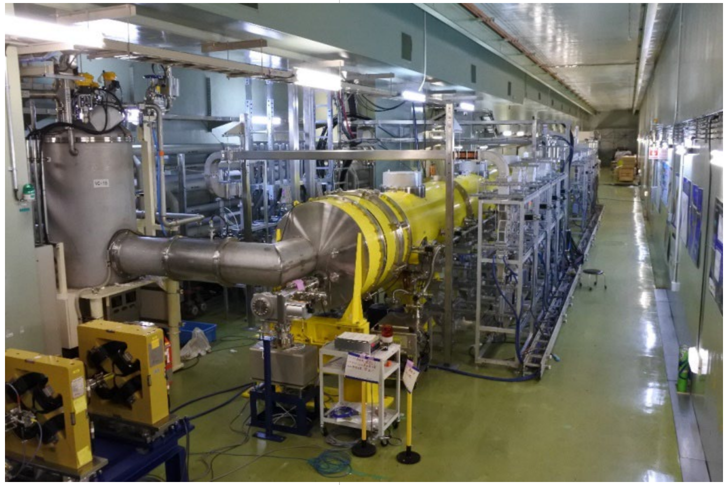
STF 1.3GHz Cryomodule

STF at KEK for future Linear Collider (ILC)

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



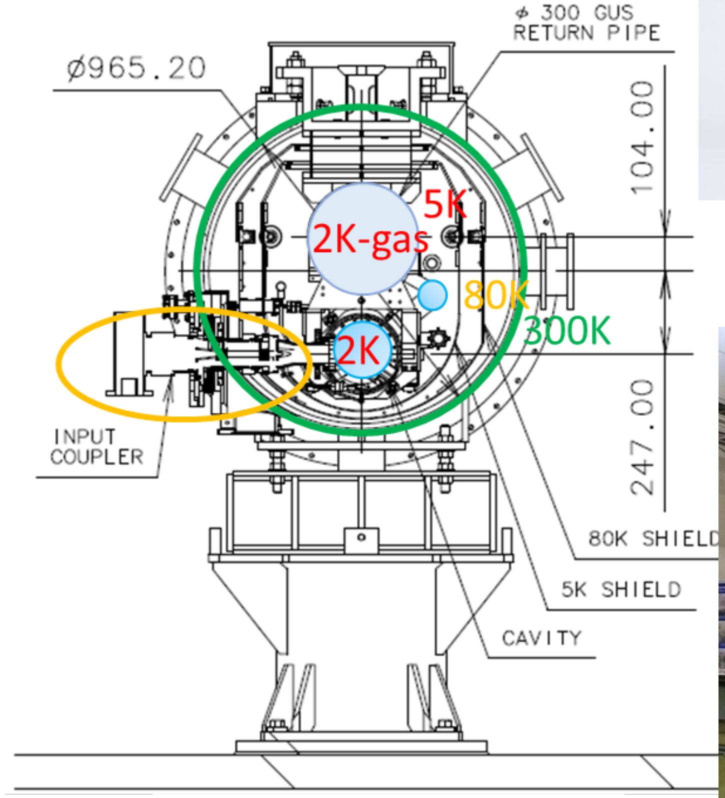




Superconducting RF cavity system for STF

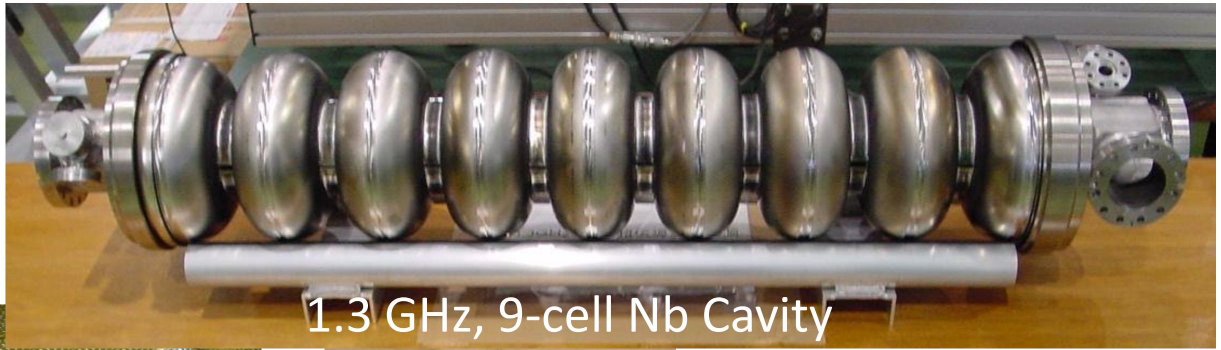
Innovation Center for Applied Superconducting Accelerators
応用超伝導加速器イノベーションセンター

Cryomodule



STF Cryomodule

Input Couplers

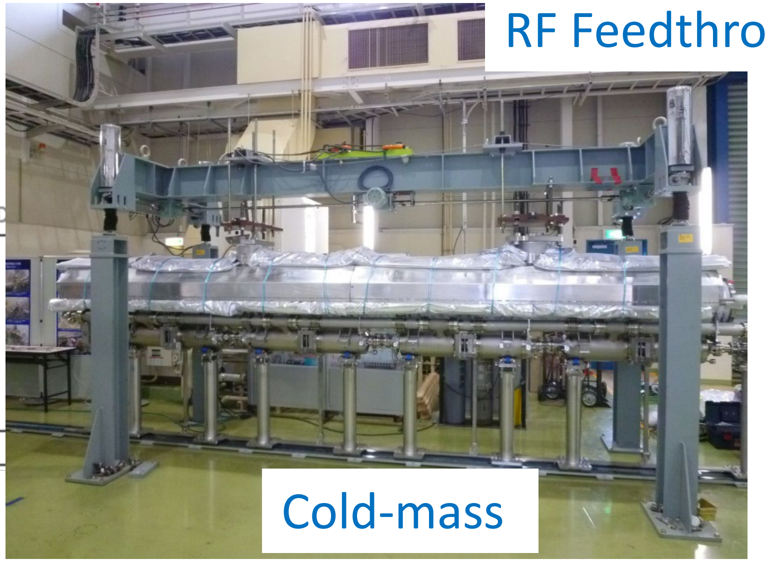


1.3 GHz, 9-cell Nb Cavity

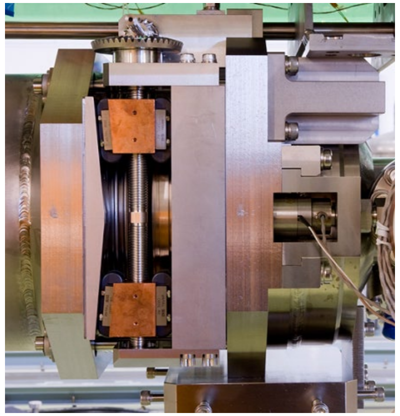
RF Feedthroughs

HOM Couplers

Magnetic Shield & He Jacket (Ti)



Cold-mass

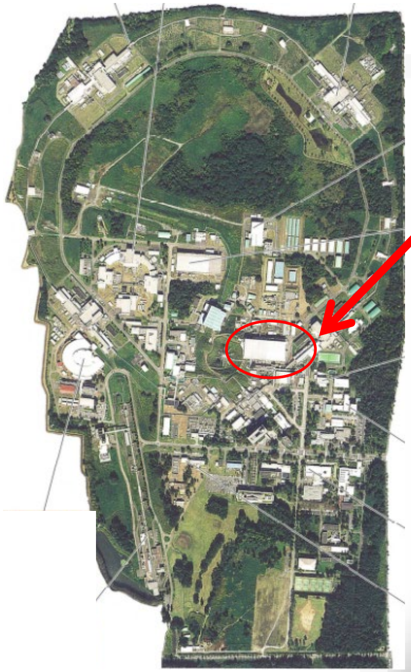


Slide-Jack Tuner

cERL at KEK for future Light Source: ERL

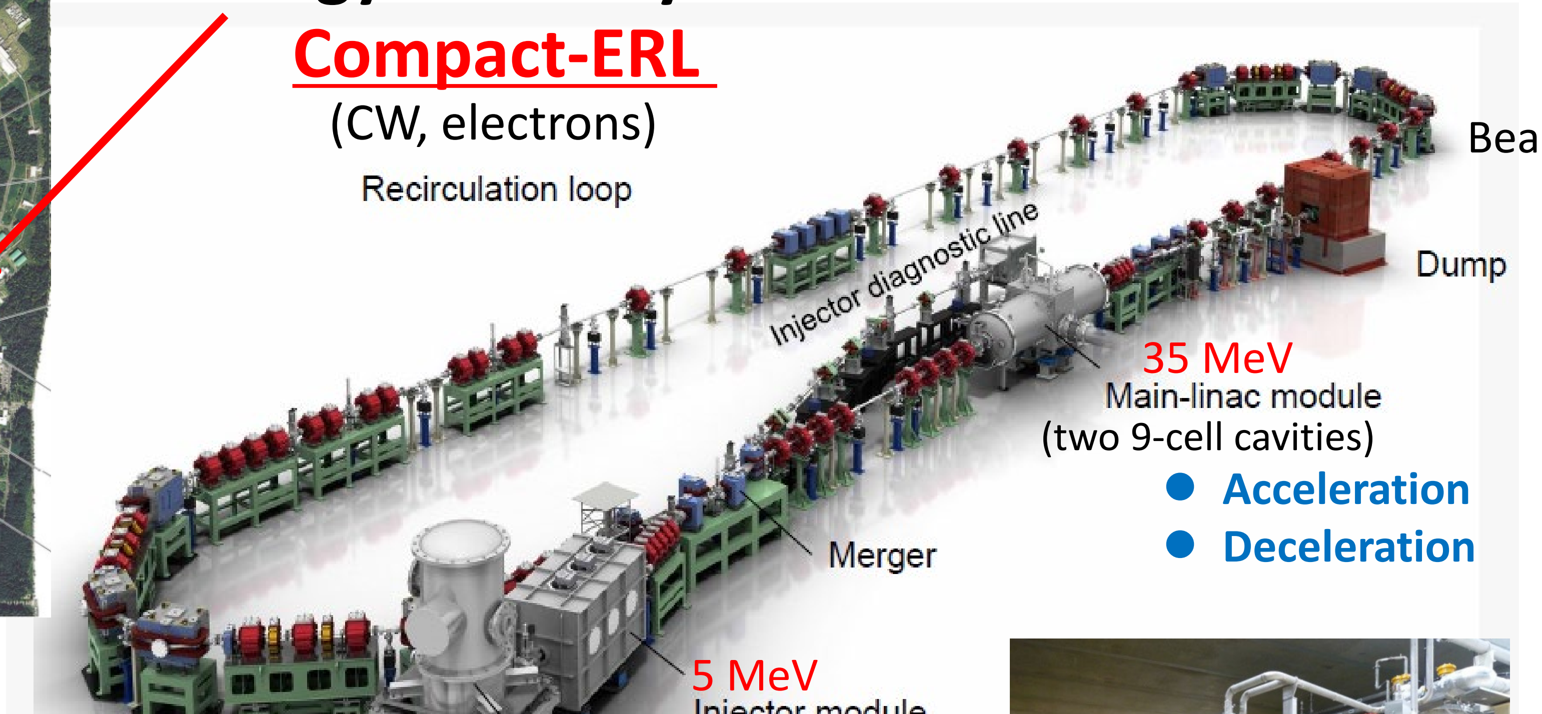
Innovation Center for Applied Superconducting Accelerators
応用超伝導加速器イノベーションセンター

Energy Recovery LINAC



Compact-ERL

(CW, electrons)



50 kW
Beam Dump

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

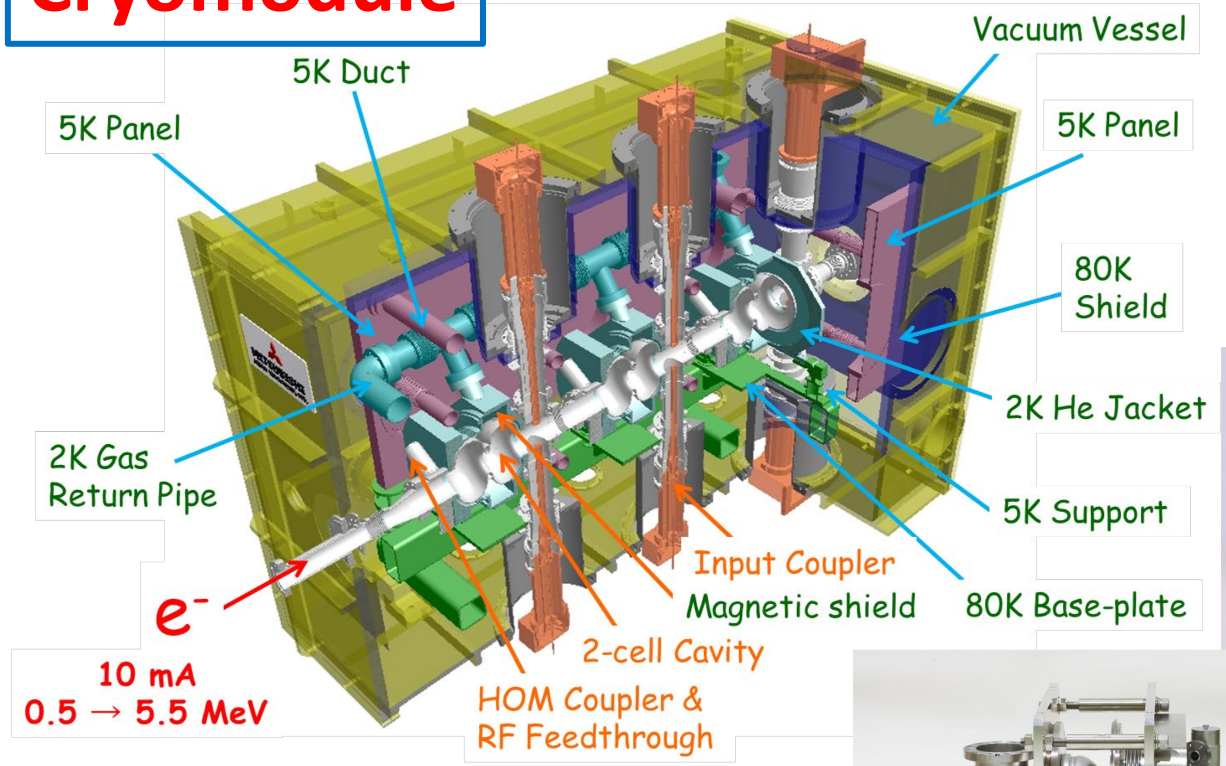
- **Acceleration**
- **Deceleration**

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

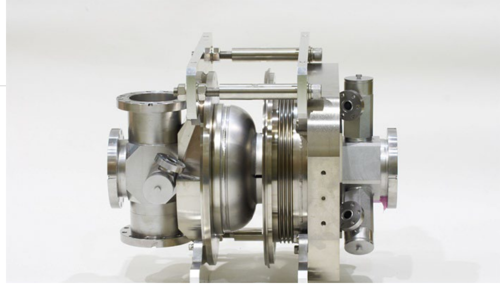


cERL Injector Cryomodule

1.3GHz, 2-cell Cavities

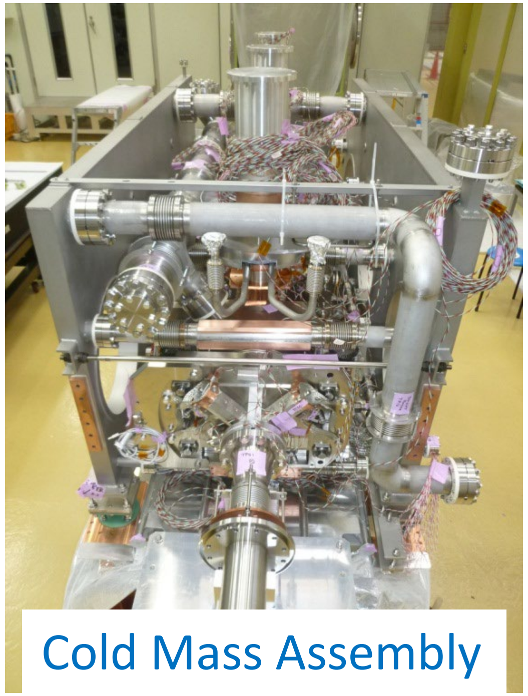
Slide-Jack Tuner

Input Couplers



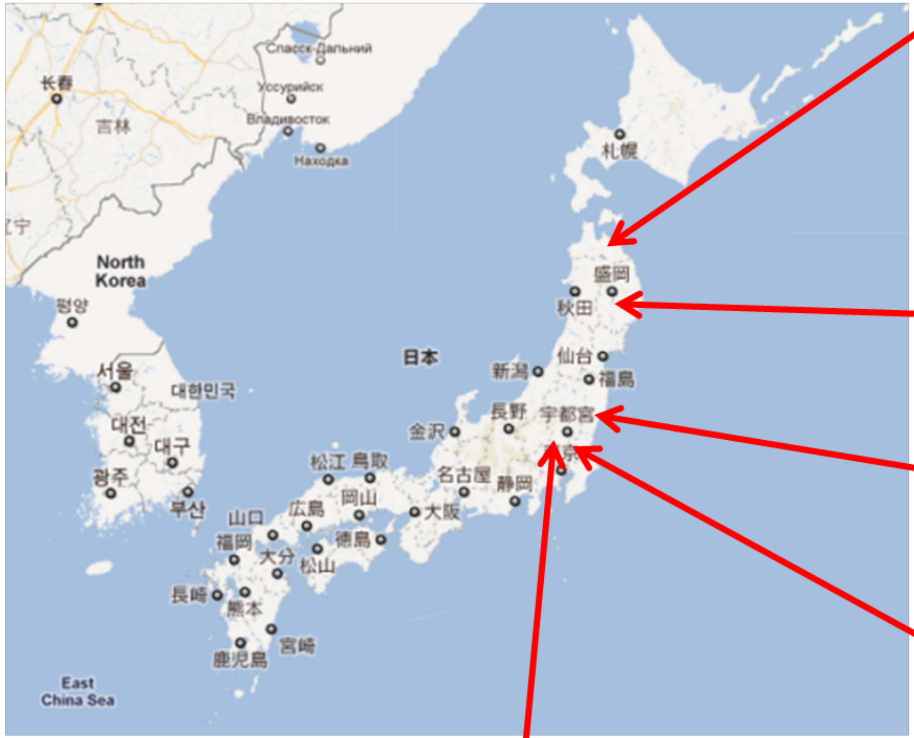
1.3GHz, 2-cell Cavity

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

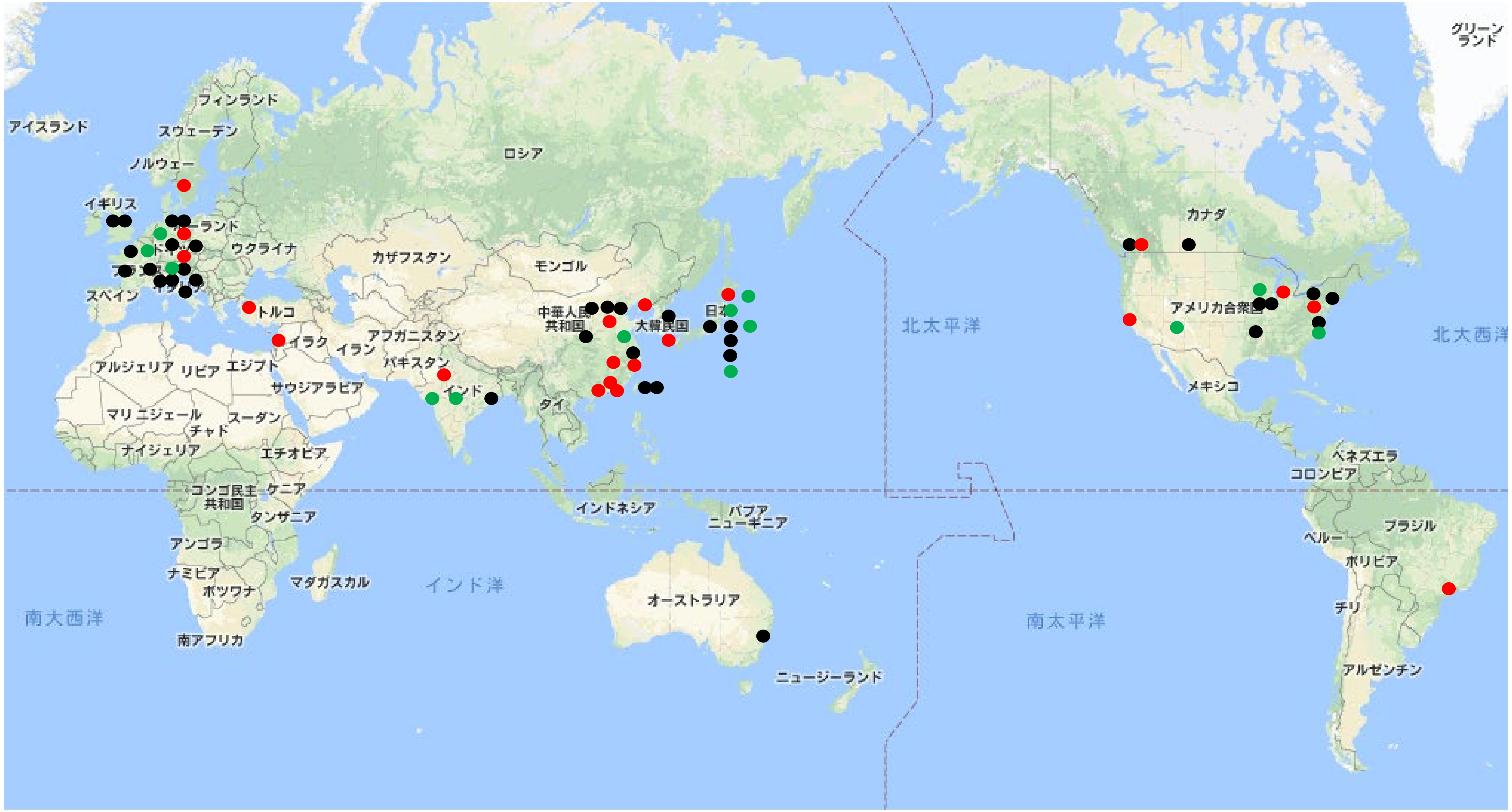
● under construction

No. of cavity : frequency : cavity structure

underline: future project

Superconducting Accelerator Projects in World

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



Operation Construction Future Plan

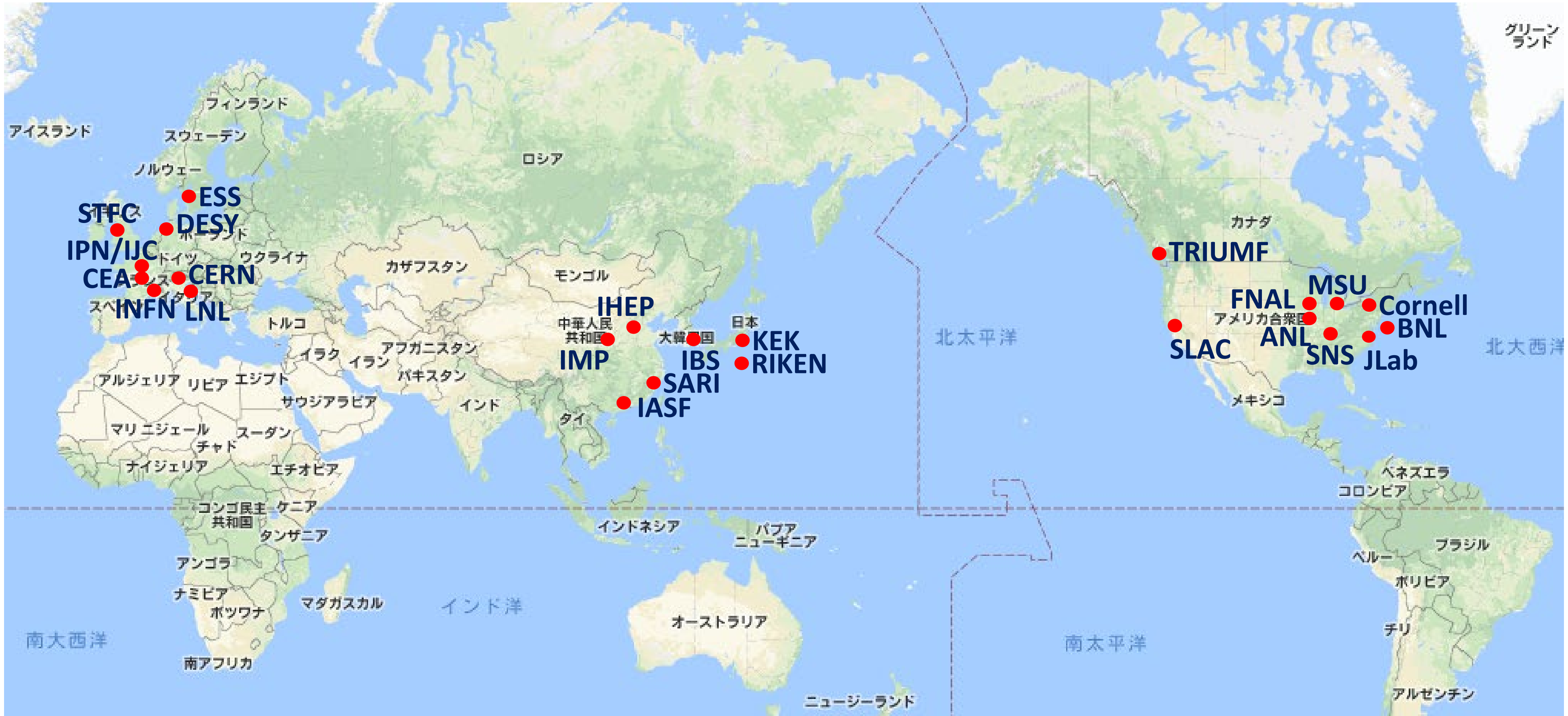
Superconducting Accelerators in Worldwide

- **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

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



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.

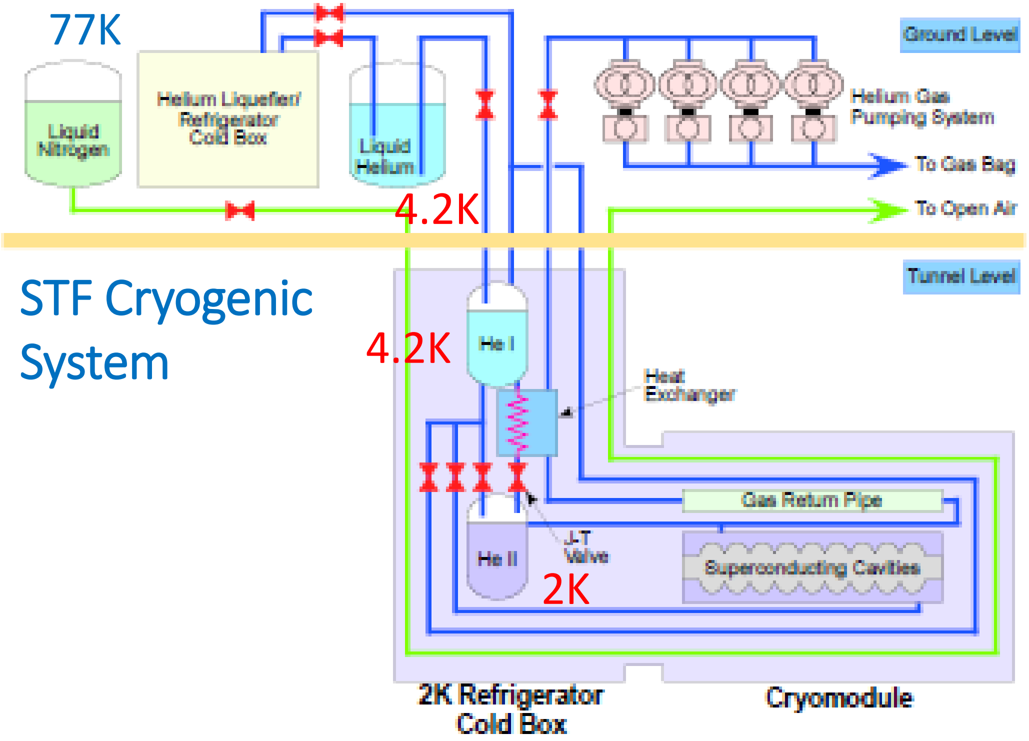
Innovation Center for Applied Superconducting Accelerators
応用超伝導加速器イノベーションセンター

Superconducting RF Cavity System (1)

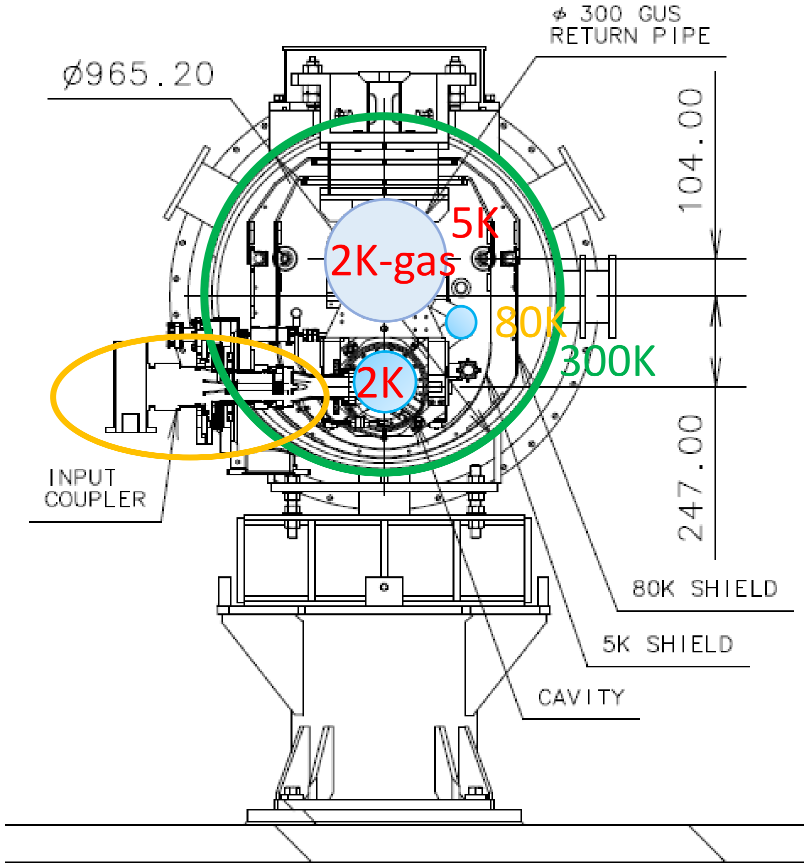
iCASA Innovation Center for Applied Superconducting Accelerators
応用超伝導加速器イノベーションセンター

Refrigerator

STF Cryogenic System



Cryomodule



STF Cryomodule

<u>Cryogenic Efficiency</u>

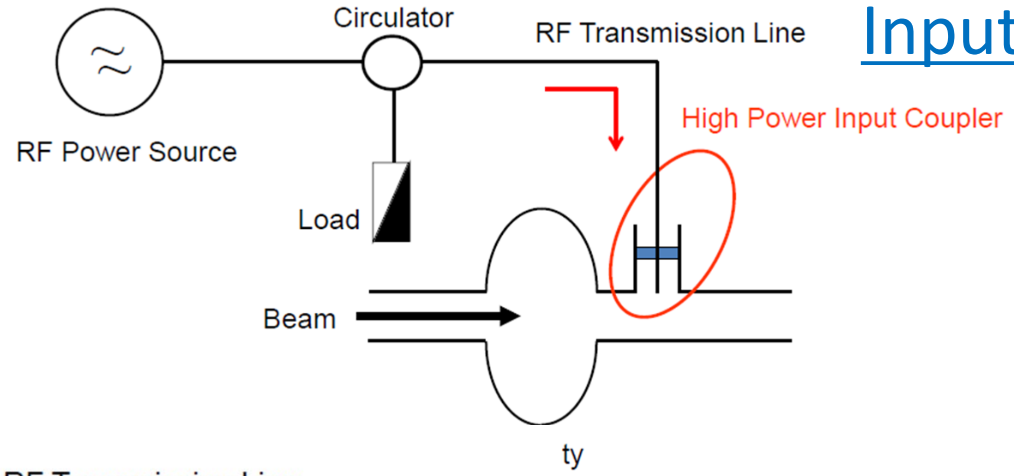
1 W at 2 K → 4.5 W at 4.2 K, (1 : 4.5)

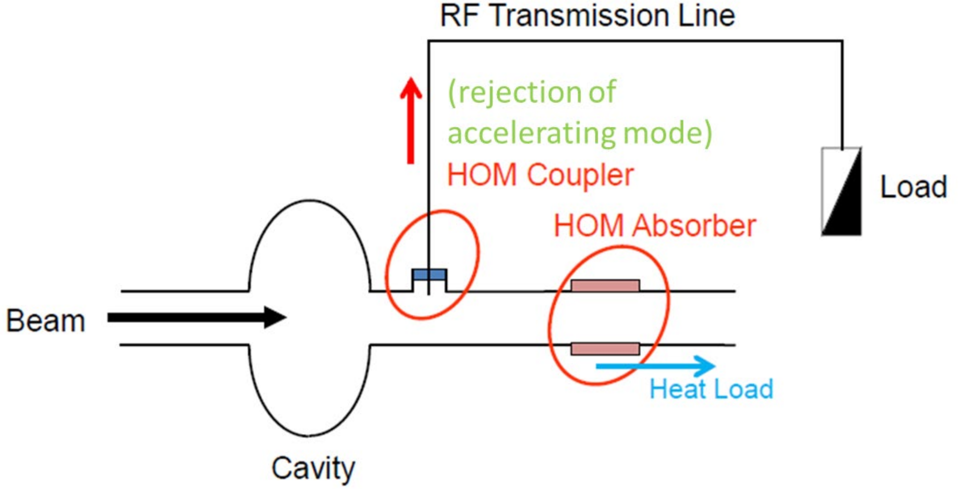
3 W at 4.2 K → AC 1 kW, (0.3%)

◆ AC 1.0 MW → 3 kW@4.2K, 700 W@2K

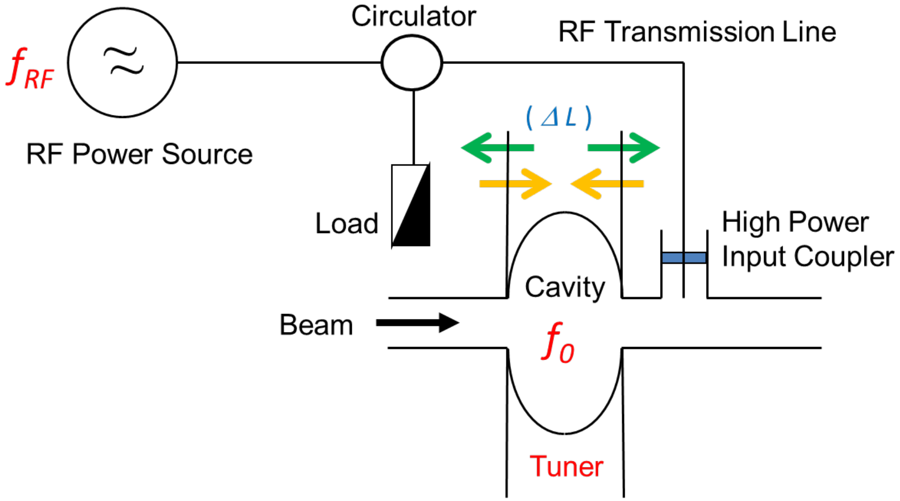
Superconducting RF Cavity System (2)

Input coupler





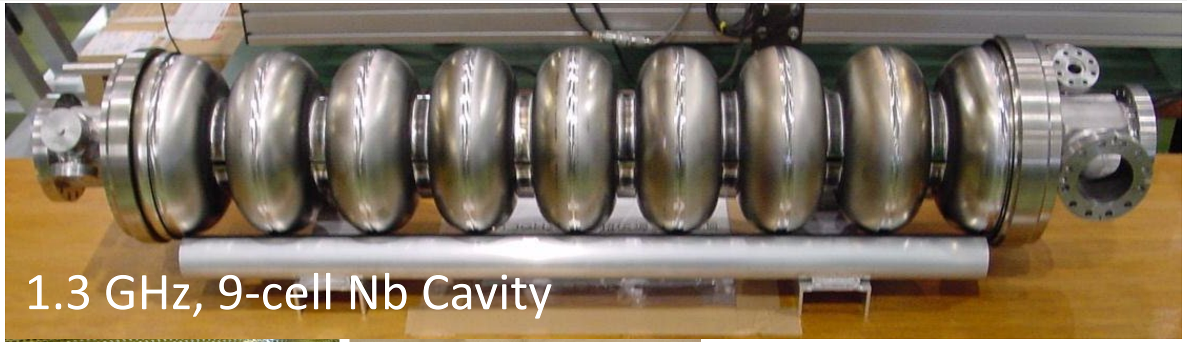
HOM coupler and absorber



Frequency Tuner

Superconducting RF Cavity System (3)

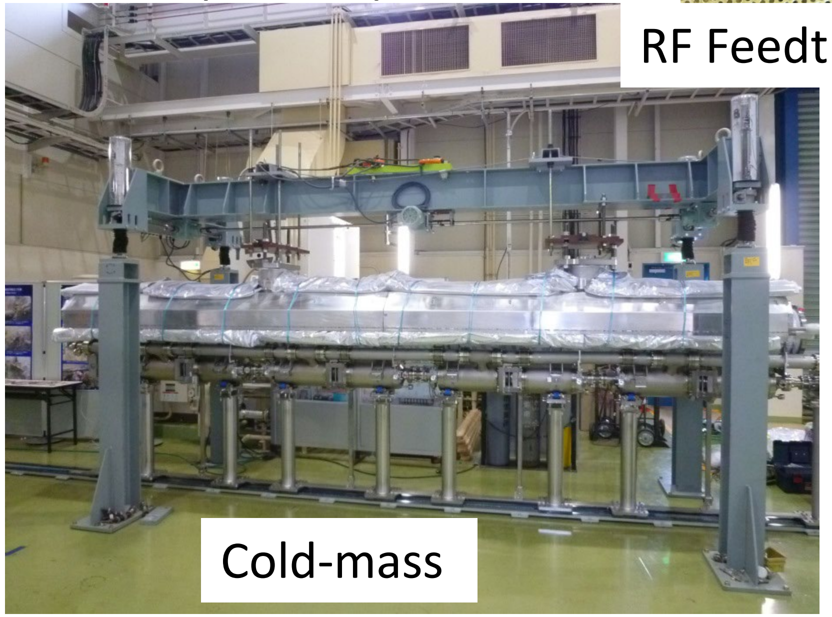
Input Coupler



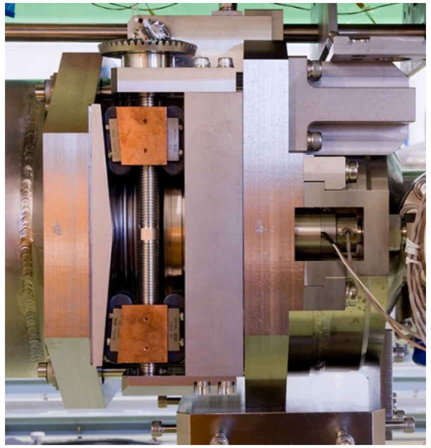
1.3 GHz, 9-cell Nb Cavity

RF Feedthrough

HOM Coupler



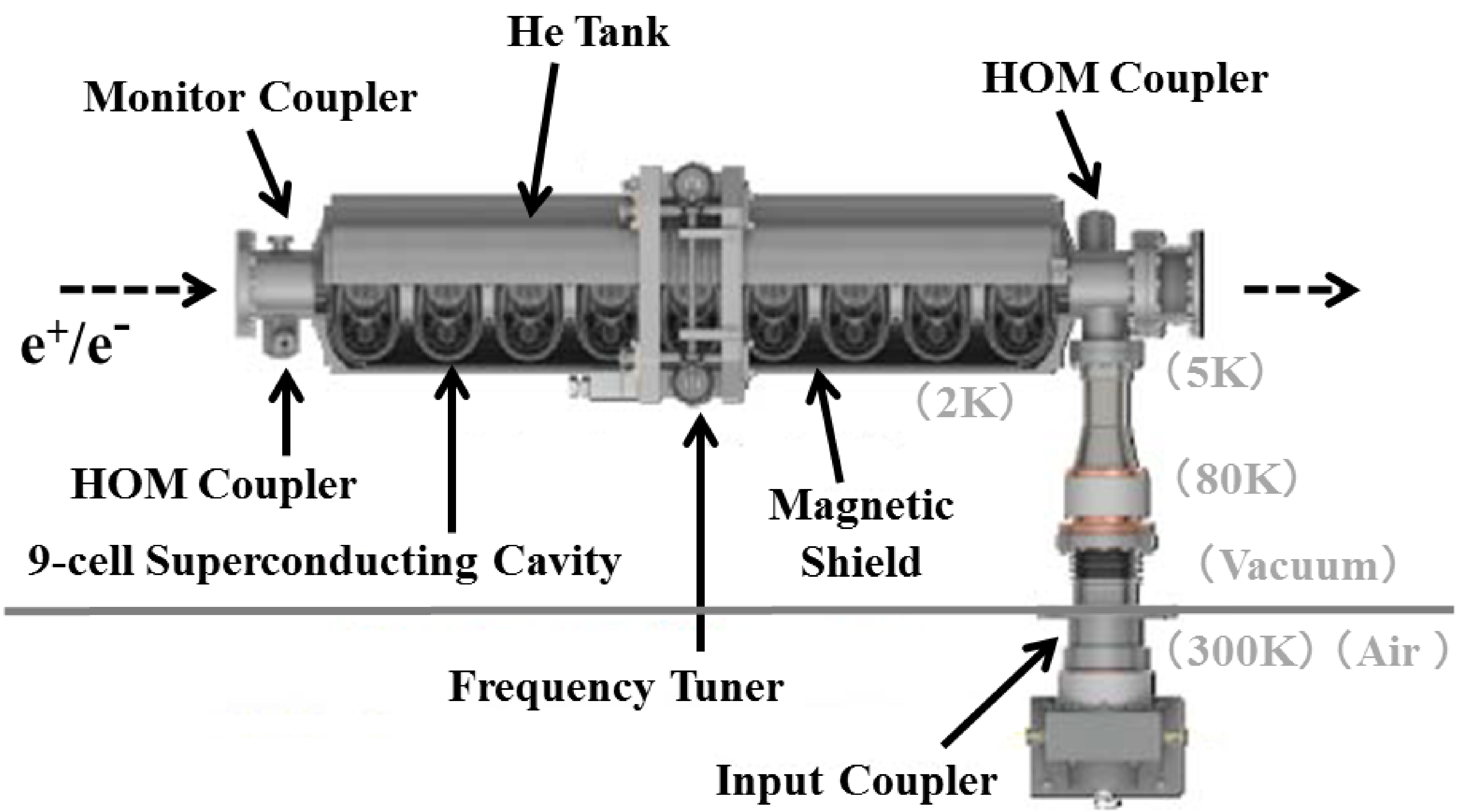
Cold-mass



Slide-Jack Tuner

Magnetic Shield
He Jacket (Ti)

Superconducting RF Cavity System (4)



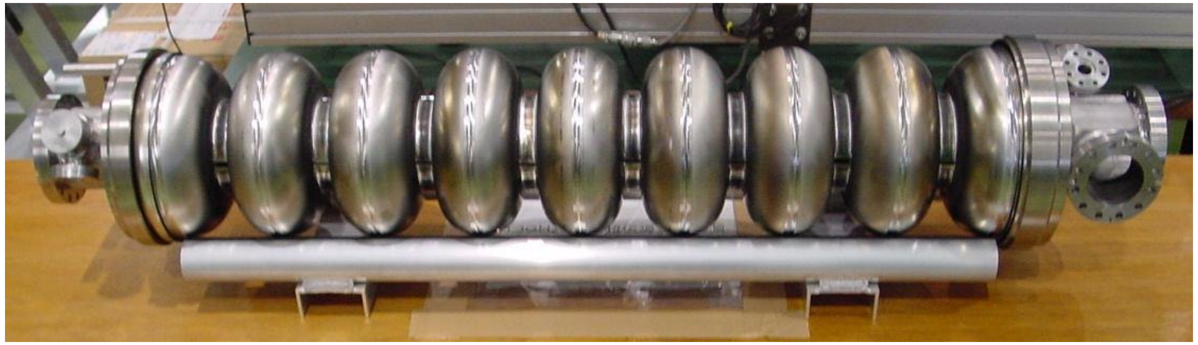
STF 9-cell SRF Cavity Package

Superconducting RF Cavity System (5)

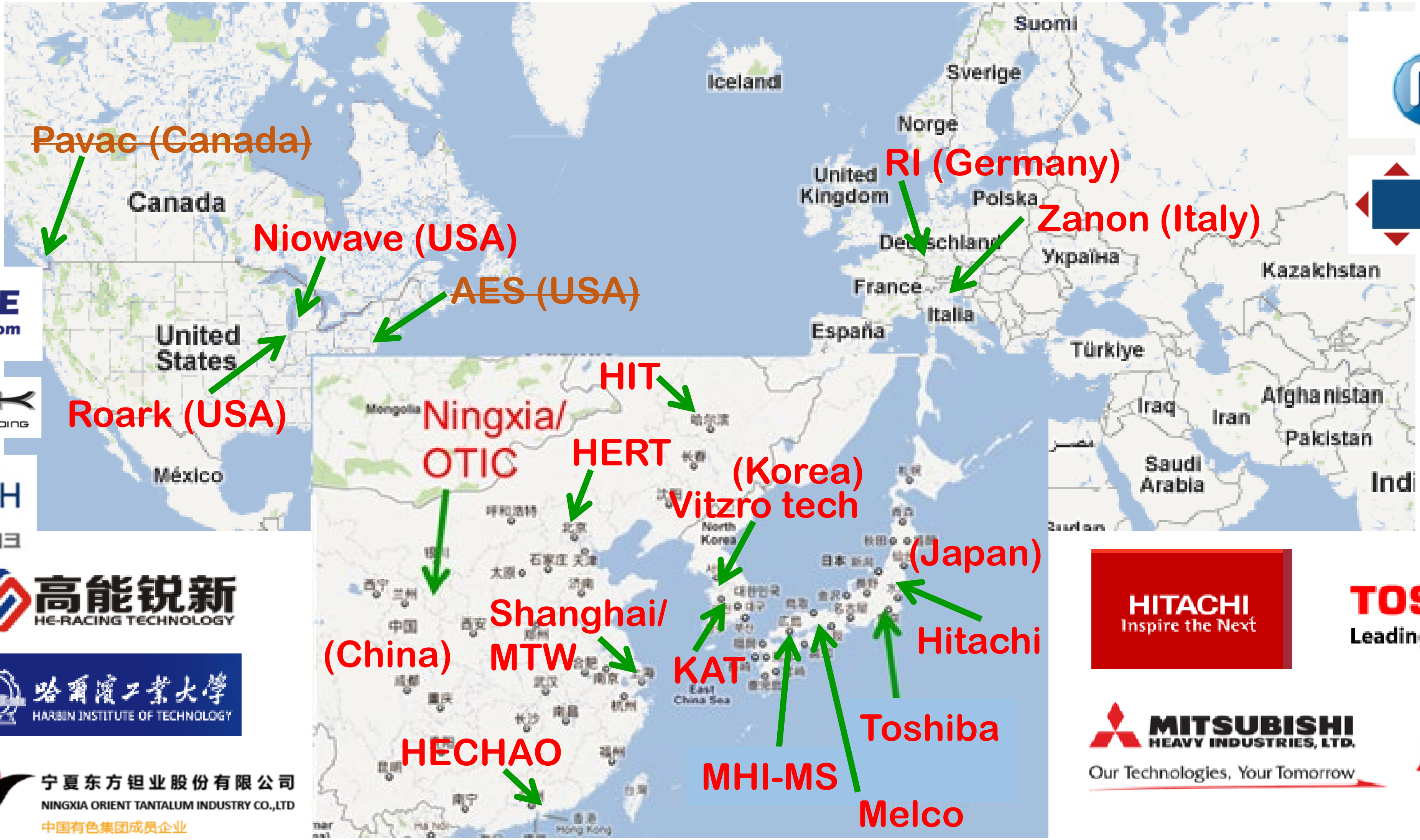
Center-cells
(Tokyo Denkai ; RRR~300 Nb)

Forming and joining properties of Nb

(Deep drawing , EBW: electron beam welding)



Cavity fabrication companies in the world



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

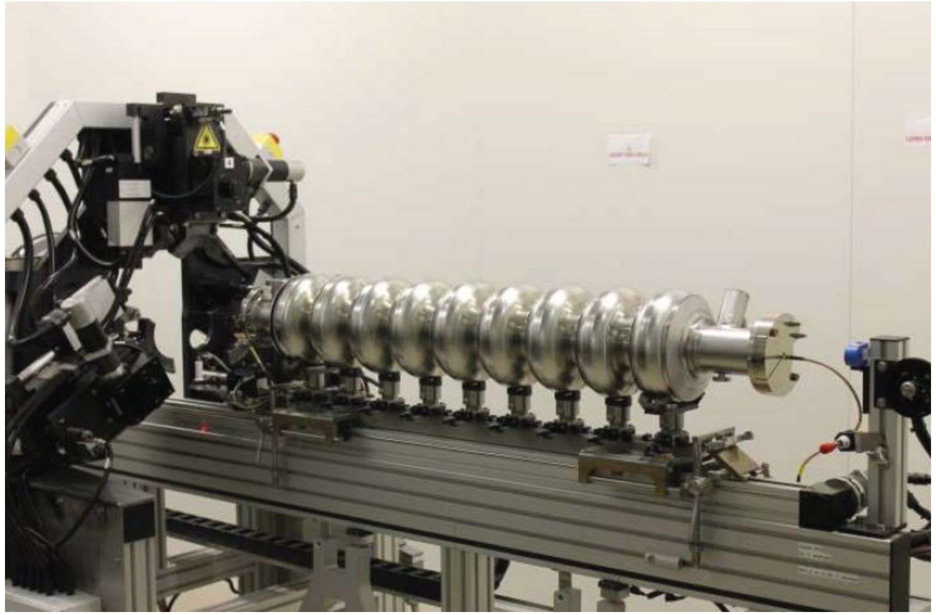
Assembly and Inspection
- Fabrication of special jigs
- Vacuum leak check
- Dimensional measurement
- RF measurement
- Frequency tuning
- Precise alignment

Special cavity fabrication tools developed by DESY

TESLA 1.3 GHz 9-cell cavity

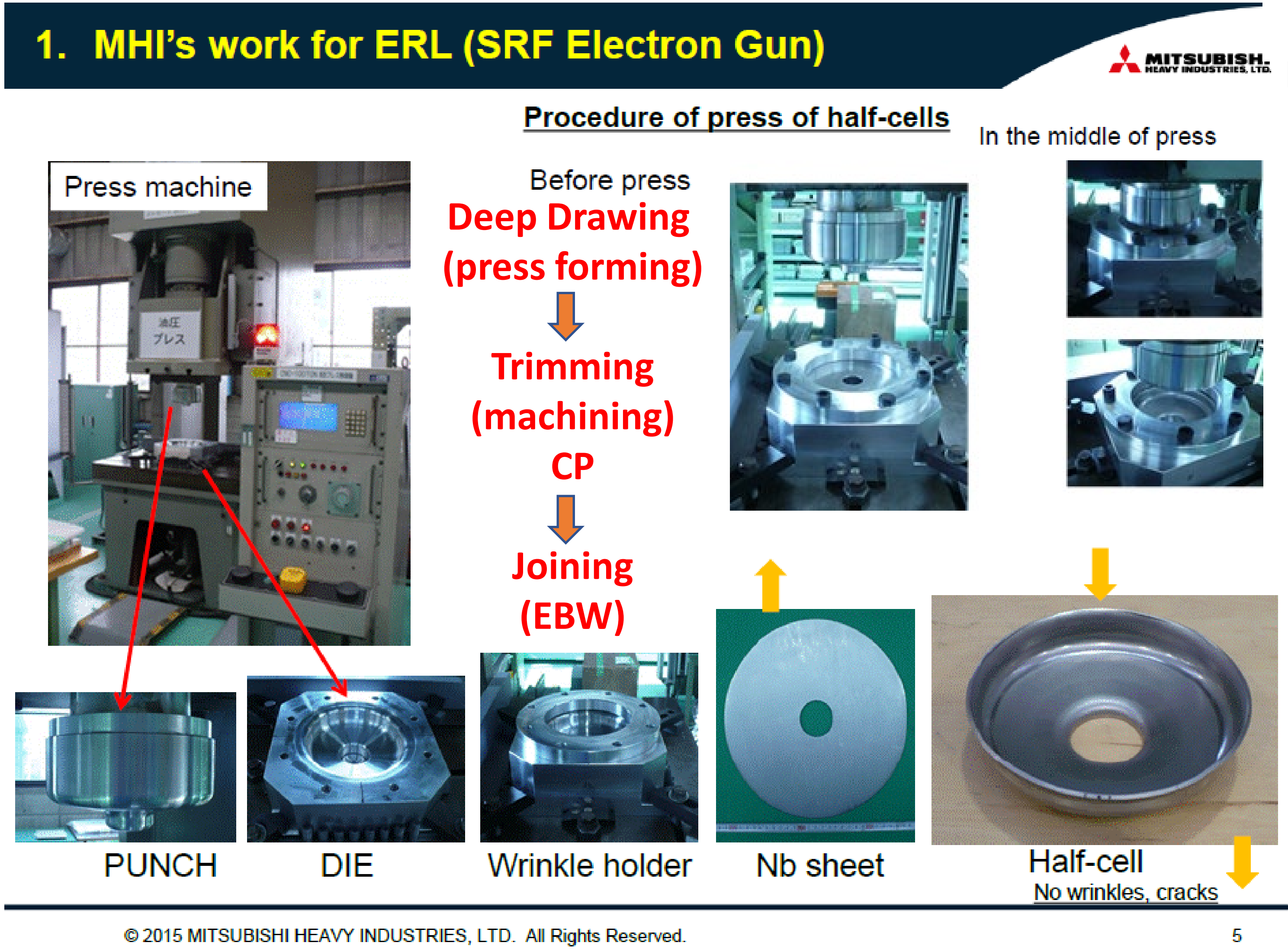
Eddy current scan of Nb sheet

Frequency measurement of half-cell/dumb-bell



Automatic pre-tuning machine

Fabrication Process of Nb Cavities



Electron Beam Welding (EBW)

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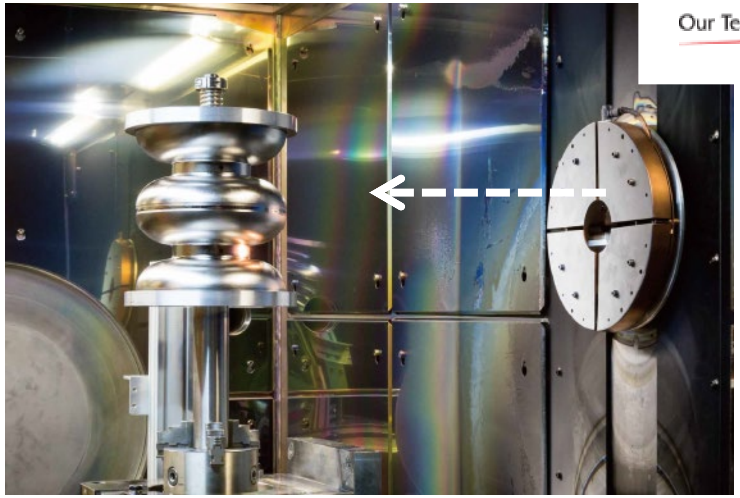
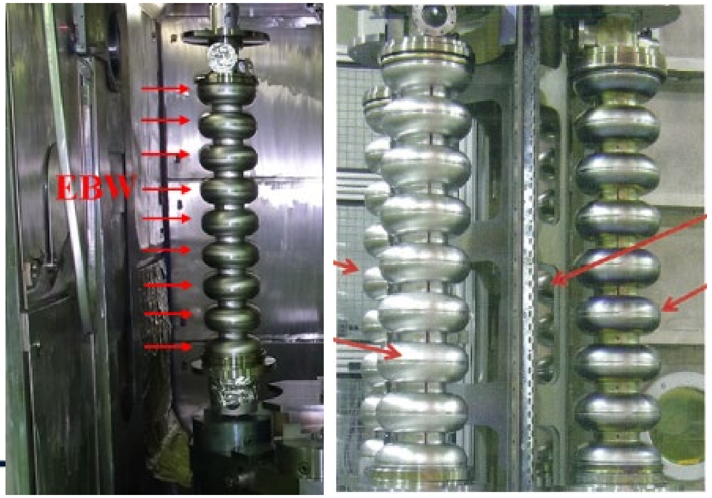
Our Technologies, Your Tomorrow

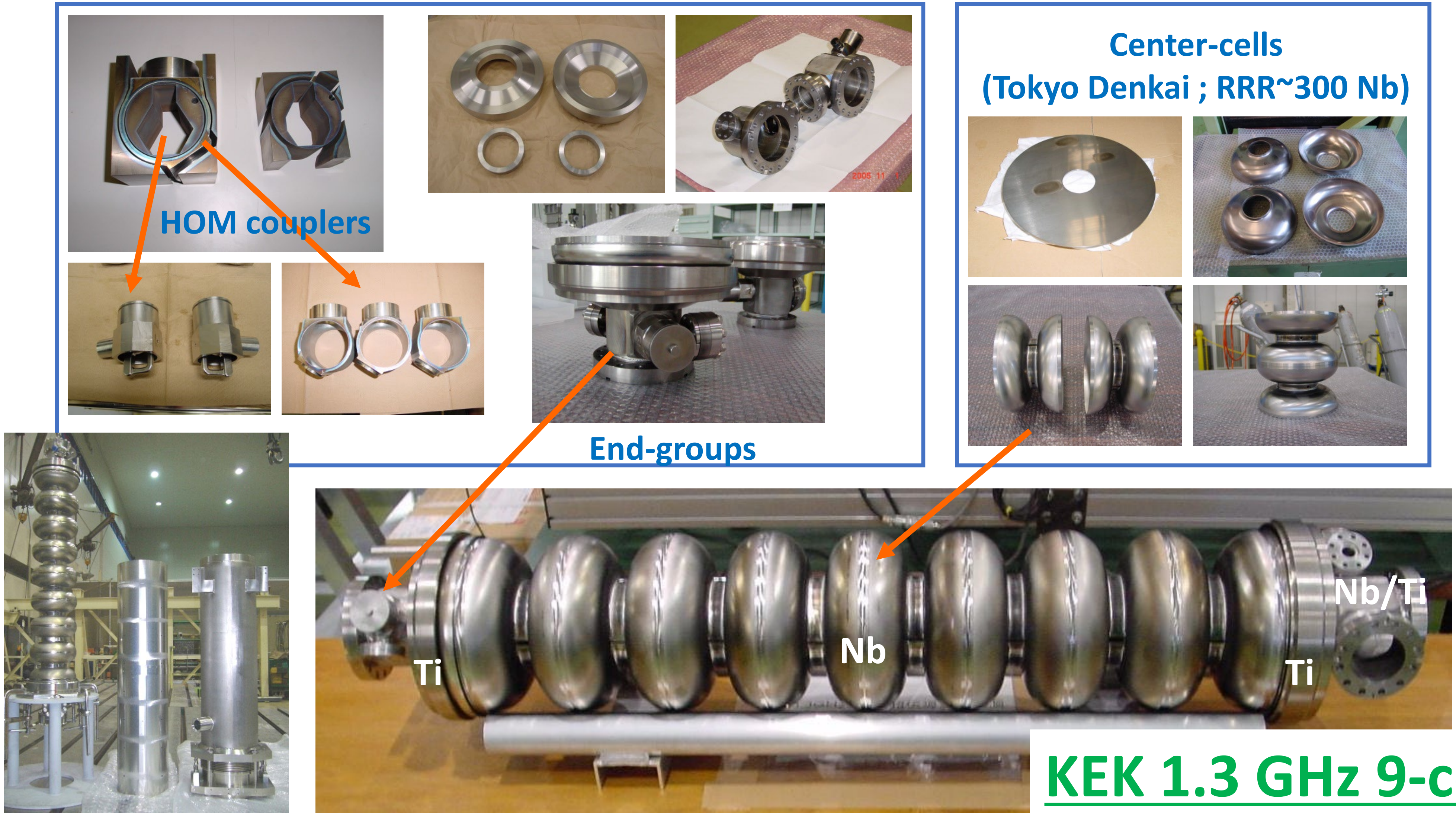


by K. Sennyu (MHI-MS)



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

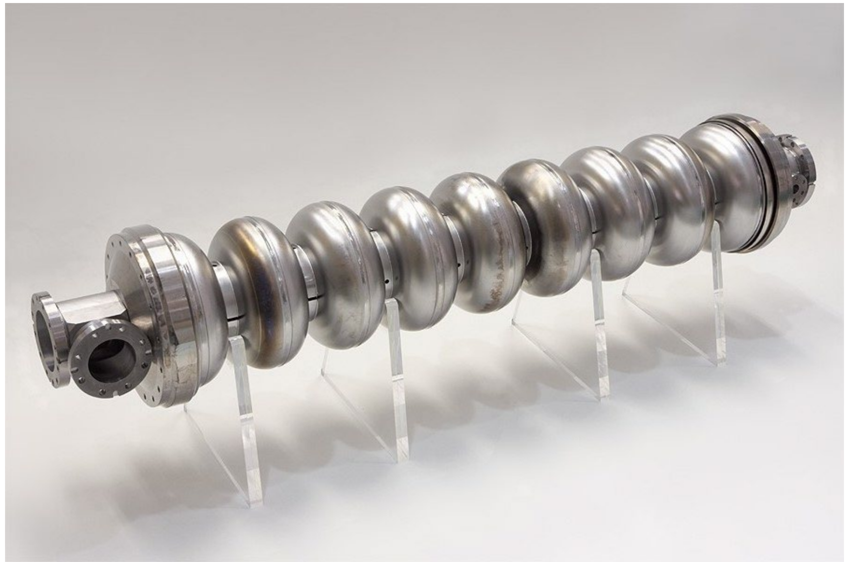
Cavity fabrication (EBW: electron beam welding)

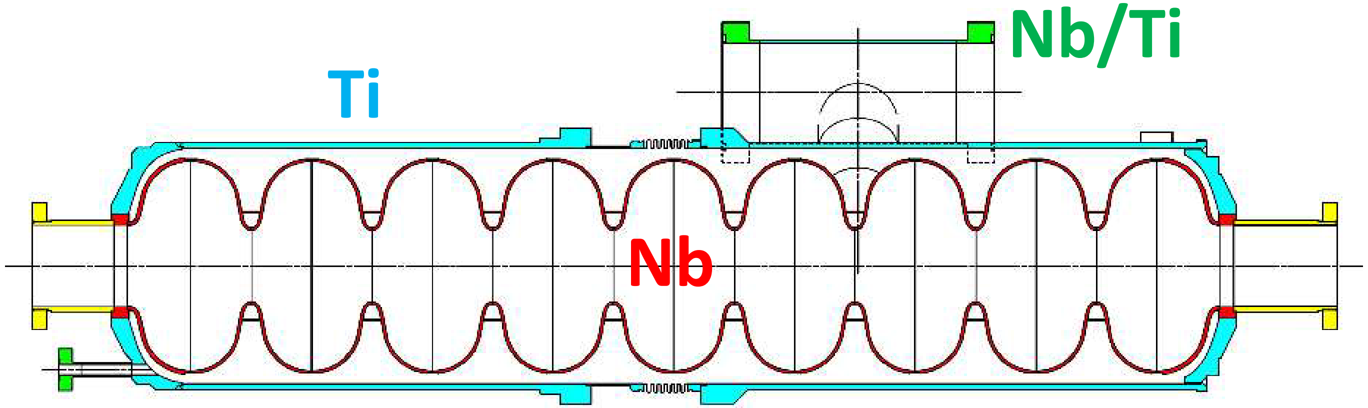


KEK 1.3 GHz 9-cell cavity

Materials and joining methods in SRF cavity

KEK 1.3 GHz 9-cell cavity

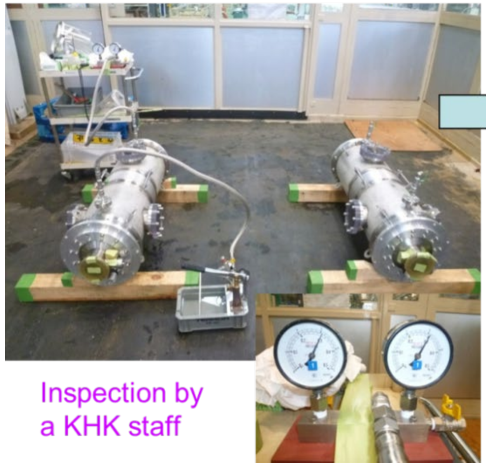




Materials	Joining Methods
Nb	(Cavity cells)
Ti	(He Tank)
Nb/Ti	(Flanges)
Nb - Nb Joining	EBW, LBW
Nb - Ti Joining	EBW
Ti - Ti Joining	TIG
Nb/Ti - Ti Joining	TIG
Nb/Ti - Nb Joining	EBW, LBW

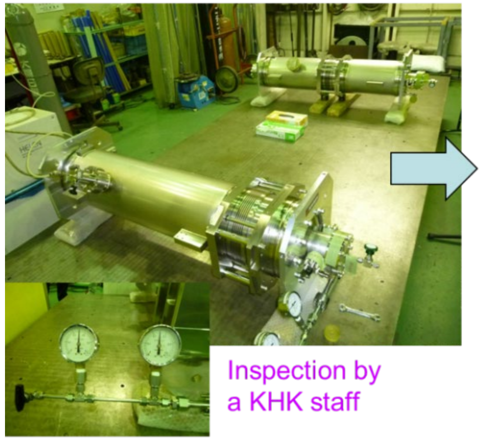
High pressure gas safety low in Japan

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)

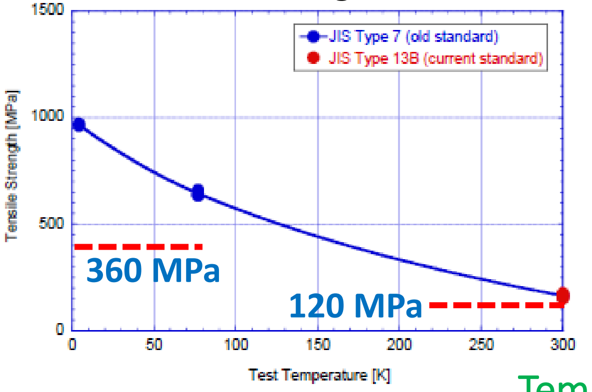


Inspection by
a KHK staff

Cavity string assembly

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

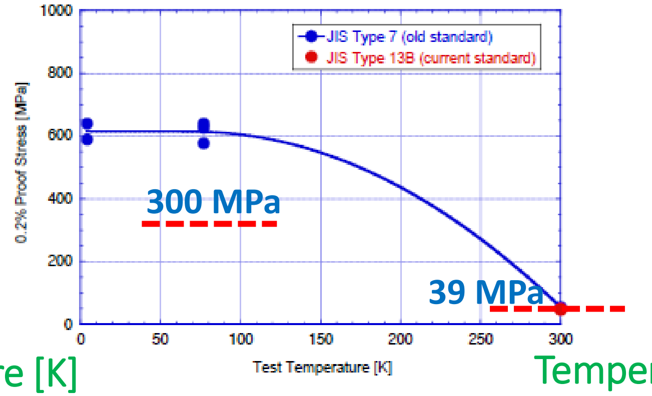
Tensile strength of Nb



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

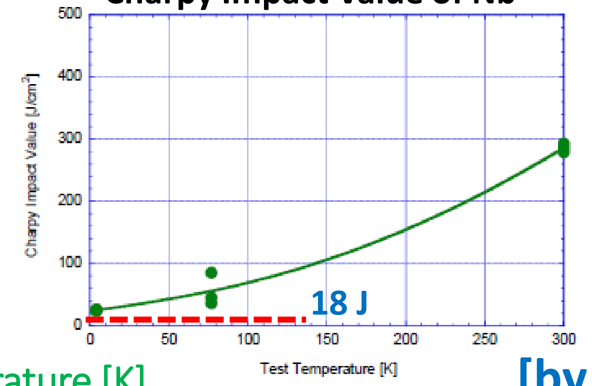


Fig. 5(b) Charpy impact value of Nb (10 mm wide).

[by H. Nakai (KEK)]

Surface treatment (smooth and clean)

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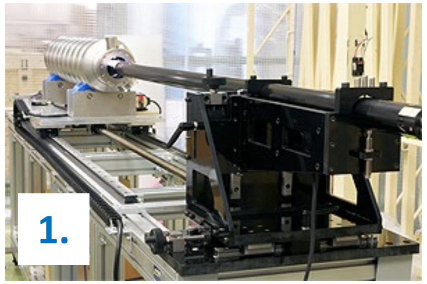
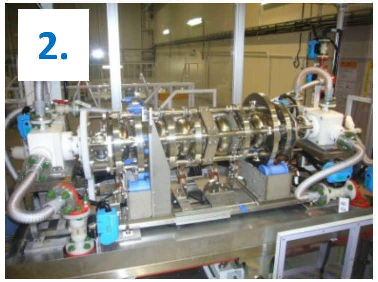
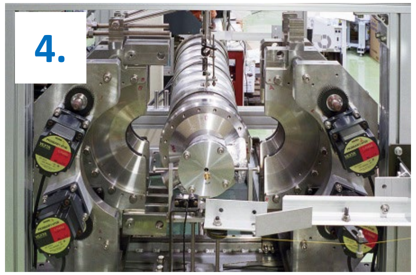


Inspection of inner surface



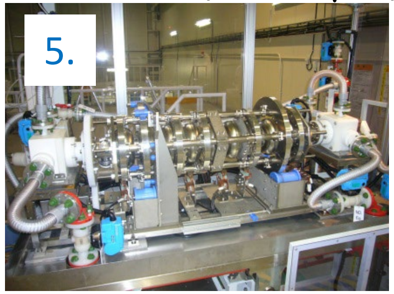
Pre-EP + EP-I (5+100 μm)

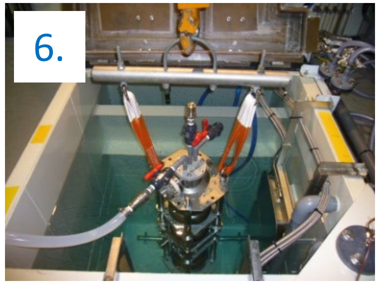
Anneal (750°C, 3h)



Pre-tuning (flatness, f_0)

EP-II
(5~20 μm)

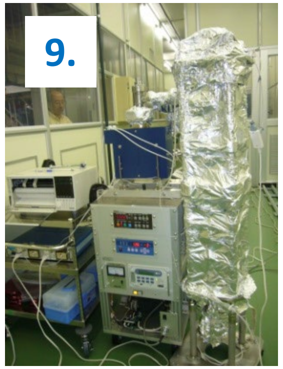




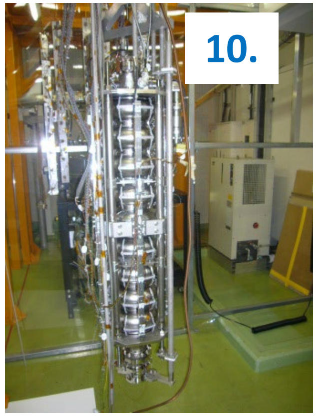
Hot bath rinsing with ultra-sonic

HPR

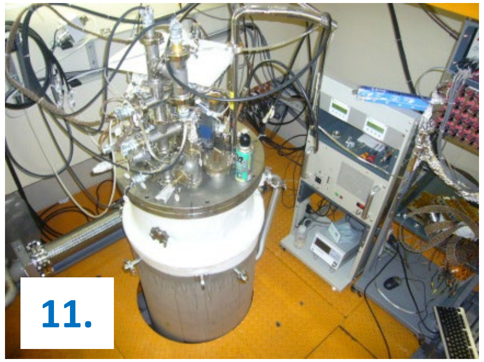
Assembly (Class 10)



Baking (120°C, 48h)
(Class 1000)



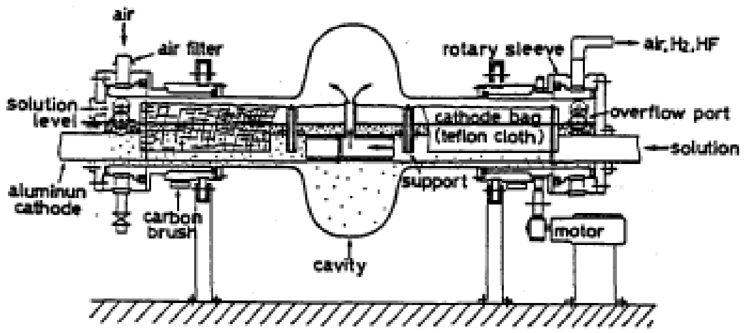
Hanging stand with T-map



Vertical Test

Electro-polishing: EP

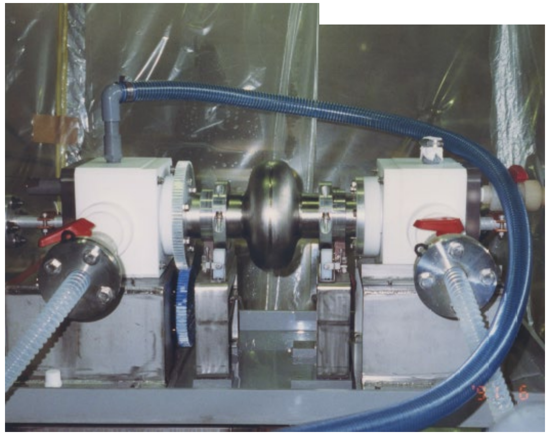
Electro-polishing Device



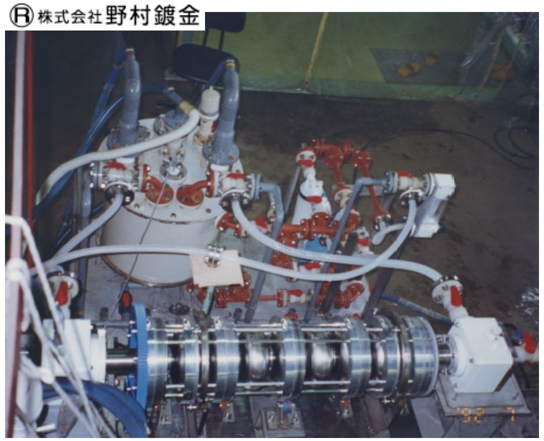
by K. Saito (4th SRF-WS in 1989')

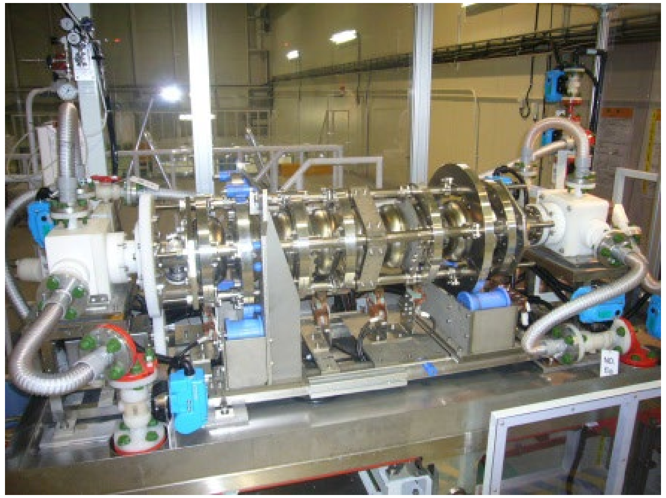
NOMURA PLATING
株式会社野村鍍金

1993'

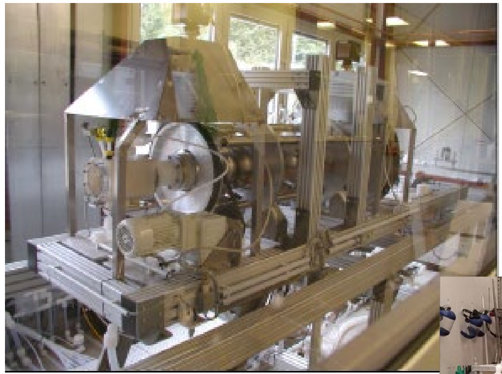


1998'

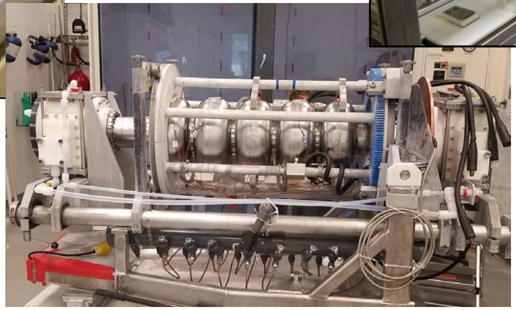




2006'
STF/KEK



DESY



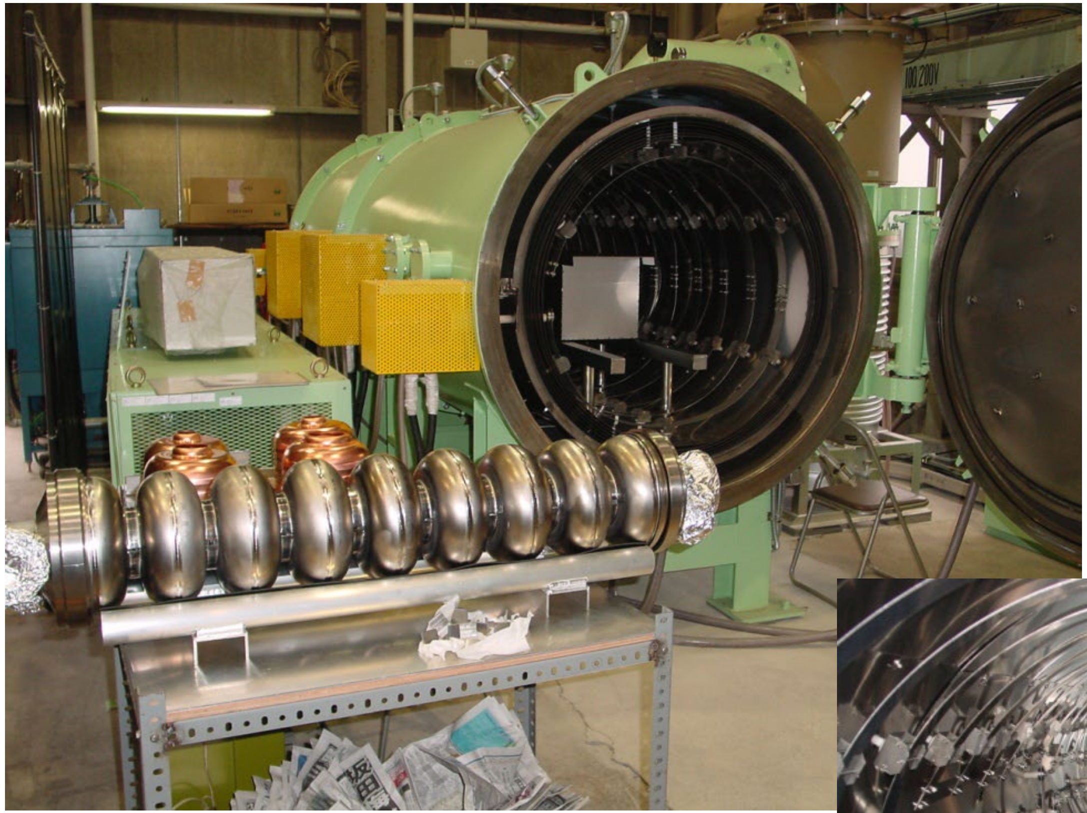
JLab

ANL/
FANL

E. ZANON/DESY
Ningxia/IHEP
Wuxi/SINAP

RI/
DESY

Vacuum furnace for heat treatment



<u>Vacuum furnace with diffusion-pump</u>

for hydrogen degassing:

max. temp. = 800 ^{o}C

1. x10^{-4} Pa at RT

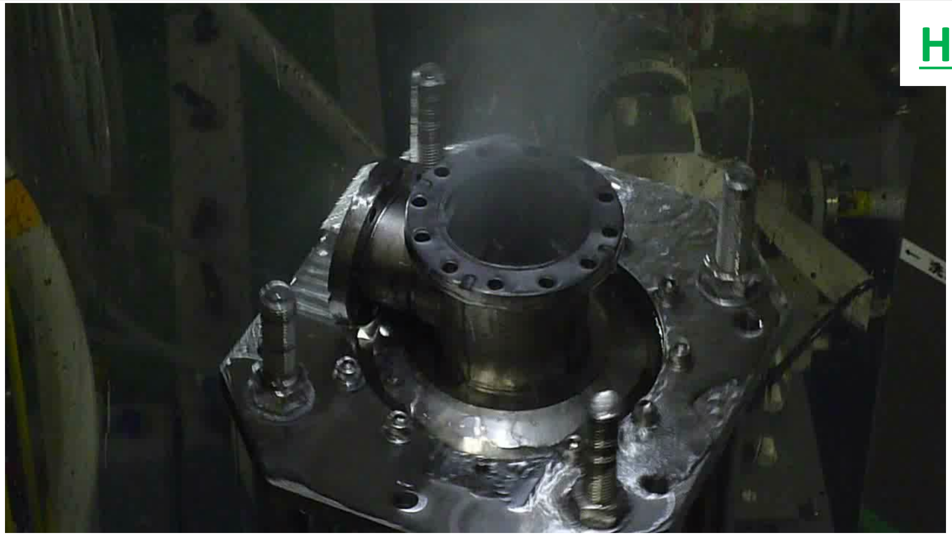
<u>New clean vacuum furnace with cryopump</u>

for N-doping and N-infusion:

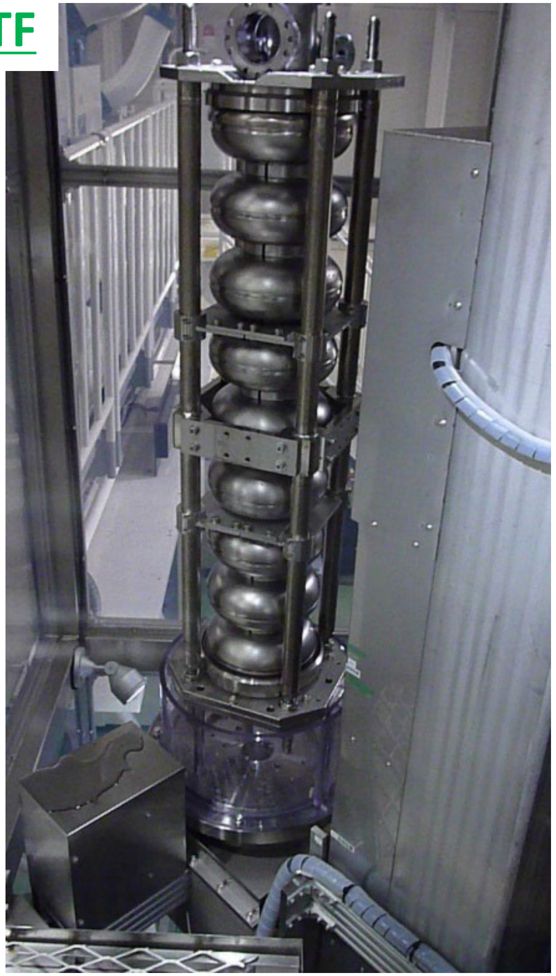
max. temp. = 1200 ^{o}C

1. x10^{-6} Pa at RT

High pressure rinsing: HPR

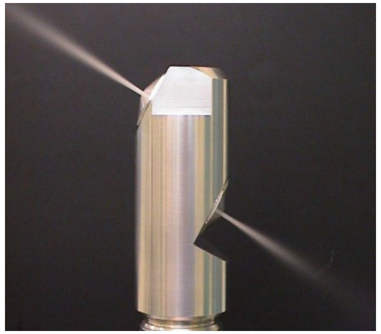


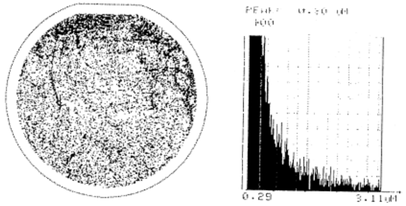
HPR-1 at STF



Pressure = 8 MPa

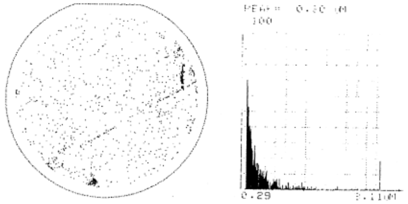
Purity = 18 MΩ・cm





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')

Nozzle: fixed

Cavity: rotation, up/down

HPR-2 at COI

Nozzle: rotation

Cavity: up/down

Cleanroom Assembly (class-10, ISO-4)

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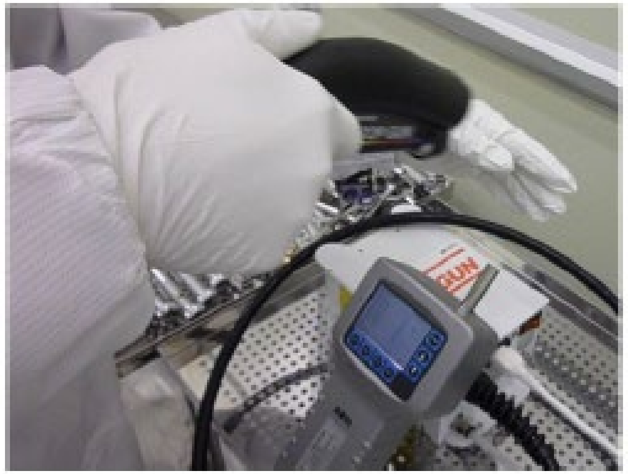

- Parts cleaning
- UPW rinsing
- Ultra-sonic bath
- Ionized gun
- Particle counter
- Ar gas flow

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

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

Summary (1)

- 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^{o}C HT, HPR, 120^{o}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.

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!

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)

Questions !