中国科学院上海高等研究院
SHANGHAI ADVANCED RESEARCH INSTITUTE, CHINESE ACADEMY OF SCIENCES

Superconducting Cavity

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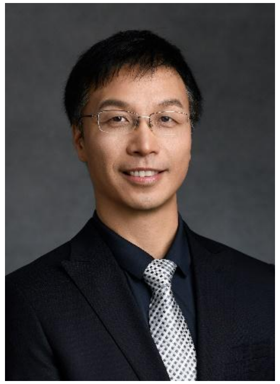
Feb. 04th, ASSCA 2026

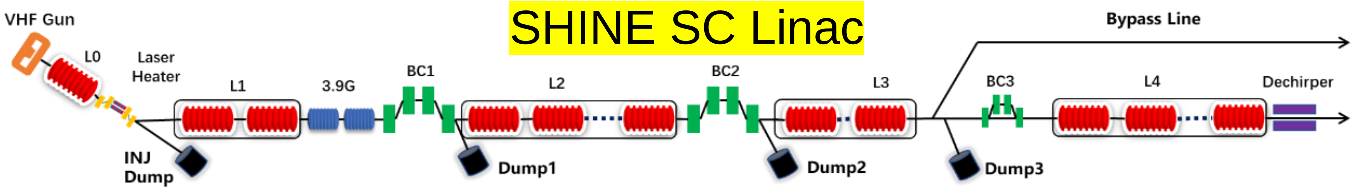
Korea University Sejong Campus, Republic of Korea

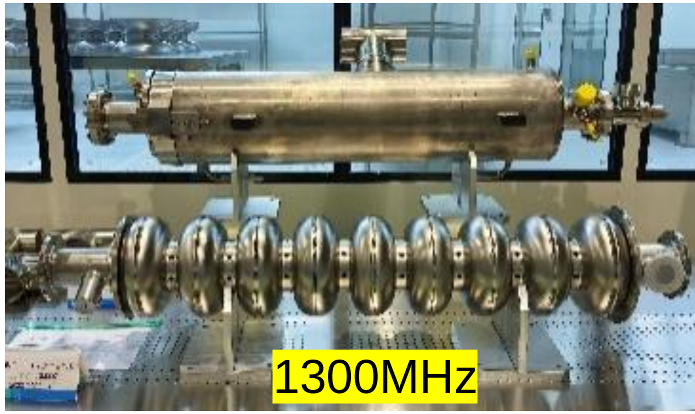
Outline

Introduction of Lecturer

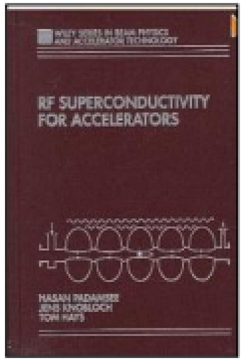


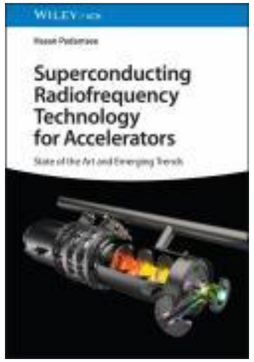
- **Dr. Hongtao HOU**
- **Shanghai Advanced Research Institute, Chinese Academy of Sciences**
- **E-mail address: houht@sari.ac.cn**
- **Involved projects:** SSRF, SSRF-II, SHINE
- **Cavities:** 500MHz single cell cavities for SSRF, 1500MHz 2-cell harmonic cavity for SSRF-II, 1300MHz cavities for SHINE





Suggested books





1. H. Padamsee, J. Knobloch, T. Hays, *"RF-Superconductivity for Accelerators"*, Wiley-VCH (1998).
2. H. Padamsee "RF superconductivity", WILEY-VCH (2009)
3. H. Padamsee "Superconducting Radiofrequency Technology for Accelerators", WILEY-VCH (2023)

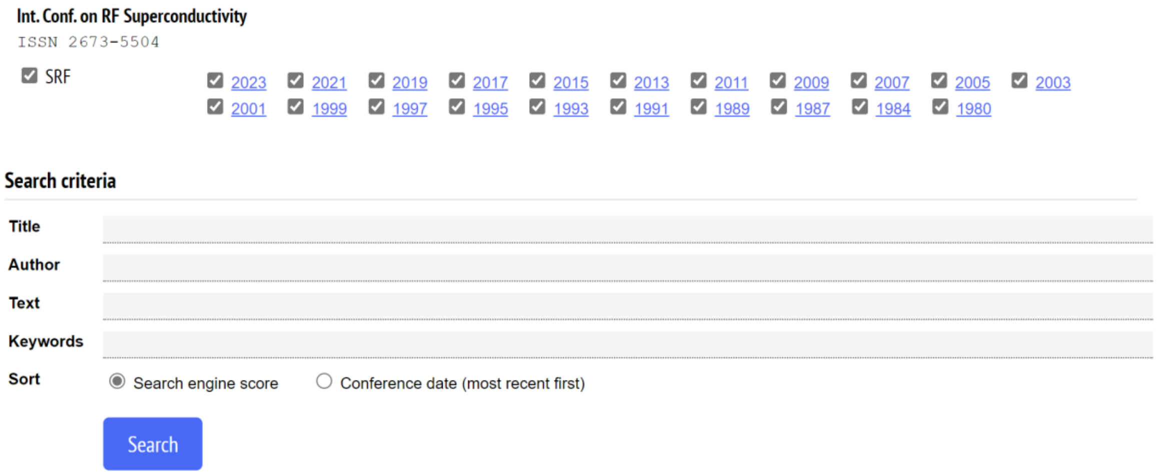
Suggested Proceedings

1. SRF conference

https://www.jacow.org/Main/Proceedings?sel=SRF#SRF

2. TTC meeting

https://tesla.desy.de/meetings/collaboration_meetings_and_ttc_workshos/



1. Introduction

- **What are RF Cavities?**
- **Normal Conducting Cavity vs Superconducting Cavity**
- **Why superconducting cavities**
- **World wide superconducting accelerators**

The roots of $J_n(x)=0$						
x_{nm}	$n=0$	$n=1$	$n=2$	$n=3$	$n=4$	$n=5$
$m=1$	2.405	3.832	5.136	6.380	7.588	8.771
$m=2$	5.520	7.016	8.417	9.761	11.065	12.339
$m=3$	8.654	10.173	11.620	13.015	14.372	
$m=4$	11.792	13.324	14.796			

The roots of $J'_n(y)=0$						
y_{nm}	$n=0$	$n=1$	$n=2$	$n=3$	$n=4$	$n=5$
$m=1$	3.832	1.841	3.054	4.201	5.317	6.416
$m=2$	7.016	5.331	6.706	8.015	9.282	10.520
$m=3$	10.173	8.536	9.969	11.346	12.682	13.987
$m=4$	13.324	11.706	13.170			

p_{mn} and q_{mn} is the m^{th} root of n^{th} Bessel function and its derivative respectively

1. RF Cavity

Maxwell Equations

Faraday's Law: $\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$

Ampère's Law: $\nabla \times \boldsymbol{H} = \frac{\partial \boldsymbol{D}}{\partial t} + \boldsymbol{J}$

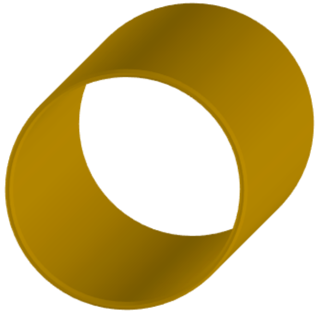
Gauss' Law (Electricity) : $\nabla \cdot \boldsymbol{D} = \rho$

Gauss' Law (Magnetism) : $\nabla \cdot \boldsymbol{B} = 0$

Where

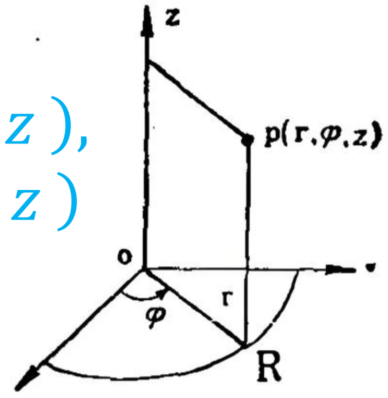
$\boldsymbol{J}$ is the current density
$\boldsymbol{E}$ is the electric field intensity
$\boldsymbol{D}$ is the electric flux density
$\boldsymbol{H}$ is the magnetic intensity field
$\boldsymbol{B}$ is the magnetic flux density
$\boldsymbol{\rho}$ is the charge density

Circular waveguides



Cylindrical coordinate system

$E(r, \varphi, z)$,
$H(r, \varphi, z)$



TE_{mnp} mode

$$
\begin{cases}
E_z = 0 \\
E_r = \dfrac{jn\omega_0\mu_0}{k_c^2 r} H_m J_n(k_c r)\sin[n(\phi-\phi_0)]e^{-jk_z z} \\
E_\phi = \dfrac{jn\omega_0\mu_0}{k_c} H_m J_n'(k_c r)\cos[n(\phi-\phi_0)]e^{-jk_z z} \\
H_z = H_m J_n(k_c r)\cos[n(\phi-\phi_0)]e^{-jk_z z} \\
H_r = -\dfrac{jk_z}{k_c} H_m J_n'(k_c r)\cos[n(\phi-\phi_0)]e^{-jk_z z} \\
H_\phi = \dfrac{jnk_z}{k_c^2 r} H_m J_n(k_c r)\sin[n(\phi-\phi_0)]e^{-jk_z z}
\end{cases}
$$

$$k_c = q_{mn}/a \qquad k_z = p\boldsymbol{\pi}/l$$

TM_{mnp} mode

$$
\begin{cases}
E_z = E_m J_n(k_c r)\cos[n(\phi-\phi_0)]e^{-jk_z z} \\
E_r = -\dfrac{jk_z}{k_c} E_m J_n'(k_c r)\cos[n(\phi-\phi_0)]e^{-jk_z z} \\
E_\phi = \dfrac{jnk_z}{k_c^2 r} E_m J_n(k_c r)\sin[n(\phi-\phi_0)]e^{-jk_z z} \\
H_z = 0 \\
H_r = -\dfrac{jn\omega_0\varepsilon_0}{k_c^2 r} E_m J_n(k_c r)\sin[n(\phi-\phi_0)]e^{-jk_z z} \\
H_\phi = -\dfrac{jn\omega_0\varepsilon_0}{k_c} E_m J_n'(k_c r)\cos[n(\phi-\phi_0)]e^{-jk_z z}
\end{cases}
$$

$$k_c = p_{mn}/a \qquad k_z = p\boldsymbol{\pi}/l$$

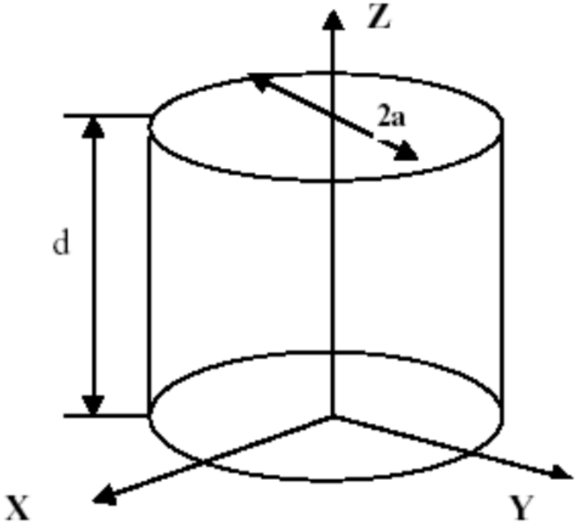
1. RF Cavities

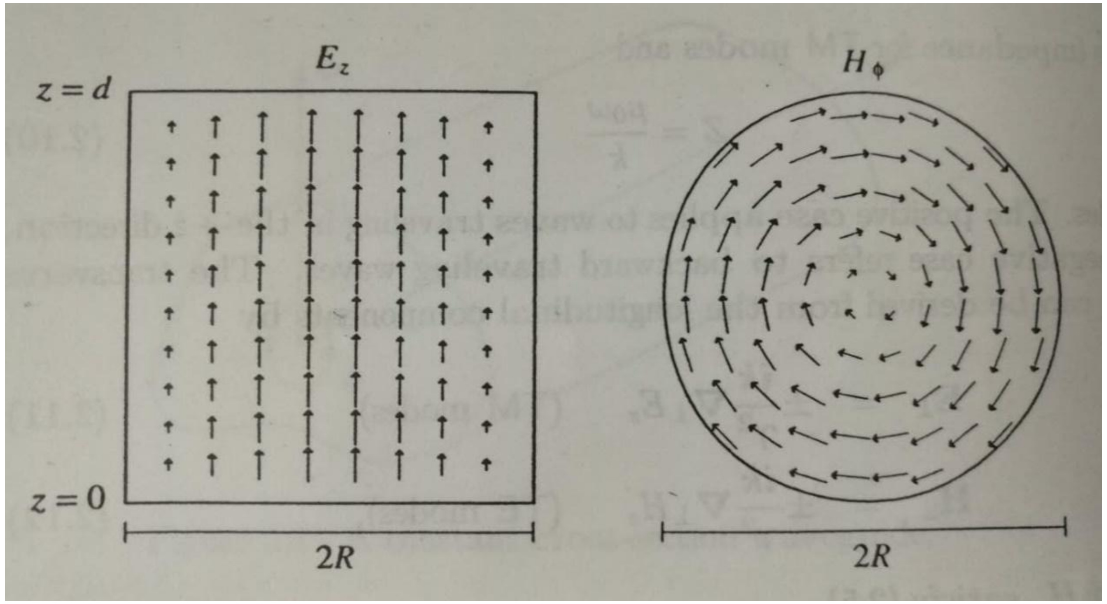
- **Add electric boundaries at both ends → Circular waveguide to pillbox cavity**
- **First mode is TM010 called accelerating mode, which has the lowest frequency, only has axis electrical field →purely Longitudinal E_z**
  - **Frequency only depends on radius, independent on length**

$$f_{010}[Hz] = \frac{2.405\ C_{light}[m/s]}{2\pi R[m]}$$

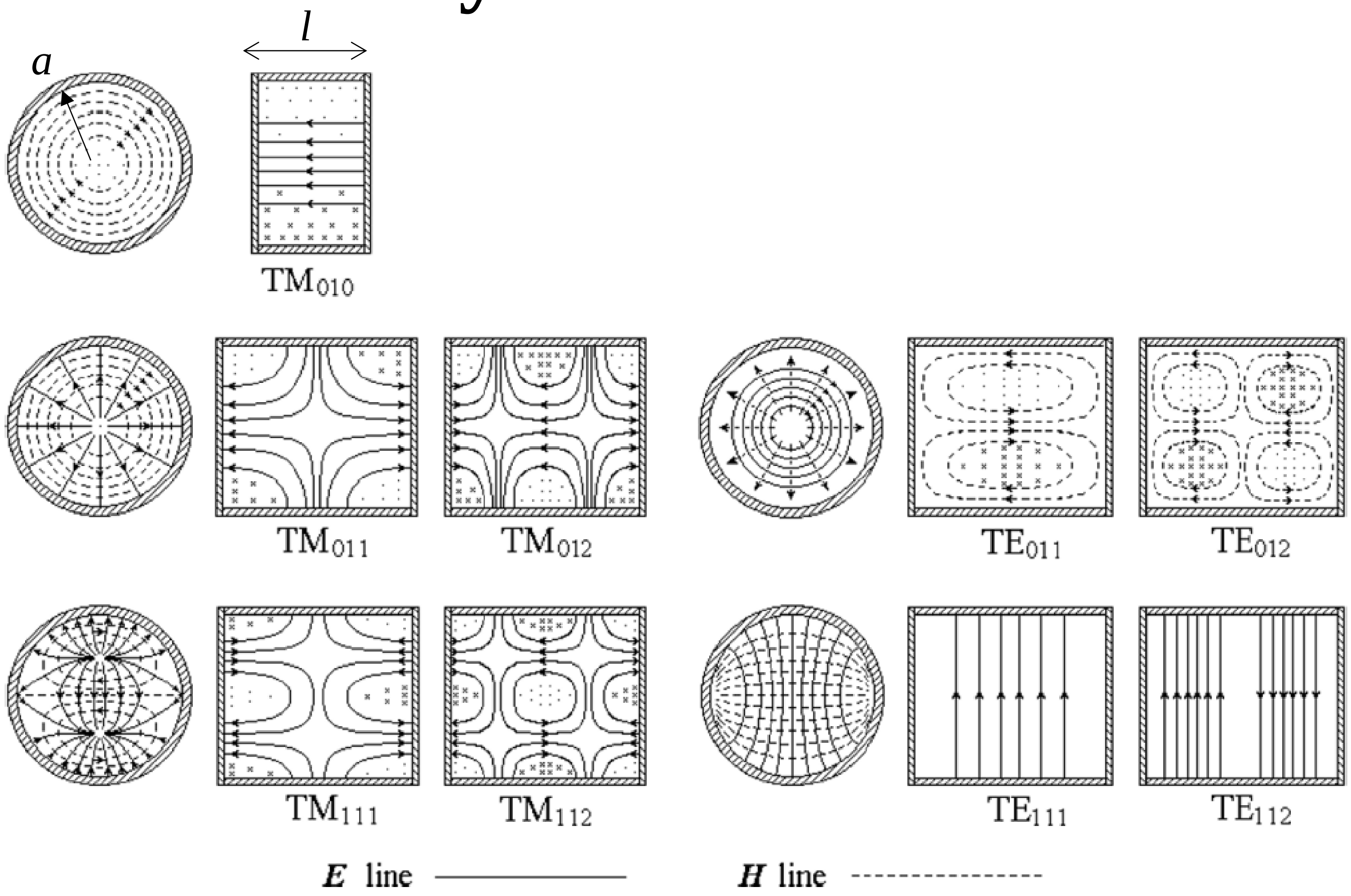
$$E_z = E_0\, J_0\left(\frac{2.405\, r}{R}\right)\cos(\omega t)$$

$$H_\phi = \frac{E_0}{\sqrt{\mu/\varepsilon}} J_1\left(\frac{2.405\, r}{R}\right)\sin(\omega t)$$

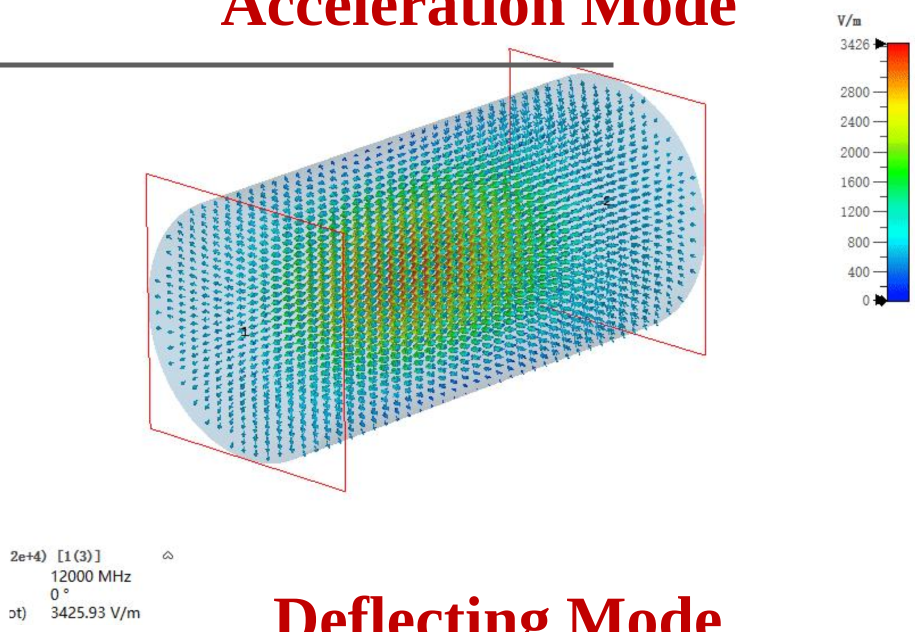




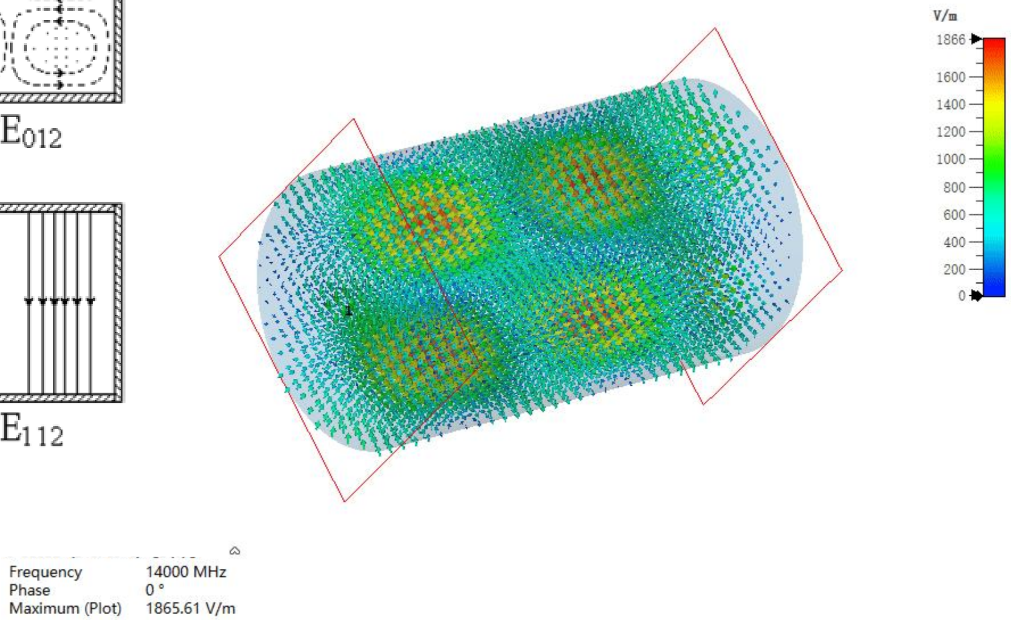
1. RF Cavity: Resonant modes



Acceleration Mode



Deflecting Mode

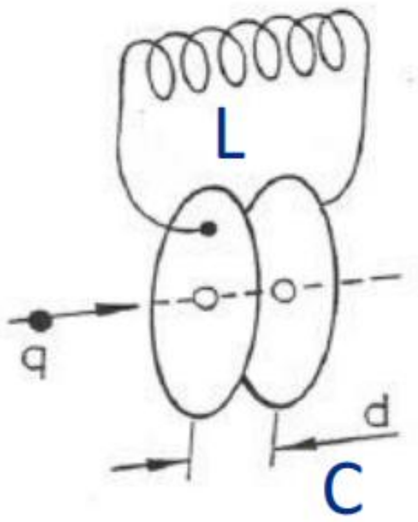


1. RF Cavity: LC circuit vs cavity

$$\omega_0=(LC)^{-1/2}$$

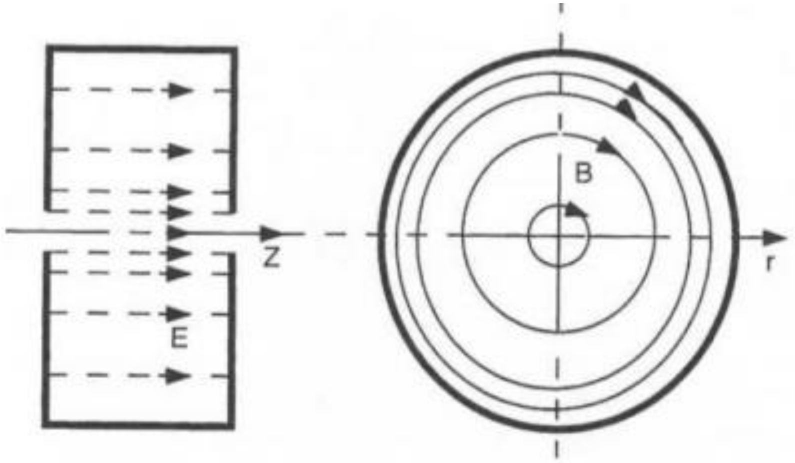
An LC circuit, the simplest form of RF resonator. This circuit and a resonant cavity share common aspects:

- Energy is stored in the electric and magnetic fields
- Energy is periodically exchanged between electric and magnetic field
- Without any external input, the stored power will turn into heat



- Electric field used for acceleration is concentrated near the axis
- Magnetic field is concentrated near the cavity outer wall

TM010



1. RF Cavities

Main parameters

- Resonant frequency f_0
- Accelerating voltage / cavity voltage V_c
- Accelerating Length L、
- Gradient E_{acc}
- Stored Energy U
- Unloaded quality Factor Q0
- Geometry factor G
- Surface Resistance Rs
- Dissipated load / Cavity power loss Pc
- Shunt Impedance R/Q
- Ratio Ep/Eacc
- Ratio Bp/Eacc
- Maximize G*R/Q

$$U = \frac{1}{2}\mu_0 \int_V |\mathbf{H}|^2 dv = \frac{1}{2}\epsilon_0 \int_V |\mathbf{E}|^2 dv$$

$$P_c = \frac{1}{2}R_s \int_S |\mathbf{H}|^2 ds \qquad Q_0 = \frac{\omega_0 \mu_0 \int_V |\mathbf{H}|^2 dv}{R_s \int_S |\mathbf{H}|^2 ds}$$

$$G = \frac{\omega_0 \mu_0 \int_V |\mathbf{H}|^2 dv}{\int_S |\mathbf{H}|^2 ds} \qquad Q_0 = \frac{G}{R_s}$$

$$R_a = \frac{V_c^2}{P_c} \qquad \frac{R_a}{Q_0} = \frac{V_c^2}{\omega_0 U}$$

$$P_c = \frac{V_c^2}{R_a} = \frac{V_c^2}{\frac{R_a}{Q_0} \times Q_0} = \frac{V_c^2}{\frac{R_a}{Q_0} \times G} \times R_s$$

Accelerator operation requirement

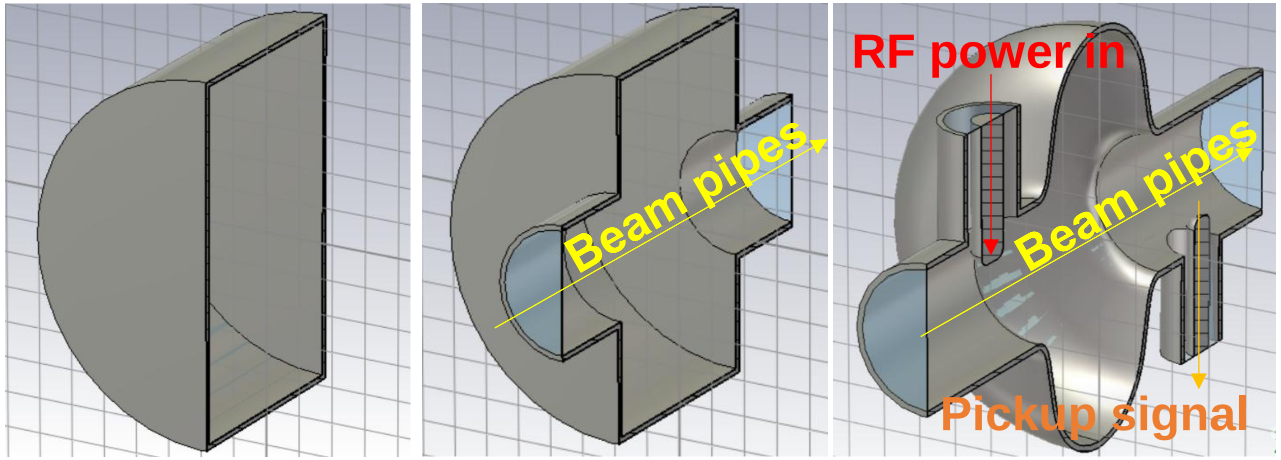
Cavity material

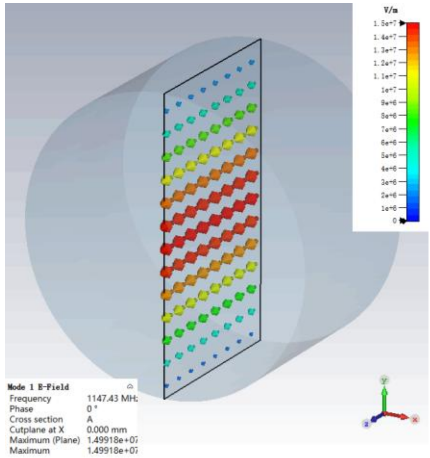
Cavity geometry

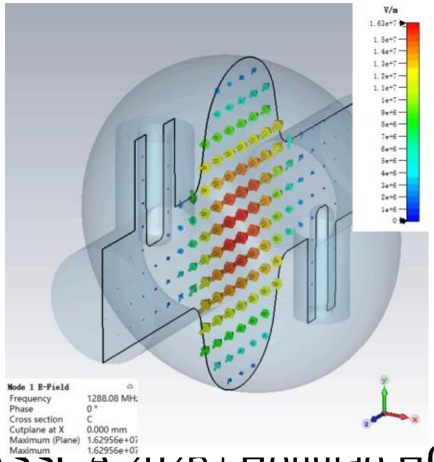
[1] F.S.He, SRF cavity and tuner, ASSCA 2025

1. RF Cavities

- **Add beam pipes for particles movement, power coupler for feeding rf power, pickup antenna for monitor & Control → pillbox cavity to “real” cavity**

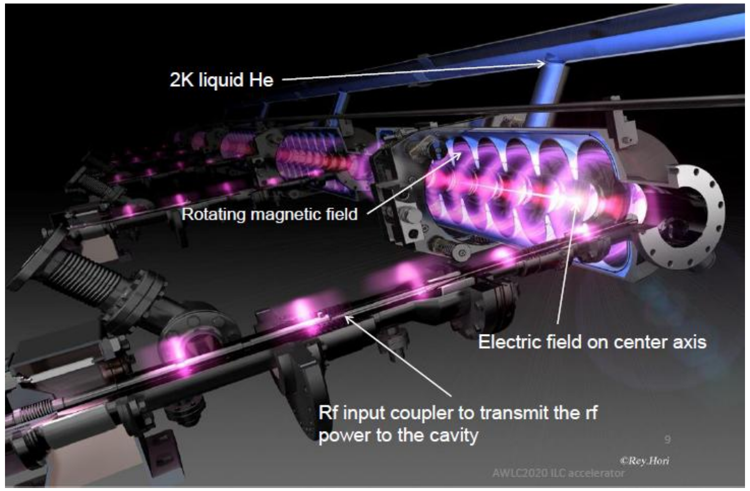




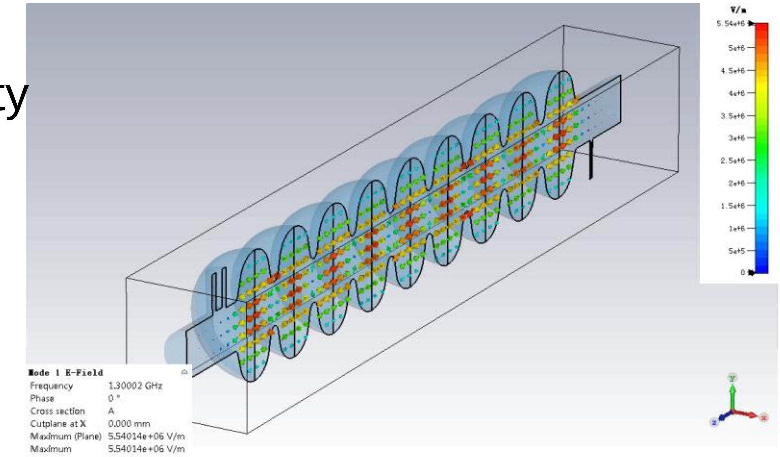


To save longitudinal space

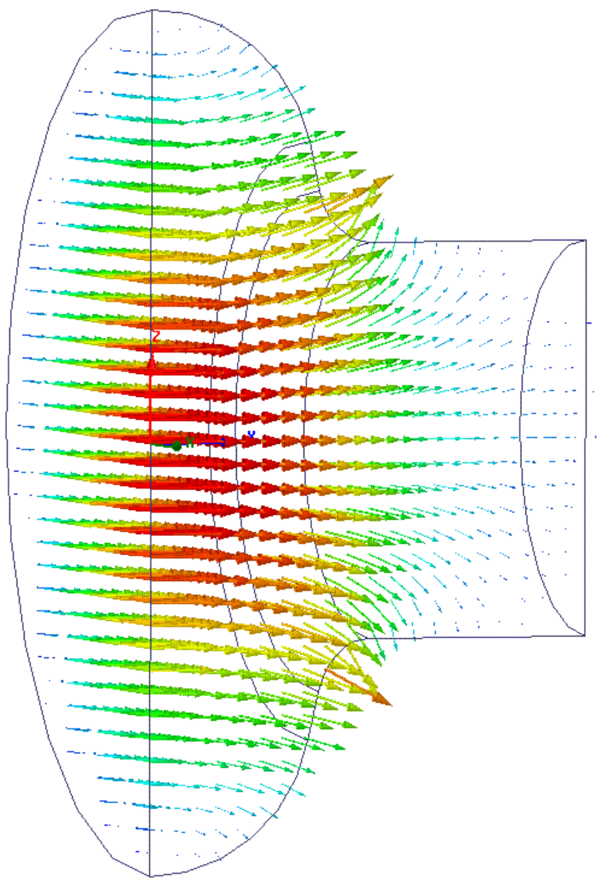
From single cell cavity to multi-cells cavity



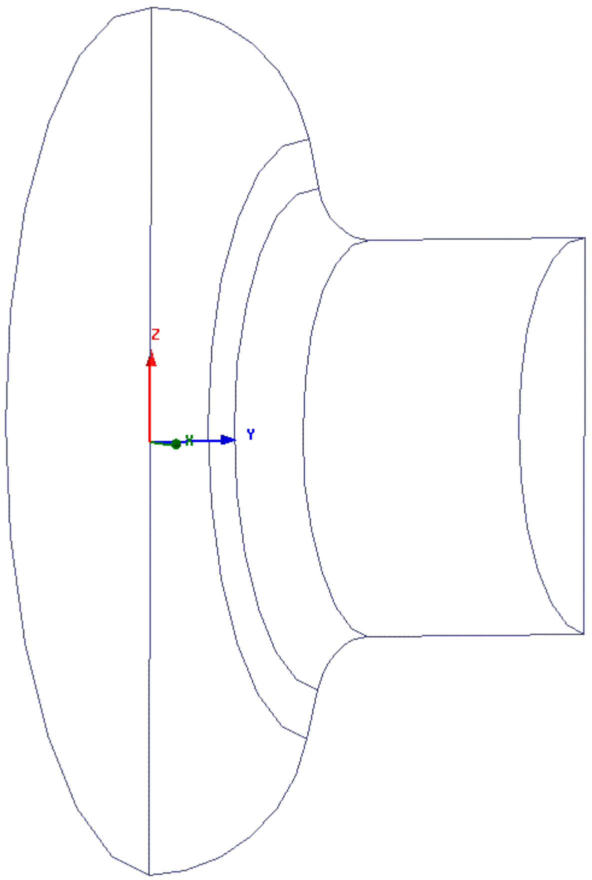
TESLA cavity:
1300MHz 9-cell cavity



TM_{010}-mode



electric field



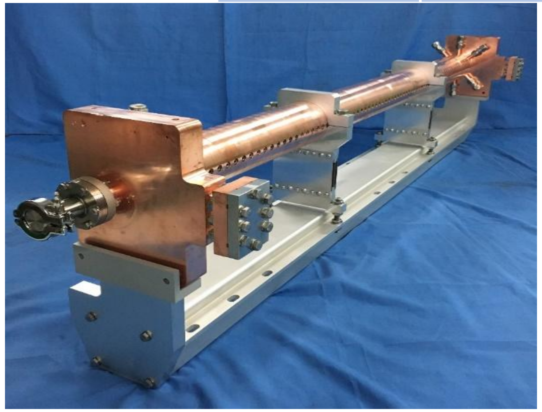
magnetic field

1. Introduction

- What are RF Cavities?
- Normal Conducting Cavity vs Superconducting Cavity
- Why superconducting
- World wide superconducting accelerators

Normal Conducting vs Superconducting

No	Name	Normal Conducting	Superconducting	Remarks
1	**Materials (typical, for real cavity)**	OFHC	Nb / Nb3Sn	
2	**Cavity Shape**	• Re-entrant • Disc loaded	• Elliptical for medium beta and high beta • Coaxial lines for low beta	Examples: • High beta cavity: TESLA cavity • Low beta cavity: HWR (Half Wave Resonator), QWR(Quarter wave Resonator), Spoke
3	**Cooling**	water	• Liquid helium • Superfluid helium	



C-band Structure

500MHz PF Cavity

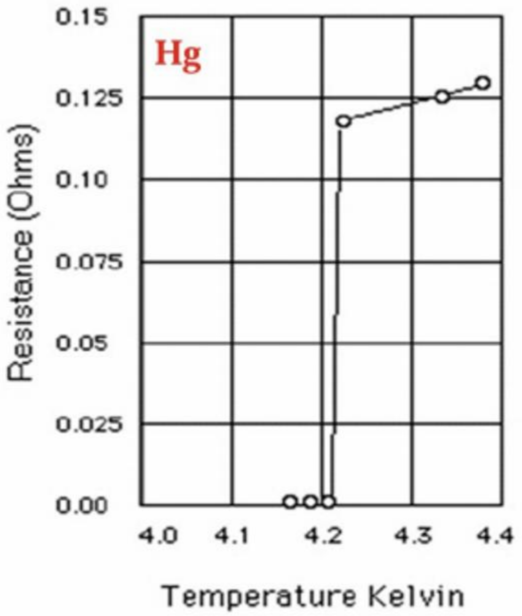
SSRF 3HC

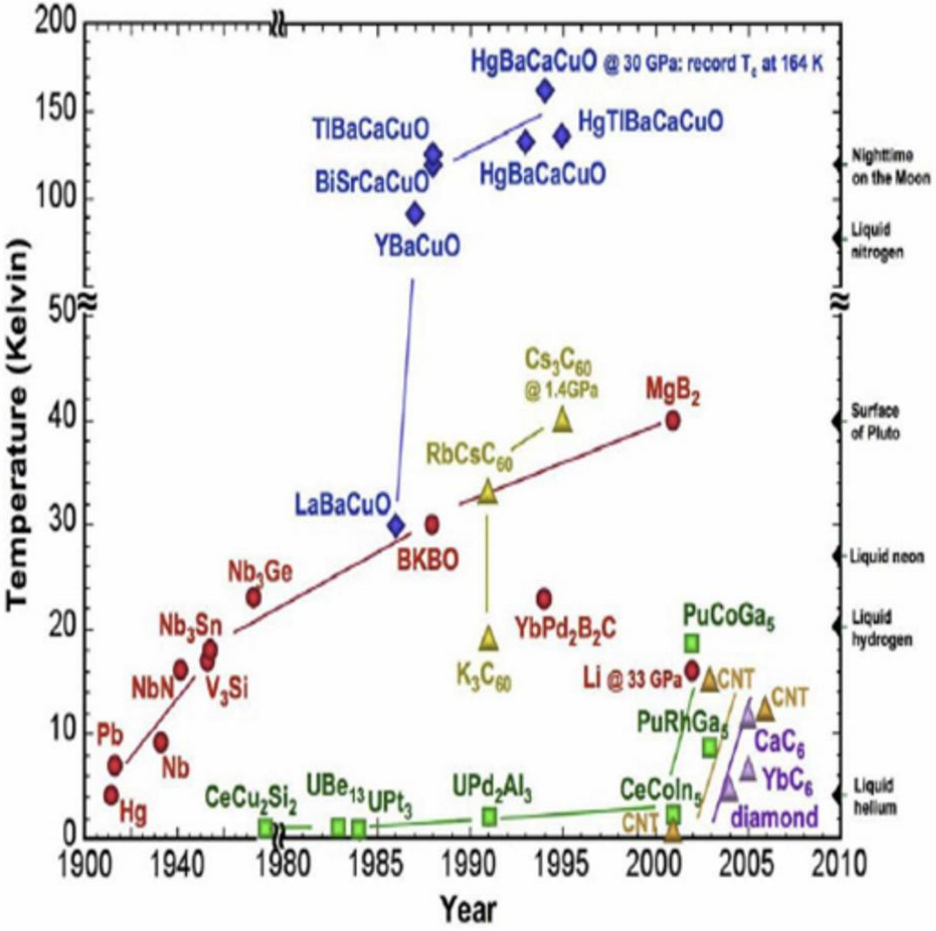
TESLA 1.3GHz cavity for SHINE

[1] Suggested books
[2] Suggested proceedings

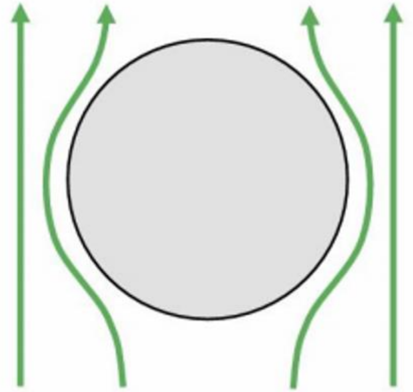
Why Superconducting? Superconductivity

Discovered in 1911 by Heike Kamerlingh Onnes and Giles Holst after Onnes was able to liquify helium in 1908. Nobel prize in 1913



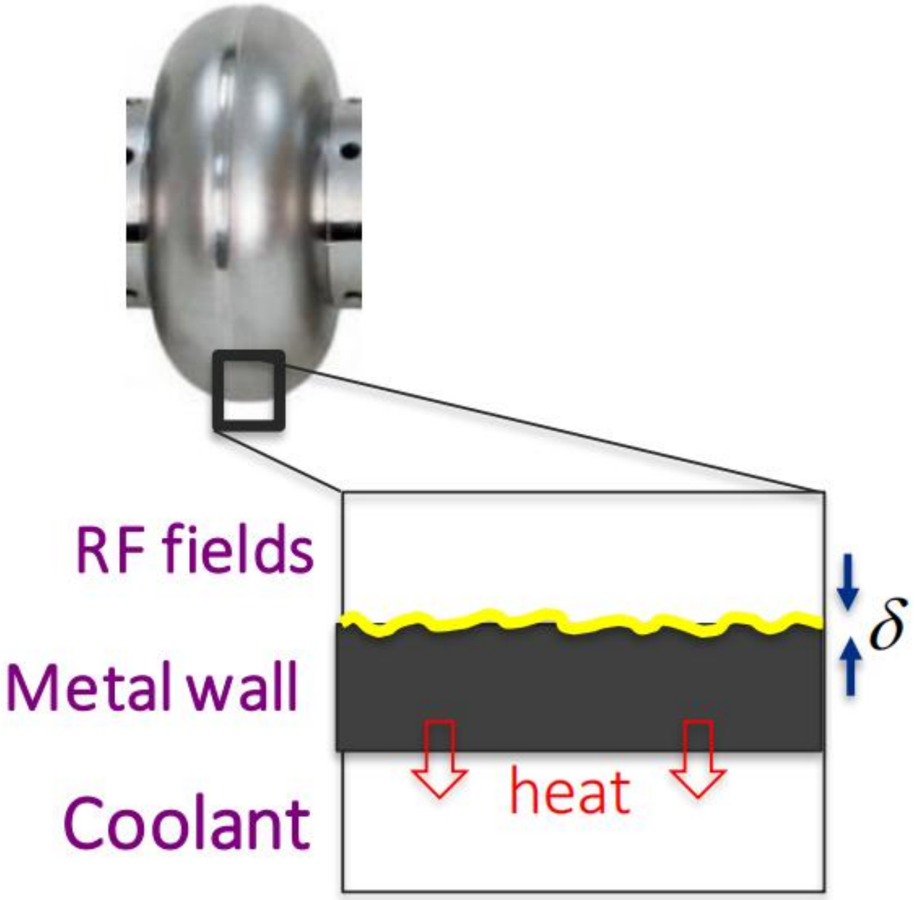


Meissner effect (1933)



Niobium: highest Tc among pure element materials, non toxic

Why Superconducting? Surface Resistance



- RF fields penetrate a ***penetration depth, δ*** the metallic cell walls and dissipate heat in the ***surface resistance, Rs***
- A coolant on the outside extracts the heat and prevents the cavity from heating above its operating temperature
- Water cooling for normal conducting cavity, liquid helium for superconducting cavity

Surface Resistance results in heat

Why Superconducting ? Surface Resistance

- **Dissipated power** in the cavity is proportional to its **surface resistance**
- The cost of cooling the cavity (coolant fluid, temperature, fluid pumping power, etc.) scales with dissipated power
- With hundreds of cavities in a particle accelerator, the cavity cooling cost forms a significant fraction of accelerator operating cost
- **Keeping low RF surface resistance is therefore necessary to reduce the accelerator operating cost.**
- Thus, superconducting cavities for CW or high Duty Factor are the choice at high gradient operation accelerators

Why Superconducting ? Surface Resistance

[3] Eiji Kako, ASSCA 2025

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) ; $\sigma = 0.58 \times 10^{8}$ $[1/\Omega\,m]$

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

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

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) ; $R_{BCS} = 7$ $[n\Omega]$

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

$R_S = 14\ n\Omega$, ($\lambda_0 = 44$ 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*

More information

For Mid-T baking cavities, Q0 maybe higher than **3.0×10^{10}**

- **SRF surface resistance is 1e6 times less!**

Why Superconducting? Surface Resistance

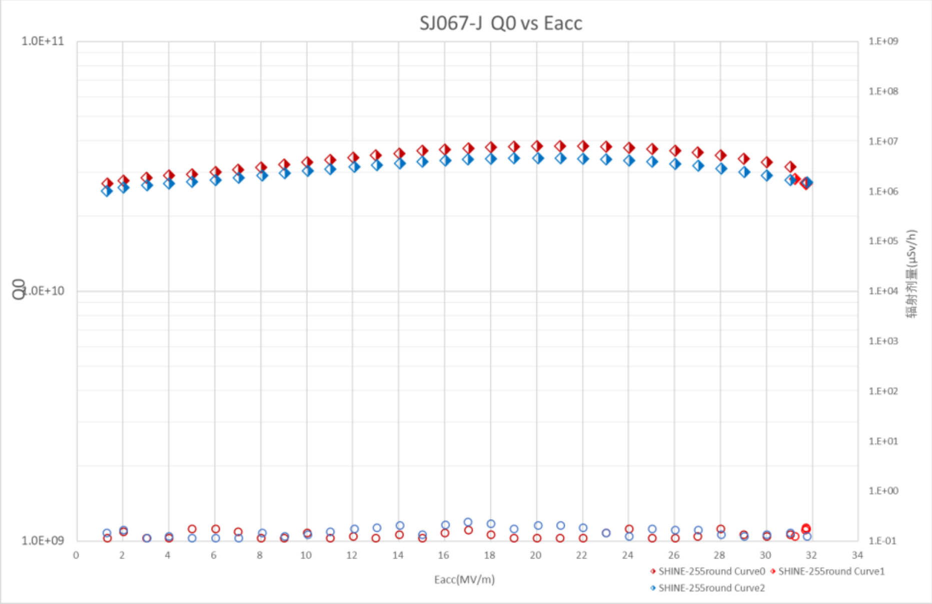
- For copper cavity at room temperature (σ=5.96e7 S/m) for 1.3 GHz, one has surface re: $R_s = \frac{1}{\sigma\delta} = \sqrt{\frac{\mu_0\omega}{2\sigma}}$ = 9.5 mOhm.
- For SRF Nb cavity at 2K one has Rs < 10 nOhm (TESLA type cavity, EP) $R_s \sim \frac{A}{T}\omega^2 \exp\left(-\frac{\Delta}{kT}\right) + R_{res}$
- **SRF surface resistance is 1e6 times less!**
- Thus, SRF cavities for CW or high Duty Factor are choice at high gradient operation accelerators

PF cavities (normal conducting) measured value at SSRF: Q0 < 4e4

表 1：PF 常温腔 RF 参数测量结果

Cavity	frequency（MHz）	Q_L	β in	β t	Q_0	Pickup 耦合度 dB	Tuner 带宽（MHz）
#1	499.650	12000	2.34	0.015	39600	-51.0	1.8
#2	499.654	12500	2.17	0.014	39625	-51.4	2.3

SHINE 1.3GHz 9-cell cavity vertical test: Q0-20~4e10



Why Superconducting? Surface Resistance vs Operation gradient

- For CW or high duty factor operation, In **Normal** linacs a huge amount of power is deposited in the copper structure: MW to have MV Pulsed operation and Low Duty Cycle.
- Copper cavities are limited
  - to gradients near 1MV/m in cw and long-pulse operation because the capital cost of the rf power and the ac-power related operating cost;
  - to surface temperature to avoid causing vacuum degradation, stresses, and metal fatigue due to thermal expansion.
- SRF Cavities
  - Lower surface resistance →High Q0→Low power dissipation on the cavity walls → Low cost for CW or high repetition large accelerators
  - Larger aperture means lower impedance, lower wake field and less influence on beam. Easier alignment and better emittance.

1. Introduction

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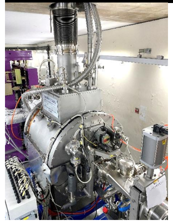
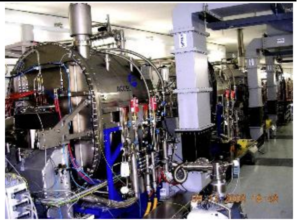
World wide superconducting Accelerators

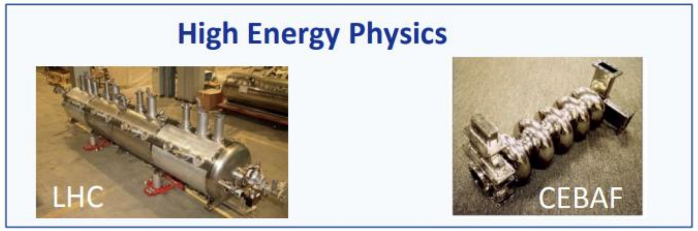
Synchrotron Radiation Light Source





And more……

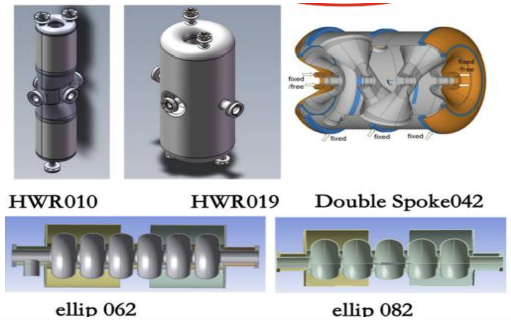
FELs…….

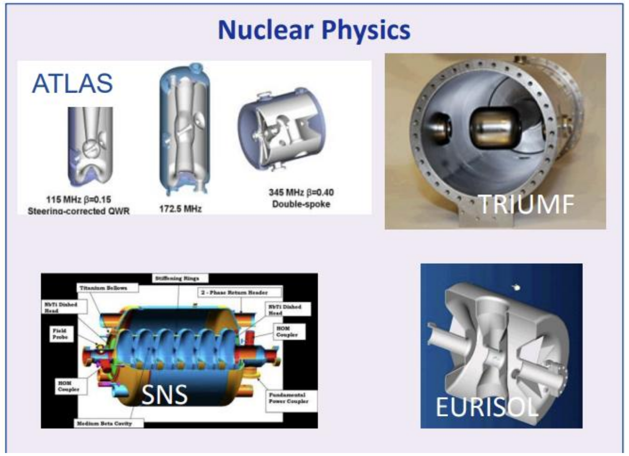


TELSA 1.3GHz 9-cell cavity

- Euro-XFEL
- SLAC-LCLSII/HE
- SHINE
- S^3FEL

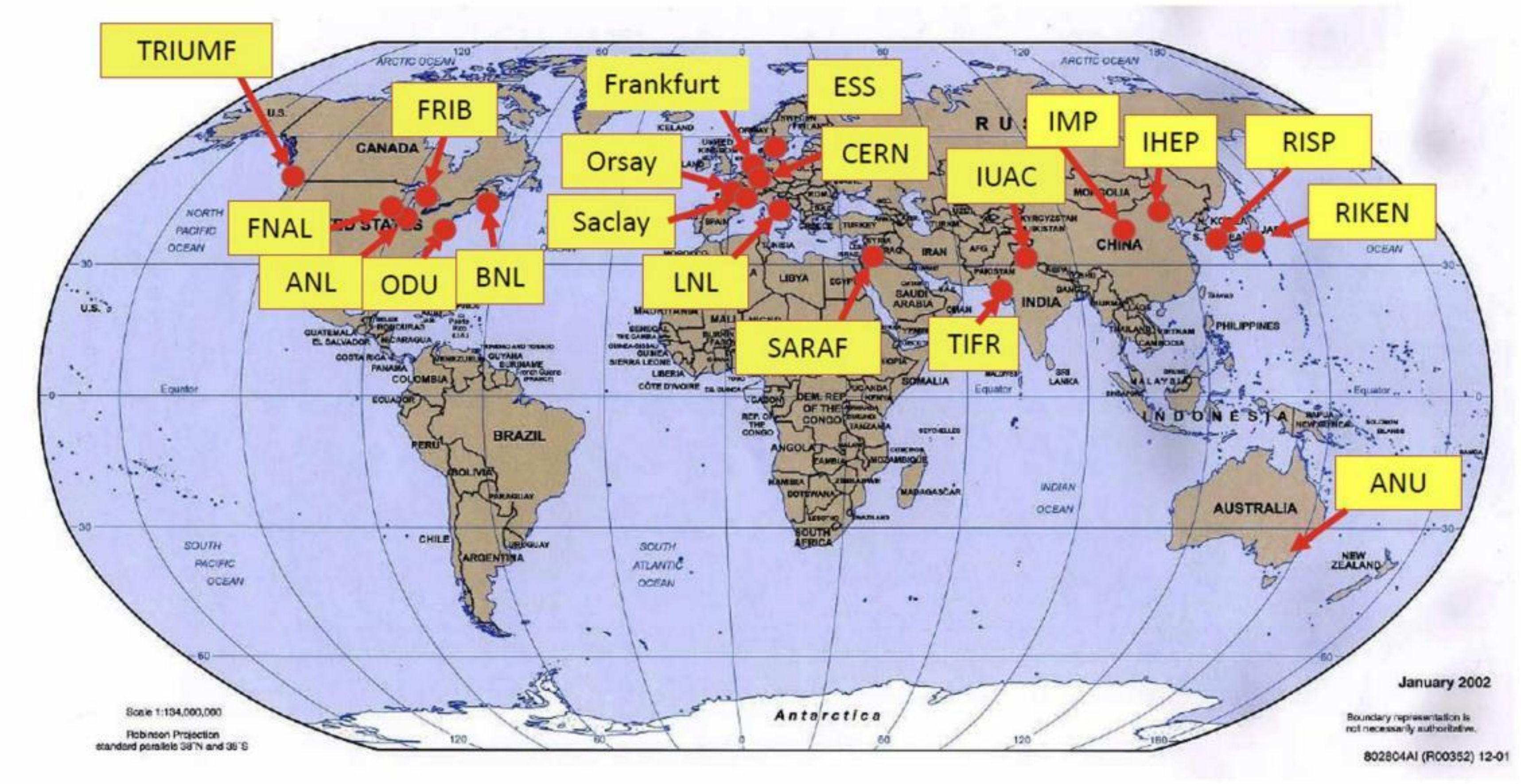
Proton and heavy ion Linacs……





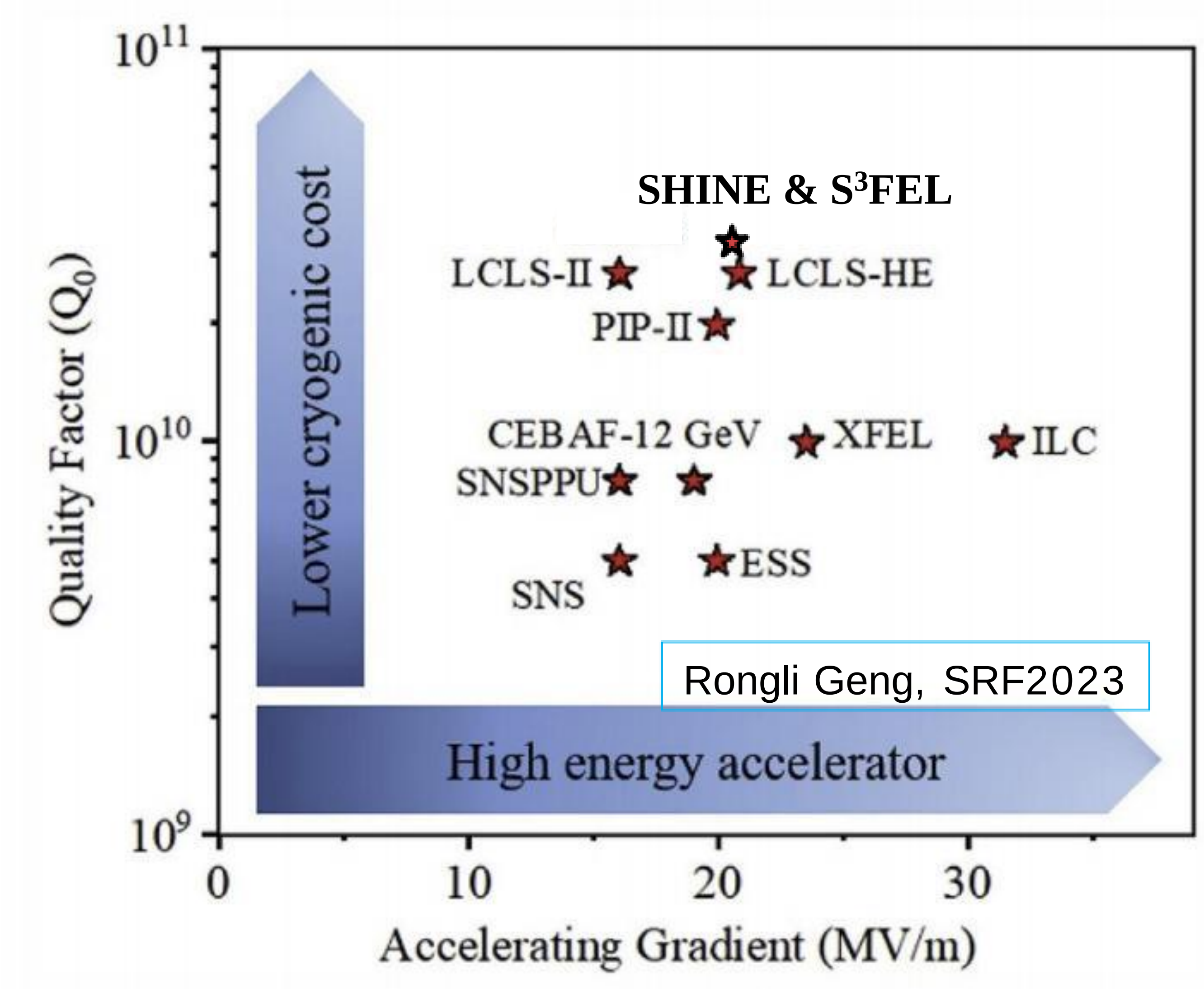
World wide superconducting Accelerators

Superconducting Non-Elliptical Cavity Community



And more……

World wide superconducting Accelerators



- **Operation:** CEBAF, SNS, E-XFEL, LCLS-II
- **Under construction:** ESS, SNSPPU, PIP-II, SHINE, LCLS-II HE, S3FEL et al.
- **Planed:** ILC etc

And more……

[3] Eiji Kako, ASSCA 2025

World wide superconducting Accelerators

- Elemental Particle Physics: (S-KEKB, BEPC, LHC, CEPC, FCC)
- Radiation Light Source: (DIAMOND, CLS, TPS, SLS, PLS, NSLS-II, HEPS, HALF, SAPS) SSRF, HEPS
- 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

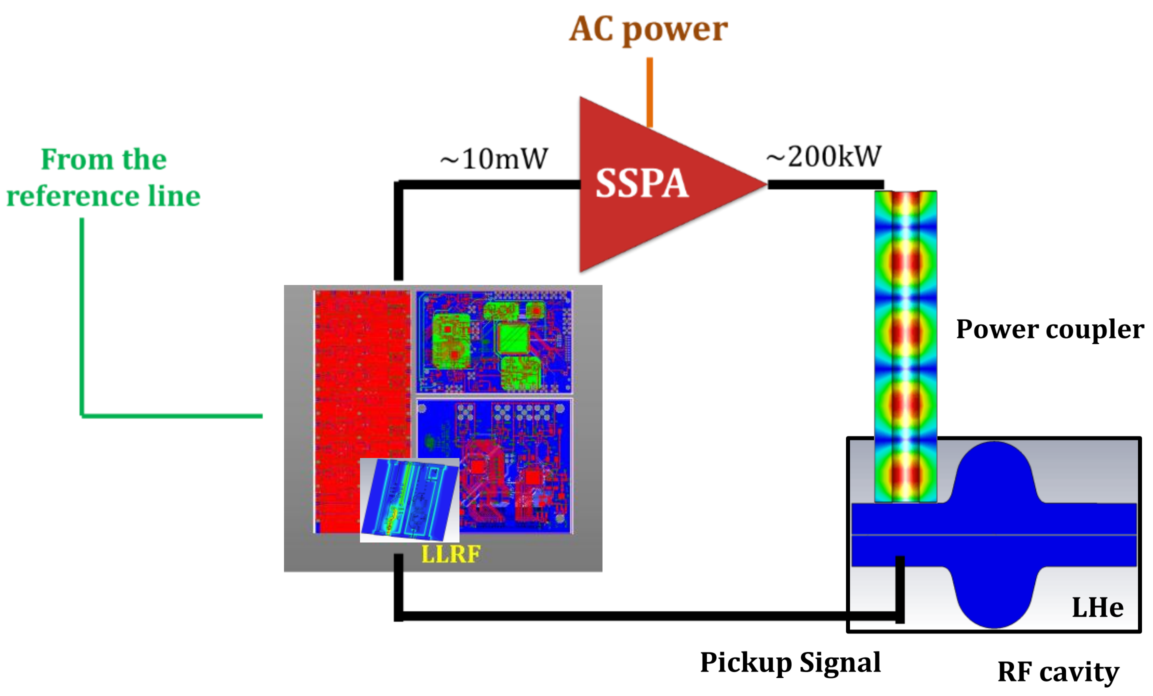
Worldwide FELs

Facility	Wavelength	Country	LINAC	Beam Energy / GeV	Rep. rate / Hz	Status
FLASH	Soft X-ray	DE	SRF	1.25	5000	Operation
European XFEL	Hard X-ray	EU	SRF	17.5	27000	Operation
LCLS-II & HE	Hard X-ray	US	SRF	4	1e6	Commissioning & Under construction
SHINE	Hard X-ray	CN	SRF	8	1e6	Under construction
S^3FEL	Soft X-ray	CN	SRF	2.5	1e6	Approved

2. SRF Cavity

- Design
- SC Materials
- Fabrication
- Post process
- Vertical test

SRF System

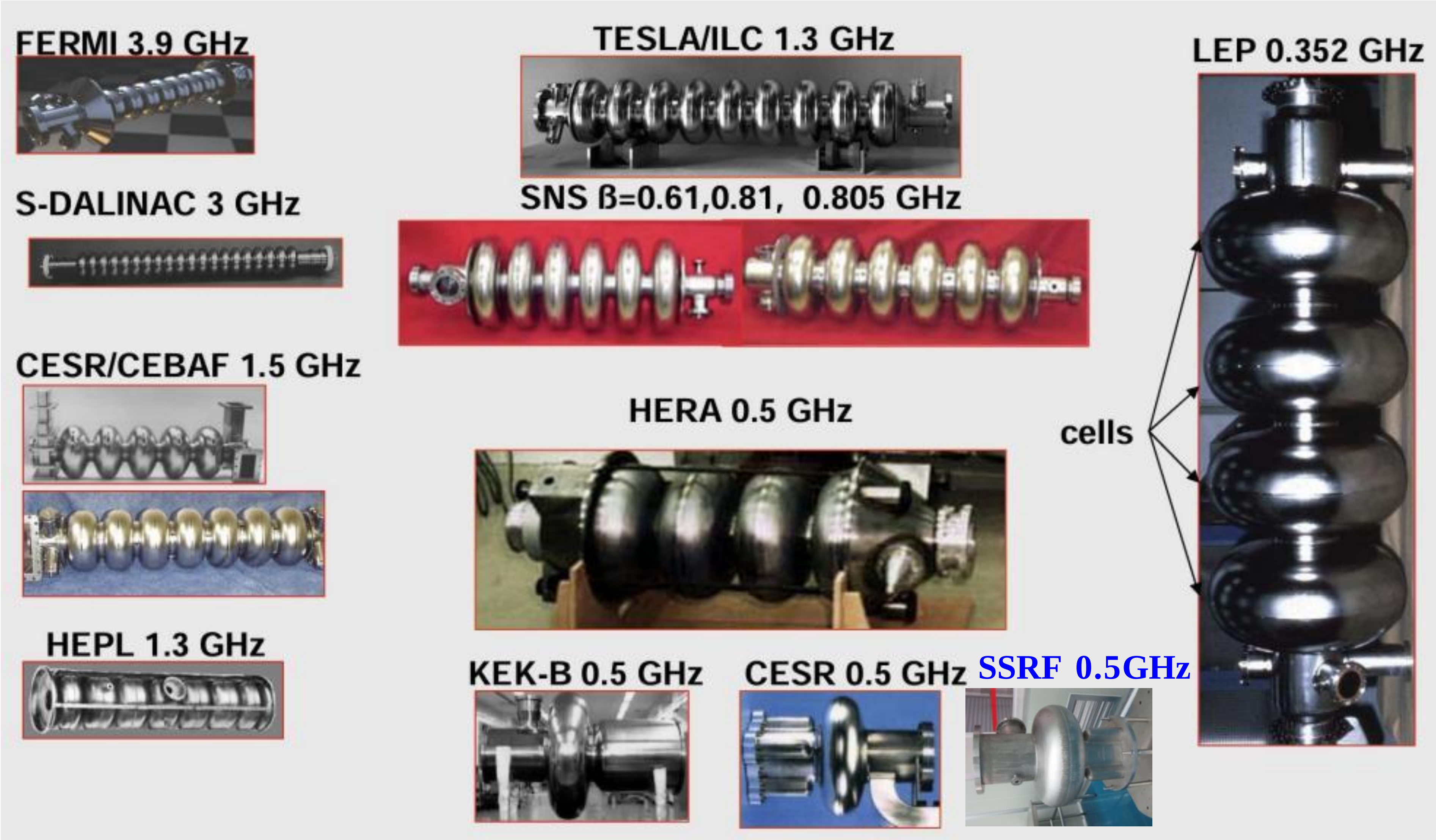


Cavity is the "heart" of RF system

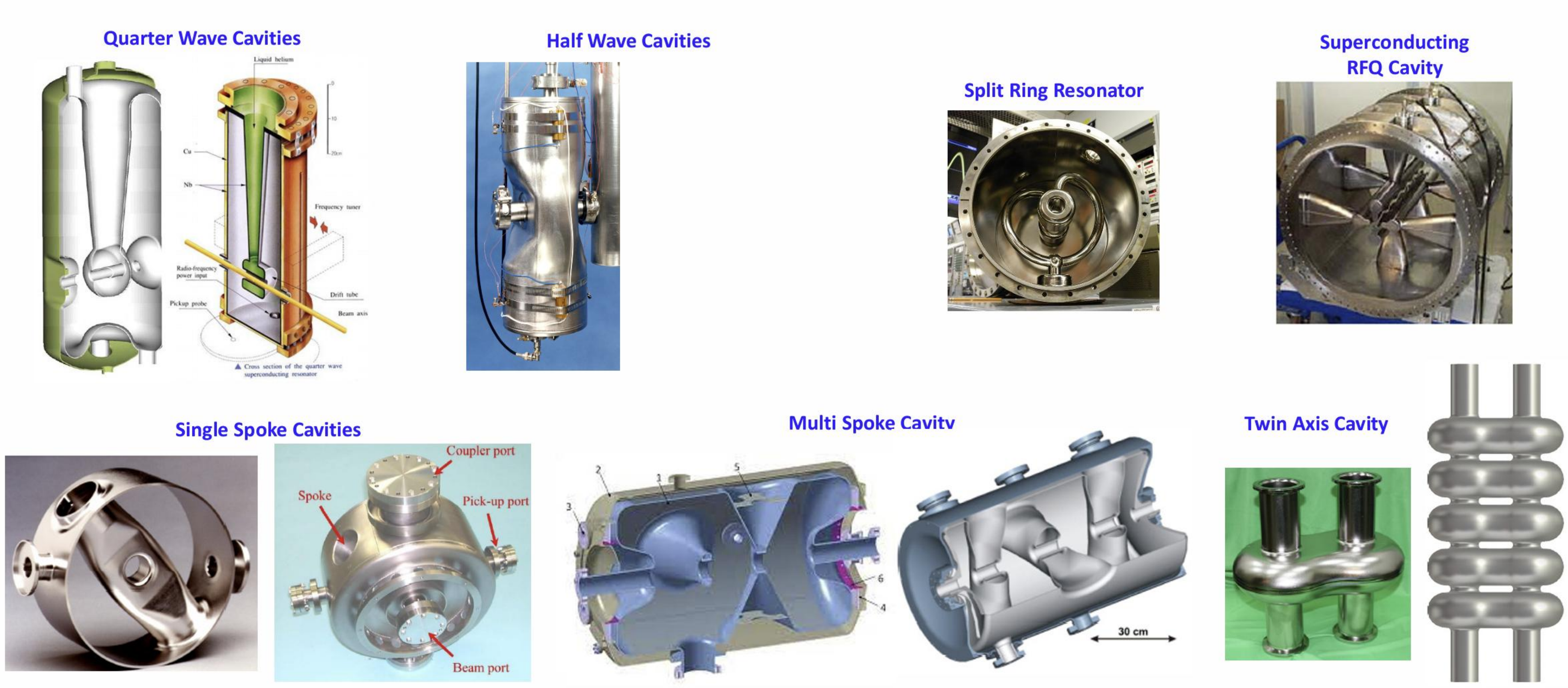
2. SRF Cavity: Elliptical

SSRF 1.5 GHz

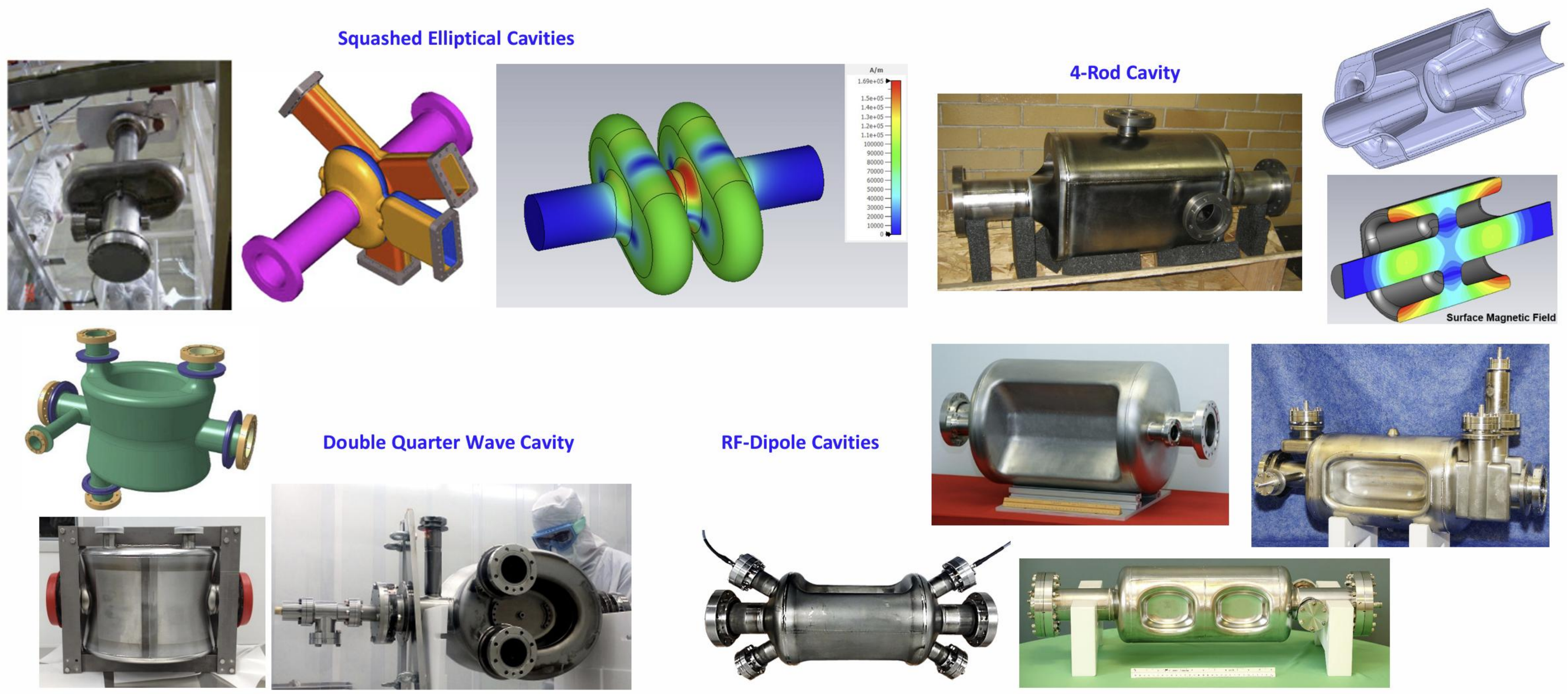
Harmonic



2. SRF Cavity: non-Elliptical



2. SRF Cavity: non-Elliptical



Now, we know lots of SRF cavity structure,

then how to design "your" cavity?

Let's go back to those key parameters

RF Cavities: for superconducting cavities

- **Main parameters**
  - Resonant frequency f_0
  - Accelerating voltage / cavity voltage V_c
  - Accelerating Length L、
  - Gradient E_{acc}
  - Stored Energy U
  - Unloaded quality Factor Q0
  - Geometry factor G
  - Surface Resistance Rs
  - Dissipated load / Cavity power loss Pc
  - Shunt Impedance R/Q
  - Minimize Ep/Eacc to have higher gradient
  - Minimize Bp/Eacc to have higher gradient
  - **Maximize G*R/Q** to decrease Pc, to save cost

$$U = \frac{1}{2}\mu_0 \int_V |\mathbf{H}|^2 dv = \frac{1}{2}\epsilon_0 \int_V |\mathbf{E}|^2 dv$$

$$P_c = \frac{1}{2} R_s \int_S |\mathbf{H}|^2 ds \qquad Q_0 = \frac{\omega_0 \mu_0 \int_V |\mathbf{H}|^2 dv}{R_s \int_S |\mathbf{H}|^2 ds}$$

$$G = \frac{\omega_0 \mu_0 \int_V |\mathbf{H}|^2 dv}{\int_S |\mathbf{H}|^2 ds} \qquad \boxed{Q_0 = \frac{G}{R_s}}$$

$$R_a = \frac{V_c^2}{P_c} \qquad \boxed{\frac{R_a}{Q_0} = \frac{V_c^2}{\omega_0 U}}$$

$$P_c = \frac{V_c^2}{R_a} = \frac{V_c^2}{\frac{R_a}{Q_0} \times Q_0} = \frac{V_c^2}{\frac{R_a}{Q_0} \times G} \times R_s$$

Accelerator operation requirement

Cavity material

Cavity geometry

RF Cavities: for superconducting cavities

- **Main parameters**
  - Resonant frequency f_0
  - Accelerating voltage / cavity voltage V_c
  - Accelerating Length L、
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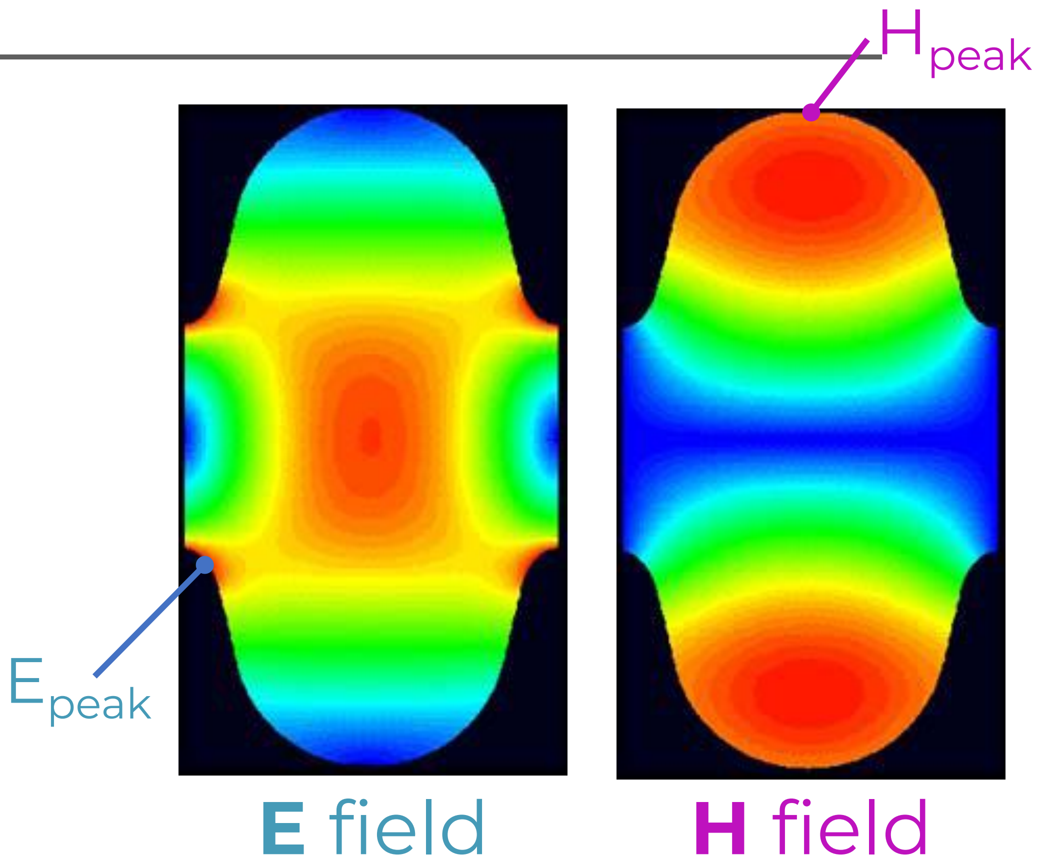


$$P_c = \frac{V_c^2}{R_a} = \frac{V_c^2}{\frac{R_a}{Q_0}\times Q_0} = \frac{V_c^2}{\frac{R_a}{Q_0}\times G}\times R_s$$

Accelerator operation requirement

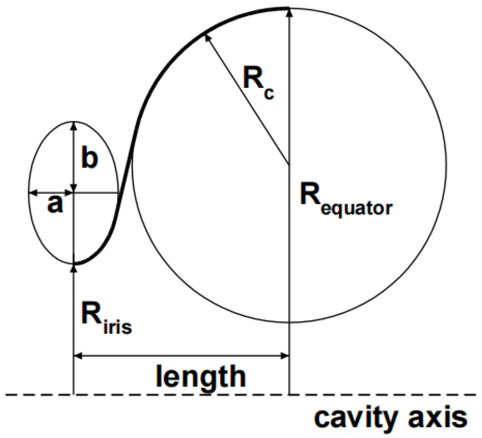
Cavity material

Cavity geometry

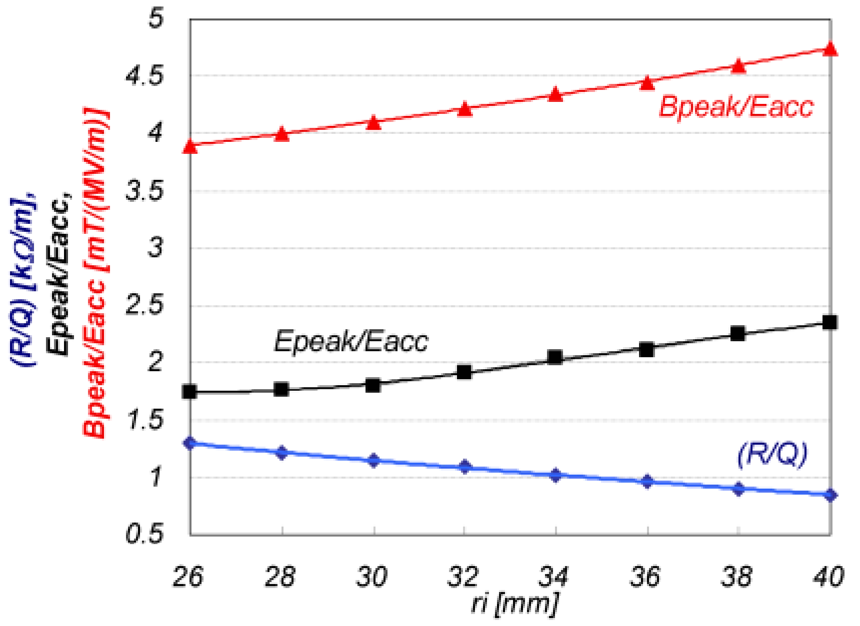
[5] Jacek Sekutowicz- SRF2013

SRF Cavity design: parameters vs performance

Criterion	*RF-parameter*	*Improve(s) when*	*Cavity examples*
Operation at high gradient	E_{peak}/E_{acc} ↓ B_{peak}/E_{acc} ↓	r_i ↓ *Iris & Equator shape*	*TESLA,* *HG CEBAF-12 GeV*
Low cryogenic losses	$(R/Q) \cdot G$ ↑	r_i ↓ *Equator shape*	*LL CEBAF-12 GeV*
High I_{beam} ↔ *Low HOM impedance*	$k_{\perp}, k_{\parallel}$ ↓	r_i ↑	*B-Factory* *RHIC cooling*



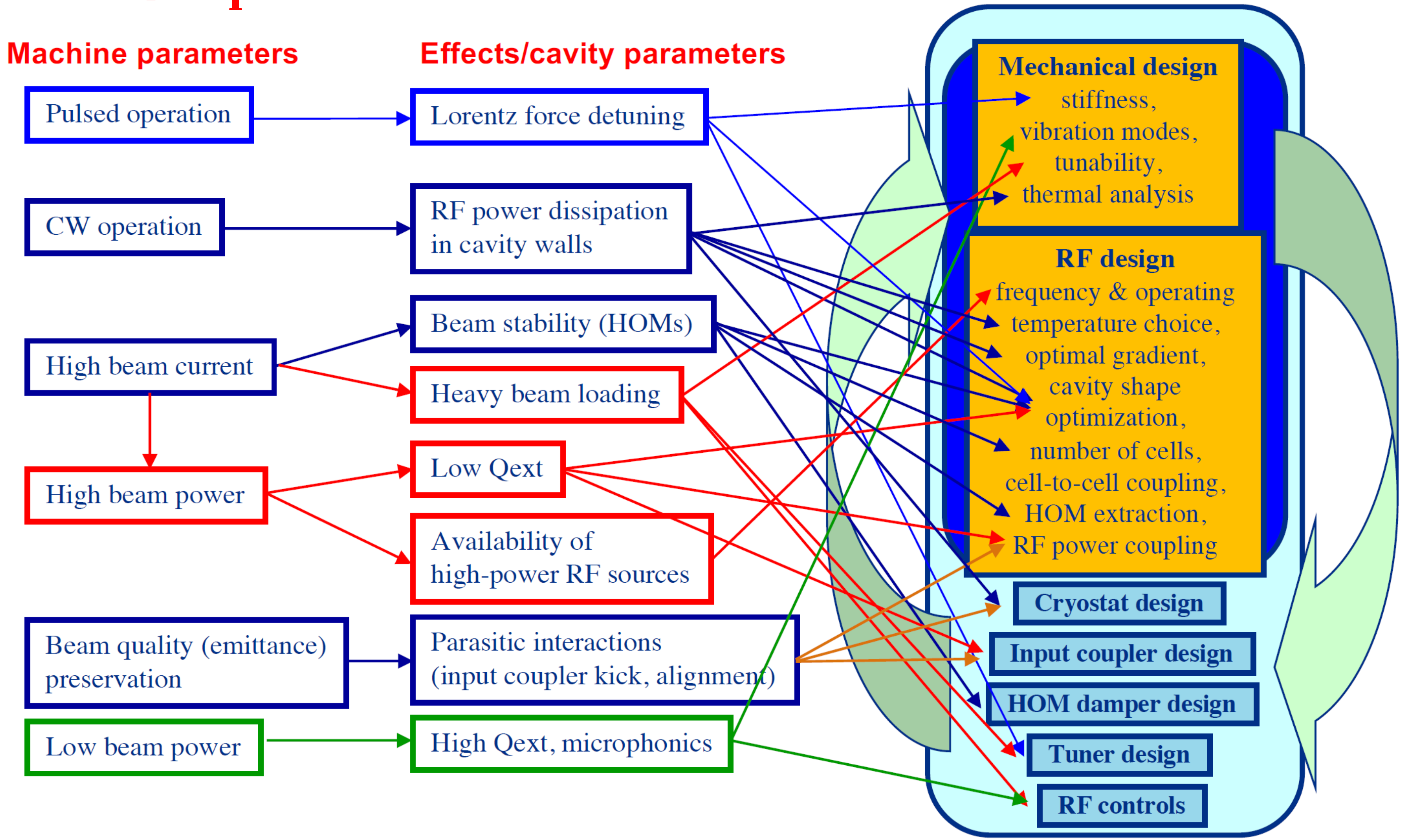
Example:
{ $(R/Q), E_{peak}/E_{acc}, B_{peak}/E_{acc}$ } vs. r_i for cell at f = 1.5 GHz



[4] Sergey Belomestnykh, *SRF2005*

SRF Cavity design: Complex——RF & Mechanical & Cryogenic

Compromise → Optimal structure



SRF Cavity design: Simulation tools

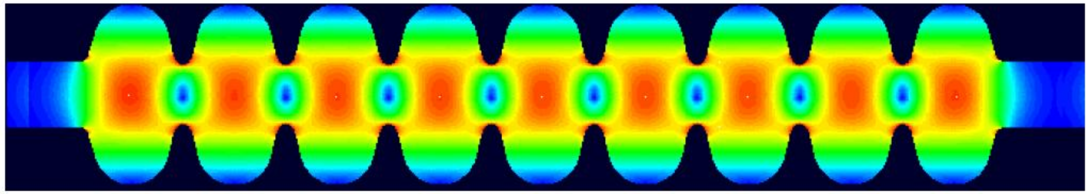
I. **Field calculations:**
  -Spectrum, (r/Q), G, β
  -Field enhancement factors
  - HFSS (3D);
  - CST(3D);
  - Omega-3P (3D);
  - Analyst (3D)
  - COMSOL (3D)

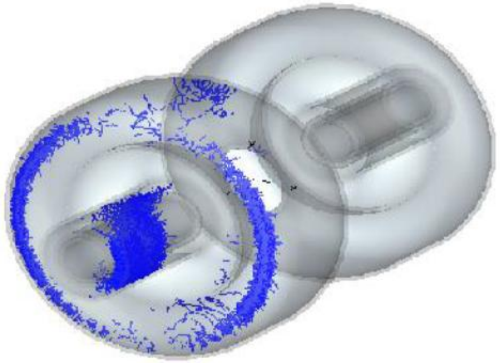
II. **Multipactoring (2D, 3D)**
  - Analyst;
  - CST (3D);
  - Omega-3P

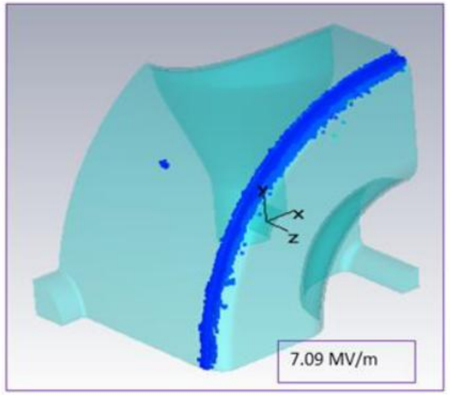
III. **Wakefield simulations (2D, 3D):**
  - GdfidL;
  - PBCI;
  - ECHO.

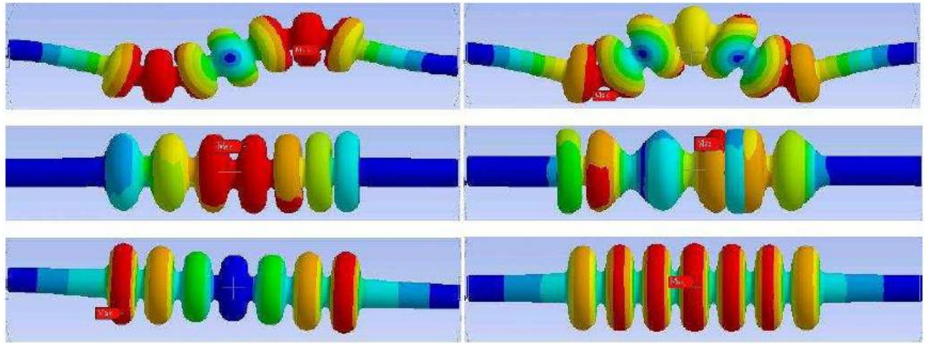
IV. **Mechanical simulations:**
  Lorenz force and Lorenz factor,
  Vibrations,
  Thermal deformations.

a. ANSYS
b. COMSOL





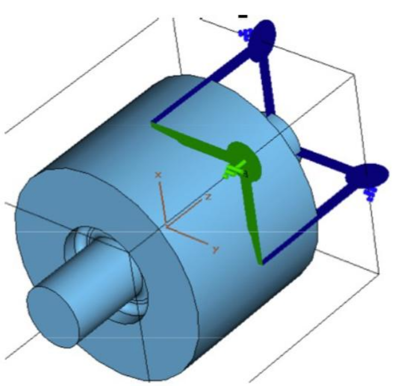


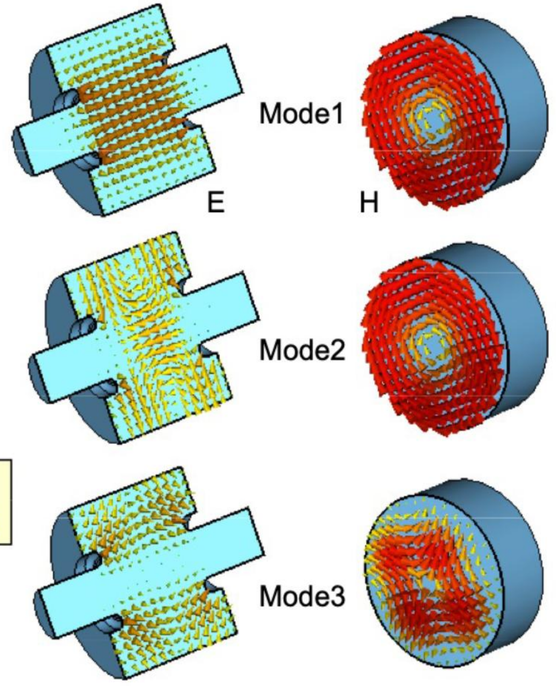


SRF Cavity design: Simulation tools

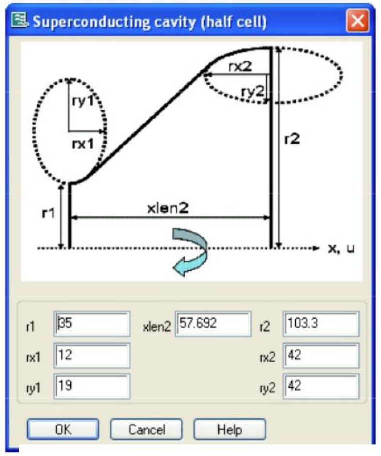
3D code example: CST MWS

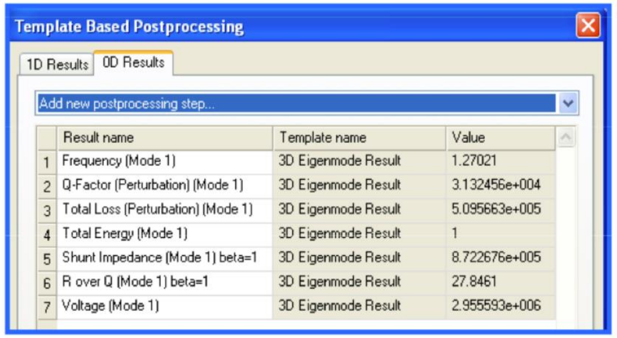
- Expensive 3D finite-element code
- User-friendly interface
- Perfect Boundary Approximation increases accuracy
- Contains different solvers:
  - Transient Solver
  - Frequency Domain Solver
  - Eigenmode Solver





3 symmetry planes ➔ only 1/8 of the volume needs to be calculated

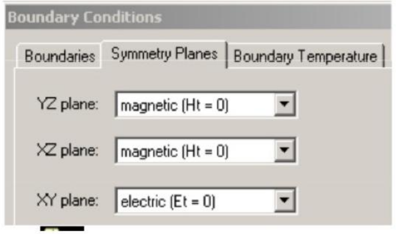



Template Based Postprocessing

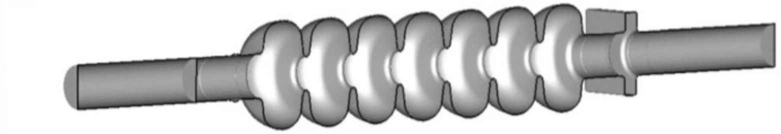
1D Results | 0D Results

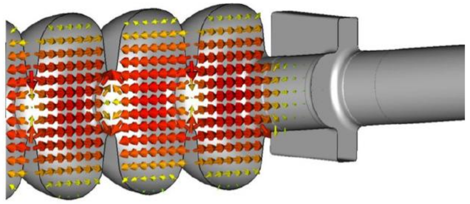
Add new postprocessing step...

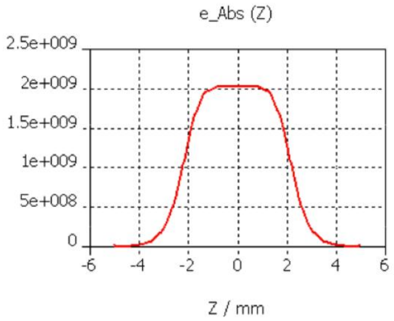
	Result name	Template name	Value
1	Frequency (Mode 1)	3D Eigenmode Result	1.27021
2	Q-Factor (Perturbation) (Mode 1)	3D Eigenmode Result	3.132456e+004
3	Total Loss (Perturbation) (Mode 1)	3D Eigenmode Result	5.095663e+005
4	Total Energy (Mode 1)	3D Eigenmode Result	1
5	Shunt Impedance (Mode 1) beta=1	3D Eigenmode Result	8.722676e+005
6	R over Q (Mode 1) beta=1	3D Eigenmode Result	27.8461
7	Voltage (Mode 1)	3D Eigenmode Result	2.955593e+006



CST
www.cst.com

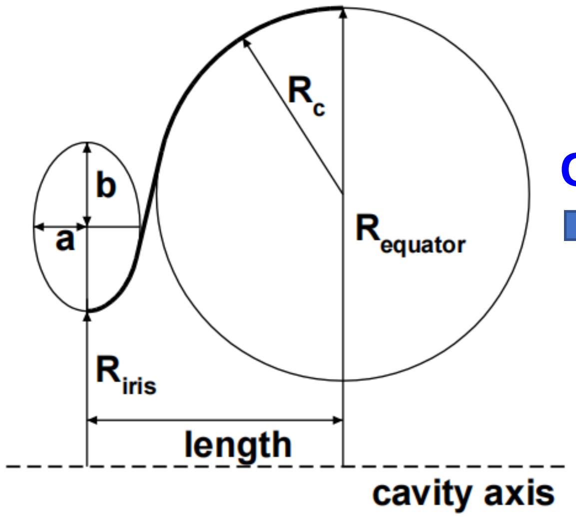




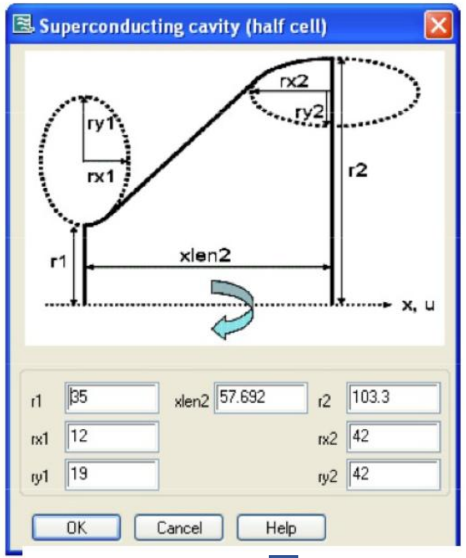


All modes are normed to 1 Joule stored energy. E / H / surface current are stored as peak values.

SRF Cavity design: TESLA cavity example

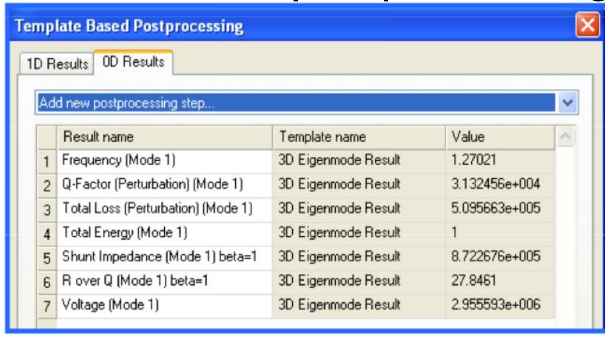


CST model



Eigen mode Simulation

postprocessing



Cavity shape parameter	Midcup	Endcup 1	Endcup 2
Equator radius R_{equat}	103.3	103.3	103.3
Iris radius R_{iris}	35	39	39
Radius R_{arc} of circular arc	42.0	40.3	42
Horizontal half axis a	12	10	9
Vertical half axis b	19	13.5	12.8
Length l	57.7	56.0	57.0

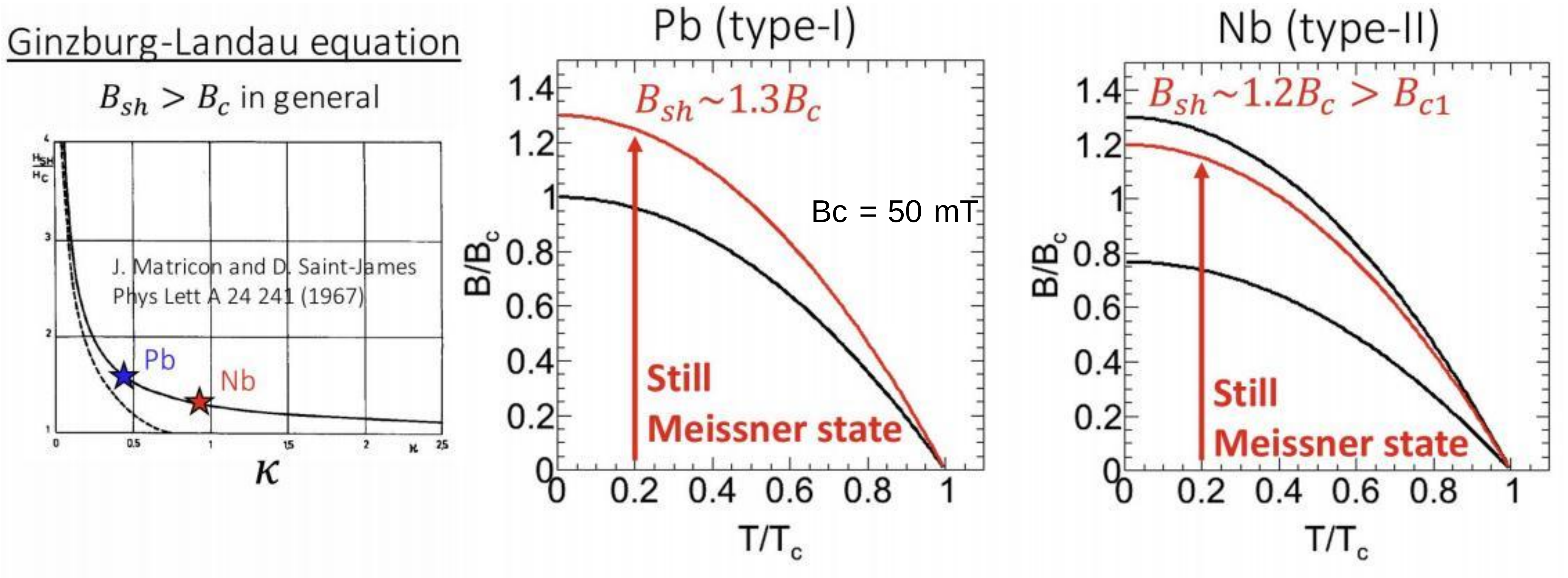
TABLE II. TTF cavity design parameters.[a]

Type of accelerating structure	Standing wave
Accelerating mode	TM_{010}, π mode
Fundamental frequency	1300 MHz
Design gradient E_{acc}	25 MV/m
Quality factor Q_0	$>5 \times 10^9$
Active length L	1.038 m
Number of cells	9
Cell-to-cell coupling	1.87%
Iris diameter	70 mm
Geometry factor	270 Ω
R/Q	518 Ω
E_{peak}/E_{acc}	2.0
B_{peak}/E_{acc}	4.26 mT MV^{-1} m^{-1}
Tuning range	±300 kHz
$\Delta f/\Delta L$	315 kHz/mm
Lorentz force detuning at 25 MV/m	≈600 Hz
Q_{ext} of input coupler	3×10^6
Cavity bandwidth at $Q_{ext} = 3 \times 10^6$	430 Hz
rf pulse duration	1330 μs
Repetition rate	5 Hz
Fill time	530 μs
Beam acceleration time	800 μs
rf power peak/average	208 kW/1.4 kW
Number of HOM couplers	2
Cavity longitudinal loss factor $k_{\parallel}$ for $\sigma_z = 0.7$ mm	10.2 V/pC
Cavity transversal loss factor $k_{\perp}$ for $\sigma_z = 0.7$ mm	15.1 V pC^{-1} m^{-1}
Parasitic modes with the highest impedance: type	TM_{011}
$\pi/9$ (R/Q)/frequency	80 Ω/2454 MHz
$2\pi/9$ (R/Q)/frequency	67 Ω/2443 MHz
Bellows longitudinal loss factor $k_{\parallel}$ for $\sigma_z = 0.7$ mm	1.54 V/pC
Bellows transversal loss factor $k_{\perp}$ for $\sigma_z = 0.7$ mm	1.97 V pC^{-1} m^{-1}

2. SRF Cavity

- **Design**
- **SC Materials**
- **Fabrication**
- **Post process**
- **Vertical test**

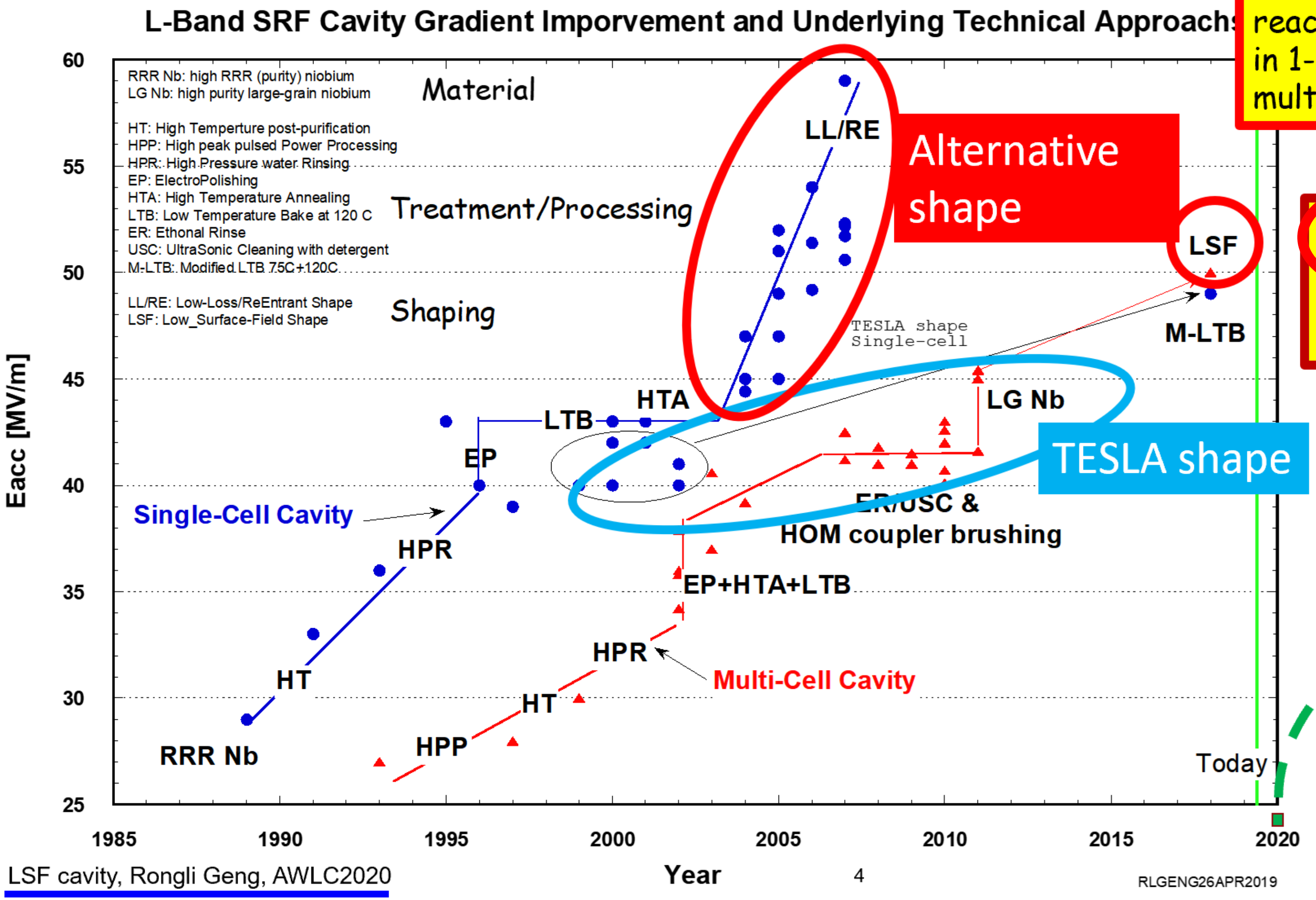
Niobium material for SRF Cavity



- **Nb:** Tc = 9.25 K, superheating field, Bsh ≈ 220 mT， **favorite material for SC cavities**
- Regarding to TELSA Shape cavity, Bp/Eacc=4.26 mT/(MV/m), Bsh at 2K is about 220 mT, meaning to have a maximum accelerating field of about **52** MV/m

Niobium material for SRF Cavity

Technical Approaches to Gradient



LSF cavity, Rongli Geng, AWLC2020

Cavity shaping led to gradient breakthrough with Nb cavities reaching robust 50 - 60 MV/m in 1-cell & sight of 50 MV/m in multi-cell since 2018

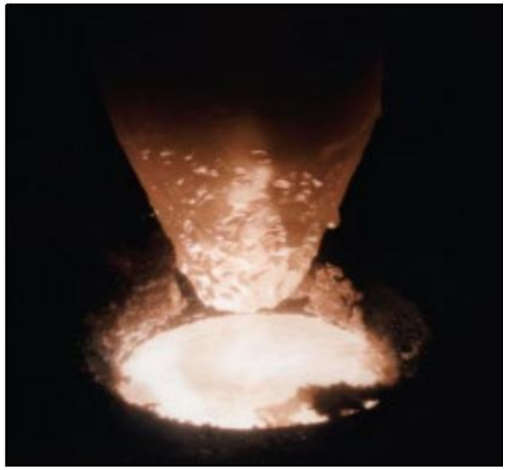
~50 MV/m observed in TESLA shape 1-cell Nb cavity with modified LTB 75°C+120°C

24 MV/m observed in today's best Nb3Sn 1-cell cavity - aiming 80 MV/m as ultimate goal

Jefferson Lab

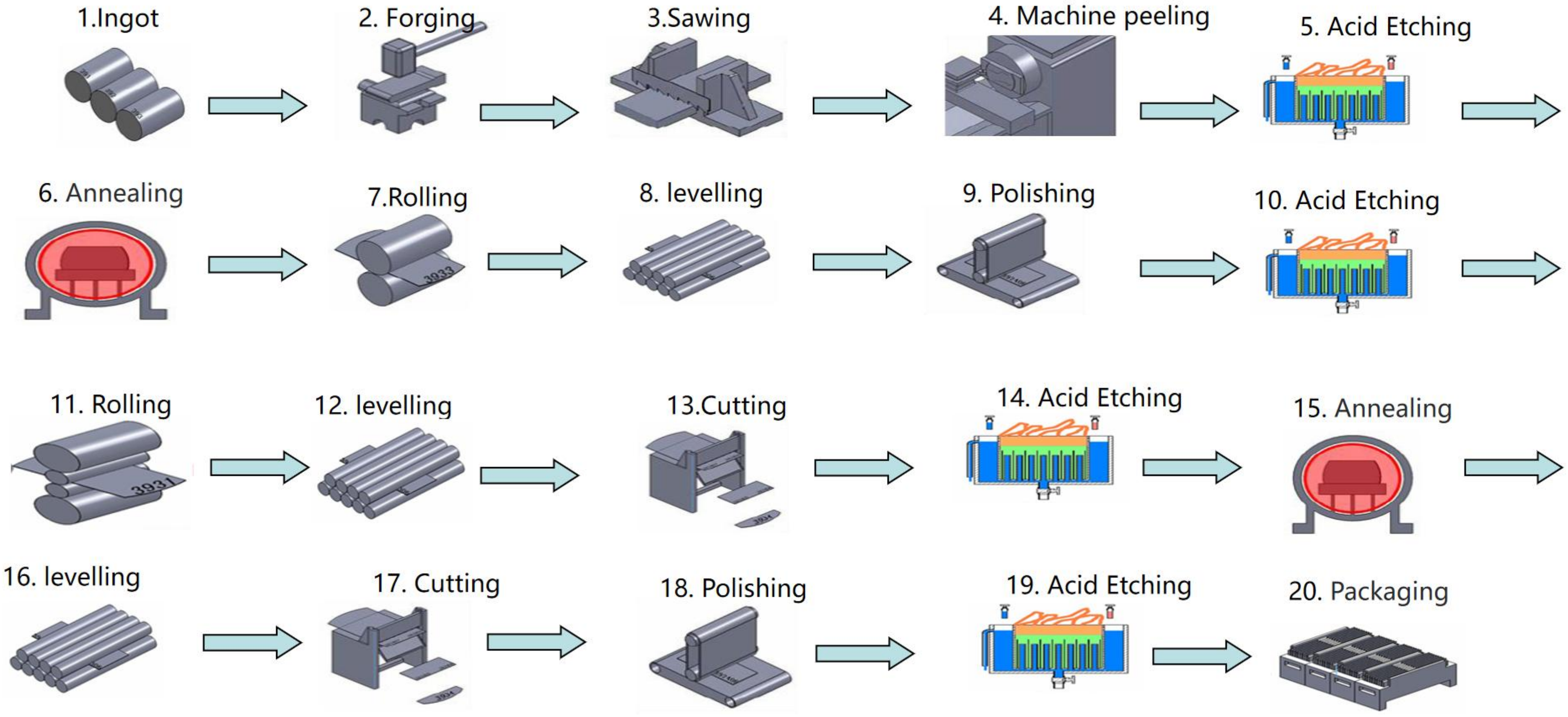
Niobium material production

Electron Beam Melting



Using EB to purify the mother material, several times, then we obtain high RRR ingot.

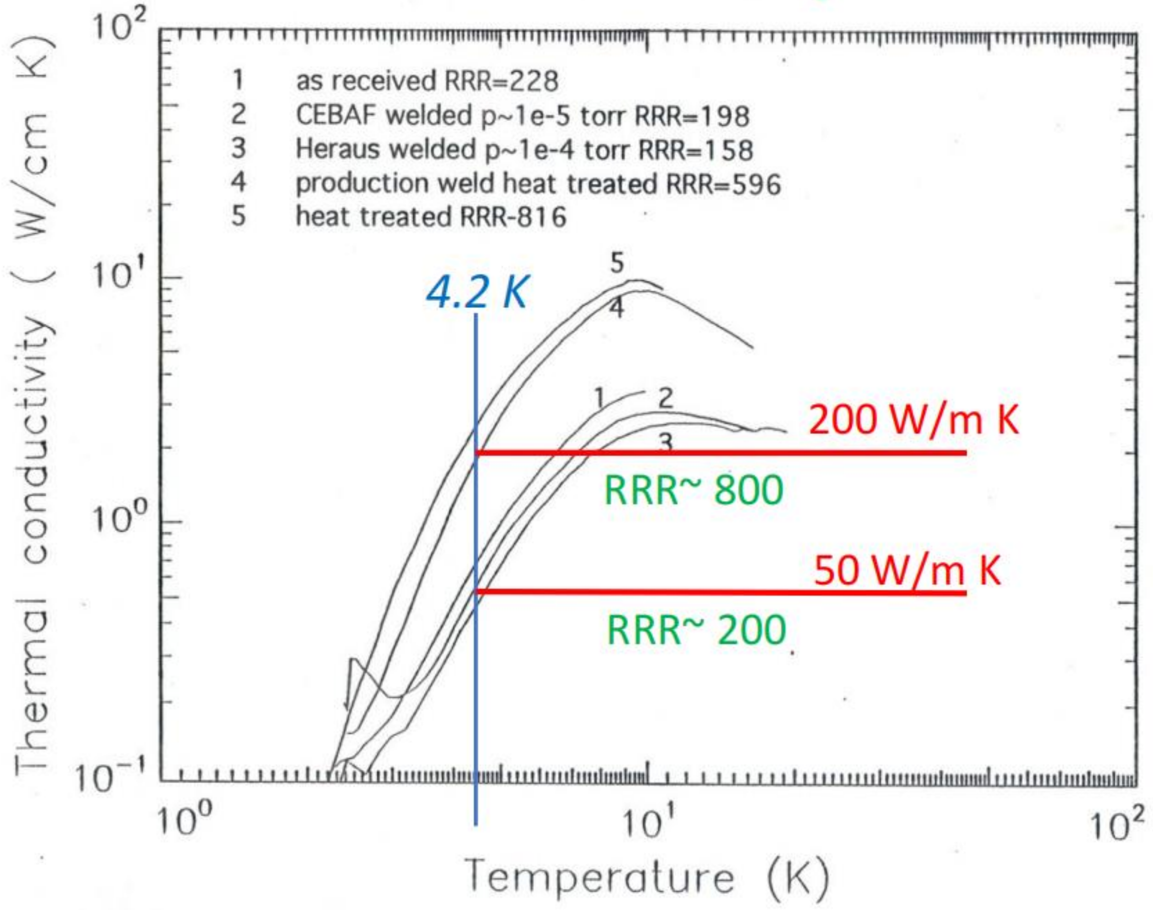
中色东方
CNMNC



[3] Eiji Kako, ASSCA 2025

Niobium properties: higher RRR, RRR> 300 for SRF cavity

Thermal conductivity of Nb



RRR : Residual Resistance Ratio

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

κ : Thermal Conductivity

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

Wiedemann-Franz's law

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

H_{quench} : Quench field

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

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.

Current high purity niobium specification for SHINE

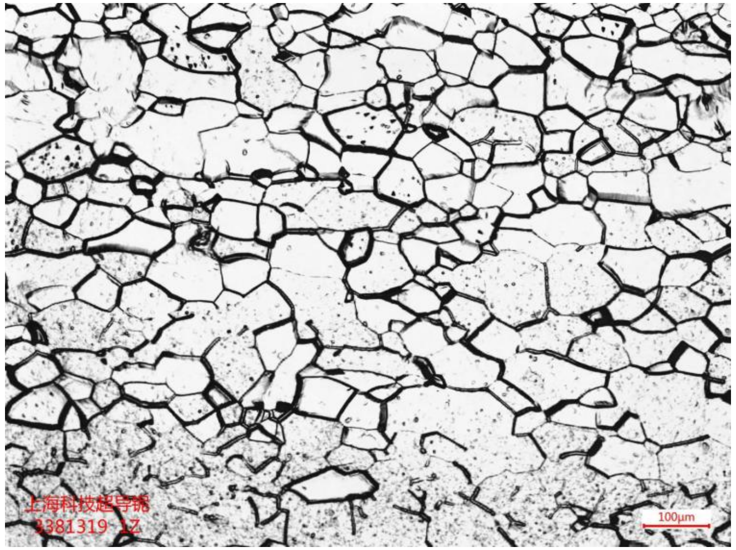
- **High quality niobium material is important to cavity quality**
- **Grain size is slightly controlled based on XFEL-007.**

Project	XFEL/LCLS-2	SHINE / Spec	SHINE / NX sheets	SHINE / TD sheets
types	fine grain	fine grain	fine grain	fine grain
element	PPM	PPM	PPM	PPM
Ta	500	500	100	<=60
W	70	50	5	< 10
Ti	50	50	3	< 10
Fe	30	30	3	< 10
Si	30	30	<3	/
Mo	50	50	10	< 10
NI	30	30	5	< 10
C	10	10	5	< 10
O	10	10	5	< 10
N	10	10	5	< 10
H	2	2	1	< 2
tensile / MPa	>140	>140	164 (average)	165 (average)
hardness / HV	<= 60	<= 60	48 ~ 58	37~ 45
Elongation % AL	> 30%	> 30%	~ 50%	> 50%
Yield strength / MPa	50-100	50-100	~ 76	~ 60
RRR sheet	> 300	> 300	437 ~ 469	> 360
grain size predomainately / (ASTM / um)	6 / 45	5 / 64 [1]	5 / 64	6 /45
grain size max (ASTM / um)	4 / 90	4 / 90	4 / 90	4 / 90
grain size min (ASTM / um)	NA	6 / 45	6 / 45	/
roughness Ra um	<1.6	<1.6	Y	Y
roughness Rt um	<15	<15	Y	Y

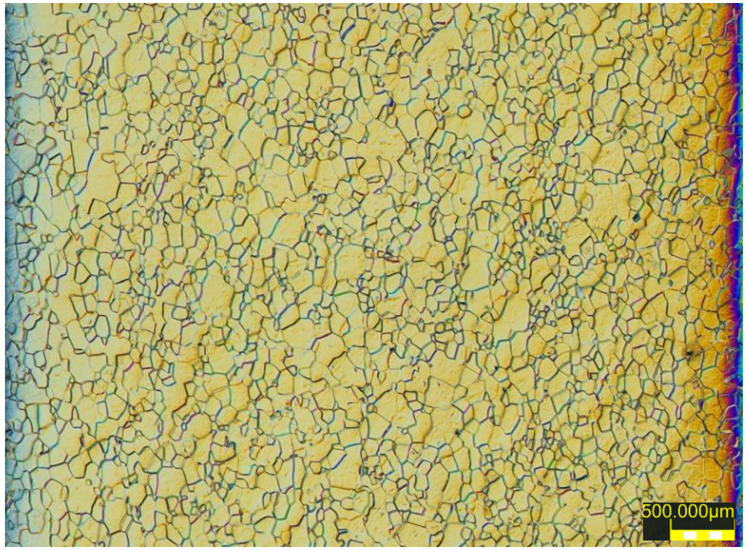
Grain size——typical value

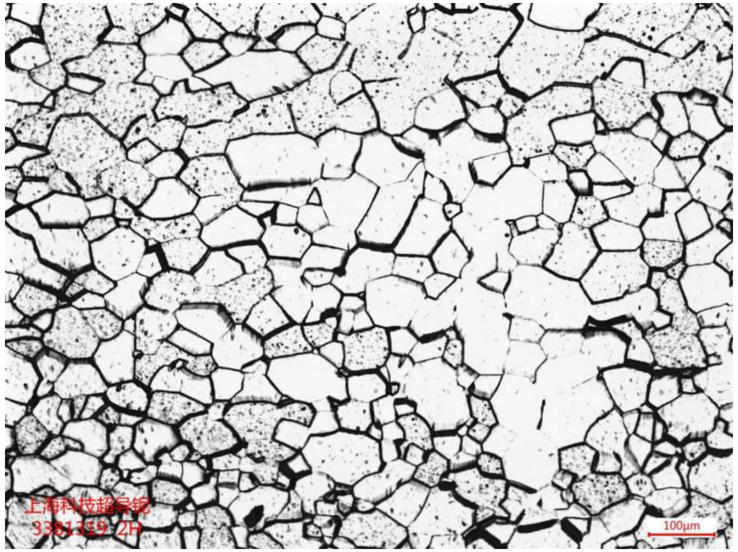
NX-3381319：ASTM 5.5

TD-Lot 63#: ASTM 6

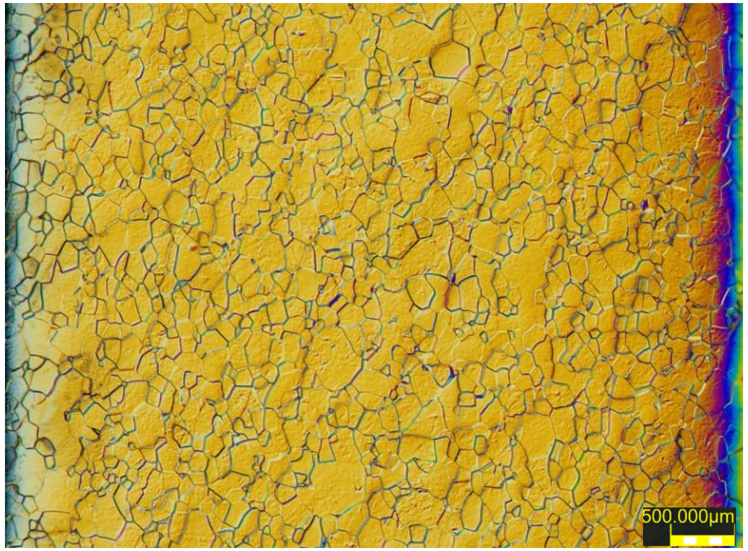


Hard





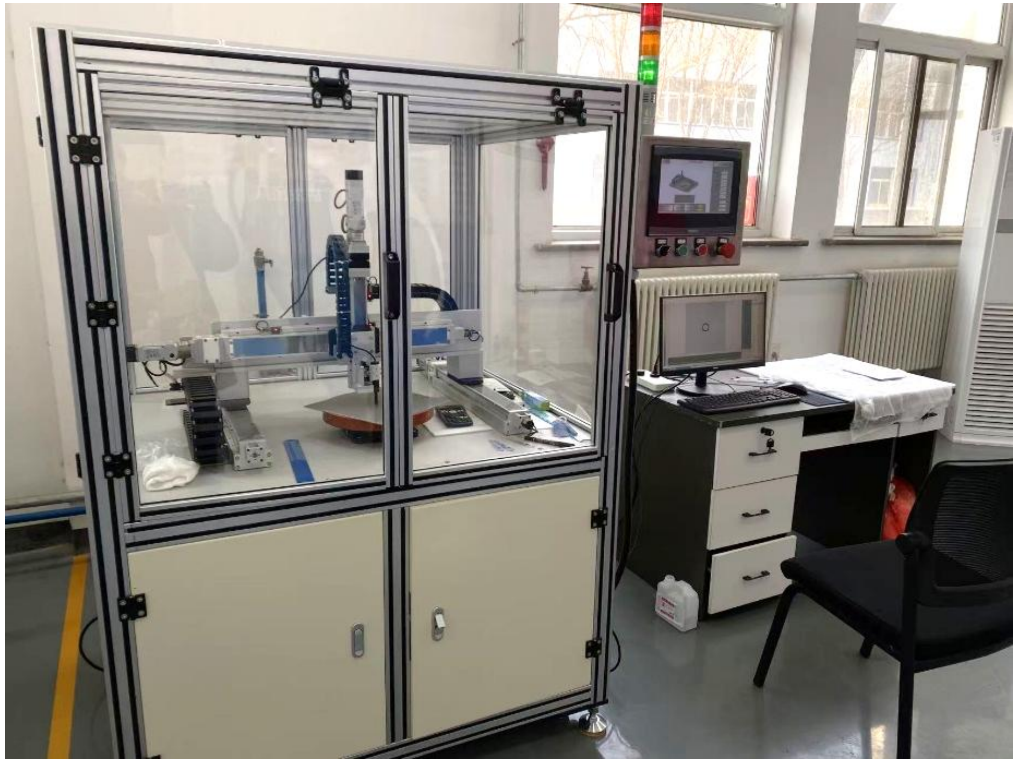
Soft



Qualification of niobium materials by eddy current machine

- Ensure Nb sheets surface is good, no defects, no scratches……
- New eddy current machines at SHINE
  - Inspect Nb sheets surface

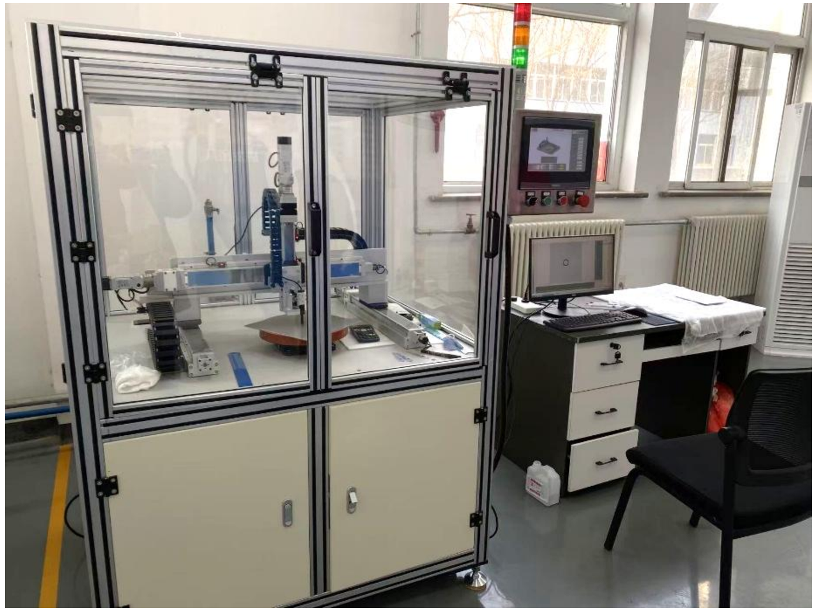
No. 1

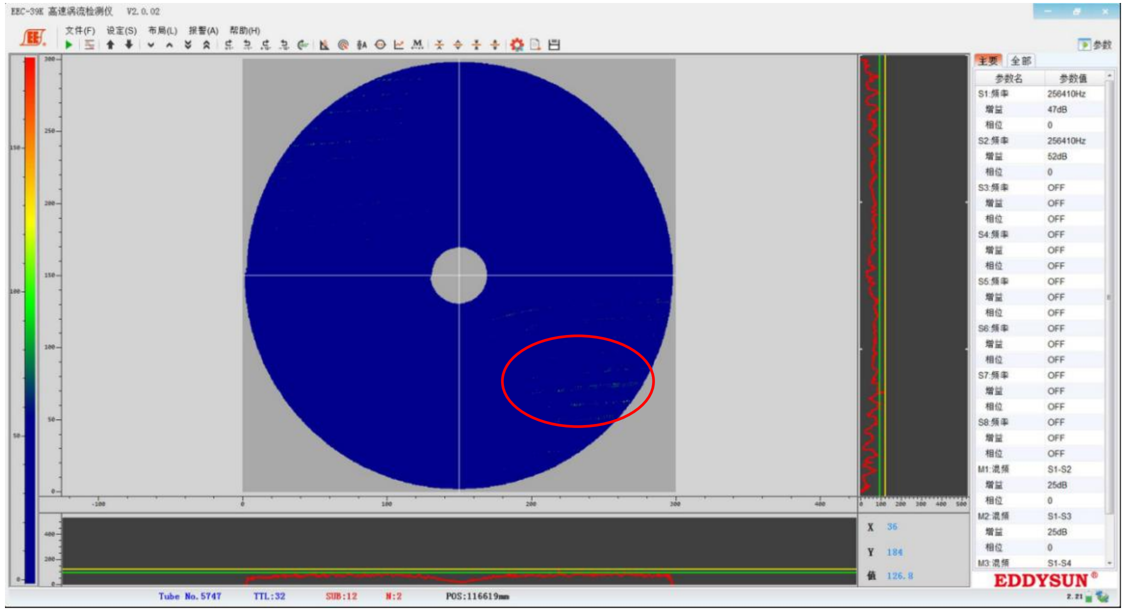


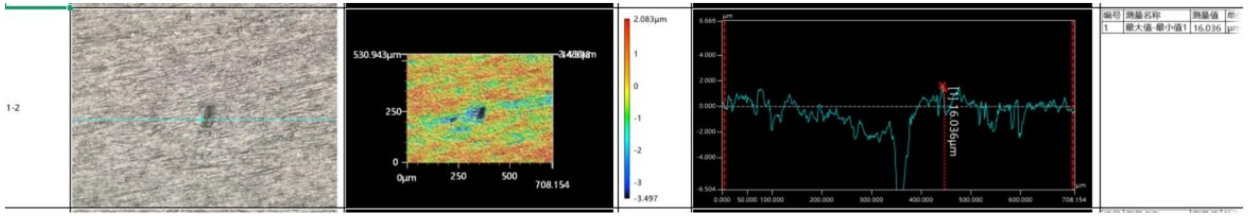
No. 2

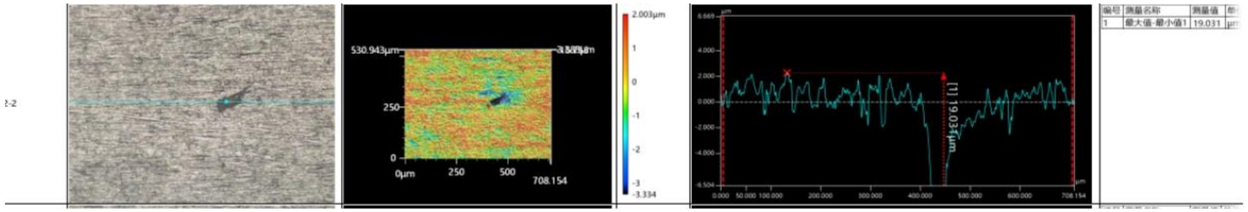
Qualification of niobium materials by eddy current machine

- **Resolution：Rt<10 um**
- **Inspection time: < 8 minutes / side**

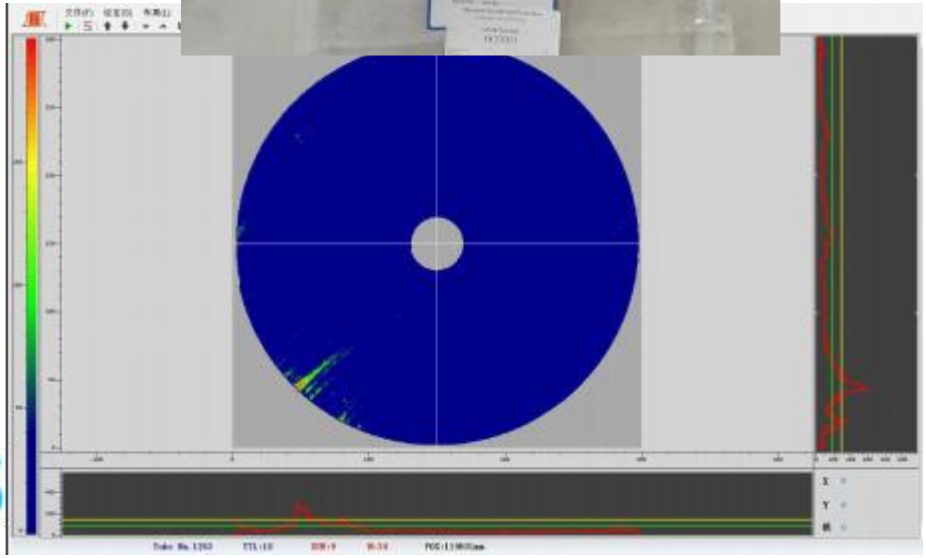


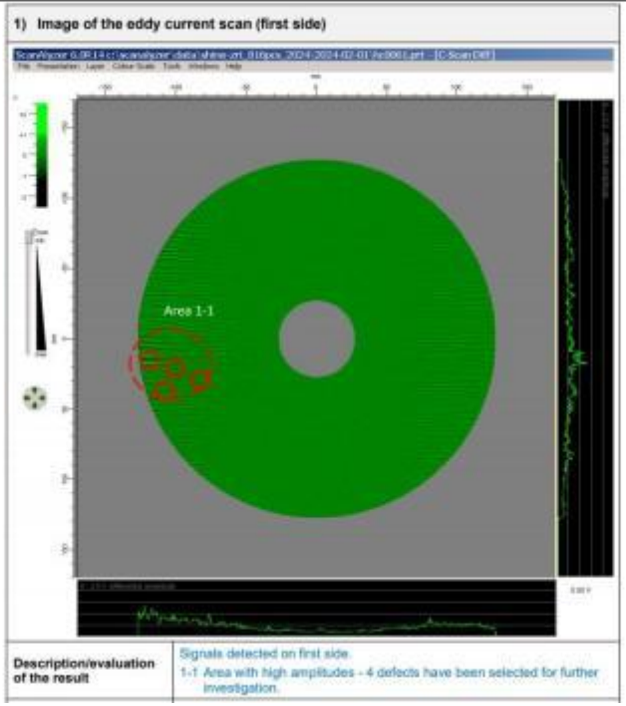


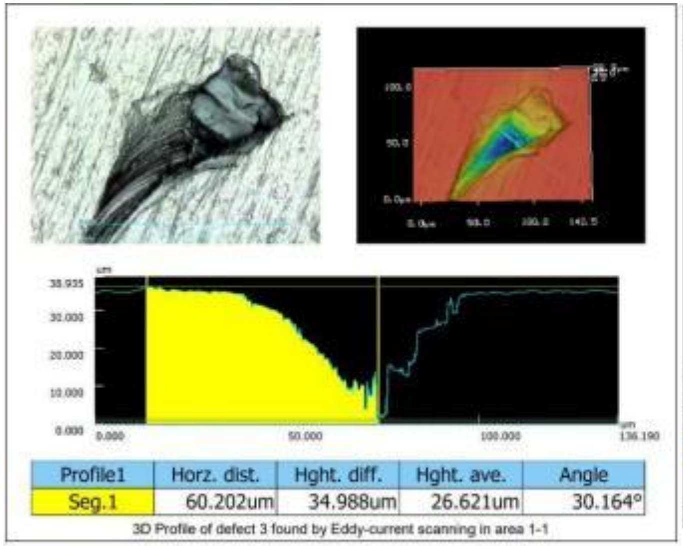


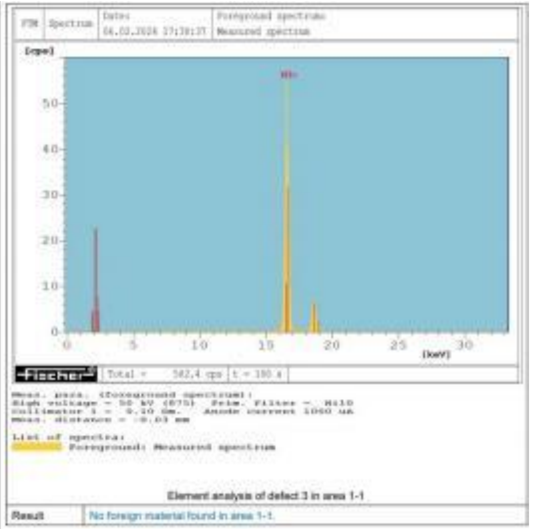


Examples: HC0061, results similar to reports of DESY





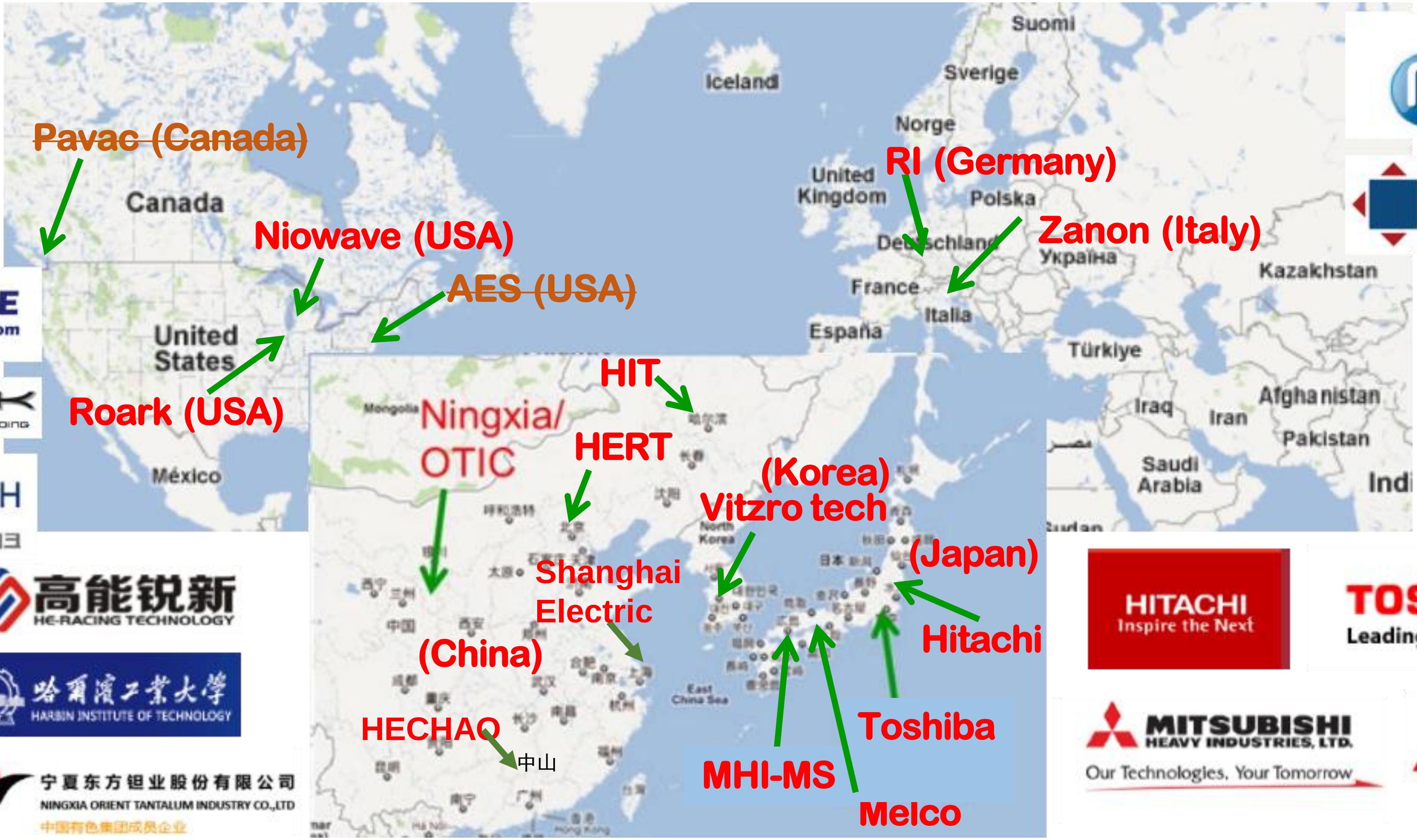




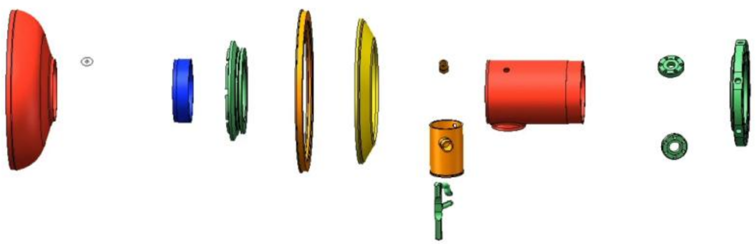
2. SRF Cavity

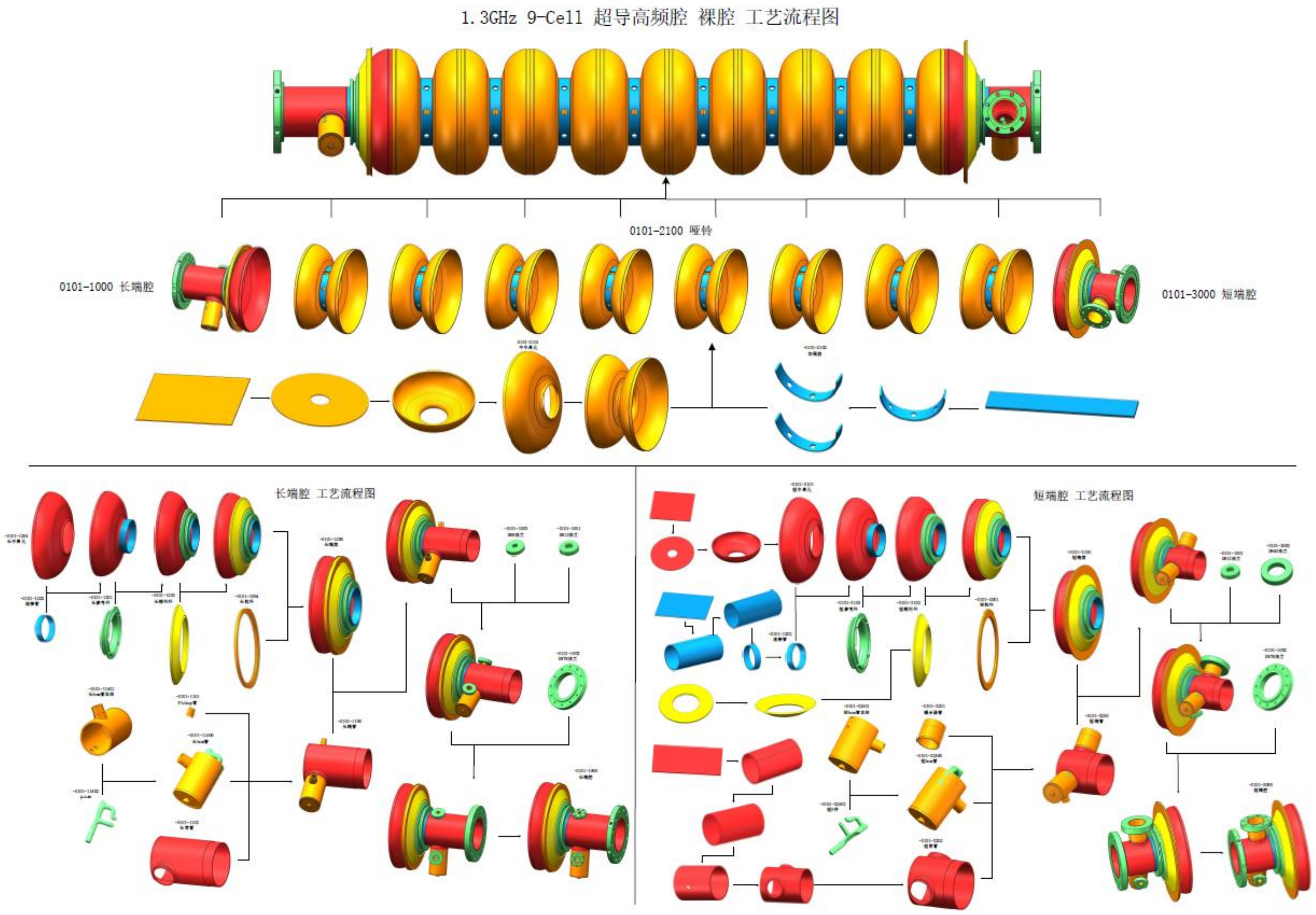
- Design
- SC Materials
- Fabrication
- Post process
- Vertical test

SRF Cavity Production Companies



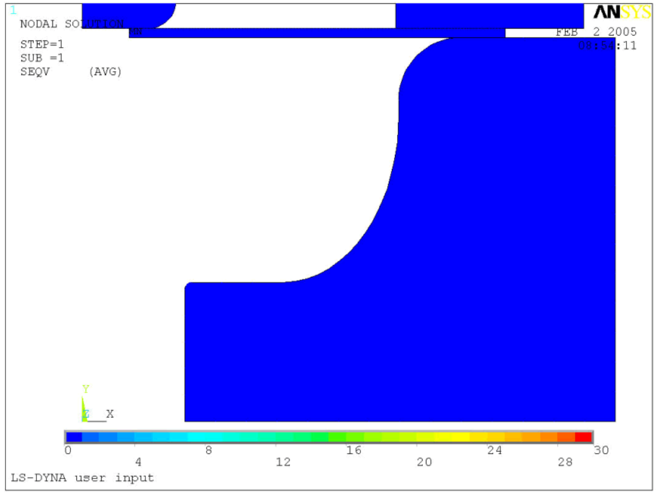
SRF Cavity fabrication: 1.3GHz 9-cell cavity

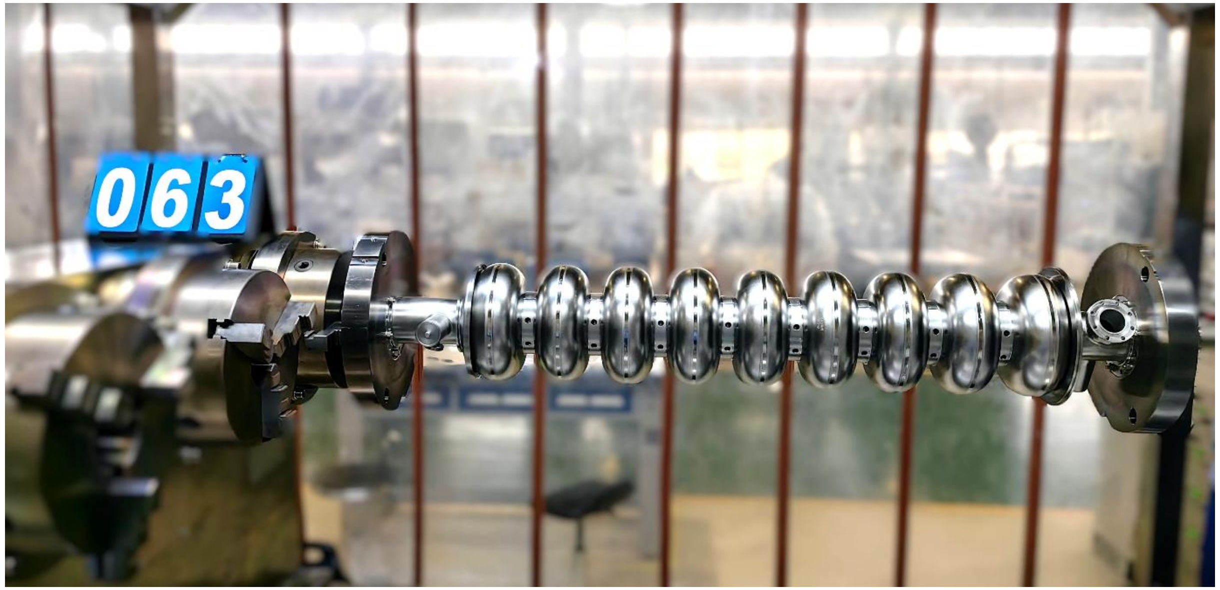




SRF Cavity Fabrication

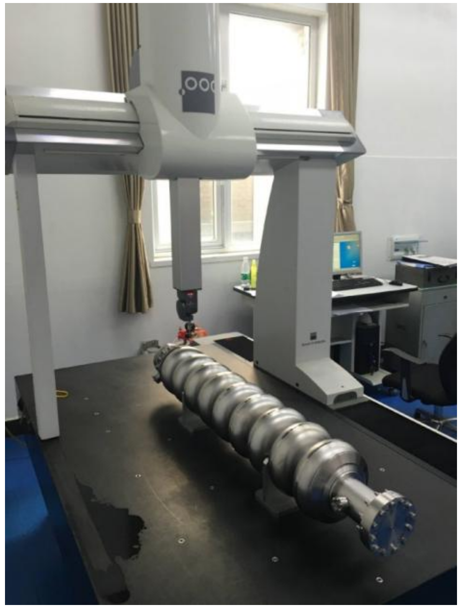
- Half cell：deep drawing
- Surface clean
- Cutting, manufacturing
- Electron beam welding



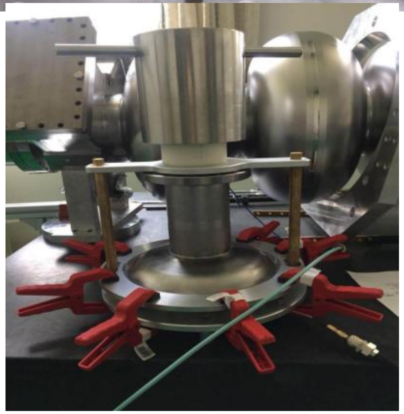
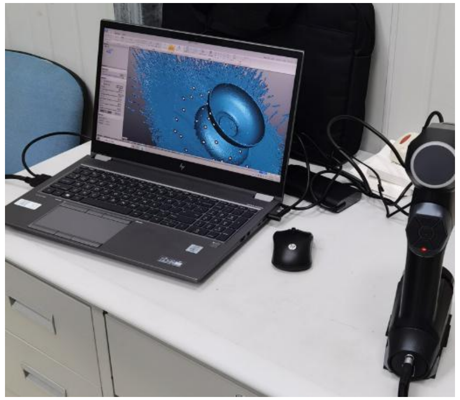


SRF Cavity Fabrication





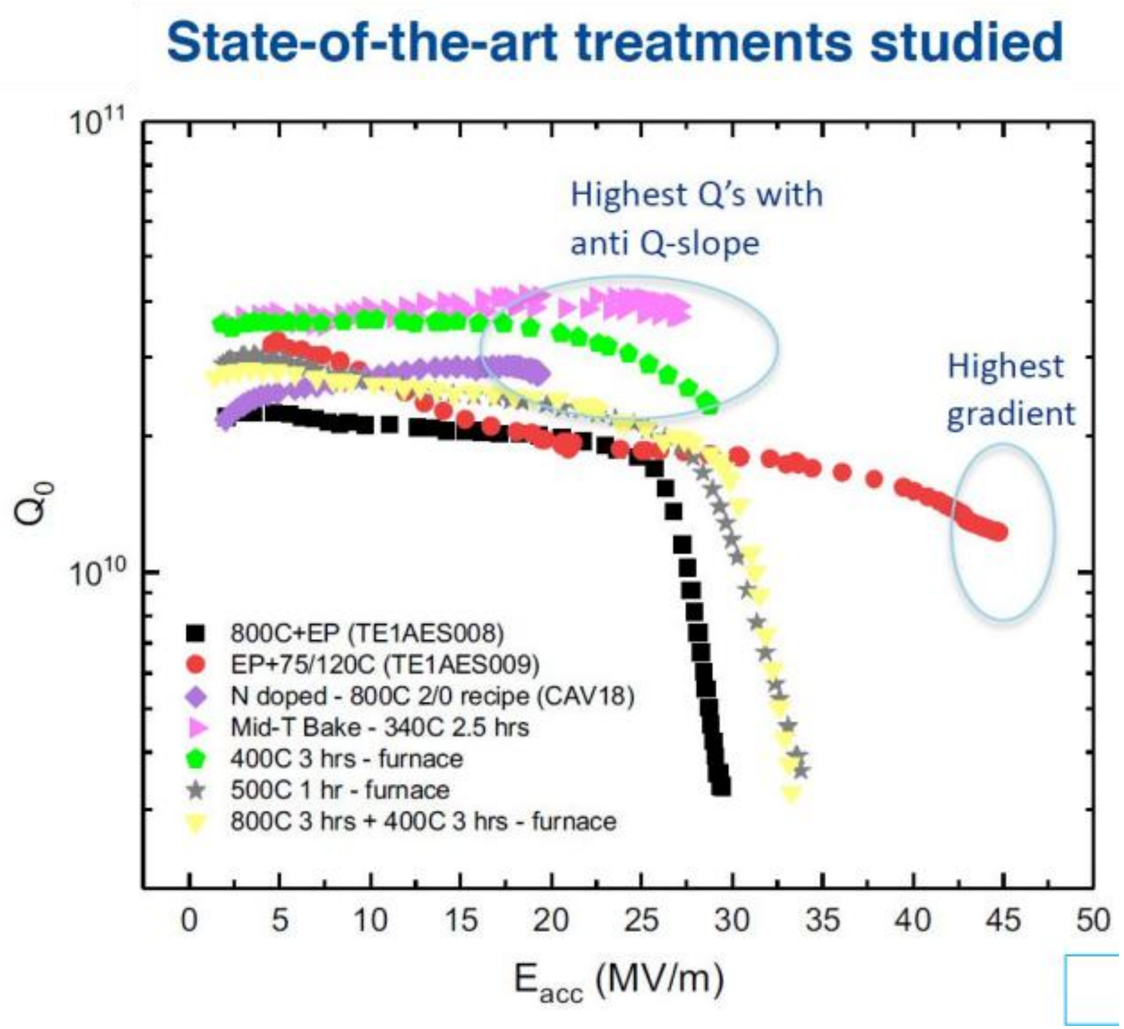




2. SRF Cavity

- Design
- SC Materials
- Fabrication
- Post process
- Vertical test

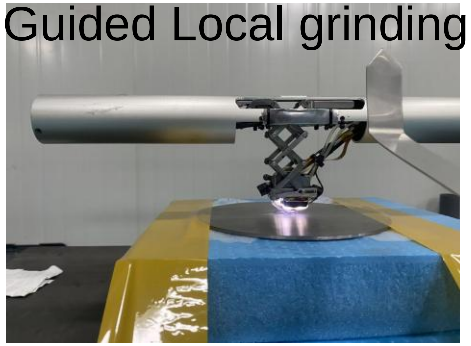
Surface treatment

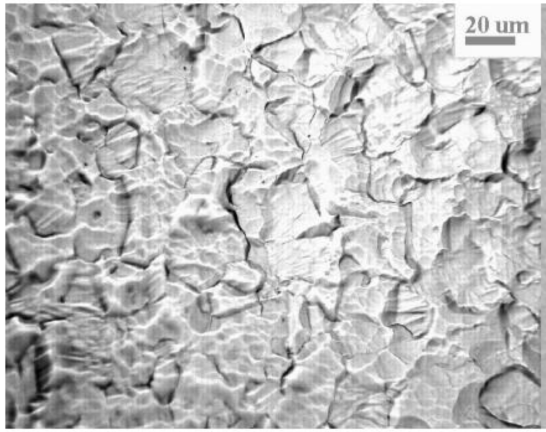
- We look forward to cavity's performance either **high-Q or high-G**
- For high-Q, N-doping and Mid-T baking is adopted for mass production
- For high-G, two-steps baking now seems to be a promised way



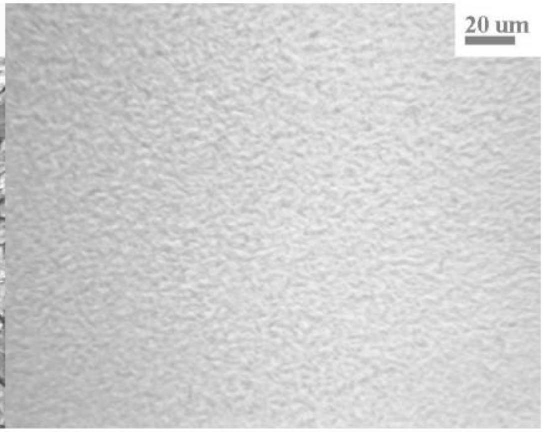
Post Process / Surface treatment

- Mechanical removal
- Ultrasonic cleaning
- Chemical polishing
  - Buffered Chemical polishing
  - Electro-polishing, for better roughness
- Heat treatment
  - High Temperature annealing 800℃~950℃
  - For high-Q: Mid-T baking, N-doping
  - For high-G: 2-steps baking (75℃+120℃)
- High pressure Rinsing with ultra-pure water
- Tuning
- Clean assembly
- Slow pumping





Niobium surface after BCP



Niobium surface after EP

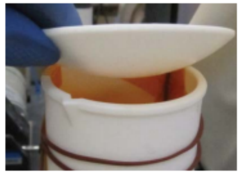
Post Process / Surface treatment

- Mechanical removal
- Ultrasonic cleaning
- Chemical polishing
  - Buffered Chemical polishing
  - Electro-polishing, for better roughness
- Heat treatment
  - High Temperature annealing
  - For high-Q: Mid-T baking, N-doping
  - For high-G: 2-steps baking (75℃+120℃）
- High pressure Rinsing with ultra-pure water
- Tuning
- Clean assembly
- Slow pumping

Buffered Chemical Polish (BCP)

Acid (Reagent Grade)
HF (49% w/w),
HNO_3 (65% w/w),
H_3PO_4 (85% w/w)

Typical Mixture
1:1:1 etching subcomponents
or 1:1:2 etching structures



Reaction:

Oxidation

Forms NO_2, Orange Brown Gas

$$6\,Nb + 10\,HNO_3 \leftrightarrow 3\,Nb_2O_5 + 10\,NO + 5\,H_2O$$

Reduction

$$3\,Nb_2O_5 + 18\,HF \leftrightarrow 3\,H_2NbOF_5 + 3\,NbO_2F + 6\,H_2O$$

Insoluble

$$3\,NbO_2F + 12\,HF \leftrightarrow 3\,H_2NbOF_5 + 3\,H_2O$$

Important for BCP

- Temperature, Time
- Acid Velocity and Distance from Inlet,
- Gas Bubble Evolution and Control
- Acid Contamination

Post Process / BCP

BCP Plant in Operation in Labs

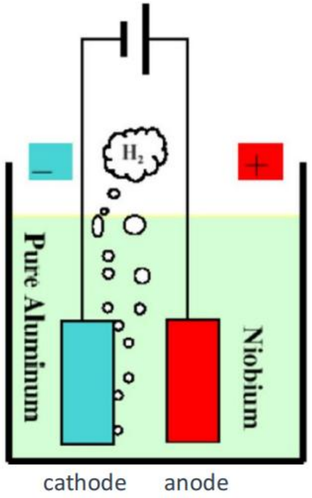
BCP Plant in Operation at Qualified Vendors

Post Process / Surface treatment

- Mechanical removal
- Ultrasonic cleaning
- Chemical polishing
  - Buffered Chemical polishing
  - Electro-polishing, for better roughness
- Heat treatment
  - High Temperature annealing
  - For high-Q: Mid-T baking, N-doping
  - For high-G: 2-steps baking (75℃+120℃)
- High pressure Rinsing with ultra-pure water
- Tuning
- Clean assembly
- Slow pumping

Electropolish (EP)

Electrolyte = 1 part HF(49%), 9 parts H_2SO_4 (96%)



Reaction:

Oxidation

$$2Nb + 5SO_4^{2-} + 5H_2O \rightarrow Nb_2O_5 + 10H^+ + 5SO_4^{2-} + 10e^-$$

Hydrogen Gas

Reduction

$$Nb_2O_5 + 6HF \rightarrow H_2NbOF_5 + NbO_2F\ 0.5H_2O + 1.5H_2O$$

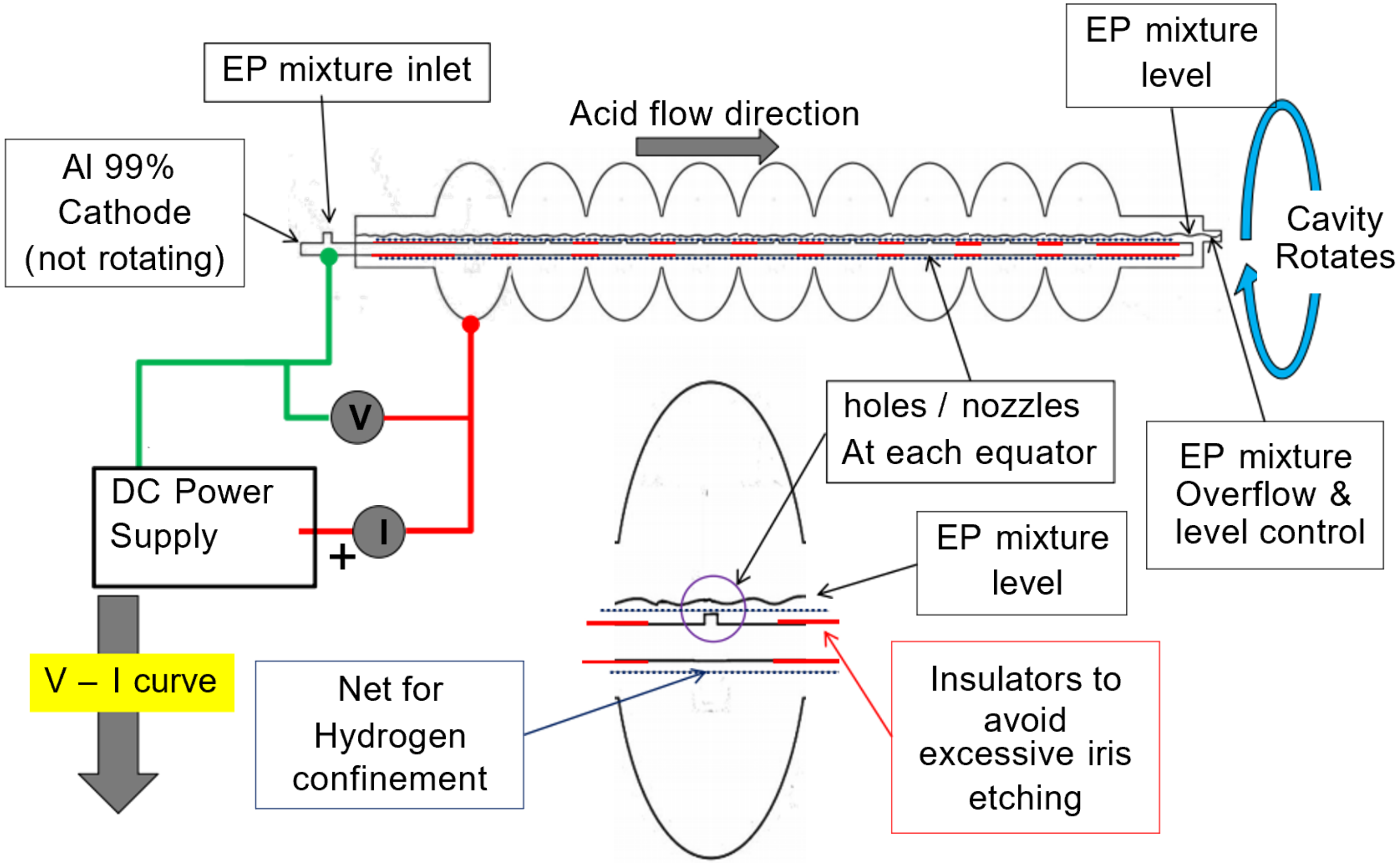
$$NbO_2F\ 0.5H_2O + 4HF \rightarrow H_2NbOF_5 + 1.5H_2O$$

Important for EP

- Temperature, Time → cold EP is important for uniform removal
- Current density → polishing area, not "etching"
- Gas Bubble Evolution and Control
- Acid Contamination

Post Process / EP

Basic EP

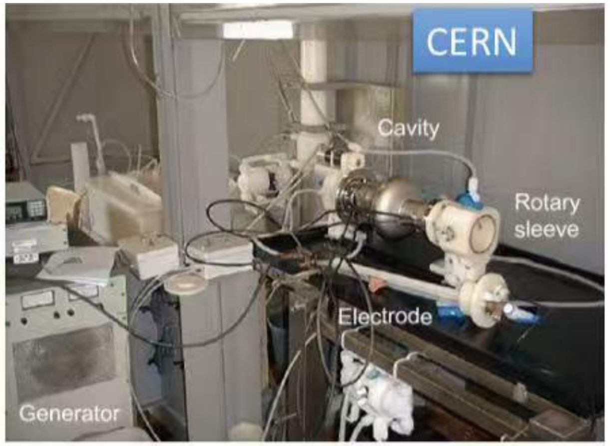


Cold EP (acid temperature 7 °C – 12 °C) or even less, improve smoothness increasing cavity performances.

High-Q0 cavities production requires cold EP whatever N-doping or Mid-T baking

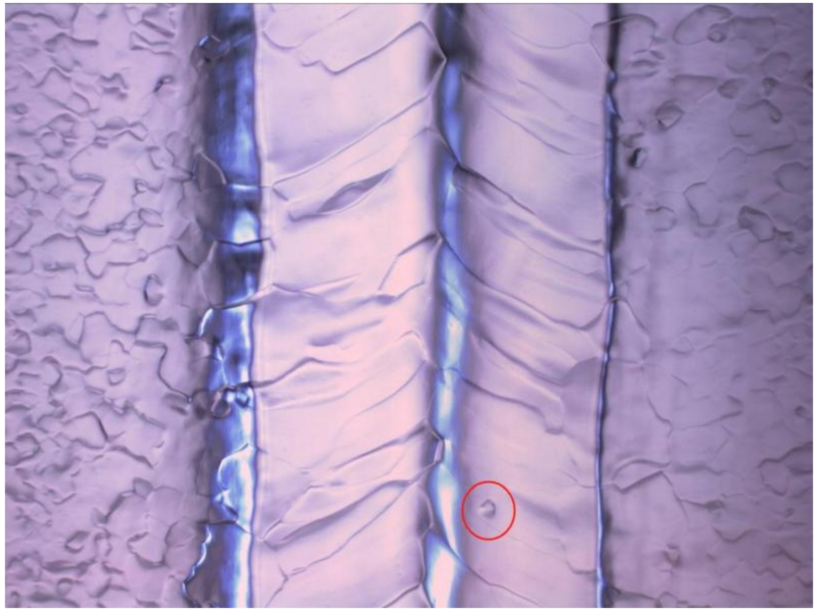
Post Process / EP

EP Systems

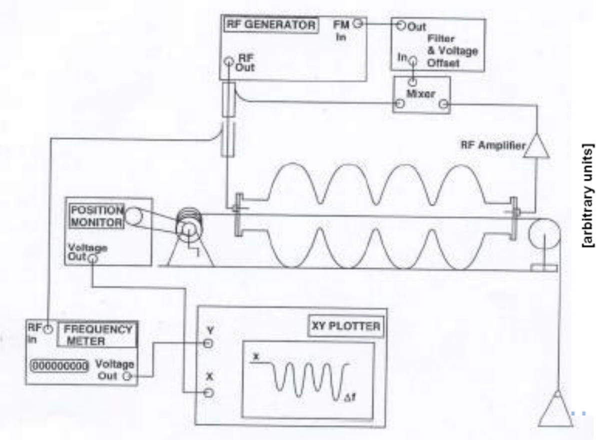


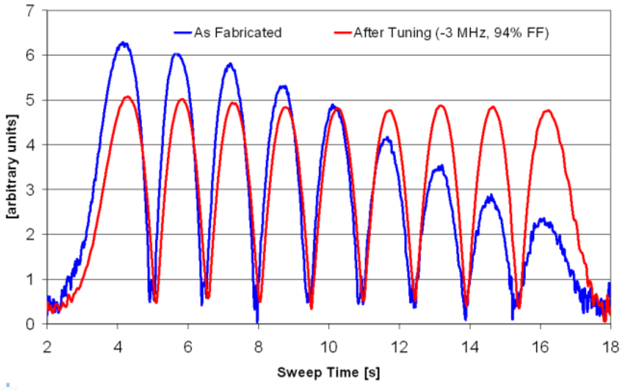
Camera inspection

- **Two step camera inspection adopted to ensure vertical tests of bare cavities are not necessary**
- **It is important for SHINE's early domestic production**
  - Firstly, incoming inspection of bare cavity→ if qualified, then go to EP process; Defects shall be removed before EP
    - Local grinding for defects at end cell, BCP flush for "dirty surface"
  - Secondly, inspection after mid-T baking→ if qualified, go to weld helium vessel; if unsure, then bare cavity will be vertical test



Pre-tuning

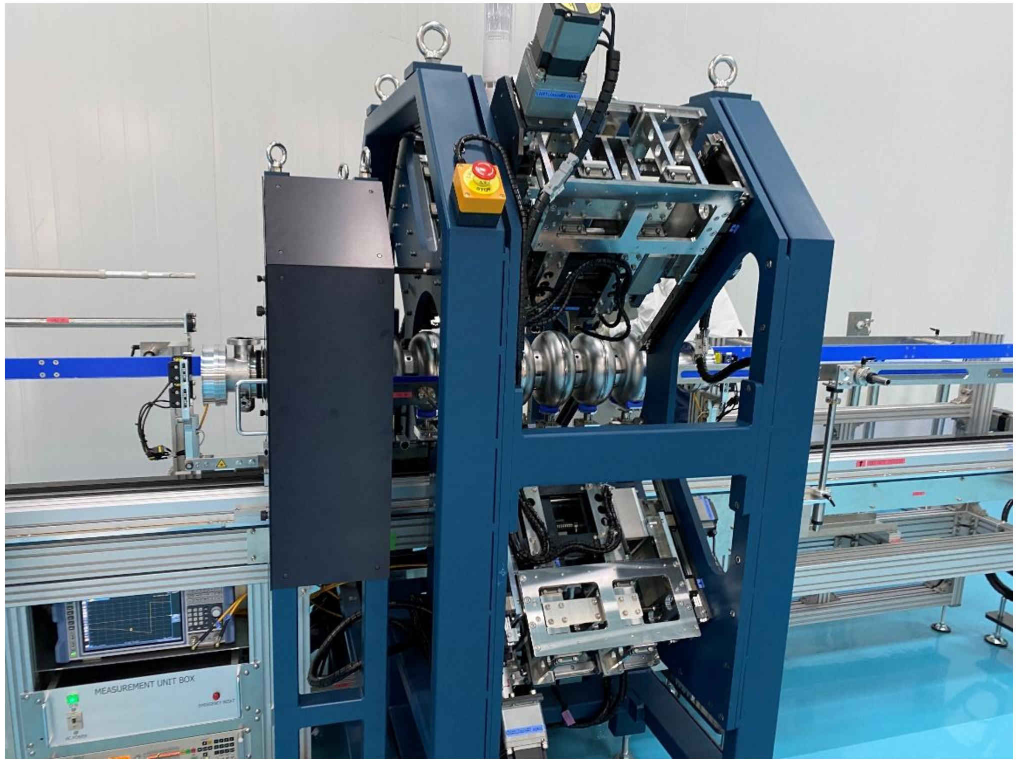




- After the treatments, the cavity needs to be tuned to the right frequency and field flatness.
- This operation is done by tuning each single cell to achieve proper field distribution
- **Bead-pull Method**

Pre-tuning machine

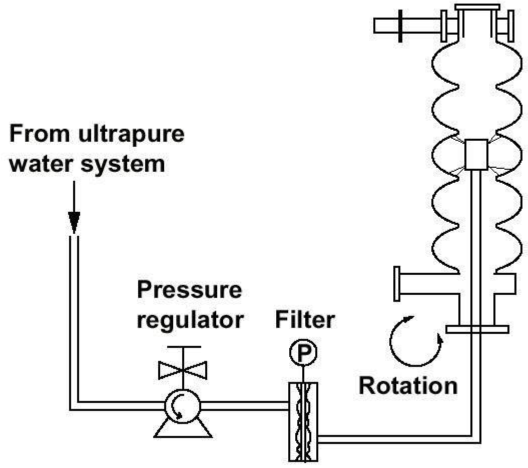
- Auto and semi-auto control modes
- To reach field flatness ≥95% and eccentricity ≤0.4 mm: less than 4 hours
- GUI, easier operation, RF experts not necessary

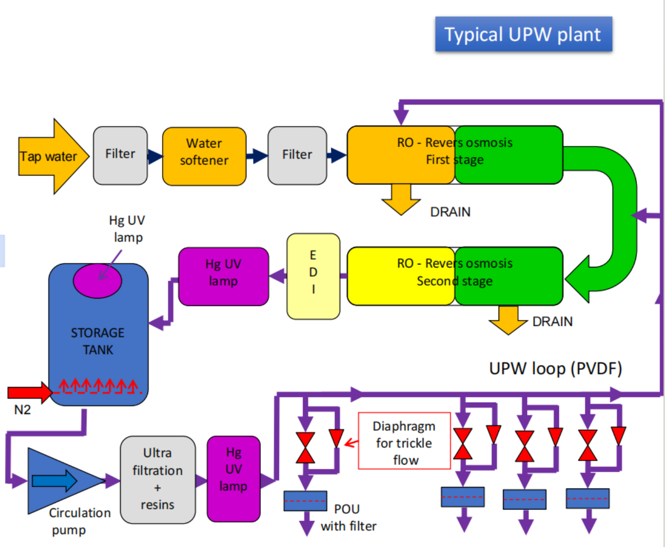


HPR: High Pressure Rinsing with ultrapure water

- HPR is used to remove particulate from the handling and residual from chemical treatments
- HPR is also used in several steps of the cavity production cycle (after bulk and final treatments, before high-T and mid-T process, before accessories assembly in clean room ISO4, etc.)
- Water jet must be moved continuously: if jet impacts stably in one-point Nb surface can be damaged
- Continuous motion of the cavity respect jets (drawing a spiral behavior that cover completely the Nb surface)
- Ultra pure (6.0) filtered (40 nm) nitrogen protection gas injection coaxial with water to reduce risk of particles entering
- Cavity must be grounded otherwise it will be electrically
- UPW Specifications

– Resistivity: 18.2 MΩ cm
– Total organic carbon (TOC): < 5 ppb
– Particulate counts (> 0.3 μm/l): < 10
– Bacteria counts: < 0.1 CFU/100 ml





HPR apparatus

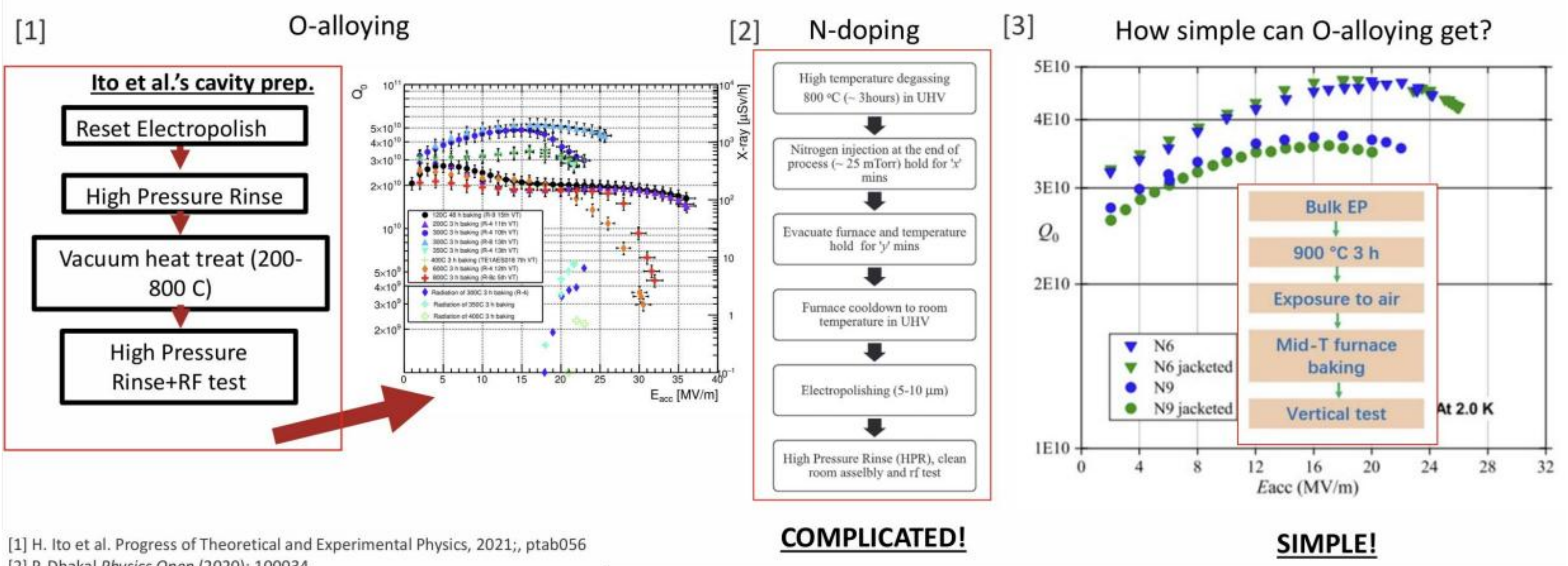
Rinsing cabinet of
“old“ DESY HPR system

Rinsing cabinet of “new“ DESY
HPR system with “plastic” cavity

CEA HPR system

SHINE HPR system

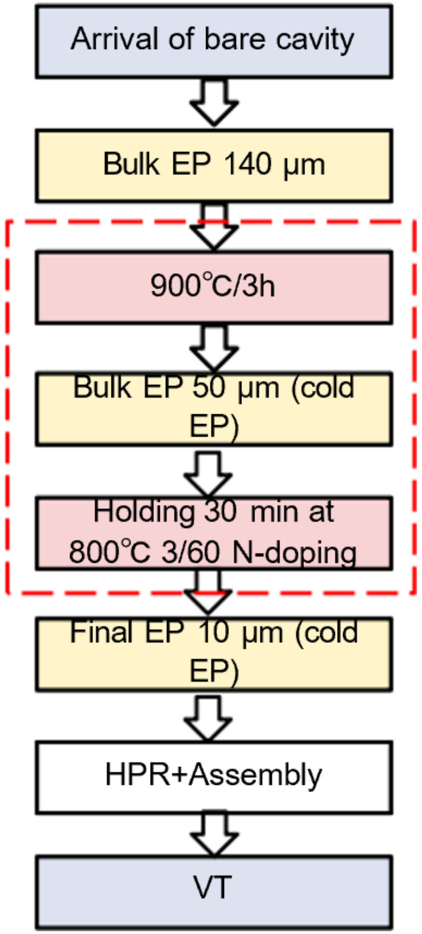
High-Q Recipes: N-doping and Mid-T Baking



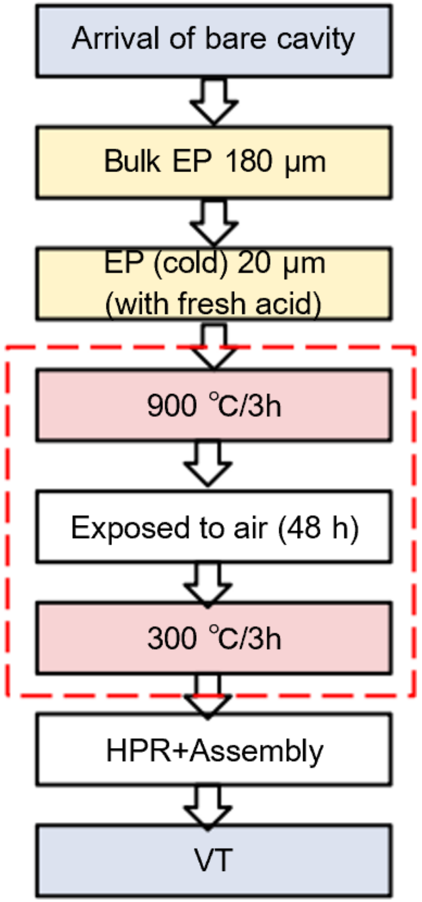
[1] H. Ito et al. Progress of Theoretical and Experimental Physics, 2021;, ptab056
[2] P. Dhakal *Physics Open* (2020): 100034.
[3] F. He, et al. *Superconductor Science and Technology* 34.9 (2021): 095005.

Cavity Surface Treatments for SHINE

SHINE Nitrogen doping recipe

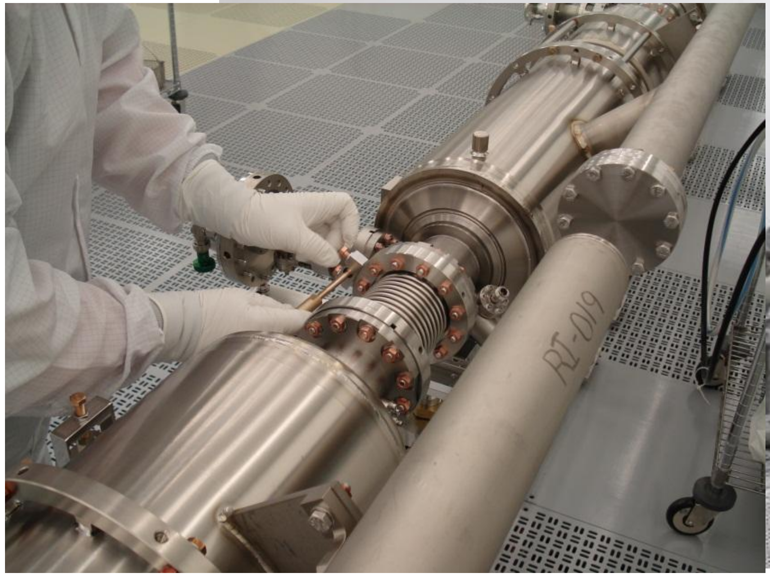


SHINE **Mid-T baking** recipe



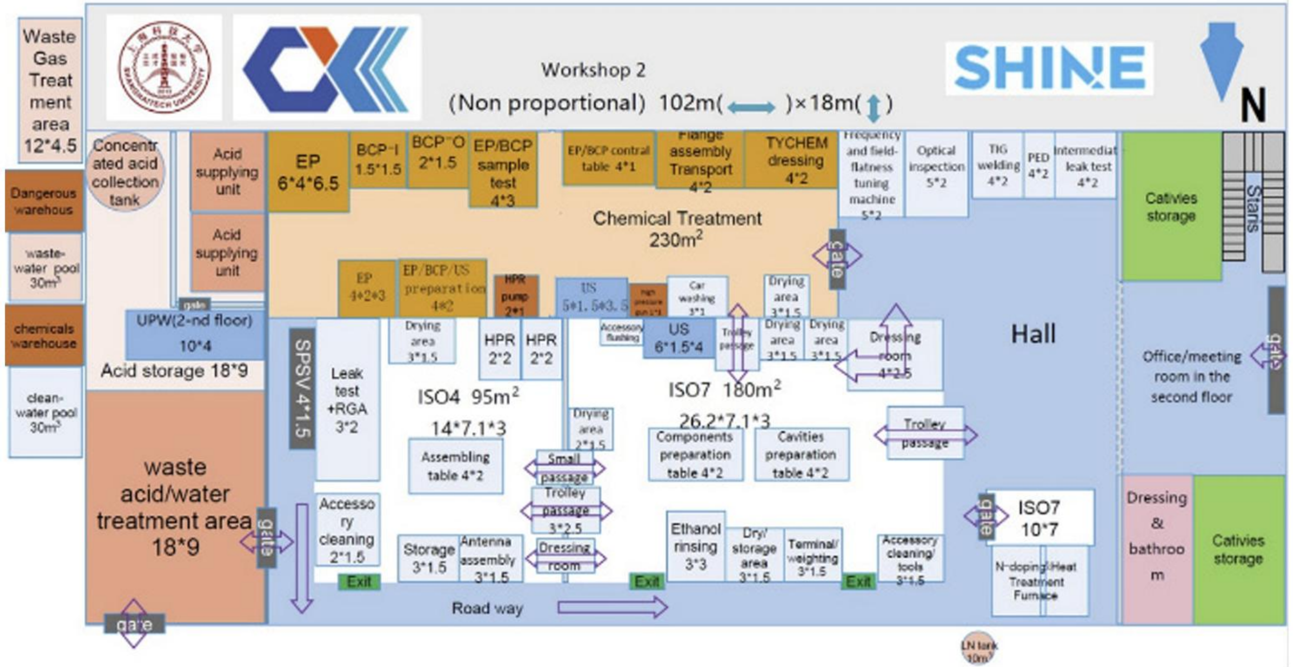
Clean assembly

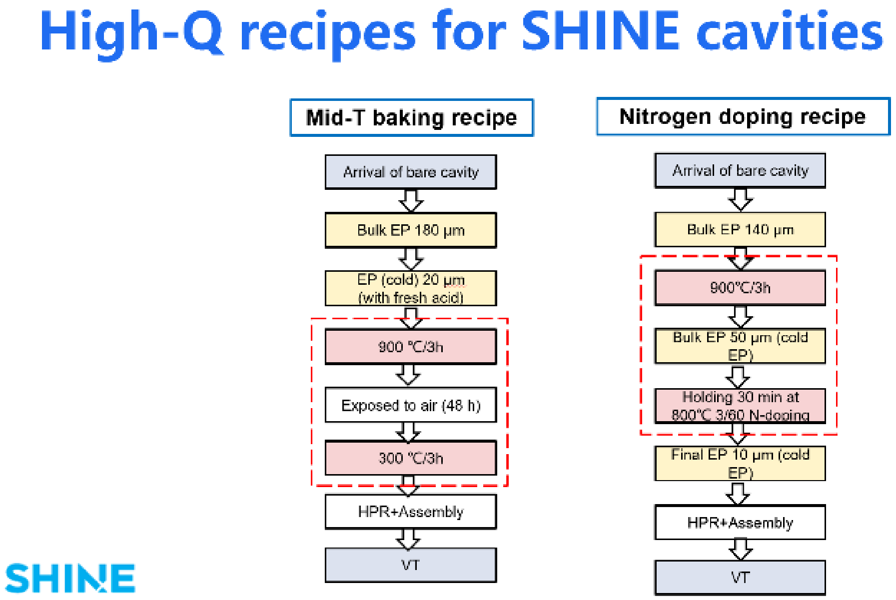
- **Clean assembly is crucial for cavity performance, especially for avoiding field emission**
- **Working area is ISO4 cleanroom**
- **Regulations shall be defined**
- **Operators must be trained**
- **Tools, studs and nuts and so on must be cleaned before enter clean room**
- **The cavity strings have to be vacuum tight to a leak rate of < 1 10-10 mbar l/sec**
- **The sealing gaskets and hardware have to be reliable and particulate-free**
- **Present choice for SRF cavities: diamond-shaped AlMg3 –gaskets + NbTi flanges + bolts**

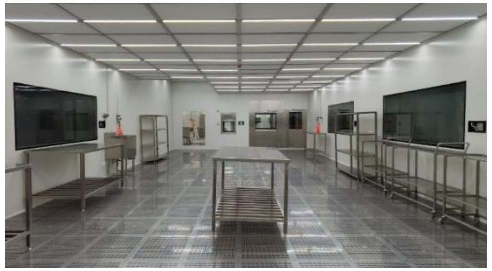


Examples——Surface treatment platform at SHINE

- Key technique：EP
- Key technique：high-Q0 recipe









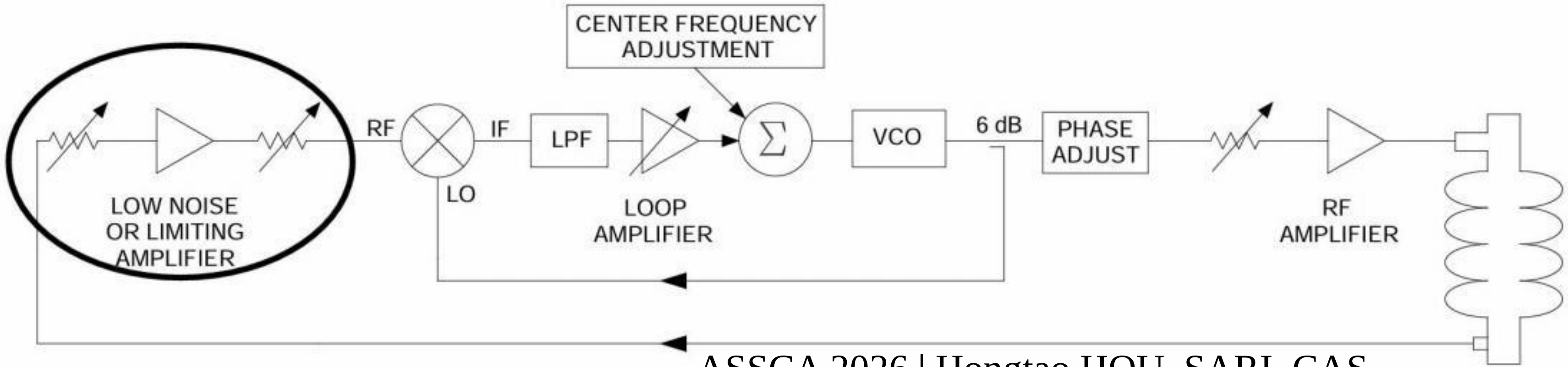

2. SRF Cavity

- Design
- SC Materials
- Fabrication
- Post process
- Vertical test

Vertical test

Vertical test plays important role to evaluate cavity performance

- Vertical testing vs horizontal testing & VTA area
- Test area design considerations & maintenance (magnetic fields)
- Personnel safety and machine protection
- RF circuits used for vertical testing
- Cryogenic circuits used for vertical testing
- Test Dewars & Inserts
- Other sensors: pressure, temperature, magnetic field probes
- Data Acquisition Methods



$$P_{diss} = P_f - P_r - P_t \qquad 4.1$$

$$\beta_i^* = \begin{cases} \dfrac{1+\sqrt{P_r/P_f}}{1-\sqrt{P_r/P_f}} & \beta_i^* > 1 \\ \dfrac{1-\sqrt{P_r/P_f}}{1+\sqrt{P_r/P_f}} & \beta_i^* < 1 \end{cases} \qquad 4.2$$

$$\beta_t = \frac{P_t}{P_f - P_r - P_t} \qquad 4.3$$

$$\beta_i = \beta_i^*(1+\beta_t) \qquad 4.4$$

$$Q_L = 2\pi f \tau_L \qquad 4.5$$

$$Q_0 = (1+\beta_i+\beta_t)Q_L \qquad 4.6$$

$$Q_t = Q_0/\beta_t \qquad 4.7$$

$$Q_{in} = Q_0/\beta_i \qquad 4.8$$

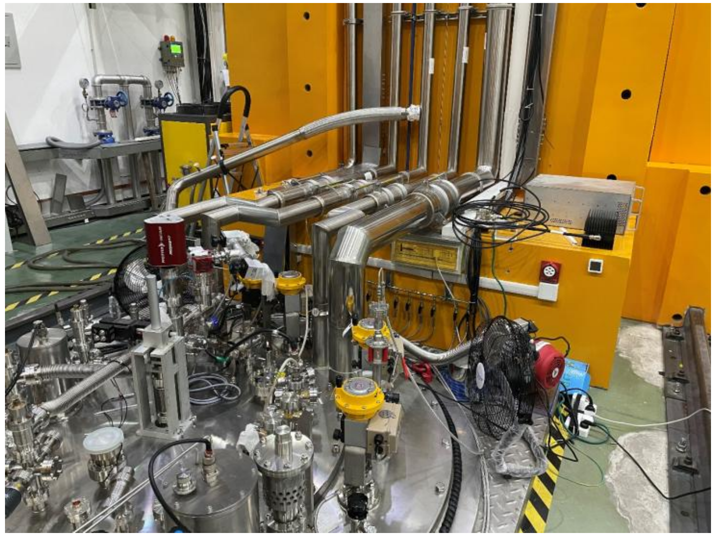
$$E_{acc} = \frac{1}{L_{eff}}\sqrt{(r/Q)\times Q_0 \times P_{diss}} \qquad 4.9$$

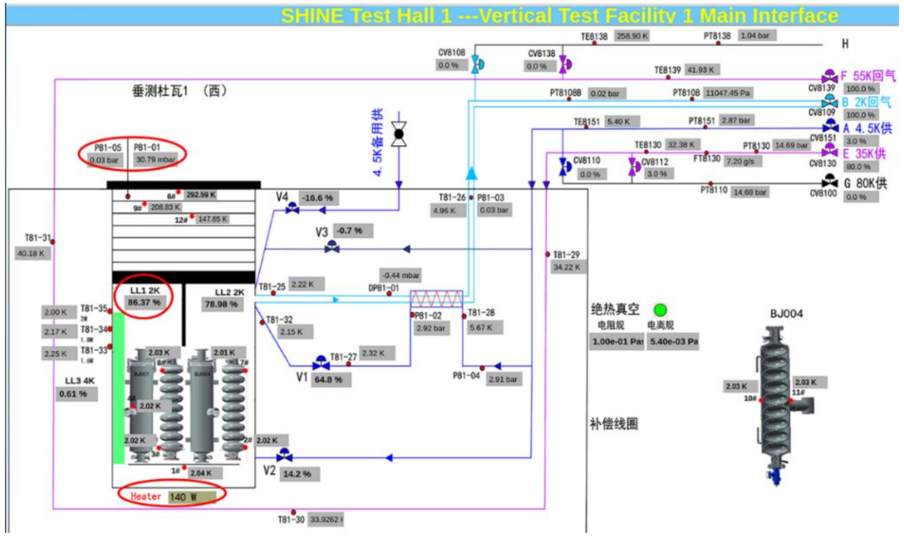
$$P_{diss} = \frac{V_{acc}^2}{(r/Q)\times Q_0} \quad P_{diss} = \frac{\omega U}{Q_0} \quad P_t = \frac{\omega U}{Q_t} \qquad 4.10$$

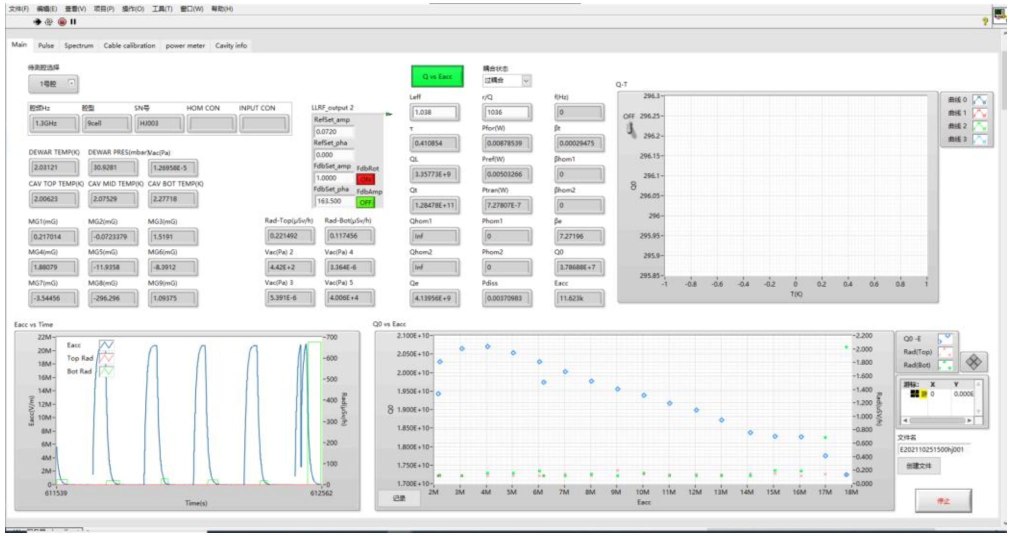
$$E_{acc} = A\sqrt{Q_0 \times P_{diss}} = A\sqrt{Q_t \times P_t} \qquad 4.11$$

$$Q_0 = \frac{P_t}{P_{diss}}Q_t = \frac{P_t}{P_f - P_r - P_t}Q_t \qquad 4.12$$

Vertical Test platform for SHINE

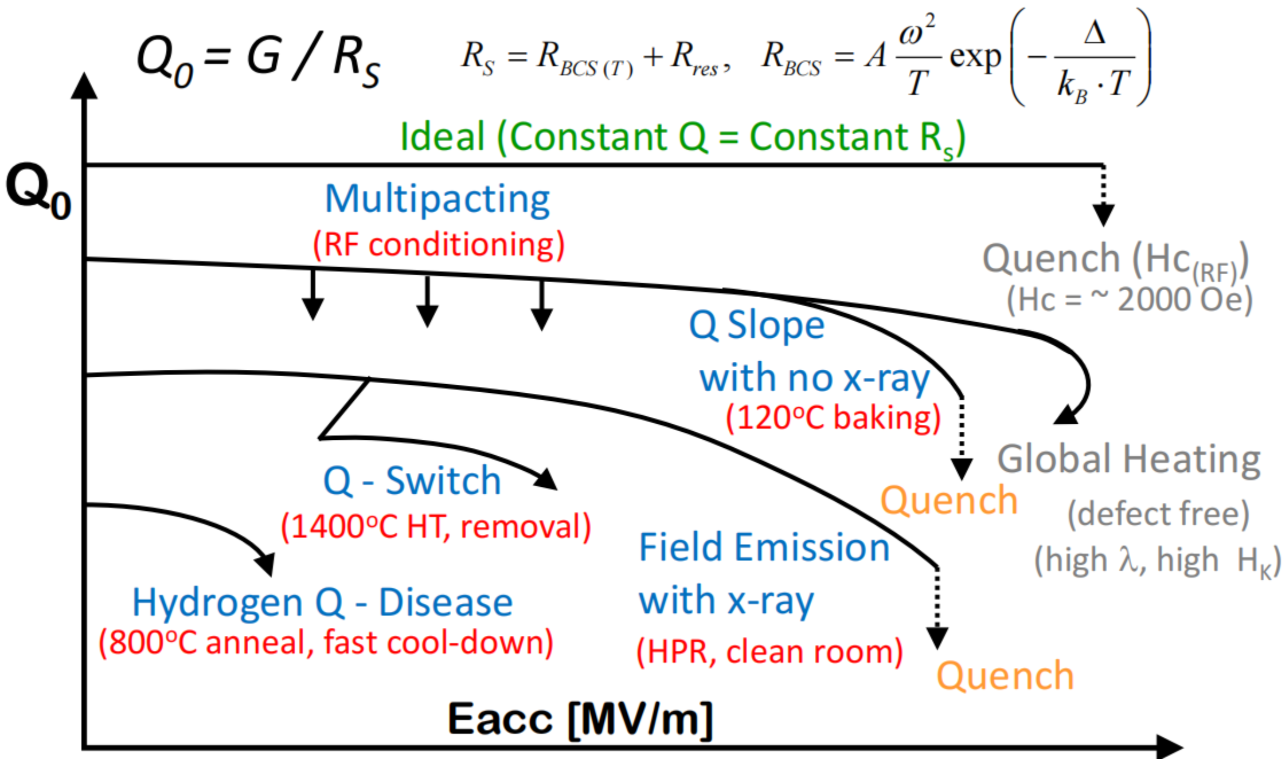






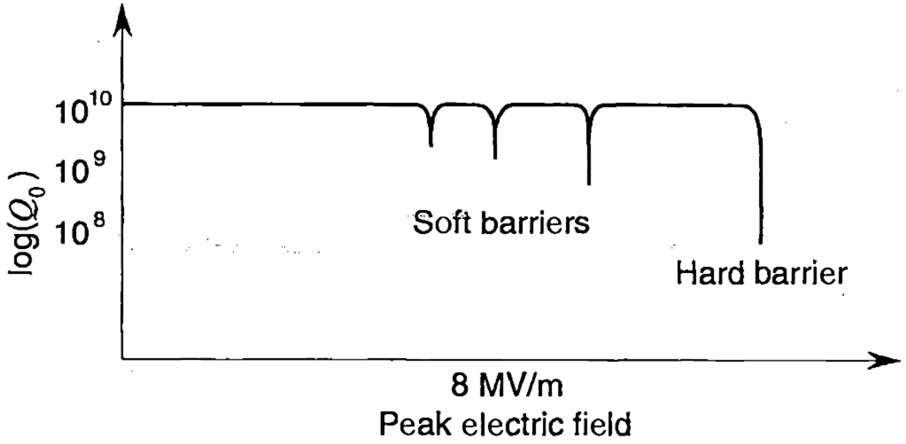
Cavity Performance Limitation

- Multipacting: soft MP barrier can be conditioned
- Field emission: some can be conditioned
  - HPR is quite effective to cure Field emission
- Quench
  - Caused by local defects
  - Remove defects by grinding, chemical polishing

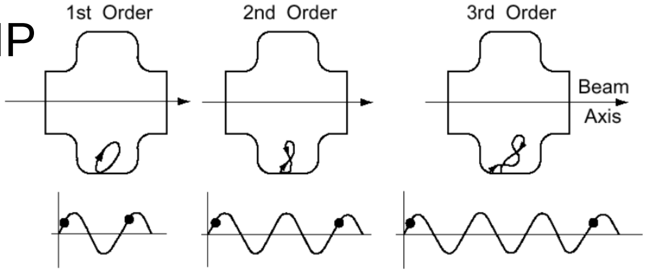


MP

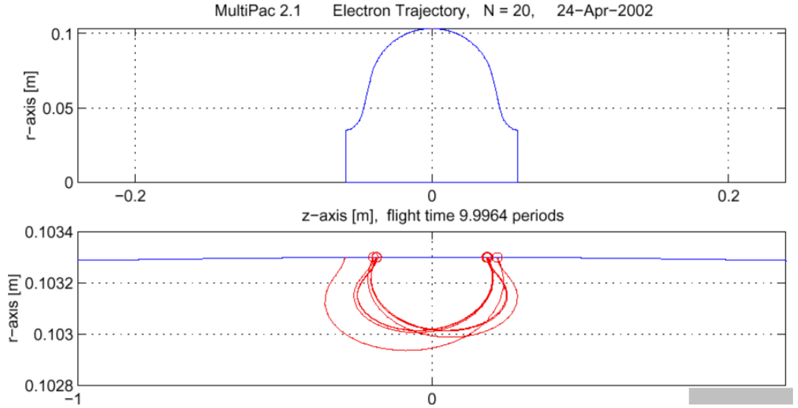
- Multipacting: soft MP barrier can be conditioned
- Surface condition influences MP
- Not good Cavity shape results in MP



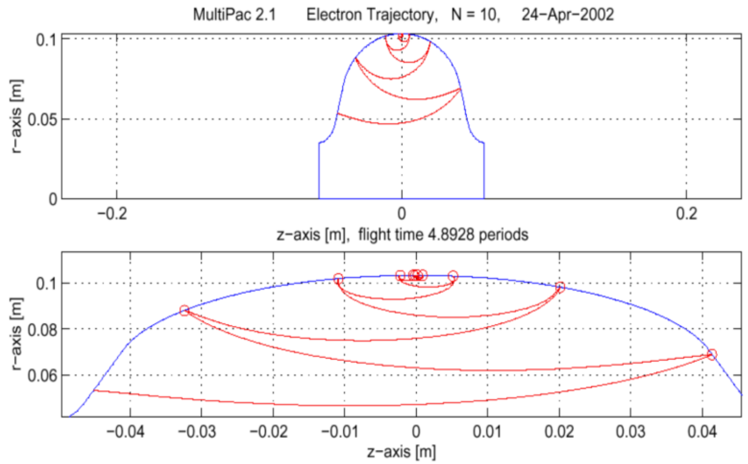
One point MP



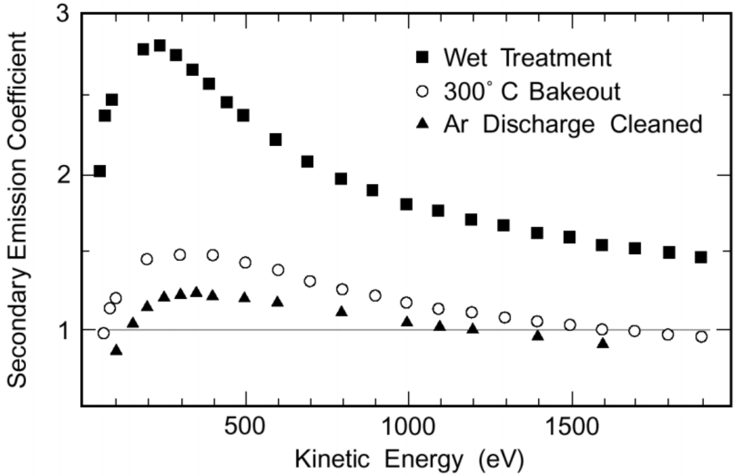
Two points MP



Two sides MP

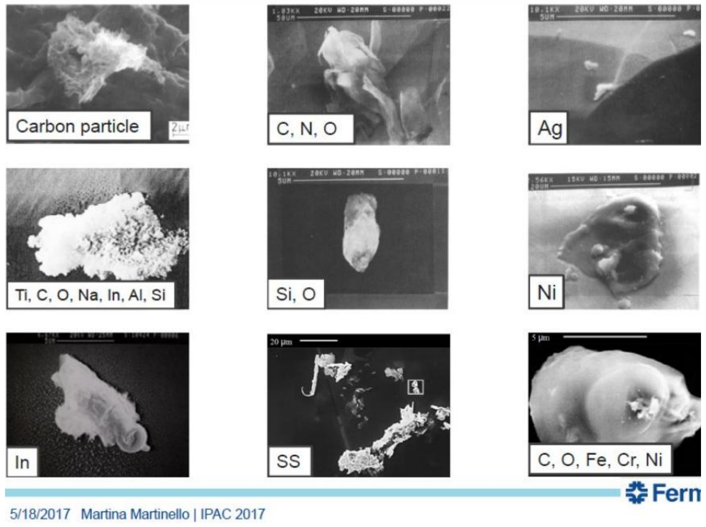


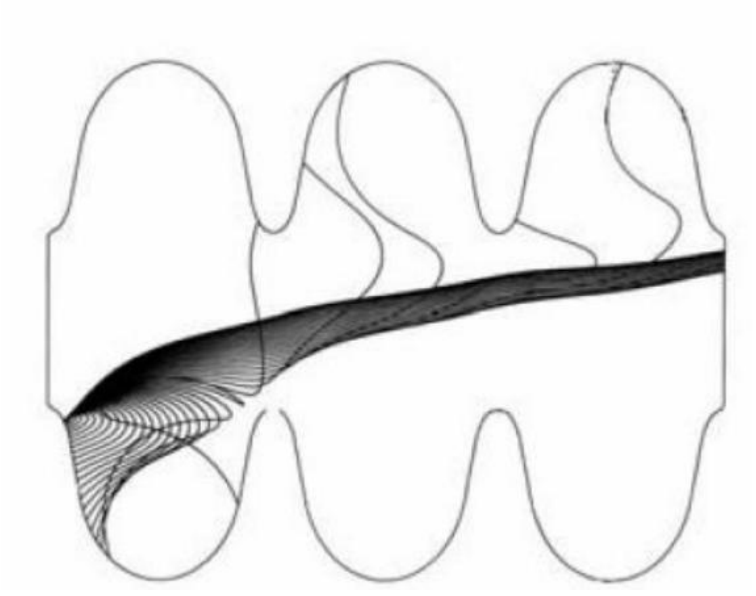
SEY curve of Nb

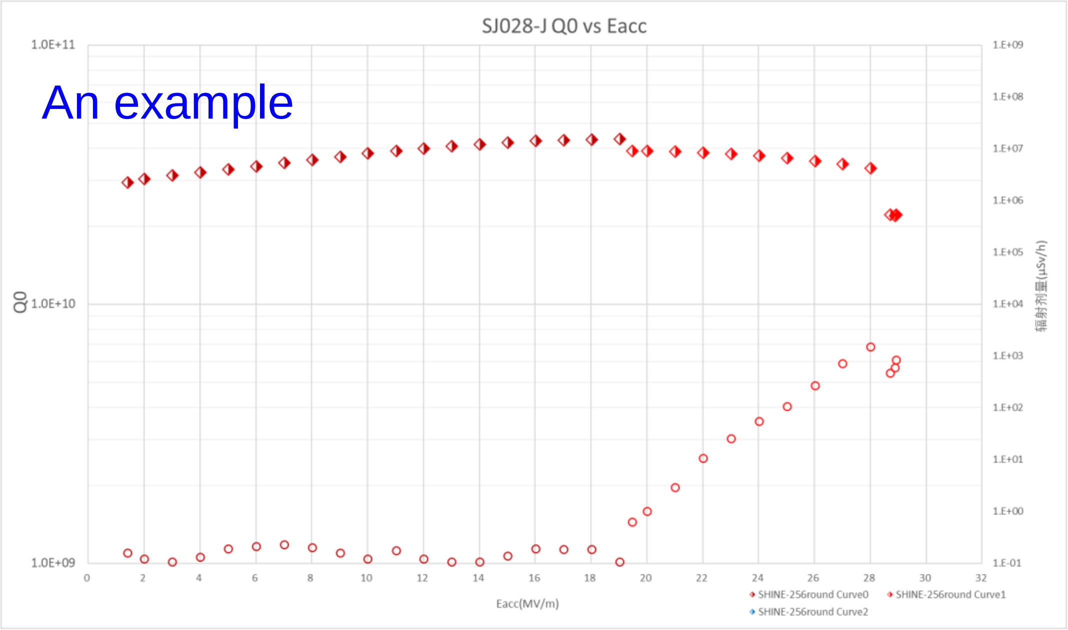


Field emission

- “dirty” surface
- Emitters can be foreign particles, metals
- When FE happens, strong X-ray radiation can be detected during vertical test
- HPR can cure Field emission

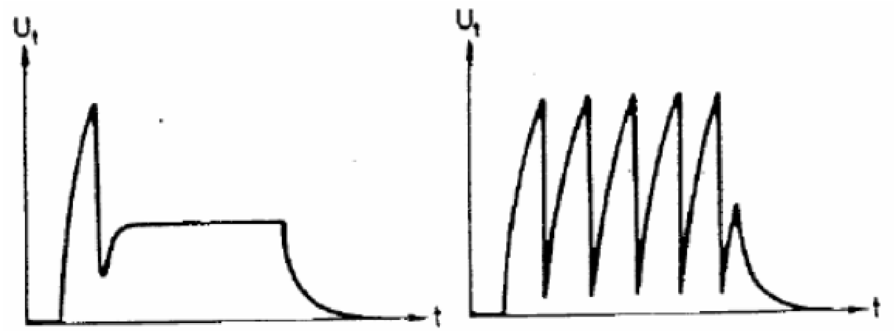


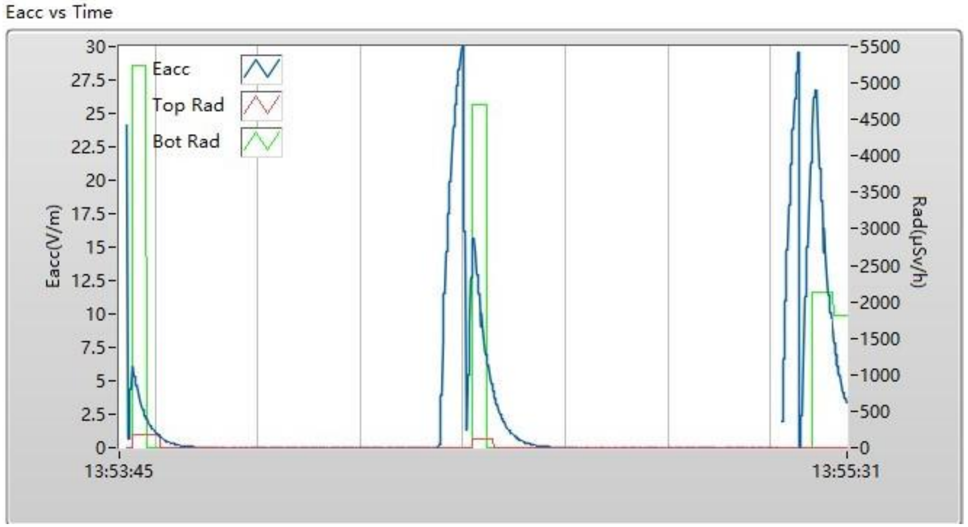


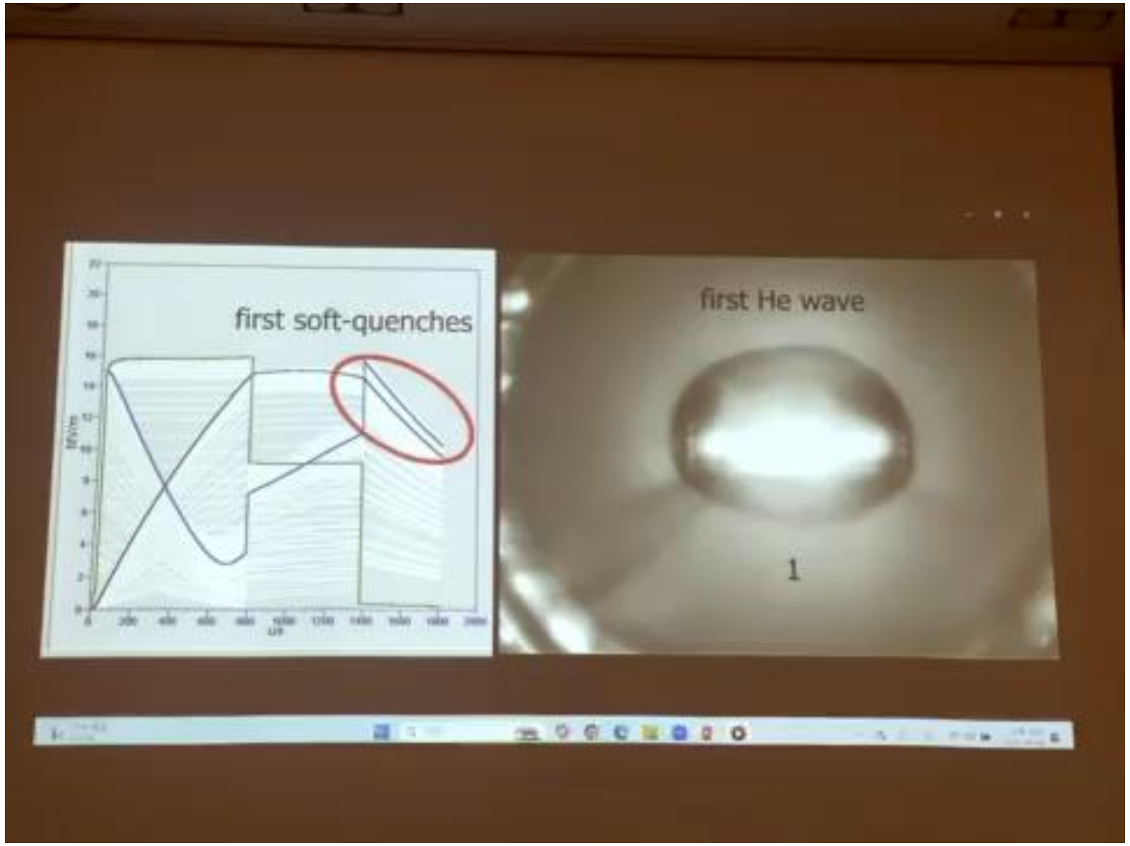


Quench / Thermal breakdown

- Generally, quench is caused by localized over-heating.
- Defects can bring quench at lower gradient







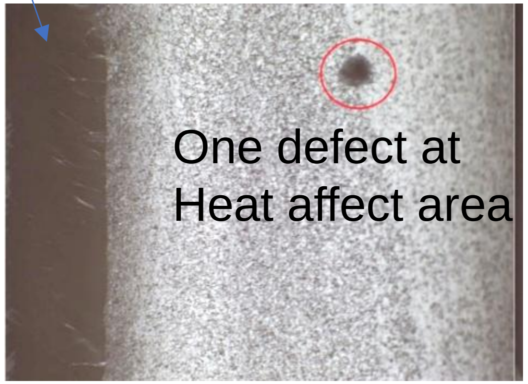
DESY, TTC 2025

Quench / Thermal breakdown

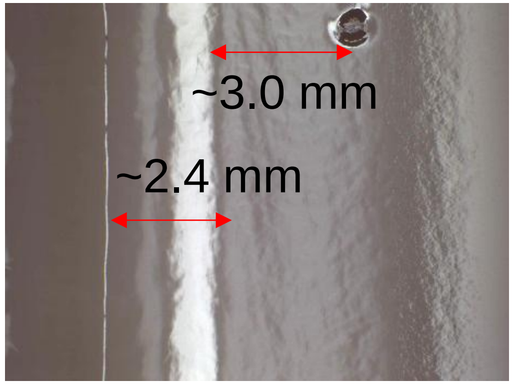
- Generally, quench is caused by localized over-heating.
- Defects can bring quench at lower gradient

Welding seam at equator

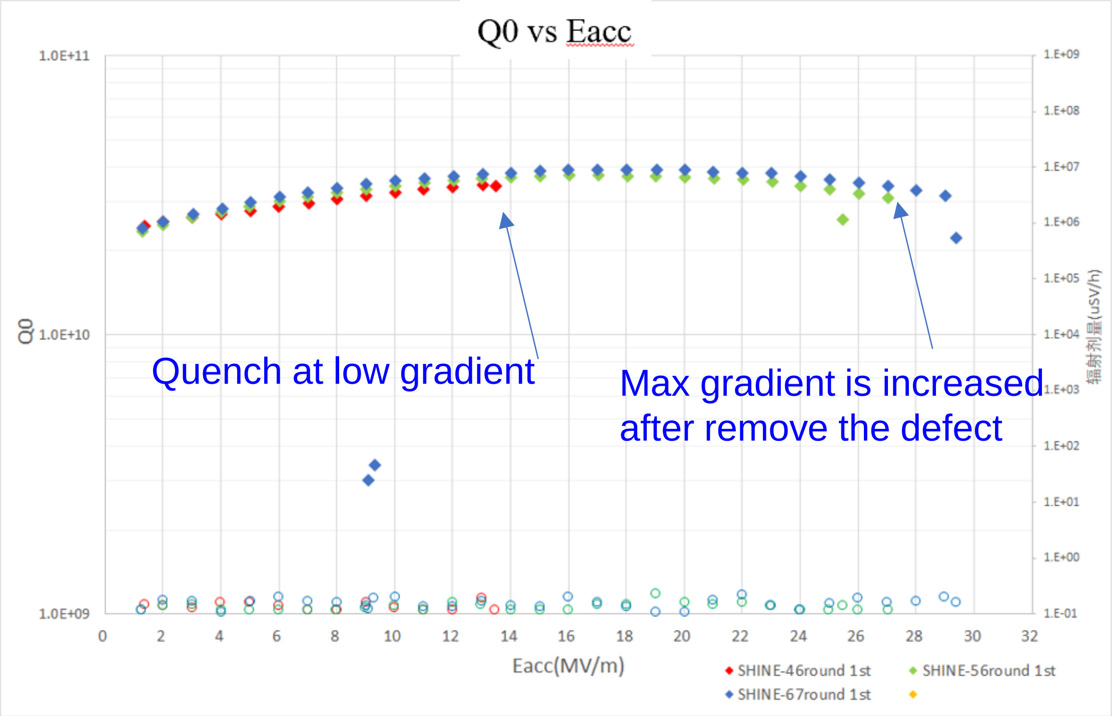
defect



Picture before EP

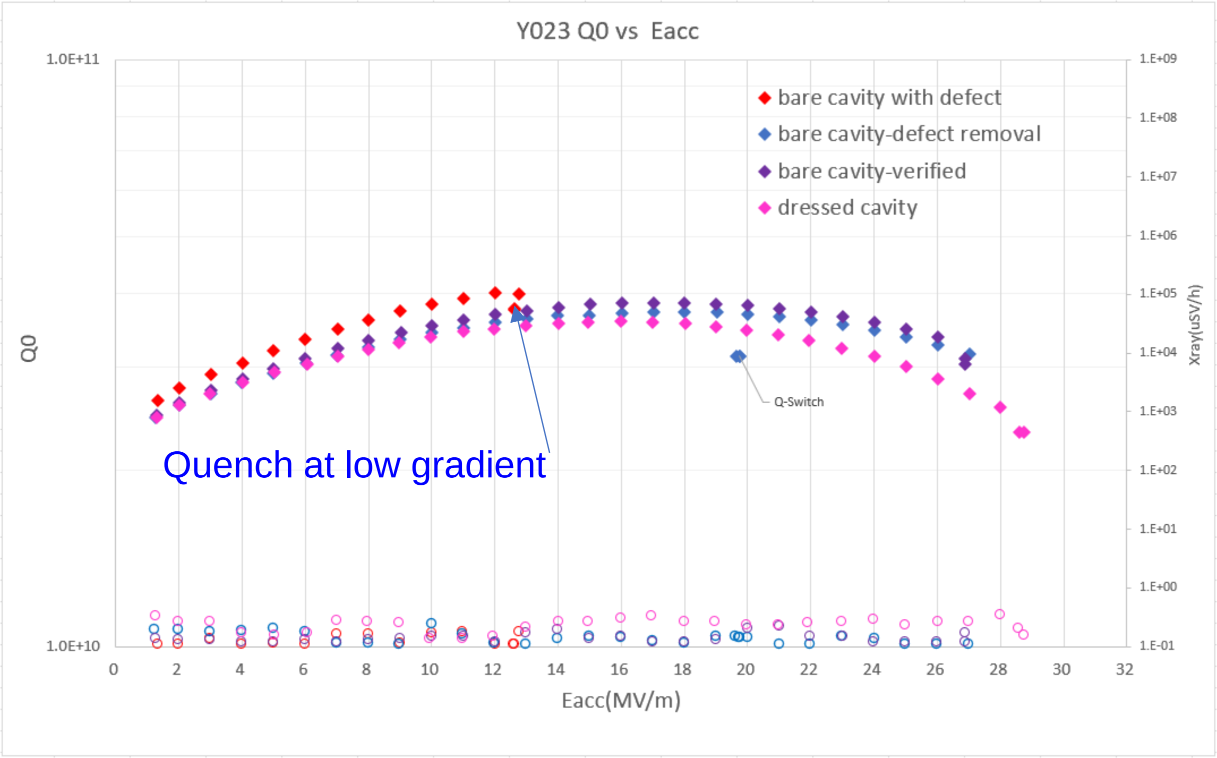


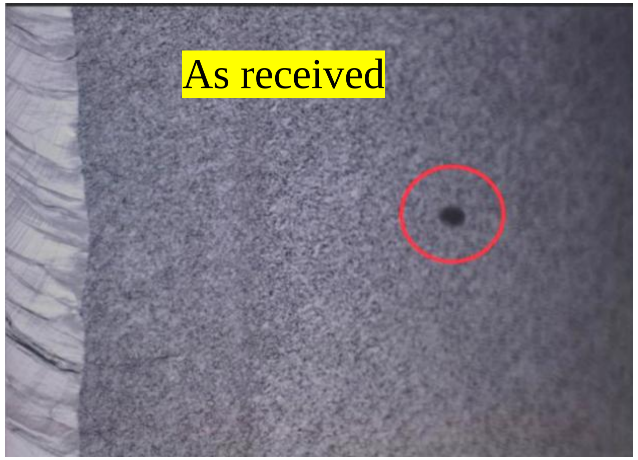
Picture after EP

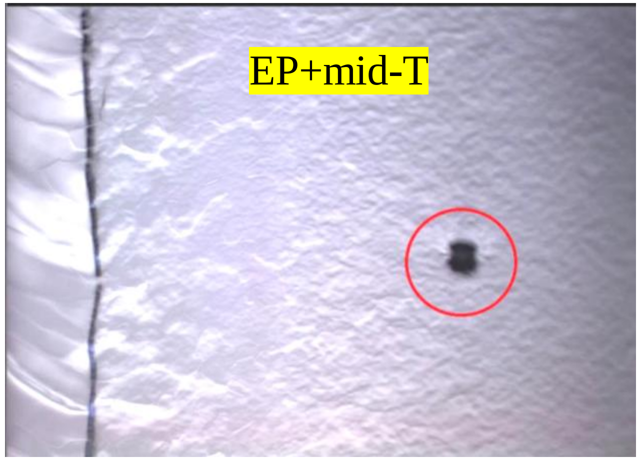


Another example

- Gradient limited by defect→ removal defect by local grinding→ Good cavity

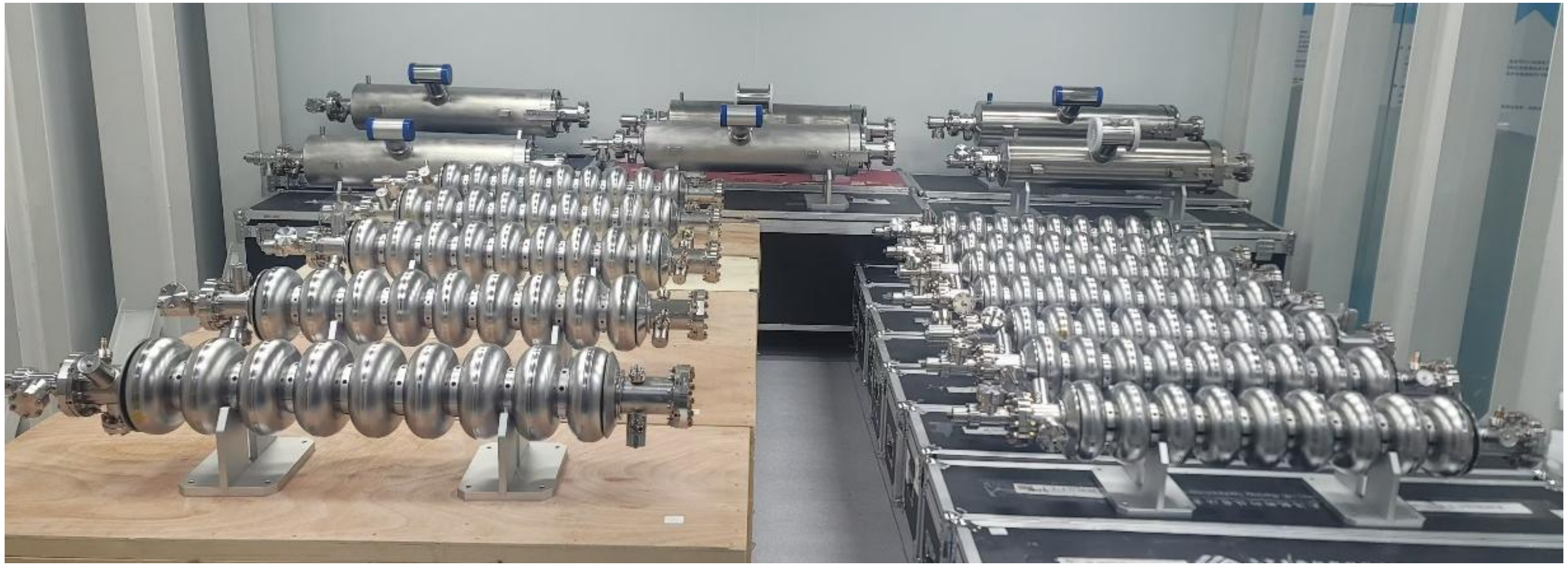






Mass production for SHINE

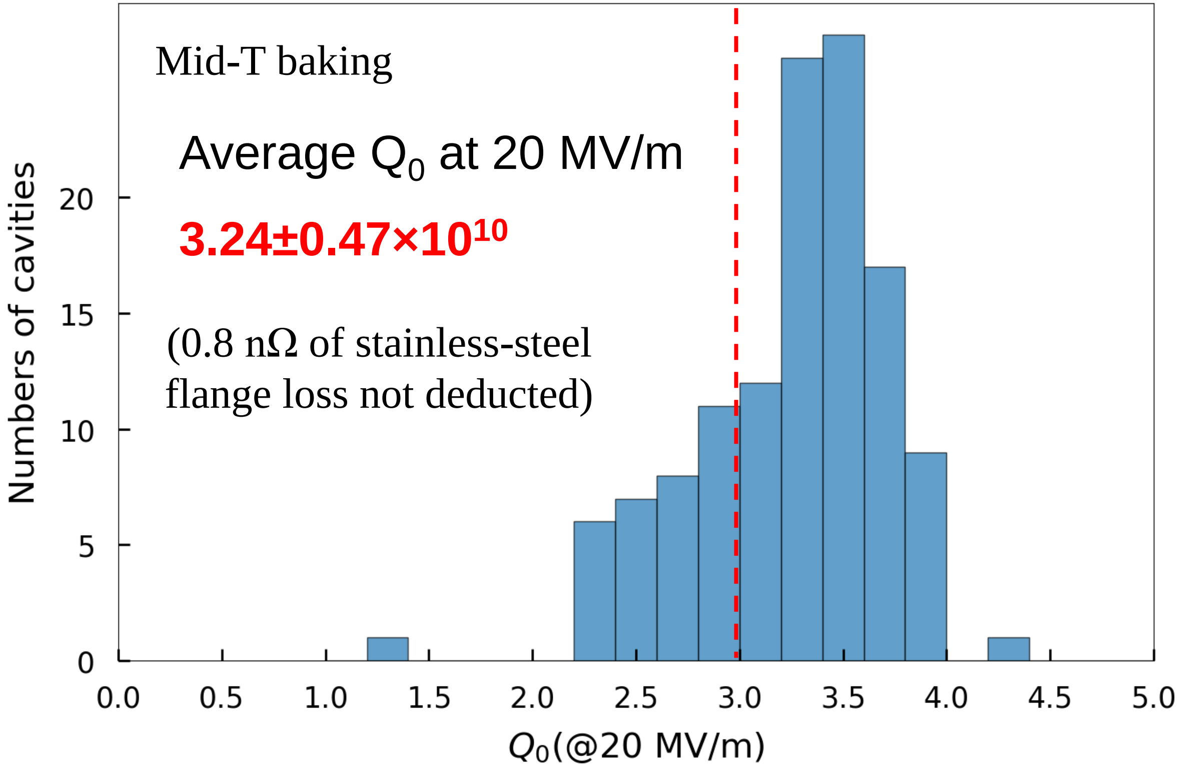
- Challenge to have qualified cavities on time
- No vertical tests on bare cavities to reduce cost and save time
- Establish acceptance criteria for dressed cavities
- Domestic suppliers for parts and materials, besides niobium sheets

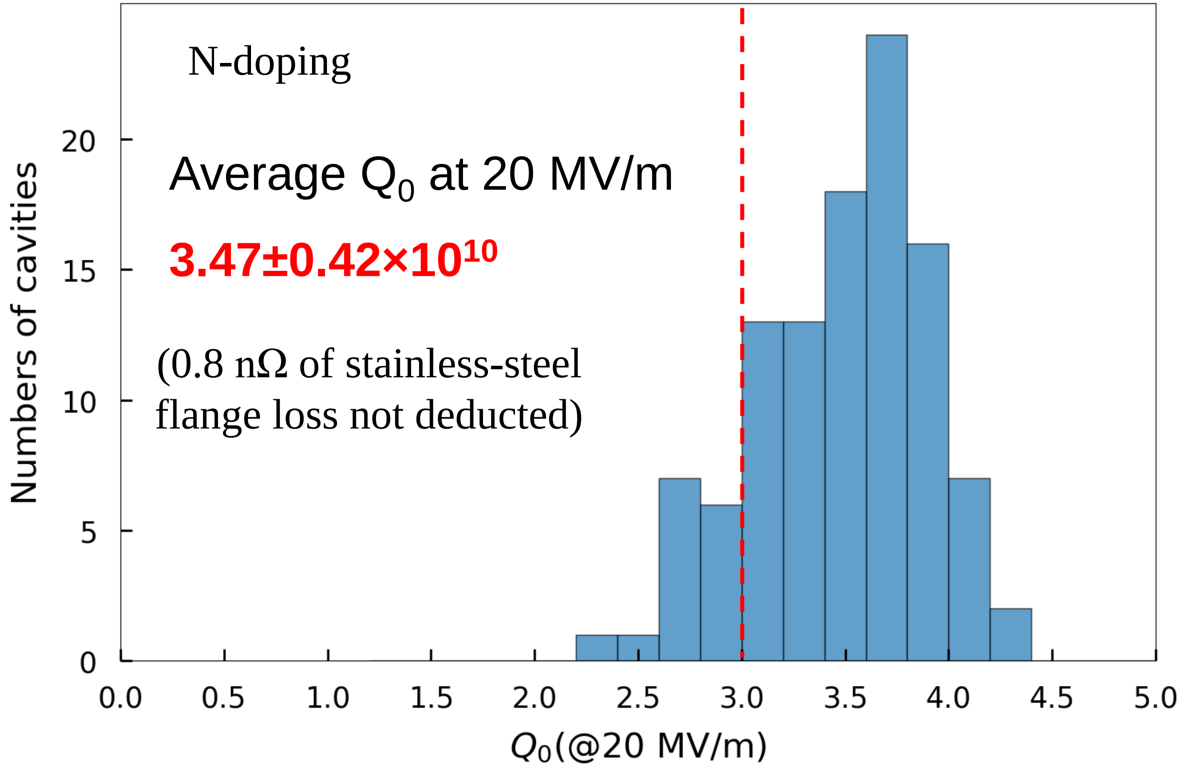


SRF 1.3GHz Cavity performance

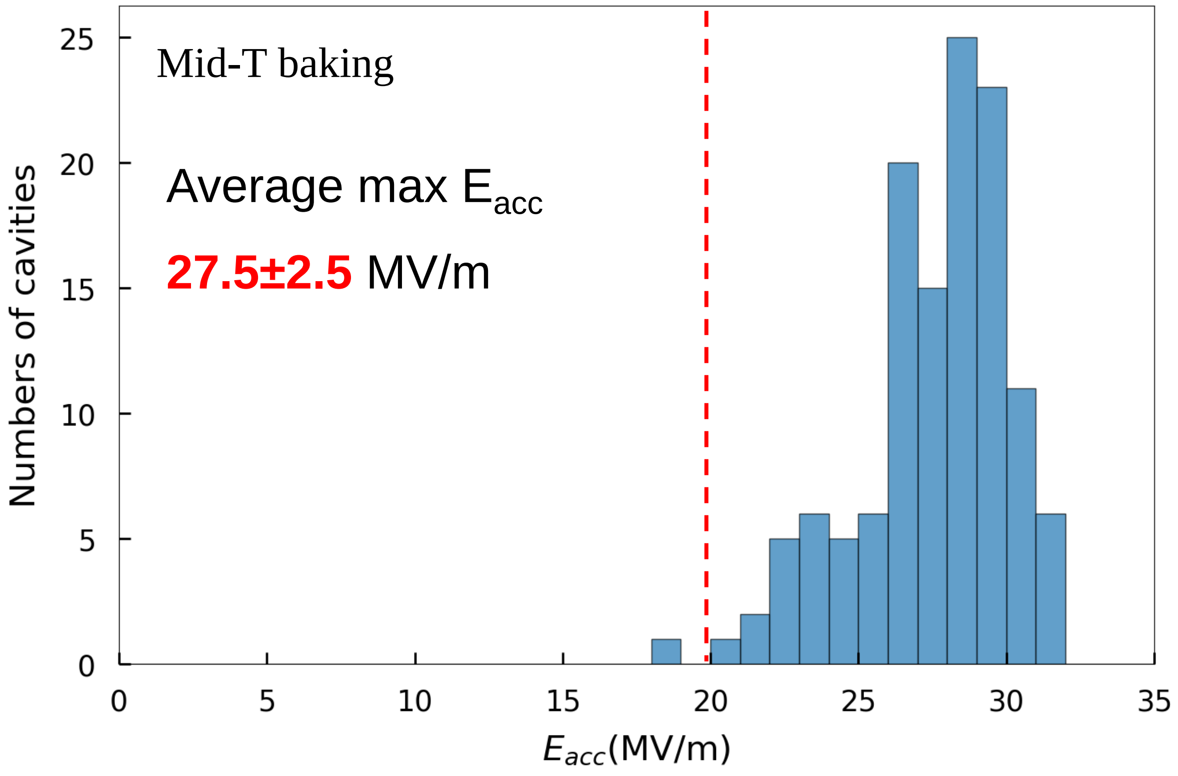
Name	Acceptance Criteria	Unit	Qualified
Shape accuracy	≤ +/- 0.2 (80%≤ +/- 0.2 mm, 20%≤ +/- 0.3 mm)	mm	Y
Eccentricity	≤ 0.4	mm	Y
Cavity Length (between flanges)	1283.4 +/- 3.0	mm	Y
Frequency of bare cavity @ in vacuum	1298.25 +/-0.1	MHz	Y
Field flatness of bare cavity	≥ 95%	/	Y
Field flatness of dressed cavity	≥ 90%	/	Y
Appearance of inner surface	defect free	/	Y (several cavities have defects)

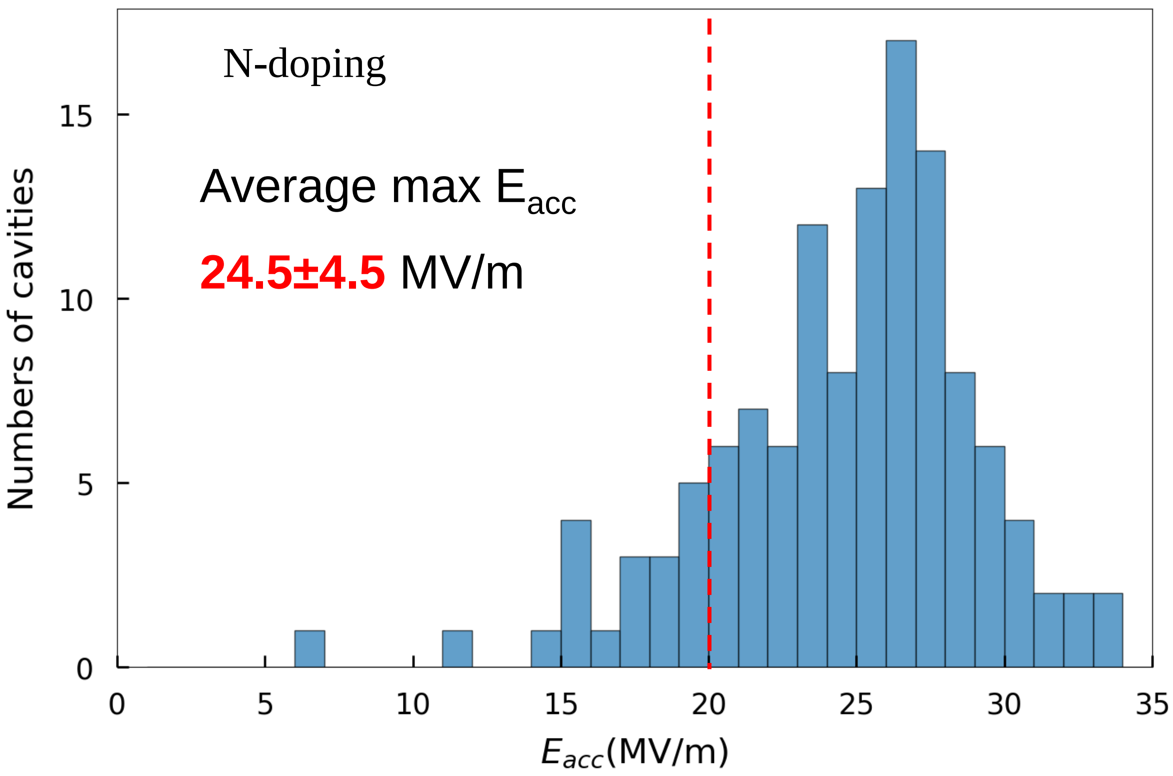
Cavity performance——Q0





Cavity performance——gradient





3. Cryomodule examples

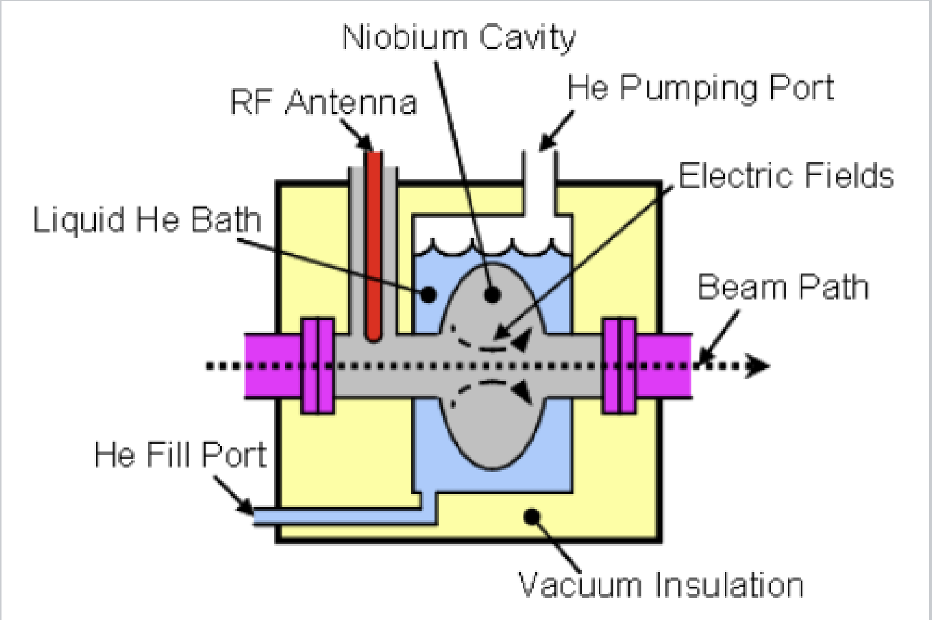
- **What are cryomodules**
- **Superconducting harmonic cavity for SSRF**
- **Twin-FPC Superconducting cavity for injector of SHINE**
- **SHINE Cryomodule**
- **Horizontal test of cryomodules**

3. Cryomodule examples

■ Wikipedia says

A **cryomodule** is a section of a modern particle accelerator composed of superconducting RF (SRF) acceleration cavities, which need very low operating temperatures (often around 2 Kelvin). The cryomodule is a complex, state-of-the-art supercooled component in which particle beams are accelerated for scientific research. The superconducting cavities are cooled with liquid helium.

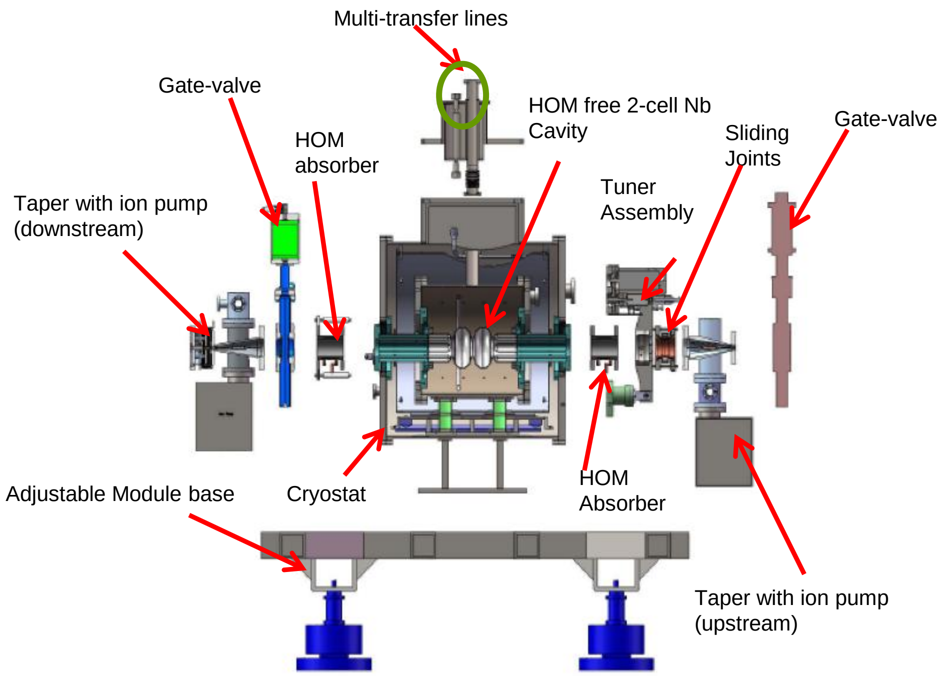
A cryomodule *section* of an accelerator is composed of superconducting cavities that accelerate the beam, also including a magnetic lattice that provides focusing and steering.



Simplified sketch of a SRF cavity in a helium bath, with RF coupling and a passing particle beam.

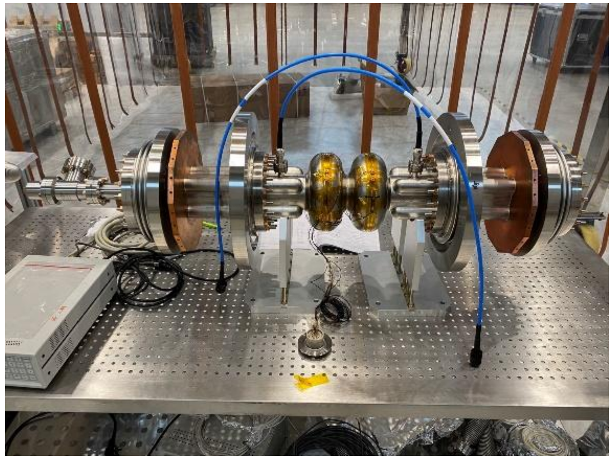
SSRF 3HC Cryomodule

- Function: lengthen bunch size, increase beam life time and improve beam quality
- Not accelerate electrons
- **Now, goal of cryomodule is clear, we will start the cavity design**



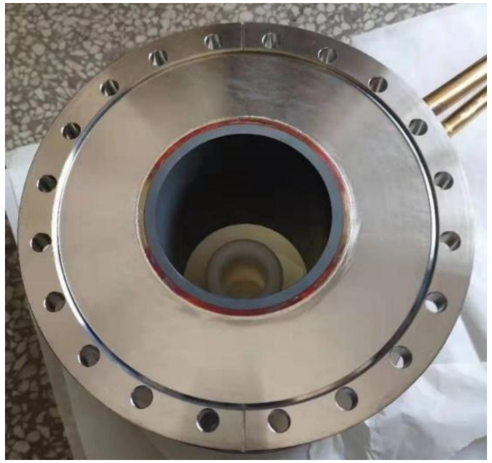
Superconducting 3HC cryomodule development

1500MHz 2-cell Nb cavity

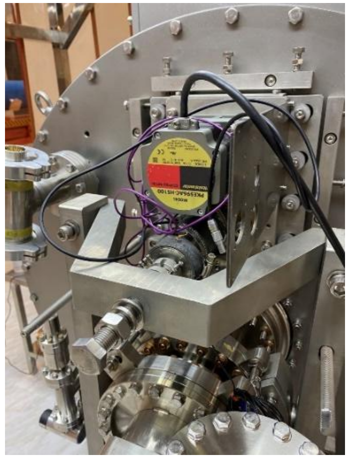


Cavity with thermal transition

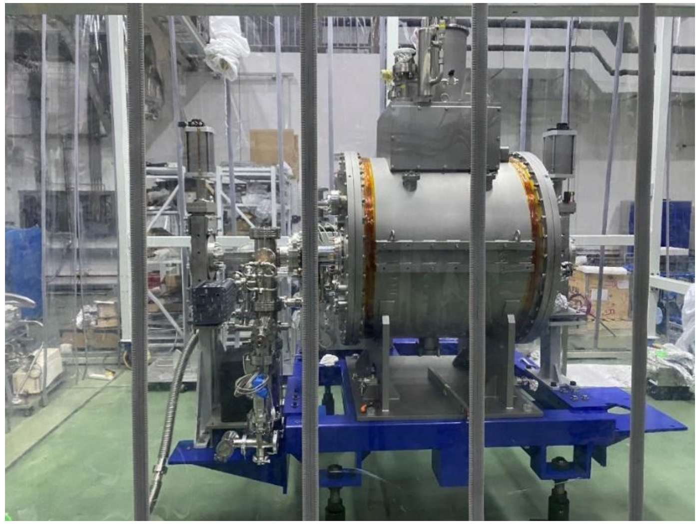
Cryostat



HOM absorber



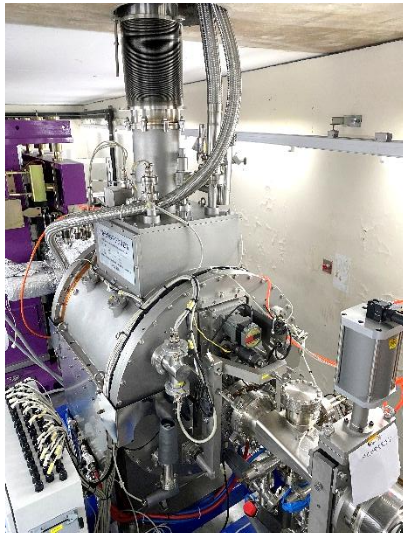
Tuner



Cryomodule Assembly

Interlock and LLRF controller

Horizontal test

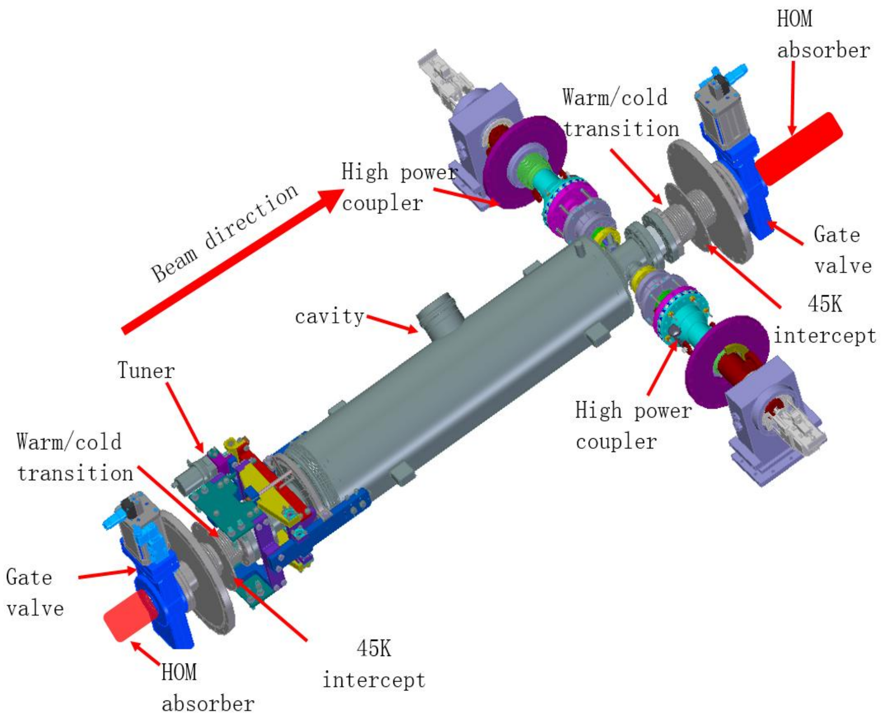


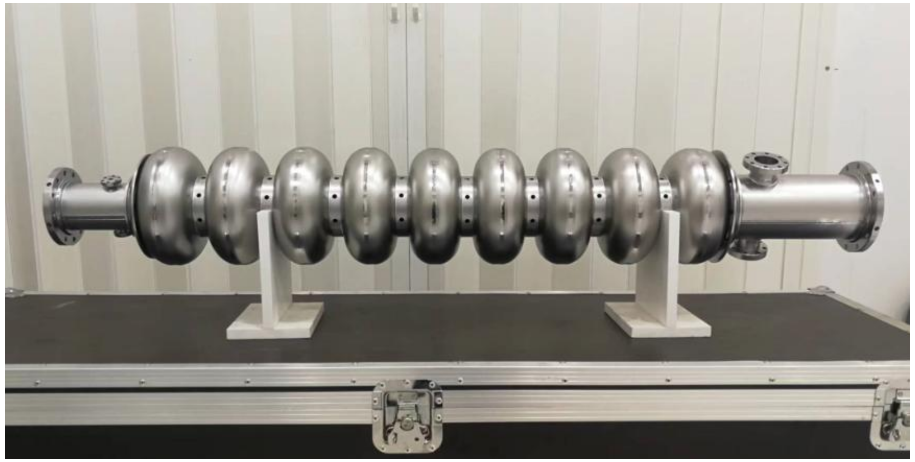
In tunnel

Twin FPC cavity for SHINE injector

Goal: to reduce influence by Asymmetric TESLA cavity structure

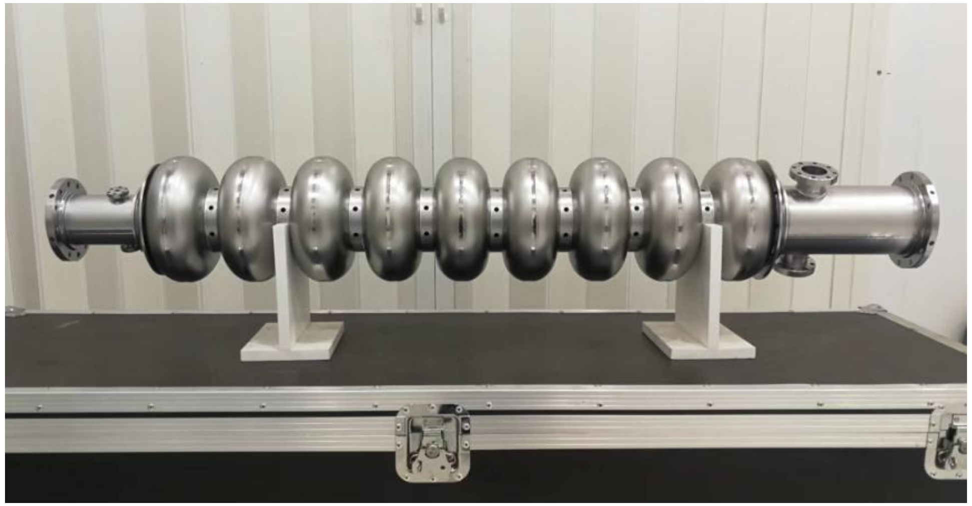
- Axial symmetry cavity
- Enlarged beam pipe at downstream for HOM propagation
- Eliminate HOM couplers
- Twin FPC located downstream
- Using CST、Mutipac、Ansys
- Beam pipe HOM absorber

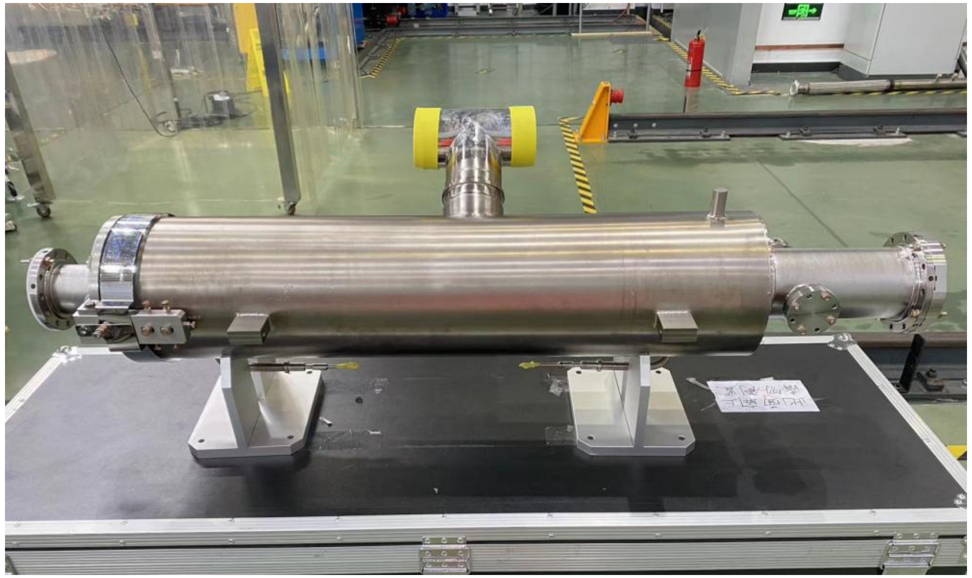


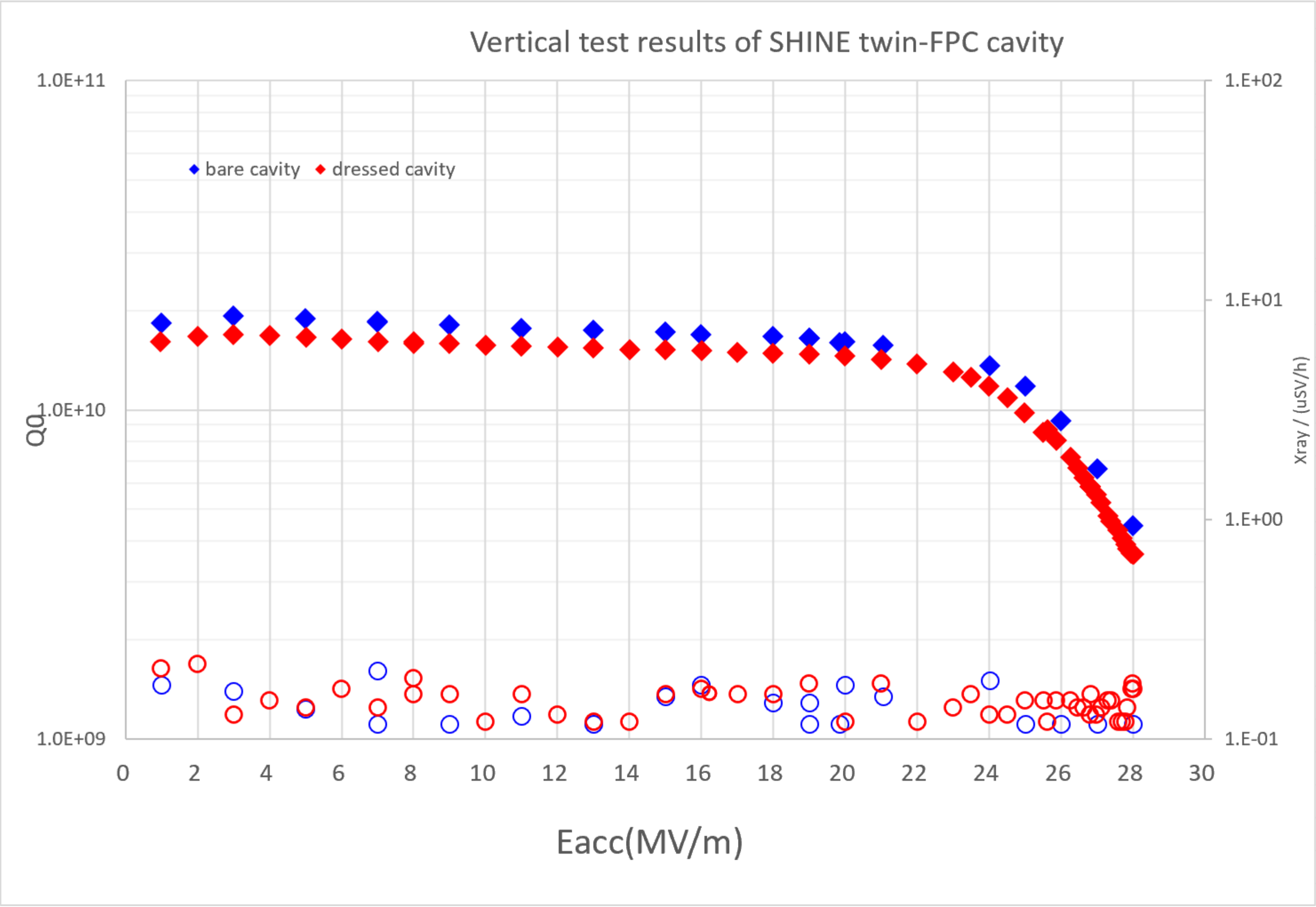


Cavity is BCP treated

Vertical test results: f=1300.146 MHz @ 2K, Q_0> 1.5 e10 @ E_{acc}=12 MV/m, E_{acc_max} ~28MV/m

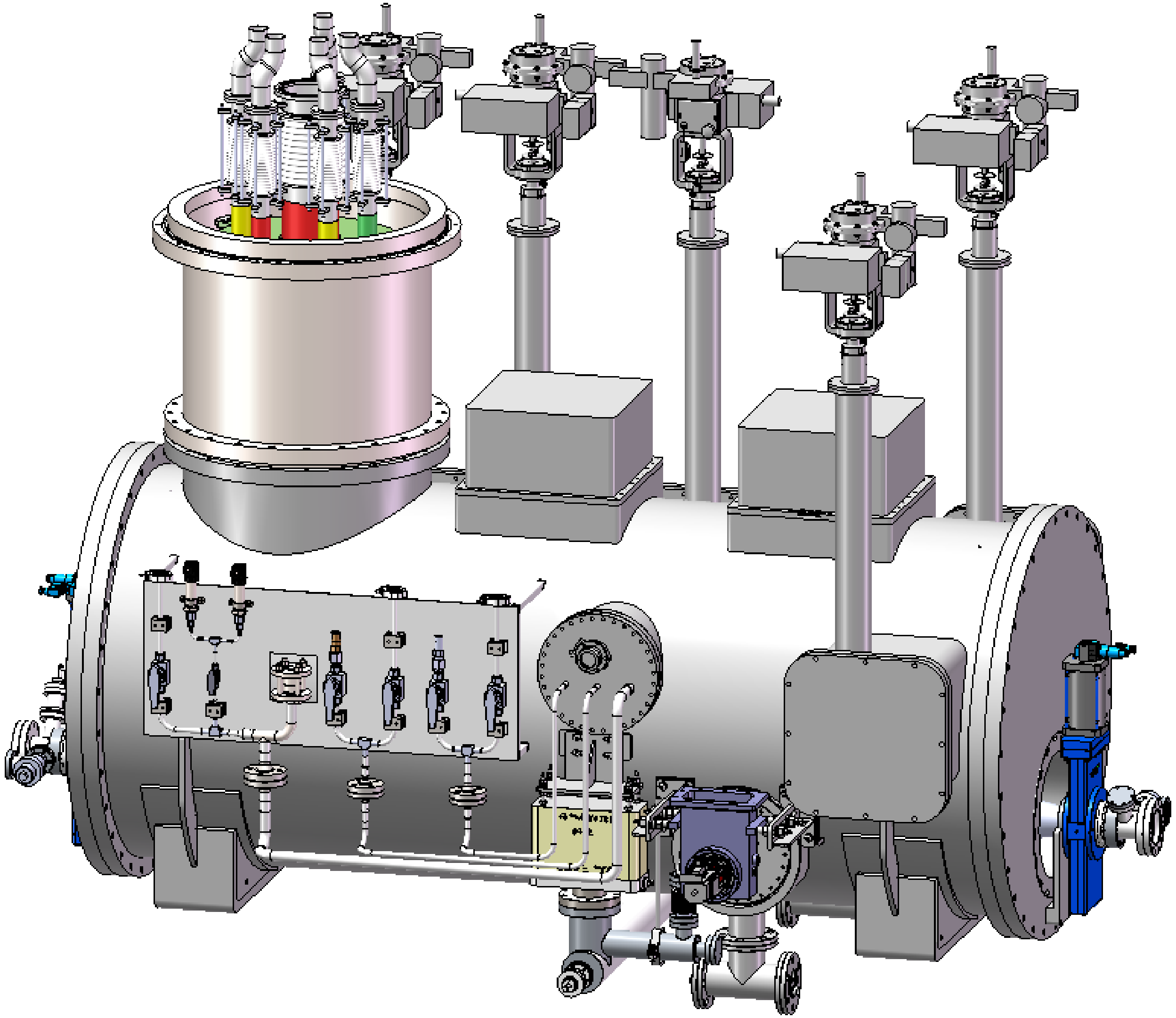






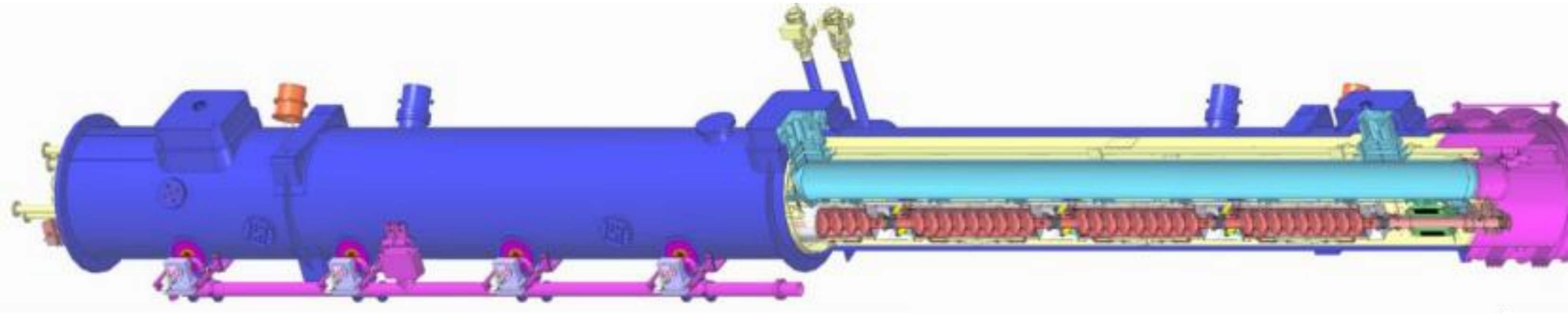
Cryomodule includes

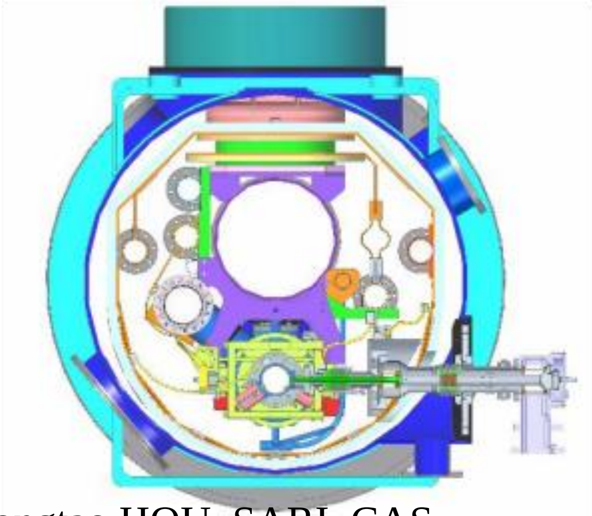
- Twin-FPC cavity
- Fundamental power coupler
- Tuner
- Cryostat
- Cryogenic pipes
- Magnetic shielding layer
- Thermal shielding layer
- Cables
- supports

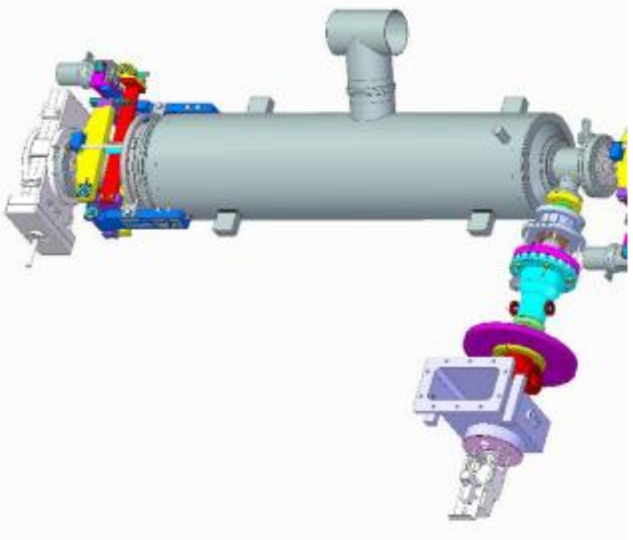


TESLA-style Cryomodule for SHINE

- **A TESLA-style cryomodule (CM)** houses eight superconducting cavities, one SC magnet and one cold BPM etc, providing cryogenic and vacuum condition, support and thermal insulation for the RF cavities;
- **Modified TESLA-style cryomodule** to accommodate CW mode operation, such as that for LCLS-II/HE, SHINE.
- **Main components in a CM**
  - 8 - 1.3GHz, 9-cell cavities
  - 8 - Couplers
  - 8 - Tuners
  - 8 - Magnetic shielding
  - 16 - HOM couplers
  - 1 - HOM absorber
  - 1 - SC magnet
  - 1 - BPM
  - 1 - Cryogenic pipe system and thermal shielding
  - 1 - Vacuum components and valves
  - 1 - Cold mass support system
  - 1 – Vacuum vessel
  - 1 - Cryomodule support system

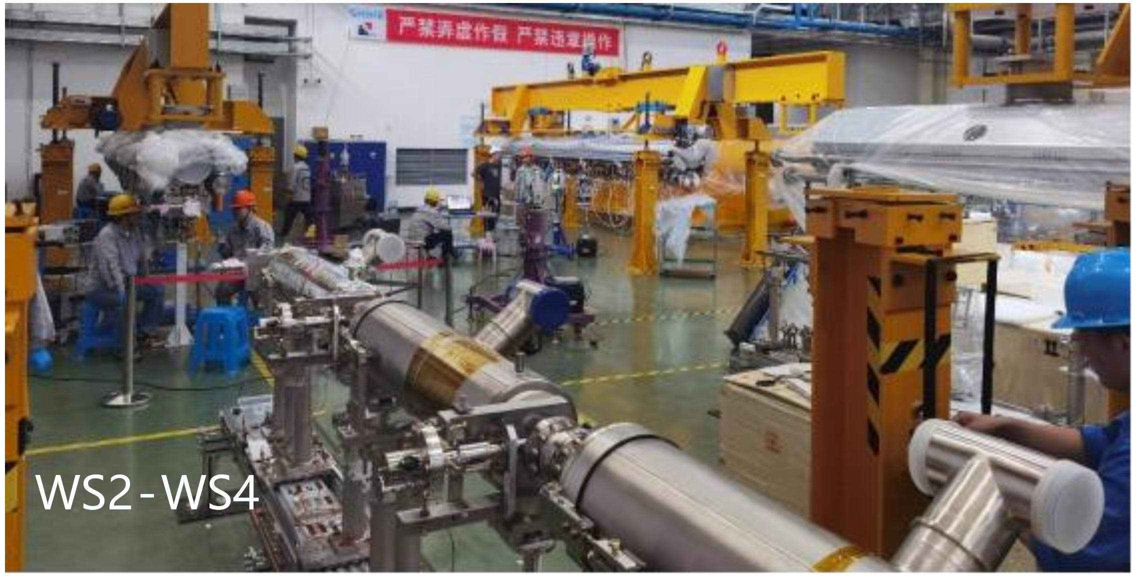






CM assembly


Higher clean standard,
Strictly training and supervising
Cavity string assembly
in ISO4 (WS1)


WS2-WS4

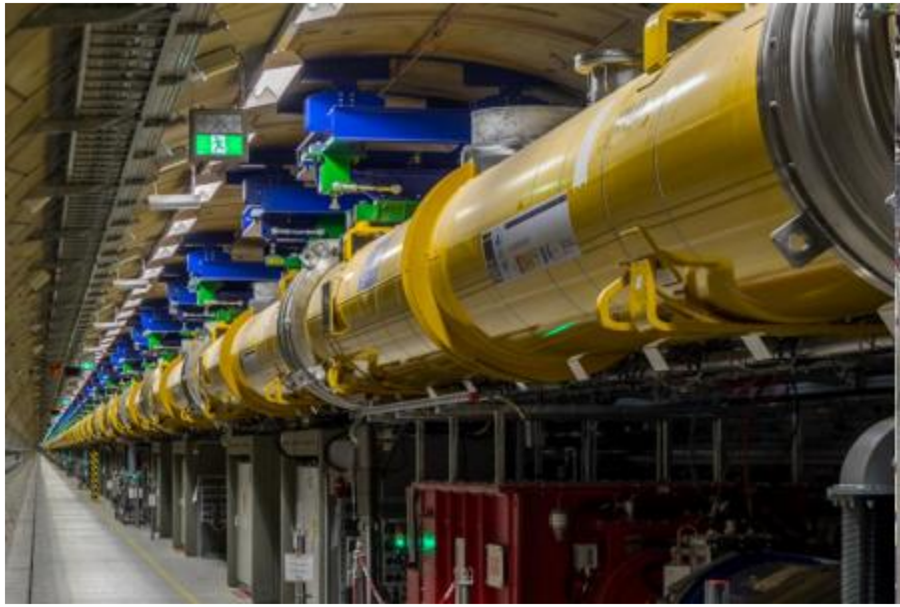

WS5


WS6

Cryomodule Horizontal Test

CMs installed in Superconducting Linacs

E-XFEL



LCLS-II/HE

SHINE

4. Summary

You may know

- What are SRF Cavities and their types and functions?
- What are SRF Cryomodules?
- Why niobium is used for SRF cavities mass production

You may want to know further

- How to decide frequency and operating temperature? Please consider……
- Future of SRF Cavities? Design regarding to accelerator machine goals
- Other material instead niobium for SRF cavities? Nb3Sn, multilayer coating?

Suggested books

1. H. Padamsee, J. Knobloch, T. Hays, *"RF-Superconductivity for Accelerators "*, Wiley-VCH (1998).
2. H. Padamsee "RF superconductivity", WILEY-VCH (2009)
3. H. Padamsee "Superconducting Radiofrequency Technology for Accelerators", WILEY-VCH (2023)

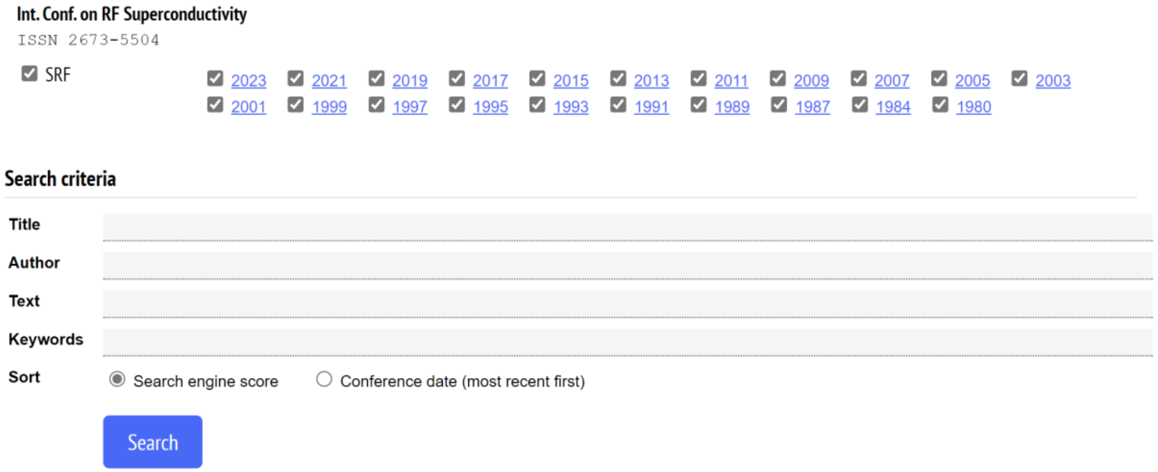
Suggested Proceedings

1. SRF conference

https://www.jacow.org/Main/Proceedings?sel=SRF#SRF

2. TTC meeting

https://tesla.desy.de/meetings/collaboration_meetings_and_ttc_workshos/



Thanks for your attention