SuperKEKB RF Accelerating Cavity System

(Improvements during LS1, etc.)

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KEK / ACCL

The 27th KEKB Accelerator Review Committee

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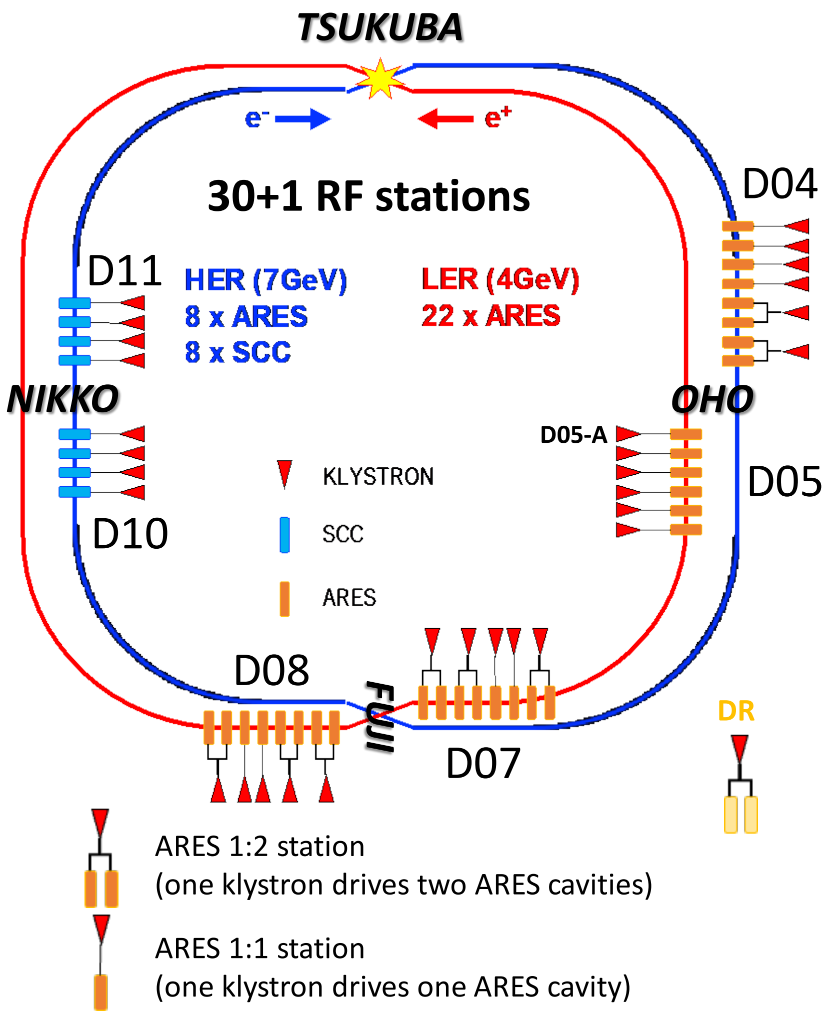
RF Accelerating Cavity System for the SuperKEKB Rings (MR & DR)

Present RF Cavity Layout

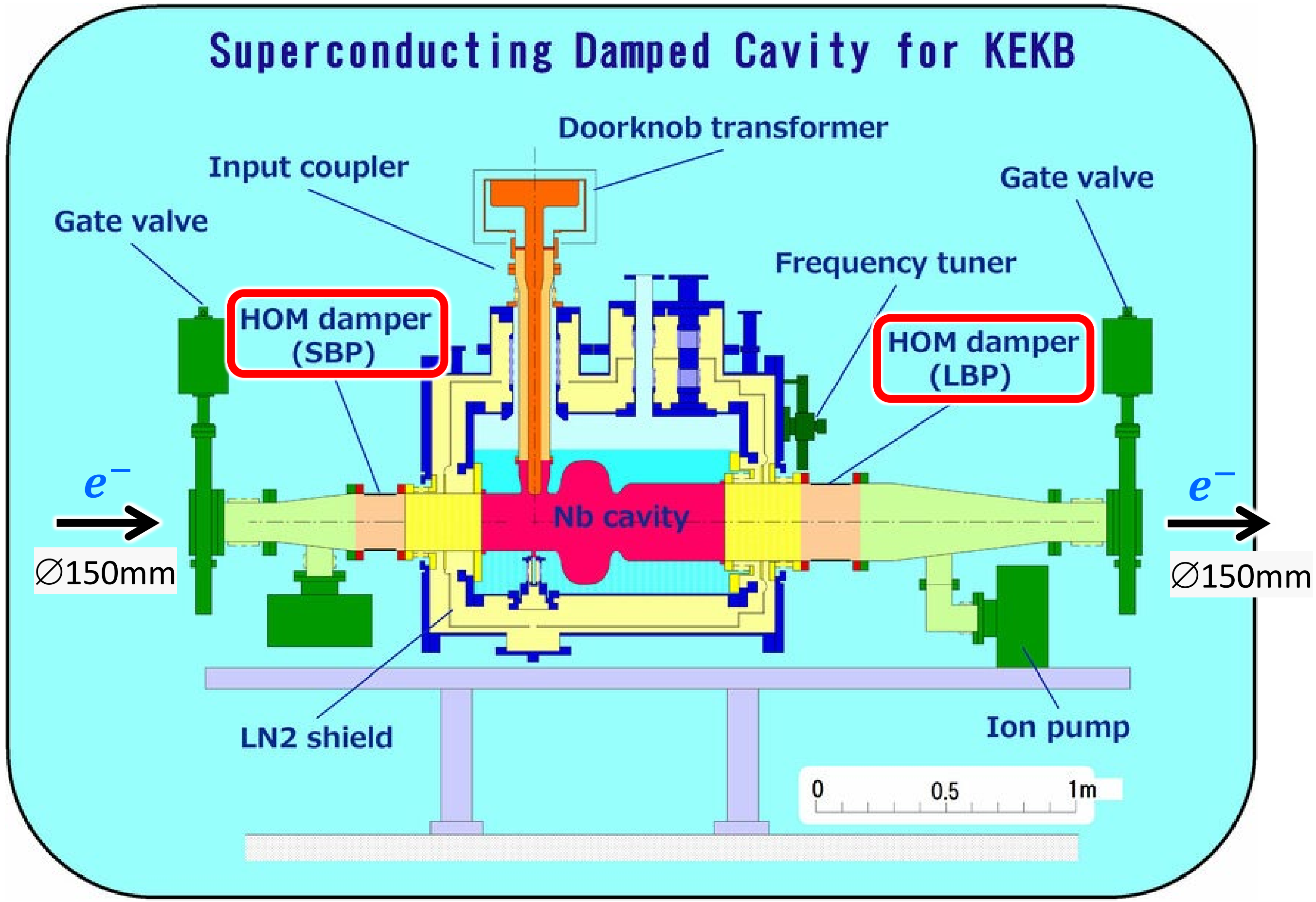


Parameter	KEKB (achieved)			
Ring	HER			LER
Energy [GeV]	8.0			3.5
Beam Current [A]	1.4			2
Number of Bunches	1585			1585
Bunch Length [mm]	6-7			6-7
Total Beam Power [MW]	~5.0			~3.5
Total RF Voltage [MV]	15.0			8.0
	ARES		SCC	ARES
Number of Cavities	10	2	8	20
Klystron : Cavity	1:2	1:1	1:1	1:2
RF Voltage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

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

Parameter	Present (achieved) SuperKEKB				
Ring	HER			LER	
Energy [GeV]	7.0			4.0	
Beam Current [A]	**1.14**			**1.46**	
Number of Bunches	2346			2346	
Bunch Length [mm]	~6			~6	
Total Beam Power [MW]	~3.1			~3.2	
Total RF Voltage [MV]	14.2			9.12	
	ARES		SCC	ARES	
Number of Cavities	4	4	8	12	10
Klystron : Cavity	1:2	1:1	1:1	1:2	1:1
RF Voltage [MV/Cav.]	0.45		1.35	0.45	
Beam Power [kW/Cav.]	130	170	260	190	230

Super-Conducting Cavities (SCCs)



∅220mm duct
TM$_{011}$, TM$_{020}$, etc.←

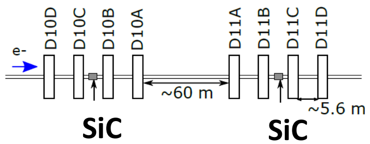
∅300mm duct
→ TM$_{110}$, TE$_{111}$, etc.

■**Single-cell single-mode 508.9 MHz cavity**

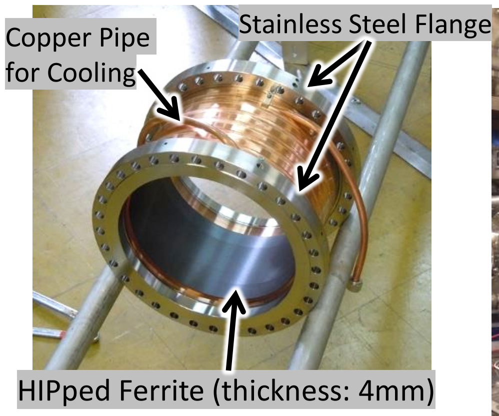
- ➢ All the HOMs are extracted to the beam ducts.

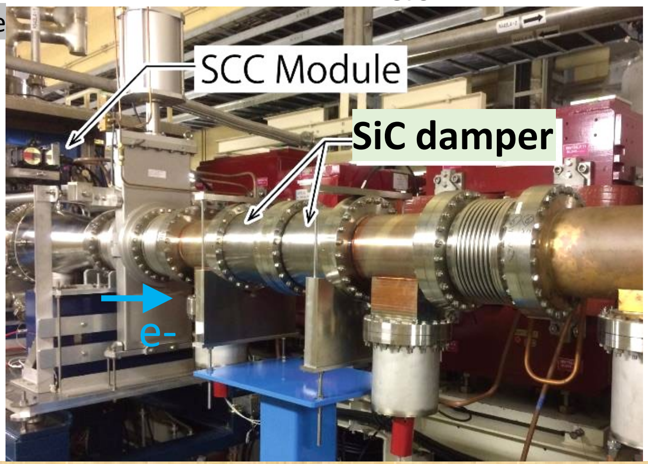
■**HOM dampers** with:

- ➢ **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** (new)
  - Added for higher HER beam currents at SuperKEKB



Ferrite damper





Improvement for SCC

(M. Nishiwaki)

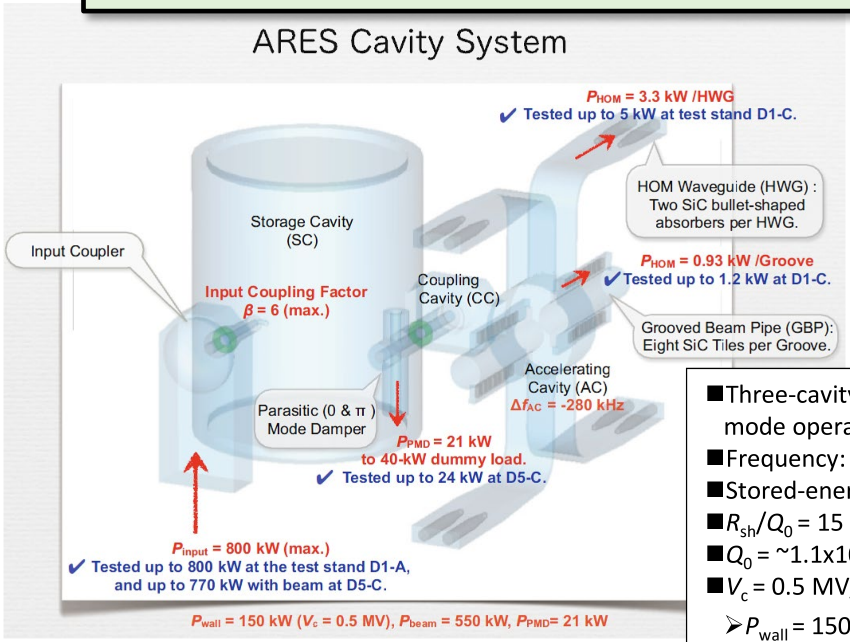
- The HER beam current is limited by the cooling capability of the chillers for the HOM dampers (Ferrite & SiC) installed near the SCC modules.
- During LS1, the chillers have been replaced by new ones with a larger cooling capacity.

  → Allowable HER beam current due to the RF system: 1.7 ➔ 2.0 A

- For higher HER beam currents than 2.0 A, we need to further upgrade the cooling capability and to add more SiC dampers.
  - During LS2?

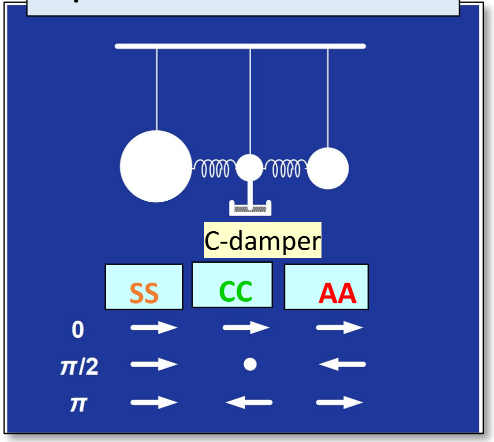
Normal-Conducting Cavities

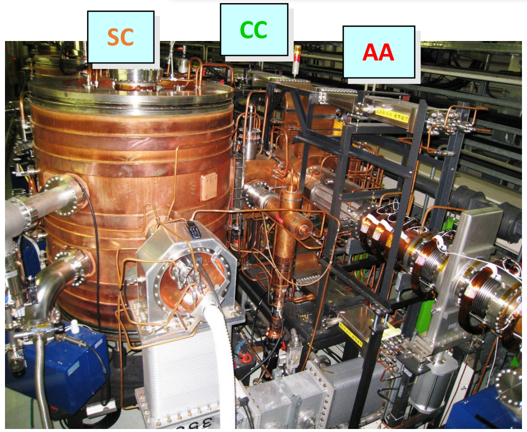
30 ARES cavities used for MR beam operation



- Three-cavity system stabilized with the π/2 mode operation
- Frequency: 508.9 MHz (π/2 mode)
- Stored-energy ratio: $U_{SS}/U_{AC} = 9$
- $R_{sh}/Q_0 = 15\ \Omega$
- Q_0 = ~1.1×10^5
- V_c = 0.5 MV/cav (spec.)
  - ➢ P_{wall} = 150kW (60kW in AC, 90kW in SC)

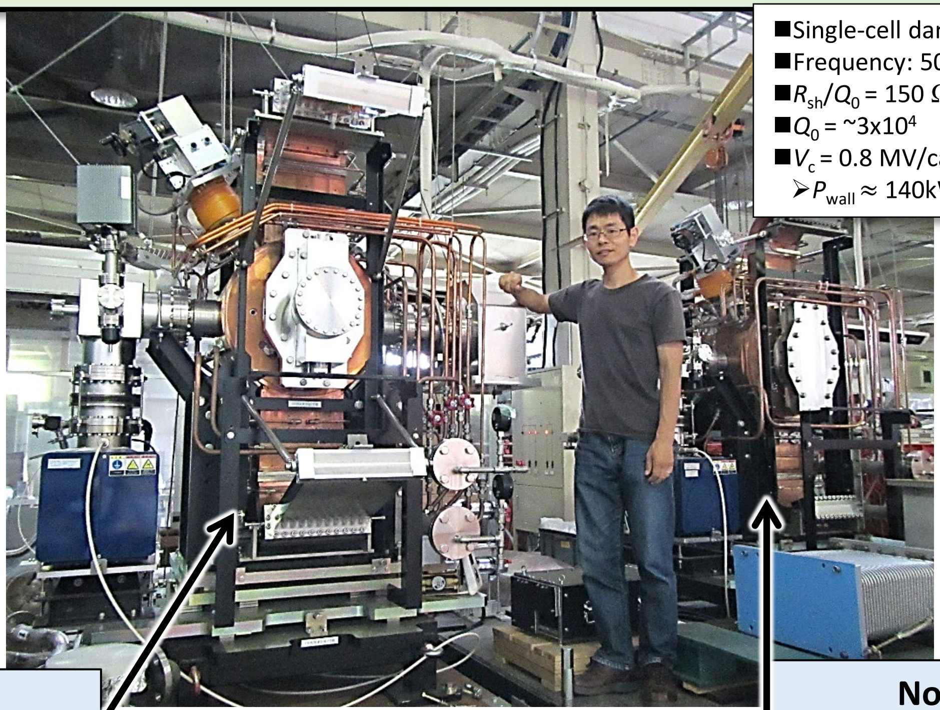
Equivalent mechanical model





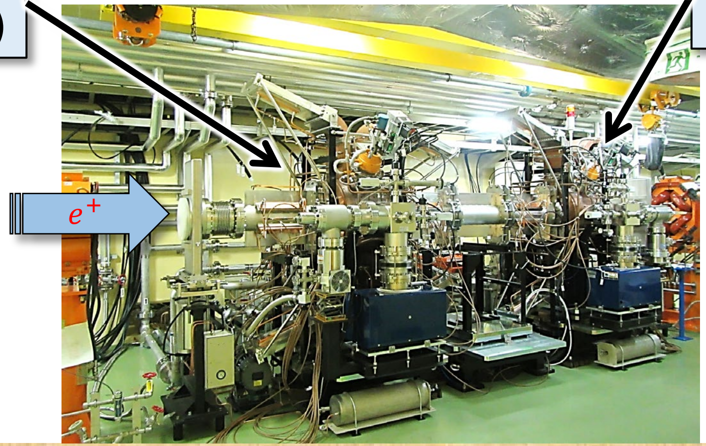
Two cavities used for DR beam operation

- Single-cell damped cavity
- Frequency: 508.9 MHz
- $R_{sh}/Q_0 = 150\ \Omega$
- Q_0 = ~3×10^4
- V_c = 0.8 MV/cav (spec.)
  - ➢ $P_{wall} \approx$ 140kW



No.2 (Upstream CAV)

No.1 (Downstream CAV)



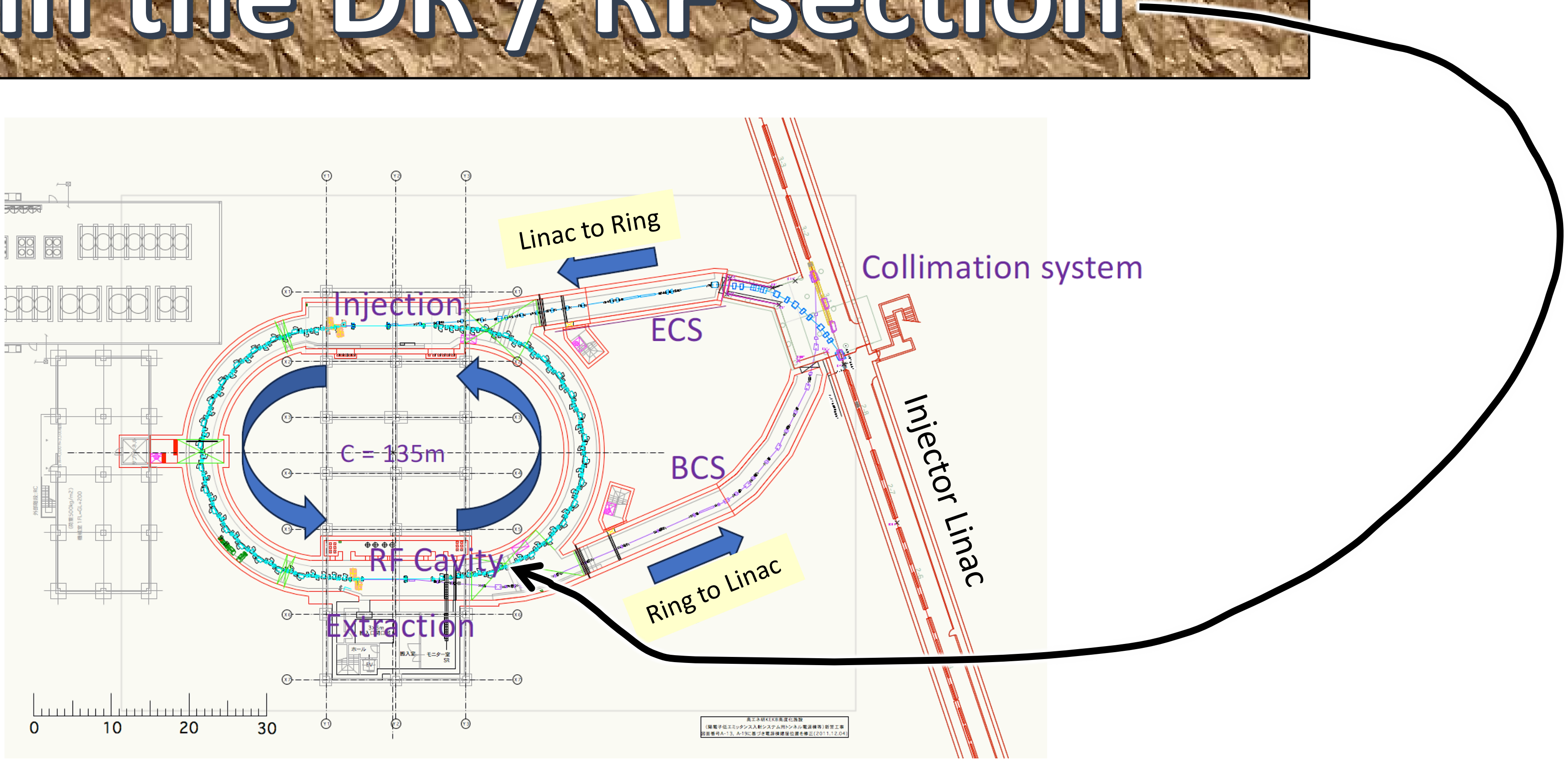
← In the DR tunnel

Improvements of the Normal-Conducting Cavity System during LS1

- 30 ARES cavities for the MR
  - **C-damper system (Attachment A)**
    - Replacement of water-cooling pumps by more powerful ones: ~25 → 40 L/min for > 20kW power capability / dummy load
      - 3.6A LER beam current ⇔ 20 kW / dummy load in the C-damper system
    - Replacement of support disks in the coaxial lines
      - From cross-linked polyethylene (radiation-hard, but low heat resistance)
      - To Teflon (high heat resistance)
  - **Replacement of high-power input couplers**
    - For four cavities: D08-C,D,E#1,E#2
    - Followed by successful high-power tests
  - **Cavity replacement in the D05-A station**
    - Due to un unusual cavity breakdown problem
    - To be explained later in detail

- Two cavities for the DR
  - **Vacuum-sealing method between the cavity and duct changed**
    - O-ring replacement (Viton (rubber) → metal)
    - To obtain much better vacuum in the DR / RF section
    - Details follows…

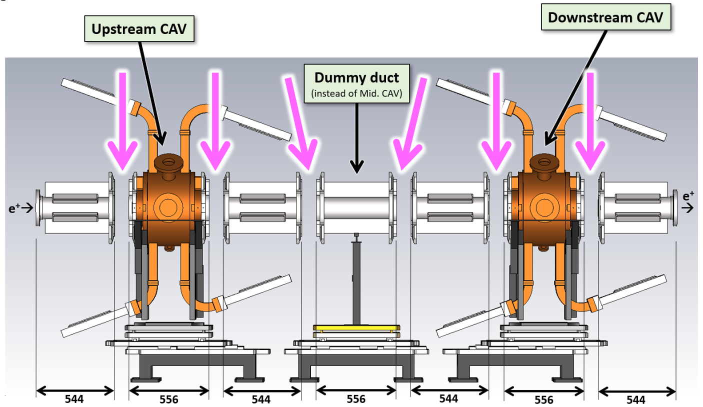
O-ring replacement in the DR / RF section

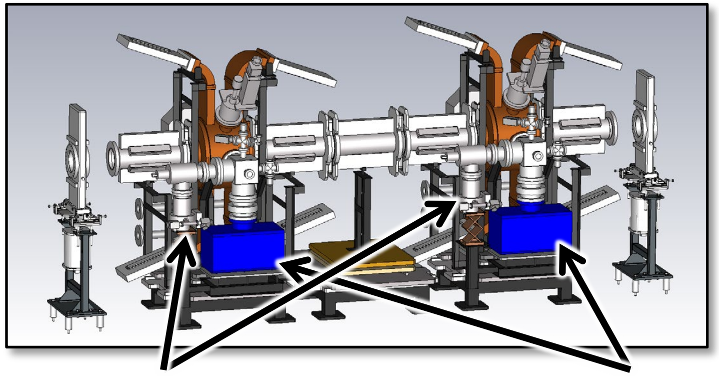


(Extracted from the M. Tawada's presentation in this ARC)

The vacuum-pressure level in the DR /RF section was high.

- **Due to the Viton O-rings (rubber) used in the connection between the RF cavities and beam ducts**
  - We used Turbo-Molecular Pumps (TMPs) in addition to sputter Ion Pumps (IPs) during beam operation.

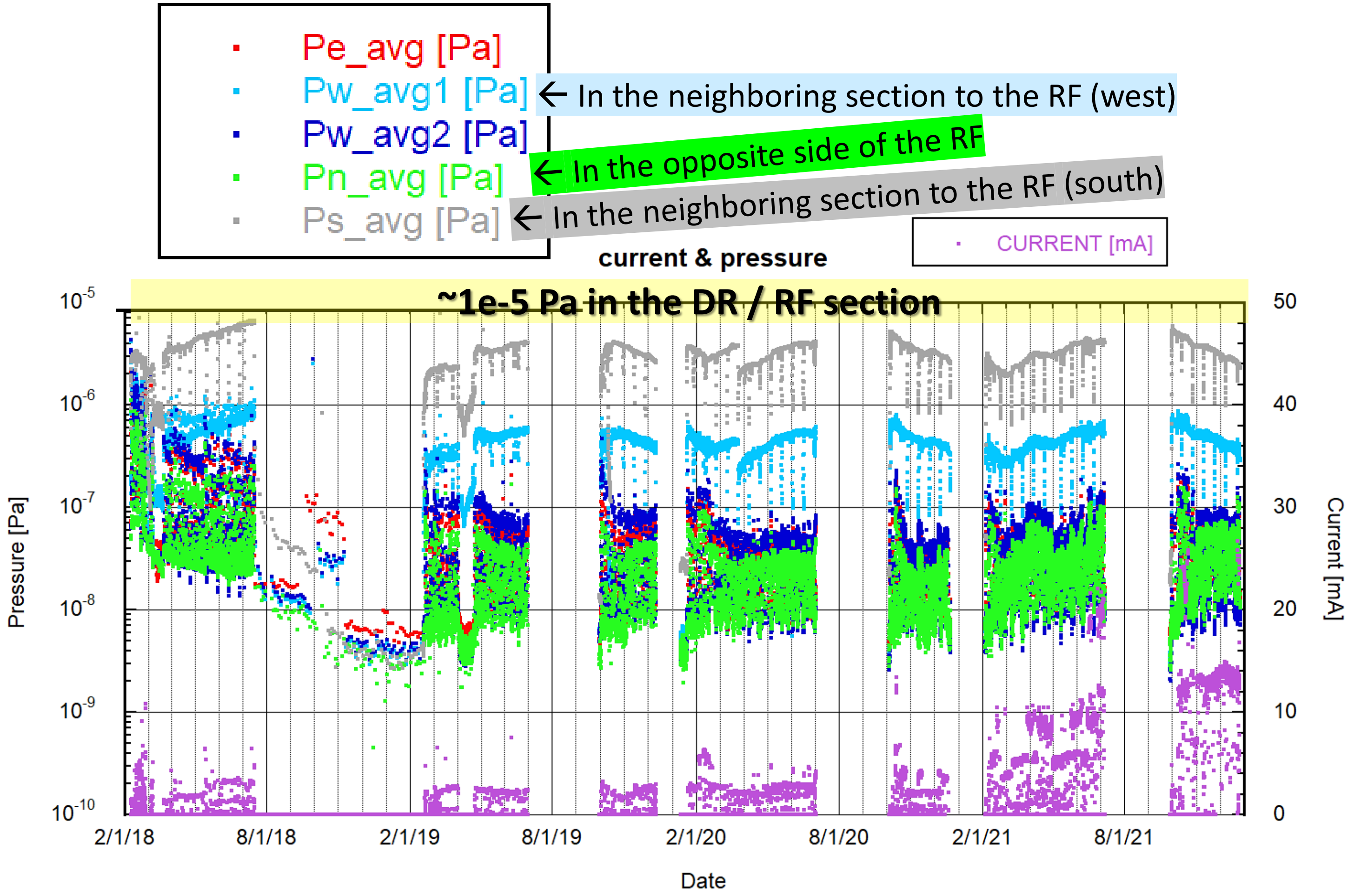




Turbo-Molecular Pump (TMP)
(300L/s each)

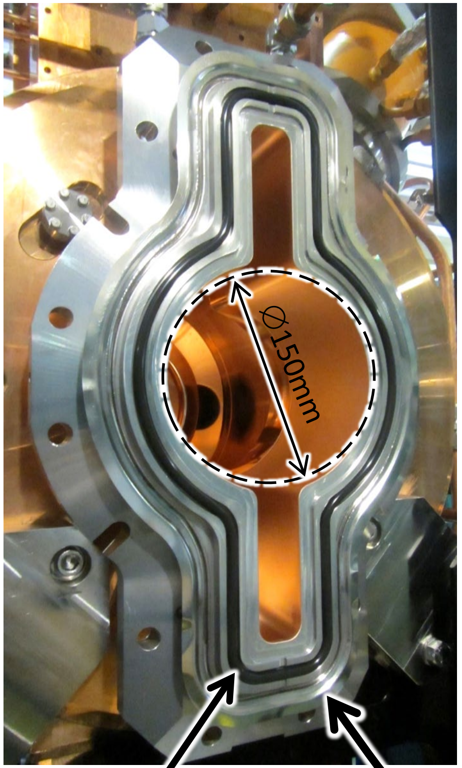
sputter-Ion Pump (IP)
(400L/s each)

The dots indicate vacuum pressures in the sections other than the RF one (courtesy of K. Shibata)

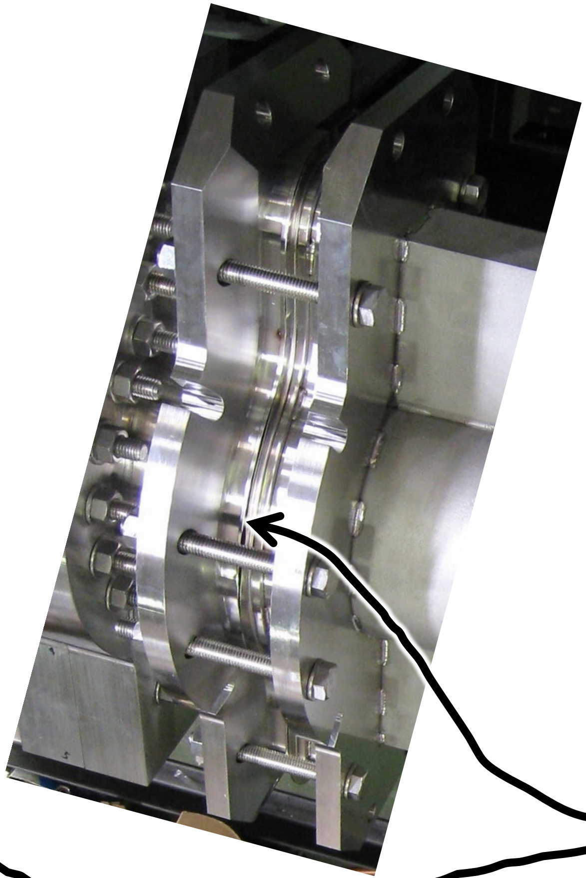


Connection between the RF cavity and beam duct

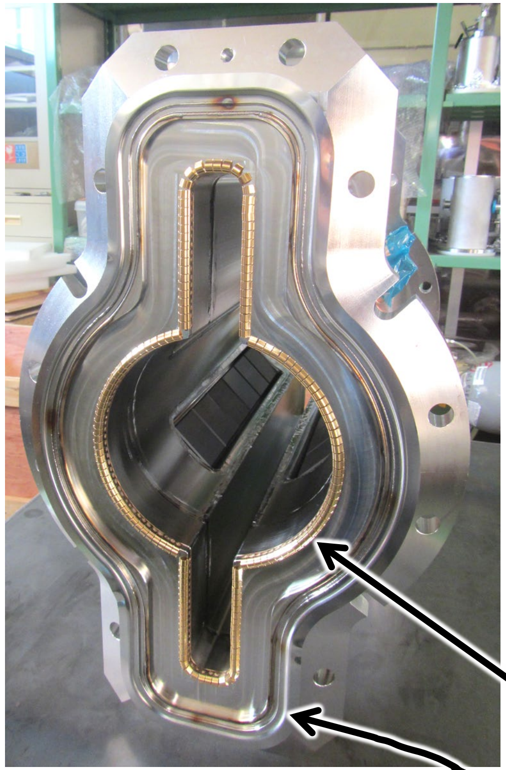
Cavity side

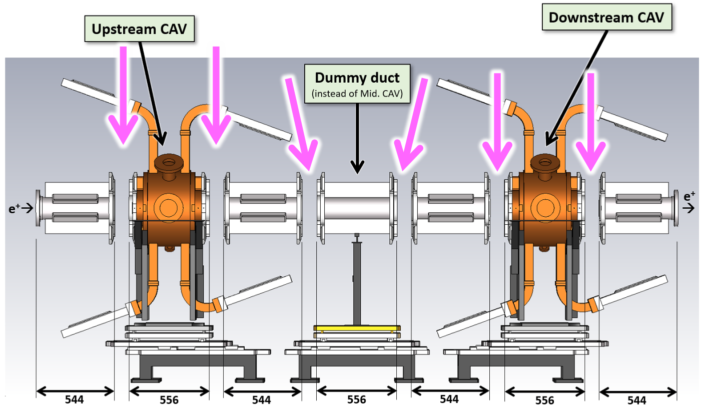


Connected



Beam-duct side





Contact fingers (Au-coated BeCu) spot-welded innermost in the flange

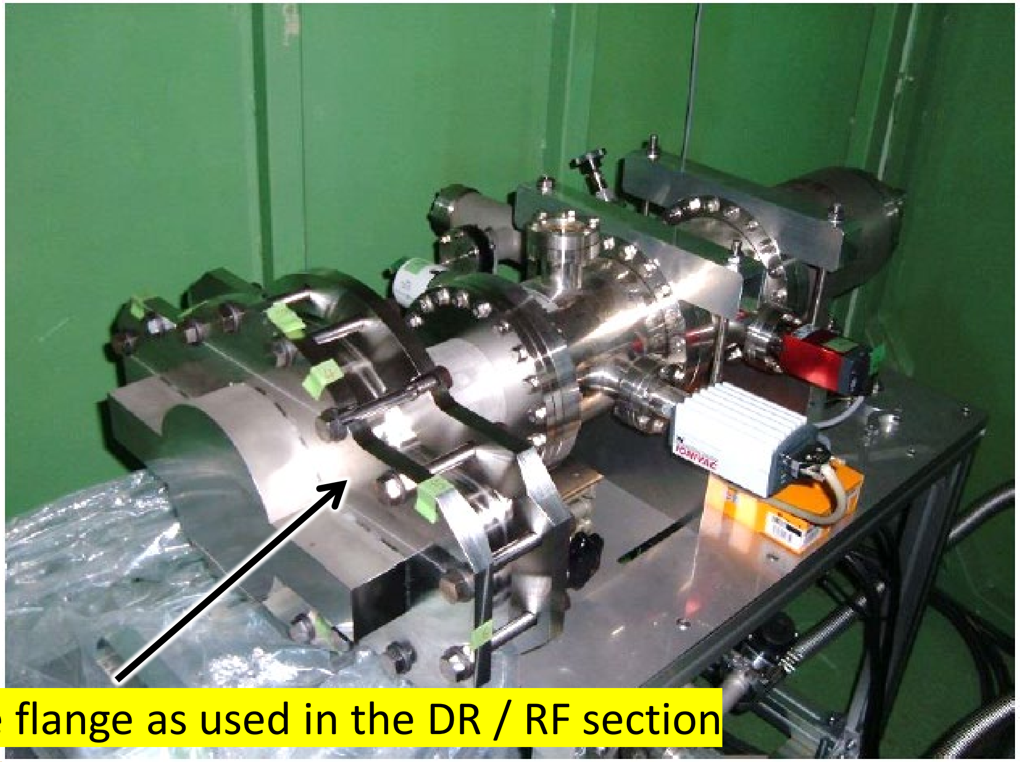
Viton O-ring
(rubber)

- ✓ **The vacuum is designed to be sealed with welding of the outermost bellows (like weld-ring gaskets)**
- ✓ **However, the welding is cost-ineffective (~100,000USD needed) and almost irreversible process.**
- ✓ **Before LS1, Viton O-rings (rubber) were used, which were not so radiation tolerant.**
- ✓ **We decided to use metal O-rings to make the hardware all-metal!**

Vacuum leak test at test bench

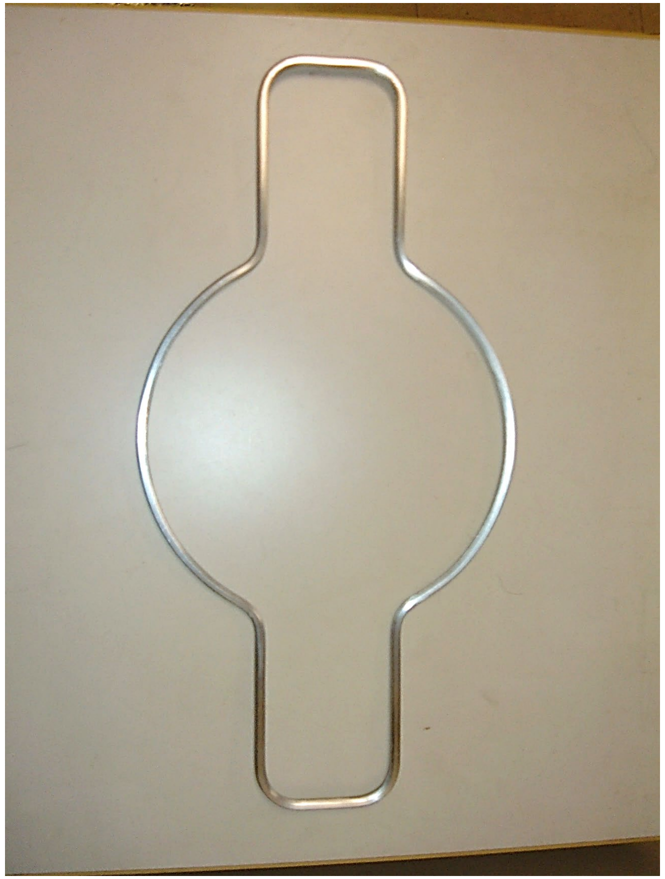
- ✓ Flange mockups used
- ✓ Heat cycles applied with ribbon heaters
- ✓ **No vacuum leak** demonstrated

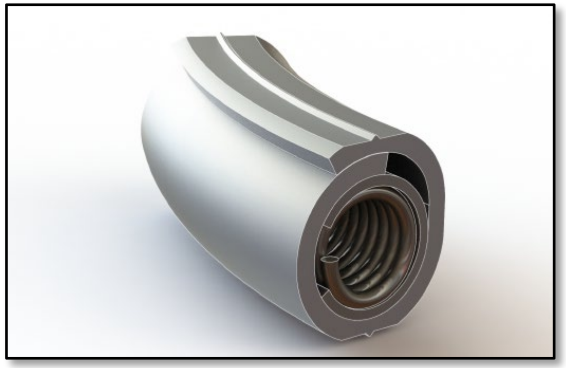
Test bench built by H. Sakai



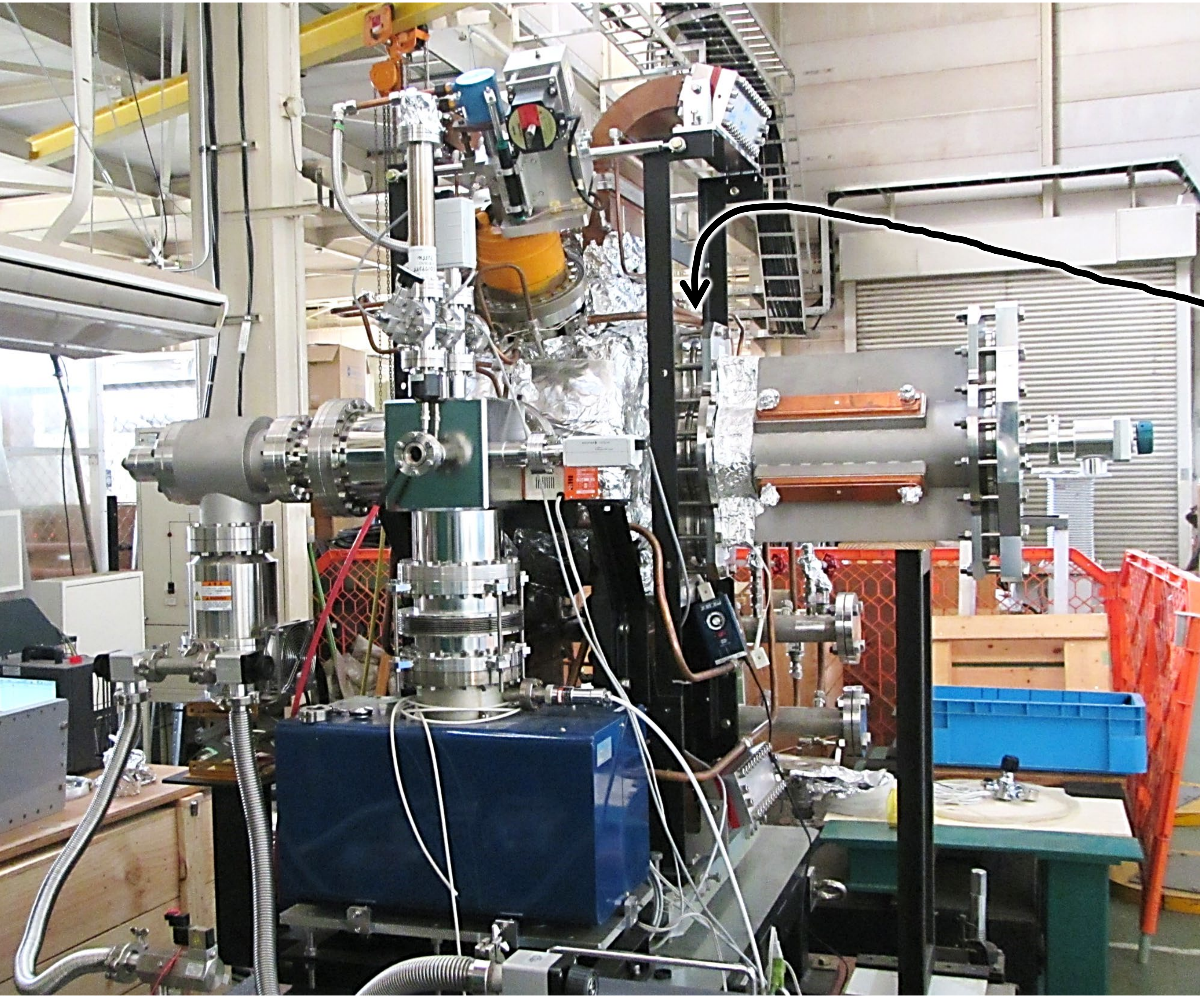
The same flange as used in the DR / RF section

Custom-made HELICOFLEX gasket

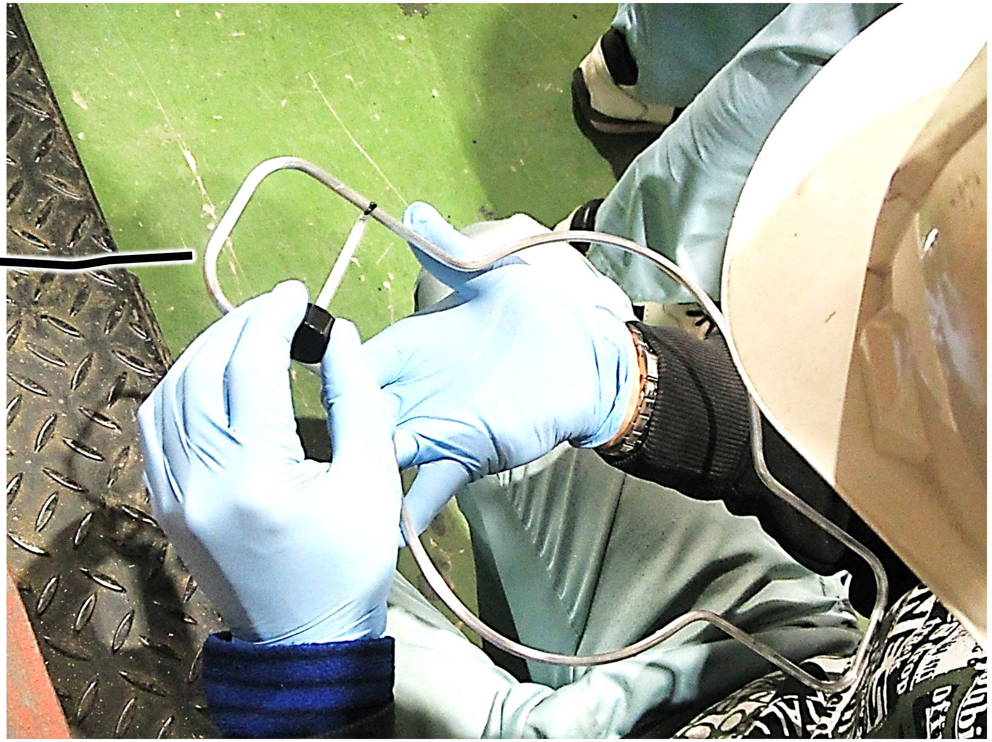




Vacuum leak test using the prototype cavity (No.0)



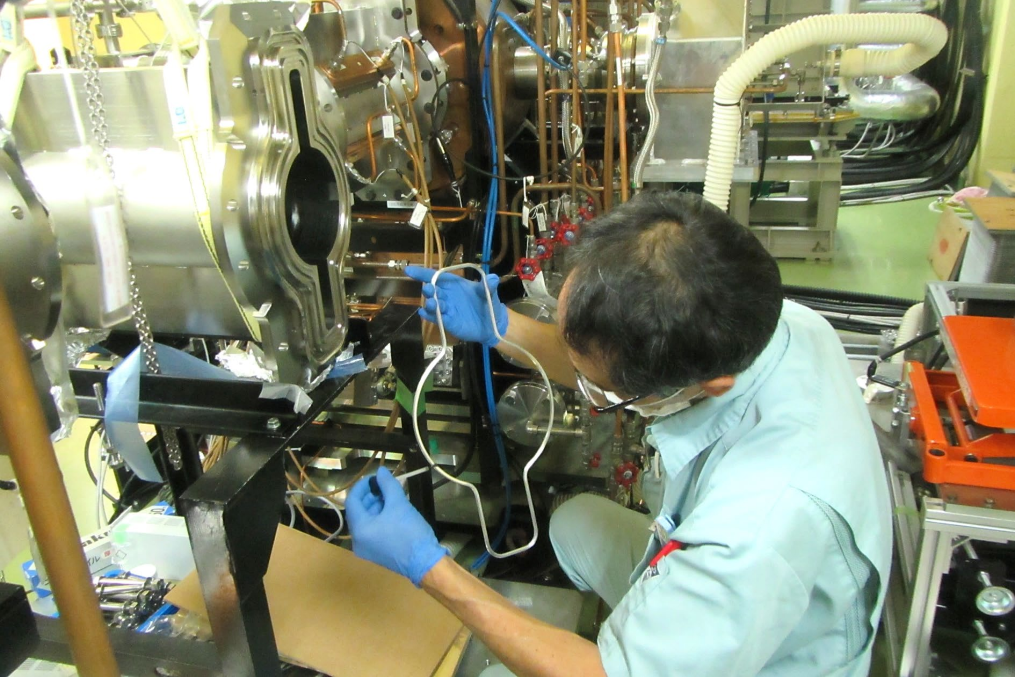
Vacseal applied

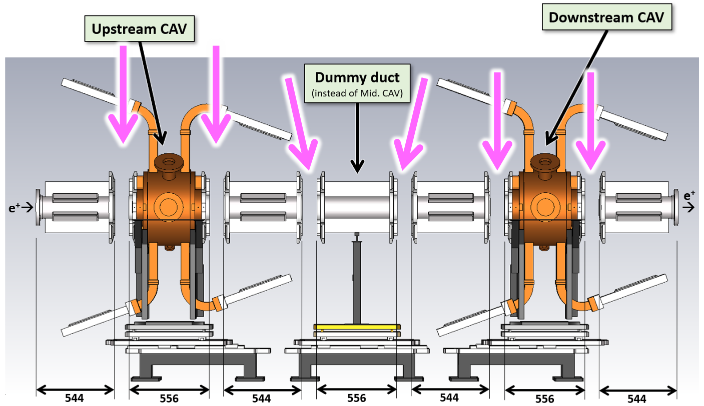


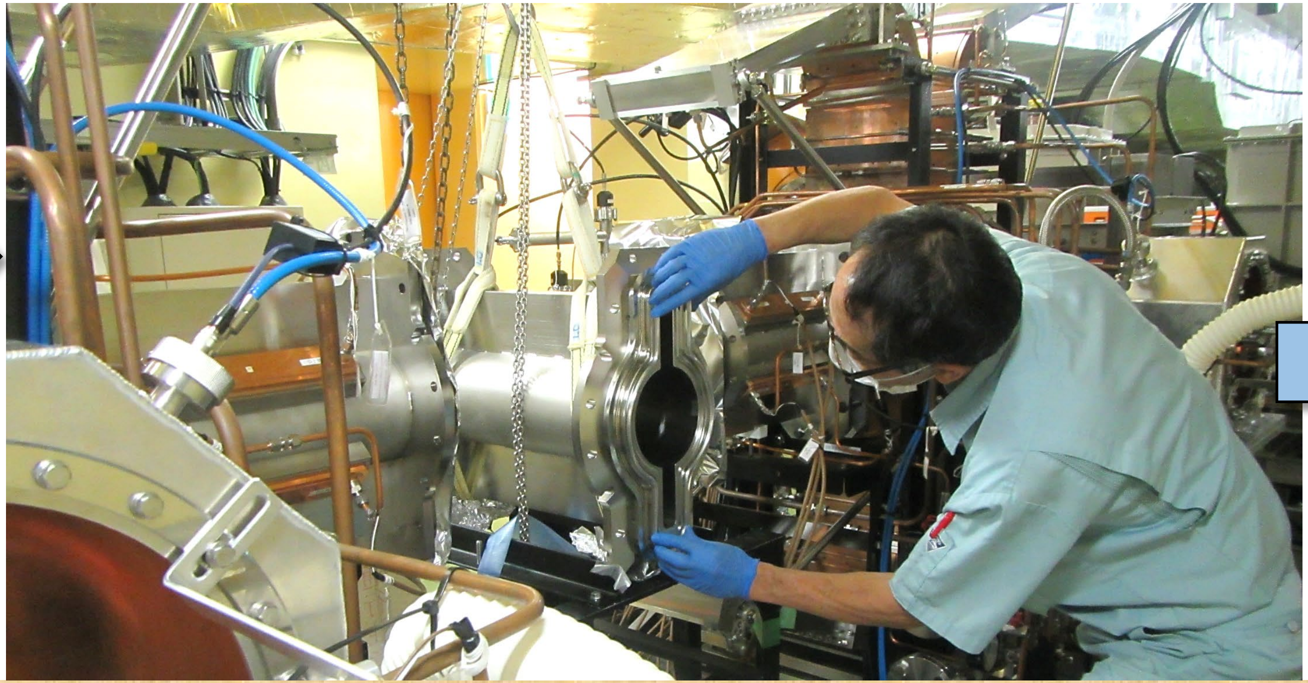
- ✓ Heat cycles with ΔT = 20°C applied using ribbon heaters
- ✓ **No vacuum leak** demonstrated

O-ring replacement in the DR / RF section

2022-10-12



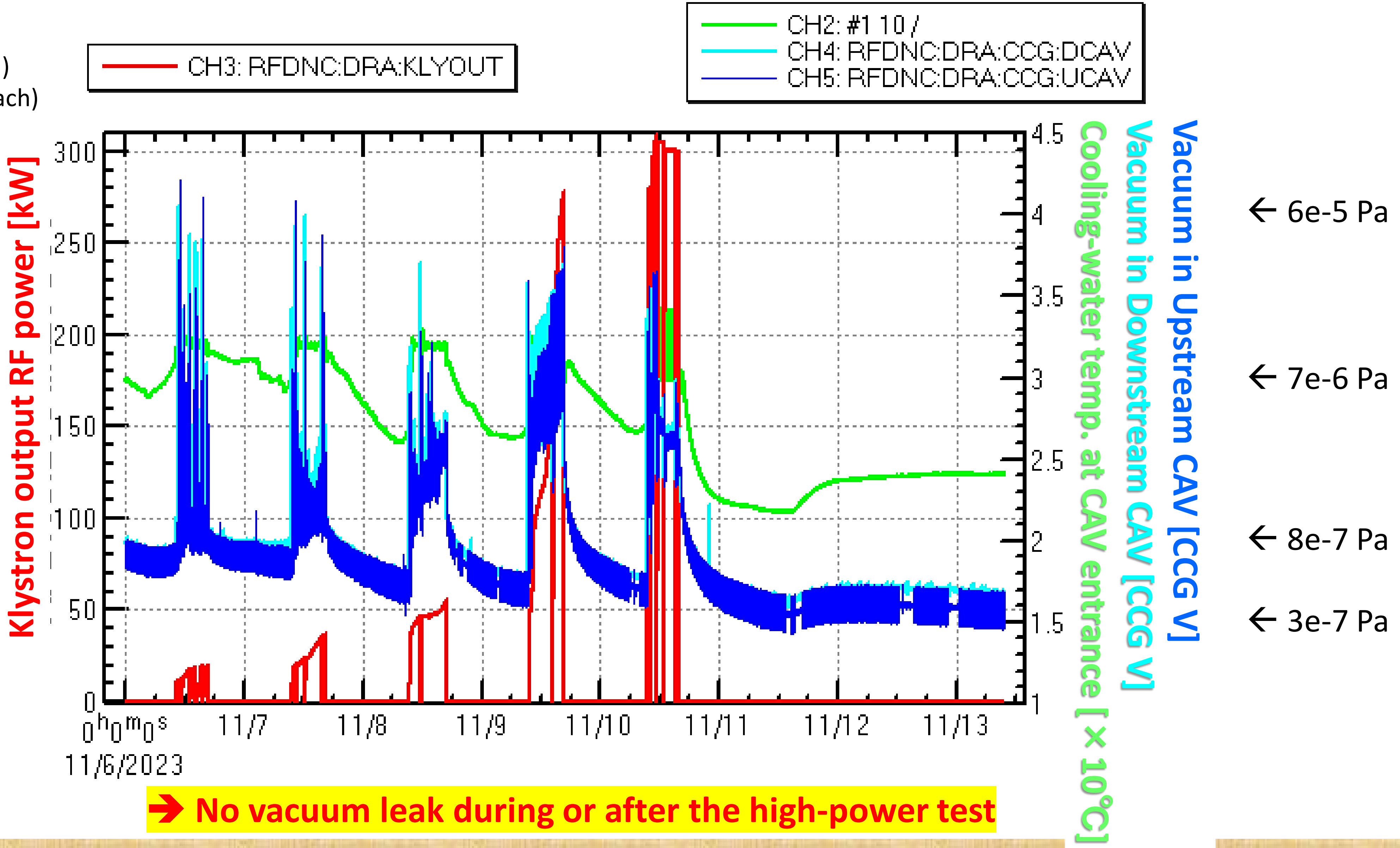




High-power test of the DR / RF cavities up to tot. V_c = 1.5 MV

> (Operational tot. V_c = 1.0 MV)

Vacuum pumping with
- ✓ Two IPs (400L/s each)
- ✓ Two TMPs (300L/s each)



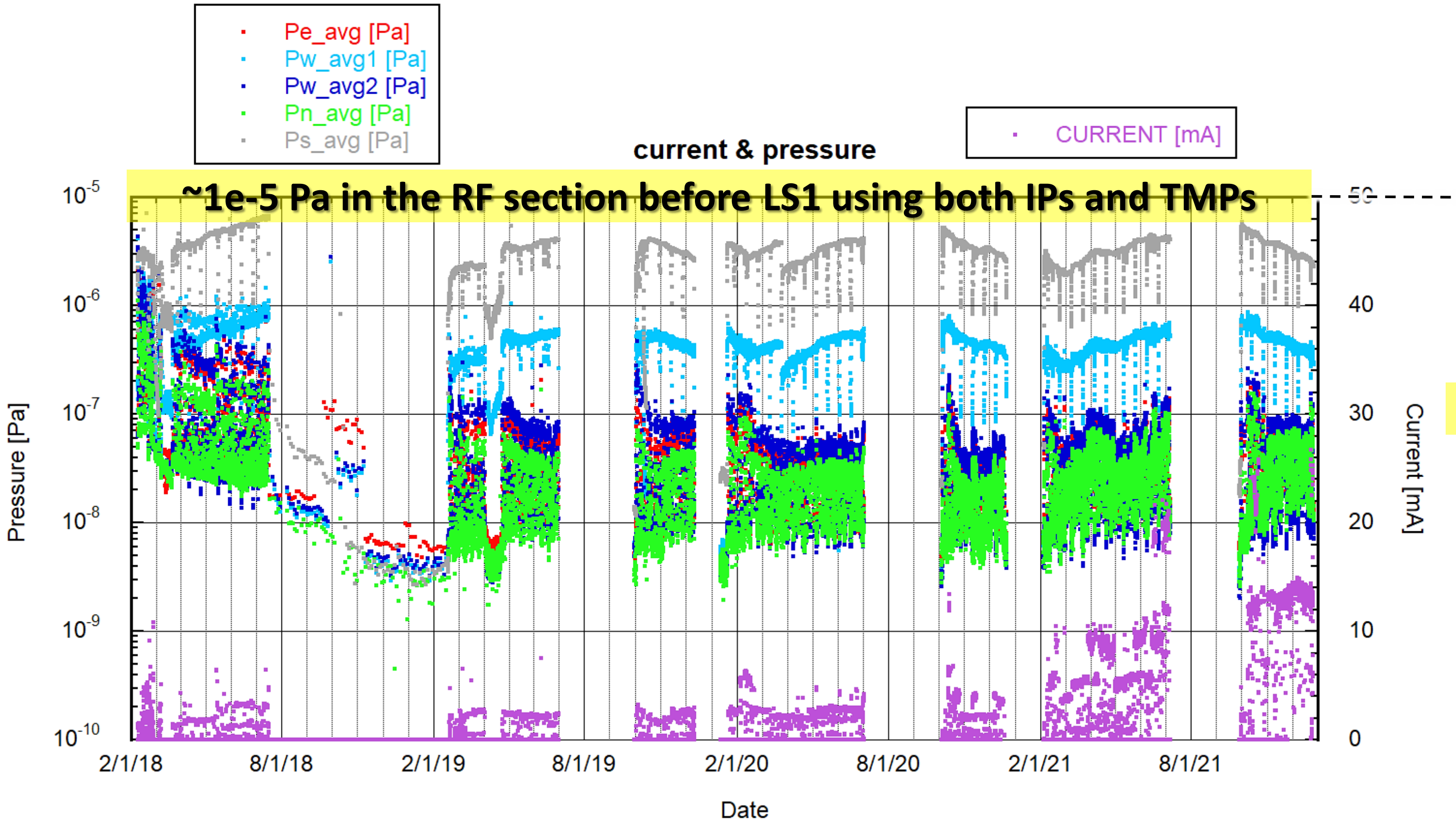
➔ No vacuum leak during or after the high-power test

DR / RF Vacuum improvement by the O-ring replacement during LS1

2022-01-25 (just before LS1)
- **5e-6 Pa**
- **RF / GVs closed**
- **tot. V_c = 1.0 MV**
- **Pumping with IPs + TMPs**

2023-11-24 (just after LS1)
- **5e-7 Pa**
- **RF/GVs closed**
- **tot. V_c = 1.0 MV**
- **Pumping with IPs + TMPs**

2024-02-05 (recent status)
- **2e-7 Pa**
- **RF/GVs closed**
- **tot. V_c = 1.0 MV**
- **Pumping with IPs only**



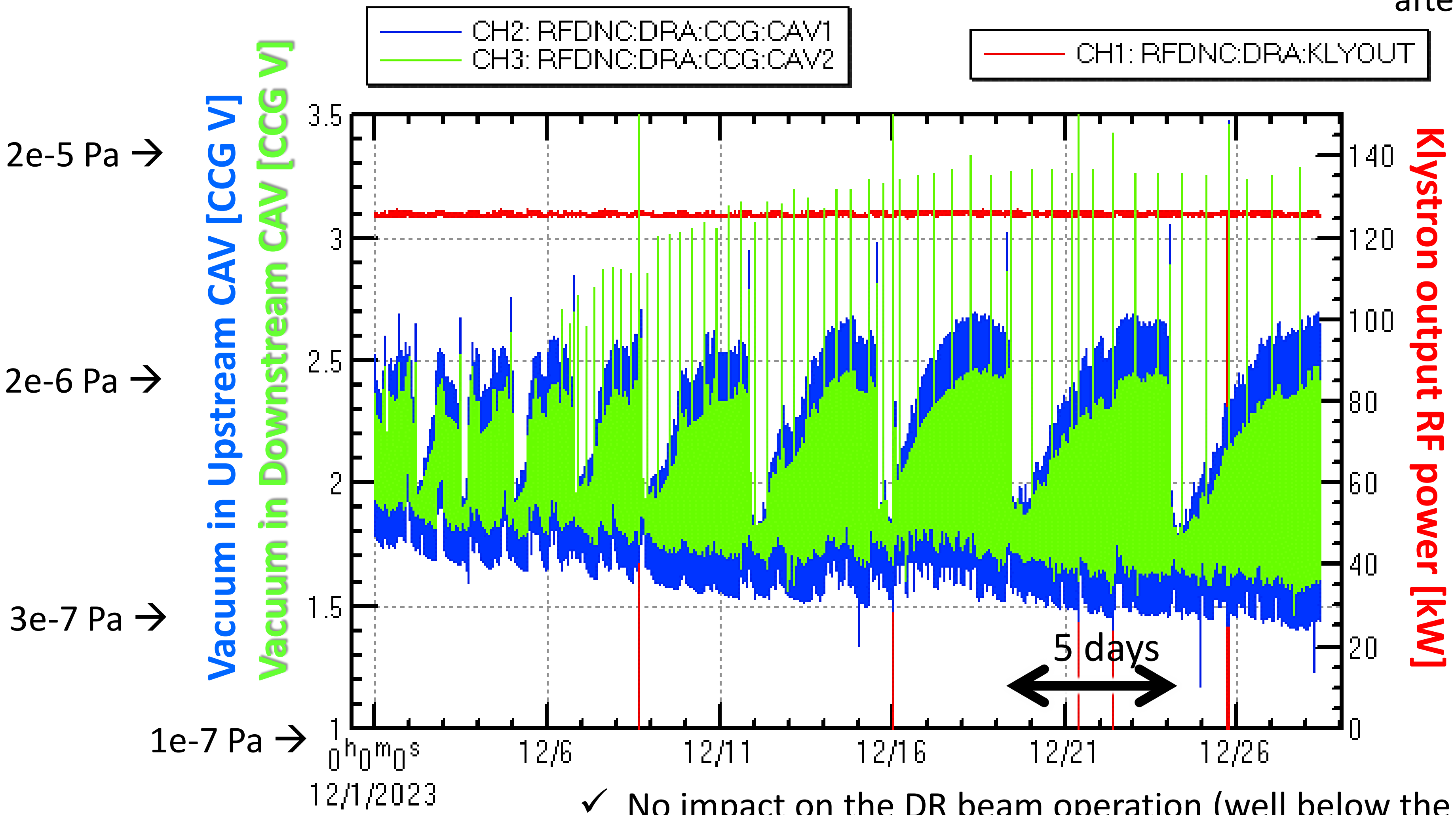
~1e-7 Pa in the recent RF section using IPs only

GV: vacuum Gate Valve
IP: sputter-Ion Pump (400L/s each)
TMP: Turbo-Molecular Pump (300L/s each)

Vacuum improvement in the DR / RF section by two orders of magnitude during DR beam operation
→ Only IPs used for beam operation

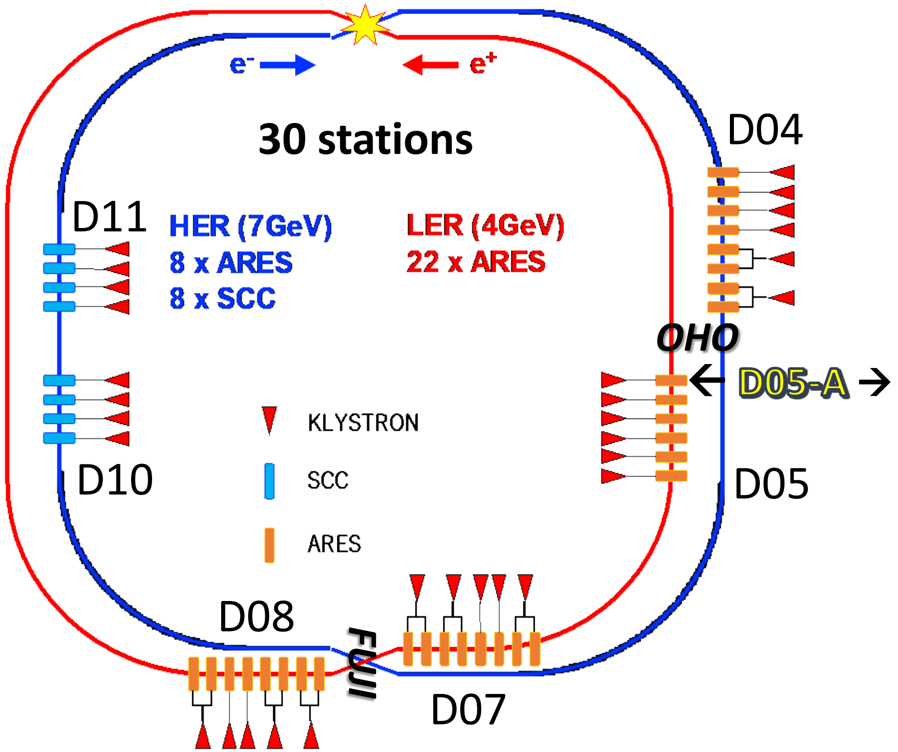
However, periodic vacuum-pressure rises appeared

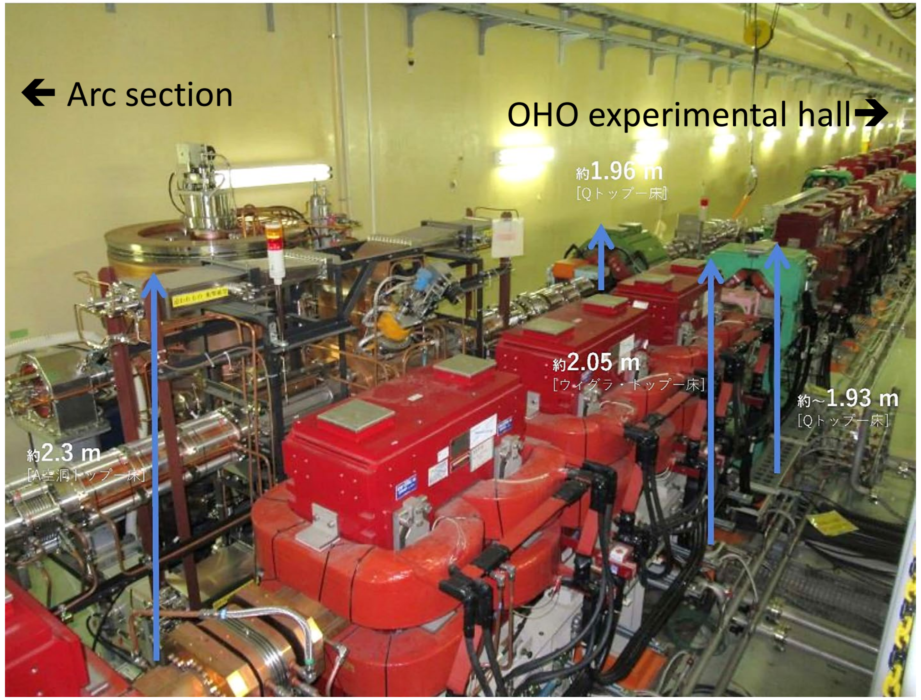
after the O-ring replacement



- ✓ No impact on the DR beam operation (well below the interlock threshold)
- ✓ Appears even with no beam
- ✓ Under investigation
- ✓ The dominant component of the gas in the pressure rises: m=2 (H_2)

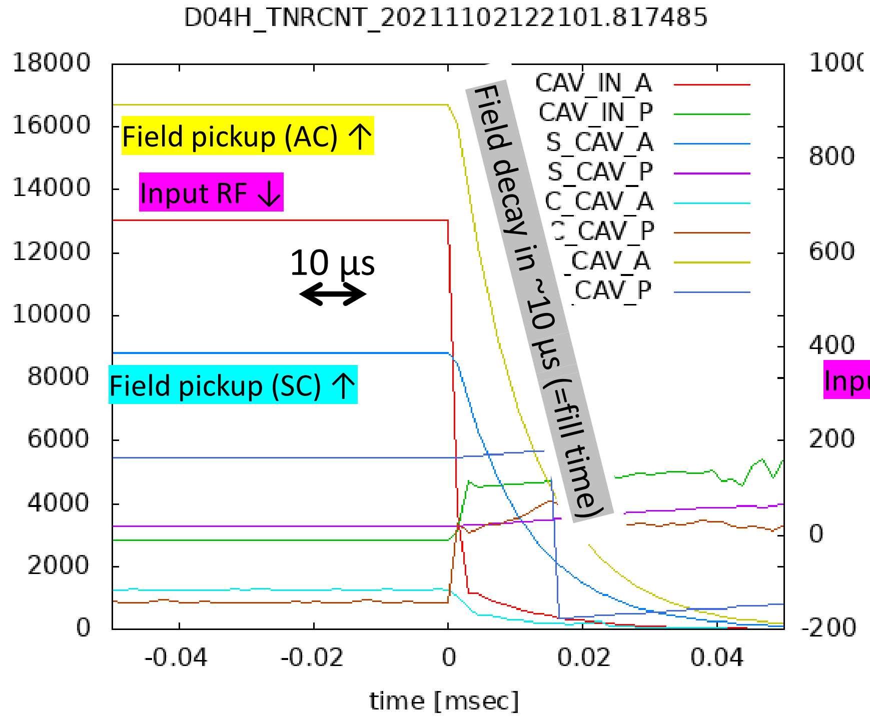
RF Cavity Replacement in the D05-A Station of the MR





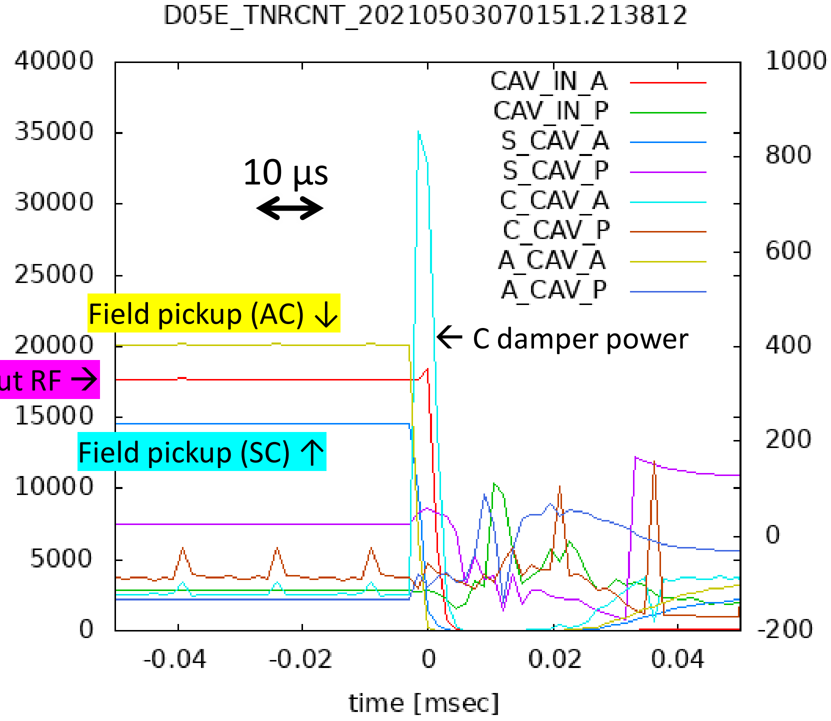
Unusual Breakdown Problem on the D05-A Cavity

RF switch manually turned off



Tail in the RF-field decay determined by the fill time (~10µs)

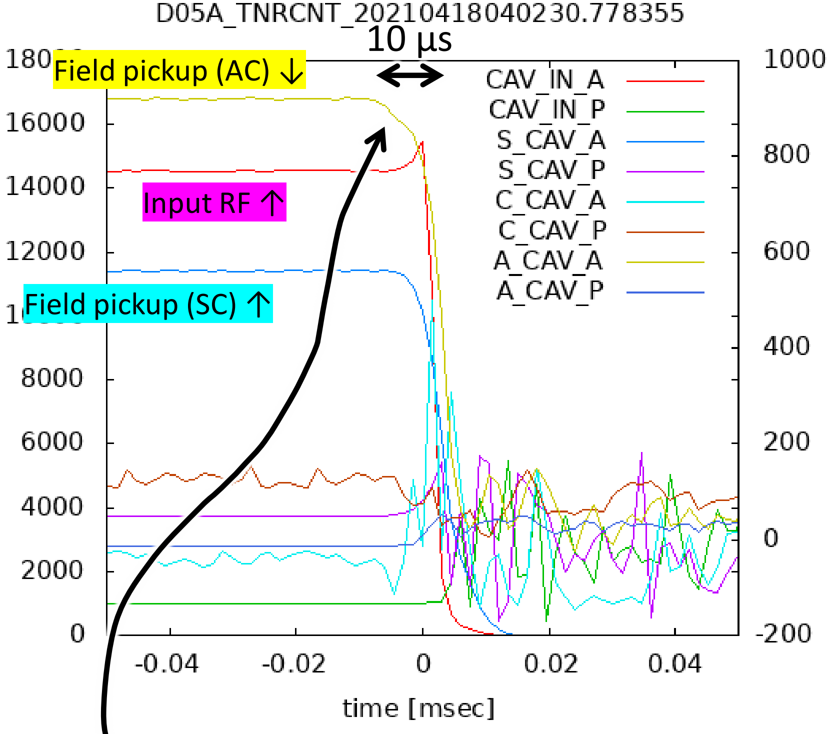
Usual cavity breakdown



Rapid drop of the RF field, which is explained as "Fireball Breakdown" in AC

(E.g. see the Attachment B)

Unusual cavity breakdown seen only in the D05-A cavity



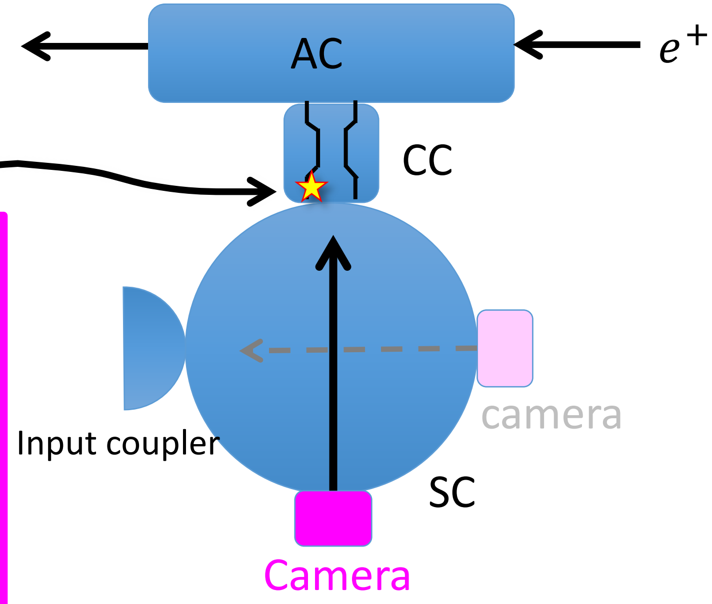
Slow drop prior to the rapid drop of the RF field

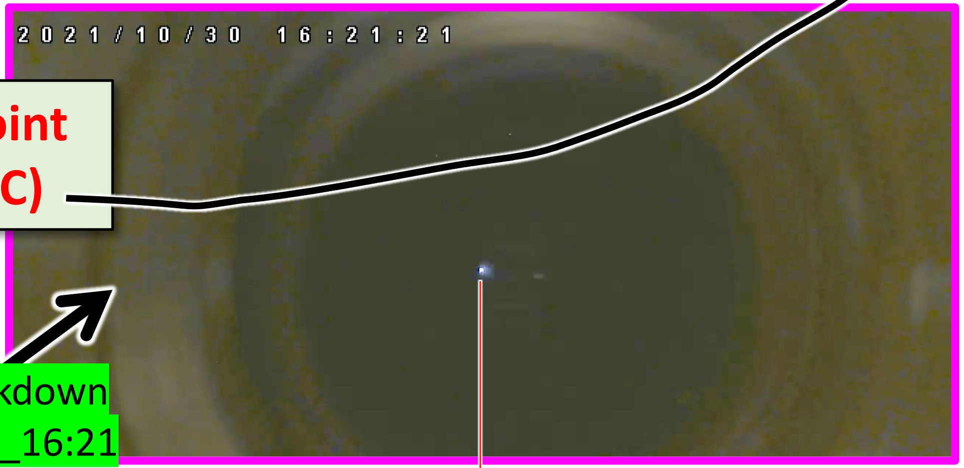
The original paper↓

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.

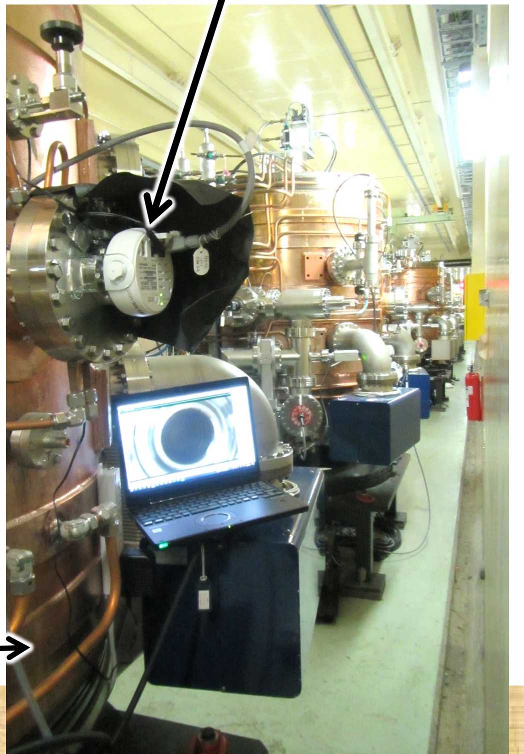
Identification of the vacuum arc point in the D05-A cavity at the moment of the unusual breakdown

- ✓ **All the light emission at the same point**
- ✓ **Vacuum arc in the coupling cavity (CC)**





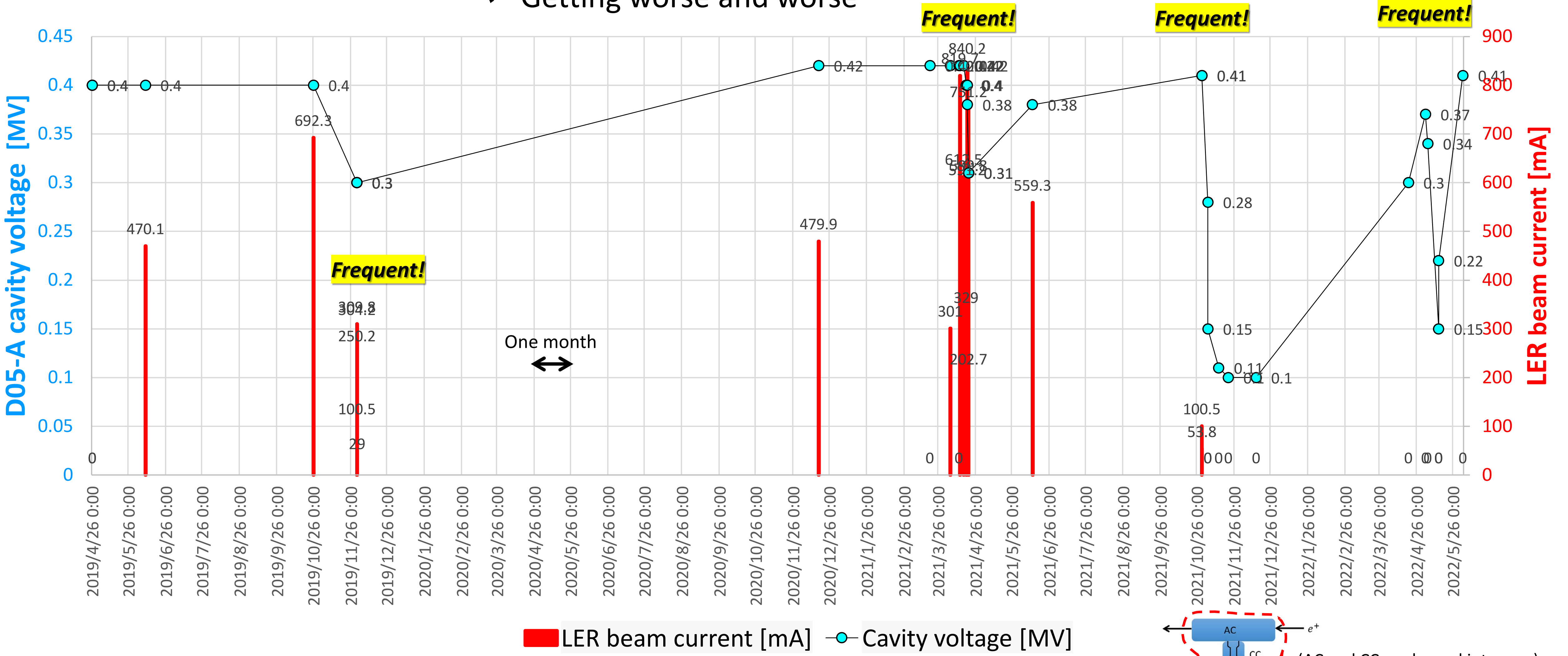
Unusual breakdown at 2021-10-30_16:21



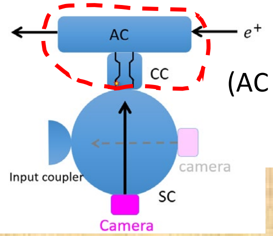
SC

History of the D05-A unusual breakdowns ●

- ✓ Occurred even with no beam
- ✓ Getting worse and worse



➔ Decided to replace the D05-A cavity (CC+AC)



(AC and CC are brazed into one.)

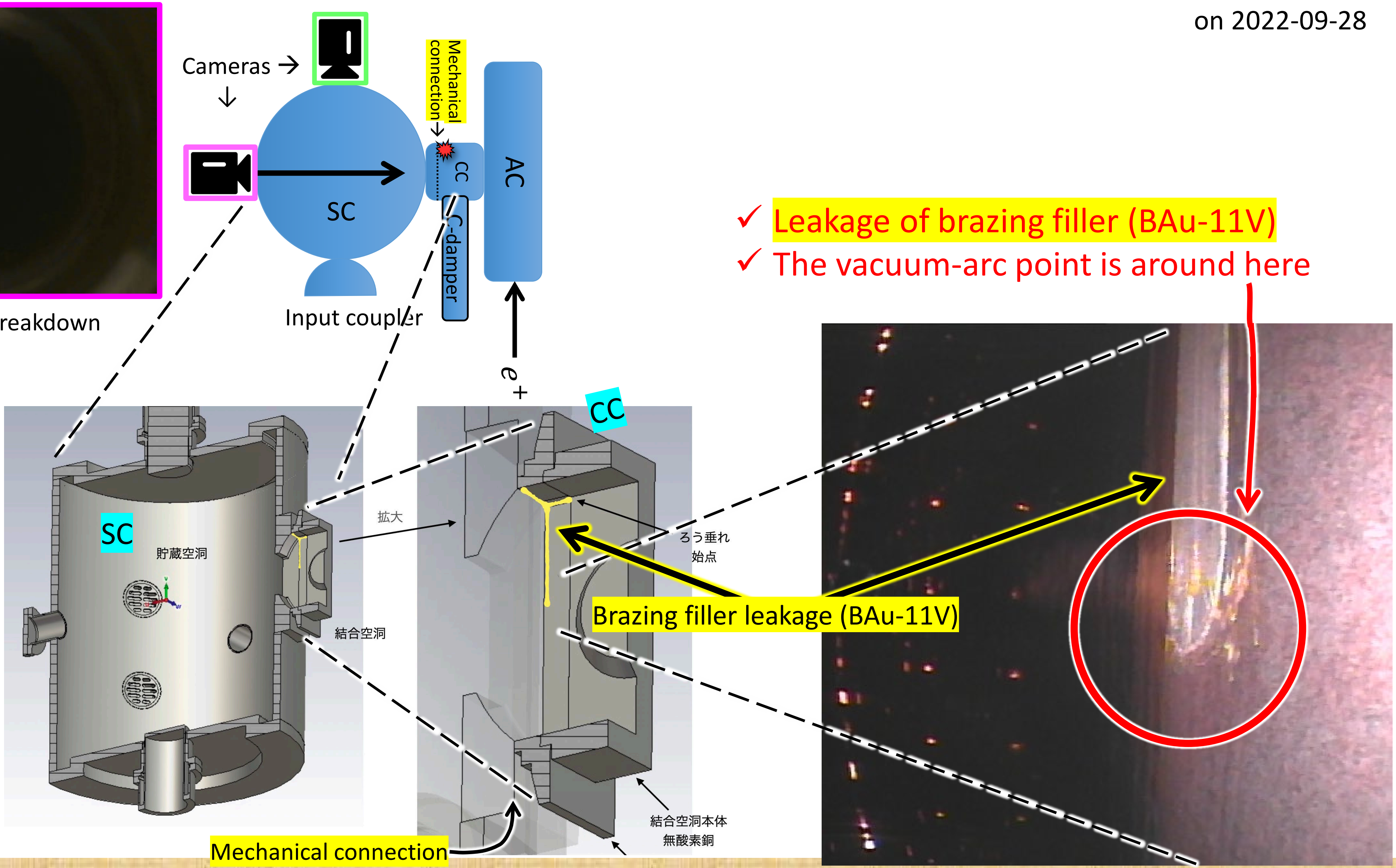
Visual inspection ➔ Leakage of brazing filler found at the vacuum-arc point

on 2022-09-28

Light emission at the unusual breakdown

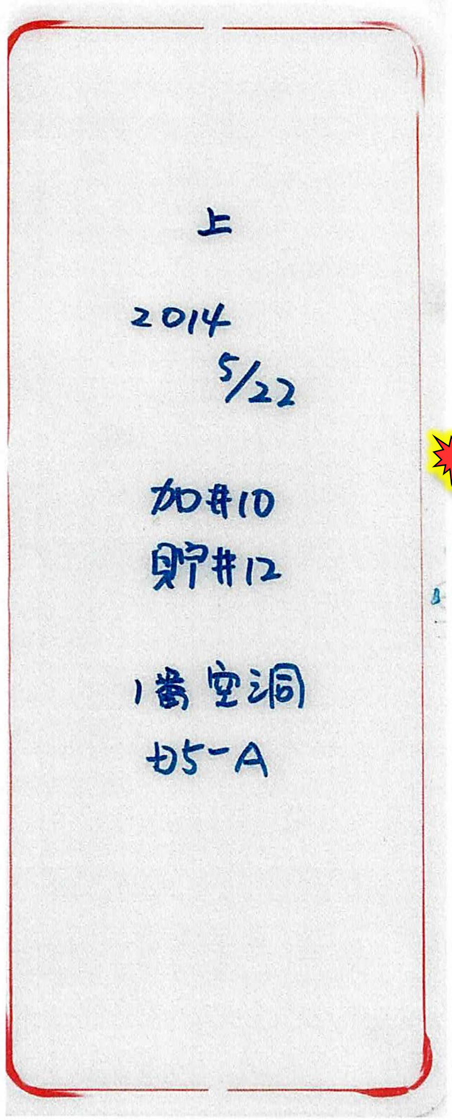
- ✓ Leakage of brazing filler (BAu-11V)
- ✓ The vacuum-arc point is around here

(3D figure made by T. Kageyama)

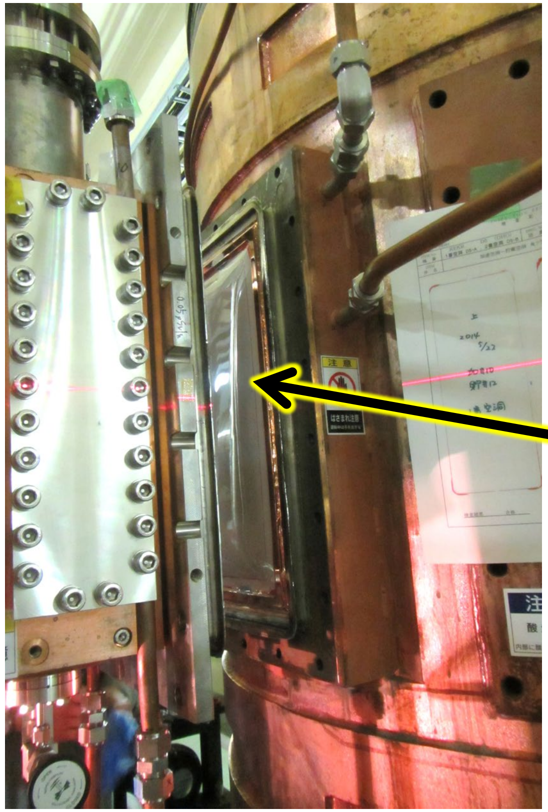


Check of the RF contact in the connection between SC and CC using pressure-sensitive paper

2014-05-22 (just after the relocation: HER→LER between KEKB and SuperKEKB)



CC ↓ SC ↓



Pressure-sensitive paper

- Perfect contact around the vacuum arc point
- Any contact failure was not a cause of the unusual cavity breakdown of the D05-A cavity.

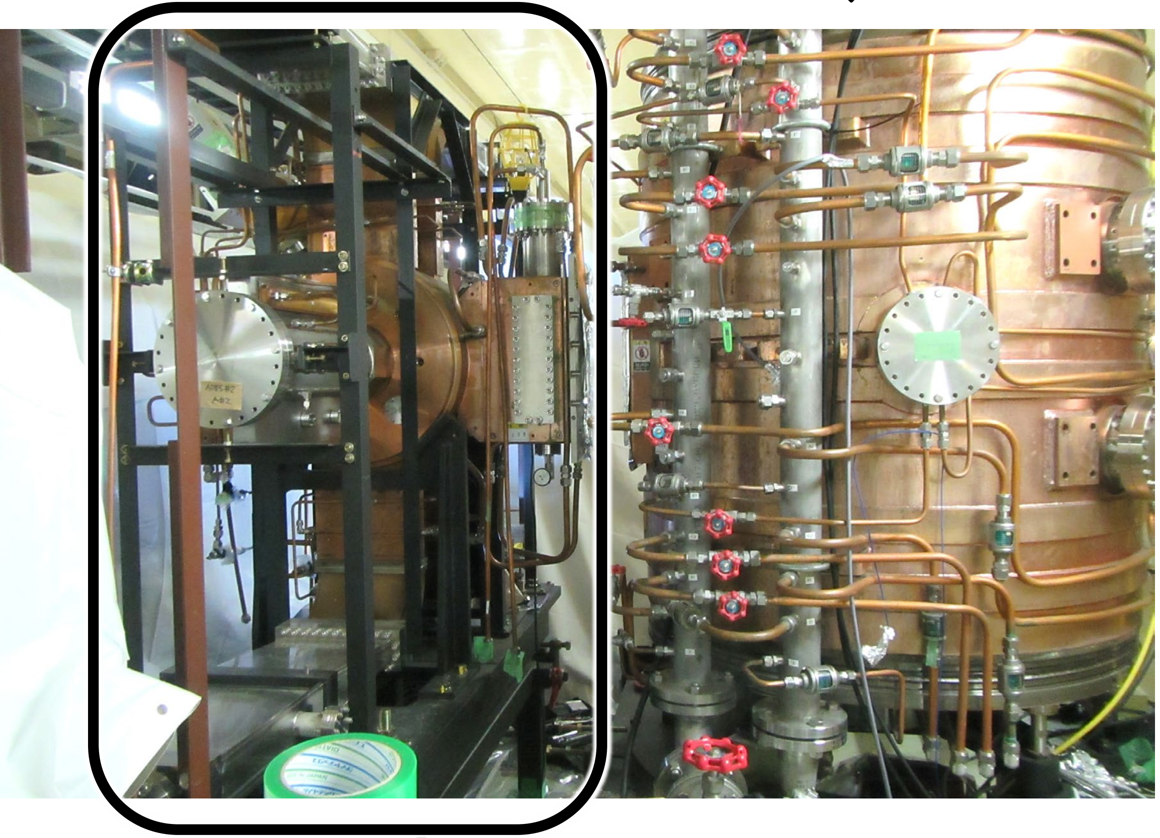
Moving the spare cavity out of the FUJI stock area

2023-01-20

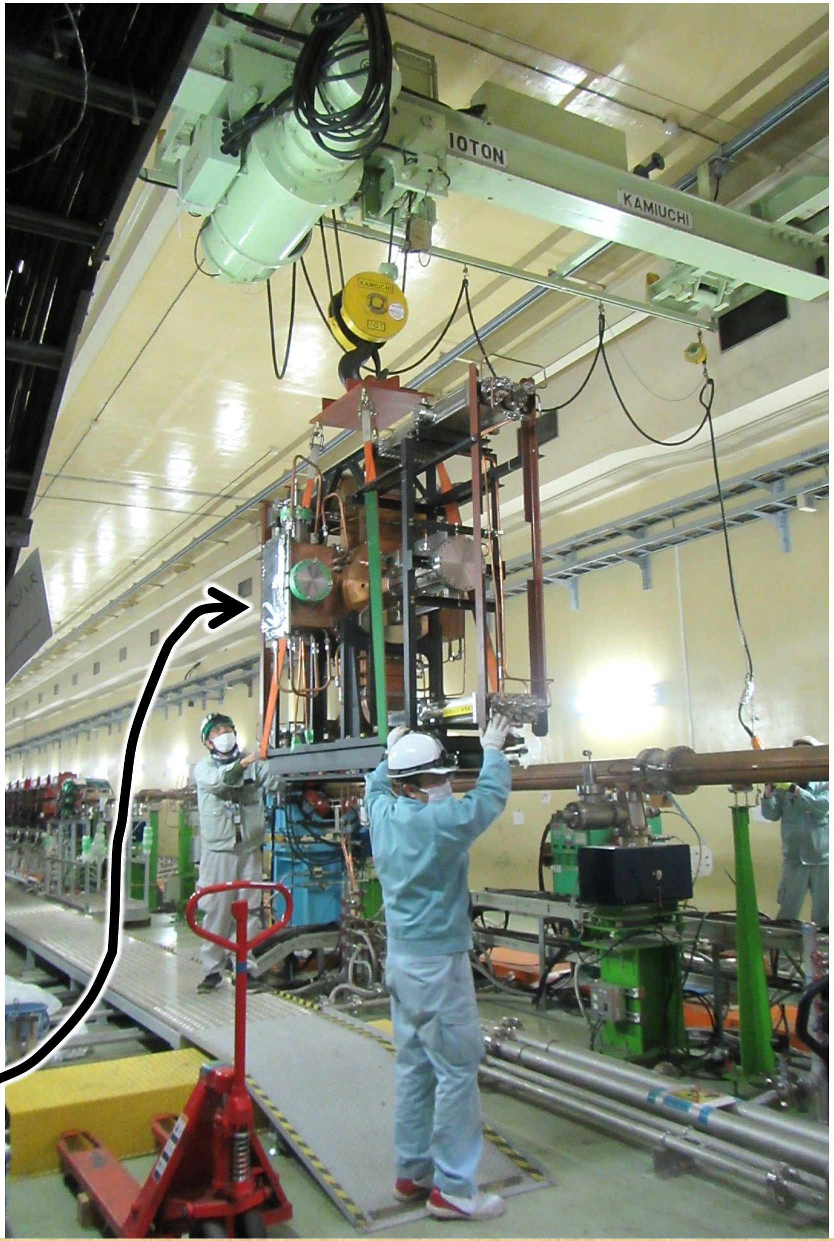
Moving the D05-A cavity (AC+CC) out of the D05 straight section

AC+CC ↓

SC ↓

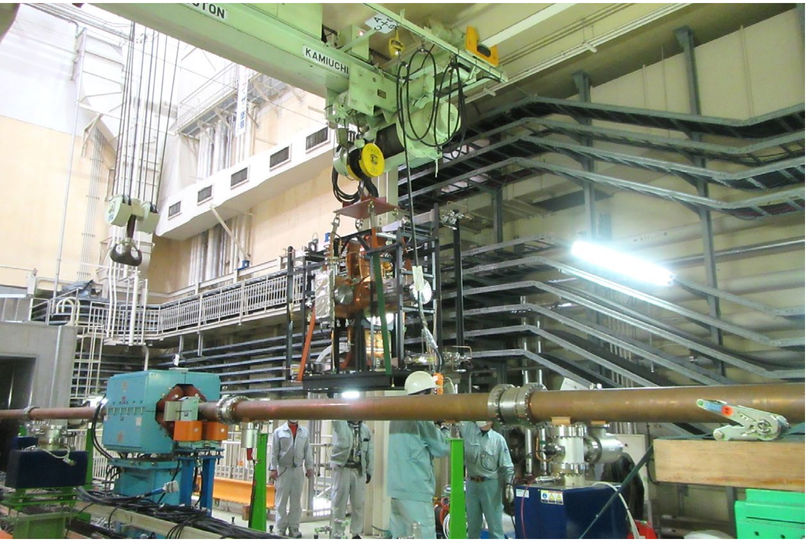


2023-01-25

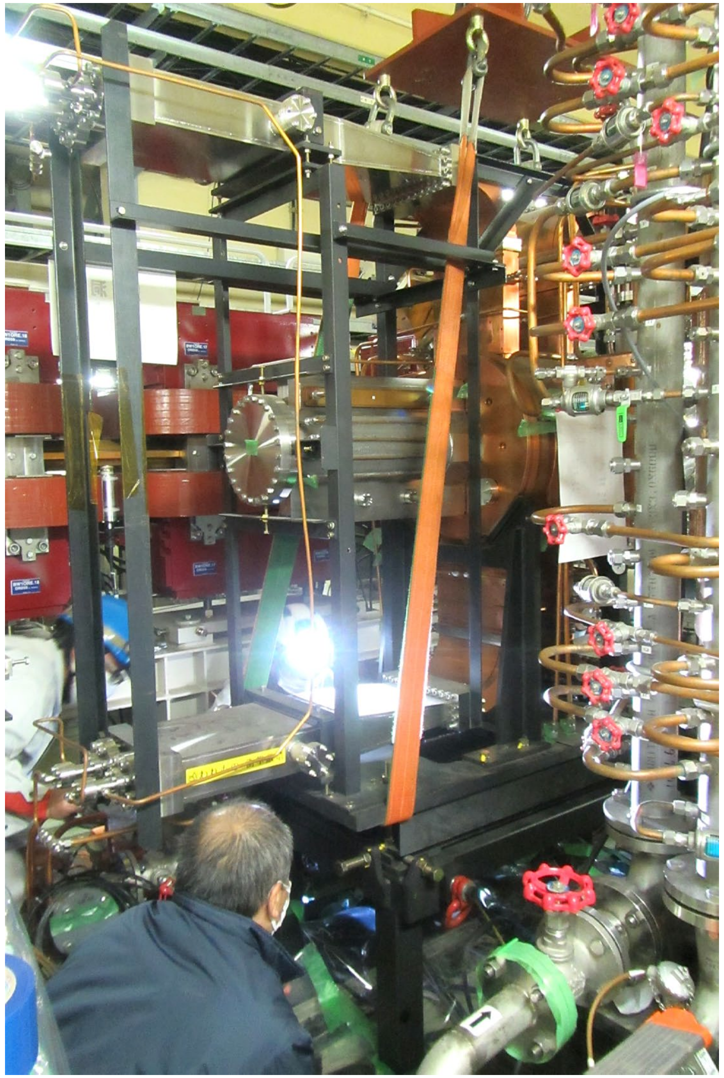


Moving the spare cavity into the D05-A station in the D05 straight section

2023-01-26

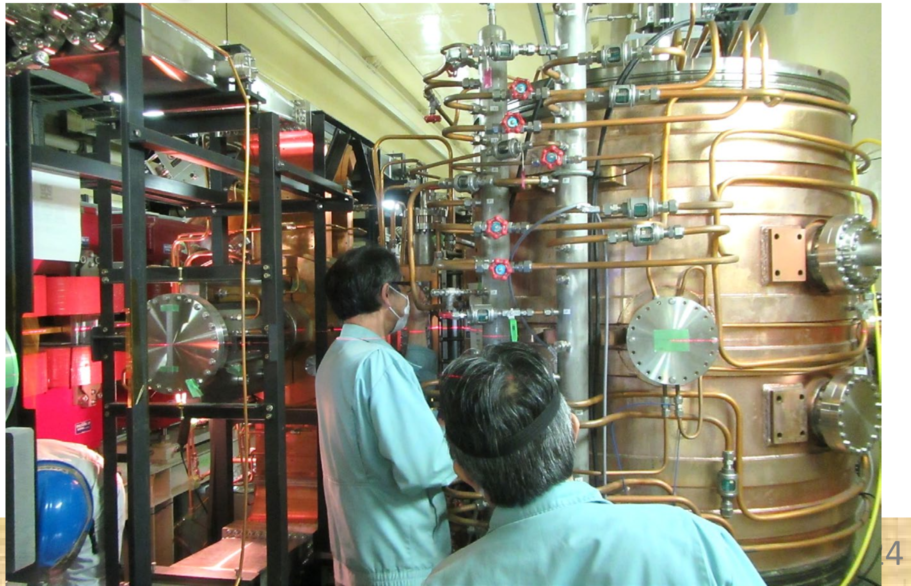


Tiny clearance!

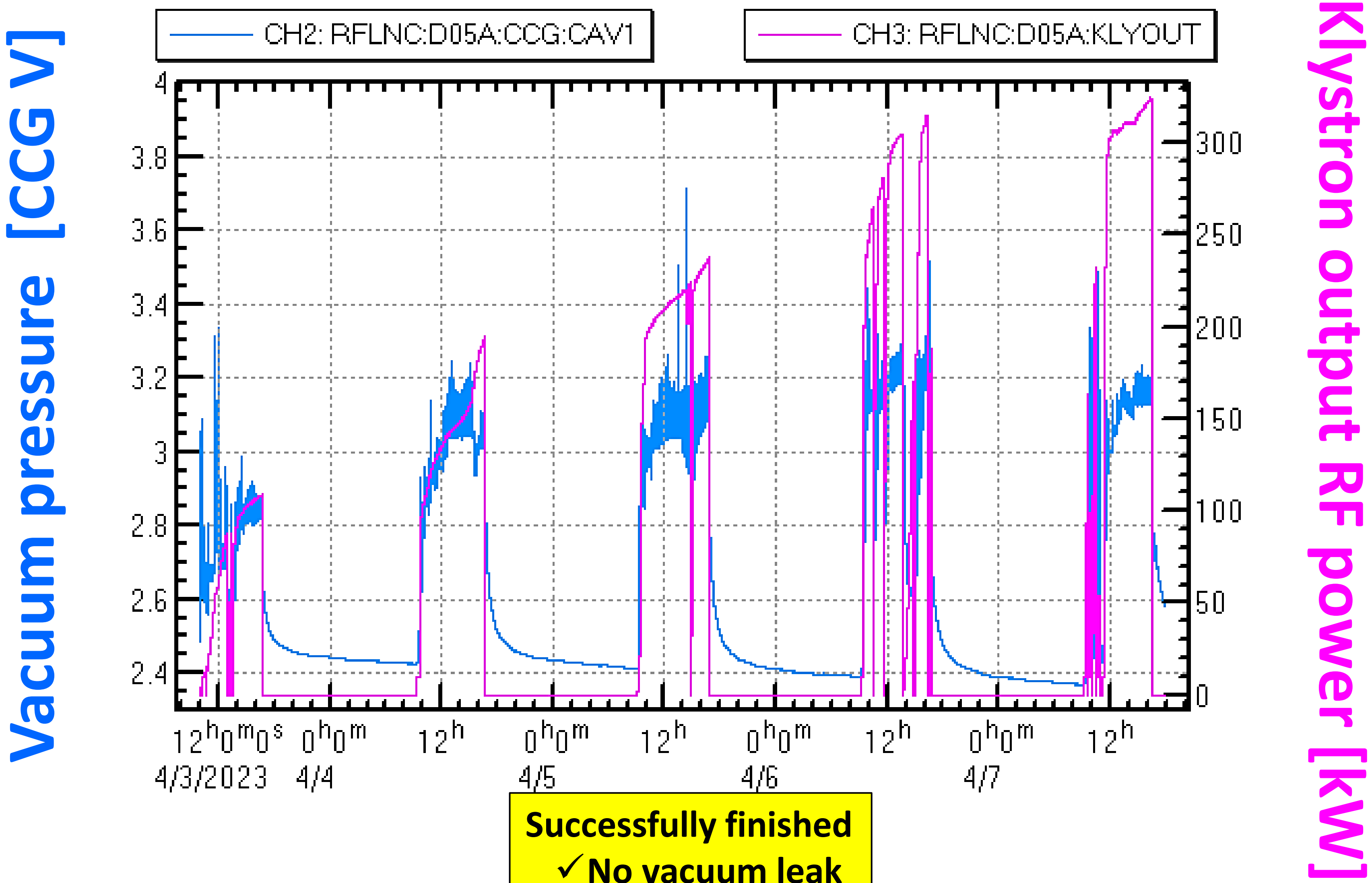


Landing in the D05-A

Alignment



High-power test of the new D05-A cavity up to 0.5 MV/cav

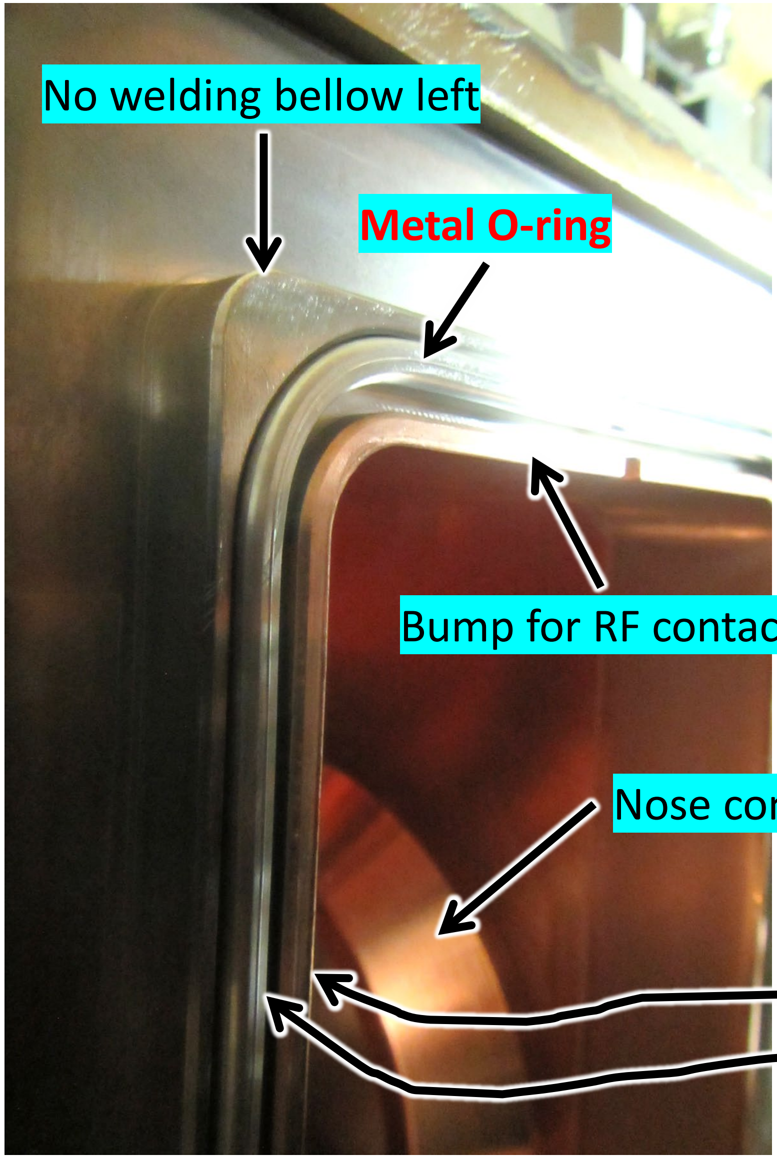


Successfully finished

- ✓ No vacuum leak
- ✓ No vacuum arc

The vacuum sealing made with a metal O-ring

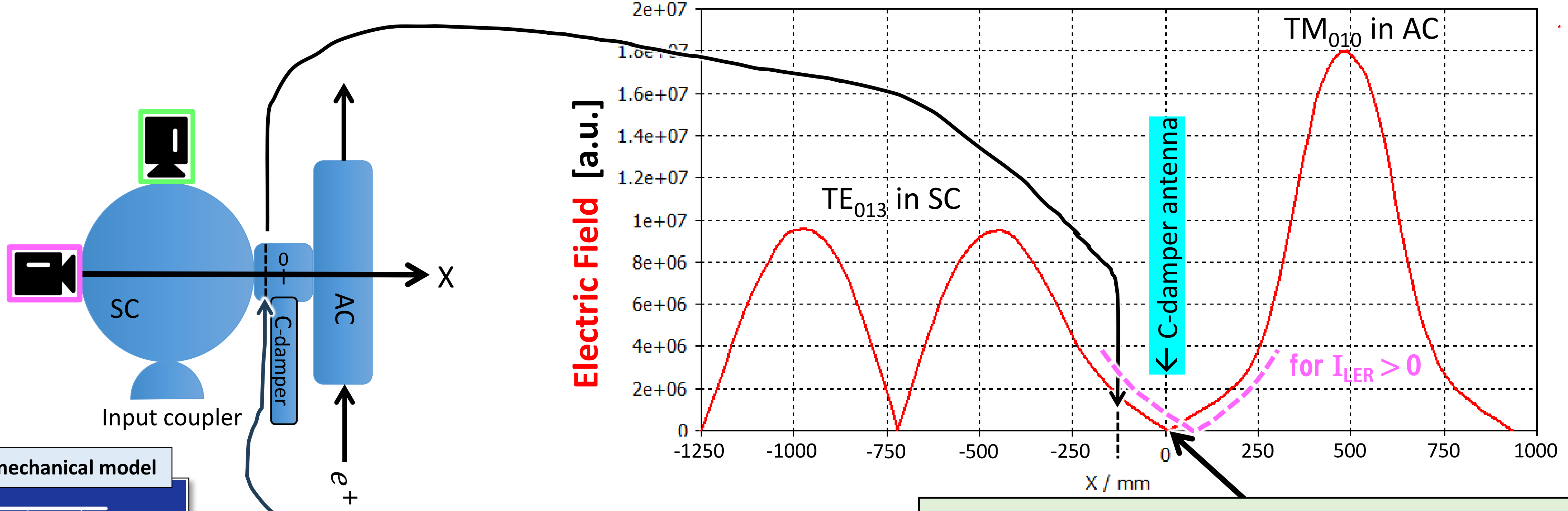
Mechanical connection surface in the CC side



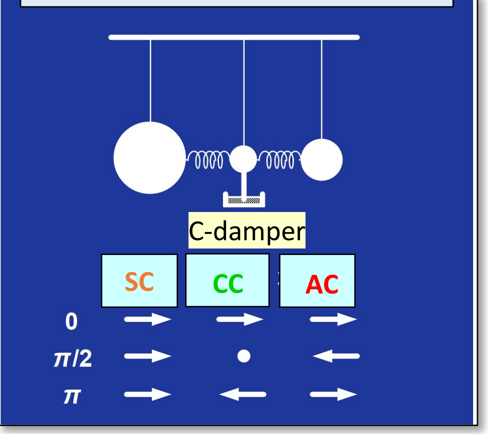
- The vacuum is designed to be sealed at the connection between SC and CC with outermost bellows welded.
- After the cavity replacement during LS1, no welding bellow left due to:
  - First welding during the KEKB era
  - Second welding during the relocation (HER → LER) between KEKB and SuperKEKB
- From the test bench result, vacuum leak occurs if we make a perfect contact at the bump for RF contact between SC and CC.
  - 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 made through the metal O-ring

ARES three-cavity system

Accelerating π/2 mode in the ARES cavity system for $I_{LER}=0$



Equivalent mechanical model



This node shifted toward X>0 for higher beam currents
➔ Higher C-damper power
➔ Higher RF field applied to the connection at X=0

Surface electric field during operation with 0.5 MV/cav and I_{LER}=0

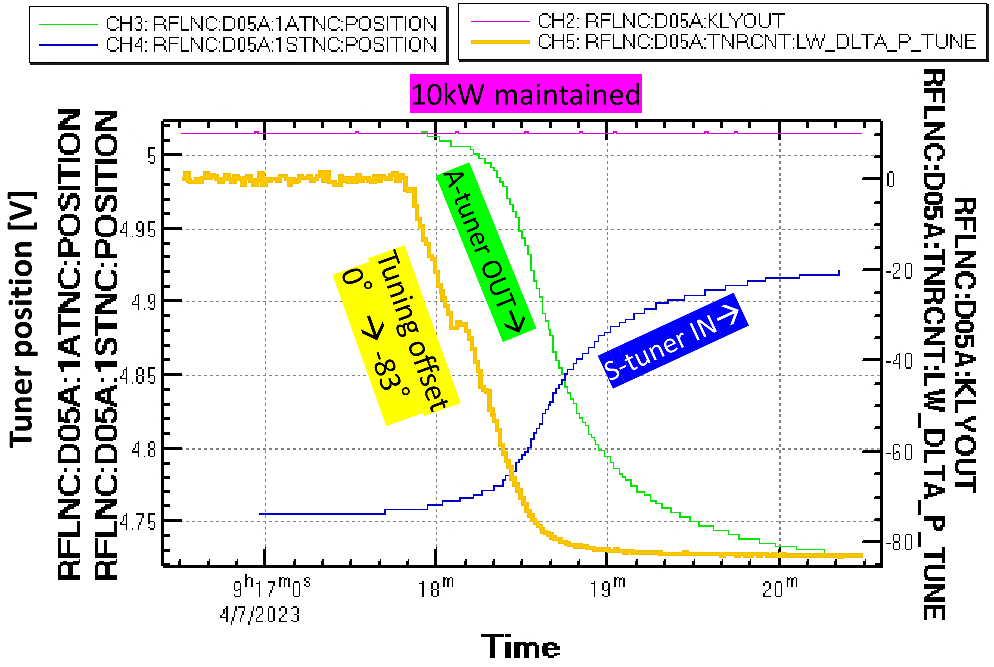
- At the connection (X=-130mm) : ~0.3 MV/m
- In AC: 7.2 MV/m (max.)

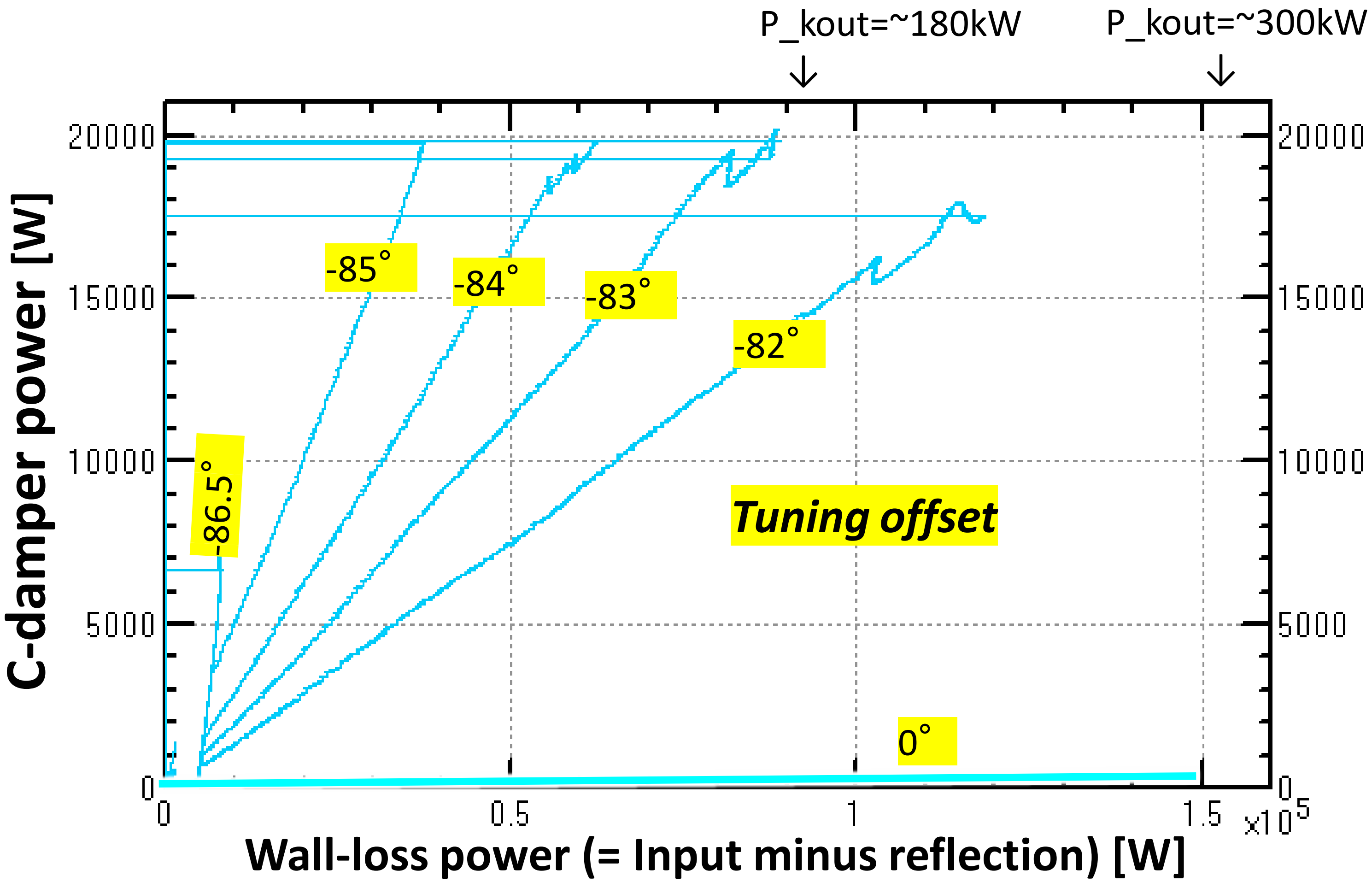
(The surface field at the connection between SC and CC) ∝ (square of the C-damper power)

D05-A high-power test with a large tuning offset

2023-04-07

***20 kW C-damper power** corresponds to beam loading with LER 3.6 A*



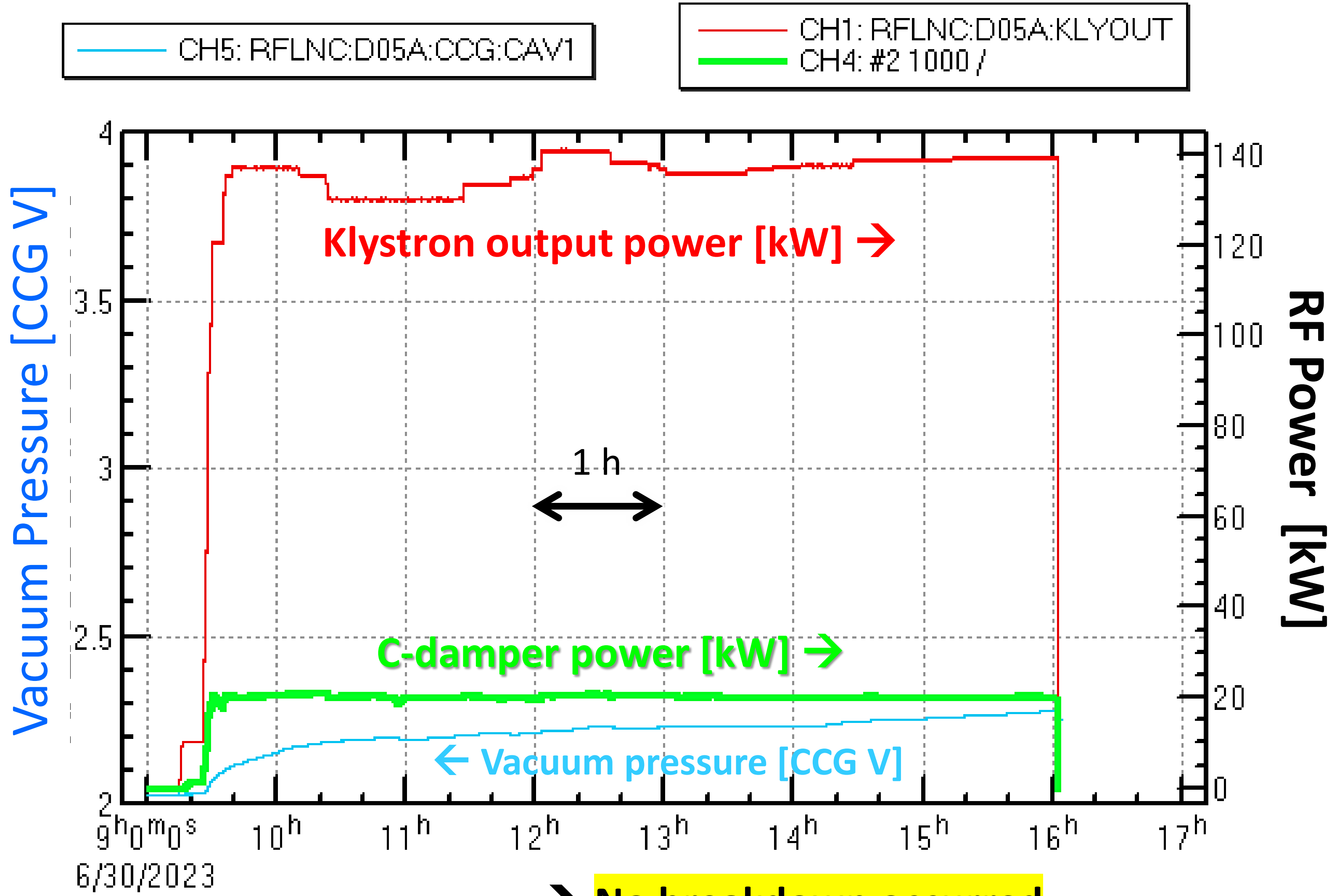


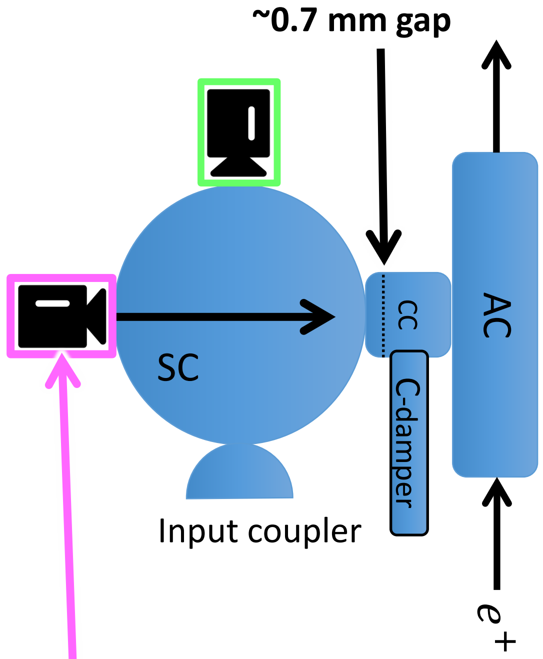
➔ Successful simulation of the beam loading of a 3.6 A LER beam current with a 20kW C-damper power!

D05-A high-power test with 20 kW C-damper power maintained for 6.5 h

2.4e-6 Pa →

7.9e-7 Pa →

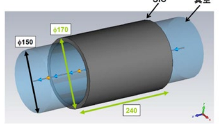




→ **No breakdown occurred**

→ **No vacuum arc observed in any frame of the recorded video**

→ **No breakdown during the 2024a beam operation so far**



Allowable LER beam current due to the RF system

(Shown in the previous ARC)

HOM Power in SCC modules

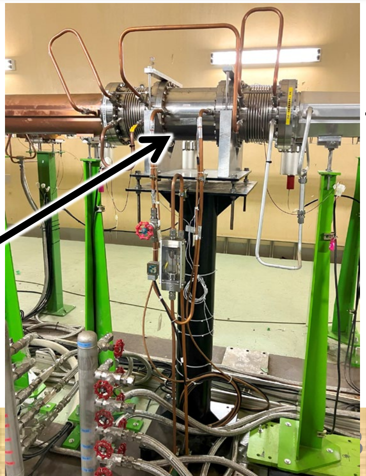
Summary of Evaluation of HOM power in SCC

- The **allowable beam current of HER is evaluated as 2 A** with some update of cooling chillers in LS1.
- In order to aim for more high current, it is necessary to **update all chillers** and **add SiC dampers**.
- **Reinforcement of the capacity of cooling water for chillers from infrastructure** (pure-water system of NIKKO area) will be also necessary.

Uncertainty not verified

- Note : In LER, the allowable beam current is estimated to be 2.6 A based on the maximum absorbed HOM power during KEKB operation by SiC dampers installed in the ARES section. Further R&D of dampers are planned to extend the limitation.

Dec. 13, 2022 KEKB ARC2022, RF system 21



- Limited by the power absorption capability of the SiC dampers installed at the end of each RF section for ARES
- We had been working to investigate the actual capability limit of the SiC dampers, and to develop how to increase the capability using an L-band (1.25GHz, CW, 50kW) high-power test stand (D1-CT).
- However, the klystron power supply (for D1-AT&CT) was broken half way through high-power testing.
- This R&D bas been halted.
- At least, we can guarantee 2.0 A.
  - ~2.5 A not sure
- **This kind of R&D for high-power components takes a long time** (e.g. serval years).
- *The broken klystron power supply is shared with D1-AT (509MHz test stand) where an important experiment was on-going to measure fundamental parameters in the fireball hypothesis for SBL.*

See → https://indico.cern.ch/event/1298949/contributions/5783882/

Summary

- **SCC**
  - The cooling capability for the HOM dampers (Ferrite & SiC) has been upgraded.
    - Allowable HER beam current due to the RF system: 1.7 → 2.0 A
- **ARES**
  - D05-A cavity had the unusual breakdown problem.
    - Vacuum arc in CC (not in AC)
    - CC+AC replaced by spare one
    - Successfully recovered with no breakdown until now including the current 2024a beam operation
- **RF cavity for DR**
  - The O-ring replacement (Viton → Metal) led to the significant vacuum improvement.
  - The strange periodic vacuum pressure rises appeared after the O-ring replacement
    - Under investigation
    - No impact on the DR beam operation
- The klystron power supply for the high-power test stands (D1-AT, D1-CT) was broken.
  - Can not perform high-power tests toward higher beam currents

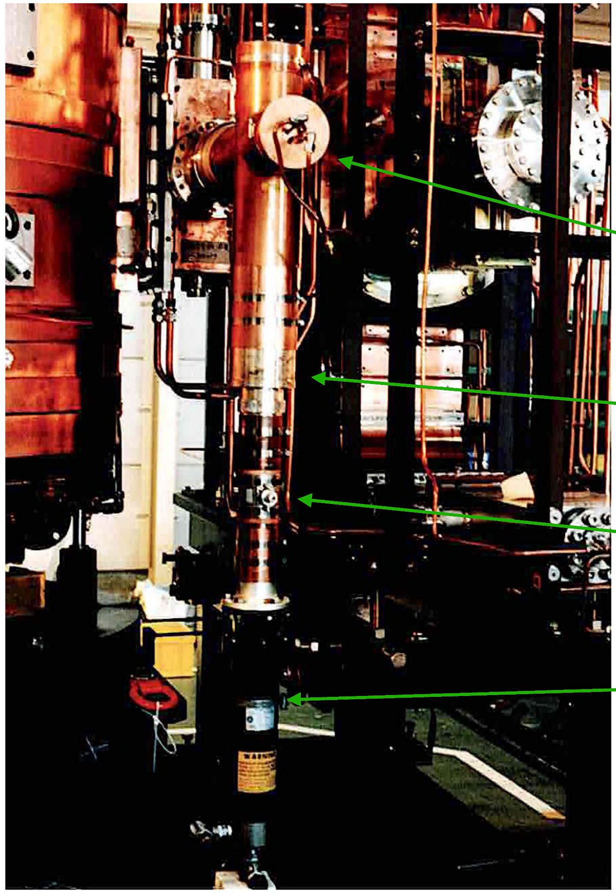
Thank you for your attention

Backup slides

[Attachment A] ARES C-damper system

BACK

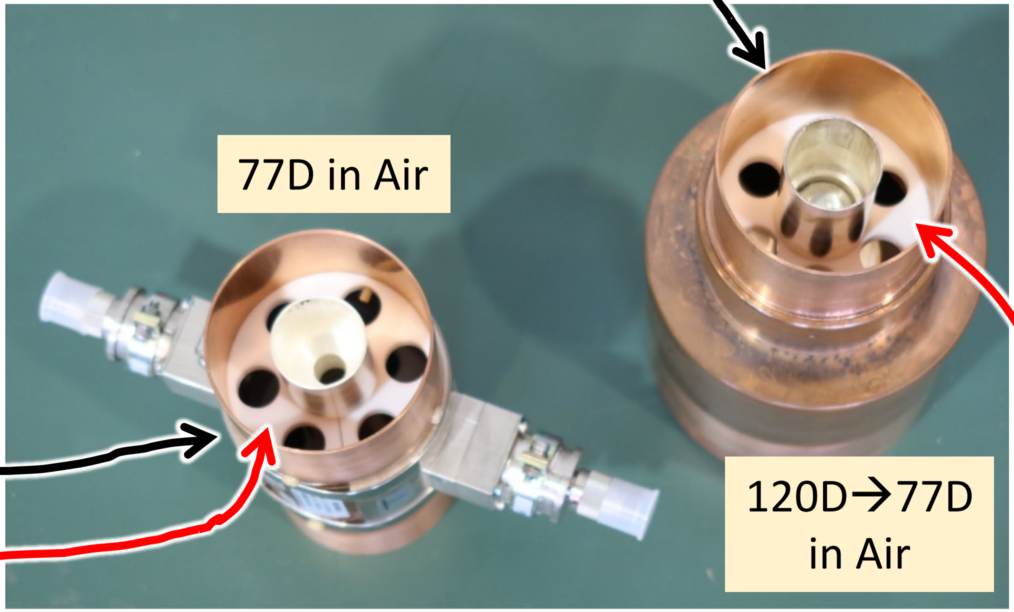
energy-Storage Cavity (SC) ↓
Coupling Cavity (CC) ↓
Accelerating Cavity (AC) ↓



↑
C-damper
(Antenna + Coaxial line + Dummy load)

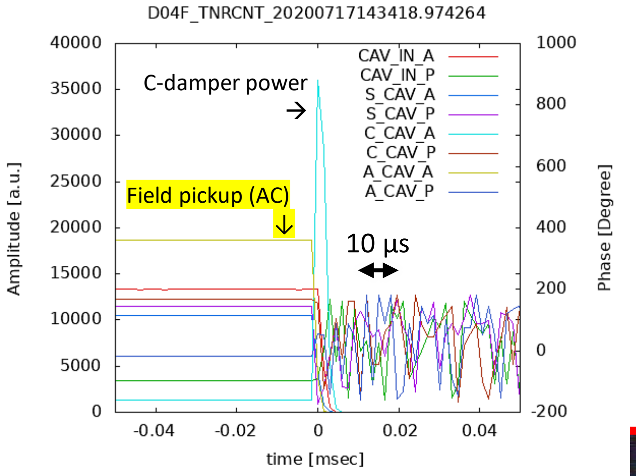
カプラによって結合空洞から取り出された
RF電力（最大約30kW）は大気側同軸管
（SuperKEKBでは強制風冷式）を通って
終端の水冷負荷に至る：

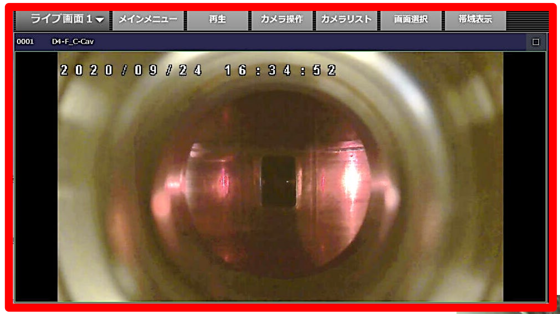
Antenna coupler
with COAX 120D out.
↓
COAX Taper
120D → 77D
↓
COAX 77D
（方向性結合器付き）
↓
Water-cooled dummy load
（入口取合：77D）
最大定格：40kW
50kW級に順次置換の予定

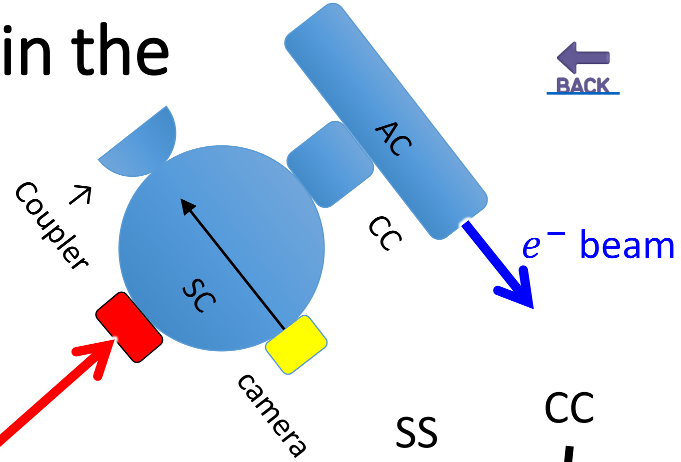


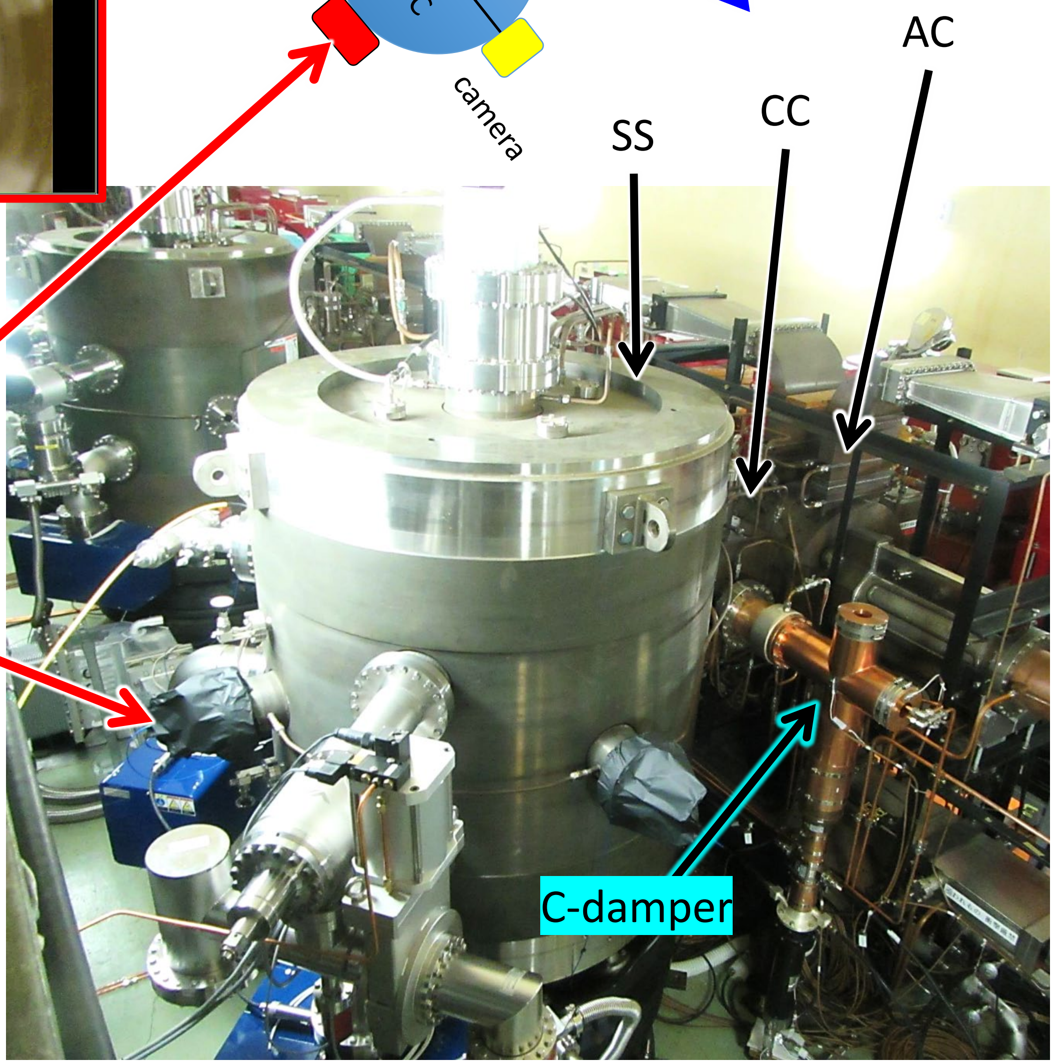
These support disks have been replaced:
Cross-linked polyethylene → Teflon

[Attachment B] Example of fireball breakdowns observed in the ARES Cavities









BACK

Video file → https://youtu.be/qtIB6kLf2j4

D04-F