Reports on SuperKEKB Ring RF System



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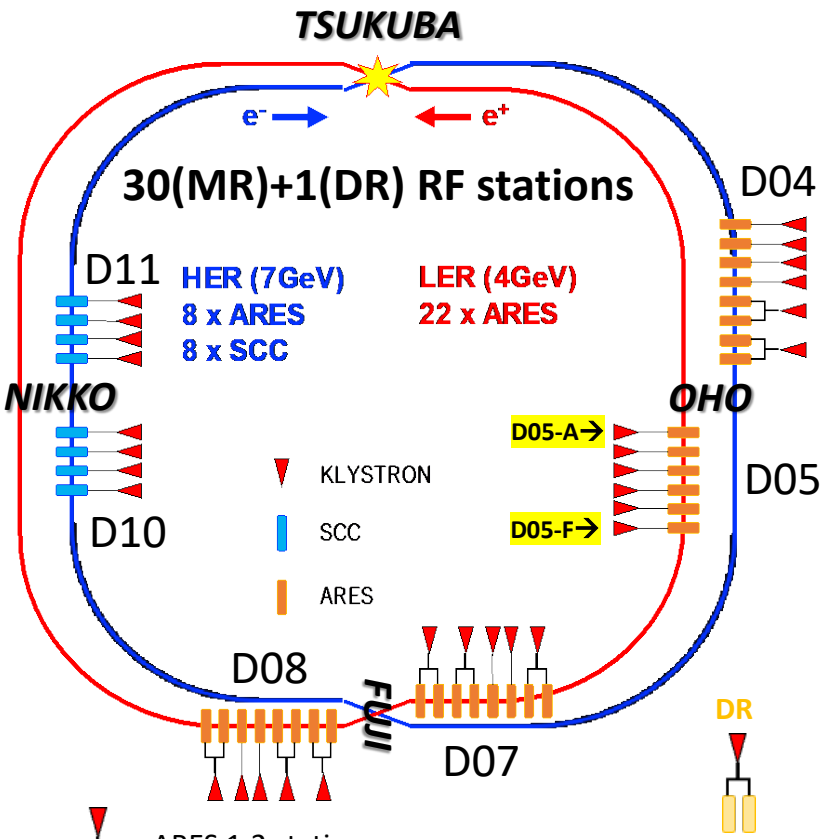
on behalf of SuperKEKB-Ring RF group

The 29th KEKB Accelerator Review Committee Meeting @ KEK

Oct. 26, 2026

RF Accelerating System for the SuperKEKB Main Ring (MR)

Present RF Cavity Layout



ARES 1:2 station
(one klystron drives two ARES cavities)

ARES 1:1 station
(one klystron drives one ARES cavity)

(Acceleration Frequency: ~508.9 MHz)

SuperKEKB operational parameters as of 2026-05-30

	LER		HER		
Energy [GeV]	4.0		7.0		
Beam current [A]	1.590		1.244		
Number of bunches	2053				
Bunch length [mm]	5.3		5.7		
Total beam power [MW]	3.1		3.4		
Total RF voltage [MV]	8.9		14.2		
Cavity type	ARES		ARES		SCC
Number of cavities	12	8 (+2)	4	4	8
Klystron : Cavity	1:2	1:1	1:2	1:1	1:1
Cavity voltage [MV/cav]	0.43 or 0.45		0.40 or 0.45		1.35
RF power to cav. [kW/cav]	~200	~400	~200	~400	~300

(Peak luminosity record (5.28×10^{34} [$cm^{-2}s^{-1}$]) with Belle II HV ON)

Cf.

Parameter	KEKB (achieved)			SuperKEKB (design)		
Ring	HER		LER	HER		LER
Energy [GeV]	8.0		3.5	7.0		4.0
Beam Current [A]	1.4		2	2.6		3.6
Number of Bunches	1585		1585	2500		2500
Bunch Length [mm]	6-7		6-7	5		6
Total Beam Power [MW]	~5.0		~3.5	8.0		8.3
Total RF Voltage [MV]	15.0		8.0	15.8		9.4
	ARES	SCC	ARES	ARES	SCC	ARES
Number of Cavities	10	2	8	20	8	8	8	14
Klystron : Cavity	1:2	1:1	1:1	1:2	1:1	1:1	1:2	1:1
RF Voltage [MV/Cav.]	0.5		1.5	0.5	0.5		1.5	0.5
Beam Power [kW/Cav.]	200	550	400	200	600	400	200	600

Contents

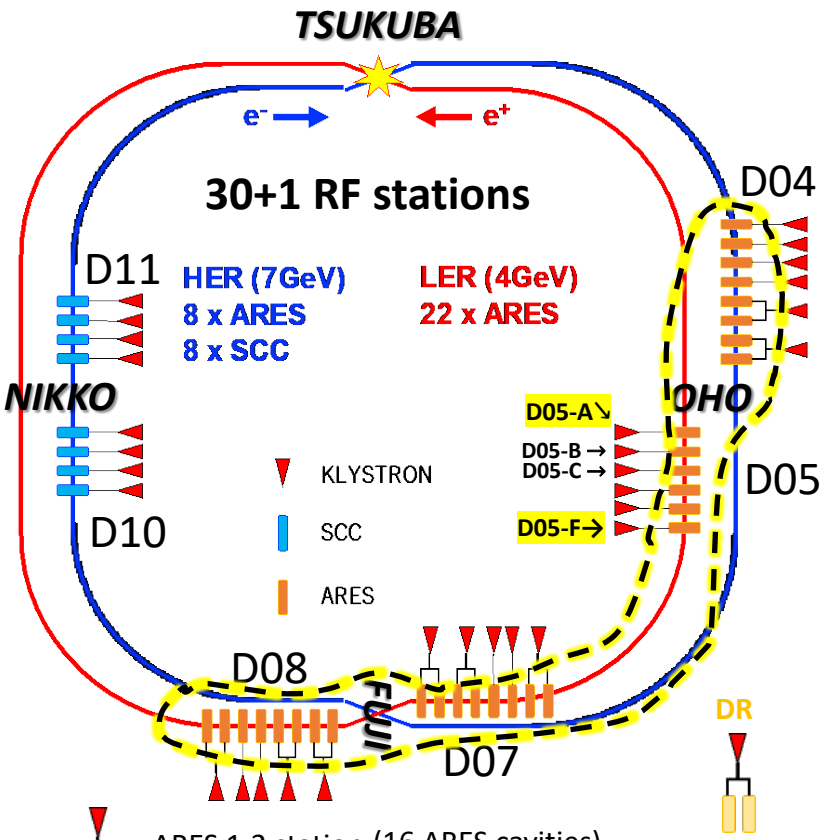
- **ARES** (Normal-conducting cavity)
  - Serious vacuum-pressure rises in OHO D05-A and D05-F ARES cavities
    - Findings and countermeasures
  - Cavity trip statistics
- **SCC** (Super-Conducting Cavity)
  - Performance recovery for a “spare” SCC
- **Klystron**
  - Increasing number of long operated klystrons
- **LLRF**
  - Old analog system to be upgraded to new digital technology


ARES

Accelerator Resonantly-coupled with Energy Storage: "ARES"

*22 sets of A+C+S cavities used for LER, and 8 for HER (**30 in total**)*

Present RF Cavity Layout



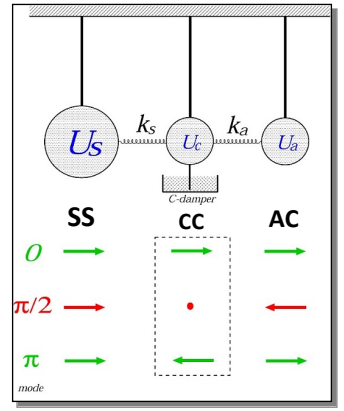
ARES 1:2 station (16 ARES cavities)
(one klystron drives two ARES cavities)

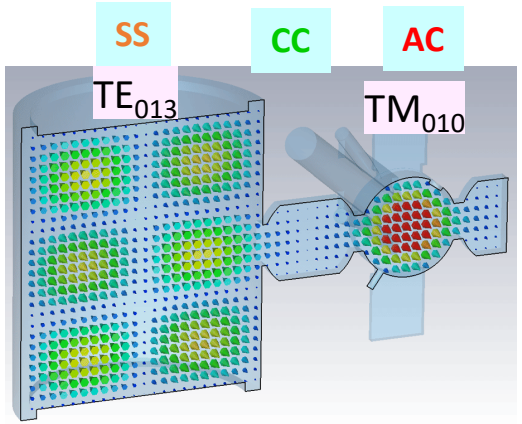
ARES 1:1 station (14 ARES cavities)
(one klystron drives one ARES cavity)

30 ARES cavities in total for MR

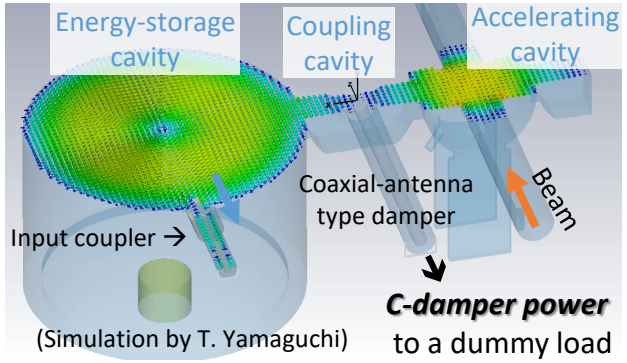
- Unique three-cavity system operated with the stable π/2 mode
- Accelerating *π/2*-mode frequency : 508.9 MHz
- $Q_0 \approx 11\times10^4$ (*π/2*-mode), 17×10^4 (only for SS)
- Vacuum pressure : ~10^{-7} Pa
- Cavity voltage (spec.) : 0.5 MV/cav (⟺ Eacc ≈ 2 MV/m)
- Wall-loss dissipation power: ~150 kW (for 0.5 MV/cav)

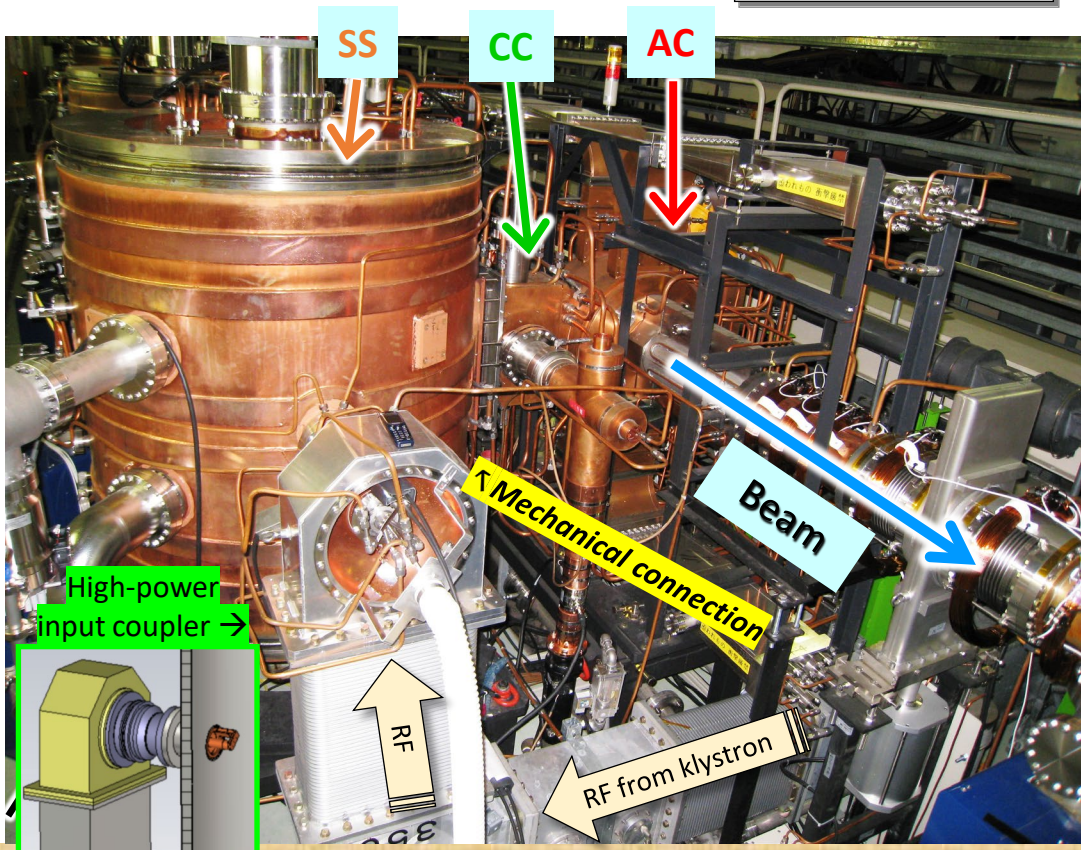
SS: Storage Cavity
CC: Coupling Cavity
AC: Accelerating Cavity





E-field of the accelerating *π/2* mode





Serious vacuum-pressure rises

- Occurred in the OHO D05-A cavity on Dec. 5th in 2025
  - Parked since then up to the end of 2026ab

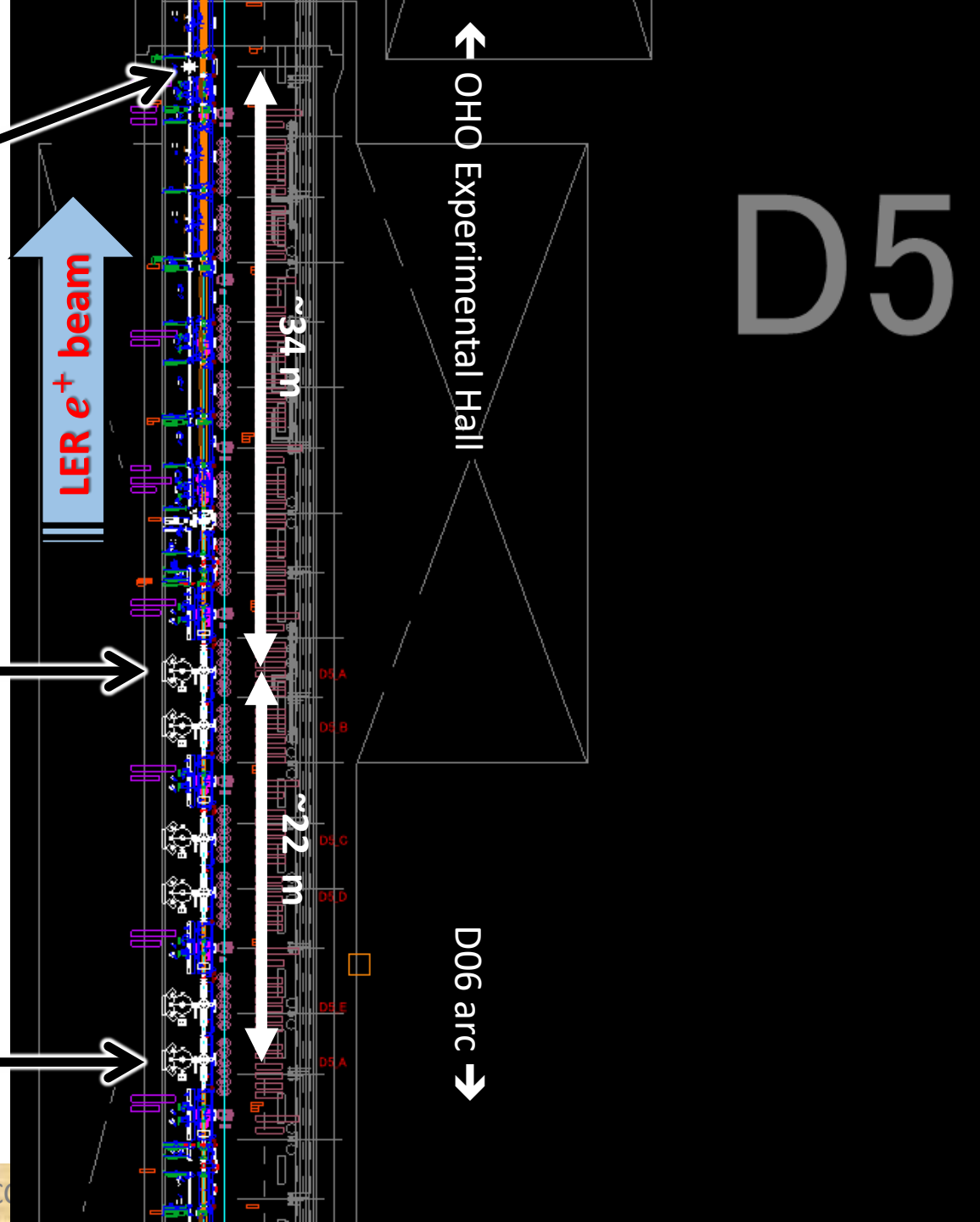
- Occurred in the OHO D05-F cavity on Apr. 15th in 2026
  - Parked since then up to the end of 2026ab

➔ **Two ARES cavities were parked in 2026b.**

ARES

D05-A, -F cavity locations

D05V1 collimator (NLC)

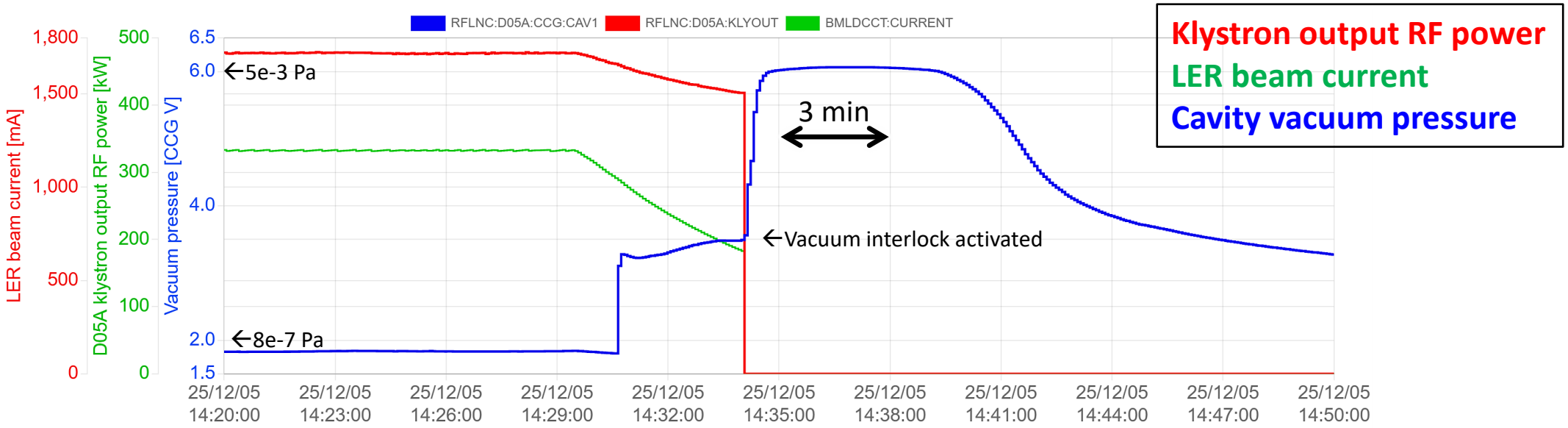


D05-A
(nearest the hall)

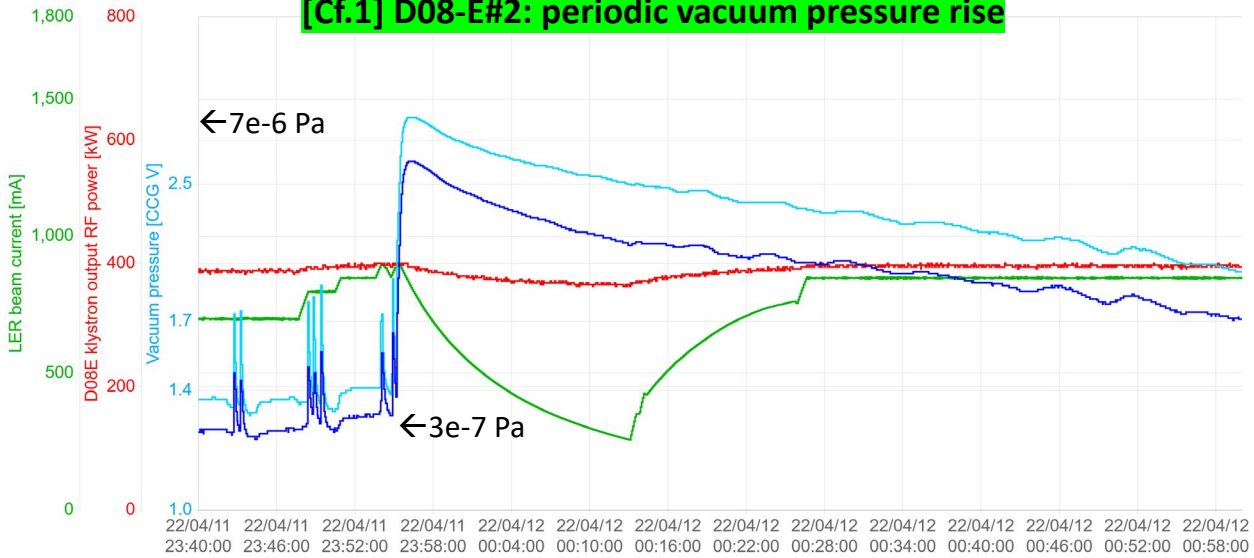
D05-F
(nearest the arc)

D05-A cavity: investigation results

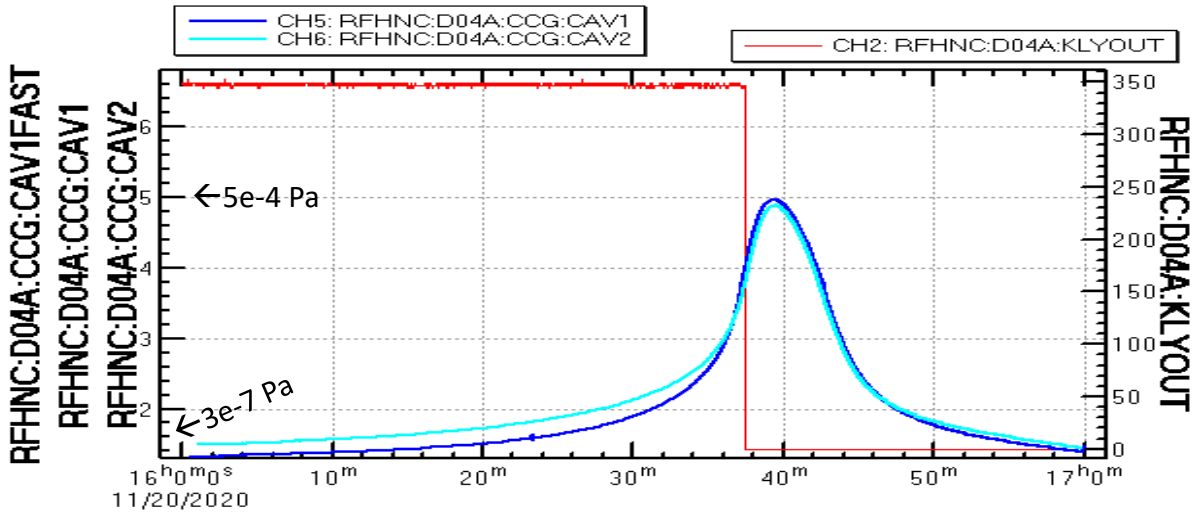
On Dec. 5th in 2025, an unprecedented vacuum-pressure rise in the OHO D05-A cavity.



[Cf.1] D08-E#2: periodic vacuum pressure rise

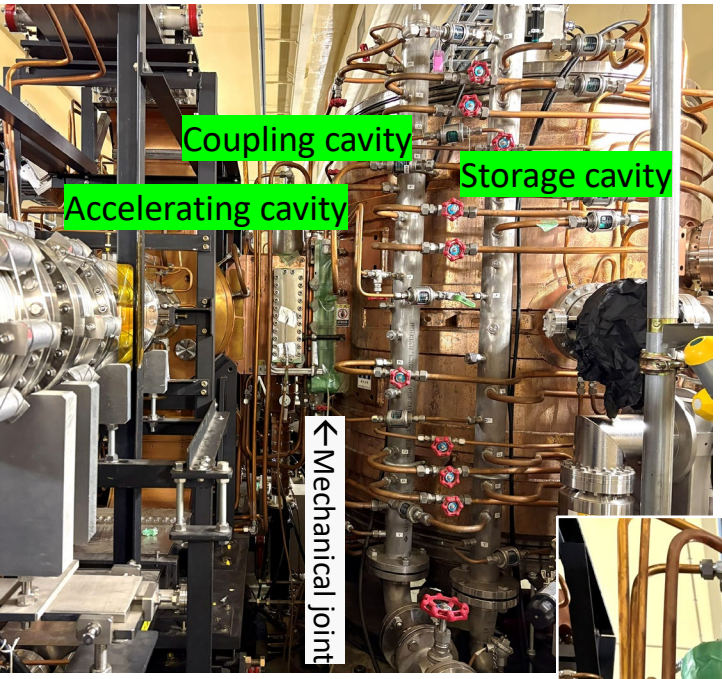


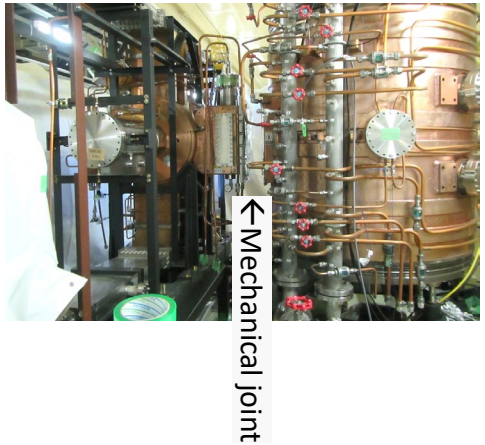
[Cf.2] D04-A: pressure rise likely due to argon instability in ion pump

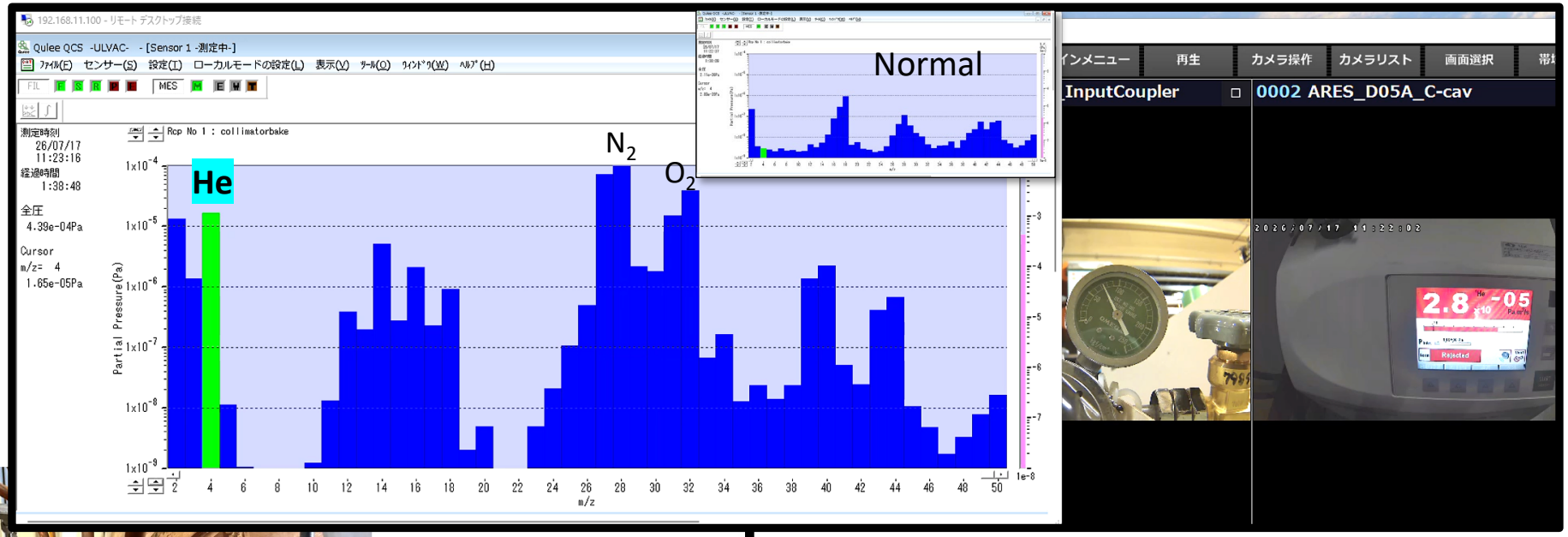


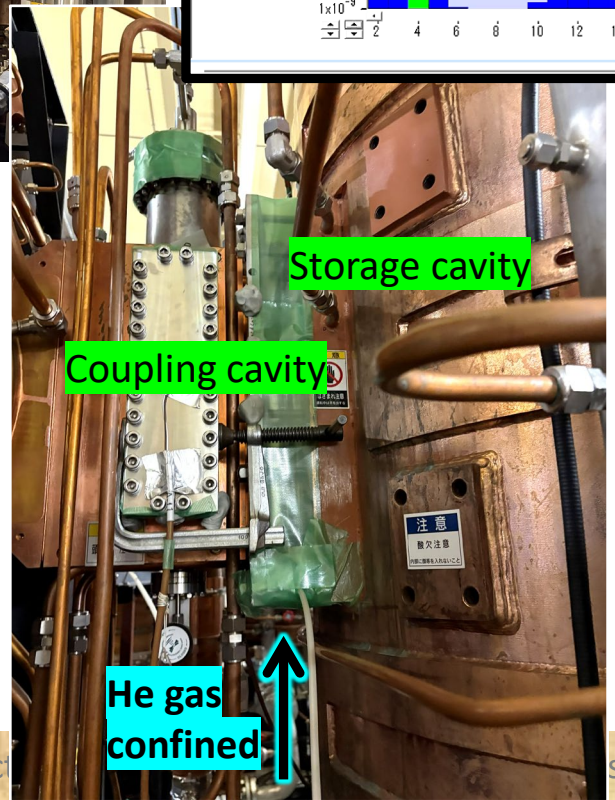
ARES

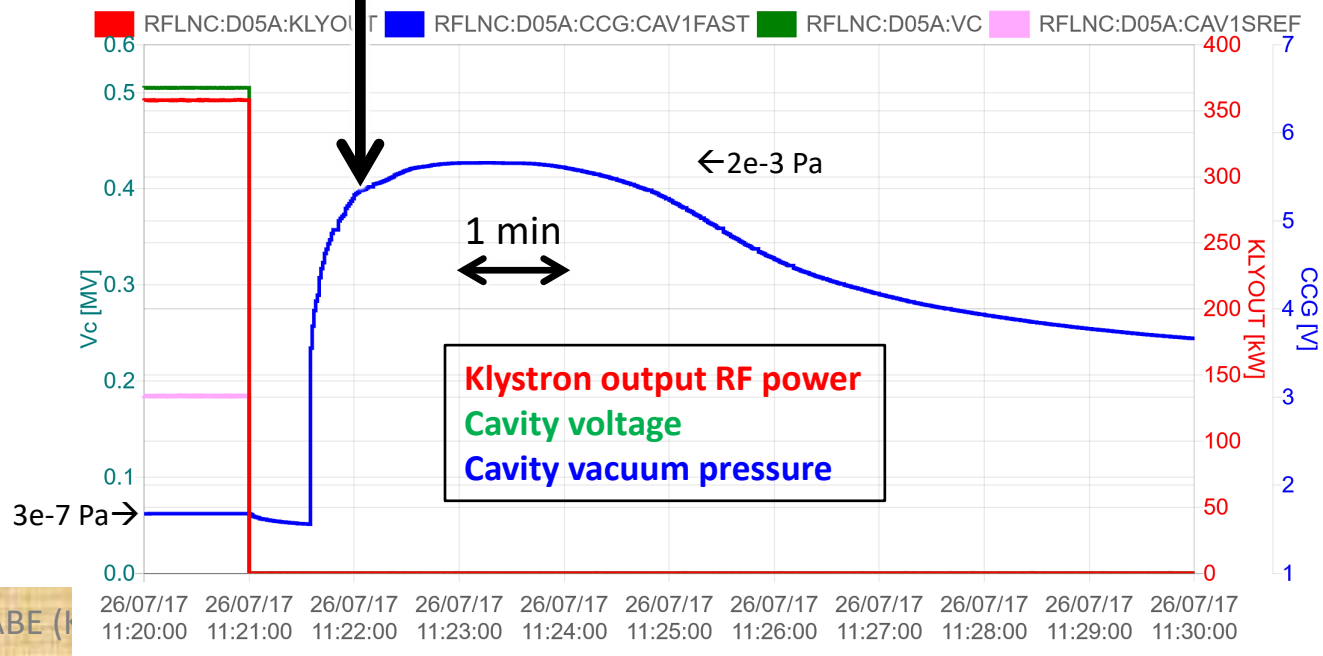
Later tests reproduced the leak at the rectangular coupling–storage cavity joint





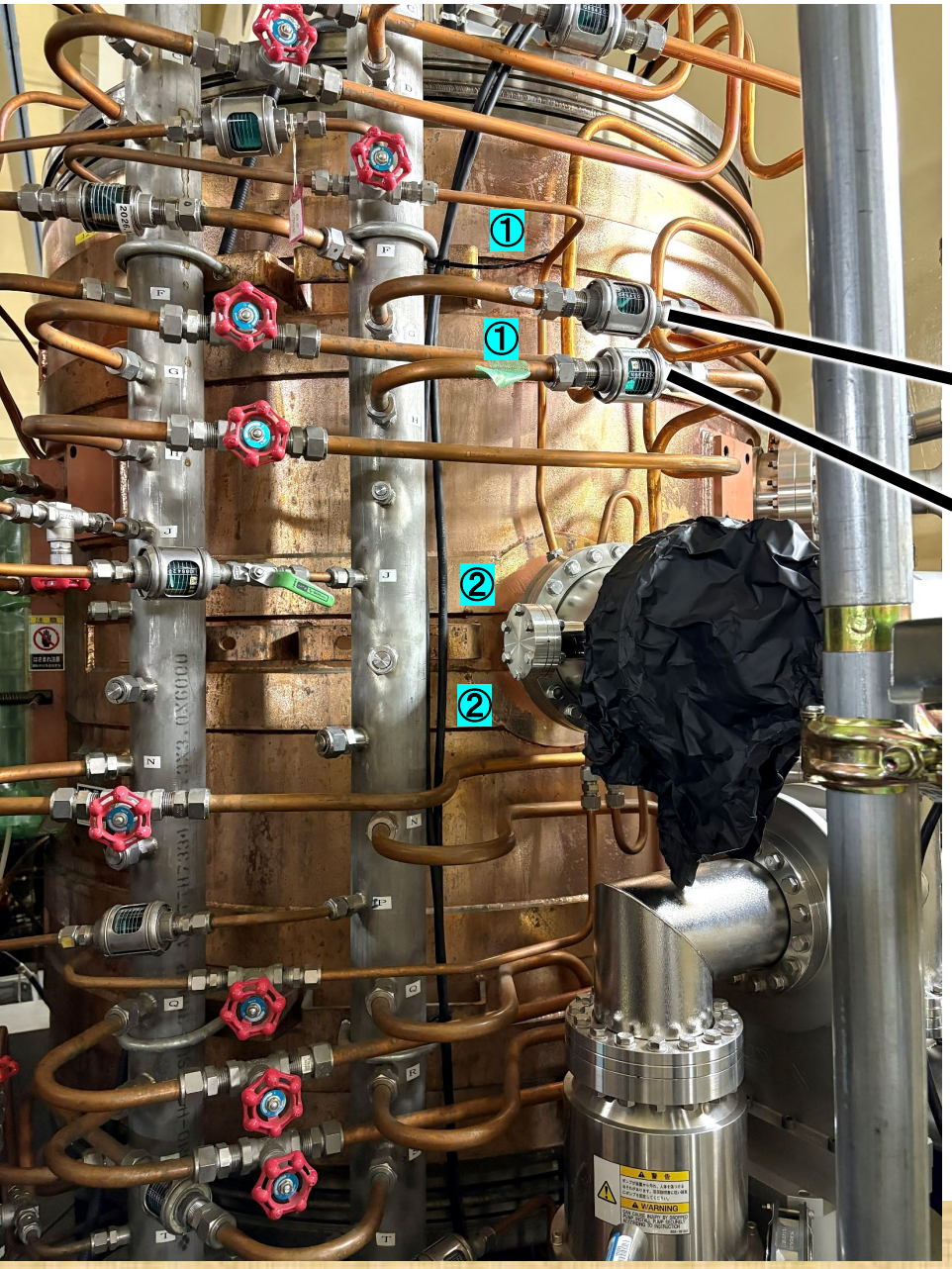


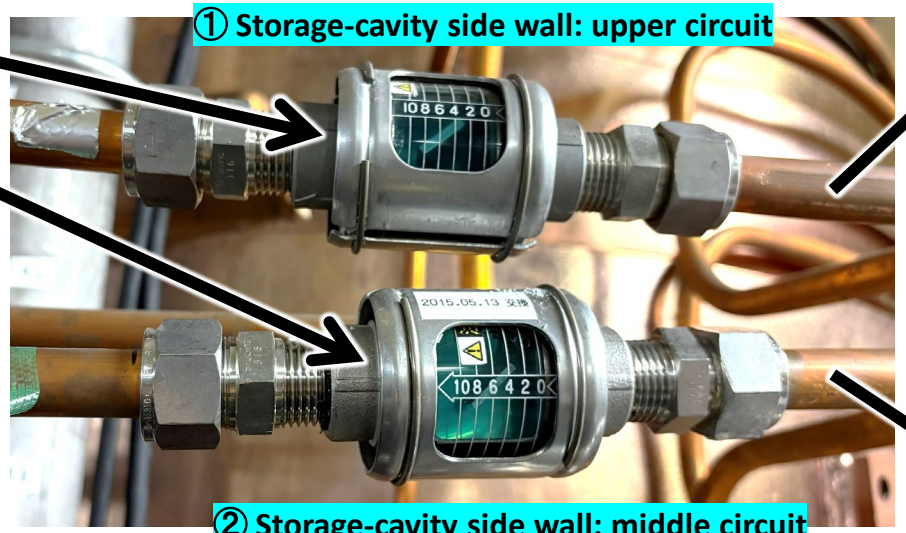




ARES

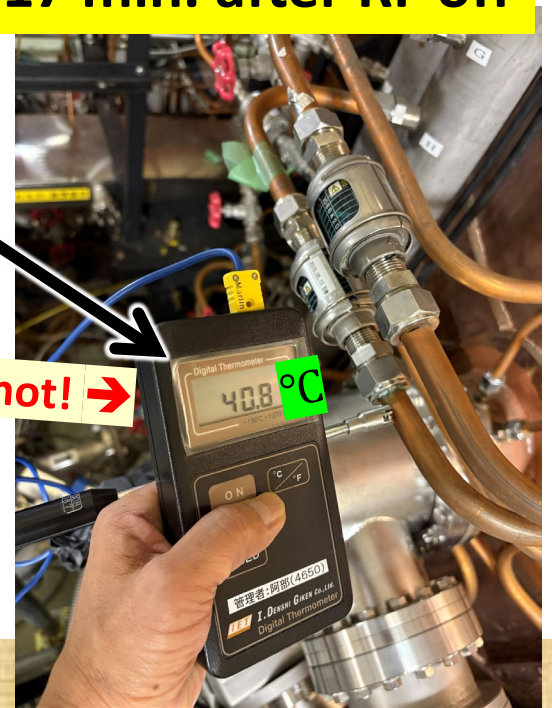
Root cause of the vacuum leak identified







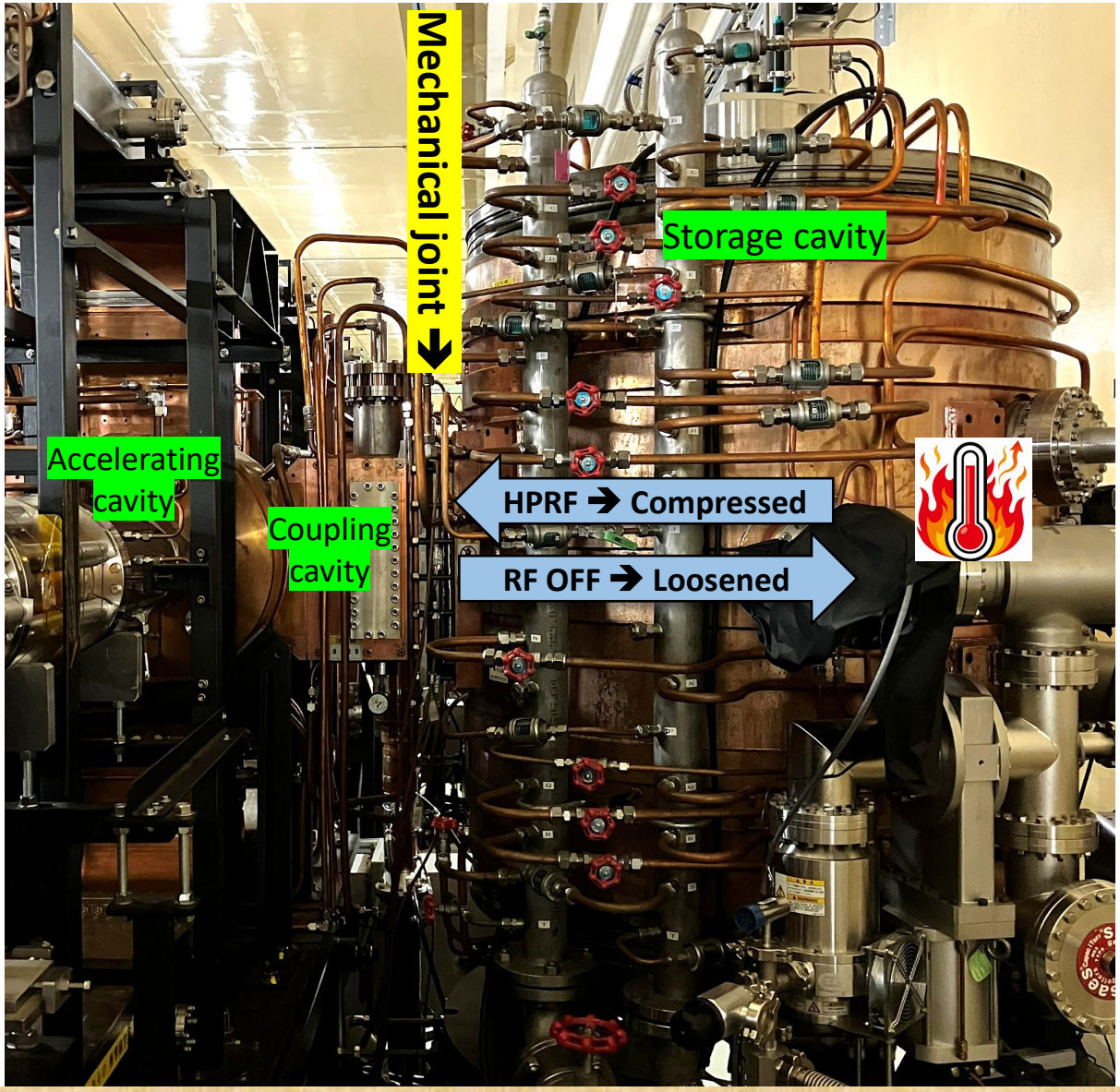
17 min. after RF off

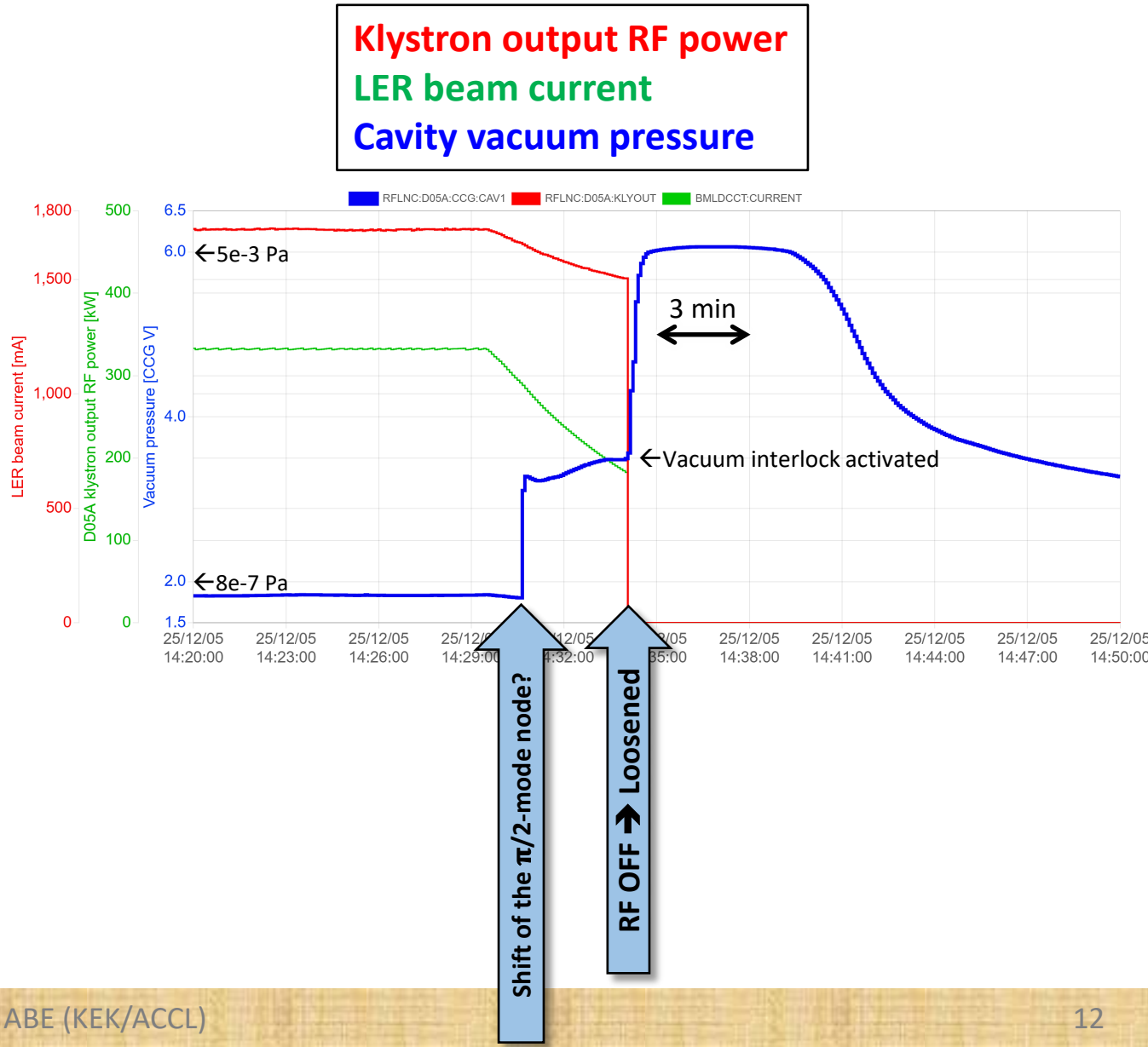


Only this circuit is abnormally hot! →

Faulty spring in the flap-type flowmeter
→ Much lower flow rate than indicated
→ Storage-cavity mid side wall under-cooled
→ Thermal deformation → vacuum leak

Mechanism of the vacuum leak

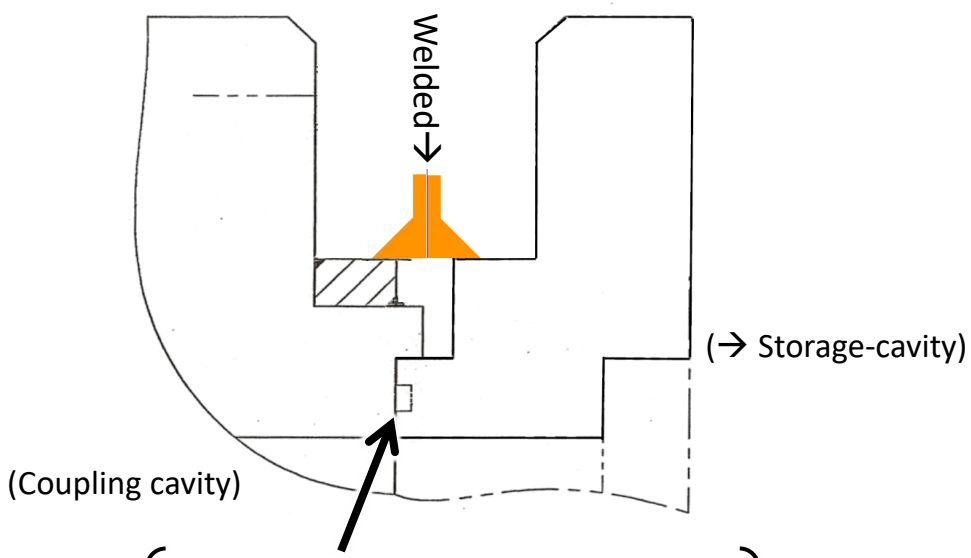




Vacuum seal at the special flange for the mechanical joint between coupling and storage cavities

ARES

For most of the ARES cavities, the vacuum seal is made by lip welding at the outermost bellows.



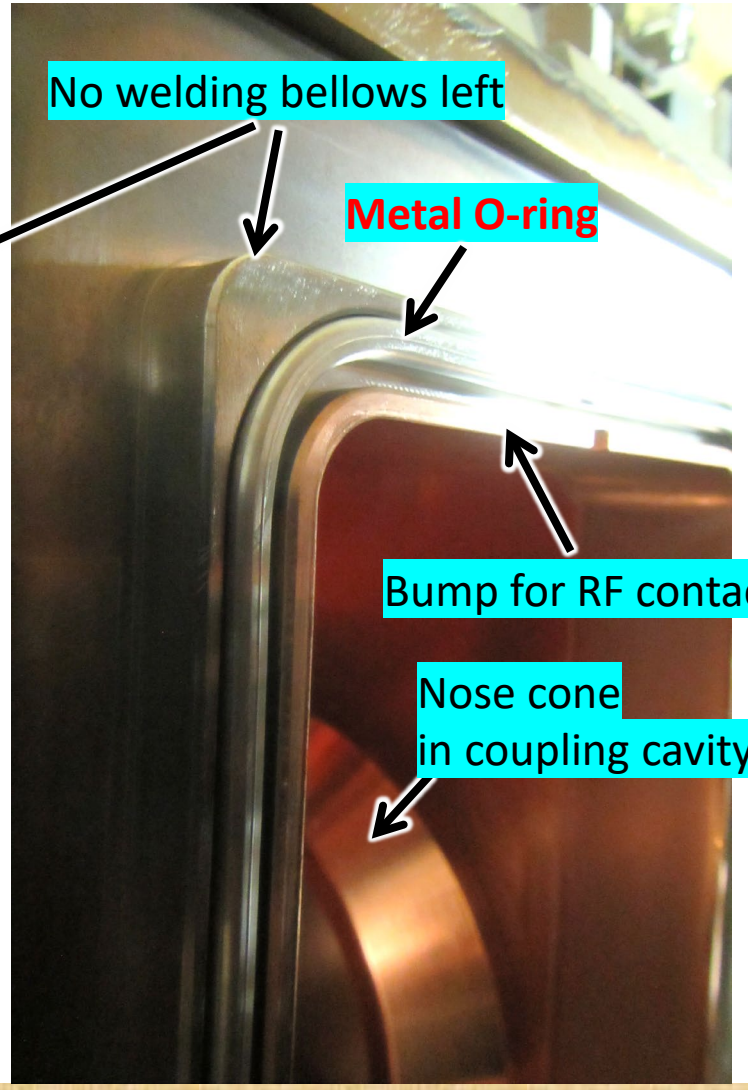
Groove for Viton O-ring
- Used in the initial phase of KEKB
- Not used for SuperKEKB

➔ No vacuum leak would occur even with that abnormal deformation of the storage cavity.

Only for D05-A cavity in LER, the vacuum seal is made by a metal O-ring.

For details, see the report in the 27th ARC

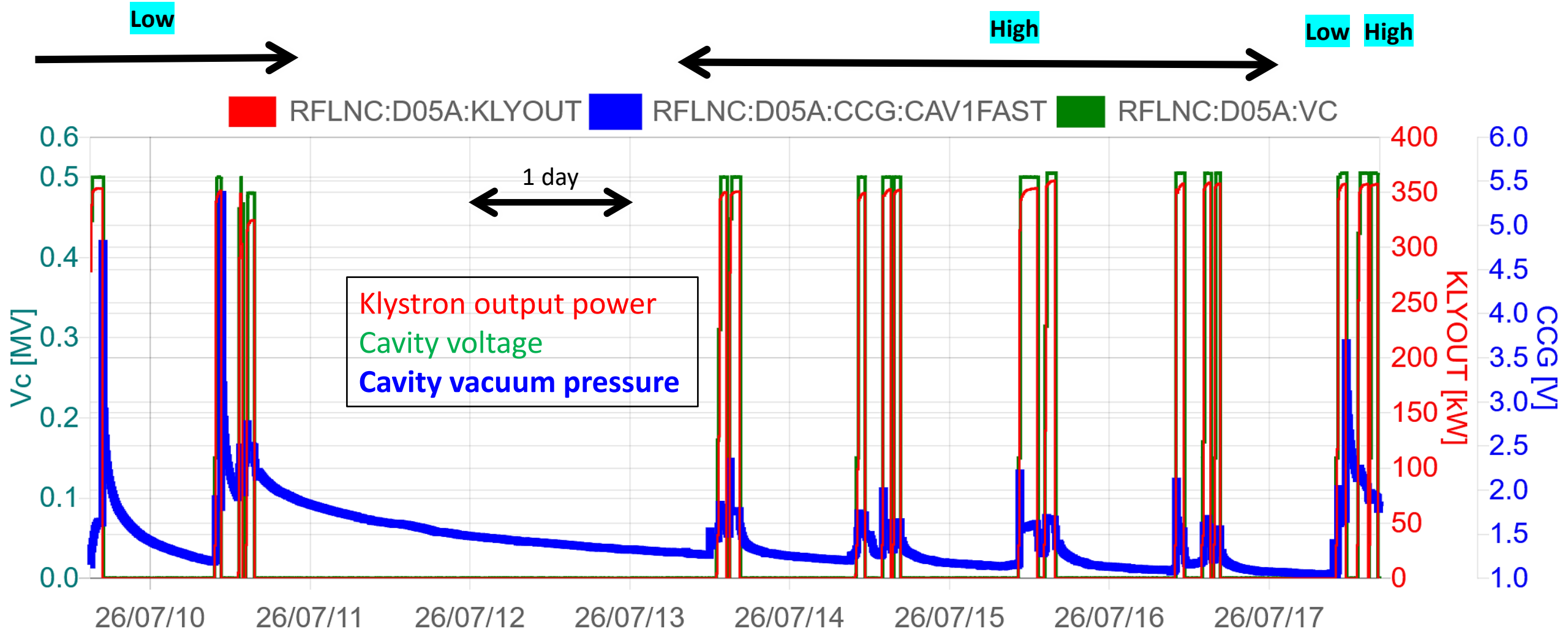




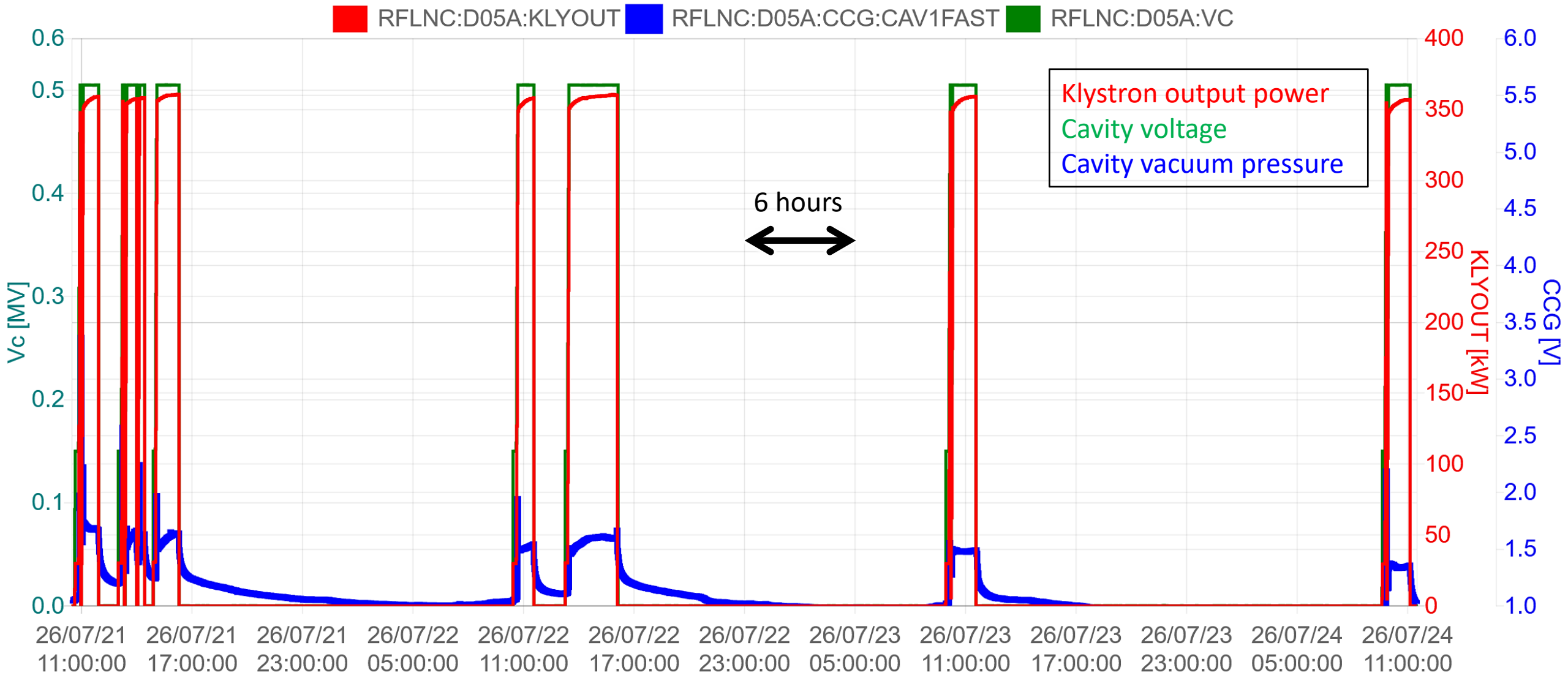
Reproducibility

Flow rate of the middle circuit on the storage-cavity side wall

Cavity voltage held at > 0.5 MV for ≥ 1 h → fully reproducible



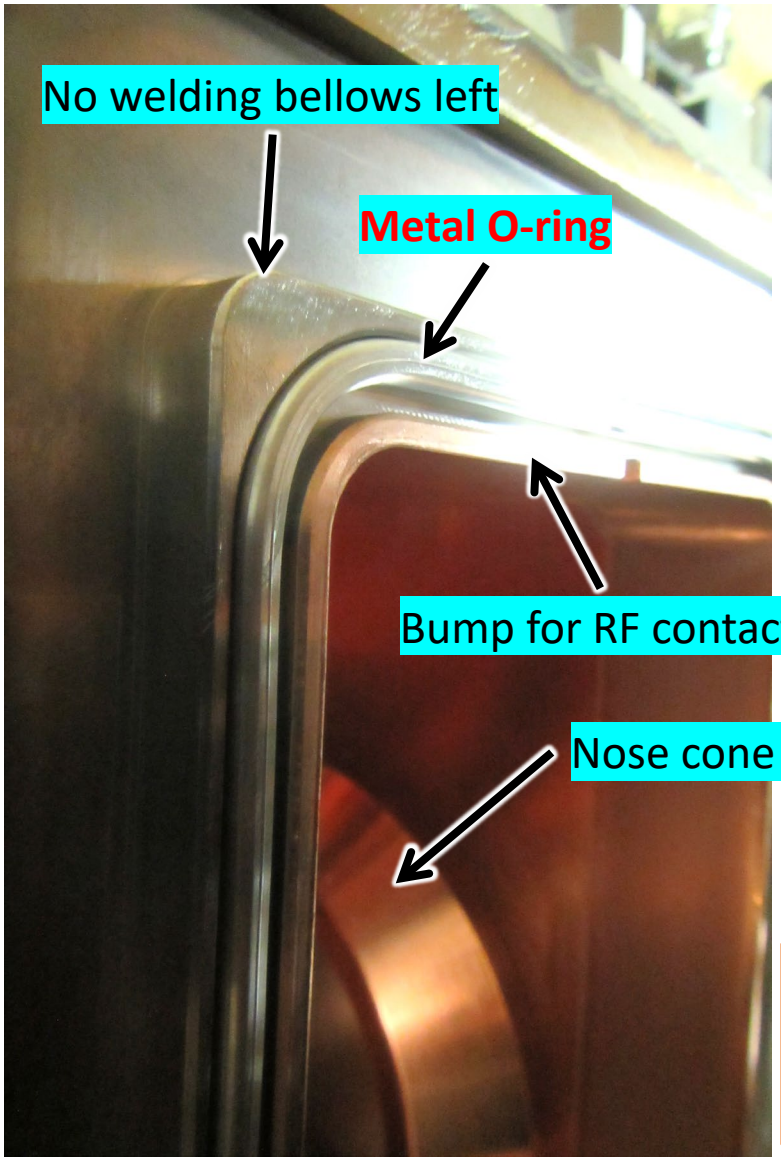
Flow raised to its proper rate → stability confirmed



➔ **No issues**

The vacuum sealing made with a metal O-ring

Special flange for the mechanical joint on the coupling-cavity side



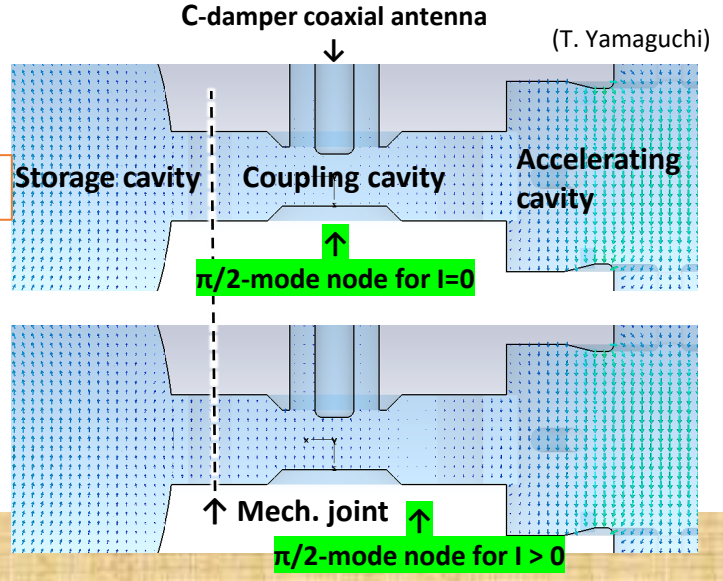
- The vacuum is designed to be sealed at the joint between coupling and storage cavities with outermost bellows welded.
- After the cavity replacement during LS1, no welding bellows left due to:
  - First welding during the KEKB era
  - Second welding during the relocation (HER → LER) between KEKB and SuperKEKB
- From the test bench result, vacuum leak occurs if we make a perfect contact at the bump for RF contact between coupling and storage cavities.
  - ARES cavity was not designed for using metal O-rings
- Decided to make a gap of ~0.7 mm at the bump for RF contact
  - No RF contact here
  - RF contact through the metal O-ring

Zero beam current → C-damper power minimal

Beam current stored → Accelerating cavity detuned
→ π/2-mode node shifts toward the accelerating cavity.
→C-damper power↑
→ RF surface field at the mechanical joint↑

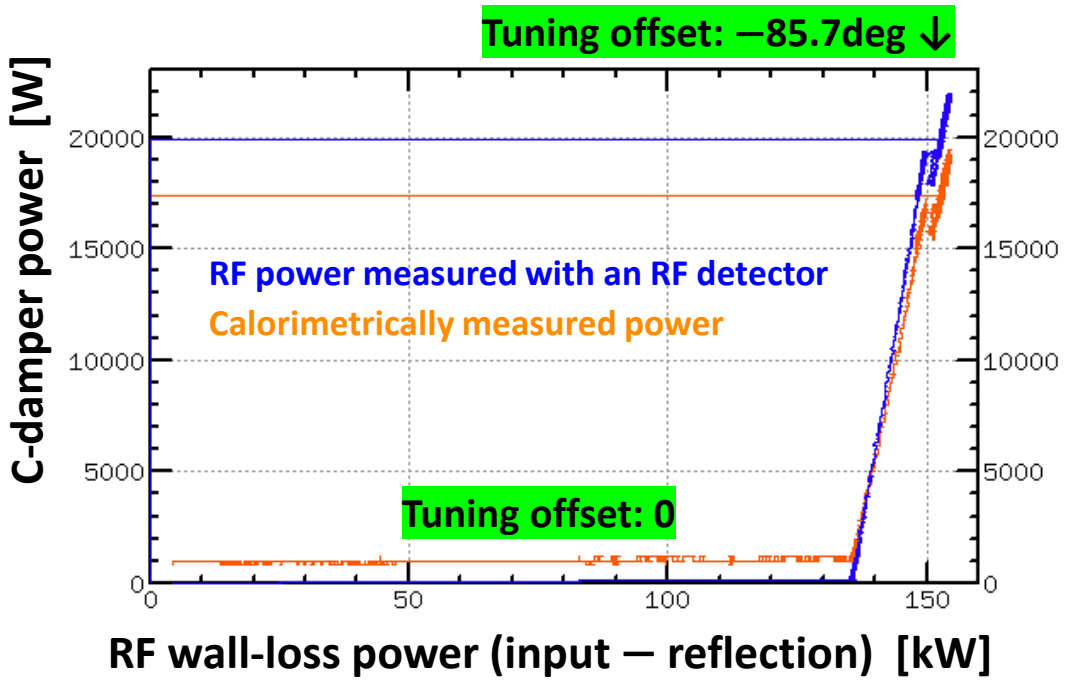
Change in the π/2-mode field distribution

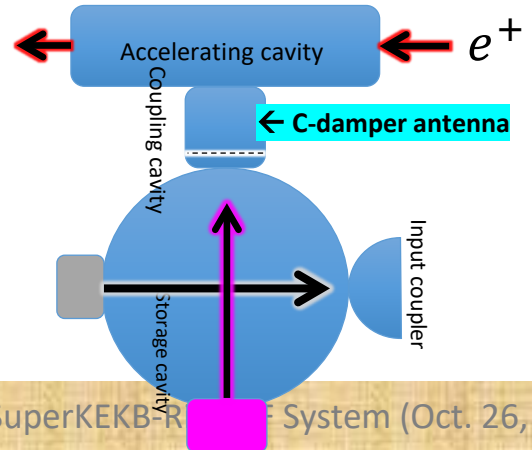
(T. Yamaguchi)

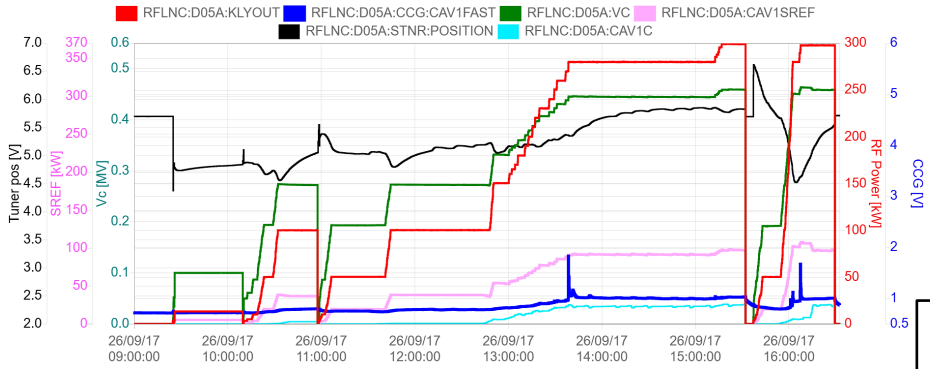


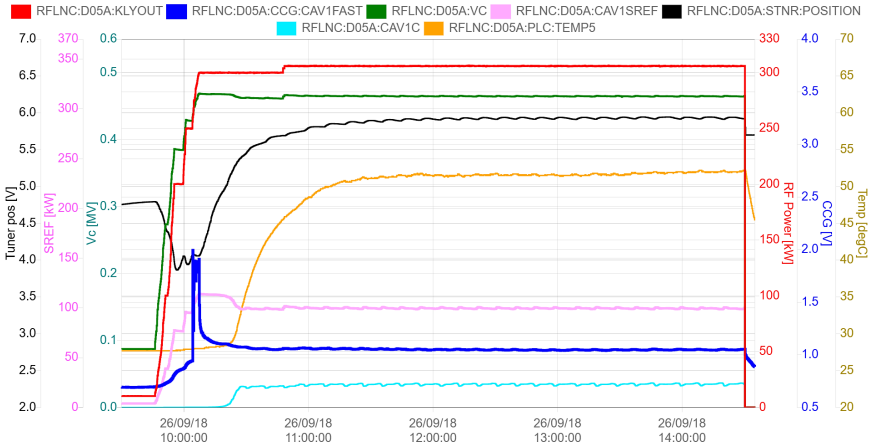
The metal O-ring at the leaking coupling–storage cavity joint also serves as the RF contact

➔ **RF-contact performance verified at the C-damper power (20 kW) expected for LER 3.6 A (design)**









Klystron output power
Cavity voltage
Cavity vacuum pressure
Storage-cavity tuner position

With a tuning offset applied, C-damper power was held at ~20 kW for ~6 h in total.

➔ No interlock activated

➔ No abnormal pressure rise

➔ No abnormal light in the coupling cavity (**camera recording** checked frame by frame)

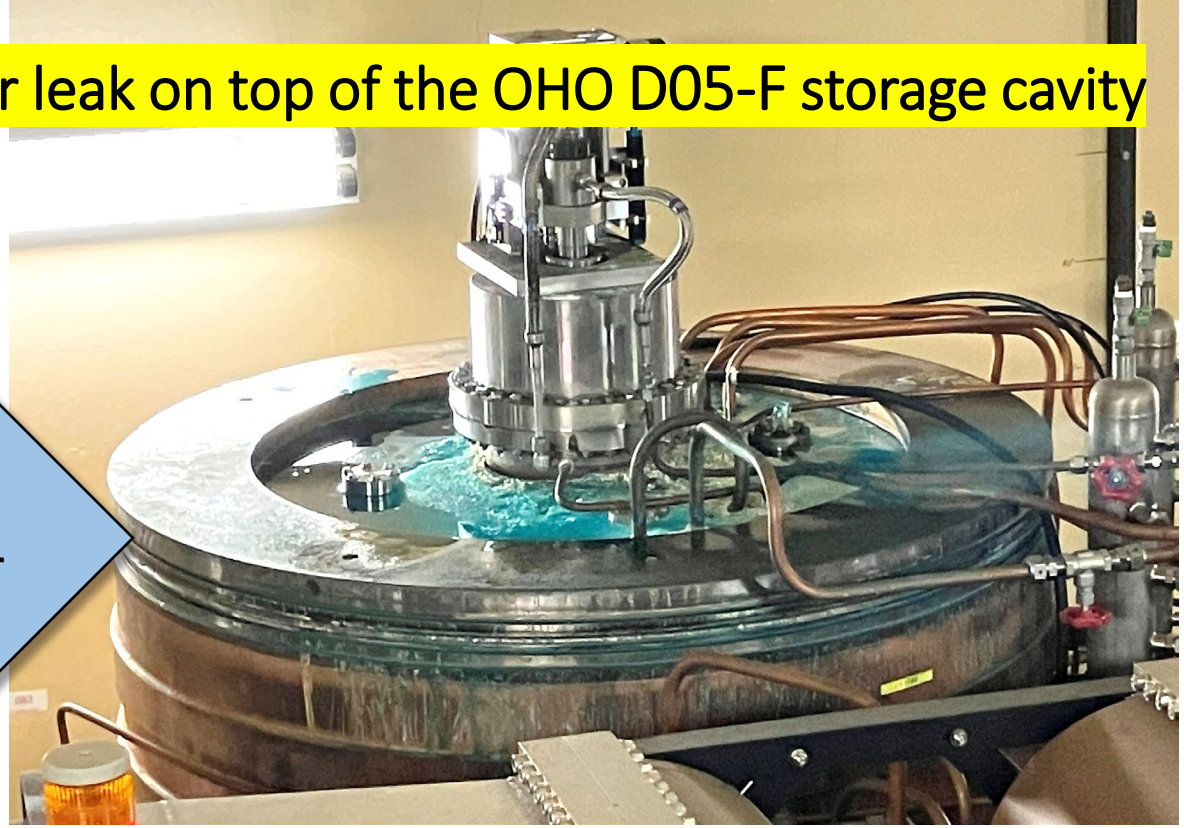
D05-F cavity: investigation results

ARES

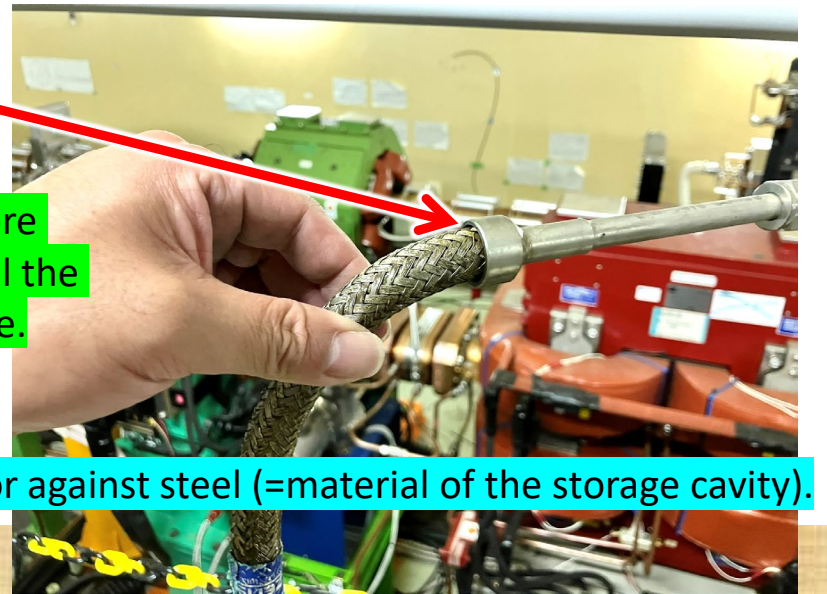
2026-04-15 (maintenance day): cooling-water leak on top of the OHO D05-F storage cavity

← Storage-cavity frequency tuner

Partial removal of cooling water

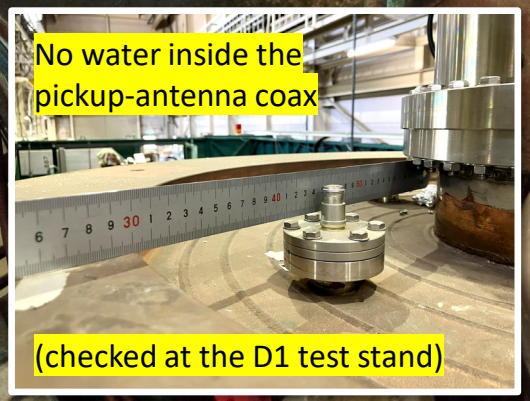


Leaking here



Because the top of the storage cavity is more than 2 meters high, we didn't realize it until the cooling water began to overflow from there.

The blue color comes from rust inhibitor against steel (=material of the storage cavity).



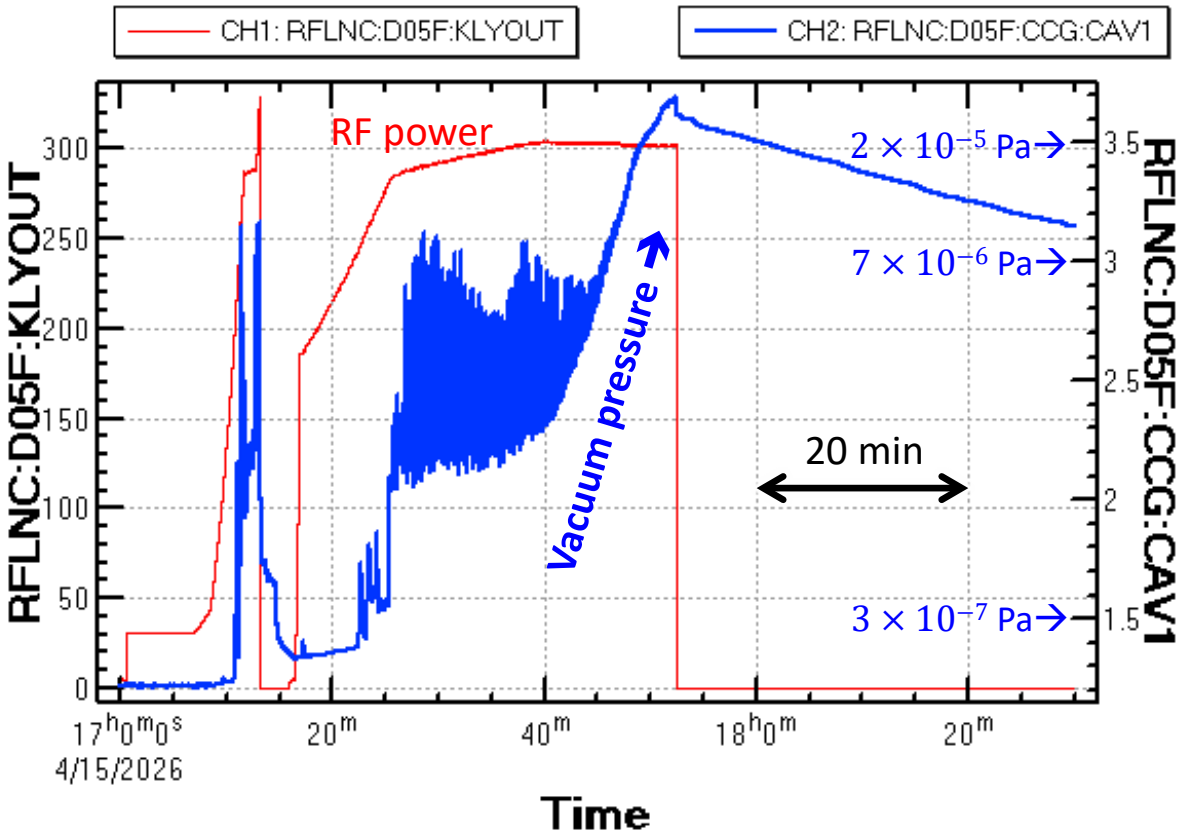
No water inside the pickup-antenna coax

(checked at the D1 test stand)

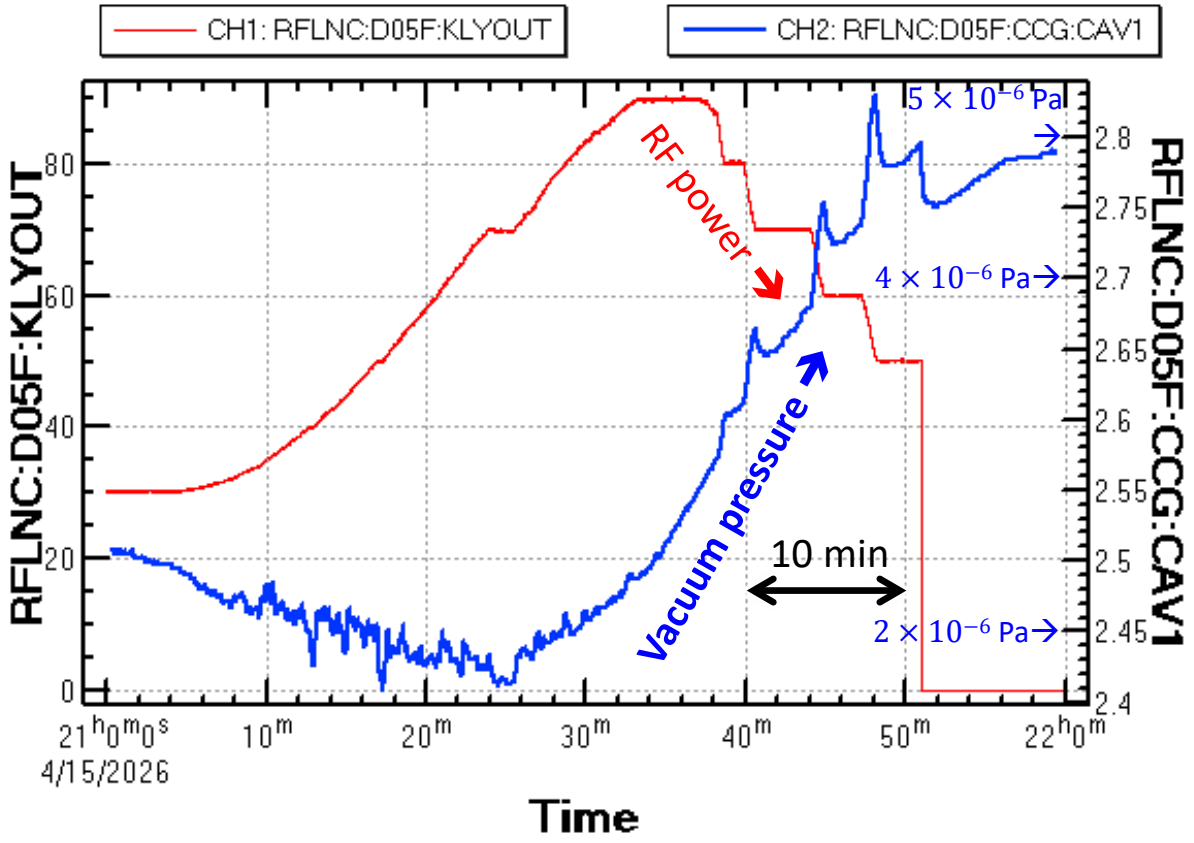
ARES

Furthermore, on the same day (2026-04-15), a vacuum burst during the restart after scheduled maintenance!

Cavity conditioning after maintenance



Abnormal: pressure kept rising even as RF was lowered



Entered the tunnel for a leak test: no leak detected

(background level: 1×10^{-10} Pa m^3 /s)

D05-F cavity detuned

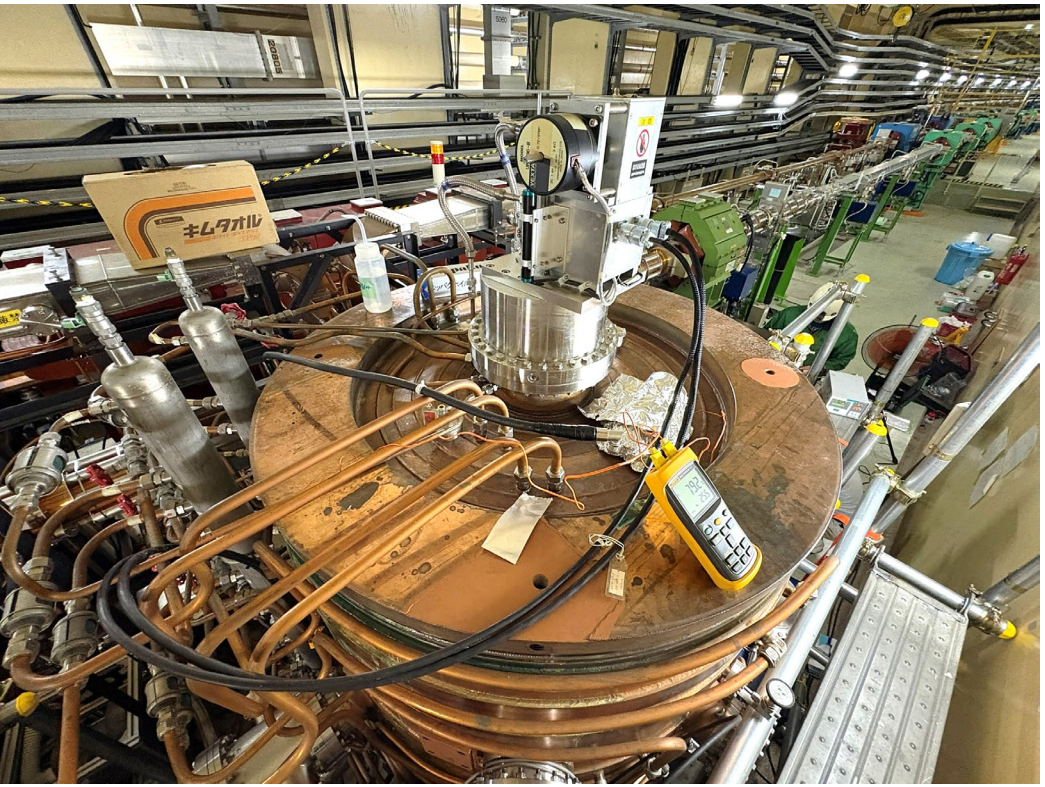
(With RF off, the pressure decreases **slowly**)

ARES

After 2026ab

2026-07-03 Cleaning done

➔ Each monitor port baked at ~80°C



➔ **Vacuum-leak test in the cold state: no leak detected**

We suspected *galvanic corrosion* between the monitor port (SUS) and storage-cavity material (carbon steel).

✓Cavity: carbon steel

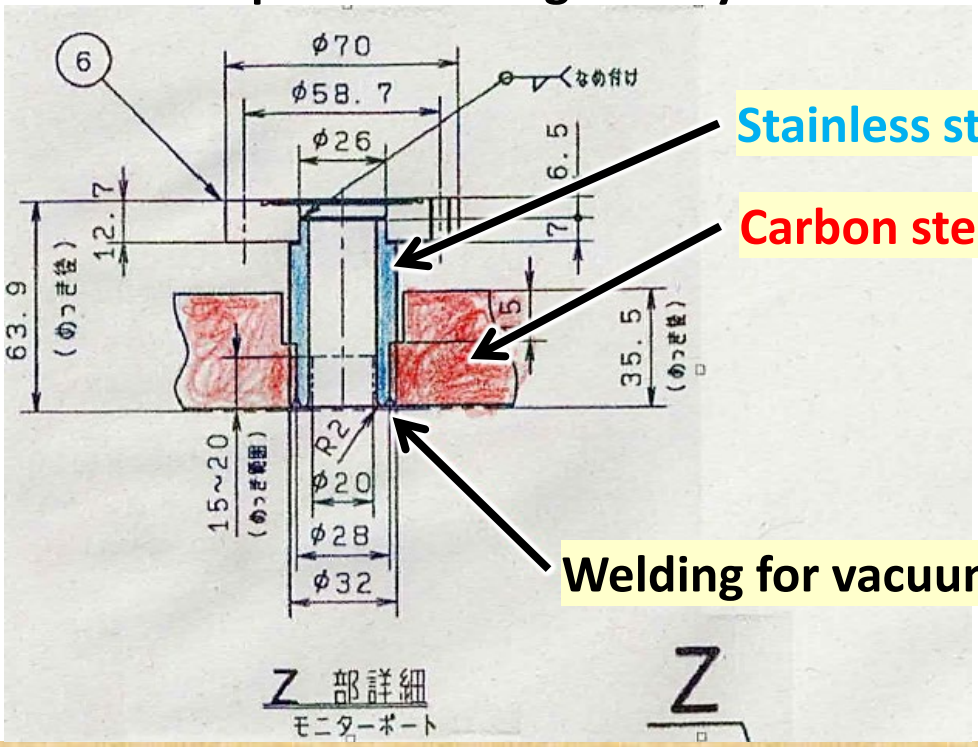
✓Port: stainless steel

➔Electrolyte between dissimilar metals

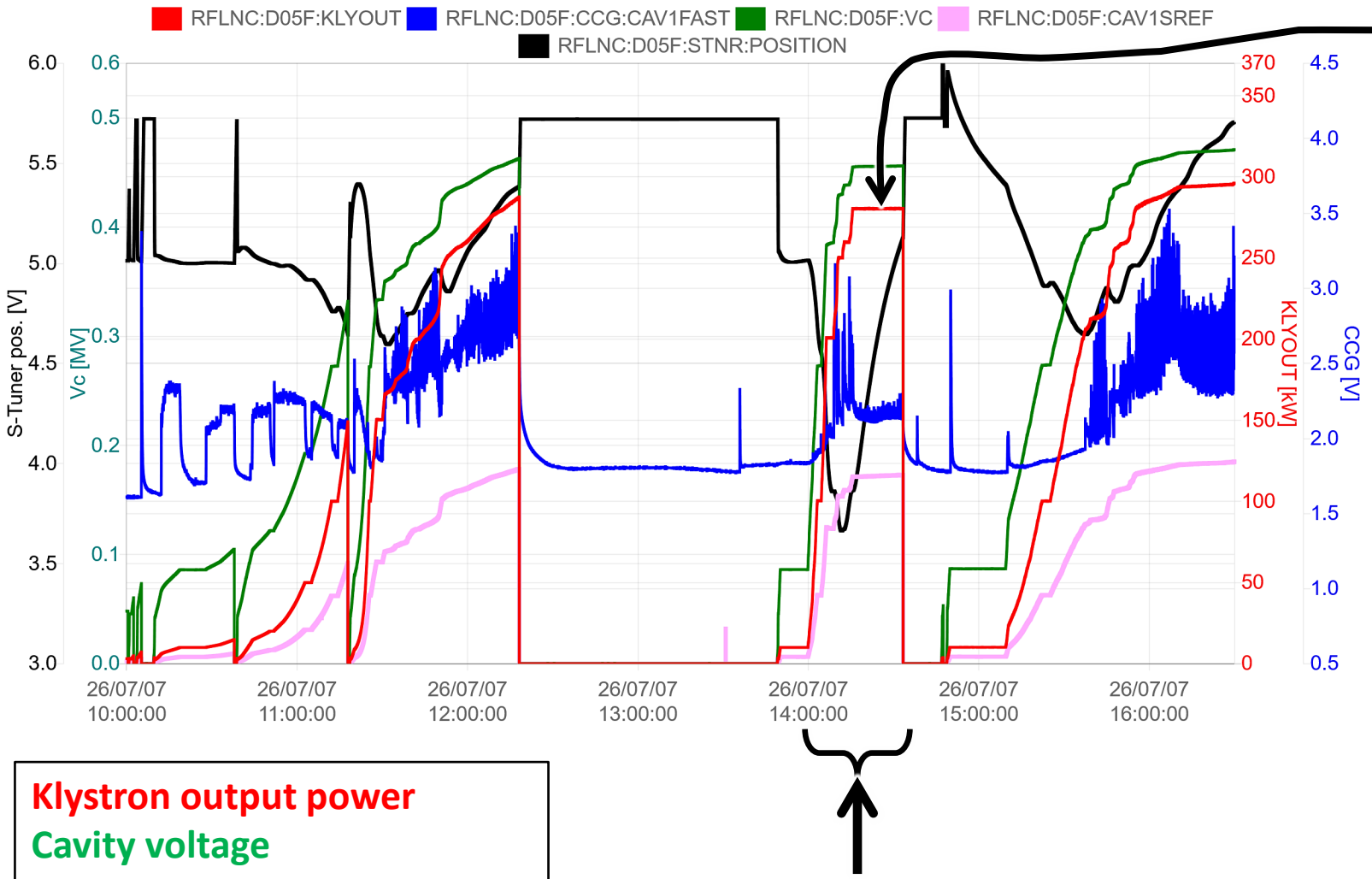
➔**Galvanic corrosion?**

(➔ vacuum leak suspected)

Monitor port for storage cavity



2026-07-07 In-situ vacuum leak test with high-power RF on





Klystron output power
Cavity voltage
Cavity vacuum pressure
Storage-cavity tuner position

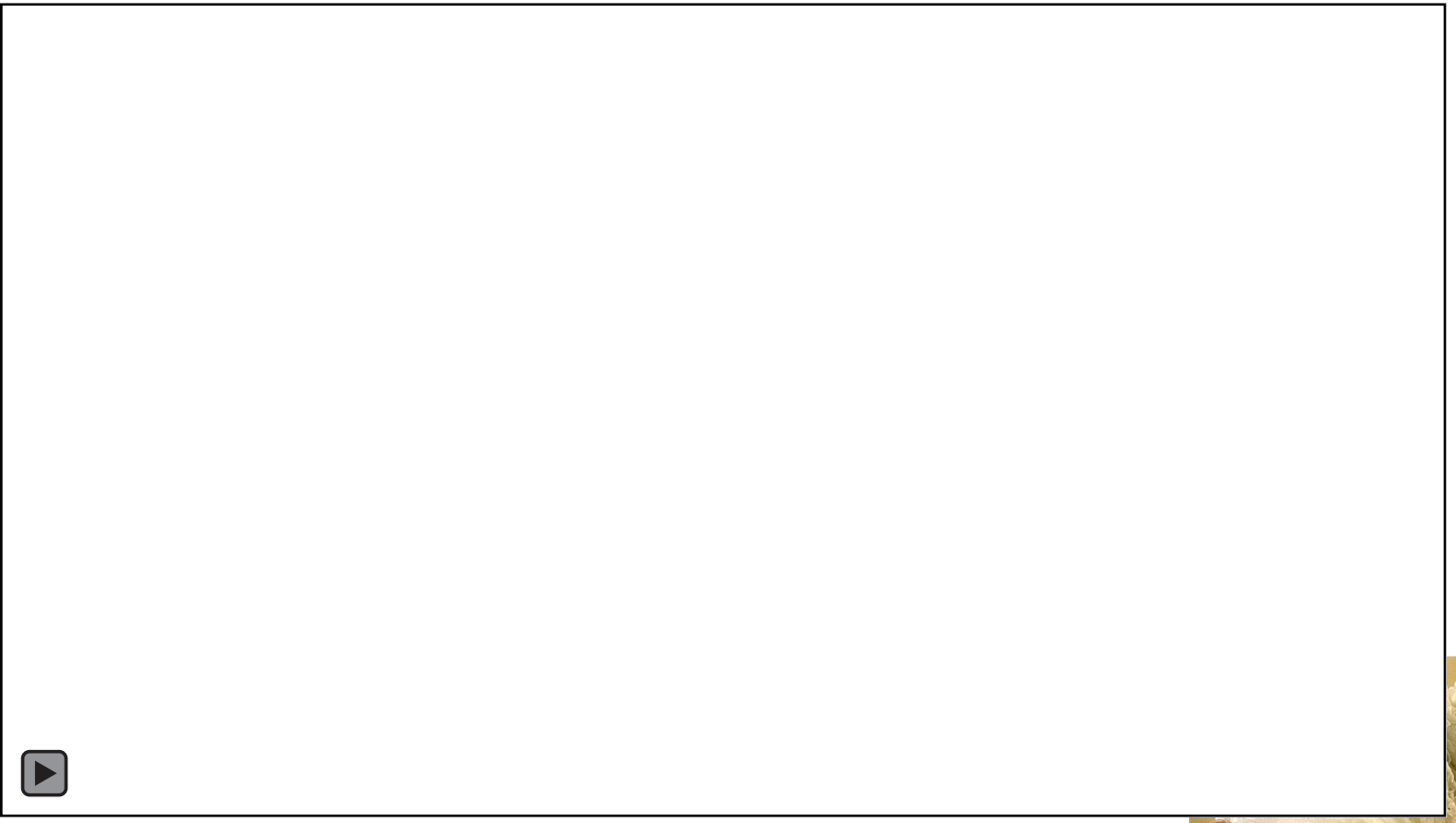
Vacuum leak test with high-power RF on (hot condition)

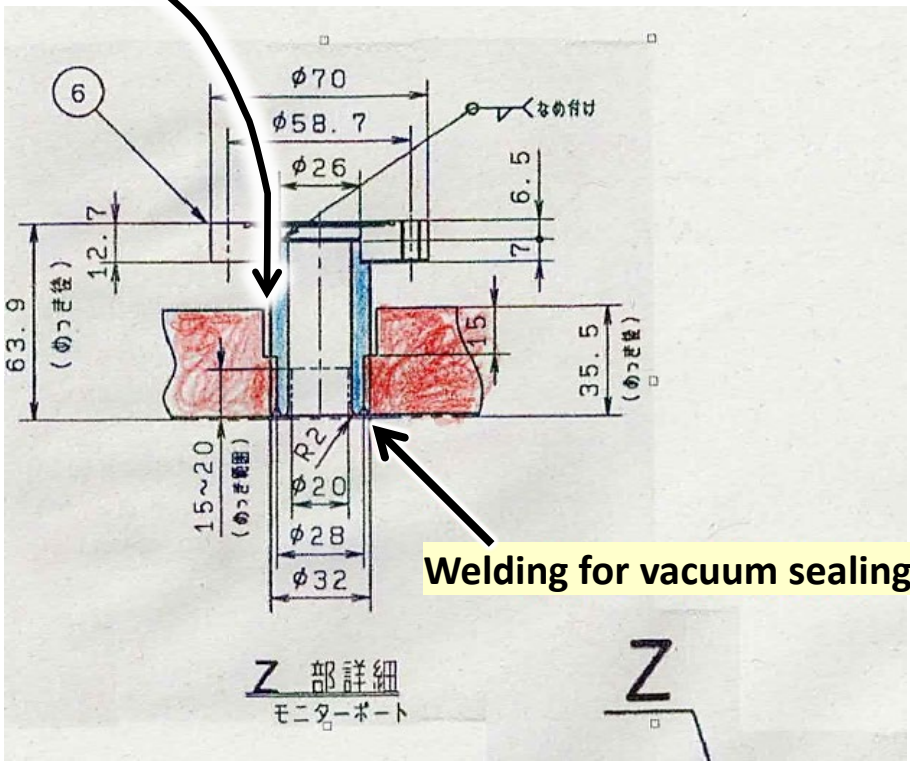
➔ **No leak detected**

Monitor port bases cleaned with a steam cleaner

ARES

(morning of Wed., July 22)





(Afterwards)

➔ **Injected acetone and ethanol**

➔ **Vacuum-leak test: no leak detected**

➔ **High-power test (0.5 MV sustained): no abnormal vacuum pressure rise**



Cleaned until the wipes came away clean

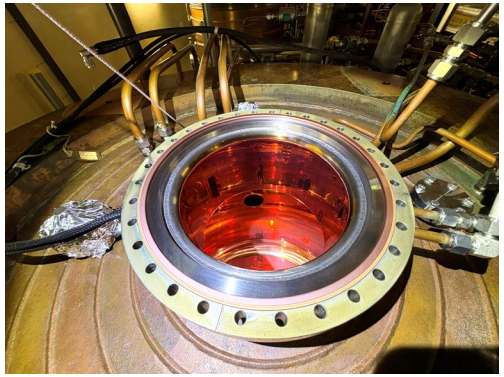


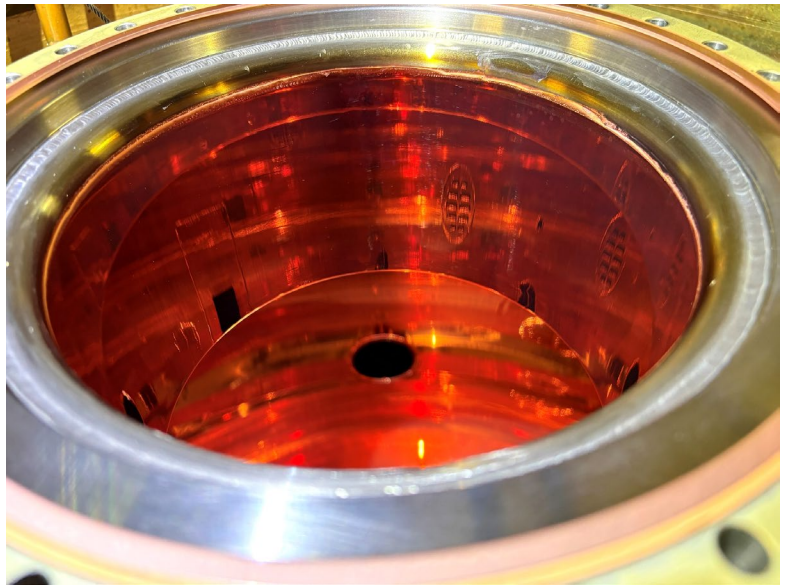
Steam cleaner

D05-F storage cavity: internal inspection

Date: Thu., Sept. 3, 2026
Present: Sakai, Abe, Kageyama, Komichi, Skillwell (Homma)

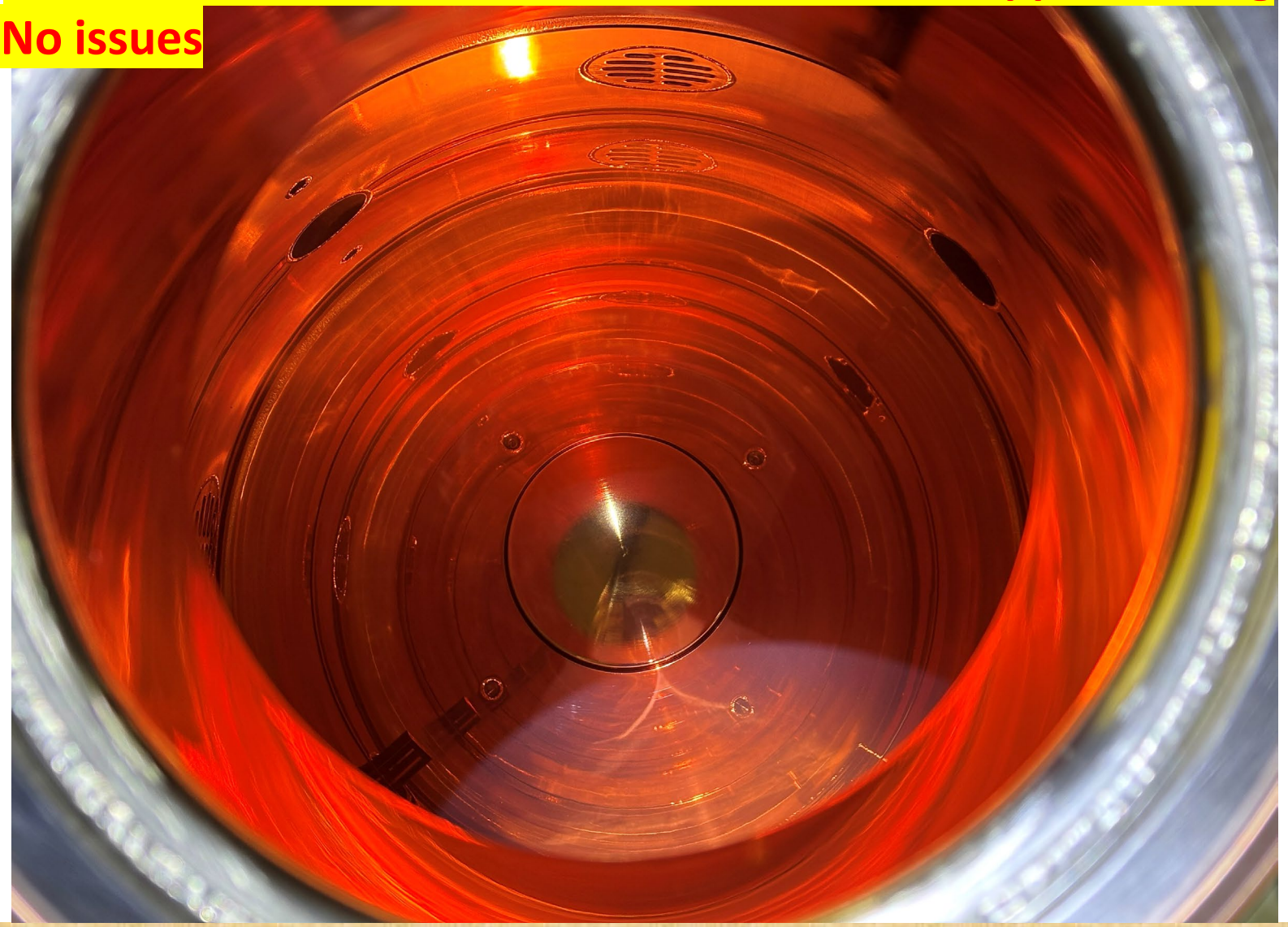




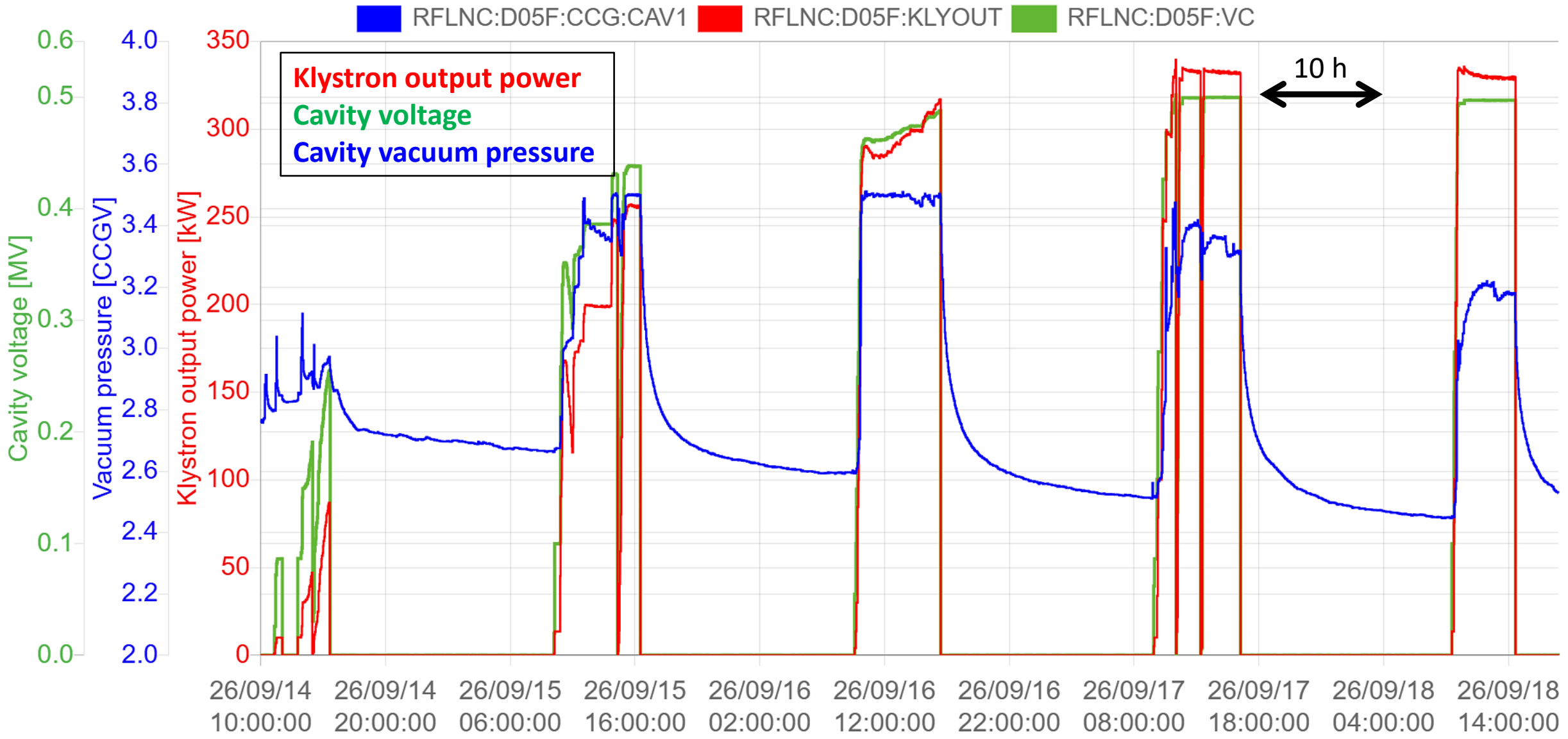


➔ **No corrosion, water stains, or defects in the copper coating**

➔ **No issues**



Subsequent high-power test (cavity voltage held at 0.5 MV) ➔ no issues



Summary of findings

- D05-A (confirmed)
  - ① Subtle flap-type flowmeter fault → too little cooling-water flow in the storage-cavity mid side-wall circuit
  - ② Abnormal deformation of the storage cavity
  - ③ Vacuum leak at the coupling–storage cavity joint

- D05-F (inferred by elimination)
  - ① Cooling-water leak on top of the storage cavity
  - ② A large volume of water accumulated over a long time
  - ③ Noticed on the regular maintenance day (Apr. 15, 2026)
  - ④ Closed the leaking **storage-tuner cooling circuit** and rushed to finish the work that day
  - ⑤ Had no choice but to return the cavity to operation before the leak area was fully cleaned
  - ⑥ **Storage-tuner cooling circuit** not restored (not confirmed, but the valve was likely left closed)
  - ⑦ That tuner's plunger heated up
  - ⑧ Pressure rise (actually not a leak, not a failure)

*(*Explains why the pressure decreased slowly after RF off, and why *the water leak and pressure rise occurred on the same day)*

Countermeasures

Set cooling-water flow **by valve rotation angle** (not with flap-type flowmeters) **with ample margin** ➔ Prevents D05-A ① from recurring

- D05-A (confirmed)
  - ① Subtle flap-type flowmeter fault → too little cooling-water flow in the storage-cavity mid side-wall circuit
  - ② Abnormal deformation of the storage cavity
  - ③ Vacuum leak at the storage–coupling cavity joint

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  - ⑦ That tuner's plunger heated up
  - ⑧ Pressure rise (actually not a leak, not a failure)

With limited time and human resources,
it is difficult to eliminate human error entirely.

On any pressure rise, always check all cooling-water flows
➔ **Would catch a valve left closed (if the inference holds)**

- ✓ *It is not practical to install flow switches on all* $26 \times 30 = 780$ *cooling-water pipes for the entire MR/ARES.*
- ✓ *The **total** cooling-water flow of each cavity is already monitored and interlocked.*

Summary of countermeasures

- **Short term**
  - Set the cooling-water flow of each branch circuit by valve rotation angle (not with flap-type flowmeters), with ample flow
    - Flap-type flowmeter readings used only as a reference
  - Whenever vacuum pressure rises, always check every cooling-water flow as well, not just perform a leak test

- **Medium term**
  - Add more sensors to the ARES cavities, including water-leak sensors, and use AI-based diagnosis and monitoring of their condition and performance

D05-A and -F cavities are normal and will return to operation without cavity replacement.

Operational status of ARES

Number of trips of the ARES cavities in 2026ab

(Distribution along the time axis)

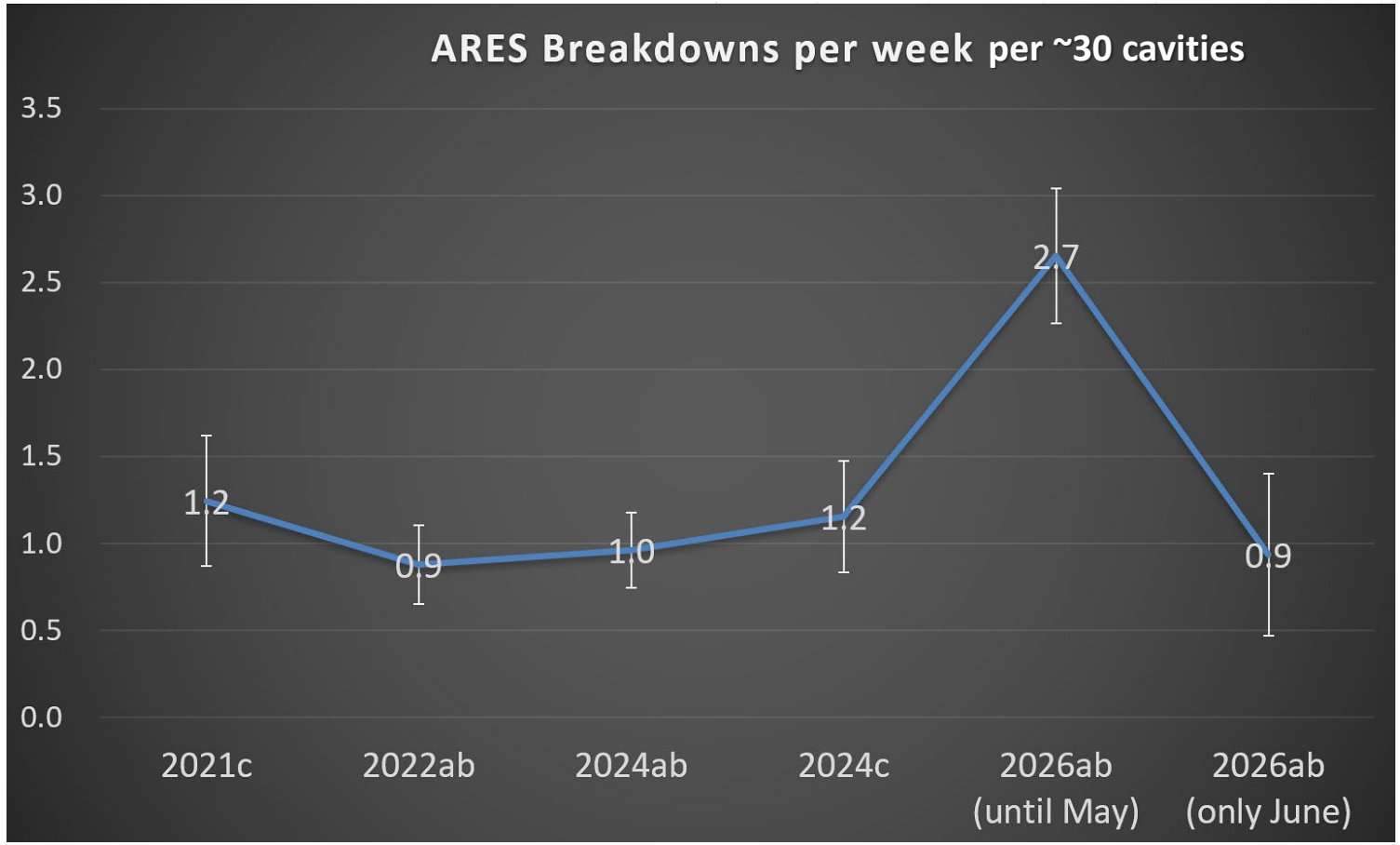


	Area	OHO														FUJI															
	Station	D4-A		D4-C		D4-E	D4-F	D4-G	D4-H	D5-A	D5-B	D5-C	D5-D	D5-E	D5-F	D7-A		D7-B		D7-C	D7-D	D7-E		D8-A		D8-B		D8-C	D8-D	D8-E	
	Cavity	#1	#2	#1	#2	#1	#1	#1	#1	#1	#1	#1	#1	#1	#1	#1	#2	#1	#2	#1	#1	#1	#2	#1	#2	#1	#2	#1	#1	#1	#2
	HER operation																														
	LER operation																														
	Operating Vc [MV/cav]	0.40	0.40	0.40	0.40	0.45	0.45	0.45	0.45	0.00	0.45	0.45	0.45	0.45	0.45	0.43	0.43	0.43	0.43	0.45	0.45	0.43	0.43	0.43	0.43	0.43	0.43	0.45	0.45	0.43	0.43
	Vac. press. [Pa]	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7
	Input Coupler	Used	Used	Used	Used	New	New	New	New	New	New	New	New	New	New	Used	Used	Used	Used	New	New	Used	Used	Used	Used	Used	Used	New	New	Used	Used
2026/6/29 to 2026/1/26	Reflection only or unknown reason																														
	Vacuum trouble																7		2				1								
	Arc coupler (not beam loss)																														
	C-damper power or cavity BD					4	3		3		3		1		3	7	1				4	1	1	1	3			3	5	5	3
	Tuner trouble			3																											
	Chiller trouble	3																													
	Other cooling wtr																														
	Others																														

- Vacuum troubles due to the breakdown of a large air conditioning system in the D07 local control room on the ground (not a cavity issue), see the backup slide
- As for the cavity breakdown, there appears to be a non-uniformity.

History of the ARES Breakdown Rate

Counting number of C-damper power interlock activation events (≈ cavity breakdowns)



↑

(Unexplained spike only for 2026ab until May 30th)

(We performed special high-power RF conditioning for ARES on May 31, but the conditioning time was not so long.)

Operation during May and June, 2026

The beam operating conditions were nearly the same in May and June.

Beam currents:

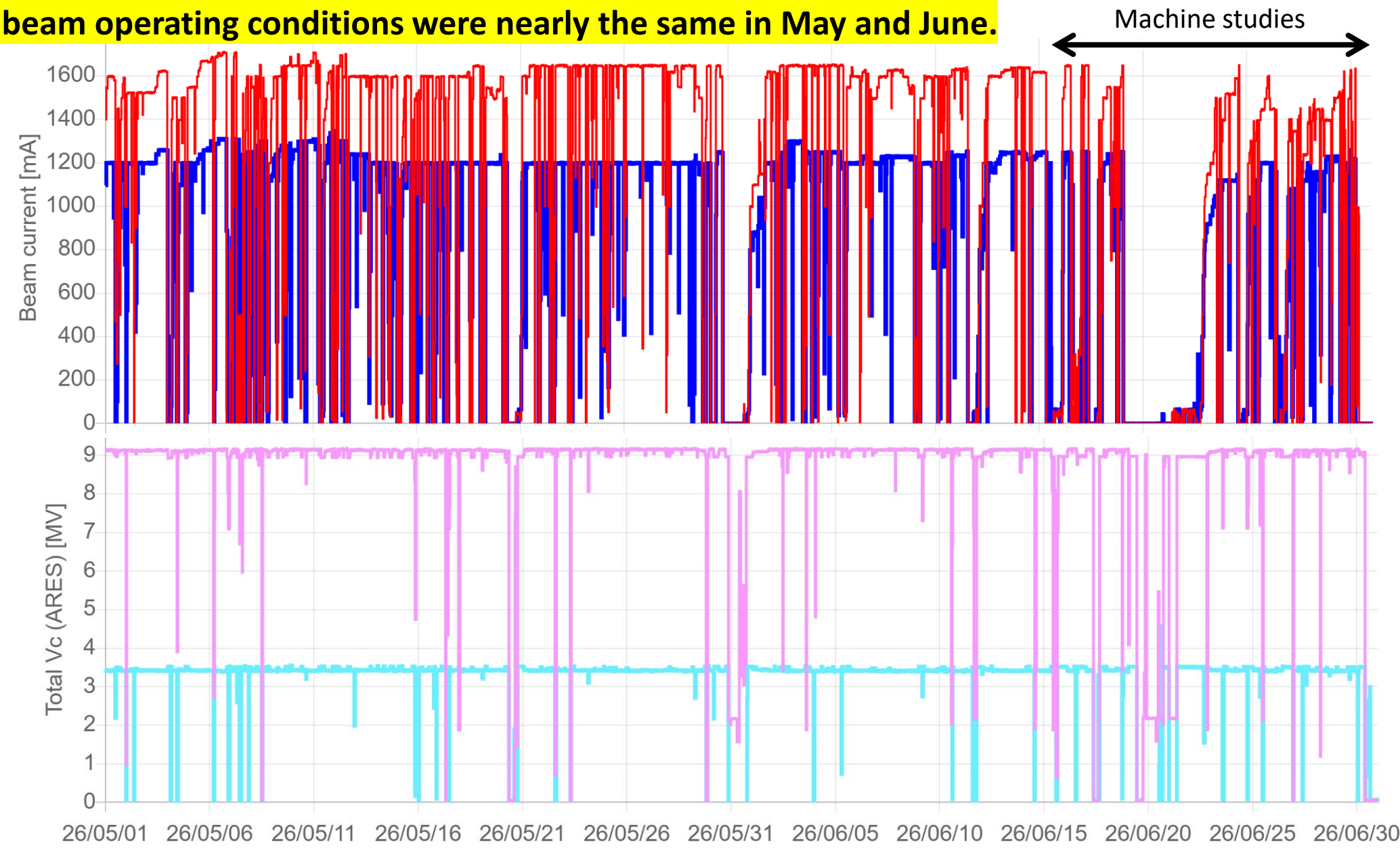
LER

HER

Total V_c (ARES):

LER

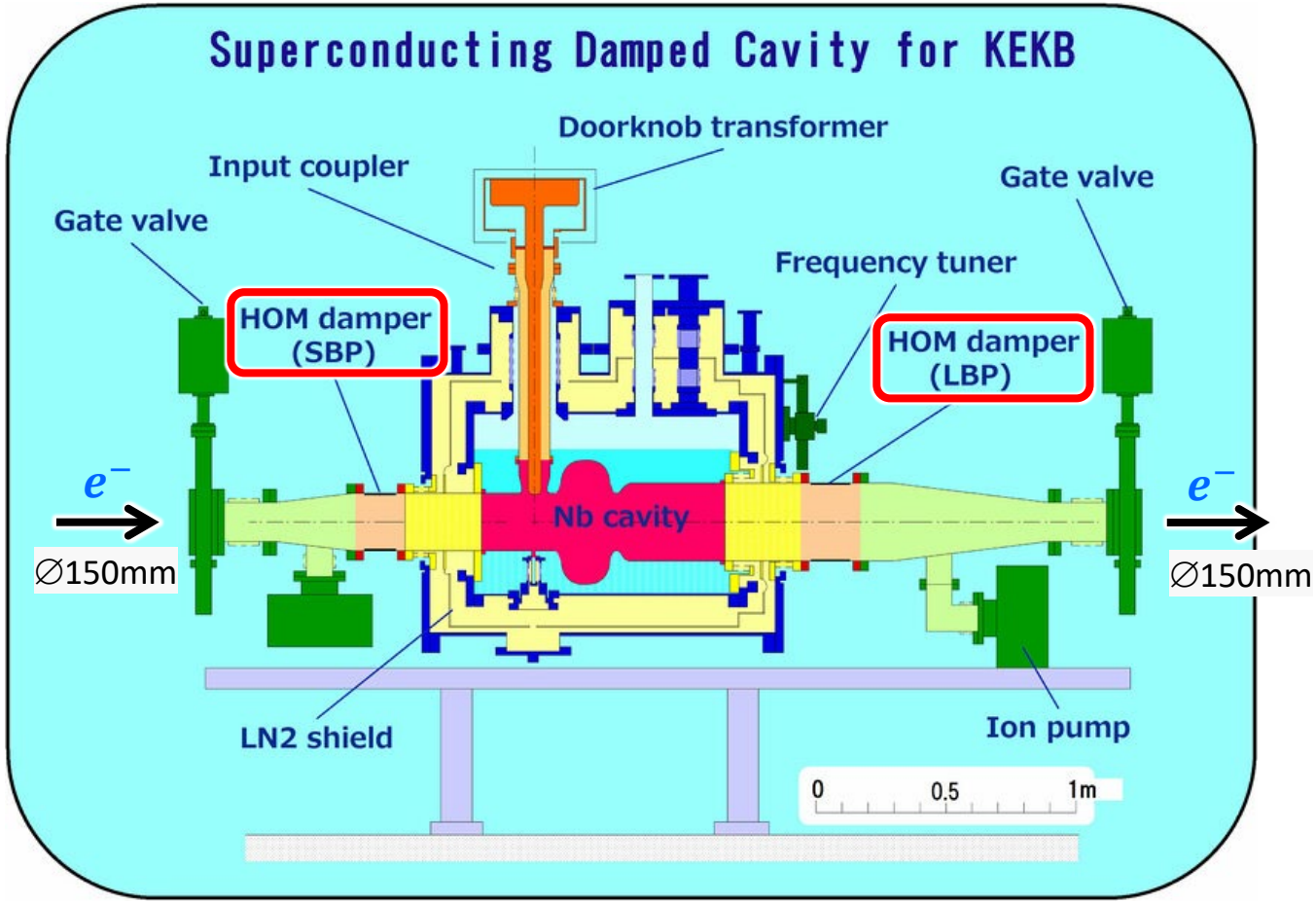
HER



Super-Conducting Cavity (SCC)

SCC

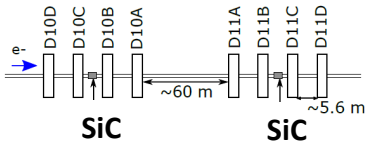
Super-Conducting Cavities (SCCs)



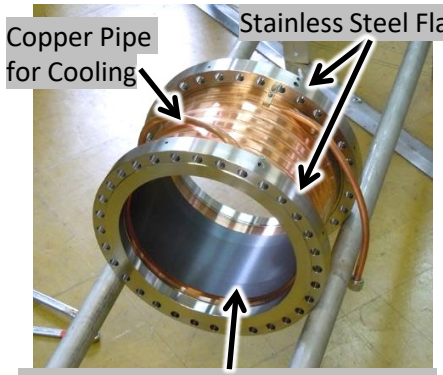
∅220mm duct ∅300mm duct

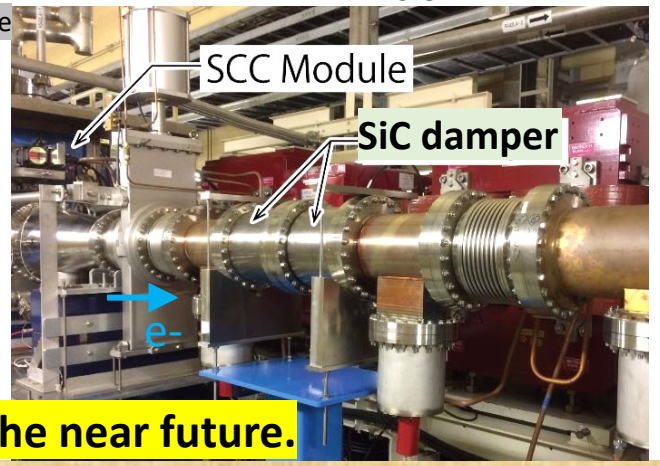
■**Single-cell single-mode 508.9 MHz cavity**
- All the HOMs are extracted to the beam ducts.

■**HOM dampers** with:
- **Ferrite** (used since KEKB)
  - 4mm-thick Ferrite (IB-004) bonded on the inner surface of a copper duct by HIPping
  - Ferrite Length: 120mm (150mm) for 220 (300) mm diameter damper as “SBP” (“LBP”)
  - Power-handling capability demonstrated: 11.7 (14.8) kW for 220 (300) mm diameter damper
- **SiC**
  - Added for higher HER beam currents at SuperKEKB



Ferrite damper



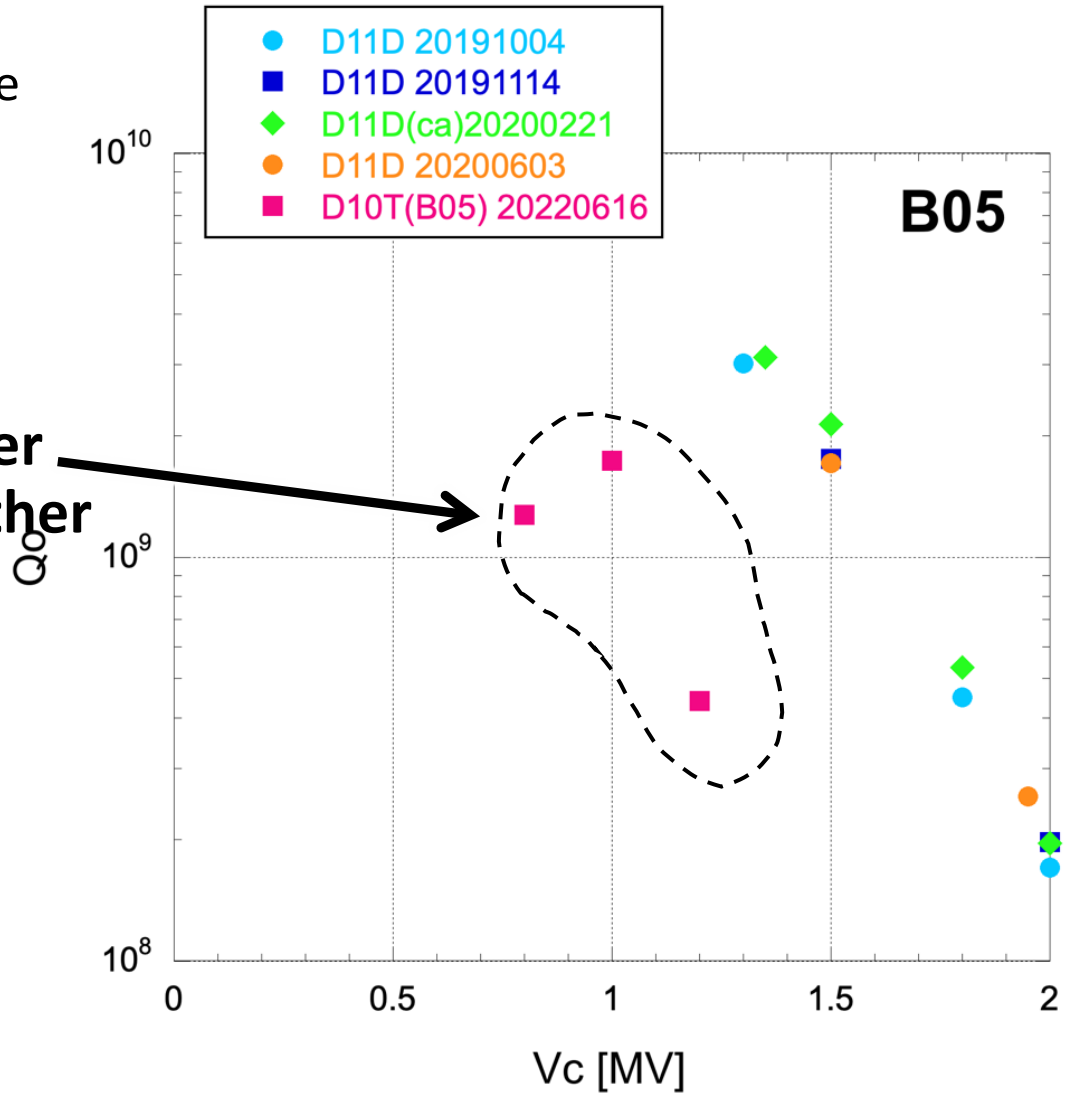


✓ **Stable operation in 2026ab**

✓ **HER beam current limited by SCC HOM dampers, but the limit is sufficiently high (2.0 A) for the near future.**

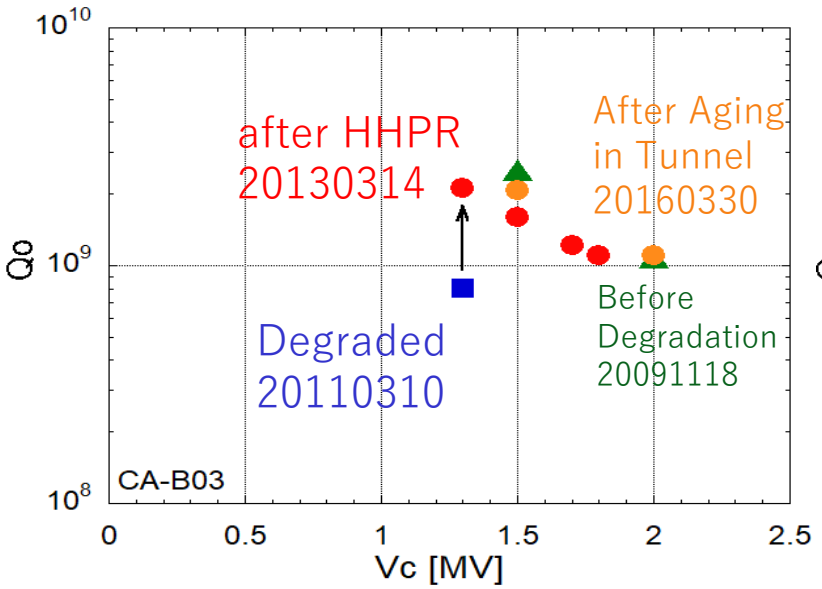
Eight SCCs in operation, and only one “spare” SCC.

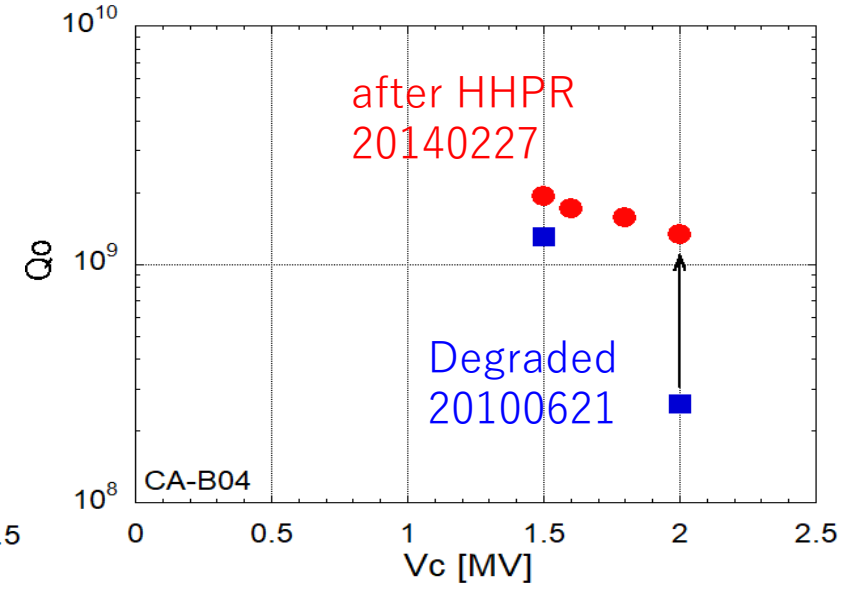
- ✓ **The “spare” SCC**
  - ✓ Was used for beam operation at the D11-D station from the beginning of KEKB until 2020.
  - ✓ In 2020, vacuum trouble ➔ parked
  - ✓ In 2021, repaired
  - ✓ In 2022, tested and performance measured
- ✓ **The measured performance (■) is significantly lower than both its earlier performance and that of the other SCCs (next slide).**

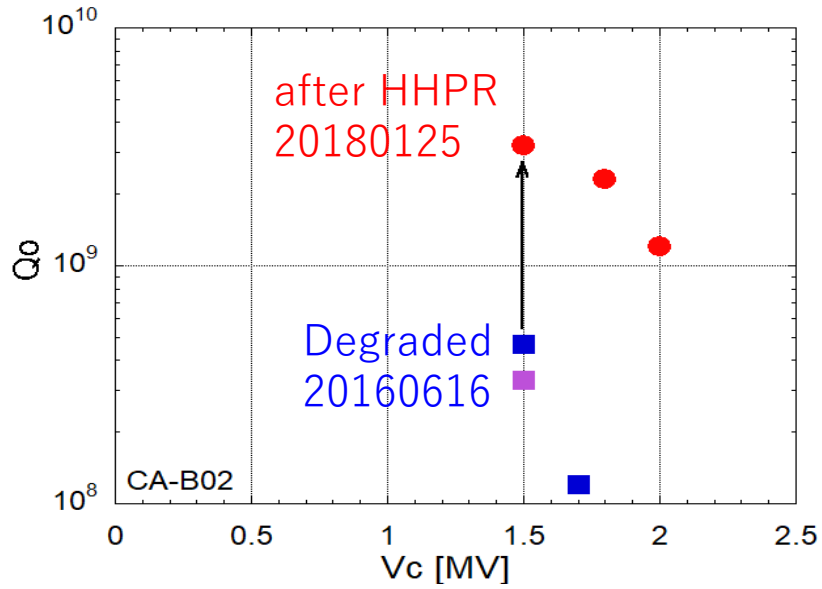


Successful performance recovery by HHPR

- **Horizontal High-Pressure Rinse (HHPR)** was applied to three SCCs with degraded performance by strong field emission.
- The cavity performance was successfully recovered in all the three cases.
- All the three SCCs were re-installed and now are operating stably in SuperKEKB-MR.







HHPR is a promising method for recovering degraded SCCs.

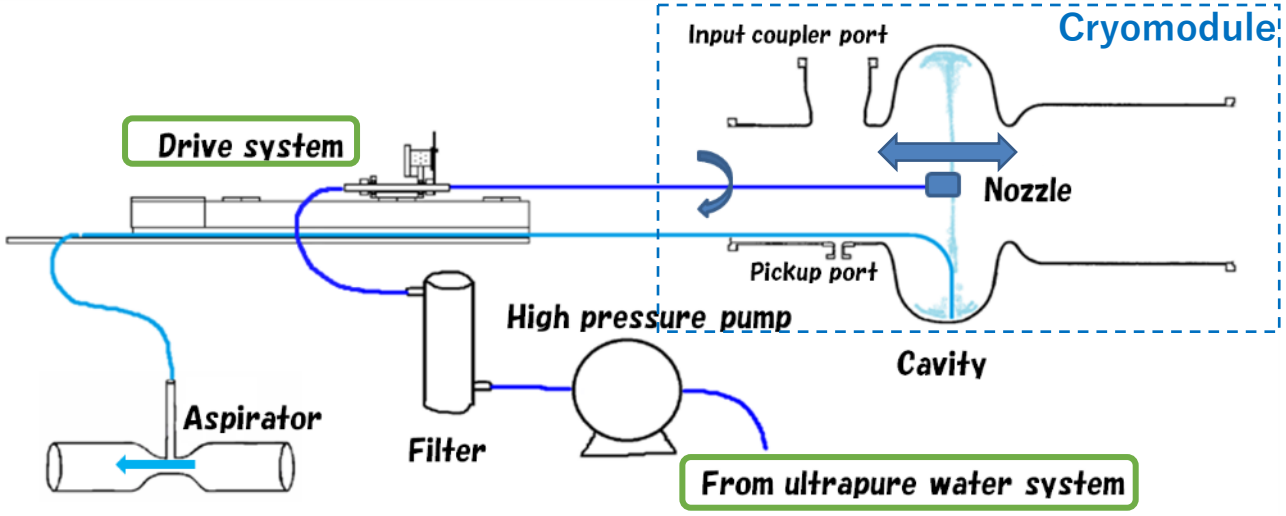
SCC

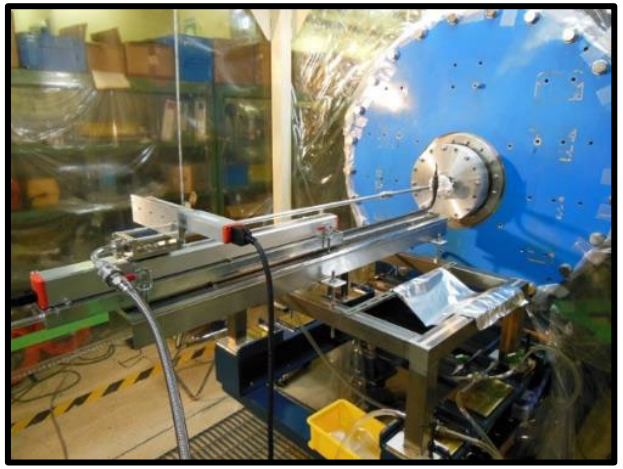
Recovery of the degraded SCC is needed for near-future high-current stable operation.

Proposed Work

- Transport the “spare” SCC from the storage area to the HHPR facility.
- Perform HHPR using the existing system.
- Conduct a high-power test to evaluate the cavity performance after HHPR.
- Prepare the spare SCC for prompt replacement in case of a serious cavity failure.

Horizontal High-Pressure Rinse (HHPR) system





Restoring the “spare” SCC performance is essential for near-future high-current stable operation.

Additional budget allocation (~20MJPY ≈ 130kUSD) is needed to carry out HHPR based on the established procedure.

High-Power RF (HPRF)

Klystron status

(↓**98 k [h] MTBF of E3786**, see the reference below.)

No.	Model	Operation time [h] and no. of klystrons			Sub-total
		< 50,000	50,000~100,000	>100,000	
30+1 used for MR+DR	E3786 (old)	1	4	**7**	12
	E3732 (current)	10 + 2(from 2027a)	5	2	19
7 spares (reused)	E3786 (old)	2	1	---	3
	E3732 (current)	4	---	---	4

3 waiting for repair	E3786 (old)	There are three klystrons that should be repaired by replacing their electron guns.	Repair of the 3 klystrons requires 100MJPY (≈ 640kUSD).
1 diagnosing fault (1)	E3786 (old)	A vacuum leak occurred in one of the klystrons in Sep. 2026 (T47A). Leak point found in the cooling water circuit in the tube (repair is difficult). * Operation time was 117,000 h. (without arcing around electron gun).	In service since 1991. The cumulative duration of water flow exceeds 300,000 h.

(2 brand-new (E3732): one delivered in 2025, the other in 2026)

Pumping the water circuit for leak check (Oct 2026).



Please refer to the following documents:
R. Kikuchi, "Operational and Lifetime Experience of High-Power Klystrons for Accelerator Facilities", 14th CWRF Workshop, September 16, 2026. ->
Our klystron statistics, based on data we provided, are included in this talk.


Super
KEKB
LLRF

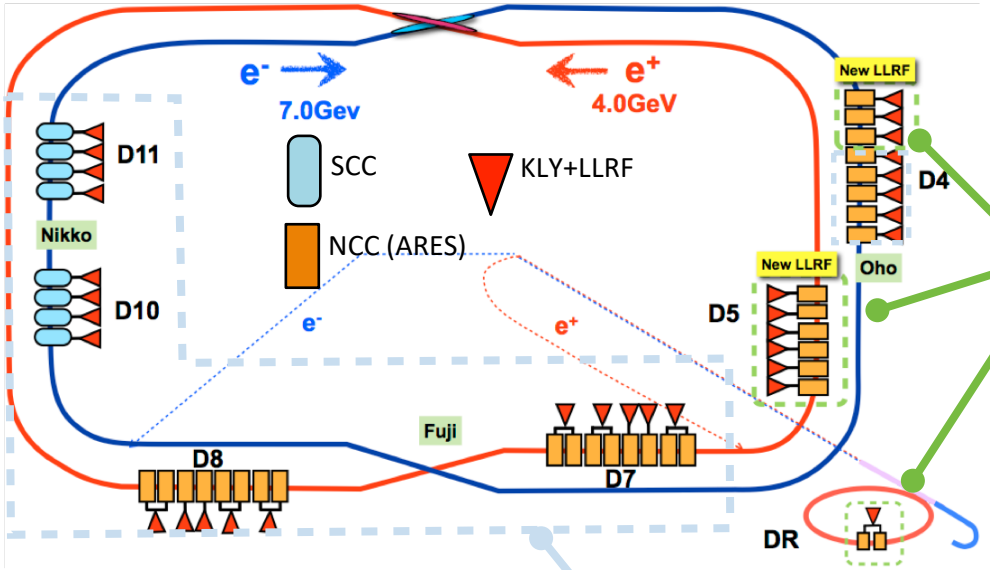
Operation Status of LLRF Control System

(Since 2018, no significant changes in the system configuration)

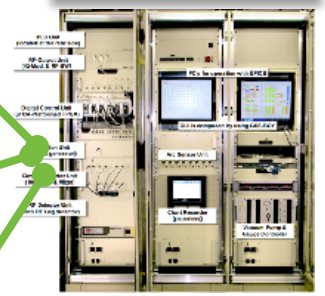
MTCA-based Digital LLRF Systems,
which were developed for SuperKEKB,
are used in the **10 RF-stations** for ARES & DR.

In the other 21 stations,
NIMBIN-Based Old Analog LLRF Systems,
which had been used since the KEKB or TRISTAN era, still in use.

CAMAC System is also still used for remote control of the old systems.



MTCA-based Digital LLRF for ARES & DR



NIM-BIN-based Old Analog LLRF for SCC&ARES



- All the LLRF systems, including the reference signal distribution and instability-dampers have been working well without fatal problems.

- Beam instabilities driven by the accelerating mode are successfully suppressed by the CBI damper and the Zero-mode damper. (CBI : Coupled Bunch Instability such as μ=-1 mode)

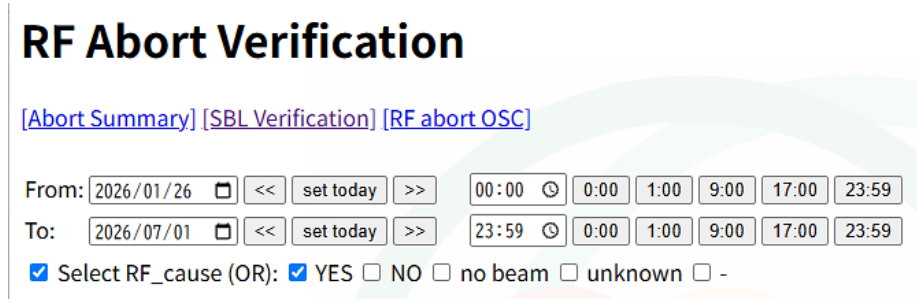
- Recent concerns are increase of failures of NIM-BINs and the modules due to aging of the old systems including CAMAC.
  - Most devices are discontinued, and number of spares is insufficient.
  - CAMAC crate controllers fail at a rate of approximately 1–2 units per year (25 systems in operation).

To upgrade the old analog systems to new digital ones, we need additional budget allocation (~50MJPY ≈ 320kUSD /station).

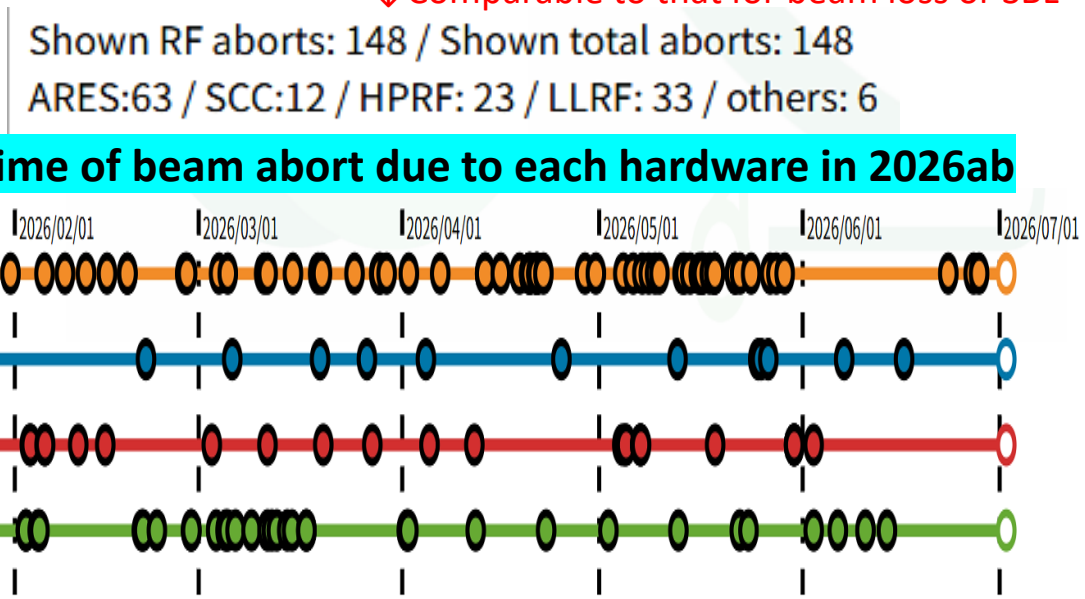
Beam Aborts and Need for Digital Upgrade

Beam Aborts in the 2026ab Run

- 31 beam aborts were attributed to LLRF hardware failures.
  - **27 aborts** were caused by analog LLRF hardware.
- **Not concentrated in specific units or modules**
- Various types of failures occurred randomly in the analog LLRF systems most probably due to aging of the modules.
- Although operation can usually be restored quickly, recurring problems with aging analog LLRF modules cause frequent beam aborts.
- Aging analog components are becoming a major concern for stable beam operation.
- Replacement parts are increasingly difficult to obtain, making long-term maintenance challenging.

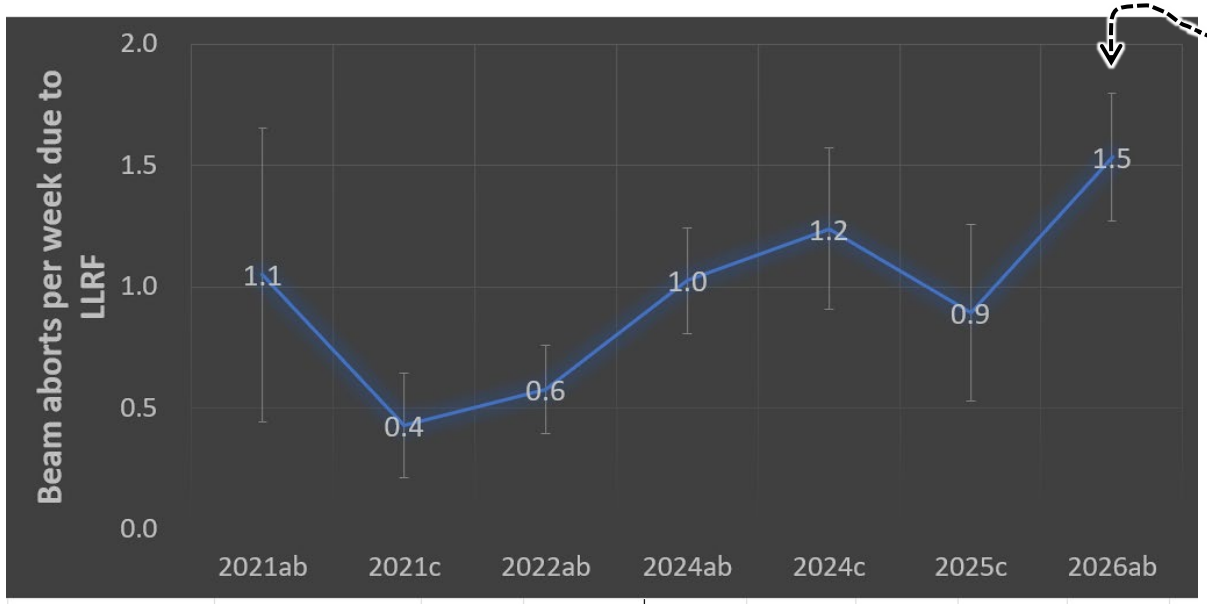


↓Comparable to that for beam loss or SBL



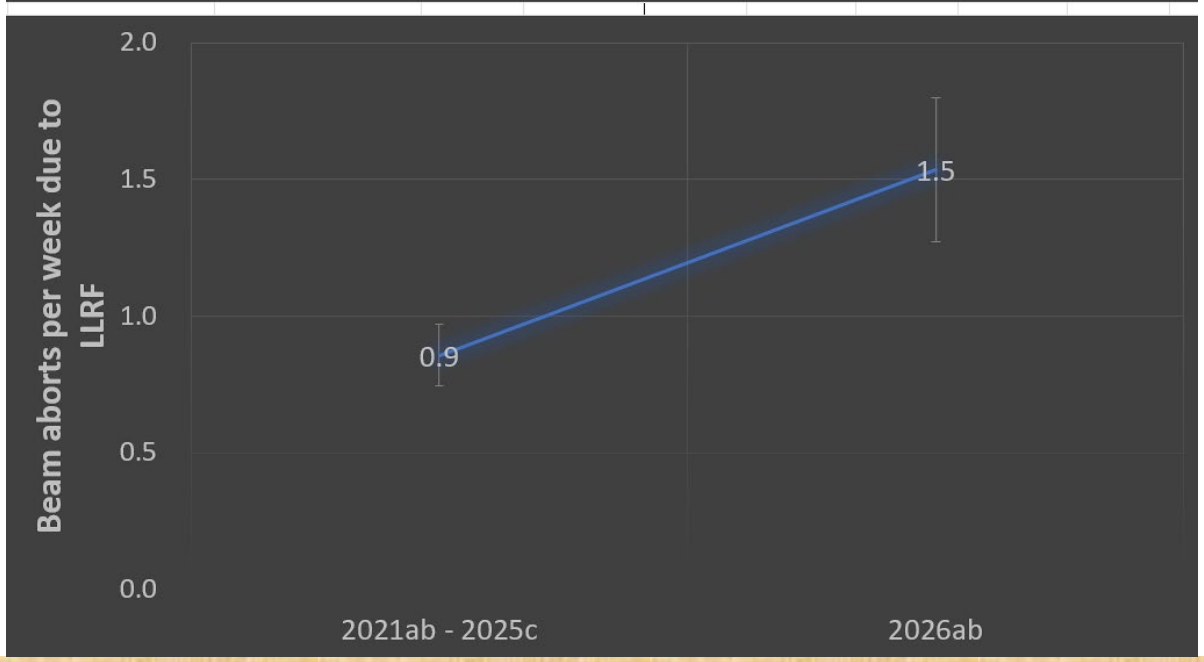
Early replacement of the aging analog LLRF systems with digital systems is essential for near-future stable beam operation.
Additional budget and resources are needed to accelerate the upgrade.

History of number of beam aborts per week due to LLRF



Mostly due to the old analog system

- Gradually increasing?
- Sign of near-future frequent malfunctions?



- Two-sigma significance in the increase compared to the past data

Summary

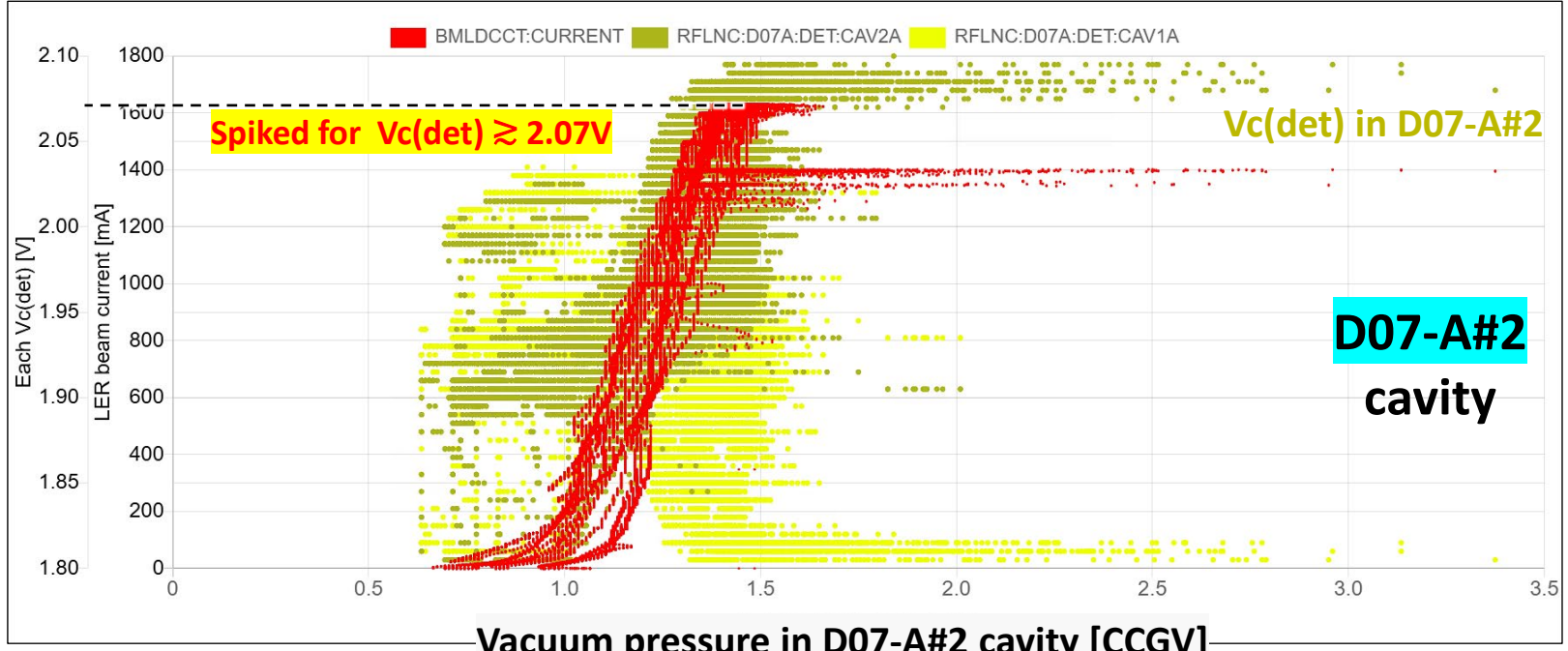
- **The RF system was operating well in 2026ab.**
- **The RF system is very unlikely to limit beam currents in the near-future beam operation.**
  - Power capability of the HOM dampers for SCC limits 2.0 A in HER.
    - To increase the limit, further update the chillers and add more SiC dampers (during LS2?)
  - Power capability of the SiC dampers for ARES probably limits ~2.6 A in LER.
    - The limit performance test to be resumed soon (next year?)
- **What concerns us is the aging of the hardware.**
  - **ARES**
    - Findings and countermeasures were shown for the D05-A and D05-F vacuum troubles.
    - The two cavities were found to be normal, and will not be replaced.
    - The root cause of both the D05-A and D05-F vacuum troubles was the aging of the hardware.
      - D05-A: deterioration in the spring in the flap-type flowmeter
      - D05-F: deterioration in the flexible SUS tube for cooling the movable tuner
    - Unexpected hardware failures due to the aging and measures taken within a limited time frame could lead to human errors.
      - AI-based technology is effective?
  - **SCC**
    - The performance of the “spare” cavity is insufficient.
    - HHPR to be applied to the “spare” SCC to make it a true spare
  - **Klystron**
    - The nine klystrons have a longer operation time than MTBF, seven of which are old-type (E3786).
    - We have seven spare klystrons, all of which are reused.
    - We have a plan to purchase a few more new klystrons in the near future.
  - **LLRF**
    - The old analog system including “ancient” parts, units, or modules since KEKB/TRISTAN may indicate signs of frequent malfunctions.
      - Should be replaced by modern digital system in the near future based on our established digital technology.

Thank you for your attention

Backup slides

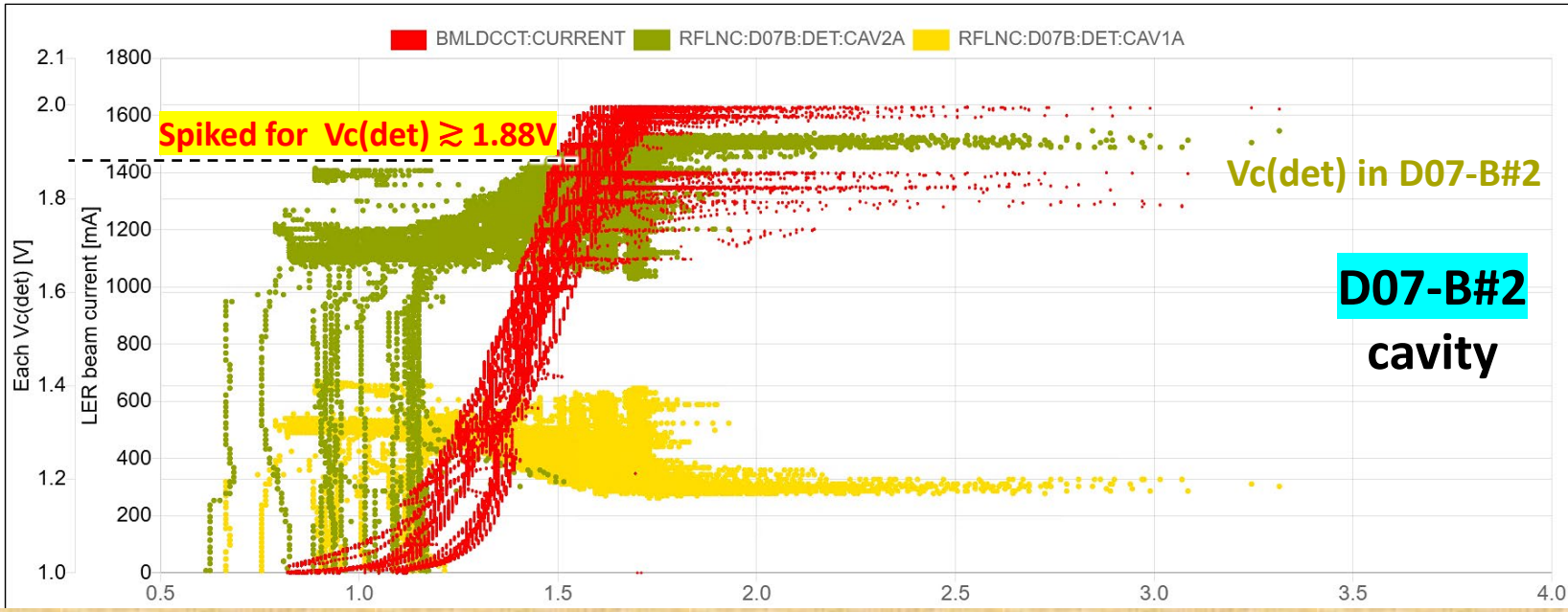
Apr. 22 to 24, 2026

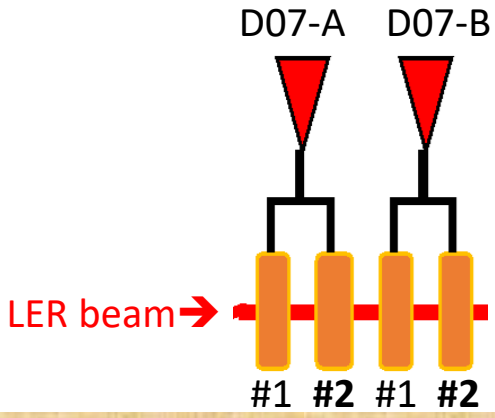
- ✓ A large air conditioning system in the D07 local control room on the ground was broken.
- ✓ The room temperature became higher than the human-body temperature.
- ✓ During this period, the vacuum pressure in D07-A#2 and D07-B#2 cavities , in particular, spiked frequently, leading to many LER beam aborts.
- ✓ The high room temperature led to malfunction in phase detectors, resulting in unexpected imbalance between #1 and #2 cavities through the vector summation of Vc.



Vacuum pressure in D07-A#2 cavity [CCGV]

LER beam current
Vc(det) in #2 cavity
Vc(det) in #1 cavity



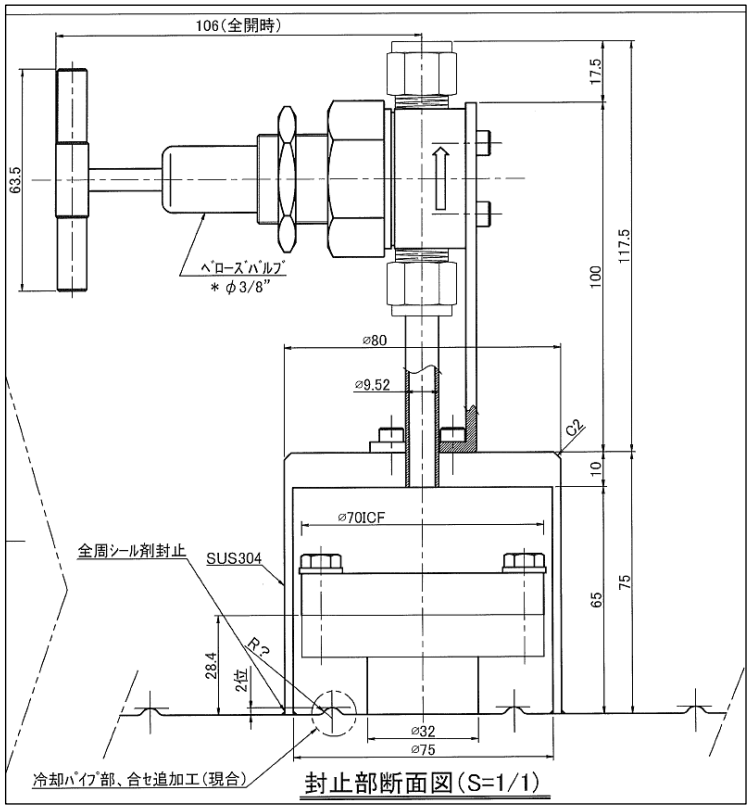


Should a monitor port on the D05-F storage cavity ever leak, we are ready to pump it out with a dedicated clamshell cup

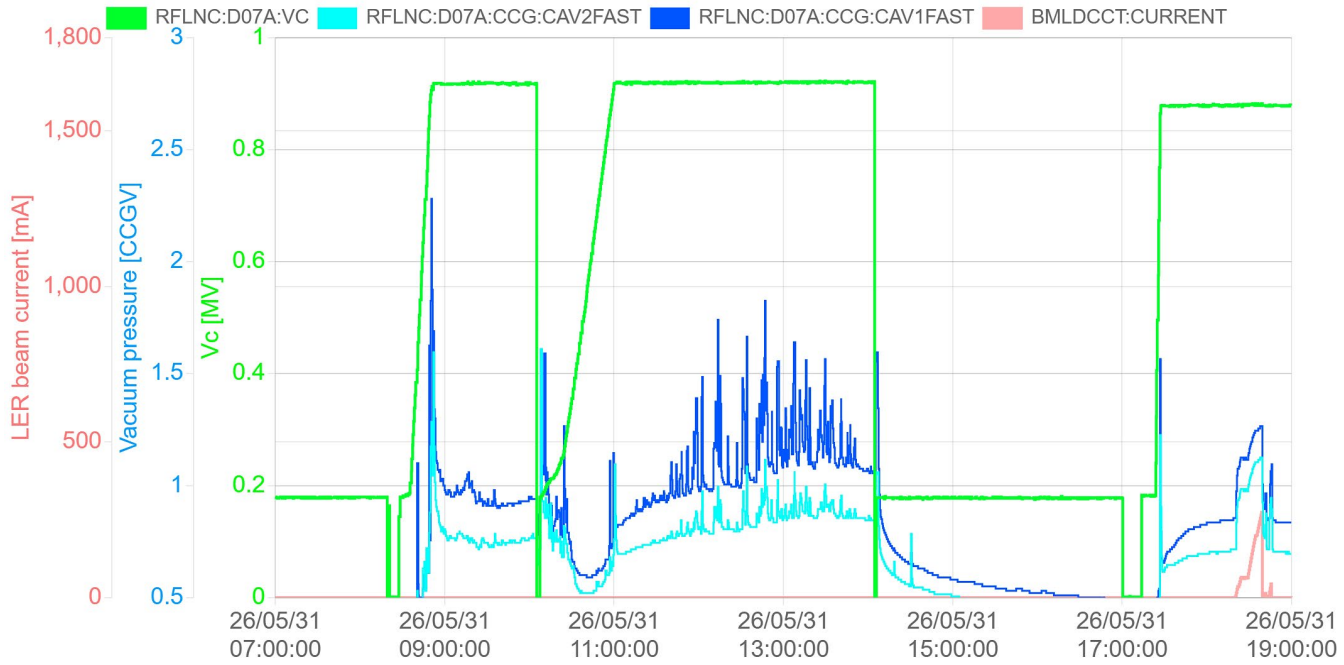
To vacuum pump





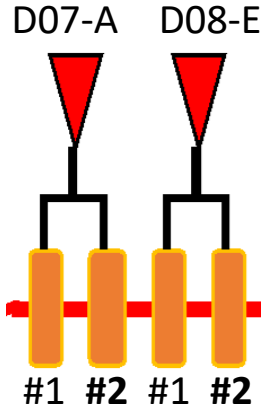


ARES cavity high-power RF conditioning on May 31st 2026



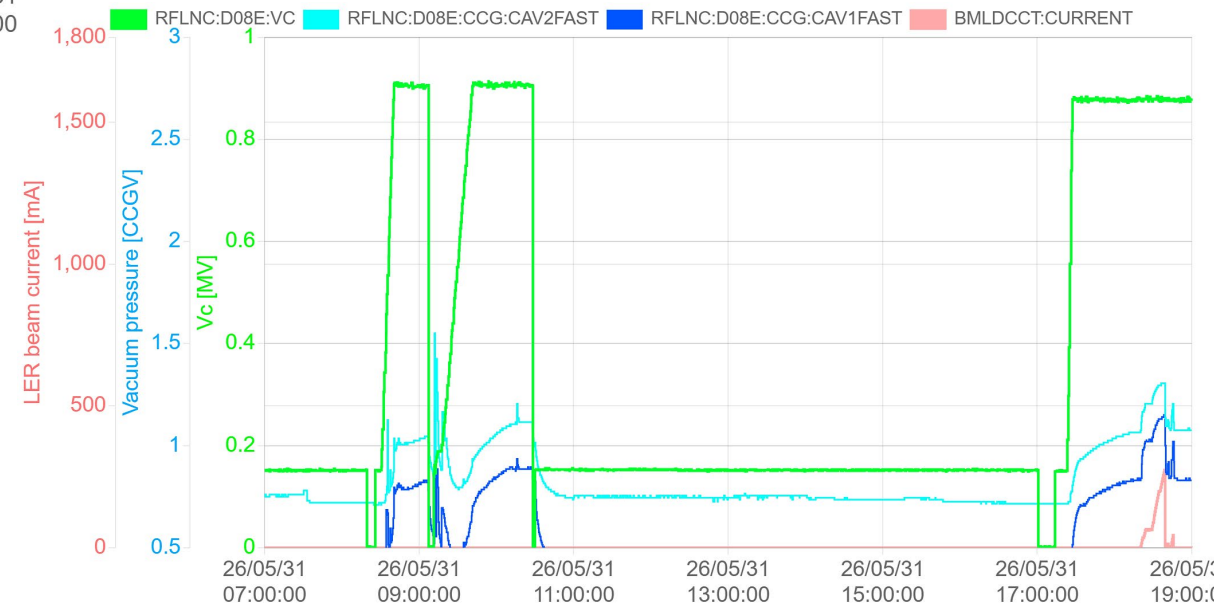
BACK

LER beam current
Cavity voltage (#1+#2)
#1 cavity vacuum pressure
#2 cavity vacuum pressure



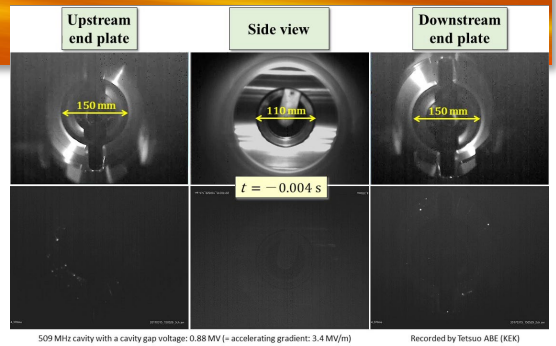
Area	OHO														FUJI															
Station	D4-A		D4-C		D4-E	D4-F	D4-G	D4-H	D5-A	D5-B	D5-C	D5-D	D5-E	D5-F	D7-A		D7-B		D7-C	D7-D	D7-E		D8-A		D8-B		D8-C	D8-D	D8-E	
Cavity	#1	#2	#1	#2	#1	#1	#1	#1	#1	#1	#1	#1	#1	#1	#1	#2	#1	#2	#1	#1	#1	#2	#1	#2	#1	#2	#1	#1	#1	#2
HER operation																														
LER operation																														
Operating Vc [MV/cav]	0.40	0.40	0.40	0.40	0.45	0.45	0.45	0.45	0.00	0.45	0.45	0.45	0.45	0.45	0.43	0.43	0.43	0.43	0.45	0.45	0.43	0.43	0.43	0.43	0.43	0.43	0.45	0.45	0.43	0.43
Vac. press. [Pa]	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7	10^-7
Input Coupler	Used	Used	Used	Used	New	New	New	New	New	New	New	New	New	New	Used	Used	Used	Used	New	New	Used	Used	Used	Used	Used	Used	New	New	Used	Used
Reflection only or unknown reason																														
Vacuum trouble																7		2			1									
Arc coupler (not beam loss)																														
C-damper power or cavity BD					4	3		3		3		1		3	7	1				4	1	1	1	3			3	5	5	3
Tuner trouble			3																											
Chiller trouble	3																													
Other cooling wtr																														
Others																														

2026/6/29 to 2026/1/26



ARES cavity breakdown is mostly caused by “fireball”.

Example of a flying fireball causing breakdown



KEK Accl. Lab. Topics (web article)

- “*Minuscule Gremlins Cause Vacuum Breakdown in Radio-Frequency Accelerating Cavities*”
  - https://www2.kek.jp/accl/eng/topics/topics190122.html

Presentations at Workshops

- T. Abe, “Fireball-Triggered Vacuum Breakdown of RF Cavities”, presented at Workshop on Dust Charging and Beam-Dust Interaction in Particle Accelerators, CERN, June 2023.
- T. Abe, "*Direct Observation of Breakdown Phenomena in Normal-Conducting Accelerating Structures: 509-MHz Continuous-Wave Cavity and 11.4-GHz Pulsed-Wave Cavity*", presented at the 12th International Workshop on Breakdown Science and High Gradient Technology (HG2019), Chamonix, France, June 2019.
- T. Abe, "*Updated Results of Breakdown Study for 509-MHz Continuous-Wave Accelerating Cavities based on Direct In-situ Observation*", presented at the 7th International Workshop on Mechanisms of Vacuum Arcs (MeVArc 2018), Puerto Rico, May 20-24, 2018.

Original papers

- T. Abe, *et al.*, "*Direct Observation of Breakdown Trigger Seeds in a Normal-Conducting RF Accelerating Cavity*", Physical Review Accelerators and Beams **21**, 122002, 2018.
- T. Abe, *et al.*, "Breakdown Study Based on Direct In-Situ Observation of Inner Surfaces of an RF Accelerating Cavity during a High-Gradient Test", Physical Review Accelerators and Beams **19**, 102001, 2016.

➔ According to this mechanism, the ARES cavity breakdown rate is primarily determined by its cavity voltage.

Session 10
No. 30

Operational and Lifetime Experience of High-Power Klystrons for Accelerator Facilities

14th CWRF
September 16, 2026
Risa Kikuchi

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CANON E

Klystron Overview

CW klystron

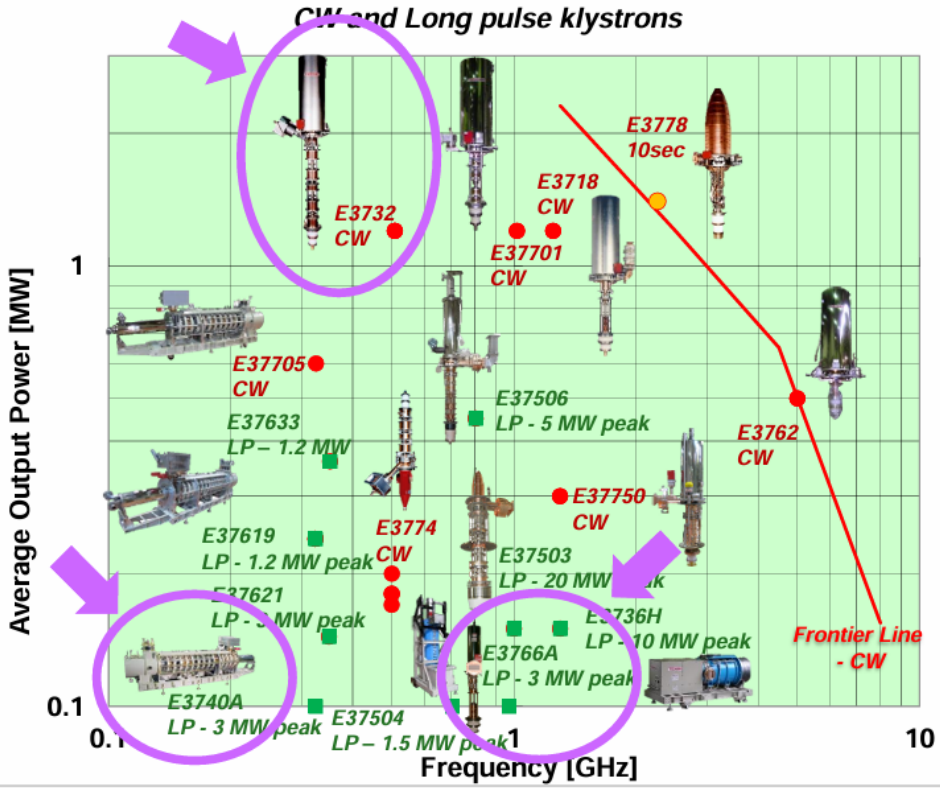
Frequency:
0.325～5 GHz

Output power:
～1.2 MW (CW)

Long pulse(LP) klystron

Frequency:
0.324～1.3 GHz

Output power:
～20 MW (Peak)
～450 kW (Average)



509 MHz 1.2 MW CW Klystron E3786/E3732

Parameter	Unit	Spec.	Parameter	Unit	Spec.
Beam voltage	kV	93	Output power	MW	1.2
Beam current	A	20.5	Efficiency	%	63
Anode voltage	kV	63.5	Gain	dB	56

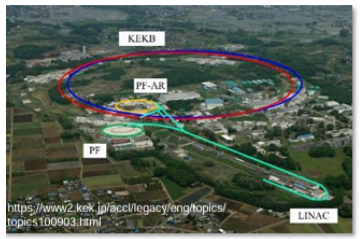
In production since the 1980s, with nearly 100 tubes operated



E3786 was developed for the TRISTAN at KEK

Successor E3732 was developed for KEKB (1990s~) based on the operational experience from TRISTAN

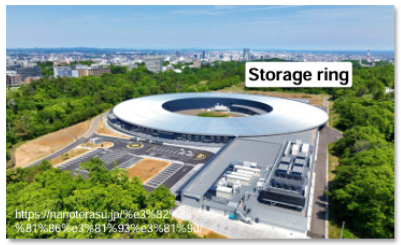
E3732 is deployed at Super KEKB (2016~) SPring-8 (1997~) NanoTerasu (2024~)



Facilities at KEK (Japan)



SPring-8 (Japan)



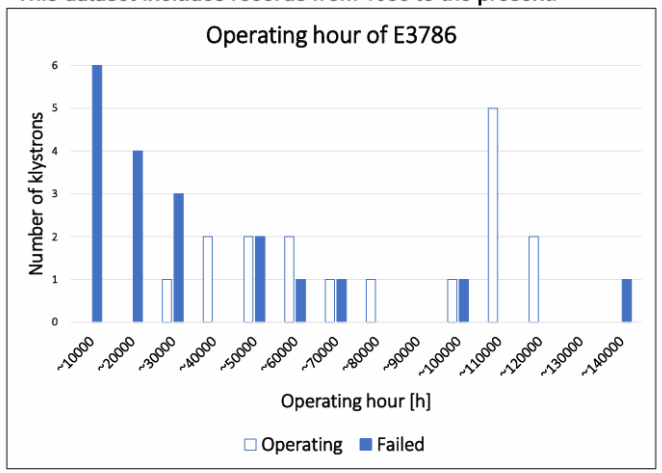
NanoTerasu (Japan)

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MTBF of E3786

E3786

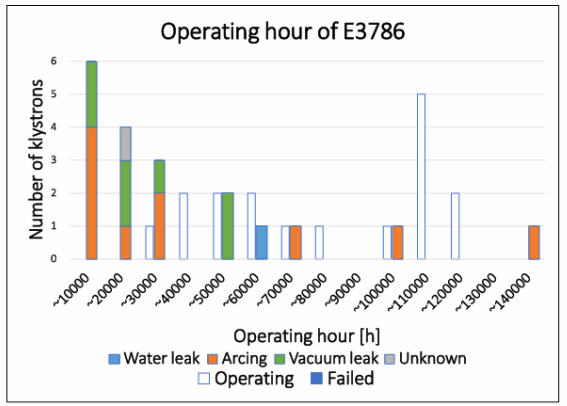
This dataset includes records from 1986 to the present.

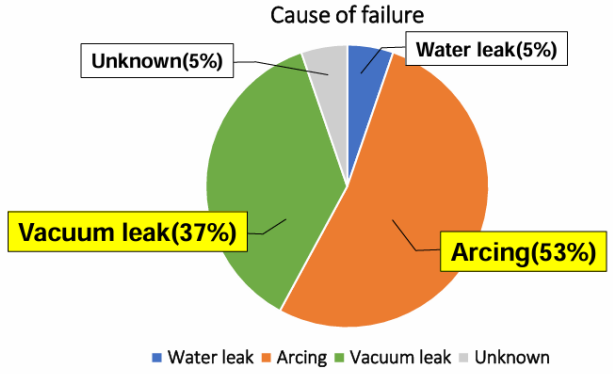


Total number of tubes	36
Number of failed tubes	19
Total operating hour	1.9 M [h]
MTBF (Mean Time Between Failures)	**98 k [h]**

Failure analysis of E3786

E3786

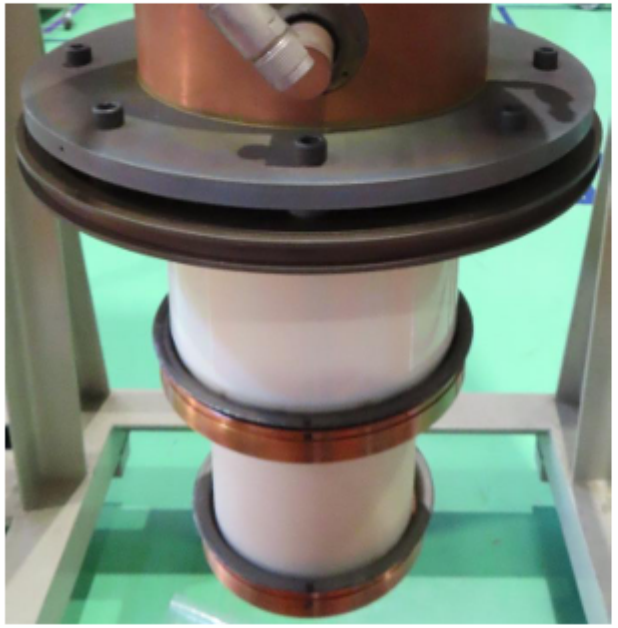




All vacuum leak occurred from brazed joints between window ceramic and metal. The arcing was negative anode current spike.

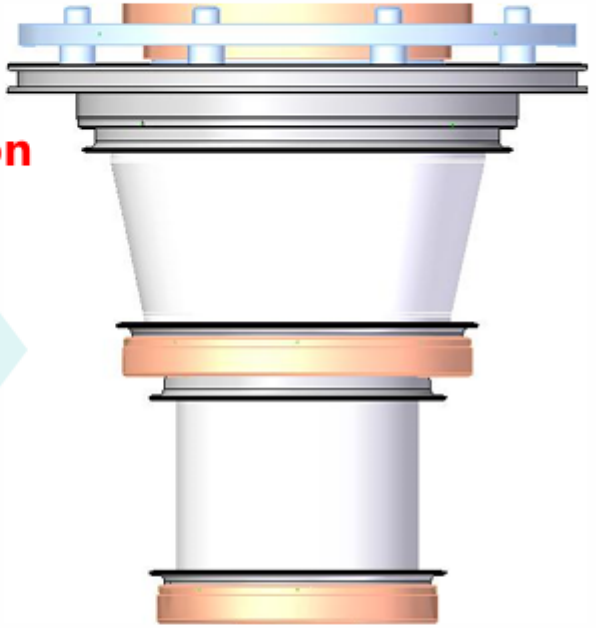
Design Improvements Applied to Electron Gun

Old Electron Gun of E3786



- ✓ **Electrode** Electric field strength reduction
  Increase the distance between anode and body
- ✓ **Anode** SEEC reduction
  Add a CrOx coating
- ✓ **Cathode** Temperature reduction
  Change from S-type to M-type

New Electron Gun of E3732



References

[1]S.Isagawa et al., "Operational Experience and Recent Upgrading of TRISTAN High Power cw Klystrons,"
Proc. 3rd European Particle Accelerator Conference, Berlin, Germany, March 1992, pp. 1206-1208.

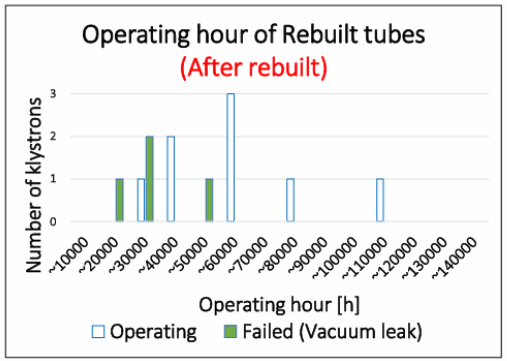
[2]M.Yoshida et al., "Characteristics and Anode Current Stabilization of TRISTAN 1.2MW CW Klystrons,"
Conference: 9. symposium on accelerator science and technology, Tsukuba (Japan), 25-27 Aug 1993.

[3] S.Isagawa et al., "Coating Techniques and Improvement of High Power CW Klystrons for TRISTAN,"
Proc. 4th European Particle Accelerator Conference, London, June-July 1994, pp. 1912-1914.

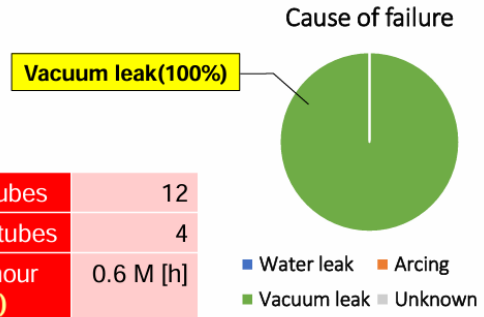
MTBF and failure analysis of Rebuilt tubes

Rebuilt tubes

In the 1990s, before starting production of E3732, failed E3786 were rebuilt by replacing their electron gun with the newly designed one.



Total number of tubes	12
Number of failure tubes	4
Total operating hour (After rebuilt)	0.6 M [h]
MTBF(After rebuilt)	138 k [h]



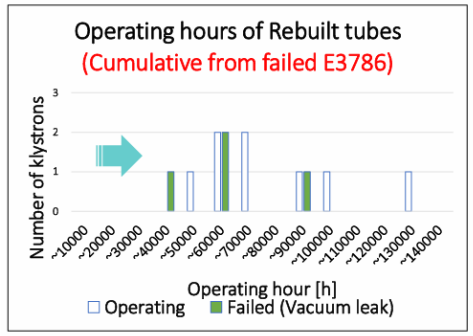
No arcing occurred.
All vacuum leak occurred between water circuit and vacuum at the window.

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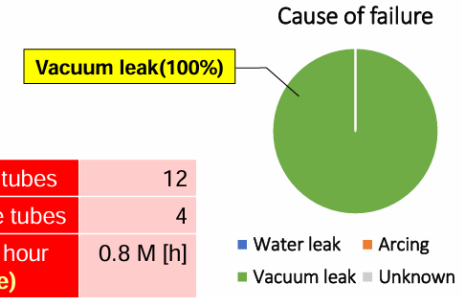
MTBF and failure analysis of Rebuilt tubes

Rebuilt tubes

In the 1990s, before starting production of E3732, failed E3786 were rebuilt by replacing their electron gun with the newly designed one.



Total number of tubes	12
Number of failure tubes	4
Total operating hour (Cumulative)	0.8 M [h]
MTBF(Cumulative)	205 k [h]



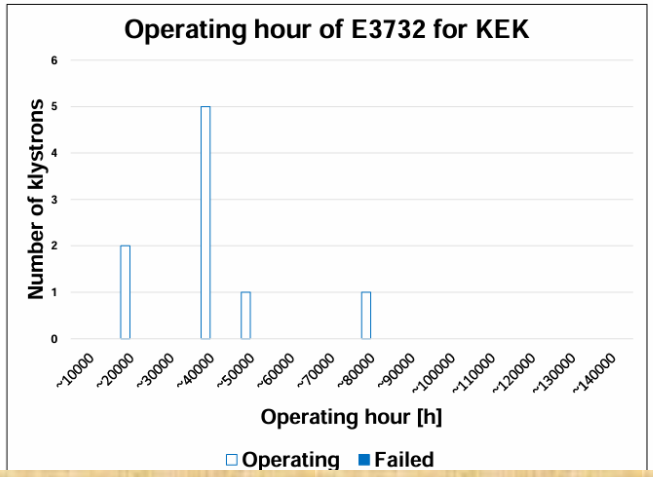
No arcing occurred.
All vacuum leak occurred between water circuit and vacuum at the window.

(C) Canon Electron Tubes & Devices Co., Ltd.

MTBF of E3732 for KEK

E3732 for KEK

E3732 has been deployed at KEK since 2003. E3732 is operated at a maximum RF power of 600kW.



Cause of failure

As of 2026, no E3732 at KEK have reached end-of-life

Water leak Arcing Vacuum leak Unknown

Total number of tubes	9
Number of failed tubes	0
Total operating hour	0.3 M [h]
MTBF	- [h]