



Superconducting accelerator

ISBA26

2026/10/21

KEK iCASA Kensei Umemori



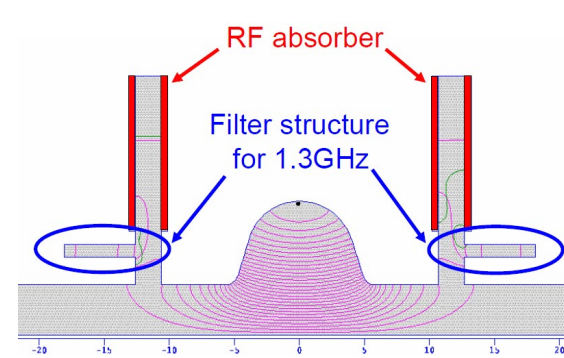
Outline



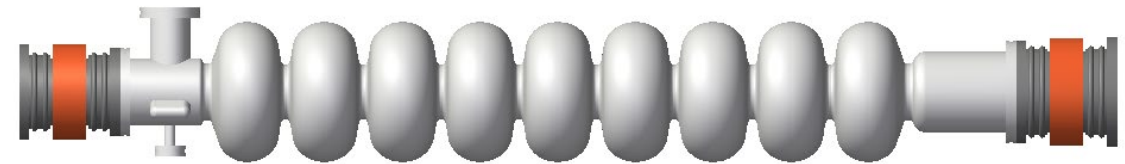
- Superconducting cavity
 - Introduction
 - Pillbox cavity and mulch-cell cavity
 - Performance limitation
 - Basic RF parameter
- Surface treatment for higher performance
 - Surface treatment and hydrogen
 - Various high-Q/high-G surface treatment
- Cryomodule
 - Cryomodule design
 - Cryomodule components
- Superconducting accelerator
- Future challenge
- Summary

Introduction of myself

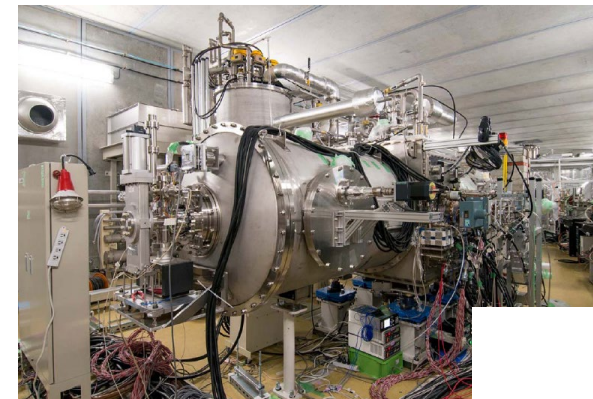
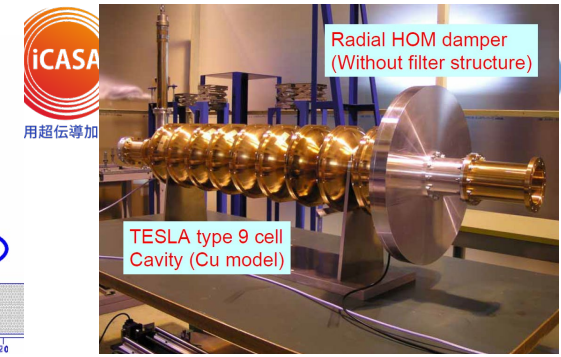
- Starting job at **KEK Photon Factory (2002)**
 - Normal conducting 500 MHz cavity
 - R&D for future project of ERL light source
- Design and development of **cERL main linac cavity/CM**
 - Design and fabrication of HOM damped 100mA CW main linac cavity
 - Construction and operation of cERL main linac cryomodule
- **High-Q/High-G study** for CW SRF cavity
 - N-doping, flux expulsion, mid-T baking (high-Q)
 - N-infusion, 2-step baking (high-G)
- Development of **ILC prototype CM**
 - One prototype CM fabrication in under going



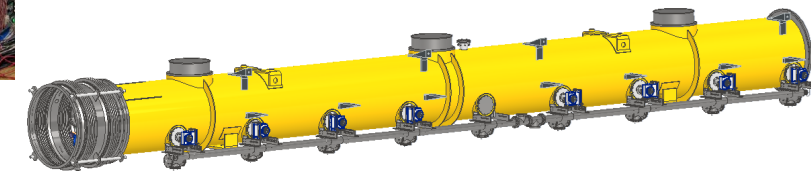
Radial HOM damper (My first work...)



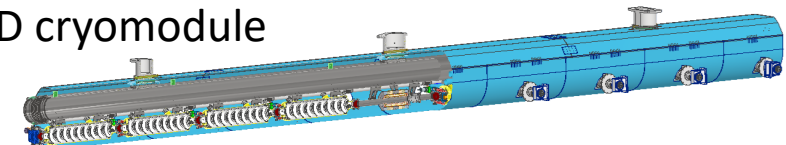
Design of cERL main linac cavity



cERL main linac cryomodule



ITN/MEXT-ATD cryomodule
(from T. Hara)



ISBA26, Super conducting accelerator

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Typical SRF cavity

- Used for acceleration of particle with (mostly) speed of light
- Normally made by Nb



Variety of SRF cavities are under operation.

- 350 MHz, 500 MHz, 650 MHz, 1300 MHz, 1500 MHz, 2600 MHz, 3900 MHz, etc.
- 1-cell, 2-cell, 4-cell, 5-cell, 6-cell, 7-cell, 9-cell, etc.
- Nb, Nb coating on Cu

Elliptical cavity

Photo:
Reidar Hahn



Elliptical cavity – the *de facto* standard for SRF

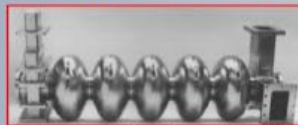
FERMI 3.9 GHz



S-DALINAC 3 GHz



CEBAF 1.5 GHz



HEPL 1.3 GHz



CESR 0.5 GHz



KEK-B 0.5 GHz



TESLA/ILC 1.3 GHz



SNS $\beta = 0.61, 0.81, 0.805$ GHz



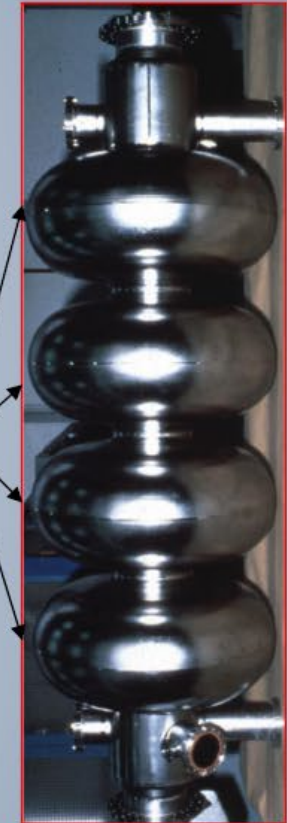
HERA 0.5 GHz



TRISTAN 0.5 GHz



LEP 0.352 GHz



cells

Low- β cavity

SRF2009 tutorial, H. Padamsee



CORNELL
UNIVERSITY
H. Padamsee

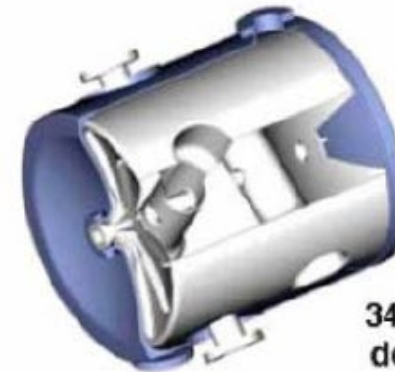
Low-Velocity Structures for Heavy Ions $\beta = v/c : 0.28 - 0.62$



115 MHz $\beta=0.15$
Steering-
corrected QWR

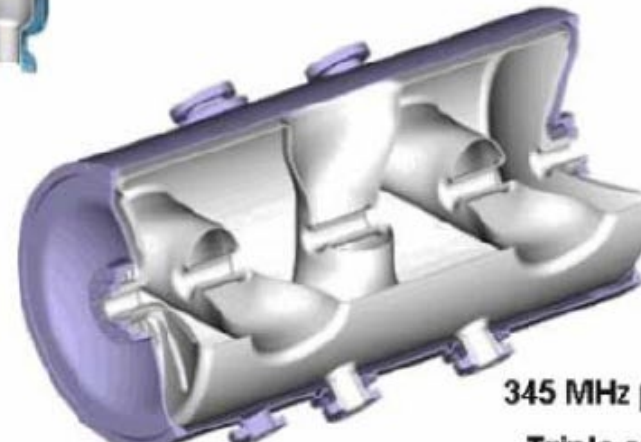
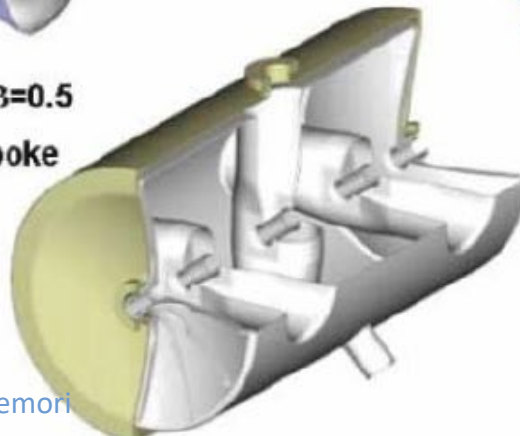


172.5 MHz
 $\beta=0.28$ HWR



345 MHz $\beta=0.4$
double-spoke

345 MHz $\beta=0.5$
Triple-spoke



345 MHz $\beta=0.62$
Triple-spoke

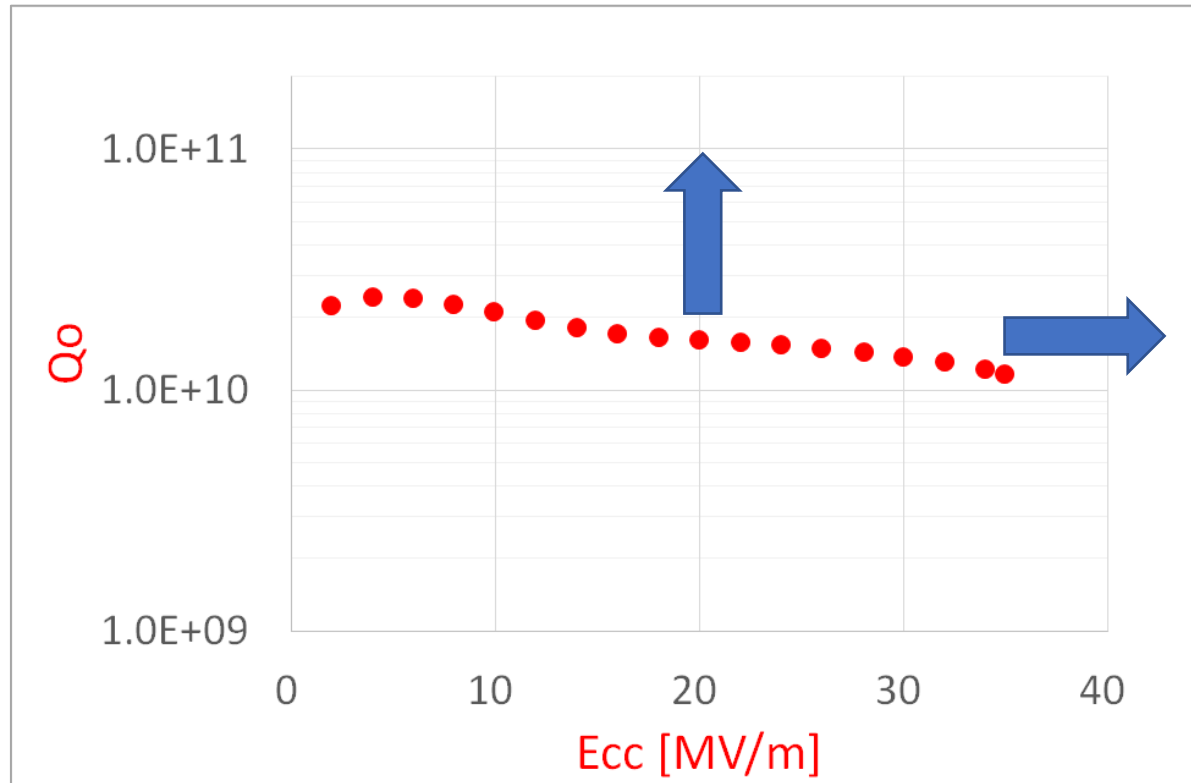
Performance of elliptical SRF cavity

High-Q (low loss), High-Gradient and High current

- Surface resistance (Surface loss)
 - Surface resistance : **several nΩ**
 - N-doping, mid-T baking push up Q_0 up to 3×10^{10} (@2K, 1.3 GHz)
 - Benefit for CW operation accelerator
- Accelerating gradient (accelerating voltage)
 - High gradient of **40~50MV/m is possible**
 - Close to theoretical limit of **critical magnetic field (~200mT)** at cavity surface.
- High current operation
 - **CW high current operation** is benefit of SRF accelerator!
 - Storage ring: **> 1 A**
 - Linac: (100~) **10mA** with ERL scheme

Very important parameters for SRF cavity

Q-value(Q_0) and Accelerating gradient (E_{acc})



Target of our study for SRF cavities
High gradient & high Q_0 (low loss)

$$Q_0 = 2\pi f \times U / P$$

U: Stored energy [J]

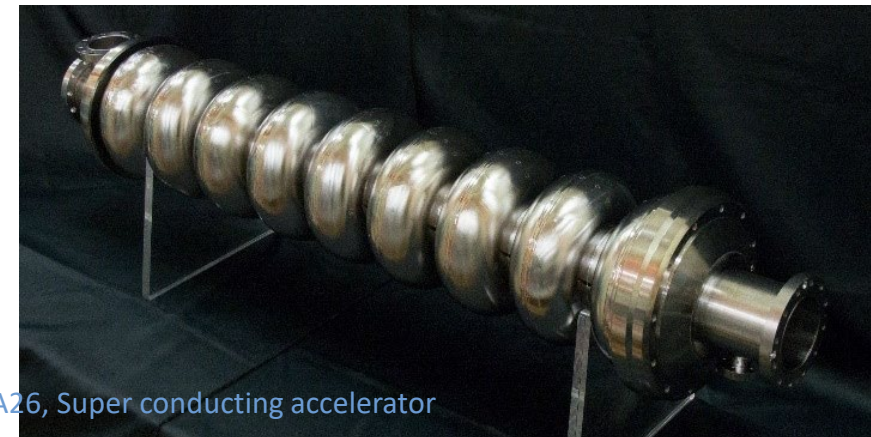
P: Surface loss [W]

f: Resonant frequency

$$Q_0 \propto 1/R_s$$

R_s : Surface resistance [Ω]

E_{acc} : Accelerating gradient [MV/m]



Surface loss and Eacc (Vacc)

CW operation vs pulse operation

$$P = \frac{V^2}{R}$$

- Surface loss is proportional to V_{acc}^2 (or E_{acc}^2)
- Following estimation $Q_0 \sim 1e10$ is used for L-band 9-cell cavity.
 - $\sim 10/40/90W$ loss for 10 /20/30 MV/m (CW)
- For the case of **CW linac** (200 cavity x 20MV/m, 4GeV, 100% duty)
 - $E_{acc} = 20MV/m$, surface loss $\sim 40W$ (100% duty)
 - Total loss = $40W \times 200$ cavity = 8kW
- For the case of **pulse linac** (8000 cavity x 31.5MV/m, 250GeV, 1% duty)
 - $E_{acc} = 30 MV/m$, 1% duty, surface loss $\sim 1 W$
 - Total loss = $1W \times 8000$ cavity = 8 kW
 - If operation is CW(100% duty), 1MW(@2K) class He refrigerator is needed and 1GW level AC power is needed.

High-Q is essential for CW machine.

Outline



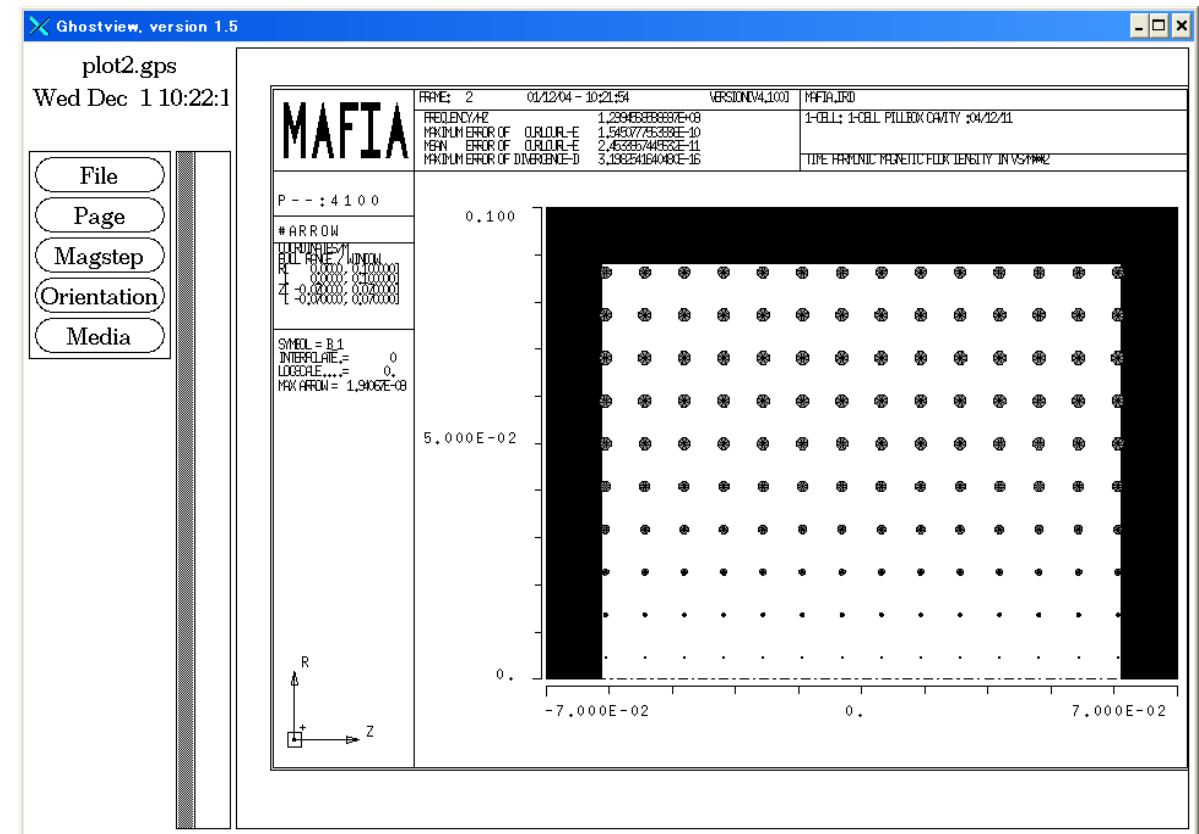
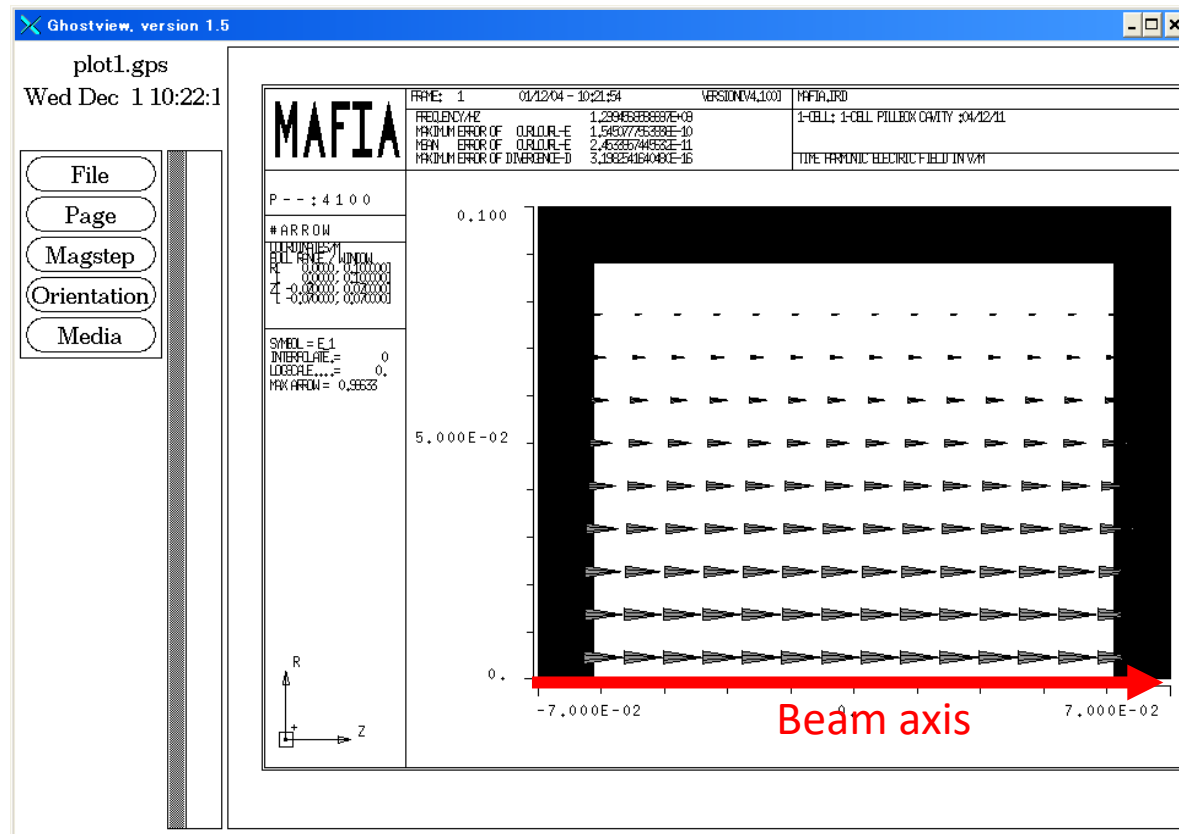
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Pillbox cavity



Pillbox cavity : Most basic shape of TM cavity

- Only the shape which EM fields can be analytically calculated.



Pillbox cavity

Solve Maxwell equation, with boundary condition of

$$\mathbf{n} \times \mathbf{E} = 0 \text{ (E: perpendicular to surface)}$$

$$\mathbf{n} \cdot \mathbf{H} = 0 \text{ (H: parallel to surface)}$$

Solution for TM₀₁₀

$$E_z = E_0 J_0 \left(\frac{2.405 \rho}{R} \right) \cos(\omega_{010} t)$$

$$H_\phi = \frac{E_0}{\eta} J_1 \left(\frac{2.405 \rho}{R} \right) \sin(\omega_{010} t + \pi)$$

$$E_\rho = E_\phi = H_z = H_\rho = 0$$

$$\omega_{010} = \frac{2.405 c}{R}$$

c (speed of light): 2.9979e8 m/s

η (vacuum impedance): 376.73 Ω

m: Axial (ϕ)

n: Radical (ρ)

p: Longitudinal (z)



Complete set of TM_{mnp} mode of pillbox cavity

$$E_z = E_0 \cos \left(\frac{p\pi z}{d} \right) J_m \left(\frac{u_{mn}\rho}{R} \right) \cos(m\phi)$$

$$E_\rho = -E_0 \frac{p\pi R}{du_{mn}} \sin \left(\frac{p\pi z}{d} \right) J'_m \left(\frac{u_{mn}\rho}{R} \right) \cos(m\phi)$$

$$E_\phi = E_0 \frac{mp\pi R^2}{\rho du_{mn}^2} \sin \left(\frac{p\pi z}{d} \right) J_m \left(\frac{u_{mn}\rho}{R} \right) \sin(m\phi)$$

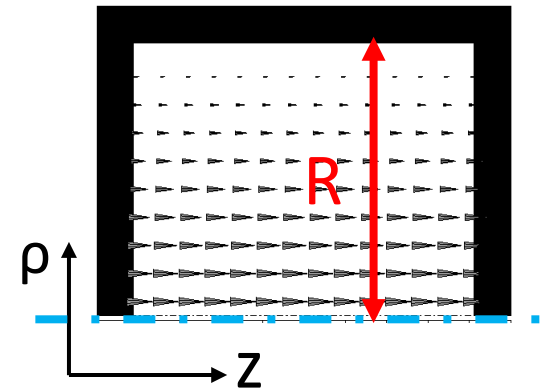
$$H_z = 0$$

$$H_\rho = iE_0 \frac{m\omega_{mnp}R^2}{\eta c \rho u_{mn}^2} \cos \left(\frac{p\pi z}{d} \right) J_m \left(\frac{u_{mn}\rho}{R} \right) \sin(m\phi)$$

$$H_\phi = iE_0 \frac{\omega_{mnp}R}{\eta c u_{mn}} \cos \left(\frac{p\pi z}{d} \right) J'_m \left(\frac{u_{mn}\rho}{R} \right) \cos(m\phi)$$

$$\gamma_{mn} = \frac{u_{mn}}{R}, \quad \omega_{mnp} = \sqrt{(\gamma_{mn}^2) + \left(\frac{p\pi}{d} \right)^2}$$

Half model of
pillbox cavity

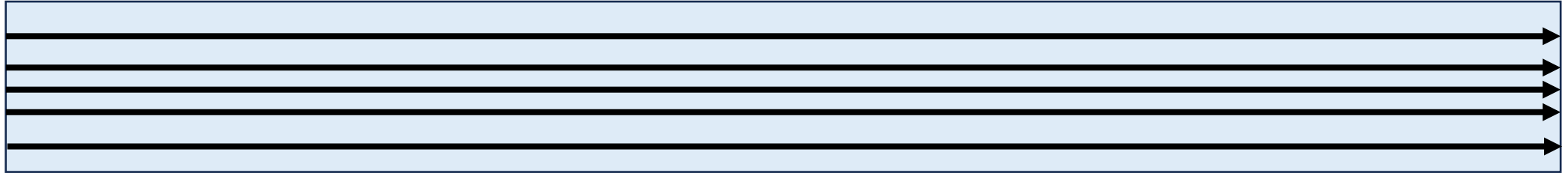


Long pillbox cavity effective?



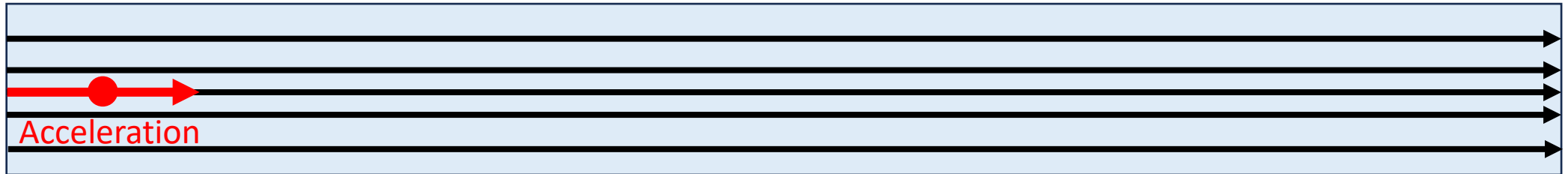
- If we fabricate long pillbox cavity, can we make high-energy machine?

Long pillbox cavity effective?



- If we fabricate long pillbox cavity, can we make high-energy machine?

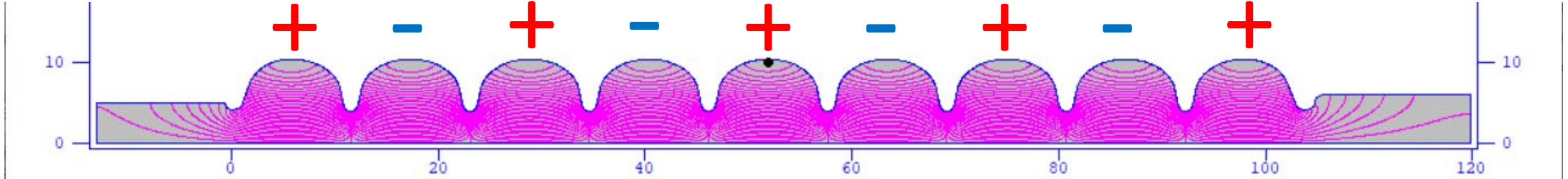
(answer) RF flip the phase $\rightarrow$ acceleration/deceleration alternately $\Rightarrow$ no energy gain



After half RF cycle...

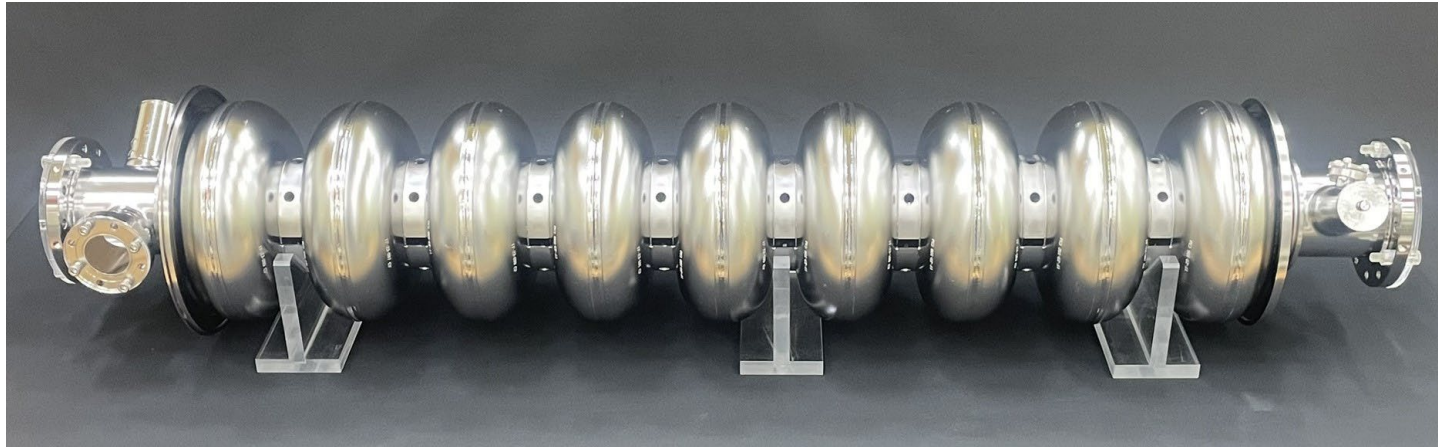


Multi-cell structure with π -mode operation



Cavity cell length = halfwave of resonant frequency

- Particle pass one cell $\rightarrow$ 180 degrees phase change
- Most efficient acceleration using pi-mode



How many cells are optimum?



- Packing factor
 - Beamtube does not contribute to beam acceleration
 - More cells are basically better.
- Higher order mode
 - Multi-cell makes huge amount of HOM's → Control of all HOM's becomes difficult
 - Multi-cell tend to generate trapped modes
- Handling of cavity
 - Too long cavity is difficult for handling of EP, HPR, assembly, test, etc.
 - 1~1.5m optimum?
- Limitation from peripheral equipment
 - Input coupler could be limitation for high current CW linac.

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Performance limitation



Superconductor has **critical magnetic field** and **critical temperature**.
Cavity performance was limited by break of superconductor.

- **Magnetic quench**

- Quench at critical field
- Defects (enhance magnetic field on surface)

- **Thermal quench**

- Field emission
- Multi-pacting
- Normal conducting material

Performance limitation(1) ~Defects~



Magnetic Quench

- Defects on cavity surface lead to quench.
- Cause of defects
 - Bad electron beam welding
 - Scratch
- Edge of defect enhance magnetic field on surface

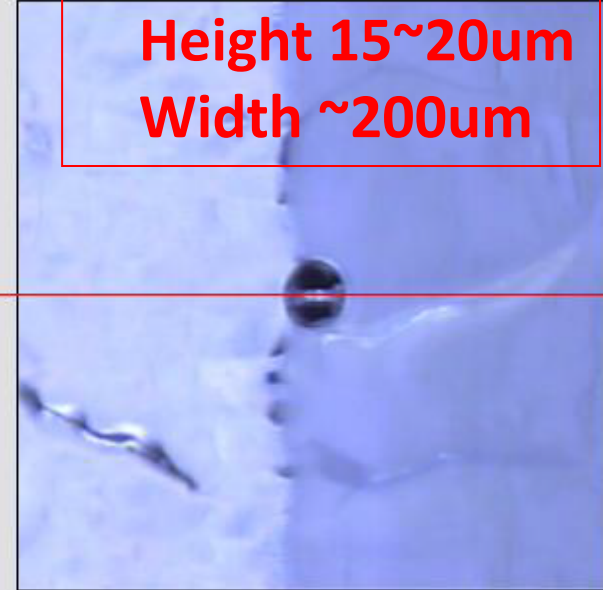
Target

Cavity surface should be defect free

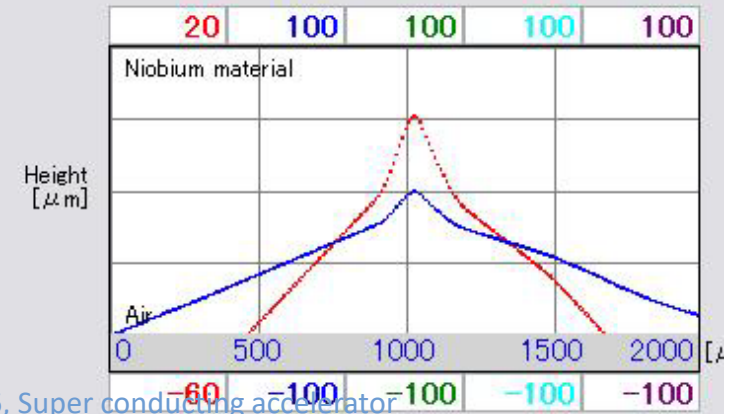
- Cavity fabrication without scratch, welding defect, etc.
- Make smooth surface by Electropolishing.

Example of pit

Height 15~20μm
Width ~200μm



Height_Trans



Correlation between defect size and quench

SRF2009, K. Watanabe

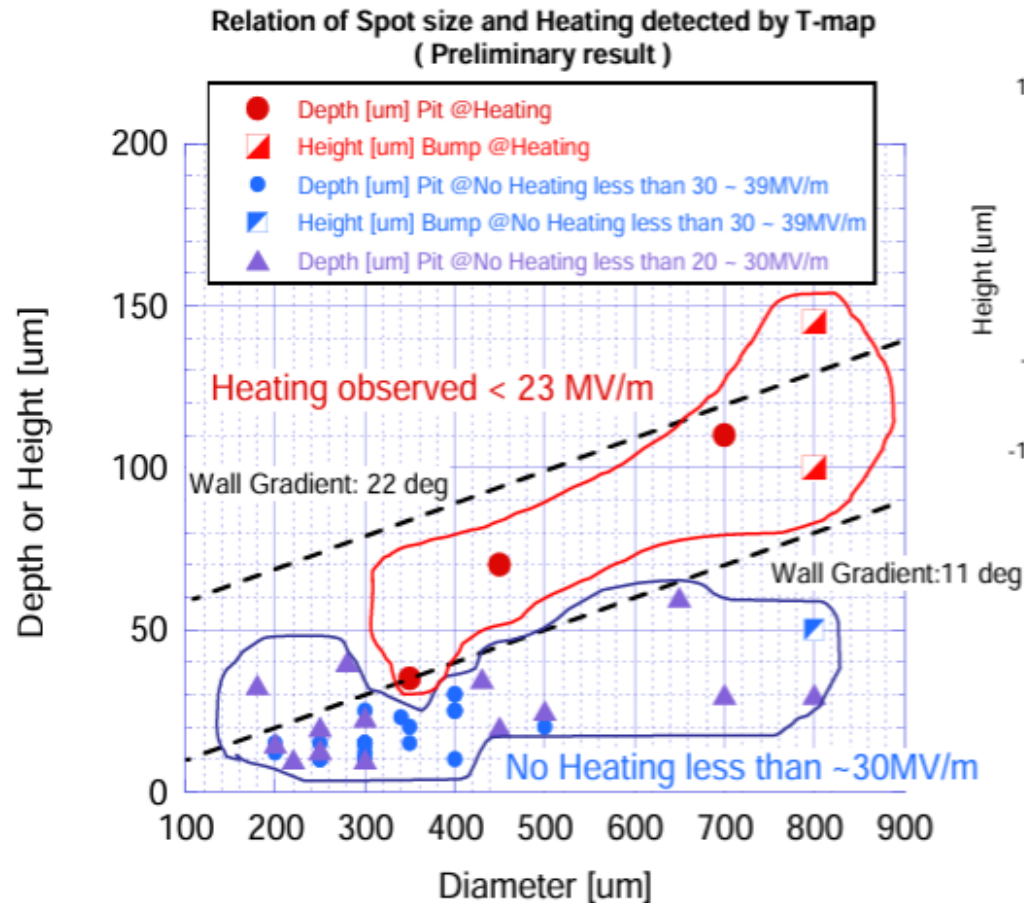
- Larger and deeper defects cause quench.
 - Edge angle is important
 - Normally we can not find defect at quench > 30 MV/m for 120C baked cavity.
 - Also, we can not find defect for N-dope or mid-T cavity, even quench < 20 MV/m.
- ↓
- Quench at high field, > 30 MV/m, mostly come from surface condition (bad superconductor)?

Current my question?

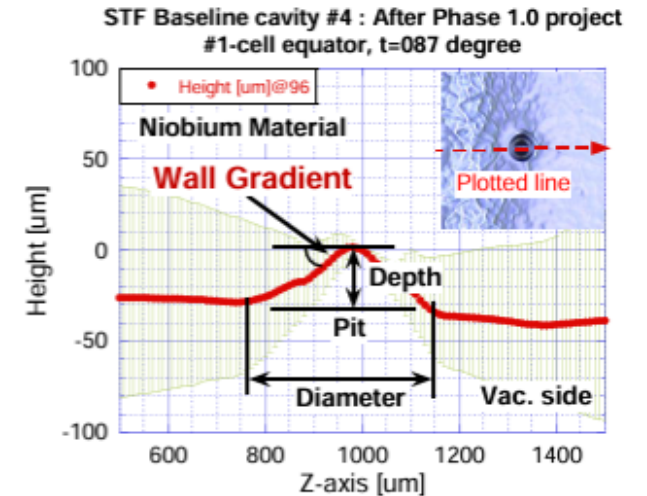


Correlation of spot size and heating (Rough estimation)

superconducting rf test facility



Sample: MHI-01 ~ MHI-09, AES-01 : 10 cavities.
Number of cell = 90 cells, Number of detected spot = 49 spots.



Larger, deeper (or higher) pits (or bumps) seem to cause quenches.

However,

* Not all of the optically observed defects lead to problems.

* Note: preliminary results of analysis which utilizes *both* the pi-mode and pass-band measurements.

Performance limitation(2)

~Field emission~

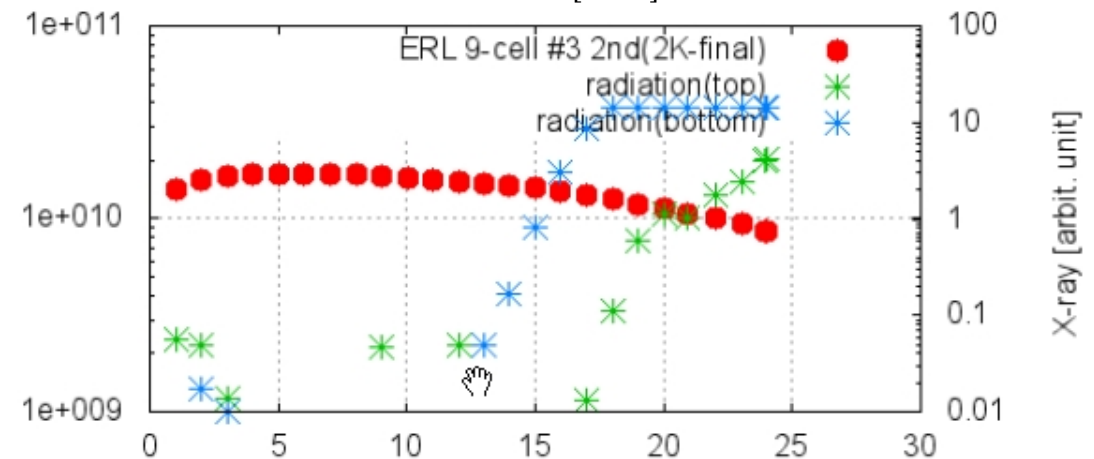
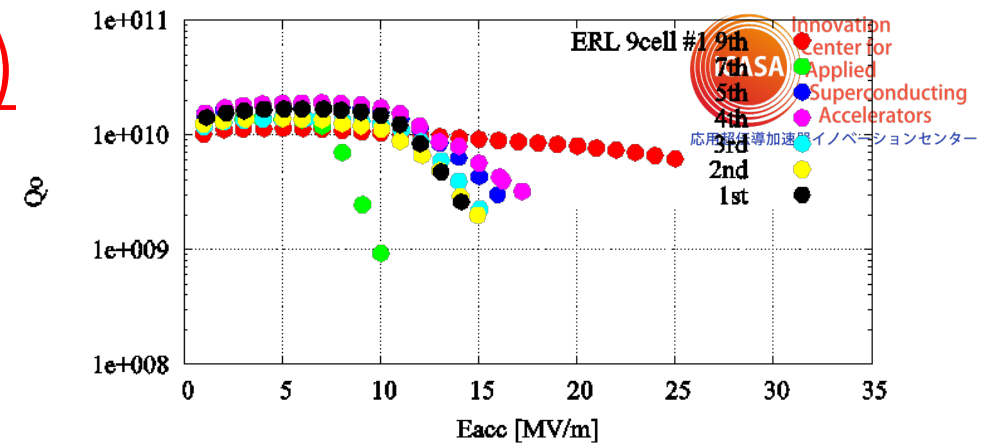
Thermal
Quench

- μm to sub- μm dust on cavity surface could become field emitter.
- Field emission can easily reduce Q-value.

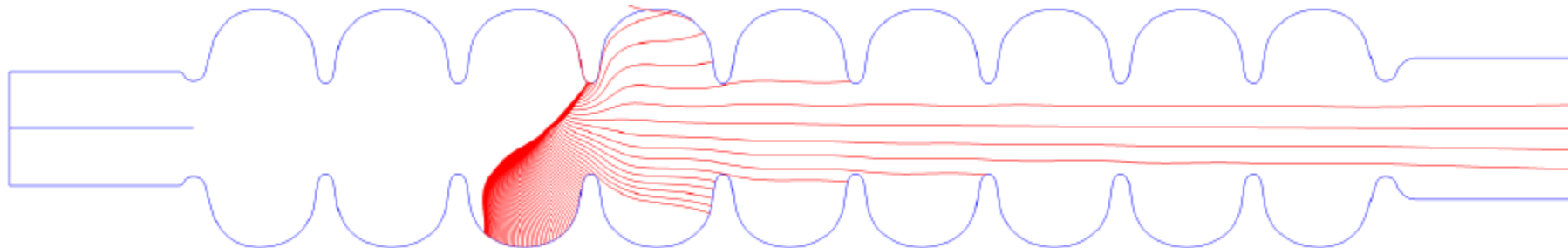
Target

Dust free assembly is important

- Clean assembly in clean room



Example of field emission



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Parameter for acceleration



Accelerating Voltage

$$V_{acc} = \left| \int Ez(r=0, z) e^{ikz} dz \right| \text{ [V]}$$

Accelerating Gradient

$$E_{acc} = \frac{V_{acc}}{L_{cavity}} = \frac{1}{L_{cavity}} \left| \int Ez(r=0, z) e^{ikz} dz \right| \text{ [V/m]}$$

Transit Time Factor

$$T = \frac{\left| \int Ez(r=0, z) e^{ikz} dz \right|}{\left| \int Ez(r=0, z) dz \right|}$$

Shunt impedance (R_{sh})

$$\frac{R_{sh}}{Q} = \frac{(V_{acc})^2}{\omega U_0} = \frac{\left| \int Ez(r=0, z) e^{ikz} dz \right|^2}{\omega U_0} \text{ [\Omega]}$$

$$E_{acc}^2 = \frac{1}{(L_{cavity})^2} \left(\frac{R_{sh}}{Q} \right) (PQ)$$

Cavity length(1.3GHz)
1cell: $\lambda/2 = 0.115 \text{ m}$
9cell: $9\lambda/2 = 1.038 \text{ m}$

$$R_{sh} = (V_{acc})^2 / P_{loss}$$

R_{sh}/Q
✕ Only depend on cavity shape

$$E_{acc} = Z \times \text{SQRT}(P_t \times Q_t)$$

Q-value

$$Q_0 = \omega \frac{U_0}{P_0} = \frac{\omega \mu \int_v H^2 dv}{R_s \int_s H^2 ds}$$

$$U_0 = \frac{\mu}{2} \int_v H^2 dv = \frac{\varepsilon}{2} \int_v E^2 dv$$

$$P_0 = \frac{R_s}{2} \int_s H^2 ds$$

$$Q_0 = \omega \frac{U_0}{P_0} = 2\pi f \frac{U_0}{P_0} = 2\pi \frac{U_0}{P_0/f}$$

$$Q_0 = \frac{G}{R_s} \text{ or } G = Q_0 R_s$$

$$G = \omega \mu \frac{\int_v H^2 dv}{\int_s H^2 ds}$$



Large stored energy (U_0)
Small surface loss (P_0)



Large Q_0

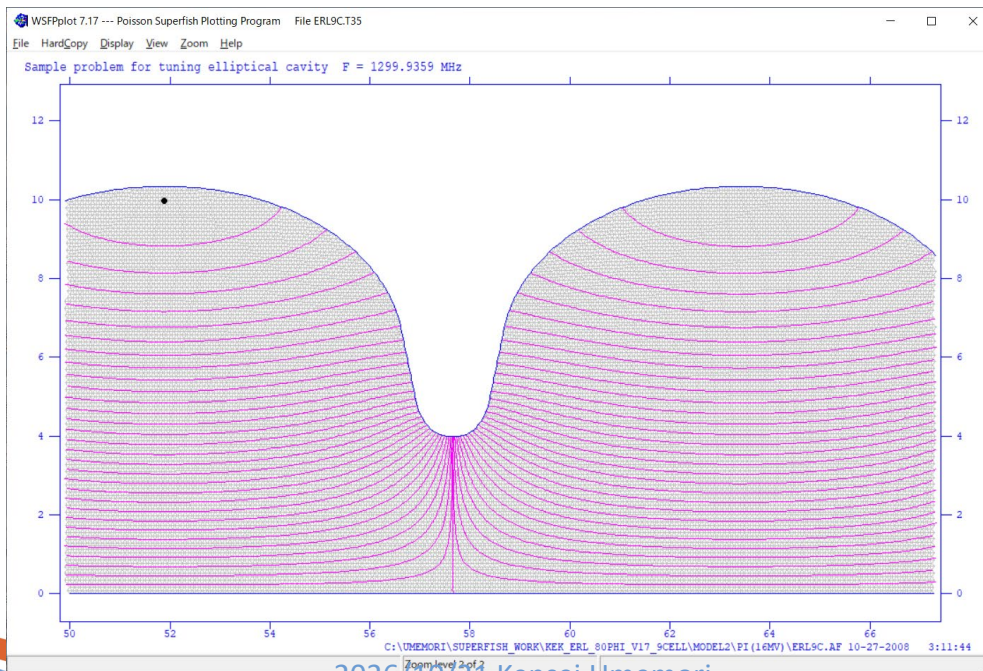
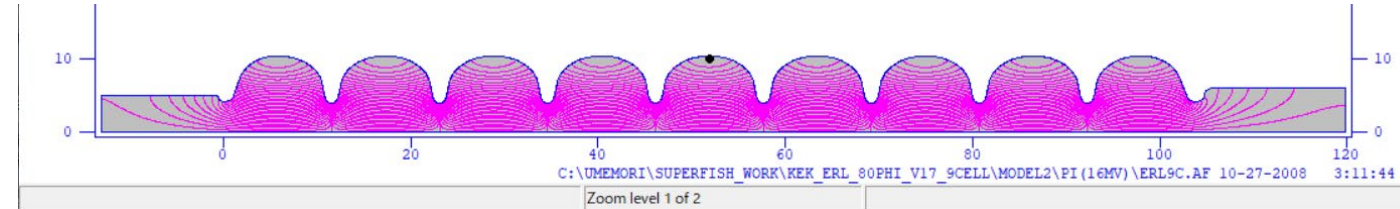
U_0 : Stored energy
 P_0/f : Energy loss / RF cycle

G : Geometrical factor
(Only depend on cavity shape)

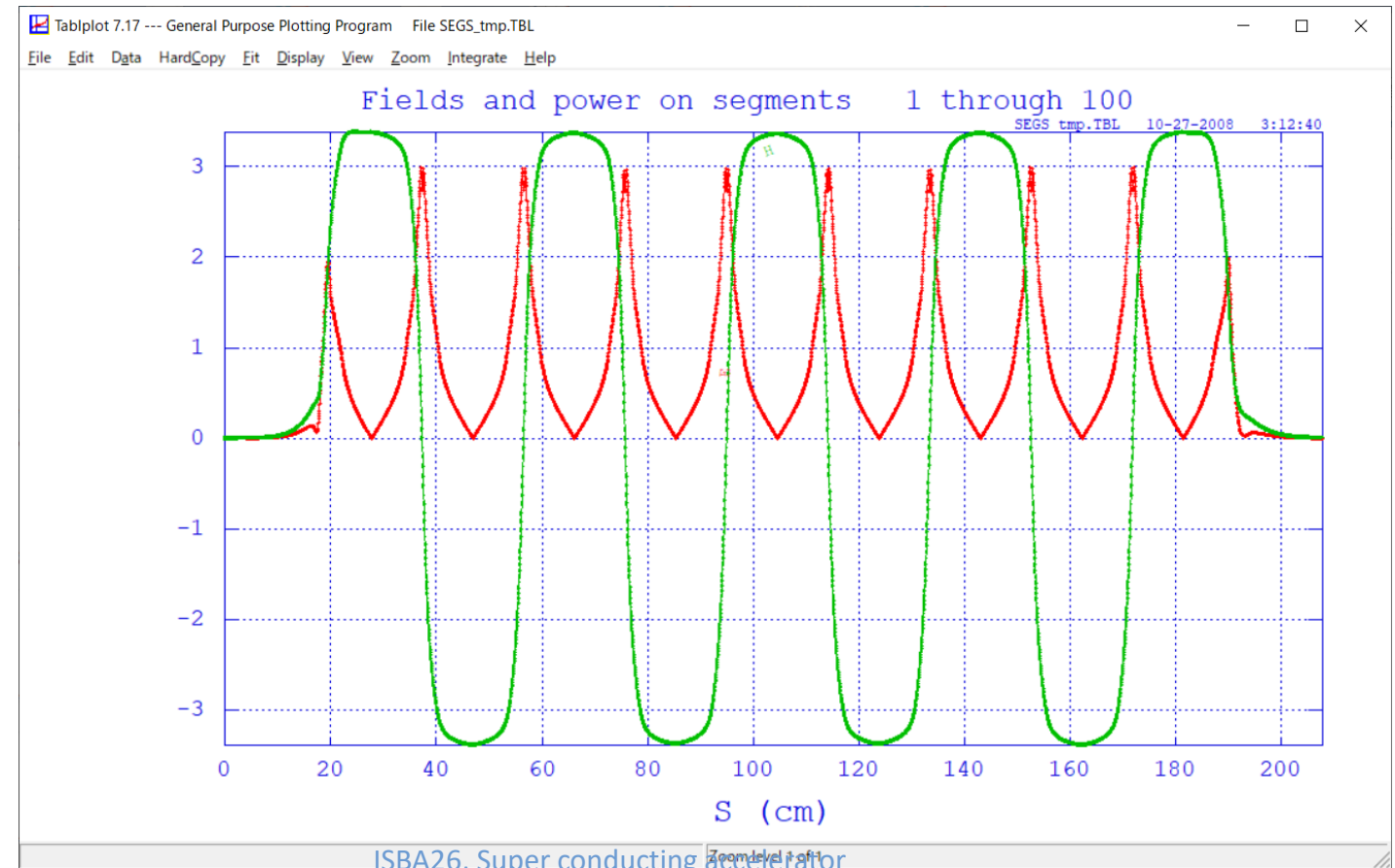
Other important parameters

- $E_{\text{peak}} / E_{\text{acc}}$
⇒ Field emission
- $H_{\text{peak}} / E_{\text{acc}}$
⇒ Magnetic quench

These are the field for cERL cavity.



2026/10/21 Kensei Umemori



ISBA26, Super conducting accelerator

Typical parameters for TESLA cavity



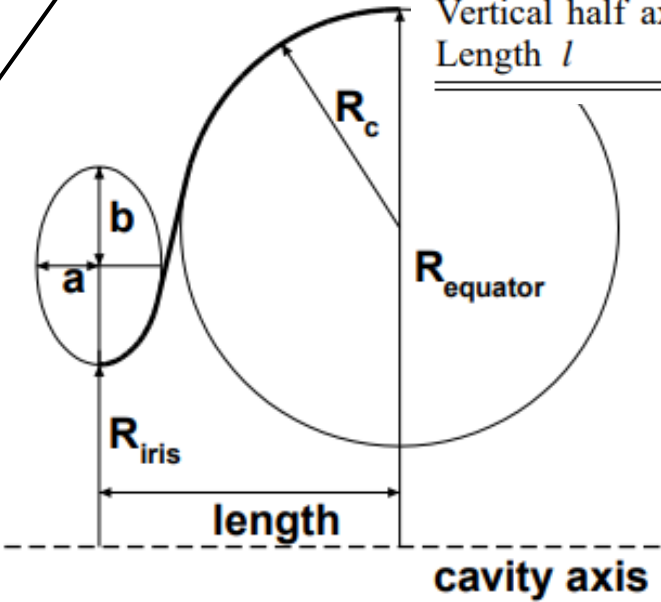
PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME 3, 092001 (2000)
Superconducting TESLA cavities

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

※ Definition of R/Q is deferent.
This number is half.

TABLE III. Half-cell shape parameters (all dimensions in 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



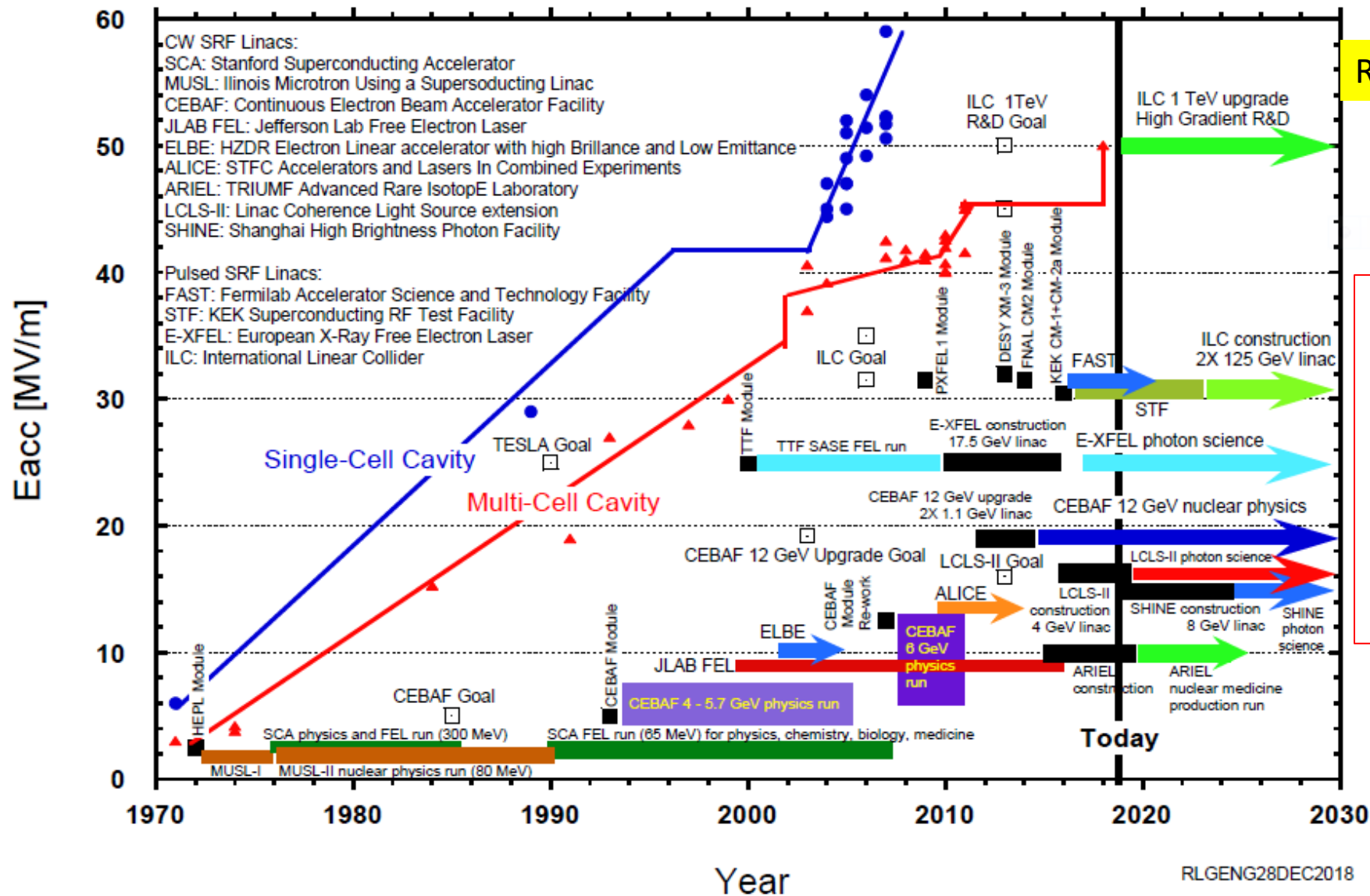
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L-band SRF Linear Accelerator Technology

Impact to Nuclear, Elementary Particle, and Photon Sciences and Medical Applications



R. Geng (JLAB)

- EBW
- EP
- HPR
- Clean assembly

Above are important for the improvement of SRF performance

Cavity Fabrication

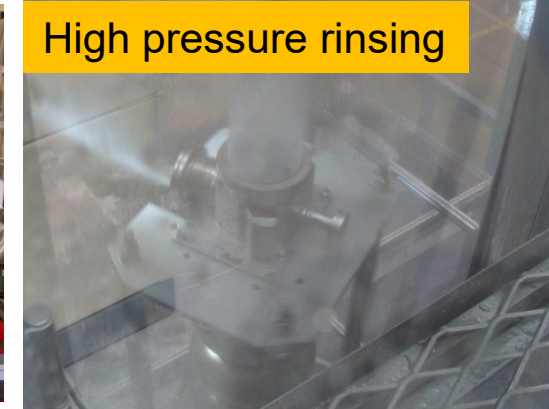
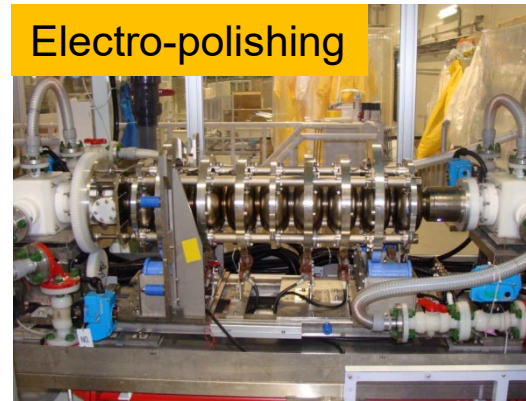
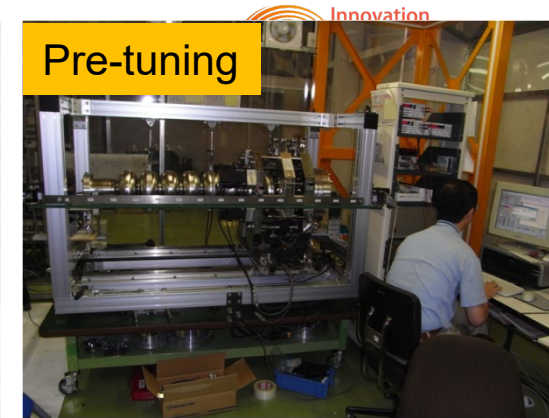
Each parts are welded by EBW (electron beam welding).

Innovation
Center for
Applied
Superconducting
Accelerators



Surface preparation (Standard recipe)

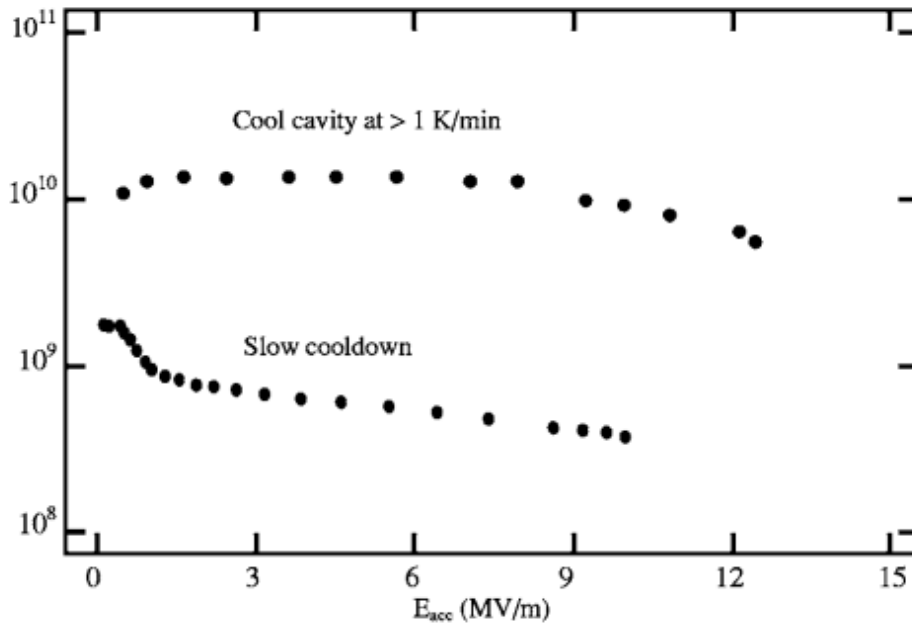
- ❑ Bulk EP(Electro-polish)~100um
- ❑ Heat treatment 800deg x 3h
- ❑ Frequency tuning
- ❑ Final EP ~20um
- ❑ Ultrasonic cleaning with detergent
- ❑ HPR(Ultra-pure water High Pressure Rinsing)
- ❑ Cavity assembly
- ❑ Baking 120 deg x 48h
- ❑ Vertical test
- ❑ Inspections



Effect of hydrogen



H-disease(Q-disease)

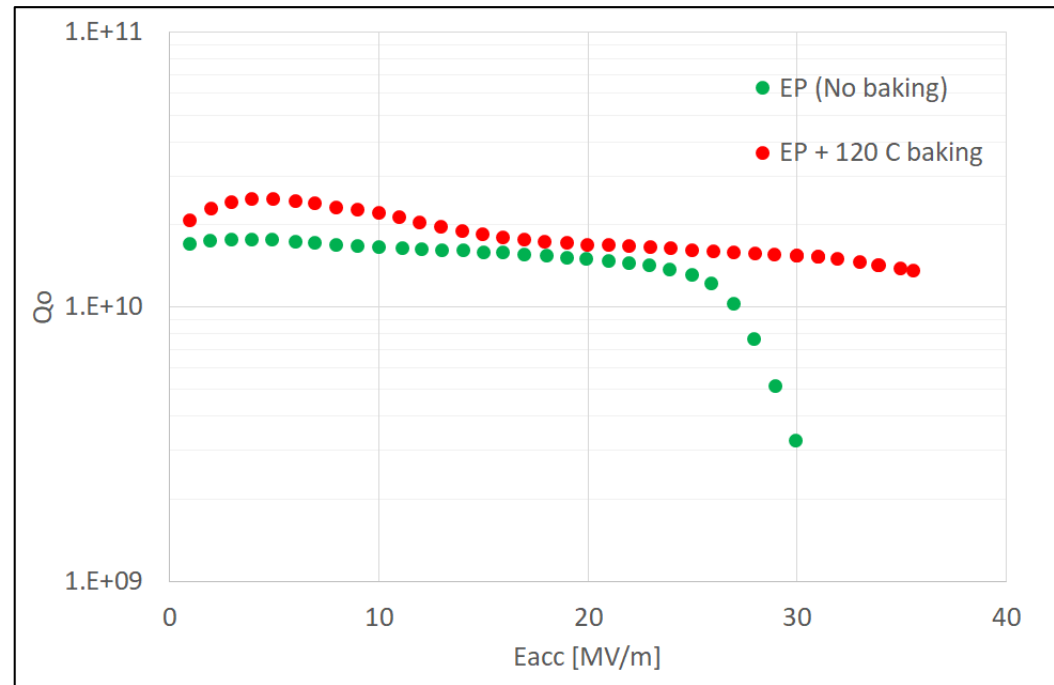


「The “Q disease” in Superconducting Niobium RF Cavities」, J. Knobloch

If cavity, with some amount of H, stay around 100K, it shows strong Q-degradation from very low gradient.

Hydrogen clearly give bad influence on Nb surface

HFQS(High Field Q-Slope)



No low temperature baking(ex. 120C, 48h baking) after EP process makes Q-degradation, above 25 MV/m.

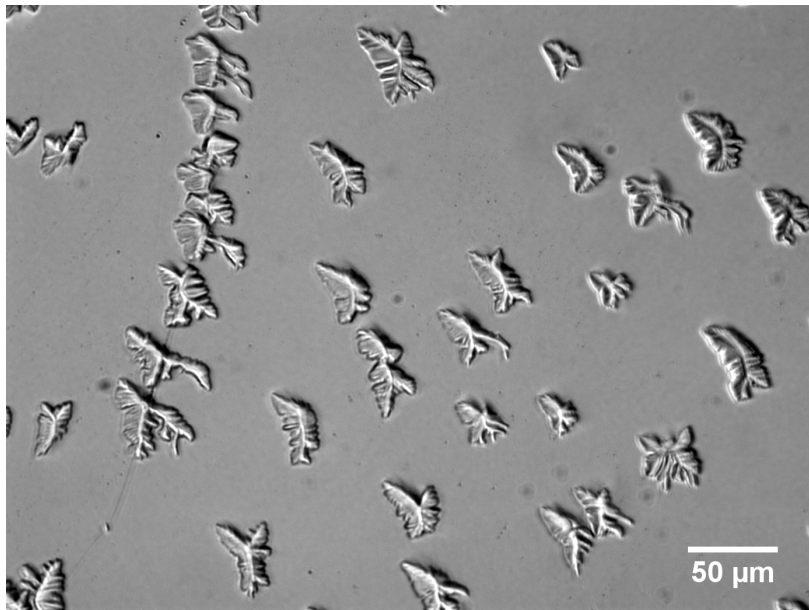
NbH at low temperature

From Shuichi Ooi (NIMS)

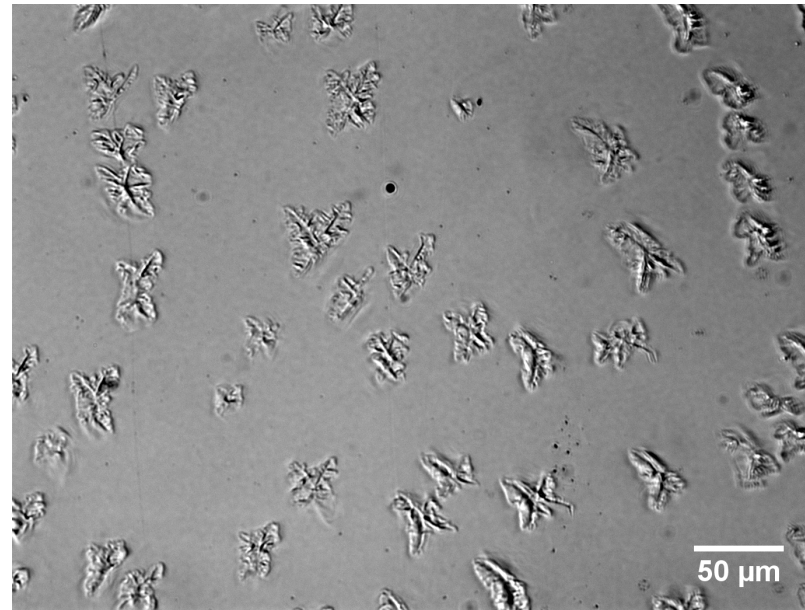
If cooldown Nb which contain large amount of H (for example, no annealing)

Cluster of NbH appear on surface during cooldown, the diffused into inside during warm-up process.

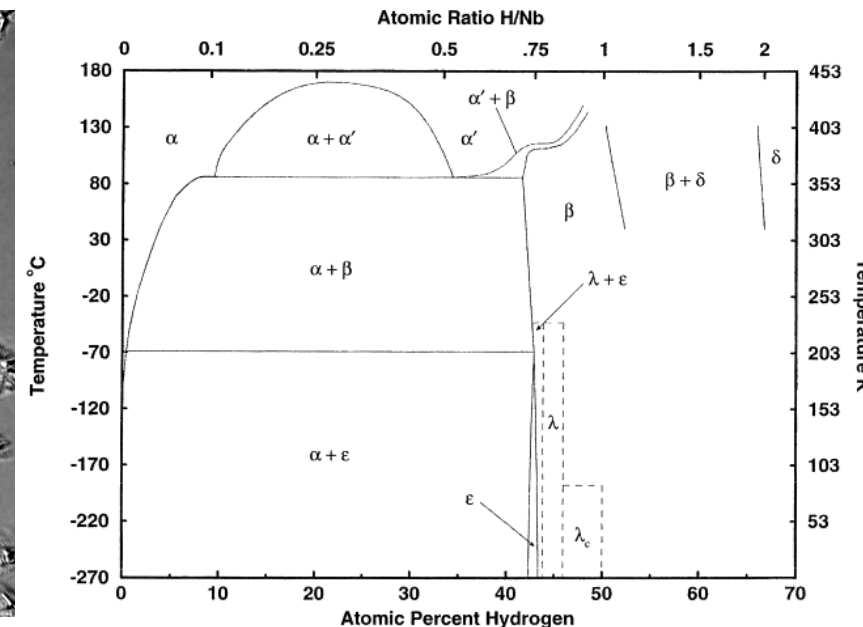
128K (During cooldown)



300 K (Cooldown->warmup)



Phase diagram of NbH

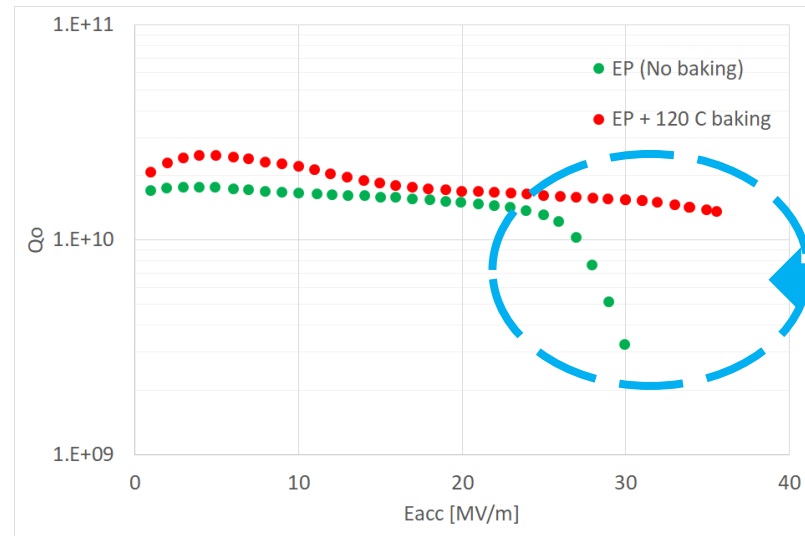


Of course, no structure before cool-down

Nb and H have an extremely high affinity, and H within Nb moves relatively freely while undergoing phase changes. $\Rightarrow$ It's a real pain for us.

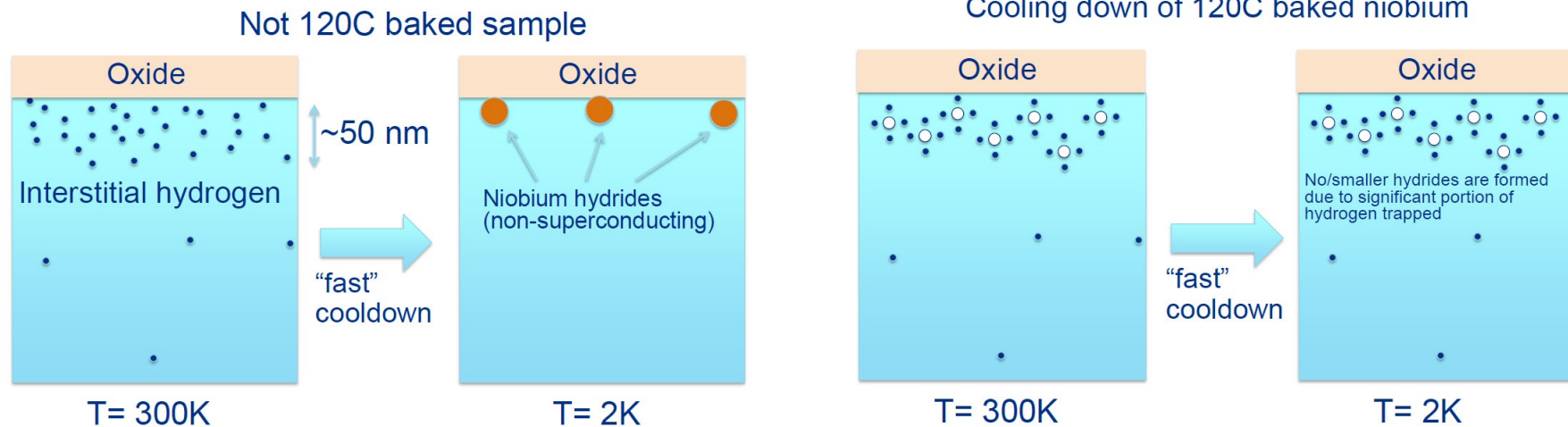
Effect of baking (120 C x 48 hours)

- De-gassing (especially water)
- Improve high field Q-values



- Does ideal treatment against H improve cavity performance?
- 120C baking ideal approach?

One hypothesis of effect of 120 C baking



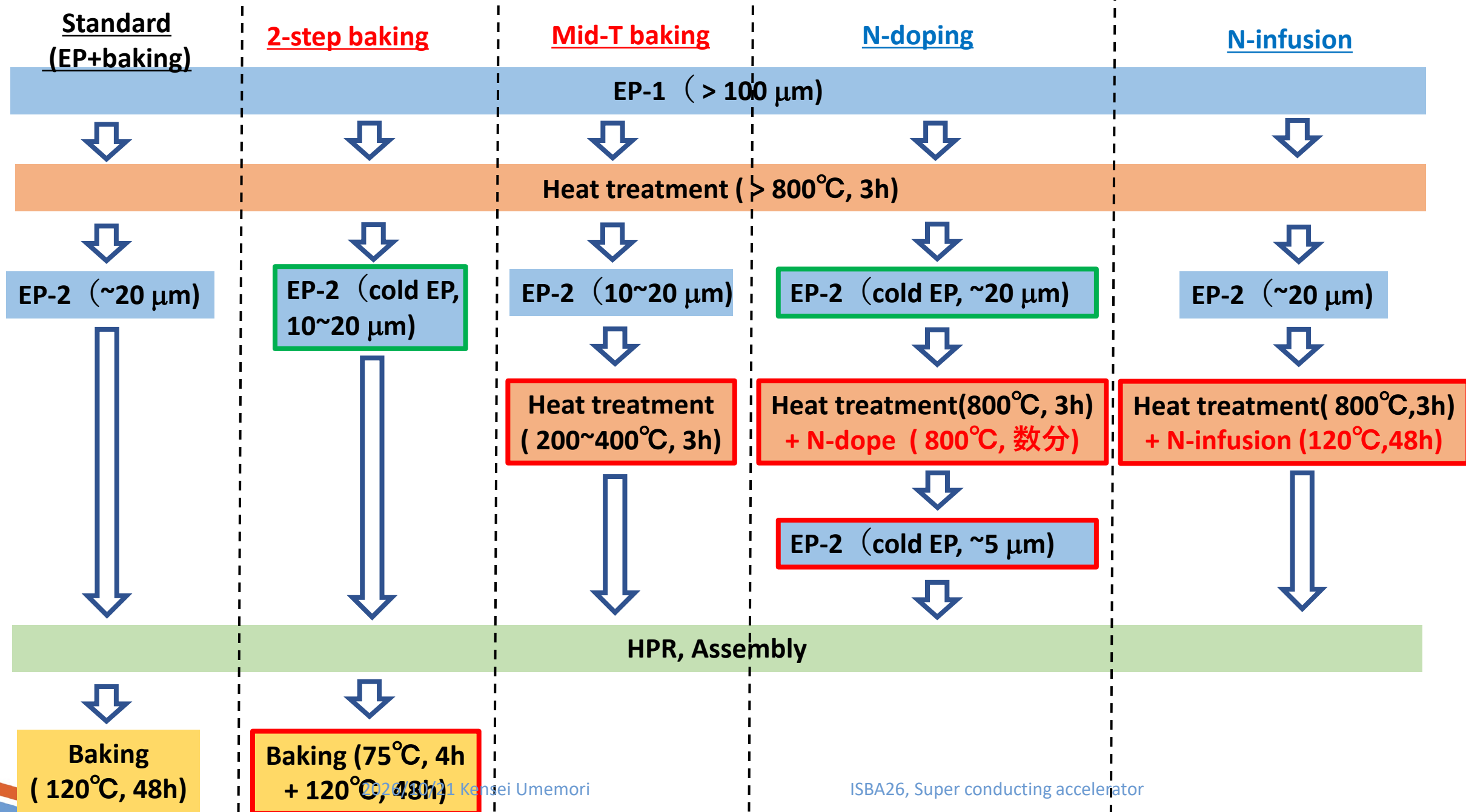
A. Romanenko, F. Barkov, L. D. Cooley, A. Grassellino, Supercond. Sci. Technol. **26** (2013) 035003

Outline



- Superconducting cavity
 - Introduction
 - Pillbox cavity and mulch-cell cavity
 - Performance limitation
 - Basic RF parameter
- Surface treatment for higher performance
 - Surface treatment and hydrogen
 - Various high-Q/high-G surface treatment
- Cryomodule
 - Cryomodule design
 - Cryomodule components
- Superconducting accelerator
- Future challenge
- Summary

Several surface treatment procedure ⇒ Cavity performance largely depend on surface treatment



2-step baking (75 C + 120 C)

A. Grassellino et al., 「Accelerating fields up to 49 MV/m in TESLA-shape superconducting RF niobium cavities via 75C vacuum bake」

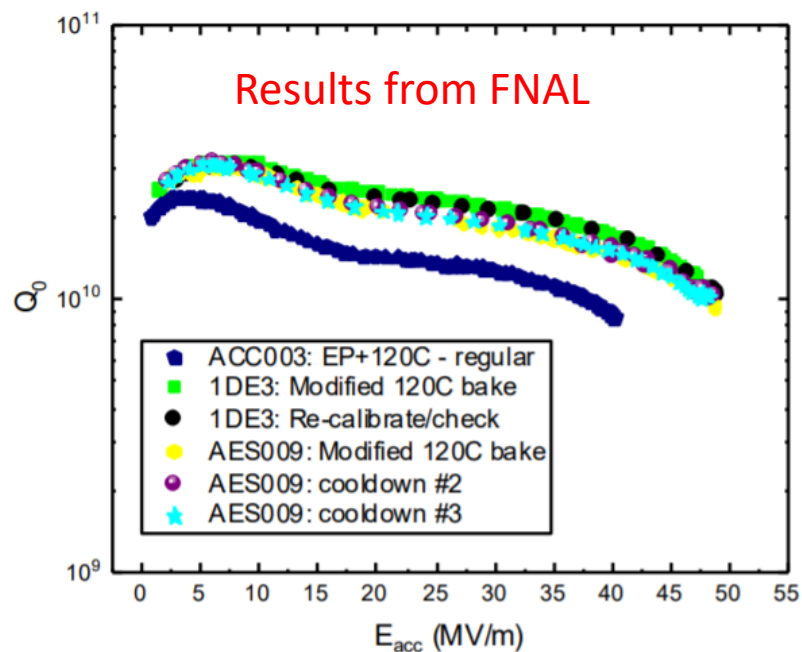
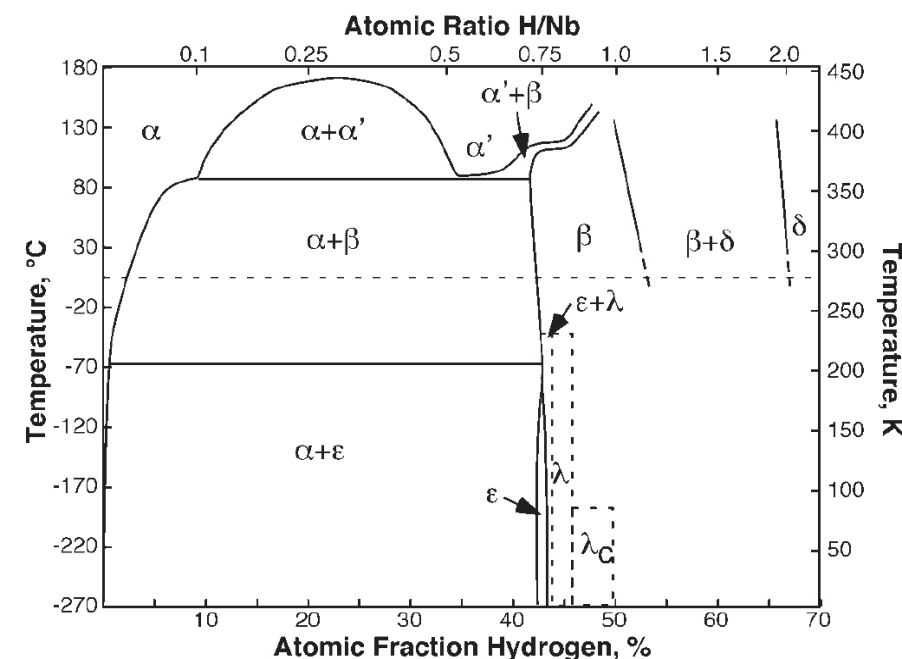
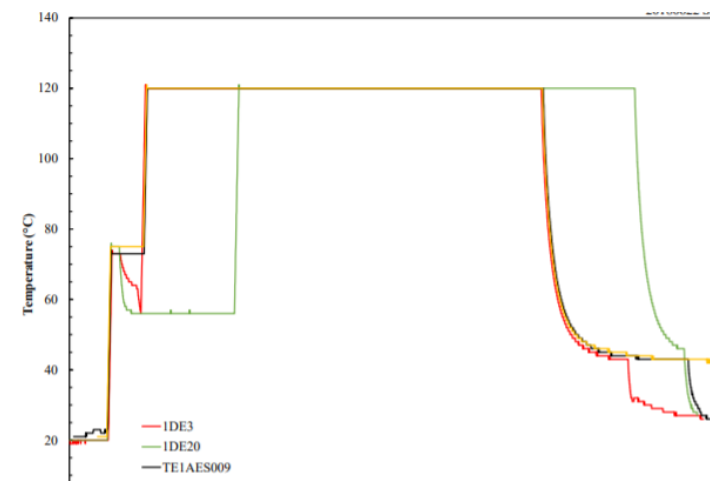


Figure 3: Comparison of 1DE3 for regular 120°C bake and for 75°C+120°C bake.

2-step baking was proposed by FNAL, which can improve E_{acc} up to 49 MV/m.



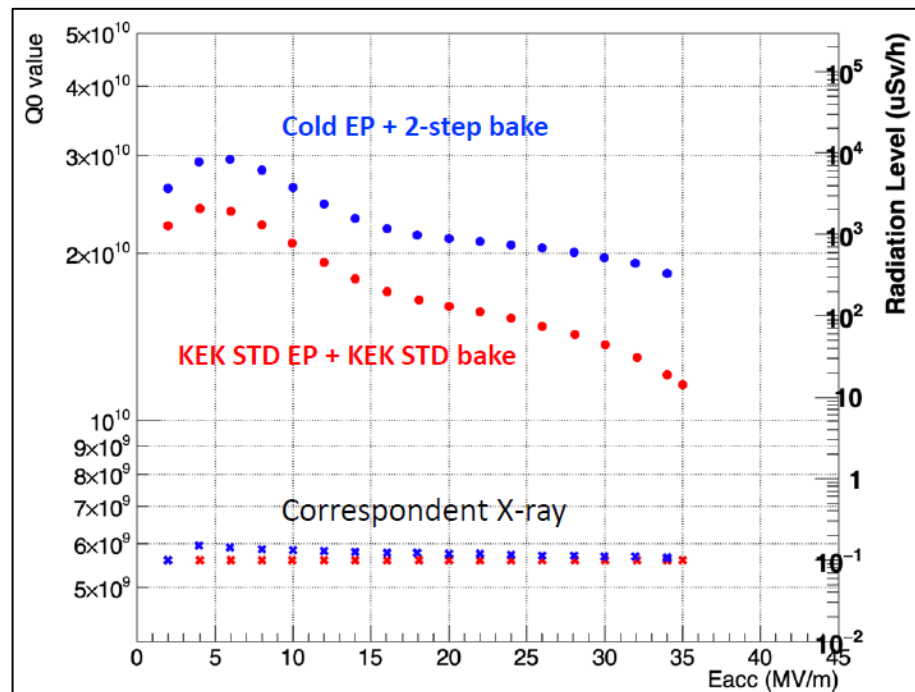
2-step baking

Ryo Katayama, TTC high-Q/high-G WG, 2022/Sep

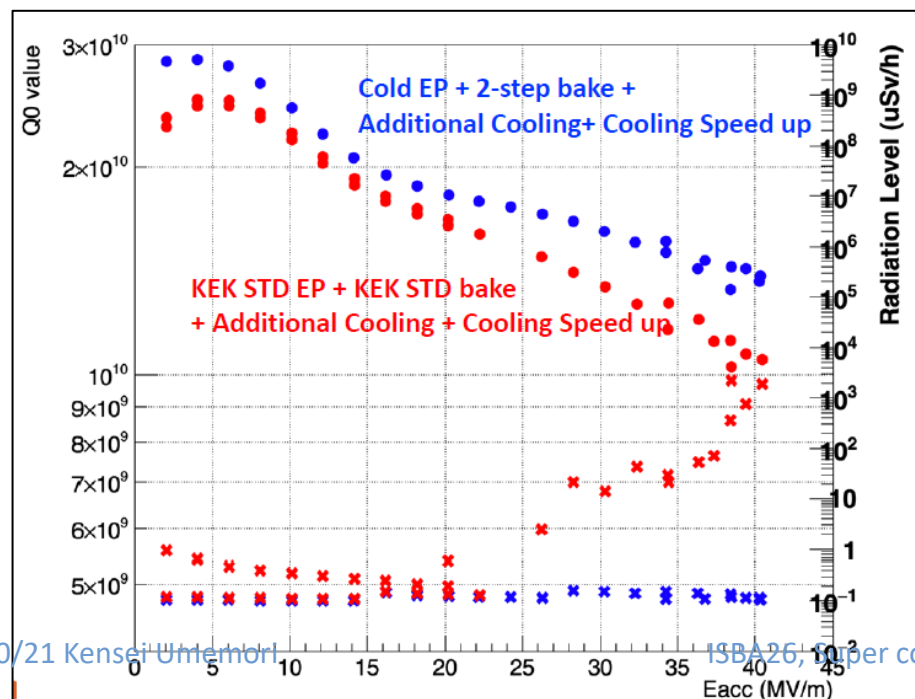
Single-cell

- Combination of Cold EP(air cooling) + 2-step baking(70-75 C, 4h + 120C, 4h) was applied to SRF cavities at KEK
- Q-value was improved by the combination of cold-EP and 2-step baking, whereas quench field was not improved.

9-cell



- R8
 - 1-cell, TESLA like, fine grain
- VT1 (baseline)
 - STD EP + STD bake
- VT24
 - Cold EP + 2-step bake (70°C)
- Q-value of VT24 was significantly enhanced compared to VT1
- Quench field was not improved.



- MT6
 - 9-cell, TESLA, fine grain
- VT9 (baseline)
 - STD EP + STD bake
- VT8
 - Cold EP + 2-step bake (70°C)
- Q-value of VT8 was significantly enhanced compared to VT9
- Quench field was not improved.

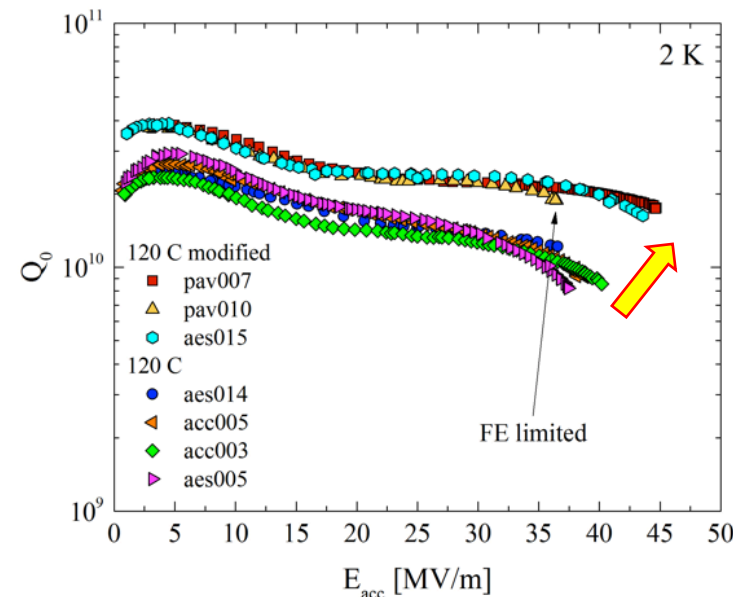
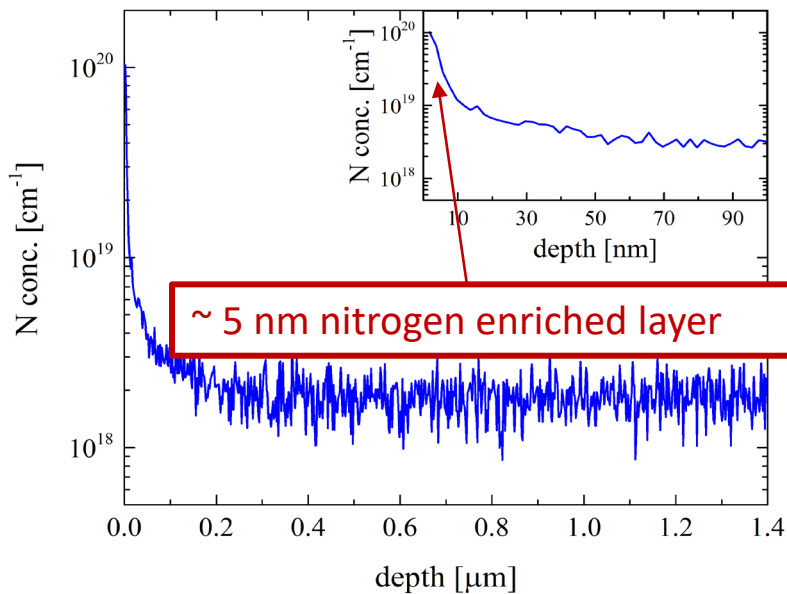
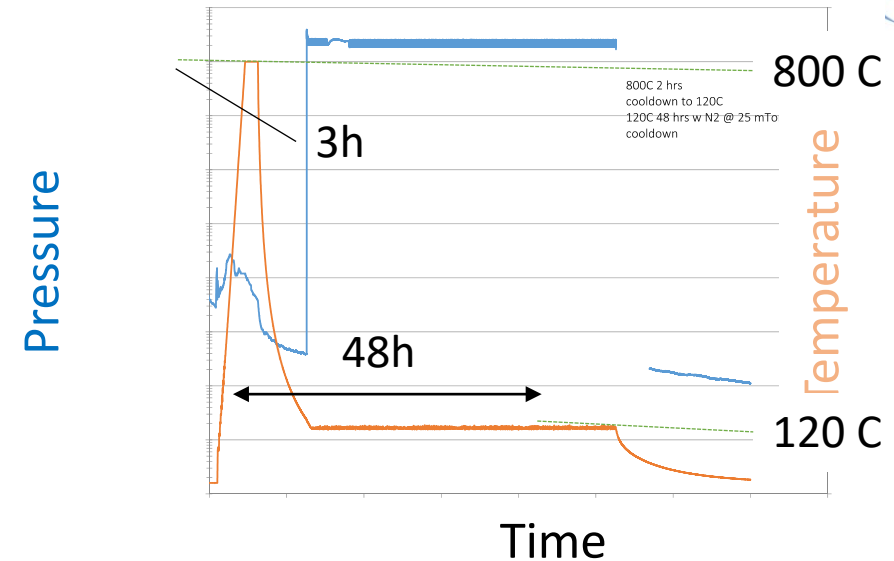
Nitrogen-infusion (N-infusion)

After high temperature heat treatment, ~Pa of N₂ is fed into the furnace at ~120C for several 10 hours.



Nitrogen goes into depth of ~ 10 nm.
No need of additional EP after N-infusion.

Achieve better-Q
Also can get better E_{acc}



Sebastian Aderhold / Anna Grassellino (TTC@Saclay)

2026/10/21 Kensei Umemori

N-infusion can improve acceleration gradient.

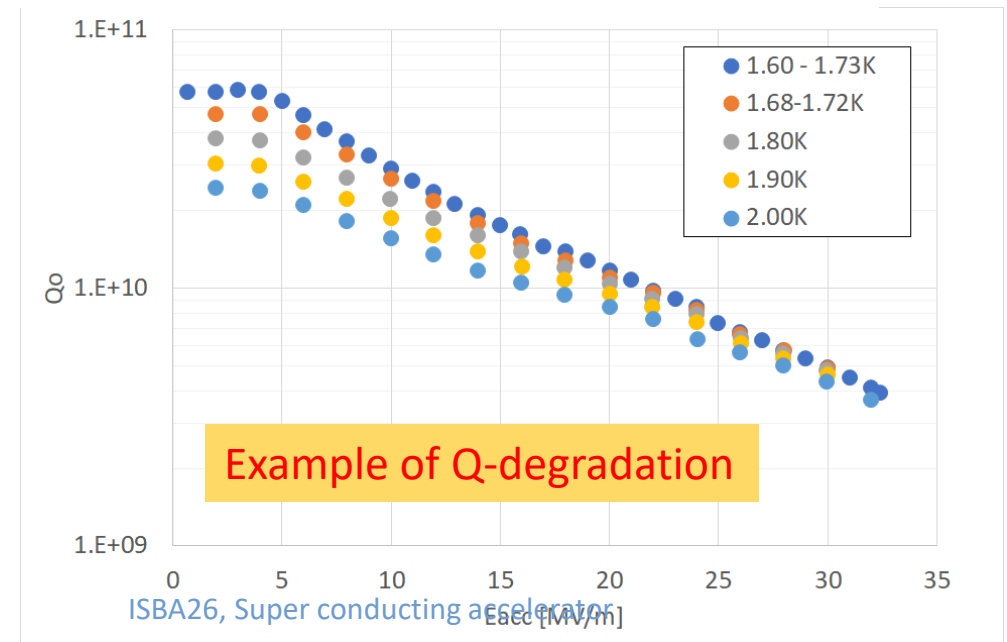
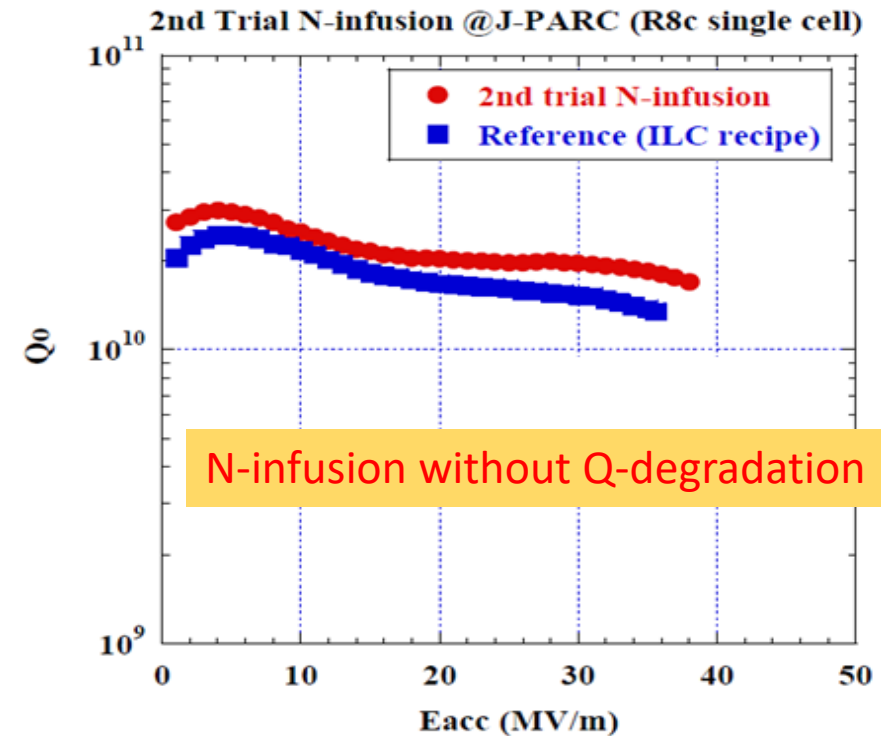
ISBA26, Superconducting accelerator

N-infusion results

#	Day (N-inf / VT)	Cavity name	# of cell	Nb	Treatment	Results	Eacc (MV/m)	Comment
1	2018/Jun	R-6	1	FG	800C, 3h + 120C, 48h, 3.3Pa N2	No Q-degradation	35	
2	2018/Jun, Jul	R-9b	1	FG	800C, 3h + 120C, 48h, 3.3Pa N2	No Q-degradation	26	Defect limited
3	2018/Jun, Jul	R-10	3	LG	800C, 3h + 120C, 48h, 3.3Pa N2	No Q-degradation	27	F.E. limited
Summer shutdown								
4	2018/Sep, Oct	R-2	1	FG	800C, 3h + 160C, 48h, 3.3Pa N2	Q-degradation	19	No defects found
5	2018/Oct	R-6	1	FG	800C, 3h + 120C, 48h (without N2)	Q-degradation	32	
Apply dedicated burning run after this period								
6	2018/Nov, Dec	R-8	1	FG	800C, 3h + 800C, 2h + 120C, 48h, 3.3Pa N2	Better Q than reference	36	
Improve cooling of cryo-pump by adding cooling-water type shielding plate								
7	2018/Dec 2019/Jan	R-9b	1	FG	800C, 3h + 800C, 2h + 160C, 48h, 3.3Pa N2	Q-degradation	24	Defect limited
8	2019/Jan, Feb	AES18	1	FG	800C, 3h + 800C, 2h + 120C, 48h, 3.3Pa N2	No Q-degradation	38	
Modify N2 injection line								
9	2019/Apr	R-4	1	FG	800C, 3h + 120C, 48h, 3.3Pa N2	Q-degradation	39	
10	2019/May	AES18	1	FG	800C, 3h + 120C, 48h, 3.3Pa N2	Q-degradation	31	
Remove cooling-water type shielding plate due to water leak trouble								
11	2019/Jun, Jul	MHI31	9	FG	800C, 3h + 800C, 2h + 120C, 48h, 3.3Pa N2	Better Q than reference	37	
12	2019/Sep	R-4	1	FG	800C, 3h + 800C, 2h + 120C, 48h, 3.3Pa N2	Q-degradation	36	

- Half of N-infusion at KEK / J-PARC showed Q-degradation due to the furnace contamination.
- Some successful results showed improvement of Q-values, which is caused by lower R_{res}.
- No cavity showed improvement of accelerating gradient.

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N-doping (Nitrogen-doping)

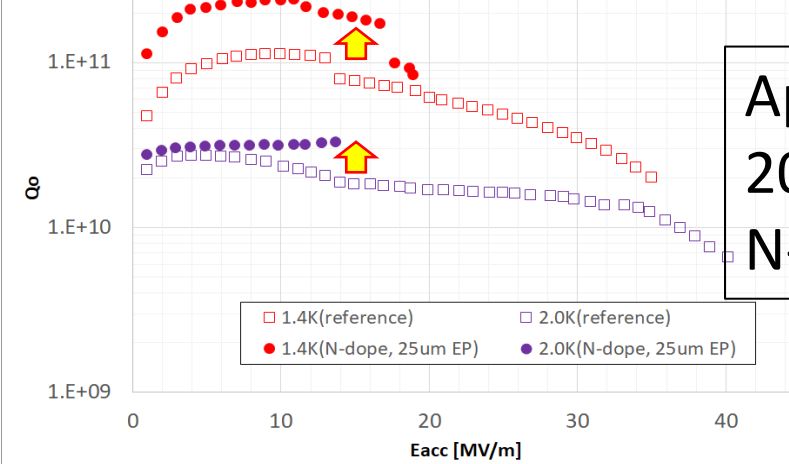
During high temperature heat treatment, ~Pa of N₂ is fed into the furnace for a few to a few 10 min.



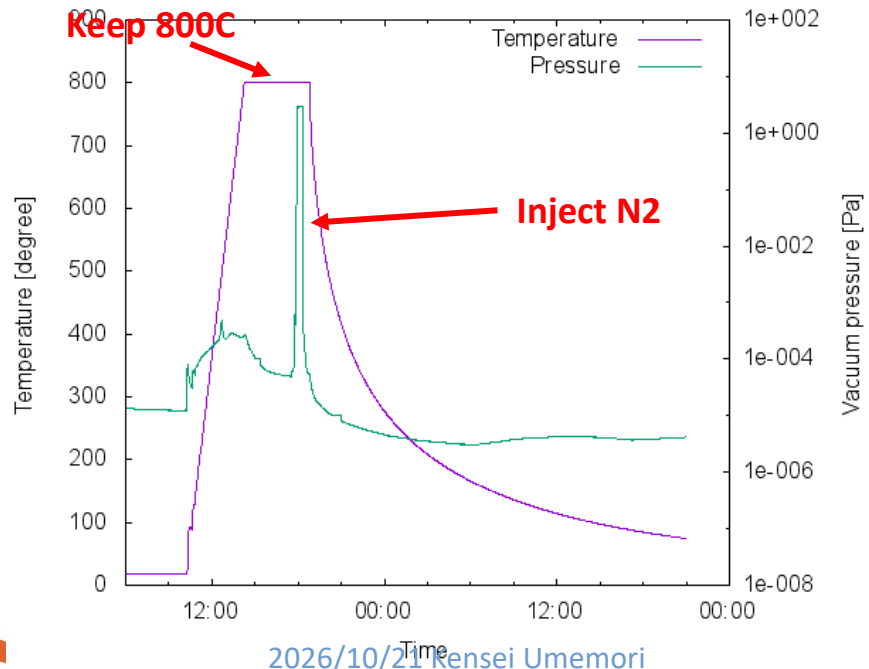
Nitrogen goes into depth of several 10 μm .

Achieve high-Q
But Eacc decrease

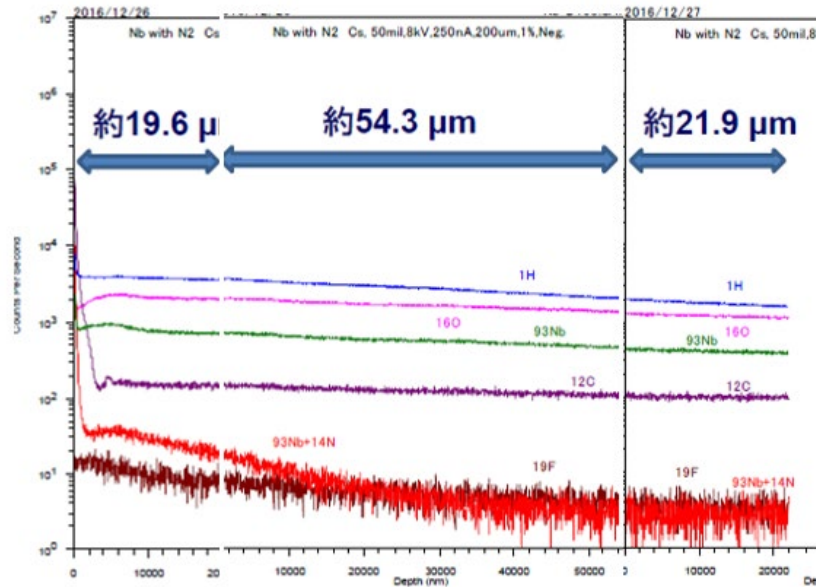
Results for KEK 1.3GHz single-cell cavity



Apply several ~
20 μm EP after
N-doping



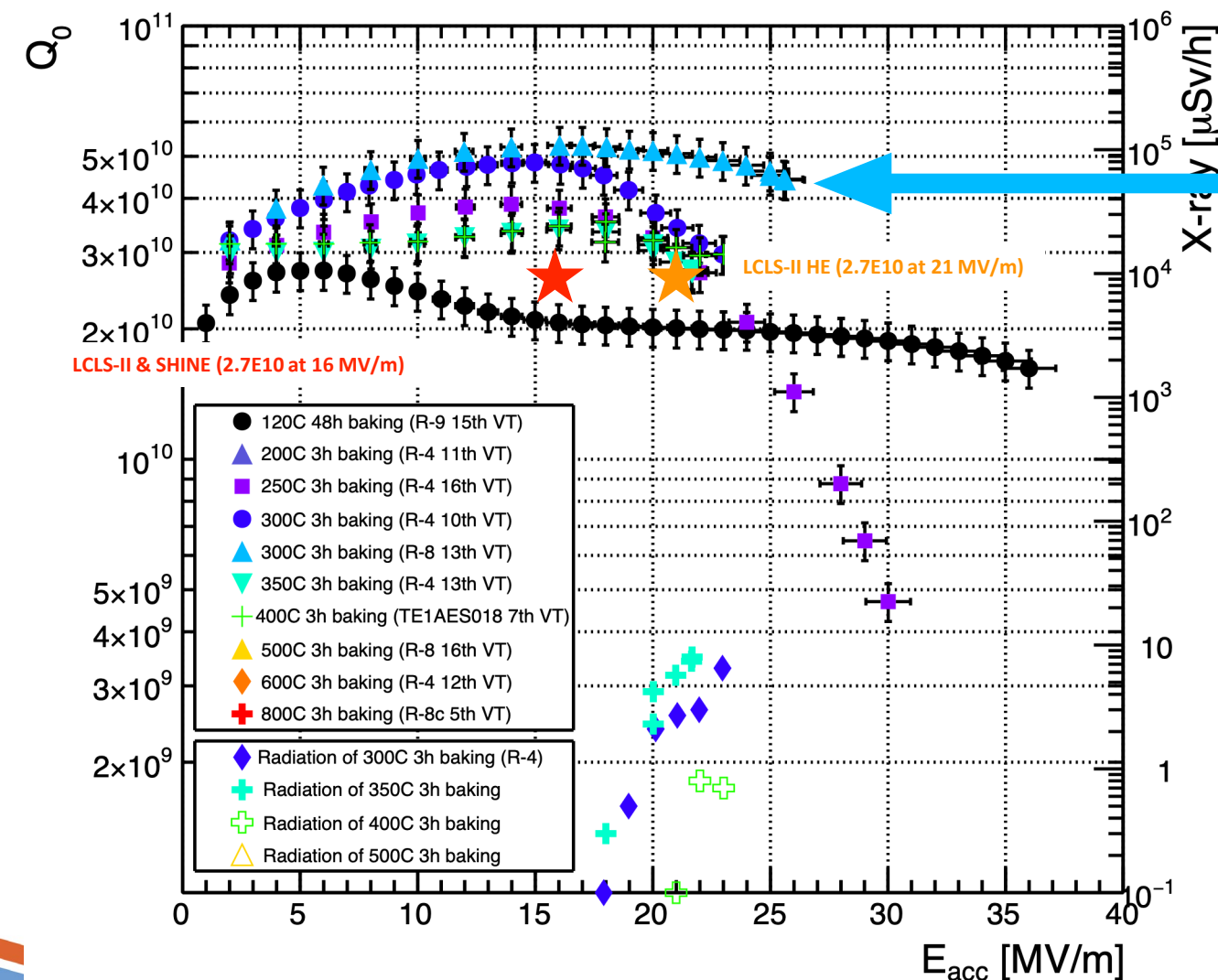
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ISBA26, Super conducting accelerator

**Furnace with diffusion
pump did not work.**
**Furnace with
cryopump work well.**

Mid-T furnace baking for single-cell cavity



300°C furnace baking (R-8)

- 5.3E10 at 16 MV/m
- 5.0E10 at 21 MV/m

2~3 times higher Q value than standard treatment

-> 1/2~1/3 times higher heat load

- Oxygen diffusion is important process to control the performance of Nb cavity.
- Suppression of HFQS is important to reach high gradient.

Effect of magnetic field surrounding cavity

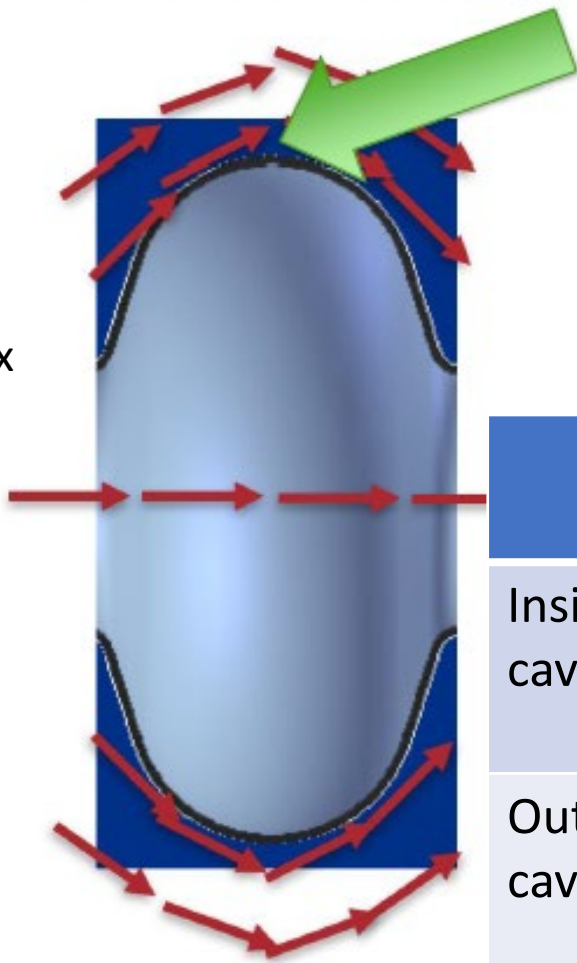
Slow cooldown

- Magnetic flux tends to be trapped to the cavity
- This trapped magnetic flux is source of surface resistance

Fast cooldown

- Magnetic flux tends to be expelled to outside of cavity
- Important technique to achieve high-Q performance of cavity

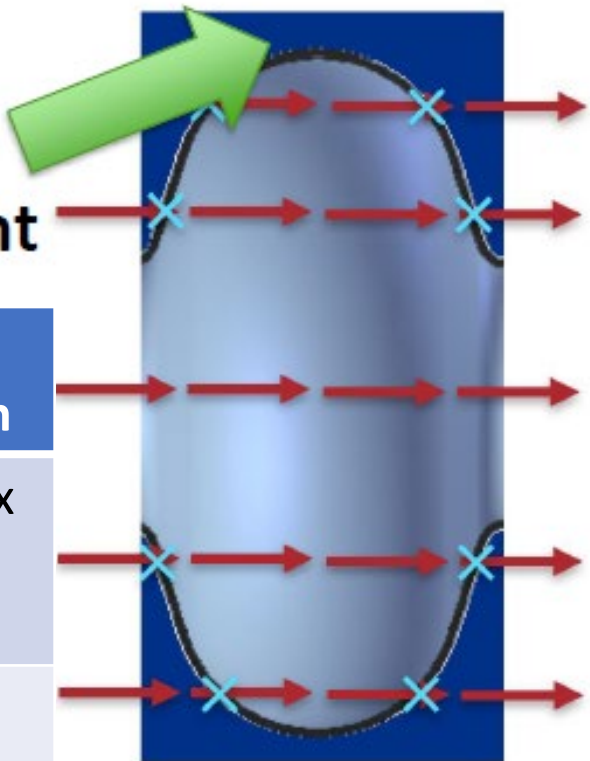
Magnetic Flux Expulsion



Magnetic field enhancement

	Full expulsion	zero expulsion
Inside cavity	No flux → Small Rres	Much flux → Large Rres
Outside cavity	Large enhancement	No enhancement

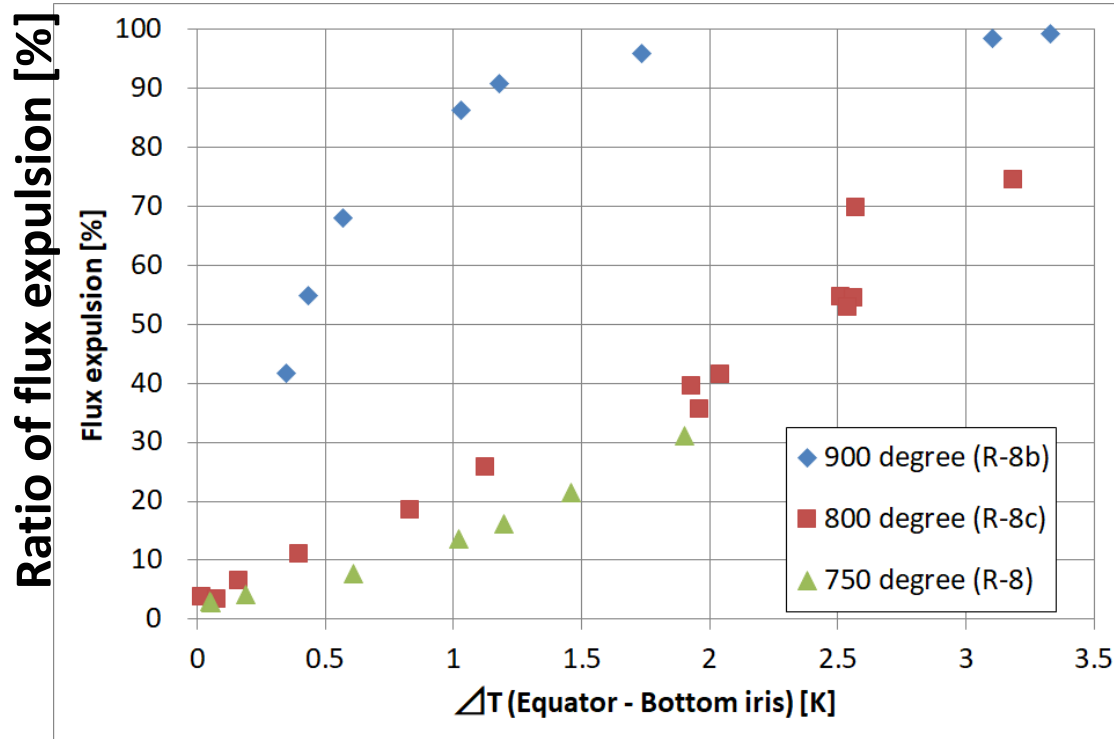
Magnetic Flux Trapping



No field enhancement

Qo and flux expulsion

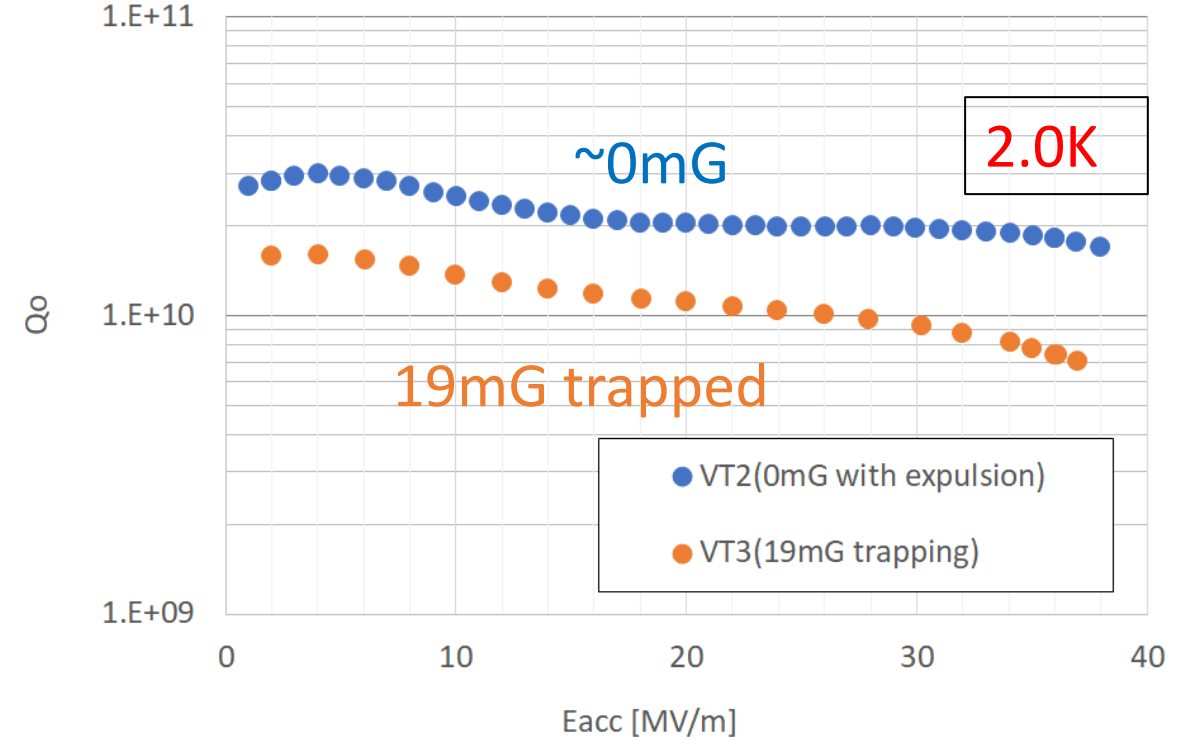
Flux expulsion is controllable.



Temperature difference at equator and iris[K]

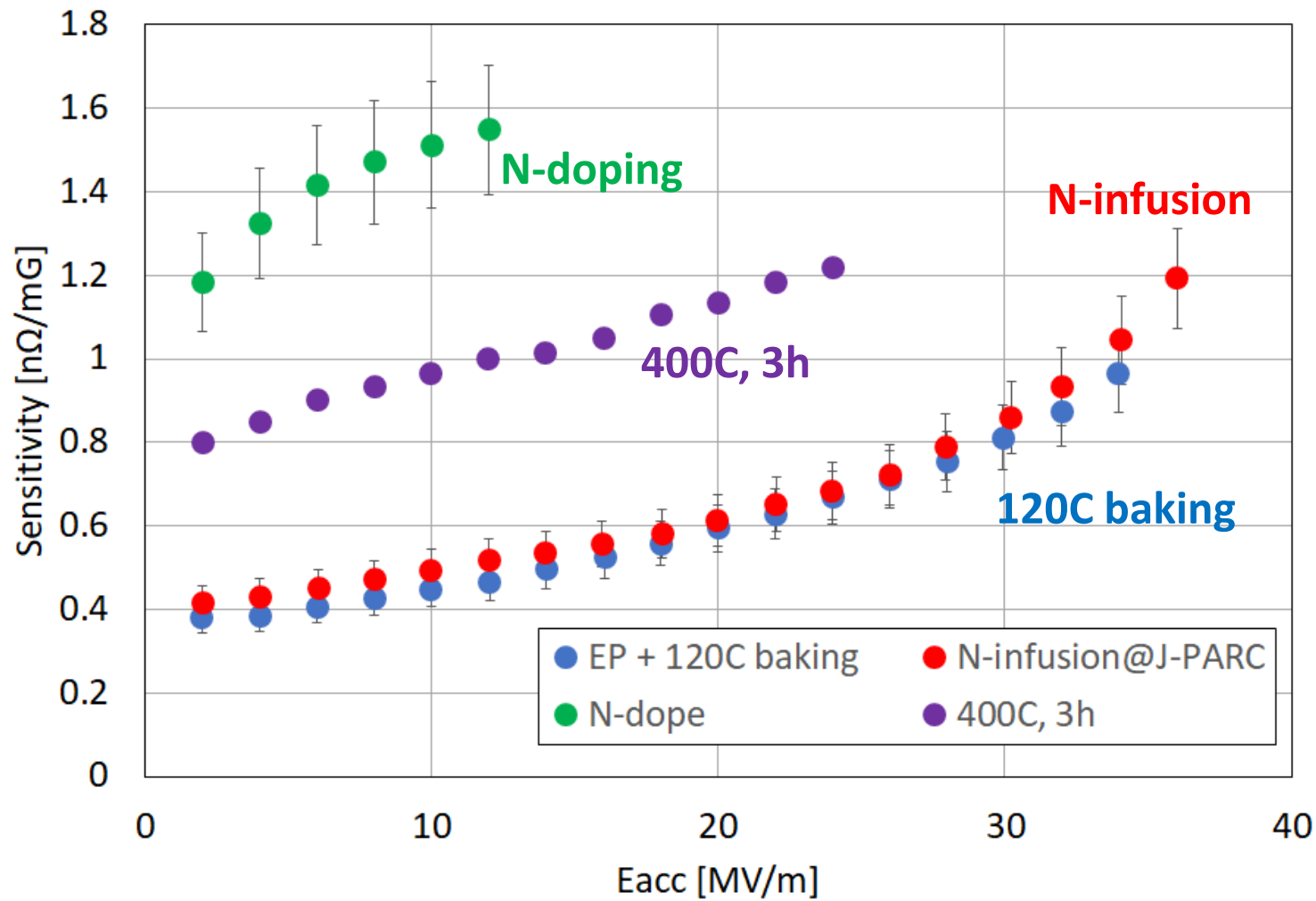
- Higher annealing temperature is effective for flux expulsion.
- Larger temperature gradient at T_c transition is effective for flux expulsion

R-8c N-infusion : Dependence on magnetic field Qo-Eacc@2.0K



- If magnetic flux is trapped to the cavity, the flux are shaken by RF field and become source of resistance.
 $\Rightarrow$ Degradation of Q-value (Increase of residual resistance)

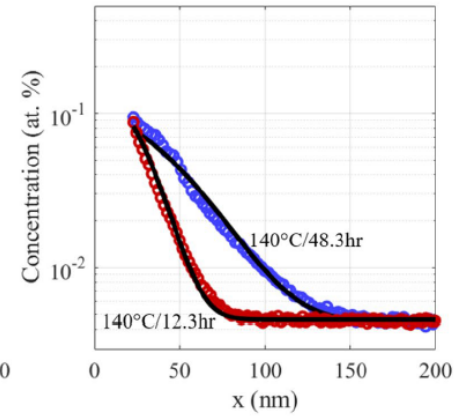
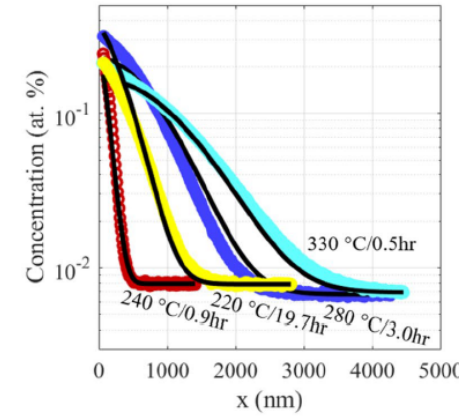
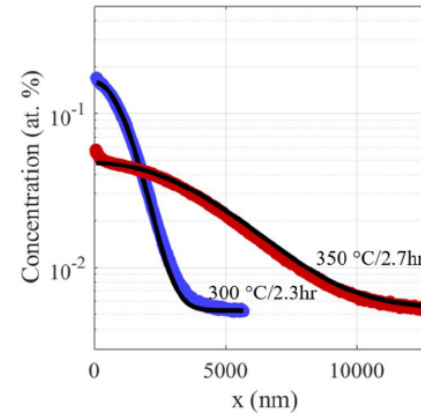
Sensitivity [$\text{n}\Omega/\text{mG}$] comparison



Sensitivity (trapped flux to residual resistance) for 400C, 3h is middle of N-infusion/EP+baking and N-doping.

Oxygen diffusion study (JLAB)

- Study of oxygen diffusion dependence on temperature and time.
- Measurement results by SIMS and simulation results are compared.
- Try to optimize the best condition of oxygen diffusion for best SRF performance.



- Measurements are consistent with Ciovati's model
- Predictability and ability to tune interstitials by changing only temperature and time of vacuum anneal
- Oxygen source is the native oxide

superficial dissolved oxygen

$$v_0 = 3.5 \text{ O \% nm}$$

$$E_{ad} = 119.9 \text{ kJ/mol}$$

$$D_0 = 0.075 \text{ cm}^2/\text{s}$$

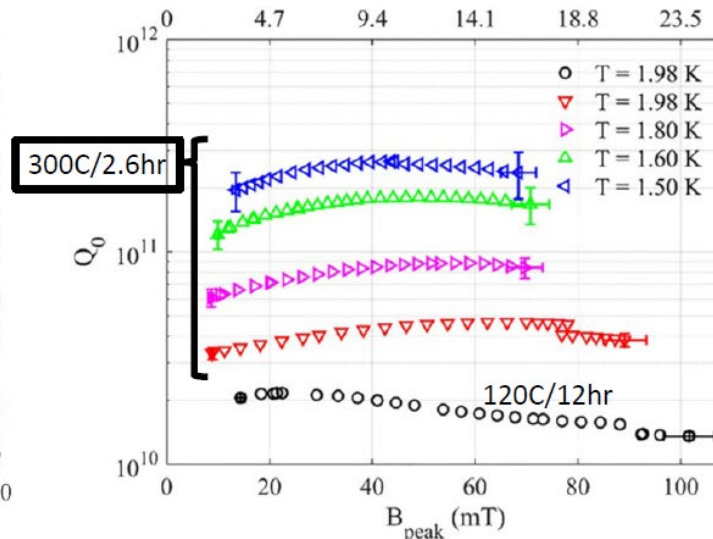
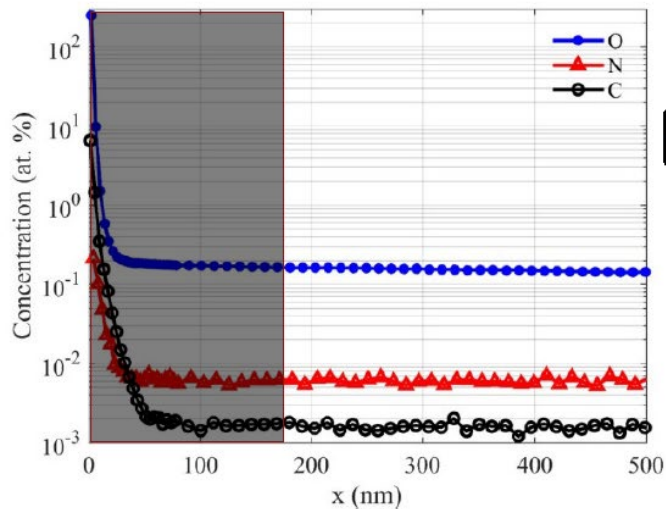
oxide dissolution

$$u_0 = 200 \text{ O \% nm}$$

$$E_{ak} = 131 \text{ kJ/mol}$$

$$A = 0.9 \times 10^9 \text{ 1/s}$$

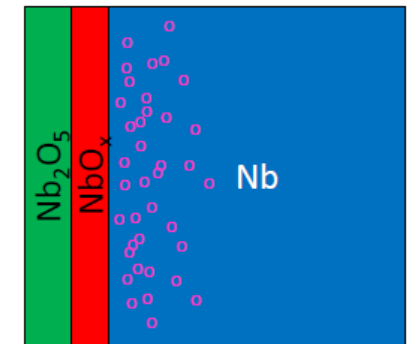
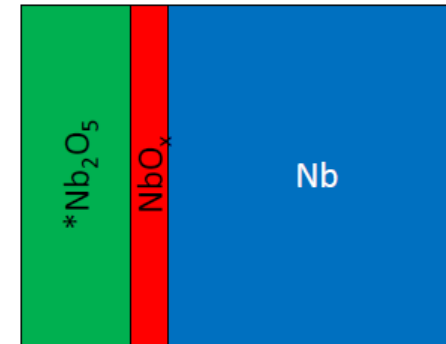
(b) E_{acc} (MV/m)



- High Q_0 still exists! Oxygen is the main alloying interstitial

Tuning Nb SRF Cavity Performance via Oxide Dissolution

13 Jefferson Lab

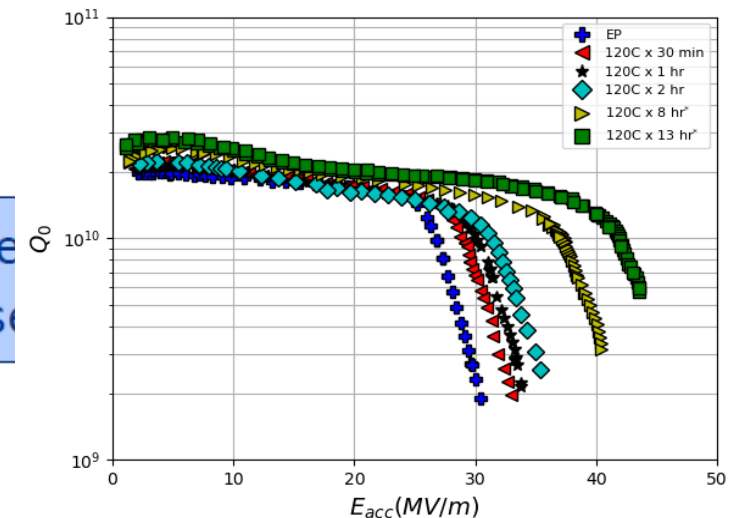
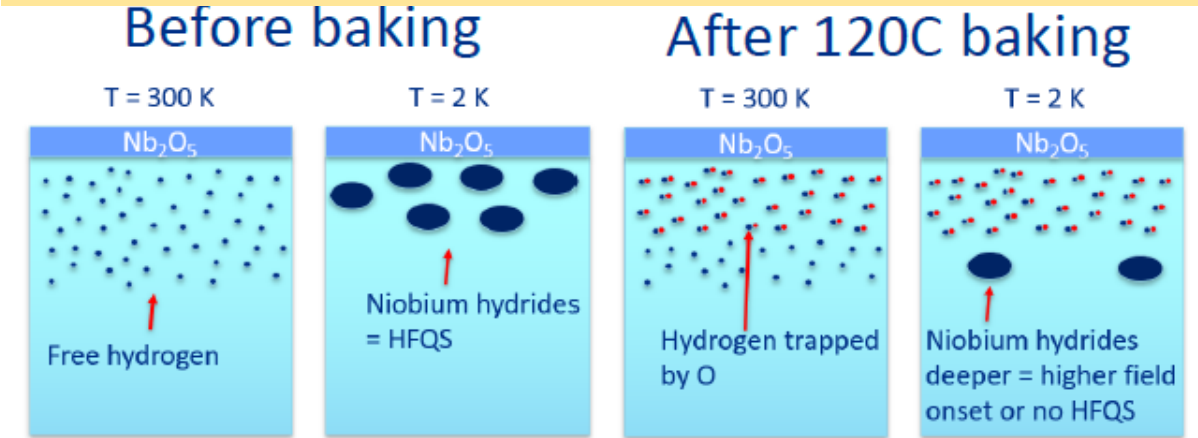
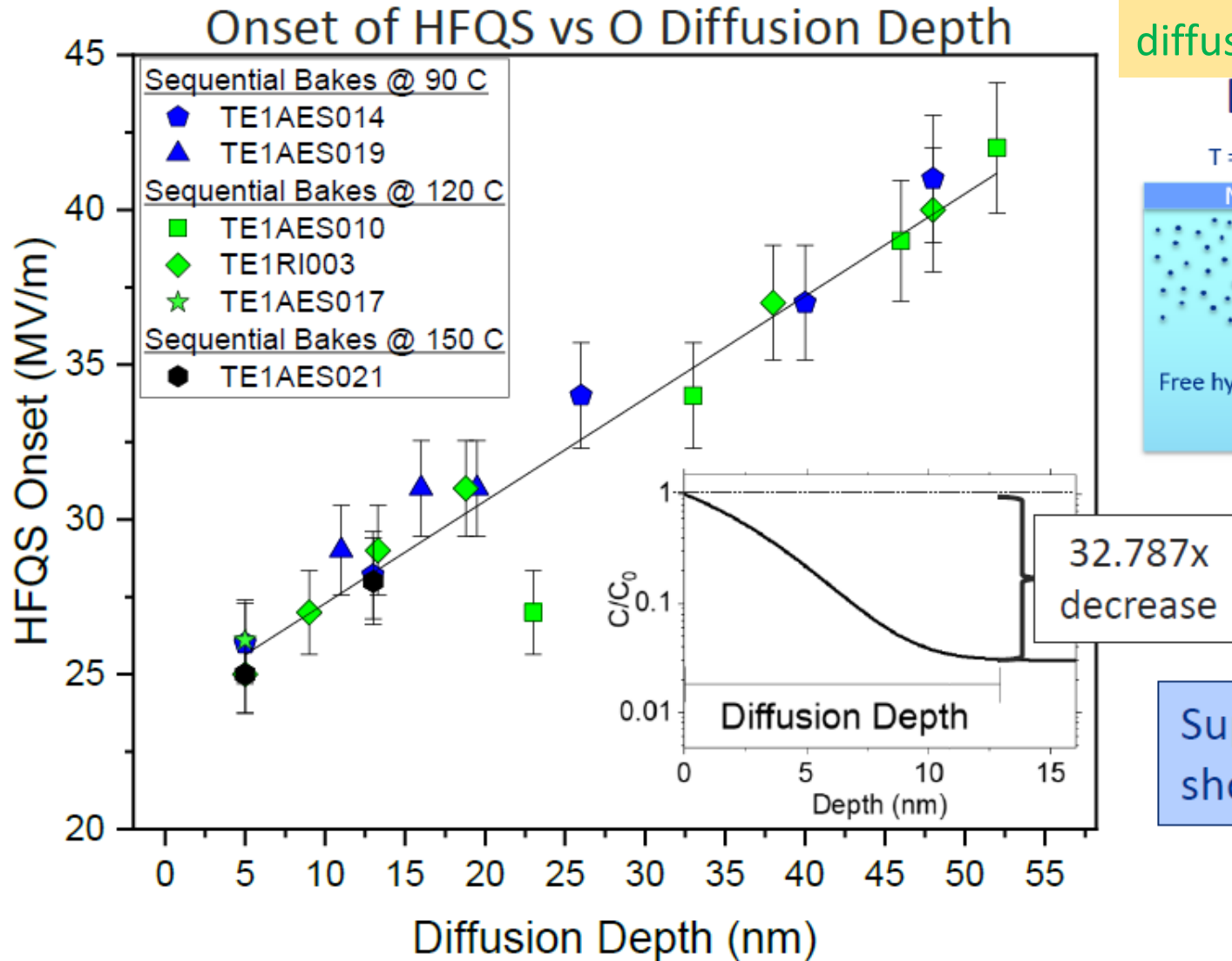


One-dimensional diffusion equation [1]

E. Lechner, "Tuning Nb Cavity Performance via Oxide Dissolution", TTC meeting (2022)

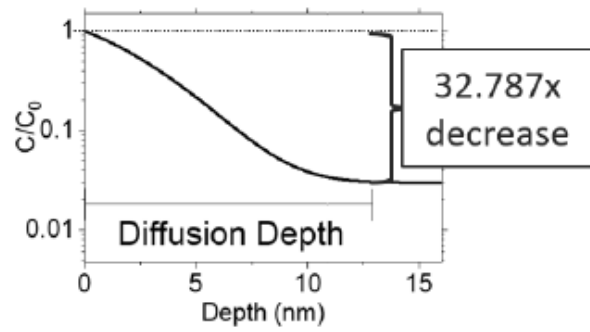
Solidifying the Role of O in the Mitigation of HFQS

Results show correlation between depth of oxygen diffusion and HFQS onset.

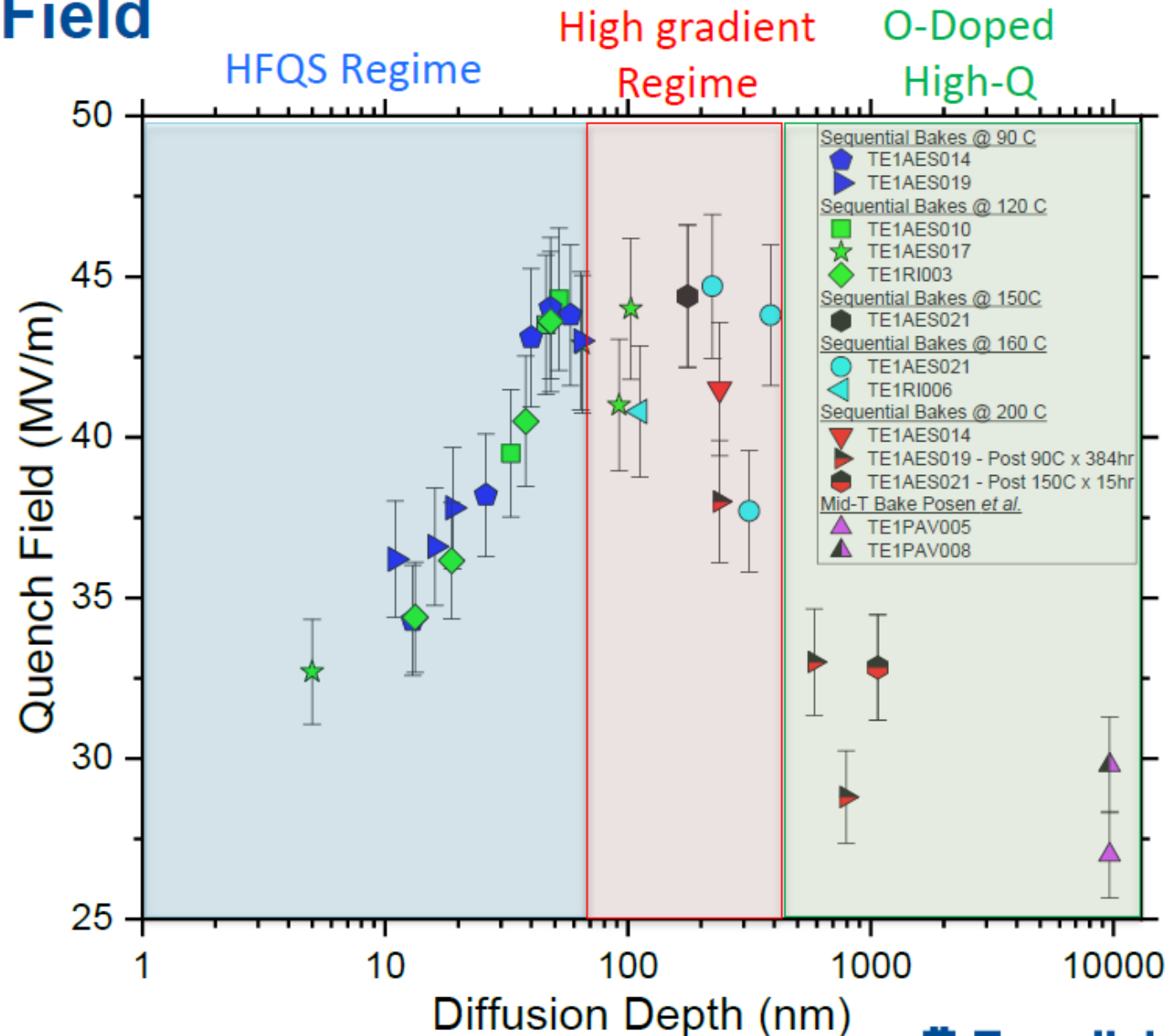


D. Bafia et al, Proceedings of SRF'2021, THPTEV016

Diffusion Depth vs Quench Field



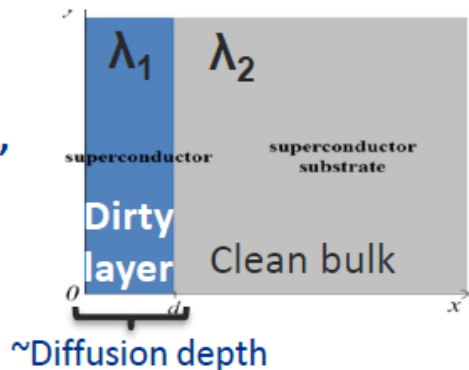
- Highest achieved quench field vs calculated diffusion depth
 - Only tests w/ no field emission shown
- Mid-T Bake data comes from Posen
S. Posen et al., PRA 13, 014024 (2020)
- Not clear if O diffusion depth or O concentration is relevant parameter





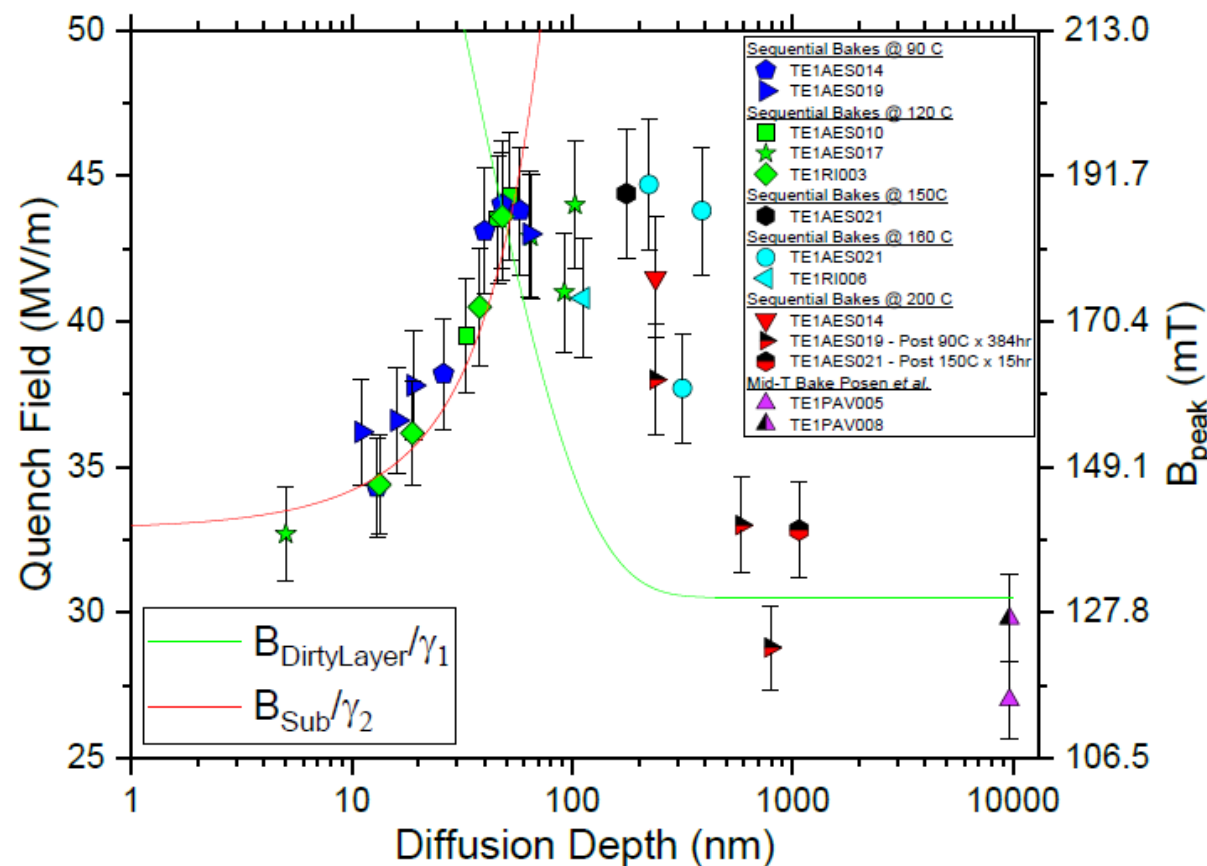
Possible Model: B Enhancement Due to SS Bilayer

T. Kubo, SUST, 30,
023001 (2017)



- Dirty layer drives **B** enhancement due to counterflowing current induced by substrate
- Calculation parameters:

Dirty Layer	Substrate
$\lambda_{\text{dirty}} = 105 \text{ nm} \rightarrow \ell = 6.6 \text{ nm}$	$\lambda_{\text{substrate}} = 40 \text{ nm}$
$B_{\text{Dirty Layer}} = 130 \text{ mT}$	$B_{\text{substrate}} = 140 \text{ mT}$
- Disagreement could be due to diffuse vs discrete interface $\rightarrow$ future work



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 - Cryomodule design
 - Cryomodule components
- Superconducting accelerator
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Cryomodule

Yasuchika Yamamoto
SRF2025 tutorial

Cryomodule consists from
various components to
accelerate beam

Detailed Drawing of ILC Cryomodule (TDR in 2013)

The cryo-vessel installing a cavity/cavities is called "**cryomodule**".

12.65m

Based on TESLA Technology

Frequency tuner

Cavity

Power coupler

Cryo-vessel

Radiation heat shield
(80K, 5K)

Support posts

Dozens of "super-insulation" layers

Helium gas return line (GRP)

80K Helium return line

8K Helium return line

40K Helium supply line

5K Helium supply line

2K Helium supply line

Cavity

Power coupler

Frequency tuner

Cross-sectional view (courtesy of DESY)

2020/09/19

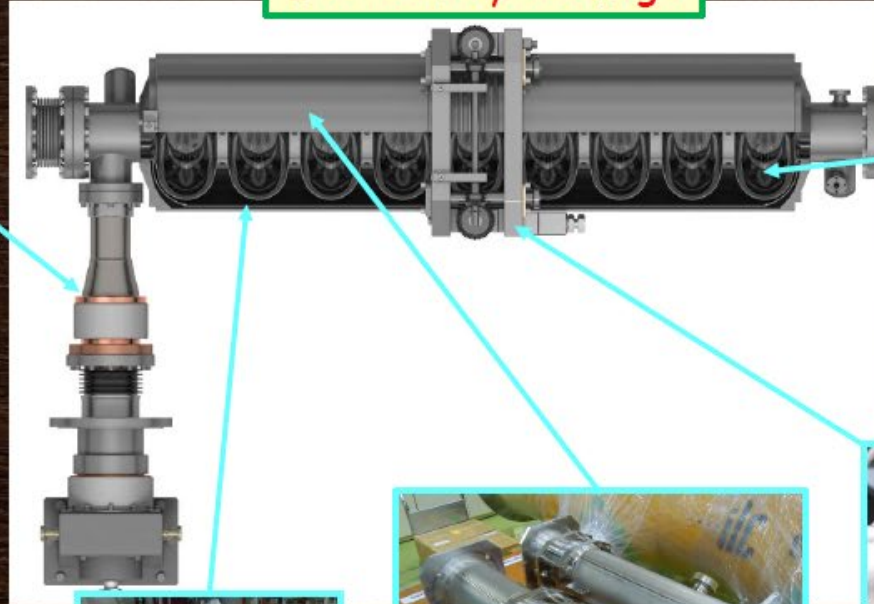


Cavity Package

Power coupler
(Copper plating on SUS316L)



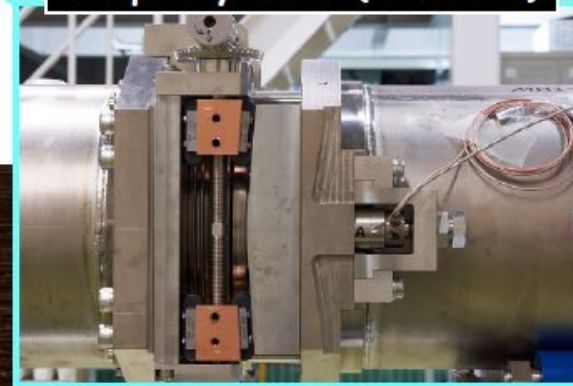
STF Cavity Package



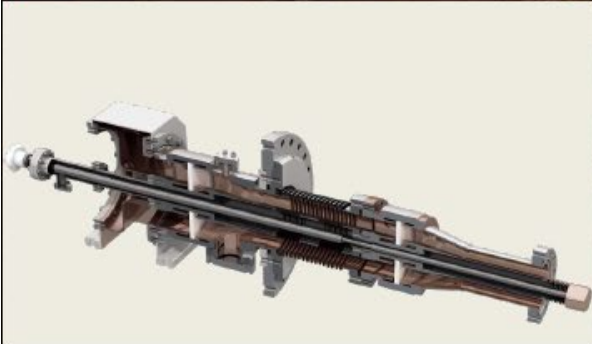
Cavity (Niobium)



Frequency tuner (SUS316L)



Cross-sectional view of power coupler
(double ceramic windows w/ TiN coating)



SRF CAVITY SYSTEM AND CRYOMODULE

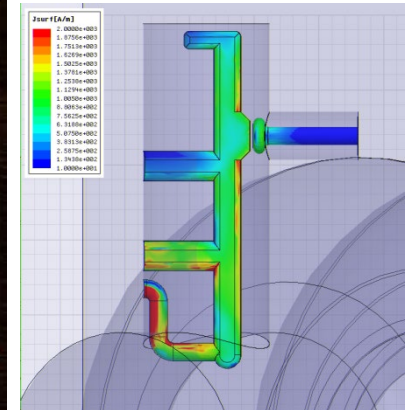
Helium tank (Titanium)



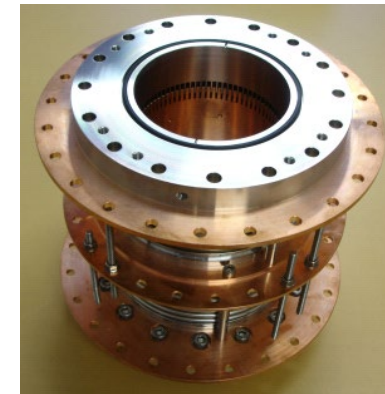
Magnetic shield (Permalloy)



HOM coupler



HOM damper



Outline



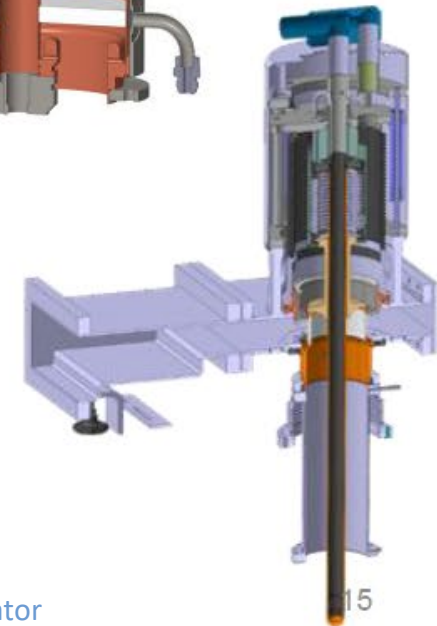
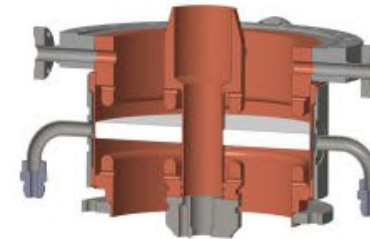
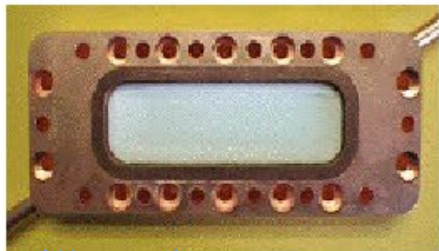
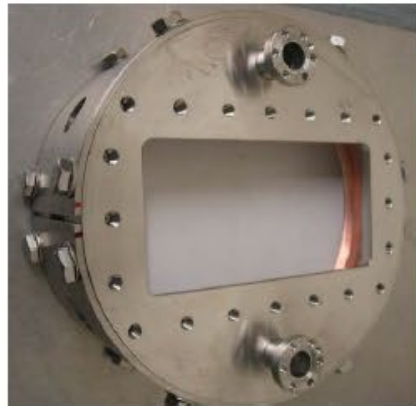
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Fundamental power coupler overview

TTC2025 tutorial
Wenkan Xu



Waveguide FPC	Coaxial FPC (circular Planar and cylindrical shell window)	Coupler feed RF power to the cavity. Cavity vacuum and air is separated by ceramics. Connect warm to cold sections.
❑ Simpler design ❑ Lower RF losses ❑ Lower surface electric field ❑ Easier to cool, but higher thermal radiation ❑ Fixed Qext	❑ More compact ❑ Smaller heat leak ❑ Easier to make variable ❑ Easier to handle multipacting ❑ Tunable Qext, but is complicated	



Frequency tuner

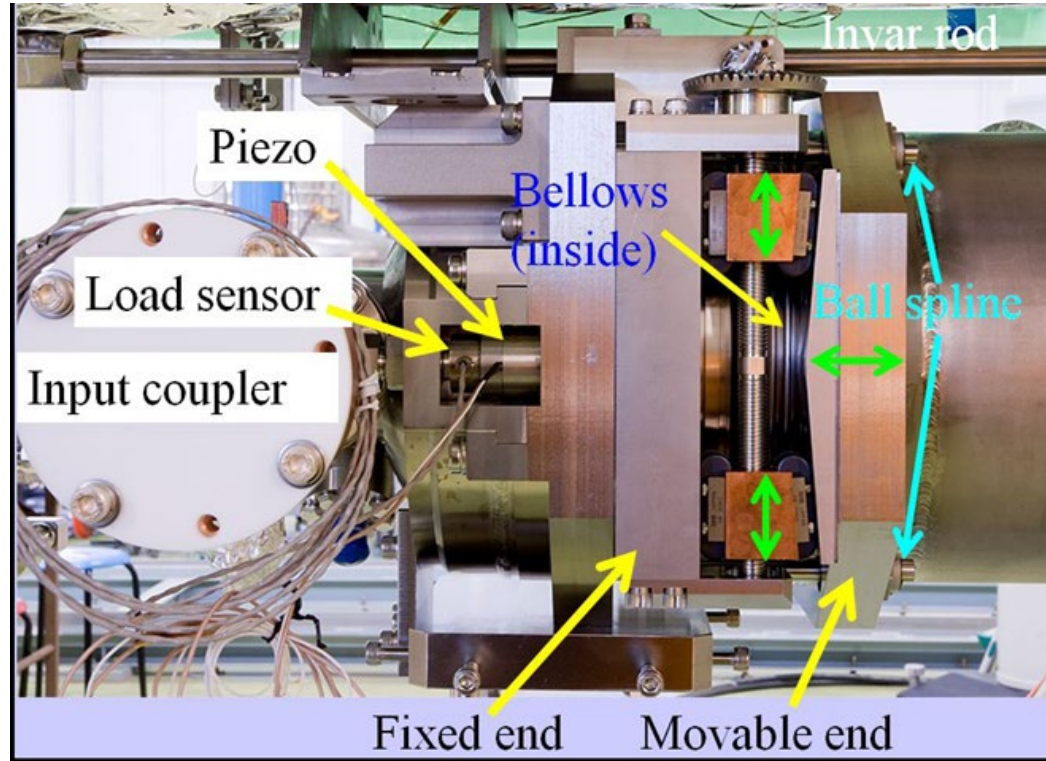
- Coarse tuning

- Mechanical tuner
- 3mm stroke for $\sim 900\text{kHz}$ change (typical spec.)
- Max. Torque $\sim 1\text{ton}$
- Controlled by motor through shaft

- Fine tuning

- Piezo tuner
- Stroke $> 4\mu\text{m}$ at low temp.
($80\mu\text{m}$ at room temp)
- Controlled by voltage
($100\sim\text{several } 100\text{ V}$)

Tuner system of STF cavity



Cavity frequency is controlled by frequency tuner

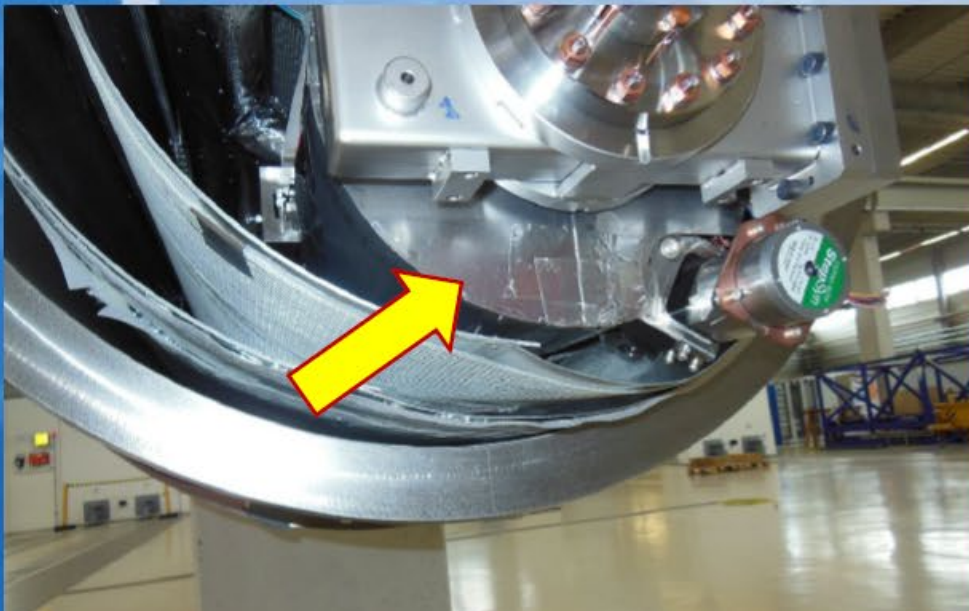
- Thermal shrinkage from RT to 2K: a few MHz
- He pressure, vibration: a few 100 Hz

Magnetic shield



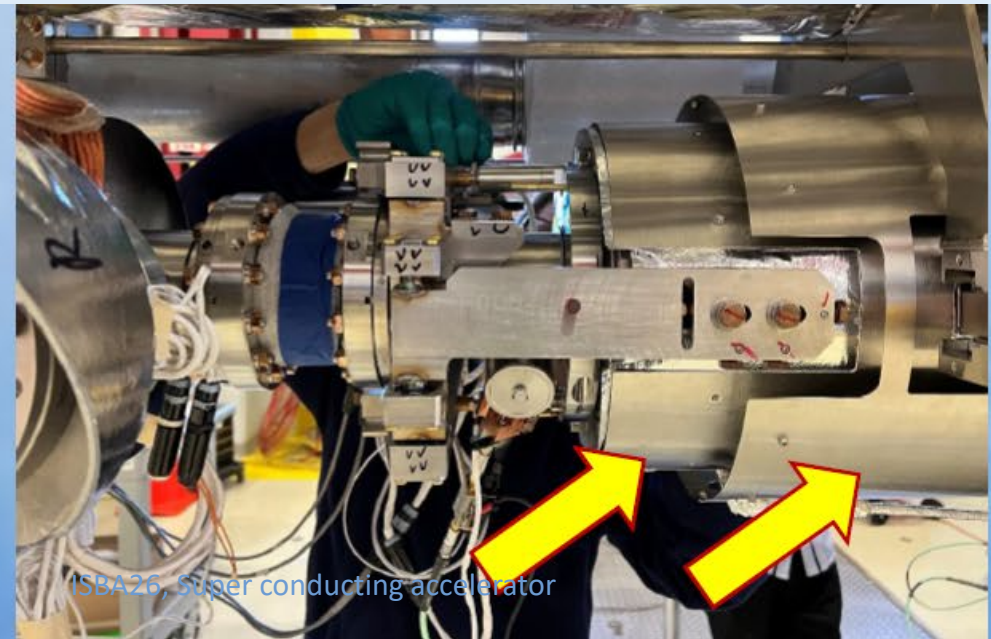
Generally, permalloy (mainly Fe-Ni) is used as magnetic shield.
E-XFEL is single shield and LCLS-II is double.
You need to consider the balance between running cost and production cost.

E-XFEL CM



LCLS-II CM

CW high-Q operation require $\sim 1\text{mG}$ level magnetic field



Pulse operation require $\sim 10\text{mG}$ level magnetic field

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ISBA26, Super conducting accelerator

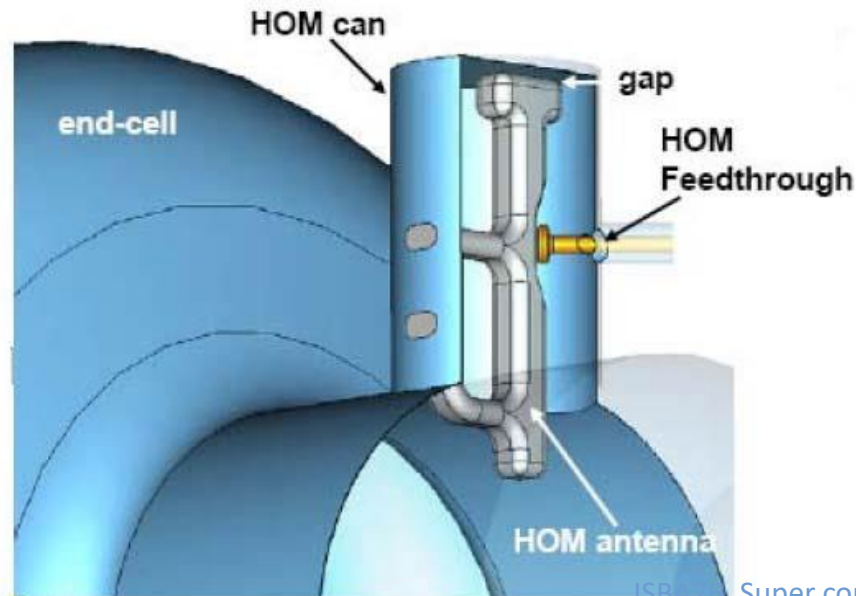
HOM coupler / HOM damper

HOM: Higher Order Mode excited inside cavity by beam.

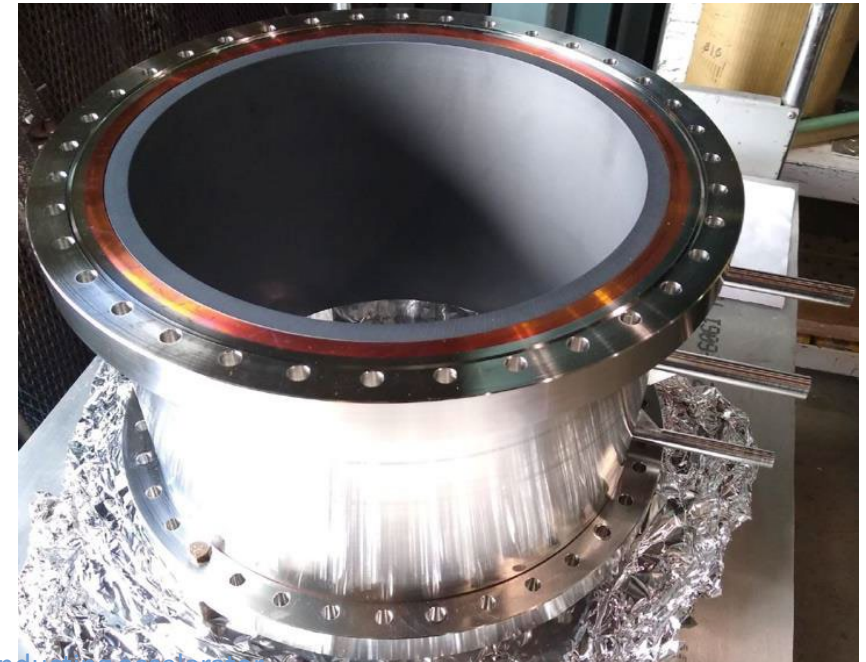
- HOM degrade beam quality. Could source of beam loss and beam current limitation.
- HOM is taken out by HOM coupler or absorbed by HOM absorber.



2026/10/21 Kensei Umemori



ISB/20, Super conducting accelerator



Outline



- Superconducting cavity
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SRF accelerator in the world



Fig. 7 Accelerator projects with SRF cavity system around the world.

Many SRF accelerators are operated and constructed world-wide.

Example of electron accelerator

- Euro-FEEL (17.5 GeV, pulse)
- LCLS-II (4~8 GeV, CW))
- SHINE (8 GeV, CW)

Example of proton, heavy ion accelerator

- FRIB (Heavy ion)
- ESS (Proton)
- PIP-II (Proton)

SRF Accelerator in Japan



RIKEN-Nishina

■ operation

● under construction

No. of cavity : frequency : cavity structure

underline: future project

QST-Rokkasho

● **IFMIF-LIPAc (deuterons)**

8 : 175MHz, HWR

A-FNS (deuterons)

8+10+12+12 : 175MHz, HWR

ILC ($e^- e^+$ collider)

8000 : 1.3GHz, 9-cell cavity

JAEA-Tokai

ADS (protons)

KEK-Tsukuba

■ **SuperKEKB ($e^- e^+$ collider)**

8 : 508MHz, 1-cell cavity

■ **cERL (electrons)**

3 : 1.3GHz, 2-cell cavity

2 : 1.3GHz, 9-cell cavity

■ **STF2 (electrons)**

2+12 : 1.3GHz, 9-cell cavity

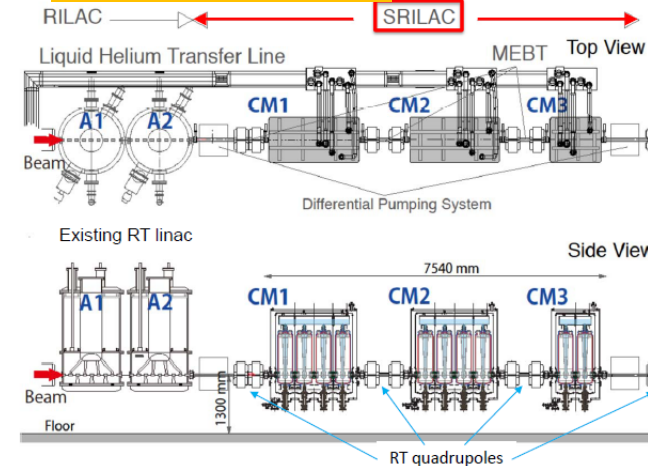
Multi-MW SC Proton Driver (protons)

● **SRILAC (heavy ions)**

4+4+2 : 73MHz, QWR

RIKEN SRILAC

Yamada, Sakamoto @TTC(CERN)



QST IFMIF-LIPAc

Kasugai, 14th Particle Accelerator Society of Japan (2017)

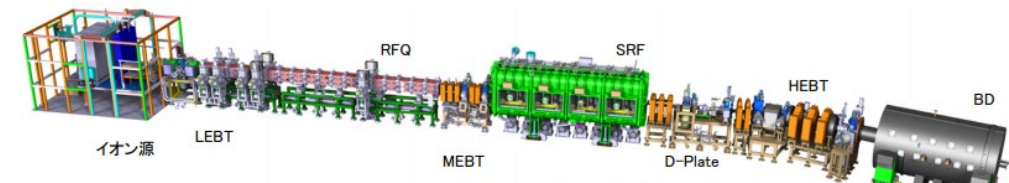
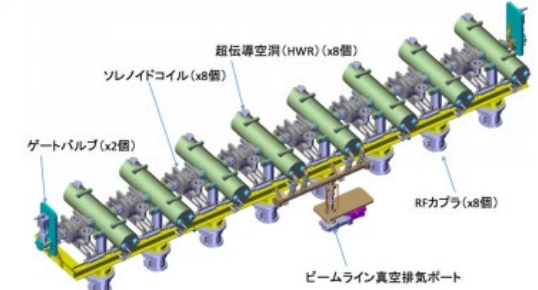
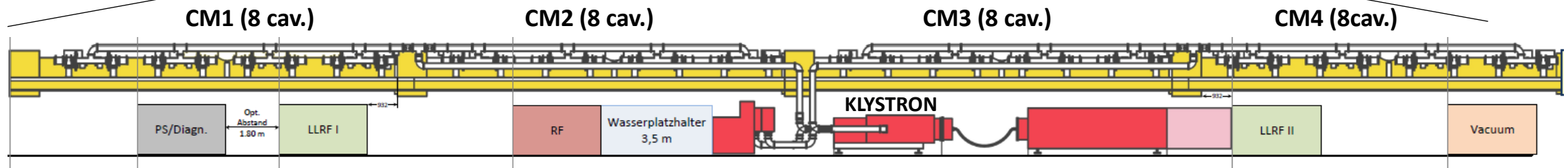
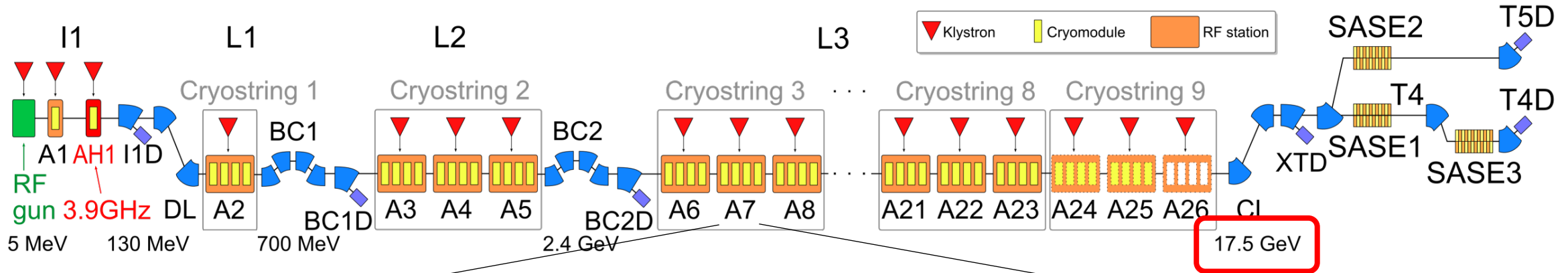


Figure 2: Conceptual design of the IFMIF-LIPAc



Eiji Kako, Journal of Cryogenics and Superconductivity Society of Japan (2019)

The European XFEL Accelerator : one RF station for 32 cavities



- 10 MW klystron to power 32 cavities
- one accelerating field RF control FB loop
- remote frequency tuning (motor / piezo) / cavity
- remote phase and external coupling tuning / cavity

- average coupler peak power 102 kW (140 kW) for low (high) runs
- average gradient **18.5 MV/m (22.5 MV/m)** for low (high) runs
- average detuning ± 10 Hz
- average $Q_{\text{ext}} = 4.6e6$ average $Q_0 = 1e10$

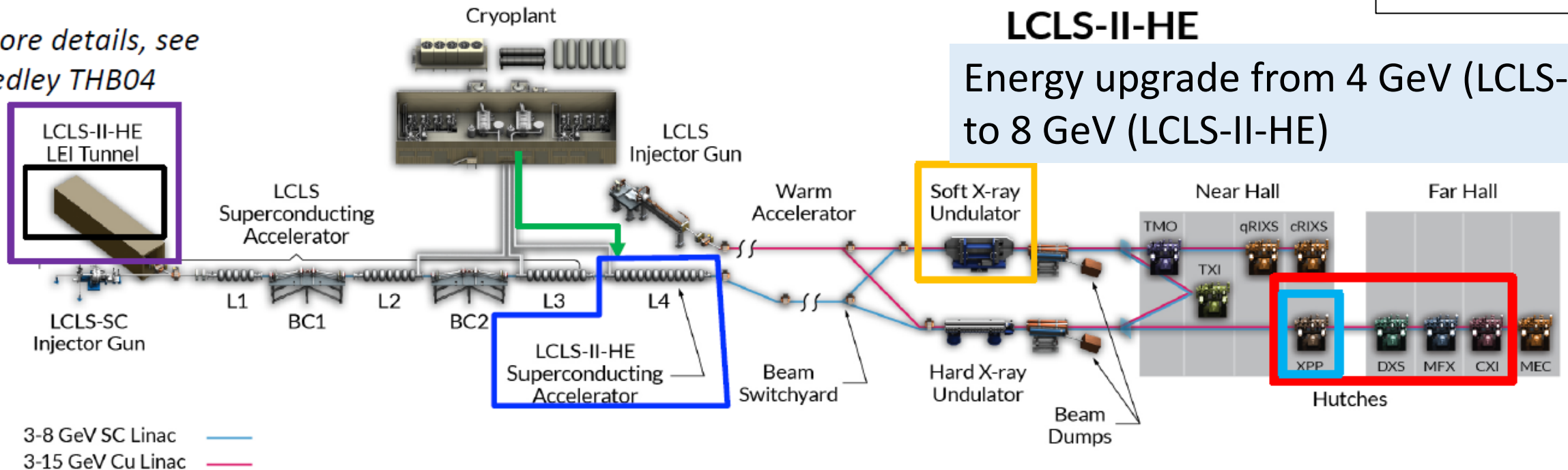
Pulse SRF accelerator for XFEL generation. 800 SRF cavities are used.

ISBA26, Superconducting accelerator

LCLS-II-HE: beamline installation starting in 2026

SRF2025,
Lauren Alsberg

For more details, see
J. Smedley THB04



1. Add 23 additional cryomodules (L4 linac) to double the LCLS-SC accelerator energy: 4 GeV to 8 GeV
2. Install new cryogenic distribution box and transfer line between the cryoplant and the new L4 linac
3. New long period soft X-ray undulator
4. Upgrade XPP instrument & enable hard X-ray photon beamlines for high average power and MHz beam rates
5. Construct new tunnel for future Low Emittance Injector (LEI)
6. Develop prototype SRF gun for the LEI

Heavy Ion accelerator.
SC-QWR are used for energy
upgrade.

2019

E: 6.5 MeV/u for $M/q=5$ → Super Heavy Elements: $Z \geq 119$

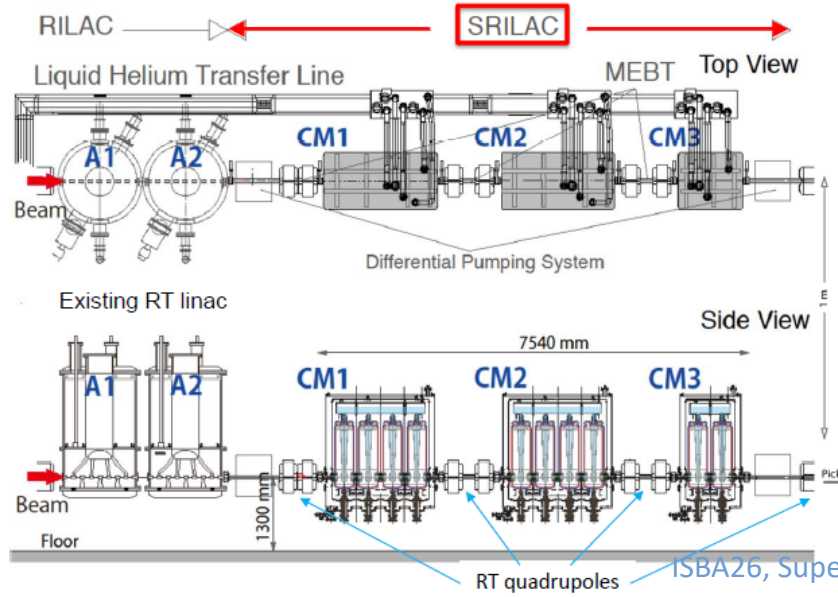
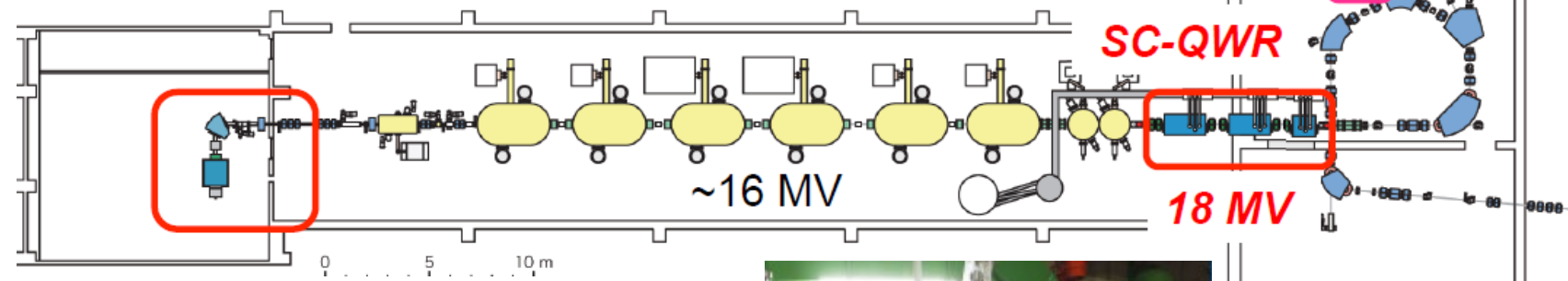
7.5 MeV/u for $M/q=4$

12 MeV/u for $M/q=2$

**RI production for
medical research**



28GHz SC-ECRIS



Yamada, Sakamoto
@TTC(CERN)



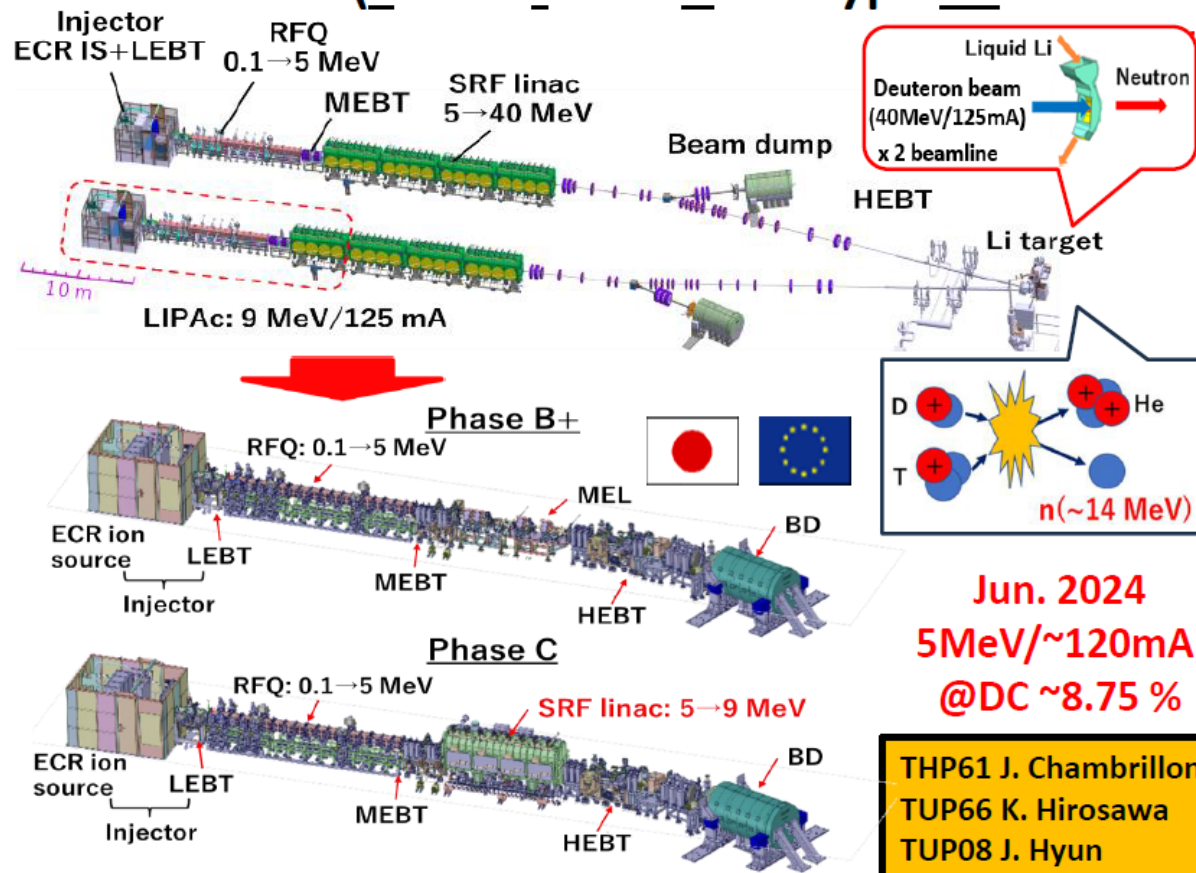
Figure 9: Photos of jacketed cavity: (1) Pre-assembly and
(2) Assembly #3 prepared for VT

RIKEN N. Sakamoto, LINAC2018

IFMIF & LIPAc project

IFMIF (International Fusion Materials Irradiation Facility)

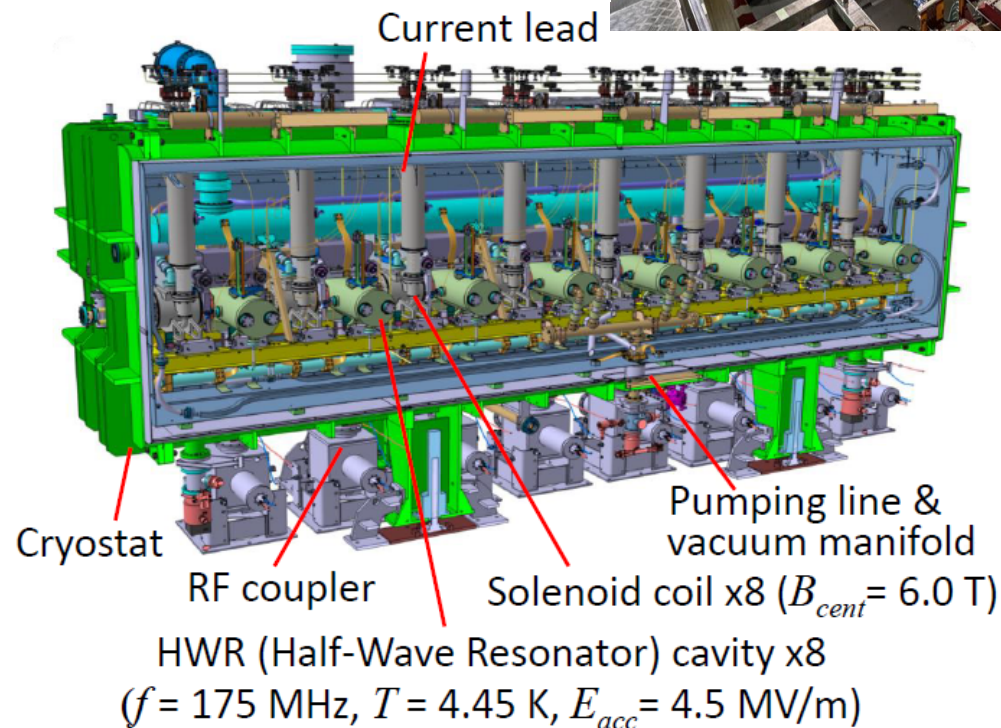
IFMIF & LIPAc (Linear IFMIF Prototype Accelerator)



The LIPAc project is ongoing at QST Rokkasho under the Broader Approach (BA) collaboration between EU and Japan.

2026/10/21 Kensei Umemori

LIPAc SRF cryomodule



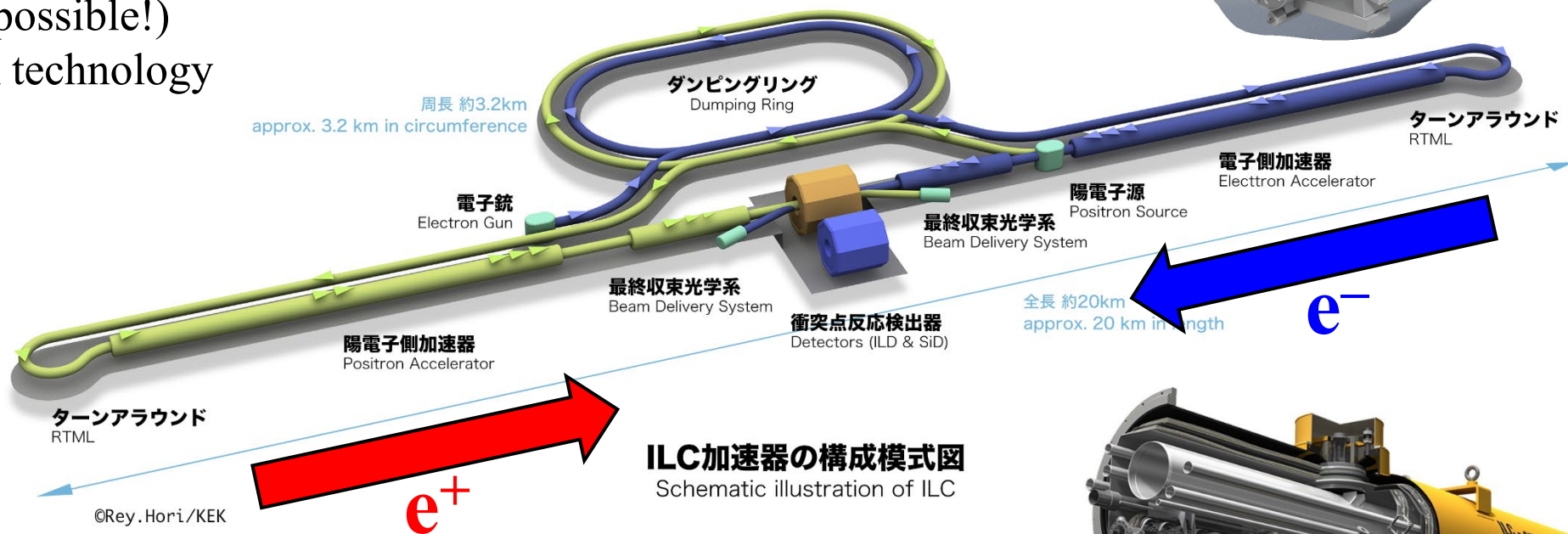
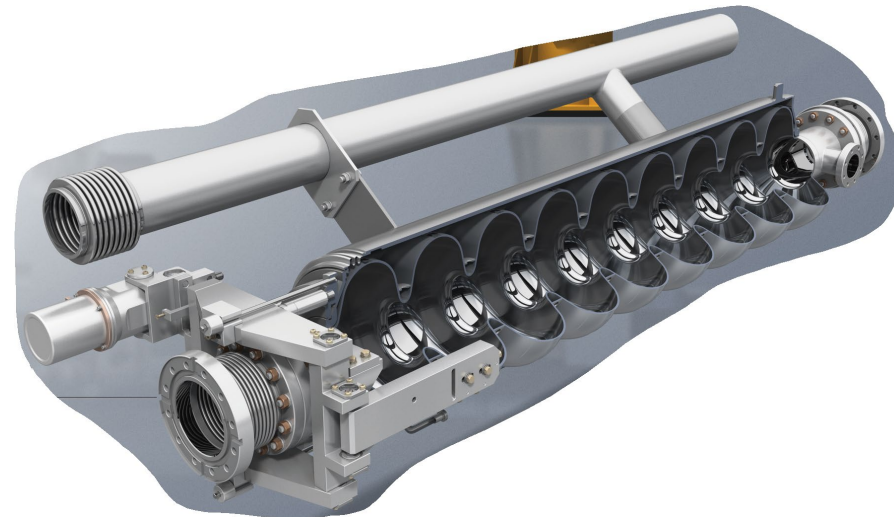
- HWR & cryogenics components : CEA
- Solenoid & current lead : CIEMAT
- RF coupler : CEA / conditioning : CIEMAT
- Assembly : F4E / legal & onsite support : QST

ISBA26, Super conducting accelerator



ILC project

- Higgs factory machine (250 GeV @ E_{CM})
- Superconducting cavity/cryomodule technology as mass production
 - Based on TESLA technology
 - ~800 cavities and ~900 Cryomodules (challenging number, but not impossible!)
- Nano beam technology



ILC Spec.	E_{acc}	Q_0
Vertical Test	35 MV/m	0.8×10^{10}
Cryomodule test	31.5 MV/m	1.0×10^{10}

>90% (successful rate)

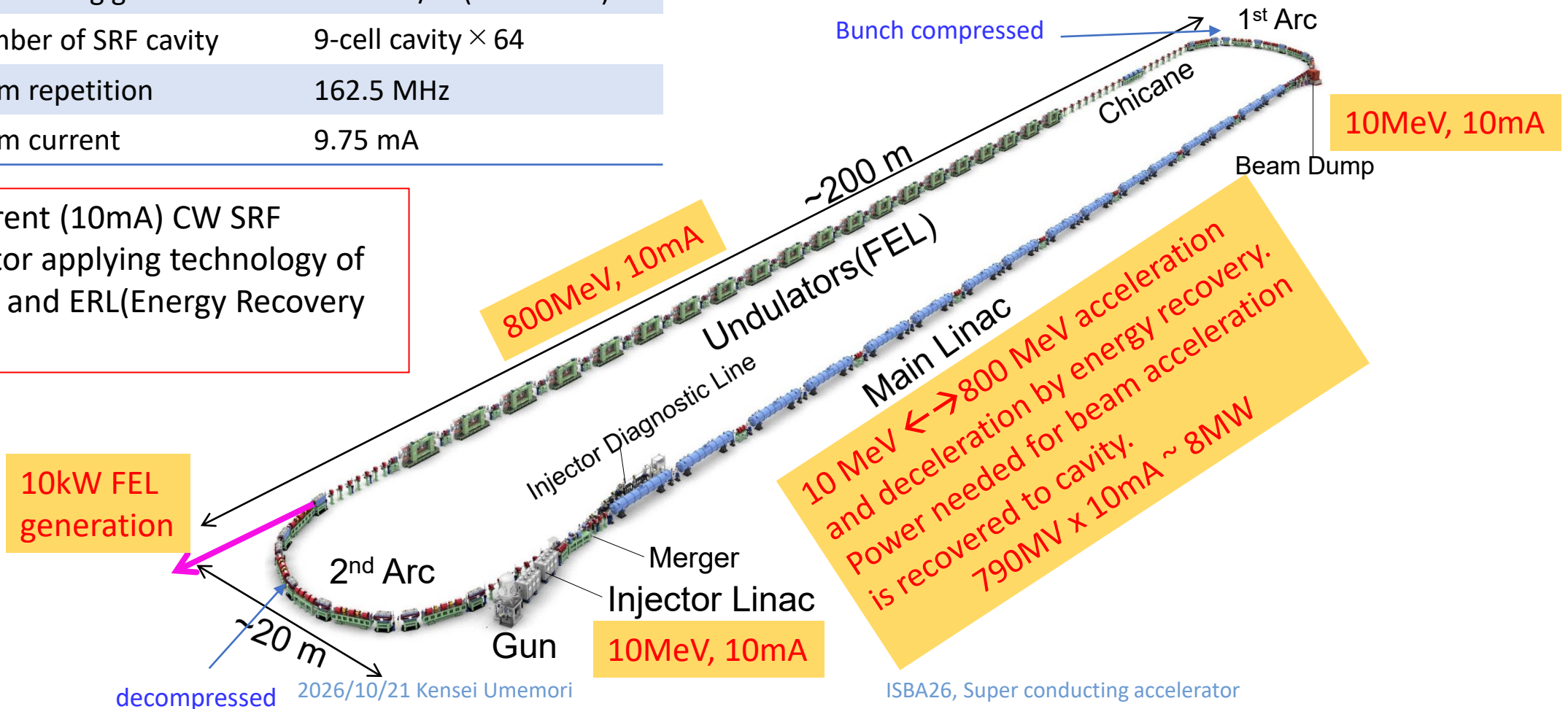
Parameter	Specification
Wavelength	13.5 nm
Output power	10 kW
Bunch charge	60 pC
Beam energy	800 MeV
Accelerating gradient	12.5 MV/m (main linac)
Number of SRF cavity	9-cell cavity $\times$ 64
Beam repetition	162.5 MHz
Beam current	9.75 mA

High current (10mA) CW SRF accelerator applying technology of SRF linac and ERL(Energy Recovery Linac)

Proposal of 10kW class ERL based EUV-FEL

✂ EUV: 13.5 nm light for lithography

Presented by Norio NAKAMURA
ERL2015 (<https://www.bnl.gov/erl2015/>)



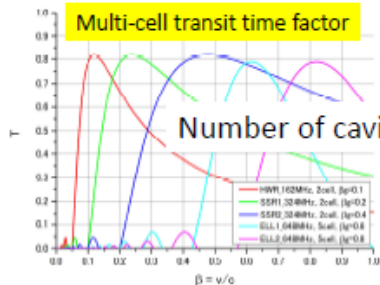
JAEA-ADS Linac

CW proton linac

- final beam energy : 1.5 GeV
- beam current : 20 mA



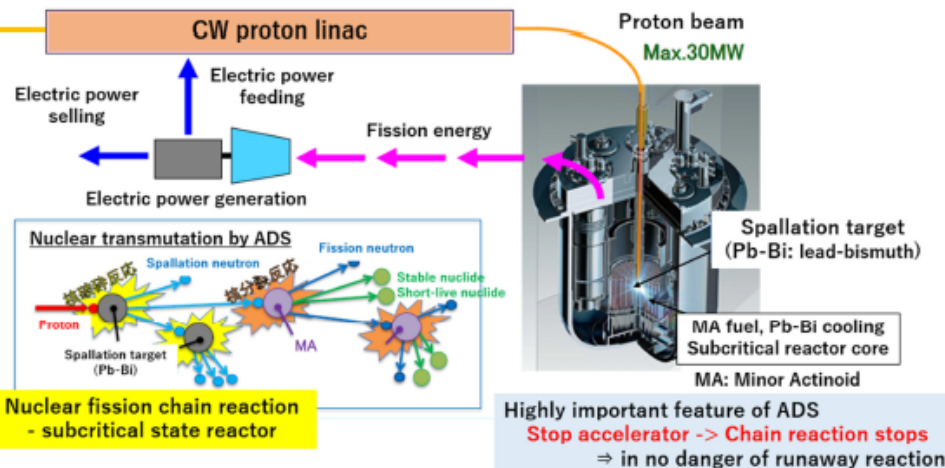
RFQ : Radio-Frequency Quadrupole
HWR : Half-Wave Resonator
SSR1 : Single-Spoke Resonator (low- β)
SSR2 : Single-Spoke Resonator (high- β)
ELL1 : Elliptical cavity (low- β)
ELL2 : Elliptical cavity (high- β)



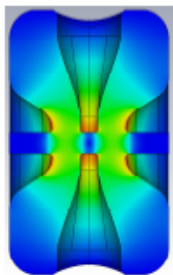
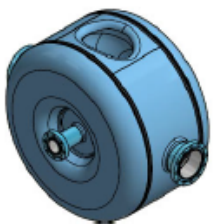
Number of cavity required for JAEA-ADS

- $\beta g = (0.1, 0.2, 0.4, 0.6, 0.8)$
- $E_0 = (8.0, 8.0, 8.0, 16.0, 16.0)$
- $\Phi_s = -30$ deg

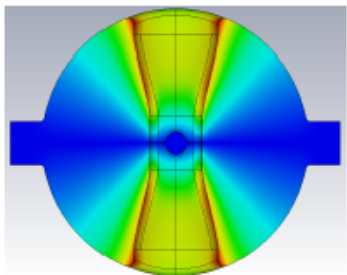
	f_0 [MHz]	Num. of cell	βg	β_{opt}	E_0 [MV/m]	$\beta g \lambda / 2$ [m]	Cavity L [m]	W_{out} [MeV]	Num. of cavity	Total L [m]
HWR	162	2	0.10	0.119	8	0.093	0.185	16	14	2.6
SSR1	324	2	0.20	0.239	8	0.093	0.185	66	50	9.3
SSR2	324	2	0.40	0.478	8	0.185	0.370	141	37	13.7
ELL1	648	5	0.60	0.615	16	0.139	0.694	409	40	27.8
ELL2	648	5	0.80	0.820	16	0.185	0.925	1508	115	106.4
合計									256	159.8



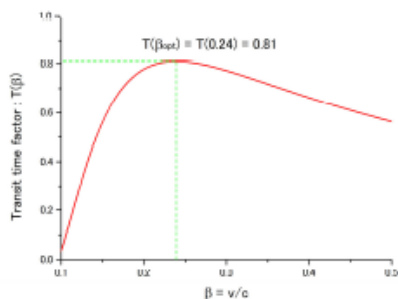
Prototype Spoke Cavity (SSR1)



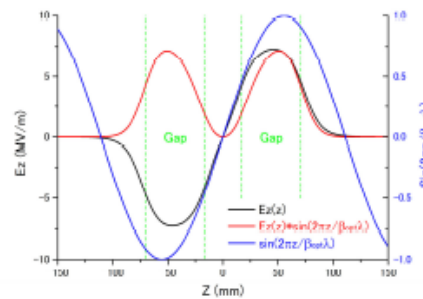
E-field



H-field



Transit time factor and optimal beta



Ez field distribution

Cavity parameter of the prototype spoke cavity

Frequency : f_0	324	MHz
Geometrical beta : β_g	0.188	
Optimal beta : β_{opt}	0.24	
Beam aperture	40	mm
Gap length	54	mm
Cavity diameter	≈ 500	mm
Cavity length	300	mm
Effective length : $L_{eff} = 2 \times (\beta_{opt} \lambda / 2)$	222	mm
Geometry factor : $G = Q_0 R_s$	90	Ω
Transit time factor : $T(\beta_{opt}) = V_{acc} / V_0$	0.81	
R over Q : $R_{sh} / Q_0 = V_{acc}^2 / \omega W$	240	Ω
E_{peak} / E_{acc}	4.1	
B_{peak} / E_{acc}	7.1	mT/(MV/m)

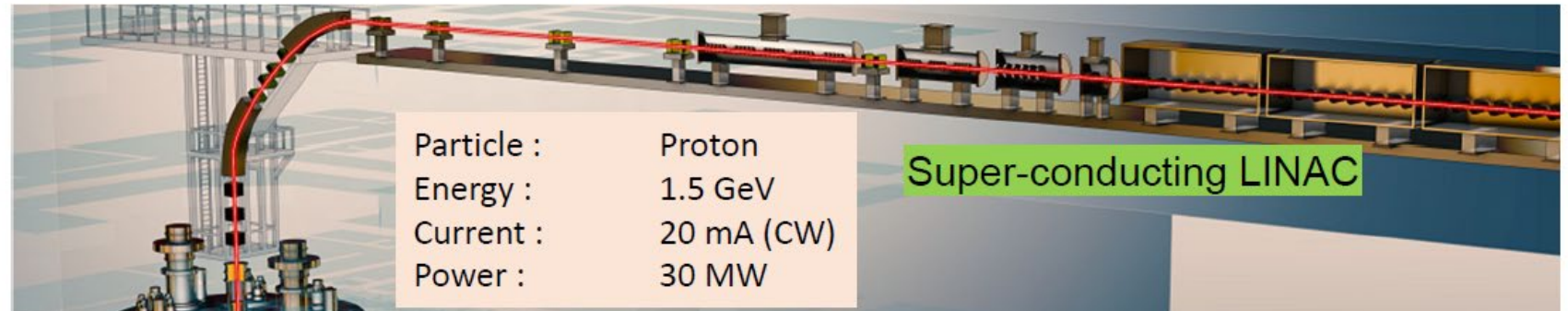
ADS proposed in JAEA

JAEA has been proposing an ADS as a future nuclear system.

In the JAEA-ADS, a high-power (30 MW) proton beam with a final beam energy of 1.5 GeV is required.

Because the accelerator needs to be operated in CW mode, a SC linac would be a suitable solution.

4th J-PARC symposium
J. Tamura

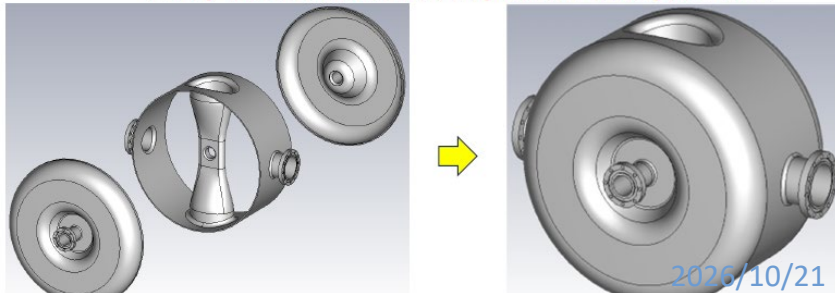


Cavity fabrication in 2024

Major three parts (body, lid-a, lid-b) has been fabricated so far.



Cavity fabrication is to be completed in fiscal year 2024.



Proposed acceleration structure of the JAEA-ADS linac



RFQ : Radio-Frequency Quadrupole
HWR : Half-Wave Resonator
SSR1 : Single-Spoke Resonator (low- β)
SSR2 : Single-Spoke Resonator (high- β)
ELL1 : Elliptical cavity (low- β)
ELL2 : Elliptical cavity (high- β)

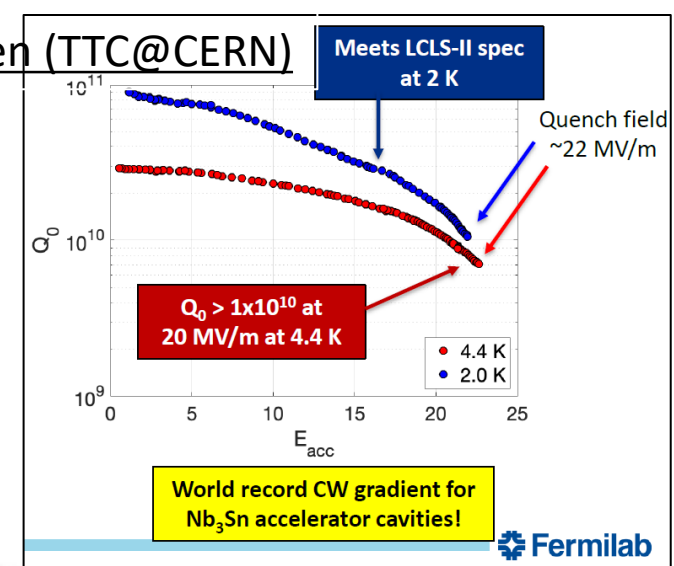
Design of compact Nb₃Sn accelerator for irradiation experiment

- Nb₃Sn SRF cavity can achieve $Q > 1e10$ at 4K.
- Conduction cooling by cryo-cooler can be possible.

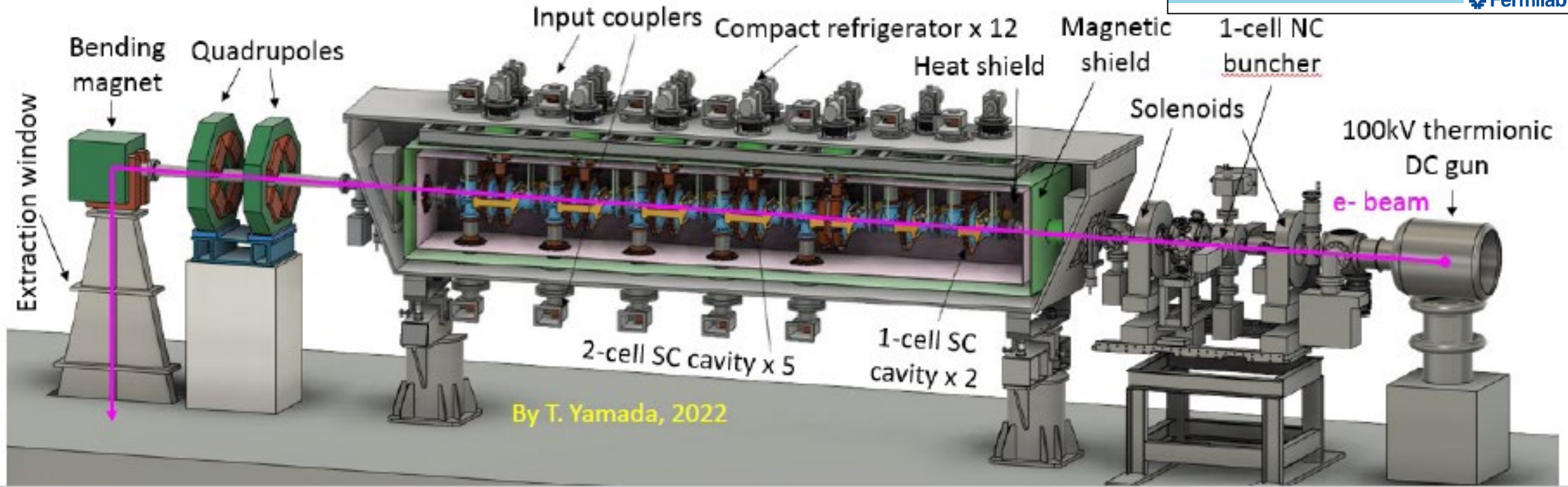


He free
compact SRF
accelerator

S. Posen (TTC@CERN)



Oliga Tanaka, TTC meeting at Aomori



Outline



- Superconducting cavity
 - Introduction
 - Pillbox cavity and mulch-cell cavity
 - Performance limitation
 - Basic RF parameter
- Surface treatment for higher performance
 - Surface treatment and hydrogen
 - Various high-Q/high-G surface treatment
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 - Cryomodule design
 - Cryomodule components
- Superconducting accelerator
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Challenge for high gradient SRF cavity



Nb SRF cavity is now close to theoretical limitation of surface magnetic field.

How to improve the performance higher?

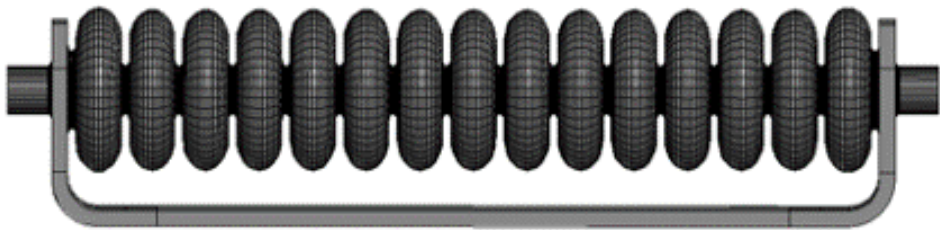
With Nb SRF cavity

- Optimization of surface treatment and cavity shape
- Traveling wave structure
- Improve average performance

Trial for non Nb cavity

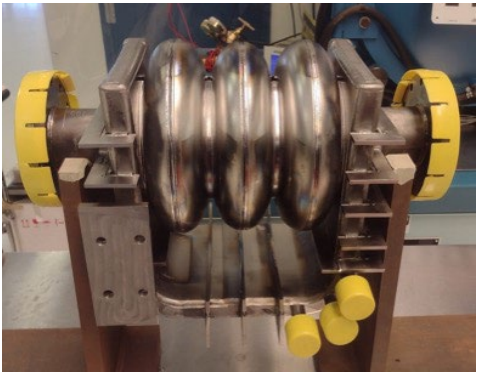
- Coating technology, Nb₃Sn, etc.
- Multi layer structure

Traveling wave cavity



Feature of TW cavity

- TW cavity is efficient, have higher transit time factor.
⇒ Can achieve higher accelerating gradient
- Most technology is common with SW cavity



If we can go to Nb theoretical limit with TW structure, > 70 MV/m is possible



Parameter	SW(TESLA)	TW	Comparison
E _{pk} /E _{acc}	2.0	1.64	18% lower
B_{pk}/E_{acc}	4.26	2.73	56% lower
R _{sh} /Q[Ω/m]	998	2367	137% higher

PRAB 25,
021001 (2022)

TABLE IV. Parameters of an optimized cell with the limiting surface fields $E_{pk}^* = 120$ MV/m and $B_{pk}^* = 200$ mT; $L - A = 5$ mm, aperture radius $R_a = 20$ mm. E_{acc}^* is the accelerating rate when the limiting surface fields are achieved.

Optimization	120/200
Phase advance θ , deg	90
A, mm	23.826
B, mm	35
a, mm	3.874
b, mm	6.777
E_{pk}/E_{acc}	1.639
B_{pk}/E_{acc} , mT/(MV/m)	2.732
R_{eq}/Q , Ohm/m	2367
α , degrees	91.74
R_{eq} , mm	97.990
v_{gr}/c	0.009315
E_{acc}^* , MV/m	73.2
$E_{acc}^* \times 2L$, MV	4.22

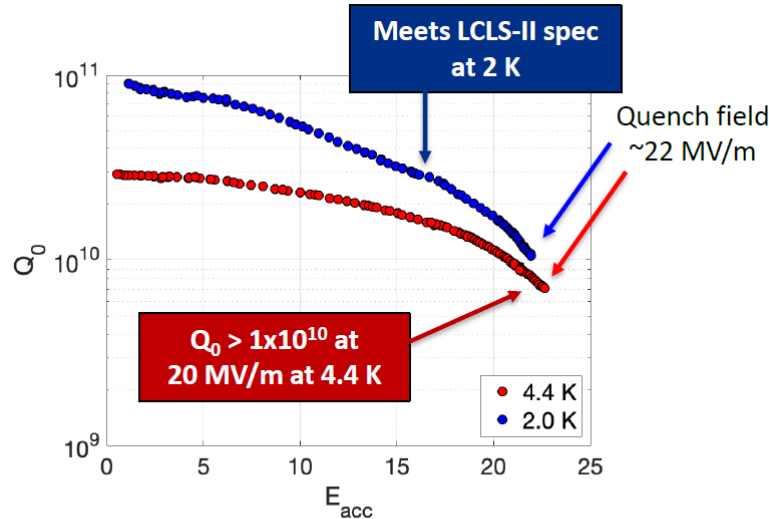


TTC2023, Fumio Furuta

Nb3Sn cavity development

- Nb3Sn coating inside Nb or Cu cavity
- Feature of Nb3Sn
 - High T_c : $\sim 18\text{K}$
 $\Rightarrow$ high Q ($1e10$) at 4K
 - High H_{sh} : 430mT
 $\Rightarrow E_{acc} \sim 80\text{MV/m}$
- Possible to realize compact He free SRF accelerator, cooled by cryo-cooler
- Beam test of Nb3Sn cavity performed at IMP and JLAB.

> 20MV/m performance of Nb3Sn cavity



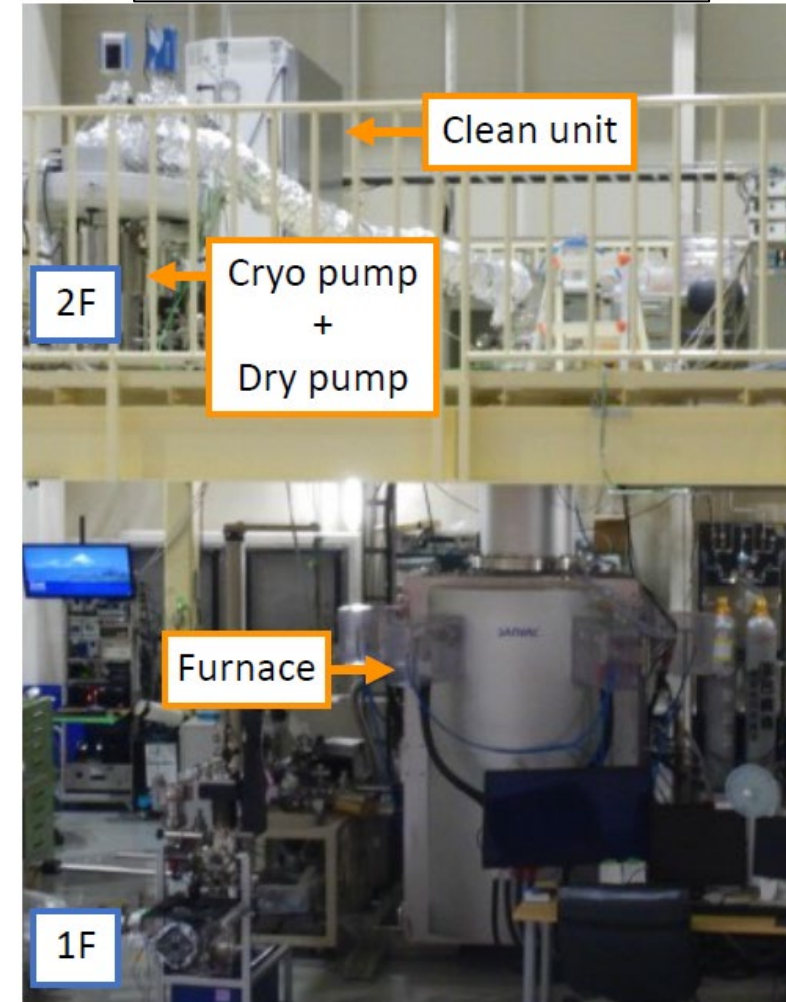
World record CW gradient for Nb₃Sn accelerator cavities!

Fermilab



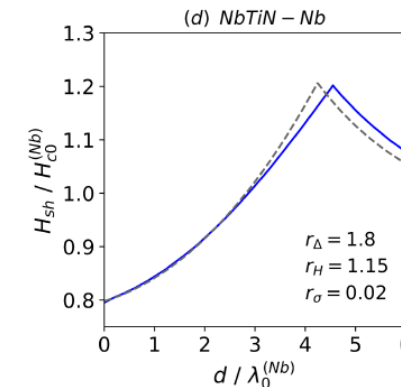
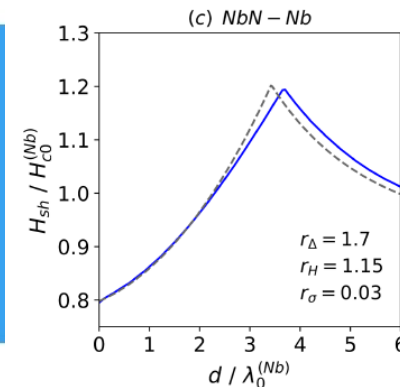
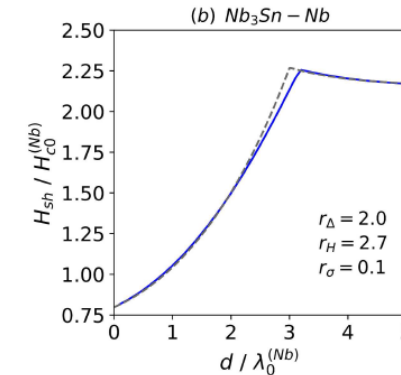
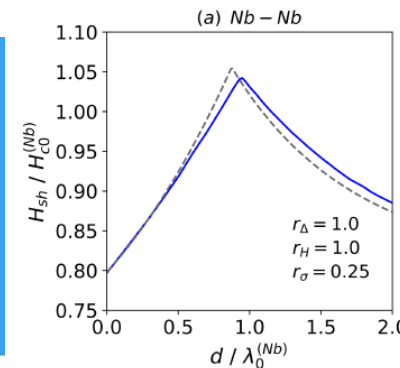
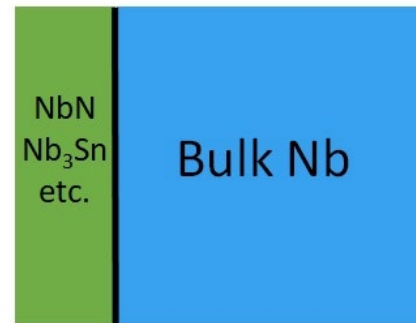
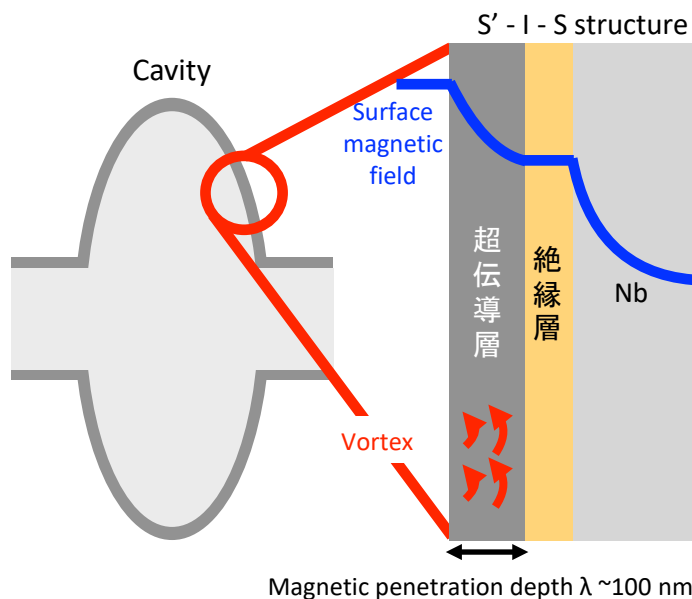
S. Posen (TTC@CERN)

TTC@Aomori, Hayato Ito



Multi-layer / SIS structure

- Multi-layer structure on cavity surface is promising approach to improve acceleration gradient (~ 100 MV/m?)
- Could enhance the theoretical field-limit from theoretical studies
- It is confirmed at the sample level
- Now trial is also on going for cavities



- A. Gurevich, Appl. Phys. Lett. **88**, 012511 (2006).
- T. Kubo, Y. Iwashita, and T. Saeki, Appl. Phys. Lett. **104**, 032603 (2014).
- A. Gurevich, AIP Adv. **5**, 017112 (2015).
- S. Posen et al., Phys. Rev. Applied **4**, 044019 (2015).
- T. Kubo, Supercond. Sci. Technol. **30**, 023001 (2017).
- V. Ngampruetikorn and J. A. Sauls, Phys. Rev. Research **1**, 012015 (2019).
- T. Kubo, arXiv:2006.12003

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Summary



- I introduced SRF cavity and SRF accelerator.
- Due to superconductivity, very small surface loss is one of merit of SRF cavity.
- Research have been carried out to improve cavity performance, to realize higher acceleration gradient and higher Q.
- Cavity performance is very sensitive to surface treatment procedure. Several procedures have been developed.
- To accelerate the beam, cavity is installed into the cryomodule with surrounding components, such as input coupler, HOM absorber, etc.
- SRF accelerators have been mainly operated for academical use, but now a days its usage is extended to industrial use too.

Announcement (Job opening at KEK)



ACCL26-2 Assistant Professor

Job No.	ACCL26-2	https://www.kek.jp/wp-content/uploads/2026/09/accl26-2e.pdf https://www.kek.jp/en/career/accl26-2e https://www.kek.jp/ja/career/accl26-2j Or contact me, e-mail: Kensei.umemori@kek.jp
Title	Assistant Professor	
Number of Job Opening	A few people	
Inst/Lab	Accelerator Laboratory	
Term	Until March 31st,2030 at the latest with the contract renewal every Japanese fiscal year. *The contract update is determined by the following: (1) Work performance, Work attitude (2) Ability of workers (3) Amount of work at the expiration contract period (4) The need for business (5) Situation of budget	
Start of the term	As early as possible after acceptance is notified	
Appl. Deadline	Application due date (to reach KEK) is before noon on Thursday, November 19, 2026 (JST)	

Job Description

The successful candidates will belong to the Accelerator Laboratory as an assistant professor employed under “ Fundamental Technology Development for Free-Electron Lasers Toward an Innovative Next-Generation EUV Lithography Light Source” project under the “ Next-Generation Semiconductor Processing Technology” of the “ Program for the Development of Key Technologies for Economic Security (K-Program)”. The candidate will be expected to engage in R&D’s related to one of the following areas, (1) superconducting RF cavities and RF technology, (2) high-current electron beam sources, (3) high-power lasers, or (4) beam dynamics and machine control in energy-recovery linacs. The workplace is the KEK Tsukuba campus. (In principle, there will be no changes to job description or work location.)