Superconducting Accelerators

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September 2, ISBA25, Shanghai

Outline

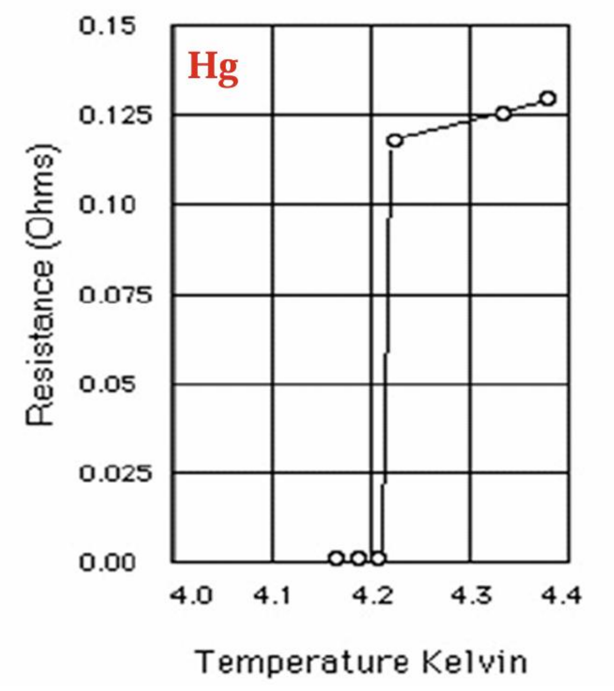
- Introduction
- Superconducting Accelerators in the World
- Tesla Cavity
  - Design
  - SC Material, Fabrication
  - Surface Treatment
  - RF Test
- Tesla Cryomodule
- Summary

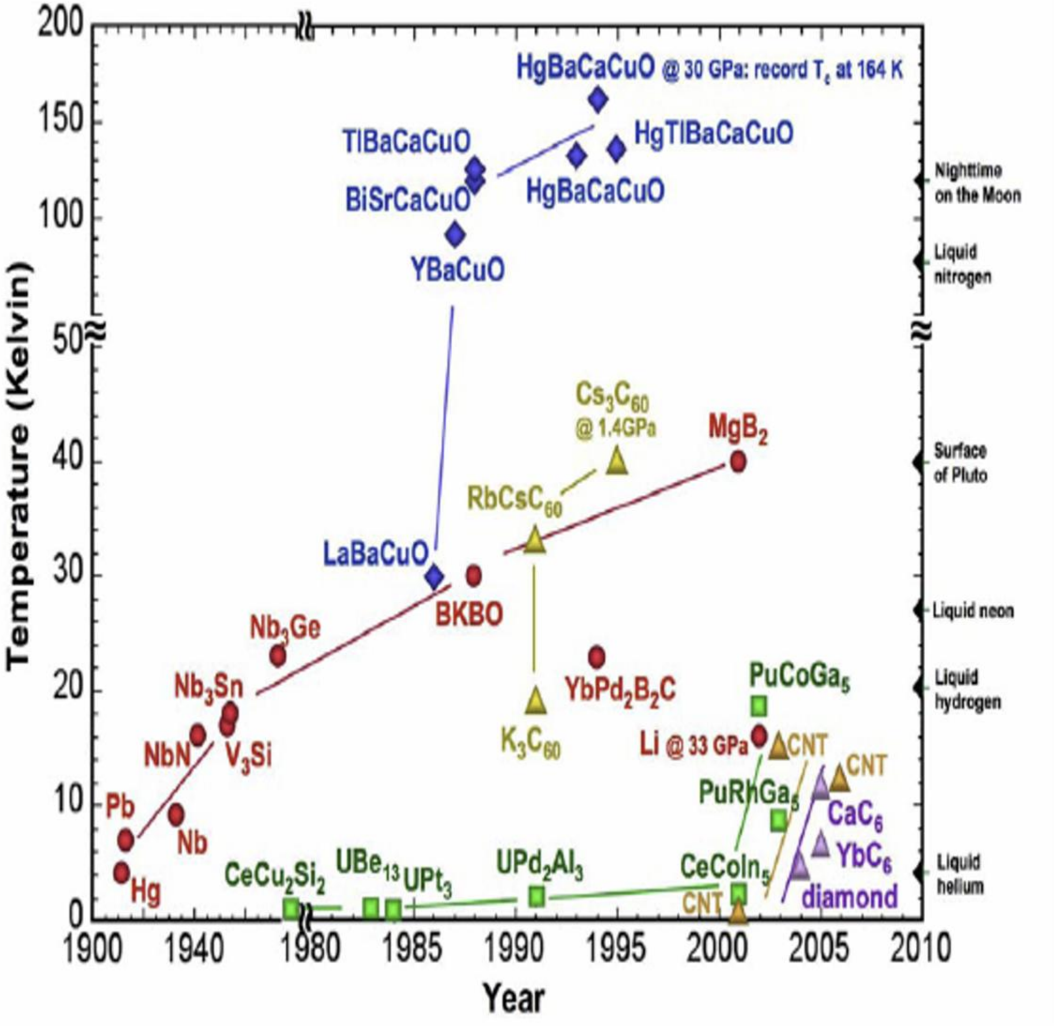
Questions you may ask

- **Why superconducting RF (SCRF)?**
- **What are the types of SCRF cavities? and their functions?**
- **How to design and fabricate a SCRF cavity?**
- **How the surface treatments can improve cavity RF performance?**
- **How to preserve cavity high performance in cryomodule?**

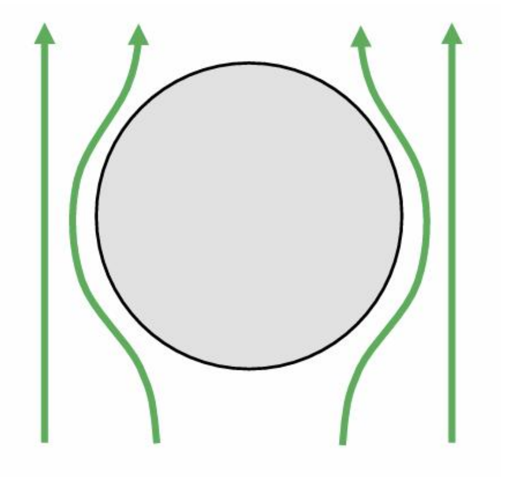
Superconductivity (SC)

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)

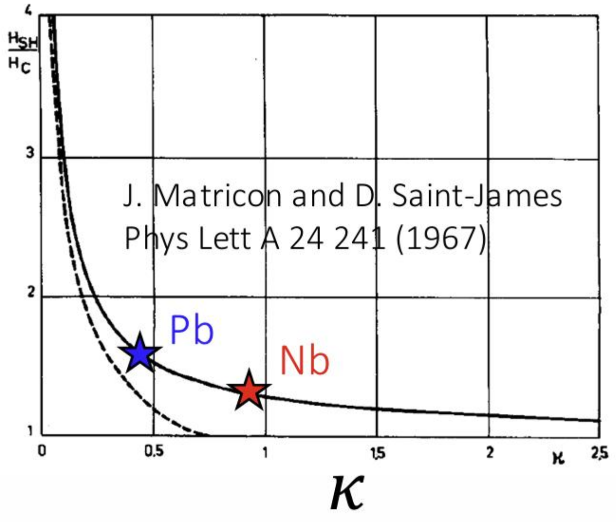


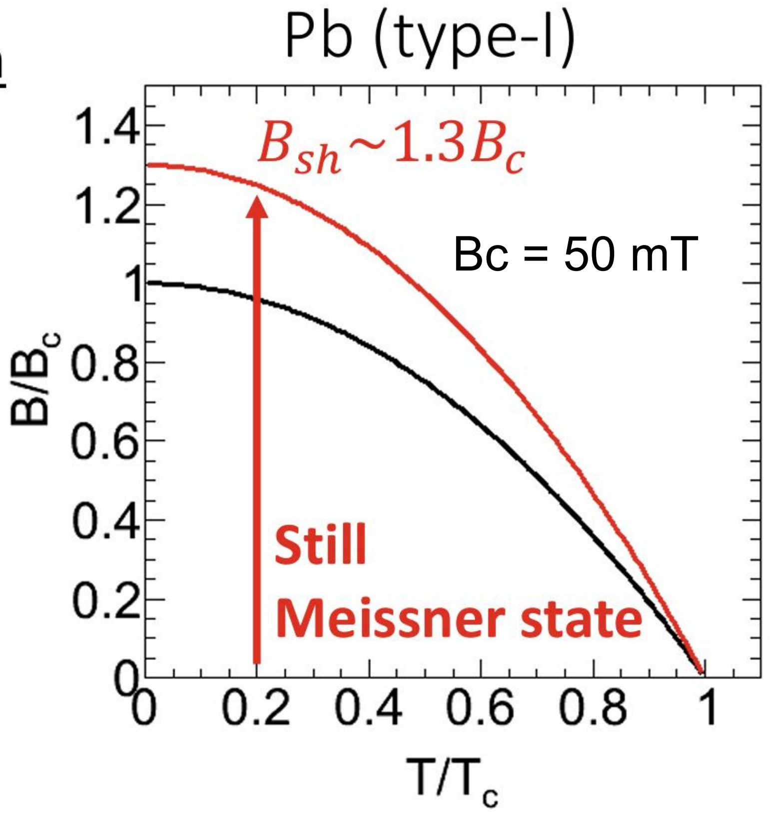
Niobium: highest Tc among pure element materials, non toxic

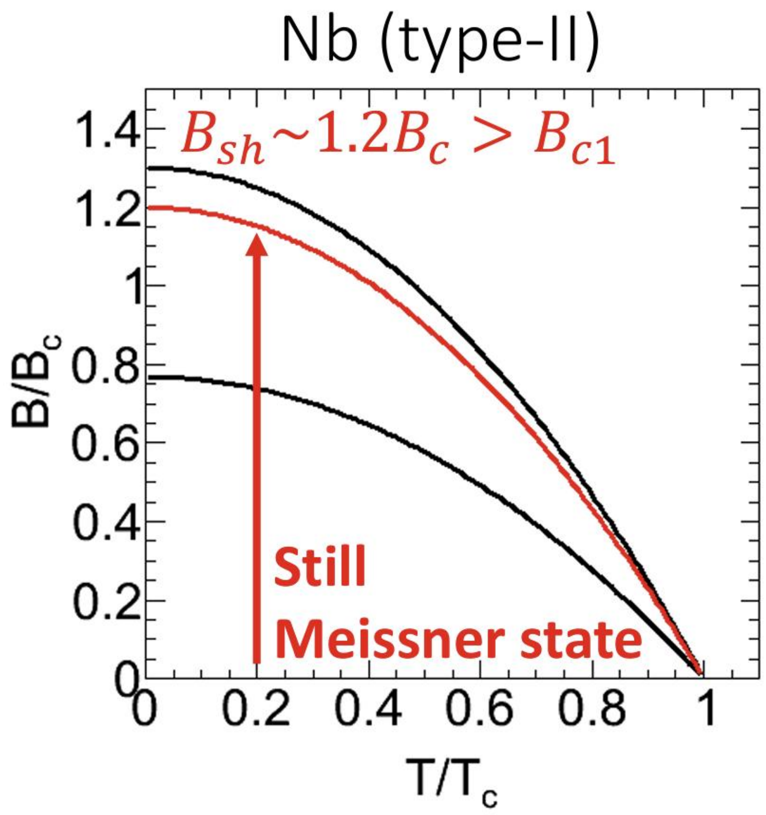
SC material for cavity- Why Nb?

Ginzburg-Landau equation

$B_{sh} > B_c$ in general







- **Nb:** Tc = 9.25 K, superheating field, Bsh ≈ 220 mT，**favorite material for SC cavities**

- For ideal niobium, Bsh at 2K is about 220 mT, which translates to a maximum accelerating field of about **52 MV/m** for a typical shape β =1 Nb structure, and roughly **30 MV/m** for a typical β <1 Nb structure.

RF to Transfer Energy to the Beam

- To give energy to a charged particle beam, one need to let it move across a region in which an electric field exists and is directed as the particle motion.

$$\Delta E_{particle} = \int \vec{F}_{Lorentz} \cdot d\vec{s} = q \int \vec{E} \cdot \vec{v}\, dt$$

- Cavity = an arbitrary volume, partially closed by the metal wall, capable to store the E-H energy

- An "RF power source" is used to fill, via a "coupler", the "RF cavity", or resonator that is the e.m. energy container from which the beam is taking its energy.

- What we ask to a good cavity?

High Q for losses:

- U = stored energy
- P_{diss} = dissipated power

$$Q = \omega \frac{U}{P_{diss}}$$

Small R_s for high Q:

- R_s = surface resistance
- G = cavity geometrical factor

$$Q = \frac{G}{R_s}$$

Surface resistances in NC and SC Cavities

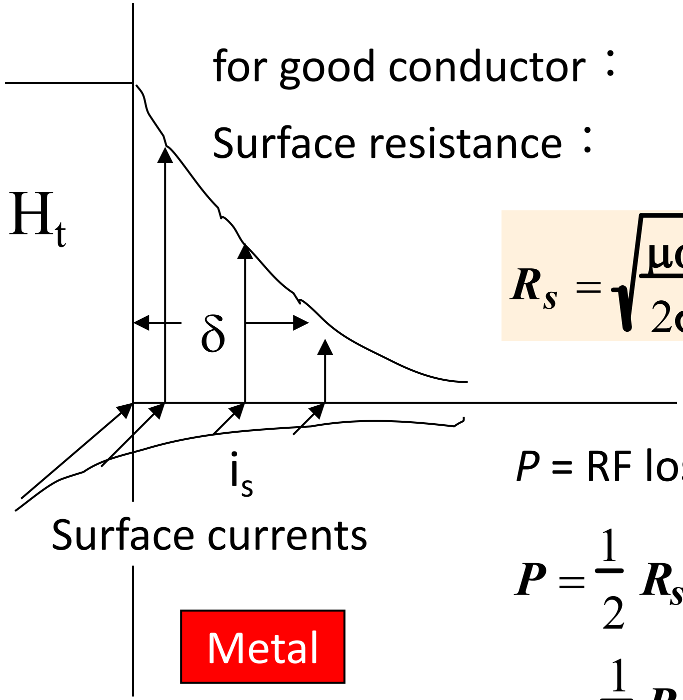
Normal conducting

δ = skin depth of microwave

for good conductor： $\dfrac{\sigma}{\omega\varepsilon} \gg 1$

Surface resistance：

$$R_s = \sqrt{\frac{\mu\omega}{2\sigma}} = \frac{1}{\sigma\delta}$$



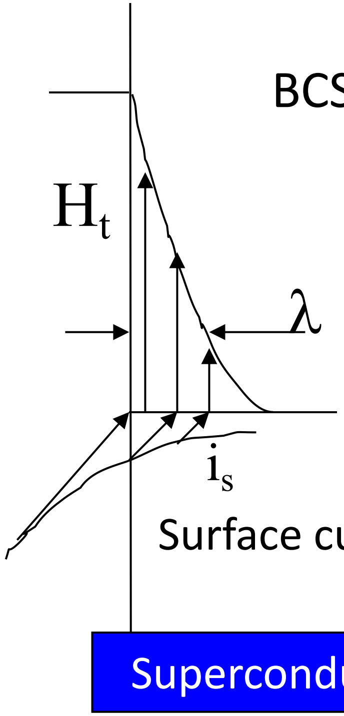
P = RF losses

$$P = \frac{1}{2} R_s \int i_s^2 \, ds$$

$$= \frac{1}{2} R_s \int H_s^2 \, ds$$

Superconducting

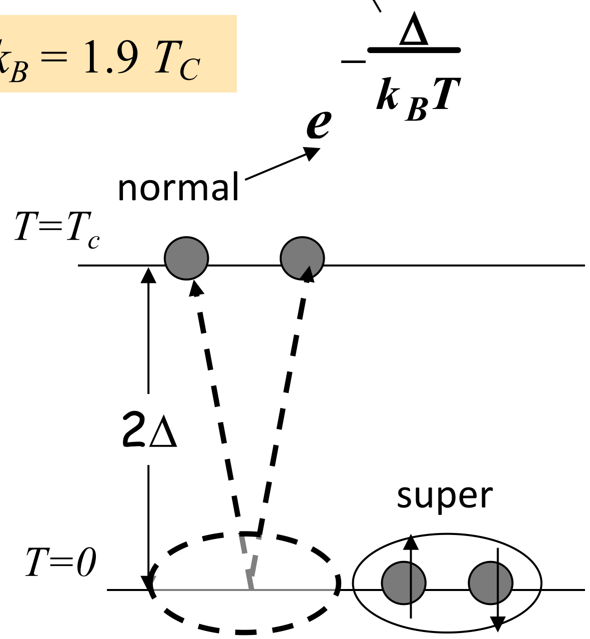
λ = London penetration depth



BCS theory

$$R_s \propto \frac{\omega^2}{T} e^{-\frac{\Delta}{k_B T}}$$

$\Delta / k_B = 1.9\ T_C$



$$Q_0 = \omega U / P = G / R_s$$

Why superconducting cavities?

- **Power dissipated** on the cavity walls to sustain the field is:

$$P_{diss} = \frac{R_s}{2}\int_S H^2 dS$$

Nb: $R_s[\mathrm{n}\Omega] = 9\times 10^4 \frac{f^2[\mathrm{GHz}]}{T[\mathrm{K}]}\exp\left(-\frac{17.6}{T[\mathrm{K}]}\right)$ $T<T_c/2$

Cu: $R_s[\mathrm{m}\Omega] = 7.8 f^{\frac{1}{2}}[\mathrm{GHz}]$

The difference ~ 10^6

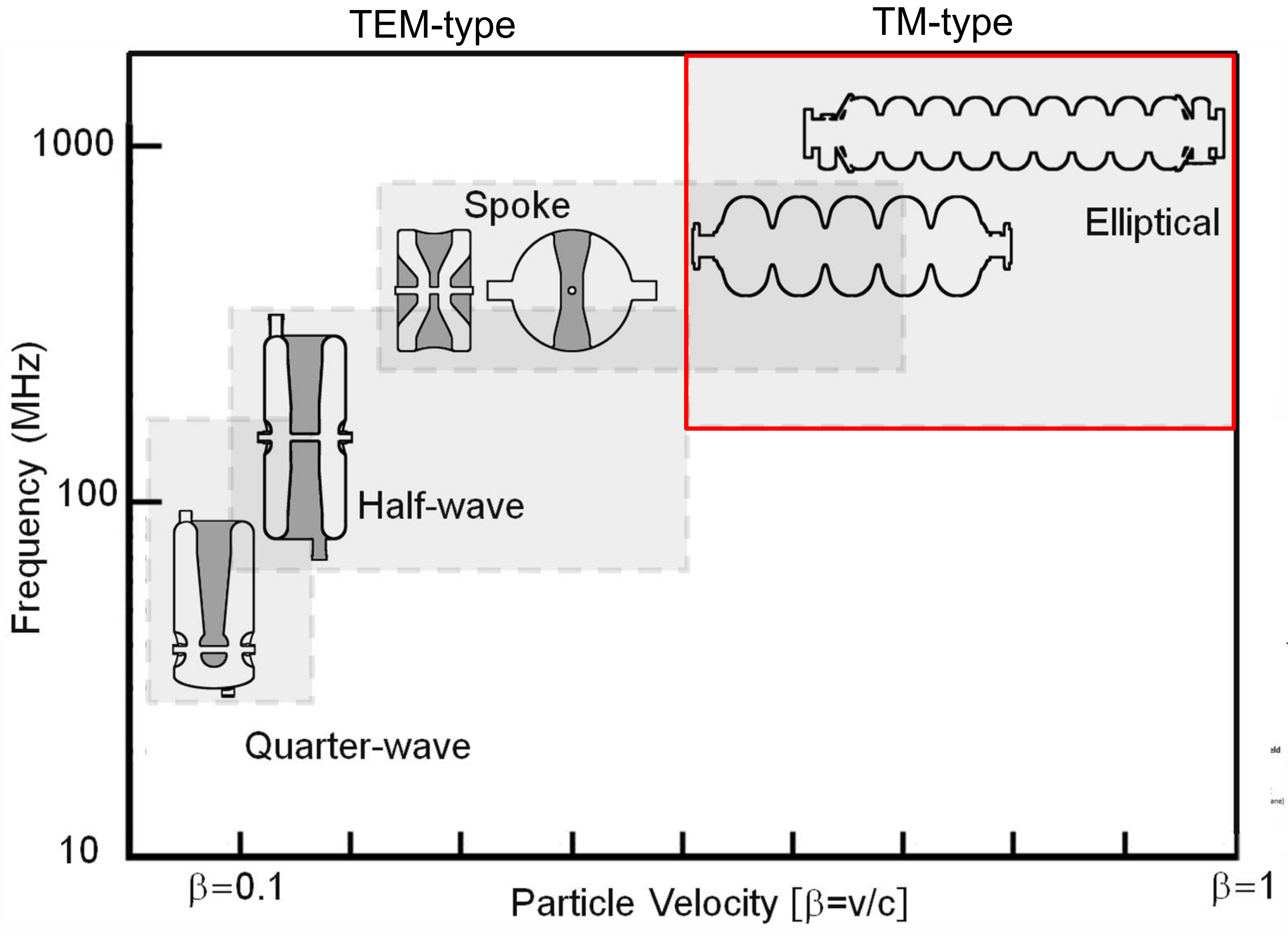
- In **Normal** linacs a huge amount of power is deposited in the copper structure: MW to have MV Pulsed operation and Low Duty Cycle;

- **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.

Why superconducting cavities?

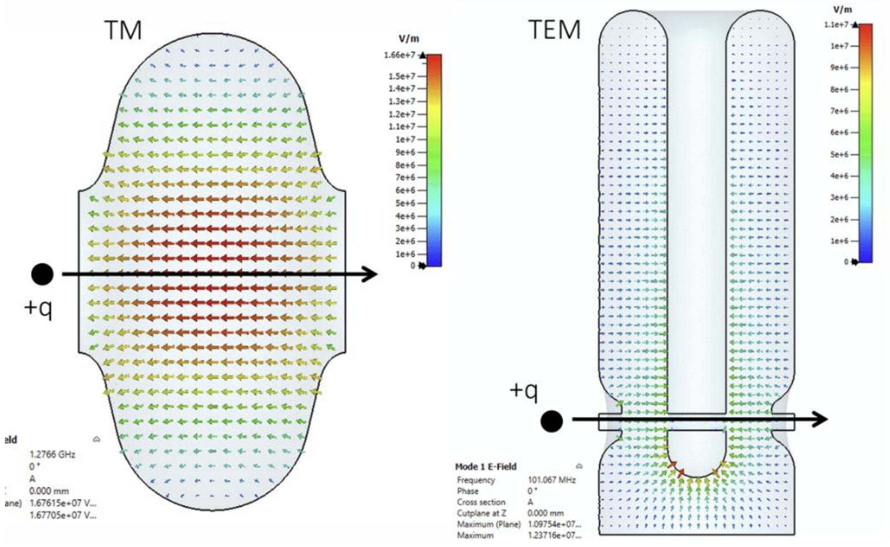
- Merits of **Superconducting cavities**
  - Low surface resistance →High Q → Low power dissipation on the cavity walls →Low cost for large accelerator
  - Affordable to have a large beam hole, reduce beam disruption and provide high quality beams for physics research or photon production.
  - Capable to provide higher voltage in cw or long-pulse operation ->SRF systems can be shorter, and thereby impose less disruption.
- **Benefit** even considering expensive cryogenic cost, for CW and long-pulse operation

SC Cavity Types



Considering:

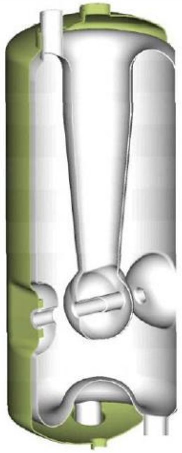
1. RF efficiency
2. Mechanical stability
3. Multipacting
4. …

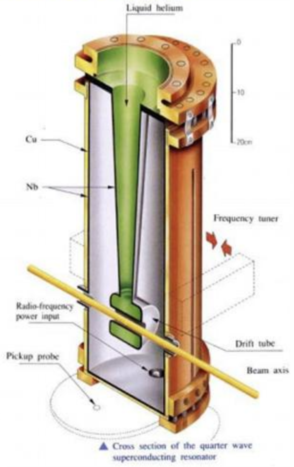


Non Elliptical SC Cavities for Acceleration

TEM Type

Quarter Wave Cavities





Half Wave Cavities

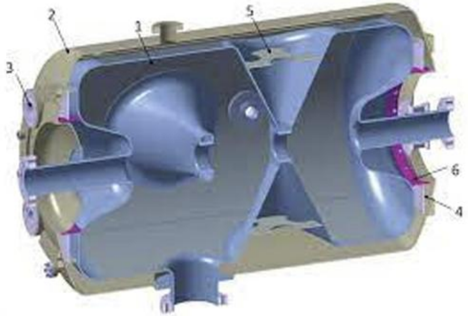
Split Ring Resonator

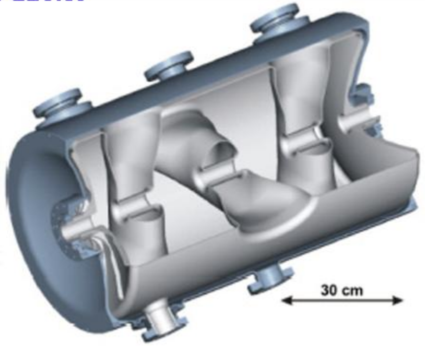
Superconducting RFQ Cavity

TE21-like mode

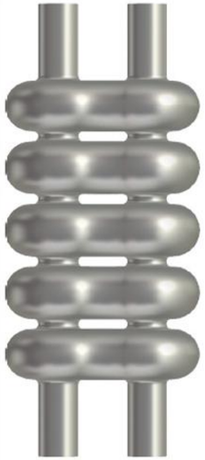
Single Spoke Cavities

Multi Spoke Cavity





Twin Axis Cavity



TEM-like mode

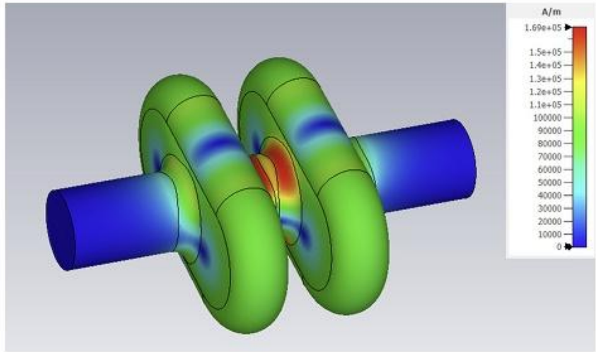
TM110-like mode

Subashini De Silva-SRF2023

Non Elliptical SC Cavities for Deflecting and Crabbing

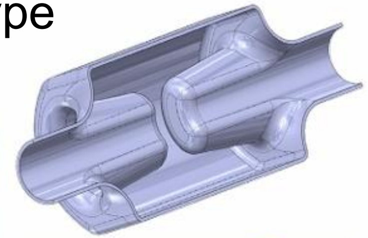
TM110-like mode

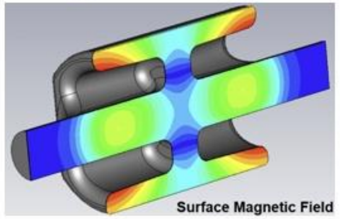
Squashed Elliptical Cavities



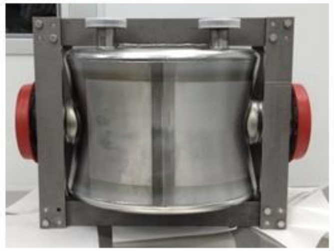
TEM Type

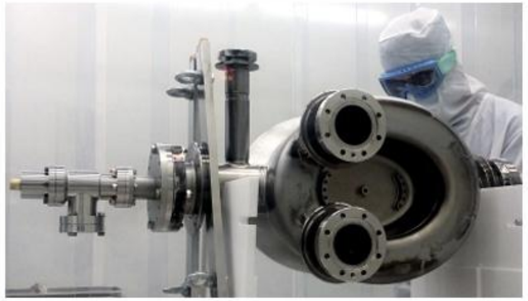
4-Rod Cavity





Double Quarter Wave Cavity





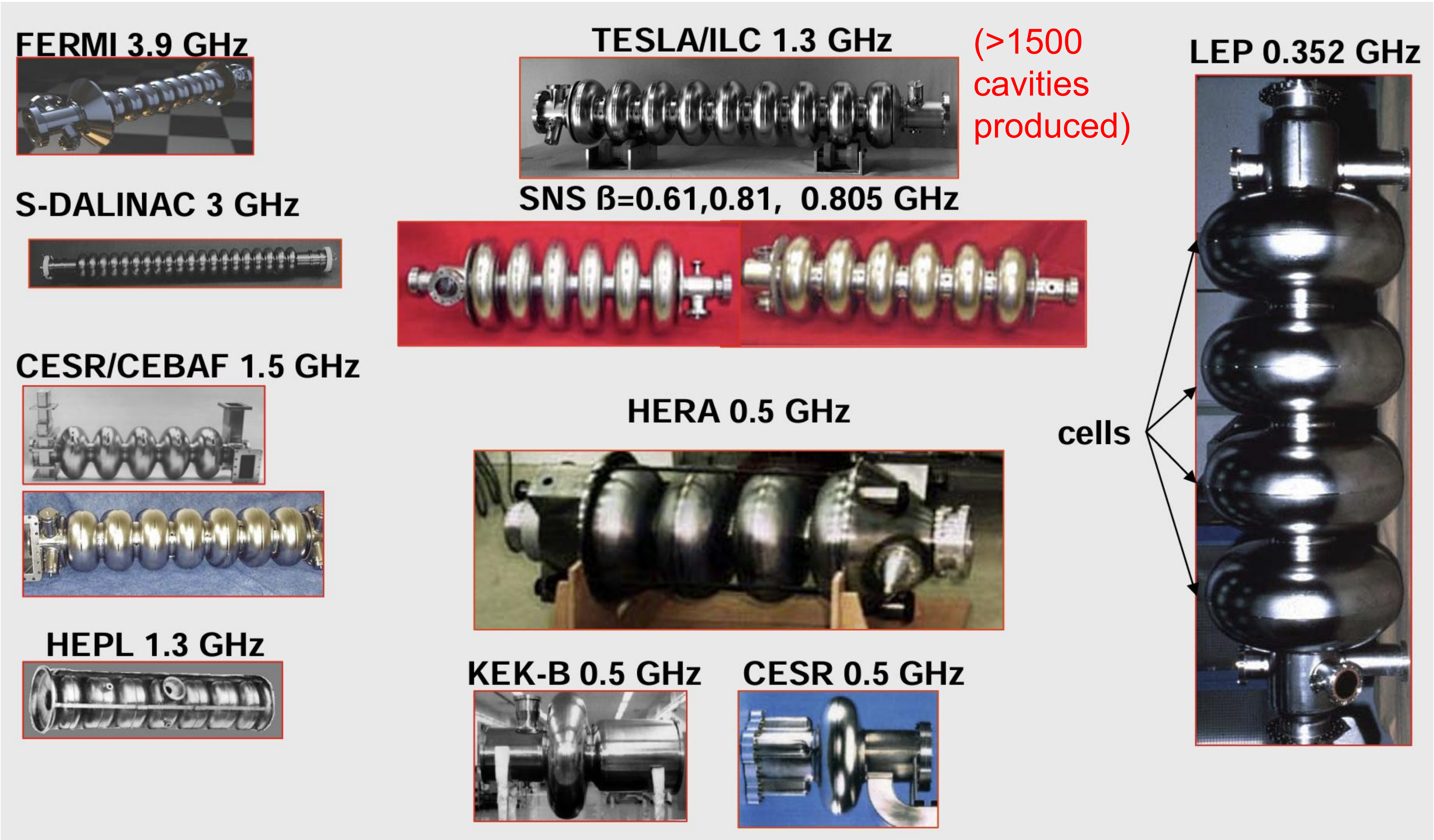
RF-Dipole Cavities

TE11-like mode

TE11-like mode

Elliptical SC Cavities

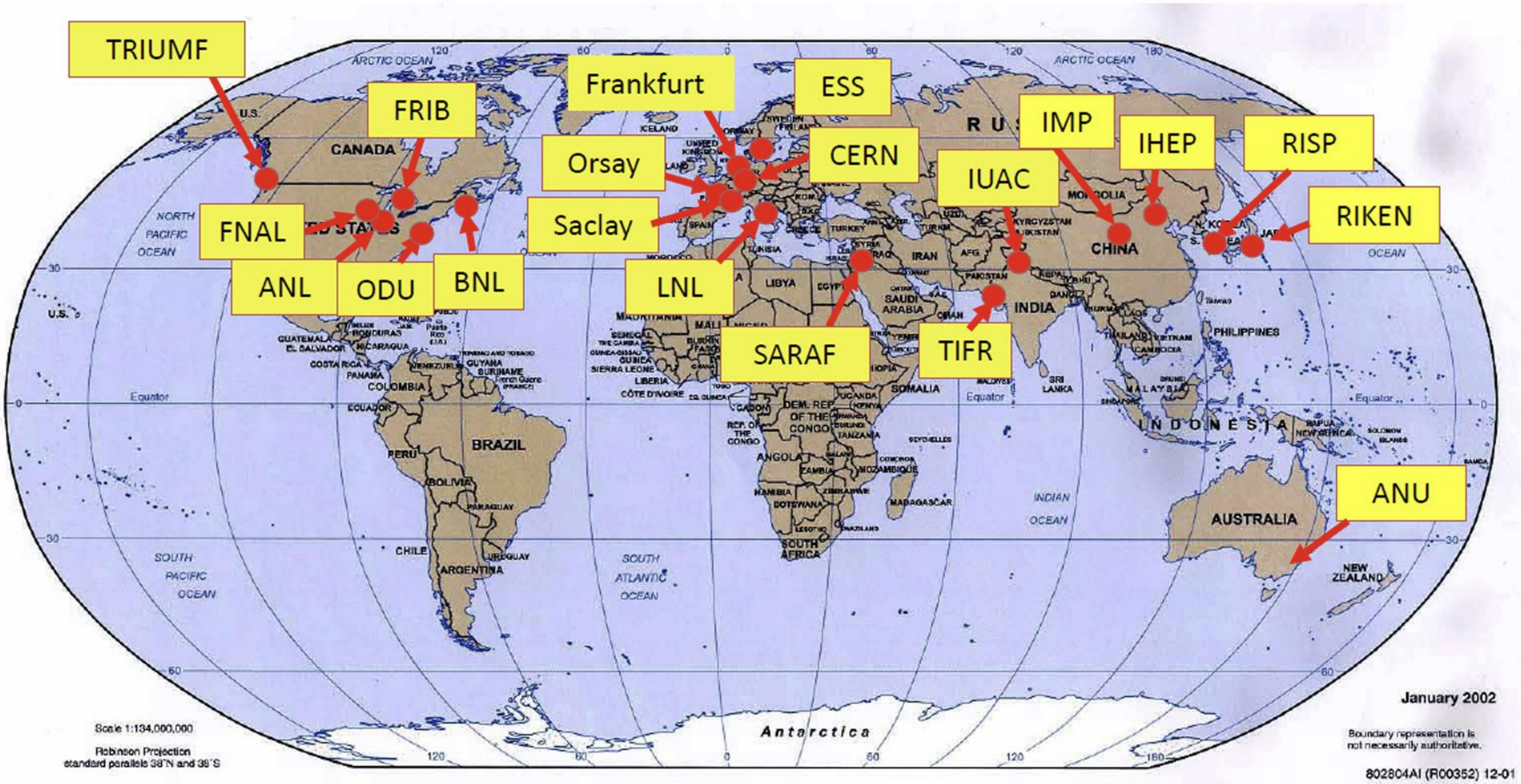
TM010-like mode



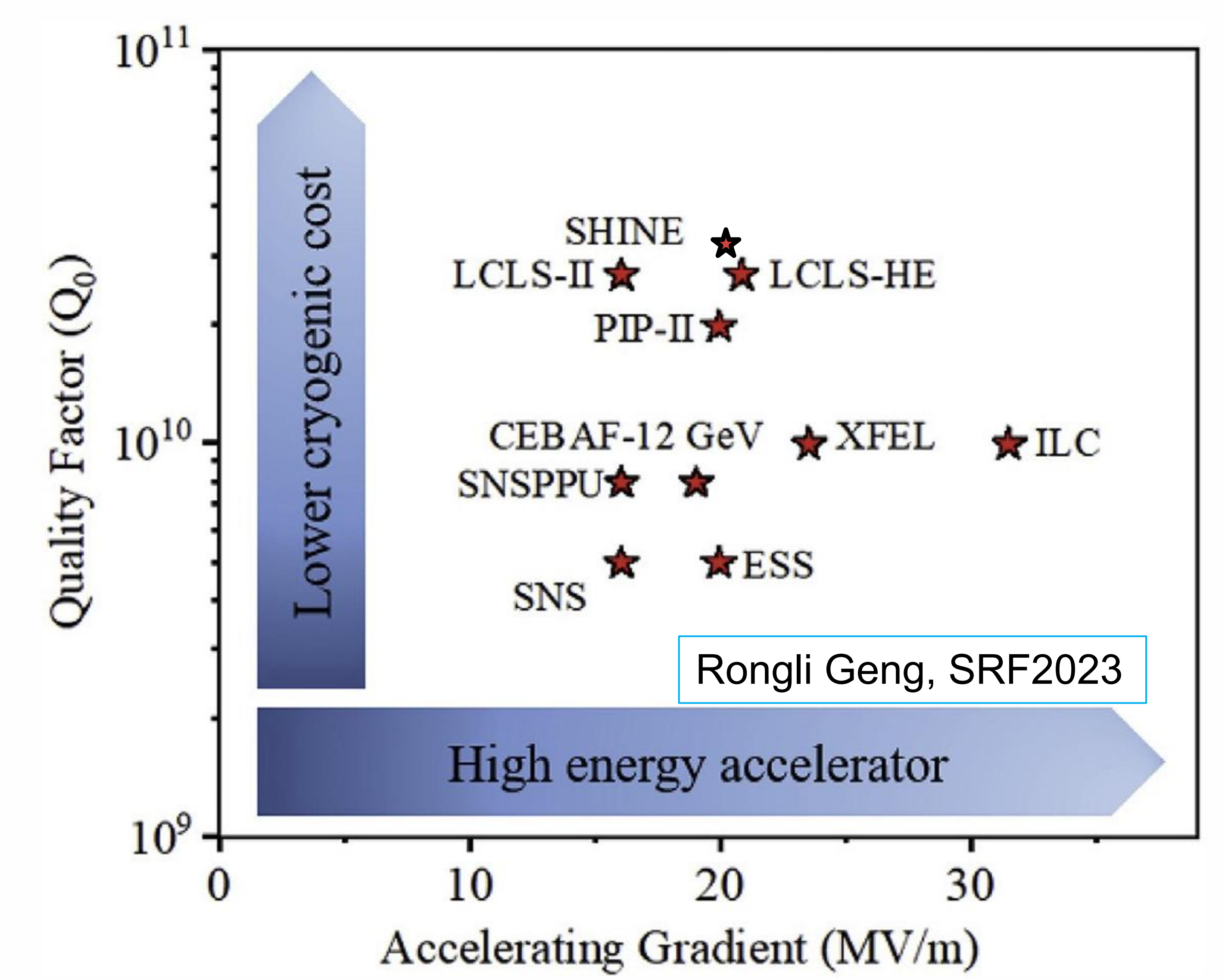
SSRF 1.5 GHz

Outline

Superconducting Non-Elliptical Cavity Community



Elliptical SC-Cavity Accelerators in the World

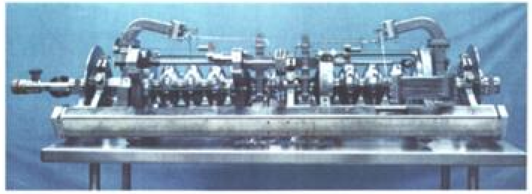


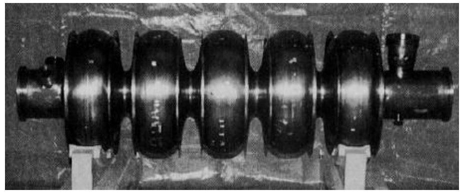
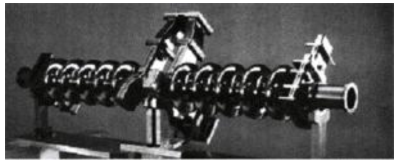
- **Operation:** CEBAF, SNS, E-XFEL, LCLS-II
- **Under construction:** ESS, SNSPPU, PIP-II, SHINE, LCLS-II HE, S^3FEL et al.
- **Planed:** ILC etc

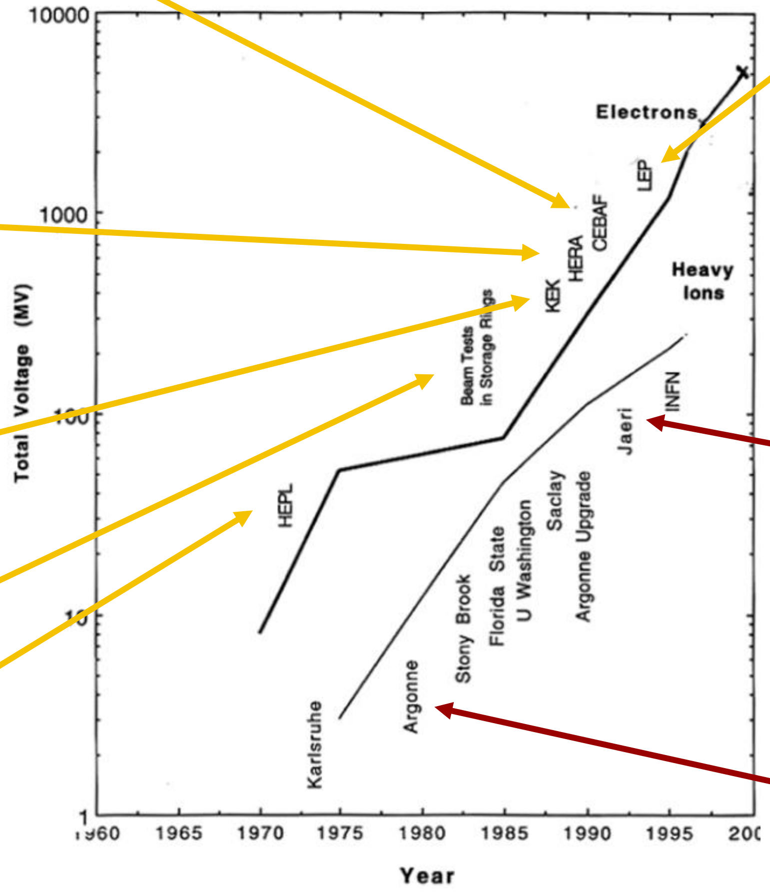
SRF Before TESLA/ILC

"Livingston Plot" from Hasan Padamnee

Total Installation > 1000 m
Provided > 5 GV



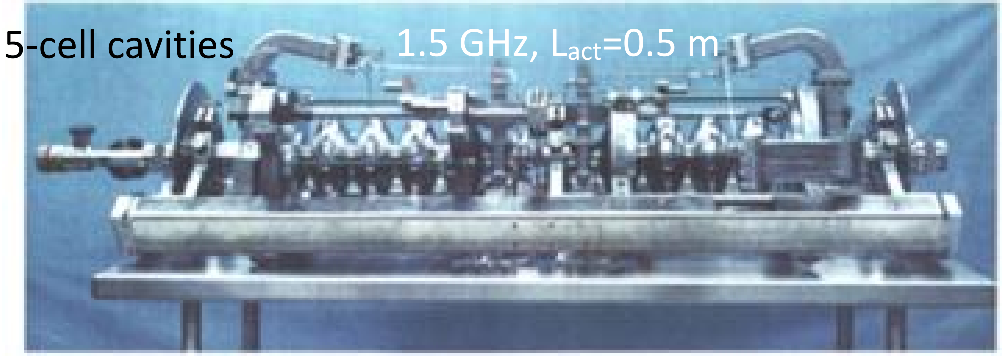


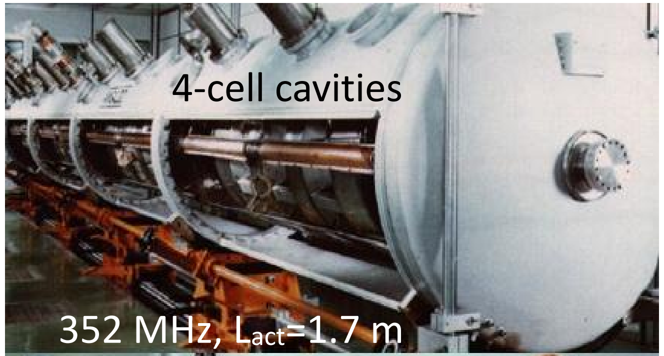
CEBAF and LEP II

CEBAF & Jlab

338 bulk niobium cavities

- Produced by industry
- Processed at TJNAF in a dedicated infrastructure





LEP II & CERN

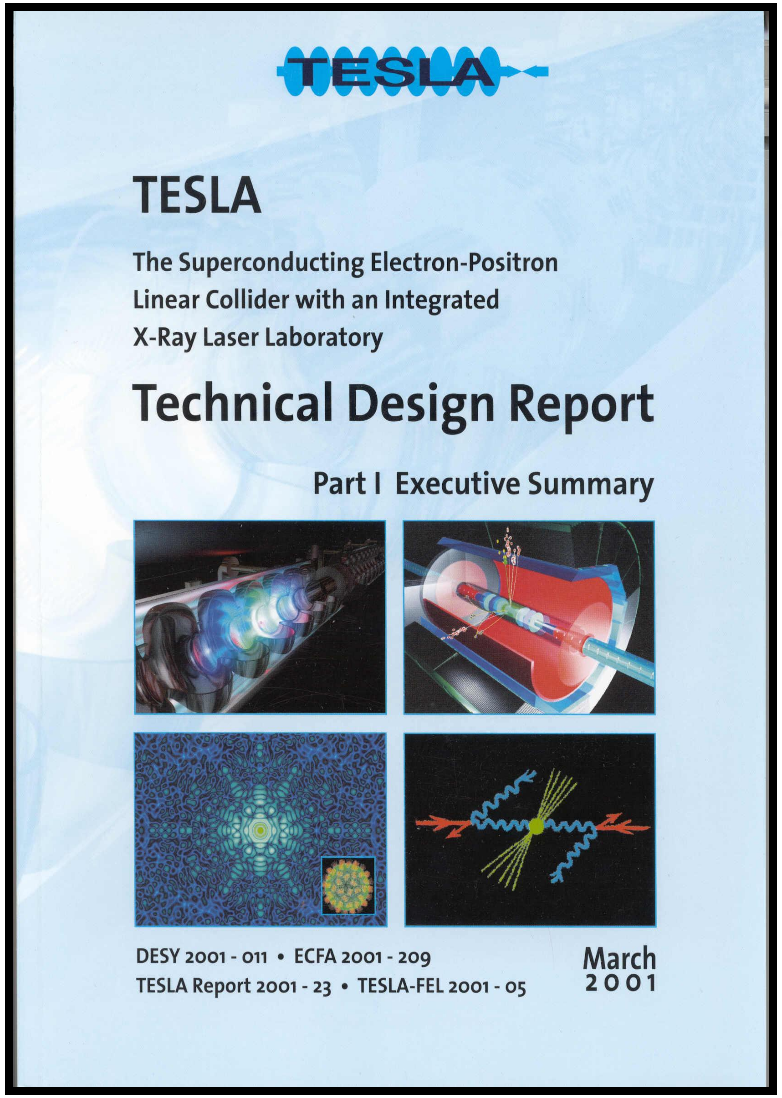
32 bulk niobium cavities

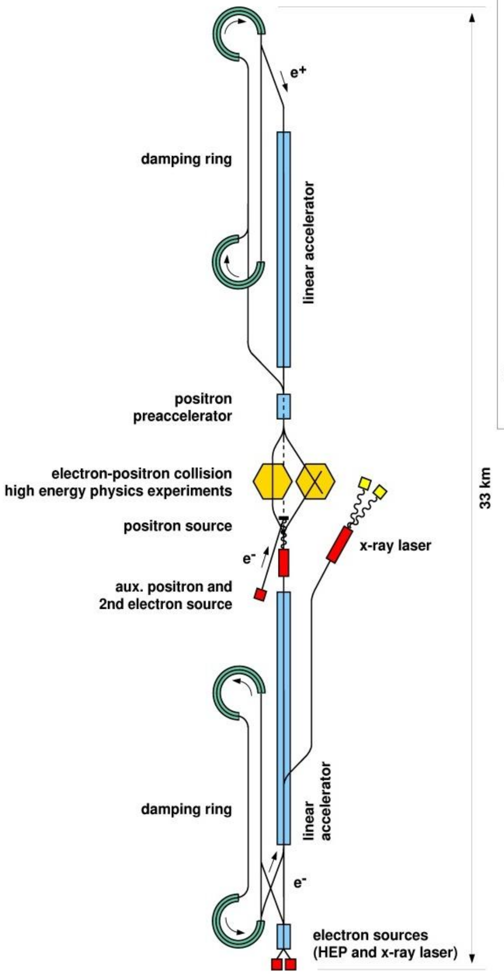
- Limited to 5 MV/m
- Poor material and inclusions

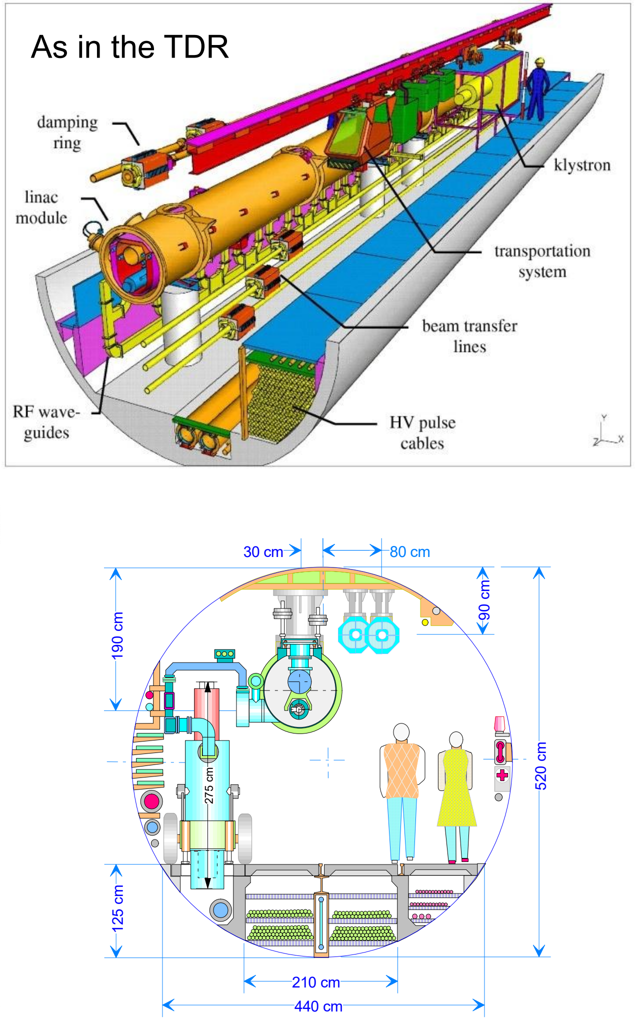
256 sputtered cavities

- Magnetron-sputtering of Nb on Cu
- Completely done by industry
- Field improved with time
  $\langle E_{acc} \rangle$ = 7.5 MV/m (Cryo-limited)

TESLA Technical Design Report 2001

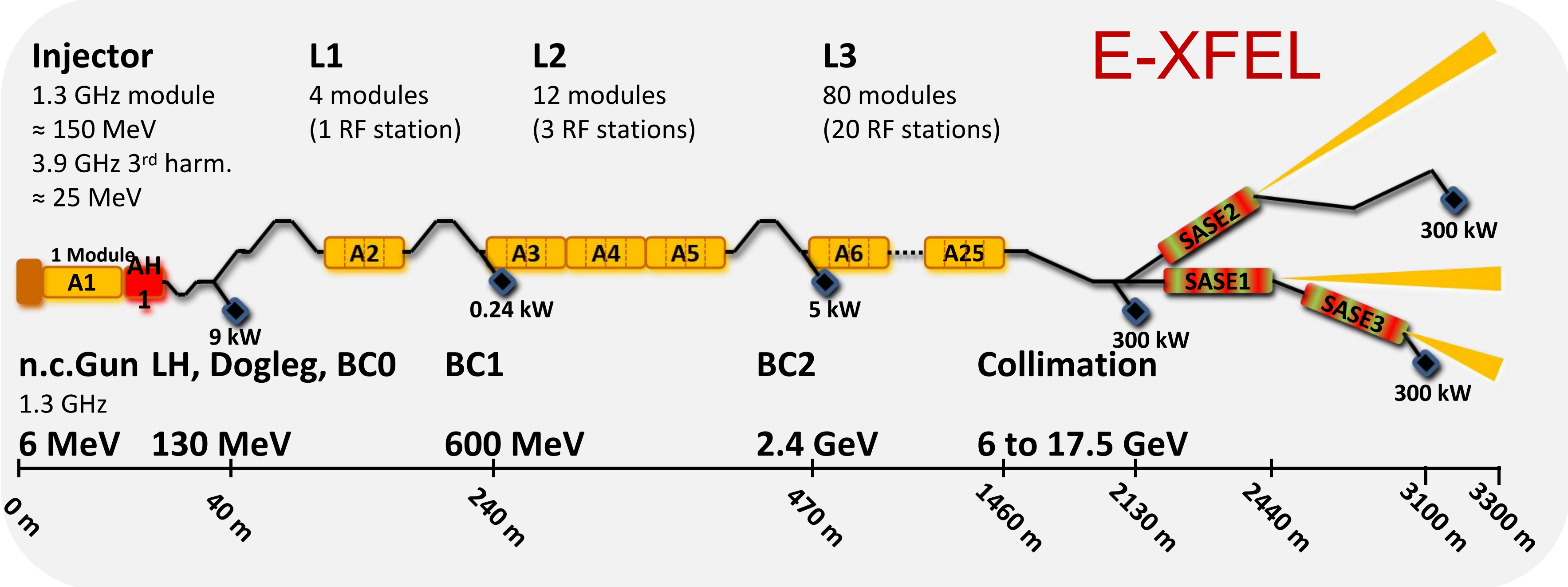


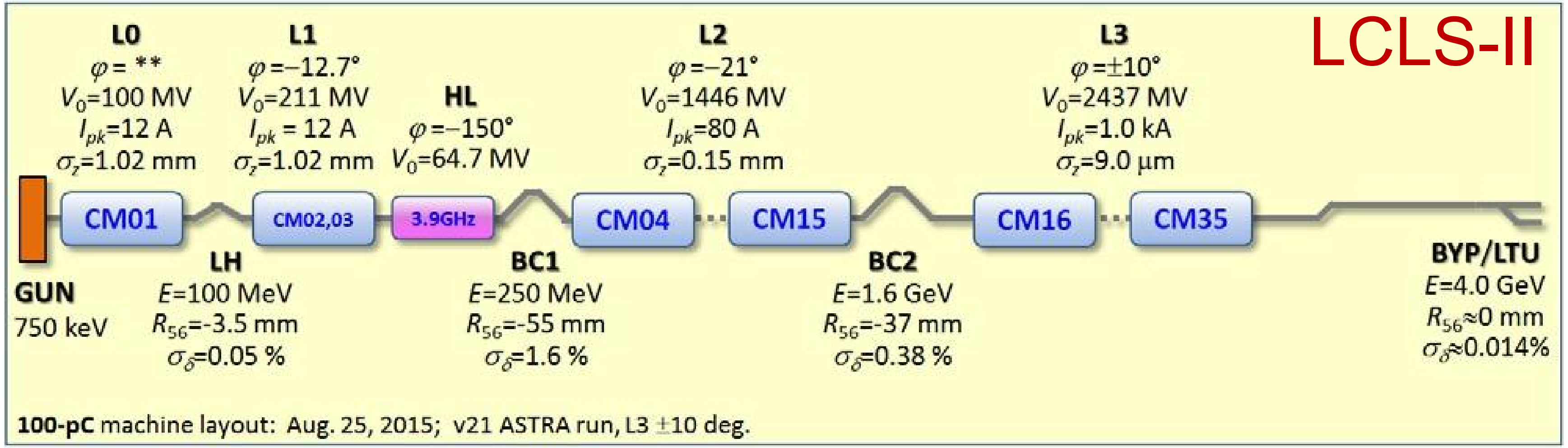




Updated tunnel cross section

E-XFEL, LCLS-II/HE & SHINE use TESLA SRF Tech.





Pulsed-mode:

- **100** sets of 1.3GHz CMs
- **1** set of 3.9GHz CM

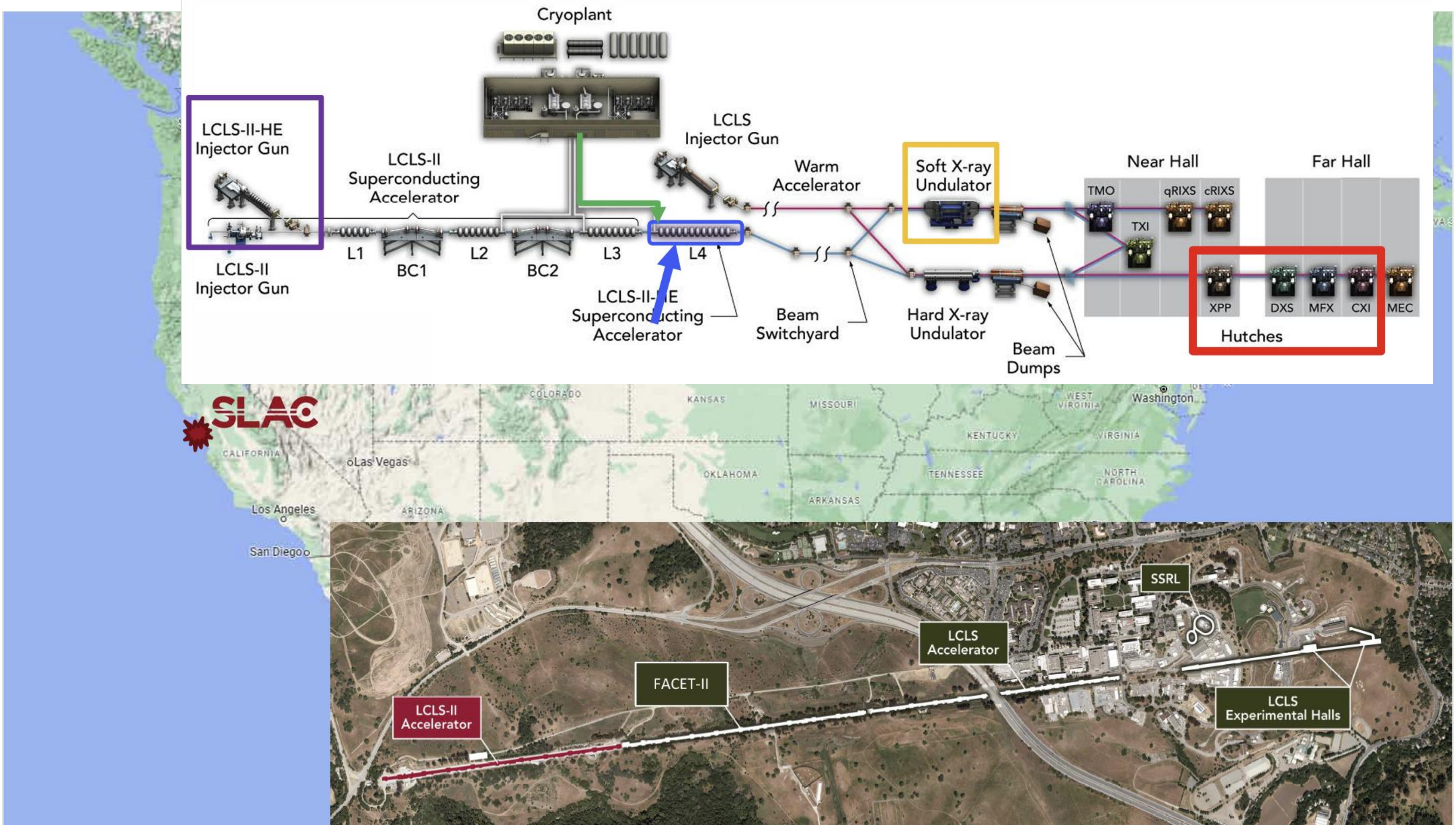
- **800** 1.3GHz cavities
- **8** 3.9GHz cavities

CW

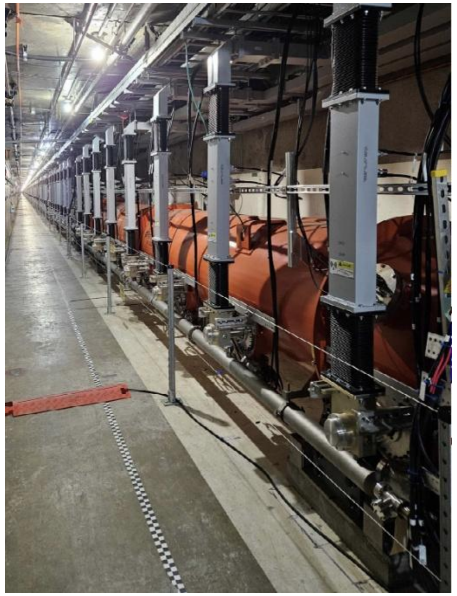
- **35** sets of 1.3 GHz CMs
- **2** sets of 3.9 GHz CMs

- **280** 1.3GHz cavities
- **16** 3.9 GHz cavities

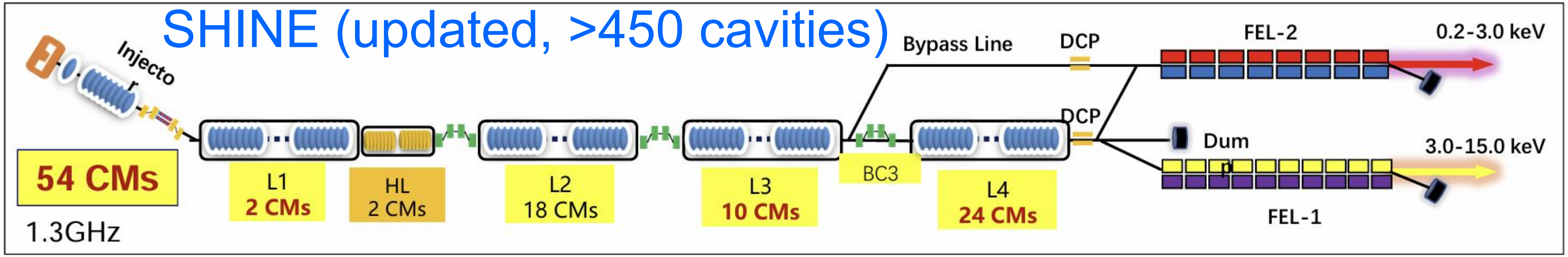
LCLS-II HE Project



- **LCLS-II HE**: Add 23 additional cryomodules (L4 linac), ~184 1.3GHz cavities
- Totally, **~ 480 cavities**



SHINE Accelerator Layout



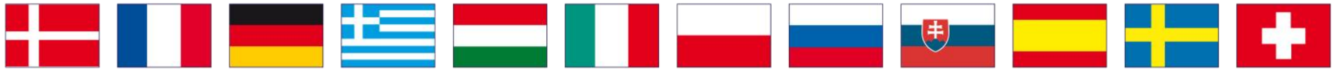
CW

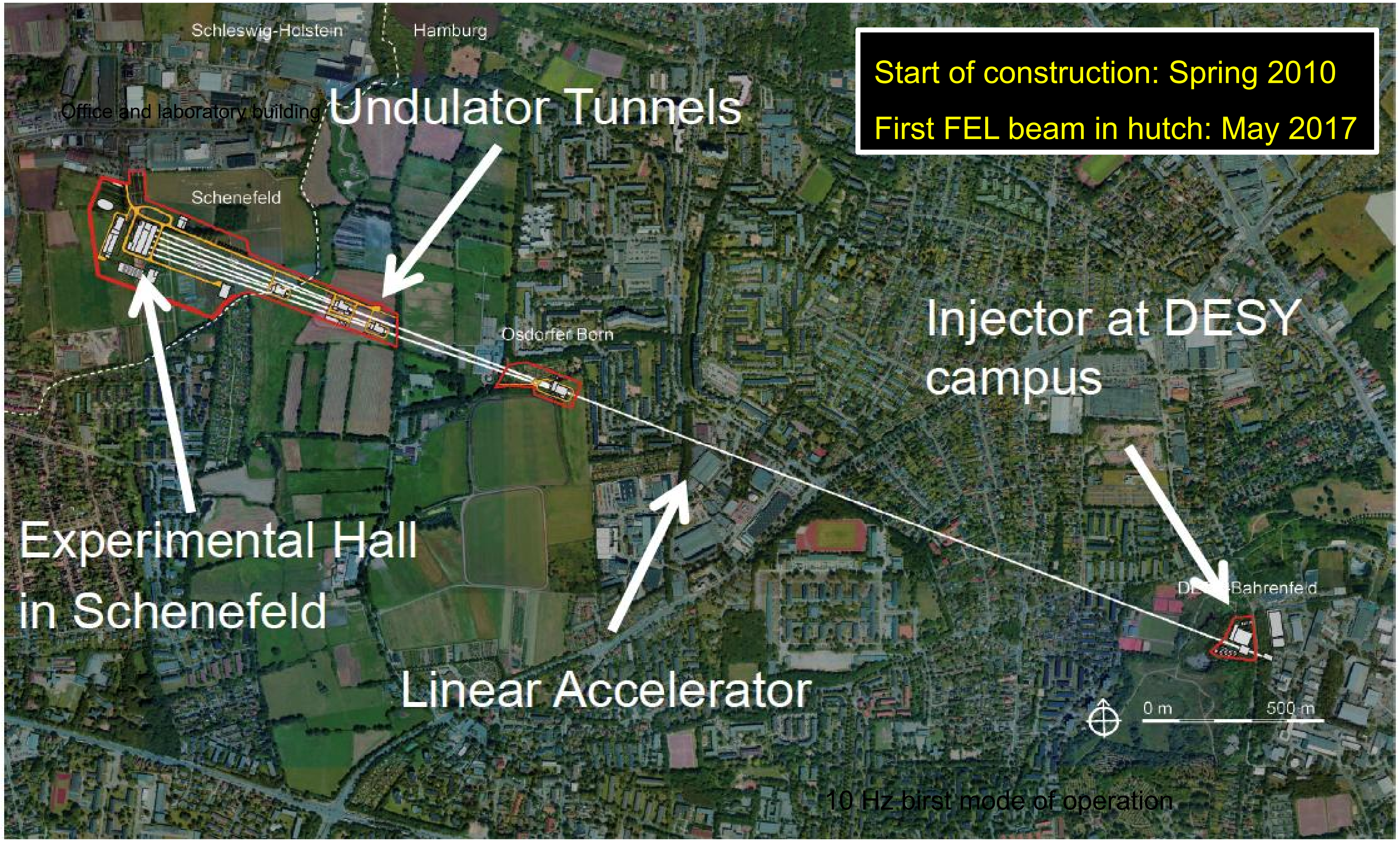
➢ XFEL Facility +100 PW Laser Facility

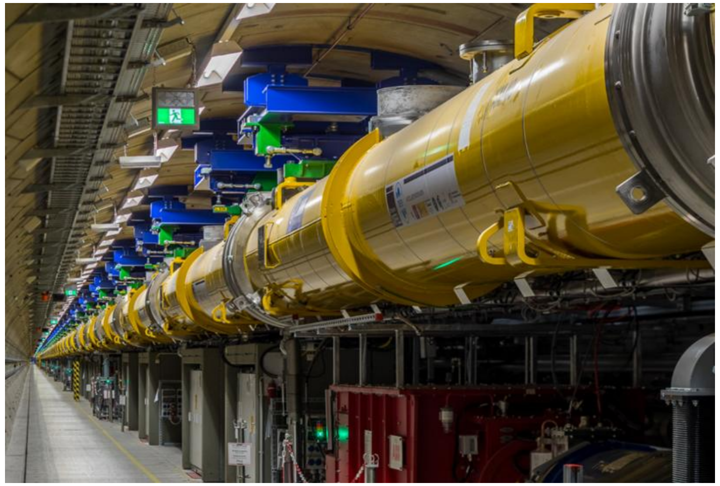
	Nominal	Range
Beam energy/GeV	8.0	4-8.6
Bunch charge/pC	50/100	10-300
Max rep-rate/MHz	1	up to 1
Photon energy/keV	0.2-15	0.2-15
Pulse length/fs	20-50	5-200
Peak brightness	5×10^{32}	1×10^{31}-1×10^{33}
Average brightness	5×10^{25}	1×10^{23}-1×10^{26}
2K Cryogenic power/kW	12	12
RF Power/MW	2.28	3.6

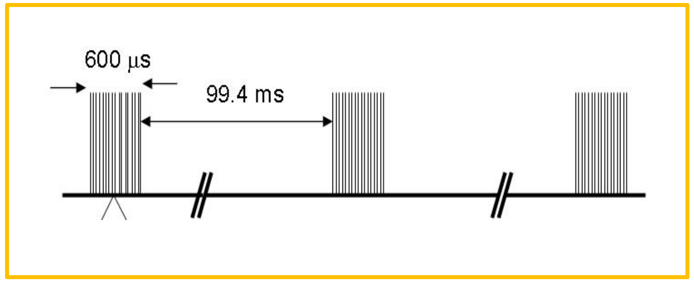
FEL Line	Nominal	Objective
FEL-I		
Photon energy/keV	3-15	3-15
Photon number per pulse @12.4keV	$>10^{10}$	$>10^{11}$
Max pulse repetition rate/MHz	0.66	1
FEL-II		
Photon energy/keV	0.2-3.0	0.2-3.0
Photon number per pulse @1.24keV	$>10^{12}$	$>10^{13}$
Max pulse repetition rate/MHz	0.66	1

The European XFEL Project



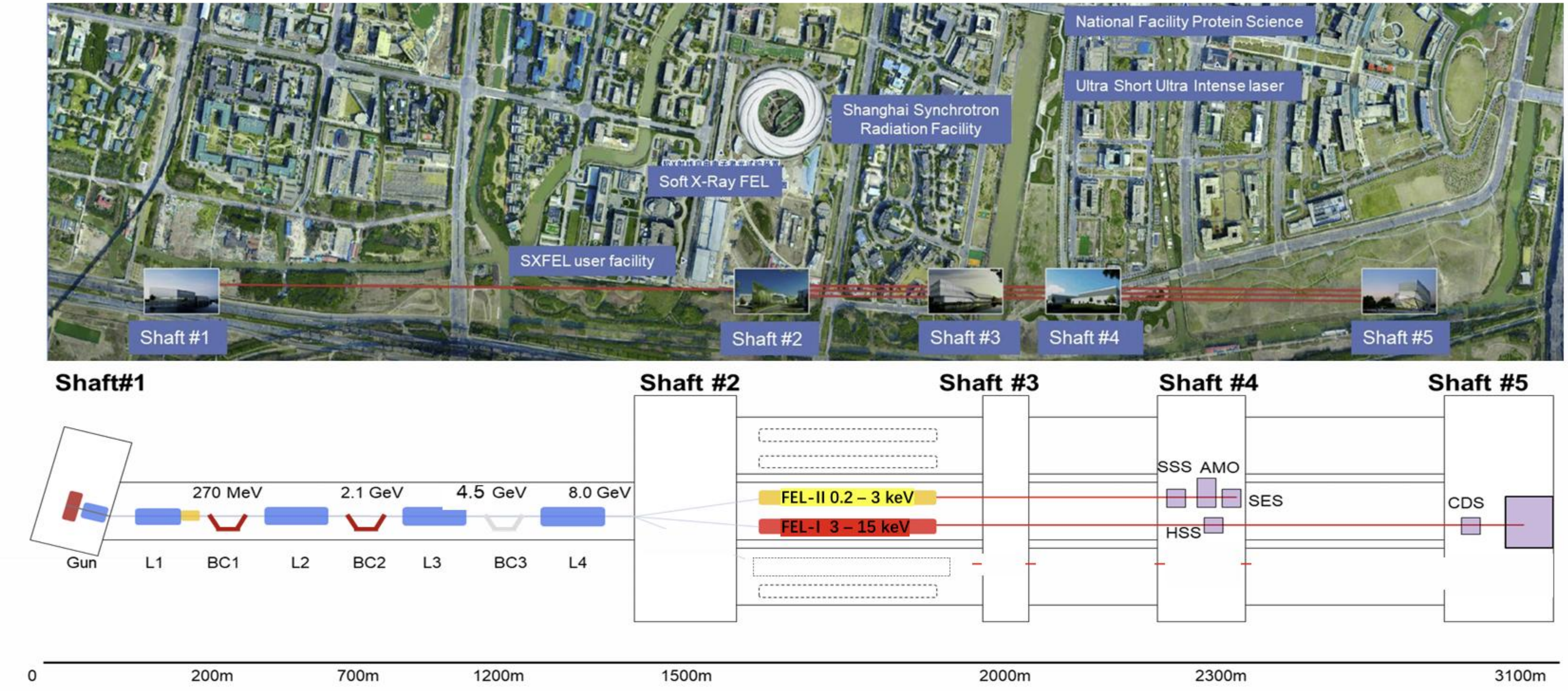






Combines extreme peak power with high average brightness

SHINE Project



- An 8 GeV SC RF linac, 2 undulator lines to deliver photons from 0.2-15 keV, up to 1 MHz pulse train with pulse duration of 1-100 fs

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Some Basic Ideas for Cavity RF Design

$$Q_0 = \frac{G}{R_s},$$

When G denotes geometry constant, Rs surface resistance

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

→ Spherical

$$R_S = A(1/T) f^2 e^{-\Delta(T)/kT} + R_0$$

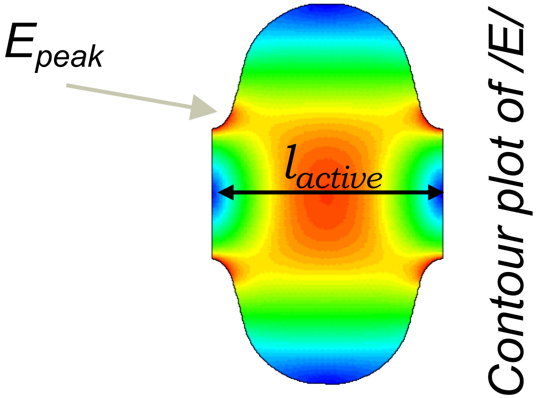
→ High Tc, low f but consider also size

$$E_{acc} = \frac{\sqrt{\omega_{acc} \cdot W_{acc} \cdot (R/Q)_{acc}}}{l_{active}}$$

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

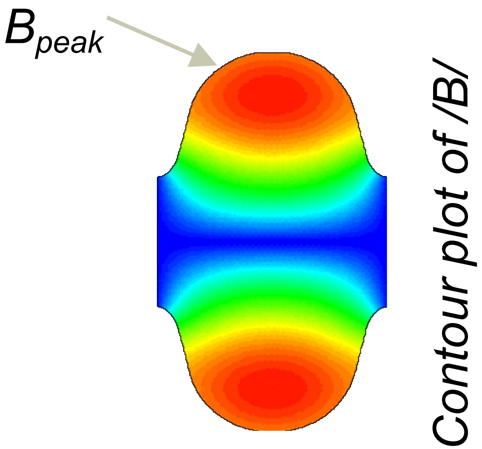
RF design - Some key parameters

$$\frac{E_{peak}}{E_{acc}}$$



Sensitivity to the field emission.

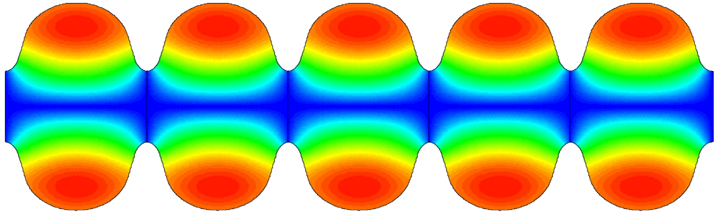
$$\frac{B_{peak}}{E_{acc}}$$



Limit in E_{acc} due to the break-down of superconductivity (Nb ~220 mT).

cell-to-cell coupling k_{cc}

The k_{cc} is relevant for the accelerating mode passband of multi-cell structures

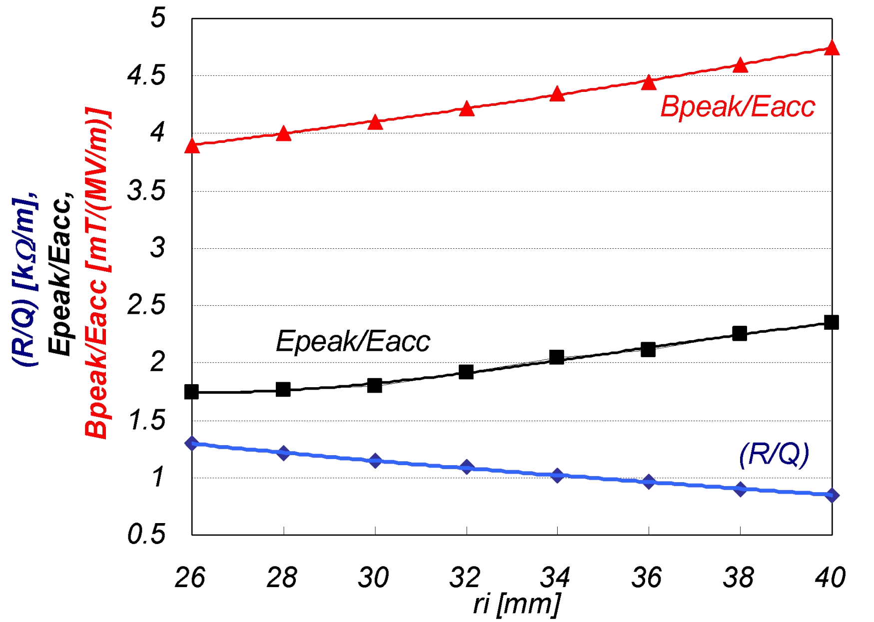


- **Multi-cell structures** are less expensive/m and allow for higher real-estate gradient.
- **Kcc** affects tuning sensitivity of field flatness, HOM damping

Criteria for Cavity Design: Accelerating Cells

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

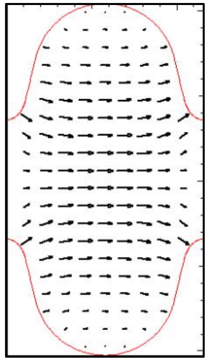
Example:
{ (R/Q), E_{peak}/E_{acc} , B_{peak}/E_{acc} }
vs. r_i for cell at f = 1.5 GHz

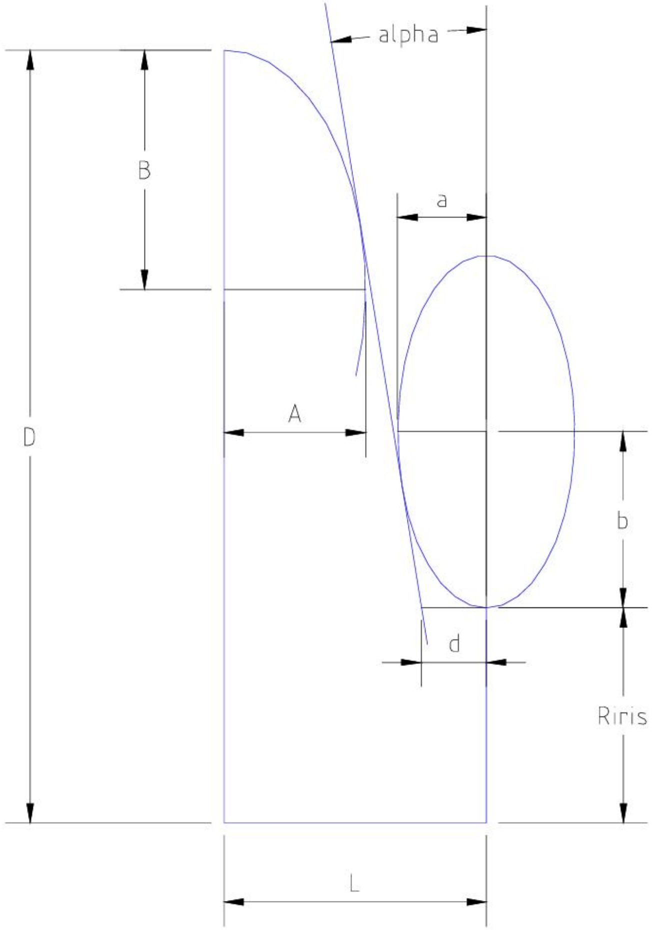


We see here that r_i is a very “powerful variable” to trim the RF-parameters of a cavity.

Jacek Sekutowicz-SRF2013

A tool for cavity design – BuildCavity (INFN)





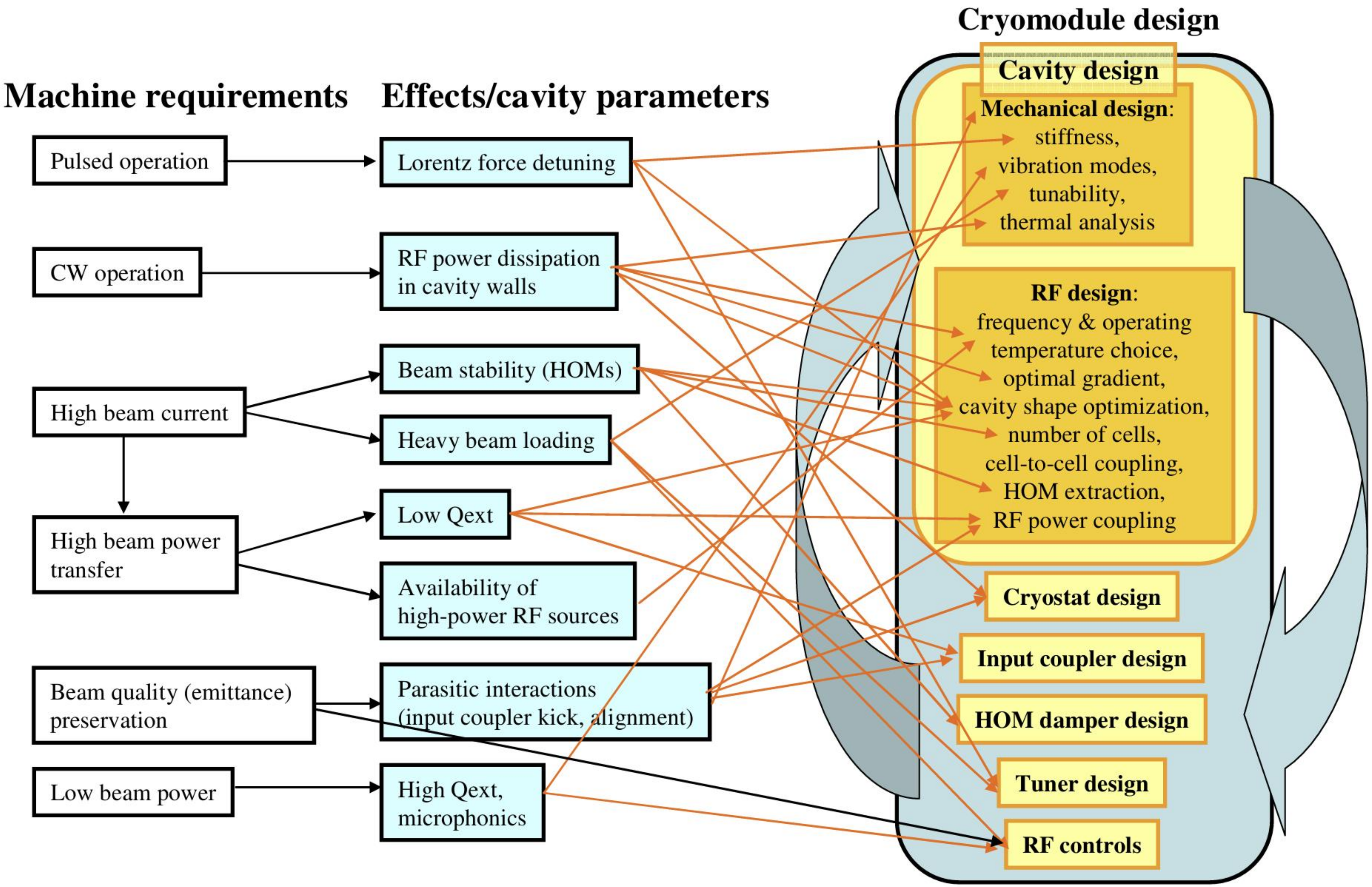
An interface to SUPERFISH code

- C Pagani, D Barni, A Bosotti, et al., - SRF2001.
- J.F. Chen, M. Moretti, C. Pagani, et al - SRF2015

Seven parameters to design a cell:

- The **cell length** (L) determines the cavity geometrical beta value.
- The cell **iris radius** (R_{iris}) is mainly determined by the cell-to-cell coupling requirements.
- The **side wall inclination** (α) **and position** (d) with respect to the iris plane can be set to achieve a tradeoff between electric and magnetic peak fields with a minor effect on cell-to-cell coupling.
- The **iris ellipse ratio** ($r=b/a$) is uniquely determined by the local optimization of the peak electric field.
- The **equator ellipse ratio** ($R=B/A$) is ruled by purely mechanical considerations and has no influence on the electromagnetic performances.
- The **cell radius** (D) is used for the frequency tuning without modifying any electromagnetic or mechanical cavity parameter.

Machine-related cavity design issues

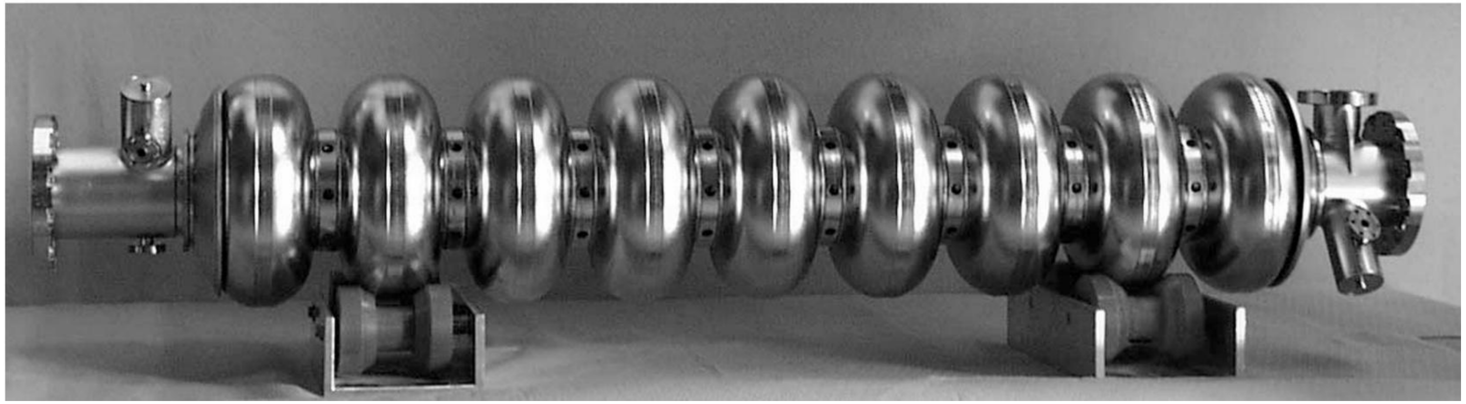


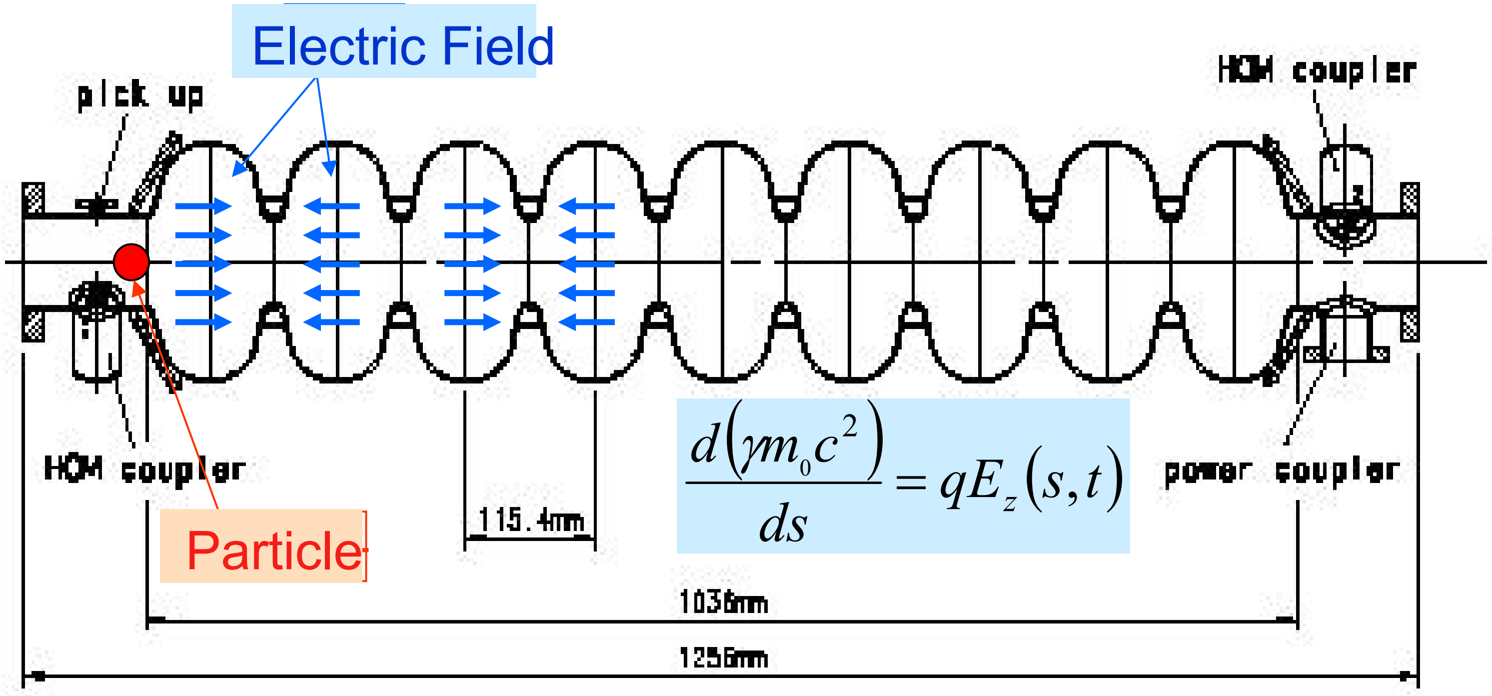
A good cavity design is an optimal balance of many parameters!

Sergey Belomestnykh, Valery Shemelin, High-β Cavity Design–A Tutorial, in *Proceedings of SRF2005 Workshop Ithaca, NY, USA: Cornell University*, 2005.

Optimized Cavity Design and Rules

Bulk Nb, 9-cell, 1.3 GHz





$$\frac{d\left(\gamma m_0 c^2\right)}{ds} = qE_z(s,t)$$

TESLA cavity parameters

R/Q	1036	Ω
E_{peak}/E_{acc}	2.0	
B_{peak}/E_{acc}	4.26	mT/(MV/m)
Df/Dl	315	kHz/mm
$K_{Lorentz}$	≈ -1	Hz/(MV/m)^2

Cavity Design - HOM Damping

Half-cell shape parameters (mm)

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

Asymmetric end cell shaping

TABLE II. TTF cavity design parameters.[a]

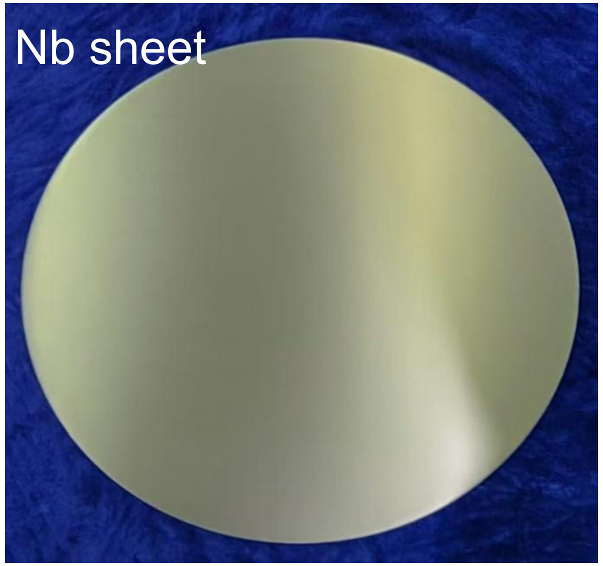
Type of accelerating structure	Standing wave
Accelerating mode	TM_{010}, π mode
Fundamental frequency	1300 MHz
Design gradient E_{acc}	25 MV/m
Quality factor Q_0	$>5 \times 10^9$
Active length L	1.038 m
Number of cells	9
Cell-to-cell coupling	1.87%
Iris diameter	70 mm
Geometry factor	270 Ω
R/Q	518 Ω
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

B. Aune, et al., Superconducting TESLA cavities, PRST-AB, 3(9), 092001 (2000).

High Purity Nb for RF Cavities

Impurity content in ppm (wt.)				Mechanical properties	
Ta	≤500	H	≤2	RRR	≥300
W	≤70	N	≤10	Grain size	≈50 μm
Ti	≤50	O	≤10	Yield strength	>50 MPa
Fe	≤30	C	≤10	Tensile strength	>100 MPa
Mo	≤50			Elongation at break	30%
Ni	≤30			Vickers hardness HV 10	≤50

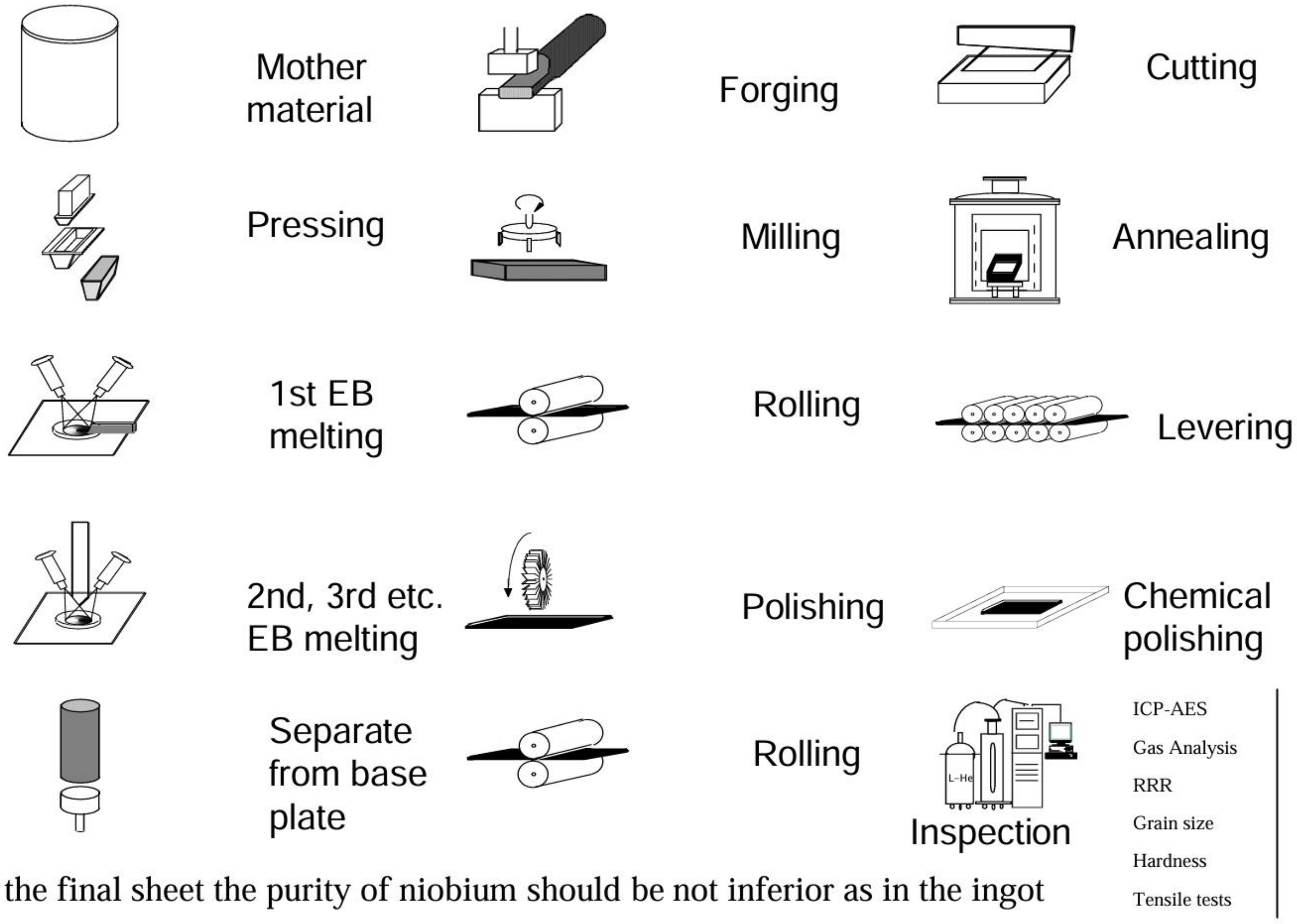
$$\mathrm{RRR} = \frac{\text{resistivity 300 K}}{\text{residual resistivity at low temperature (normal state)}}.$$



Diameter 265 mm and thickness 2.8 mm for 1.3 GHz cavity

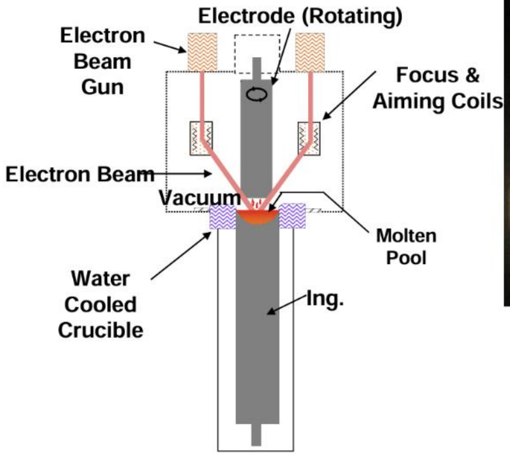
Nb Sheet Production

Fabrication of Nb sheets at Tokyo Denkai



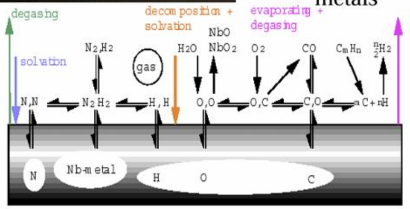
In the final sheet the purity of niobium should be not inferior as in the ingot

Mass production of high purity Nb for RF cavities



Electron Beam melting of Nb

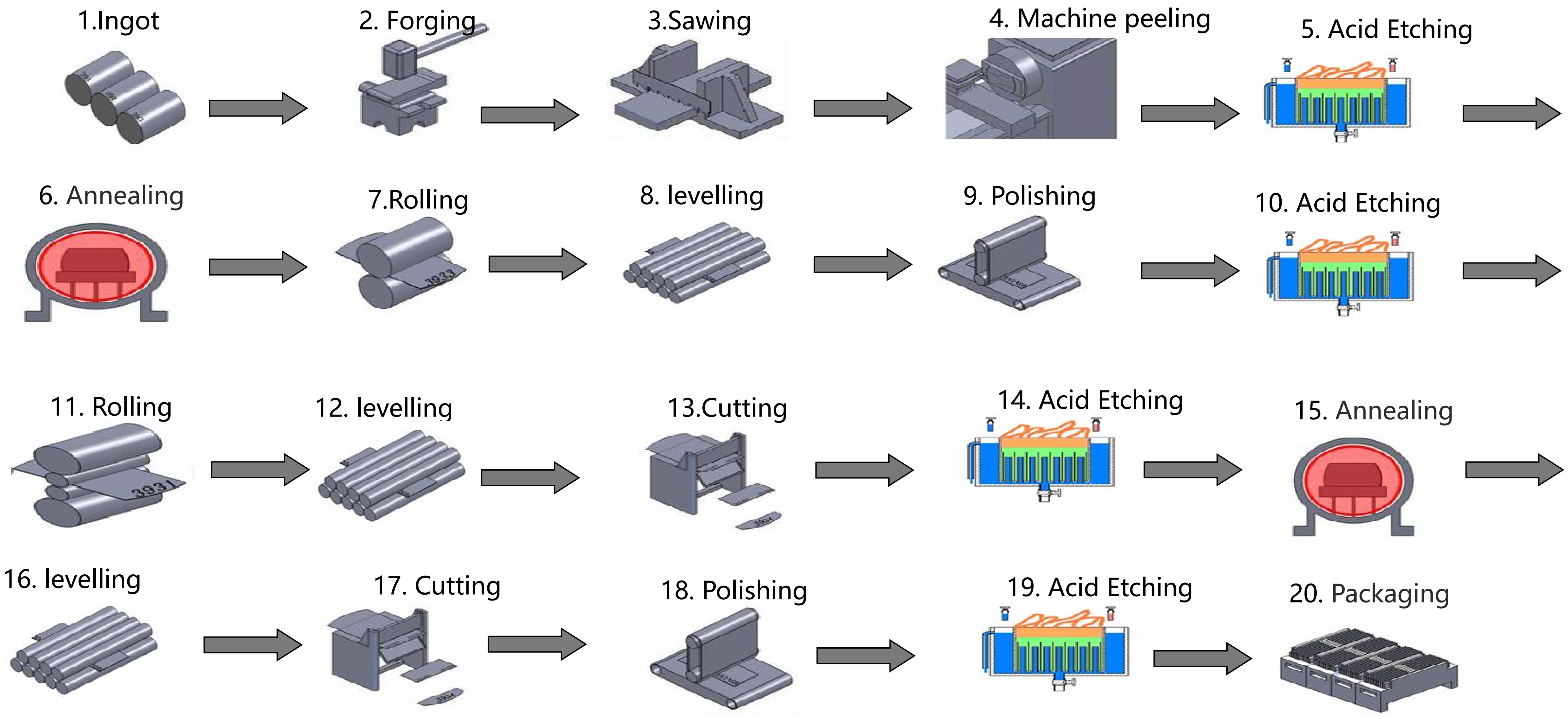
EB furnace for melting of refractory metals



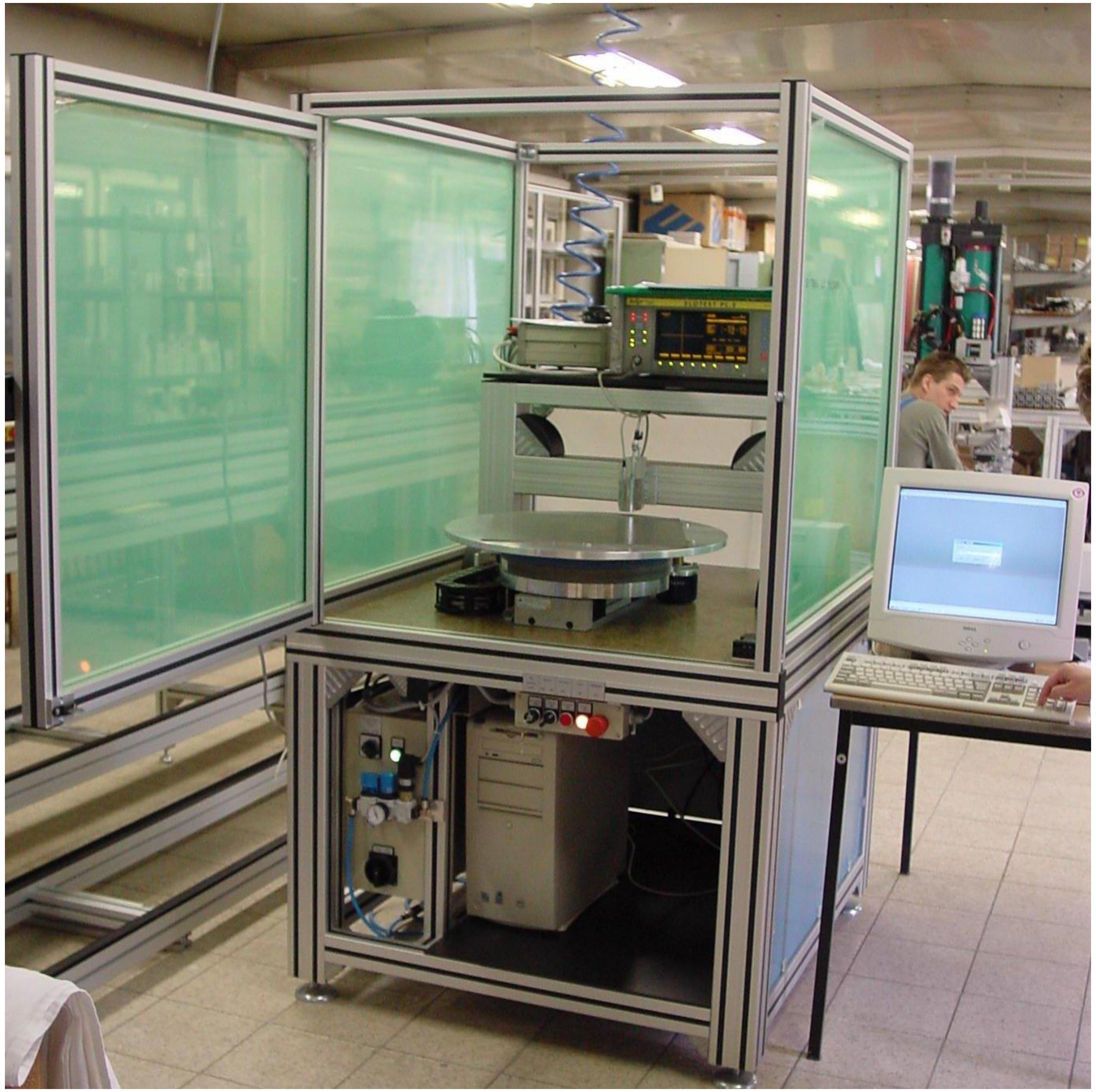
The melting temperature is a compromise between the maximization of purification and minimization of the material losses by evaporation.

Niobium Production Process

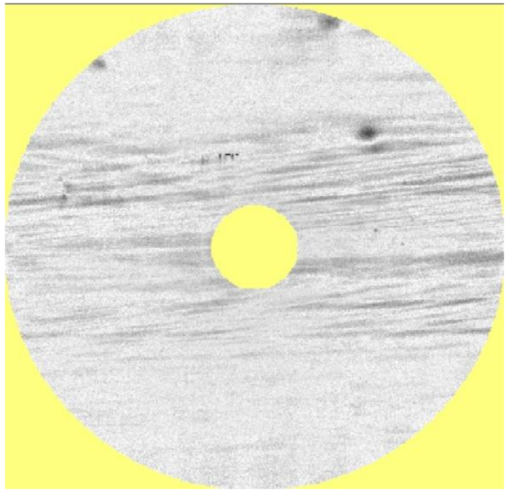
Guan Lu, OTIC Nb,
TTC2024



Eddy Current Scanning for Nb Sheets



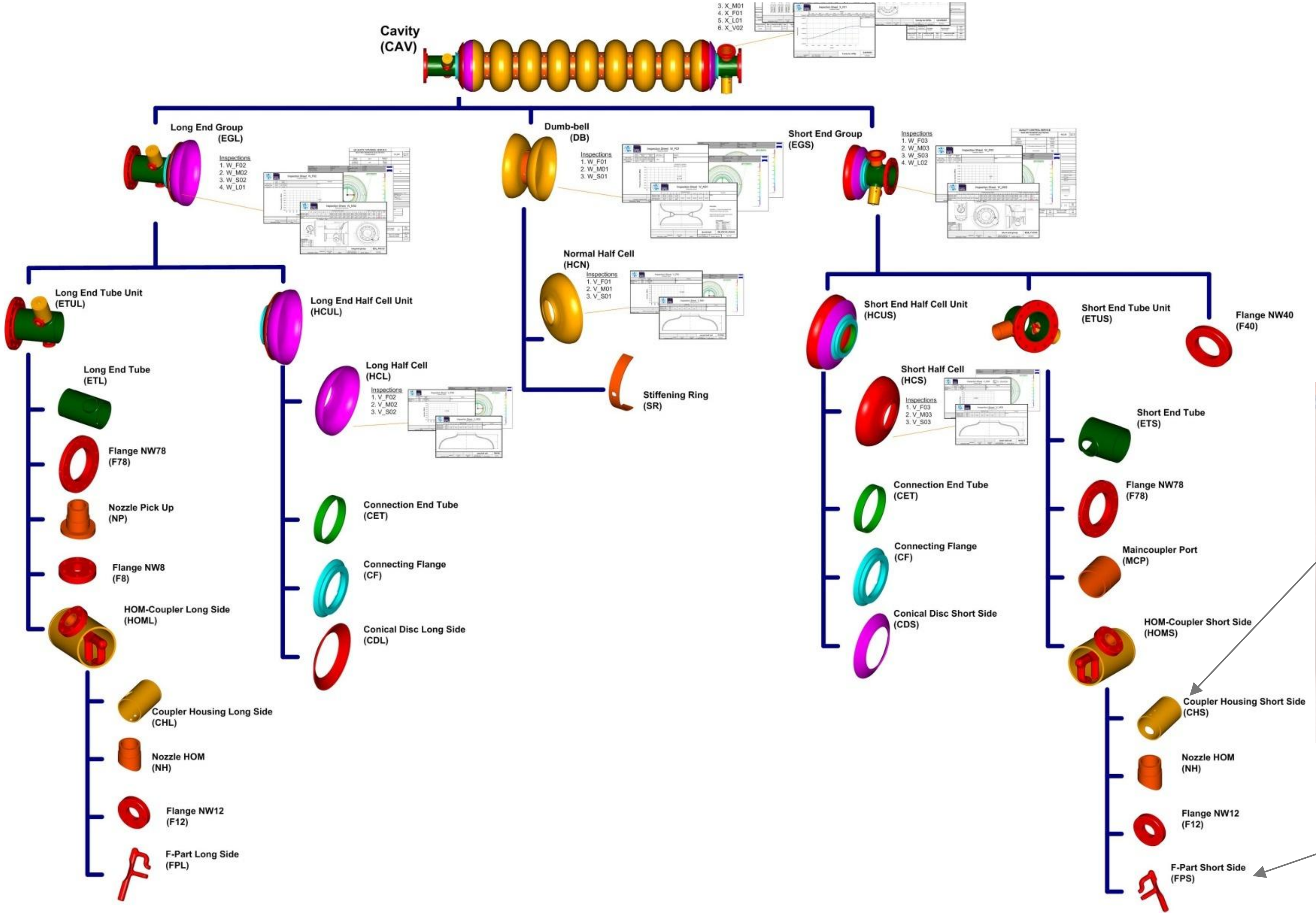
Scanning results



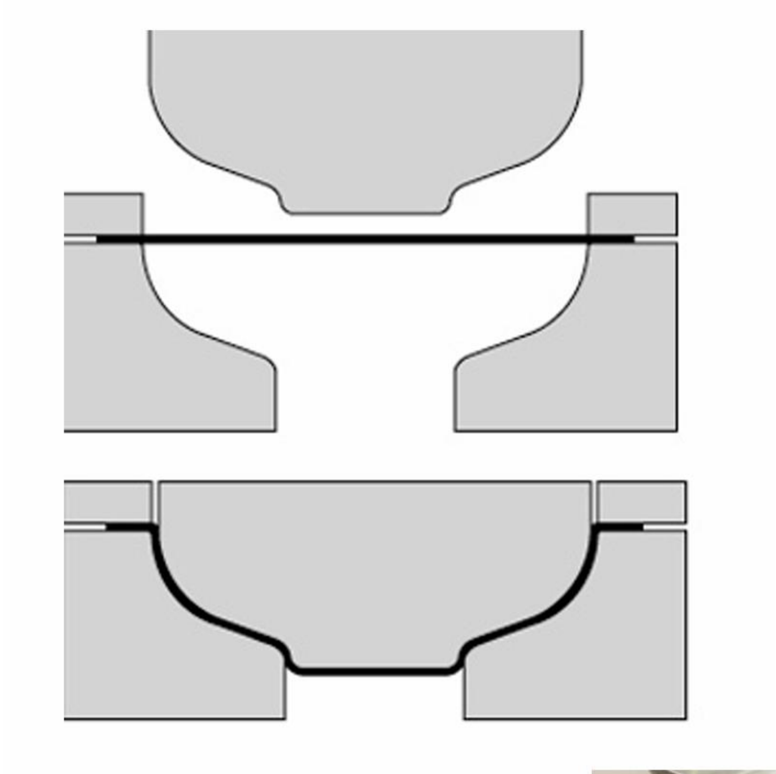
- Rolling marks and defects are visible on a niobium disk to be used to print a cavity half-cell.
- Surface analysis is then required to identify the inclusions

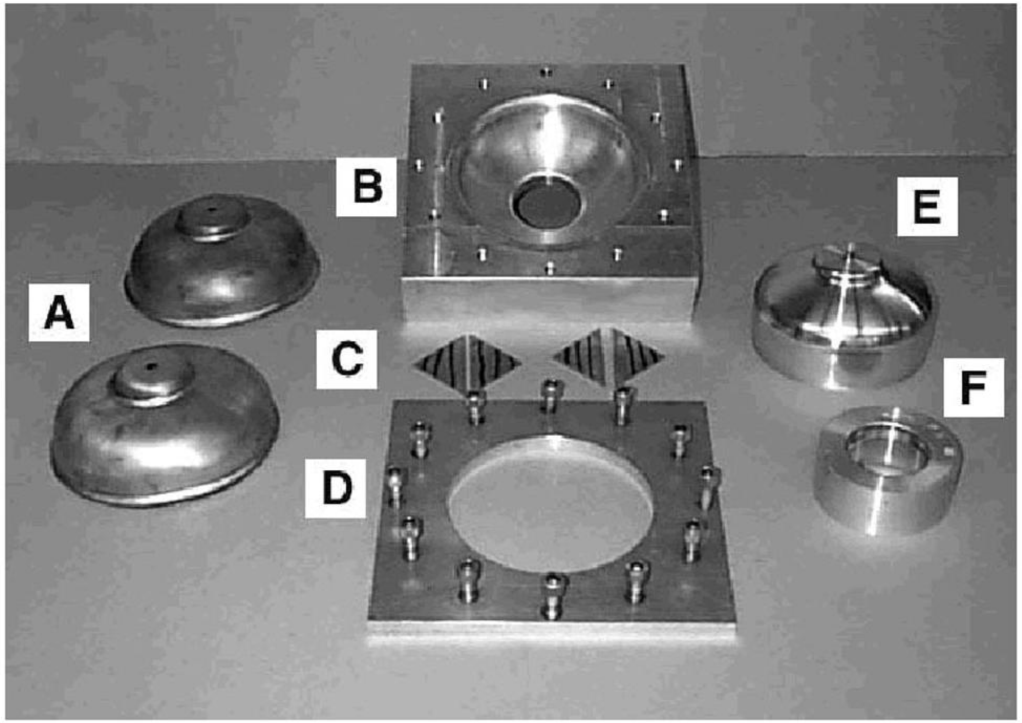
Nb sheets, passed the ECS, are used for cavity fabrication

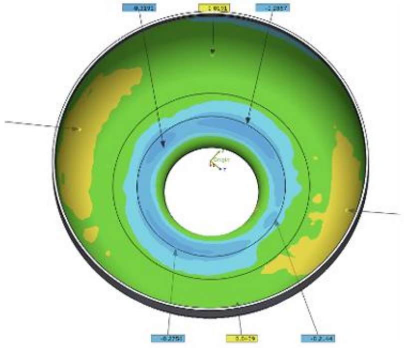
Fabrication of SC Nb Cavity



Fabrication – Deep Drawing with Hydraulic Press





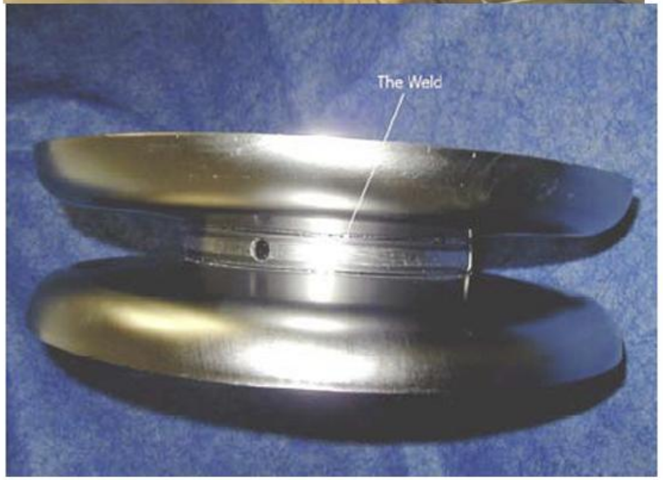


Fabrication – Electron Beam Welding

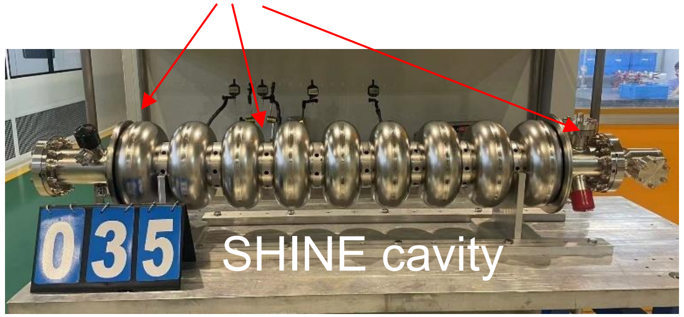
Dumbbells

Tack- Welding:	4 tacks, focused beam
Voltage :	50 kV
Current:	15 mA
Rotational Speed :	20 inches/min
Distance of gun to work : 6 "	
Final weld Current:	33 mA
Rotational speed:	18"/min
Focussing:	elliptical pattern

Stiffening Rings



All Nb parts with EBW



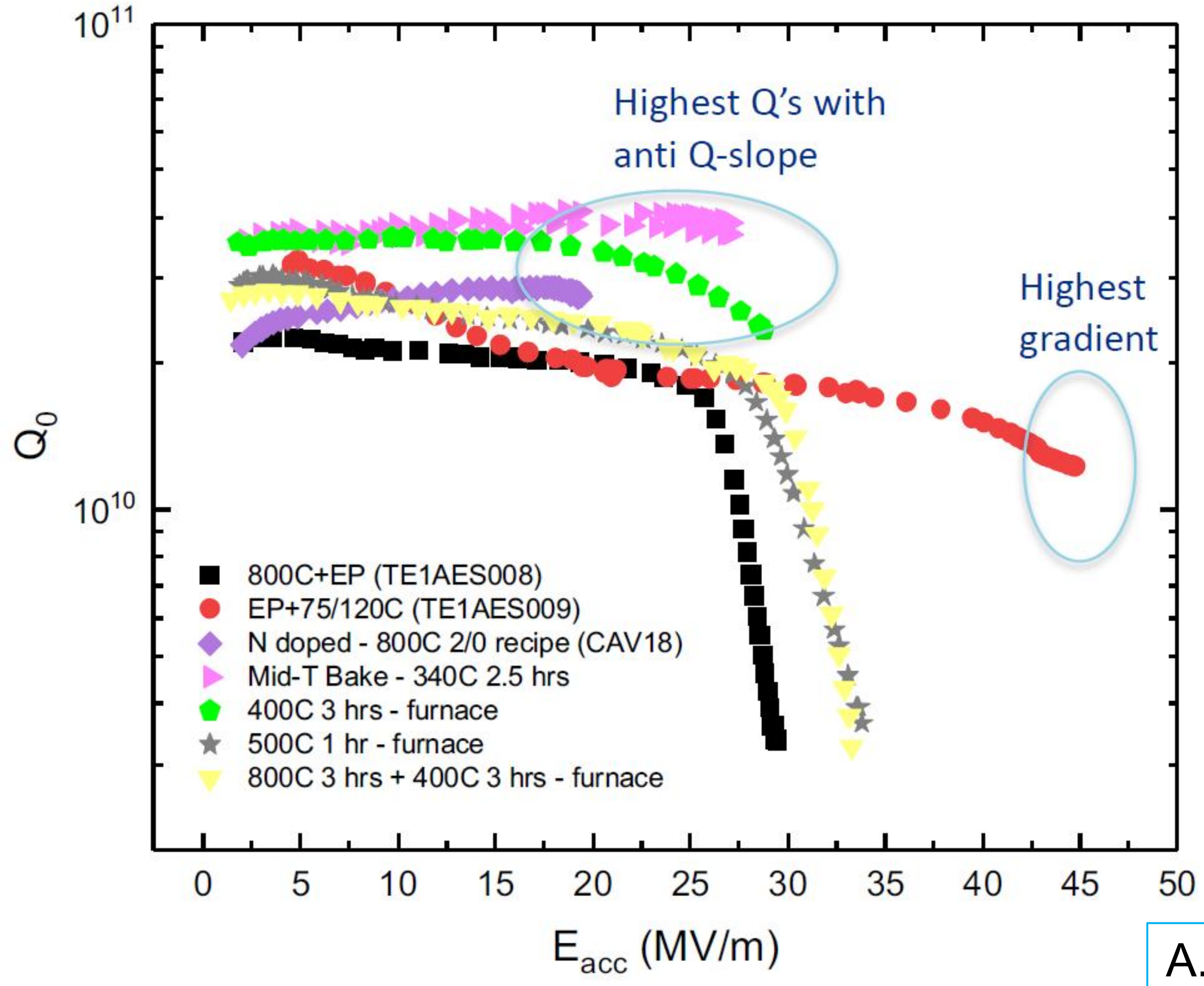
Dumbell Fabrication process

1. Mechanical measurement
2. Cleaning (by ultra sonic [us] cleaning +rinsing)
3. Trimming of iris region and reshaping of cups if needed
4. Cleaning
5. Rf measurement of cups
6. Buffered chemical polishing + Rinsing (for welding of Iris)
7. Welding of Iris
8. Welding of stiffening rings
9. Mechanical measurement of dumb-bells
10. Reshaping of dumb bell if needed
11. Cleaning
12. Rf measurement of dumb-bell
13. Trimming of dumb-bells (Equator regions)
14. Cleaning
15. Intermediate chemical etching (BCP /20- 40 μm)+ Rinsing
16. Visual Inspection of the inner surface of the dumb-bell local grinding if needed + (second chemical treatment + inspection)

Electron Beam Welding (JLab), Rongli Geng, SRF2023l

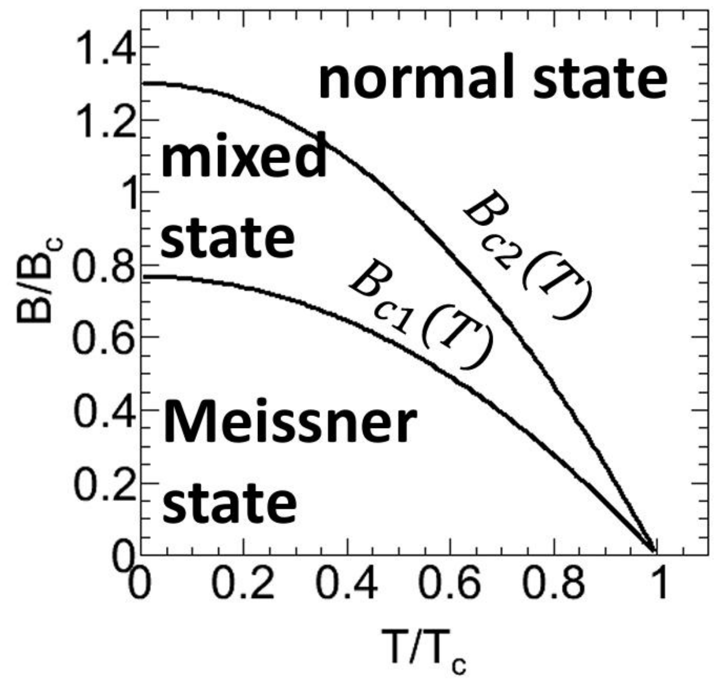
Surface Treatments: Crucial to Cavity RF Performance

State-of-the-art treatments studied



Type-2

$$\kappa = \frac{\lambda}{\xi} > \frac{1}{\sqrt{2}} = 0.71$$

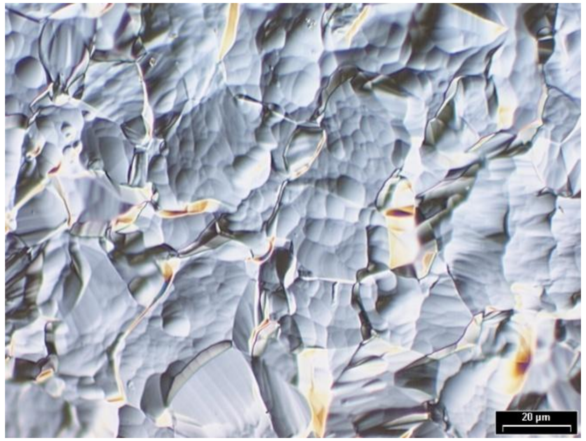


$$\kappa_{Nb} \sim \frac{36\text{ nm}}{39\text{ nm}} \sim 0.92$$

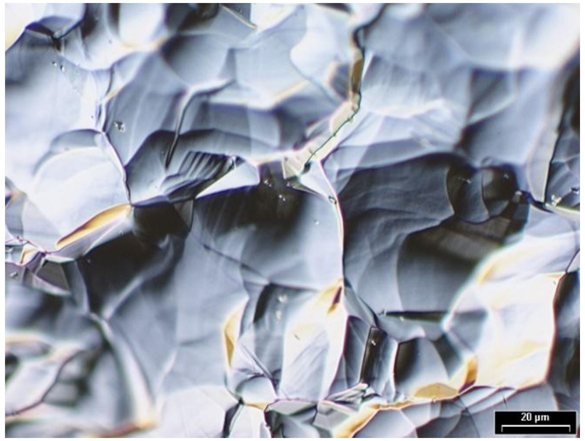
A. Romanenko, SRF2021

Key Device: Electro-Polishing (EP) for Smoother Surface

Nb sheet as delivered



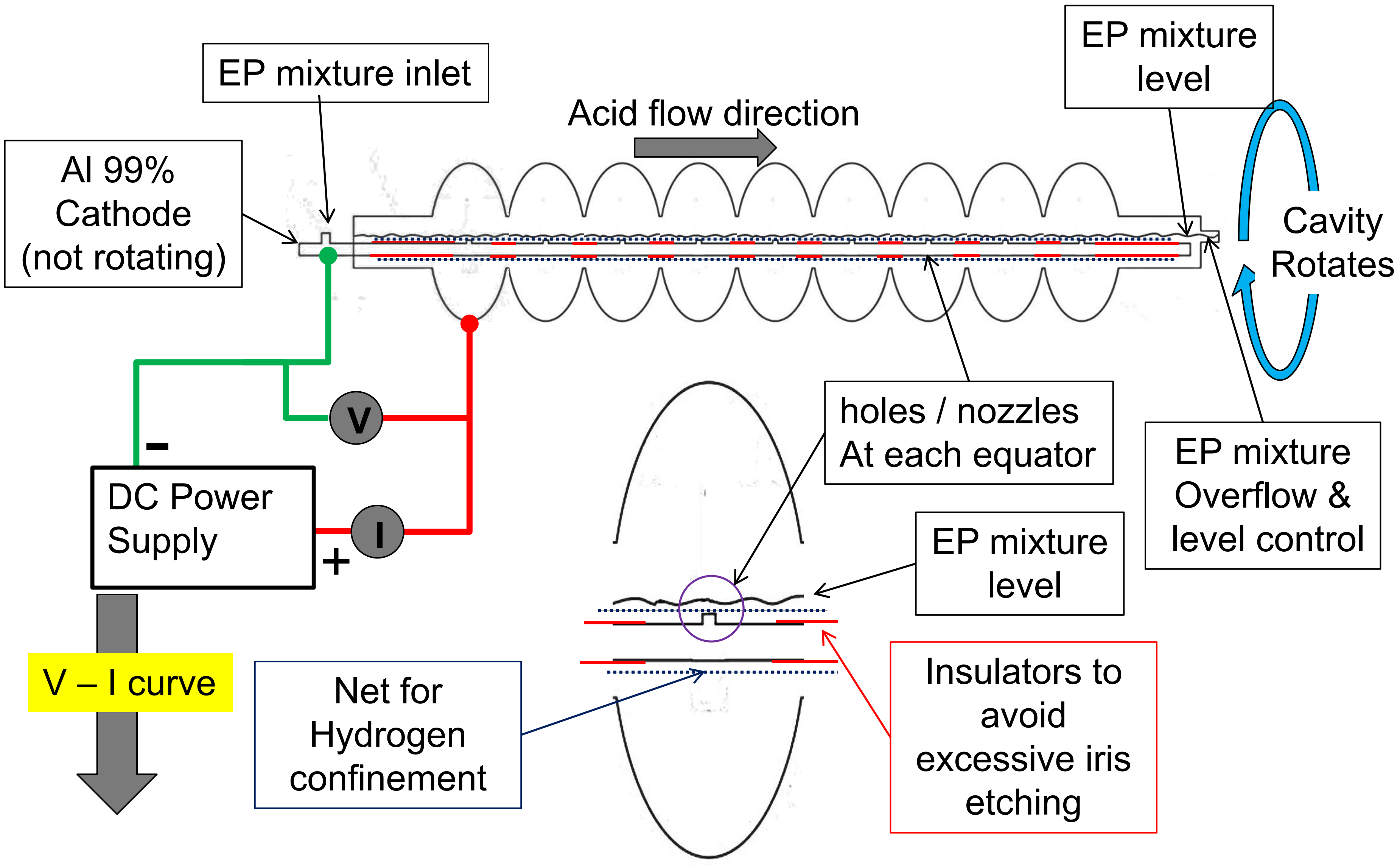
After 120 μm of BCP



After120 μm of EP

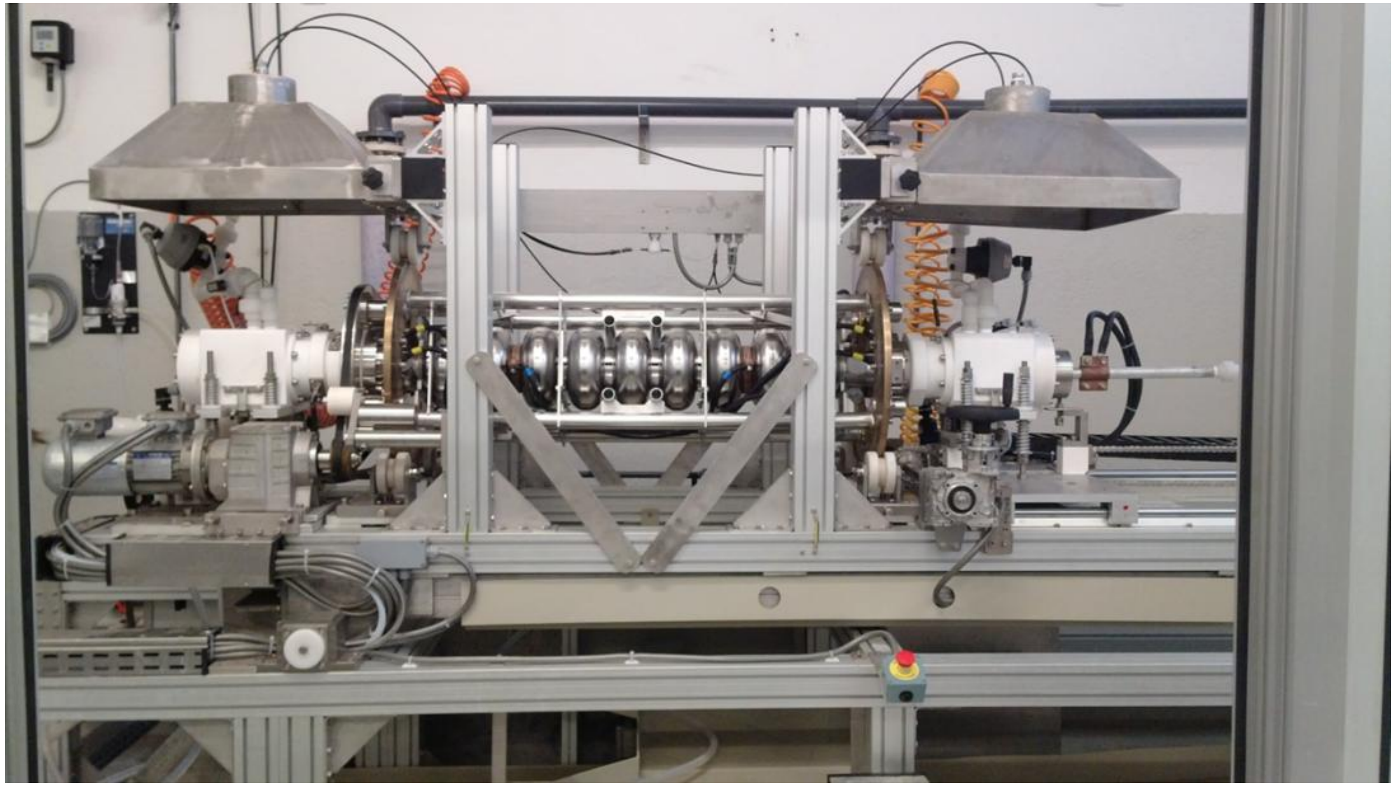
Main difference between BCP and EP: smoothening of grain boundaries.

EP for SRF cavities: Basic Concepts



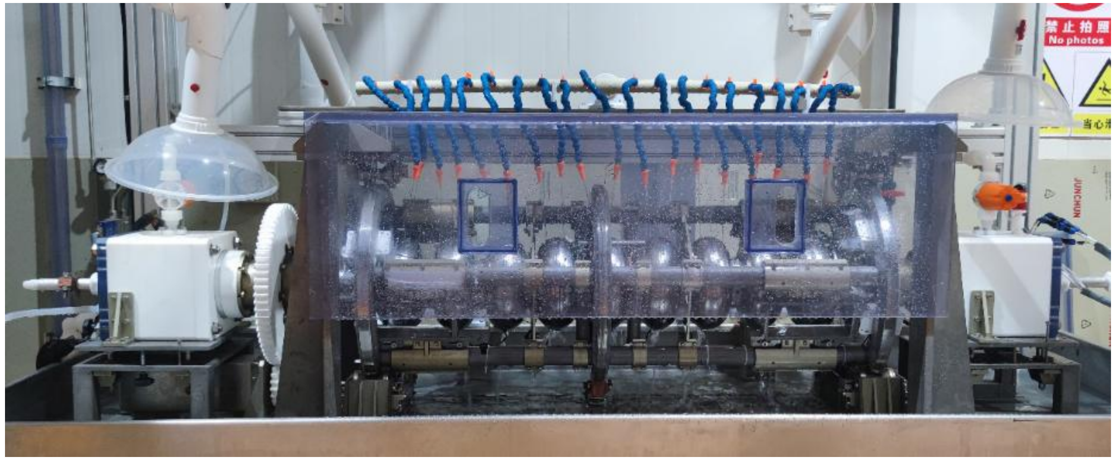
Reference EP System

EP System in Industry (EZ)



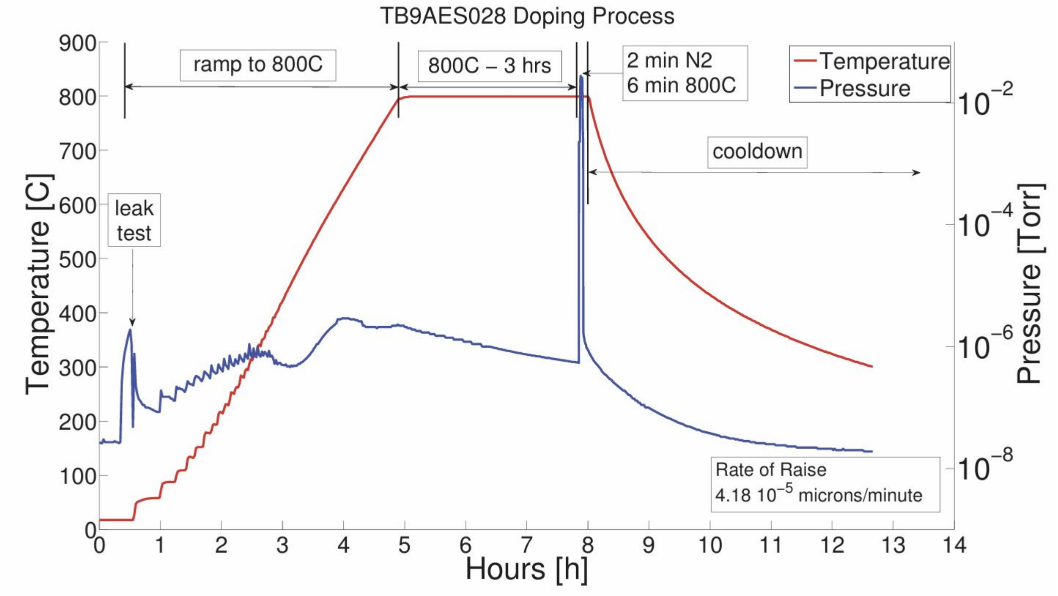
EP System at DESY

SHINE EP System in Wuxi



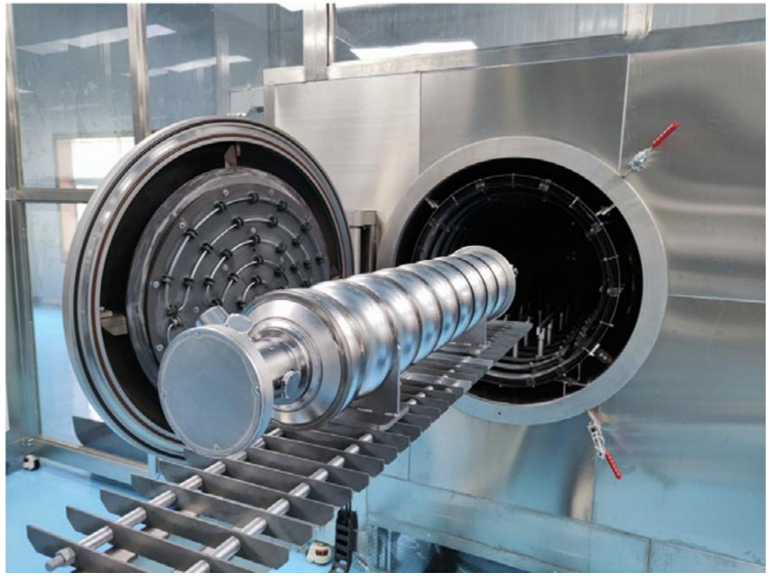
Key Device: High vacuum Furnaces

Fermilab furnace

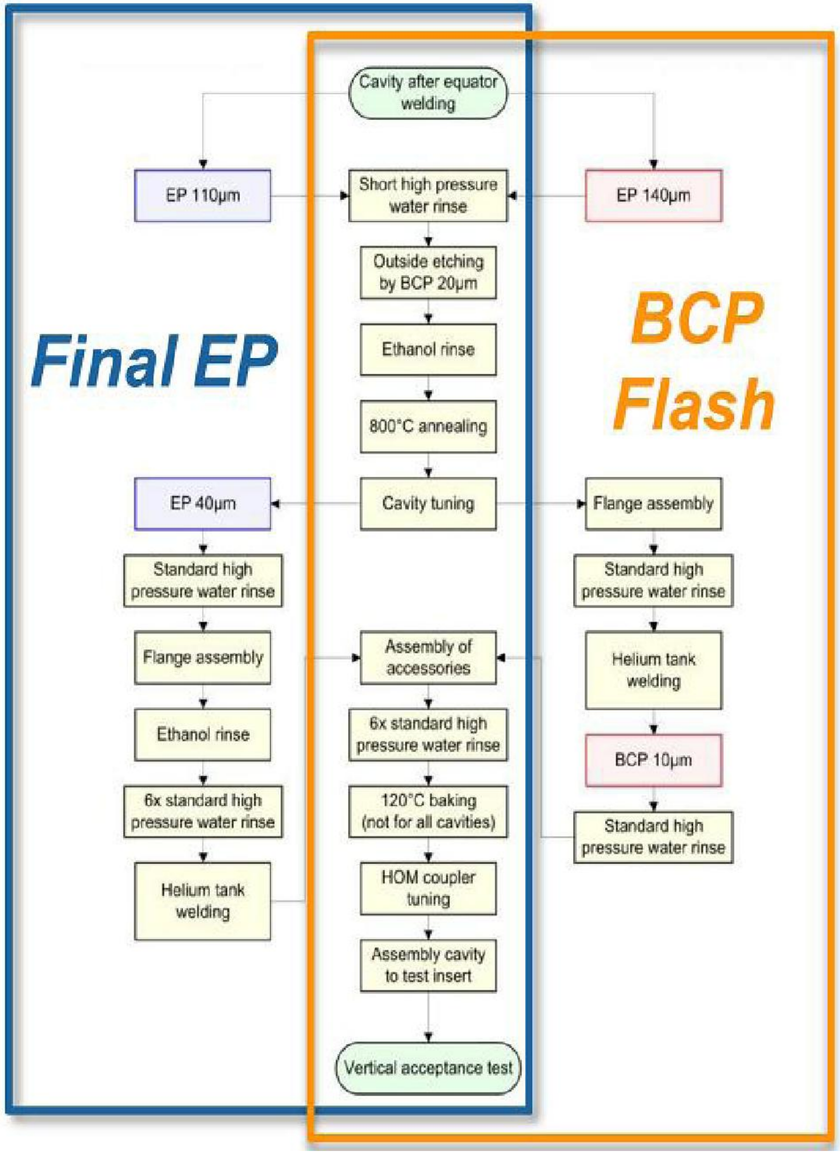


KEK furnace

SHINE small furnace



Surface treatment for E-XFEL Cavity (high gradient)



Prior surface treatment.

EP 110-140 μm (main EP), ethanol rinse, outside BCP, 800°C annealing, tuning

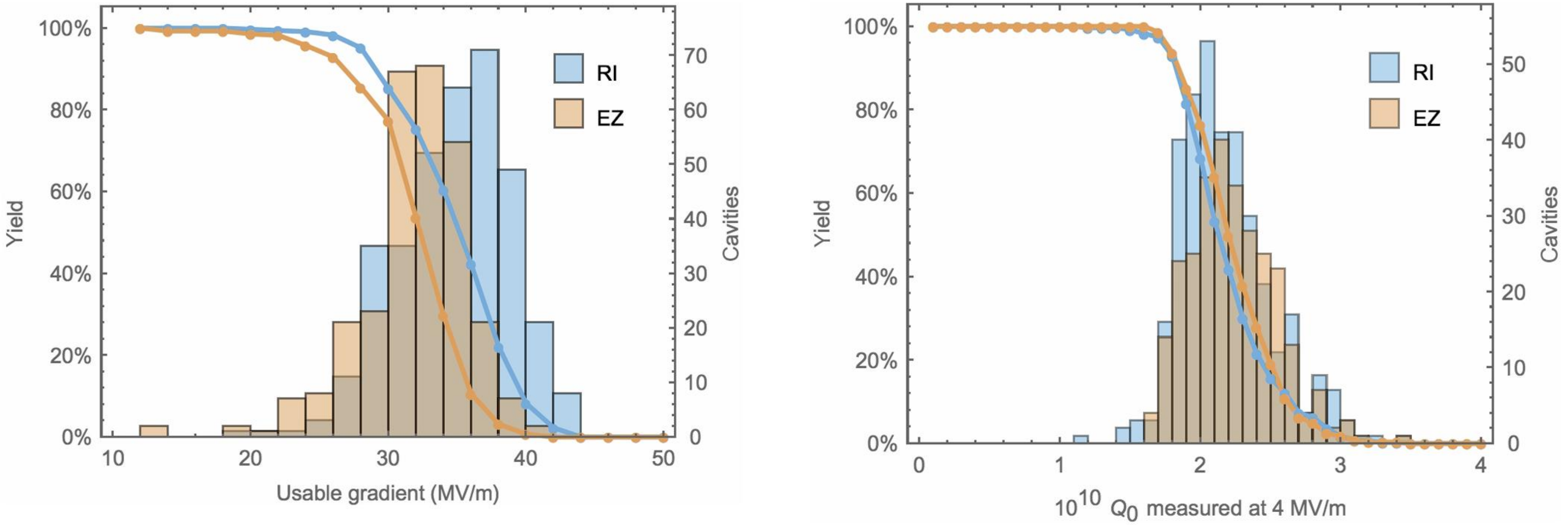
Final surface treatment - two alternative options

1. Final EP of 40 μm, ethanol rinse, high pressure water rinsing (HPR) and 120°C bake
2. Final BCP of 10 μm (BCP Flash), HPR and 120°C bake.

Integration of the helium tank, assembly of HOM, pick up and high Q antennas before vertical RF test

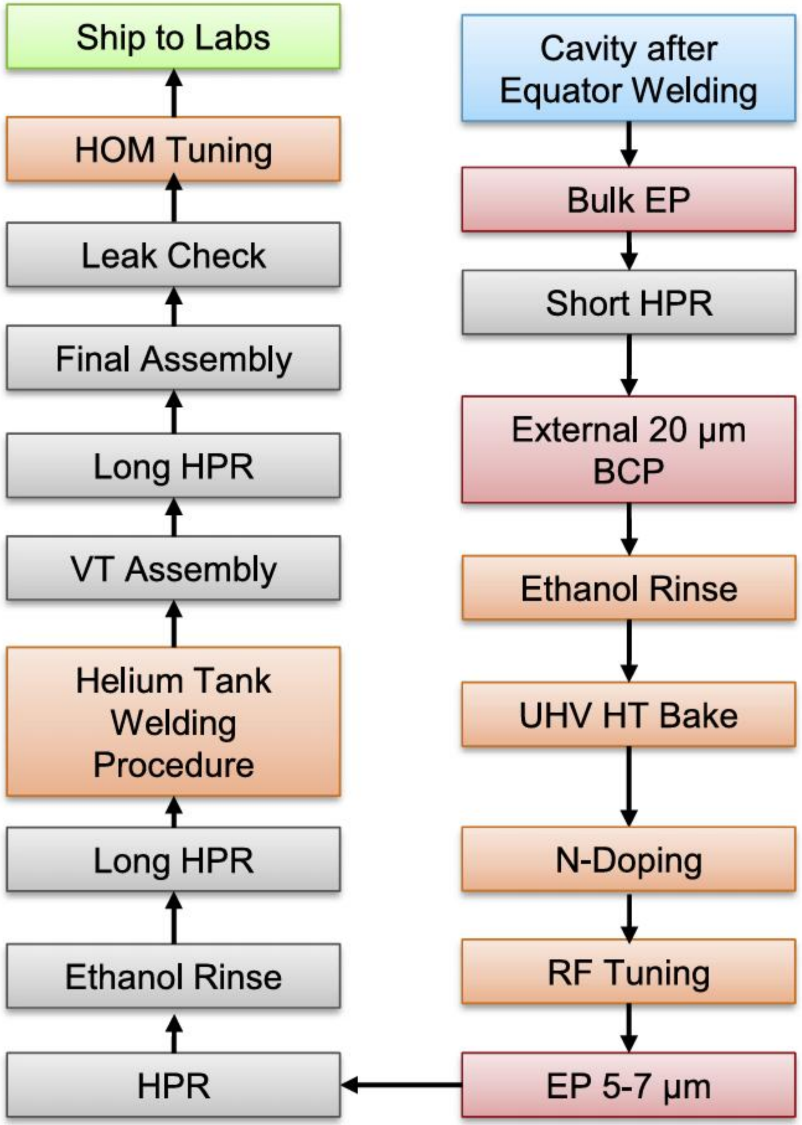
E-XFEL Cavity Vertical Test Results

- E-XFEL cavity recipe: EP + 800 °C/3h + EP/BCP + 120 °C/48h
- Vertical test results



- D. Reschke et al, PRAB, 20(4), 042004 (2017).

Cavity Surface Treatments for LCLS-II/HE



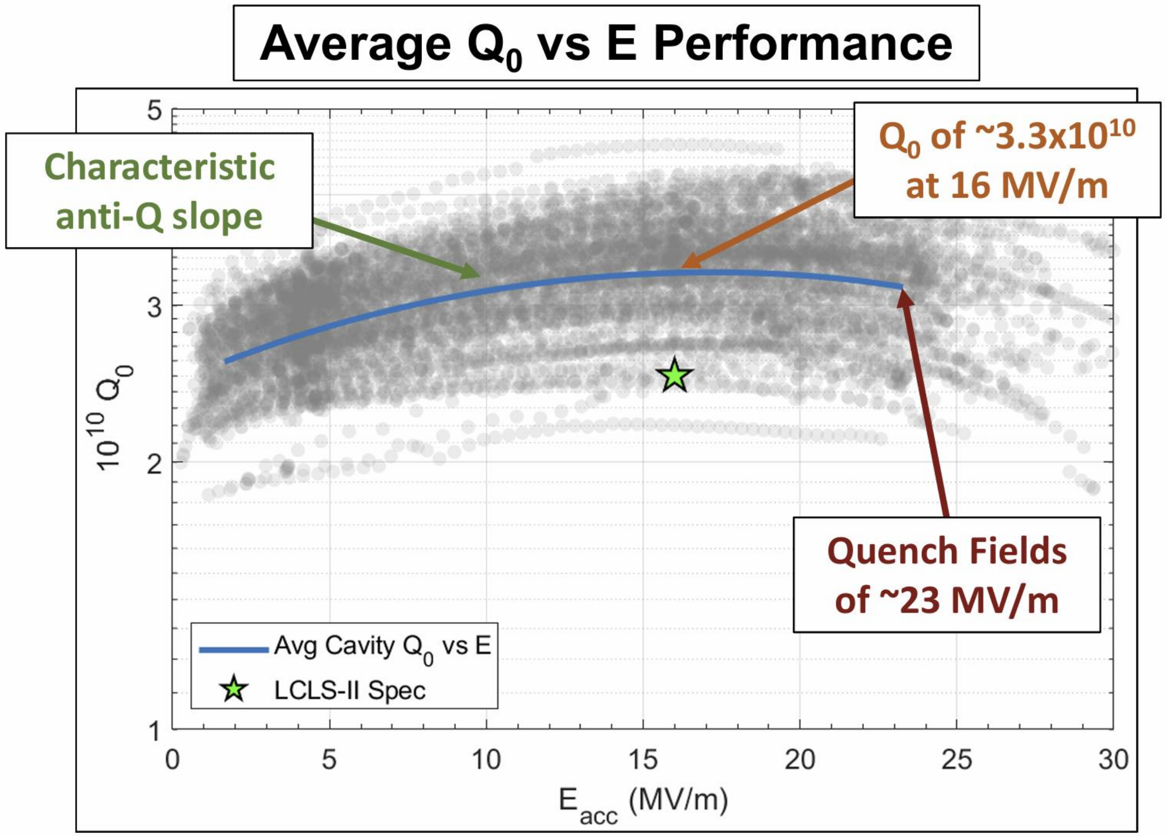
LCLS-II-HE recipe

LCLS-II	LCLS-II-HE
Bulk EP	Bulk EP 1
High Temperature Furnace Treatment & Doping (2N6)	High Temperature Furnace Treatment
	Bulk EP 2 (last portion cold)
	Doping (2N0)
Fine EP	Fine EP (all cold)

D. Gonnella et al, NIMA, 883 (2018); James Maniscalco, TTC2023

LCLS-II and LCLS-II HE Cavities

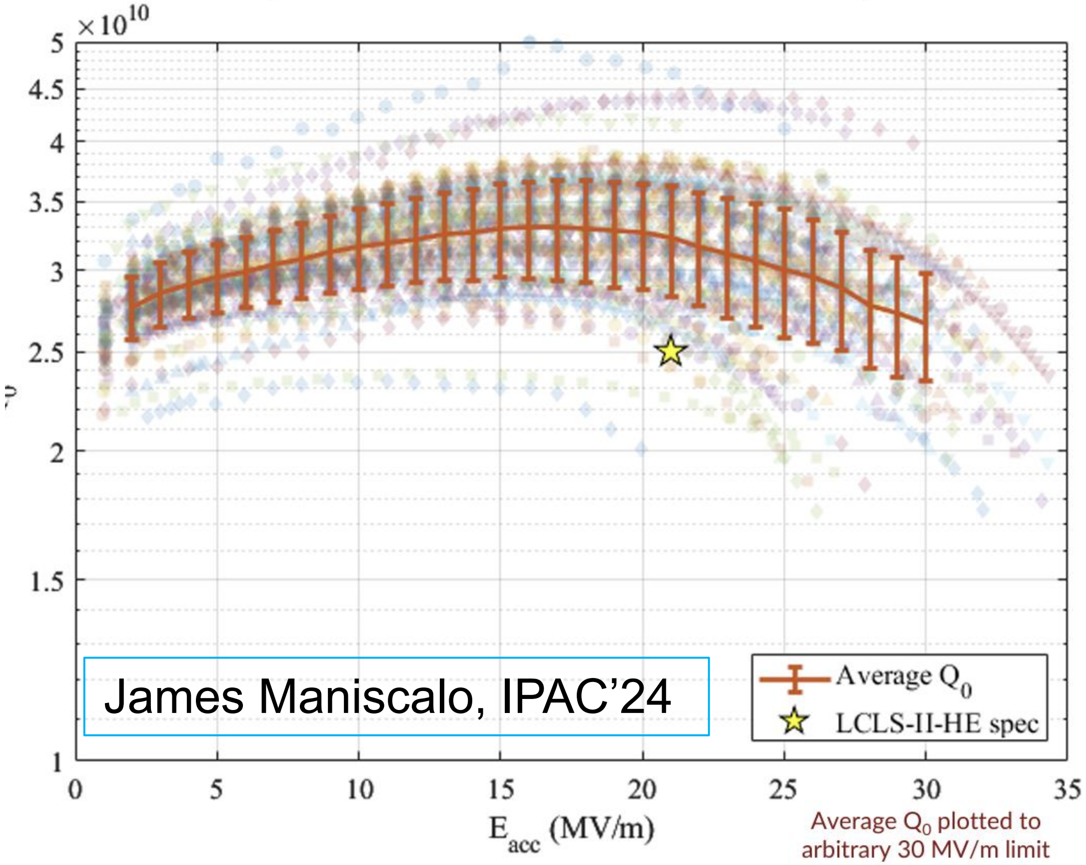
Nitrogen-Doping for LCLS-II (373 cavities)



Dan Gonnella, June 2023

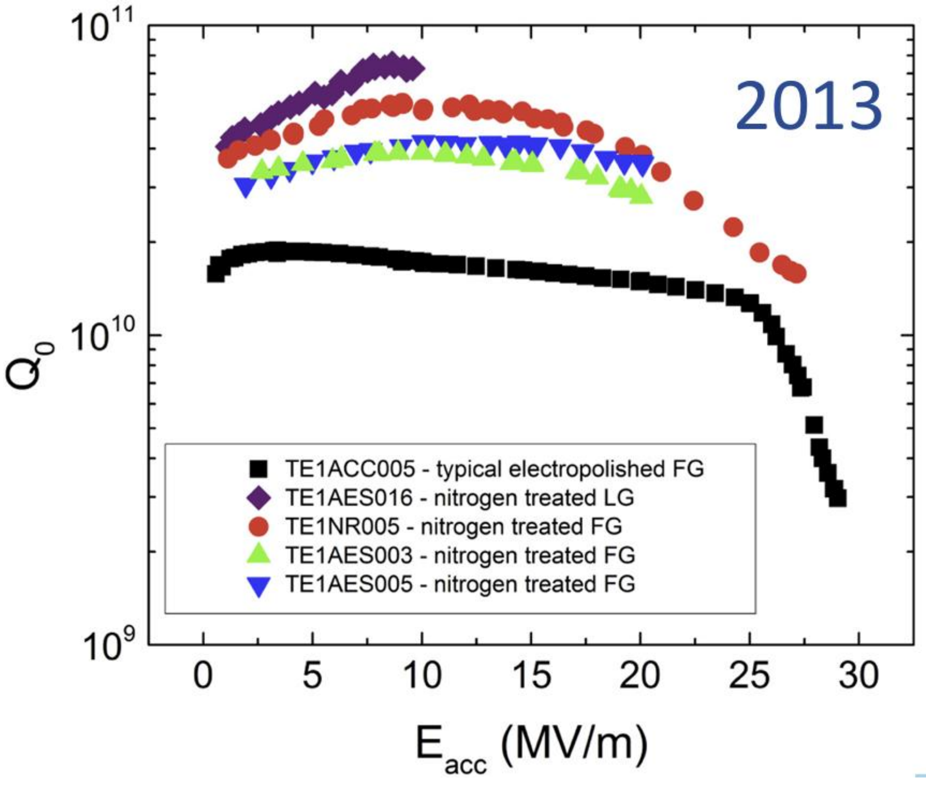
LCLS-II HE

All cavities with no FE

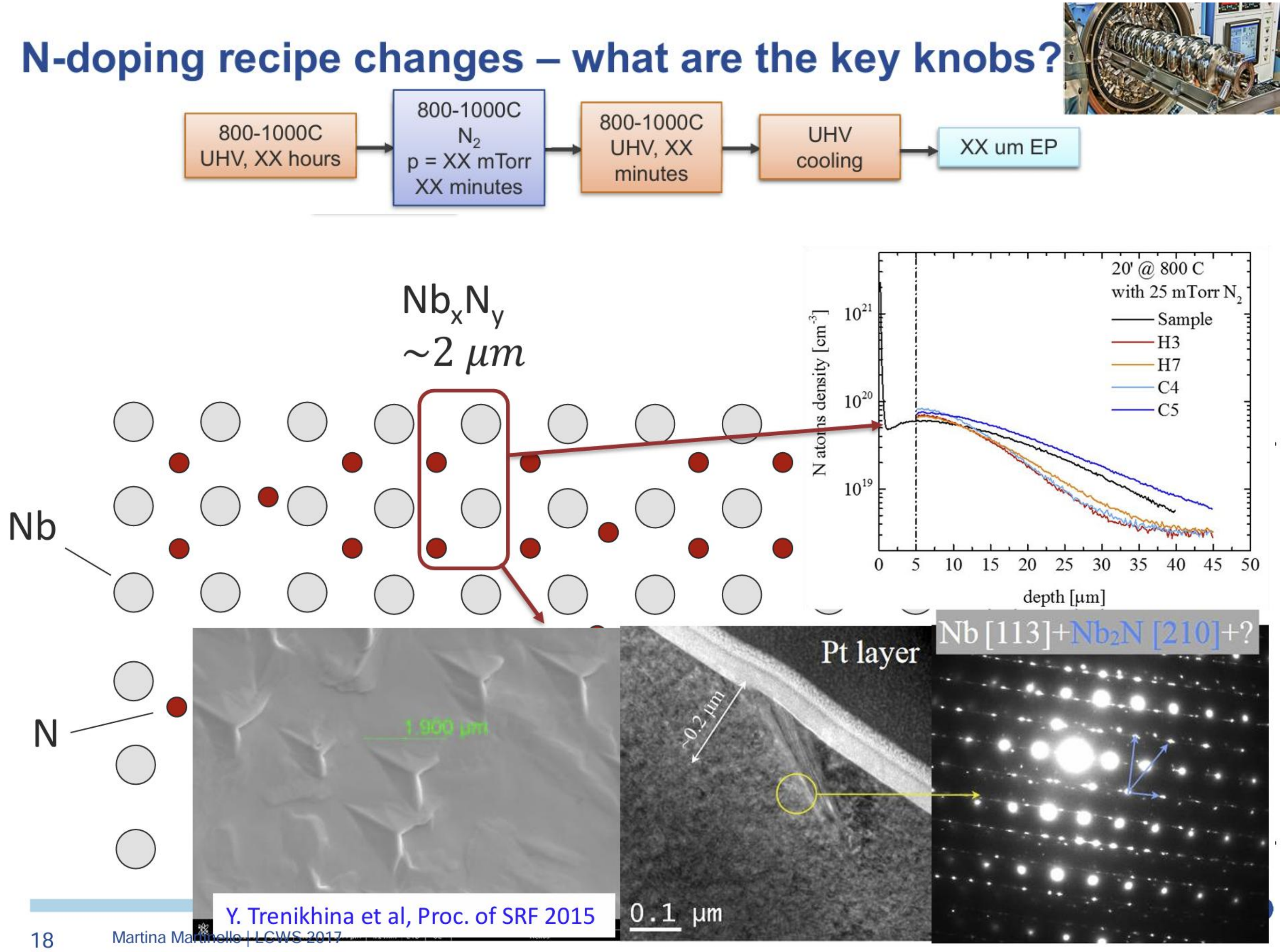


Average max Eacc = **27.3 MV/m**
Average Q0@20 MV/m = **3.3 E+10**

Understanding the Mechanism of High Q



Anna Grasselino, SRF2019



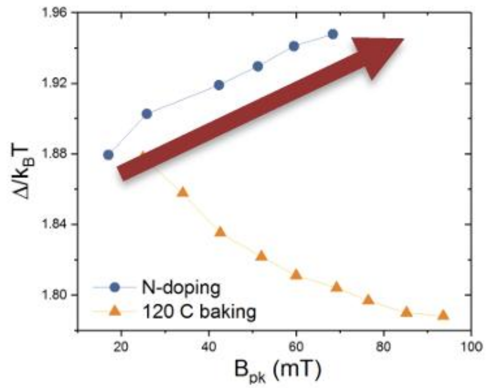
Mechanism of High Q

$$Q_0 = \frac{G}{R_s} = \frac{\omega_0 U}{P_d} \qquad R_S = A\, e^{-\frac{\Delta}{k_B T}} + R_{res}$$

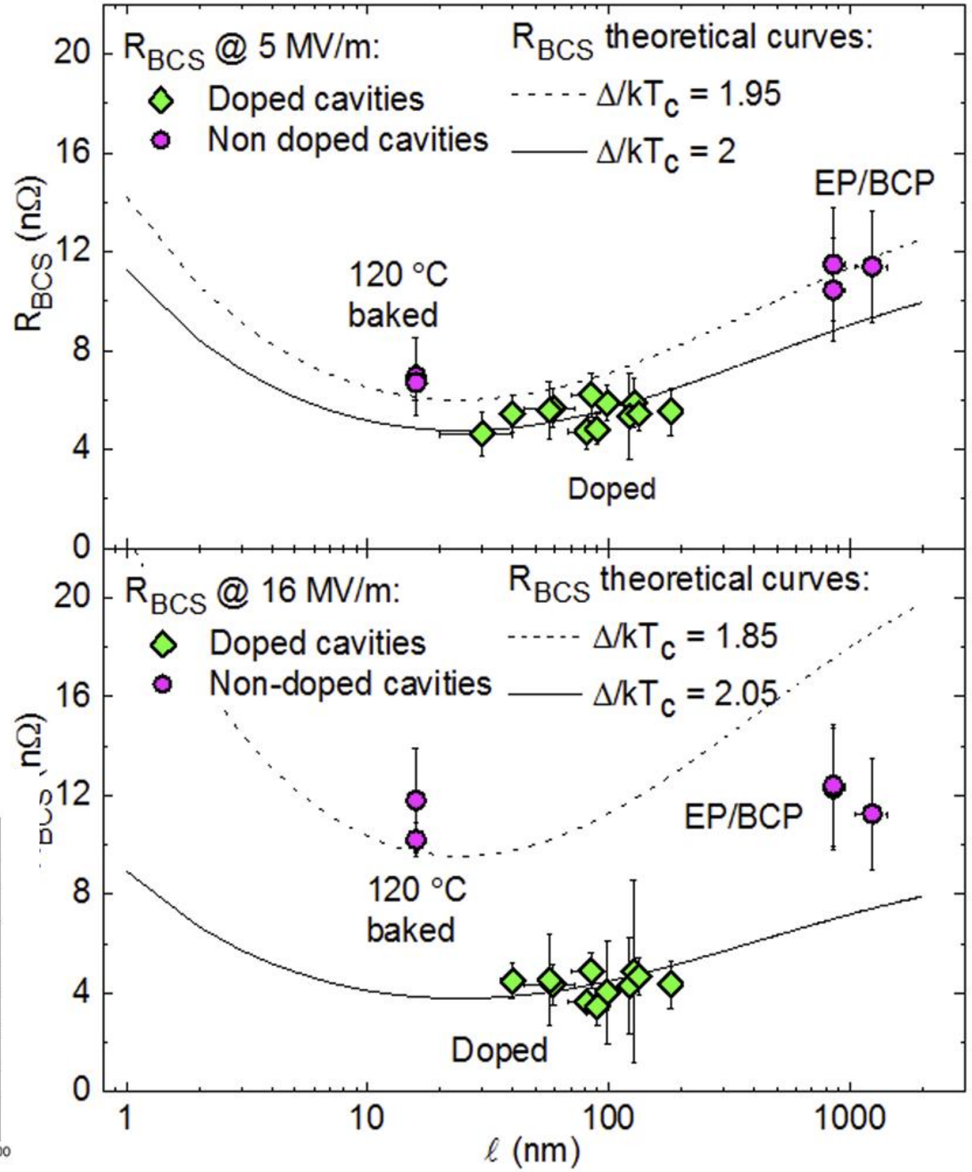
- Surface resistance decomposition:

$$R_S\,(2\,K) = R_{BCS}\,(2\,K) + R_{Fl} + R_0$$

1. $R_{BCS}\,(2\,K)$: BCS surface resistance at $2\,K$
2. R_{Fl}: Trapped flux surface resistance
3. R_0: Intrinsic residual resistance



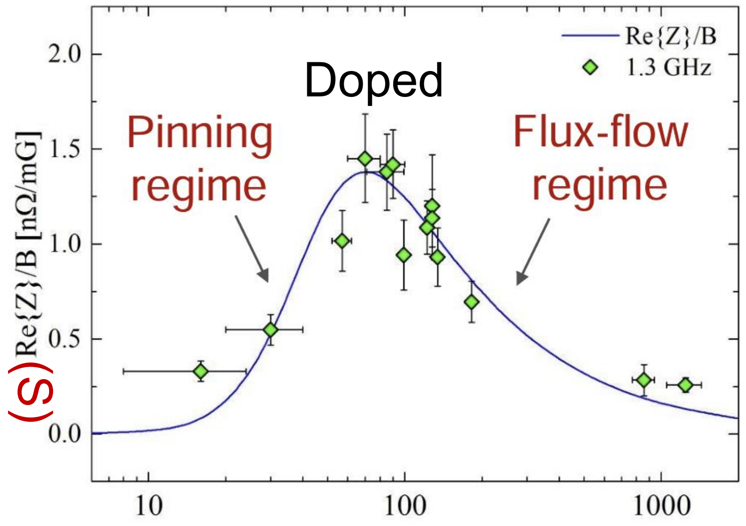
Martina Martinello -SRF2017

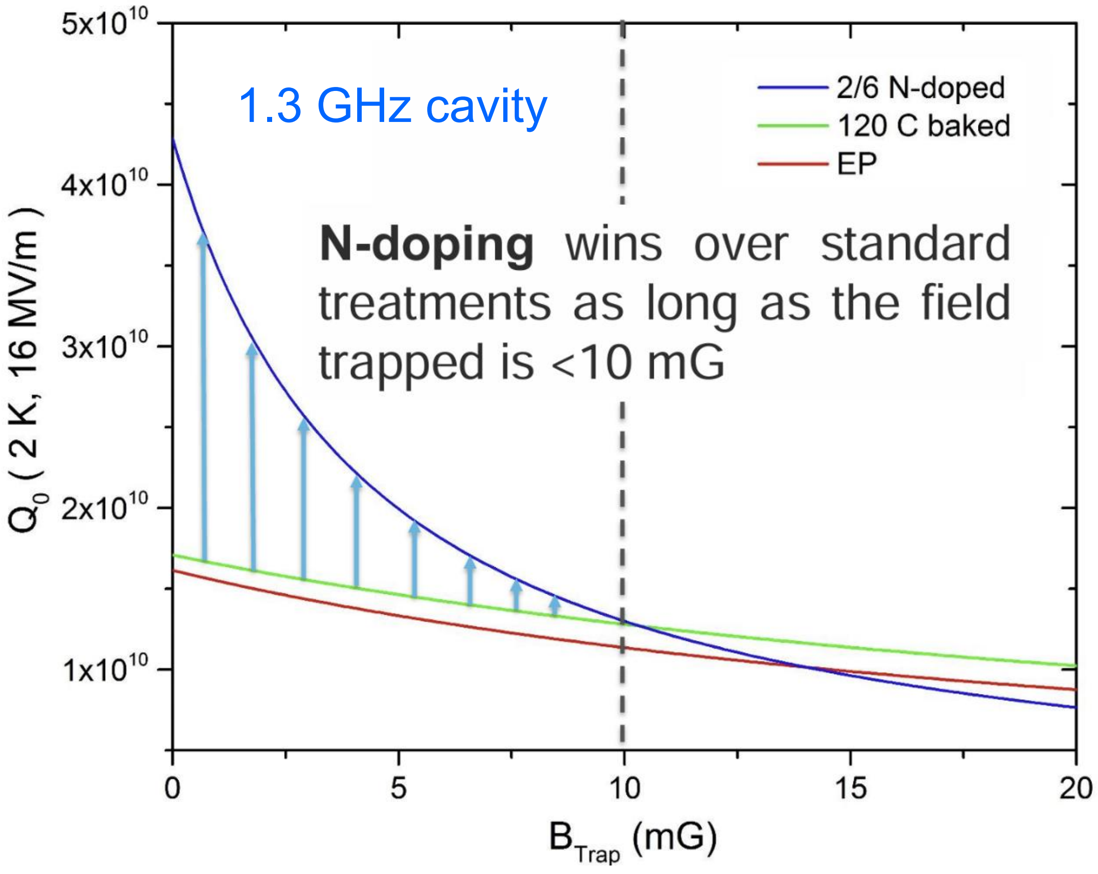


High-Q: Reducing Trapped Flux

$$R_S\,(2\,K) = R_{BCS}\,(2\,K) + R_0 + \boxed{R_{Fl}}$$

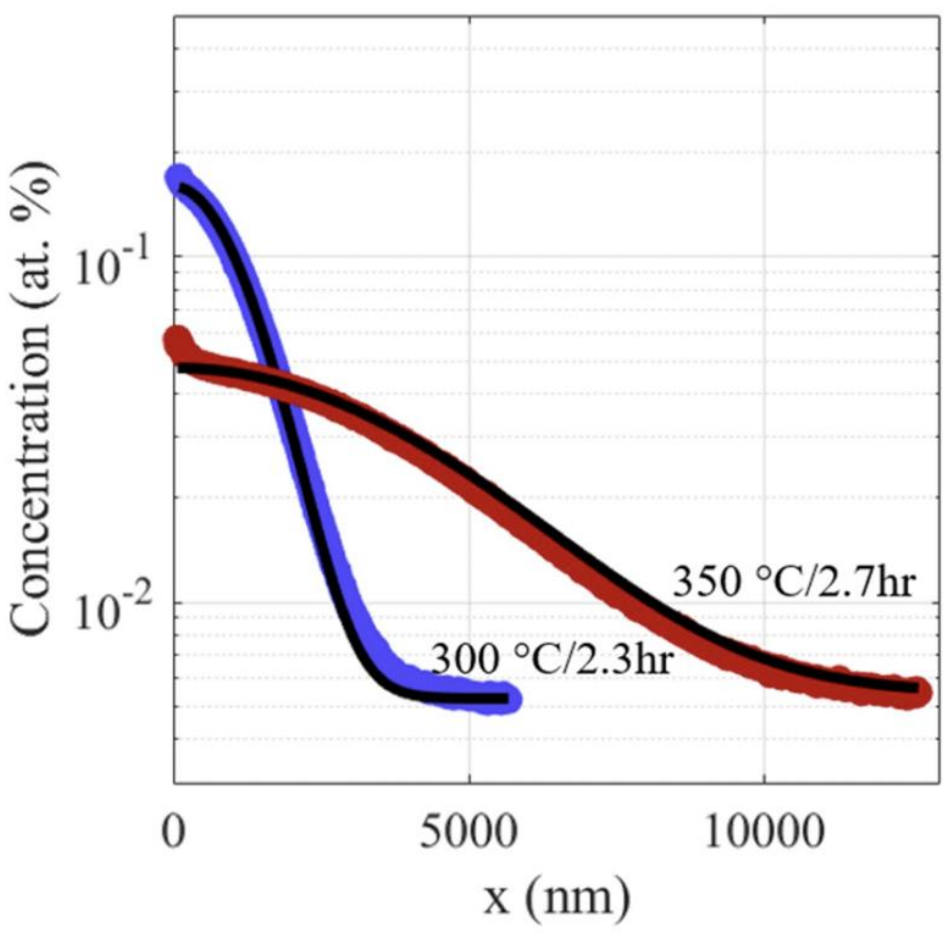
$$R_{Fl} = B_{trap} \cdot S$$





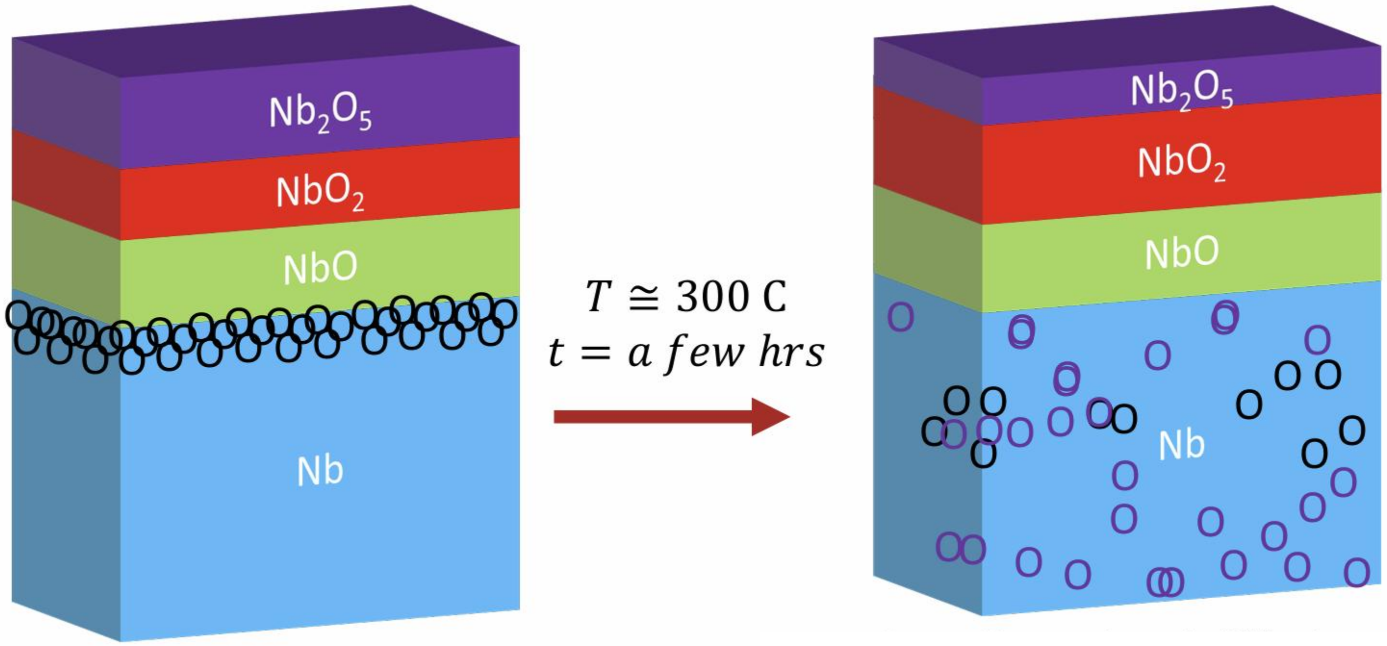
- **Methods:**
  - Reduce residual B (magnetic shielding, degaussing)
  - Enhance flux expulsion (cavity annealing at high temperature, fast cooldown)

Mechanism of High-Q (Mid-T)



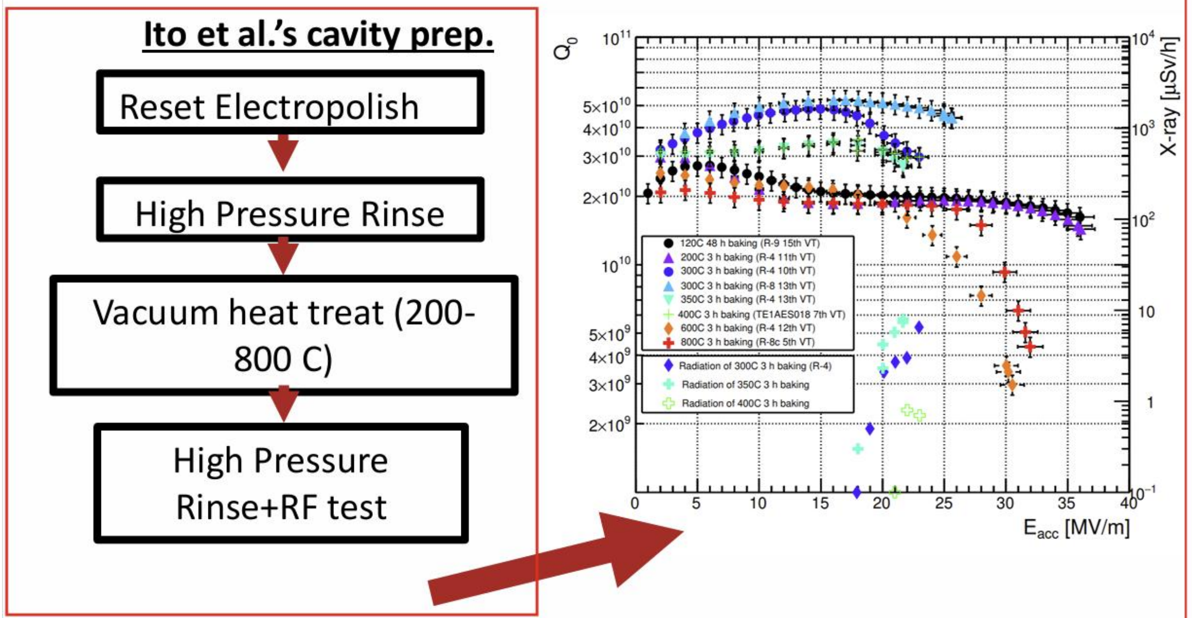
Eric Lechner, TTC2020

- Oxygen shown as major contributor at ~0.1 at %. A similar concentration of N in N doped cavities.

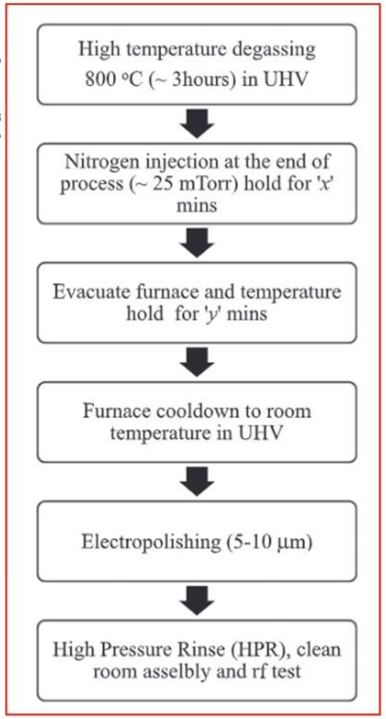


High-Q Recipes: N-doping and Mid-T Baking

[1] O-alloying

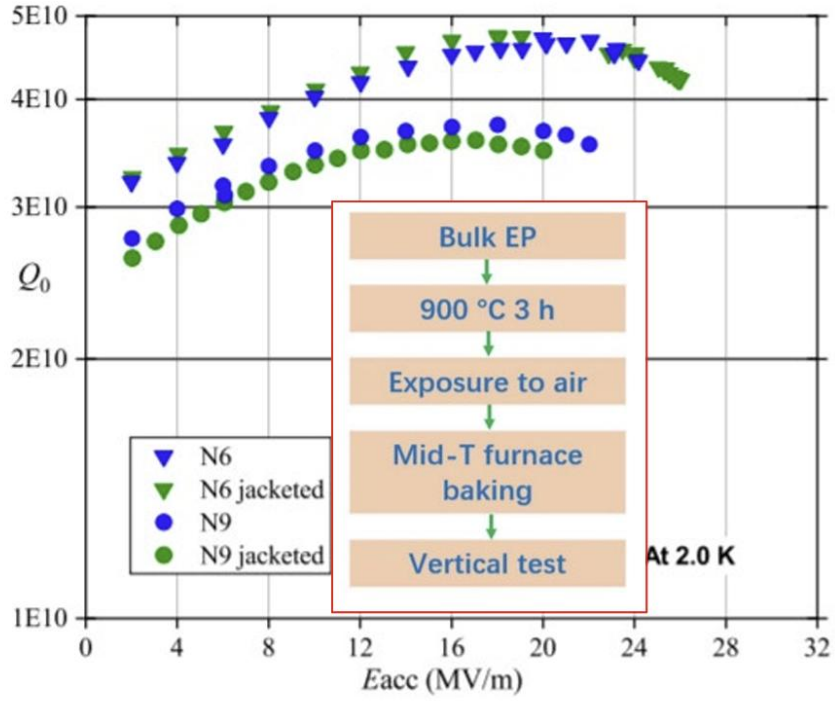


[2] N-doping



COMPLICATED!

[3] How simple can O-alloying get?



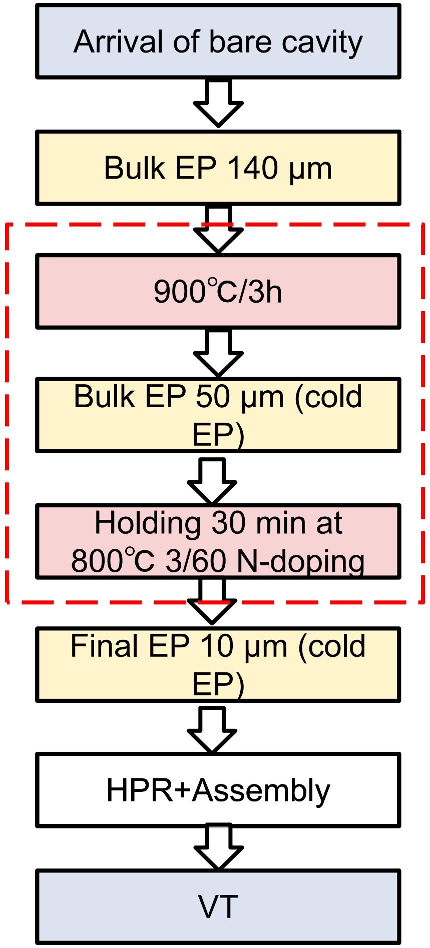
SIMPLE!

[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.

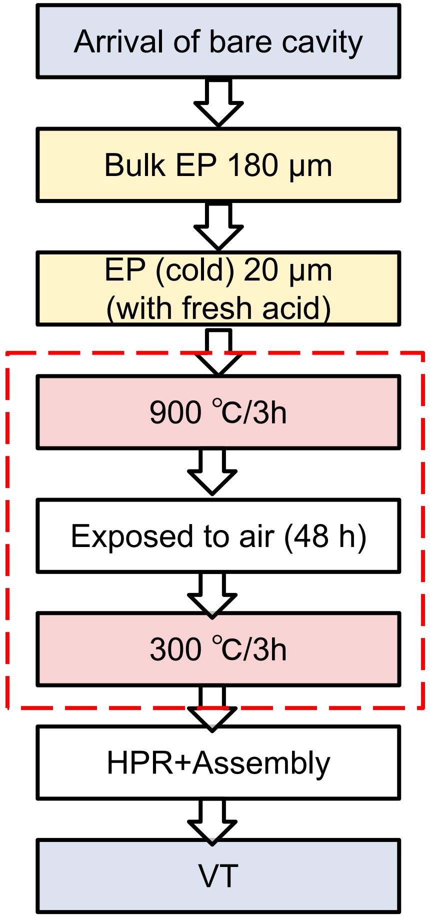
Eric Lechner, TTC2020

Cavity Surface Treatments for SHINE

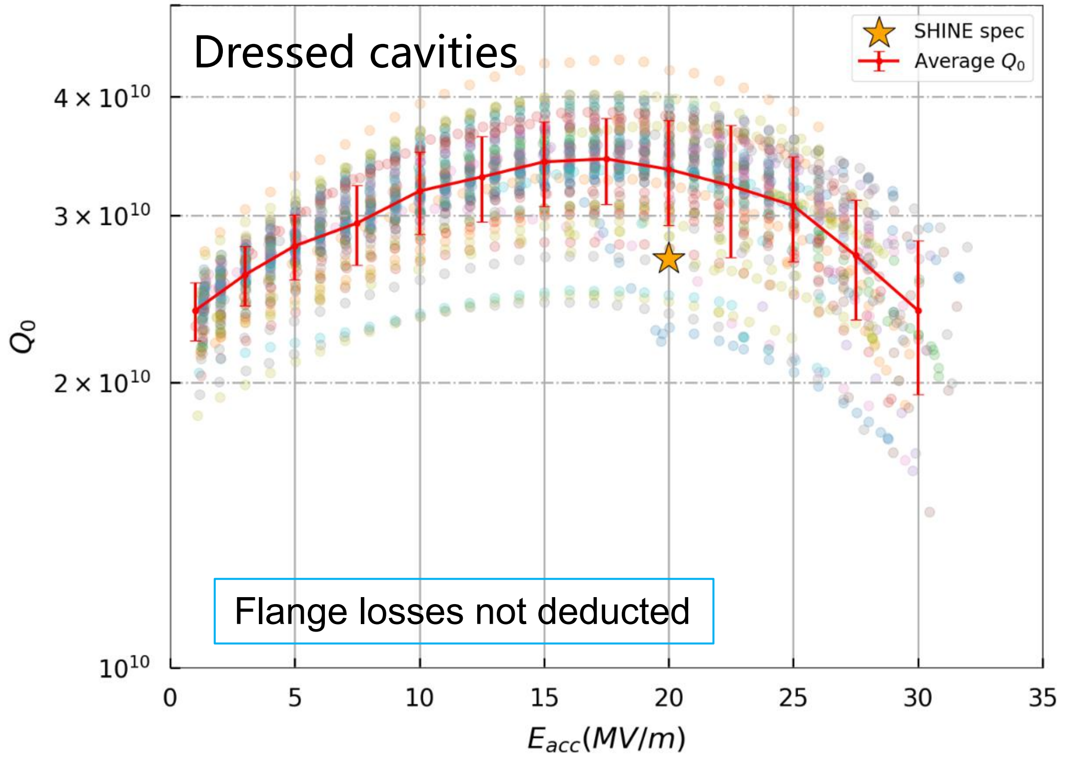
SHINE Nitrogen doping recipe



SHINE **Mid-T baking** recipe



SHINE Production – Mid-T VT results (87 cavities, July 2025)

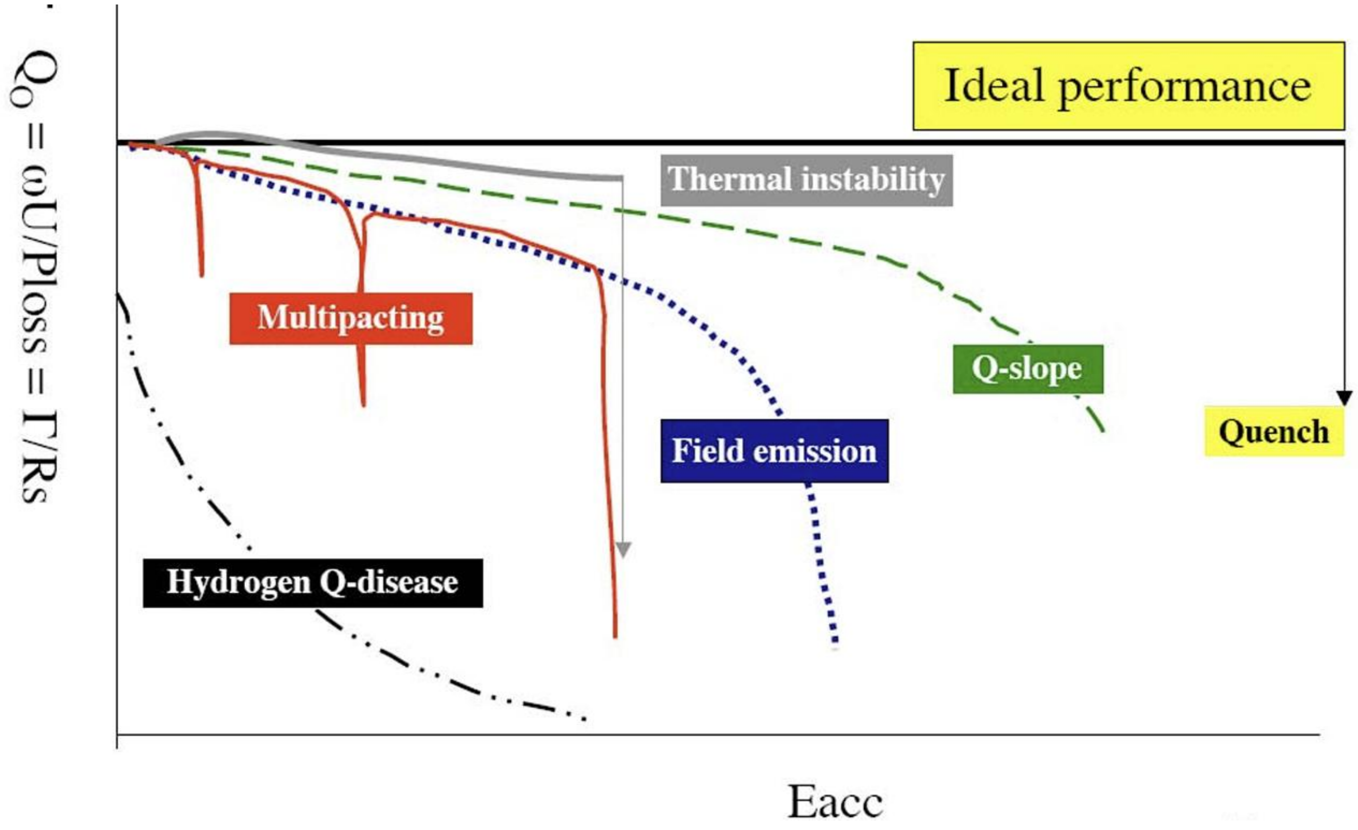


Average max Eacc = **27.3 MV/m**

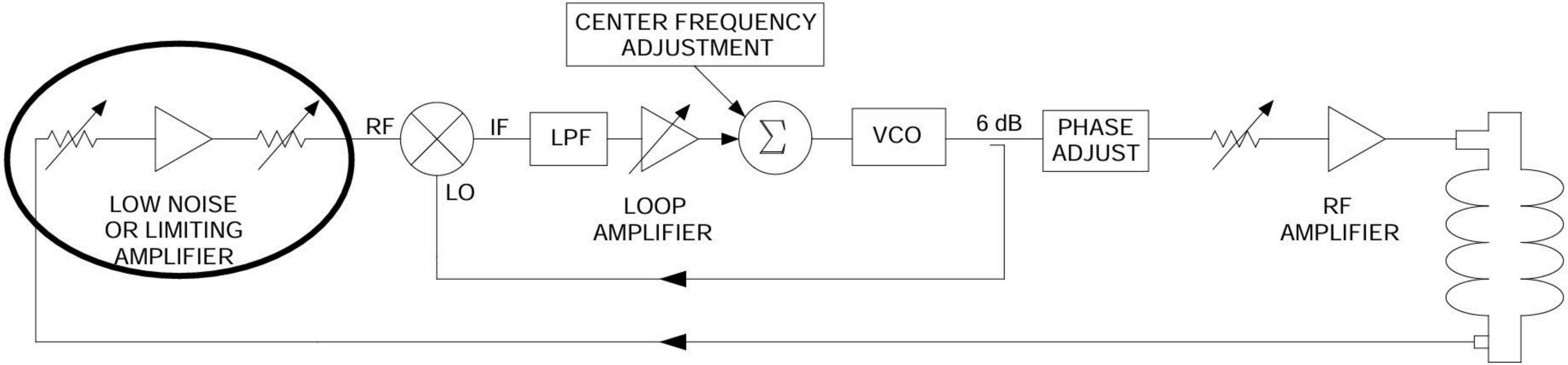
Average Q0@20 MV/m = **3.3 E+10**

Vertical test

- **Testing ensures cavities meet specifications for**
  - Accelerating Gradient
  - Qo
  - Field Emission onset (if present)
  - Measure resonant modes / passbands etc



Basic Scheme of Vertical Test



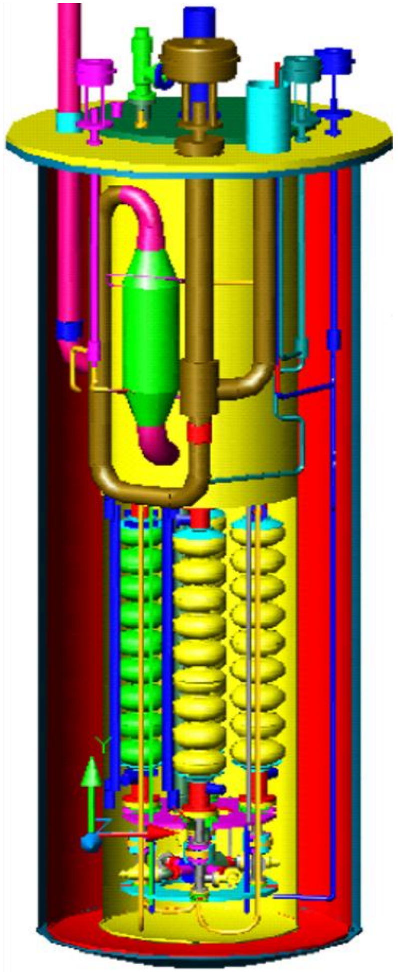
$$Q_0 = \left(1 + \frac{1 + cp\sqrt{P_{ref} / P_{fwd}}}{1 - cp\sqrt{P_{ref} / P_{fwd}}} \left(1 + \frac{P_{FP}}{P_{Disp}} \right) + \frac{P_{FP}}{P_{Disp}} \right) Q_L$$

This equation becomes more complicated if there are more than 2 ports on the cavity

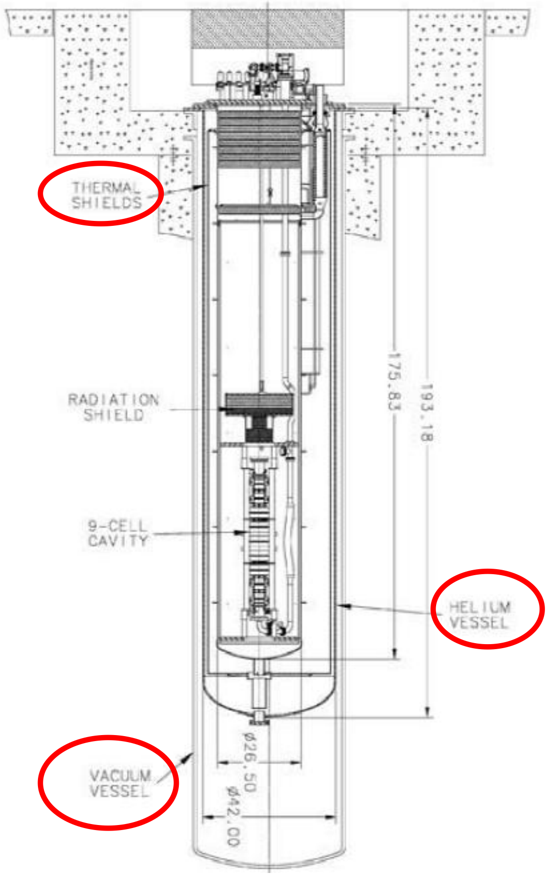
$$E_{acc} = \sqrt{Q_0 P_{Disp} \frac{(r/Q)}{L}}$$

Vertical Test Stands

Vertical TEST Infrastructure at DESY



Vertical TEST stand at FNAL



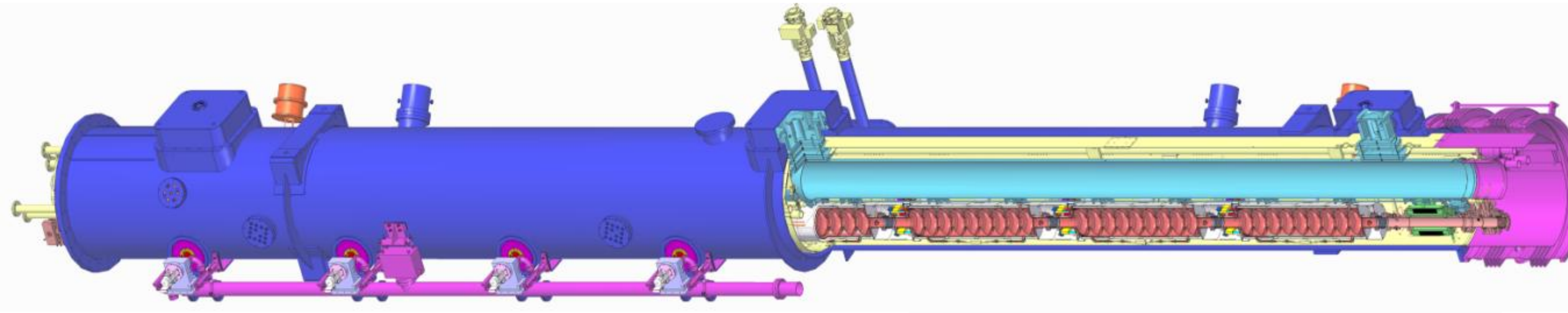
Vertical TEST stand at SHINE

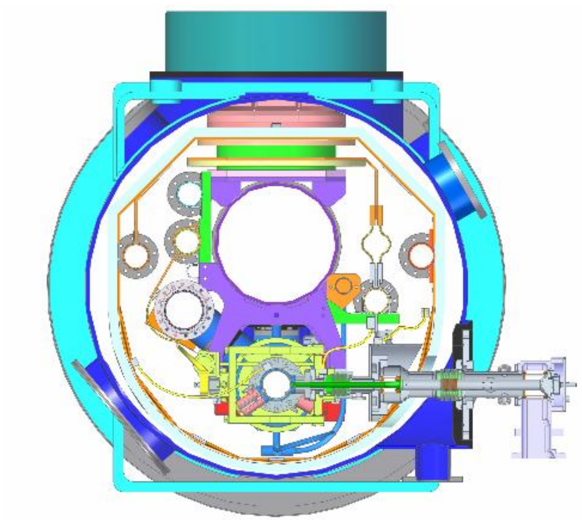
Outline

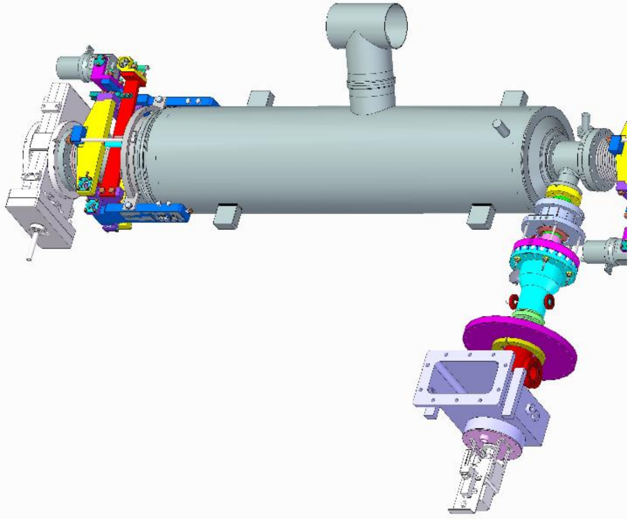
- Introduction
- Superconducting Accelerators in the World
- Tesla Cavity
  - Design
  - SC Material, Fabrication
  - Surface Treatment
  - RF Test
- Tesla Cryomodule
- Summary

TESLA-style Cryomodule

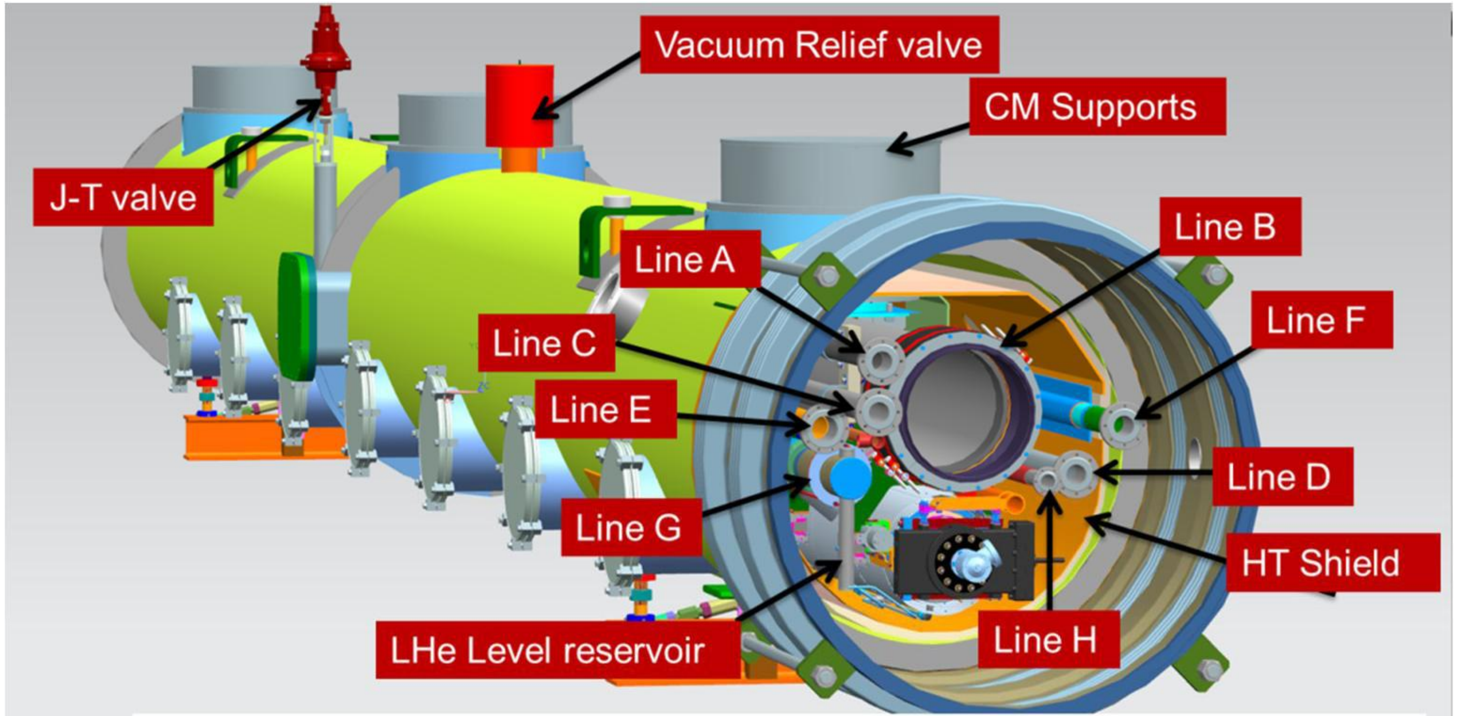
- **A TESLA-style cryomodule (CM)** houses eight superconducting cavities, one SC magnet and one cold BPM etc, providing cryogenic and vacuum condition, support and thermal insulation for the RF cavities;
- **Modified TESLA-style cryomodule** to accommodate CW mode operation, such as that for LCLS-II/HE, 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





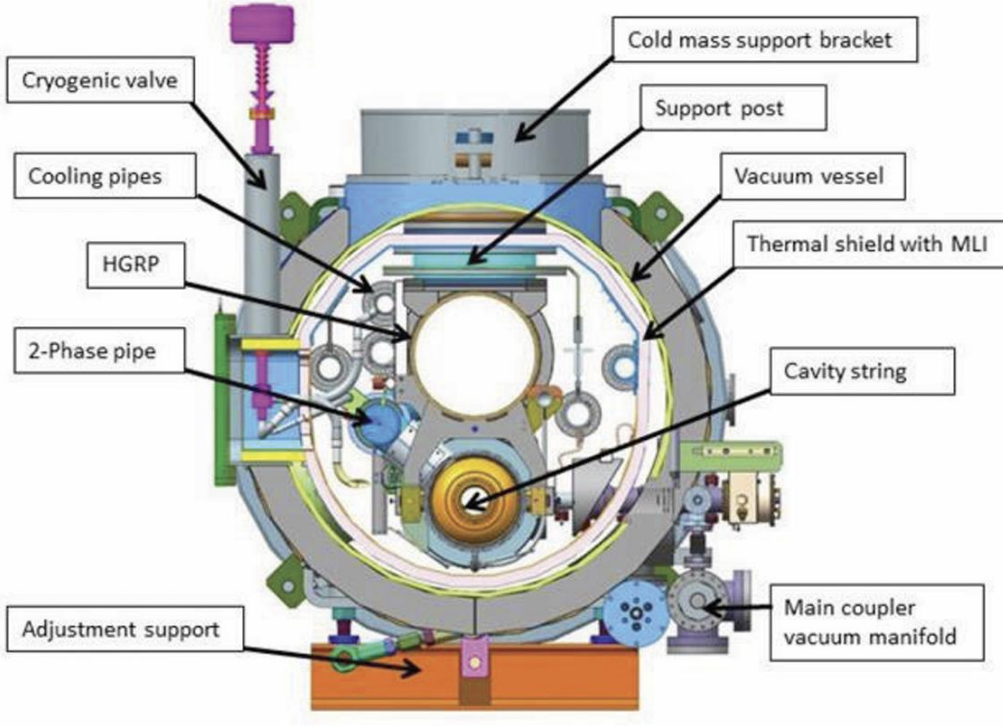


Cryomodule Structure



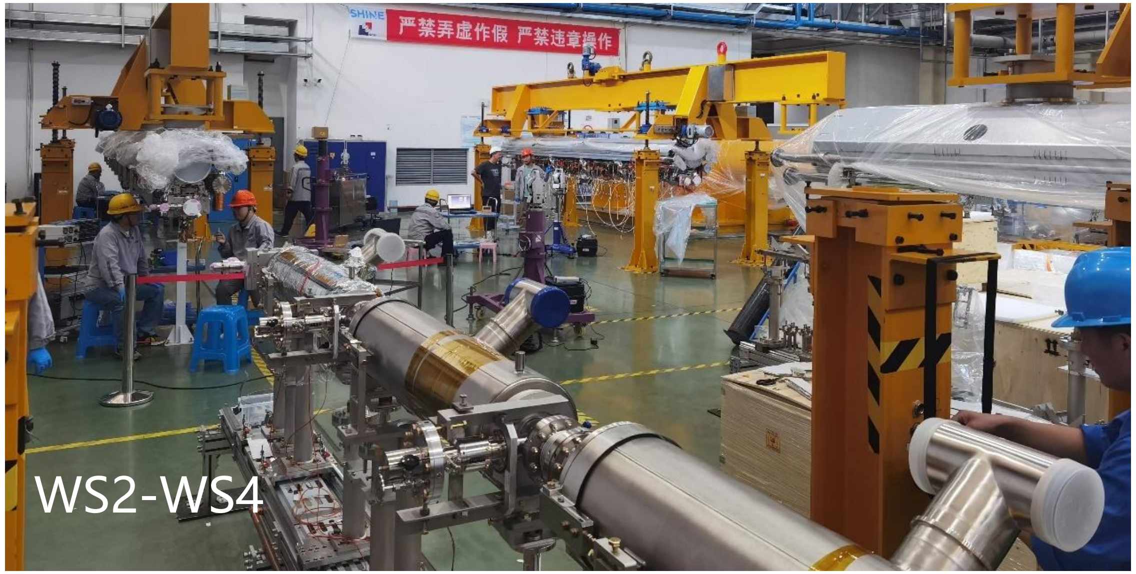
A. 2.2 K subcooled supply
B. Gas return pipe (GRP)
C. Low temperature intercept supply
D. Low temperature intercept return
E. High temperature shield supply
F. High temperature shield return
G. 2-phase pipe
H. Warm-up/cool-down line

LCLS-II Director's Review, August 19-21, 2014

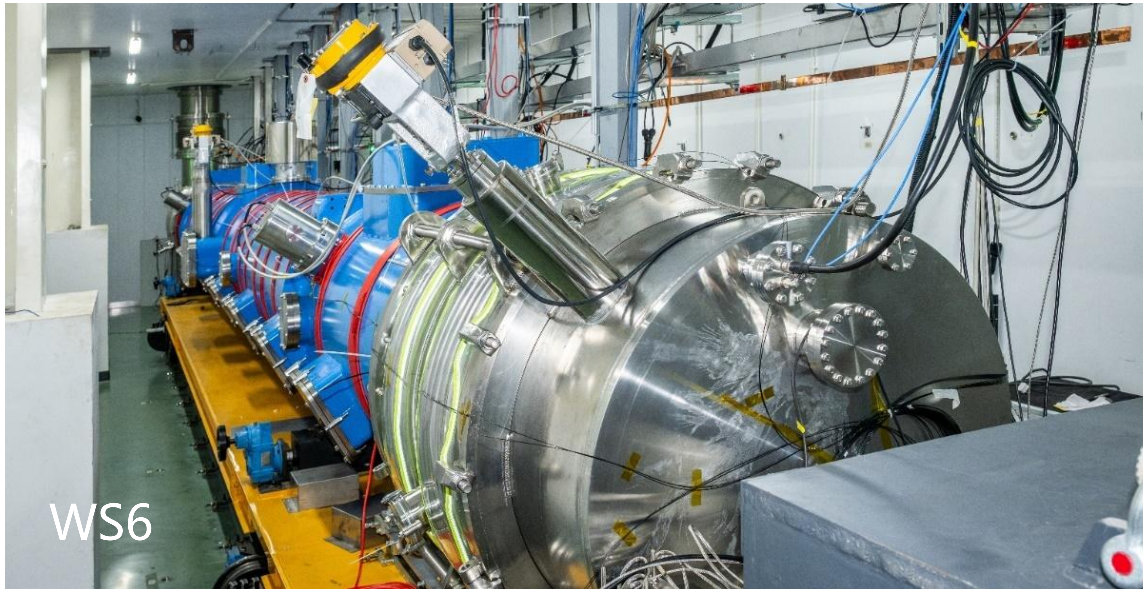


CM assembly


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


严禁弄虚作假 严禁违章操作
WS2-WS4


WS5


WS6

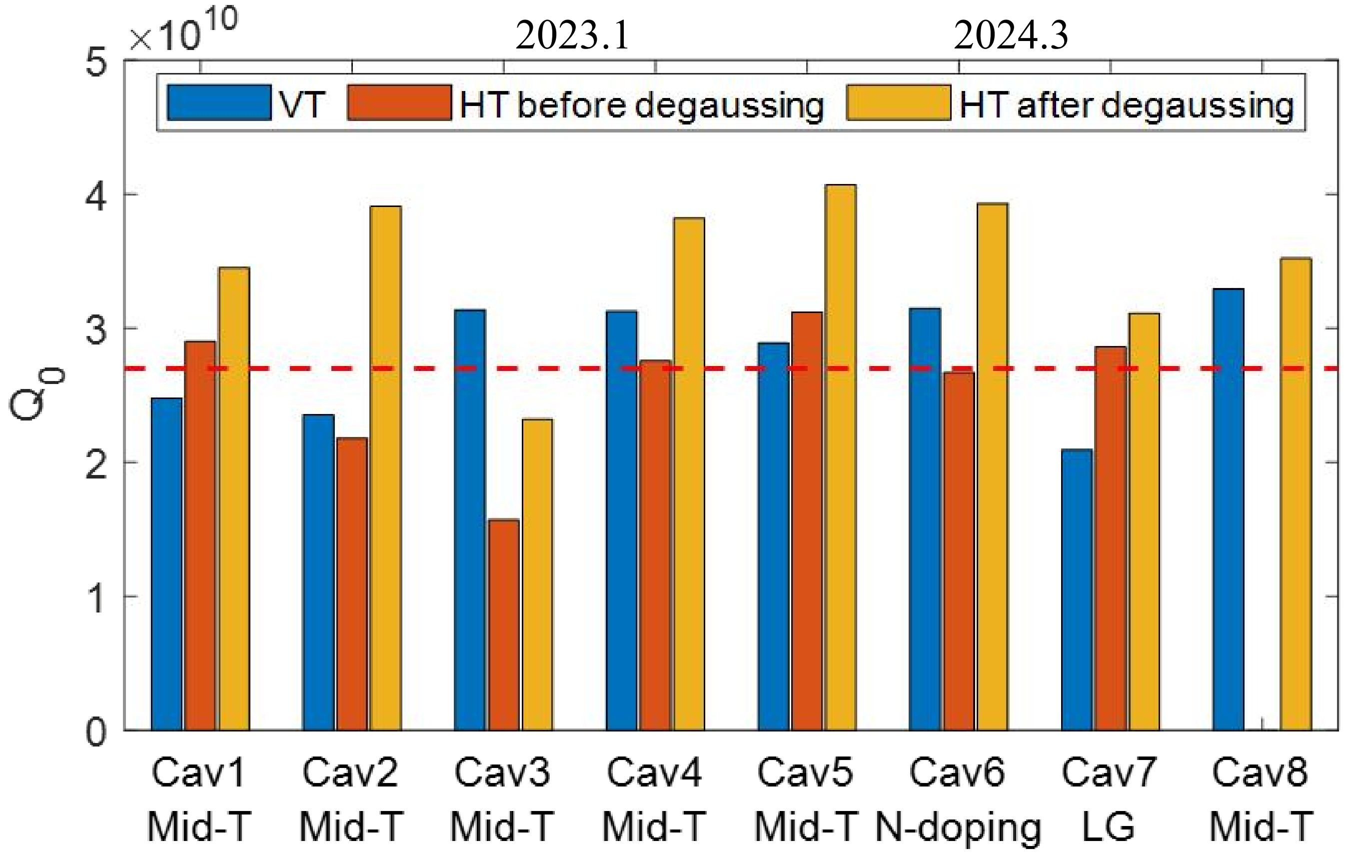
Degaussing of the SHINE Prototype High-Q CM

- After CM degaussing, average Q_0 improved from 2.4 to 3.0 E+10 (~20%).

Ten single-axis fluxgates readings inside and outside cavity He-tank:

10 mGs before degaussing

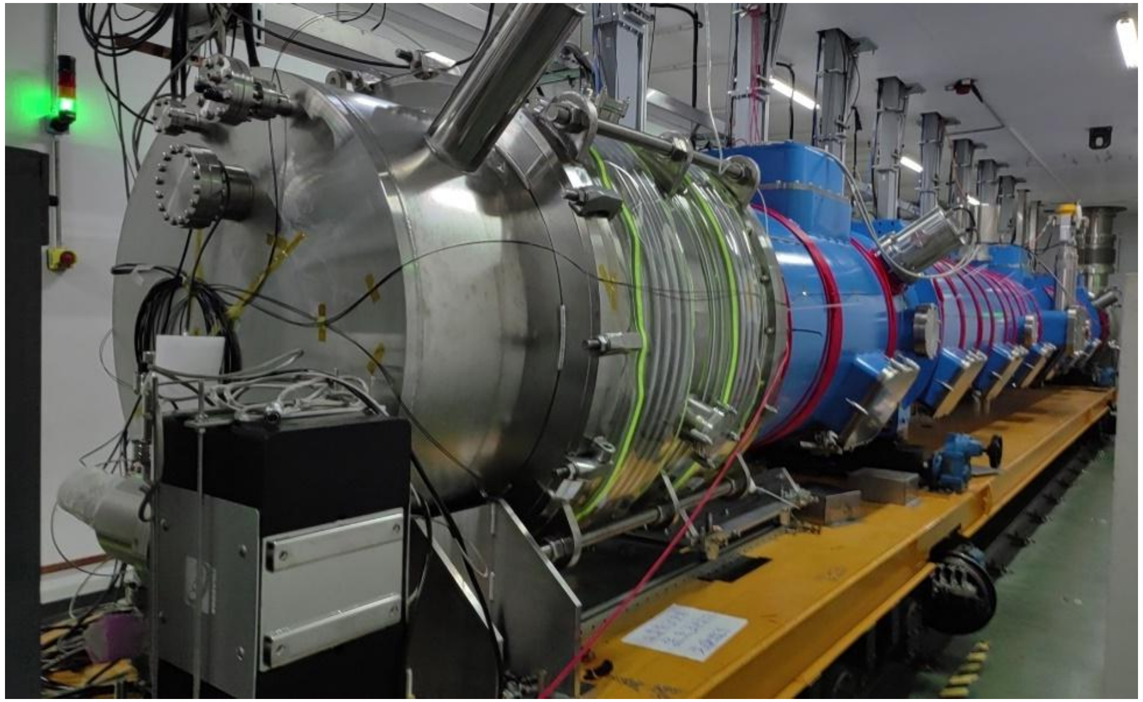
1 mGs after degaussing



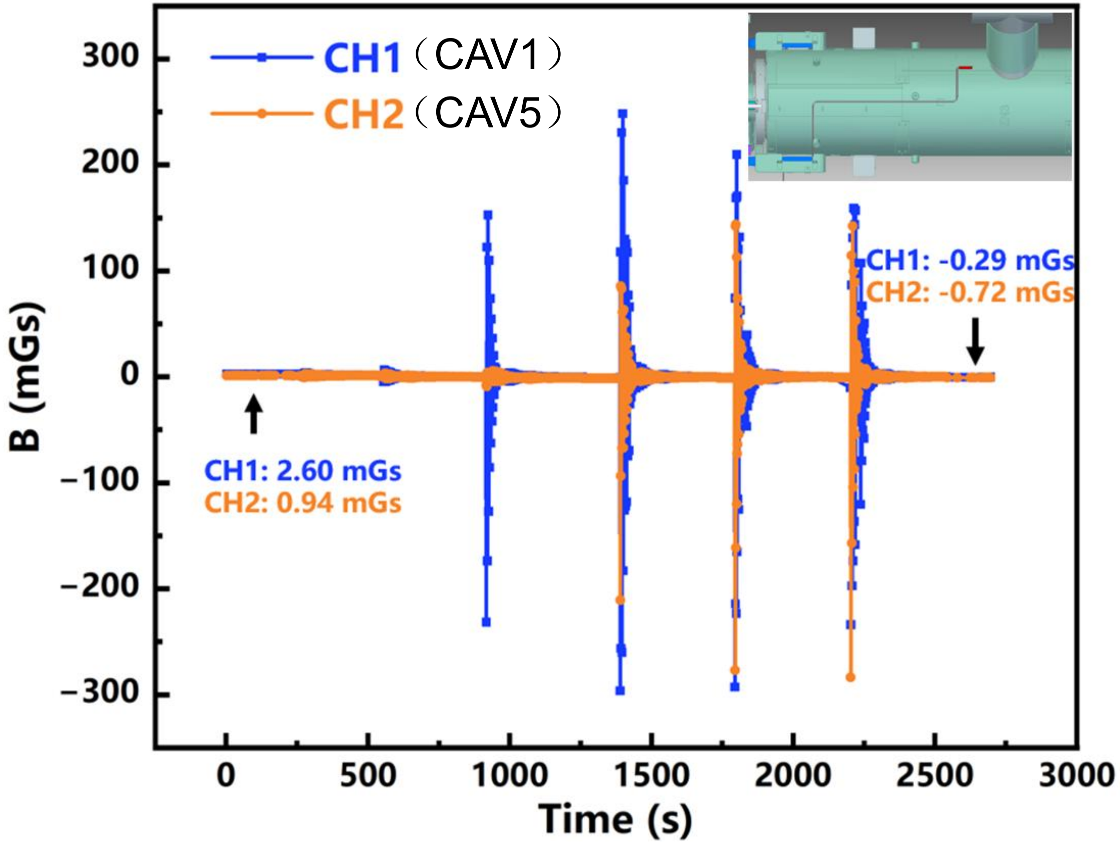
2024.3, Q_0 measurements: **3.0×10^{10}** @135MV

Degaussing for SHINE High-Q CM

- **In-situ degaussing was performed at HT stand before cooling down or at 45 K**
- **Less than 1 mGs can be achieved**



SHINE CM03

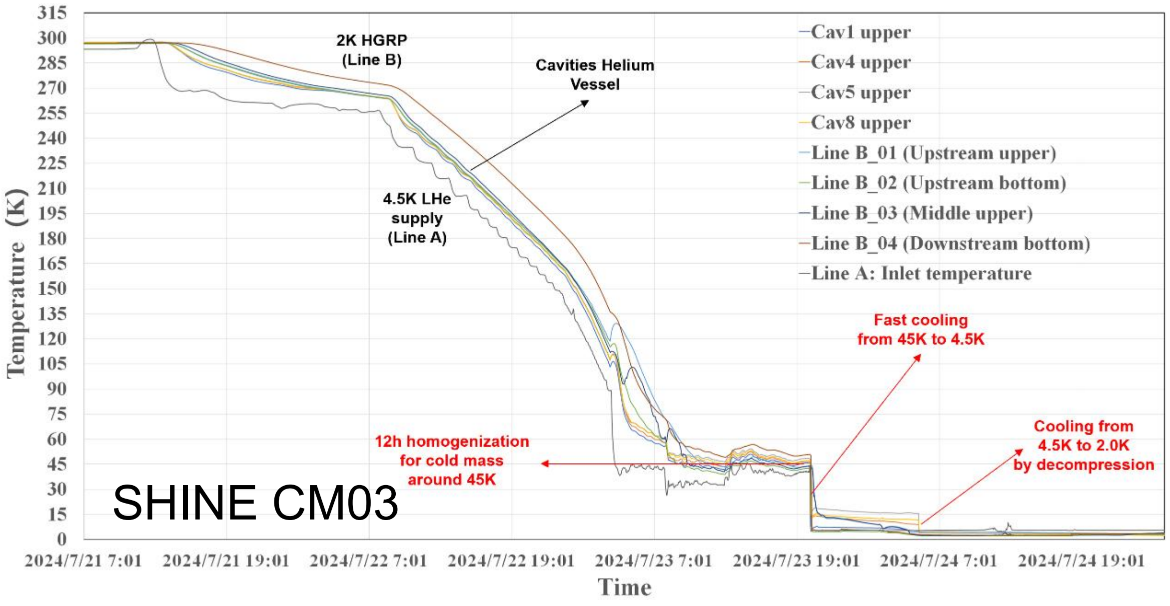


Degaussed at room temperature

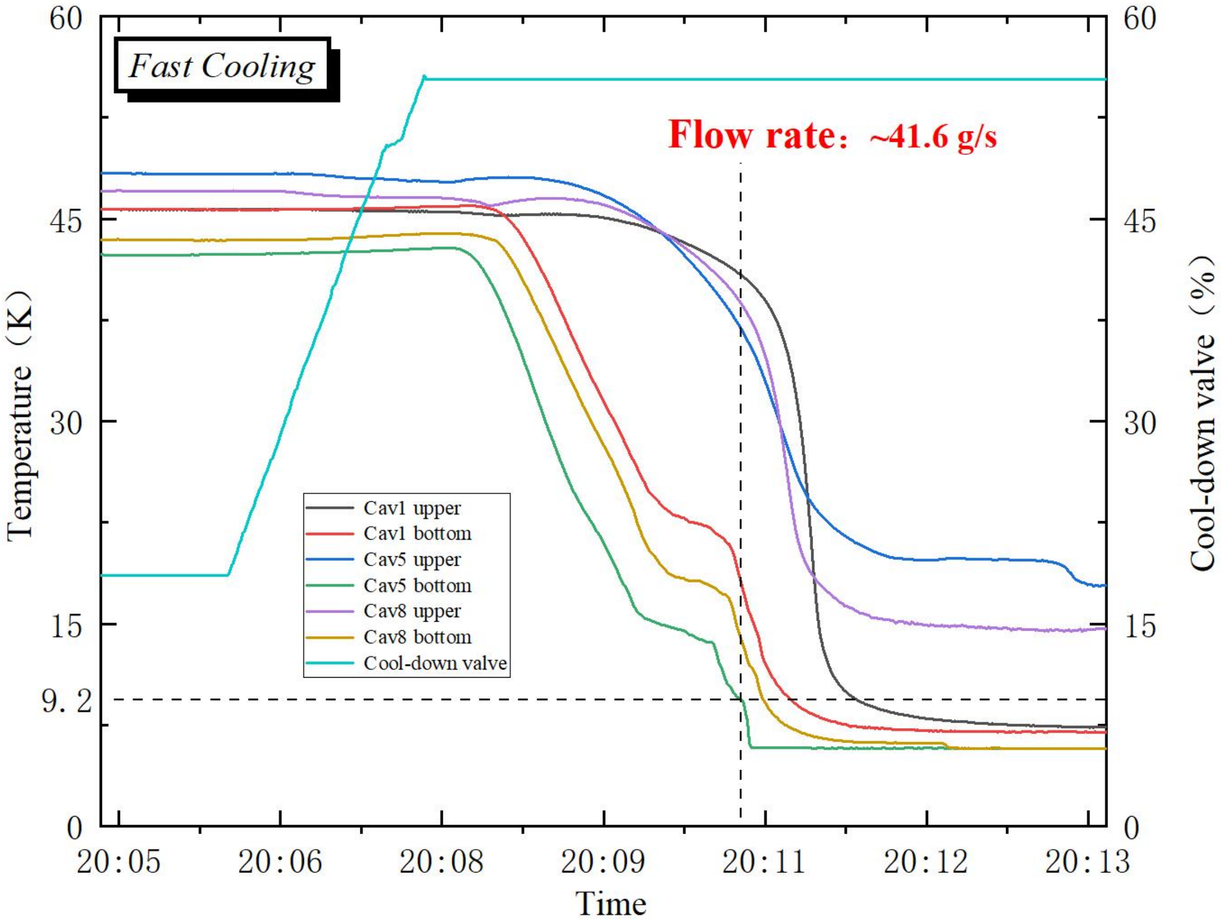
Cooling Down for High-Q CM

Example: SHINE CM03-MT

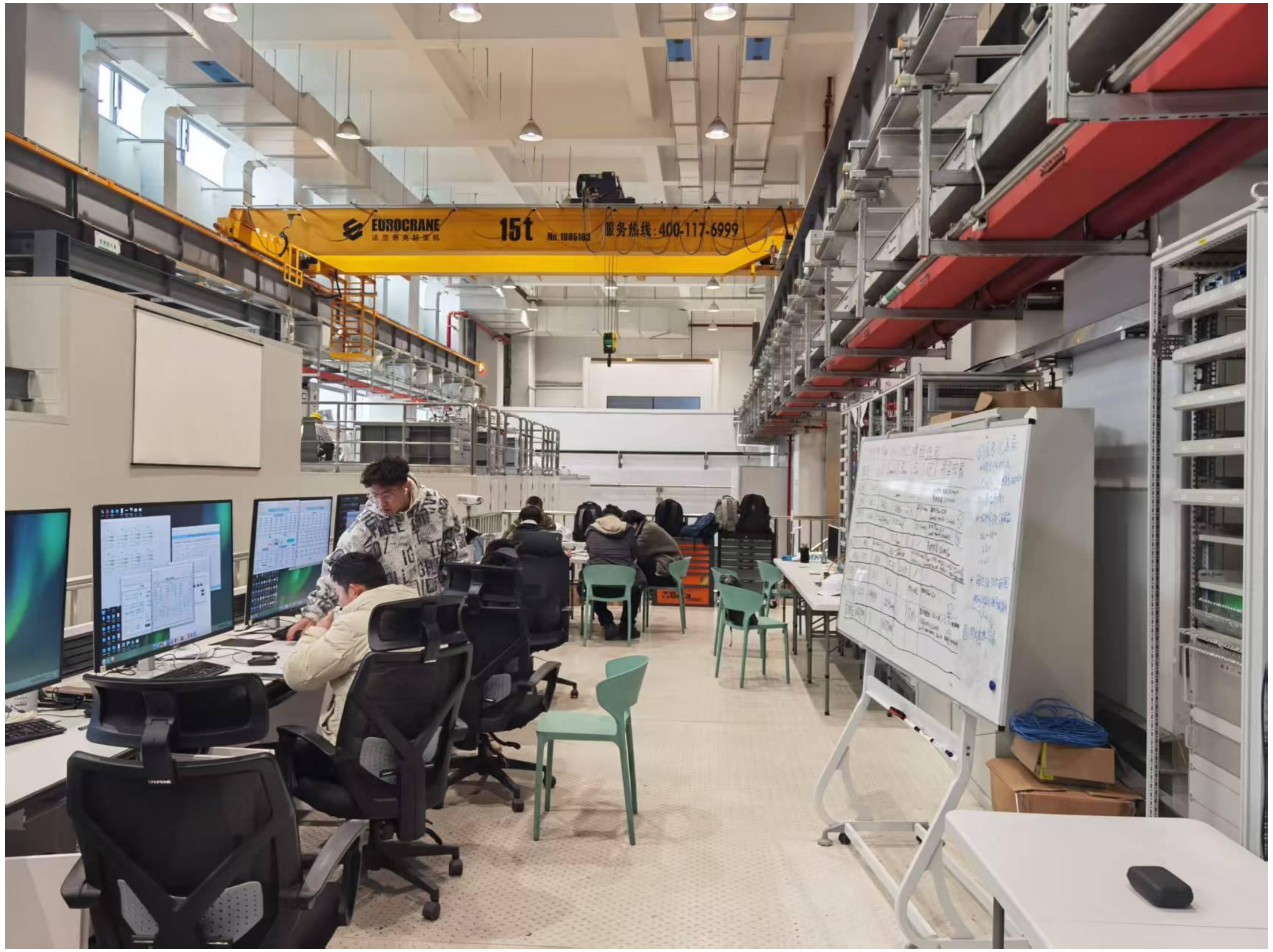
- **From 300 K to 45 K, average cooling rate ~ 6 K/h, followed by 12 h homogenization**
- **From 45 K to 4.5 K, fast cooling with a He flow rate ~41.6 g/s for flux expulsion**



T-sensors mounted outside of He-tank



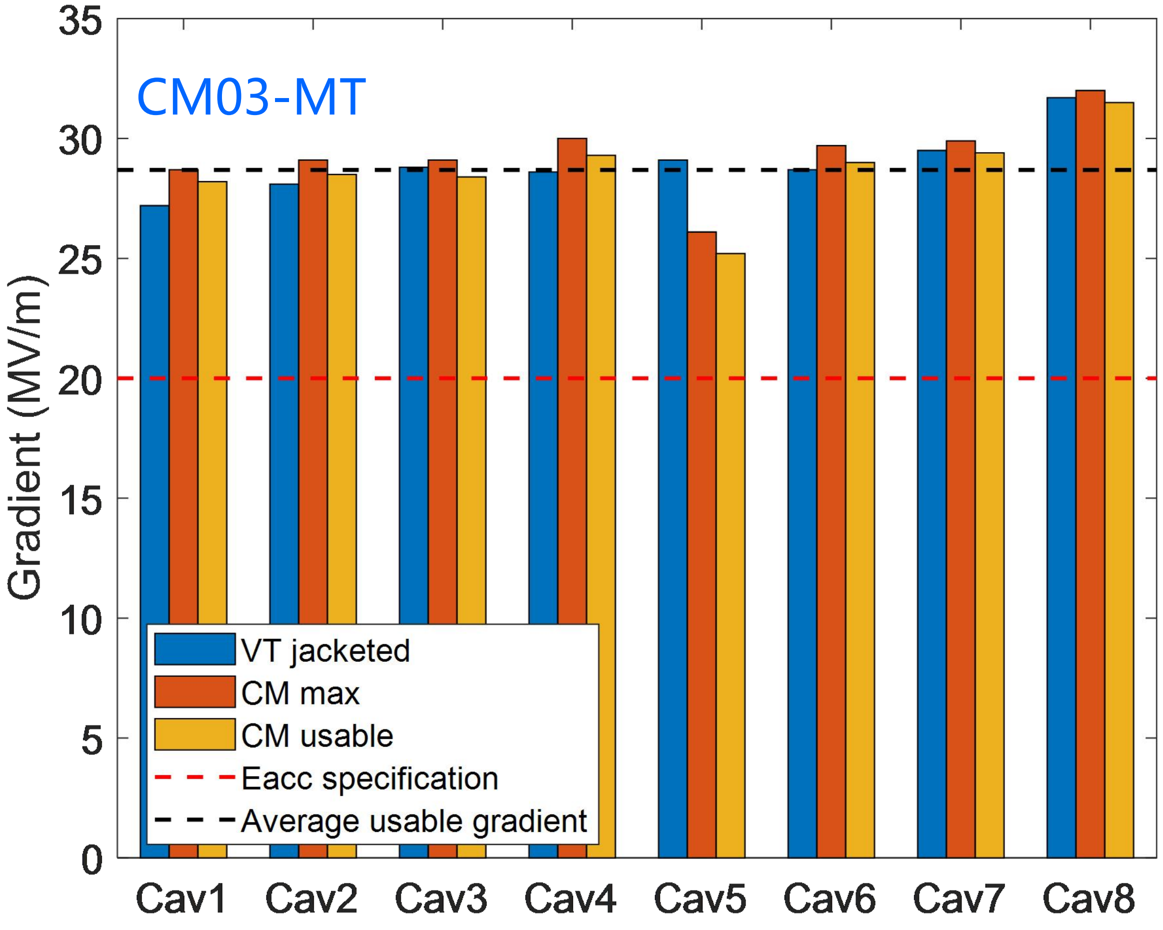
Cryomodule Horizontal Test



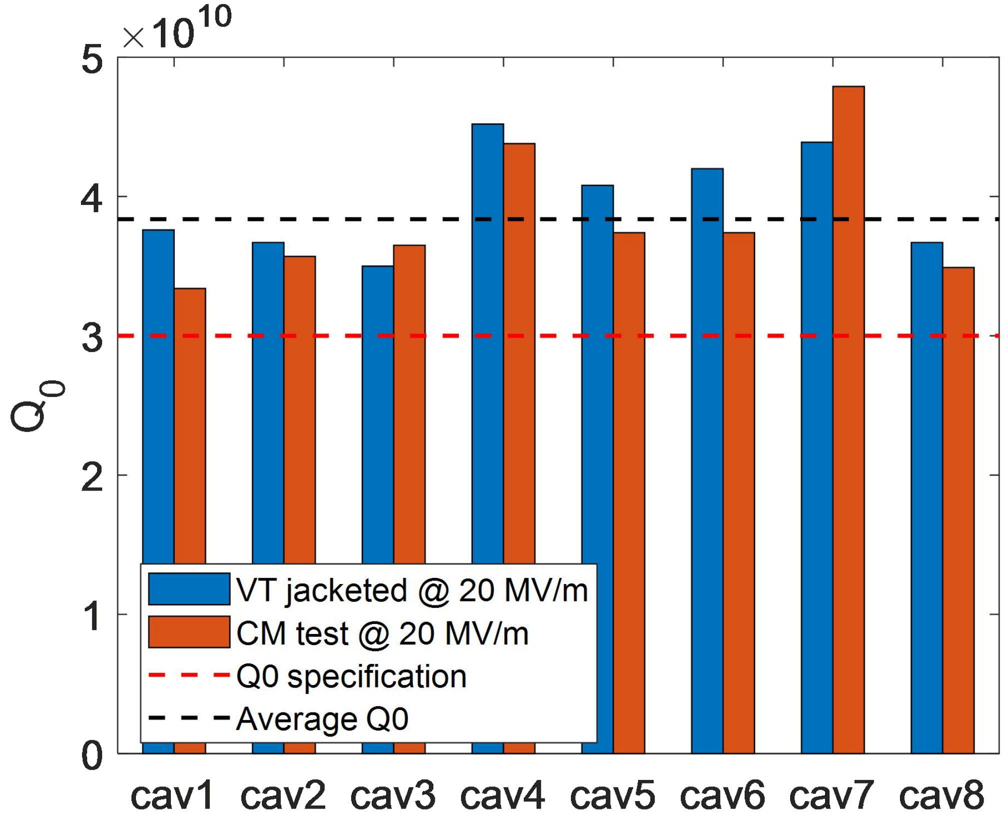
Horizontal Test Results

- **Example: SHINE CM03**

Almost full gradient maintained from VT to HT, except cav5, which is limited by HOM heating. FE Free.

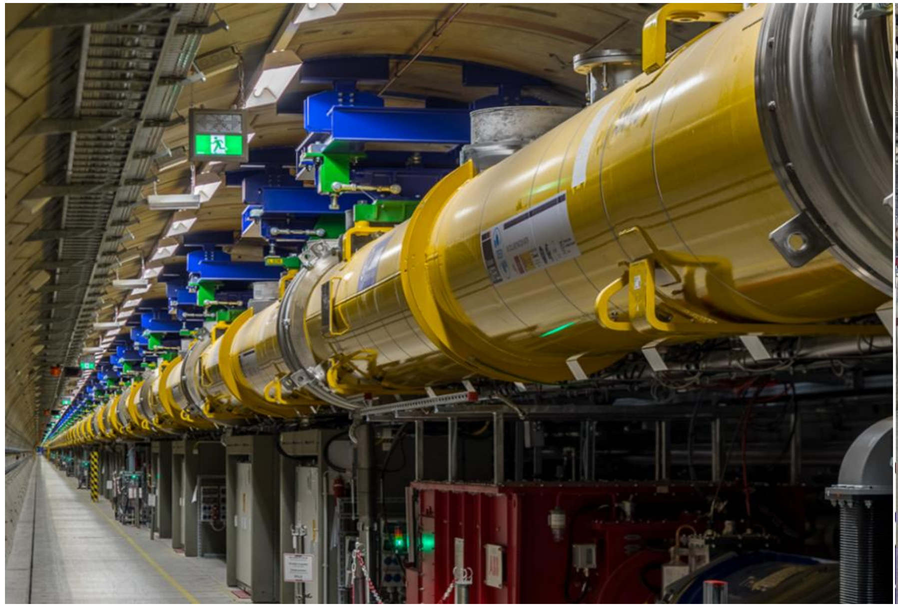


Almost full Q_0 maintained from VT to HT

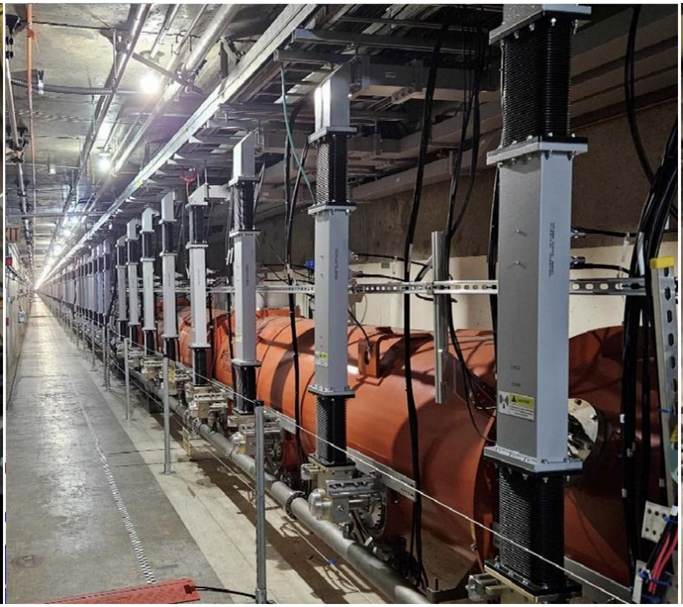


CMs installed in Superconducting Linacs

E-XFEL



LCLS-II/HE



SHINE

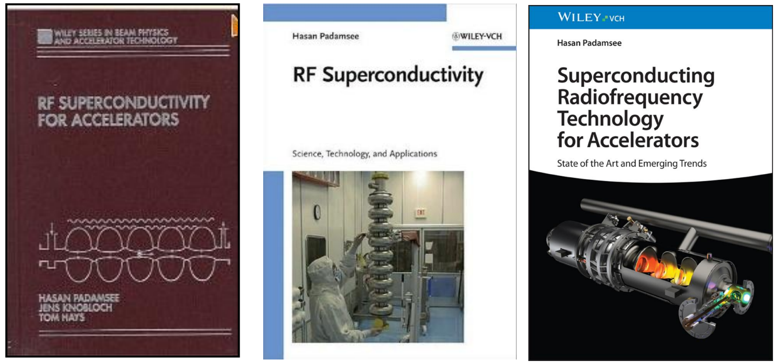
Beam commissioning, operation

Outline

Summary - Questions you may answer

- **Why superconducting RF (SCRF)?**
- **What are the types of SCRF cavities? and their functions?**
- **How to design and fabricate a SCRF cavity?**
- **How the surface treatments can improve cavity RF performance?**
- **How to preserve cavity high performance in cryomodule?**

More information: SRF text book and proceedings



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)

JACoW.org

4. Proceedings of all SRF conferences:
https://www.jacow.org/Main/Proceedings?sel=SRF#SRF

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Thanks for your attention!