High pressure gas safety and cavity performance in MEXT-ATD/ITN

2024/Dec/16

IHEP-KEK collaboration meeting

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Outline

- Target of SRF cavity development
- Status of High Pressure Gas Safety application
- Surface treatment and expected performance of SRF cavity
- Summary

Target for SRF cavity development

- **Cavity fabrication**
  - Fabricate FG and MG TESLA-type 9-cell cavities
- **Apply High Pressure Gas Safety (HPGS) act in Japan**
  - First application to Refrigeration safety regulation
  - Application for Japanese domestic and over-sea cavities
- **Apply optimum surface treatment**
  - 900C heat treatment
  - 2-step baking
- **Confirm the performance of the cavity**
  - VT: Eacc > 35 MV/m, Qo > 1e10(@35MV/m or Eacc(max))
    - ✓ Eacc acceptance: 35 MV/m ± 20%(7 MV/m)
  - CM: Eacc > 31.5 MV/m, Qo > 1e10(@31.5MV/m or Eacc(max))
  - More than 90% acceptance ratio is required.

5-years plan for SRF cavities

Production Schedule of Cavity and Ancillaries for 5-year Plan (FY starts from April in Japan)

		JFY2023				JFY2024				JFY2025				JFY2026				JFY2027			
		CY2023			CY2024				CY2025				CY2026				CY2027				CY2028
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Fabrication	1-cell FG				1	3															
	1-cell MG					2															
	9-cell FG	1 (prototype)				2				1											
	9-cell MG					1 + 1 (training?)				1											
	9-cell MG (oversea)				press test					2											
VT	VT for recipe establishment																				
	VT for success yield																				
He tank	Helium tank wedling							training													
CM	Cavity string assembly																				
	CM production																				
	CM assembly																				
	CM test ① w/ low power																				
	CM test ② w/ high power																				

prototype: following HPGS

training: not following HPGS

※ EU/US/Asia have plan to fabricate HPGS regulated SRF cavities.

Japanese domestic cavity

FY2023～FY2025：Cavity fabrication

FY2024～2026 spring：Surface treatment

2026 summer～2026 end：He jacket welding

Over-sea cavity

FY2025：Cavity fabrication

～2026 spring：Surface treatment

2026 summer～2026 end：He jacket welding

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Present status of HPGS application for SRF cavities

- Preparing documents for KHK (The High Pressure Gas Institute of Japan) for FG cavity with He jacket.
- Completed mechanical test for all materials (Nb, NbTi, Ti and welding sample)
- Stress analysis of the SRF cavity with He tank was completed.
- Document was submitted to KHK at September.

We prepared document for

- First cavity which will be fabricated at KEK-CFF
- FG cavity
- 900C heat treatment
- ILC cavity (TESLA shape + short & short beam tubes) design
- Apply for refrigerator safety regulation

Our strategy on HPGS application to KHK

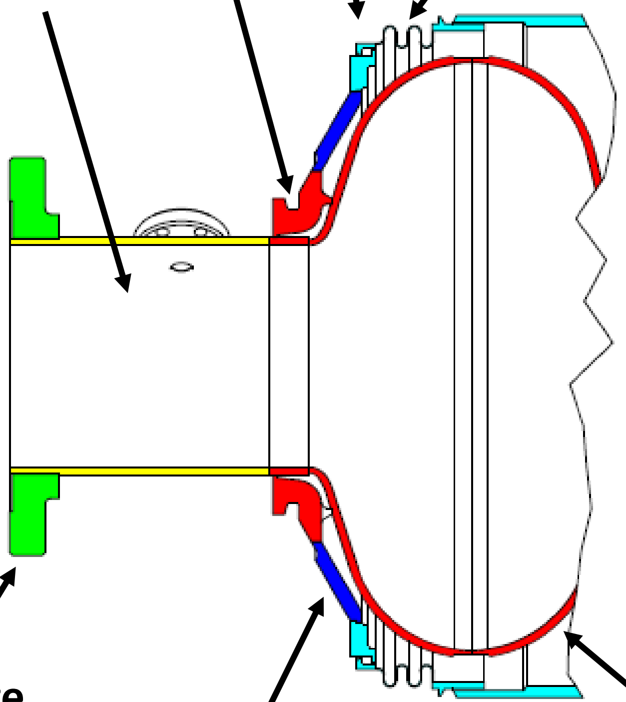
- We prepare following 3 applications separately to KHK
  - Cavity & He jacket
  - Chimney (Ti/SUS clad material) ⇒ clad material might have another difficulty
  - 2-phase pipe (SUS)

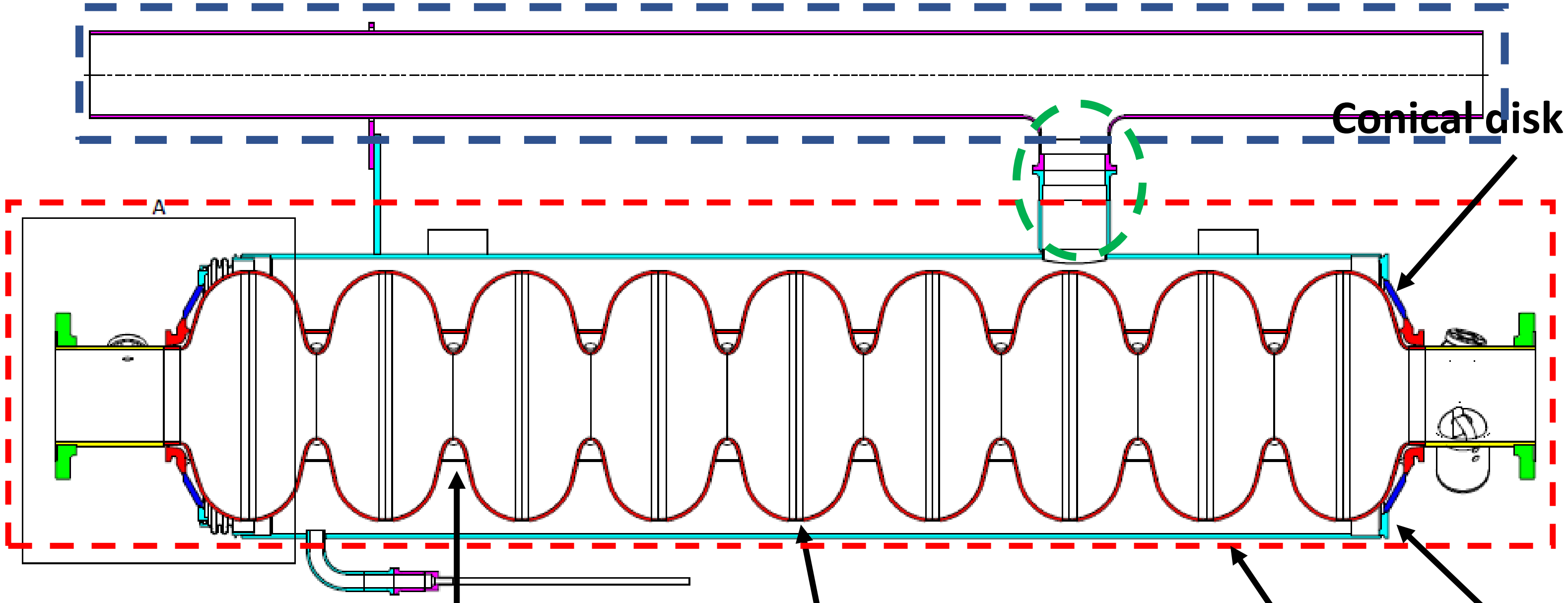
- Now we mostly concentrate on the application of “cavity + He jacket”.

Later, we will combine these 3 components. And also joint the pipes for CM/cryogenic connection.

Red ：Cavity(Nb)
Yellow ：Beamtube (Nb), out of HPGR
Blueが ：Conical disk (NbTi)
Green ：Flange (NbTi), out of HPGR
Light blue ：He jacket (Ti)
Purple ：Pipe (SUS316L)

Inside Red box: Cavity + He jacket (Nb & Ti & NbTi)
Inside Green circle: Chimney (SUS/Ti clad material)
Inside Purple box: 2-phase pipe (SUS316L)





Contents of “Special technology standard”

- Following issues which are not described in exemplified standards
  - Material: Nb, NbTi, Ti (< 80K)
  - Structure of cavity ： Too complicated shape. No use of equations.

- Following standards are declared and safety is confirmed.
  - Allowable stress on materials and welding joints

    ⇒ Estimation and confirmation by tensile tests
  - Definition of minimum thickness of dressed cavity and calculation of maximum stress for each parts

    ⇒ Decide minimum thickness of dressed cavity

    ⇒ Stress calculation by ANSYS
  - Confirm the strength of cavity is large enough for operation

    ⇒ Confirm allowable stress > maximus stress

List of mechanical test (Tensile & Charpy impact test)

〇：test was done　△：sample is under preparation

	RT	80K	4.2K
High RRR Nb (RRR > 270)	〇	〇	〇
Low RRR Nb (40 < RRR < 150)	〇	〇	〇
NbTi (Nb45%, Ti55%)	〇	〇	〇
Ti type-2 (Japanese standard)	〇	〇	〇
H-RRR Nb & H-RRR Nb EBW	〇	〇	〇
H-RRR Nb & L-RRR Nb EBW	〇	〇	〇
L-RRR Nb & NbTi EBW	〇	〇	〇
NbTi & Ti type-2 EBW	〇	〇	〇
Ti type-2 & Ti type-2 TIG	〇	〇	〇

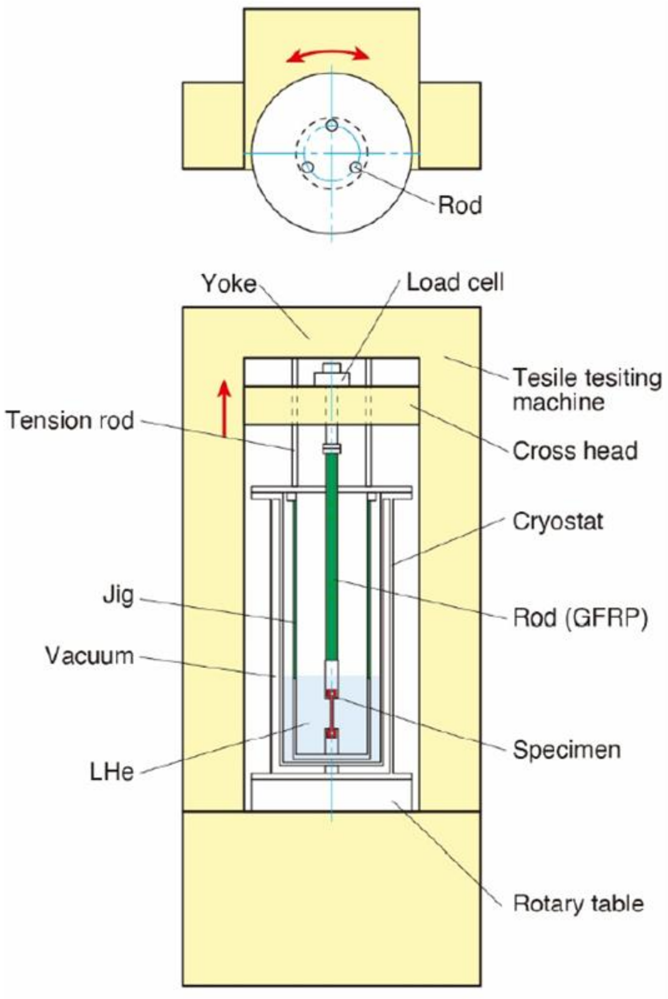
KEK-CFF group working very hard for sample preparation and mechanical test.

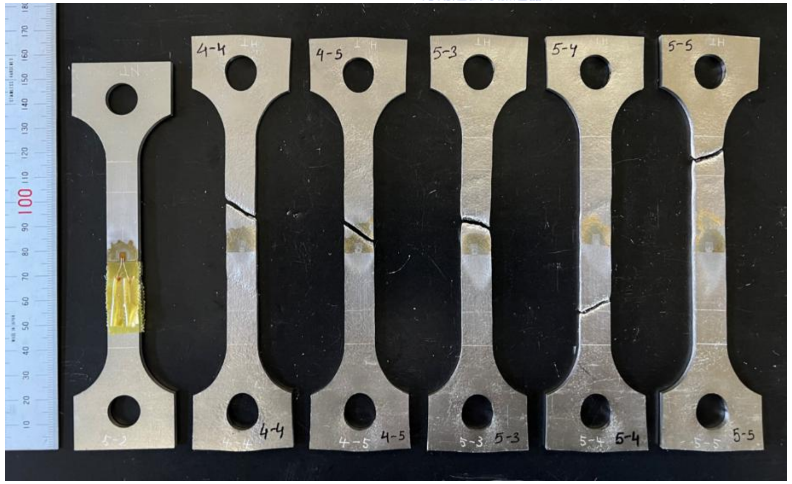
⇒ Allowable stress is estimated from the mechanical test results.

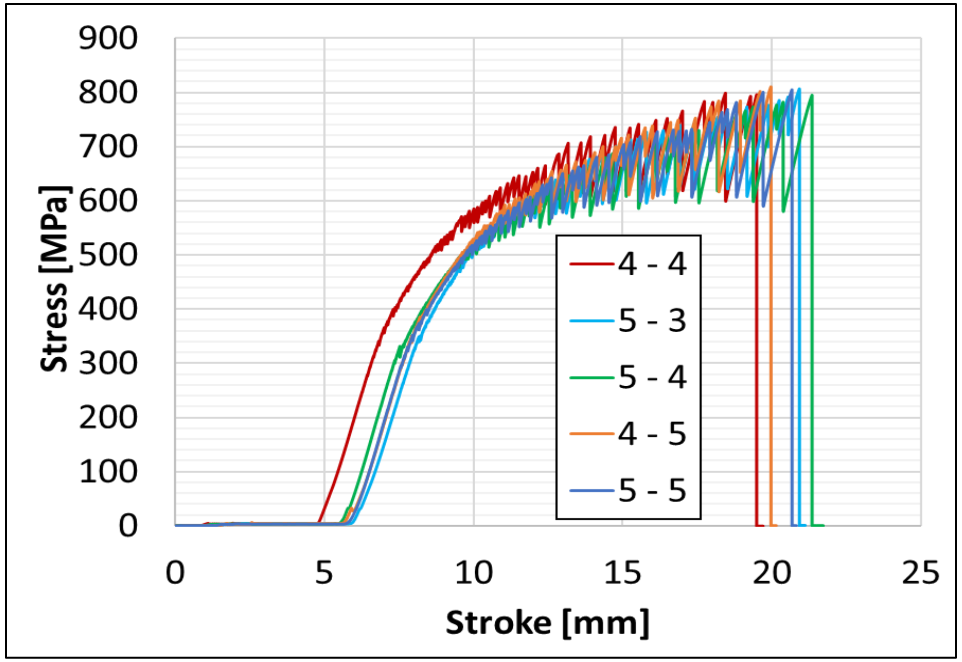
All test samples were heat treated at 900 C.

Tensile test performed at KEK

Mechanical test setup under Liquid Helium



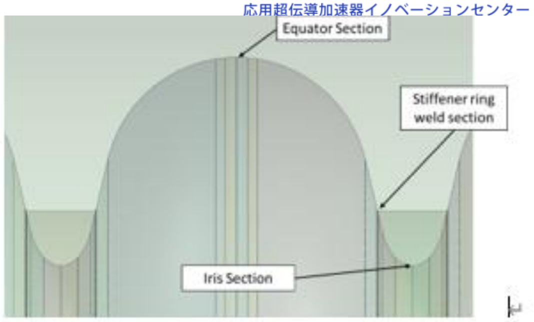


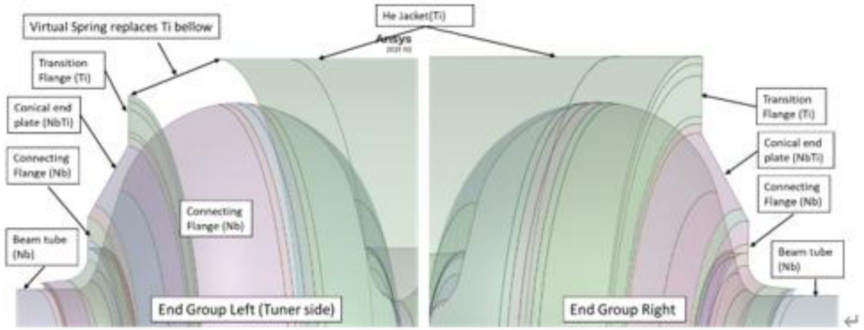


Stress analysis by ANSYS

- Stress simulation was carried out by using ANSYS.
- Simulation was done for the following 3 cases.

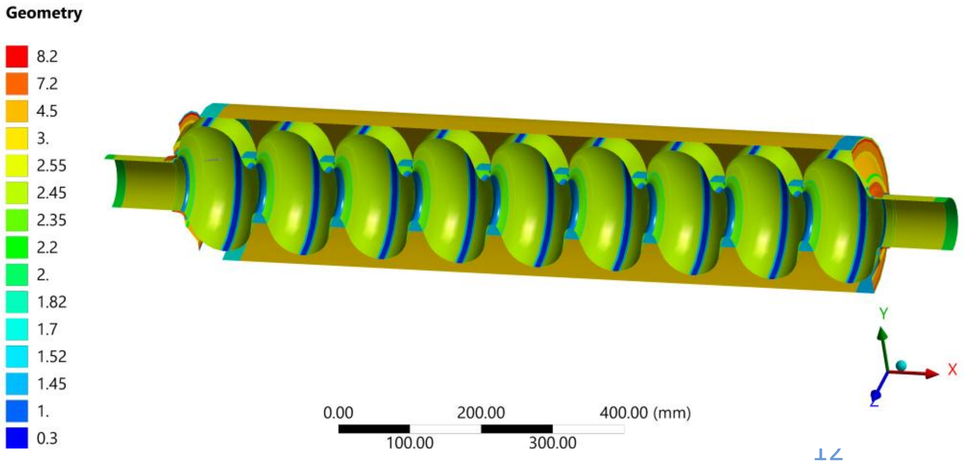
	Pressure [MPa]			Temperature (degree)	Tuner external load or allowable extension
	Inside Cavity	Between cavity and jacket	Outside jacket		
CASE-A	0	0.2	0	40	0.65 mm
CASE-B	0	0.2	0	40 to -271.4	0.65 mm
CASE-C	0	0.2	0	-271.4	-3.0 mm





Original TESLA cavity design is enough strong to satisfy the allowable maximus stress estimated from the tensile test results.

※ No need to change TESLA cavity design.



Generated stress (by ANSYS)

Allowable stress
(Including type of stress, welding efficiency factor)

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

Table 3-5: Stress data for Case C, 0.2 MPa, -271.4 °C and 3 mm tuner displacement (compression motion).

Material	Evaluation Site	Stress Class	Stress Intensity [MPa]	Allowable Stress with Joint Efficiency [MPa]
HNb	Center Cells (2 - 8)	P_m	47.0	100
HNb	End Cells (1 & 9)	P_m	36.9	
HNb - HNb	Equator section weld	P_m	27.4	70 (100×0.7)
	Iris section weld	P_m	33.7	
	End Cell R - CET weld	P_L	15.4	105 (1.5×100×0.7)
	End Cell L - CET weld	P_L	19.5	
HNb - LNb	Stiffener ring Weld	P_L	42.8*	105 (1.5×100×0.7)
	End Cell - CF weld	P_L	61.8**	
	CET - CF Weld	P_L	15.9	
Ti	He Jacket	P_m	12.9	150
Ti - Ti	He Jacket-bellow Weld	P_L	31.8	135 (1.5×150×0.6)
	TF – He Jacket Weld	P_L	82.4	
LNb - NbTi	CD – CF Weld	P_L	49	105 (1.5×100×0.7)
NbTi - Ti	CD – TF Weld	P_L	67.1	157.5 (1.5×150×0.7)

Material	Evaluation Site	Stress Class	Stress Intensity [MPa]	Allowable Stress with Joint Efficiency [MPa]
HNb	Center Cells (2 - 8)	P_m+P_b	69.8	150 (1.5×100)
HNb	End Cells (1 & 9)	P_m+P_b	60.4	
HNb - HNb	Equator section weld	P_m+P_b	28.0	105 (1.5×100×0.7)
HNb - HNb	Iris section weld	P_m+P_b	47.3	
HNb - HNb	End Cell R - CET weld	P_L+P_b	16.5	105 (1.5×100×0.7)
HNb - HNb	End Cell L - CET weld	P_L+P_b	23.9	
HNb - LNb	Stiffener ring Weld	P_L+P_b+Q	148.3*	210.0 (3×100×0.7)
HNb - LNb	End Cell - CF weld	P_L+P_b+Q	187.3**	
HNb - LNb	CET - CF Weld	P_L+P_b+Q	15.5	
Ti	He Jacket	P_m+P_b	14.1	225 (1.5×150)
Ti - Ti	He Jacket-bellow Weld	P_L+P_b+Q	37.2	270 (3×150×0.6)
Ti - Ti	TF – He Jacket Weld	P_L+P_b+Q	220.0	
LNb - NbTi	CD – CF Weld	P_L+P_b+Q	57.0	210.0 (3×100×0.7)
NbTi - Ti	CD – TF Weld	P_L+P_b+Q	225.4	315 (3×150×0.7)

* Includes factor of 1.062 multiplication
**Includes factor of 1.23 multiplication

CASE-C
Pressure & thermal & tuner load

- Left table shows list of generated stress at 2K, with max. tuner compression (3mm).
- Generated stress at all the place is less than the allowable stress.

Confirm that the allowable stress is less than max. stress for all the place.

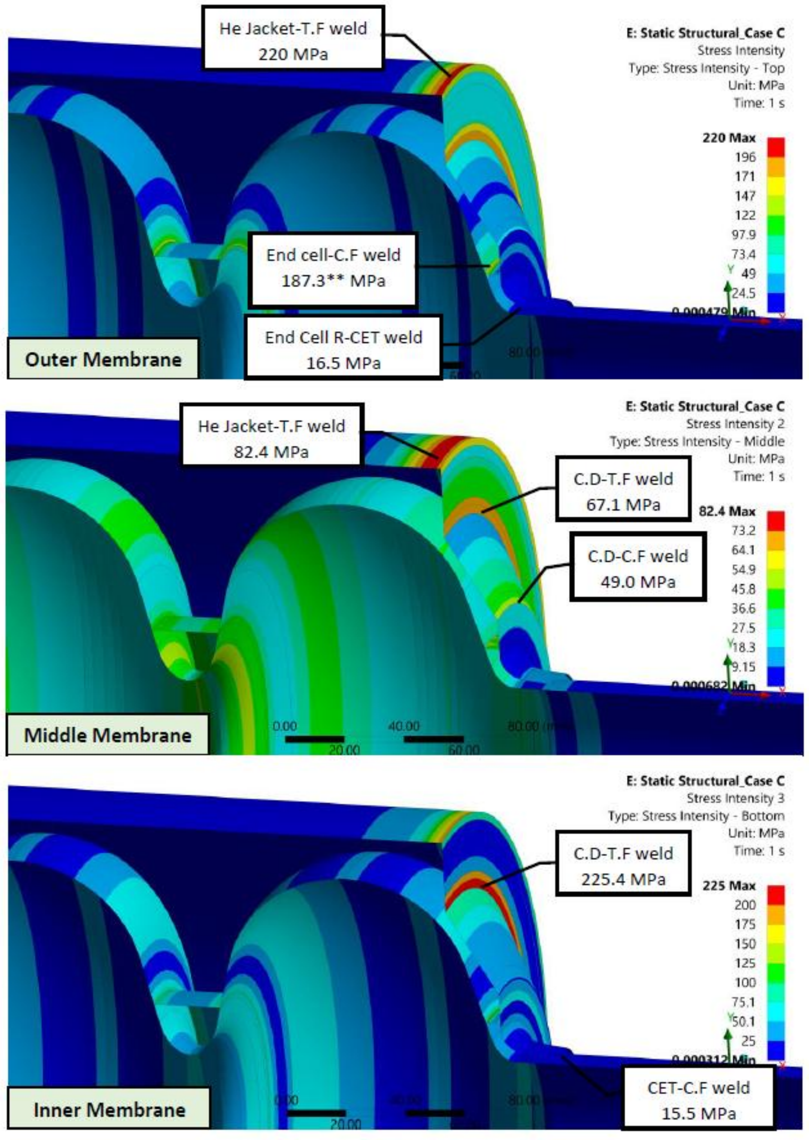


Figure 17: Case-C: End Group coupler side stress-intensity (3 mm compression).

Expected list of inspections / documents / etc.

- Mill sheets of materials
- Thickness measurements for important parts
- Welding record
- Half cut model to confirm details of thickness after welding
- Mechanical test of welding samples during fabrication process
  - Tensile test
  - Bending test
- Record of heat treatment
- Pressure test
  - Cavity: 1.5 times pressure test by water (0.3 MPa)
  - Jacket: 1.5 times pressure test by water (0.3 MPa)
  - Dressed cavity: 1.25 times pressure test by gas (0.25 MPa) & Dye penetration test for welding joints
- Leak test

Basically, same procedure is applied to Japanese domestic and over-sea fabricated cavities.

Regulation for the mechanical test could be the item to be applied to KHK.

「1.5 times pressure test by gas for dressed cavity」 will be the item to be negotiated with KHK.

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Proposal of surface treatment for SRF cavities

TDR

Bulk EP (100~120 μm)

⇩

Heat treatment (800℃, 3h)

⇩

Final EP (40μm)

⇩

HPR Assembly

⇩

Baking (120℃, 48h)

Proposal of surface treatment for SRF cavities

TDR

Bulk EP (100~120 μm)
⇩
Heat treatment (800℃, 3h)
⇩
Final EP (40μm)
⇩
HPR Assembly
⇩
Baking (120℃, 48h)

⇨

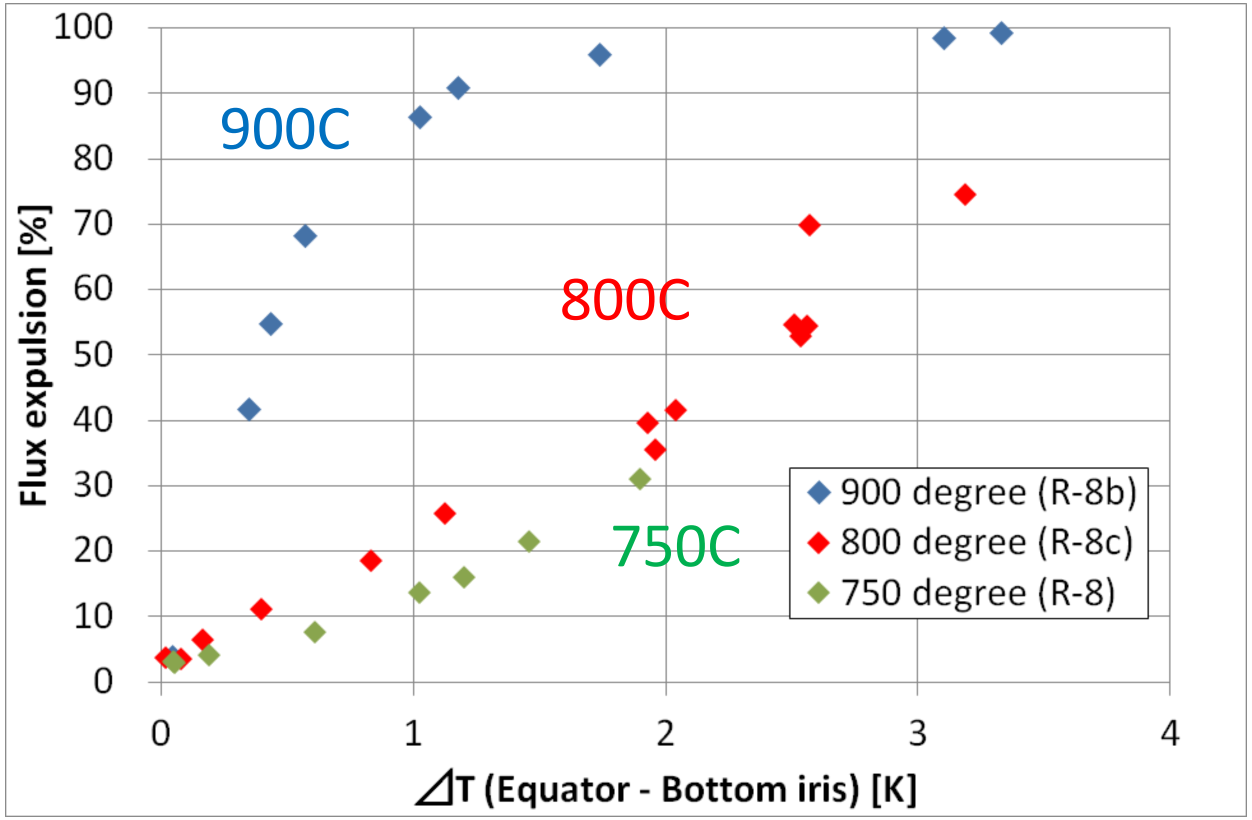
Our Proposal

Bulk EP (150 μm)
⇩
Heat treatment (900℃, 3h)
⇩
Final EP (cold EP, 20μm)
⇩
HPR Assembly
⇩
2-step Baking (75℃, 4h + 120℃, 48h)

- Apply 2-step baking to try higher gradient and higher Qo.
- 900C heat treatment for better flux expulsion and better residual resistance.
- Chose optimum EP removal thickness to obtain better yield.
- Cold EP combined with 2-step baking may help to improve cavity performance.
- Do not apply outside CP at KEK.

Flux expulsion

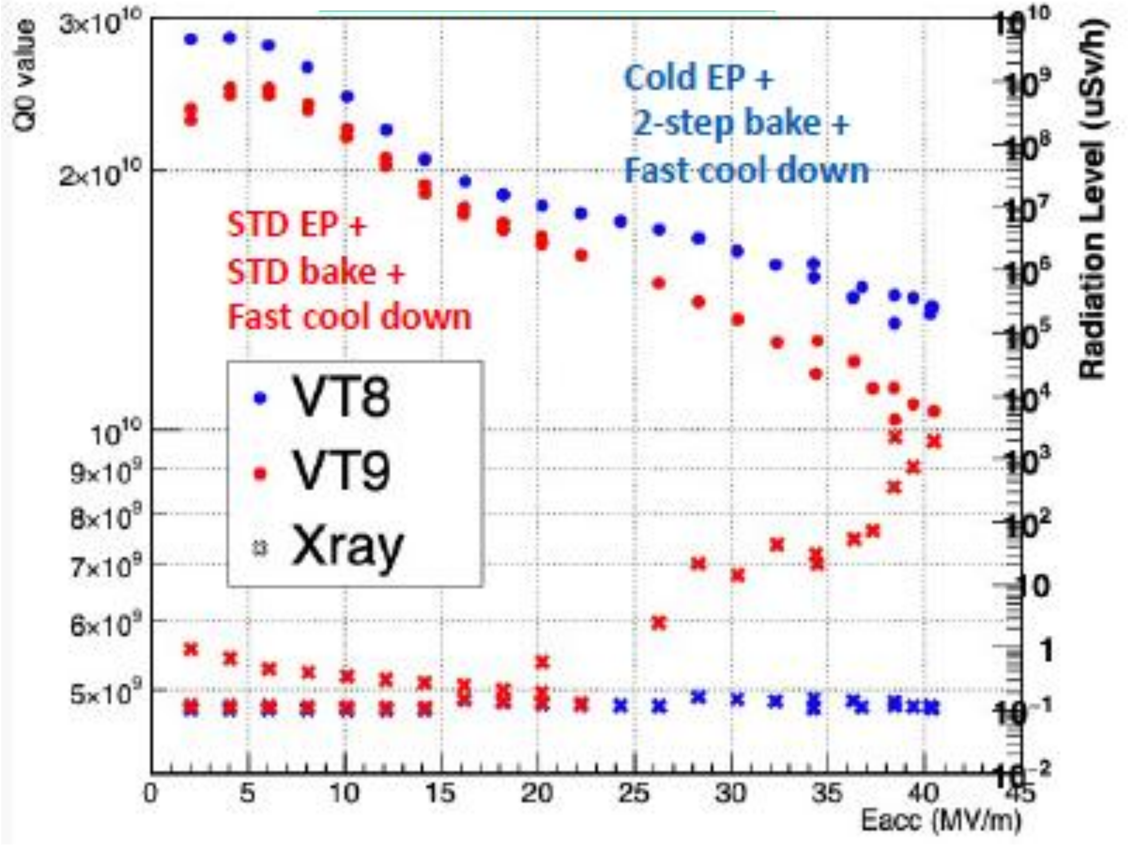
Typical flux expulsion results taken at KEK for single-cell cavities



- 900C heat treatment can drastically improve the flux expulsion.
- It is noted that this phenomena depends on material (vendor).

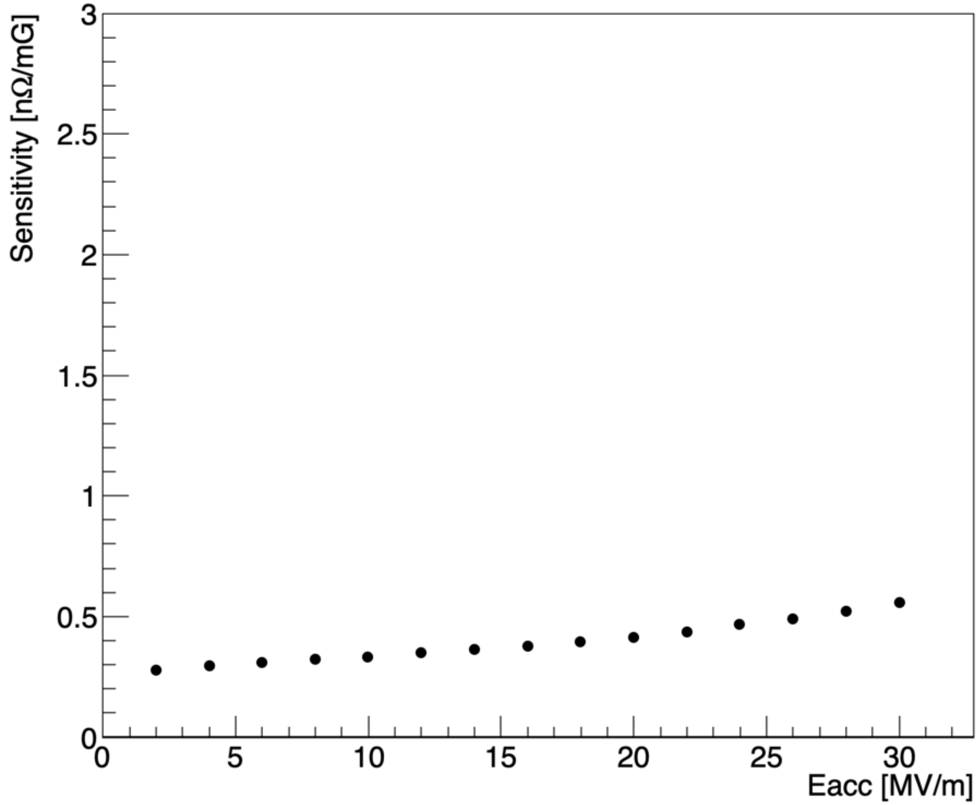
2-step baking results and sensitivity

Typical VT results for 9-cell cavity



- Could reach Eacc > 40 MV/m for 9-cell.
- Q-value tends to be higher.

Sensitivity for 2-step baked cavity
From single-cell cavity measurement



- Sensitivity to the trapped flux is low for 2-step baked cavity.
- Sensitivity is higher for higher gradient

Expected performance vs trapped flux

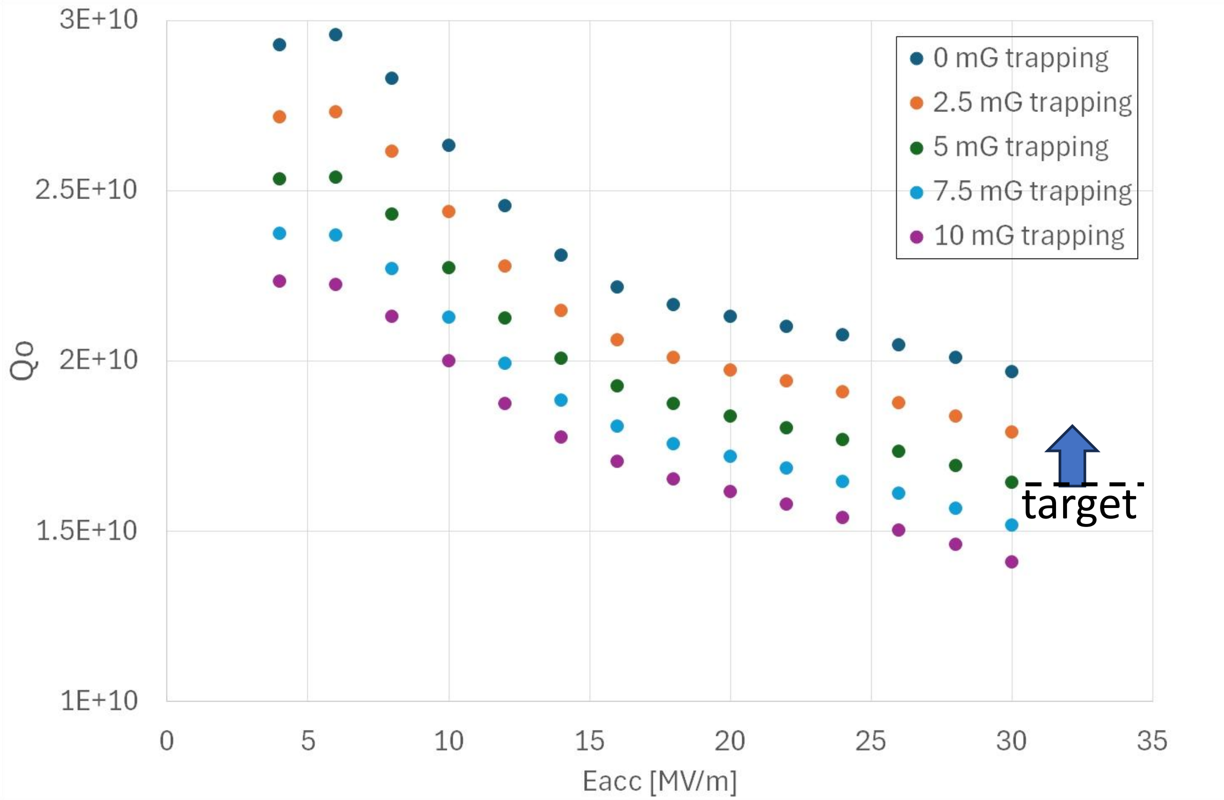
Below is the expected performance (Q, Rs) of 2-step baked cavity at 2K, under the condition of magnetic flux trapping of 0, 2.5, 5, 7.5, 10 mG.

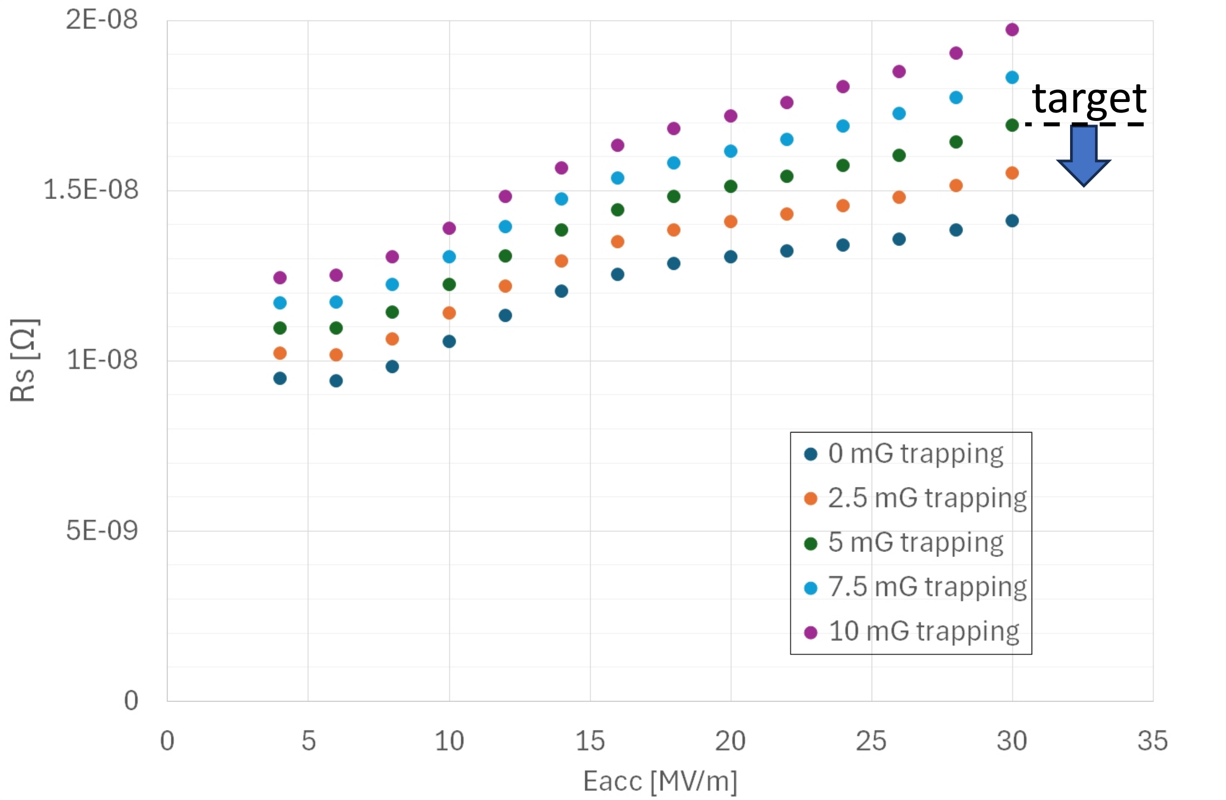
⇒ Target: Flux trapping < 5 mG (Qo > 1.6e10)

(expectation from KEK single-cell cavity data)

To reduce trapped field

- 900C heat treatment
- Magnetic hygiene
- Magnetic shield
- Flux expulsion
- Fast cooldown?





Summary

- HPGS application progress
  - Document for “special technical standard pre-evaluation” for Japanese domestic 9-cell Nb cavity with He jacket is almost done.
  - Huge efforts have been devoted to mechanical tests of materials. Those are completed, expect just one sample.
  - KHK committee for the review was held. Modification required.
  - Documents for other components and cavities are under preparation.
- Surface treatment
  - We proposed 2-step baking, 900C heat treatment and optimized removal thickness of EP, in order to improve cavity performance.
  - Eacc > 40 MV/m is achieved for FG 9-cell cavities.