Operating Experience of SRF System at High Beam Current in SuperKEKB

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Contents

- Overview of SuperKEKB and RF system
- Superconducting Cavity –SCC– in SuperKEKB
  - High Power Input Coupler
  - Large HOM Power
  - Horizontal High-Pressure Rinse (HHPR)
  - Operation Statistics
- Summary

Overview of SuperKEKB

- Searching for "new physics" beyond the Standard Model
- e-/e+ asymmetric energy ring collider for B-meson physics
- Circumference of 3 km
- Aiming High Luminosity

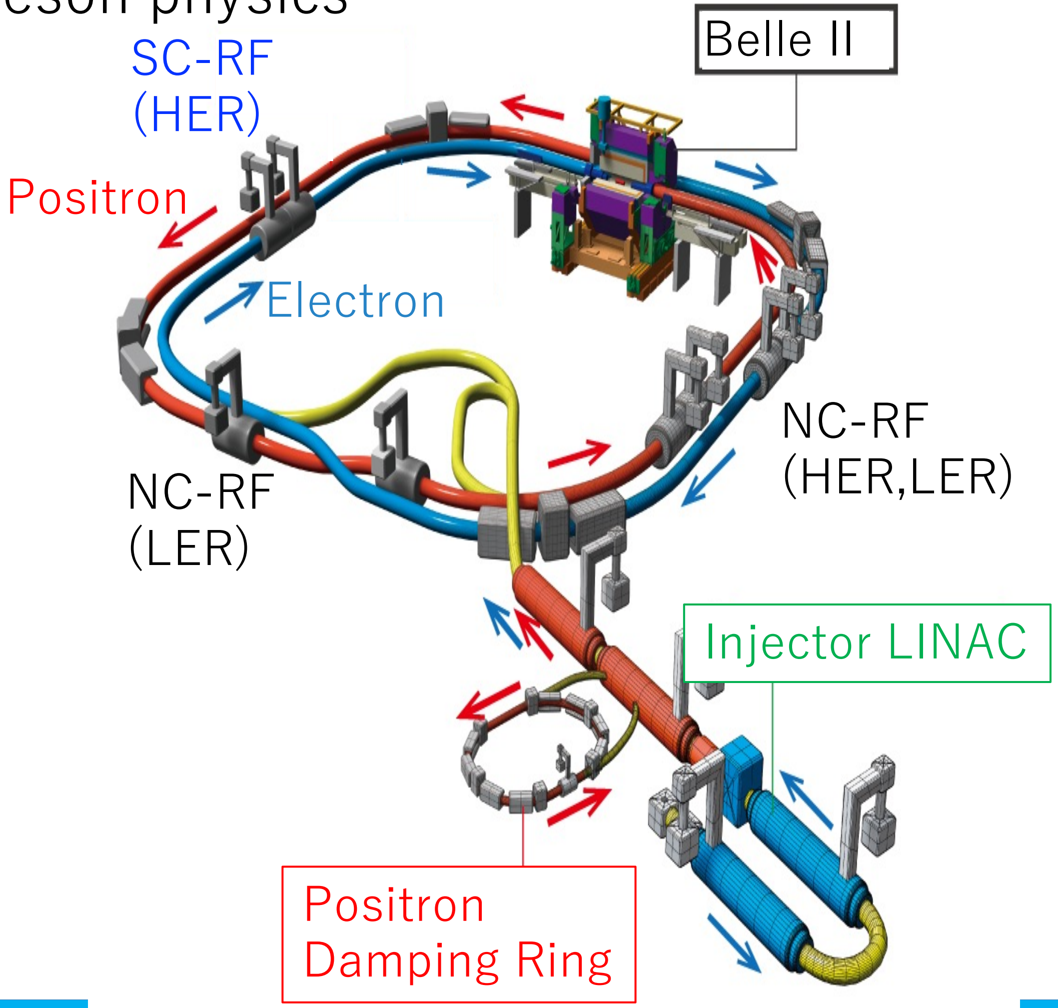
  on the order of $\mathbf{10^{35}}$ **/cm²/s**

  several 10 times of KEKB achieved

  - **Nano-beam scheme** with colliding beams of 10μm x 40nm
  - **Increase of Beam Intensity**
    - (achieved) 1.14 A for HER, 1.46 A for LER

Peak luminosity of 4.65×10^{34} /cm²/s was recorded in June 2022.

	LER	HER
Particle	positron	electron
Energy	4 GeV	7 GeV
Beam Current (design)	3.6 A	2.6 A

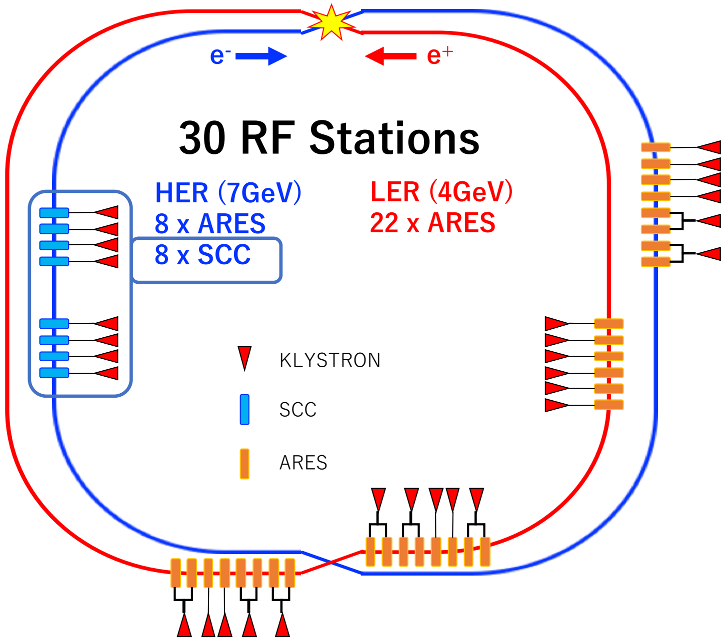


Overview of RF System and Beam Operation

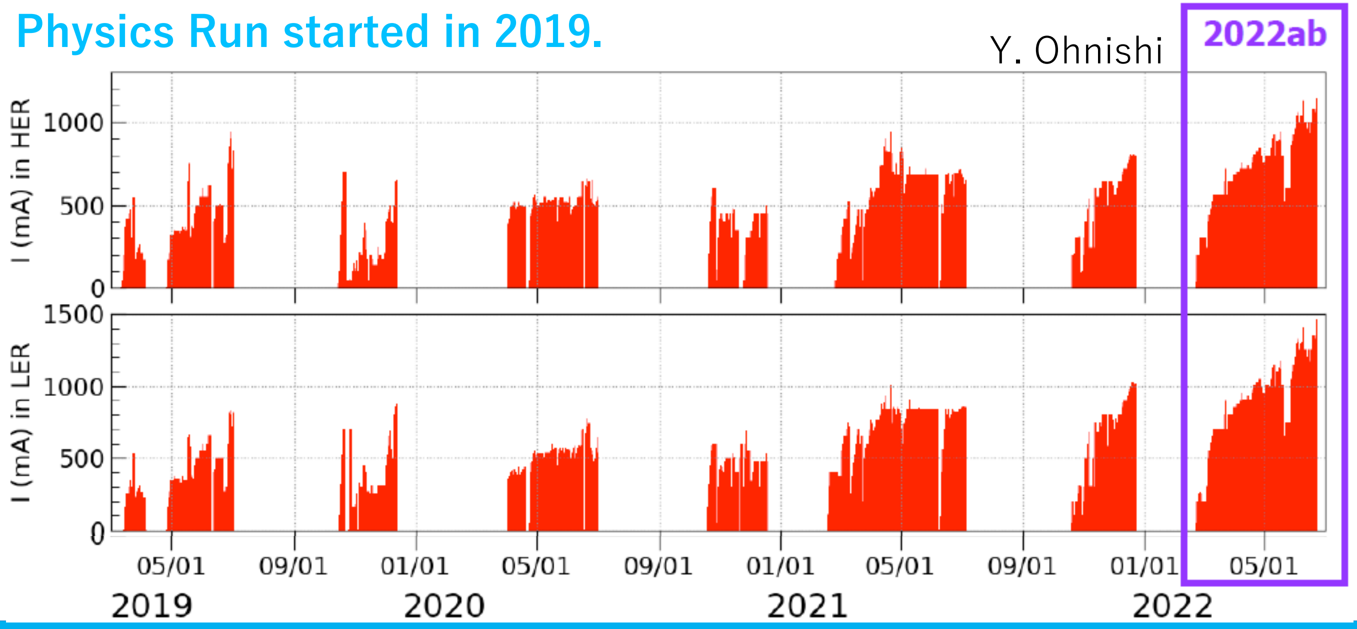
RF-Related Parameters

Parameter	KEKB (achieved)				SuperKEKB (design)				SuperKEKB (achieved)				
Ring	HER			LER	HER		LER		HER			LER	
Energy [GeV]	8.0			3.5	7.0		4.0		7.0			4.0	
Beam Current [A]	1.4			2	**2.6**		**3.6**		**1.14**			**1.46**	
Number of Bunches	1585			1585	2500		2500		2346			2346	
Bunch Length [mm]	6-7			6-7	**5**		6		~6			~6	
Total Beam Power [MW]	~5.0			~3.5	8.0		8.3		~3.1			~3.2	
Total RF Voltage [MV]	15.0			8.0	15.8		9.4		14.2			9.12	
	ARES		SCC	ARES	ARES	**SCC**	ARES		ARES		**SCC**	ARES	
Number of Cavities	10	2	8	20	8	8	8	14	4	4	8	12	10
Klystron : Cavity	1:2	1:1	1:1	1:2	1:1	1:1	1:2	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		0.45		1.35	0.45	
Beam Power [kW/Cav.]	200	550	400	200	600	**400**	200	600	130	170	**260**	190	230

Layout of RF system



Physics Run started in 2019.



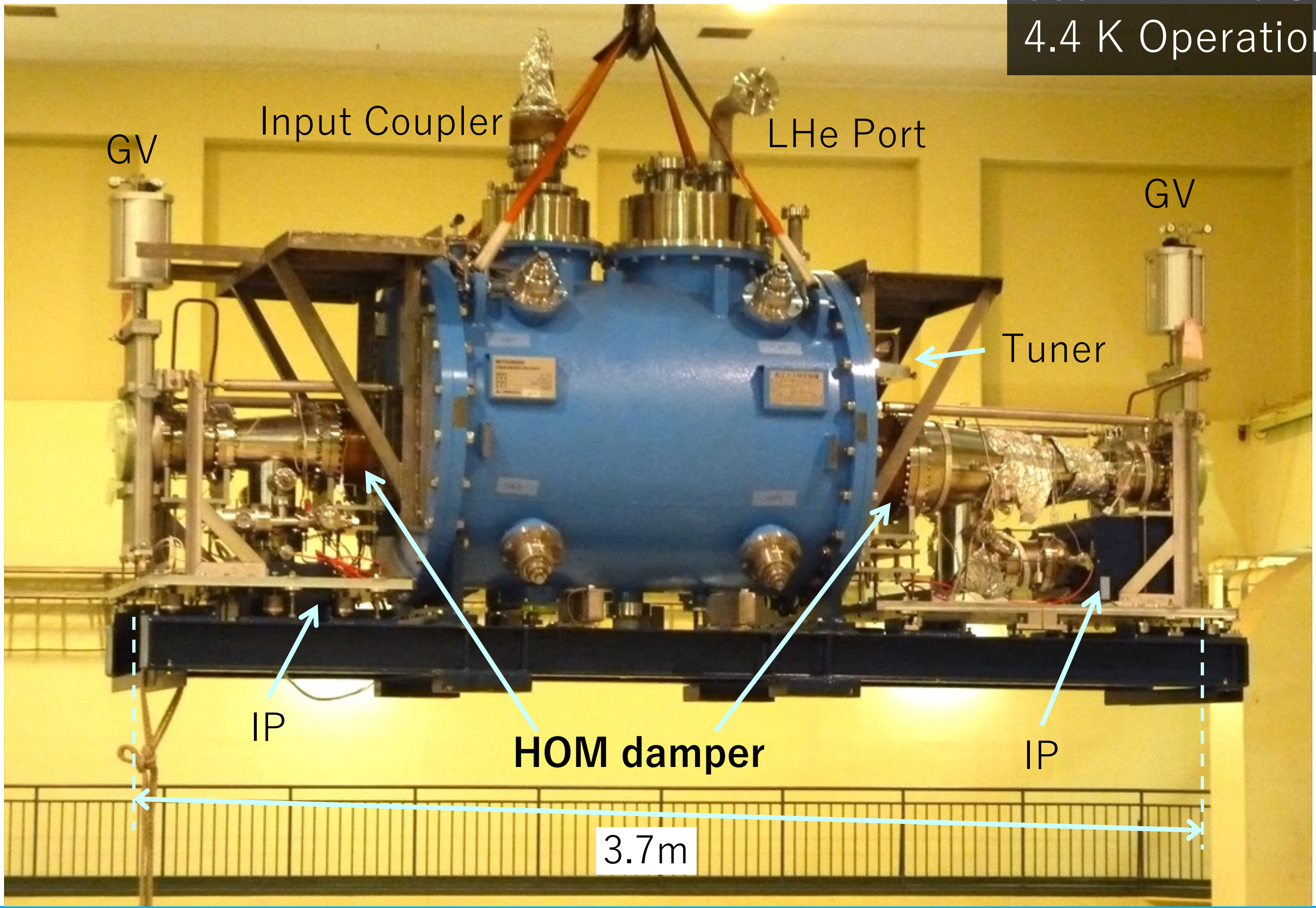
Re-using RF system with reinforcements to handle twice high beam current and large beam power

Basic Beam Operation Schedule

- Beam operation (Physics Run) : 6~7 months/year (with summer and winter shutdown)
- SCC cooling and warm-up : 2 cycles / year
- Regular maintenance day in operation term : 8 hours every 2 or 3 weeks

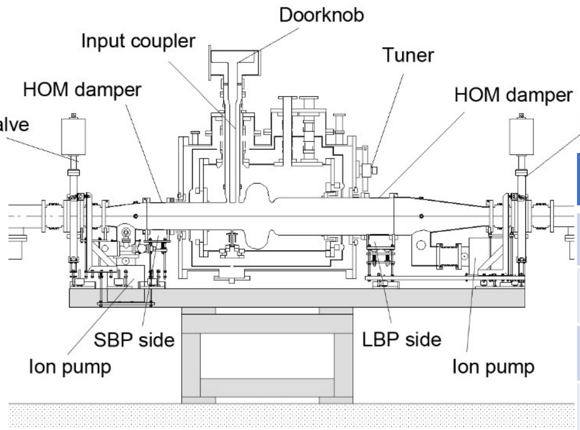
SCC Module of SuperKEKB

509 MHz Nb Single-cell Cavity
4.4 K Operation



SCC in SuperKEKB

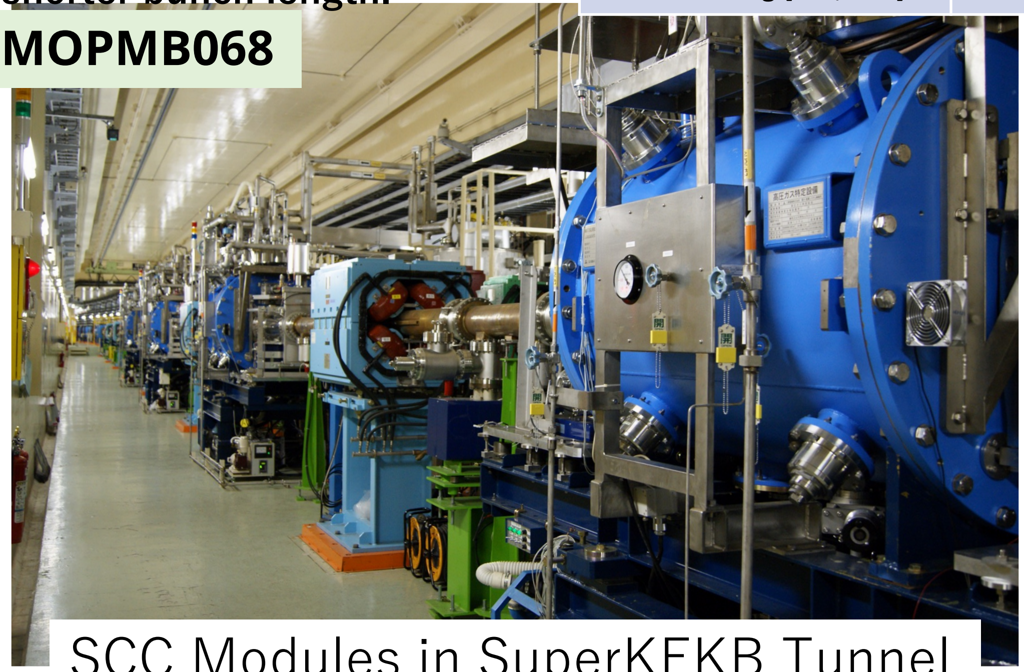
- 509 MHz Nb Single-cell HOM-damped Cavity, 4.4 K Operation
- 8 SCC Modules in HER (electron ring) & One Spare Module
- Reused from KEKB (including Cryogenic system)
- Beam power and cavity voltage are kept as those of KEKB by sharing with ARES (normal conducting) cavities.
- Main Issues in SuperKEKB for SCC
  - **Large HOM power is expected due to twice high beam current and shorter bunch length.**
    - **Additional SiC HOM damper** ←**Okada-san's Poster: MOPMB068**
  - Degradation of RF performance of Qo
    - Horizontal High-Pressure Rinse



SuperKEKB-SCC Design Parameters	
Number of Cavities	8
Max. Beam Current [A]	2.6
RF Voltage [MV/cav.]	1.5
External Q	5E+4
Unloaded Q at 2MV	1E+9
Beam Loading [kW/cav.]	400
HOM Loading [kW/cav.]	37

Usual Operation of Cavity

- **Warming up to room temperature twice a year**
  - Safety inspection of cryogenics; pressure gauge, safety valve, etc
  - Cavity free from frequency tuner during warming up and cooling down
  - **Coupler conditioning with bias voltage before cooling**
- **Regular maintenance day of every 2 or 3 weeks**
  - Visual inspections
  - **Cavity conditioning**

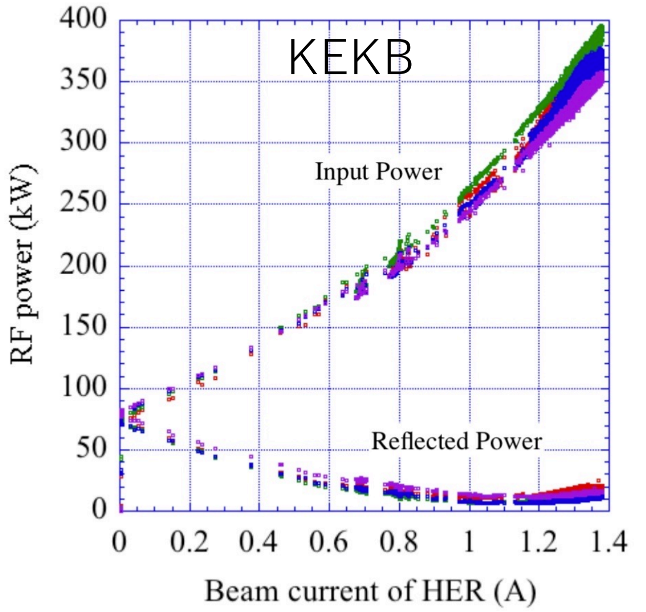


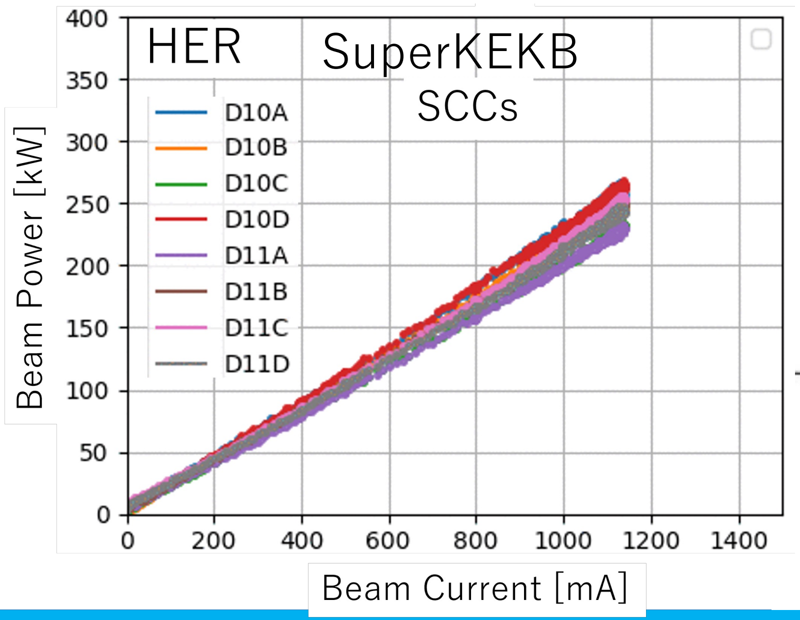
SCC Modules in SuperKEKB Tunnel

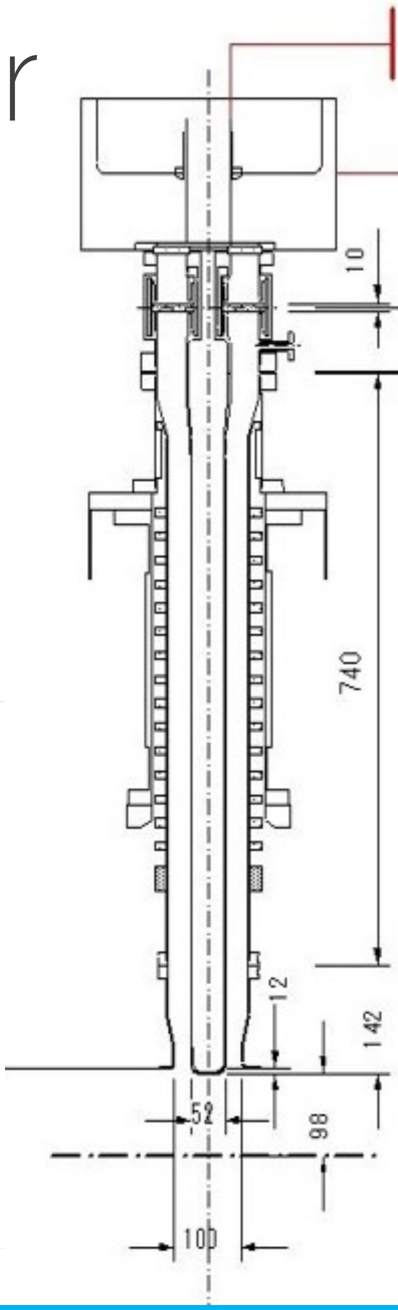
High Power Input Coupler

- Coaxial antenna-type input coupler
- $Q_{\mathrm{ext}} = 5 \times 10^4$
- $P_{\mathrm{b.max}}$= **400 kW** at 1.4 A (achieved)

- SuperKEKB : Design current 2.6 A
- No change of Q_{ext} to avoid contamination of cavity
- Beam power delivered by SCC can be kept by sharing with ARES cavities by giving the phase-offset.



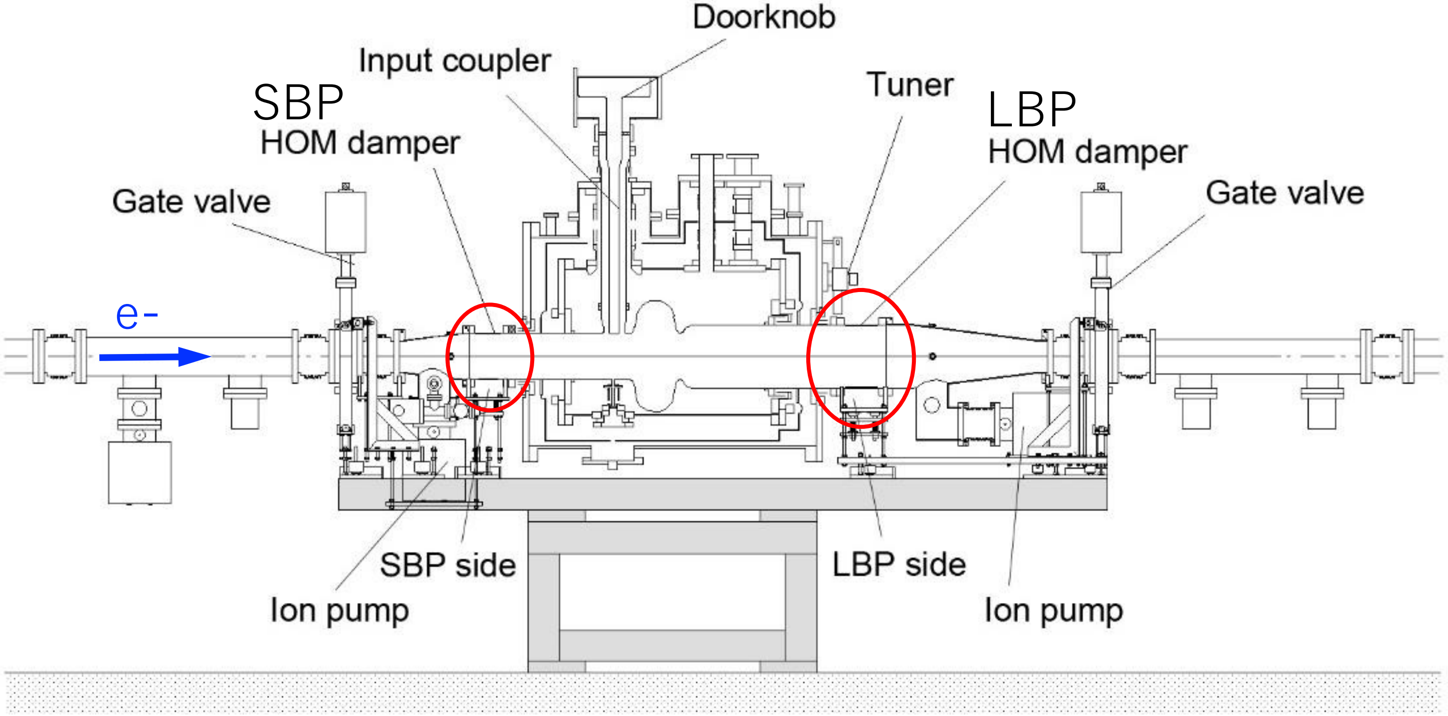


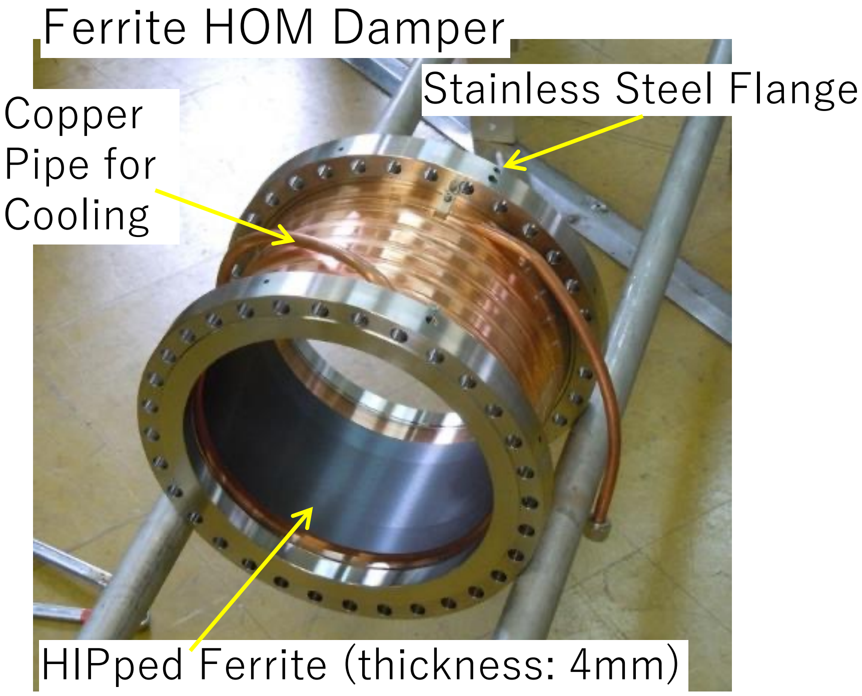


Large HOM Powers

←**Okada-san's Powers Poster: MOPMB068**

- HOMs can propagate toward beam pipes due to large aperture size.
- A Pair of Ferrite HOM dampers for each SC module
  - ➢SBP damper : ϕ220 x t4 x L120
  - ➢LBP damper : ϕ300 x t4 x L150
  - ➢Max. absorbed power in KEKB : **16 kW/cavity** (1.4A, σ=6mm, 10nC/bunch)





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SuperKEKB :

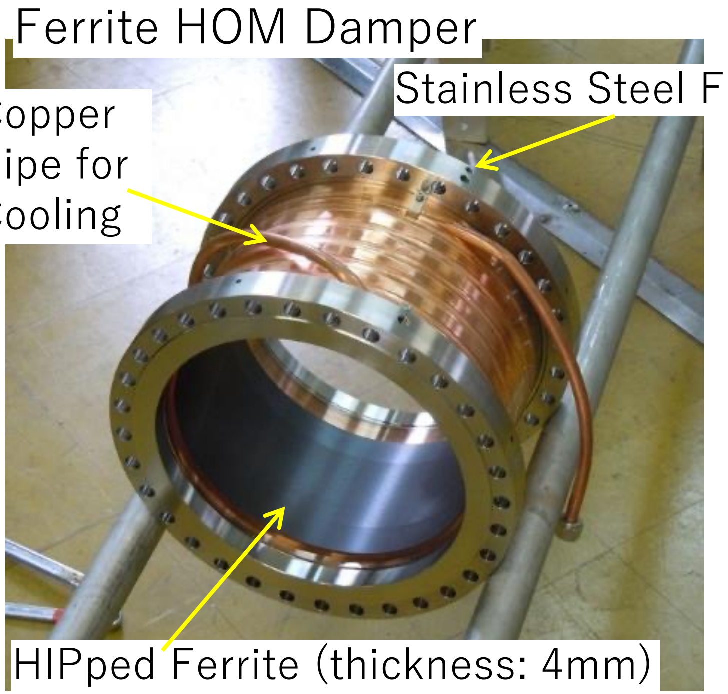
Twice High Current and Shorter Bunch Length

> 30 kW in design current (2.6A)

higher than allowable level of ferrite damper

To reduce the load of ferrite dampers, two set of SiC dampers have been installed. The effect of SiC damper have been confirmed in the beam operation.

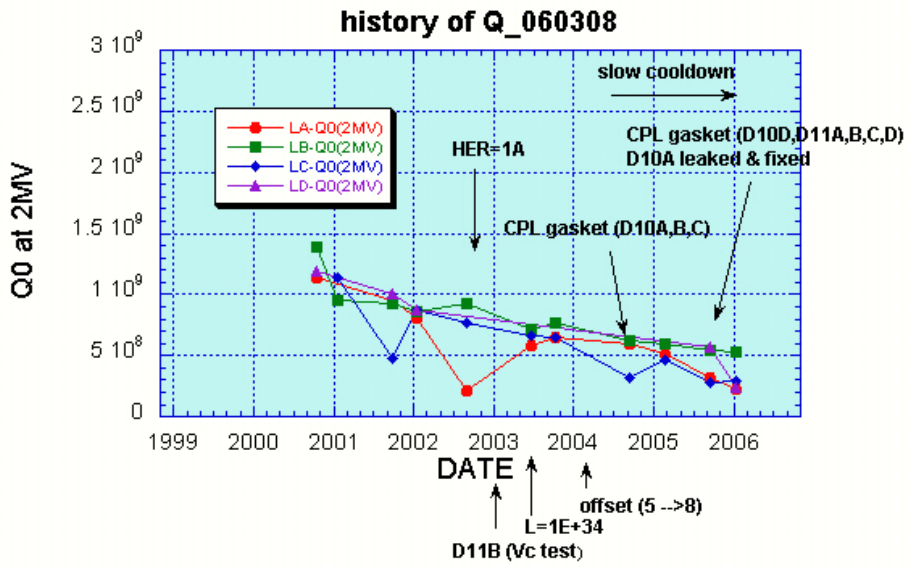
More additional SiC dampers are required.

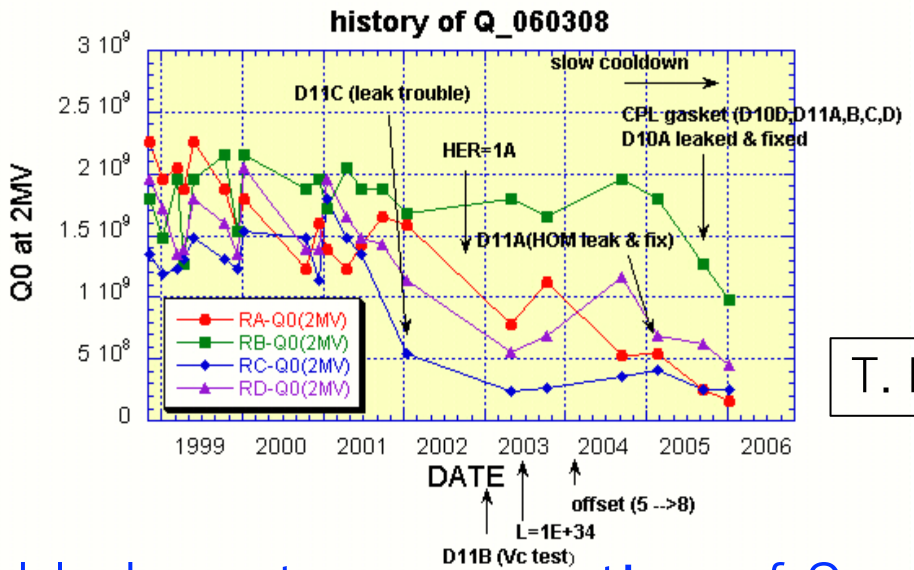


Degradation of Cavity Performance

RF performance of SCCs are degraded in the long-term operation.

- Q_0 of several cavities were significantly degraded at ~2MV with Field Emission (FE).
- Degradation might be due to particle contamination during
  - repair of vacuum leak.
  - replacement of input coupler gaskets to change Q_{ext}.
- Degradation increases a load on the refrigerator and makes beam operation difficult.



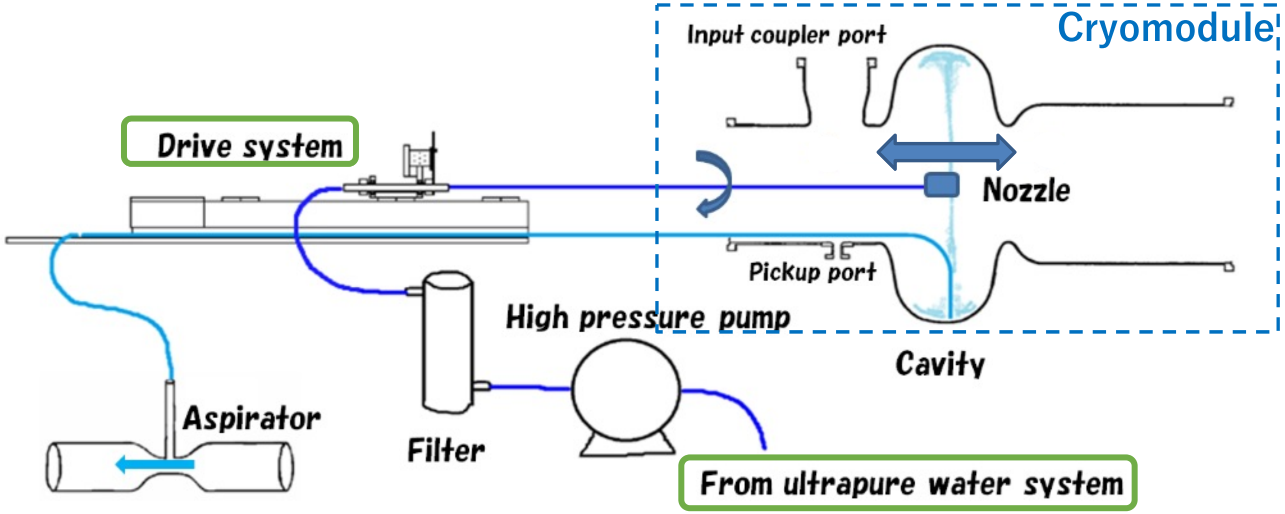


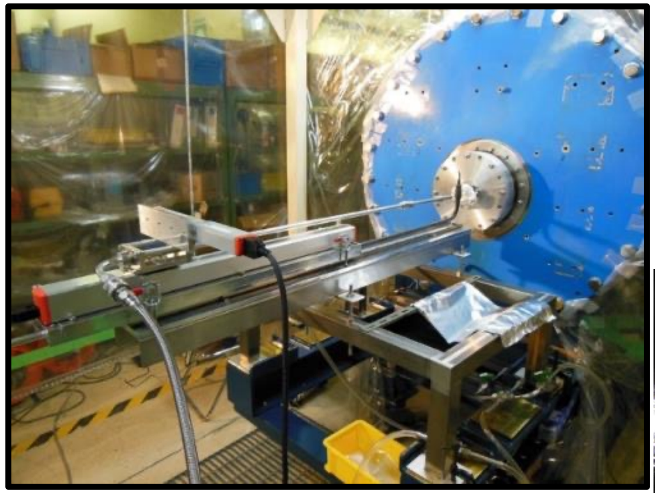
T. Furuya

Performance recovery is desirable for stable long-term operation of SuperKEKB.

Horizontal High-Pressure Rinse (HHPR) system

- New High-Pressure Rinse (HPR) with ultrapure water system was developed.
- We can apply HPR to the cavity in the cryomodule.
- The system is equipped with automatic nozzle driving system in horizontal and rotational.
- Input coupler and both end groups, including ferrite HOM damper, taper chamber, bellows chamber, ion pump, vacuum gauges and GV, are removed before HHPR in a clean booth.
- Water in the cell is pumped up by aspiration system during rinsing.
- Only cell and iris area are rinsed.

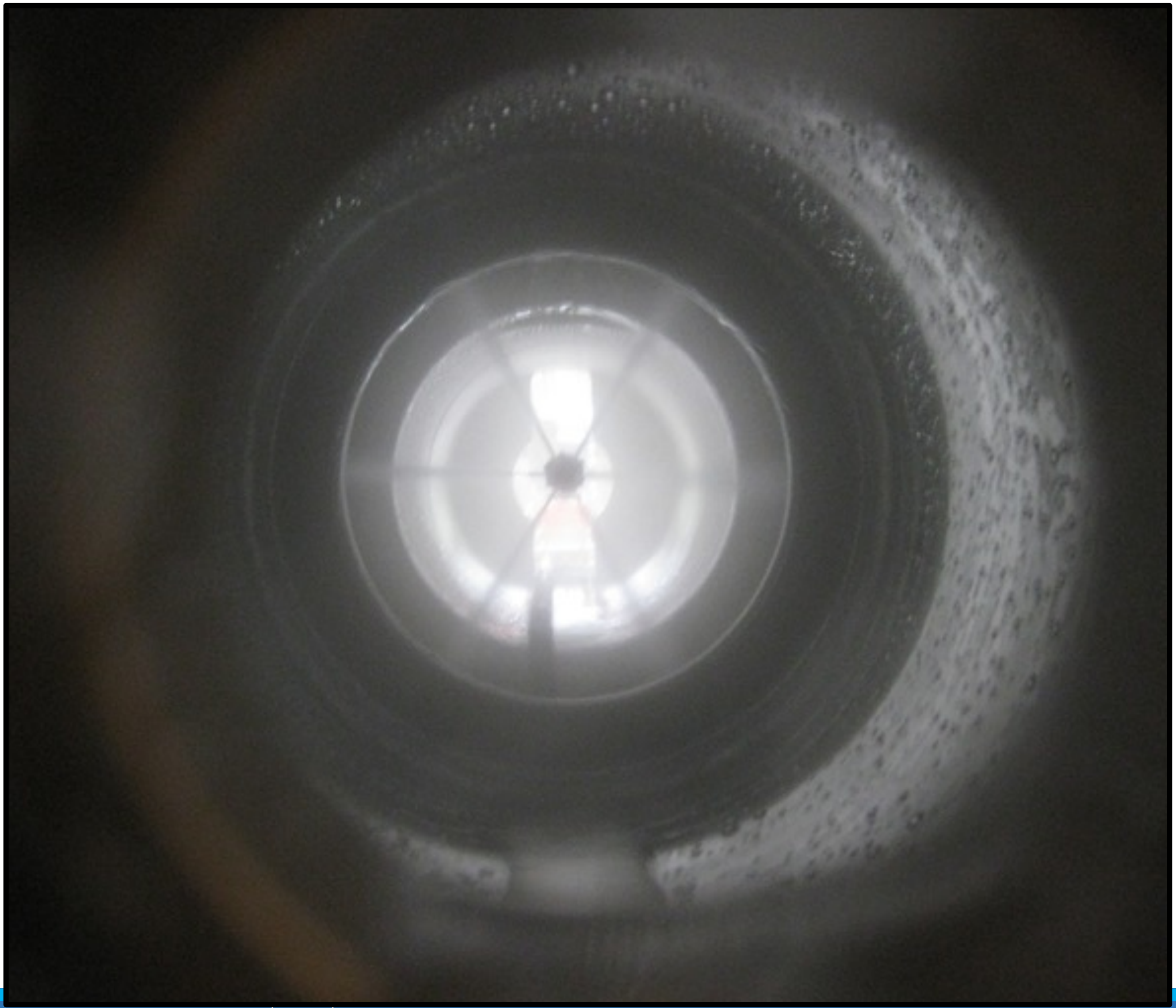




HHPR Parameters	
Water Pressure	7 MPa
Nozzle	ϕ0.54mm x 6
Driving speed	1 mm/sec.
Rotation speed	6 deg./sec.
Rinsing time	15 min.

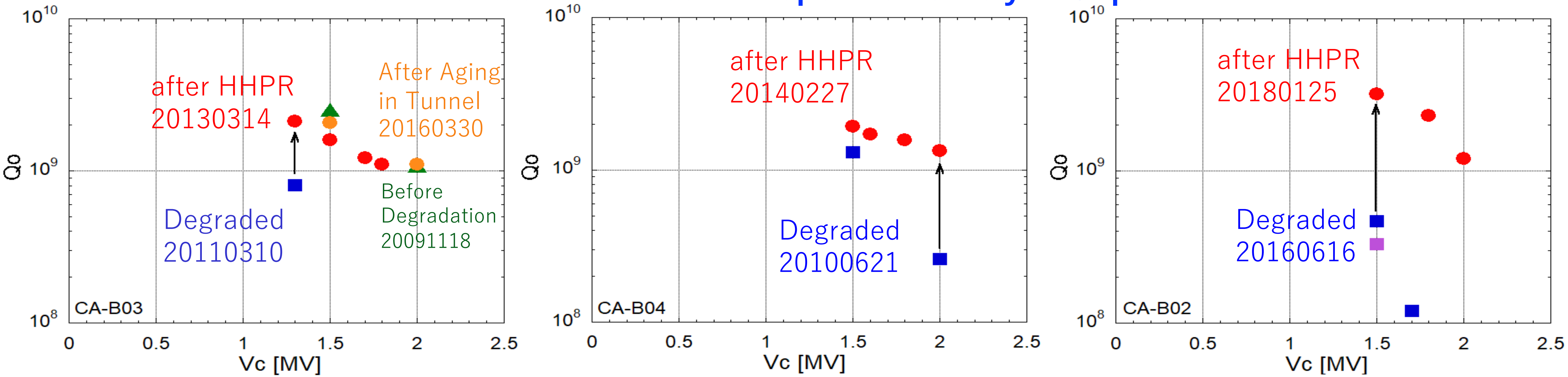
Stainless Steel Nozzle

HHPR -Rotating Water Jets-



Performance Recovery by HHPR

- We have already applied HHPR to three cryomodules degraded by strong FE.
- HHPRed modules were tested with high power at 4K.
- Before cooling, baking were not performed.
- **Cavity performances were successfully recovered.**
- **All three cavities have been installed and operated stably in SuperKEKB.**



We are planning to perform the HHPR in the accelerator tunnel. There are many difficulties such as maintaining cleanliness, working in narrow spaces, and supplying ultrapure water. However, it has the great advantage that no extensive work is required to move the cavity out of the tunnel. We will continue R&D.

Operation Statistics of SRF System

➢ Beam Aborts caused by SRF system is not often.

- Collect signals of RF, beam, LM, etc to find the last message from the beam and to know the true cause of each beam abort

- **Multipacting breakdown of Cavity**
- **Electric breakdown of Piezo actuator for freq. tuner**
  - Due to Insulation failure because of humidity
  - Cavity can be operated without piezo by changing tuner control settings. Recovered in 30 min.
  - Fixed by dehumidification using desiccant (silica gel)
- **Failure of Chiller for HOM dampers**
  - Due to aging degradation. Replacement is on going.
  - By bypass piping to the spare and the next chillers. Recovered in 30 min.

excluding due to LLRF and HPRF

Beam Aborts caused by	Recovery time	2019	2020	2021	2022
MP in Cavity	2-3 min.	2	2	12	7
Piezo breakdown	< 1 hour	6	5	1	0
Chiller failure	< 1 hour	1	1	3	0
Others		0	0	2	2
Total		9	8	18	9
Trip Rate [/day/8 cavities]		0.06	0.04	0.09	0.07
Operation days		149	180	196	121
All aborts (>50mA, including LER single) *except injection tuning		-	~650*	~1100	~730

SRF system is stable even at 1-A beam operation.

◆ Recent failures affected beam operation

➢ Cavity Leak : In Oct. 2020, during cooling. The start of HER beam operation was delayed one day.

- The cavity was detuned in the 2-months beam operation and replaced with the spare cavity in the winter shutdown.

➢ Failure of Tuner : Beam operation was suspended for 3 hours to replace the tuner.

Summary

- SuperKEKB is steadily increasing the beam current and continues to update own luminosity record.
- SRF system is operating stably with low trip rate at large beam currents of 1.14 A for HER so far.
- Maximum beam power delivered by SCC was 400 kW in KEKB operation. The power can be kept by sharing with ARES cavities by giving the phase-offset.
- Large HOM power which is higher than allowable level of ferrite dampers is predicted. More additional SiC dampers are required to reduce the load of ferrite dampers.
- To realize stable long-term beam operation, HHPR has been established to recover the performance of the cavity.

Thank you for your attention.