SuperKEKB operating experience of RF system at high current

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- Normal Conducting Cavity –ARES–
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    - μ=-1, -2 and -3 modes
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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
- Target Peak Luminosity

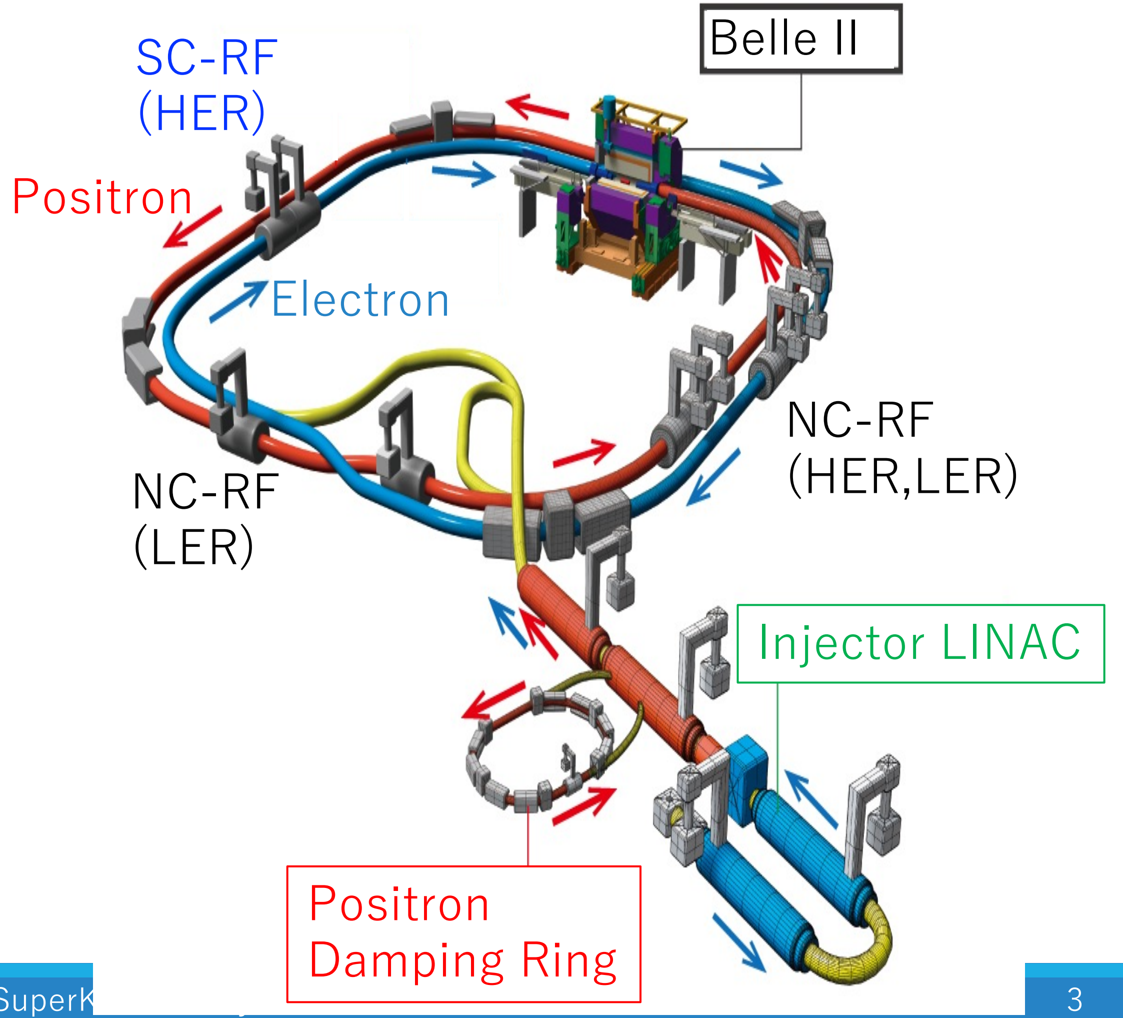
  8×10^{35} /cm^2/s = 800 /nb/s

  40 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} /cm^2/s was recorded in June 2022.

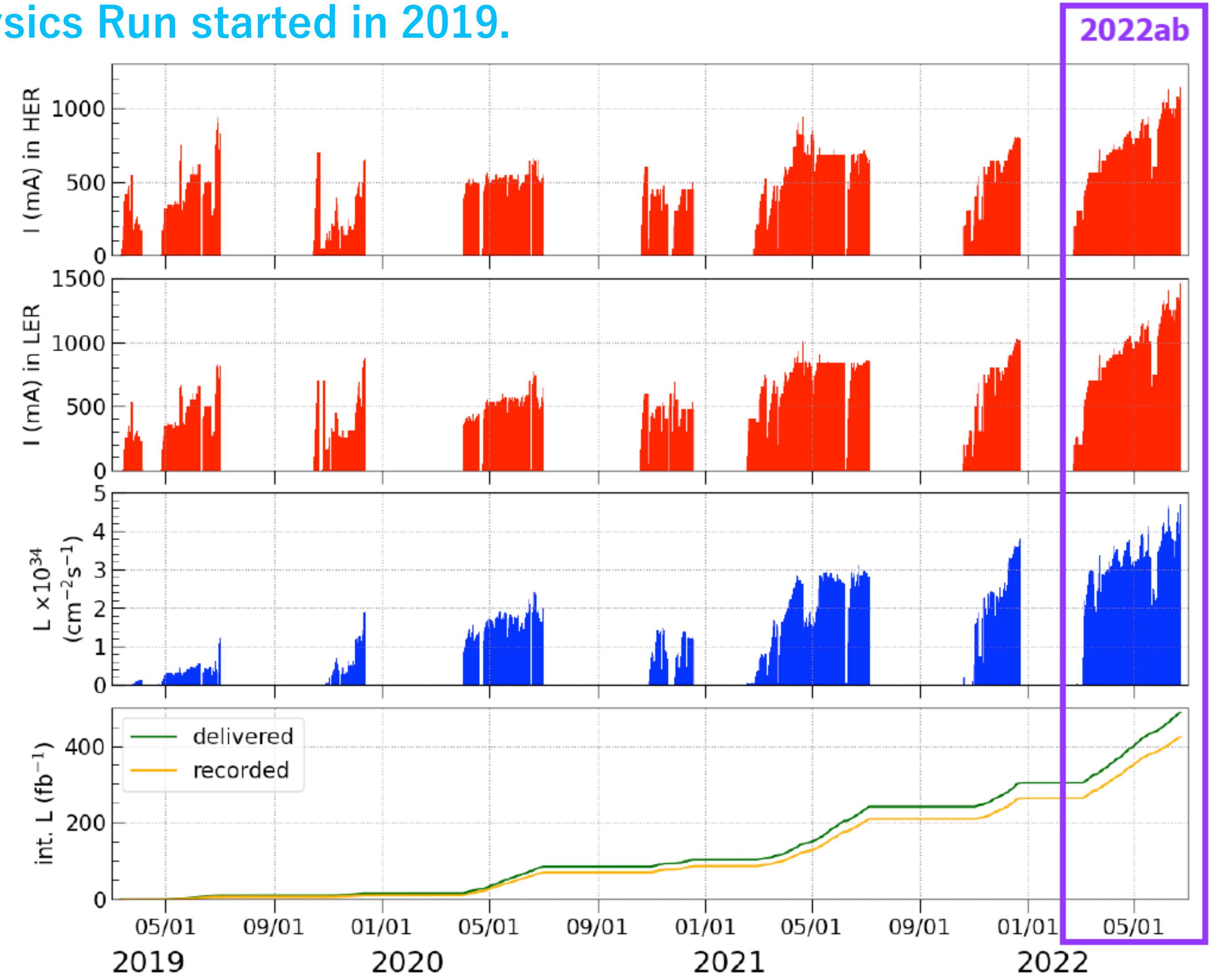
	LER	HER
Particle	positron	electron
Energy	4 GeV	7 GeV
Beam Current (design)	3.6 A	2.6 A



Operation History of SuperKEKB

Y. Ohnishi

Physics Run started in 2019.



Achieved Beam Current

1145 mA electron (HER)

1460 mA positron (LER)

Peak Luminosity

4.65×10^{34} cm^{-2}s^{-1}

(4.71×10^{34} cm^{-2}s^{-1}) (Belle II HV off)

Integrated Luminosity (recorded)

424 fb^{-1} / 491 fb^{-1} (delivered)

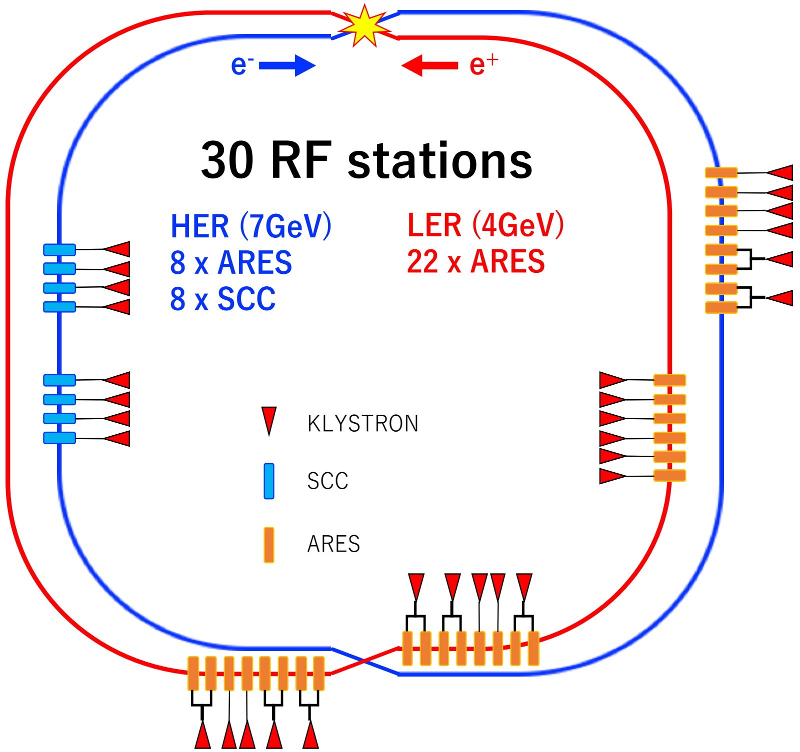
Overview of RF system

Re-use with reinforcements to handle twice high beam current and large beam power

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	SuperKEKB (achieved)				
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



Upgrade items

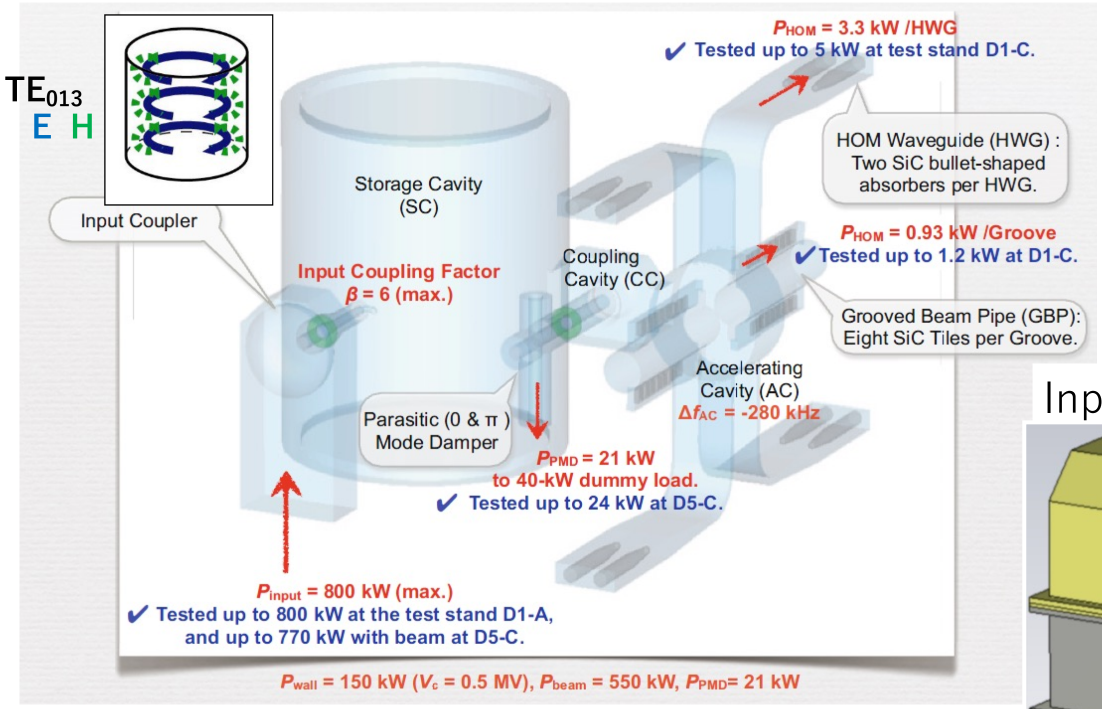
- Increasing the number of RF stations where one klystron drives one ARES (Normal Conducting Cavity), called 1:1 station.
- ARES (Normal Conducting Cavity)
  - Changing Input Coupling β from 3 (1:2) to 5 (1:1).
- SCC (Superconducting Cavity)
  - Installation of additional HOM damper
- HPRF
  - Replacement of Klystrons with higher gain and more stable ones
- LLRF
  - Replacing with new digital LLRF a part of ARES 1:1 stations
  - Development of new CBI damper

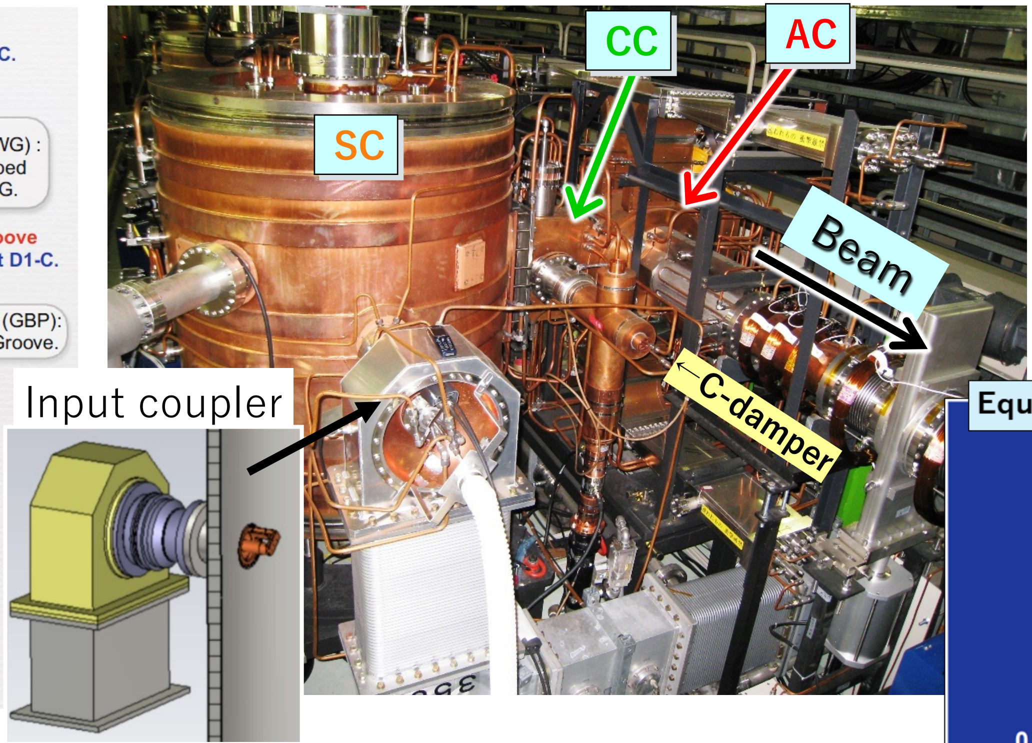
Resent operation status (2022ab, 4months)
# of Beam Aborts caused by RF system : 72
: 0.6 aborts/day
(Total # of beam aborts : >1300)

ARES : Accelerator Resonantly coupled to Energy Storage

Unique cavity specialized for KEKB

T. Abe

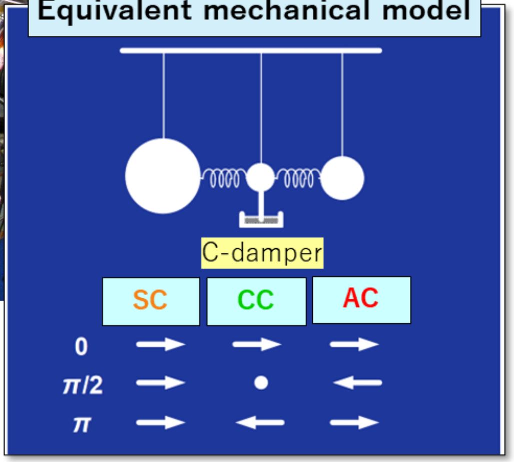




Parameters	
Freq.	509 MHz
R_{sh}/Q_0	15Ω
Q_0	~1.1x10^5
V_c (spec.)	0.5MV/cav.
P_{wall}	150kW

(60kW in AC, 90kW in SC)

Equivalent mechanical model



■Three-cavity system is stabilized with **π/2 mode** operation

- ➢SC has large stored energy : $U_{sc}/U_{ac} = 9$
- ➢Optimum detuning of $f_{\pi/2}$ is reduced as $\Delta f_{\pi/2} = \Delta f_{ac}/(1 + U_{sc}/U_{ac})$
- ➢CBIs driven by the accelerating mode is suppressed.

- ➢Parasitic 0 and π modes can be damped selectively out of CC by an antenna-type damper.

■**Cavity trip rate** ≈ 0.5/cavity/4 months (during 2022ab operation) for the 30 ARES cavities

- ➢**No significant change since the KEKB era.**
- ➢**Very stable for beam operation so far**

ARES

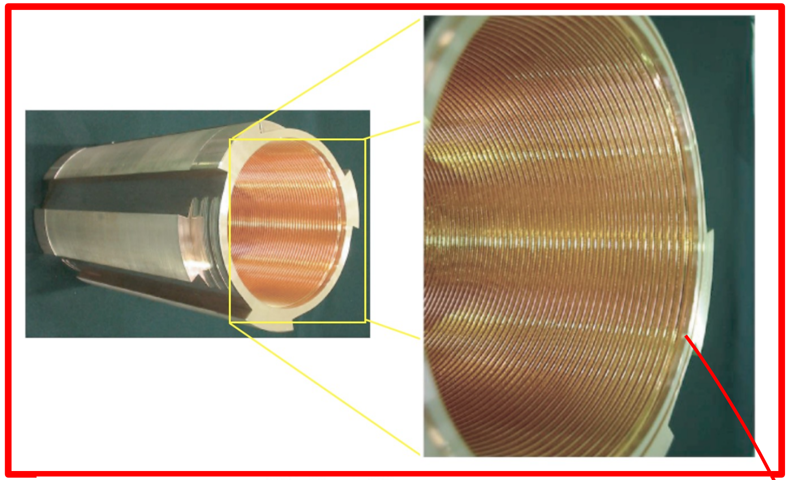
Upgrades of the high-power input coupler for SuperKEKB

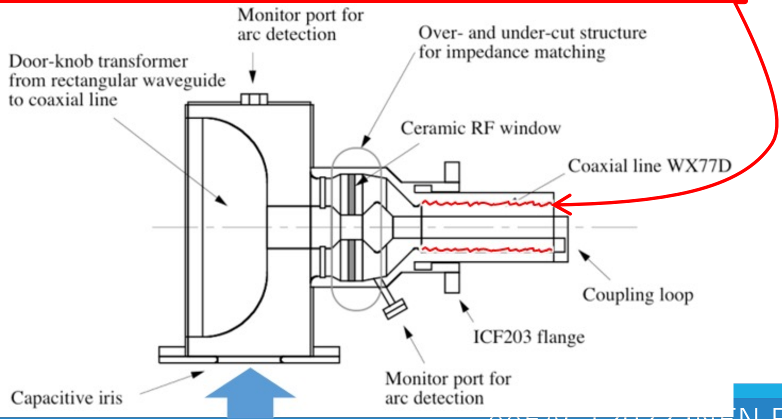
For the higher RF power (400 → 800kW max.) and higher beam currents (< 2A → 3.6A max.)

T. Abe

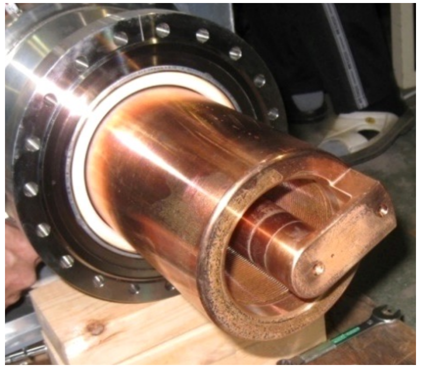
Fine grooving of the coaxial line to completely suppress multipactoring

T. Abe, et al., Phys. Rev. Accel. Beams 13, 102001 (2010)

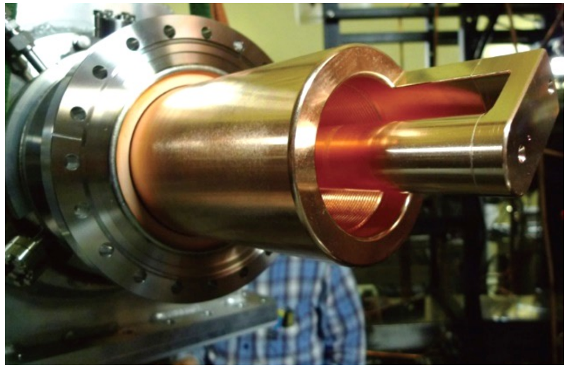




Increased input coupling (β_{max} = 3→6, β_{set} = 5) needed for the stations with the **Kly:Cav=1:1 configuration** to accelerate beams with the design current of LER



Used for KEKB



With an increased input coupling for SuperKEKB

The 14 input couplers used for SuperKEKB beam operation have:

- **the fine-groove structure with no multipactoring observed so far**
- **the increased coupling**

→ No trouble so far

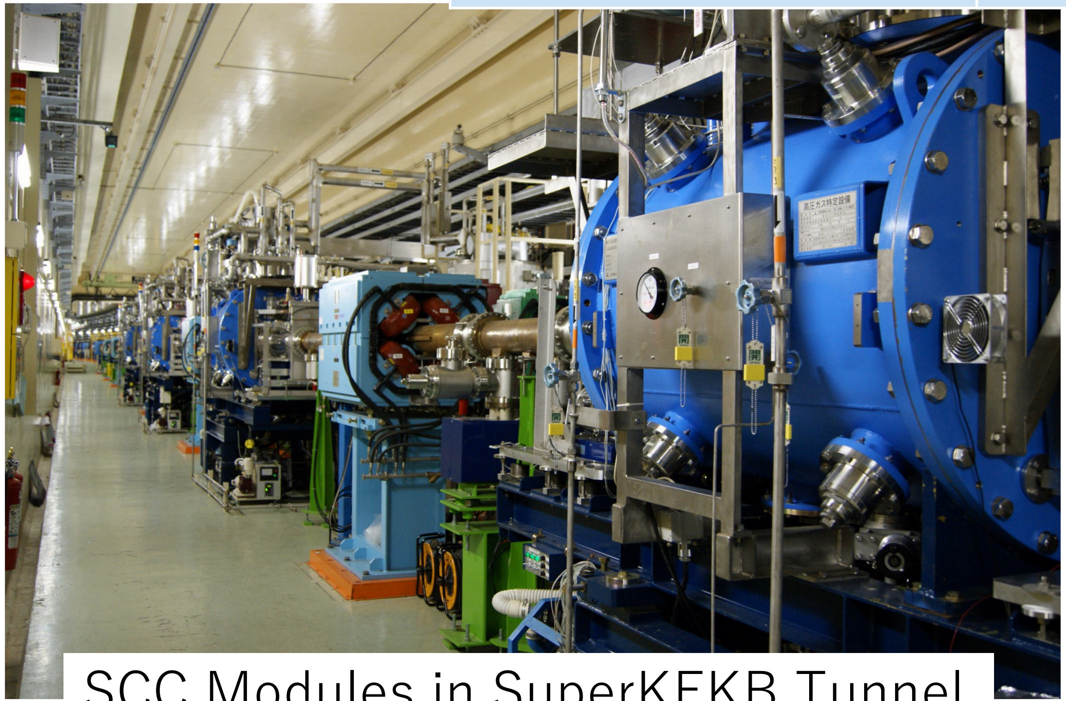
SCC

- 509 MHz Nb Single-cell HOM-damped Cavity, 4.4 K Operation
- 8 SCC Modules in HER (electron ring)
- Re-use of SRF system of KEKB
- Sharing the beam power and accelerating voltage with ARESs by giving phase-offset
- 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**
  - 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**

Resent Operation Status (Trip rate)

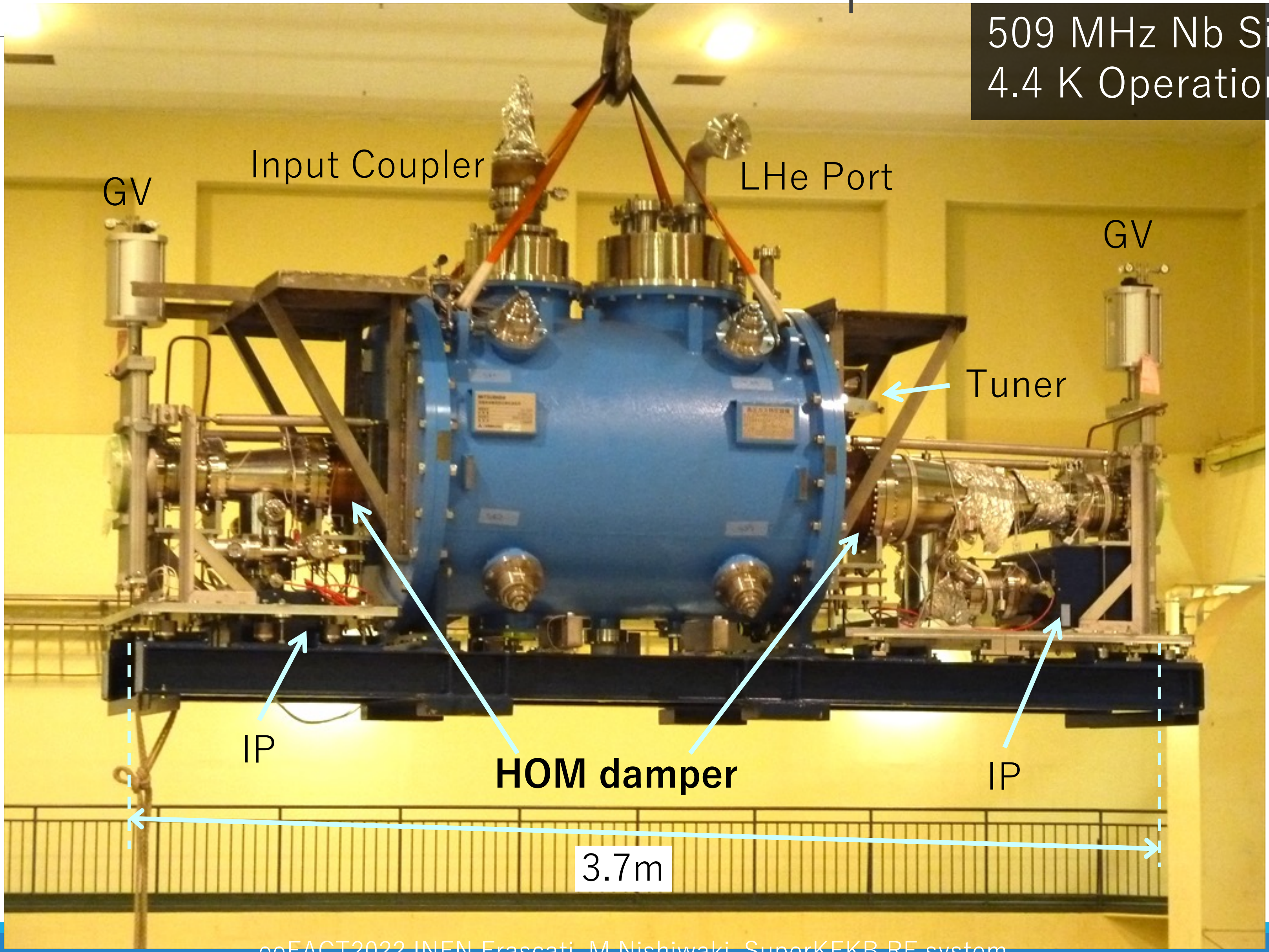
- Very stable beam operation
- **Trip rate : 1.1/cavity/4 months(2022ab)**
  (except due to LLRF and High-power system)
- By discharging in cavity or input coupler and trouble of peripheral devices (chillers, tuners and so on)



SCC Modules in SuperKEKB Tunnel

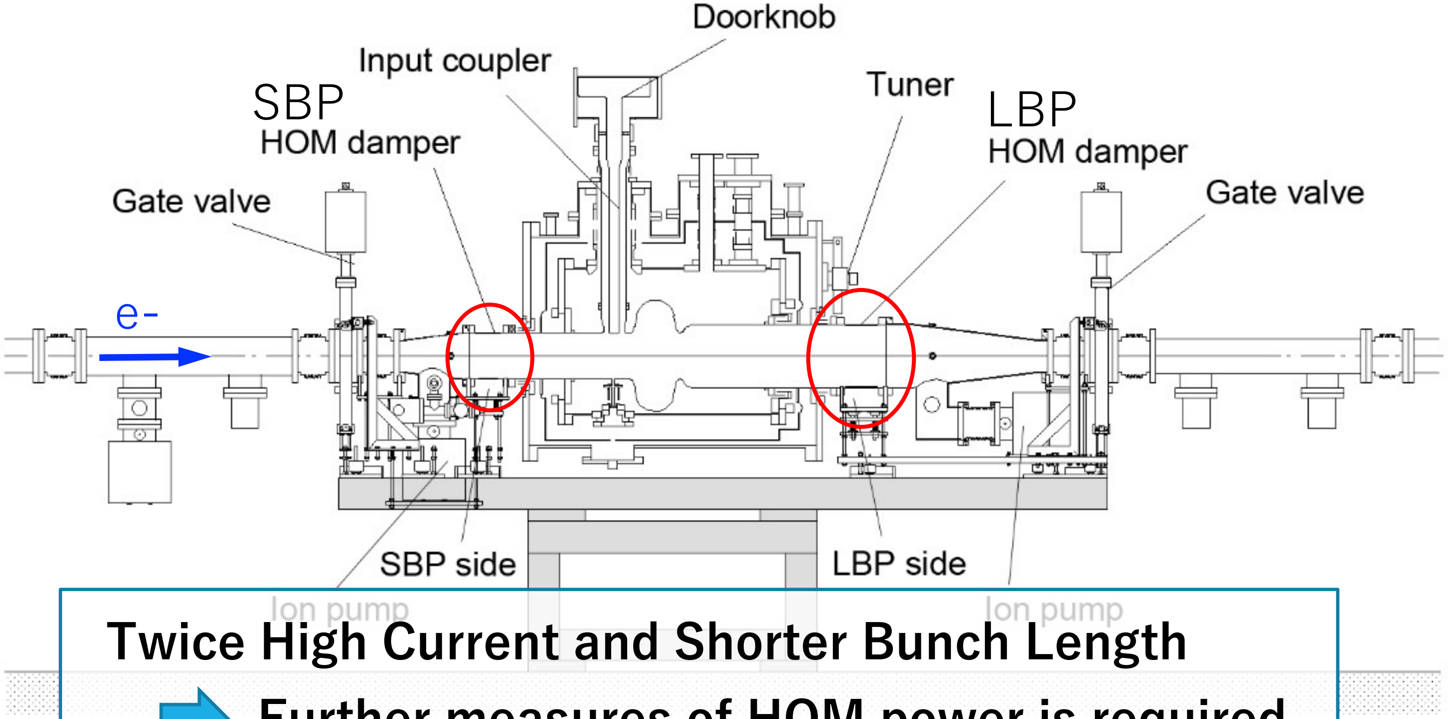
SCC Module of SuperKEKB

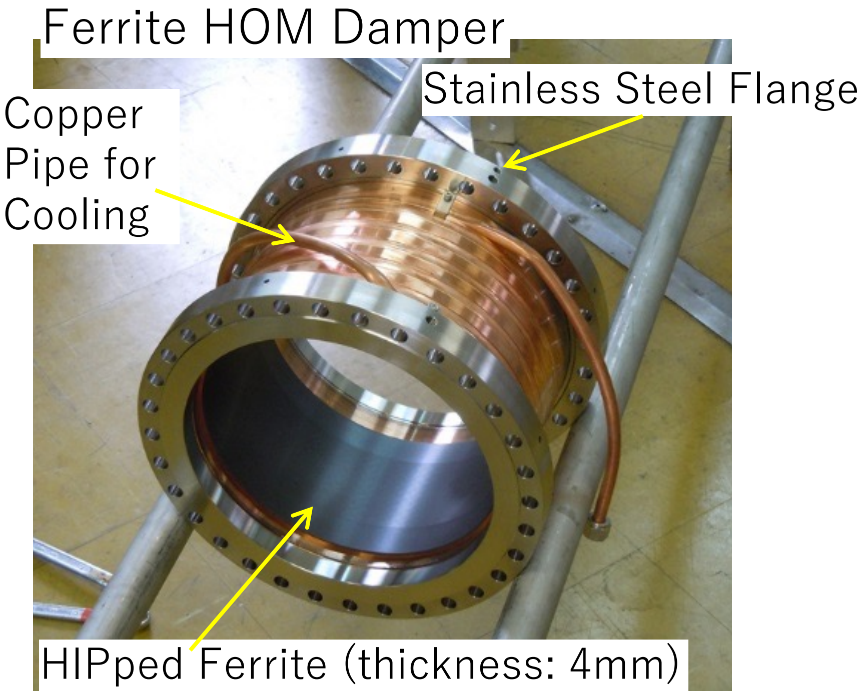
509 MHz Nb Single-cell Cavity
4.4 K Operation



Existing HOM dampers from KEKB operation

- 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)



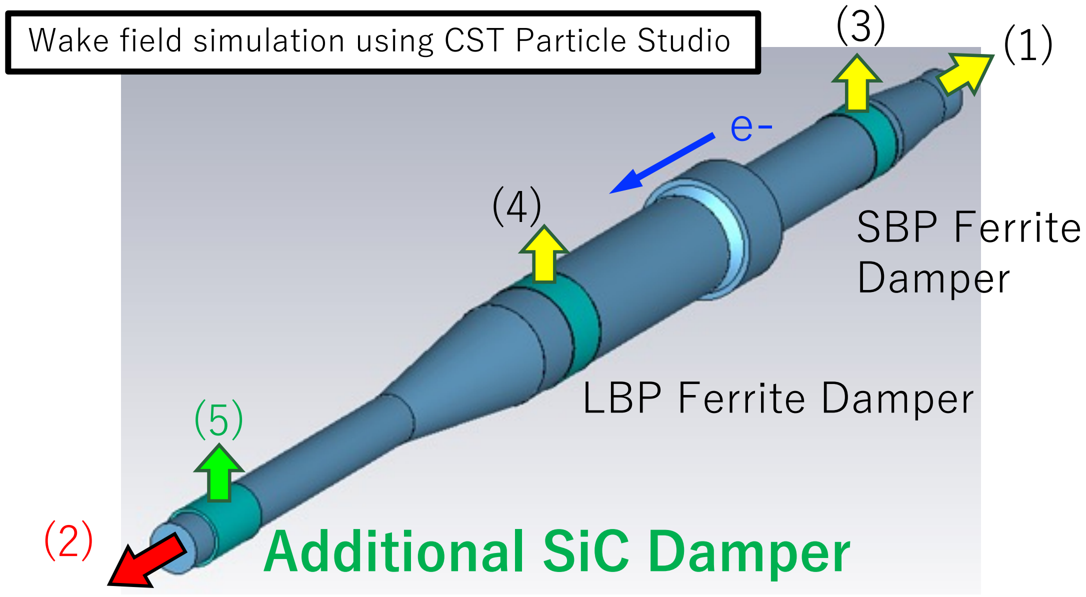


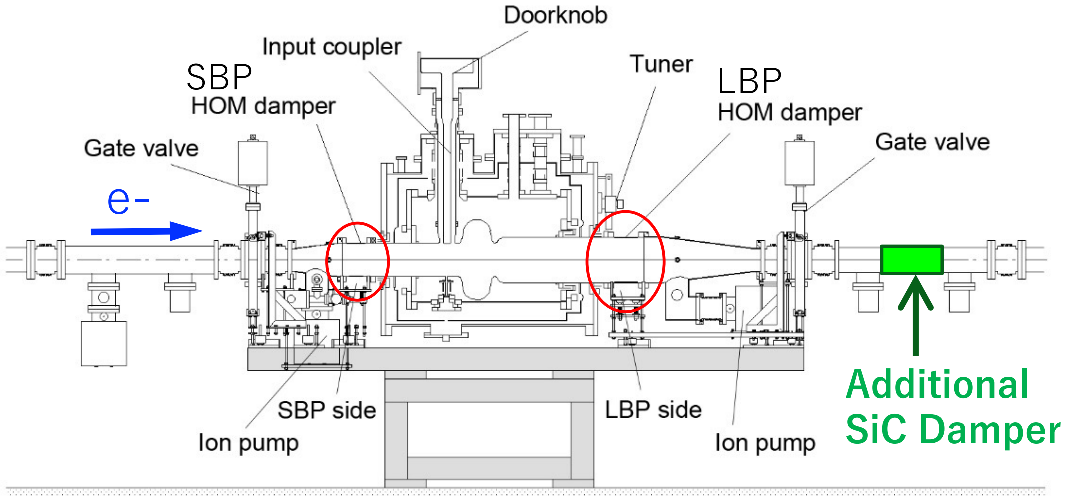
Twice High Current and Shorter Bunch Length

➡ **Further measures of HOM power is required.**

M.Nishiwaki, et al., Proc. of SRF2015, THPB071

Estimation of HOM Power Flow



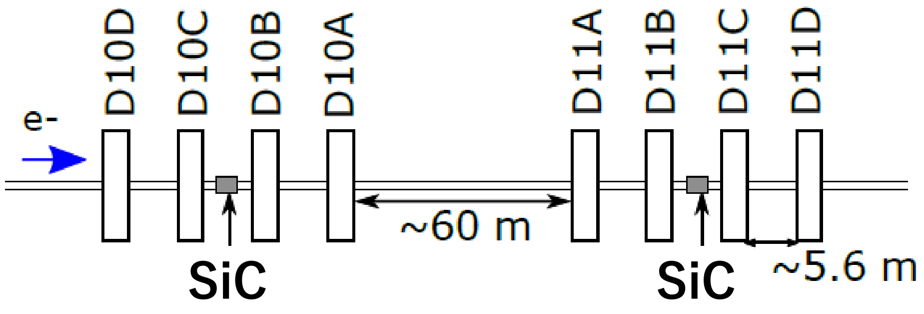


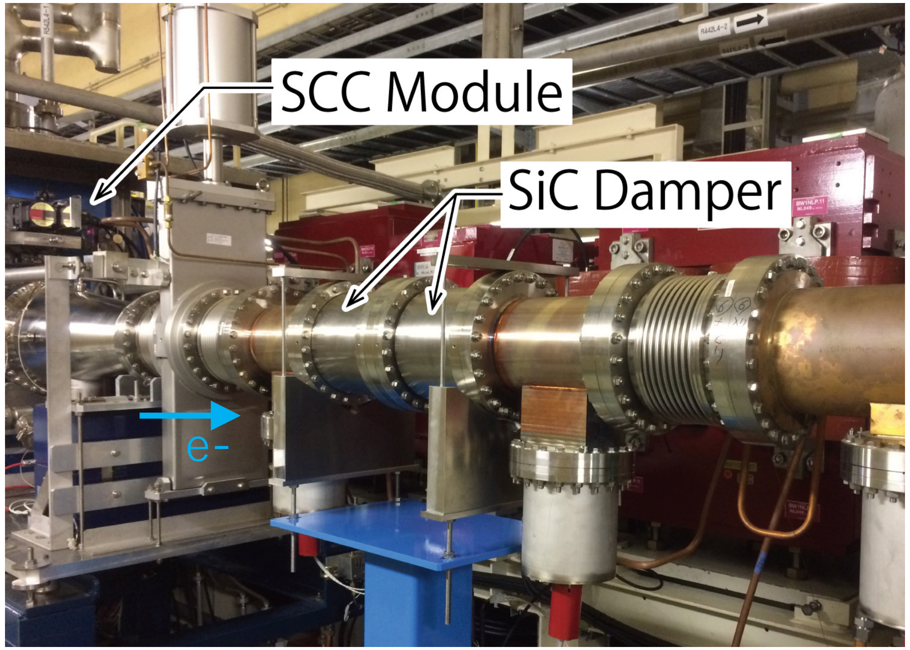
	Eq.LF [V/pC]	HOM Load @2.6A[kW]	Eq.LF [V/pC]	HOM Load @2.6A[kW]
(1) Emit into upstream	0.05	1.3	0.05	1.4
(2) Emit into downstream	0.58	15.7	0.15	4.0
(3) Abs. by SBP Ferrite	0.32	8.6	0.35	9.5
(4) Abs. by LBP Ferrite	0.43	11.7	0.47	12.8
Total	1.38	37.4	1.02	27.7
(5) Abs. by additional SiC	--	--	0.97	26.1

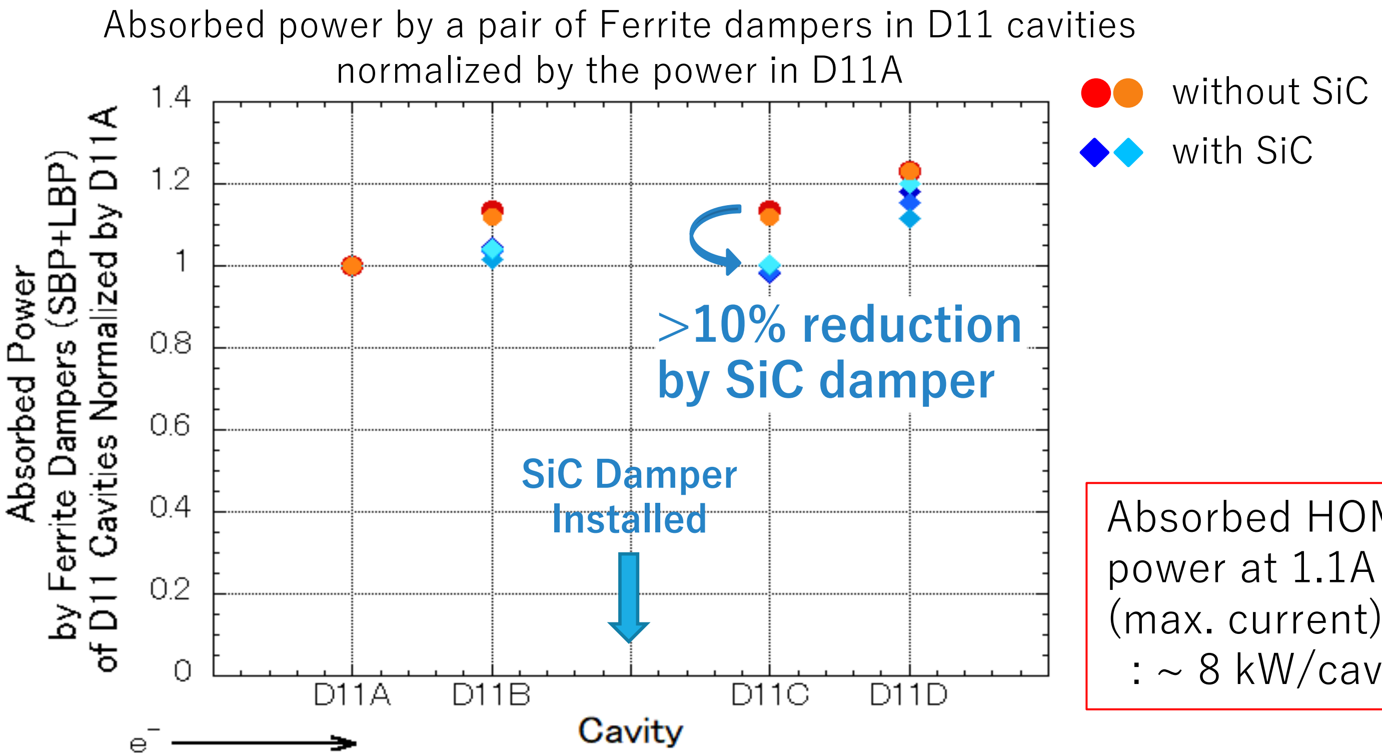
- Loads of SBP(3) and LBP(4) ferrite dampers are not large.
- Large HOM power is emitted through the downstream beam pipe(2).
- The emitted power becomes the load of the downstream cavity.
- **Additional SiC damper**(5) can absorb enough emission power. **The emission power is reduced to one-third.**
- SiC damper can be installed without vacuum breaking of the cavity.

Results of Beam Test with SiC Damper

Layout of 8 SCCs and SiC dampers







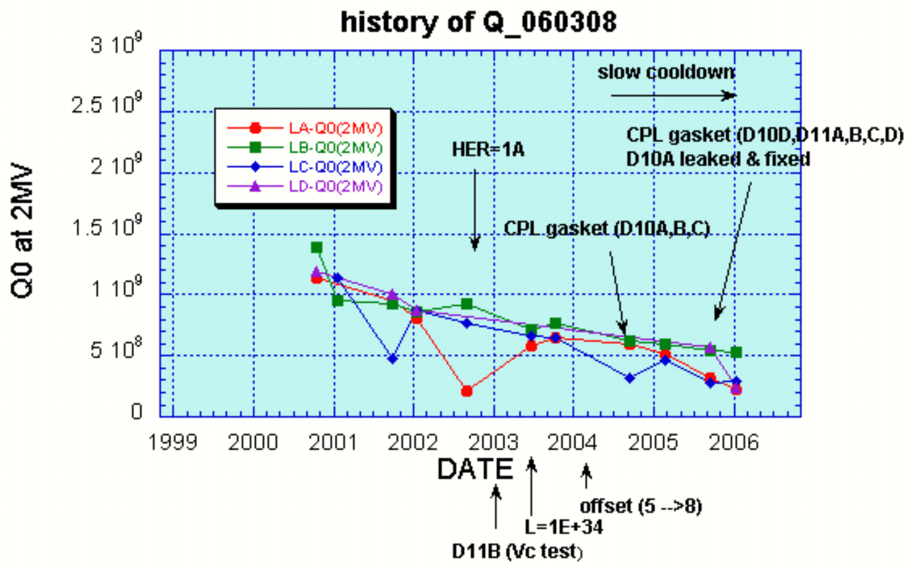
Absorbed HOM power at 1.1A (max. current) : ~ 8 kW/cavity

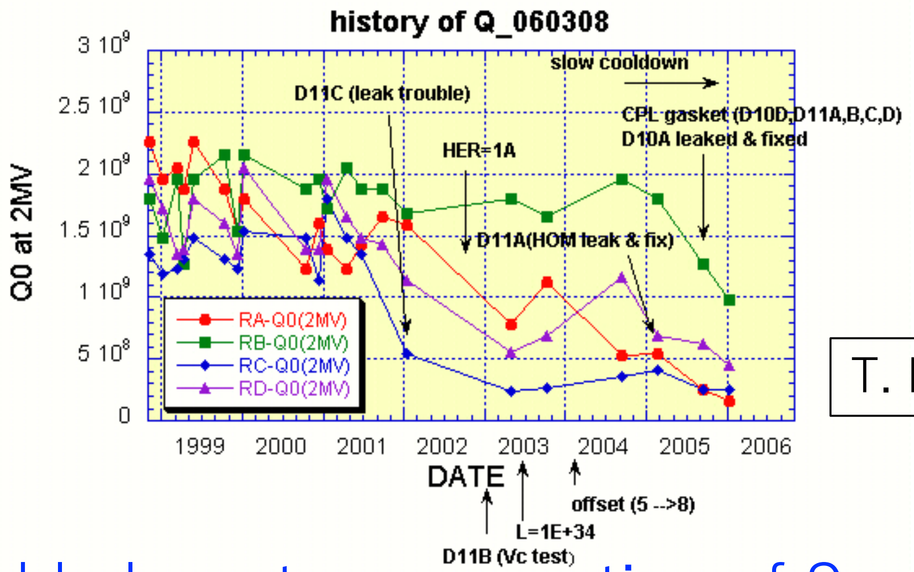
Two set of SiC dampers have been installed to SCC section for beam test. **The HOM power absorbed by the ferrite dampers of downstream cavities (D11C in plot) were reduced >10% after SiC damper installation.** It was confirmed that the additional SiC damper is effective to reduce the load of downstream cavities. For the future high current operation, SiC dampers will be installed to all SCC modules.

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.





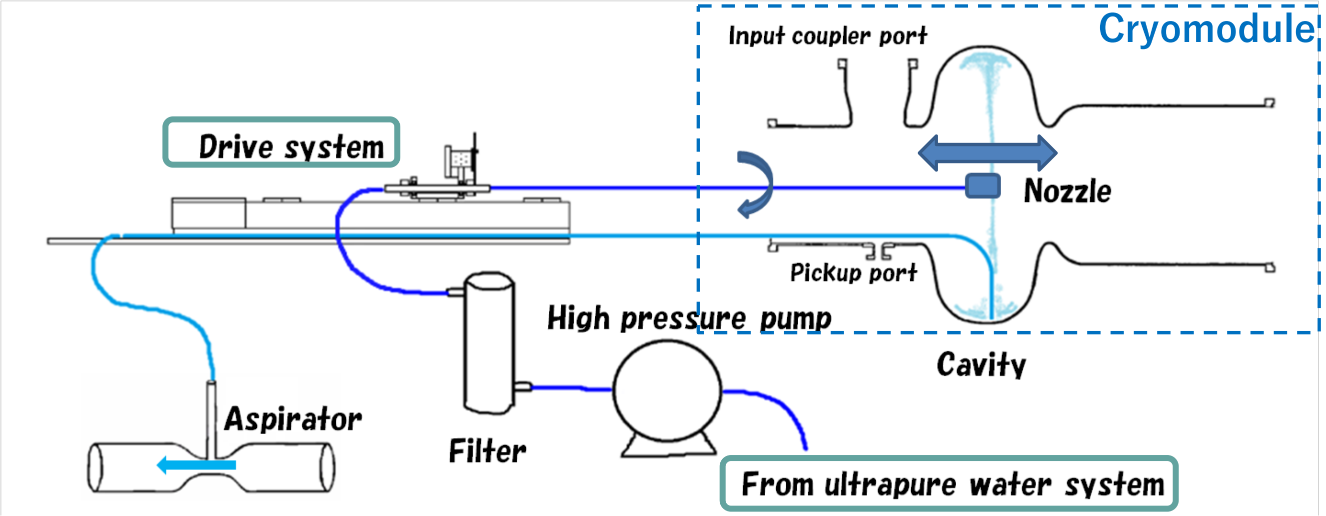
T. Furuya

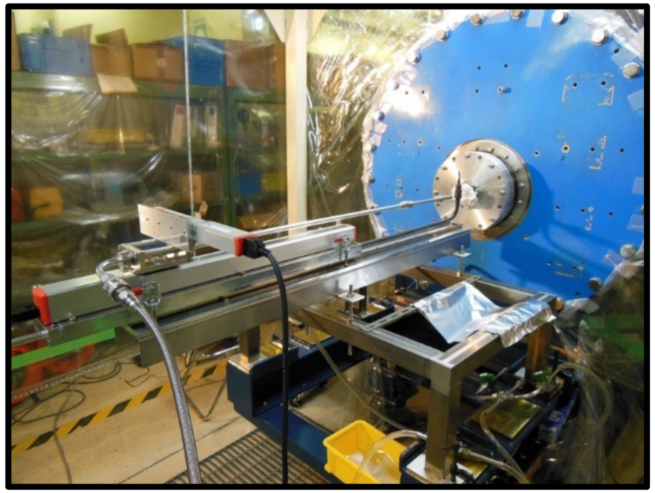
Performance recovery is desirable for stable long-term operation of SuperKEKB.

Y.Morita, et al., Proc. of SRF2015, MOPB116

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.



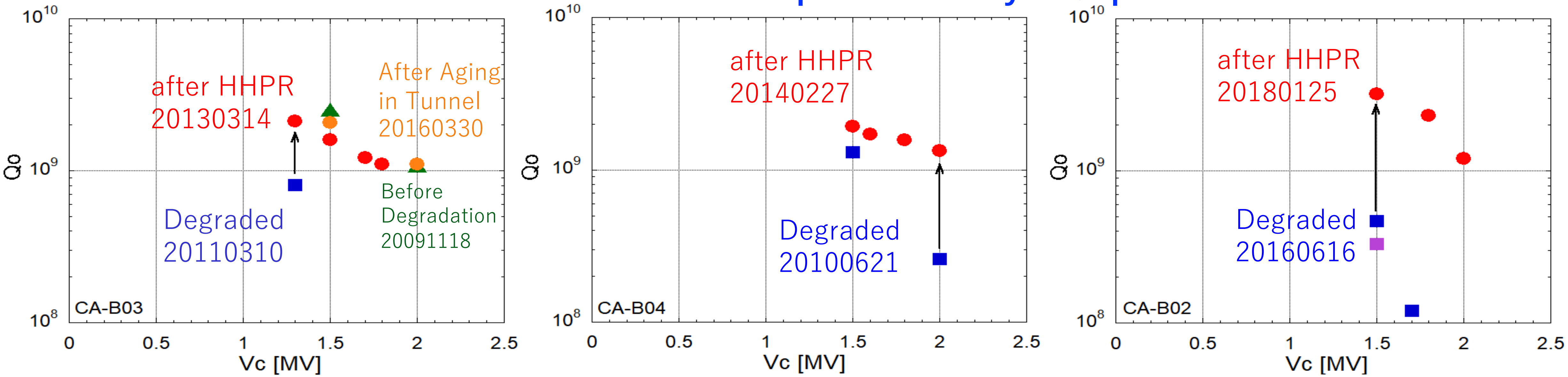


HHPR Parameters	
Water Pressure	7 MPa
Nozzle	ϕ0.54mm x 6
Driving speed	1 mm/sec.
Rotation speed	6 deg./sec.
Rinsing time	15 min.

Y.Morita, et al., Proc. of SRF2015, MOPB116

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.

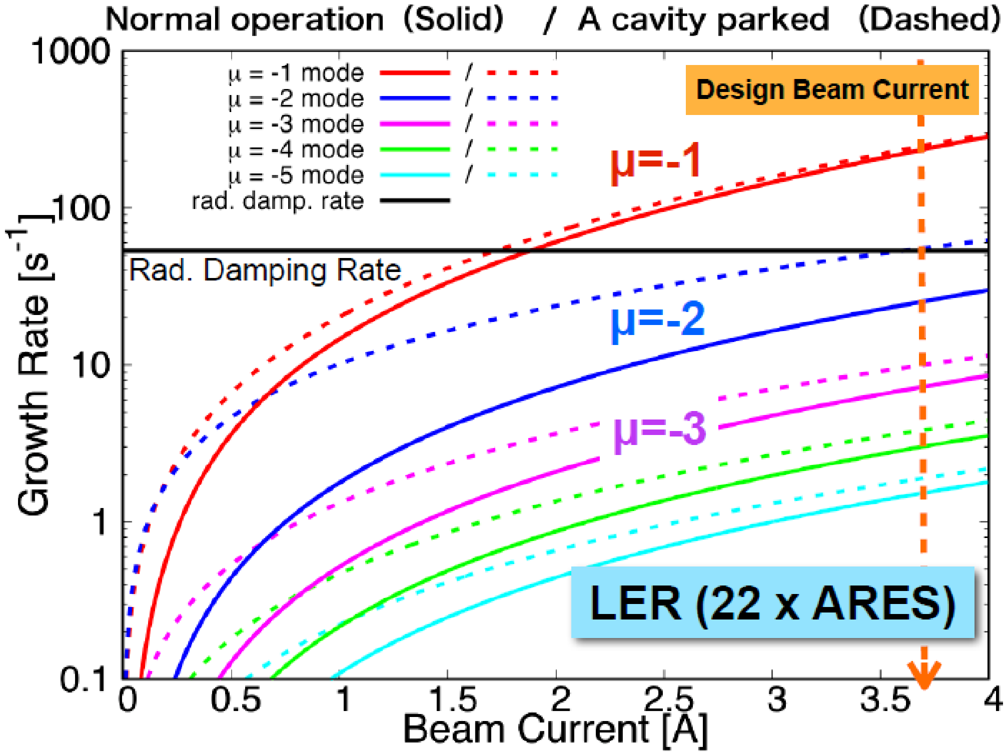
High Beam Current-related issues in RF system

- In RF system of SuperKEKB, some systems to cope with instabilities due to large beam current are working well.
- Coupled Bunch Instability (CBI) due to HOM
  - ➢ARES and SCC are designed as HOM-damped structure with HOM absorbers.
  - ➢Additionally, a bunch-by-bunch feedback system is effective.
- Coupled Bunch Instability (CBI) due to accelerating mode
  - μ =-1, -2 and -3 modes
    - ➢New CBI damper system
  - Zero-mode related to Robinson stability
    - ➢Direct RF feedback (DRFB)
    - ➢Zero-mode damper (ZMD)
- Bunch Gap Transient
  - ➢Propose the measures to mitigate the phase difference

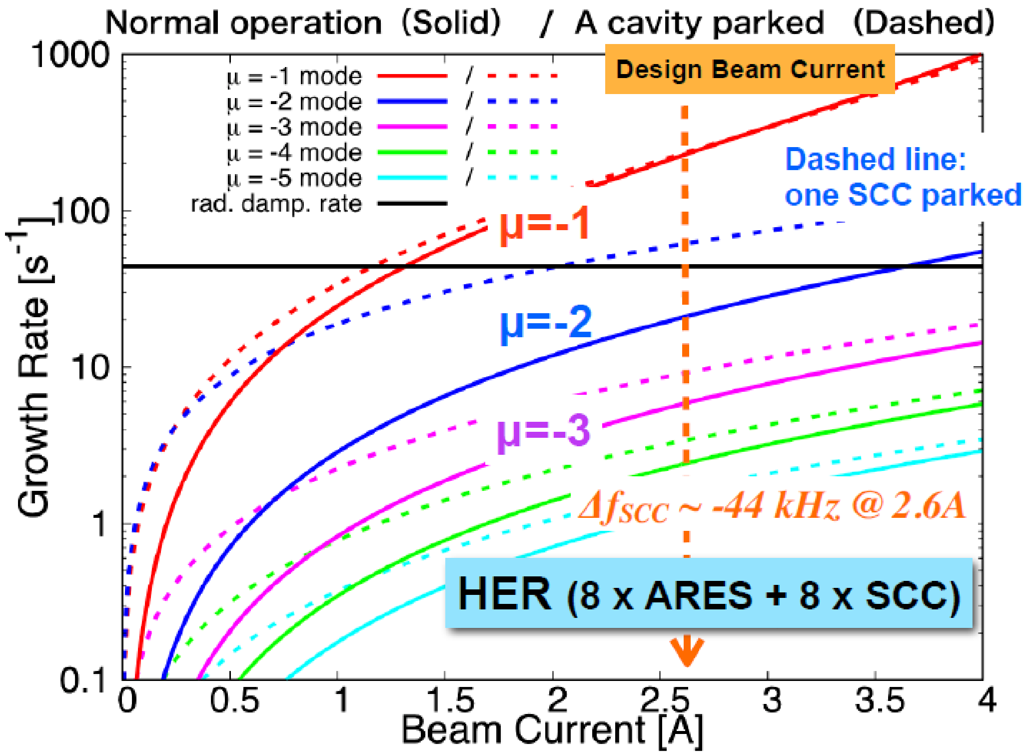
K. Hirosawa et al., Nucl. Instrum. Methods. Phys. Res. A 951, 163044, 2019.

Estimation of the growth rates of CBI

LER



HER

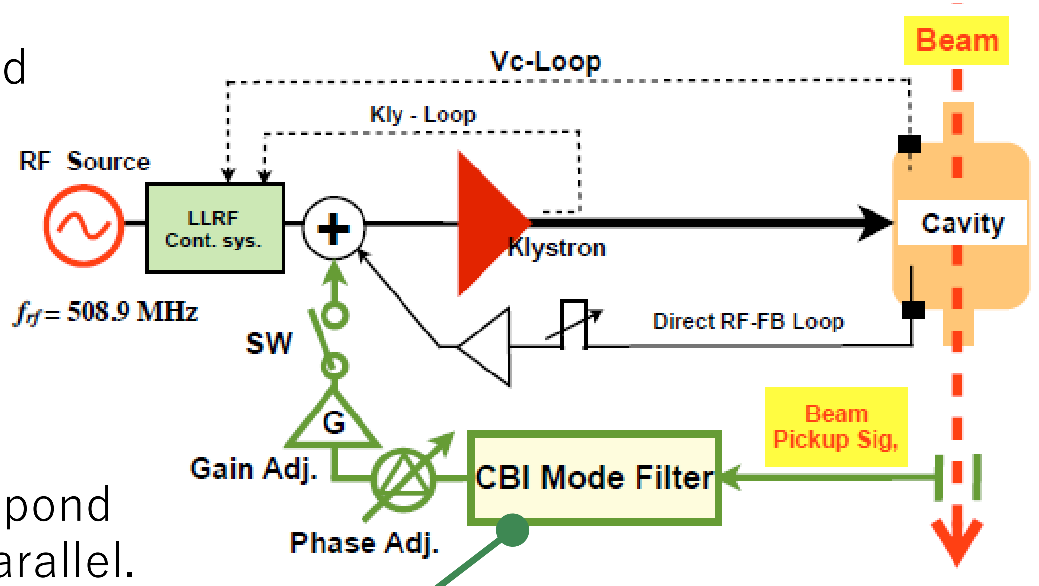


Threshold currents for μ=-1 mode are quite below the design current.
When there are parked cavities, μ=-2 mode also has no margin.
New CBI damper system has been developed and installed.

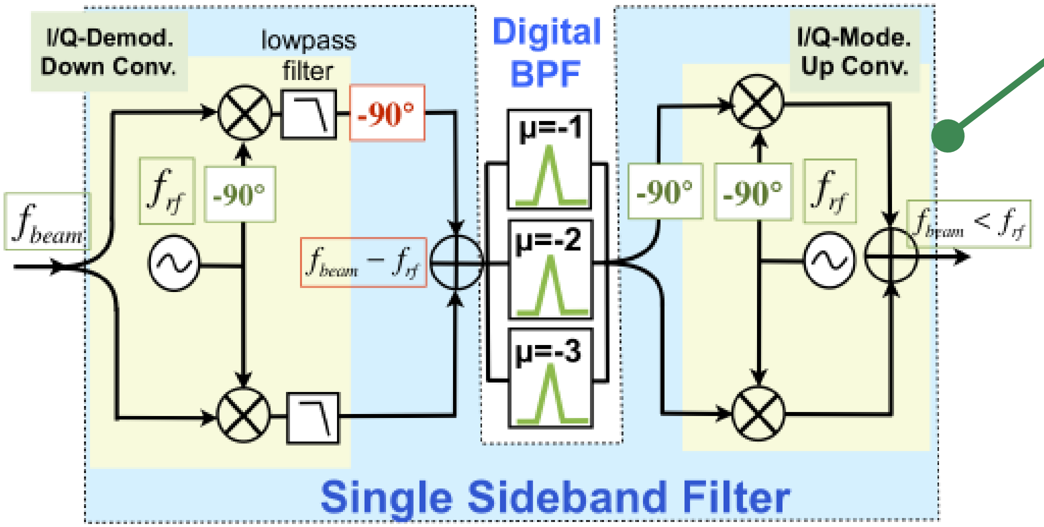
K. Hirosawa et al., Nucl. Instrum. Methods. Phys. Res. A 951, 163044, 2019.

CBI damper system

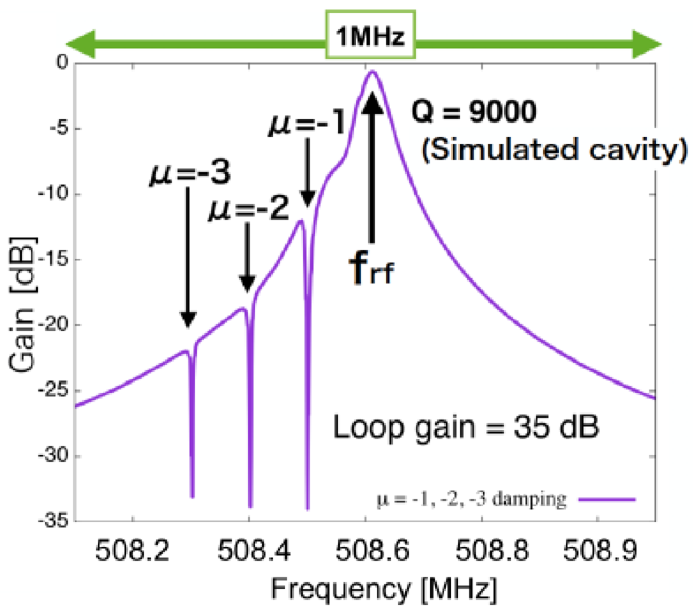
The damper system is installed to ARES station with digital LLRF system.



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



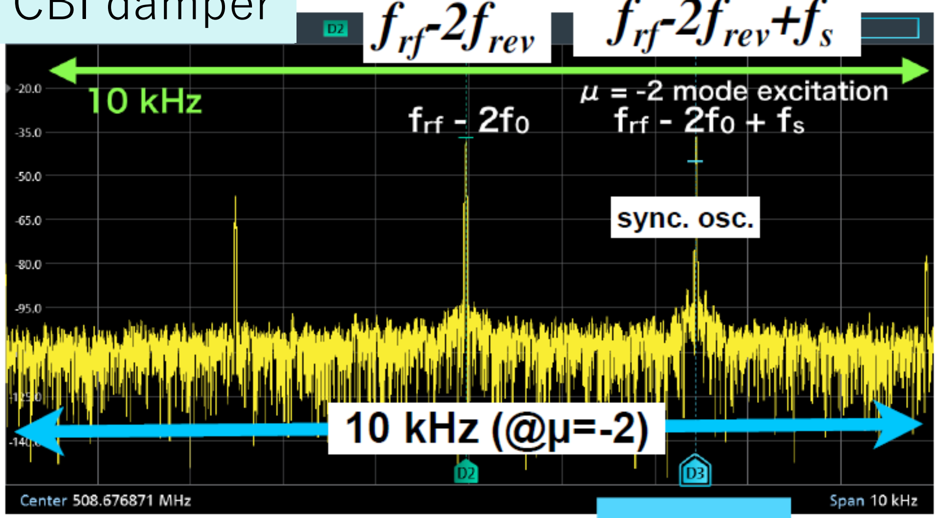
Frequencies correspond μ =-1, -2 and -3 modes are racked successfully.

The new CBI damper system is working in SuperKEKB LER and HER.

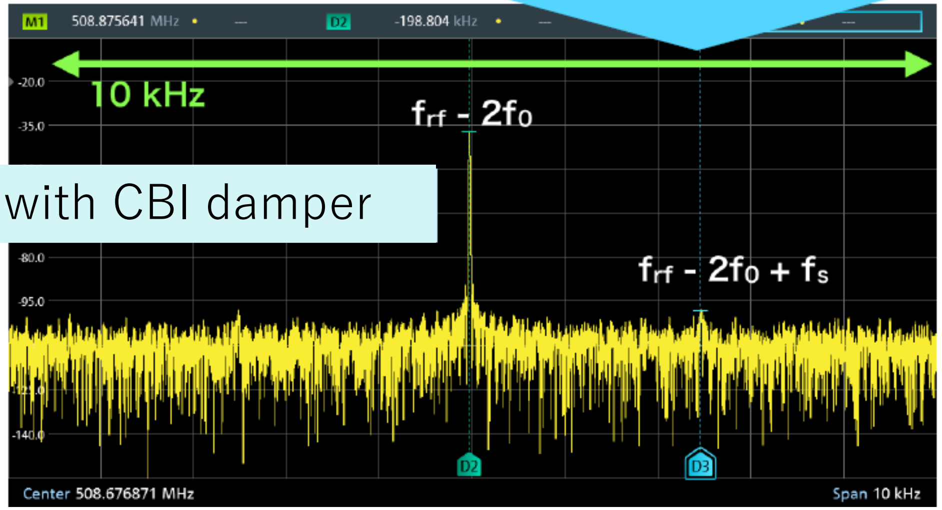
K. Hirosawa et al., Nucl. Instrum. Methods. Phys. Res. A 951, 163044, 2019.

Example of CBI damper operation

without CBI damper



μ=-2 mode was excited purposely by large detuning SCC.



with CBI damper

Peak disappeared by CBI damper.

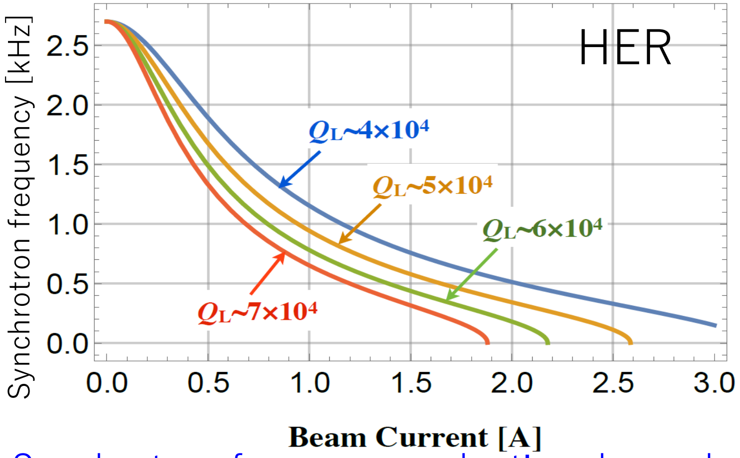
Up to 1.46 A for LER and 1.14 A for HER,
CBI is not a problem with this damper systems.

K.Akai, et al., Proc. of PASJ2022, P320.

Zero-mode stability related to Robinson stability

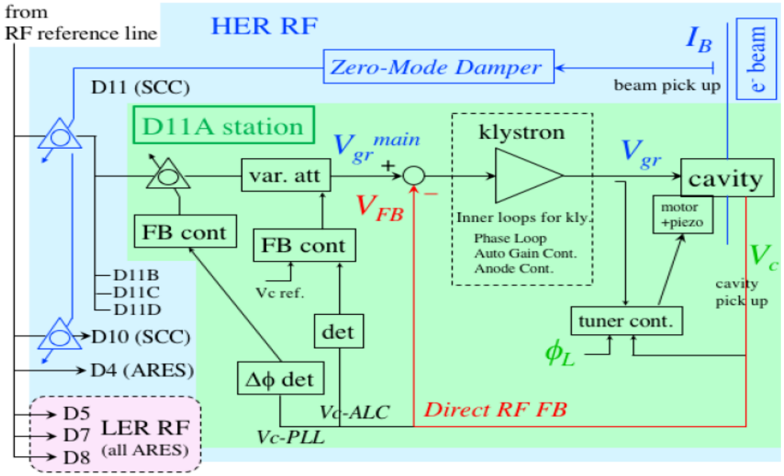
- In high current operation, synchrotron frequency reduction is expected due to coherent oscillation (zero-mode).
- To mitigate the beam-loading effect, Direct RF feedback (DRFB) and Zero-mode damper (ZMD) are working.

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



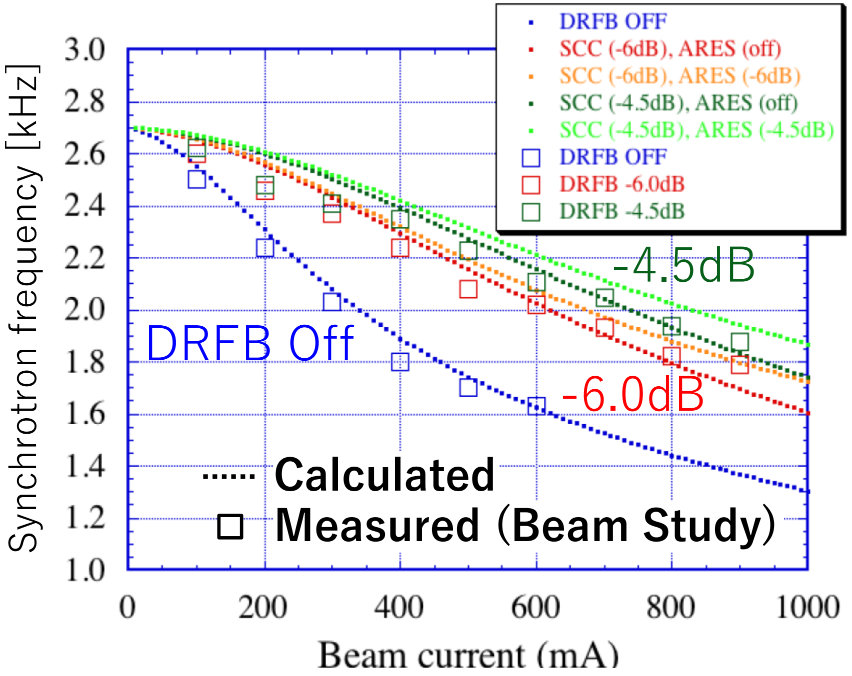
Synchrotron frequency reduction depends on Q_L. But, changing Q_L of SCC should be avoided due to the need for vacuum work and the risk of surface contamination.

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 current 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 is not a problem with the DRFB and ZMD so far.

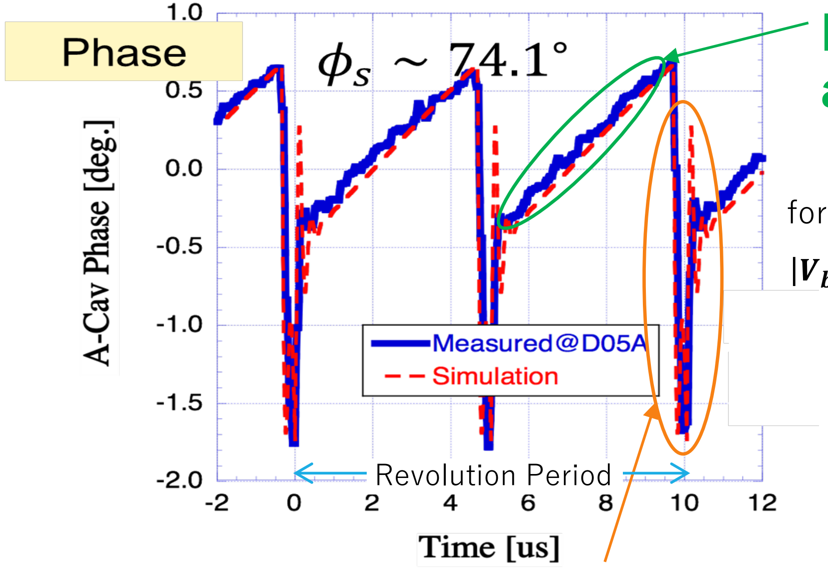
T.Kobayashi and K.Akai, Phys. Rev. Accel. Beams 19, 062001, 2016.

Calculation and measurement of Bunch Gap Transient

- The bunch gap modulates the amplitude and phase of the accelerating cavity field.
- The longitudinal synchronous position is shifted bunch-by-bunch along the train. It is meaning that the collision point of each bunch is shifted.
- Although this effect has not yet become a major problem, it will be a loss of luminosity.

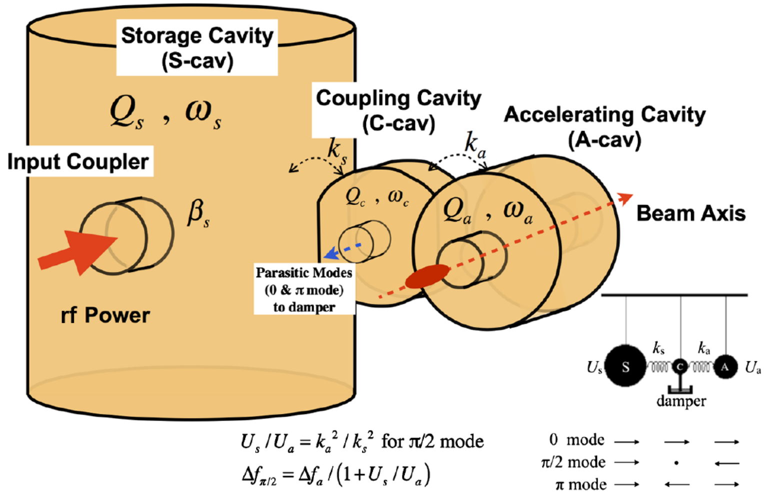
Calculation and measurement of phase change in ARES A-cavity (LER, 1A, 2gaps)

$\Delta f \sim -102[\mathrm{kHz}](\mathrm{including} - 5°\mathrm{offset})$



Phase modulation along train

Rapid phase change at bunch gap



for simulation

$$|V_b| = I_b Q_a \left(\frac{R}{Q}\right)_a = I_b Q_a \left(\frac{R}{Q}\right)\left(\frac{U_{tot}}{U_a}\right)$$

➢ The rapid phase change is attributed to the parasitic 0 and pi mode of ARES.

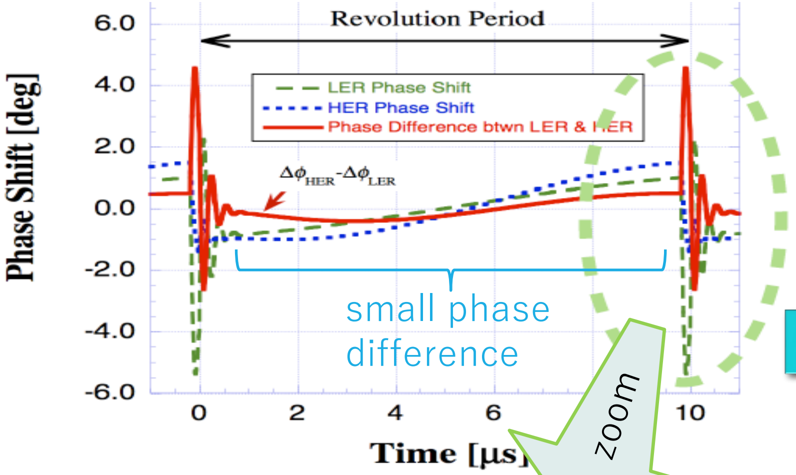
➢ **The feed-forward control cannot be available in our RF system** for the measures to reduce the phase modulation due to the gap transient, because the **klystron performance (bandwidth ~100kHz, output power) is not enough** to cancel the rapid phase modulation.

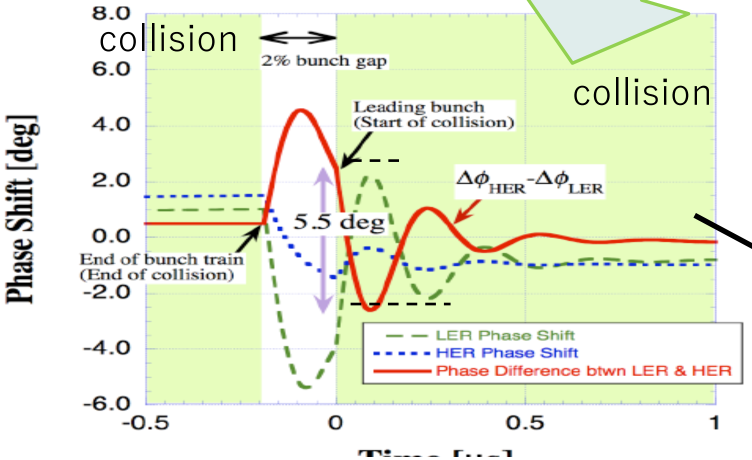
T.Kobayashi and K.Akai, Phys. Rev. Accel. Beams 19, 062001, 2016.

Estimation of phase difference between LER and HER ($\Delta\phi_{HER} - \Delta\phi_{LER}$)

Calculation at design beam currents with 1 gap

Smaller phase difference
→ Smaller loss of luminosity

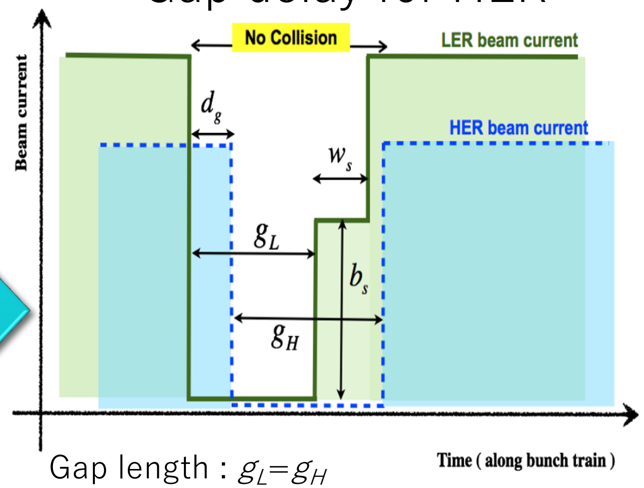




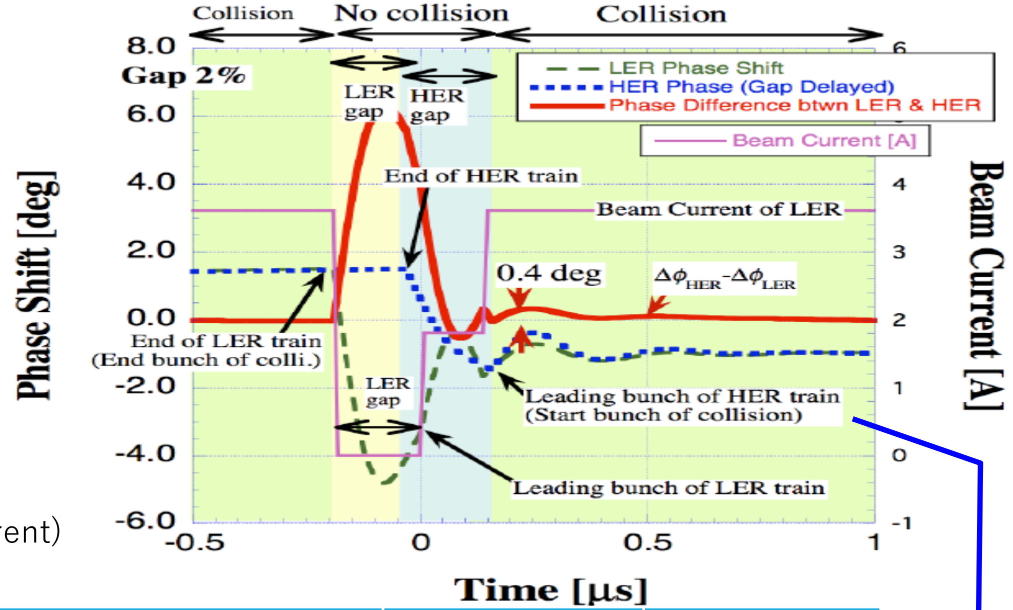
Large phase difference at leading part of collision

Simulation study to mitigate the phase difference

- Change filling pattern at leading part of LER (with step)
- Gap delay for HER



Gap length : $g_L = g_H$
LER step height : b_s (half of nominal current)
HER delay : d_g , LER step length : w_s



Mitigation Method	Bunch gap $g_L = g_H$	HER delay d_g	Relative phase difference $\lvert\Delta\phi_{HER} - \Delta\phi_{LER}\rvert$ [deg.] Leading Part	Relative phase difference Along Train	Longitudinal displacement @IP (σ_z=5mm)	Rate of num. of colliding bunches
No care	**2%**	**no delay**	**5.5**	**0.9**	**0.44 σ_z**	**-**
HER delay Only	2%	200ns	2.4	0.9	0.19 σ_z	-2%
	3%	300ns	<0.2	1.6	0.13 σ_z	-4%
LER step + HER delay	**2%**	**160ns**	**0.4**	**0.5**	**0.07 σ_z**	**-1.6%**

Summary

- SuperKEKB is steadily increasing the beam current and continues to update own luminosity record.
- RF system of SuperKEKB is operating stably at large beam currents of 1.14 A for HER and 1.46 A for LER.
- ARES and SCC systems work stably with low trip rates.
- It is confirmed that additional SiC HOM dampers for SCC reduce HOM load of ferrite dampers of downstream cavities. In the future, SiC dampers will be installed to downstream of all cavities.
- To control instabilities, such as CBI and coherent oscillation due to large beam current, CBI damper, DRFB and ZMD are working well.
- Mitigation method of the beam phase difference between LER and HER due to bunch gap transient effect is proposed: the relative phase change at IP can be reduced by optimization of the gap delay and bunch fill pattern.

Thank you for your attention!