Reports on SuperKEKB RF System

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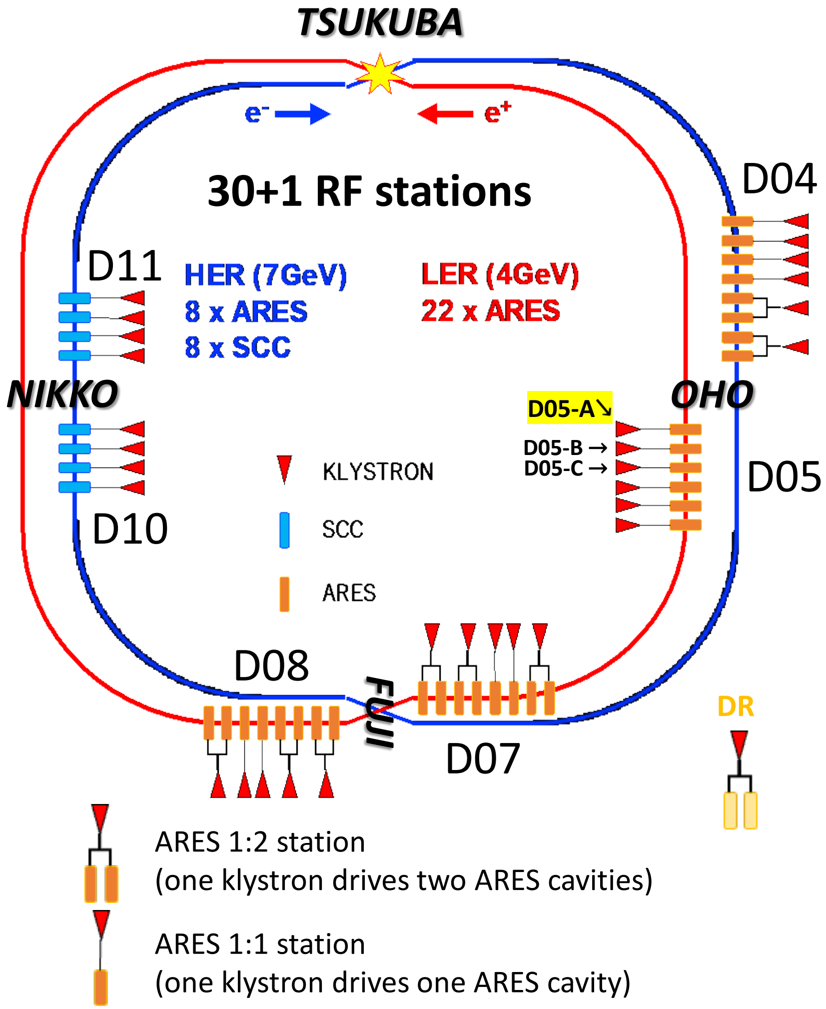
KEK / ACCL
on behalf of SuperKEKB RF group

The 28th KEKB Accelerator Review Committee

2025-01-15

RF Accelerating System for the SuperKEKB Main Ring (MR)

Present RF Cavity Layout



SuperKEKB operational parameters at 2024-12-27_01:40:59

	LER		HER		
Energy [GeV]	4.0		7.0		
Beam current [A]	1.632		1.259		
Number of bunches	2346				
Bunch length [mm]	~6		~6		
Total beam power [MW]	~3.2		~3.4		
Total RF voltage [MV]	9.3		14.2		
Cavity type	ARES		ARES		SCC
Number of cavities	12	10	4	4	8
Klystron : Cavity	1:2	1:1	1:2	1:1	1:1
Cavity voltage [MV/cav]	0.40 or 0.45		0.40 or 0.45		1.35
Input RF power [kW/cav]	~200	~400	~200	~400	~300

Cf.

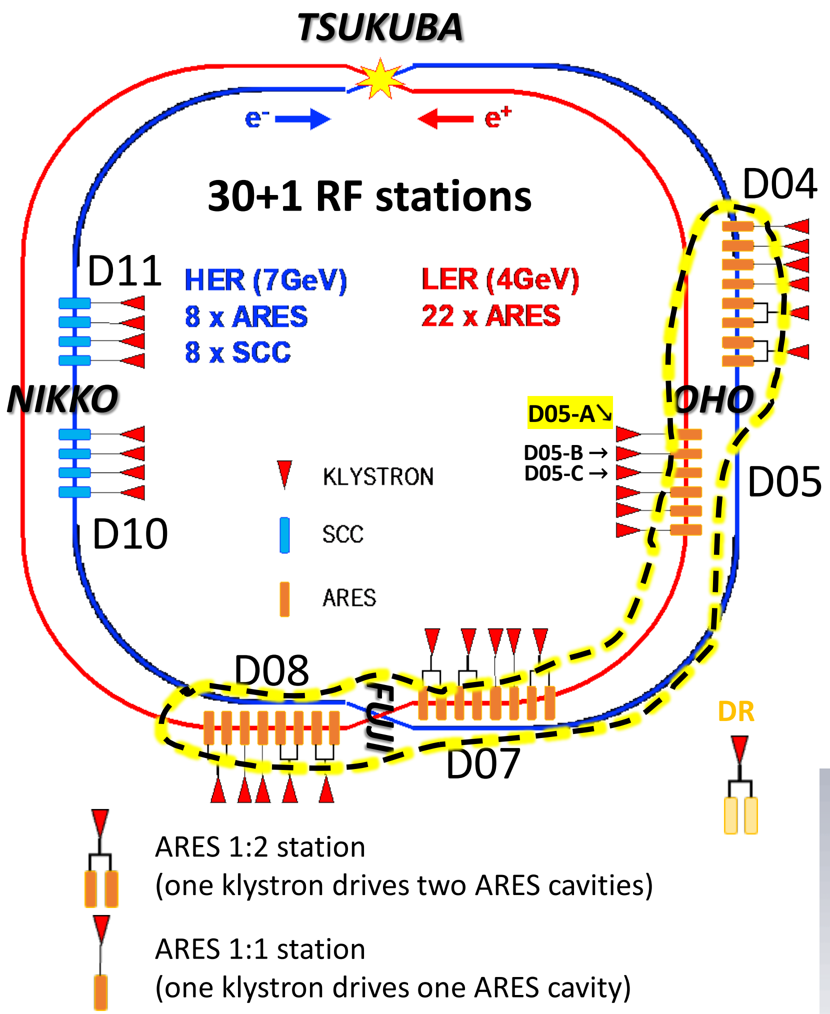
Parameter	KEKB (achieved)				SuperKEKB (design)			
Ring	HER			LER	HER		LER	
Energy [GeV]	8.0			3.5	7.0		4.0	
Beam Current [A]	1.4			2	2.6		3.6	
Number of Bunches	1585			1585	2500		2500	
Bunch Length [mm]	6-7			6-7	5		6	
Total Beam Power [MW]	~5.0			~3.5	8.0		8.3	
Total RF Voltage [MV]	15.0			8.0	15.8		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

ARES

Accelerator Resonantly-coupled with Energy Storage: "ARES"

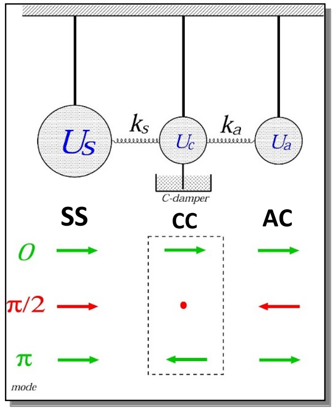
*22 sets of A+C+S cavities used for LER, and 8 for HER (**30 in total**)*

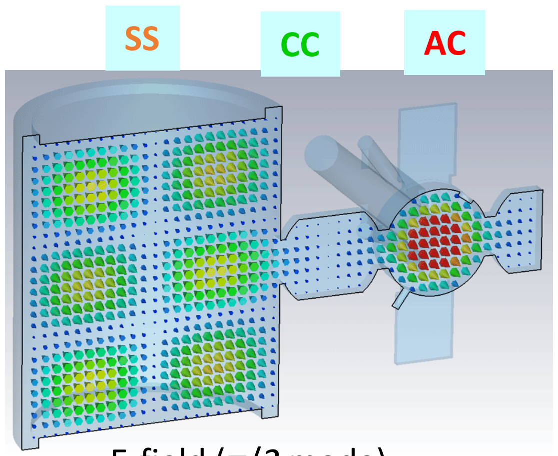
Present RF Cavity Layout



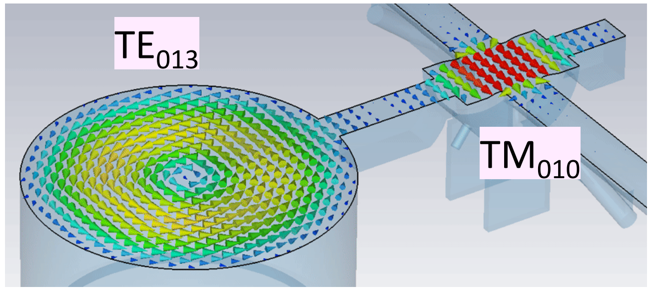
- Unique three-cavity system operated with the stable π/2 mode
- Accelerating $\pi/2$-mode frequency : 508.9 MHz
- Q_0 = ~11×10[4] ($\pi/2$-mode), ~17×10[4] (only for SS)
- Vacuum pressure : ~10^{-7} Pa
- Cavity voltage (spec.) : 0.5 MV/cav (⇔ Eacc ≈ 2 MV/m)
- Wall-loss dissipation power: ~150 kW (for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

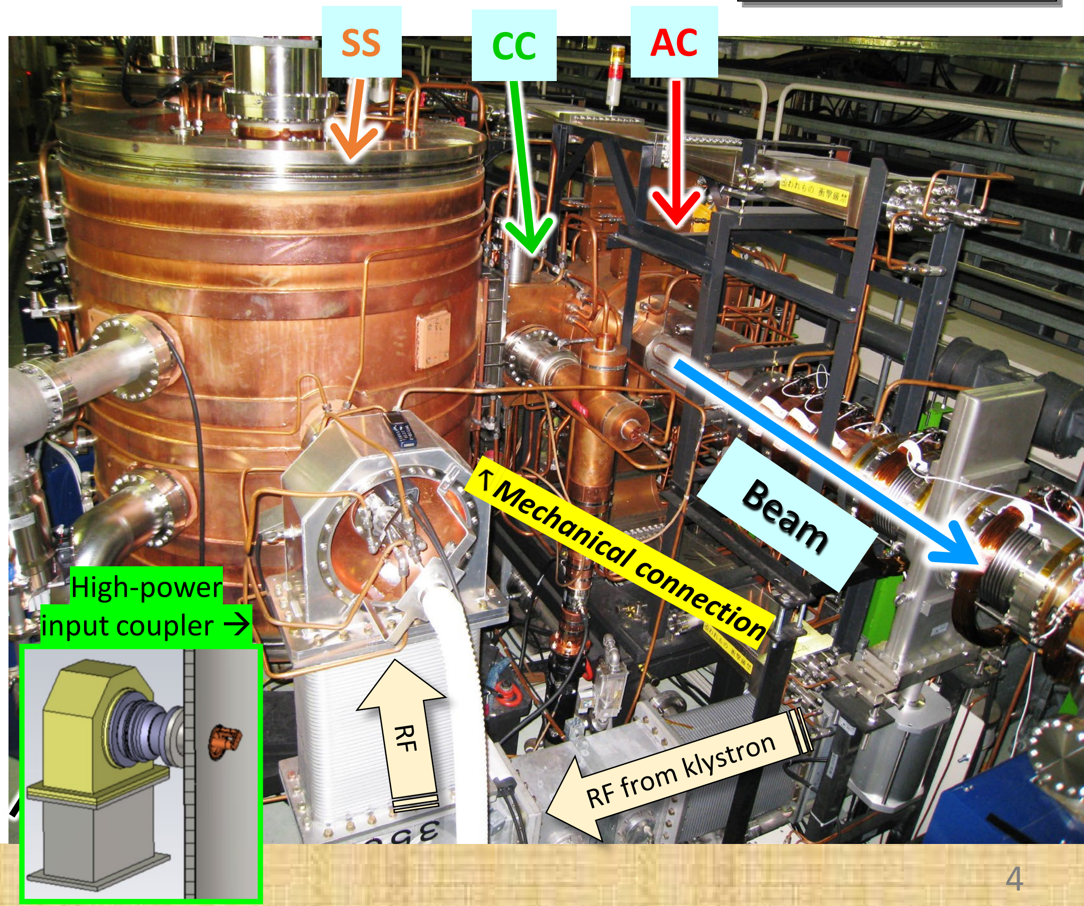
SS: Storage Cavity
CC: Coupling Cavity
AC: Accelerating Cavity



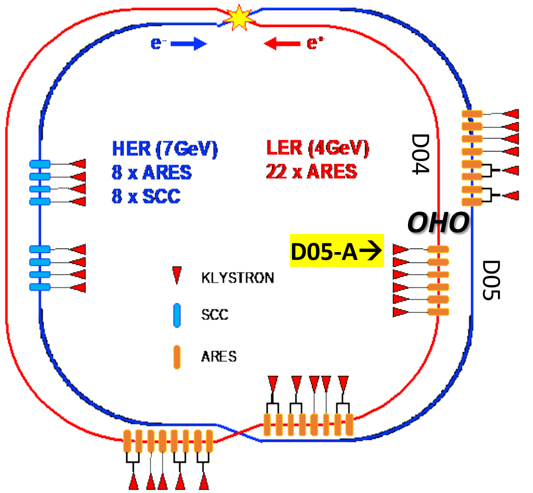


E-field ($\pi/2$ mode)





D05-A cavity

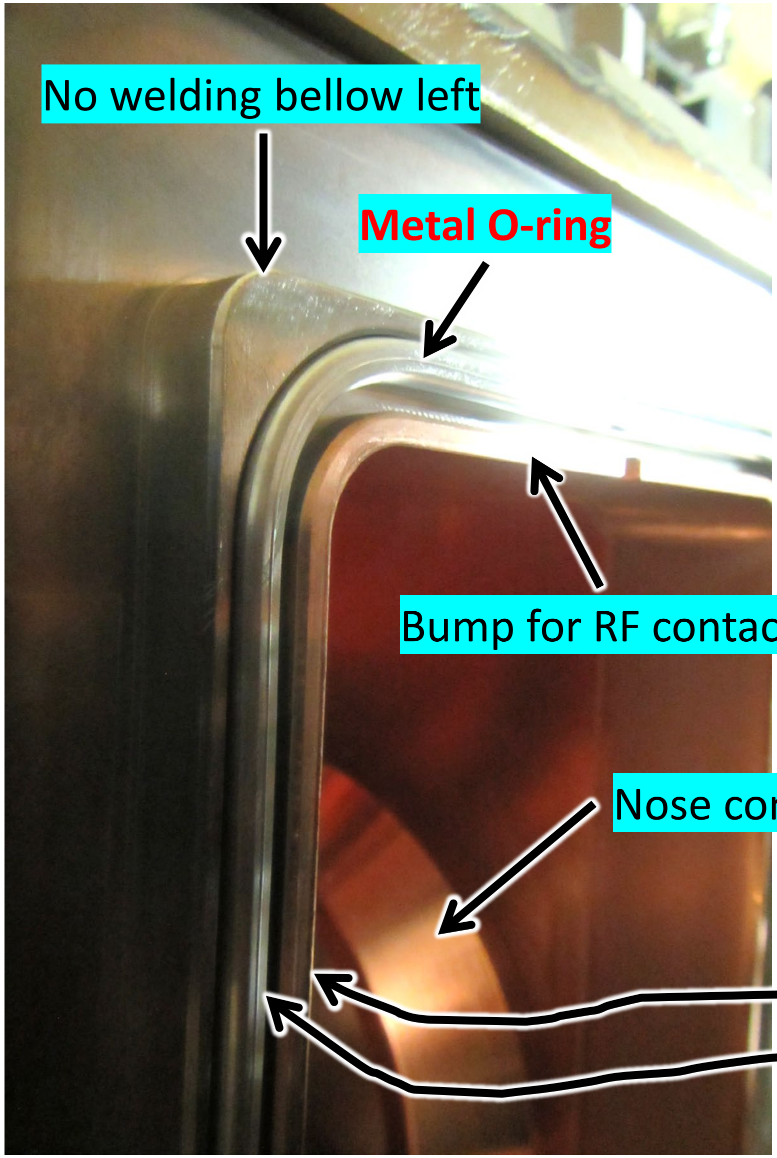


- Had an unusual breakdown problem.
  - Already reported to the 27th KEKB Accelerator Review Committee
  - Also see the backup slides for the details.
- Unusual light emission observed inside the coupling cavity at the moment of each unusual breakdown
  - Leakage of the brazing filler found at the light emission point inside the coupling cavity
- The cavity was replaced by a spare one during LS1.
- However, we needed to make a ~0.7mm gap at the RF contact of the mechanical connection between the coupling and storage cavities.
  - Passed a high-power test with a large tuning offset to simulate a beam loading of 3.6 A

R23.1: Instrument and carefully watch the temperature of the flange in DO5-A which may have anomalous heating from both accelerating RF currents as well as beam induced HOM power.

The vacuum sealing made with a metal O-ring

Mechanical connection surface in the coupling-cavity side

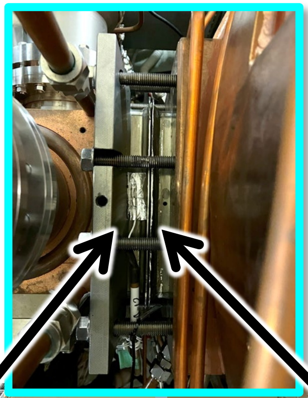


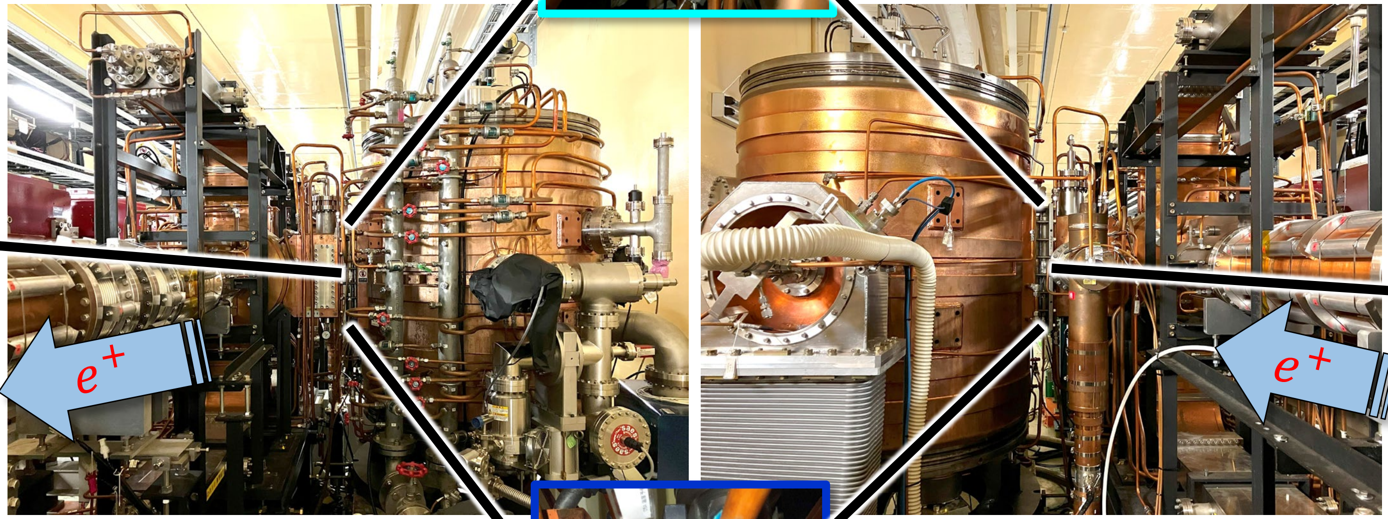
- The vacuum is designed to be sealed at the connection between SC and CC with outermost bellows welded.
- After the cavity replacement during LS1, no welding bellow left due to:
  - First welding during the KEKB era
  - Second welding during the relocation (HER → LER) between KEKB and SuperKEKB
- From 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

Four thermocouples attached to the connection flange per cavity

Midpoint on the side (downstream of e⁺)

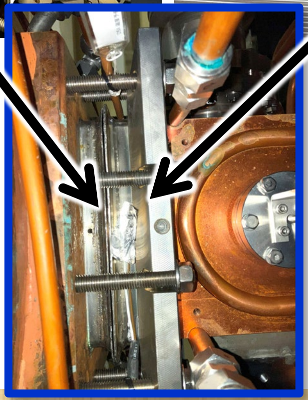
Midpoint on the top





Midpoint on the side (upstream of e⁺)

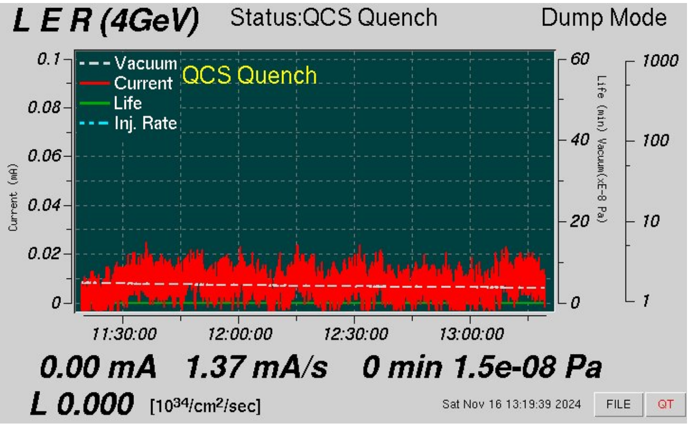
Midpoint on the bottom



For comparison, thermocouples were also attached to the D05-B and D05-C cavities in the same way, where the two cavities have no gap at the RF contact.

Temperature measurements in 2024c (1/2)

(During the recovery from the QCS quench)



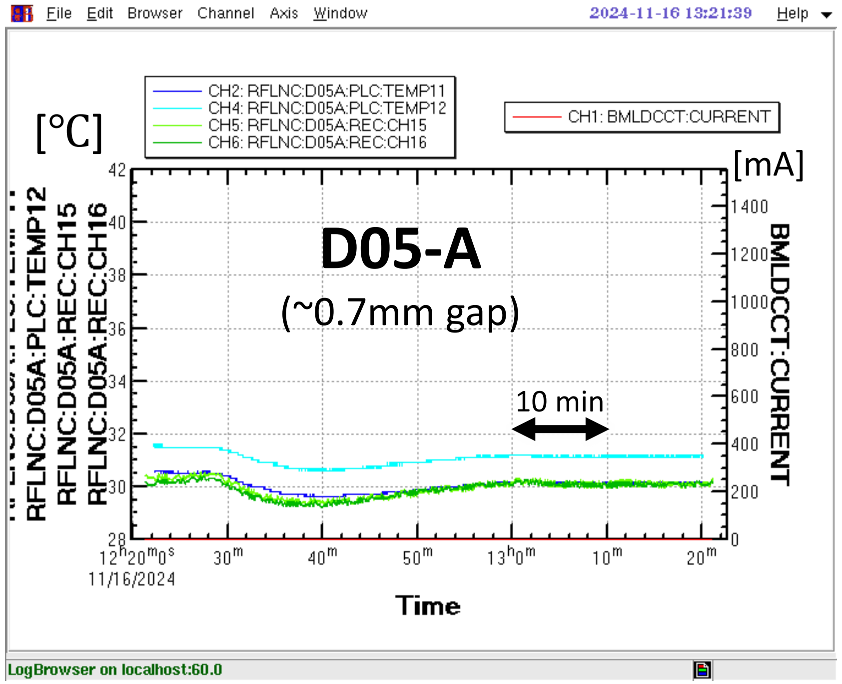
- ✓ No beam
- ✓ Input RF power: ~25 kW/cav
- ✓ Cavity voltage: 0.15 MV/cav

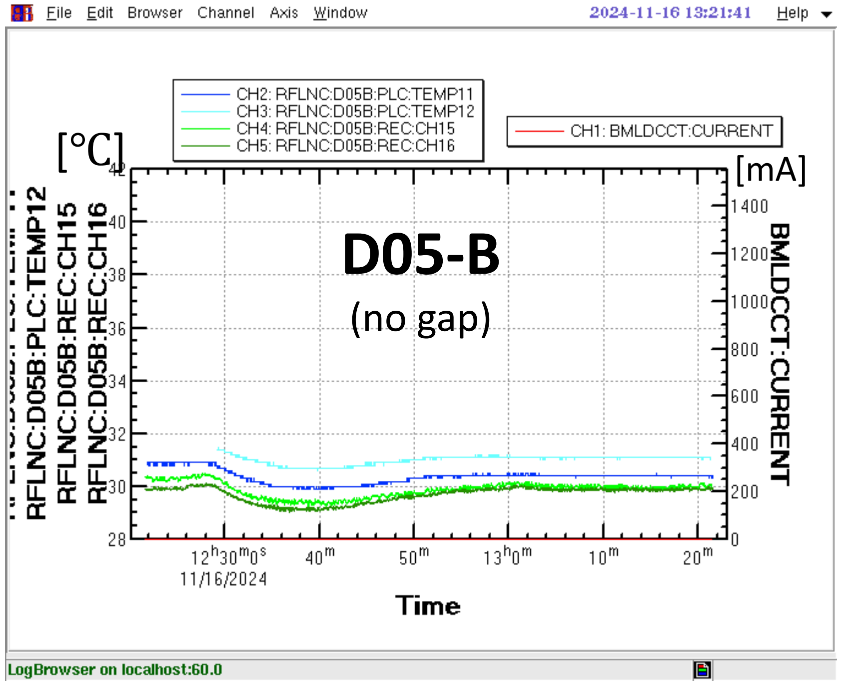
--- Midpoint on the top

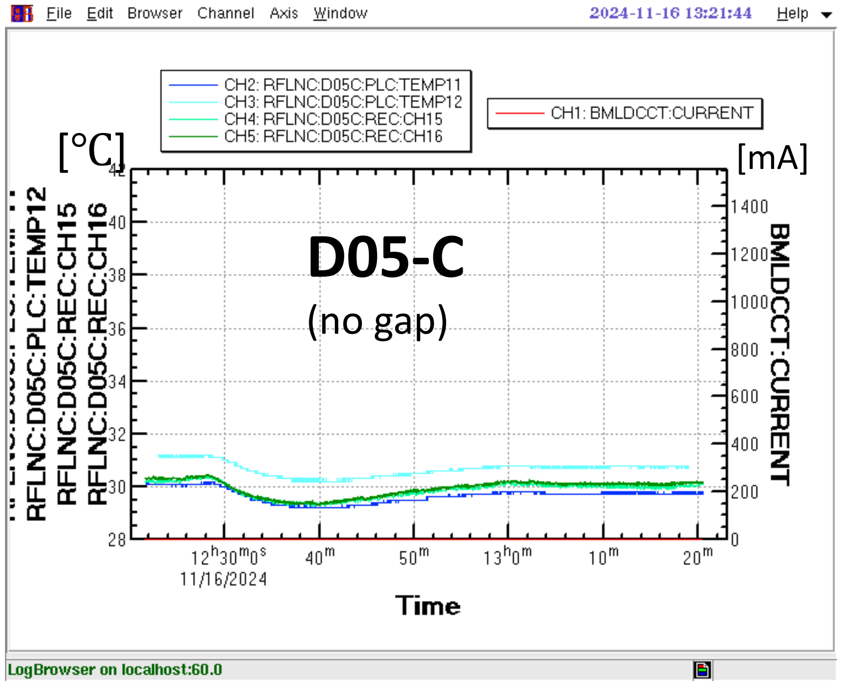
--- Midpoint on the bottom

--- Midpoint on the side (downstream of e+)

--- Midpoint on the side (upstream of e+)



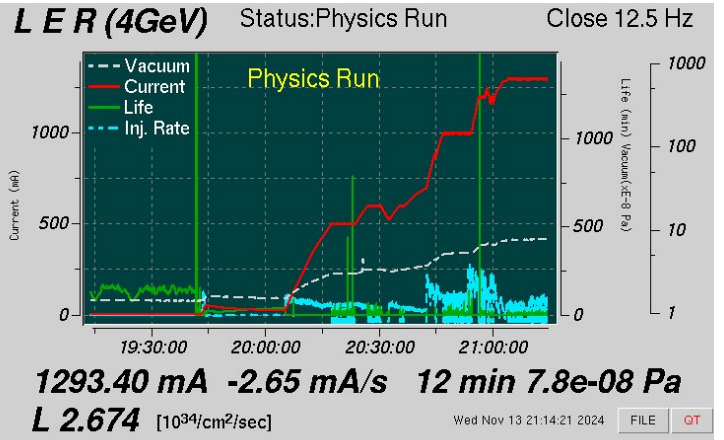




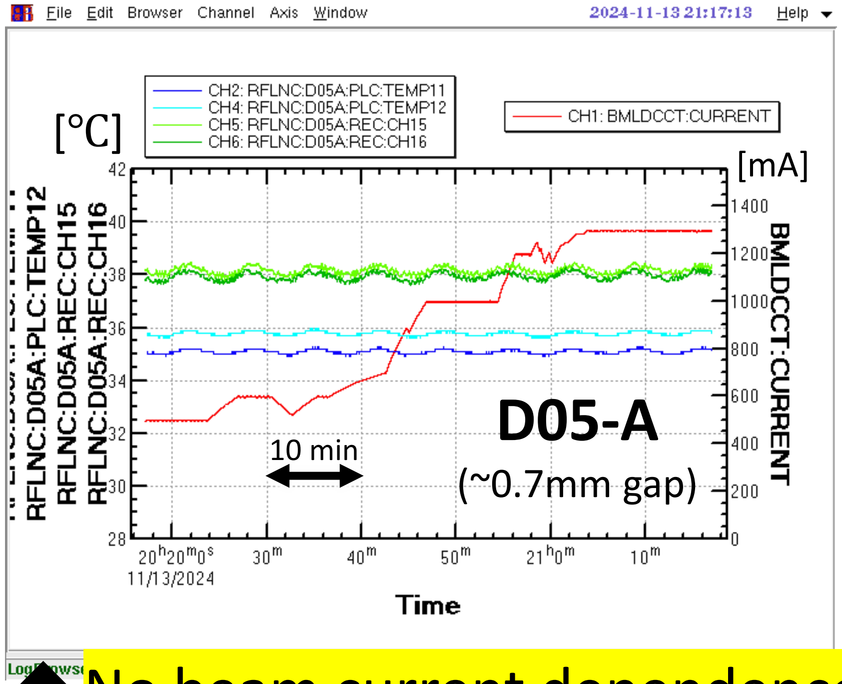
~30degC (≈ temperature of the cooling water)

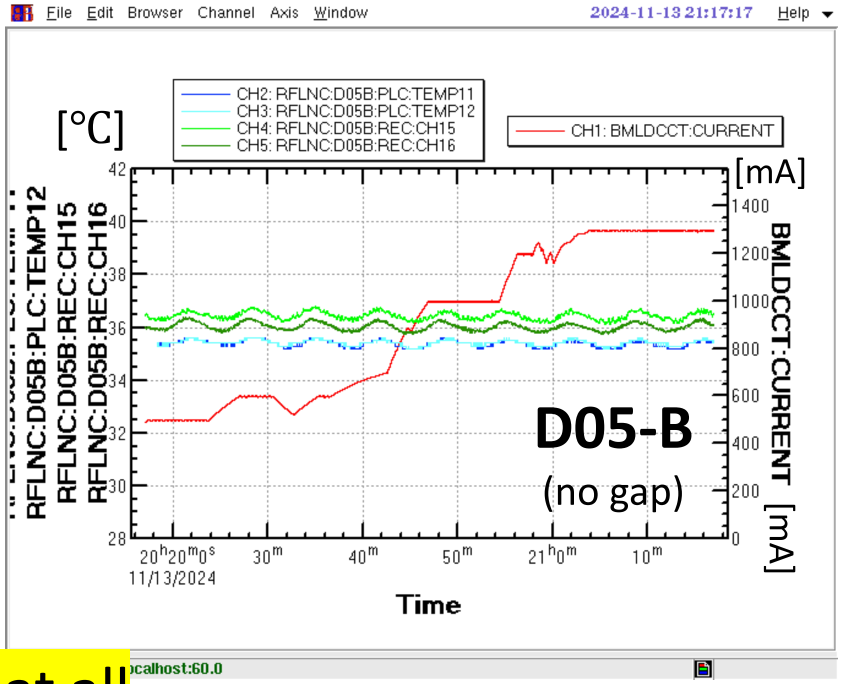
Temperature measurements in 2024c (2/2)

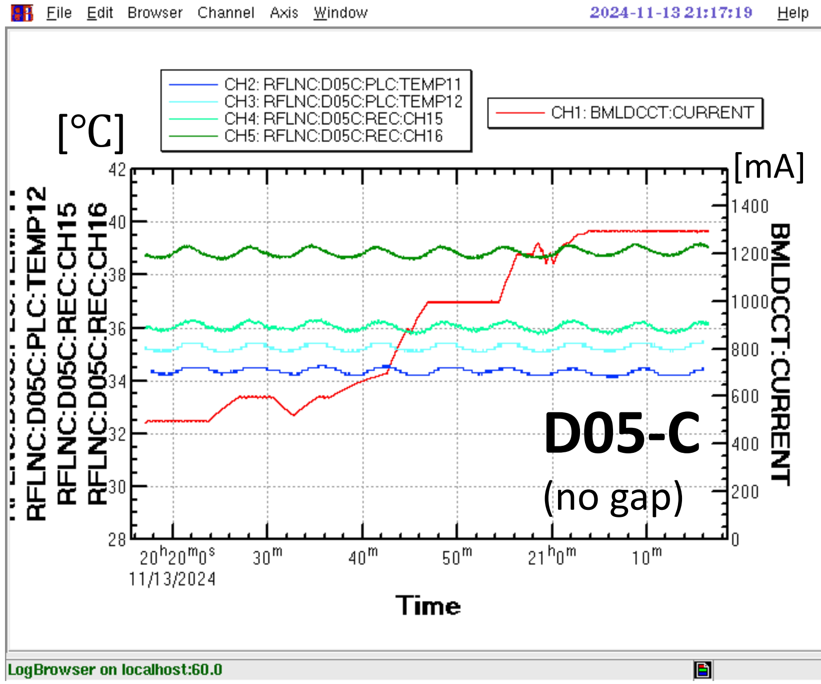
✓ With increasing the LER beam current up to 1.3 A
✓ Input RF power: ~400 kW/cav
✓ Cavity voltage: 0.45 MV/cav



--- Midpoint on the top
--- Midpoint on the bottom
--- Midpoint on the side (downstream of e⁺)
--- Midpoint on the side (upstream of e⁺)
--- LER beam current







- ◆ No beam current dependence at all
- ◆ No anomalous heating found

ARES cavity trip statistics during 2024ab

Station / Cavity	D4-A #1	D4-A #2	D4-C #1	D4-C #2	D4-E #1	D4-F #1	D4-G #1	D4-H #1	D5-A #1	D5-B #1	D5-C #1	D5-D #1	D5-E #1	D5-F #1	D7-A #1	D7-A #2	D7-B #1	D7-B #2	D7-C #1	D7-D #1	D7-E #1	D7-E #2	D8-A #1	D8-A #2	D8-B #1	D8-B #2	D8-C #1	D8-D #1	D8-E #1	D8-E #2	DR Up-stream	DR Down-stream
Area	OHO														FUJI																DR	
As of 2024-02-19: HER operation																																
As of 2024-02-19: LER operation																																
As of 2024-02-19: Operating Vc [MV/cav]	0.43	0.43	0.43	0.43	OFF	OFF	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.40	0.40	0.40	0.40	0.45	0.45	0.40	0.40	0.40	0.40	0.40	0.40	0.45	0.45	0.40	0.40	0.50	0.50
As of 2024-02-19: 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
As of 2024-02-19: 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	New	New
2024/2/5 to 2024/6/30: Reflection only or unknown reason				1													4															
2024/2/5 to 2024/6/30: Vacuum trouble																																
2024/2/5 to 2024/6/30: Arc coupler (not beam loss)																																
2024/2/5 to 2024/6/30: C-damper power or cavity BD							1			2	2	3		1				3		3			1					2	2			
2024/2/5 to 2024/6/30: Tuner trouble																																
2024/2/5 to 2024/6/30: Chiller trouble																													3			
2024/2/5 to 2024/6/30: Other cooling wtr																																
2024/2/5 to 2024/6/30: Others																																
Remarks					Klystron PS trouble		Old D4-C-#1,#2 cav.; Had serious multipacting problem reported in the 10th KEKB Review																									

	D4	D5	D7	D8	DR
Number of trips:	2	8	10	8	0
/cav	0.3	1.3	1.3	1.0	0.0

2024ab

Operation days	146	
# of operated MR cav	28	
Trip Rate (MR)	0.6	[/cav/90days]
Trip Rate (DR)	0.0	[/cav/90days]

Average: 1.34 trips/ring(HER&LER)/week

ARES cavity trip statistics during 2024c

As of 2024-12-27

2024/10/9 to 2024/12/27

Area	OHO													
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
Cavity	#1	#2	#1	#2	#1	#1	#1	#1	#1	#1	#1	#1	#1	#1
HER operation														
LER operation														
Operating Vc [MV/cav]	0.40	0.40	0.40	0.40	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
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
Input Coupler	Used	Used	Used	Used	New	New	New	New	New	New	New	New	New	New
Reflection only or unknown reason														
Vacuum trouble													1	
Arc coupler (not beam loss)														
C-damper power or cavity BD					3	3		1				2	1	1
Tuner trouble														
Chiller trouble														
Other cooling wtr														
Others														
Remarks							Old D4-C-#1,#2 cav.; Had serious multipacting problem reported in the 10th KEKB Review							

Area	FUJI																DR	
Station	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	#2	#1	#2	#1	#2	#1	#1	#1	#2	Up-stream	Down-stream
HER operation																		
LER operation																		
Operating Vc [MV/cav]	0.40	0.40	0.40	0.40	0.45	0.45	0.40	0.40	0.40	0.40	0.40	0.40	0.45	0.45	0.40	0.40	0.50	0.50
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
Input Coupler	Used	Used	Used	Used	New	New	Used	Used	Used	Used	Used	Used	New	New	Used	Used	New	New
Reflection only or unknown reason																		
Vacuum trouble																		
Arc coupler (not beam loss)																		
C-damper power or cavity BD						1	1											
Tuner trouble																		
Chiller trouble																		
Other cooling wtr																		
Others																		
Remarks																		

	D4 (OHO)	D5 (OHO)	D7 (FUJI)	D8 (FUJI)	DR
Number of trips:	7	5	2	0	0
/cav	0.9	0.8	0.3	0.0	0.0

2024c

Operation days	79	
# of operated MR cav	30	
Trip Rate (MR)	0.5	[/cav/90days]
Trip Rate (DR)	0.0	[/cav/90days]

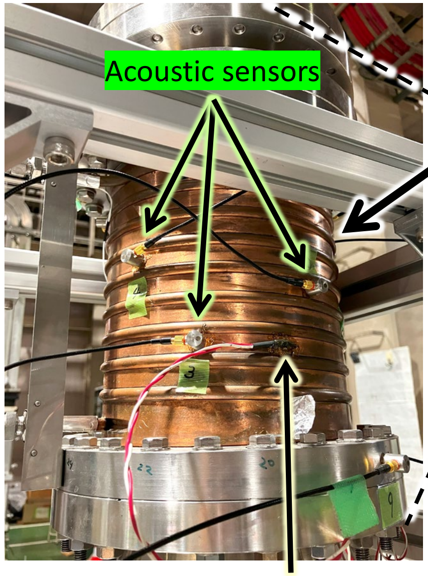
Average: 1.24 trips/ring(HER&LER)/week

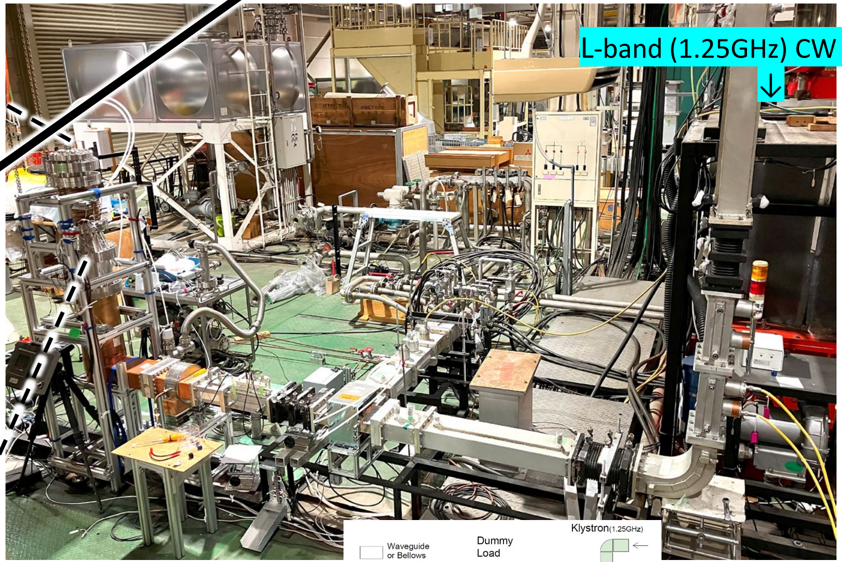
- ✓ The average cavity trip rate is almost the same as before.
- ✓ The cavity trips are distributed among many cavities, not concentrated in a few cavities.
- ✓ The D05-A cavity has never tripped during 2024ab+c after the cavity replacement in LS1.

R23.2: Repair the klystron test stand to allow resumption of off-line testing.

- The broken klystron power supply for the test stands will be repaired next fiscal year in 2025.
  - The repair cost is estimated to be ~50 million JPY (≈ 0.3 million USD).
- This power supply can drive one of the two klystrons for D1-CT, D1-AT

Limit performance test of SiC HOM duct @ D1-CT





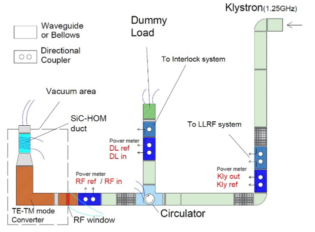
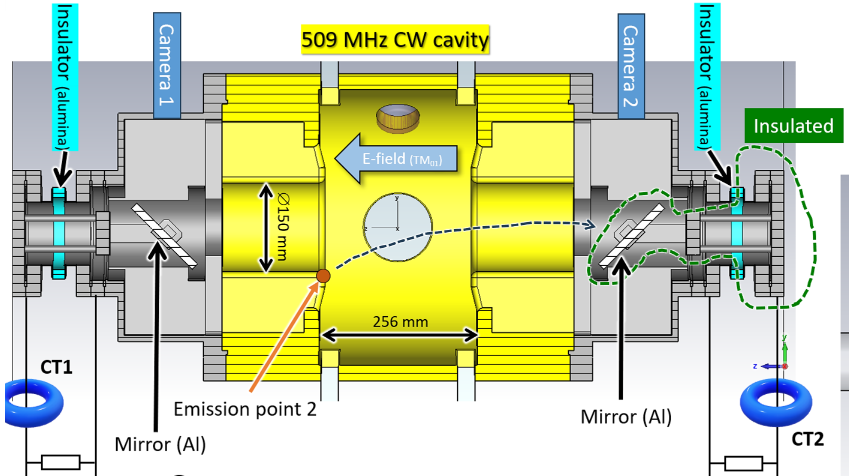
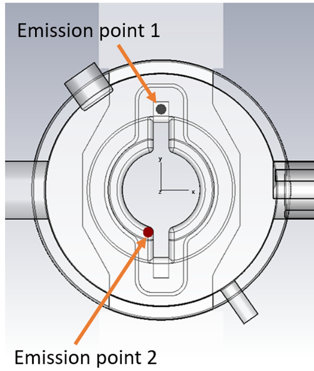


Figure 4: Schematic view of the high power test setup in D1-CT for the SiC-HOM duct.

RF cavity breakdown study @ D1-AT



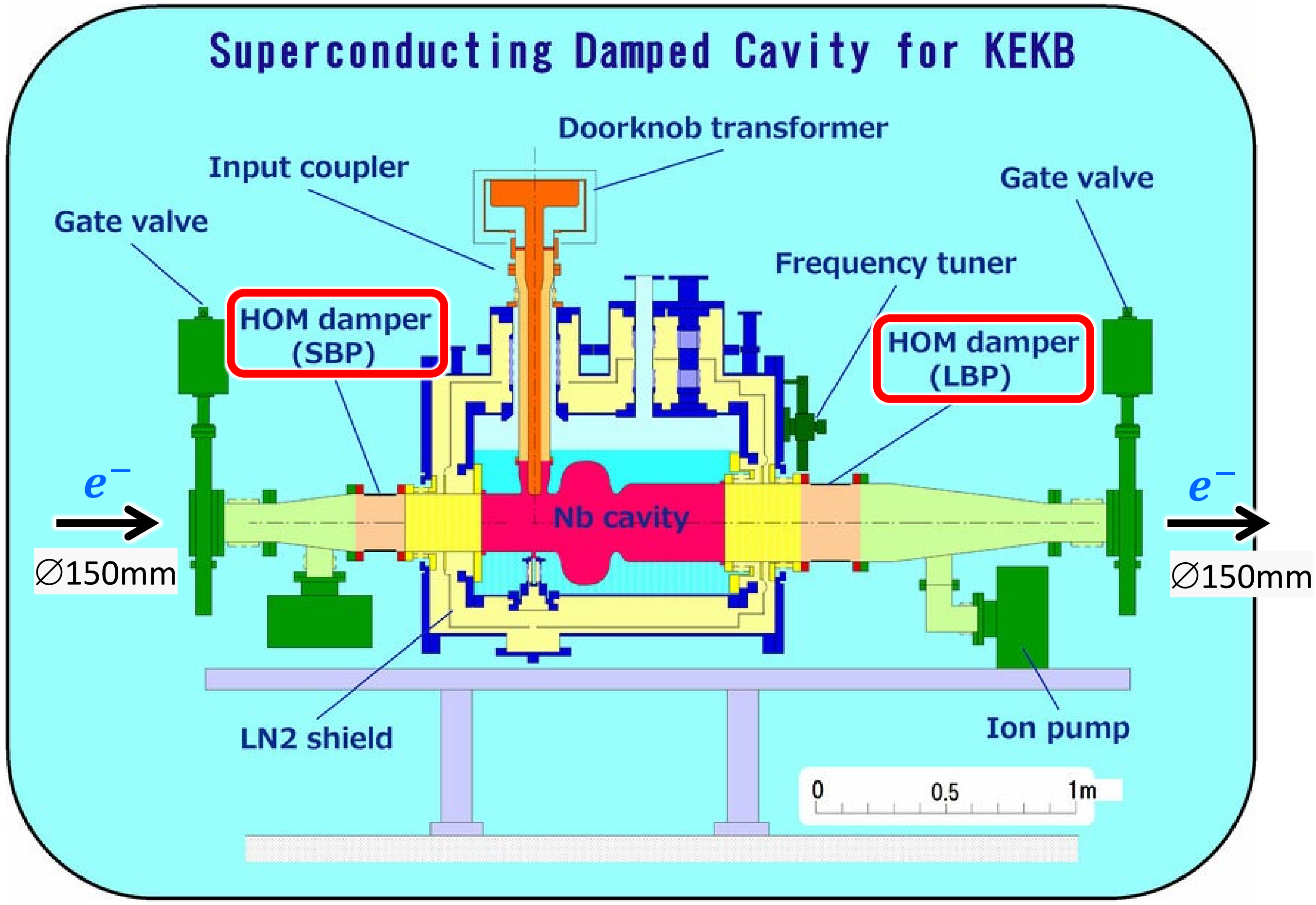
Suggests huge currents (peak) (> 100A!?)



① Assuming "(light emission point) = (e^- emission point)"
② In this case, Camera 2 can identify the emission point.
③ Percentage of e^- reaching the mirror to be estimated with PIC sim.

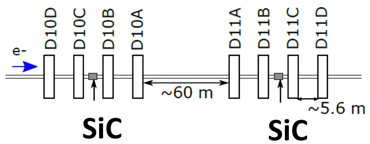
Super-Conducting Cavities (SCCs)

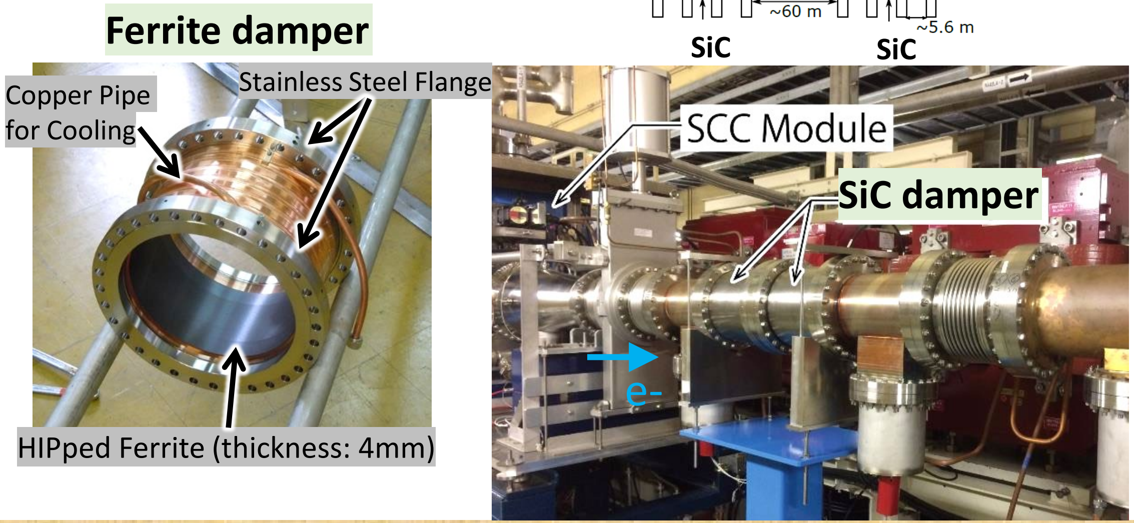
Super-Conducting Cavities (SCCs)



∅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





SCC operation summary in 2024ab+c

- The 8 SCCs have been operating stably.
- V_c : 1.35 MV/cav or 1.60 MV/cav (to compensate the parked ARES cavities in 2024ab)
- Beam aborts due to the SCC system in 2024ab+c (233 days)
  - Cavity Breakdown : 8
  - Piezo Tuner Trouble : 5
  - Peripheral : 3

Piezo Tuner Trouble

- Sudden breakdown occurred without any warning signs such as an increase in leakage current in 3 piezo actuators.
- The cause is currently unknown. But they were all produced in 2018, the oldest set we have.
- Possible deterioration in the insulation performance over time
- We are trying to prepare more spares.

Update on the cooling capacity for the HOM dampers

- New cooling method using cooling water for the magnet system has been tested for one of two SiC dampers in 2024c.
  - ➔ Found enough cooling capacity and the ~30degC temperature was maintained.
  - ➔ No problems were observed in 2024c operation.
- We will apply this cooling method to other SiC dampers for higher HER beam currents in the future.
- For higher HER currents than 2.0 A, it is necessary to update all the chillers and add more SiC dampers (during LS2?).
- Further R&D and measures are needed against higher HOM powers.

Klystron

Klystron

[Troubles during 2024ab+c]

・E3786 T54 (D04-A）replaced due to deterioration in the voltage resistance @ 5/13
Spot-knocking did not fix the problem. → Plan to upgrade it to higher specifications of E3732 to improve the reliability.
Upgrading to E3732: Replacement of electron gun/first cavity, output window, and ion pumps.

・E3732 T22B (D04-E) replaced due to vacuum deterioration at startup and HV aging effect not lasting @8/22
Although the location of the vacuum leak could not be identified, testing will be carried out at a test station to determine whether the device is usable or not.
Usability criteria: The effect of HV aging can be maintained for more than two weeks.
＊ Currently, we are using three klystrons with a history of vacuum leak, where 0.5 to 3 days of HV aging required.

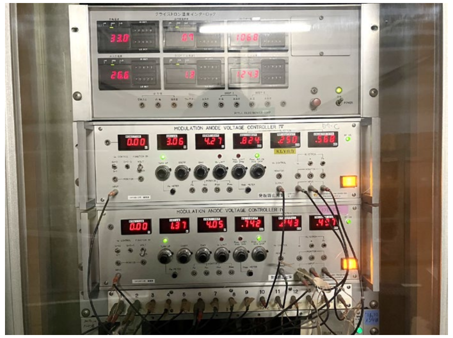
[Responding to 27th Recommendations]

・**R24.1: Test at least one of the spare klystrons to make sure there is always a ready replacement in case of failure during the run.**
➔The spare klystron (T20A, stored for 10 years) was tested last year. HV aging took one day.
The other spare klystron (T25A, stored for 14 years) will be tested this year.

・**R24.2: Closely monitor the klystron inventory for any further signs of aging**
➔There are currently four spare klystrons, but one more will be added in July.
If the T54 can be upgraded, six spare klystrons will be sufficient.
Gun Perveance is being monitored for signs of deterioration, but there has been no change under current operating conditions (Po<500kW).
The cathode efficiency of the T27 (operating for 130,000 hours) will be measured to check whether emissions have decreased or not.

Klystron Anode Voltage (V_A) Controller

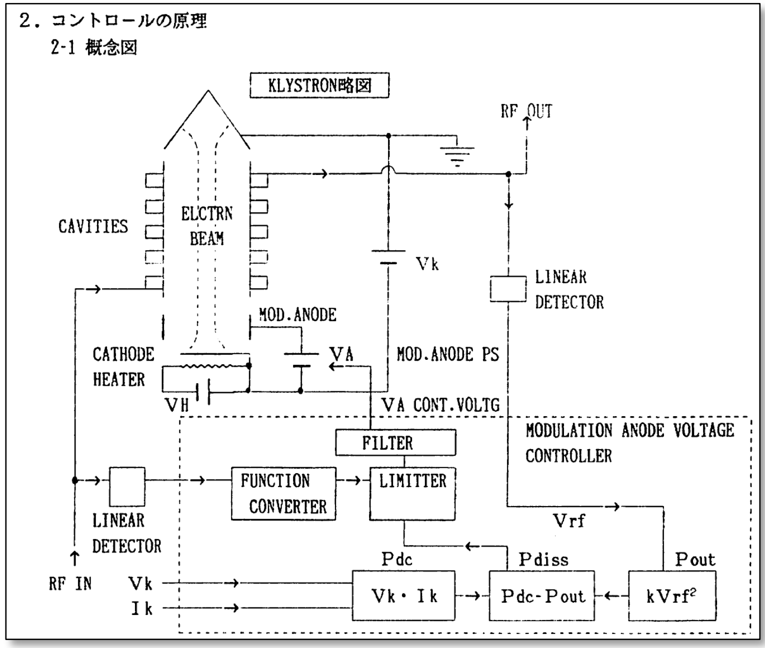
The current anode controllers are very old, developed in 1970's.



Consists of only analog circuits with:

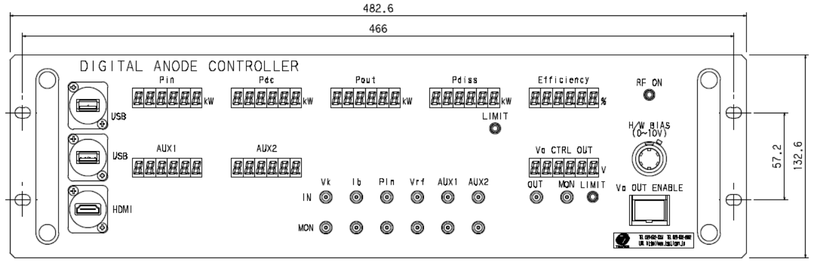
- **No flexibility** for control method
  - Precise control to improve power efficiency can't be implemented.
- **No remote control**
  - Adjustments must be made on-site and too complex. (the controller is in each of the 38 RF stations.)
- **Difficulty in future maintenance**
  - End of production of some parts
  - Redesigning with alternative parts is costly.

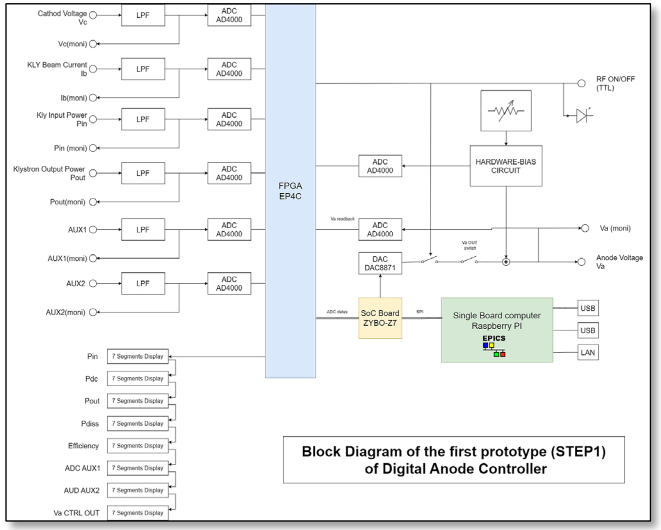
⇒Development of the new Klystron Anode Controller.



New Klystron Anode Voltage Controller
(*Digital* control)

First prototype production is underway this FY.





- **EPICS based remote control**
  - ➢Much easier adjustment works
  - ➢Labor-saving
- **Flexible control with FPGA**
  - Initially, the current control method will be followed.
  - More sophisticated and efficient control is to be developed and implemented. (for improving power efficiency and reducing operational costs.)

R24.4: Continue to seek energy savings such as modulation anode automated control, and remote adjustment of klystron voltages. Study which amounts of energy could be saved, and estimate the effort and time scale to implement the more sophisticated control.

~90kW/klystron saving expected for ~500kW output from klystron
➔ ~2.7MW saving in the MR (⟺ ~27 million JPY saving /month)
(Cf. The 30 digital anode controllers cost ~30 million JFY.)

High-Power RF

R24.3: Continue anti-aging maintenance and updates of RF stations to preserve reliability.

Measures against the aging facilities

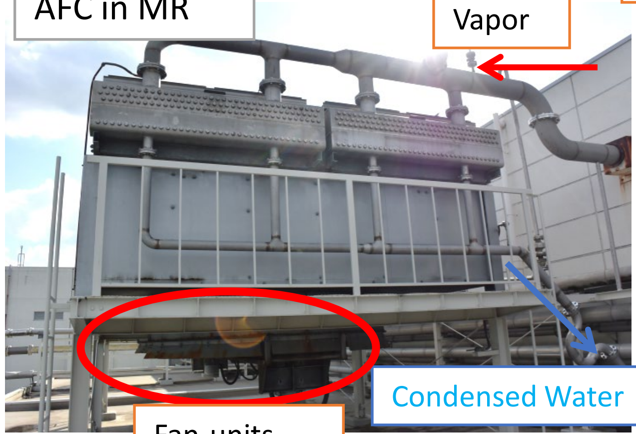
- Klystron cooling system:

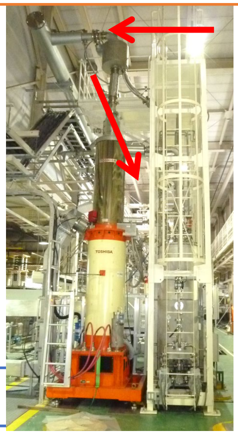
Renovation work is underway for the air-cooling towers used in the vapor cooling system.
The entire renovation in the MR will be completed within several years, so that we will be able to use them for additional 20 years.

The main work will be the renewal of the aging fan-hoods and beam for mounting cooling fans. (One unit will be completed by Mar. 2025).
The remaining 5 units for the MR will be renovated in stages over a period of 4-5 years.
In addition, the renewal of the air-cooled fan drive system (fan-motor and inverter) is expected to be completed in 1-2 years.

- **Waveguide system**:

It is working smoothly without any trouble.





LLRF

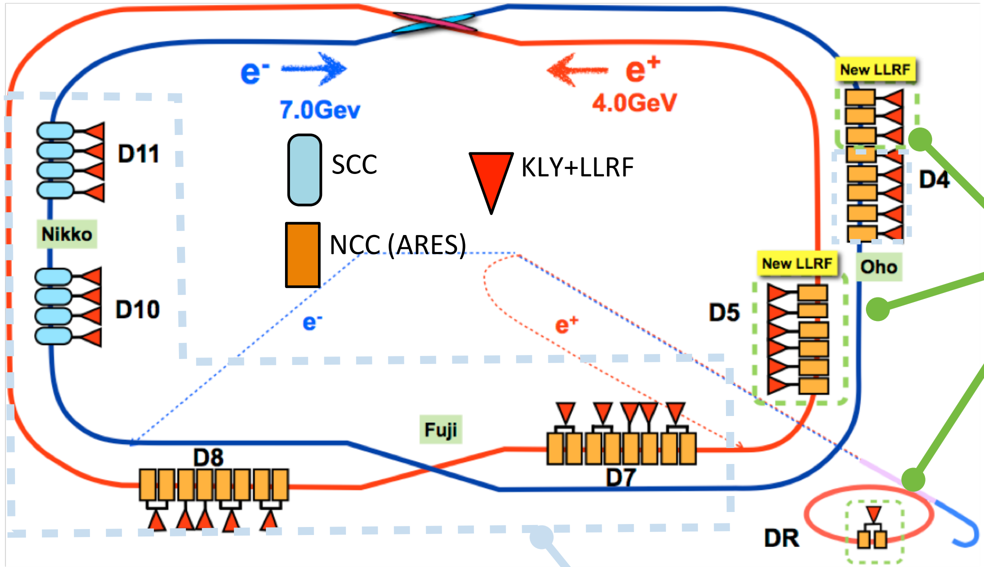
Operation Status of LLRF Control System

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

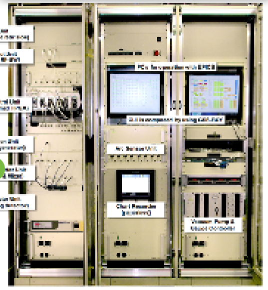
MTCA-based Digital LLRF Systems,
which was developed for SuperKEKB,
are applied to **10 RF-stations** for ARES & DR.

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

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.
(The most devices are discontinued, and the spares are not enough.)
Even the digital systems with FPGAs&linux, developed in 2012, are becoming out-of-dateness.

Upgrade of the old analog systems to new digital ones is required, but it is difficult due to the insufficient budget and time.

Cryogenics

Recommendations:

- **R22.1: Apply for funding to upgrade the control system.**

→Yes. We have an estimation for the upgrade. It's about 100 million JPY (≈ 0.6 million USD).

- **R22.2: Develop a contingency plan as to how one could act should the 35-year-old cryogenics**

→ Equipment maintenance is performed every year according to a schedule. All the equipment has spares or can be purchased soon. Time required to recover from serious damage or failure is estimated to be within a few weeks.

- **R22.3: Consider possible energy savings by improving controls or reconfiguring the plant.**

→ Shutting down some compressors can reduce power consumption (rated ~2.9MW→~2.3MW), but that requires additional liquid nitrogen, which is costly (more money needed to run it).

Summary

- **The RF system has been working well so far for < 2.0 A.**

- **In the next operation of 2025c**
  - Higher beam currents expected for higher luminosities
  - First experience with > 2.0 A

- **Beam current limiting factors**
  - Power capability of the HOM dampers for SCC (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 (~2.5 A? in LER)
    - The limit performance test to be resumed

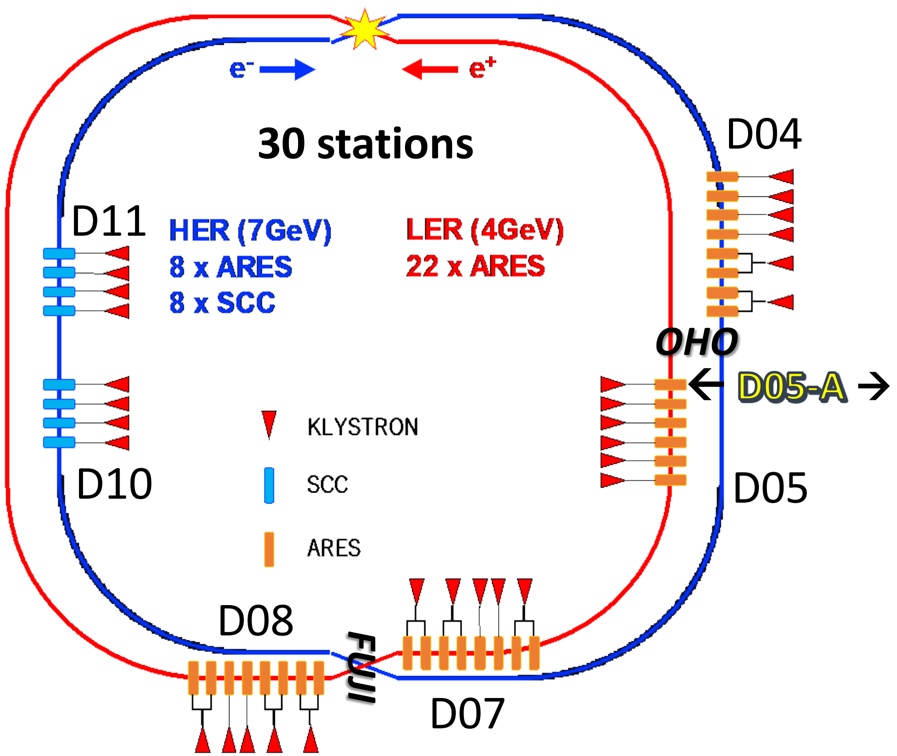
Thank you for your attention

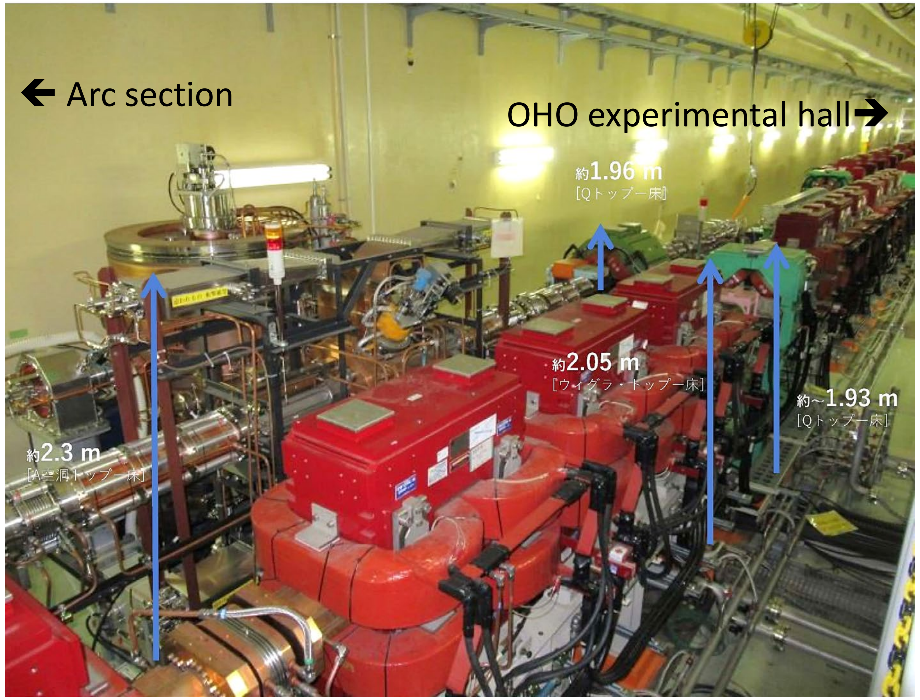
Backup slides

BACK

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

Reported to the 27th KEKB Accelerator Review Committee, 2024

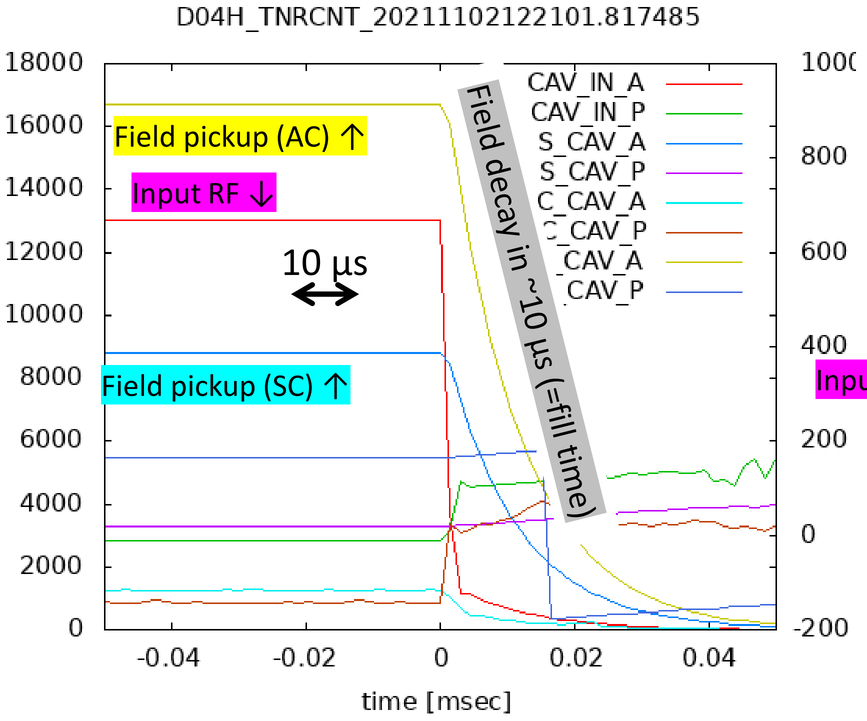




Unusual Breakdown Problem on the D05-A Cavity

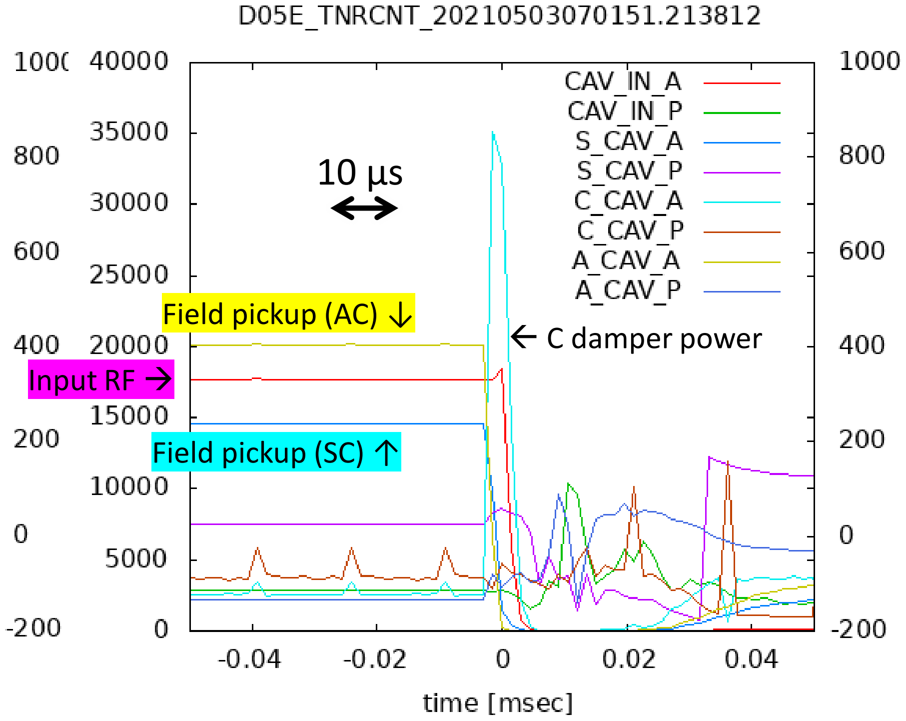
BACK

RF switch manually turned off



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

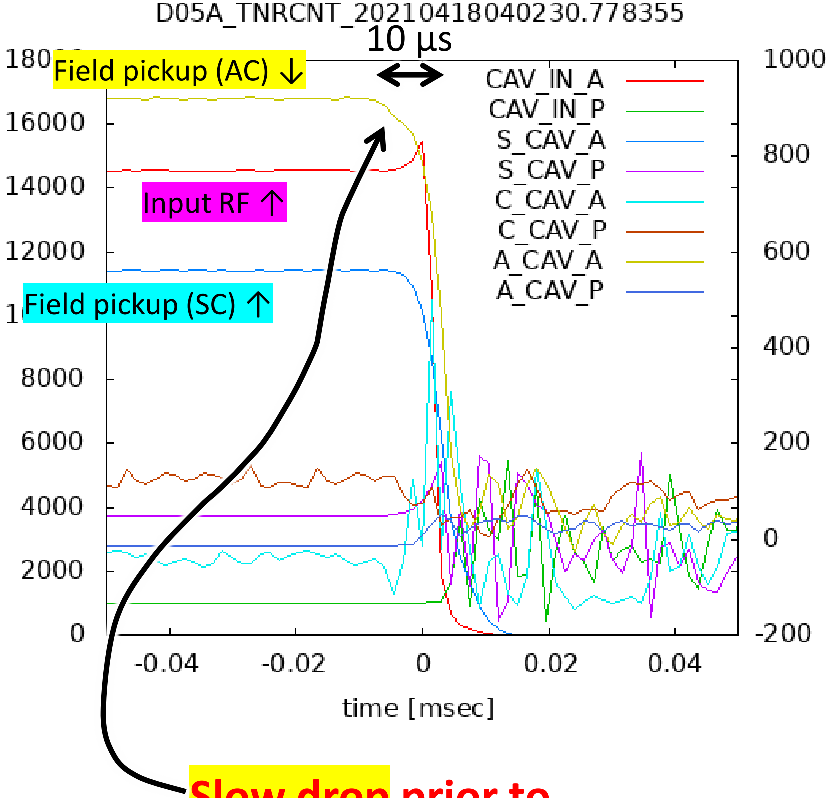
Usual cavity breakdown



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↓

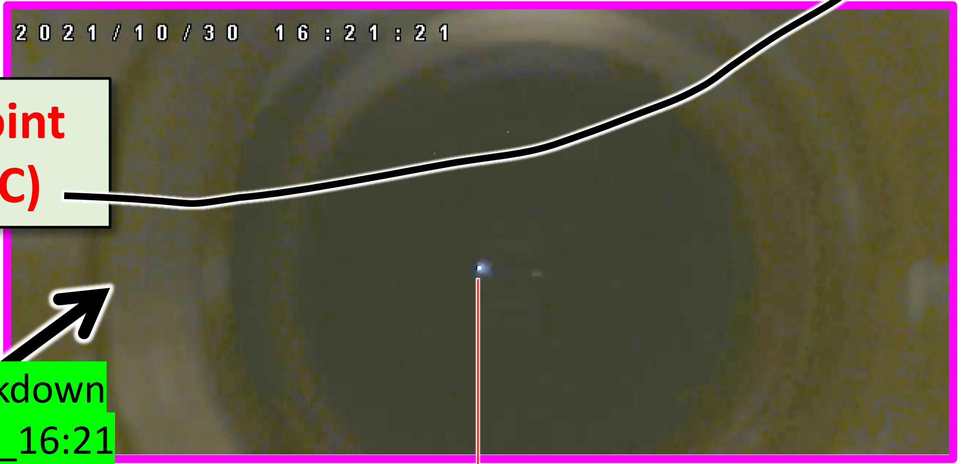
[T. Abe, *et al.*, "*Direct Observation of Breakdown Trigger Seeds in a Normal-Conducting RF Accelerating Cavity*", Physical Review Accelerators and Beams **21**, 122002, 2018.](#)

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

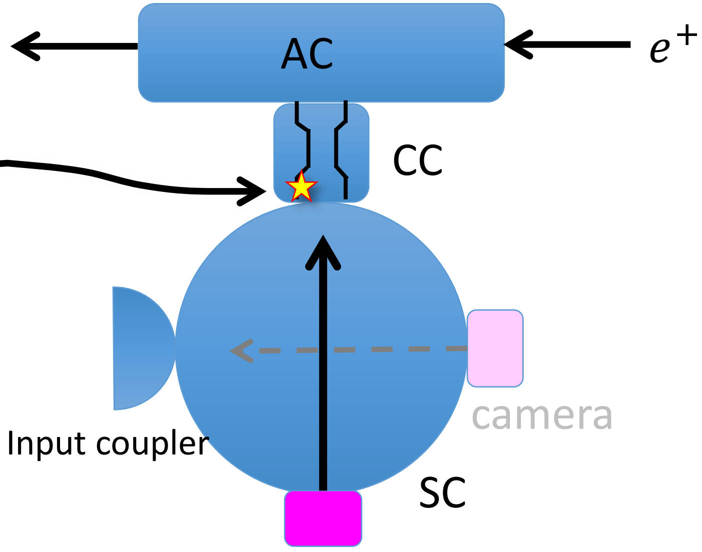
BACK

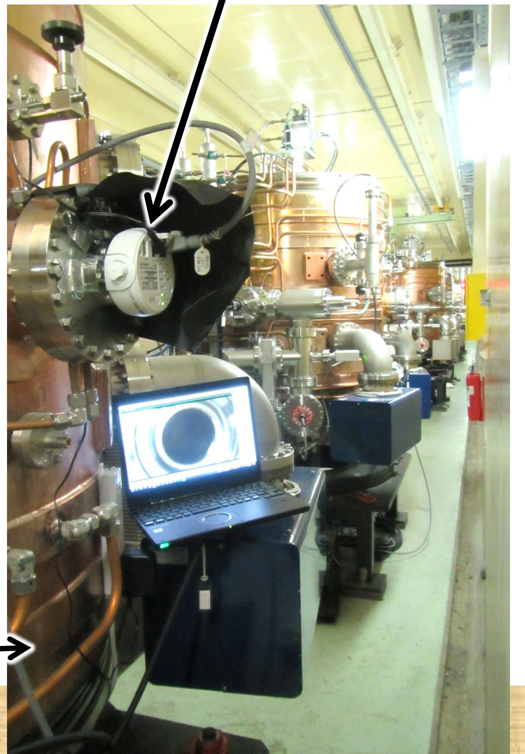
- ✓ **All the light emission at the same point**
- ✓ **Vacuum arc in the coupling cavity (CC)**

Unusual breakdown at 2021-10-30_16:21



During stable high-power operation with 340 kW input

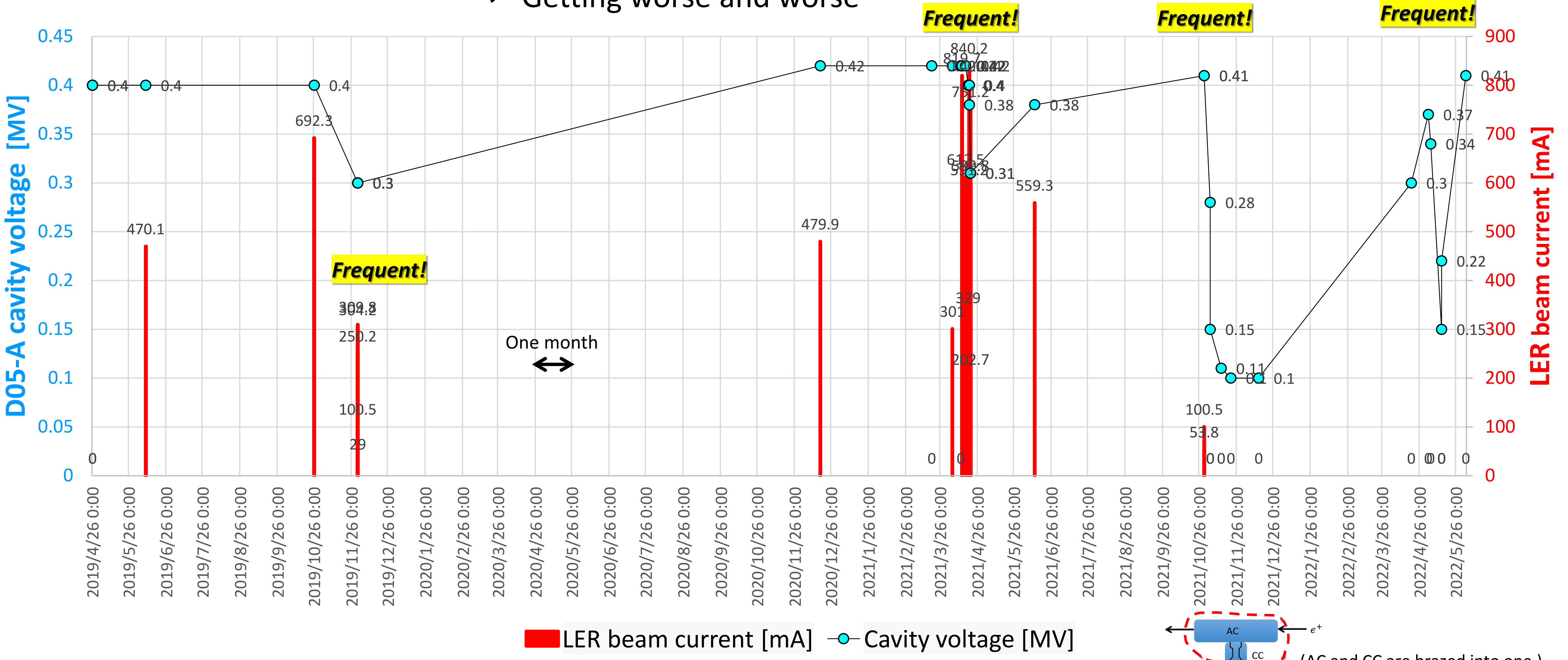


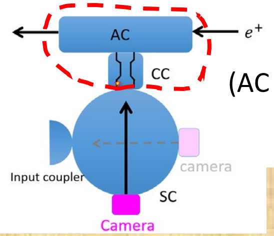


SC

History of the D05-A unusual breakdowns

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





(AC and CC are brazed into one.)

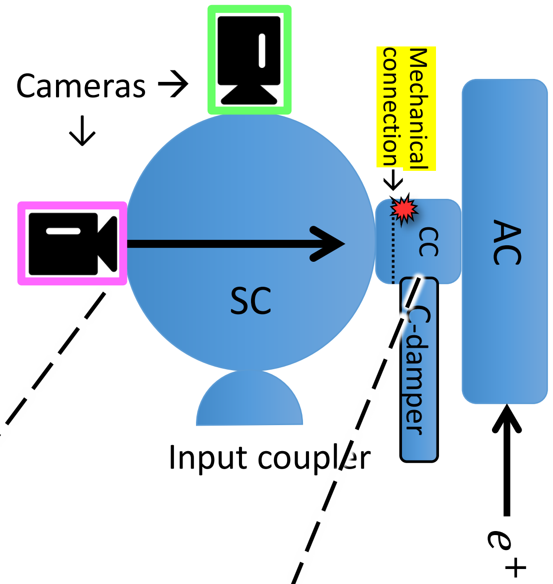
➔ Decided to replace the D05-A cavity (CC+AC)

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

on 2022-09-28

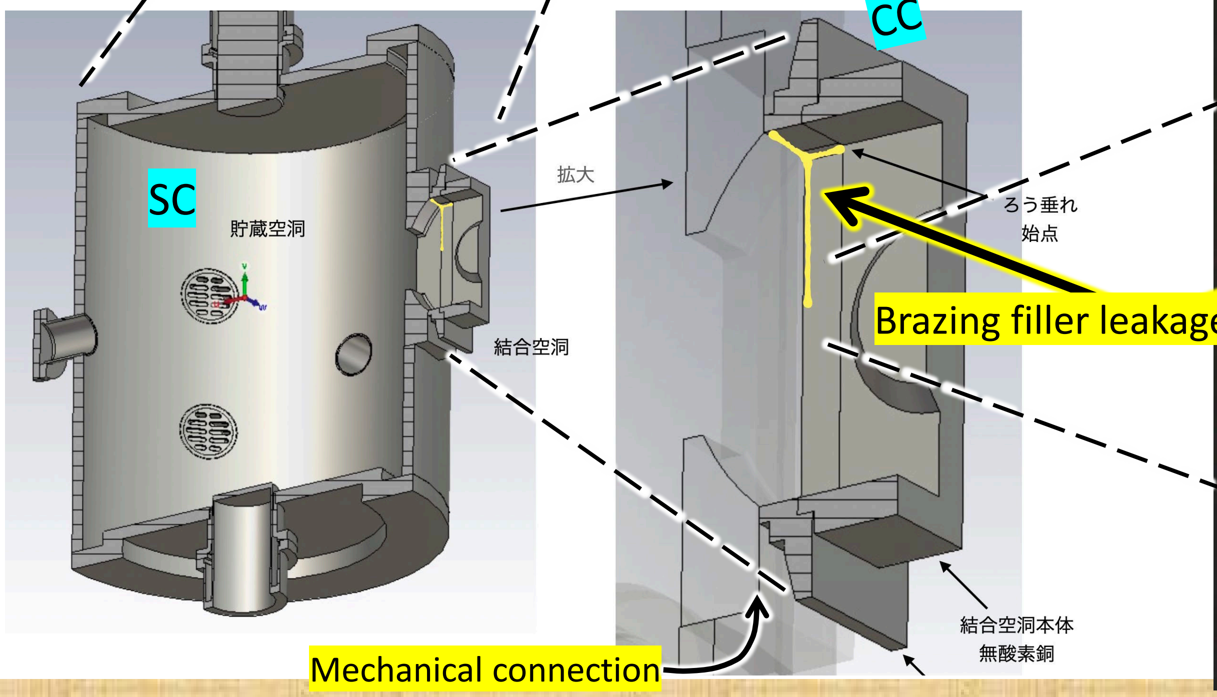
BACK

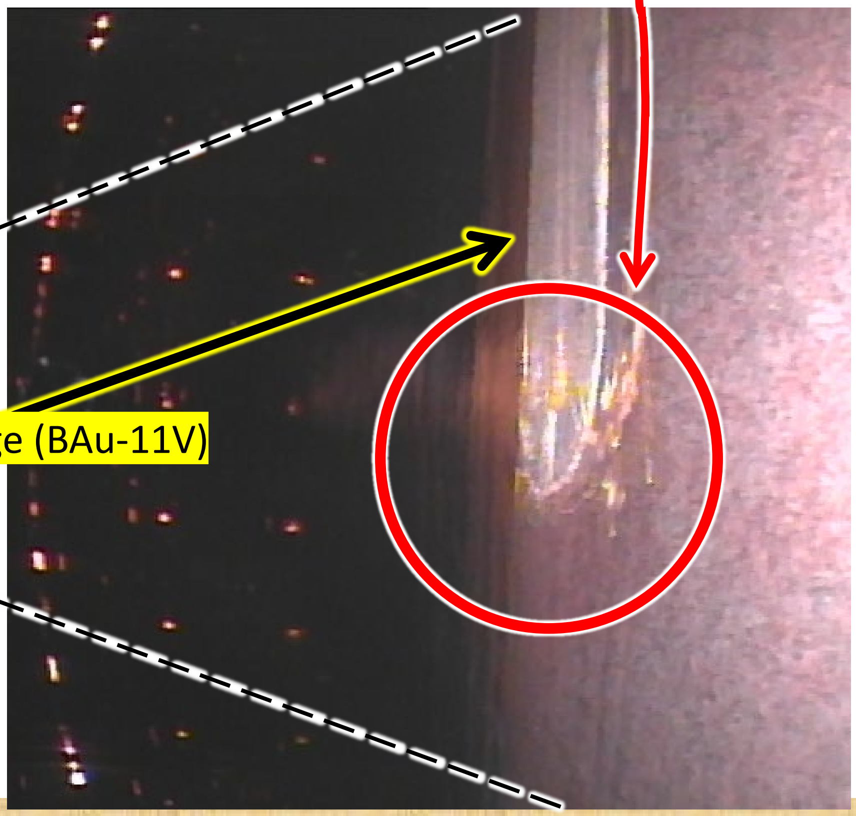
Light emission at the unusual breakdown



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

(3D figure made by T. Kageyama)

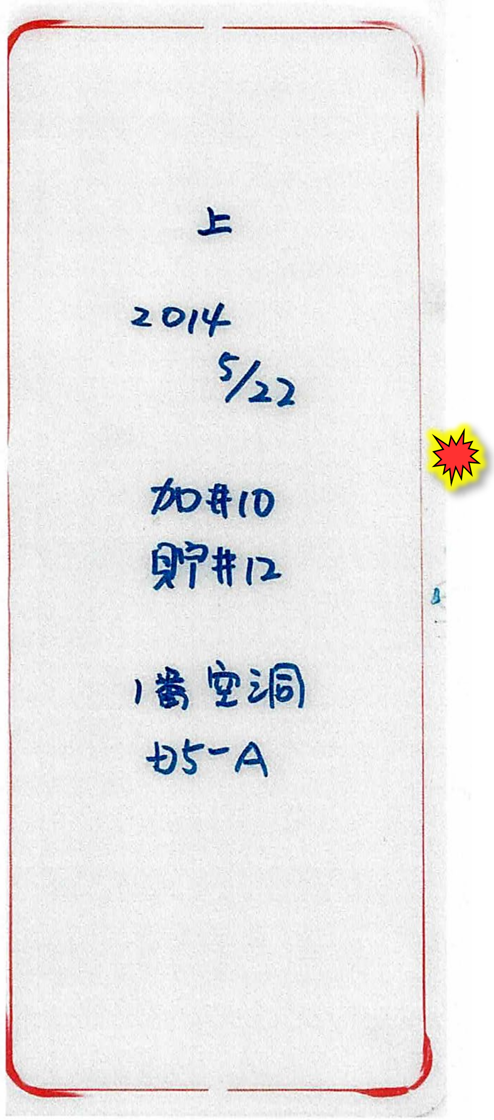


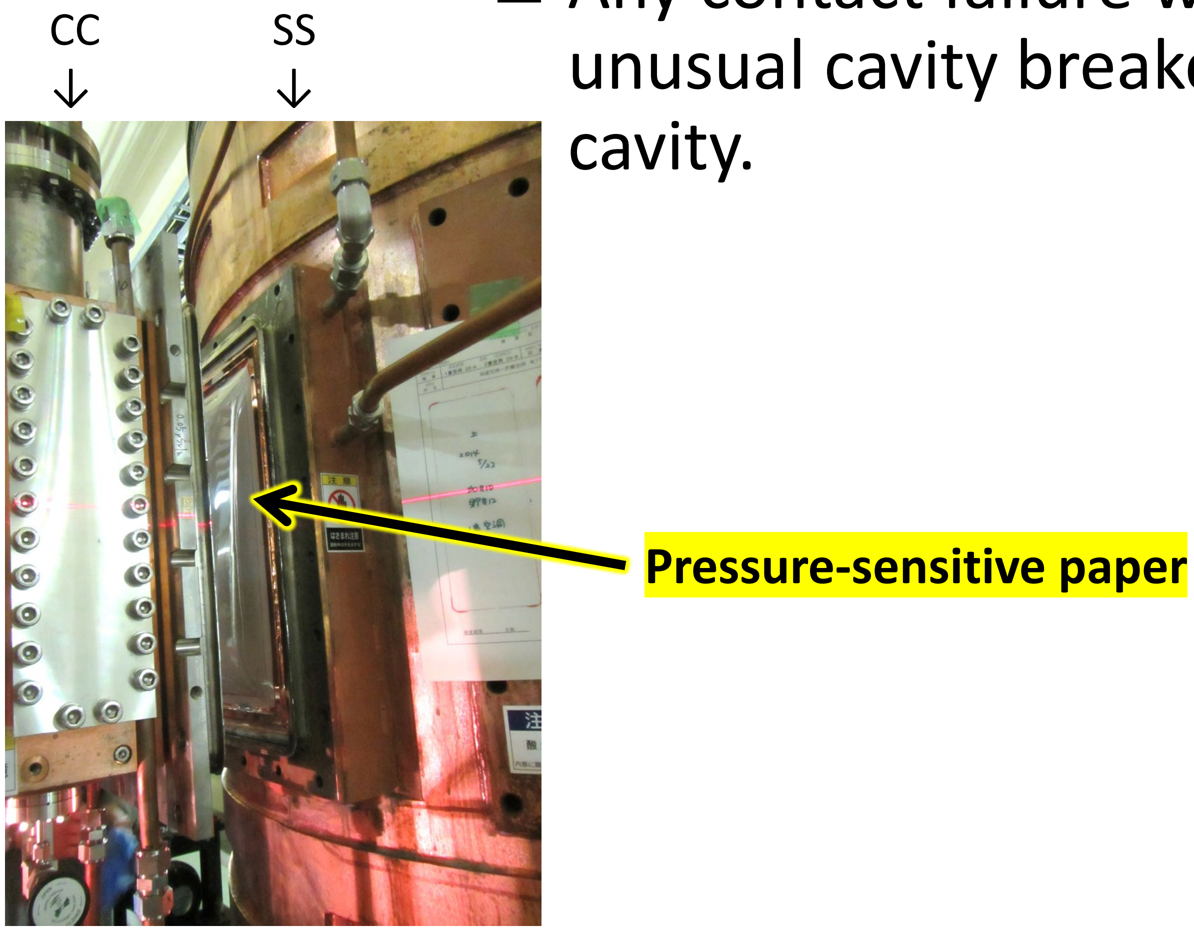


Check of the RF contact in the connection between SC and CC using pressure-sensitive paper

BACK

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





- 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

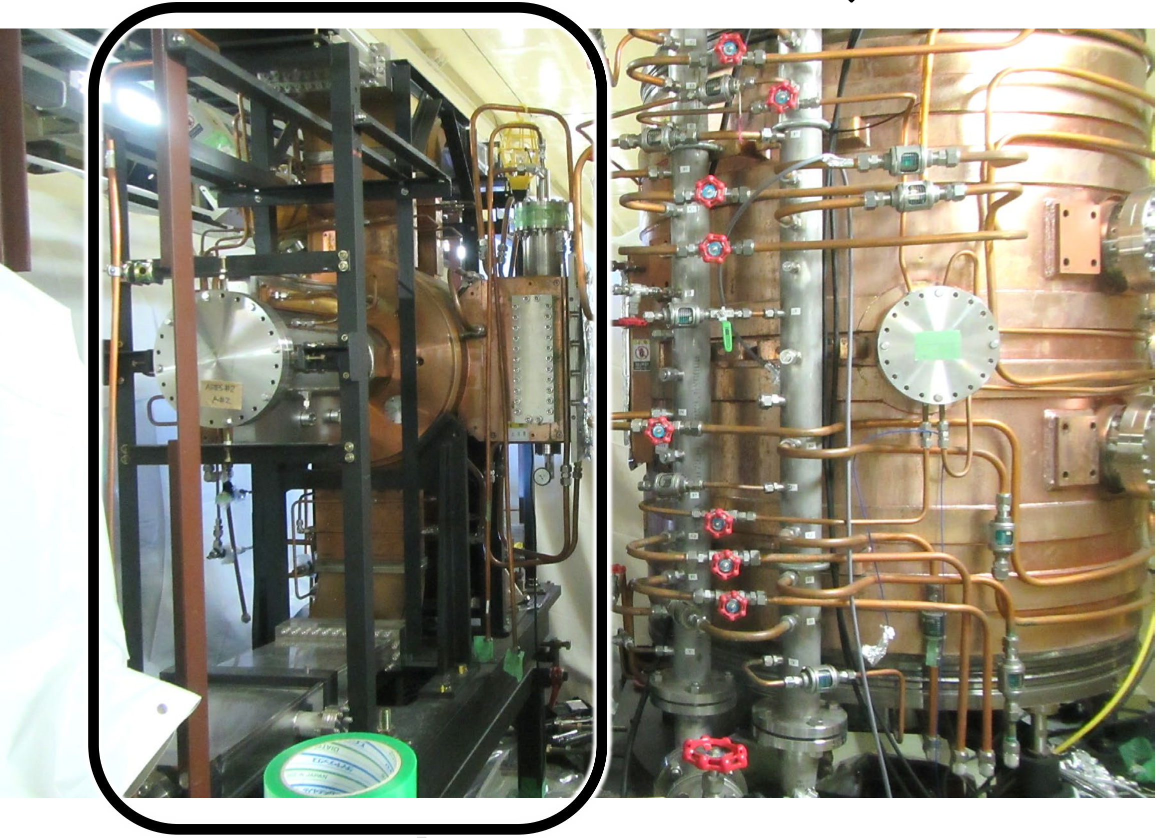
BACK

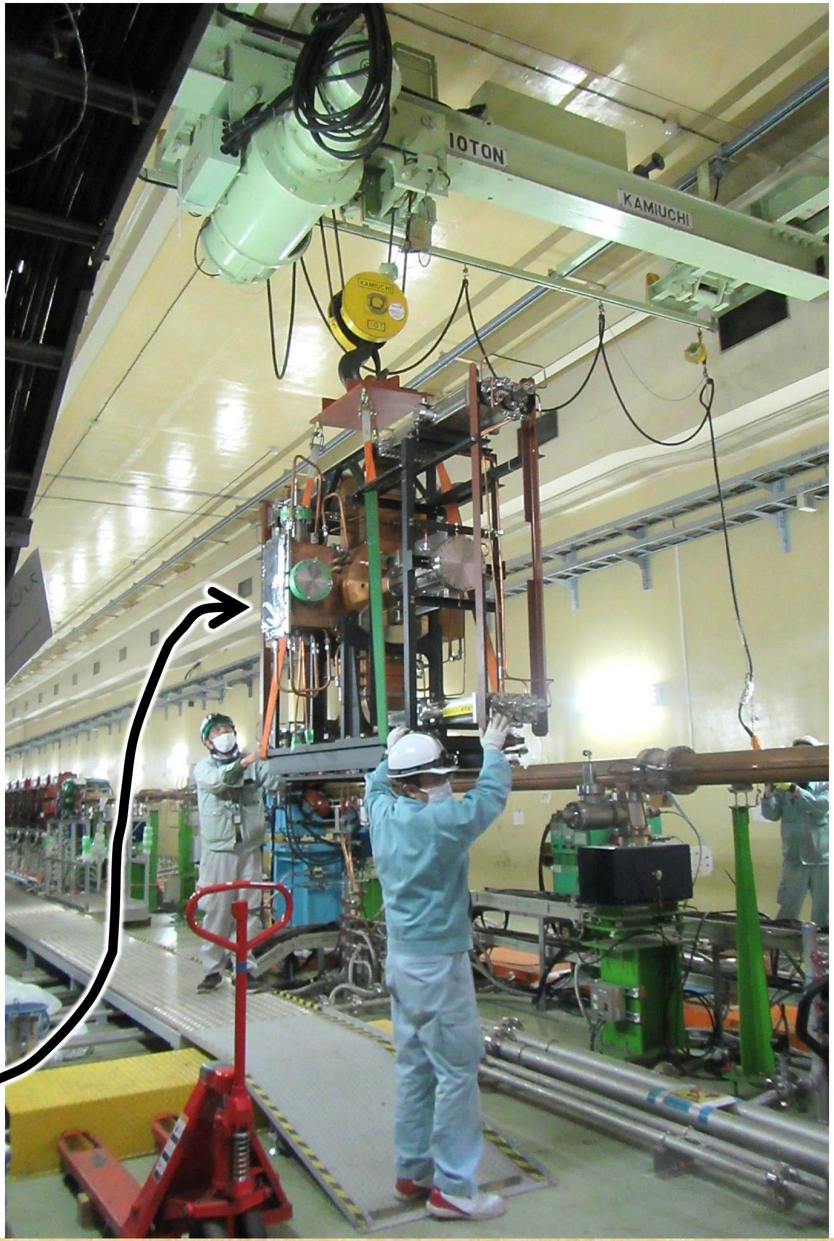
2023-01-20

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

AC+CC ↓

SC ↓





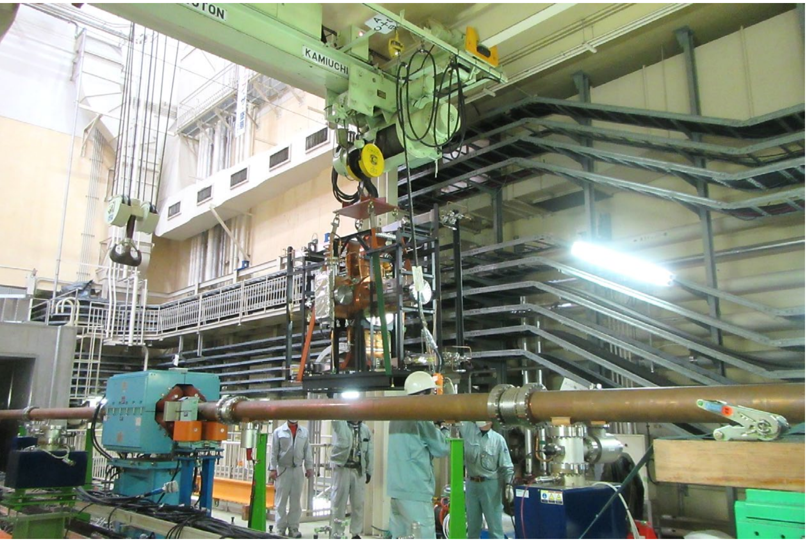
2023-01-25

BACK

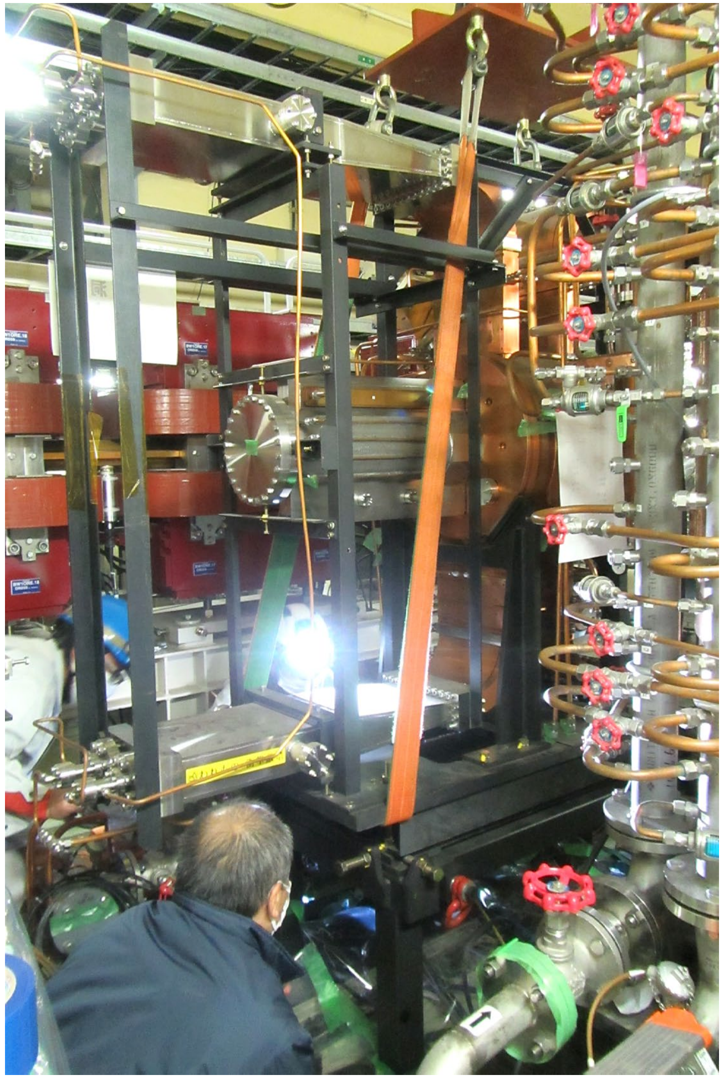
Moving the spare cavity into the D05-A station in the D05 straight section

BACK

2023-01-26

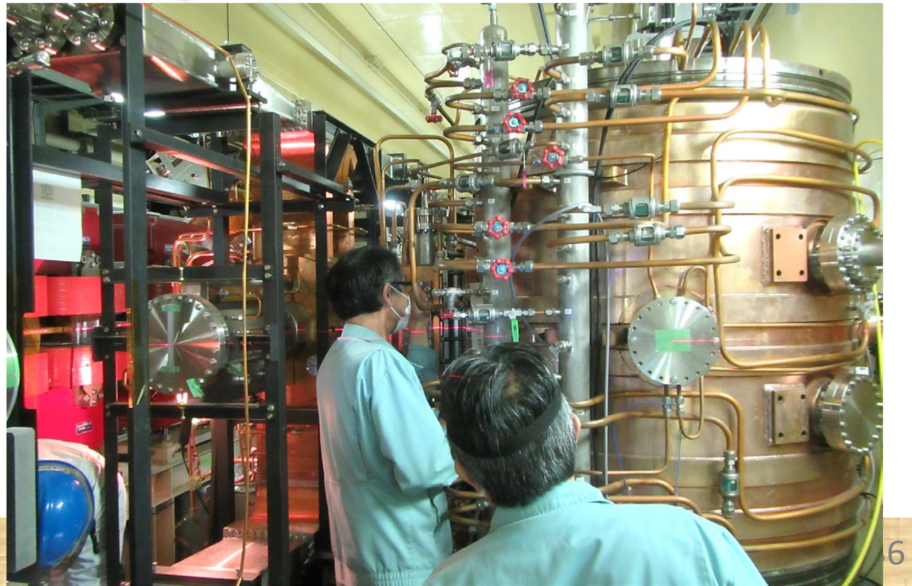


Tiny clearance!



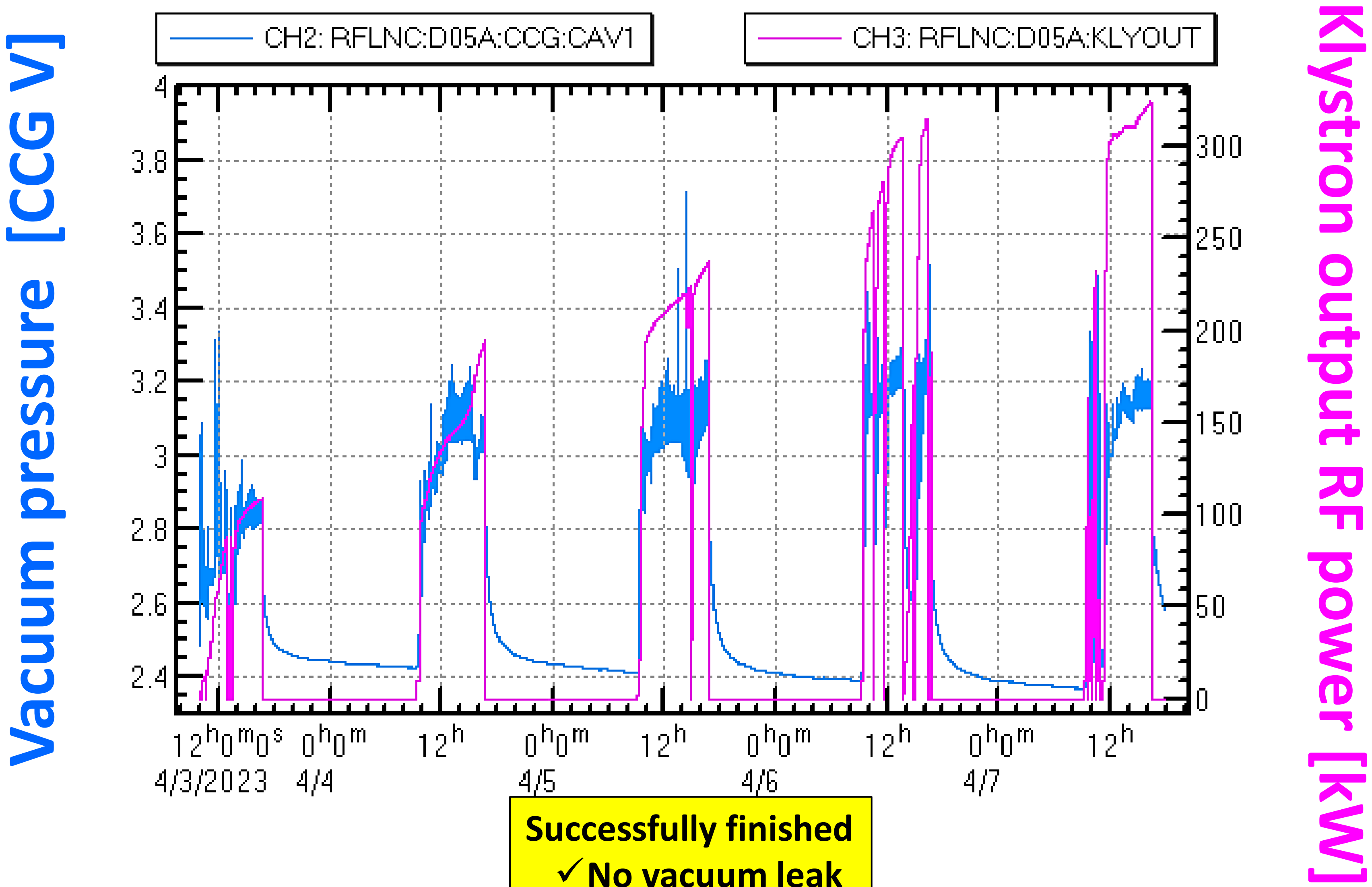
Landing in the D05-A

Alignment



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

BACK

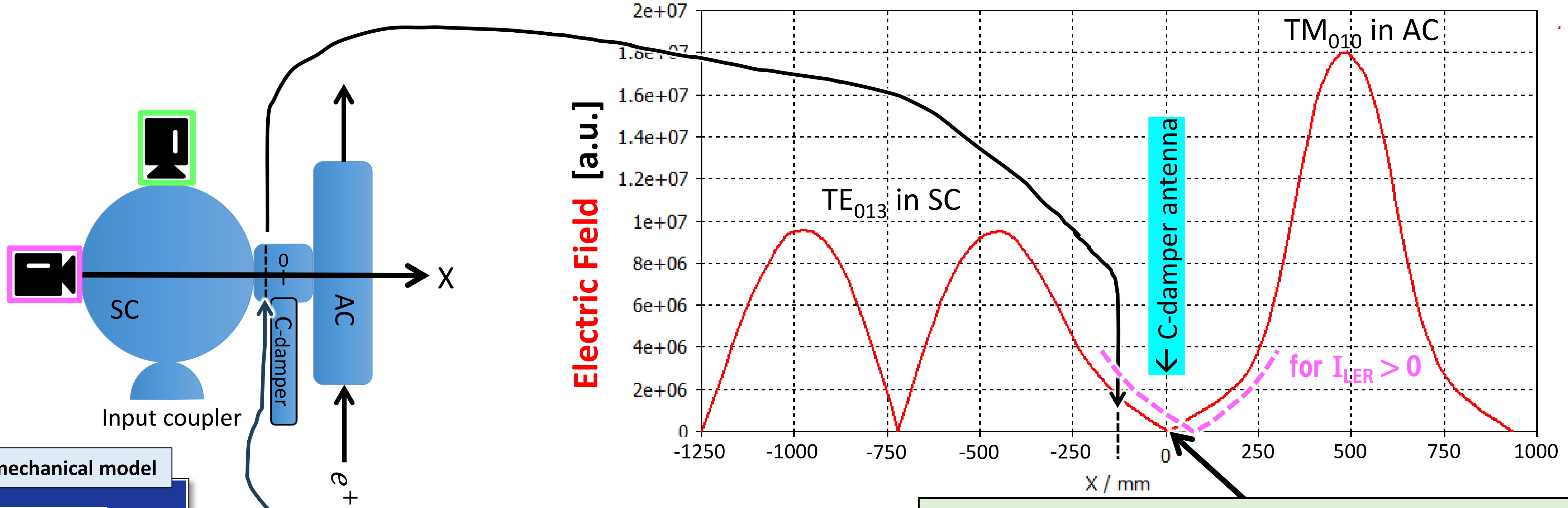


Successfully finished
- ✓No vacuum leak
- ✓No vacuum arc

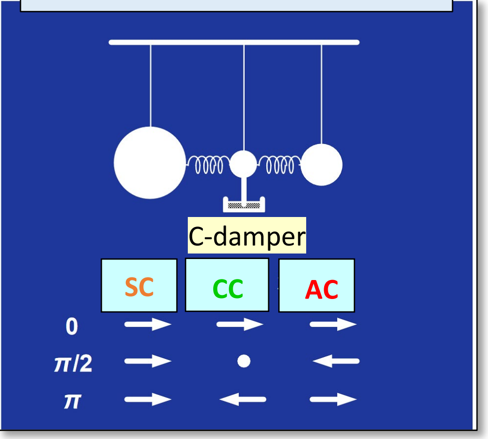
ARES three-cavity system

BACK

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.)

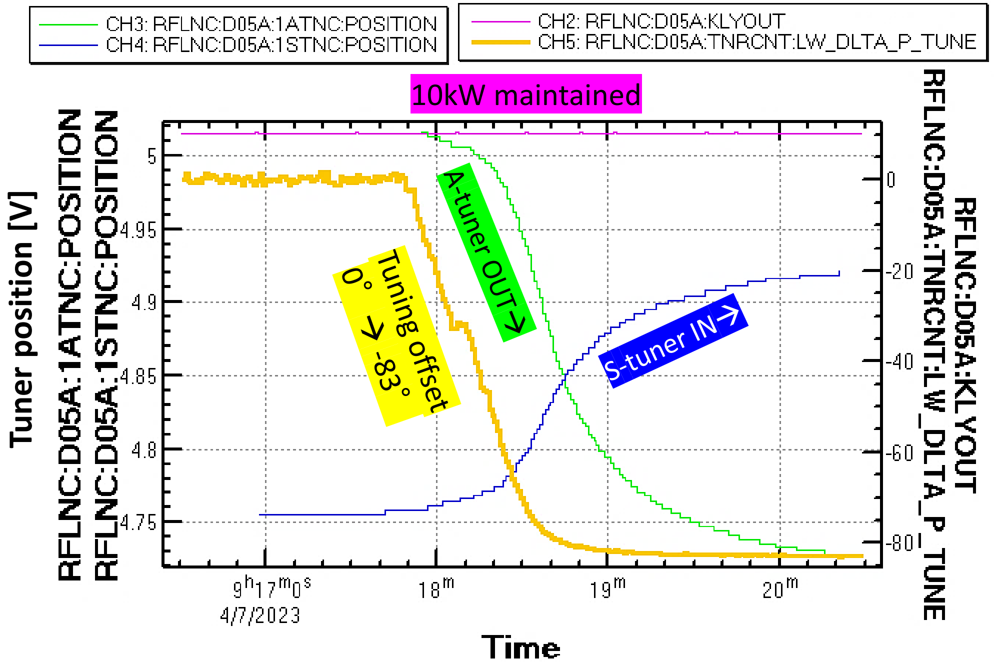
(The surface field at the connection between SC and CC) ∝ (square of the C-damper power)

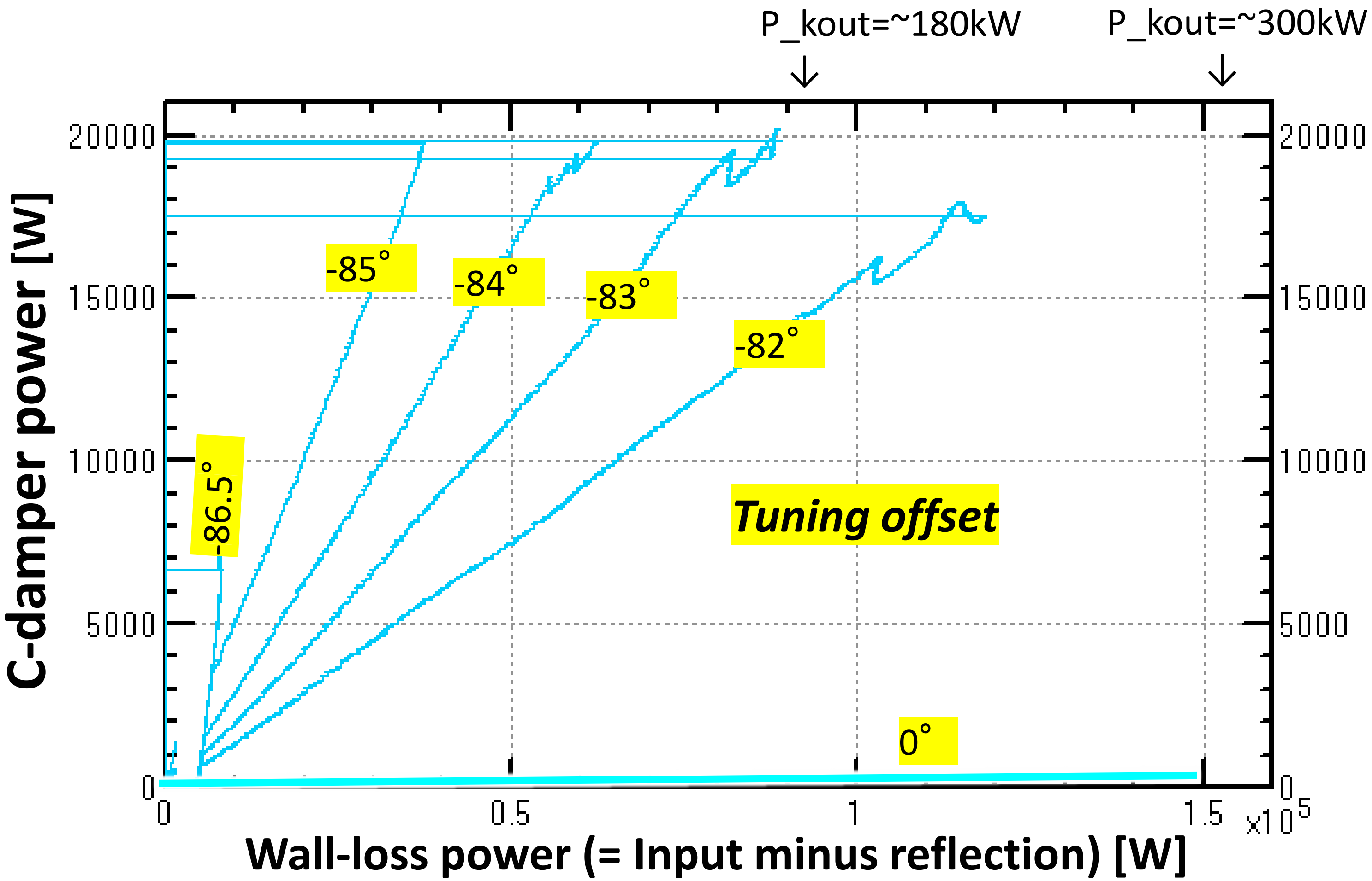
D05-A high-power test with a large tuning offset

BACK

2023-04-07

<u>20 kW C-damper power</u> corresponds to beam loading with LER 3.6 A

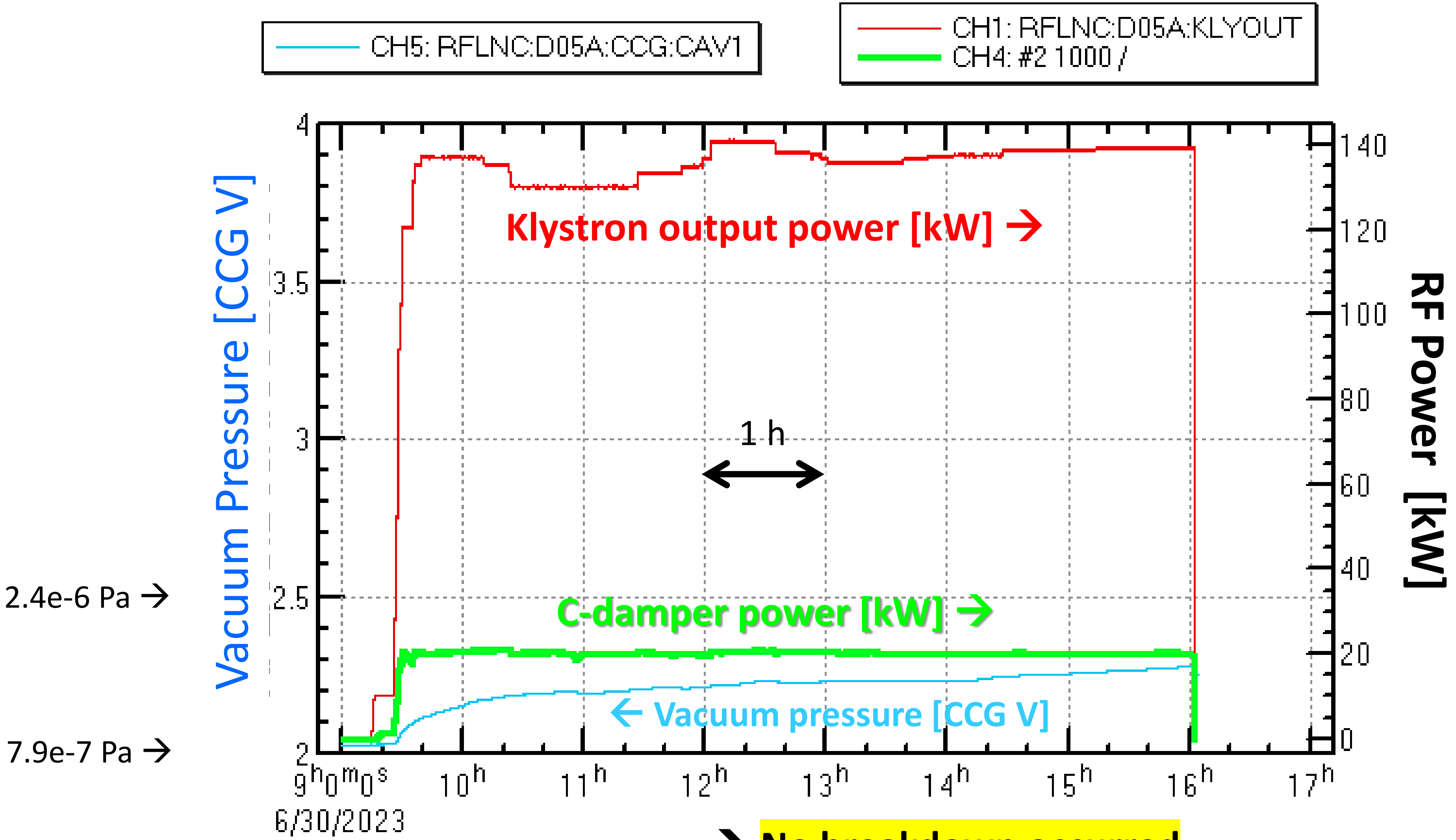


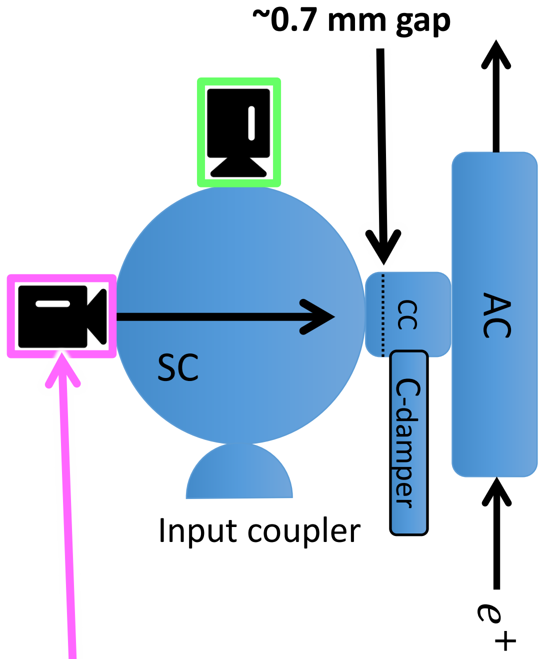


➔ Successful simulation of the beam loading of a 3.6 A LER beam current with a 20kW C-damper power!

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

BACK





➔ No breakdown occurred

➔ No vacuum arc observed in any frame of the recorded video

➔ No breakdown during the 2024a+bc beam operation so far

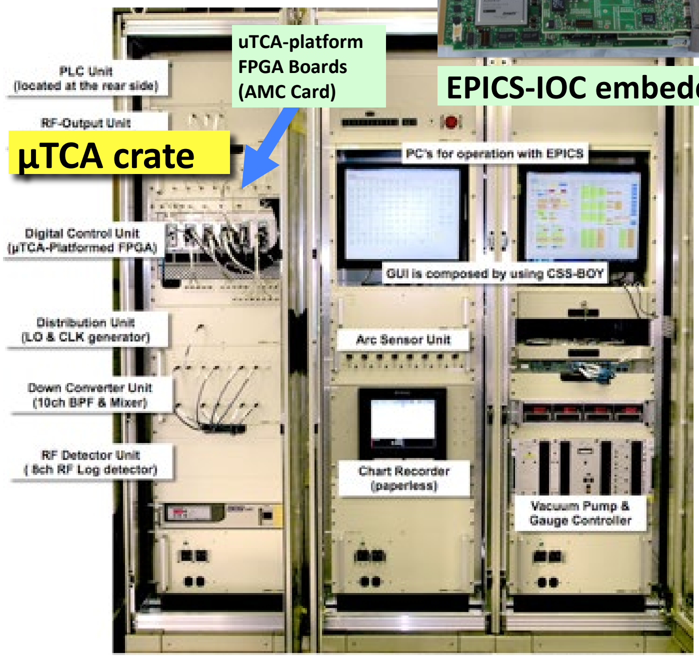
Digital LLRF Control System

The Digital LLRF control system has been newly developed in 2012 for higher accuracy and more flexibility.

New LLRF System for one klystron

16-bit ADC x 4ch,
16-bit DAC x 2ch

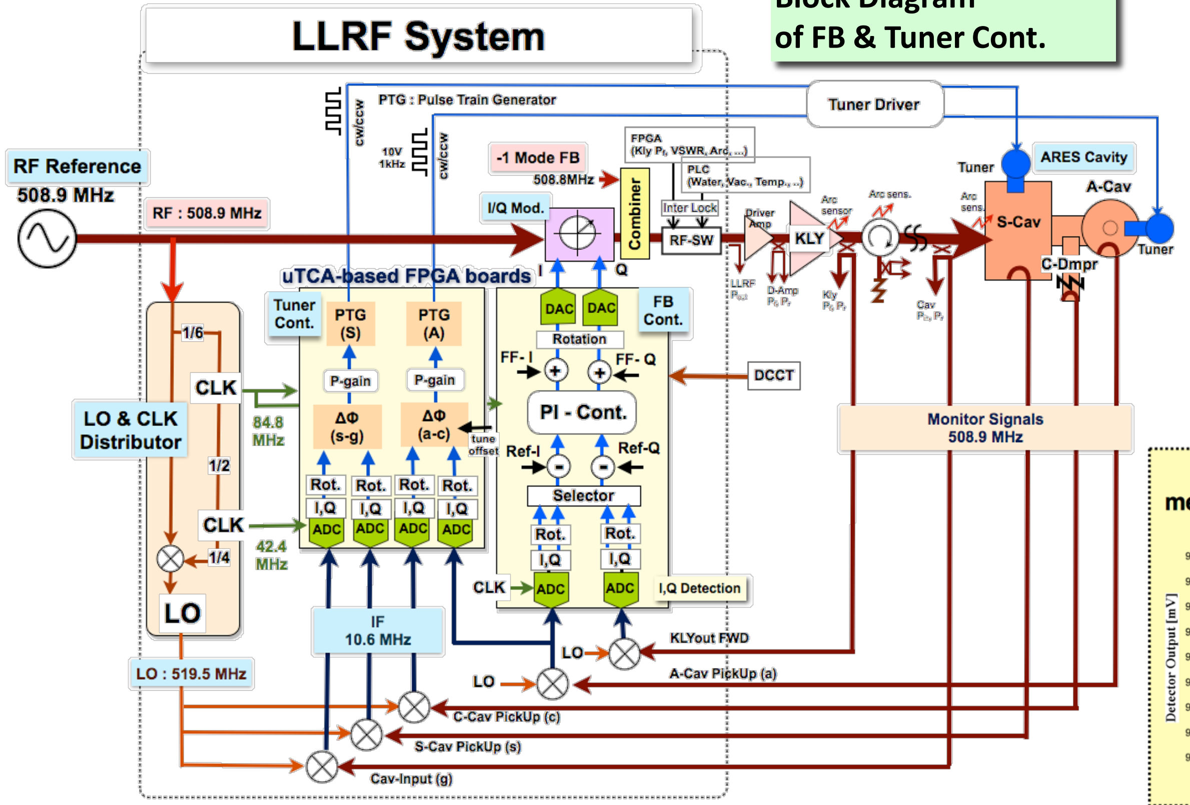
EPICS-IOC embedded



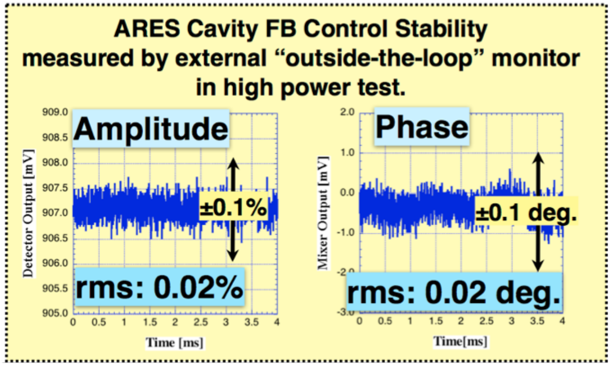
- Consisting of µTCA-platformed FPGA boards (AMC), & PLC.
- EPICS-IOC with Linux-OS is embedded in each of them.
- Common hardware for both of ARES & Superconducting Cavity.
- Klystrons (LLRF) : Cavity unit = 1 : 1 (SuperKEKB)

Completely remotely controllable

Block Diagram of FB & Tuner Cont.



Regulation Performance

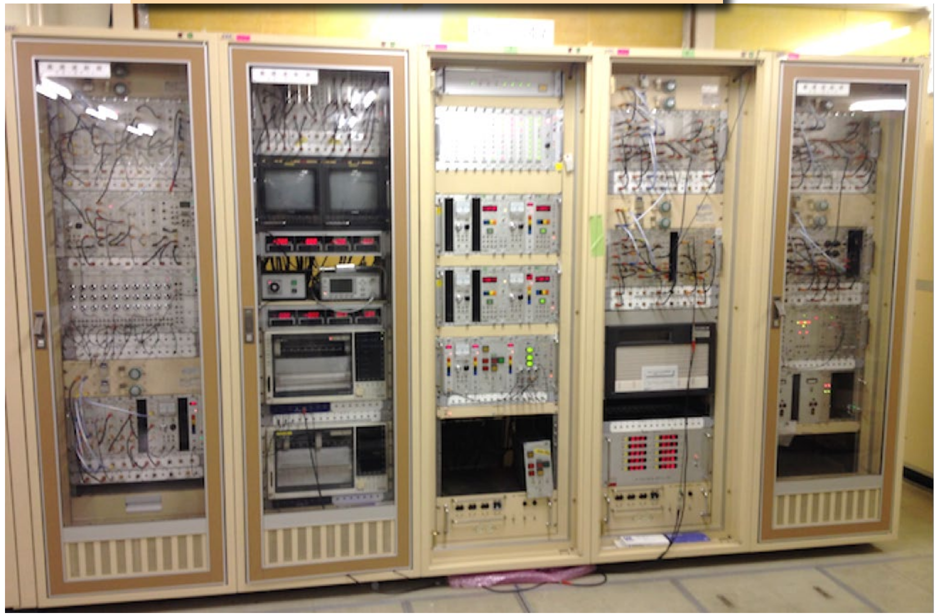


- It is dominated by µTCA-platformed FPGA boards for higher accuracy and more flexibility.
- In this system, I/Q components are handled by FPGA for vector control instead of amplitude and phase.
- The good performance was demonstrated in the high power test with ARES cavity. The regulation stability was 0.02% in amplitude and 0.02 deg. in phase.

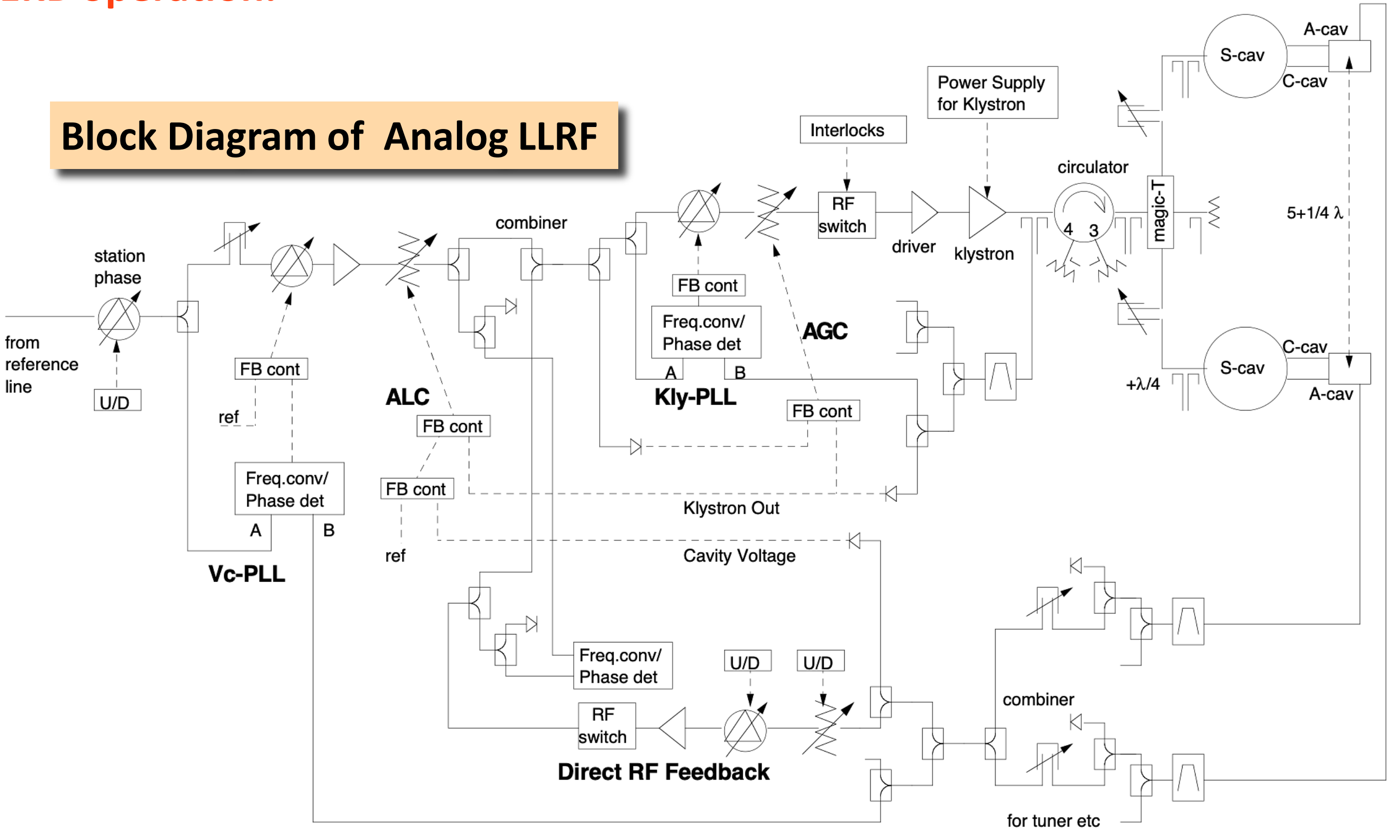
Old Analog LLRF Control System

Most stations are still operated by the old analog LLRF systems, which had been used since the KEKB operation.

Analog LLRF used since the KEKB operation

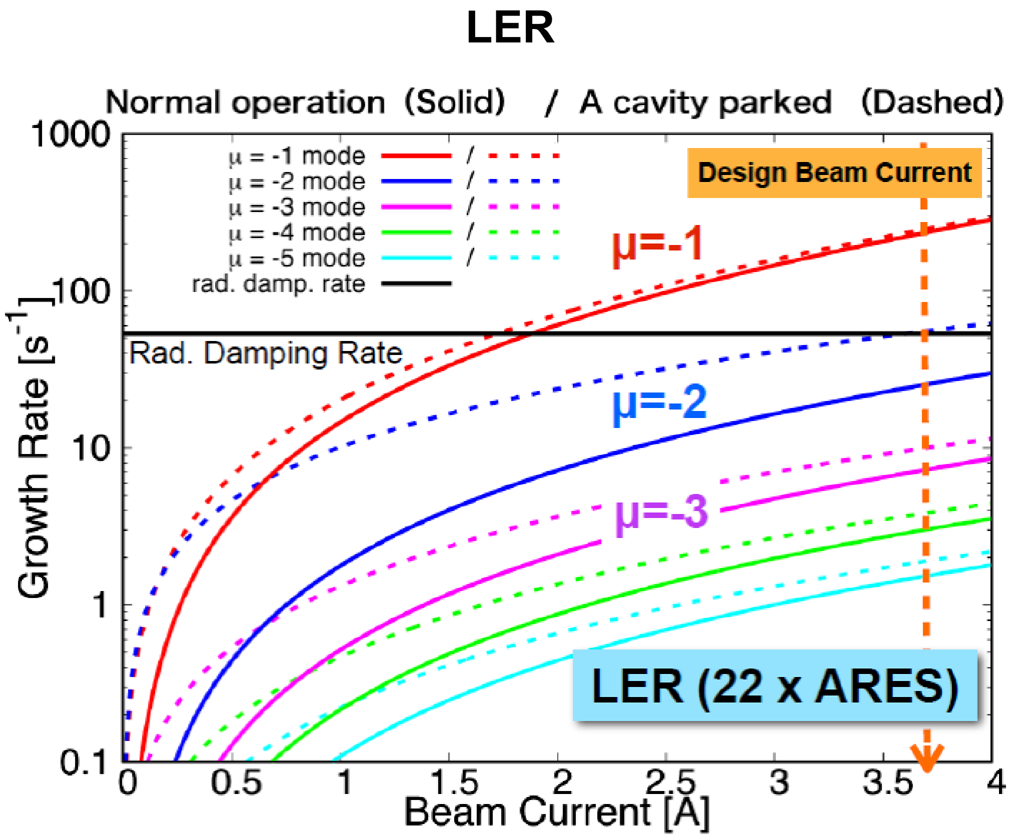


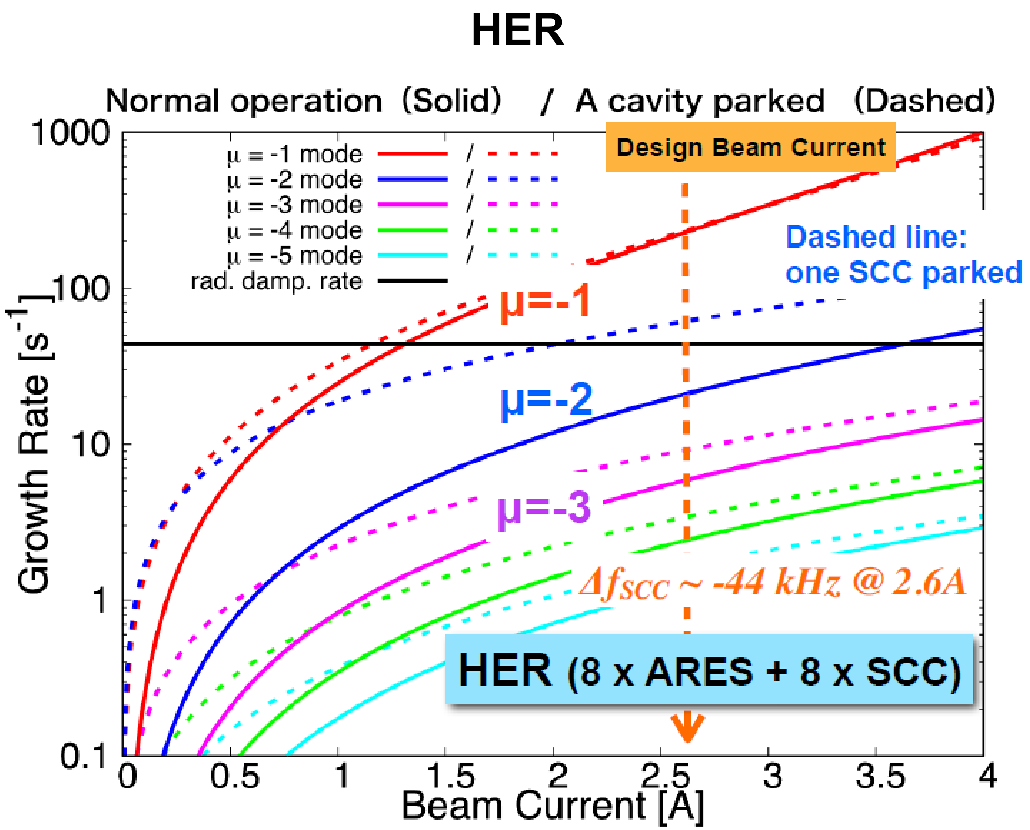
Block Diagram of Analog LLRF



- These systems are **composed of combination of NIM standard analogue modules.**
- They are **controlled remotely via CAMAC system**.
- All systems are barely working without serious troubles.
  However, some NIM modules failed during operation. They were replaced by spare ones.
- Most of the devices are discontinued, and the number of spares are not enough.

Estimation of Growth Rates of Coupled Bunch Instability (CBI)





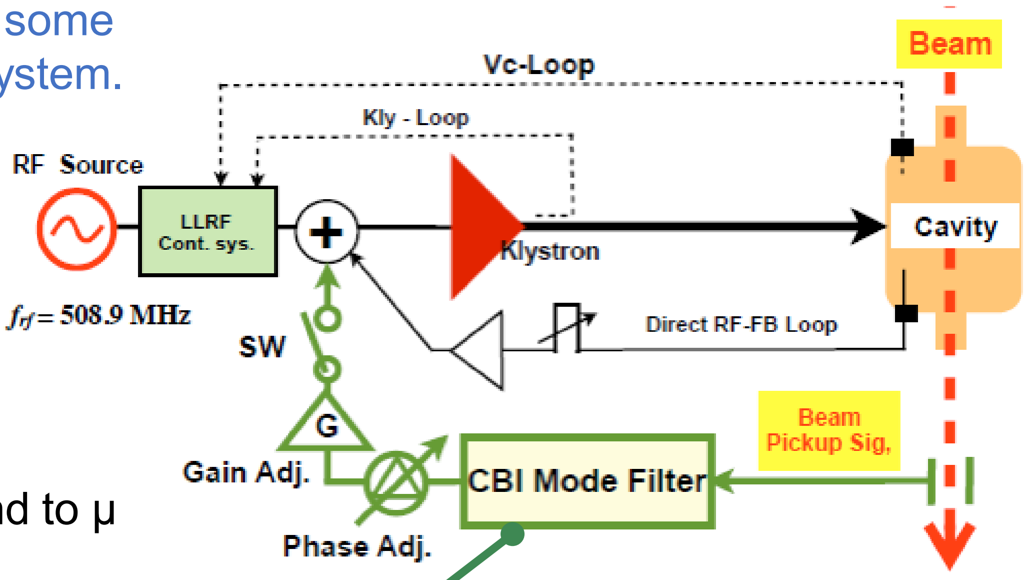
Threshold currents for μ=-1 mode are quite below the design current.
When there are parked cavities, μ=-2 mode also has no margin.
New CBI damper system has been developed and installed.

K. Hirosawa et al., Nucl. Instrum. Methods. Phys. Res. A 951, 163044, 2019.

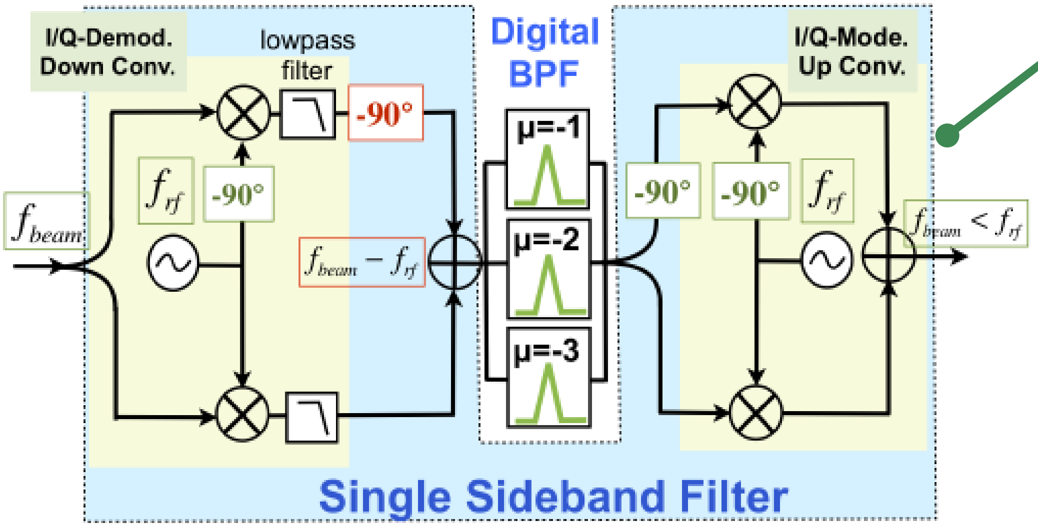
CBI Damper System

K. Hirosawa et al., Nucl. Instrum. Methods. Phys. Res. A 951, 163044, 2019.

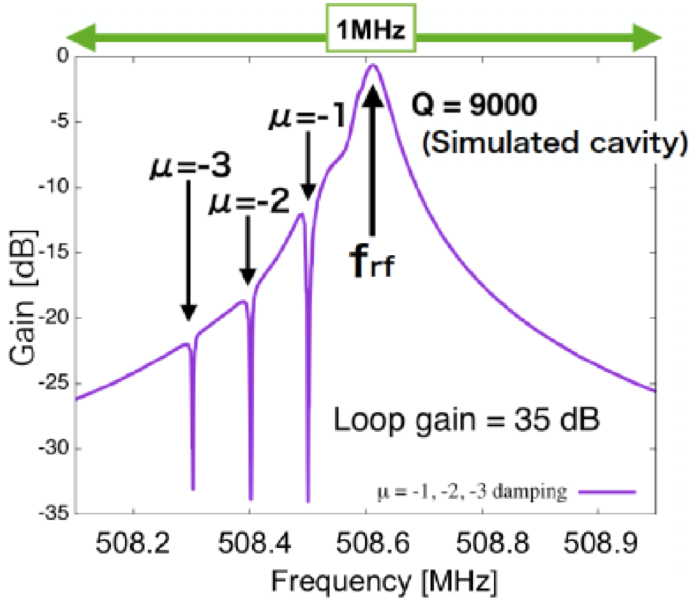
The damper system is installed to some ARES stations with digital LLRF system.



The damper system can correspond to μ =-1, -2 and -3 modes in parallel.



FB loop test result of the CBI mode filter for a simulant cavity



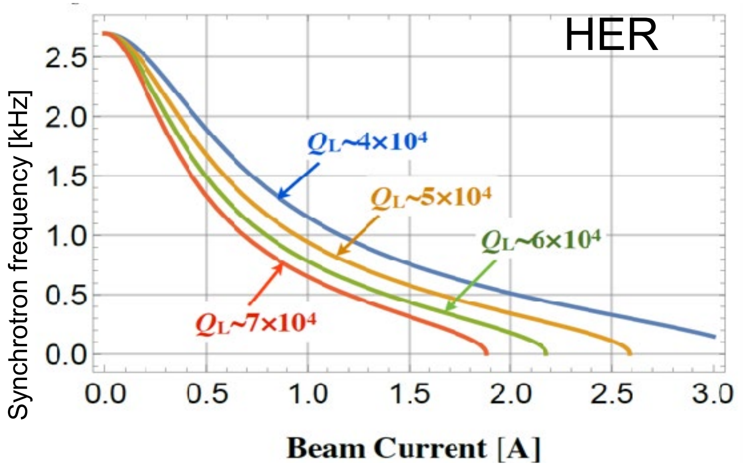
Impedances at the frequencies corresponding to μ =-1, -2 and -3 modes are suppressed by the damper.

Zero-mode Instability related to Robinson Stability

K.Akai, PRAB 25, 102002 (2022).

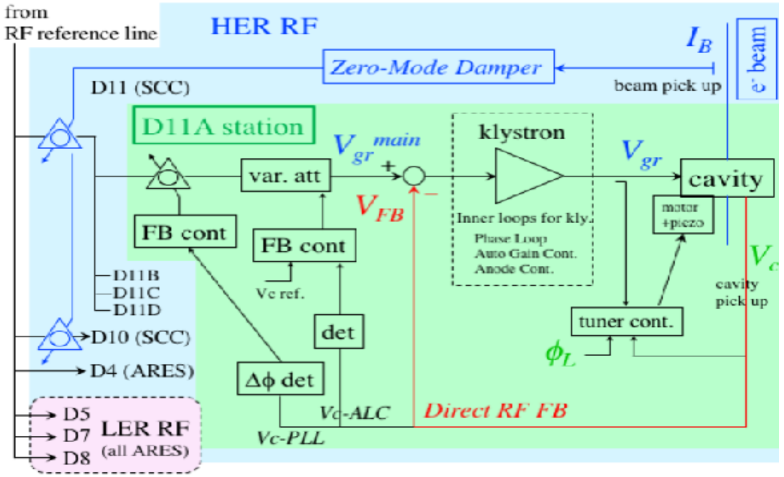
- In high current operation, synchrotron frequency reduction is expected due to coherent oscillation (zero-mode).
- To mitigate the beam-loading effect, Direct RF feedback (DRFB) and Zero-mode damper (ZMD) are working.

Calculated coherent oscillation frequencies with **simplified one SCC** for various Q_L (**without FB** for instabilities)



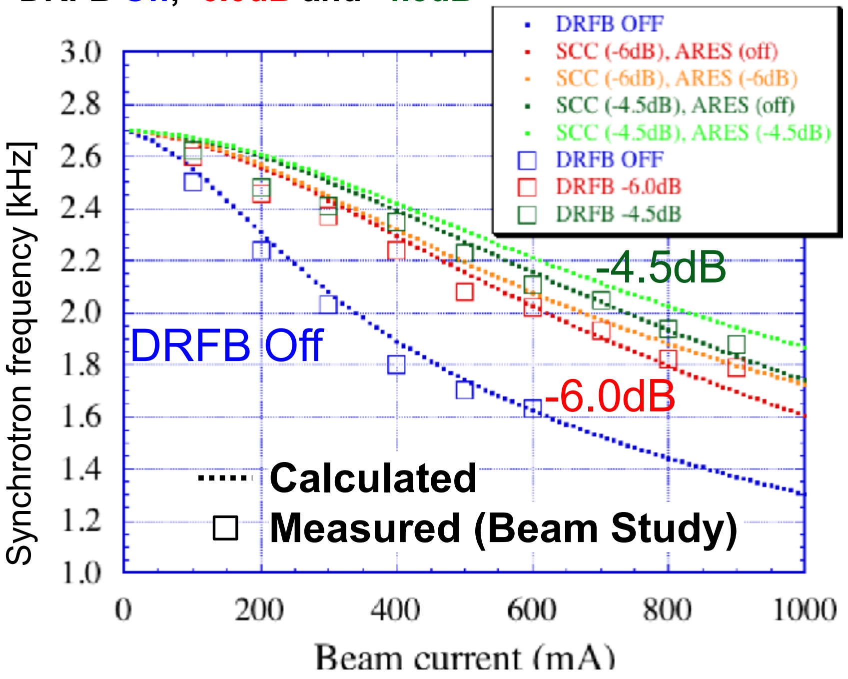
Synchrotron frequency reduction depends on Q_L. But, changing Q_L of SCC should be avoided due to the need for vacuum work and the risk of surface contamination.

Block diagram of LLRF with DRFB and ZMD (Focused on SCC station in HER)



Effective impedance of cavity and beam loading are reduced by DRFB. ZMD is tuned its phase to suppress the coherent oscillation.

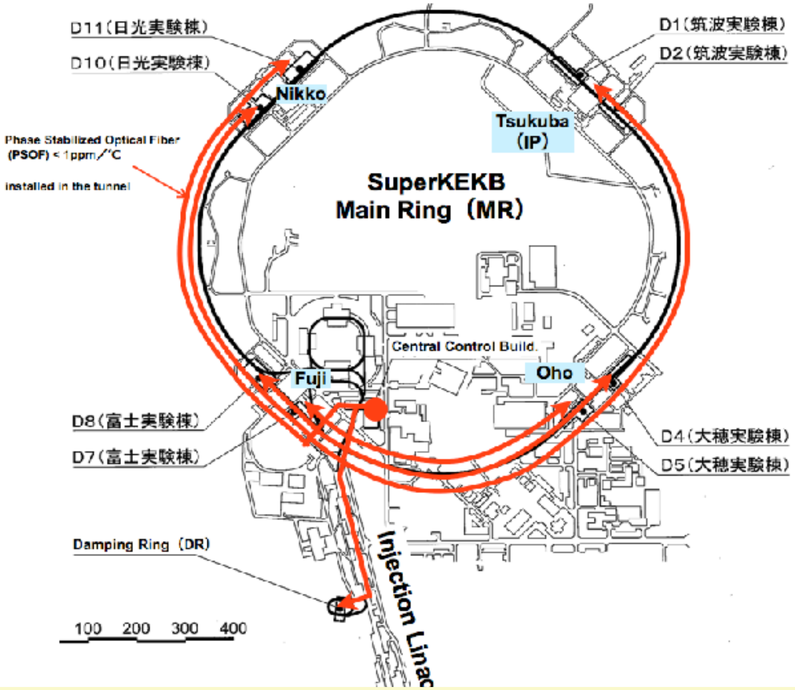
Calculated and measured coherent oscillation frequencies in **actual HER (ARES + SCC) with DRFB** **Off**, **-6.0dB** and **-4.5dB**

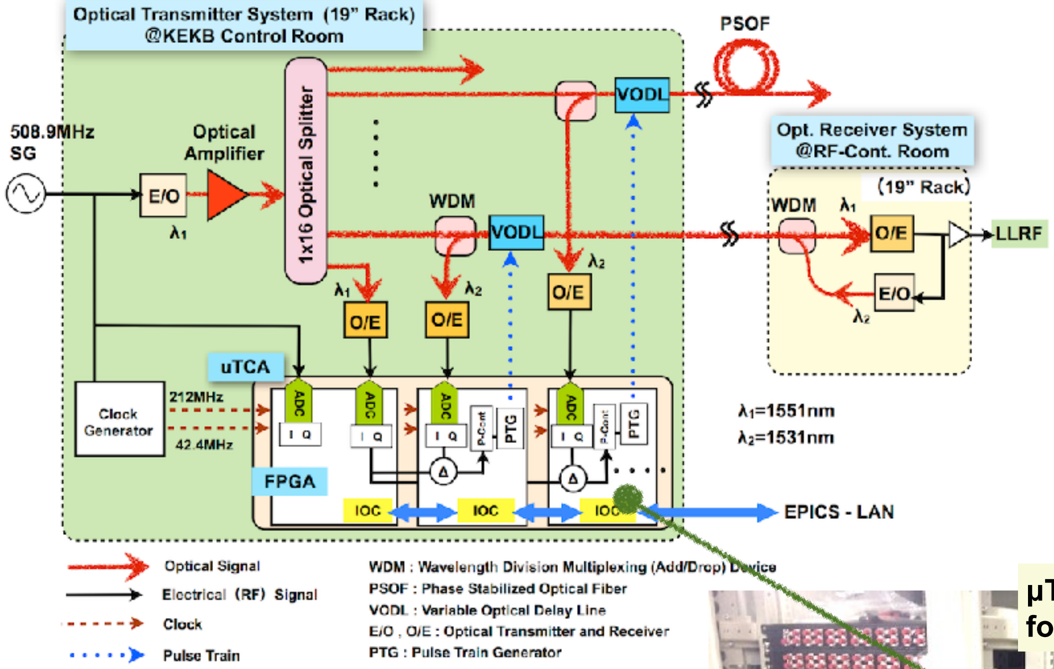


- **The higher beam currents can be stored stably by DRFB and ZMD in beam study.**
- There is no discrepancy between the quantitative analysis and the beam study results.
- Coherent oscillation instability can be suppressed by the DRFB and ZMD so far.

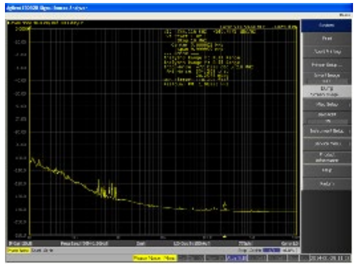
RF Reference Distribution System

- RF reference signal is optically distributed into 8 sections by means of “Star” topology configuration from the central control room (CCR).
- For the thermal phase drift compensation, variable optical delay line (VODL) is controlled digitally by using μTCA board at CCR for all the transfer lines. The VODL is a mechanical type. The stepping motor is controlled by the μTCA boards with pulse train outputs like cavity-tuner control.
- For the phase monitor, direct sampling method is applied by using 14-bit ADC boards. It is under sampling at 212 MHz for 509-MHz RF signal.





Low SSB Phase Noise



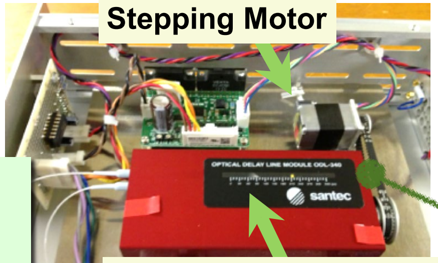
Short term stability (time jitter) : < 100 fs (rms)

Long term stability (pk-pk) : ±0.1° @508.9MHz = ±0.55 ps

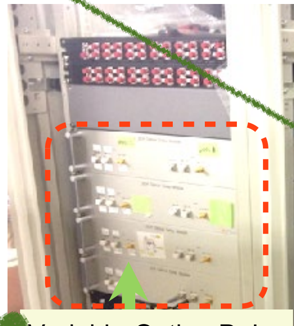
(attributed to property of the optical delay control)

It is working successfully without troubles, and also completely reproduces the RF phases and the collision point for restart after long shutdown.

Stepping Motor



Variable Optical Delay Line (Mechanical type)



Variable Optica Delay Lines (VODLs) for 8 transmissions

μTCA-based FPGAs for the VODLs control

Direct sampling method is applied for 509-MHz RF. (under sampling at 212 MHz)

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